Symmergent Gravity, Seesawic New Physics, and their Experimental Signatures

Durmuş Demir

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

Abstract

The standard model of elementary particles (SM) suffers from various problems, such as power-law ultraviolet (UV) sensitivity, exclusion of general relativity (GR), and absence of a dark matter candidate. The LHC experiments, according to which the TeV domain appears to be empty of new particles, started sidelining TeV-scale SUSY and other known cures of the UV sensitivity. In search for a remedy, in this work, it is revealed that affine curvature can emerge in a way restoring gauge symmetries explicitly broken by the UV cutoff. This emergent curvature cures the UV sensitivity and incorporates GR as symmetry-restoring emergent gravity (symmergent gravity, in brief) if a new physics sector (NP) exists to generate the Planck scale and if SM+NP is fermi-bose balanced. This setup, carrying fingerprints of trans-Planckian SUSY, predicts that gravity is Einstein (no higher-curvature terms), cosmic/gamma rays can originate from heavy NP scalars, and the UV cutoff might take right value to suppress the cosmological constant (alleviating fine-tuning with SUSY). The NP does not have to couple to the SM. In fact, NP-SM coupling can take any value from zero to \( \Lambda_{SM}^2 / \Lambda_{NP}^2 \) if the SM is not to jump from \( \Lambda_{SM} \approx 500 \text{ GeV} \) to the NP scale \( \Lambda_{NP} \). The zero coupling, certifying an undetectable NP, agrees with all the collider and dark matter bounds at present. The seesawic bound \( \Lambda_{SM}^2 / \Lambda_{NP}^2 \), directly verifiable at colliders, implies that: (i) dark matter must have a mass \( \lesssim \Lambda_{SM} \), (ii) Higgs-curvature coupling must be \( \approx 1.3\% \), (iii) the SM RGEs must remain nearly as in the SM, and (iv) right-handed neutrinos must have a mass \( \lesssim 1000 \text{ TeV} \). These signatures serve as a concise testbed for symmergence.
I. INTRODUCTION

The SM, a spontaneously broken renormalizable quantum field theory (QFT) of the strong and electroweak interactions, has shown good agreement with all the experiments performed so far [1, 2]. Its parameters have all been fixed experimentally. This does, however, not mean that it is a complete theory. Indeed, it is plagued by enigmatic problems like destabilizing UV sensitivities [3], exclusion of gravity [4], and absence of a dark matter candidate [5], which are impossible to address without new physics beyond the SM (BSM). Schematically,

\[ \text{BSM} = \text{gravity (GR)} + \text{new QFT beyond the SM (NP)} \]  

in which the general relativistic (GR) structure of gravity is revealed by various experiments [6] and observations [7]. The NP is under way at colliders [2] and dark matter searches [8].

Quantum correction to the Higgs boson mass, quadratically sensitive to UV boundary [3], exceeds the Higgs boson mass just above the electroweak scale. This means that the SM must stop working below the TeV scale. It does not stop, however. Indeed, the LHC has confirmed the SM [2] up to multi-TeV energies. This contradiction between the SM loops and the LHC can be eliminated only if the NP in (1) improves the SM in a way without introducing any new interacting particles. The present work approaches this puzzling requirement via proof-by-contradiction, that is, it begins by assuming that the NP is absent (Sec. II up to Sec. IV) and, at a later stage, it ends up with NP through the consistency of the induced gravitational constant (Sec. V).

The GR must be incorporated into the SM [6, 7]. This has been attempted with classical GR [9] (despite [10]), quantized GR [11] (despite [12, 13]), and emergent GR [14] (see also [15, 16]). The present work incorporates curvature into the SM effective action in flat spacetime (Sec. II) by building on the nascent ideas proposed in [17, 18] and subsequent developments voiced in [19, 22]. It incorporates gravity in a way restoring the gauge symmetries broken...
by the UV cutoff \cite{23} (Sec. III and IV) and in a form involving a nontrivial NP sector (Sec. V) to induce the gravitational constant. This gauge symmetry-restoring emergent gravity, *symmergent gravity* \cite{20–22} in brief, sets up a framework (Sec. VI) in which

1. curvature arises to neutralize power-law UV sensitivities and the associated problems,

2. GR emerges along with the restoration of gauge invariance,

3. gravitational constant necessitates an NP sector,

4. SM + NP possesses exact fermi-bose balance and the induced gravitational constant is suggestive of a trans-Planckian SUSY breaking \cite{24},

5. the UV boundary can be fixed, in principle, by suppression of the cosmological constant (with no immediate solution for the cosmological constant problem \cite{25} though)

so that there arise a number of descriptive signatures with which symmergence can be probed via decisive experiments (Sec. VII):

1. Higher-curvature terms are predicted to be absent. This excludes, for instance, $f(R)$ gravity \cite{26} and agrees well with the current cosmological data \cite{7}.

2. NP scalars with trans-GZK \cite{27} VEVs are predicted to give cause to cosmic rays \cite{28} (digluon) as well as gamma rays \cite{29} (diphoton) via certain Planck-suppressed higher-dimension operators.

3. Symmergence does not necessitate any SM-NP coupling for it to work. This property, not found in the known SM completions (SUSY, extra dimensions, compositeness and others \cite{30}) for which a sizable SM-NP coupling is essential, provides a rationale for stabilizing the electroweak scale against the SM-NP mixing. Indeed, if the SM-NP coupling goes like $m_{H}^2/m_{NP}^2$, then the Higgs boson mass $m_{H}$ remains within the allowed limits. This seesawic (seesaw-wise) structure leads to various testable features:

(a) It is predicted that heavier the NP larger the luminosity needed to discover it. This distinctive feature can be probed at present \cite{31} and future colliders \cite{32, 33}.

(b) It is also predicted that the right-handed neutrinos \cite{34} must weigh below a 1000 TeV (see also \cite{35}). This bound can be tested at future colliders \cite{36} if not at the near-future SHiP experiment \cite{37}.
(c) It turns out that the SM couplings (gauge and non-gauge) must run as if NP is absent if the NP lies sufficiently above the electroweak scale. This feature, which rests on the fact that symmergence leaves behind only logarithmic sensitivity to the UV boundary \[39\], can be tested at present \[31\] and future colliders \[32, 33\].

(d) Symmergence accommodates both ebony (having only gravitational interactions with the SM) \[18, 40\] and dark (having seesawic couplings to the SM) matters. They both agree with the current bounds. The latter, thermal dark matter, is predicted to weigh below the electroweak scale. This agrees with current limits and can be tested further in future searches \[8, 41\].

(e) It is predicted that, in the SM, non-minimal Higgs-curvature coupling equals 1.3% at one-loop and remains so unless the NP lies near the electroweak scale. This coupling, too small to drive the Higgs inflation \[42\], can serve as a testbed at collider experiments \[43\] if not in the astrophysical or cosmological environments.

The work is concluded in Sec. VIII.

II. UV BOUNDARY, EFFECTIVE SM AND UV SENSITIVITY PROBLEMS

The NP needed to complete the SM, roughly sketched in (I), can be elucidated only after a complete picture of the SM in regard to its UV boundary and UV sensitivity.

