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The "Ether–world" and Elementary Particles

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Abstract:

We discuss a scenario of "the path to physics at the Planck scale" where todays theory of the interactions of elementary particles, the so called Standard Model (SM), emerges as a low energy effective theory describing the long distance properties of a sub–observable medium existing at the Planck scale, which we call "ether". Properties of the ether can only be observable to the extent that they are relevant to characterize the universality class of the totality of systems which exhibit identical low energy behavior. In such a picture the SM must be embedded into a "Gaussian extended SM" (GESM), a quantum field theory (QFT) which includes the SM but is extended in such a way that it exhibits a quasi infrared (IR) stable fixed point in all its couplings. Some phenomenological consequences of such a scenario are discussed.

1 The Path to Physics at the Planck Scale

The current development in the theory of elementary particles is largely triggered by the attempt to unify gravity with the SM interactions at the Planck scale $\Lambda_P \sim 10^{19}$ GeV. A high degree of symmetry is required in order to cure the problems with ultraviolet divergences. The well known symmetry pattern is: **M–THEORY** $\sim$ **STRINGS** and all that $\leftarrow$ **SUGRA** $\leftarrow$ **SUSY** $\leftarrow$ **SM**, with arrows pointing towards more symmetry, provided we neglect symmetry breakings by masses and other soft breaking terms.

Experience from condensed matter physics and a number of known facts suggest that a completely different picture could be behind what we observe as elementary particle interactions at low energies. It might well be that many known features and symmetries we observe result as a consequence of "blindness for details" at long distances of some unknown kind of medium which exhibits as a fundamental

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cutoff the Planck length. The symmetry pattern thus could look like: **E**THER $\sim$ **Planck medium** $\rightarrow$ **QFT** $\simeq$ **GESM** $\rightarrow$ **SM**. Unlike in renormalized QFT, here the relationship between bare and renormalized parameters obtains a physical meaning. Such ideas are quite old ([1, 2, 3, 4] and many others) and in some aspects are now commonly accepted among particle physicists. Physics at the Planck scale cannot be described by local quantum field theory. The curvature of space-time is relevant and special relativity is modified by gravitational effects. One expects a world which exhibits an intrinsic cutoff corresponding to the fundamental length $a_P \simeq 10^{-33}$ cm. But not only Poincaré invariance may break down, also the laws of quantum mechanics need not hold any longer at Λ_P . The "microscopic" theory at distances a_P is unknown, but we know it belongs to the "universality class" of possible theories which exhibit as a universal low energy effective asymptote the known electroweak and strong interactions as well as classical gravity. Long distance universality is a well known phenomenon from condensed matter physics, where we know that a ferromagnet, a liquid-gas system and a superconductor may exhibit identical long range properties (phase diagram, critical exponents etc.). Our hypothesis could be that there exist some kind of a "Planck solid", for example. We should mention right here that there is a principal difference between a normal solid and a "Planck solid"; of the latter we only can observe its long range properties, the critical or quasi–critical behavior, its true short range properties will never be observable since we will never be able to built a "Planck microscope" which would allow us to perform experiments at Λ_P . Also the observations which tell us about the properties of the early universe will never suffice to pin down in detail the structure at distances a_P. A possible "ether-theory" can be only a theory of universality classes, dealing with the totality of possible systems which exhibit identical critical behavior. It is a non–trivial task to specify possible candidate models belonging to the universality class which manifests itself as the SM at low energies. Here at best, we may illustrate some points, which allow us to make plausible the viability of such a picture. The approach discussed here is based on the experimentally well established physics and theory of critical phenomena which teaches us the emergence of local Euclidean renormalizable QFT as a low energy effective structure (see e.g.[2, 5]).

