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## VACUUM ENERGY AND THE COSMOLOGICAL CONSTANT

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The accelerating expansion of the Universe points to a small positive value for the cosmological constant or vacuum energy density. We discuss recent ideas that the cosmological constant plus LHC results might hint at critical phenomena near the Planck scale.

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### 1. Introduction

Accelerating expansion of the Universe was discovered in the observations of distant Supernovae 1a,<sup>1,2</sup> and recognised by the 2011 physics Nobel Prize. Interpreted within Einstein's theory of General Relativity, the accelerating expansion of the Universe is driven by a small positive cosmological constant or vacuum energy density perceived by gravitational interactions called dark energy, for reviews see Refs. 3–18. Cosmology observations point to an energy budget of the Universe where just 5% is composed of atoms, 26% involves dark matter (possibly made of new elementary particles) and 69% is dark energy.<sup>19</sup> The vacuum dark energy density extracted from astrophysics is  $10^{56}$  times smaller than the value expected from the Higgs potential in Standard Model particle physics, which also comes with the opposite negative sign. Understanding this vacuum energy is an important challenge for theory and connects the Universe on cosmological scales (the very large) with subatomic physics (the very small).

What might dark energy be telling us about the intersection of particle physics and gravitation? In this paper we focus on the interface of spontaneous symmetry breaking, vacuum energy and possible critical phenomena close to the Planck scale (Section 3). We first briefly review key issues in dark energy science and the vacuum energy in particle physics (Sections 1 and 2). General Relativity and the Standard Model of particle physics work excellently everywhere they have been tested in experiments. Complementary ideas on the cosmological constant are surveyed in Section 4. Conclusions are given in Section 5.

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The simplest explanation of dark energy is a small positive value for the cosmological constant in Einstein's equations of General Relativity. Einstein's equations link the geometry of spacetime to the energy-momentum tensor

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = -\frac{8\pi G}{c^2}T_{\mu\nu} + \Lambda g_{\mu\nu}. \quad (1)$$

Here  $R_{\mu\nu}$  is the Ricci tensor which is built from the metric tensor  $g_{\mu\nu}$  and its derivatives,  $R$  is the Ricci scalar and  $T_{\mu\nu}$  is the energy-momentum tensor. The left-hand side describes the geometry and the right-hand side describes the energy content of the gravitational system. Writing

$$\Lambda = 8\pi G\rho_{\text{vac}} + \Lambda_0, \quad (2)$$

the cosmological constant tells us about the energy density of the vacuum  $\rho_{\text{vac}}$  perceived by gravitational interactions  $\langle T_{\mu\nu} \rangle_{\text{vac}} = -\frac{g_{\mu\nu}}{c^2}\rho_{\text{vac}}$ ;  $\Lambda_0$  a possible counterterm. Being proportional to  $g_{\mu\nu}$ , a positive cosmological constant corresponds to negative pressure in the vacuum perceived by gravitational interactions. If the net vacuum energy is finite it will have gravitational effect. The vacuum energy density receives possible contributions from the zero-point energies of quantum fields and condensates associated with spontaneous symmetry breaking.

The vacuum is associated with various condensates. The QCD scale associated with quark and gluon confinement is around 1 GeV while the electroweak scale associated with the  $W^\pm$  and  $Z^0$  boson masses is around 250 GeV. These scales are many orders of magnitude less than the Planck-mass scale  $1.2 \times 10^{19}$  GeV. If the net vacuum energy is finite it will have gravitational effect. The vacuum energy density associated with dark energy measured in astrophysics experiments is characterised by a scale around 0.002 eV, typical of the range of possible light neutrino masses, and a cosmological constant which is 56 orders of magnitude less than the value expected from the Higgs condensate with no extra new physics. Why is this vacuum "dark energy" density finite and positive, and why so very small?

There is no strong evidence in the present data that dark energy is anything other than a time independent cosmological constant. The most recent Planck measurements of the Cosmic Microwave Background (CMB) point to a Universe that is spatially flat to an accuracy of 0.5 %, <sup>19</sup> consistent with the  $\Lambda$ CDM 6 parameter standard cosmological model. The value quoted by Planck for the ratio of vacuum pressure to dark energy density  $w = p/\rho$  assuming time independent dark energy is  $w = -1.006 \pm 0.045$ . The next generation of experiments will investigate possible time dependence in the dark energy equation of state as well as making new precision large distance tests of General Relativity.

