

# The Standard Model of particle physics as a conspiracy theory and the possible role of the Higgs boson in the evolution of the early universe \*

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I am considering Veltman’s “The Infrared - Ultraviolet Connection” addressing the issue of quadratic divergences and the related huge radiative correction predicted by the electroweak Standard Model (SM) in the relationship between the bare and the renormalized theory, commonly called “the hierarchy problem” which usually is claimed that this has to be cured. After the discovery of the Higgs particle at CERN, which essentially completed the SM, an amazing interrelation of the leading interaction strengths of the gauge bosons, the top-quark, and the Higgs boson showed up amounting that the SM allows for a perturbative extrapolation of the running couplings up to the Planck scale. The central question concerns the stability of the electroweak vacuum, which requires that the running Higgs self-coupling stays positive. Although several evaluations seem to favor the meta-stability within the experimental and theoretical parameter-uncertainties, one should not exclude the possibility that other experiments and improved matching conditions will be able to establish the absolute stability of the SM vacuum in the future. I will discuss the stable vacuum scenario and its impact on early cosmology, revealing the Higgs boson as the inflaton. It turns out that the Standard Model’s presumed “hierarchy problem” and similarly the “cosmological constant problem” resolve themselves when we understand the SM as a low energy effective tail that is emergent from a cutoff-medium at the Planck scale. “The Infrared - Ultraviolet Connection” conveyed by the Higgs boson mass renormalization appears in a new light when the energy dependence of the SM couplings is taken into account. The bare Higgs boson mass square then changes sign below the Planck scale where it is activating the Higgs mechanism. At the same time, it reveals that the SM towards the Planck scale is in the symmetric phase, where the Higgs potential provides a high dark energy density triggering inflation, and four heavy Higgs bosons which decay and thereby are reheating the inflated early universe.

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\* To the memory of our distinguished colleague and guide Prof. Martinus Veltman with his remarkable record in particle physics

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## 1. Introduction and Overview

I review some points advanced by Martinus Veltman [1, 2] which allow us to understand better what is behind the electroweak (EW) Standard Model's peculiar structure and how this fits perfectly into attempts to consider the Standard Model (SM) as a low energy effective theory of a cutoff fine-grained “ether” at the Planck scale  $\Lambda_{\text{Pl}}$ . The discovery of the Higgs boson [3, 4] by the ATLAS and CMS Collaborations at the LHC at CERN [5, 6] opened a new book in particle physics. We now see the SM in a new light, not so much because the Higgs boson has been found finally, but much more because of the very special mass, the Higgs boson proved to have. In fact the heaviest SM states, the weak gauge bosons, the top-quark, and the Higgs boson, interact with each other in such a way that the leading SM couplings fall into a very narrow window which allows for a stable Higgs vacuum up to the Planck scale and, equally surprising, the SM remains accessible to perturbation theory up to the Planck scale.

The reason seems to be a kind of self-organized conspiracy between SM couplings with an amazing balance between bosonic and fermionic contributions in the renormalization group evolution of parameters as a function of the energy. With the other couplings given, the Higgs boson self-coupling  $\lambda$  appears to be self-tuned to let us understand the SM as emergent from the Planck medium. If the Higgs vacuum remains stable up to the Planck scale, the SM would shape the dynamics of the early universe, with inflation, reheating, and what else triggered by the Higgs system. The Higgs potential inevitably would provide a huge strongly time-dependent cosmological constant that shapes inflation and consequently also modifies the time-dependence of the Hubble constant (see e.g. [7]). While effective SM parameters change little after the time of Big-Bang nucleosynthesis, early cosmology may be shaped in a previously unexpected manner. Indeed, the Higgs boson is the only SM particle that directly couples to gravity, as a leading contribution to the energy-momentum tensor in Einstein's field equations. The relevant object is the Higgs potential

$$V(\phi) = \frac{m^2(\mu^2)}{2} \phi^2 + \frac{\lambda(\mu^2)}{24} \phi^4,$$

depending on the renormalization scale  $\mu$ , and, provided  $\lambda$  stays positive, the SM vacuum remains stable. The Higgs boson mass renormalization relation

$$m_{H0}^2 - m_H^2 = \delta m_H^2 = \frac{\Lambda_{\text{Pl}}^2}{(16\pi^2)} C(\mu),$$

relating the bare mass  $m_{H0}$  to the renormalized  $m_H$ , which Veltman addressed in [8] as “Infrared - Ultraviolet Connection”, obtains a new deeper meaning if we are taking into account that SM parameters are scale-dependent. It happens that the renormalization counterterm, depending sensitively on the precise actual SM parameters, shows a zero  $C(\mu_0) = 0$  at about  $\mu_0 \sim 10^{16}$  GeV at which bare and renormalized Higgs masses are coinciding. Below the zero, where the bare mass square is negative, the SM falls into the broken phase where the Higgs boson, like all other massive SM particles, acquires a mass set by the Higgs boson vacuum expectation value (VEV)  $v \sim 246$  GeV as the relevant scale. Above the zero, in the symmetric phase, the effective mass is  $m_0^2 = m_{H0}^2/2 = (m_H^2 + \delta m_H^2)/2$  effectively determined by the dominating counterterm:

$$m_0^2 \sim \delta m^2 \simeq \frac{\Lambda_{\text{Pl}}^2}{32\pi^2} C(\mu).$$

Together with the vacuum expectation value of the potential the Higgs system provides a sufficient amount of dark energy to trigger inflation, while the four heavy unstable Higgs states, which are existing in the symmetric phase, via their decays are reheating the universe. SM reheating is efficient again by peculiarities of SM physics. The existence of the third family with a strong coupling to the Higgs field let the Higgs bosons decay predominantly into top/anti-top, top/anti-bottom, etc. quark pairs and their charge conjugates; this heavy quark radiation later materializes during the EW phase transition by cascading into the much lighter quark species which are forming ordinary matter. While dark energy is an SM product the origin of the dark matter still remains a mystery in this scenario.

## 2. Veltman’s “derivation” of the Standard Model in the light of the Standard Model as a low energy effective field theory

One of Martinus Veltman’s dedications has been his drive to find a renormalizable theory for the weak interactions and to scrutinize the electroweak theory which after all culminated in the SM of particle physics. The younger particle physicists learning the SM from textbooks may have little knowledge about the obstacles one had to surmount before the established structure had been unveiled as the true theory of electroweak phenomena. The maybe strange-looking structure of the SM as a gauge theory based on the local symmetry group  $\mathcal{G}_{\text{SM}} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  (gauge couplings  $g_3$ ,  $g_2$  and  $g_1$ ) broken down to  $SU(3)_c \otimes U(1)_{\text{e.m.}}$  by the Higgs mechanism exhibits a pattern that really cries for explanations. Veltman’s curiosity has been focused more on the question of what makes the SM so unique, rather than to question its validity and to declare its structure unnatural.

His cardinal point in defending the SM and questioning most of the proposed SM extensions has been that, due to the minimal Higgs structure, the SM unavoidably predicts a massless photon [9], which in most other models have to be imposed as an extra condition, which then is causing a fine-tuning issue<sup>1</sup> [1]. In a remarkable paper [2]<sup>2</sup> he has given a partial but very enlightening answer by listing the general conditions which essentially allow us to derive the SM. Veltman's list of assumptions is the following:

- 1) local field theory
- 2) interactions follow from a local gauge principle
- 3) renormalizability
- 4) masses derive from the minimal Higgs system (one physical scalar only)
- 5) the right handed singlet neutrino  $\nu_R$ , which we know must exist, does not carry hypercharge.

The last assumption looks somewhat ad hoc, but we accept it. The consequences of the assumptions stated above are remarkable<sup>3</sup> (see also [11,12]):

- [1] breaking  $SU(2)_L$  by a minimal Higgs sector automatically leads to a global  $U(1)_Y$ , which can be gauged,
- [2] maximal parity violation of the weak interaction  $SU(2)_L$ ,
- [3] with  $\Theta_W$  the electroweak mixing angle, and  $M_W, M_Z$  the masses<sup>4</sup> of the  $W$  and  $Z$  bosons, the tree-level relation  $\rho = M_W^2/(M_Z^2 \cos^2 \Theta_W) = 1$ , is a parameter independent number and hence not subject to renormalization. It derives from the accidental global "custodial"  $SU(2)_{\text{cust}}$  symmetry of the Higgs system.
- [4] The existence of the strictly massless photon (one zero-eigenvalue in the spin-1 boson mass-matrix),
- [5] parity conservation of QED,
- [6] the validity of the Gell-Mann-Nishijima relation  $Q = T_3 + \frac{Y}{2}$ ,
- [7] fermion family structure (lepton-quark conspiracy –  $U(1)_Y$  anomaly cancellation),
- [8] charge quantization (if  $Y_{\nu_R} = 0$  then  $Q_i = T_{3i} + Y_i/2$  fixes  $Q_i$ ).