2 Low energy effective theories

The typical example we have in mind is the Landau-Ginsburg theory as an effective "macroscopic" description of a real superconductor. For a given microscopic system we may envisage the construction of the low energy effective theory by means of a renormalization semi–group transformation á la Kadanoff (block spin picture) Wilson (cutoff renormalization group), which is a very general physical concept in statistical physics not restricted to QFT. Let us assume that a possible object in the universality class of interest is described by a classical statistical system with fluctuation variables $S_\alpha = S_{\alpha 0} + S_{\alpha 1}$, where the S_i $(i = 0, 1)$ in momentum space have support $S_0 : \ 0 \leq p \leq \Lambda/2$ and $S_1 : \ \Lambda/2 \leq p \leq \Lambda$, respectively, and eliminating the short distance

fluctuations in the partition function yields

$$Z = \int \prod dS_\alpha e^{-H(S_\alpha)|_g} = \int \prod dS_{\alpha 0} \prod dS_{\alpha 1} e^{-H(S_{\alpha 0}+S_{\alpha 1})|_g} = \int \prod dS_{\alpha 0} e^{-H'(S_{\alpha 0})|_{g'=Rg}}$$

where g' are the effective couplings of the effective theory and the effective theory is suitable for calculating properties of the original system at $p < \Lambda/2$. This process of lowering the cutoff by a factor of two may be iterated in order to find the long range (low energy) asymptote we are looking for.

Multi-pole forces arise in a natural way in such a scenario, for which it is important to assume "space-time" to have some arbitrary dimension $d \geq 4$ (see below). Since we assume all kind of fields and excitations living at the Planck scale, there exists a long ranged potential behaving as $\Phi \sim -\frac{1}{r^{d-2}}$ for $(r \to \infty)$. For weaker decay the thermodynamic limit would not exist. Stronger decay leads to sub-leading terms at long distances. A multi-pole expansion leads to moments of the form

$$\partial_i \Phi = (d-2)\, \frac{x_i}{r^d} \ , \quad \partial_j \partial_i \Phi = (d-2) \left\{ \frac{\delta_{ij}}{r^d} - d \frac{x_i x_j}{r^{d+2}} \right\} \ , \quad \cdots$$

which naturally mediate interactions between fluctuation variables q, A_i, Q_{ij}, $\cdots$ characterized by "energy" forms:

$$H = q_1 q_2 \Phi \ , \quad -q_1 A_{2i} \partial_i \Phi \ , \quad q_1 Q_{2ij} \partial_j \partial_i \Phi \ , \quad A_{1i} A_{2j} \partial_j \partial_i \Phi \ , \quad \cdots \ .$$

"Charge neutrality" for large distances requires $q = 0$. Dipole–dipole interaction, for example,

$$H = -\sum K_{x-y,ik} A^i_x A^k_y$$

thus have a kernel

$$\tilde{K}_{ik}(q) = m^2 \left(d \frac{q_i q_k}{q^2} + \delta_{ik} \right) + c \left(-d q_i q_k + q^2 \delta_{ik} \right) + O(q^4)$$

and the propagators shows a from known from the massive gauge-boson in the 't Hooft gauge

$$\tilde{G}_{q,ij} = \left(\tilde{K}_q \right)^{-1}_{ij} = \left(\delta_{ij} - \frac{g + bq^2}{g + bq^2 + m^2 + q^2} \frac{q_i q_j}{q^2} \right) \frac{1}{m^2 + q^2} \ ,$$

which demonstrates that spin 1 gauge bosons enter in a natural way. Note that modes are observable only if they *propagate*, which implies that the leading low q–terms $\bar{\psi} \gamma^\mu \partial_\mu \psi$, $\partial_\mu \phi \partial^\mu \phi$, $F_{\mu\nu} F^{\nu\mu}$, $\cdots$ determine the normalization (wave function renormalization) and this fixes the rules for dimensional counting. Also note that by "renormalization" of the Bose fields and the couplings one can always arrange the q^2–term in the bilinear part to be Euclidean invariant (Liu-Stanley theorem). A similar statement should hold for fermions. A detailed investigation of possible low energy structures is very elaborate. Here we mention a simplified Ansatz (assumed

to), which was discussed as a way to derive non–Abelian gauge–theories from "tree unitarity" requirements [6]. For simplicity we assume an Euclidean invariant action at the Planck scale. Consider only three types of particle species: scalars ϕ_a, fermions ψ_α and vector-bosons $W_{i\mu}$ with covariant propagators. Since here we do not refer to tree unitarity but to low energy expansion (IR power–counting) we need consider only terms which are not manifestly irrelevant