A. UV Boundary

The Higgs mass-squared \(m_H^2\), measured to be \((m_H^2)_{\text{LHC}} \approx (125 \text{ GeV})^2\) at the LHC \[44\], is overwhelmed by the quantum correction \[3\]

\[
\delta m_H^2 = c_H \Lambda^2
\]

in which \(\Lambda\) is the UV boundary of the SM, and

\[
c_H = \frac{3}{16\pi^2 \langle H \rangle^2} (4m_t^2 - 2M_W^2 - M_Z^2 - m_H^2) \approx 5.14 \times 10^{-2}
\]

is the loop factor. The correction \[2\], a one-loop SM effect, grows quadratically with \(\Lambda\) and exceeds \((m_H^2)_{\text{LHC}}\) already at \(\Lambda = \Lambda_W\), where

\[
\Lambda_W \approx 550 \text{ GeV}
\]
lies just above the electroweak scale $|\langle H \rangle| \approx 246.22$ GeV. This low-lying $\Lambda_W$, which can be changed slightly by incorporating subleading $\log m_H/\Lambda$ corrections to (2), is a characteristic feature of the SM spectrum and the experimental result $(m_H^2)_{LHC}$. It implies that the SM must stop working at $\Lambda_W$. It does not stop, however. Indeed, the LHC experiments show that the SM continues to hold good up to multi-TeV energies without any new field. This contradictory UV overextension is the problem. There is no clear solution. There is even no clear way to search for a solution. There is, however, a possibility that a mechanism, not necessarily unique, might be constructed via proof-by-contradiction \[18, 20\], that is, by first

constructing the SM effective action below $\Lambda_W$ assuming that
\[ S_{\text{eff}} (\eta) = S_{\text{tree}} (\eta, F) + \delta S_{\log} (\eta, F, \log \frac{\Lambda_W}{\Lambda_U}) + \delta S_O (\eta, \Delta^2) + \delta S_H (\eta, \Delta^2) + \delta S_V (\eta, \Delta^2) \] (7)

and then

revealing necessity of the NP for incorporation of gravity and neutralization of the destabilizing $\Lambda_U$ sensitivities.
\[ \text{(6)} \]

The first step sets up a UV boundary $\Lambda_U$ and reveals SM’s UV sensitivity. The second, on the other hand, uncovers NP via induction of gravity and fixes $\Lambda_U$ in terms of the NP scale.

B. SM Effective Action

In accordance with (5), integration of the fast modes (fields with energies $\gtrsim \Lambda_W$) out of the SM spectrum gives an effective action for slow modes $F$ (fields with energies $\lesssim \Lambda_W$) \[45\]

\[ \Delta^2 = \Lambda_U^2 - \Lambda_W^2 \] (8)
is the UV-EW gap. The tree-level SM action $S_{\text{tree}}$ and the logarithmic corrections $\delta S_{\log}$ both lie below $\Lambda_W$. But, the other three

$$\delta S_O = - \int d^4 x \sqrt{-\eta} \left\{ (2c_O \Lambda_W^2 + c_\gamma m_\gamma^2) \Delta^2 + c_O \Delta^4 \right\}$$

(9)

$$\delta S_H = - \int d^4 x \sqrt{-\eta} c_H \Delta^2 H^\dagger H$$

(10)

$$\delta S_V = \int d^4 x \sqrt{-\eta} c_V \Delta^2 \text{Tr}[V_\mu V^\mu]$$

(11)

pull the SM off the electroweak scale depending on how large $\Delta^2$ is. They tend to destabilize the SM and it is this destabilization that necessitates a neutralization mechanism. Their Wilson coefficients $c_{O,\ldots,V}$ involve only the ratio $\frac{\Lambda_W}{\Lambda_U}$

as the measure of the EW-UV hierarchy.

C. UV Sensitivity Problems

The power-law quantum corrections in (9), (10) and (11) give cause to serious destabilization problems. They are tabulated in Table I. The cosmological constant problem (CCP) [25], caused by $\delta S_O$, exists only when gravity is present. The big hierarchy problem (BHP) [3] (gauge hierarchy problem) refers to quadratic UV sensitivities of the Higgs (from $\delta S_H$) and $W/Z$ (from $\delta S_V$) masses. The electric charge or color breaking (CCB) [23], on the other hand, arises from the photon and the gluon mass terms in $\delta S_V$ (purely quadratic in $\Delta$). The SM is impossible to make sense in the UV before these problems are satisfactorily resolved.

D. Impossibility of Renormalizing Away CCP, CCB and BHP

The SM is a renormalizable QFT. If so, why isn’t it possible to include $\delta S_{\log}$, $\delta S_O$, $\delta S_H$, $\delta S_V$ into a renormalization of $S_{\text{tree}}$ to get rid of the problems in Table I? Because $\Delta$ is physical. Indeed, $\Lambda_U$ can pertain to gravity or NP sectors [3]. Moreover, there is simply no place to hide $\delta m_{\gamma,g}^2 = c_{\gamma,g} \Delta^2 \neq 0$ since $(m_{\gamma,g}^2)_{\text{tree}} = 0$. These problems are therefore physical and their solutions entail physical changes on the SM (like inclusion of gravity).
Table I. Quantum corrections and problems they give cause to. The coefficients \( c_f, \ldots, c_g \) are loop factors that depend on \( \Lambda_W/\Lambda_U \). (CCP, with \( \tilde{c}_O = c_O + (2c_O\Lambda_W^2 + c_f \, m_f^2)/\Delta^2 \), exists only in curved geometry hence the grey color.)

| \( \delta S_\log \) | \( \delta S_H \) | \( \delta S_V \) | \( \delta S_O \) | Problem |
|-------------------|----------------|----------------|----------------|--------|
| \( \delta V \)  | \( \neq 0 \) | 0 | 0 | \( \tilde{c}_O \Delta^4 \) | CCP |
| \( \delta m_{H}^2 \) | \( \neq 0 \) | 0 | 0 | \( c_H \Delta^2 \) | BHP |
| \( \delta m_{W}^2 \) | \( \neq 0 \) | 0 | \( c_W \Delta^2 \) | BHP |
| \( \delta m_{Z}^2 \) | \( \neq 0 \) | 0 | \( c_Z \Delta^2 \) | BHP |
| \( \delta m_{\gamma}^2 \) | 0 | 0 | \( c_\gamma \Delta^2 \) | CCB |
| \( \delta m_{g}^2 \) | 0 | 0 | \( c_g \Delta^2 \) | CCB |

III. HOW NOT TO INCORPORATE GRAVITY INTO EFFECTIVE SM

Gravity is incorporated into classical field theories in flat spacetime by first mapping the flat metric \( \eta_{\mu\nu} \) into a putative curved metric \( g_{\mu\nu} \) as

\[
\eta_{\mu\nu} \hookrightarrow g_{\mu\nu}
\]

in view of general covariance \[46\], and then adding curvature of the Levi-Civita connection

\[
\gamma \Gamma^\lambda_{\mu\nu} = \frac{1}{2} g^{\lambda\rho} \left( \partial_\mu g_{\nu\rho} + \partial_\nu g_{\mu\rho} - \partial_\rho g_{\mu\nu} \right) \quad (14)
\]

to make \( g_{\mu\nu} \) dynamical. The added curvature sector, ignoring ghosts, can involve all curvature invariants \[47\]. It can involve, for instance, the Ricci tensor \( R_{\mu\nu} \) in traced \( (R = g^{\mu\nu} R_{\mu\nu}) \), squared \( (R_{\mu\nu} \, R^{\mu\nu}) \) or in any other invariant form. This curvature-by-hand method, a standard procedure for classical field theories, leads to

\[
S_{\text{eff}}(g) = - \int d^4x \sqrt{-g} \left\{ \tilde{M}^2 R + \tilde{\alpha} R^2 + \tilde{\beta} R^{\mu\nu} R_{\mu\nu} + \cdots \right\} \quad (15)
\]

when applied to the SM effective action in \[7\]. The problem with this action is that \( \tilde{M}, \tilde{\alpha}, \tilde{\beta}, \cdots \) are all inherently incalculable \[18, 20, 21\]. This is because matter loops have already been used up in forming the flat spacetime effective action \( S_{\text{eff}} \), and there have remained thus no loops to induce any extra interaction, with or without curvature. This incalculability constraint, which reveals the difference between classical and effective field theories, renders the tentative action \[15\] unphysical. It is in this sense that the general covariance \[46\] is
not adequate for incorporating curvature into effective SM. In essence, what is needed is a separate covariance relation between the scales in $S_{\text{eff}}$ (say, $\Lambda^2_W$ or $\Delta^2$) and curvature \[19\] so that gravity can be incorporated in a way involving no arbitrary, incalculable constants.