Here we have to add that the requirement of renormalizability also enforces **the existence of a physical neutral spin 0 particle, the Higgs bo-**

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<sup>1</sup> The simplest supersymmetric model accidentally escapes this problem and predicts a zero photon mass.

<sup>2</sup> For related considerations see [10].

<sup>3</sup> The interested reader really should take the time and have a look at Veltman's surprisingly simple derivation.

<sup>4</sup> I denote physical masses by capital the related  $\overline{\text{MS}}$  masses by lower case letters.

**son**<sup>5</sup>. We do not know why right-handed neutrinos are sterile i.e. do not couple to gauge bosons; they only couple to the Higgs field. Nevertheless, this property fits with a minimality principle “not more than necessary”. In the SM of electroweak interactions, neutrinos originally were assumed to be massless although it has not been required by the SM gauge symmetry structure but had to be imposed by an extra global  $U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$ , implying that right-handed neutrinos did not exist (or did not couple to anything) such that neutrinos had to be massless. This is definitely ruled out by the observation of neutrino oscillations, meaning that each of the subgroups  $U(1)_\ell$  is only partially conserved. Indeed, lepton-flavor number conservation is not an emergent property but is resulting from the smallness of the neutrino masses. In other words,  $e$ ,  $\mu$ , and  $\tau$  only differ in the way they couple to the Higgs boson, while they have identical couplings to the gauge bosons.

Another striking property of the SM is the GIM-mechanism [13], the tree-level absence of flavor changing neutral currents, which in the SM by its renormalizability is manifestly implemented, but which requires fine-tuning in most extensions of the SM. The discrete  $Z_2$  symmetry (called R-parity) often imposed on the extended two-doublet Higgs system is not an emergent property (i.e. renormalizability does not require it).

One of the most important insights into how we perceive nature’s underlying structure has been discovered by Ken Wilson (Nobel Prize 1982 for his theory for critical phenomena in connection with phase transitions) in the early 1970s when he developed the systematic approach to understanding quantitatively the emergence of long-distance physics (macroscopic properties) from the short distance properties of the underlying microscopic systems [14] (see e.g. [15, 16]). Quite generally, the microscopic systems are exhibiting an intrinsic short distance scale i.e. they represent systems exhibiting a cutoff  $\Lambda$  and allow for a low-energy expansion in  $x = E/\Lambda$ . Dropping the suppressed terms (i.e. the positive powers in  $x$ ), the expansion yields a low energy effective tail which appears as an emergent low energy structure. In case of statistical mechanics type systems the low-energy effective structure turns out to be given by a renormalizable Euclidean Quantum Field Theory (QFT) which is universal for a wide class of systems of different short-distance properties. A groundbreaking discovery. Thereby, a non-trivial long-range tail emerges as a  $D = 4$  world because in  $D > 4$  only non-interacting free field tails are left<sup>6</sup>. The  $D - 4$  extra dimensions are

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<sup>5</sup> If not generated by the Higgs mechanism, the particle masses affect renormalizability in the  $SU(2)_L$  weak-interaction sector, which means that it is the  $SU(2)_L$  which has to be spontaneously broken by the minimal Higgs system.

<sup>6</sup> In condensed matter physics this is known as the Landau criterion [17], and is the basis for the  $\varepsilon$ -expansion about  $D = 4$  in critical phenomena [18].

hidden, unobservable when watched from far away. No need for curled-up (compactified) extra-dimensions. Renormalizable  $D = 4$  Euclidean QFTs are equivalent to Minkowski QFTs (Osterwalder-Schrader theorem), the basic structure on which our understanding of particle physics is relying. Note that this mathematical equivalence is a property of the long-distance tail and thus a Euclidean  $D \geq 4$  dimensional short distance system may naturally show its appearance to us as a  $(3,1)$ -dimensional Minkowski space-time, i.e. also Lorentz-invariance (pseudo-rotations) is an emergent symmetry, means, also here we got rid of the “ether”. This could mean that also time is an emergent property that only exists in the low energy tail perceived. Thereby renormalizability and analyticity are the key ingredients. Based on the Euclidean-Minkowskian equivalence Wilson himself developed the tool for solving non-perturbative hadron physics based on Euclidean lattice Quantum Chromodynamics (QCD)<sup>7</sup>.

Originally, the SM [9, 13, 19] is a minimal renormalizable completion of Fermi’s weak interaction + QED, supplemented by QCD [20] and two more fermion families. But now “what is not capable of surviving at long distances does not exist there” (Darwin revisited). The SM appears as a natural minimal emergent structure in a low energy expansion from a cutoff system sitting at the Planck scale! But this is not the only consequence: in fact, in this kind of scenario, the SM which we supplemented by the Planck cutoff, leads to unexpected consequences concerning its high-energy behavior. The latter is governed by the bare (unrenormalized) theory, which must have been the relevant theory in the very hot early universe.

Important points are:

- the relationship between the renormalized and bare theory is calculable,
- taking into account the energy dependence of parameters is mandatory now, this also concerns possible power corrections (relevant operators: Higgs mass term and vacuum energy given by the Higgs potential and its VEV  $\langle V(\phi) \rangle$ ,
- leading irrelevant operators of dim 5 (may affect neutrino masses) and dim 6 (baryon number violating, required in baryogenesis) [21] naturally can play significant roles during the advent of the EW phase transition expected at about  $10^{16}$  GeV. Especially the dim 6 operators are com-

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<sup>7</sup> In contrast to the Planck cutoff regularized SM case (discussed below), here the cutoff provided by the inverse lattice spacing can’t be chosen very large, which causes serious problems in controlling lattice artifacts in the continuum limit. Therefore it is mandatory to keep the  $SU(3)_c$  non-Abelian local gauge symmetry exact on the lattice, because symmetry violating effects could not be controlled by an expansion in the cutoff in an efficient manner. In practice, the expansion parameter  $E/\Lambda$  would by far not be small enough such that the symmetry breaking terms would be suppressed as much that the symmetry would be restored accurately.

pletely suppressed at experimentally accessible energies, but in case the EW phase transition happened at very high energies not too far below the Planck mass  $M_{\text{Pl}}$ , they are still significant enough to play their role in producing the baryon asymmetry,

- a surprising outcome of the conspiracies between SM couplings is that within the SM charge screening is an exceptional property, anti-screening the rule. Apart from the non-perturbative QCD confinement regime at energies below the hadron mass scales, the SM and in particular, its high energy phase (early cosmology) are under control by perturbation theory.

I see plenty of evidence that the SM is emergent in the Wilsonian sense [14] as a renormalizable low energy tail of a cutoff system, the “ether”, sitting at the Planck scale  $\Lambda_{\text{Pl}}$ . The equivalent Planck mass  $M_{\text{Pl}} = (c\hbar/G_N)^{\frac{1}{2}} \simeq 1.22 \times 10^{19}$  GeV, dimensionally determined by Newtons gravitational constant  $G_N$ , is one of the fundamental parameters in physics and the only one representing a fundamental cutoff equivalent to a minimal length. In an expansion in  $E/\Lambda_{\text{Pl}}$  most short distance details get lost and we only see what is not suppressed by positive powers of  $E/\Lambda_{\text{Pl}}$ . Note that the cutoff in our case is not just a tool to regularize ultra-violet (UV) singularities, but represents a true physical reality behind what we see from far away. Such a UV-completed system allows us to perform a low energy expansion in the cutoff. Thereby, in the low energy tail the symmetries emerge which usually are absent within the “ether”. Since in the low energy expansion all details concerning the UV behavior are lost, it is not a problem that details about the UV completion remains unknown. Here the universality of the long-range tail is a key phenomenon well known from condensed matter systems. There is a big variety of systems having an identical tail but differ in the infinite tower of irrelevant dimension  $d_{\mathcal{O}} > 4$  operators. When we attempt to extrapolate the SM to very high scales we expect the next leading  $d_{\mathcal{O}} = 6$  operators to show up when the expansion parameter  $x = E/\Lambda_{\text{Pl}}$  is about 0.1 producing a 1% effect, i.e. SM physics can be valid up to not far below the Planck scale. When going too close to the Planck scale the expansion of course ceases to make sense. This does not mean that we lose control of the physics which derives from the fine-grained Planck system (think for example of a lattice-type SM as a prototype; that the symmetries of the continuum SM cannot be fully kept on a lattice [22] does not harm the emergent SM as a long-distance tail, as we will argue below). The SM together with its cutoff UV-completion we call Low Energy Effective

Standard Model (LEESM)<sup>8</sup>.

