Symmergent Gravity and Ultraviolet Stability

Durmuş Demir
Department of Physics, İzmir Institute of Technology, TR35430, İzmir, Turkey

Abstract

In this talk, I discuss how gravity can emerge in a way restoring the gauge symmetries that are explicitly broken by the UV cutoff, and show how this symmergent gravity kills the destabilizing UV sensitivity of the Standard Model. I also show that physics beyond the Standard Model is necessary for inducing the gravitational constant. It does not have to interact with the SM but it can. The resulting setup is in broad agreement with the existing collider, astrophysical and cosmological searches. The right-handed neutrinos are predicted to weigh below a 1000 TeV.

Keywords: Emergent Gravity, Hierarchy Problem, Physics Beyond the SM.

1. INTRODUCTION

The Standard Model (SM), a spontaneously broken renormalizable quantum field theory (QFT) of the strong, electroweak and inertia (through the Higgs field H) interactions, has shown good agreement with all the experiments performed so far [1, 2]. It describes physics at the electroweak scale $\Lambda_W \approx 246.2\,\text{GeV}$. It excludes gravity, that is to say, it lives exclusively in flat spacetime.

In spite of its phenomenological successes, the SM is far from being a complete theory. This is because it is plagued by enigmatic problems like destabilizing UV sensitivities [3], exclusion of gravity [4], absence of cold a dark matter candidate (CDM) [5], and oscillations of neutrinos [6]. These problems cannot be addressed without new physics beyond the SM and, on phenomenological grounds, it is not difficult to anticipate that

$$\text{new physics} = \underbrace{\text{gravity}}_{GR} + \underbrace{\text{a QFT beyond the SM containing right-handed neutrinos } (BSM)}_{\text{feebly interacting}} \tag{1.1}$$

where general relativistic (GR) structure of gravity is set by the working LCDM model of the universe [7], and feebly interacting nature of the BSM sector is hinted at by negative results at colliders and other searches [2, 7, 8, 9].

It is by macroscopic reality that incorporation of GR into the SM is foremost among all the problems plaguing the SM. In fact, inconsistency of the classical GR [10] and unavailability of quantized GR [11, 12] can be taken to imply that the whole process of incorporation is actually emergence of GR upon the SM + BSM setup. The way GR emerges depends on the underlying mechanism [13] as is known, for instance, from Sakharov's induced gravity [14].

Voiced in this talk is a new mechanism [15, 16, 17] in which gravity, in stark contrast to those in the literature [13], emerges in a way restoring gauge symmetries that are explicitly broken by the UV cutoff [18]. It is for its symmetry-driven, emergent nature that it is called *symmergent gravity*. It leads to a curved spacetime QFT wherein

1. destabilizing UV sensitivities disappear in agreement with the measured Higgs boson mass [19],
2. symmergent gravity, devoid of any higher-curvature terms, conforms to the observed LCDM structure [7],
3. non-interacting CDM becomes a potential possibility as confirmed by negative searches [9],
4. new particles in the TeV domain stop being a necessity as encouraged by the current LHC data [2],
5. and finally, right-handed neutrinos are to have masses below 1000 TeV reminding previous determinations [20].

The following sections give hows, whys and whats of these points.

2. DESTABILIZING UV SENSITIVITIES OF THE SM

If the ATLAS and CMS experiments have revealed anything other than the Higgs boson it is that the SM holds good up to several TeVs [2]. This is the energy reach at the LHC. It will get higher and higher at future colliders of higher and higher energy. It separates the known physics below from the unknown physics above. One known thing about the unknown physics is that the field-theoretic structure describing it, the SM or the SM plus some BSM, must come to a halt at some UV boundary Λ_U. This field-theoretic end point, a genuinely physical scale rather than a regularization tool, must exist to seed the Planck mass $M_{Pl} \approx 2.4 \times 10^{18}$ GeV upon the emergence of gravity.

In general, what is tested at a collider of energy reach Λ_x is the effective QFT below Λ_x. This is true also for the LHC, which seems to have found merely the particles and couplings of the SM within the resolving power of 30 fb^{-1} luminosity. This experimental result, despite its attest of the SM around Λ_x, can tell nothing about high energies especially when the BSM is scale-separated. In this case, a prudent approach would be to let the SM reign everywhere up to Λ_u, study the effective SM below Λ_w, and determine the ignored BSM through physical consistency. In this context, in terms of frequency E, integration of the fast modes $\psi_{\Lambda_W<E<\Lambda_U}$ out of the SM leads to a QFT of the slow modes $\psi_{E<\Lambda_W}$, where ψ collectively denotes all the leptons and quarks as well as the Higgs and gauge bosons in the SM. This low-energy QFT is described by the SM effective action