IV. CURVING AWAY CCB

The gauge part $\delta S_V (\eta, \Delta^2)$, which must be neutralized for color and electromagnetism to remain exact and electroweak breaking to be spontaneous, poses a vexed problem due to strict masslessness of the photon and the gluon. It can be tackled via neither the Stueckelberg method \[48\] nor the spontaneous symmetry breaking \[49\]. It can, nonetheless, be tackled by furthering the nascent ideas proposed in \[17\] (takes $\delta S_O$, $\delta S_H$, $\delta S_V$ to affine spacetime) and \[18\] (attempts at restoring gauge symmetry within the GR with fixed $\Lambda^2_U + \Lambda^2_W$) and subsequent advancements voiced in \[19\]–\[22\].

A. $\delta S_V (\eta, \Delta^2)$ in a New Light

It proves useful to start with the obvious identity \[18\]–\[19\]

$$\delta S_V (\eta, \Delta^2) = \delta S_V (\eta, \Delta^2) - I(\eta, V) + I(\eta, V)$$  \hspace{1cm} (16)

in which the gauge-invariant kinetic construct

$$I(\eta, V) = \int d^4 x \sqrt{-c_V} \operatorname{Tr} \left\{ \eta_{\mu\alpha} \eta_{\nu\beta} V^{\mu\nu} V^{\alpha\beta} \right\}$$  \hspace{1cm} (17)

is subtracted from and added back to $\delta S_V$. This construct, involving the loop factor $c_V$ and the field strength tensor $V_{\mu\nu}$, leads to

$$\delta S_V (\eta, \Delta^2) = -I(\eta, V)$$

$$+ \int d^4 x \sqrt{-c_V} \operatorname{Tr} \left\{ V^{\mu} \left(-D^2_{\mu\nu} + \Delta^2 \eta_{\mu\nu}\right) V^{\nu} \right\}$$

$$+ \int d^4 x \sqrt{-c_V} \operatorname{Tr} \left\{ \partial_{\mu} \left( \eta_{\alpha\beta} V^{\alpha} V^{\beta\mu} \right) \right\}$$  \hspace{1cm} (18)

if, at the right hand side of \[16\], $\delta S_V$ is replaced with \[11\], “$- I(\eta, V)$" is left untouched, and yet “$+ I(\eta, V)$" is integrated by-parts to involve $D^2_{\mu\nu} = D^2 \eta_{\mu\nu} - D_{\mu} D_{\nu} - V_{\mu\nu}$ where $D_{\mu}$
is gauge-covariant derivative. This recast $\delta S_V$ gets to curved spacetime via (13) to become

$$\delta S_V (g, \Delta^2) = -I(g, V)$$

$$+ \int d^4x \sqrt{-g} c_V \text{Tr} \left\{ V^\mu \left( -\mathcal{D}_\mu^2 + \Delta^2 g_{\mu\nu} \right) V^\nu \right\}$$

$$+ \int d^4x \sqrt{-g} c_V \text{Tr} \left\{ \nabla_\mu \left( g_{\alpha\beta} V^\alpha V^\beta_\mu \right) \right\} \tag{19}$$

where $\mathcal{D}_\mu$ is the gauge-covariant derivative with respect to the covariant derivative $\nabla_\mu$ of the Levi-Civita connection $^g\Gamma^\lambda_{\mu\nu}$, and $\mathcal{D}_\mu^2 = \mathcal{D}_\mu \mathcal{D}_\nu - V_{\mu\nu}$.

B. $\delta S_V (g, \Delta^2)$ in a New “Curvature”

Is there a simple way of killing $\delta S_V (g, \Delta^2)$? Yes, there is. Indeed, $\delta S_V (g, \Delta^2)$ vanishes identically if $\Delta^2 g_{\mu\nu}$ is replaced with $R_{\mu\nu} (\Gamma)$. This illuminative feature, not to be confused with derivation of gravity from self-interacting spin-2 fields in flat spacetime [50], is pitifully problematic because $\Delta^2 g_{\mu\nu} \hookrightarrow R_{\mu\nu} (\Gamma)$ contradicts with $\eta_{\mu\nu} \hookrightarrow g_{\mu\nu}$. If it were not for this contradiction, emergence of curvature from $\Delta^2 g_{\mu\nu}$ would solve the CCB [18–21].

The contradiction can be avoided by introducing, for instance, a more general map [22]

$$\Delta^2 g_{\mu\nu} \hookrightarrow \mathbb{R}_{\mu\nu} (\Gamma) \tag{20}$$

in which $\mathbb{R}_{\mu\nu} (\Gamma)$ is the Ricci curvature of a symmetric affine connection $\Gamma^\lambda_{\mu\nu}$ (which bears no relation to the Levi-Civita connection $^g\Gamma^\lambda_{\mu\nu}$). This new map removes contradiction because while $\mathbb{R}_{\mu\nu} (\Gamma) \hookrightarrow \Delta^2 g_{\mu\nu}$ fixes the affine connection, $g_{\mu\nu} \hookrightarrow \eta_{\mu\nu}$ does the metric [22]. It throws $\delta S_V (g, \Delta^2)$ in (19) into metric-affine geometry [51, 52] to give it the “massless” form

$$\delta S_V (g, \mathbb{R}) = -I(g, V)$$

$$+ \int d^4x \sqrt{-g} c_V \text{Tr} \left\{ V^\mu \left( -\mathcal{D}_\mu^2 + \mathbb{R}_{\mu\nu} (\Gamma) \right) V^\nu \right\}$$

$$+ \int d^4x \sqrt{-g} c_V \text{Tr} \left\{ \nabla_\mu \left( g_{\alpha\beta} V^\alpha V^\beta_\mu \right) \right\} \tag{21}$$

whose by-parts integration gives

$$\delta S_V (g, \mathbb{R}, R) = \int d^4x \sqrt{-g} c_V \text{Tr} \left\{ V^\mu \left( \mathbb{R}_{\mu\nu} - R_{\mu\nu} \right) V^\nu \right\} \tag{22}$$

under the condition that $c_V$ must be held unchanged or, equivalently, the EW-UV hierarchy

$$\frac{\Lambda_W}{\Lambda_U} \text{ must be held unchanged} \tag{23}$$
while the affine curvature arises as in \(^{(20)}\). This preservation is crucial for ensuring that the SM is indeed stabilized at \(\Lambda_W \ll \Lambda_U \) \(^{[3]}\).

The CCB attains a solution only if \(\delta S_V (g, R, R)\) in \(^{(22)}\) is suppressed. And suppression occurs in case \(\Gamma^\lambda_{\mu\nu}\) approaches to \(g \Gamma^\lambda_{\mu\nu}\). Coincidentally, GR arises only if \(\Gamma^\lambda_{\mu\nu}\) does not involve any geometric degrees of freedom not found in \(g \Gamma^\lambda_{\mu\nu}\). This approach, which occurs under specific conditions \(^{[51,53]}\) to be revealed in the sections below, leads to the algebraic solution \(^{(22)}\)

\[
\Gamma^\lambda_{\mu\nu} = g \Gamma^\lambda_{\mu\nu} + \frac{\mathcal{O}_3 (H, V)}{M_{Pl}^2} \tag{24}
\]

where \(\mathcal{O}_3 (H, V)\) are dimension-3 Higgs and gauge composites. This particular solution for connection suppresses \(\delta S_V\) as

\[
\delta S_V (g, R, R) = 0 + \int d^4x \sqrt{-g} \frac{\mathcal{O}_6 (H, V)}{M_{Pl}^2} \tag{25}
\]

to restore color and electromagnetism and ensure spontaneity of the electroweak breaking modulo Planck-suppressed dimension-6 Higgs and gauge field composites \(\mathcal{O}_6 (H, V)\).