The Universe appears to good description as homogeneous and isotropic with Friedmann-Lemaitre-Robertson-Walker (FLRW) metric

$$ds^2 = c^2 dt^2 - a^2(t) \left[ \frac{dr^2}{1 - Kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right]. \quad (3)$$

Here  $a(t)$  is the scale factor which tells us about the sizes of spatial surfaces with  $t$  the cosmic time;  $K$  is the three-space curvature constant ( $K = 0, +1, -1$  for a spatially flat, closed or open Universe). For a flat FLRW Universe consisting just of matter, radiation or a finite cosmological constant, the energy densities and scale factor behave in an expanding Universe as

$$\begin{aligned} \rho_{\text{matter}} &\sim a^{-3}, & a(t) &\propto t^{\frac{2}{3}} \\ \rho_{\text{radiation}} &\sim a^{-4}, & a(t) &\propto t^{\frac{1}{2}} \\ \rho_{\text{vac}} &= \frac{\Lambda}{8\pi G} \sim a^0, & a(t) &\propto e^{Ht} \end{aligned} \quad (4)$$

where  $H = \dot{a}/a$  is the Hubble constant. Condensates that fill all space contribute to  $\rho_{\text{vac}}$ . Where they are confined within matter their contribution forms part of  $\rho_{\text{matter}}$ .<sup>20</sup> When the density of matter (including both visible and possible dark matter) dominates, the expansion decelerates due to normal gravitational attraction. When the Universe expands to the point that matter becomes dilute and the matter density falls below the vacuum energy density, then the expansion of the Universe changes from deceleration to acceleration. Supernovae 1a observations tell us that this occurred about five billion years ago, corresponding to redshift about one. Given their very different time dependence, it is interesting that the matter and dark energy contributions to the energy budget of the Universe should be so similar at the present time. Is there something “special” about “today”? Weinberg<sup>21</sup> has argued that (large scale) structure formation stops when  $\rho_{\text{vac}}$  starts dominating. If  $\rho_{\text{vac}}$  were too large, there would be no galaxies.

In addition to trying to understand the cosmological constant puzzle in terms of vacuum energy, there is also vigorous theoretical activity aimed at understanding dark energy either by introducing a (time dependent) ultra-light scalar field with finite vacuum expectation value to describe the evolution of dark energy in the vacuum or, alternatively, modification of long range gravitation to describe the accelerating expansion of the Universe. These approaches commonly assume that particle physics contributions to the vacuum energy are cancelled by some (unknown) symmetry or gravitational counterterm and then try to interpret the dark energy in terms of the new model dynamics.

Each scenario comes with its own theoretical and phenomenological challenges.<sup>12</sup>

General Relativity has proved very successful everywhere the theory has been tested from distances of micrometers through the solar system to extra galactic measurements.<sup>22</sup> At short distances, recent torsion balance experiments<sup>23</sup> have found that Newton’s Inverse Square Law holds down to a length scale of  $56 \mu\text{m}$ . Comparable precision is achieved in experiments with ultracold neutrons,<sup>24</sup> with the next generation of experiments targeting length scales in the range  $0.1 - 100 \mu\text{m}$ .<sup>25</sup> Precision tests of General Relativity observables in the strong field regime of double pulsars have been verified at the level of 0.05%.<sup>26</sup> Studies of gravitational lensing from distant galaxies are also in very good agreement with General Relativity predictions.<sup>27</sup>

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The expanding Universe might be associated with time dependent dark energy,<sup>28,29</sup> perhaps connecting the present period of accelerating expansion with initial inflation. Time dependent dark energy might, in turn, be associated with time variation in other fundamental constants,<sup>30</sup> *e.g.* the fine structure constant  $\alpha$ , the ratio of electron to proton masses  $\mu_{ep}$  (which measures the ratio of the electroweak to QCD scales), and/or Newton's constant  $G$ . For a flat FLRW Universe Einstein's equations give<sup>30</sup>

$$\frac{d}{dt}[G(\rho_{\text{matter}} + \rho_{\text{vac}})] + 3 G H (\rho_{\text{matter}} + \rho_{\text{vac}}) = 0. \quad (5)$$