$$\begin{aligned} S_{eff}\left(\eta,\psi,\frac{\Lambda_W}{\Lambda_U},\Lambda_U^2-\Lambda_W^2,\Lambda_U^2+\Lambda_W^2\right) &= S_{tree}\left(\eta,\psi\right)+\delta S_{log}\left(\eta,\psi,\log\frac{\Lambda_W}{\Lambda_U}\right) \\ &+ \delta S_O\left(\eta,\Lambda_U^2-\Lambda_W^2,\Lambda_U^2+\Lambda_W^2\right)+\delta S_H\left(\eta,H,\Lambda_U^2-\Lambda_W^2\right)+\delta S_V\left(\eta,V,\Lambda_U^2-\Lambda_W^2\right) \end{aligned} \quad (2.1)$$

in which $\eta_{\mu\nu}$ is the flat metric, $\psi \equiv \psi_{E<\Lambda_W}$ are the slow SM fields, $H \equiv H_{E<\Lambda_W}$ is the slow Higgs field, and$V_\mu \equiv V_{\mu\, E<\Lambda_W}$ are the slow gauge fields (photon, gluon, W and Z). These fields, whose wavelengths are longer than $1/\Lambda_w$, interact via loop-induced couplings of varying UV sensitivity.

The IR scale Λ_w and the UV scale Λ_u appear in the SM effective action S_{eff} in three distinct combinations. The first

$$\frac{\Lambda_W}{\Lambda_U} \quad (2.2)$$

is the IR/UV hierarchy, which must be preserved for gauge/gravity hierarchy to form correctly upon the incorporation of gravity. The second

$$\Lambda_U^2+\Lambda_W^2 \quad (2.3)$$

is the highest scale in the setup, and it must be what sets M_{Pl} while gravity emerges. The third

$$\Lambda_U^2-\Lambda_W^2 \quad (2.4)$$

is the UV-IR splitting, which is hard to make sense at this stage but, as will be shown in the sequel, it seeds the spacetime curvature. It is these three combinations that make the effective SM to sense the UV boundary differently in different sectors. The tree-level SM action S_{tree} and the logarithmic corrections δS_{log} both lie at the Fermi scale. But, the other three

$$\delta S_O = -\int d^4x\sqrt{-\eta}\, c_O\!\left(\frac{\Lambda_W}{\Lambda_U}\right)(\Lambda_U^2-\Lambda_W^2)(\Lambda_U^2+\Lambda_W^2) \quad (2.5)$$

$$\delta S_H = -\int d^4x\sqrt{-\eta}\, c_H\!\left(\frac{\Lambda_W}{\Lambda_U}\right)(\Lambda_U^2-\Lambda_W^2)H^\dagger H \quad (2.6)$$

$$\delta S_V = \int d^4x\sqrt{-\eta}\, c_V\!\left(\frac{\Lambda_W}{\Lambda_U}\right)(\Lambda_U^2-\Lambda_W^2)\mathrm{Tr}\Big[V_\mu V^\mu\Big] \quad (2.7)$$

lie at the UV boundary such that their Wilson coefficients c_O, c_H, c_V depend only on the hierarchy in (2.2). It is these UV-born quantum corrections that destabilize the SM. In effect, they give cause to four major problems:

1. The shift in the vacuum energy

$$\delta V = c_O\left(\Lambda_U^2-\Lambda_W^2\right)\left(\Lambda_U^2+\Lambda_W^2\right) \quad (2.8)$$

   inflicted by δS_O varies quartically with the UV scale via the sum (2.3) times the difference (2.4). It poses no problem in flat spacetime but it can give cause to the notorious *cosmological constant problem* [21] depending on how gravity emerges. This indeed is what happens in Sakharov's induced gravity[14].

2. The correction to the Higgs boson mass

$$\delta m_H^2 = c_H\left(\Lambda_U^2-\Lambda_W^2\right) \quad (2.9)$$

   from δS_H varies quadratically with the UV scale through (2.4), and gives cause to the fatal *big hierarchy problem* [3, 22].

3. The change in the gauge boson masses

$$\delta M_V^2 = c_V\left(\Lambda_U^2-\Lambda_W^2\right) \quad (2.10)$$

   due to δS_V varies quadratically with the UV scale through (2.4), and leads to *explicit breaking of color and electromagnetism* [18].

4. The correction to the Higgs boson mass

$$\left(\delta m_H^2\right)_F \propto \lambda_F m_F^2 \log \frac{m_F}{\Lambda_U} \tag{2.11}$$

due a BSM field F with mass m_F and coupling λ_F to the SM fields can destabilize the SM when $\lambda_{HF} m_F^2 \gtrsim \Lambda_W^2$. This problem, the so-called *little hierarchy problem* [23], is caused not by the UV physics but by the mixing between the SM and the BSM.

It is only after the solution of these four problems that the SM can qualify as the working model of physics at the Fermi scale. Their solutions are what this talk is all about.