C. Symmergence Principle

The results above can be organized as a principle to apply to UV sensitivities of any given QFT. Indeed, it turns out that gravity can be incorporated into a flat spacetime QFT with UV-IR gap \(\Delta\) and metric \(\eta_{\mu\nu}\) by first letting \(^{[46]}\)

\[
\eta_{\mu\nu} \hookrightarrow g_{\mu\nu} \tag{26}
\]

and then \(^{(22)}\)

\[
\Delta^2 g_{\mu\nu} \hookrightarrow \mathcal{R}_{\mu\nu} (\Gamma) \tag{27}
\]

so that if

\[
\mathcal{R}_{\mu\nu} (\Gamma) \sim R_{\mu\nu} (g \Gamma) \tag{28}
\]

then CCB gets suppressed and GR emerges as gauge symmetry restoring emergent gravity or, briefly, symmergent gravity. This three-step procedure will hereon be called symmergence.
V. NP SECTOR

So far, entire study has been based on the SM in view of the basic assumption in (5). Now, the NP pops up in accordance with (6).

A. Necessity of NP

Under (13) and (20), the Higgs and vacuum sectors of the flat spacetime effective action in (7) transforms as

$$\delta S_O + \delta S_H \rightarrow \int d^4x \sqrt{-g} \left\{ -q R + \frac{c_O}{16} (R)^2 \right\}$$

(29)
after defining the scalar affine curvature

$$\mathbb{R}(g, \Gamma) = g^{\mu\nu} \mathbb{R}_{\mu\nu}(\Gamma)$$

(30)
and introducing

$$q = \frac{c_O}{2} \Lambda_W^2 + \frac{c_f}{4} m_f^2 + \frac{c_H}{4} H^4 + \frac{c_O}{8} R$$

(31)
for convenience. The right-hand side of (29) forms the curvature sector of the SM effective action in metric-affine geometry [51–53]. The apparent gravitational scale, $\frac{c_O}{2} \Lambda_W^2 + \frac{c_f}{4} m_f^2$, is wrong in both sign ($c_O < 0$ in the SM) and size ($c_f m_f^2 < \Lambda_W^2$ in the SM). It is for this reason that an NP sector (of new fields $\mathcal{F}'$) must be introduced so that the new gravitational scale

$$(c_O + c_O') \Lambda_W^2 + \frac{c_f}{2} m_f^2 + \frac{c_{f'}}{2} m_{f'}^2$$

(32)
can come out right thanks to either the NP spectrum ($c_O'$) or the NP scale ($m_{f'}$). In fact, its one-loop value

$$\frac{1}{64\pi^2} \left( \text{Str} [1] \Lambda_W^2 + \text{Str} [m^2] \right)$$

(33)
makes it clear that the NP must have either a crowded ($\text{Str} [1] \sim 10^{35}$) [20, 22] or a heavy ($\text{Str} [m^2] \gtrsim M_{Pl}^2$) bosonic sector.

B. Non-Necessity of SM-NP Coupling

Emergence of the gravitational scale does not necessitate any SM-NP coupling. The SM and NP do not have to interact. The NP sector can therefore come in three different kinds:
1. **Ebony NP.** This kind of NP has no non-gravitational couplings to the SM \[40\]. It forms an insular sector (composed of, for instance, high-rank non-Abelian gauge fields and fermions \[18, 20\]). In view of the present searches, which seem all negative, this ebony, pitch-dark NP shows good agreement with all the available data \[8\].

2. **Dark NP.** This type of NP is neutral under the SM but couples to it via Higgs, hypercharge and lepton portals \[18, 34, 54\]. Indeed, at the renormalizable level, scalars \(H'\), Abelian vectors \(V'_\mu\) and fermions \(N'\) can couple to the SM via

\[
S_{\text{int}} = \int d^4x \sqrt{-g} \left\{ \lambda_{HH'}^2 (H^\dagger H) (H'^\dagger H') + \lambda_{BZ'} B_{\mu\nu} Z'^{\mu\nu} + [\lambda_{HN'} \mathcal{L} H N' + \text{h.c.}] \right\}
\]

(34)

in which the couplings \(\lambda_{HH'}^2, \lambda_{BZ'}, \lambda_{HN'}\) can take, none to significant, a wide range of values with characteristic experimental signals \[8, 41\].

3. **Visible NP.** In this case, the NP is partly or wholly charged under the SM (e.g., \(H'\) in (34) can be an SU(2) doublet) \[18\]. It couples to the SM with SM coupling strengths, and it seems to have already been sidelined by the current bounds \[2, 55\].

The NP sector, whose subsectors are depicted in Fig. 1 can be of any composition (ebony to dark), can have any couplings (none to significant) and can lie anywhere (from \(\Lambda_W\) to \(\Lambda_U\)) as long as the gravitational scale in (32) comes out right. Non-necessity of any sizable NP-SM couplings is what distinguishes the NP of the symmergence from SUSY, extra dimensions, composites models and others \[30\] where a sizable SM-NP coupling is a necessity. These models seem to have been marginalized by the current LHC bounds \[2\].
C. SM-NP Hierarchy and Electroweak Stability

The Higgs part of (29) makes it clear that the quadratic UV sensitivity in flat spacetime changes to Higgs-curvature coupling in metric-affine spacetime. This solves the BHP [3]. In the presence of NP, however, the Higgs sector is destabilized by not only the BHP but also the SM-NP coupling [18, 20, 56]. Indeed, the SM-NP interactions in (34), for instance, lead to a new Higgs mass correction (in addition to $\delta S_H$ in (10))

$$\delta S_H' = \int d^4x \sqrt{-g} \sum_{f'} \tilde{c}_H \lambda^2_{f'} m^2_{f'} \log \frac{m_{f'}}{\Lambda_U} H^\dagger H$$

(35)

Figure 2. The allowed and disallowed regions according to the electroweak stability bound in (36).

with a loop factor $\tilde{c}_H$. This is sensitive to not $\Lambda_U$ but $m_{f'}$. The problem is that heavier the NP larger the shift in the Higgs mass and stronger the destabilization of the electroweak scale. The more serious problem is that symmergence can do nothing about it. In fact, no UV completion can do anything about it. The reason is that problem is caused by coupling between two scale-split QFTs and there can hardly exist any solution other than suppression of the coupling itself. In SUSY, extra dimensions and compositeness SM-NP coupling is a must for them to work [30, 56]. In symmergence, however, SM-NP coupling is not a necessity [18, 20, 22]. It works with any coupling strengths such as the seesawic ones

$$\lambda^2_{f'} \lesssim \frac{m^2_{f'}}{m^2_{f'}}$$

(36)

with which the Higgs mass shift in (35) falls below the Higgs mass to ensure stability of the electroweak scale. This seesawic structure, explicated in Fig. 2 implies that heavier the NP weaker its coupling to the SM.
VI. GRAVITY SECTOR

Gravity is incorporated into the SM + NP. But, what is incorporated is metric-affine
gravity [51–53] not the GR. Discussed below is the way GR symmerges.