Experiments give strong constraints<sup>31,32</sup> on the possible time dependence of  $\alpha$  and  $\mu_{ep}$  from precision quantum optics experiments (time = today),<sup>33-35</sup> molecular clouds in space (time = some billion years ago)<sup>36,37</sup> and the Cosmic Microwave Background (when the Universe was 380 000 years old).<sup>38</sup> Quantum optics measurements give  $\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17} \text{ yr}^{-1}$ <sup>34</sup> and the combination  $\dot{\alpha}/\alpha = (-0.7 \pm 2.1) \times 10^{-17} \text{ yr}^{-1}$  and  $\dot{\mu}_{ep}/\mu_{ep} = (0.2 \pm 1.1) \times 10^{-16} \text{ yr}^{-1}$ ,<sup>35</sup> where the latter measurement assumes time constancy of nuclear magnetic moments. From molecular clouds in space (time = 7.5 billion years ago)  $\dot{\mu}_{ep}/\mu_{ep} < 2 \times 10^{-17} \text{ yr}^{-1}$ .<sup>36</sup> Planck measurements of the CMB<sup>38</sup> give  $\alpha/\alpha_0 = 0.9989 \pm 0.037$ . The most sensitive parameter to possible change in the dark energy density is  $\mu_{ep}$ . Time dependence of Newton's constant is constrained from a range of experiments from the solar system to the CMB with measured bound typically about  $\dot{G}/G < 10^{-11} \text{ yr}^{-1}$ .<sup>32</sup> Fritsch and Sola<sup>30</sup> emphasise that the present experimental bounds on change of the nucleon mass and  $\Lambda_{\text{QCD}}$  are compatible with the corresponding bounds on cosmic evolution of  $G$  and  $\rho_{\text{vac}}$ . Time dependent couplings are commonly interpreted in the theoretical literature in terms of the time dependence of some new scalar field which couples to matter.<sup>39</sup>

If we model dark energy by the matrix element of a time dependent scalar field, one requires that this scalar has very small mass, today of order  $10^{-33} \text{ eV}$ , with Compton wavelength bigger than the inverse Hubble radius to avoid clumping and to ensure uniform distribution in the present Universe.<sup>40,41</sup> What protects this tiny mass from quantum radiative corrections? Coupling a near massless scalar to Standard Model particles will introduce a "fifth force" (which is not gauged unlike the other forces of nature). At the present time there is no experimental evidence for any such interaction so couplings between the new scalar and matter must be very much suppressed. Wetterich et al.<sup>42</sup> have argued that dark energy to neutrino coupling might lead to neutrino lumps that might be looked for in future astrophysics experiments. Coupling to a time dependent scalar field will in general induce time dependence in the fundamental constants.

## 2. Vacuum energy and the cosmological constant

The vacuum energy receives possible contributions from the zero-point energy associated with quantisation as well as condensate contributions induced by the Higgs

mechanism and dynamical symmetry breaking.

Quantisation introduces zero-point vacuum energies for quantum fields and therefore, in principle, can affect the geometry through Einstein's equations. Before normal ordering the zero-point energy of the vacuum is badly divergent, being the sum of zero-point energies for an infinite number of oscillators, one for each normal mode, or degree of freedom of the quantum fields.<sup>43</sup> Before interactions, the vacuum (or zero-point) energy is

$$\rho_{\text{vac}} = \frac{1}{2} \sum \{\hbar\omega\} = \frac{1}{2} \hbar \sum_{\text{particles}} g_i \int_0^{k_{\text{max}}} \frac{d^3k}{(2\pi)^3} \sqrt{k^2 + m^2}. \quad (6)$$

Here  $\frac{1}{2}\{\hbar\omega\}$  denotes the eigenvalues of the free Hamiltonian and  $\omega = \sqrt{k^2 + m^2}$  where  $k$  is the wavenumber and  $m$  is the particle mass;  $g_i = (-1)^{2j}(2j + 1)$  is the degeneracy factor for a particle  $i$  of spin  $j$ , with  $g_i > 0$  for bosons and  $g_i < 0$  for fermions. The minus sign follows from the Pauli exclusion principle and the anti-commutator relations for fermions.