What makes Veltman’s “derivation” of the SM structure so instructive? As mentioned before, the SM gauge and Higgs structures, and the derived consequences just listed, at first sight, look unexpected and motivated many possible repairs: mirror fermions, grand unification, supersymmetric extensions, and many more. However, the peculiar features of the SM are immediate consequences of the general assumptions 1) to 5) above, which (besides the last point) are emergent structures when we accept that the SM is a low energy effective theory of a far away cutoff system. Maybe the most striking insight is that non-Abelian local gauge symmetries, mathematics-wise a self-evident generalization of the Abelian local gauge symmetry familiar from QED, are emergent. The question about the origin of non-Abelian local gauge symmetries has attracted attention after ’t Hooft’s proof of the renormalizability of gauge theories [23]. Calculations [24–31] (also see [32]) have shown that non-Abelian symmetry is a consequence of dropping the non-renormalizable terms showing up in the high energy behavior of tree-level matrix elements of physical processes, by imposing a tree-unitarity requirement. In fact in the LEESM scenario “dropping” is an automatic feature that derives from the strong suppression of the questionable terms. Obviously, the non-Abelian gauge structures require team-play between entries in gauge group multiplets. What is more natural than excitation modes of the hot Planck medium grouped in doublets and triplets as the simplest choices besides possible singlets? Still, what at first sight looks almost impossible, namely that the strange-looking SM structure may naturally emerge as a long-distance structure turns out to be the consequence of the fact that in the low energy expansion only a relatively small number of effective interaction vertices are seen, a tremendous simplification as we cast away an infinite tower of power-suppressed terms, related to higher-dimensional operators. The renormalizable tail, which we can see, naturally must satisfy all requirements renormalizability imposes if we, also, accept that this is to be achieved in the simplest possible (minimal) way. Remarkably, local non-Abelian gauge symmetry, as well as chiral symmetry, are mandatory for renormalizability and therefore both symmetries are naturally emergent in the low energy tail. The crux in this game is that renormalizability predicts the existence of the Higgs boson! But also that the weak interactions are maximally P violating while the QED sector is strictly P conserving are automatic consequences as a simple calculation shows [2]. While the

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<sup>8</sup> While the SM as a renormalizable QFT by itself makes predictions free from any cutoff effects (for renormalized and observable quantities parametrized in terms of measured renormalized parameters), the LEESM is an extension of the SM where the relationship between renormalized and bare parameters has a physical meaning, which also has been broached by Veltman’s “The Infrared - Ultraviolet Connection” [8].



non-Abelian gauge structure implies the characteristic gauge-cancellations resulting from the interplay of the coupling strength of all those different vertices which involve the gauge fields, the emergence of the important Abelian subgroup  $U(1)_Y$  looks much more to be a mystery. But as the calculations show, also here the minimal Higgs scenario automatically implies a  $U(1)_Y$  symmetry and a massless photon after the spontaneous  $SU(2)_L$  breaking.

There is another hidden symmetry deriving from a minimal Higgs system, the custodial symmetry, which is at the heart of the tree-level identity  $\rho = M_W^2/(M_Z^2 \cos^2 \Theta_W) = 1$  (up to finite SM radiative corrections  $\Delta\rho$ ) [33–35]. The  $\rho$ -parameter<sup>9</sup> is the flagpole for heavy states because quantum corrections at next to leading order are determined by the difference of the self-energies of the  $Z$  and the  $W$  bosons

$$\Delta\rho = \frac{\Pi_Z(0)}{M_Z^2} - \frac{\Pi_W(0)}{M_W^2} + \text{subleading terms}$$

and for dimensional reasons corrections are expected to be proportional to the mass square  $M_X^2$  of the heavy virtual state of mass  $M_X > M_Z$  contributing to the gauge boson self-energies. Most prominent is the top-quark contribution to  $\Delta\rho$  proportional to  $G_\mu M_t^2$  [35]. Precision measurements of  $\Delta\rho$  by the LEP experiments provided an important hint for the discovery of the top-quark at the Tevatron. Large effects only show up for heavier fermion-doublets with a large mass splitting like the top-bottom quark doublet  $(t,b)$  where  $m_t \gg m_b$ . Since  $G_\mu M_f^2 = y_f^2/(2\sqrt{2})$  where  $y_f$  is the Yukawa coupling of a fermion  $f$ ,  $\Delta\rho$  effectively measures the weak isospin splitting within the  $(t,b)$ -doublet which results from the difference in the top- and bottom-quark Yukawa couplings.

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<sup>9</sup> Here a special feature of the weak corrections comes into play: the non-decoupling of heavy particles. This is in contradistinction to the Appelquist-Carazzone theorem [36], which infers that heavy states of mass  $M$  are essentially without a trace at energies sufficiently below the heavy particle threshold. More precisely, effects are  $O(E/M)$  or smaller, in reactions at energies  $E \ll M$ . This does not apply in the weak sector of the SM where masses and couplings are strongly correlated, while it is valid in QED and QCD. This means for example that electroweak top-quark contributions do not only show up above the top-quark threshold. In the approximation  $M_t, M_H \gg M_Z$  the top-quark and the Higgs boson give a contribution

$$\begin{aligned} \rho(0) \equiv G_{\text{NC}}(0)/G_\mu(0) = & 1 + \frac{3\sqrt{2}G_\mu}{16\pi^2} \left\{ M_t^2 \right. \\ & \left. + \left( \frac{M_W^2}{1 - M_W^2/M_H^2} \ln M_H^2/M_W^2 - \frac{M_Z^2}{1 - M_Z^2/M_H^2} \ln M_H^2/M_Z^2 + \dots \right) \right\}, \end{aligned}$$

to the  $\rho$  parameter at **zero** momentum transfer.  $G_{\text{NC}}(0)$  and  $G_\mu(0) = G_\mu$  are the neutral and charged current effective Fermi-constants at vanishing momentum, respectively.

The custodial symmetry is responsible also for the absence of leading virtual Higgs boson effects which could contribute to  $\Delta\rho$ . There are no corrections proportional to  $G_\mu M_H^2$  but only proportional to the logarithmic term  $G_\mu M_W^2 \log(M_H^2/M_W^2)$  when  $M_H^2 \gg M_W^2$ , what made it more difficult to gather reliable information about the Higgs boson mass from electroweak precision measurements before the Higgs particle's discovery. Remains the CP violation, which was discovered as a per-mille effect in neutral kaon decays and is known as a compelling condition for the dynamical emergence of the baryon-asymmetry in the universe during baryogenesis (Sakharov conditions [37]). In the SM this is achieved automatically by the triple-replica family structure which has been proposed by Kobayashi-Maskawa [38] (see also [13, 39]). The predicted 3-family quark-flavor mixing pattern (CKM-matrix) later has been confirmed in  $B$  meson decays to happen precisely as predicted.

In place of a dogma believing that the misunderstood<sup>10</sup> hierarchy-problem (see e.g. [41]) is an illness of the SM which must be cured, e.g., by supersymmetrization of the SM as one possibility, Veltman has stressed many times the fact that within the minimal SM the zero photon mass is a prediction, not subject to renormalization, while in most SM extensions (see however footnote<sup>1</sup> and [42]) the prediction is lost and has to be imposed as an extra condition, i.e., it has to be fine-tuned [1]. Indeed, most extensions of the SM require non-minimal Higgs sectors: Two Doublet Higgs Models (TDHM), SUSY extensions like the Minimal Supersymmetric SM (MSSM), Grand Unified Theories (GUT), left-right symmetric models, the Peccei-Quinn approach to the strong CP problem, inflaton models base on an extra scalar field and many more. The masslessness of the photon is one of the most basic facts of life (no life otherwise), so why should we make this fundamental property to be something we have to arrange by hand?

In contrast, a minimalist emergent structure makes the SM pretty unique:

- I think we now can well understand how various excitations in the hot chaotic Planck medium can conspire to develop a pattern like the SM as a low energy effective structure.
- Renormalizability as a consequence of the low energy expansion and the very large gap between the EW and the Planck scales plus certain minimality (not too little but not too much e.g. only up to symmetry triplets) determines the SM structure without much freedom. One could expect that as a next extended SM structure confined  $SU(4)$  fermion quartets could provide a bound state spectrum providing dark matter [43], analogous to how QCD is supplying the bulk of ordinary matter (98% binding energy).

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<sup>10</sup> See my analysis in [12, 40].