A. Symmergent GR

The problem is to determine how metric-affine gravity can reduce to GR. This reduction,
which is what the third stage of symmergence in (28) is all about, is decided by the dynamics
of the affine connection. The latter is governed by the affine part of the SM + NP action

\[
\int d^4x \sqrt{-g} \left\{ -Q_{\mu\nu}(\Gamma) + \frac{(c_O + c_O')}{16} \left( \mathcal{R} \right)^2 \right\}
\]

in which

\[
Q_{\mu\nu} = (q + q')g_{\mu\nu} - c_V \text{Tr}\{V_\mu V_\nu\} - c_{V'} \text{Tr}\{V'_\mu V'_\nu\}
\]

extends the \( q \) in (31) to the NP sector as \( q' = q\left(c_O \to c_O', \ c_H \to c_{H'}, \ c_F \to c_{F'}\right) \). The equation of motion for \( \Gamma^\lambda_{\mu\nu} \) [51]

\[
\Gamma_{\nu\lambda} Q_{\mu\nu} = 0
\]

assumes the solution

\[
\Gamma^\lambda_{\mu\nu} = g^\lambda_{\mu\nu} + \frac{1}{2}(Q^{-1})^\lambda_\rho \left( \nabla_\mu Q_{\rho\nu} + \nabla_\nu Q_{\rho\mu} - \nabla_\rho Q_{\mu\nu} \right)
\]

which expresses \( \Gamma^\lambda_{\mu\nu} \) in terms of its own curvature \( R_{\mu\nu}(\Gamma) \) through \( q \) and \( q' \). This dependence
on curvature is critical because if it is the case then \( \Gamma^\lambda_{\mu\nu} \) obeys a differential equation through (40) and carries extra geometrical degrees of freedom not found in \( g^\lambda_{\mu\nu} \) [53]. This means
that \( R_{\mu\nu}(\Gamma) \) must disappear from \( Q_{\mu\nu} \) for GR to symmerge, and it does so if

\[
c_O + c_O' = 0 \ \text{or, equivalently, Str [1] = 0}
\]

or, equivalently, SM + NP has equal bosonic and fermionic degrees of freedom. This fermi-
bose balance does of course not mean a proper SUSY model as because SM-NP couplings
do not have to support a SUSY structure [30]. All it does is to trim \( Q_{\mu\nu} \) down to

\[
\dot{Q}_{\mu\nu} = \left( \frac{M^2}{2} + \frac{c_\phi}{4} \phi^\dagger \phi \right) g^{\mu\nu} - c_V \text{Tr}\{\mathcal{V}^\mu \mathcal{V}^\nu\}
\]
where \( \phi = \{ H, H' \} \) are scalars in SM + NP, \( V_\mu = \{ V_\mu, V'_\mu \} \) are vectors in SM + NP, and

\[
M^2 = \frac{c}{2} m_f^2 + \frac{c'}{2} m_f'^2, \quad \frac{1}{\text{1-loop}} \text{Str} \left[ m^2 \right] \frac{64\pi^2}{16(1)} \tag{43}
\]

is the apparent gravitational scale. Now, GR can symmerge because \( \Gamma^\lambda_{\mu\nu} \) is an auxiliary field (algebraic solution) that contains no geometrical degrees of freedom beyond \( g \Gamma^\lambda_{\mu\nu} \). The only side effect is the Planck-suppressed \( \phi \) and \( V_\mu \) composites \( \mathcal{O}_n (\phi, V) \) that arise in connection

\[
\Gamma^\lambda_{\mu\nu} = g \Gamma^\lambda_{\mu\nu} + \left( \nabla^2 \right)_{\mu\nu} + \frac{\nabla^\lambda \nabla^\nu - \nabla^\lambda \nabla^\nu}{M^2} + \frac{\mathcal{O}_5 (\phi, V)}{M^4} \tag{44}
\]

and spread to curvature

\[
\mathbb{R}_{\mu\nu} (\Gamma) = R_{\mu\nu} (g \Gamma) + \left( \nabla^2 \right)_{\mu\nu} + \frac{\nabla^\lambda \nabla^\nu - \nabla^\lambda \nabla^\nu}{M^2} + \frac{\mathcal{O}_6 (\phi, V)}{M^4} \tag{45}
\]

with \( \left( \nabla^2 \right)_{\mu\nu} = \nabla^\alpha \nabla_\mu \delta^\beta_{\nu} + \nabla^\alpha \nabla_\nu \delta^\beta_{\mu} - \Box \delta^\alpha_{\mu} \delta^\beta_{\nu} - \nabla_\nu \nabla_\mu g^{\alpha\beta} \). This particular affine curvature leads to the reductions

\[
\int d^4x \sqrt{-g} \frac{M^2}{2} \mathbb{R} \sim \int d^4x \sqrt{-g} \left\{ \frac{M^2}{2} R(g) \right\} \tag{46}
\]

\[
\int d^4x \sqrt{-g} \phi^\dagger \phi \mathbb{R} \sim \int d^4x \sqrt{-g} \left\{ \phi^\dagger \phi R(g) \right\} \tag{47}
\]

\[
\int d^4x \sqrt{-g} \text{Tr} \left[ \nabla^\mu \left( \mathbb{R}_{\mu\nu} - R_{\mu\nu} \right) \nabla^\nu \right] \sim \int d^4x \sqrt{-g} \left\{ 0 \right\} \tag{48}
\]

up to higher-order operators of the form \( \mathcal{O}_6 (\phi, V)/M^4 \). The gauge part vanishes and thus GR gets incorporated into the SM + NP

\[
\int d^4x \sqrt{-g} \left\{ - \left( \frac{M^2}{2} + c \phi^\dagger \phi \right) R(g) + \frac{\mathcal{O}_6 (\phi, V)}{M^2} \right\} \tag{49}
\]

as the Einstein-Hilbert action for non-minimally coupled scalars \( \phi = H, H' \). 

**B. Gravitational Constant**

The fundamental scale of gravity, as follows from (49), is given by

\[
M_{Pl}^2 = M^2 + \frac{c \phi}{2} \phi^\dagger \phi \frac{1}{\text{1-loop}} \text{Str} \left[ m^2 \right] \frac{64\pi^2}{16} + \frac{c_{\phi}^{(1)}}{2} \phi^\dagger \phi \tag{50}
\]
in which the vacuum contribution becomes important when \( \sum_{H'} c_{H'} \langle H'^* H' \rangle \sim M^2 \). The first part, identical to (43), implies that the bosonic sector of the NP must be either crowded \( (n_B^' \sim 10^{35} \text{ and } m_{f^'} \gtrsim \Lambda_W) \) [18, 20, 22] or heavy enough \( (n_B^' \sim \text{much less yet } m_{f^'} \lesssim \Lambda_U) \) for it to be able to induce the trans-Planckian scale \( 8\pi M_{Pl} \).

The NP sector, needed for induction of the gravitational scale as in (50), might have structure. Indeed, given the fermi-bose balance in \( \text{SM+NP} \) and given also that \( \text{Str} \left[ m^2 \right] \) in (50) is reminiscent of the mass sum rule in broken SUSY [24, 30], it turns out that the SM and NP, with the seesawic couplings in (36), might be remnants of a trans-Planckian SUSY broken around \( 8\pi M_{Pl} \). In fact, this might provide an explanation for why symmergence must start with flat spacetime \( \text{SM + NP} \) in that the alleged SUSY theory, whose breaking occurs with an anomalous \( U(1) \) factor [24] to generate the nonzero sum rule in (50), cannot couple to gravity due to the anomaly. In other words, flat spacetime QFT might be viewed as a signature of SUSY. These features can be useful for probing trans-Planckian physics but a complete NP model, which presumably is subject matter of a whole different study, is not an urgency as far as the gravitational constant is concerned.

C. Suppression of CCB

Nullification of the gauge part in (48) ensures that color and electromagnetism are restored and electroweak breaking is rendered spontaneous up to doubly Planck-suppressed \( \phi \) and \( \nu_\mu \) composites. This is important for assuring neutralization of the CCB in accordance with the symmergence principle. What is more important is that the Planck-suppressed terms in (49)

\[
\int d^4 x \sqrt{-g} \left\{ \frac{\hat{Q}^{\mu\nu} (\nabla^2)^{\alpha\beta}_{\mu\nu} \hat{Q}_{\alpha\beta}}{M_{Pl}^2} + \frac{\mathcal{D}_S(\phi, \nu)}{M_{Pl}^4} \right\}
\]

(51)

generate no gauge boson mass terms thanks to the differential operator \( (\nabla^2)^{\alpha\beta}_{\mu\nu} \).