The mass scale appearing in the zero-point energy depends on the ultraviolet regularisation. Eq.(6) for  $\rho_{\text{vac}}$  is quartically divergent in the cut-off  $k_{\text{max}}$ . If we take  $k_{\text{max}}$  of order the Planck scale where we expect quantum gravity effects to become important,  $M_{\text{Pl}} = \sqrt{\hbar c/G} = 1.2 \times 10^{19}$  GeV, then we obtain a value for  $\rho_{\text{vac}}$  which is  $10^{120}$  times too big. Zero-point energies are, in themselves, not Lorentz covariant without a corresponding vacuum pressure,  $\rho_{\text{vac}} = -p_{\text{vac}}$ . If one instead evaluates the integral in Eq.(6) using dimensional regularisation  $\overline{\text{MS}}$  instead of a cut-off on the 3-momentum, then one finds<sup>14</sup>

$$\rho_{\text{vac}} = -p_{\text{vac}} \simeq -\frac{1}{2} \hbar g_i \frac{m^4}{64\pi^2} \left[ \frac{2}{\epsilon} + \frac{3}{2} - \gamma - \ln\left(\frac{m^2}{4\pi\mu^2}\right) \right] + \dots \quad (7)$$

for the contribution from particles with mass  $m$ , that is proportional to the fourth power of the particle mass instead of the ultraviolet cut-off  $k_{\text{max}}$ . Zero-point contributions would cancel in a world with exact supersymmetry because of the sign change between boson and fermion contributions in Eq.(6).

In quantum field theory (without coupling to gravity) the zero-point energy is removed by normal ordering so that the zero of energy is defined as the energy of the vacuum. This can be done because absolute energies here are not measurable observables. Before we couple to gravity, only energy differences have physical meaning, *e.g.* in Casimir processes<sup>44,45</sup> which measure the force between parallel conducting plates in QED and which contribute a ‘‘cavity term’’ to the mass of the proton in Bag models of quark confinement. The net vacuum energy is measured only through large distance gravity and astrophysics.

Suppose one can argue away zero-point contributions to the vacuum energy. For example, the Casimir force can also be calculated without reference to zero-point energies.<sup>44</sup> One still has condensates associated with spontaneous symmetry breaking. Condensates which carry energy enter at various energy scales in the

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Standard Model. The Higgs condensate gives

$$\rho_{\text{vac}}^{\text{ew}} \sim -(250 \text{ GeV})^4, \quad (8)$$

56 orders of magnitude larger and with opposite negative sign to the observed value

$$\rho_{\text{vac}} \sim +(0.002 \text{ eV})^4. \quad (9)$$

The QCD quark condensate gives about  $-(200 \text{ MeV})^4$ . If there is a potential in the vacuum it will, in general, correspond to some finite vacuum energy. Why should the sum of many big numbers (plus any possible gravitational counterterm) add up to a very small number?

The Higgs and QCD condensates form at different times in the early Universe, suggesting some time dependence to  $\rho_{\text{vac}}$ . Further large condensate contributions might be expected also in Grand Unified Theories.

### 3. Vacuum energy and high-scale phenomena

What might the cosmological observations and particle physics be telling us ?

It is interesting that the dark energy or cosmological constant scale  $0.002 \text{ eV}$  in Eq.(9) is of the same order that we expect for the light neutrino mass<sup>.15,46-49</sup> Light neutrino mass values  $\sim 0.004\text{-}0.007 \text{ eV}$  are extracted from studies of neutrino oscillation data assuming normal hierarchy and values less than about  $0.02 \text{ eV}$  are obtained with inverted hierarchy.<sup>50,51</sup> That is, one finds the phenomenological relation

$$\mu_{\text{vac}} \sim m_\nu \sim \Lambda_{\text{ew}}^2/M \quad (10)$$

where  $M \sim 3 \times 10^{16} \text{ GeV}$  is logarithmically close to the Planck mass  $M_{\text{Pl}}$  and typical of the scale that appears in Grand Unified Theories. There are also theoretical hints that this large mass scale might perhaps be associated with dynamical symmetry breaking, see below. The gauge bosons in the Standard Model which have a mass through the Higgs mechanism are also the gauge bosons which couple to the neutrino. Is this a clue? The non-perturbative structure of chiral gauge theories is not well understood. If taken literally Eq.(10) connects neutrino physics, Higgs phenomenon in electroweak symmetry breaking and dark energy to a new high mass scale which needs to be understood.