3. GAUGE INVARIANCE AND EMERGENT CURVATURE

The gauge part δS_V is disastrous. It must be neutralized for color and electromagnetism to be exact and electroweak breaking to be spontaneous. One possible mechanism, which was first proposed in [15, 16] and furthered in [17], neutralizes δS_V by incorporating curvature in a way restoring gauge invariance. To elucidate the mechanism rigorously, the first move is to form the overt identity

$$\delta S_V \left(\eta, V, \Lambda_U^2 - \Lambda_W^2\right) = \delta S_V \left(\eta, V, \Lambda_U^2 - \Lambda_W^2\right) - I(\eta, V) + I(\eta, V) \tag{3.1}$$

in which the gauge-invariant kinetic construct

$$I(\eta, V) = \int d^4x \sqrt{-\eta} \frac{c_V}{2} \mathrm{Tr} \left\{ \eta_{\mu\alpha} \eta_{\nu\beta} V^{\mu\nu} V^{\alpha\beta} \right\} \tag{3.2}$$

is subtracted from and added back to δS_V. This construct, composed of the loop factor c_V and the field strength $V_{\mu\nu}$, conduces to

$$\delta S_V \left(\eta, \Lambda_U^2 - \Lambda_W^2\right) = -I(\eta, V) + \int d^4x \sqrt{-\eta} c_V \mathrm{Tr} \Big\{ V^\mu \left(-D^2 \eta_{\mu\nu} + D_\mu D_\nu + V_{\mu\nu} + \left(\Lambda_U^2 - \Lambda_W^2\right) \eta_{\mu\nu} \right) V^\nu + \partial_\mu \left(\eta_{\alpha\beta} V^\alpha V^{\beta\mu} \right) \Big\} \tag{3.3}$$

if, at the right hand side of (3.1), δS_V is replaced with its expression in (2.7), "$-\, I(\eta, V)$" is kept untouched, and "$+\, I(\eta, V)$" is integrated by-parts in terms of the gauge-covariant derivative D_μ.

The second move is to go from the flat spacetime of $\eta_{\mu\nu}$ to curved spacetime of a putative curved metric $g_{\mu\nu}$. This change, occurring under the auspices of the equivalence principle, is implemented via the generalization

$$\eta_{\mu\nu} \hookrightarrow g_{\mu\nu} \tag{3.4}$$

under which the identity (3.3) takes the form

$$\delta S_V \left(g, \Lambda_U^2 - \Lambda_W^2\right) = -I(g, V) + \int d^4x \sqrt{-g} c_V \mathrm{Tr} \Big\{ V^\mu \left(-{}^{g}D^2 g_{\mu\nu} + {}^{g}D_\mu {}^{g}D_\nu + V_{\mu\nu} + \left(\Lambda_U^2 - \Lambda_W^2\right) g_{\mu\nu} \right) V^\nu + {}^{g}\nabla_\mu \left(g_{\alpha\beta} V^\alpha V^{\beta\mu} \right) \Big\} \tag{3.5}$$

where ${}^{g}D_\mu$ is gauge-covariant derivative with respect to the covariant derivative ${}^{g}\nabla_\mu$ of the Levi-Civita connection ${}^{g}\Gamma^\lambda_{\mu\nu}$. This action is, however, far from complete. The reason is that it lacks the curvature invariants required to make sure that the putative curved metric $g_{\mu\nu}$ is not a mere renaming of the flat metric $\eta_{\mu\nu}$.

The third move is, therefore, incorporation of curvature into (3.5). This matter, not as straightforward as it seems, can be tackled in two distinct ways:

3.1. *Added curvature.*

The first way that comes to mind, which is the standard procedure for carrying classical field theories into curved geometry, is to add appropriate curvature invariants by hand. In this context, the identity (3.5) takes form

$$\widetilde{\delta S}_V \left(g, \Lambda_U^2 - \Lambda_W^2\right) = \delta S_V \left(g, \Lambda_U^2 - \Lambda_W^2\right) - \int d^4x \sqrt{-g} \Big\{ \tilde{M}^2 g^{\mu\nu} R_{\mu\nu} \left({}^{g}\Gamma\right) + \text{ higher-curvature terms} \Big\} \tag{3.6}$$

after adding by hand an Einstein-Hilbert term with fundamental scale $\tilde{M}$ and possible higher-curvature terms. The problem with this action, apart from the persistence of gauge symmetry breaking, is that neither $\tilde{M}$ nor various couplings in higher-curvature terms are calculable. This is because matter loops have all been used up in forming the flat spacetime effective action S_{eff}. There are thus no loops left to induce any extra interaction, with or without curvature. This incalculability constraint, which reveals the difference between classical and effective field theories in regard to their images in curved spacetime, renders (3.6) completely unphysical. It thus follows that adding curvature by hand does simply not work.