D. Cosmological Constant and the UV Boundary

The total vacuum energy at one loop

\[
V(\Lambda_U) = V_{\text{tree}}(\langle \phi \rangle) + \frac{1}{64\pi^2} \text{Str} \left[ m^4 \left( \log \frac{m^2}{\Lambda_U^2} - \frac{1}{2} \right) \right]
\]

(52)
is composed of the tree-level potential plus the loop corrections involving the UV scale $\Lambda_U$. It does not have to be small. In fact, it can readily exceed the current observational bounds to give cause to the CCP [25]. Needless to say, the CCP arises from not the $\Delta^4$ sensitivity in (11) (which is neutralized by symmergence as in (29)) but the energies released by the electroweak (and QCD) and possible NP transitions as well as the zero-point energies of all the SM + NP fields. The question of how these distinct energy sources, making up (52), can conspire to yield the observed value $V_{obs} = (2.57 \times 10^{-3} \text{eV})^4$ [7] is what the CCP is all about [25]. Indeed, the empirical equality

$$V(\Lambda_U^0) = V_{obs}$$ (53)

gives a fix on the UV boundary in that the solution $\Lambda_U = \Lambda_U^0$ expresses $\Lambda_U$ in terms of the SM and NP parameters. This solution can hardly make any sense unless the aforementioned energy sources are put in relation by some governing rule. Indeed, a rule, which might be a remnant of the trans-Planckian SUSY above $8\pi M_{Pl}$ [59], can prevent fine-tuning to lead to a physically viable $\Lambda_U^0$.

**VII. EXPERIMENTAL TESTS**

Symmergent gravity and the NP it necessitates agree with all the existing bounds thanks to their prediction that gravity is Einstein (as in [7]), missing matter can be ebony (as in [8]), and non-SM interactions are not a necessity (as in [2]). In case of experimental discoveries, however, they can be probed with conclusive tests via the dark matter and SM-NP couplings.

**A. Higher-Curvature Terms**

Symmergence leads uniquely to Einstein gravity. It excludes all higher-curvature terms. This is an important result since extinction of higher-curvature terms is impossible to guarantee in a theory in which general covariance is the only symmetry. To this end, the question of why it is not $f(R)$ gravity [26] but just the GR has an answer in symmergence. And current observations [7] seem to have already confirmed the symmergence.
Figure 3. The NP scalar $H'$ can have sizeable decay rates at large VEV.

B. Cosmic Rays

The Planck-suppressed $\phi$ and $V_\mu$ composites in (51) do not produce any mass terms. They can produce, however, sizable signals if the NP scalars $H'$ develop large VEVs (compared to $M_{Pl}$). This effect, as depicted in Fig. 3, leads to observable effects. The $H'$ decays into two gluons of GZK energy \[27\], for instance, occurs at a rate

$$\Gamma (gg) \approx \left( \frac{c_{H'}}{10^{-2}} \right)^2 \left( \frac{c_g}{10^{-2}} \right)^2 \left( \frac{m_{H'}}{10^{11} \text{ GeV}} \right)^5 (8.08 \text{ min})^{-1} \tag{54}$$

with $\langle H' \rangle \simeq m_{H'}$. These gluons can partake in ultra high energy cosmic rays \[28\] upon hadronization. The diphotons, produced similarly, can contribute to diffuse gamma-ray background \[29\]. These events, which weaken at low $\langle H' \rangle$, are cosmic probes of symmergence.

C. Collider Searches

One immediate implication of the bound \[36\] is that heavier the NP larger the luminosity needed to probe them at colliders. This can prove important in designing accelerators and detectors, as implied by the exemplary analyses below.
Figure 4. Basic search channels for NP scalars ((a) and (b)) and NP vectors ((c) and (d)).

1. NP Scalars and Vectors

One way to see if the underlying model is symmergence or not is to measure scalar and vector masses and then determine if their production cross sections comply with the seesawic couplings in [36]. For instance, $m_{H'}$ can be measured from either of $HH \rightarrow H' \rightarrow HH$ in Fig. 4 (a) or $HH \rightarrow H'H'$ in Fig. 4 (b) such that the ratio of their cross sections

$$\frac{\sigma(HH \rightarrow H' \rightarrow HH)}{\sigma(HH \rightarrow H'H')} \simeq \left(\frac{m_H^2}{m_{H'}^2}\right)^2$$

acts as an efficient probe of symmergence. This procedure works also for the $Z'$ scatterings in Fig. 4 (c) and Fig. 4 (d). These $2 \rightarrow 2$ scatterings (and various other channels) can be directly tested at present [31] and future [32–33] colliders.
2. **Right-Handed Neutrinos**

Symmergence has testable implications also for right-handed neutrinos. Indeed, if the bound \( \text{(36)} \) is to be respected and if the active neutrinos are to have correct masses \( (m_\nu \lesssim 1 \text{ eV}) \) then the right-handed neutrinos must have masses \( \text{[34, 35]} \)

\[
m_{N'} \lesssim 1000 \text{ TeV} \tag{56}
\]

which can be probed at future experiments (based presumably on Higgs factories and accelerator neutrinos \text{[36]} \) if not indirectly at the near-future SHiP experiment \text{[37]} \). For \( m_\nu \lesssim 0.1 \text{ eV} \text{[38]} \), as revealed with recent cosmological data, the bound in \( \text{(56)} \) increases by an order of magnitude.

**D. Running Couplings**

Symmergence leaves behind only logarithmic sensitivity to the UV boundary. This remnant sensitivity, with all gauge symmetries restored, can naturally be interpreted in the language of dimensional regularization. Indeed, the formal correspondence \text{[18, 20, 22, 39]} \)

\[
\log \left( \frac{\Lambda_0}{\Lambda_W} \right)^2 = \frac{1}{\epsilon} + \log \left( \frac{\Lambda_U}{\mu} \right)^2 \tag{57}
\]

expresses all amplitudes in terms of the renormalization scale \( \mu \) after subtracting \( 1/\epsilon \) terms in \( \overline{\text{MS}} \) scheme. Their independence from \( \mu \) leads to the well-known RGEs. The important point here is that dimensional regularization arises as a result, not as a regularization method chosen from the beginning. The testable feature is that the SM couplings and masses must run as in the SM at all scales unless the NP lies close to \( \Lambda_W \). It can be directly tested at present \text{[31]} \) and future \text{[32, 33]} \) colliders.

**E. Dark Matter**

Symmergence has candidates for missing matter in both the ebony and dark NP sectors. The question of which one is preferred by nature can be answered only by observations (on, for instance, less-baryonic galaxies like cosmic seagull \text{[60]} \).

The dark NP can be probed directly \text{[8, 41]} \). The scalar field \( H' \) in \text{[34]} \), for instance, develops a vanishing VEV, \( \langle H' \rangle = 0 \), and becomes stable if it is real and has odd \( \mathbb{Z}_2 \) parity.
with respect to $H$. It is stable but its density is depleted by not only the expansion of the Universe but also the coannihilations into the SM fields as $H' H' \to W^+ W^-, ZZ, \bar{t} t, \cdots$. The coannihilations into $W/Z$ are Goldstone-equivalent to $H' H' \to HH$ in Fig. 4(b) so that $H'$ scalars attain the observed relic density $[8, 61]$ if

$$\lambda_{HH'}^4 \left( \frac{\text{GeV}}{m_{H'}} \right)^2 \approx 10^{-7}$$

(58)
or, impliedly,

$$m_{H'} \lesssim 367 \text{ GeV}$$

(59)
after using the seesawic structure in (36) for $\lambda_{HH'}$. This bound on $m_{H'}$, which makes sense barely as it lies beneath $\Lambda_W$, implies that thermal dark matter cannot weigh above the electroweak scale. (Non-thermal dark matter, belonging presumably to the ebony NP, is free from this bound.) This means that symmergence can be probed by measuring the dark matter mass $[8, 41]$ and contrasting it with (59) or, more safely, with $\Lambda_W$.