We next argue how this physics might be connected, first treating neutrino chirality by analogy with the “spins” in an Ising-like system that becomes active near the Planck mass.<sup>15</sup> Then, in Section 3.2 we discuss recent LHC results which, when evolved to large scales, suggest stability or metastability of the Standard Model vacuum and which might hint at possible critical phenomenon at some very large scale.

#### 3.1. Neutrinos and the subatomic vacuum

Changing the external parameters of the theory can change the phase of the ground state. For example, QED in 3+1 dimensions with exactly massless electrons is be-

lied to dynamically generate a photon mass.<sup>52</sup> In the Schwinger Model for 1+1 dimensional QED on a circle, setting the electron mass to zero shifts the theory from a confining to a Higgs phase.<sup>53</sup>

In Standard Model particle physics QED is manifest in the Coulomb phase, QCD is manifest in the confinement phase and the weak interaction is manifest in the Higgs phase. The  $W^\pm$  and  $Z^0$  gauge bosons which have a mass through the Higgs mechanism are also the gauge bosons which couple to the neutrino and the QED photon and QCD gluons are massless. What happens to the structure of non-perturbative propagators and vacuum energies when we turn off the coupling of the gauge bosons to left- or right-handed fermions?

Consider Yang-Mills SU(2) with and without parity violation. Pure Yang-Mills theory and Yang-Mills theory coupled to fermions are both confining theories but the mechanism is different for each. Confinement is intimately connected with dynamical chiral symmetry breaking.<sup>54</sup> Scalar confinement implies dynamical chiral symmetry breaking and a fermion condensate  $\langle \bar{\psi}\psi \rangle < 0$ . This scalar condensate is absent if there is no right-handed fermion participating in the interaction. Suppose that the theory is ultraviolet consistent, *e.g.* that it is embedded in a larger theory to ensure anomaly cancellation necessary for gauge invariance and renormalisability. Switching off the coupling of SU(2) gauge bosons to right-handed fermions must induce some modification of the non-perturbative propagators. Either confinement is radically reorganised or one goes to a Coulomb phase or to a Higgs phase whereby the Coulomb force is replaced by a force of finite range with finite mass scale and the issues associated with infrared slavery are avoided.

We next suppose the confinement to Higgs transition applies. That is, we suppose that the non-perturbative ground state of chiral gauge theory is in a Higgs phase. Anomaly cancellation in the ultraviolet is required by gauge invariance and renormalisability. If some dynamical process acts to switch off the coupling of left- or right-handed fermions, it will have important consequences for the theory in the ultraviolet limit and should therefore be active there. If symmetry breaking is dynamical and hence non-perturbative it will appear with coefficients smaller than any power of the running coupling. Suppose an exponentially small effect.<sup>55</sup> Dynamical symmetry breaking then naturally induces a symmetry breaking scale  $\Lambda_{\text{ew}}$  which is much smaller than the high energy scales in the problem  $M_{\text{cutoff}}$ . If we take the mass scale  $M_{\text{cutoff}}$  to be very large, *e.g.* close to the Planck scale, then the expression

$$\Lambda_{\text{ew}} = M_{\text{cutoff}} e^{-c/g(M_{\text{cutoff}}^2)} \ll M_{\text{cutoff}} \quad (11)$$

naturally leads to hierarchies. Symmetry breaking effects at very large scales are suppressed by the exponential with the result that  $\Lambda_{\text{ew}}$  is the mass scale appearing in the particle theory which describes the energy domain probed in laboratory experiments. In Eq. (11) if we take the ratio of the weak scale  $\Lambda_{\text{ew}}$  to the mass scale in Eq.(10), then  $\Lambda_{\text{ew}}/M \sim 10^{-14}$ . If we take the ultraviolet mass scale to be the Planck mass, then  $\Lambda_{\text{ew}}/M_{\text{Pl}} \sim 10^{-17}$ .