3.2. Emergent curvature.

Curvature must be born from an existing mass scale for not to plague (3.5) with unknown, incalculable parameters. It can actually be conjectured to emerge from the single mass scale $\Lambda_U^2 - \Lambda_W^2$ in (3.5) via the generalization

$$\left(\Lambda_U^2 - \Lambda_W^2\right) g_{\mu\nu} \hookrightarrow R_{\mu\nu}\left(\Gamma\right) \tag{3.7}$$

in which $\Gamma^\lambda_{\mu\nu}$, an affine connection with Ricci curvature $R_{\mu\nu}(\Gamma)$, is a new geometrical field bearing no relationship to metric $g_{\mu\nu}$ and its Levi-Civita connection ${}^g\Gamma^\lambda_{\mu\nu}$. The affine curvature $R_{\mu\nu}\left(\Gamma\right)$, as remarked below (2.4), throws the identity (3.5) into metric-affine geometry [24] in the metamorphic form

$$\delta S_V\left(g, R\left(\Gamma\right)\right) = -I(g,V) + \int d^4x\sqrt{-g}c_V \mathrm{Tr}\Big\{V^\mu\left(-{}^gD^2 g_{\mu\nu} + {}^gD_\mu {}^gD_\nu + V_{\mu\nu} + R_{\mu\nu}\left(\Gamma\right)\right)V^\nu + {}^g\nabla_\mu\left(g_{\alpha\beta}V^\alpha V^{\beta\mu}\right)\Big\} \tag{3.8}$$

in which each and every gauge field is massless yet the SM gauge symmetries are still explicitly broken. This breaking is because connection is not Levi-Civita but affine ($\Gamma^\lambda_{\mu\nu} \neq {}^g\Gamma^\lambda_{\mu\nu}$). And affine structure is mandatory for nonvanishing curvature in (3.7) to be consistently reconciled with the flat metric in (3.4). Indeed, reduction of (3.8) to (3.3), for instance, proceeds without contradiction simply because while the first step $R_{\mu\nu}\left(\Gamma\right) \rightsquigarrow \left(\Lambda_U^2 - \Lambda_W^2\right) g_{\mu\nu}$ fixes the affine connection, the second step $g_{\mu\nu} \rightsquigarrow \eta_{\mu\nu}$ does the metric. On the other side of the coin, the one-step reduction $g_{\mu\nu} \rightsquigarrow \eta_{\mu\nu}$ in metrical geometry, which reconciles vanishing curvatures in (3.6) with the flat metric in (3.4), is already consistent. The two geometries are contrasted in Table 1 in different aspects.

	Gravity Theory	Field Theory	Road to Flat Spacetime Field Theory (*e.g.* (3.3))
Added Curvature (*e.g.* (3.6))	metrical gravity (GR)	Classical	$g_{\mu\nu} \rightsquigarrow \eta_{\mu\nu}$
Emergent Curvature (*e.g.* (3.8))	metric-affine gravity	Effective	$R_{\mu\nu}\left(\Gamma\right) \rightsquigarrow \left(\Lambda_U^2 - \Lambda_W^2\right) g_{\mu\nu} \,/\!\!/\, g_{\mu\nu} \rightsquigarrow \eta_{\mu\nu}$

TABLE 1: Contrasting metrical (*added* curvature) and metric-affine (*emergent* curvature) geometries in regard to their gravitational and field-theoretic structures as well as their reduction to the flat spacetime.

The quirky thing about the affine connection $\Gamma^\lambda_{\mu\nu}$ is that it is dynamically driven towards ${}^g\Gamma^\lambda_{\mu\nu}$. In other words, its equation of motion possesses the solution

$$\Gamma^\lambda_{\mu\nu} = {}^g\Gamma^\lambda_{\mu\nu} + \mathcal{O}\left(\frac{\Lambda_W^3}{M_{Pl}^2}\right) \tag{3.9}$$

as will be revealed in the next section when curvature sector is completed by the image of $\delta S_O + \delta S_H$ under (3.7). This relation between $\Gamma^\lambda_{\mu\nu}$ and ${}^g\Gamma^\lambda_{\mu\nu}$ ensures that the metric-affine action (3.8) is dynamically equivalent to the metrical action

$$\begin{aligned}\delta S_V\left(g, R\left({}^g\Gamma\right)\right) &= -I(g,V) + \int d^4x\sqrt{-g}c_V \mathrm{Tr}\left\{V^\mu\left(-{}^gD^2 g_{\mu\nu} + {}^gD_\mu {}^gD_\nu + V_{\mu\nu} + R_{\mu\nu}\left({}^g\Gamma\right) + \mathcal{O}\left(\frac{\Lambda_W^6}{M_{Pl}^4}\right)\right)V^\nu + {}^g\nabla_\mu\left(g_{\alpha\beta}V^\alpha V^{\beta\mu}\right)\right\}\\ &= -I(g,V) + I(g,V) + \mathcal{O}\left(\frac{\Lambda_W^4}{M_{Pl}^4}\right)\\ &\approx 0\end{aligned} \tag{3.10}$$

whose vanishing ensures that the SM gauge symmetries are all restored up to Planck-suppressed small breaking effects. It therefore is guaranteed that $SU(3)_C \otimes U(1)_{EM}$ remains unbroken at all scales, and $SU(2)_L \otimes U(1)_Y$ gets broken spontaneously and only spontaneously at the electroweak scale M_{EW}. This is made possible by the emergence of curvature in (3.7) and the dynamical equivalence in (3.9).