$$\begin{aligned}\mathcal{L} &= \bar{\psi}_\alpha \left\{ L^i_{\alpha\beta} P_- + R^i_{\alpha\beta} P_+ \right\} \gamma^\mu \psi_\beta W_{\mu i} + \tfrac{1}{2} D_{ijk} W^k_\mu \left(W^j_\alpha \partial_\mu W^{\alpha i} - W^i_\alpha \partial_\mu W^{\alpha j} \right) \\ &+ \bar{\psi}_\alpha \left\{ C^{+b}_{\alpha\beta} P_+ + C^{-b}_{\alpha\beta} P_- \right\} \psi_\beta \phi^b + \tfrac{1}{2} K^b_{ij} W^i_\mu W^j_\mu \phi_b \\ &+ \tfrac{1}{2} T^i_{ba} W^i_\mu \ (\phi_a \partial_\mu \phi_b - \phi_b \partial_\mu \phi_a) + \tfrac{1}{4} M^{ij}_{ab} W_{\mu i} W_{\mu j} \phi_a \phi_b\end{aligned}$$

with arbitrary interaction matrices of the fields. The extraction of the leading low energy asymptote is equivalent to the requirement of renormalizability of S–matrix elements, and this has been shown to necessarily be a non–Abelian gauge theory which must have undergone a Higgs mechanism if the gauge bosons are not strictly massless. Since terms of order $O(E/\Lambda_P)$ are automatically suppressed in the low energy regime only a renormalizable effective field theory can survive as a tail, the possible renormalizable theories on the other hand are known and are easy to classify. Thus gauge symmetries and in particular the non–Abelian ones appear as a conspiracy of different modes "self–arranged" in such a way the $O((E/\Lambda_P)^n)$–terms $(n > 0)$ are absent. Also anomaly–cancelation and the related quark–lepton duality (family structure) are easily understood and natural in such a context. To an accuracy of $E/\Lambda_P = 10^{-3}$ we are thus dealing with a renormalizable local QFT of the "spontaneously broken gauge theory" (SBGT) type at a scale 10^{16} GeV. As we shall argue below this cannot be just the SM.

The fact that there are only a few possible forms for the low energy effective theories is particularly attractive and tells us that symmetries and particular mathematical properties may be interpreted to emerge as low energy patterns.

The low energy expansion in terms of field monomials makes sense only in the vicinity of a second (or higher) order phase transition point where the system exhibits long range correlations and is described in the long range limit by an effective conformal quantum field theory characterized by an infrared stable fixed point. It is well known that for dimensions $d > 4$ such effective theories turn out to be Gaussian (free field) theories. Non–trivial theories with a stable ground state are possible only for dimensions $d \leq 4$. At the boarder case $d = 4$ non-trivial long range interactions set in and we expect effective couplings to be weak and therefore perturbation theory to work[2]. The quasi–triviality but non-triviality in this scenario is due to the fact that a huge but finite cutoff, namely Λ_P, exist in the underlying physics. Such a scenario explains why elementary particle interactions, up to scales explored so far, are described by renormalizable quantum field theory and why we can do perturbation theory. Note that space-time "compactifies itself" by the decoupling of the $n = d-4$ extra dimensions.

In $d = 4$ space-time dimensions there exist infinitely many infrared "irrelevant" (non–renormalizable) operators of dimension > 4 (scaling like $(E/\Lambda_P)^n$ with $n \geq 1$); but there exist only relatively few infrared "marginal" (strictly renormalizable)

dimension 4 operators (scaling like $\ln^n(E/\Lambda_P)$ with $n \geq 1$) and even fewer infrared "relevant" (super–renormalizable) operators of dimension < 4 (scaling like $(\Lambda_P/E)^n$ with $n \geq 1$). The dimension ≤ 4 operators characterize a renormalizable QFT. The relevant operators must be tuned for criticality in order that the low energy expansion makes sense. This fine tuning is of course the main obstacle for such a vision to be convincing. Unlike in a condensed matter physics laboratory we cannot tune by hand the temperature and the external fields for criticality. However, since we have good reasons to assume that there exist a dense variety of fluctuations and modes it is conceivable that at long distances we just see those modes which "conspire" precisely in such a way as to allow for long distance fluctuations. This conspiracy is nothing but the "symmetry patterns" which emerge at long distances. Other existing modes just are frozen at short distances and are not observable. The "critical dimension" $d = 4$ is crucial for the scenario to work because weakly interacting large scale fluctuations are expected to govern the quasi critical region. As we mentioned above, gauge symmetries are particularly easy to understand within this context. The gauge groups expected in such a scenario of course are the ones which follow by conspiracy of "particles" in singlets, doublets, triplets, etc. exactly as we observe them in the real world. Thus, while a $U(1) \otimes SU(2) \otimes SU(3) \otimes \cdots$ pattern looks to emerge in a natural way, we never would expect higher dimensional multiplets to show up if the particular symmetry would not be there already a the Planck scale. Also the repetition of fermion family patterns, known in the SM, looks to be a rather natural possibility in our approach.