We next consider a phenomenological trick to investigate the different scales

in the problem. Analogies between quantum field theories and condensed matter and statistical systems have often played an important role in motivating ideas in particle physics. Here we consider a possible analogy between the neutrino vacuum and the Ising model of statistical mechanics where the “spins” in the Ising model are associated with neutrino chiralities.<sup>15</sup> The free energy for the statistical “spin” system plays the role of the vacuum energy density in quantum field theory.<sup>56</sup>

The ground state of the Ising model exhibits spontaneous magnetisation where all the spins line up and the internal energy per spin and the free energy density of the spin system go to zero with corrections dampened by the exponential factor  $e^{-\beta J}$ . Here  $J$  is the spin-spin coupling in the Ising Hamiltonian

$$H = -J \sum_{i,j} (\sigma_{i,j} \sigma_{i+1,j} + \sigma_{i,j+1} \sigma_{i,j}) , \quad (12)$$

$\beta = \frac{1}{kT}$  where  $k$  is Boltzmann’s constant and  $T$  is the temperature. For an Ising system with no external magnetic field the free energy density is equal to minus the pressure

$$P = - \left( \frac{\partial F}{\partial V} \right)_T \quad (13)$$

– that is, the model equation of state looks like a vacuum energy term in Einstein’s equations of General Relativity,  $\propto g_{\mu\nu}$ .

We take  $J \sim +M$  to be large and close to the Planck mass. The exponential suppression factor  $e^{-2\beta J}$  then ensures that non-renormalisable fluctuations associated with the Ising-like interaction are negligible in the ground state, which is in the spontaneous magnetisation phase involving just left-handed “neutrinos”. Following our previous discussion, it seems reasonable to believe that the SU(2) gauge symmetry coupled to the neutrino is now spontaneously broken, that is the SU(2) gauge symmetry associated with the  $W^\pm$  and  $Z^0$  bosons is in the Higgs phase.

Weak interactions mean that we have two basic scales in the problem:  $J \sim M$  and the electroweak scale  $\Lambda_{\text{ew}}$  induced by spontaneous symmetry breaking. For a spin model type interaction, the ground state with left-handed “spin” chiralities is characterised by vanishing energy density. Excitation of right-handed chiralities is associated with the large scale  $2M$ . Then the mass scale associated with the vacuum for the ground state of the combined system (spin model plus gauge sector) one might couple to gravity reads in matrix form as

$$\mu_{\text{vac}} \sim \begin{bmatrix} 0 & -\Lambda_{\text{ew}} \\ -\Lambda_{\text{ew}} & -2M \end{bmatrix} \quad (14)$$

with the different terms depending how deep we probe into the Dirac sea. Here the first row and first column refer to left-handed states of the spin model “neutrino” and the second row and second column refer to the right-handed states. The off-diagonal entries correspond to the potential in the vacuum associated with the dynamically generated Higgs sector. Eq.(14) looks like the see-saw mechanism<sup>57–60</sup>



proposed to explain neutrino masses. Diagonalising the matrix for  $M \gg \Lambda_{\text{ew}}$  gives the light mass eigenvalue

$$\mu_{\text{vac}} \sim \Lambda_{\text{ew}}^2/2M \quad (15)$$

– that is, the phenomenological result in Eq.(10). Here the electroweak contribution  $\Lambda_{\text{ew}}$  is diluted by the “spin” potential in the vacuum. The resultant picture<sup>15</sup> is a Higgs sector characterised by scale  $\Lambda_{\text{ew}}$  embedded in the “spin” polarised ground state that holds up to the ultraviolet scale  $2M$ . That is, the Standard Model including QCD acts like an “impurity” in the “spin” polarised vacuum.

### 3.2. Stability of the Standard Model vacuum

Results from the LHC experiments ATLAS, CMS and LHCb are in good agreement with the Standard Model with (so far) no evidence of new physics. The Higgs boson discovered at LHC<sup>61,62</sup> is consistent with Standard Model expectations.<sup>63</sup> It is an open question whether at a deeper level this boson is elementary or of dynamical origin. Recent precision measurements of the electron electric dipole moment, EDM, are consistent with zero (with upper bound  $|d_e| < 8.7 \times 10^{-29} e \text{ cm}$ ), constraining possible new sources of CP violation from beyond the Standard Model up to scales similar to or larger than those probed at the LHC.<sup>64,65</sup> The next generation electron EDM experiments expect to probe up to the 100 TeV scale. Precision measurements of the neutron and nuclear EDMs<sup>66</sup> and tests of CPT and Lorentz invariance<sup>67</sup> are so far all consistent with the Standard Model.