There is an unsaid delicacy in (3.10), however. Indeed, its first line can yield the second via by-parts integration if c_V is constant. This means that

$$\frac{\Lambda_W}{\Lambda_U} \text{ must be kept unchanged} \tag{3.11}$$

while curvature emerges through (3.7). This is a pivotal condition. It ensures, in accordance with (2.2), that the IR/UV hierarchy is preserved. It also ensures that c_O, c_H and similar coefficients in δS_{log} all remain unchanged under (3.7).

Having associated $\Lambda_U^2 - \Lambda_W^2$ to curvature as in (3.7) and preserved Λ_U/Λ_W as in (3.11), what remains to be interpreted is the sum $\Lambda_U^2 + \Lambda_W^2$. It is the largest scale in the setup and, as remarked below (2.3), it should pertain to M_{Pl}. It therefore is conceivable that

$$\Lambda_U^2 + \Lambda_W^2 \text{ must also be kept unchanged} \tag{3.12}$$

under (3.7). It is thanks to the constraints (3.11) and (3.12) that the curved spacetime SM effective action to be established will carry Λ_U and Λ_W as its UV and IR scales.

4. SYMMERGENT GRAVITY

Under the generalizations (3.4) and (3.7), the flat spacetime SM effective action in (2.1) varies to take the metric-affine form

$$S_{eff}\left(g,\psi,\frac{\Lambda_w}{\Lambda_u},R(\Gamma),\Lambda_u^2+\Lambda_w^2\right) = S_{tree}(g)+\delta S_{log}(g)+\delta S_O\left(g,R(\Gamma),\Lambda_u^2+\Lambda_w^2\right)+\delta S_H\left(g,R(\Gamma)\right)+\delta S_V\left(g,R(\Gamma)\right) \quad (4.1)$$

$$= S_{tree}(g)+\delta S_{log}(g)+\delta S_V\left(g,R({}^g\Gamma)\right)-\int d^4x\sqrt{-g}\left(Q^{\mu\nu}R_{\mu\nu}(\Gamma)-c_V\mathrm{Tr}\{V^\mu V^\nu\}R_{\mu\nu}({}^g\Gamma)\right) \quad (4.2)$$

if the conditions in (3.11) and (3.12) are met. The vacuum, Higgs and gauge sectors in (4.1) combine to give

$$Q^{\mu\nu} = \frac{M_{Pl}^2}{2}g^{\mu\nu}+\frac{c_H}{4}H^\dagger H g^{\mu\nu}-c_V\mathrm{Tr}\{V^\mu V^\nu\} \quad (4.3)$$

in (4.2) such that the Planck scale takes shape as

$$M_{Pl}^2=\frac{c_O}{2}\left(\Lambda_u^2+\Lambda_w^2\right) \quad (4.4)$$

in accordance with the remarks below (2.3). The action (4.2) stays stationary against variations in $\Gamma^\lambda_{\mu\nu}$ if

$$\nabla_\lambda Q^{\mu\nu}=0 \quad (4.5)$$

the solution of which

$$\Gamma^\lambda_{\mu\nu}={}^g\Gamma^\lambda_{\mu\nu}+\frac{1}{2}Q^{\lambda\rho}\left({}^g\nabla_\mu(Q^{-1})_{\nu\rho}+{}^g\nabla_\nu(Q^{-1})_{\rho\mu}-{}^g\nabla_\rho(Q^{-1})_{\mu\nu}\right) \quad (4.6)$$

reduces to the solution in (3.9) due to enormity of the Planck scale. Inclusion of the spin connection [24, 25] does not affect this result.

The connection in (4.6), with the approximate form in (3.9), causes the action (4.2) to gain to the metrical equivalent

$$S_{eff}\left(g,\psi,\frac{\Lambda_w}{\Lambda_u},R({}^g\Gamma),M_{Pl}^2\right)=S_{tree}(g,\psi)+\delta S_{log}\left(g,\psi,\log\frac{\Lambda_w}{\Lambda_u}\right)-\int d^4x\sqrt{-g}\left\{\frac{M_{Pl}^2}{2}g^{\mu\nu}R_{\mu\nu}({}^g\Gamma)+\frac{c_H}{4}H^\dagger H g^{\mu\nu}R_{\mu\nu}({}^g\Gamma)\right\} \quad (4.7)$$

up to $\mathcal{O}(\Lambda_w^6/M_{Pl}^2)$ higher-dimension, curvature-free SM operators that can potentially break gauge symmetries as in (3.10). This action is nothing but the curved spacetime SM effective action. Its gravity sector, which is precisely the Einstein-Hilbert action, has emerged through (3.4) and (3.7) and restored the SM gauge symmetries dynamically through (3.9). It can be called *symmergent gravity* to highlight its symmetry-restoring, emergent nature. Its physics implications fall into two broad categories:

1. The action (4.7) is wholly set by the flat spacetime loops. This leads to three momentous features:
   a) In gravity sector, the Wilson coefficients c_O and c_H have no relation to the corresponding DeWitt coefficient a_1 [14, 26] pertaining to QFTs in curved backgrounds. The two, contrasted in Table 2, might therefore be distinguished via the Higgs dynamics in strong gravity regions [27].
   b) In fields sector, the logarithmic part, with all symmetries restored, can naturally be interpreted in the language of *dimensional regularization*. Indeed, the evidential correspondence

   $$\log\frac{\Lambda_u}{\Lambda_w}=\frac{1}{\epsilon}+\log\frac{\mu}{\Lambda_w} \quad (4.8)$$

   expresses the SM amplitudes in terms of the matching scale μ after subtracting $1/\epsilon$ terms in MS or $\overline{\mathrm{MS}}$ renormalizations. Their independence from μ leads to the renormalization group equations.
   c) In curvature sector, higher-curvature terms like $\left(g^{\mu\nu}R_{\mu\nu}({}^g\Gamma)\right)^2$, $R_{\mu\nu}({}^g\Gamma)R^{\mu\nu}({}^g\Gamma),\dots$ are absent even at the $\mathcal{O}(\Lambda_w^6/M_{Pl}^2)$ order. This property makes a case for the Einstein gravity.
2. The action (4.7) is cleared of all power-law UV sensitivities. This leads to three stabilization features:
   a) The UV-sized gauge boson mass corrections in (2.10) have all vanished thanks to the symmergent nature of gravity. This means that *color* and *electromagnetism* are both restored up to tiny $\mathcal{O}(\Lambda_w^6/M_{Pl}^2)$ breaking effects.
   b) The UV-sized Higgs mass correction in (2.9) has turned into the Higgs-curvature coupling. This means that the *big hierarchy problem* is solved.
   c) The UV-sized vacuum energy in (2.8) has metamorphosed to become the Einstein-Hilbert term. This means that the *cosmological constant* has shrunk from $\mathcal{O}(M_{Pl}^2)$ down to $\mathcal{O}(m_\nu^2)$.

   In symmergent gravity, the *cosmological constant problem* is resolved only in the UV end. The remnant $\mathcal{O}(\Lambda_w^4)$ vacuum energy gets contributions from rest energies, electroweak breaking and parton-hadron transition. These physically distinct contributions, bearing at most logarithmic UV sensitivity, measure tantalizingly bigger than the observational value $\mathcal{O}(m_\nu^4)$. This is the IR end of the cosmological constant problem. It is yet to be understood.

In consideration of these properties, symmergent gravity is contrasted with Sakharov's induced gravity in Table 2.

	Gravity Sector	Ultraviolet Sensitivity	Cosmological Constant	Higgs Mass	Color and Electromagnetism
Induced Gravity	Einstein-Hilbert + Higher Curvature	Quartic, Quadratic, Logarithmic	$\Lambda_u^4/M_{Pl}^2 \simeq M_{Pl}^2$	$\simeq M_{Pl}$	Broken
Symmergent Gravity	Metric-Affine $\cong$ Einstein-Hilbert	Logarithmic	$\Lambda_w^4/M_{Pl}^2 \simeq m_\nu^2$	$\simeq \Lambda_w$	Exact

TABLE 2: Contrasting symmergent gravity with Sakharov's induced gravity [14] for $M_{Pl} \cong \Lambda_u$.

5. PHYSICS BEYOND THE SM

Symmergent gravity, structuring M_{Pl} as in (4.4), must ensure that gravity is attractive $(c_O > 0)$ and is the weakest force $\left(\Lambda_u^2 + \Lambda_w^2 < M_{Pl}^2\right)$. Both of these constraints are satisfied if

$$c_O > 2 \tag{5.1}$$

as concluded from (4.4). Direct calculation gives

$$c_O = \frac{n_b - n_f}{64\pi^2} \tag{5.2}$$

at one loop in a QFT with n_b bosons and n_f fermions. In the SM, $n_b^{SM} - n_f^{SM} = -62 < 0$. This means that the SM must necessarily be extended, as anticipated in (1.1), by some BSM sector with n_b^{BSM} bosons and n_f^{BSM} fermions such that

$$n_b^{BSM} - n_f^{BSM} > 1325 \tag{5.3}$$

at one loop. To be able to satisfy this one-loop bound or more general condition (5.1),

the BSM sector must be quartically UV sensitive like (2.5) in the SM (5.4)

but quadratic and logarithmic sensitivities are not a necessity. Moreover, since all that is required of it is to enable (5.1) and (5.3),

the BSM sector does not have to interact with the SM unless experiment reveals that it must. (5.5)

This property is precisely what distinguishes symmergence from the other known completions of the SM (supersymmetry, extra dimensions and compositeness). In symmergent gravity, BSM fields, which can have, none to significant, any couplings to the SM, come in three distinct classes, as indicated in Figure 1. In the other completions, however, BSM fields (superpartners, Kaluza-Klein modes, technifermions) have significant couplings to the SM, and they therefore fall into the SM-charged BSM class in Figure 1.