F. Higgs-Curvature Coupling

The non-minimal Higgs-curvature coupling $[58]$, symmergement of the Higgs quadratic UV sensitivity in (10), is a model-dependent loop factor. It has the numerical value

$$\frac{c_H}{4} \approx 1.29 \times 10^{-2}$$

(60)
as follows from (3). This prediction is specific to the SM spectrum. It changes by an amount $\propto \lambda_{HH'}^2$ in the presence of the NP. This change, as ensured by the bound (36), can be significant only if the NP lies close to the electroweak scale. This means that the questions of if the underlying mechanism is symmergence and if the NP is heavy or not can be conclusively probed by measuring $c_H$.

Obviously, $c_H$ is too small to facilitate the Higgs inflation $[42]$. It can, nevertheless, give cause to observable effects in strong gravitational fields (e.g. early universe and black hole horizons) or Planckian-energy particle scatterings $[43]$.

The non-minimal $H'$-curvature coupling $[58]$ is expected to have similar features. Indeed, $c_{H'}$ in (49) can be directly computed with a concrete NP model. It may differ significantly from $c_H$. In fact, what drives cosmic inflation could well be $H'$ not $H$ $[18, 20]$.
VIII. CONCLUSION

Needless to repeat, symmergence propounds a novel framework in which notorious problems of the SM can be consistently addressed. It incorporates GR into the SM with a seesawic NP sector, and can be probed conclusively via various experimental tests ranging from collider searches to dark matter. Highlighted in Fig. 5 are the salient features of the symmergent GR plus seesawic NP setup. It is clear that symmergence with a seesawic NP leads to a natural and viable setup with various testable predictions.

Figure 5. Fundamental aspects of the symmergent GR plus seesawic NP setup.

The mechanism needs be furthered in certain aspects, however. One aspect refers to trans-Planckian SUSY, its breaking mechanism, and its possible role in solving the CCP. Another aspect concerns the metric-affine gravity in that it can lead to GR-like geometry in small curvature limit but behave affinely and conformally in high curvature limit so that a complete solution [22] may reveal unprecedented structures (in place of, say, black hole solutions in GR). These two and various other aspects need be studied in detail to have a complete understanding of symmergence. Experimental tests are of paramount importance to decide if symmergence is realized in nature or not.

This work is supported in part by TÜBİTAK grant 115F212. The author is grateful to Hemza Azri, Dieter van den Bleeken and Tekin Dereli for fruitful discussions on especially
the emergent affine gravity. He thanks S. Vagnozzi for bringing Ref. [38] to his attention.

[1] M. Tanabashi et al. [Particle Data Group], Phys. Rev. D 98, 030001 (2018).
[2] B. Vachon [ATLAS and CMS Collaborations], Int. J. Mod. Phys. A 31, 1630034 (2016).
[3] L. Susskind, Phys. Rev. D 20 (1979) 2619; M. J. G. Veltman, Acta Phys. Polon. B 12 (1981) 437; J. L. Feng, Ann. Rev. Nucl. Part. Sci. 63, 351 (2013) [arXiv:1302.6587 [hep-ph]]; G. F. Giudice, PoS EPS (2013) 163 [arXiv:1307.7879 [hep-ph]]; M. Dine, Ann. Rev. Nucl. Part. Sci. 65, 43 (2015) [arXiv:1501.01035 [hep-ph]].
[4] G. ’t Hooft, Stud. Hist. Phil. Sci. B 32 (2001) 157.
[5] V. C. Rubin, W. K. Ford, Jr., N. Thonnard, and M. Roberts, Astron. J. 81 (1976) 687.
[6] C. M. Will, Einstein Stud. 14, 81 (2018).
[7] N. Aghanim et al. [Planck Collaboration], Planck 2018 results. VI. Cosmological parameters, arXiv:1807.06209 [astro-ph.CO].
[8] J. Liu, X. Chen and X. Ji, Nature Phys. 13 (2017) 212 [arXiv:1709.00688 [astro-ph.CO]]; L. Baudis, European Review 26 (2018) 70 [arXiv:1801.08128 [astro-ph.CO]].
[9] K. Eppley and E. Hannah, Found. Phys. 7, 51 (1977); T. W. B. Kibble and S. Randjbar-Daemi, J. Phys. A 13, 141 (1980); J. Mattingly, Phys. Rev. D 73 (2006) 064025 [gr-qc/0601127].
[10] S. A. Fulling, Phys. Rev. D 7 (1973) 2850; V. Mashkevich, Notes on Quantum Field Theory in Curved Spacetime: Problems Relating to the Concept of Particles and Hamiltonian Formalism, arXiv:0706.1802v2 [physics.gen-ph].
[11] R. Hedrich, Phys. Phil. 2010, 016 (2010) [arXiv:0908.0355 [gr-qc]]; B. Schulz, Review on the quantization of gravity, arXiv:1409.7977 [gr-qc].
[12] J. Mattingly, Einstein Stud. 11, 327 (2005); S. Carlip, Class. Quant. Grav. 25, 154010 (2008) [arXiv:0803.3456 [gr-qc]]; S. Boughn, Found. Phys. 39 (2009) 331 [arXiv:0809.4218 [gr-qc]].
[13] P. A. R. Ade et al. [BICEP2 and Planck Collaborations], Phys. Rev. Lett. 114, 101301 (2015) [arXiv:1502.00612 [astro-ph.CO]].
[14] A. D. Sakharov, Dokl. Akad. Nauk Ser. Fiz. 177, 70 (1967) [Sov. Phys. Usp. 34, 394 (1991)]; M. Visser, Mod. Phys. Lett. A 17, 977 (2002) [gr-qc/0204062].
[15] E. P. Verlinde, JHEP 1104, 029 (2011) [arXiv:1001.0785 [hep-th]].
[16] S. Carlip, Stud. Hist. Phil. Sci. B 46, 200 (2014) [arXiv:1207.2504 [gr-qc]].
[17] D. Demir, *A Mechanism of Ultraviolet Naturalness*, arXiv:1510.05570 [hep-ph].

[18] D. Demir, Adv. High Energy Phys. **2016** (2016) 6727805 [arXiv:1605.00377 [hep-ph]]; *Naturalizing Gravity of the Quantum Fields, and the Hierarchy Problem*, arXiv:1703.05733 [hep-ph].

[19] D. Demir, *Curved Equivalence Principle and Hierarchy Problem*, talk at “XIth International Conference on the Interconnection Between Particle Physics and Cosmology” (PPC2017), 22-26 May 2017, Corpus Christi, Texas, USA [http://sci.tamu.edu/events/ppc/]

[20] D. Demir, *Symmergent Gravity*, talk at “Beyond Standard Model: From Theory To Experiment Workshop” (BSM2017), 17-21 December 2017, Hurghada, Egypt [https://indico.cern.ch/event/607442/]

[21] D. Demir, *Symmergent Gravity and Ultraviolet Stability*, talk at “High Energy Physics, Astrophysics and Cosmology Workshop” (HEPAC2018), 8-9 February 2018, Istanbul, Turkey [http://yefak.org/yefak-2018-giris/]

[22] D. Demir, *Symmergent Gravity and Ultraviolet Physics*, talk at “Quantization, Dualities and Integrable Systems Workshop” (QDIS-16), 21-23 April 2018, Istanbul, Turkey [https://sites.google.com/view/qdis2018/]

[23] M. E. Peskin and D. V. Schroeder, *An Introduction to quantum field theory*, Reading, USA: Addison-Wesley (1995); M. D’Attanasio and T. R. Morris, Phys. Lett. B **378** (1996) 213 [hep-th/9602156].