- Minimality is not a new concept in physics as we know e.g. from the principle of least action or the SM as a minimal renormalizable extension of QED plus Fermi theory.
- The 3 fermion-families are required so that CP violation emerges naturally, and to open the possibility that baryogenesis can find an explanation within the SM. While normal matter requires sufficiently light quarks, i.e. small Yukawa couplings, the cooperation of couplings that eventually allows the SM to extend up to the Planck scale is only possible when Yukawa couplings in the ballpark of the gauge-couplings and the Higgs self-coupling exist, which is what is achieved with the third family only. A fourth family<sup>11</sup> obviously would spoil the feature of the SM that we can understand it as emergent from a Planck medium.
- It is interesting to note that QCD based on  $SU(3)_c$  local gauge-symmetry requires massless gluons. Massless gauge fields, in this case, are not only required by renormalizability but are also a condition for confinement to work. We also note that, in contrast to the electroweak sector with its 3 fermion-family structure where CP violation is automatically generated, CP violation in QCD is obtained only if we add an extra CP violating term to the Lagrangian. Indeed, this extra CP violation is not something that the low energy expansion generates necessarily unless it is inherent as a property of the “ether” itself. Indeed, CP violation seems to be absent in strong interactions and axions may not be required to exist. Keep in mind that  $P$  and  $CP$  violations are emergent in the electroweak sector and certainly are absent in the primordial “ether” medium, if not one would expect to find different  $P$ - and  $CP$ -violation patterns in the SM. Interestingly, also symmetry breaking can be an emergent feature, like maximal  $P$  violation out of a  $P$  invariant medium shows.

In what follows I review the most striking consequences of a LEESM scenario which I worked out in some details in [44, 45] (for a summary see also [46]), for the case that SM couplings are such that an extrapolation up to  $M_{\text{Pl}}$  is possible. The difference between stability and meta-stability depends on a difference in the calculation of the  $\overline{\text{MS}}$  top-quark Yukawa coupling from the top-quark mass [47]. Because of confinement in QCD, the top-quark as a colored object is not observable by itself but only a color-screened state of it. Therefore the on-shell top-quark mass usually taken as an input in the matching conditions is not what the experiment sees directly. In the end, the

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<sup>11</sup> Given the LEP and LHC 4th family mass bounds at least some of the members would have to be heavier than the top quark and the corresponding large Yukawa couplings would imply dramatic changes in the extrapolation of the SM parameter running. Also, the measured bounds of the  $\rho$  parameter essentially rule out having further fermion doublets with substantial mass splittings.

$\overline{\text{MS}}$  top-quark Yukawa coupling is not observable and is not unambiguously fixed by experiment. It rather depends on theory input, which is not fully under control because the color screening is a non-perturbative issue.

### 3. On the running SM couplings

That for a quantum field theory (QFT) coupling constants are not constant but are renormalization scale-dependent as prescribed by the renormalization groups (RGs) is known since renormalization of QFTs is known. Screening (like Abelian gauge couplings) or anti screening (like non-Abelian gauge couplings) effects let couplings grow or diminish as a function of the energy scale, respectively. These effects are well known and for the QED fine structure constant  $\alpha_{\text{QED}}(s)$  (screening) and the QCD strong interaction constant  $\alpha_s(s)$  (anti-screening) experimentally well established, where  $s$  is the center of mass energy square at which a process takes place. Of interest are the gauge couplings  $g_1$ ,  $g_2$  and  $g_3$  together with the top-quark Yukawa coupling  $y_t$  and the Higgs self-coupling  $\lambda$ , where the latter two are determined from the top-quark mass and the Higgs boson mass, respectively, via the mass-coupling relations. A crucial point here concerns the matching conditions which are required to calculate the  $\overline{\text{MS}}$  parameters from experimentally determined observables like the physical masses.

The discovery of the Higgs boson with a mass of about 125 GeV revealed an amazing conspiracy between the gauge couplings, the top-quark Yukawa coupling and the Higgs boson self-coupling. These leading couplings turn out to be falling into a narrow window [48–51] which allows us to extrapolate the SM parameters up to the Planck scale as displayed in Fig. 1. Whether this window is matched perfectly or is almost missing the bottom of the stability valley is a matter of controversy and depends on the implementation of the matching conditions which are required to calculate the  $\overline{\text{MS}}$  parameters in terms of physical couplings and/or masses. While most analyses are based on [52, 53] and predict a meta stable effective Higgs potential (see also [54–56]), a slightly modified evaluation of  $\overline{\text{MS}}$  parameters based on [57] revealed vacuum stability [12, 44]. I adopt the view:

*“Although other evaluations of the matching conditions seem to favor the meta-stability of the electroweak vacuum within the experimental and theoretical uncertainties, one should not exclude the possibility that other experiments and improved matching conditions will be able to establish the absolute stability of the Standard Model in the future.”*

Very exciting, and for me it has been completely unexpected, all SM couplings except the  $U(1)_Y$  coupling  $g_1$  behave like non-Abelian ones, i.e., they show anti-screening properties [59]. This means that perturbation theory works and gets better if we extrapolate to the Planck scale. Taking the  $\overline{\text{MS}}$  couplings at the  $Z$  boson mass scale as [12, 44]  $g_1 \simeq 0.350$ ,  $g_2 \simeq 0.653$ ,

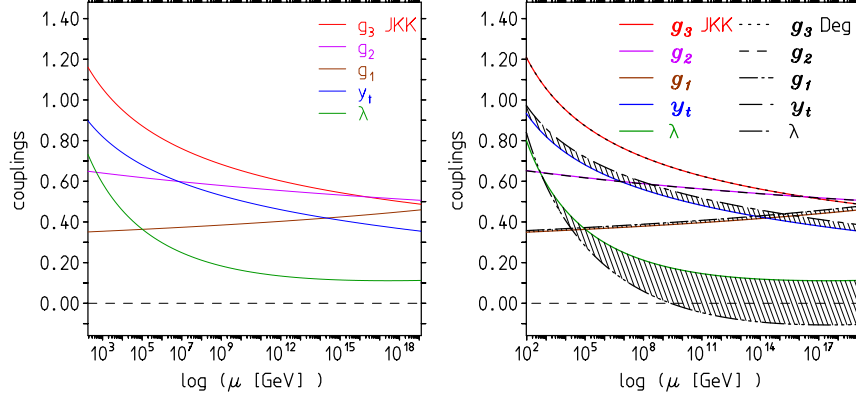


Fig. 1. Running SM parameters from the  $Z$  mass scale up to  $M_{\text{Pl}}$ . Left: on-shell vs  $\overline{\text{MS}}$  parameter matching based on F.J., Kalmykov, Kniehl [57] (JKK). Right: the same in comparison with Shaposnikov et al. [52], Degrassi et al. [53] (Deg) matching. Using JKK input parameters the vacuum remains stable, with Deg input vacuum stability breaks down at about  $10^9$  GeV and enters in a metastable state of the effective potential [58] (i.e. including radiative corrections). Small cause, great impact, just by changing a little the input parameters, most sensitive on  $y_t$ , we get a completely different behavior of the Higgs system towards the Planck era. The shaded space illustrates the parameter-matching controversy, which concerns  $y_t$  at  $M_Z$ . Plots adapted from [44].

$g_3 \simeq 1.220$ ,  $y_t \simeq 0.935$  and  $\lambda \simeq 0.807$ , the following picture arises<sup>12</sup>. While the gauge couplings behave as expected,  $g_1$  as infrared (IR) free,  $g_2$  and  $g_3$  as asymptotically (ultraviolet) free (AF), with leading coefficients exhibiting the related coupling only, and denoting  $c = \frac{1}{16\pi^2}$ , we have

$$\beta_1 = \frac{41}{6} g_1^3 c \simeq 0.00185; \quad \beta_2 = -\frac{19}{6} g_2^2 c \simeq -0.00558; \quad \beta_3 = -7 g_3^3 c \simeq -0.08049,$$

the leading top-quark Yukawa  $\beta$ -function given by

$$\begin{aligned} \beta_{y_t} &= \left( \frac{9}{2} y_t^3 - \frac{17}{12} g_1^2 y_t - \frac{9}{4} g_2^2 y_t - 8 g_3^2 y_t \right) c \\ &\simeq 0.02327 - 0.00103 - 0.00568 - 0.07048 \\ &\simeq -0.05391 \end{aligned}$$

<sup>12</sup> The RG equations  $\mu \frac{d}{d\mu} g_i(\mu) = \beta_i(g_i)$  ( $i = 1, 2, 3$ ),  $\mu \frac{d}{d\mu} y_t(\mu) = \beta_{y_t}(y_t, \dots)$  and  $\mu \frac{d}{d\mu} \lambda(\mu) = \beta_\lambda(\lambda, \dots)$  for the  $\overline{\text{MS}}$  couplings  $g_i, y_t$  and  $\lambda$  define the  $\overline{\text{MS}}$  running couplings as functions of the  $\overline{\text{MS}}$  energy scale  $\mu$ . The  $\overline{\text{MS}}$  renormalization scheme is the appropriate parametrization for the high energy behavior  $\mu \gg M_t$  where  $M_t$  is the top-quark mass, the largest of the SM masses.