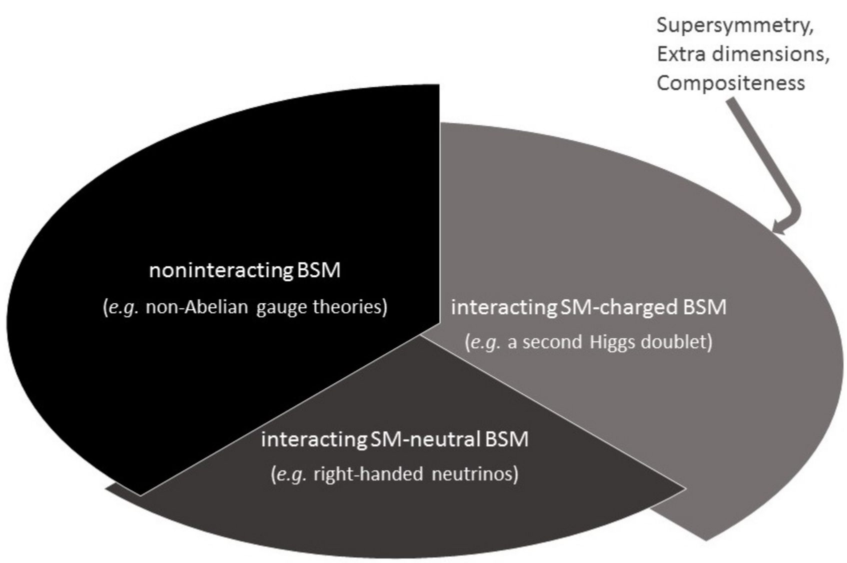

FIGURE 1: Three possible subclasses of the BSM fields in symmergent gravity.

5.1. Noninteracting BSM.

This BSM subclass is made up of the SM-singlet fields that do not couple to the SM fields. It could be modeled using, as highlighted in Figure 1, non-Abelian gauge bosons X_μ of high-rank gauge groups like

$$\mathcal{G}_{BSM} = SO(51), SU(3)^{83}, SU(5)^{26}, SU(26), E(8)^3, \dots \tag{5.6}$$

and also SM-singlet fermions χ charged under $\mathcal{G}_{BSM}$ so that $n_{X_\mu} - n_\chi$ satisfies the bound (5.3). Its action

$$S_{BSM}(g, R) = \int d^4x \sqrt{\|g\|} \left\{ -\frac{1}{2}\text{Tr}\left\{ g_{\mu\alpha} g_{\nu\beta} X^{\mu\nu} X^{\alpha\beta} \right\} + \overline{\chi}(i\not{D} - m_\chi)\chi \right\} \tag{5.7}$$

involves no interaction terms with the SM because hypercharge (no Abelian gauge fields in the BSM), lepton (no singlet fermions in the BSM), and Higgs (no scalars in the BSM) portals are all sealed off. It gives cause to three observable effects:

1. If the gauge group $\mathcal{G}_{BSM}$ confines then hadrons of χ or glueballs of X_μ can source the CDM [5]. If not, χ itself sources it. The resulting CDM, in either case, is pitch-dark or *ebony* in that no experiment can detect it. In fact, the present experimental fact [9] that the CDM seems to reveal itself via only gravitational interactions can be taken as an indication for this ebony matter.

2. Mesons of χ and glueballs of X_μ can source also dynamical dark energy. It affects cosmic evolution differently than the cosmological constant and, in the face of the most recent CMB measurements preferring the cosmological constant, its role might be to interpolate between the values of Hubble constant obtained by CMB and local luminosity measurements [28].

3. In symmergent gravity, cosmological constant is reduced by some 60 orders of magnitude compared to Sakharov's induced gravity. There are, however, another 60 orders of magnitude to go to agree with observations. This extra stage can be facilitated by ultra-light (much lighter than Λ_W) non-interacting particles in the BSM since some yet-to-be-found mechanism acting on them can reduce the cosmological constant from the neutrino scale down to the Hubble scale [21] (see Table 2).

The noninteracting BSM, which would crystallize further with the solution of the cosmological constant problem, may well be the underlying reason for not detecting any new particles in collider, astrophysical and cosmological searches.