3 Natural properties at low energies

Above we outlined that known empirical facts about structural properties of elementary particle theory find a natural explanation in low energy effective theories. Usually quantum mechanics and special relativity, four dimensionality and renormalizability are independent inputs. Detailed investigations confirm that all these properties may be understood as consequences of the existence of an "ether" in the appropriate universality class. At long distances we observe: 1.) Local quantum field theory; note that the equivalence of Euclidean QFT and Minkowski QFT is a general property of any renormalizable QFT (Osterwalder–Schrader theorem). The analyticity properties allow for the necessary Wick rotation. In its Minkowski version QFT incorporates quantum mechanics and special relativity, which thus show up as low energy structures more or less automatically[5]. 2.) Space–time dimension $d = 4 = 3 + 1$. 3.) Interactions are renormalizable and thus described by a Lagrangian which includes low dimensional monomials of fields only. 4.) Weak coupling and perturbative nature of elementary particle interactions; this is natural only if we require the low energy effective QFT in $d = 4$ to exhibit a trivial (Gaussian) IR fixed point, which is the natural candidate for the low energy effective theory to stabilize. Since in addition we have to require the SM to part of it we call it "Gaussian extended SM" (GESM). It is weakly interacting at low energies due to the existence of the large but finite cutoff. 5.) Local gauge symmetries with small gauge groups;

they provide the dynamical principle which fixes the interactions of the SM and of Einstein's theory of gravity (equivalence principles). 6.) The existence of a large finite physical cutoff implies that the relationship between bare and renormalized quantities are physical.

Basis of all this is the equivalence of statistical mechanics near criticality and quantum field theory. There are only a few low range theories possible (conformal quantum field theories characterized by a few properties like global symmetries, dimension etc.) Also the equivalence of the path integral quantization and the canonical quantization is more than an accident within this context.

Further consequences are briefly discussed in the following: i) Since we need a quasi Gaussian IR fixed point, asymptotic freedom as seen in the SM must be lost at higher energies; this requires $N \geq 9$ families to exist. The asymptotic freedom of QCD and in the $SU(2)_L$ coupling are a consequence of the decoupling of the heavier fermions. ii) Since the relationship between bare and renormalized parameters must be physical, positivity of counter terms etc. must be required, which has direct consequences for vacuum stability and positivity of both the bare and the renormalized Higgs potential, for example. iii) QFT properties are expected to be violated once E/Λ_P, $(E/\Lambda_P)^2, \cdots$ terms come into play; at $E \simeq 10^{16}$ GeV one might expect 0.1% effects. This might be important to remember in the attempts to solve the puzzle of baryogenesis, for example.

The simplest GESM may be obtained by adding more (heavier) fermion families to the SM. For a SM with N families the one–loop counter terms for the $U(1)_Y$, $SU(2)_L$ and $SU(3)_c$ couplings read

$$\delta g/g = c_g \ \ln(\Lambda^2/\mu^2)$$

with

$$\begin{aligned} c_{g'} &= \tfrac{g'^2}{24\pi^2}\,(5/3\ N + 1/8), \\ c_g &= \tfrac{g^2}{24\pi^2}\,(N - 11/2 + 1/8), \\ c_{g_s} &= \tfrac{g_s^2}{16\pi^2}\,(4/3\ N - 11), \end{aligned}$$