It is interesting to consider the possibility that the Standard Model might work up to a scale close to the Planck mass<sup>68</sup> with stable or metastable vacuum, as well the implications for possible deeper structure and the vacuum energy puzzle. Possibly, the Standard Model might be emergent as the long range tail of some critical Planck system.<sup>74</sup> Whilst the Standard Model has proved very successful everywhere it has been tested we know that some extra physics needed to explain the very small neutrino masses, the baryon asymmetry and strong CP problems as well as dark matter and inflation. The scale of this new physics is as yet unknown and not yet given by experiments.

Recent perturbative renormalisation group (RG) calculations suggest that the Standard Model vacuum with the measured Higgs and top quark masses  $m_H = 125.15 \pm 0.24 \text{ GeV}$  and  $m_t = 173.34 \pm 0.76 \text{ GeV}$ <sup>69</sup> might be stable or metastable (with half-life much greater than the present age of the Universe).<sup>70–74</sup> An unstable vacuum would require some new interaction at higher scales. Which scenario occurs is sensitive to technical details in calculating  $\overline{\text{MS}}$  parameters in terms of physical ones and how one should include tadpole diagrams to be consistent with gauge invariance. The important issue here is that the  $\beta$  function for the Higgs four-boson self-coupling  $\lambda$  has a zero and when (if at all) this coupling  $\lambda$  crosses zero (either around  $10^9 \text{ GeV}$ <sup>70,71</sup> or perhaps not at all<sup>73,74</sup>). These calculations assume perturbative evolution of the Standard Model up to the highest possible scales of

order the Planck mass without coupling to additional “new physics” (including any possible quantum gravity or possible dark matter candidates) in the evolution. The RG calculations involve three families of fermions active in the RG equations and the Higgs boson is taken as elementary in these calculations.

Vacuum stability is very sensitive to the exact values of the Higgs and top-quark masses. For the measured value of  $m_t$ ,  $m_H$  is very close to the smallest value to give a stable vacuum with the vacuum being at the border of stable and metastable. With modest changes in  $m_t$  and  $m_H$  (increased top mass and/or reduced Higgs mass) the Standard Model vacuum would be unstable.<sup>70–74</sup> If the vacuum is indeed stable up to the Planck mass, perhaps there is some new critical phenomena to be understood in the extreme ultraviolet? One is led to consider the possibility that there is no new scale between the electroweak scale and some very high scale close to the Planck mass.

Radiative corrections to the Higgs mass in the ultraviolet are very interesting. The running Higgs mass  $m_H$  is related to the bare mass  $m_{0H}$  through

$$m_H^2 = m_{0H}^2 - \delta m_H^2, \quad \delta m_H^2 = \frac{M_{\text{Pl}}^2}{16\pi^2} C_1 \quad (16)$$

where  $\delta m_H^2$  is the mass counterterm and

$$C_1 = \frac{6}{v^2} (M_H^2 + M_Z^2 + 2M_W^2 - 4M_t^2) = 2\lambda + \frac{3}{2}g'^2 + \frac{9}{2}g^2 - 12y_t^2. \quad (17)$$