not only depends on  $y_t$  but also on mixed terms with the gauge couplings which have a negative sign. Interestingly, the QCD correction is the leading contribution and determines the behavior, to be opposite from a pure Yukawa behavior. Notice the critical balance between the dominating strong- and the top-Yukawa couplings: QCD dominance requires  $g_3 > \frac{3}{4} y_t$  in the gaugeless limit ( $g_1, g_2 = 0$ ). Similarly, the  $\beta$ -function of the Higgs self-coupling, given by

$$\begin{aligned}\beta_\lambda &= (4\lambda^2 - 3g_1^2\lambda - 9\lambda g_2^2 + 12y_t^2\lambda + \frac{9}{4}g_1^4 + \frac{9}{2}g_1^2g_2^2 + \frac{27}{4}g_2^4 - 36y_t^4)c \\ &\simeq 0.01650 - 0.00187 - 0.01961 + 0.05358 + 0.00021 + 0.00149 + 0.00777 \\ &\quad - 0.17401 \simeq -0.11595\end{aligned}$$

is dominated by the top-quark Yukawa contribution and not by the  $\lambda$  coupling itself, again opposite from a pure Higgs system behavior. Here the sign of the  $\beta$ -function flips when  $\lambda < \frac{3}{2}(\sqrt{5}-1)y_t^2$  in the gaugeless ( $g_1, g_2 = 0$ ) limit. This I call true teamwork. It means that running the couplings up to the Planck scale they have to conspire there such that at long distances, we can see what we see. This light particle low energy physics is only possible for specific couplings and by the self-organized symmetries like local gauge symmetry and chiral symmetry which let emerge such light states of masses  $M_X \lll \dots M_{\text{Pl}}$ . We note that all calculations of the running parameters are based on full 2-loop matching-conditions [52–55, 57] for the input  $\overline{\text{MS}}$  couplings and 3-loop RG  $\overline{\text{MS}}$   $\beta$ -functions [60–62]. Here one should keep in mind, that the physical parameters extracted from experimental data and used as an input, in general, do not include full 2-loop electroweak corrections, so the quoted uncertainties may well be underestimated and there is definite room for improvements. For our set of input parameters, the relevant running  $\overline{\text{MS}}$  parameters at the Planck scale are of comparable size in the range 0.51 for  $g_2$  being the largest here and 0.35 for  $y_t$  being the smallest, with  $\sqrt{\lambda}$  at 0.375 slightly larger in our normalization. This couplings "pattern" at  $M_{\text{Pl}}$  is supporting the view that what was able to penetrate to low energies originates from a unifying medium. Note that approximations like the gaugeless case ( $g_1 = g_2 = 0$ ) or assuming  $\lambda \approx 0$  are not viable approximations near  $M_{\text{Pl}}$  neither anywhere at lower energy scales.

#### 4. Exploiting "The Infrared - Ultraviolet Connection"

Veltman's "The Infrared - Ultraviolet Connection" concerns the only quadratic UV divergences of the SM which in the symmetric phase concerns the mass square term in the Higgs potential

$$m_0^2 = m^2 + \delta m^2 ; \quad \delta m^2 = \frac{\Lambda_{\text{Pl}}^2}{32\pi^2} C \quad (1)$$

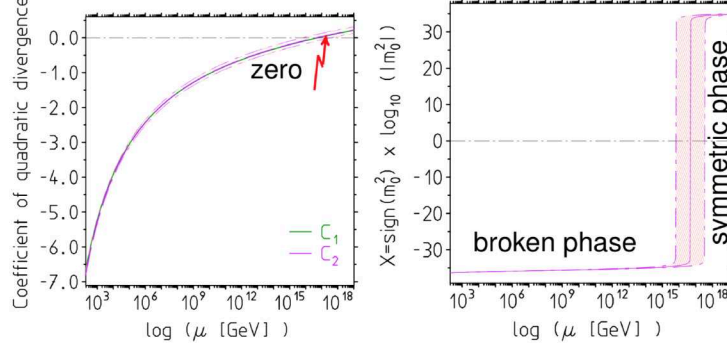


Fig. 2. The EW phase transition in the SM. Left: the zero in  $C_1$  and  $C_2$  for  $M_H = 125.10 \pm 0.14 \text{ GeV}$ . Right: shown is  $X = \text{sign}(m_0^2) \times \log_{10}(|m_0^2|)$ . At  $M_{\text{Pl}}$  we have  $m_0^2 \sim \delta m^2 \simeq \frac{\Lambda_{\text{Pl}}^2}{32\pi^2} C(\mu = \Lambda_{\text{Pl}}) \simeq (0.0295 \Lambda_{\text{Pl}})^2$ . A difference between  $C_1$  and  $C_2$  is barely visible on the plot. The shaded bands illustrate the Higgs mass dependence in a range  $[124, 126] \text{ GeV}$ . Adapted from [12].

which communicates the relationship between the bare  $m_0$  (short distance UV) and the renormalized mass  $m$  (low energy IR). The one-loop coefficient function  $C_1$  [8] may be written as (neglecting the small light fermion Yukawa couplings)

$$C_1 = \frac{6}{v^2} (M_H^2 + M_Z^2 + 2M_W^2 - 4M_t^2) = 2\lambda + \frac{3}{2}g'^2 + \frac{9}{2}g^2 - 12y_t^2 \quad (2)$$

and is uniquely determined by dimensionless couplings. Surprisingly, taking into account the scale dependence of the SM couplings, the coefficient of the quadratic divergence of the Higgs mass counterterm exhibits a zero (see Fig. 2 left panel). This has been emphasized in [63, 64] (see also [65]), where the 2-loop result  $C_2$  is also given but represents a minor correction only, i.e. we have  $C(\mu) \simeq C_1(\mu) \simeq C_2(\mu)$ . The important point is that in the LEESM setup the cutoff is physical, meaning that UV singularities have turned into finite but eventually large numbers.

According to (1), the SM for the given parameters makes a prediction for the bare mass parameter  $m_0^2 = \text{sign}(m_0^2) \times 10^X$  of the Higgs potential, where  $X$  is displayed in the right panel of Fig. 2. In the broken phase we have  $m_0^2 = \frac{1}{2}(m_H^2 + \delta m_H^2)$ , which is calculable! What happens is:

- the coefficient  $C(\mu) \simeq C_1(\mu) \simeq C_2(\mu)$  exhibits a zero, for  $M_H = 125 \text{ GeV}$  at about  $\mu_0 \sim 1.4 \times 10^{16} \text{ GeV}$ , clearly but not far below  $\mu = M_{\text{Pl}}$ ,
- at the zero of the coefficient function the counterterm  $\delta m^2 = m_0^2 - m^2 = 0$  ( $m$  the  $\overline{\text{MS}}$  mass) vanishes and the bare mass changes sign,

- the sign change *triggers* a *phase transition* (PT), the *Higgs mechanism*, that is inducing masses simultaneously for the weak gauge-bosons and for all fermions, note that the Higgs field exhibits as many different couplings as there are different massive SM particles,
- the large  $m_0$  and the large  $V(0) = \langle V(\phi) \rangle$  (see below) for  $\mu > \mu_0$  in the symmetric phase initiate **cosmic inflation** when temporarily the potential dominates the kinetic term  $V(\phi) \gg \frac{1}{2} \dot{\phi}^2$ , where  $\dot{\phi} = d\phi/dt$ .
- At the transition point  $\mu_0$  we have  $m_0 = m(\mu_0^2)$  and a bare Higgs field VEV  $v_0 = v(\mu_0^2)$ , where  $v(\mu^2)$  is the  $\overline{\text{MS}}$  renormalized VEV; the power cutoff-effects appear nullified at  $\mu_0$ ! Note that  $v$  is characteristic for long-range order (order parameter) and shows-up for  $\mu < \mu_0$  only. In the high energy phase,  $\mu > \mu_0$  which extends up to  $M_{\text{Pl}}$  we have  $v \equiv 0$ , no point to expect  $v = O(M_{\text{Pl}})$ . Where is the hierarchy problem?
- Furthermore there is a jump in the vacuum density, which agrees with the renormalized one:  $-\Delta\rho_{\text{vac}} = \frac{\lambda(\mu_0^2)}{24} v^4(\mu_0^2)$ , and thus is being  $O(v^4)$  and **not**  $O(M_{\text{Pl}}^4)$  as often claimed.