respectively. The corresponding β–functions must all be positive (IR fixed point condition) in the weak coupling limit. For the Abelian coupling we have $c_{g'} > 0$ in any case. For the non-Abelian couplings $c_g > 0$ provided $N \geq 6$ and $c_{g_s} > 0$ provided $N \geq 9$, i.e. they must be matter dominated. Note that for the unbroken $U(1)_{\rm em}$

$$c_e = \sin^2\Theta_W c_g + \cos^2\Theta_W c_{g'} = \frac{e^2}{24\pi^2}\,(8/3\ N - 11/2 + 1/4) > 0$$

for $N \geq 2$. In our scheme there is a prediction for

$$\tan^2\Theta_{W\,\rm eff} = (g'^2/g^2)_{\rm eff} = \frac{g'^2(1+2\delta g'/g')}{g^2(1+2\delta g/g)} \sim \frac{24N-129}{40N+3}.$$

It is positive only provided $N \geq 6$ and we obtain $\sin^2\Theta_W$=0.05814,0.16321,0.19333,0.23356 and 0.37500 for N=6,8,9,11 and ∞. Note that more realistic estimates must include appropriate threshold/decoupling effects. Of course the existence of additional

fermion families is possible, although additional light neutrinos are excluded as we know.

We finally have to worry about the quadratic divergences i.e. the tuning of the relevant parameters for criticality[8]. In the SM, utilizing dimensional regularization, the quadratic divergences show up as poles at $d = 2$ and this solely concerns the Higgs mass counter term [7]

$$\delta m_H^2 = \tfrac{1}{16\pi^2 v^2}\{A_0(m_H)\, 3m_H^2 + A_0(M_Z)\,(m_H^2 + 6M_Z^2) + A_0(M_W)\,(2m_H^2 + 12M_W^2) \\ + \textstyle\sum_{f_s} A_0(m_f)\,(-8m_f^2) + \cdots\}$$

where

$$A_0(m) = \Lambda^2 (m^2/\mu^2)^{(d/2-1)}\,(4\pi)^{-d/2}\,\Gamma(1-d/2)$$

and thus

$$\delta m_H^2 \sim 6(\Lambda/v)^2(m_H^2 + M_Z^2 + 2M_W^2 - 4m_f^2)$$

and the IR fixed point condition requires[9]

$$m_H \simeq (4(m_t^2 + m_b^2) - M_Z^2 - 2M_W^2)^{1/2} \sim 318 \quad \text{GeV}.$$

This lowest non–trivial order consideration seems to predict a reasonable value of the Higgs mass. Since we are in a perturbative regime higher order perturbative corrections modify the precise value of the prediction but they cannot affect the existence of a solution which is not ruled out by experiment. Actually, current precision measurements very strongly suggest that the Higgs coupling is fairly weak (SM fits favor $m_H < 420$ GeV at 95 % C.L. and thus $\lambda = m_H^2/(2v^2) < 1.5$ which leads to an expansion parameter about $\alpha_\lambda = \lambda^2/(4\pi) \sim 0.18$). In fact the symmetry which constrains the scalar mass here is dilatation invariance. Of course, like in SUSY theories, the cancelations of the contributions is only possible between fermionic and bosonic degrees of freedom. This prediction should not be taken too serious. First of all it does not include the effects from the extra heavy fermion families which must exist in this scheme. More serious is the expectation that such a result cannot be universal, it is expected to depend on the actual structure of the "bare" theory, which is unknown. On the other hand renormalizable SBGT is in effect up to energies of about 10^{16} GeV and below that standard gauge invariance and RG arguments apply.

At this point we should remember 't Hooft's naturalness argument: "Small" masses are natural only if setting them to zero increases the symmetry of the system[4]. Indeed a light particle spectrum (IR relevant terms) must be the result of a "conspiracy" i.e. modes conspire to form approximately multiplets of some symmetry which protects the masses from large renormalizations: light fermions require approximate chiral symmetry, light vector bosons require approximate local gauge symmetry, light scalars require approximate super symmetry or approximate dilatation symmetry. Remember that dilatation invariance implies conformal invariance.

The view developed in the previous sections has to be worked out in more details in many respects. There are many open problems, for example, concerning the origin

of fermions. I think this is a promising framework which should be considered seriously. One big advantage is that it has non–trivial phenomenological consequences which are testable in the not too far future.

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