[24] G. R. Dvali and A. Pomarol, Phys. Rev. Lett. **77**, 3728 (1996) [hep-ph/9607383]; Nucl. Phys. B **522**, 3 (1998) [hep-ph/9708364]; P. Binetruy and E. Dudas, Phys. Lett. B **389**, 503 (1996) [hep-th/9607172].

[25] Y. B. Zeldovich, JETP Lett. **6**, 316 (1967); S. Weinberg, Rev. Mod. Phys. **61**, 1 (1989).

[26] A. De Felice and S. Tsujikawa, Living Rev. Rel. **13**, 3 (2010) [arXiv:1002.4928 [gr-qc]].

[27] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, JETP Lett. **4**, 78 (1966) [Pisma Zh. Eksp. Teor. Fiz. **4**, 114 (1966)].

[28] P. Bhattacharjee and G. Sigl, Phys. Rept. **327**, 109 (2000) [astro-ph/9811011].

[29] M. Fornasa and M. A. Sanchez-Conde, Phys. Rept. **598**, 1 (2015) [arXiv:1502.02866 [astro-ph.CO]].

[30] C. Csaki, C. Grojean and J. Terning, Rev. Mod. Phys. **88**, 045001 (2016) [arXiv:1512.00468 [hep-ph]]; C. Csaki and P. Tanedo, *Beyond the Standard Model*, arXiv:1602.04228 [hep-ph].

[31] V. Khachatryan et al. [CMS Collaboration], Eur. Phys. J. C **75**, 186 (2015) [arXiv:1412.1633]
[32] D. d’Enterria et al., Proceedings, High-Precision \( \alpha_s \) Measurements from LHC to FCC-ee: Geneva, Switzerland, October 2-13, 2015 [arXiv:1512.05194 [hep-ph]].

[33] H. Baer et al., The International Linear Collider Technical Design Report - Volume 2: Physics, [arXiv:1306.6352 [hep-ph]].

[34] L. Canetti, M. Drewes and M. Shaposhnikov, Phys. Rev. Lett. 110, no. 6, 061801 (2013) [arXiv:1204.3902 [hep-ph]].

[35] F. Vissani, Phys. Rev. D 57 (1998) 7027 [hep-ph/9709409]; P. Chattopadhyay and K. M. Patel, Nucl. Phys. B 921 (2017) 487 [arXiv:1703.09541 [hep-ph]].

[36] D. Demir, C. Karahan, B. Korutlu and O. Sargn, Eur. Phys. J. C 77, no. 9, 593 (2017) [arXiv:1708.07956 [hep-ph]].

[37] G. De Lellis, EPJ Web Conf. 179, 01002 (2018); P. Mermod, Right-handed neutrinos: the hunt is on!, [arXiv:1704.08635 [hep-ex]].

[38] S. Vagnozzi, E. Giusarma, O. Mena, K. Freese, M. Gerbino, S. Ho and M. Lattanzi, Phys. Rev. D 96, 123503 (2017) [arXiv:1701.08172 [astro-ph.CO]].

[39] K. Hagiwara, S. Ishihara, R. Szalapski and D. Zeppenfeld, Phys. Rev. D 48, 2182 (1993); G. Cynolter and E. Lendvai, Cutoff Regularization Method in Gauge Theories, [arXiv:1509.07407 [hep-ph]].

[40] Y. Tang and Y. L. Wu, Phys. Lett. B 758, 402 (2016) [arXiv:1604.04701 [hep-ph]]; Y. Ema, K. Nakayama and Y. Tang, [arXiv:1804.07471 [hep-ph]].

[41] F. Kahlhoefer, Int. J. Mod. Phys. A 32, 1730006 (2017) [arXiv:1702.02430 [hep-ph]].

[42] F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B 659, 703 (2008) [arXiv:0710.3755 [hep-th]].

[43] J. Ren, Z. Z. Xianyu and H. J. He, JCAP 1406, 032 (2014) [arXiv:1404.4627 [gr-qc]].

[44] G. Aad et al. [ATLAS and CMS Collaborations], Phys. Rev. Lett. 114 (2015) 191803 [arXiv:1503.07589 [hep-ex]].

[45] O. Cheyette, Nucl. Phys. B 297, 183 (1988); S. H. H. Tye and Y. Vtorov-Karevsky, Int. J. Mod. Phys. A 13, 95 (1998) [hep-th/9601176].

[46] J. D. Norton, Rep. Prog. Phys. 56 (1993) 791.

[47] S. M. Carroll, A. De Felice, V. Duvvuri, D. A. Easson, M. Trodden and M. S. Turner, Phys.
[48] B. Kors and P. Nath, Phys. Lett. B 586, 366 (2004) [hep-ph/0402047]; H. Ruegg and M. Ruiz-Altaba, Int. J. Mod. Phys. A 19, 3265 (2004) [hep-th/0304245].

[49] J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. 127, 965 (1962); S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967).

[50] S. Deser, Gen. Rel. Grav. 1, 9 (1970) [gr-qc/0411023]; Class. Quantum Grav. 4 L99-L105 (1987); Gen. Rel. Grav. 42, 641 (2010) [arXiv:0910.2975 [gr-qc]].

[51] F. Bauer and D. A. Demir, Phys. Lett. B 665 (2008) 222 [arXiv:0803.2664 [hep-ph]]; Phys. Lett. B 698 (2011) 425 [arXiv:1012.2900 [hep-ph]].

[52] F. W. Hehl, J. D. McCrea, E. W. Mielke and Y. Ne’eman, Phys. Rept. 258, 1 (1995) [gr-qc/9402012].

[53] D. Vassiliev, Annalen Phys. 14, 231 (2005) [gr-qc/0304028]; V. Vitagliano, T. P. Sotiriou and S. Liberati, Annals Phys. 326, 1259 (2011) Erratum: [Annals Phys. 329, 186 (2013)] [arXiv:1008.0171 [gr-qc]].

[54] S. Y. Choi, C. Englert and P. M. Zerwas, Eur. Phys. J. C 73, 2643 (2013) [arXiv:1308.5784 [hep-ph]].

[55] M. Escudero, A. Berlin, D. Hooper and M. X. Lin, JCAP 1612, 029 (2016) [arXiv:1609.09079 [hep-ph]].

[56] R. Barbieri and A. Strumia, The 'LEP paradox', [hep-ph/0007265]; A. Birkedal, Z. Chacko and M. K. Gaillard, JHEP 0410 (2004) 036 [hep-ph/0404197]; R. Foot, A. Kobakhidze, K. L. McDonald and R. R. Volkas, Phys. Rev. D 89 (2014) 115018 [arXiv:1310.0223 [hep-ph]].

[57] D. A. Demir, Phys. Lett. B 701, 496 (2011) [arXiv:1102.2276 [hep-th]].

[58] V. Faraoni, Phys. Rev. D 53, 6813 (1996) [astro-ph/9602111]; D. A. Demir, Phys. Lett. B 733 (2014) 237 [arXiv:1405.0300 [hep-ph]].

[59] E. Witten, Mod. Phys. Lett. A 10, 2153 (1995) [hep-th/9506101]; G. R. Dvali, Cosmological constant and Fermi-Bose degeneracy, [hep-th/0004057]; T. Banks, Int. J. Mod. Phys. A 29, 1430010 (2014) [arXiv:1402.0828 [hep-th]].

[60] V. Motta et al., Astrophys. J. 863, L16 (2018) [arXiv:1808.02828 [astro-ph.GA]].

[61] C. P. Burgess, M. Pospelov and T. ter Veldhuis, Nucl. Phys. B 619, 709 (2001) [hep-ph/0011335].