The second important quantity we have not taken into account so far is the vacuum energy  $V(0) = \langle V(\phi) \rangle$  related to the quartic UV singularity [45]. Again, in the LEESM scenario, the vacuum energy is a calculable quantity. Considering the Higgs boson doublet-field  $\Phi(x)$ , in the symmetric phase  $SU(2)$  symmetry implies that while  $\langle \Phi(x) \rangle \equiv 0$  the composite field  $\Phi^+ \Phi(x)$  is a singlet such that the invariant vacuum energy is represented just by simple Higgs-field loops, the self-contractions of the Higgs fields in the potential. With

$$\langle 0 | \Phi^+ \Phi | 0 \rangle = \frac{1}{2} \langle 0 | H^2 | 0 \rangle \equiv \frac{1}{2} \Xi ; \quad \Xi = \frac{\Lambda_{\text{Pl}}^2}{16\pi^2} , \quad (3)$$

we obtain a cosmological constant (CC) given by

$$V(0) = \langle V(\phi) \rangle = \frac{m^2}{2} \Xi + \frac{\lambda}{8} \Xi^2 = \frac{\Lambda_{\text{Pl}}^4}{(16\pi^2)^2} \frac{1}{8} (2C + \lambda) . \quad (4)$$

A Wick ordering type of rearrangement of the Lagrangian also leads to a shift of the effective mass

$$m'^2 = m^2 + \frac{\lambda}{2} \Xi = m^2 + \frac{\Lambda_{\text{Pl}}^2}{32\pi^2} (C + \lambda) . \quad (5)$$

For our values of the  $\overline{\text{MS}}$  input parameters the zero in the Higgs mass counter term and hence the phase transition point gets shifted downwards as follows

$$\mu_0 \approx 1.4 \times 10^{16} \text{ GeV} \rightarrow \mu'_0 \approx 7.7 \times 10^{14} \text{ GeV} . \quad (6)$$



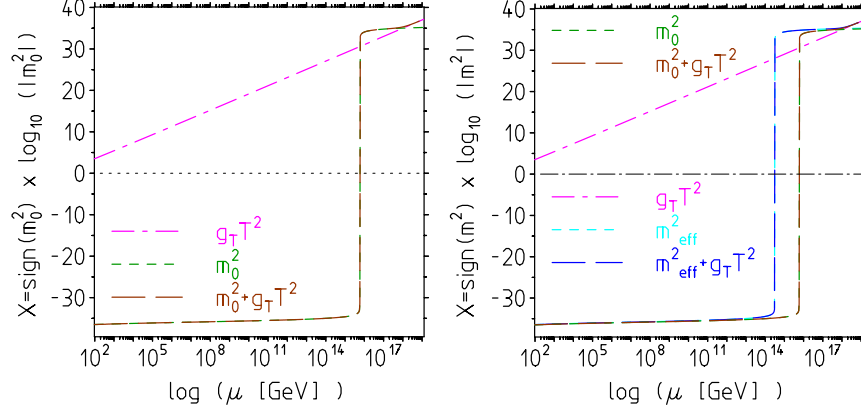


Fig. 3.  $X$  as displayed in the right panel of Fig. 2 including leading finite temperature correction to the potential  $V(\phi, T) = \frac{1}{2}(g_T T^2 + m_0^2)\phi^2 + \frac{\lambda}{24}\phi^4 + \dots$  with  $g_T = \frac{1}{16}[3g_2^2 + g_1^2 + 4y_t^2 + \frac{2}{3}\lambda]$  from [66] affecting the phase transition point. Left: for the bare case  $[m^2, C_1]$ . Right: with adjusted effective mass from vacuum rearrangement  $[m_{\text{eff}}^2 = m'^2, C'_1 = C_1 + \lambda]$ . In the case  $\mu_0$  sufficiently below  $M_{\text{Pl}}$ , the case displayed here, finite temperature effects affect the position of the phase transition little, while the change of the effective mass by the vacuum rearrangement is more efficient. The finite temperature effect with our parameters is barely visible. Updated from [12] (where  $X$  has been displayed on a  $\log$  axis, falsely labeled as  $\log_{10}$ ).

The shift is shown in the right panel of Fig. 3 together with finite temperature effects displayed separately in the left panel. We notice that the SM predicts a huge CC at  $M_{\text{Pl}}$ :

$$\rho_\phi \simeq V(\phi) \sim (1.29 \Lambda_{\text{Pl}})^4 \sim 6.13 \times 10^{76} \text{ GeV}^4, \quad (7)$$

which is exhibiting a very weak scale dependence (running couplings) such that we are confronted with the question how to get rid of this huge quasi-constant? Remember that  $\rho_\phi$  has no direct dependence of  $a(t)$  which is the decreasing radius of the Friedman universe. An intriguing structure again solves the puzzle. The effective CC counterterm has a zero, which again is a point where renormalized and bare quantities are in agreement:

$$\rho_{\Lambda 0} = \rho_\Lambda + \delta\rho_\Lambda; \quad \delta\rho_\Lambda = \frac{\Lambda_{\text{Pl}}^4}{(16\pi^2)^2} X(\mu) \quad (8)$$

with  $X(\mu) \simeq \frac{1}{8}(2C(\mu) + \lambda(\mu))$  which has a zero close to the zero of  $C(\mu)$  when  $2C(\mu) = -\lambda(\mu)$ . Note that  $C(\mu) = -\lambda(\mu)$  is the shifted Higgs transition point.

Again we find a matching point  $\rho_{\Lambda 0} = \rho_{\Lambda}$  between the low-energy and the high-energy world. At this point, the memory of the quartic Planck scale enhancement gets lost, as it should be since we know that the low energy phase does not provide access to cutoff effects.

Crucial point is that

$$X(\mu) = 2C + \lambda = 5\lambda + 3g_1^2 + 9g_2^2 - 24y_t^2 \quad (9)$$

acquires positive bosonic contribution and negative fermionic ones, with different scale-dependence<sup>13</sup>.  $X$  can vary dramatically (pass a zero), while individual couplings are weakly scale-dependent with  $y_t(M_Z)/y_t(M_{\text{Pl}}) \sim 2.7$  the biggest and  $g_1(M_Z)/g_1(M_{\text{Pl}}) \sim 0.76$  the smallest change. Obviously, the energy dependence of any of the individual couplings would by far not be able to sufficiently diminish the originally huge cosmological constant. Only the existence of a zero in the coefficient function  $X(\mu)$  is able to provide the dramatic reduction of the effective CC, by nullifying the huge cutoff-sensitive prefactor. Since inflation is tuning the total energy density into the critical density, the one of a flat geometry, the renormalized dark energy density can only be a fraction of the critical density, what we know it is. Fig. 4 illustrates the behavior of the power enhanced quantities  $m_{\text{eff}}^2(\mu) = m_0^2(\mu)$  and  $\rho_{\Lambda}(\mu)$  as a function of “time” in units  $1/\log_{10} \mu$ , where  $\mu$  is the energy scale, decreasing as the universe is cooling down.

## 5. Remark on the impact on inflation

Everybody knows the SM hierarchy problem. True, the SM predicts a large bare Higgs potential mass in the symmetric phase i.e. for  $\mu > \mu_0$ . Is this a problem? Is this unnatural? In any case, it is a prediction of the SM! Formally, for  $\mu < \mu_0$ , in the low energy phase, (1) predicts a large negative  $m_0^2$  which triggers the Higgs mechanism, but it has no physical meaning because the physical Higgs boson mass now is determined by the curvature of the Higgs potential at its rearranged minimum at  $\phi = v$ .

At low energy, we see what we see (what is to be seen): the renormalizable, renormalized SM as it describes close to all we know up to LHC energies<sup>14</sup> and which is devoid of cutoff effects. What if we go to very very

<sup>13</sup> Unbroken SUSY would require a perfect cancellation to happen at all scales. Broken SUSY would largely eliminate the quadratic and quartic enhancements which are the driving effects for our scenery. Within the SM the cancellation between bosonic and fermionic entries only happens at some point which seems to require fine-tuning. No problem, the energy scan, the evolution of the universe provides, accomplishes it for us.

<sup>14</sup> Apart from such never clarified  $2\sigma$  deviations like e.g. the  $\sin^2 \Theta_W$  measurement by SLD and LEP, the new measurement of the muon  $g-2$  at Fermilab [67] now reveals a  $4.2\sigma$  deviation. Similarly, the LHCb Collaboration observes a  $3.1\sigma$  deviation in lepton universality [68].