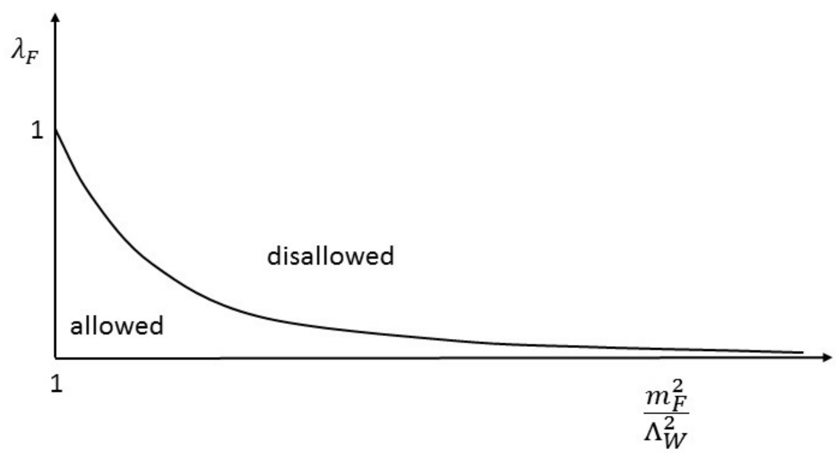

FIGURE 2: The allowed and disallowed regions in λ_F–m_F^2 plane according to the Higgs stability constraint (5.9).

5.2. Interacting SM-neutral BSM.

This BSM subclass involves SM-singlet fields that directly interact with the SM. They can be scalars S, Abelian gauge bosons V_μ and right-handed neutrinos N which, respectively, couple to the SM Higgs field as $\lambda_S(H^\dagger H)(S^\dagger S)$, the hypercharge gauge boson B_μ as $\sqrt{\lambda_V} B_{\mu\nu} V^{\mu\nu}$, and the lepton doublet L as $\sqrt{\lambda_N}\, \overline{L} H N$. Their loops lead to the Higgs mass shifts

$$\left(\delta m_H^2\right)_F \propto \lambda_F\, m_F^2 \log \frac{m_F}{\Lambda_U} \tag{5.8}$$

which exceeds m_H^2 itself when $\lambda_F\, m_F^2 \gtrsim \Lambda_W^2$. These corrections are induced not by the UV boundary but by the SM-BSM mixing. Their suppression is therefore a field-theoretic problem [29]. And solution lies not in trying to suppress $\left(\delta m_H^2\right)_F$ despite large $\lambda_F\, m_F^2$ but in constructing an SM completion that naturally admits

$$\lambda_F\, m_F^2 \lesssim \Lambda_W^2 \tag{5.9}$$

for each and every $F = S, V, N$. It is here that symmergence again comes to the fore because its workings do not necessitate any SM-BSM mixing and imposition of the bound (5.9) poses no problem at all.

The constraint (5.9), according to which heavier the BSM fields tinier their couplings to the SM fields, corresponds to the region below the solid curve in Figure 2. It is in this limited domain that the SM remains stable. And the right-handed neutrinos happen to have a mass

$$m_N \lesssim 1000\,\text{TeV} \tag{5.10}$$

if they are to obey the bound (5.9) and yield the active neutrino masses $m_\nu < 1$ eV [8, 20].

There are at present no experimental signals for scalars S and vectors V_μ but they, if discovered in future, are expected to obey (5.9). Nevertheless, the SM-singlet scalars S play a crucial role in modeling strong CP problem, baryogenesis, inflation and flavor [17], wherein the bound (5.9) is commonly employed to separate the high-scale physics from the SM.

5.3. Interacting SM-charged BSM.

This BSM subclass involves SM-charged fields like extra Higgs doublets, squarks, Kaluza-Klein modes, technifermions and the like. However, the bound (5.9) with $\lambda_F \sim \mathcal{O}(1)$ implies that such SM-charged BSM fields must weigh at the electroweak scale. But then current LHC bounds [2] imply that such fields do possibly not exist at all. In other words, the light gray region in Figure 1 must be empty.

6. CONCLUSION

Symmergent gravity, emergence of gravity for gauge symmetry reason, is a new phenomenon. It neutralizes the destabilizing UV sensitivities in the SM by incorporating Einstein gravity and predicts a crowded SM-neutral BSM sector that can weakly interact with the SM. It does not necessitate any interactions between the SM and the BSM, and thus, sets a playground for interpreting the current collider, astrophysical and cosmological results.

Symmergent gravity, as a new framework, can be furthered in different directions. One direction, as emphasized in the text, refers to the cosmological constant problem. Indeed, the cosmological constant has to be reduced from the neutrino scale down to the Hubble scale to agree with observations. This is a highly intricate problem in that the BSM physics must have requisite structures to neutralize the SM vacuum energy. Besides the cosmological constant, dark energy, dark matter and SM-neutral BSM can be modeled in parallel with experimental developments.

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