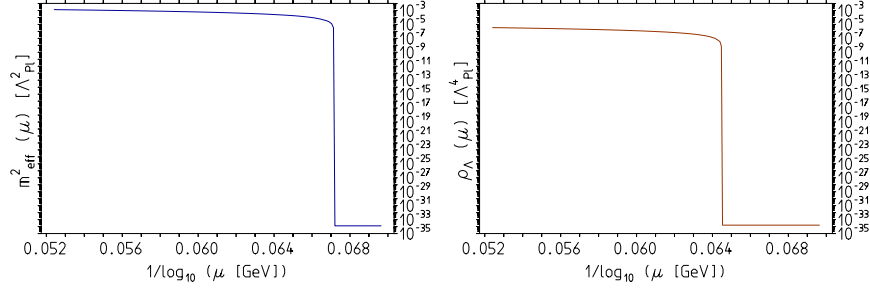


Fig. 4. The Higgs potential effective  $m_{\text{eff}}^2$  [left] and the dark energy density  $\rho_\Lambda$  [right], in units of  $\Lambda_{\text{Pl}}$ , as functions of “time”, represented here by  $1/\log_{10} \mu$ , where  $\mu$  represents the energy at that time. Below the matching point  $\mu_{\text{CC}}$ , where  $\rho_\Lambda \simeq 1.6 \times 10^{-47}$  in Planck mass units, we show a scaled up to  $\rho_\Lambda \times 10^{13}$  value of the present dark energy density  $\mu_{0\Lambda}^4$  with  $\mu_{0\Lambda} \simeq 0.00171$  eV. Note:  $\rho_\Lambda(t)$  includes besides the large positive  $V(0)$  also negative contributions from vacuum condensates, like  $\Delta\rho_{\text{EW}}$  from the Higgs mechanism and  $\Delta\rho_{\text{QCD}}$  from the chiral phase transition. Reproduced from [12].

high energies even close to the Planck scale? Since for  $\mu > \mu_0$  the SM predicts the bare  $m_0^2$  to be positive, we are in the symmetric phase with zero Higgs boson VEV  $v = 0$  where we start to see the bare theory i.e. the SM with its bare short distance effective parameters. In the symmetric phase, all particle masses vanish except for the now four mass-degenerate **very heavy Higgs bosons**. A calculation shows that near below the Planck scale the potential mass term is dominating and the Higgs particles can be moving at most very slowly, i.e. the potential energy<sup>15</sup>

$$V(\phi) = \frac{m^2}{2} \phi^2 + \frac{\lambda}{24} \phi^4 = V(0) + \frac{m'^2}{2} : \phi^2 : + \frac{\lambda}{24} : \phi^4 :$$

is large while the kinetic energy  $\frac{1}{2} \dot{\phi}^2$  is small. The Higgs boson contributes to the energy-momentum tensor in Einstein’s gravity equations, providing a pressure  $p = \frac{1}{2} \dot{\phi}^2 - V(\phi)$  and an energy density  $\rho = \frac{1}{2} \dot{\phi}^2 + V(\phi)$ . A tick after the Big Bang at Planck time  $t_{\text{Pl}}$  the slow-roll condition  $\frac{1}{2} \dot{\phi}^2 \ll V(\phi)$  is satisfied during some time, where  $p \approx -V(\phi)$ ,  $\rho \approx +V(\phi)$  so that  $p = -\rho$ . This means  $\rho = \rho_\Lambda$  represents **dark energy**! i.e., the system exhibits an unusual equation of state, which however could be known from ferromagnetic systems [69]. So we learn that the Higgs boson in the early universe provides huge dark energy (DE)! Note that the latter includes two

<sup>15</sup> By  $: \phi^n :$  we denote Wick ordering, which means that  $\phi$ -field self-contraction are to be omitted.

different parts  $V(\phi) = V(0) + \Delta V(\phi)$ , a static Higgs potential VEV plus a part that depends on the dynamics of the Higgs field.

The huge DE provides **anti-gravity** which is inflating the universe! Indeed the Friedman equation  $\frac{da}{a} = H(t) dt$  predicts an exponential growth of the radius  $a(t)$  of the universe as  $a(t) = \exp Ht$ ,  $H(t)$  the Hubble constant  $H \propto \sqrt{V(\phi)}$ . Inflation stops quite quickly as the field decays exponentially according to the field equation  $\ddot{\phi} + 3H\dot{\phi} \simeq -V'(\phi)$ . At some point, the Higgs potential mass term will be the dominant term  $V(\phi) \approx \frac{m^2}{2} \phi^2$  and we have a harmonic oscillator with friction which predicts Gaussian inflation, as it is observed in Cosmic Microwave Background (CMB) sky maps [70]. LEESM inflation automatically passes through the Gaussian phase before inflation halts as it follows from the Higgs field dynamics. All this tells us that the Higgs boson is the inflaton, always under the assumption the SM couplings at the end will turn out to allow for an extrapolation up to  $M_{\text{Pl}}$ .

If inflation happens it tunes the total energy density to be that of a **flat space**, which has the particular value  $\rho_{\text{crit}} = \mu_{\text{crit}}^4$  with  $\mu_{\text{crit}} = 0.00247 \text{ eV}$ . From the CMB data, we know that today  $\rho_{\Lambda} = \mu_{0,\Lambda}^4$  with  $\mu_{0,\Lambda} = 0.00171 \text{ eV}$ . With the ongoing expansion (cooling) the dark energy density will be approaching  $\mu_{\infty,\Lambda} = 0.00247 \text{ eV}$ . In any case, the large early cosmological constant gets tamed by inflation to be *part of the critical flat space density*. No cosmological constant problem either? In any case, inflation is proven to have happened by observation and inflation requires the existence of a scalar field [71, 72]. The Higgs field is precisely such a field we need and within the SM it has the properties which promote it to be the inflaton.

All other inflaton models must assume a least one additional scalar sectors to exist where neither the shape of the potential nor the parameters are known a priori. In this case, all “predictions” have to be tailored to reproduce what you attempt to predict like e.g. the spectral indices deriving from CMB data. Higgs inflation is very different. We know the Higgs boson properties and the mechanism providing the dark energy. Although this looks pretty straightforward it is delicate, because of the high sensitivity to the SM parameters and their uncertainties and missing higher-order corrections. Higgs inflation is an SM prediction, with all parameters calculable, except the value of the Higgs field in the Higgs potential. To get the required amount of inflation, about  $N_e \approx 60$  e-folds ( $N_e = \ln[a(t_{\text{end}})/a(t_{\text{initial}})]$  with  $t_{\text{initial/end}}$  the time inflation starts/ends) are required to cover the CMB causal cone, one needs  $\phi_0 = 4.5 M_{\text{Pl}}$  at Planck time. This is not unreasonable because the medium is extremely hot with a Hubble constant of about  $H_i \simeq 17 M_{\text{Pl}}$ , given by the SM spectrum and the Stefan-Boltzmann law. The huge field strength at  $M_{\text{Pl}}$  decays exponentially in a very short time.

As we know, for arbitrary scales  $\mu$ , the compensation between positive

bosonic terms and negative fermionic terms within the SM is incomplete. Exact supersymmetry would amount to a perfect cancellation in both cases, for  $m_0^2$  and  $\langle V(0) \rangle$ , by the supersymmetric partners of the SM particles. However, the running of the SM parameters actually also happens to completely cancel bosonic and fermionic contributions at some point. This depends on the proper conspiracy of the SM couplings. That the cancellation only happens at a particular scale thereby is not important. In fact, the existence of a matching point solves both the hierarchy problem as well as the cosmological constant problem. The nullification of the power-enhanced terms happens dynamically, without imposing supersymmetry or alternative mechanisms designed to avoid quadratic divergences. Such matching points, if they exist below the Planck scale, are always met at some point since the expansion of the universe implies the necessary energy scan.

## 6. Conclusion

I have elaborated how Tini Veltman's understanding of the SM structure provides a convincing picture of the SM as a low energy effective theory deriving from a Planck medium. Minimality seems to be the guiding principle and favors the SM as a viable low energy emergent structure. I do not know any SM extension which is not suffering from additional fine-tuning issues, while pretended SM naturalness problems are used to motivate such extensions. Admittedly, also for the SM parameters, the majority of them particle-Higgs-boson couplings, we have no idea about what determines their values, which are covering 14 orders of magnitude between the neutrino masses of order  $10^{-3}$  eV and the top-quark mass at  $1.72 \times 10^{11}$  eV. However, the Higgs boson discovery has told us that there is a "teamwork" of the leading SM couplings, which can reveal a particular link of the SM to the Planck world. This may be seen as a hint that a kind of self-organized system may be at work within the primordial "ether"<sup>16</sup>. Looking at the primordial hot chaotic medium with the eyes of a distant observer we see the chaos through the filter which only lets through the long-distance physics. The corresponding cooperation of the different interactions, balancing bosonic versus fermionic contributions in running couplings, seems to be even more

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<sup>16</sup> Let me quote here WIKIPEDIA [73]: Self-organization, also called spontaneous order, is a process where some form of overall order arises from local interactions between parts of an initially disordered system. The process can be spontaneous when sufficient energy is available, not needing control by any external agent. It is often triggered by seemingly random fluctuations, amplified by positive feedback. The resulting organization is wholly decentralized, distributed over all the components of the system. As such, the organization is typically robust and able to survive or self-repair substantial perturbation. Chaos theory discusses self-organization in terms of islands of predictability in a sea of chaotic unpredictability.

striking when we are considering the consequences for the “Infrared - Ultraviolet Connection” first broached by Veltman. The possible impact of these conspiracies is the SM prediction of Higgs inflation and reheating after the Big Bang. I have presented only a gross picture that derives from the leading power-enhanced LEESM effects. For consideration of finite temperature effects within the LEESM Higgs-inflation scenario I refer to Fig. 3 and [44, 45], which also include a discussion of reheating and possible impacts for explaining the baryon-asymmetry in the universe. Also, the bare Higgs potential is subject to radiative corrections [58] which generates an effective potential on which the meta-stable vacuum scenarios are relying. In [12] I have shown that when power-enhanced corrections are taken into account in the stable vacuum case these radiative corrections have little impact on the leading pattern.

ATLAS and CMS results, the milestone discovery of the SM Higgs boson together with the absence of any hints of beyond the SM (BSM) physics, may have unexpectedly revolutionized particle physics, namely showing that the SM has higher self-consistency (conspiracy) than expected and previous arguments for the existence of new physics may turn out not to be compelling. I see the SM as a low energy effective theory of some cutoff system at  $M_{\text{Pl}}$  consolidated. The crucial point is the enormous gap between  $M_{\text{Pl}}$  and from what we can see, which includes all SM particles. Dark energy and inflation are unavoidable consequences of the SM provided new physics does not disturb the SM prediction substantially.

My main theses are:

- 1) The SM as a renormalized QFT has no hierarchy problem, rather its LEESM extension provides a hierarchy solution for inflation in the early universe. Over the fairly weak logarithmic scale dependence of the running parameters, only the leading relevant operators like the Higgs potential and the Higgs boson mass term are power enhanced and hence able to “talk” with the Planck regime conspicuously.
- 2) A super-symmetric or any other extension of the SM cannot be motivated by the (non-existing) hierarchy problem.
- 3) In the early symmetric phase the quadratically enhanced bare mass term in the Higgs potential together with the quartically enhanced Higgs potential VEV trigger **inflation** shortly after the Big Bang. The relevant time-dependent power corrections are providing a strongly time-dependent CC, which is shown in Fig. 4. This also implies a strongly time-dependent Hubble constant in the early universe which possibly could solve the existing Hubble constant puzzle [7].
- 4) As the hot universe cools down after the Big Bang, the running of the SM couplings let the bare Higgs potential mass  $m_0^2$  flip sign from a large

positive to a large negative value. This is triggering the **Higgs mechanism** at about  $\mu_0 \sim 10^{16}$  GeV. In the broken phase<sup>17</sup> the Higgs boson is naturally as light as other SM particles which are generated by the Higgs mechanism, i.e. including the Higgs boson mass itself all masses are determined by the mass-coupling relations  $M_W^2 = \frac{1}{4} g^2 v^2$ ,  $M_Z^2 = \frac{1}{4} (g^2 + g'^2) v^2$ ,  $M_f^2 = \frac{1}{2} y_f^2 v^2$ ,  $M_H^2 = \frac{1}{3} \lambda v^2$ . Like all other particles, the Higgs mass appears generated by the non-vanishing VEV  $v \neq 0$ . Note that  $v$  is **not** Planck scale enhanced as at the Higgs phase transition point the renormalized and the bare mass coincide (the  $\Lambda_{PI}$  enhanced correction is zero at the transition point) and in the high energy phase when  $\mu > \mu_0$  up to  $M_{PI}$  we have  $v \equiv 0$ . So, provided new physics does not disturb the SM pattern substantially, dark energy and inflation are unavoidable consequences of the SM Higgs system in our bottom-up approach.

- 5) The Higgs mechanism terminates inflation and triggers the **electroweak phase transition; reheating** likely proceeds via the four heavy decaying Higgs particles into fermion pairs (predominantly top/anti-top quark-pairs) just before the system jumps into the broken phase. Again, no non-SM particles needed to provide reheating.

All that necessitates reconsidering the early pre-Higgs phase epoch of cosmology. The SM then is in the symmetric phase, which takes a very different form from known physics in the broken phase. In place of the massless photon which emerges at the electroweak phase transition, in the symmetric phase we have all the SM gauge bosons as massless radiation fields together with the massless Weyl fermions. At these times there are four very heavy Higgs particles that drive inflation and reheating. A more detailed understanding of the EW phase transition is required and could unveil surprises.

Epilogue: The sharp dependence of the Higgs vacuum stability on the SM input parameters and possible SM extensions and the vastly different scenarios which can result as a consequence of minor shifts in parameter space makes the stable vacuum case a particularly interesting one and it could reveal the Higgs particle as “the master of the universe”. After all, it is commonly accepted that dark energy is the stuff shaping the universe both at very early as well as at the late times.

A lot of details have to be worked out to scrutinize the whole picture. On the SM side, the major issue for the future is the very delicate **conspiracy between SM couplings**, which means that precision determinations

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<sup>17</sup> The large negative  $m_0^2$  ceases to act as a Higgs boson mass and loses its observability. After the memory on the cutoff has been lost at that point, within the broken phase the cutoff has no further meaning than as a UV regulator and there is no reason to choose it to be the Planck cutoff.

of the parameters now turn to be more important than ever. Precision measurements of top-quark and Higgs boson properties should be a prime challenge for the LHC and the ILC/FCC-ee projects. Precision values for  $\lambda$ ,  $y_t$  and  $\alpha_s$  from the high energy frontier should go together with a program aiming to provide more precise low energy hadronic cross section measurements at low energy hadron facilities together with lattice QCD calculations of hadronic vacuum polarization effects which would allow one to reduce hadronic uncertainties in  $\alpha(M_Z)$  and  $\alpha_2(M_Z)$ .

The mayor open issues: where is dark matter? can we explain baryon asymmetry? what triggers the see-saw mechanism explaining the smallness of neutrino masses? what is tuning the strong CP problem?

While these questions could not be answered under the presumptions of the standard paradigm based on the belief that going to higher energies reveals more symmetry and a structurally simpler world exhibiting supersymmetry, higher symmetry groups, super-gravity, and strings, I think one should reconsider them under the aspect of the **paradigm of emergence**, where nature uncovers more complexity at very high energy and symmetries are emergent at low energies. It is time to reflect the prejudices which are guiding speculations on BSM physics on the path towards higher energies and higher precision. Searching for emergent structures beyond the SM seems to be a more promising strategy to actually find what is missing in the SM and could be proven one day. While I argued that the LEESM emergence scenario conflicts with hierarchy-problem motivated SM extensions, the LEESM does not exclude BSM physics which we know we have to incorporate in any case, like **dark matter** (e.g. in the form of  $SU(4)$  confined bound states as studied in [43]), Majorana neutrinos<sup>18</sup>, axions, etc. Last but not least the scenario is easy to falsify: find a 4th family fermion, a SUSY particle, or whatever modifies SM quadratic effects or the SM parameter running pattern substantially.

Since the SM parameters, as they have been fixed by experimental data within their uncertainties and to the extent that the conversion to  $\overline{MS}$  parameters theory-wise is under control, in their cooperation are very very close (at  $1.3\sigma$  as inferred in [54]) if not on the spot to match the window of Higgs vacuum stability and SM extend-ability up to the gravity ruled Planck scale, the Higgs-inflation option remains an exciting scenario. Why

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<sup>18</sup> The 3 singlet neutrinos  $\nu_R$  needed to allow the neutrinos to have masses generated by the Higgs mechanism are included in the SM and must exhibit corresponding Yukawa couplings. The neutral Weyl-fermions could be Majorana particles and if so they would also have a singlet Majorana mass term which is allowed by renormalizability but is not protected by any symmetry. Then like the Higgs boson mass in the symmetric phase these Majorana particles would have Planck scale induced very heavy masses which would induce a see-saw mechanism and explaining the lightweights of the observed neutrinos in the broken phase [74].



the relevant parameters, the gauge couplings, the top-quark Yukawa coupling, and the Higgs potential self-coupling determined via the Higgs boson mass, should have values barely missing the option that the scalar field which is required by inflation may be identified as the SM Higgs boson field remains to be clarified. So stay tuned, beware of an unstable vacuum. After all, it is the vacuum on which our cosmos rests!

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