Here  $v$  is the Higgs vacuum expectation value,  $\lambda$  is the Higgs self-interaction coupling,  $g'$  and  $g$  are the electroweak couplings and  $y_t$  is the top quark Yukawa coupling. The small value of  $m_H^2$  relative to  $M_{\text{Pl}}^2$  is the hierarchy problem and connected to discussions<sup>75</sup> of naturalness. Taking the couplings in the formula for  $C_1$  to be RG scale dependent and the measured Higgs and top quark masses, Jegerlehner<sup>74</sup> has argued that  $C_1$  crosses zero at a scale  $\sim 10^{16}$  GeV, logarithmically close to the Planck mass. He argues that the sign change in the Higgs bare mass squared triggers the Higgs mechanism with a first order phase transition if the Standard Model is understood as the low energy effective theory of some cutoff system residing at the Planck mass.<sup>74, 76, 77</sup> In this scenario the Higgs might act as the inflaton at higher mass scales in a symmetric phase characterised by a very large bare mass term.<sup>78, 79</sup> Note that the Higgs and top quark masses are taken to be time independent in these calculations. Further, the electroweak Higgs contribution to the vacuum energy density  $-\frac{\lambda}{24}v^4$  obeys a similar expression to Eq.(17) and crosses zero at a similar scale about  $10^{16}$  GeV so the renormalised version of this quantity can be much less than the bare version at scales close to the Planck mass.

It is interesting that the scale  $\sim 10^{16}$  GeV found in this calculation also arises (modulo Yukawa couplings) in the see-saw mechanism for neutrino masses and in the “spin” model argument for dynamical symmetry breaking in Section 3.1, as well as in Grand Unified Theories. The scale of inflation is related to the tensor to scalar ratio  $r$  in B modes in the cosmic microwave background through  $V_{\text{inflation}} \sim \left(\frac{r}{0.01}\right)^{\frac{1}{4}} 10^{16}$  GeV.<sup>80</sup> A finite value of  $r$  would be evidence of gravitational waves

from the inflationary period. If ongoing and future measurements converge on a positive signal in the region  $0.001 < r < 0.1$ , then this would point to a scale of inflation in the same region close to  $10^{16}$  GeV.

The issue of vacuum stability is important. If some critical process is at work, then one might speculate that the Standard Model is itself emergent, as the long range tail of a critical Planck system. The emergence scenario differs from the paradigm of unification with maximum symmetry at the highest possible energies, with a unification big gauge group spontaneously broken through various Higgs condensates to the Standard Model, with each new condensate introducing an extra large contribution to the vacuum energy and the cosmological constant. In the emergence scenario one might expect violations of gauge and possibly Lorentz invariance as well as renormalisability at scales close to the Planck mass. Perhaps the gauge theories of particle physics and also General Relativity are effective theories with characteristic energy of order the Planck scale.<sup>81</sup> The idea that local gauge symmetries might be emergent dates to early work of Bjorken<sup>82,83</sup> who suggested that the photon might be a Goldstone boson associated with spontaneous breaking of Lorentz invariance. There are strong experimental constraints on possible Lorentz invariance violation.<sup>67</sup> Bjorken has further suggested that any breakdown of gauge symmetries, with the activation of gauge degrees of freedom and a preferred choice of gauge associated with emergent gauge symmetry, might vanish in the limit of vanishing dark energy.<sup>83,84</sup> Emergence ideas are further discussed in Refs. 76, 77, 85, 86, 87. Patterns in fermion masses have been interpreted<sup>88,89</sup> to suggest that perhaps there is a deeper structure to matter and that perhaps the fermions and  $W^\pm$  and  $Z^0$  bosons might be composite. Perhaps it is possible to re-interpret these ideas also in terms of an emergent Standard Model?

Ideas about the cosmological constant based on emergence phenomena in condensed matter physics have also been suggested.<sup>90</sup> If the vacuum of particle physics acts like a cold quantum liquid in equilibrium, then its pressure vanishes unless it is a droplet in which case there will be surface corrections scaling as an inverse power of the droplet size. Vacuum dark pressure scales with the vacuum dark energy density and is measured by the cosmological constant which scales as the inverse square of the Hubble length  $R = 1/H$  (or “size” of the Universe), *viz.*  $\Lambda = 8\pi G\rho_{\text{vac}} = 3H^2 = 3/R^2$  in a Universe dominated by dark energy.

#### 4. Complementary ideas

We briefly mention other ideas involving the cosmological constant and gravitational dynamics or where  $M_{\text{Pl}}$  plays a vital role.

Brandenberger et al.<sup>92</sup> and Polyakov<sup>93</sup> have argued that de Sitter space is unstable in the presence of quantum fields. Gravitational waves propagating in a background spacetime affect the dynamics of the background. Gravitational backreaction might generate a negative contribution to the cosmological constant in the terminating of inflation and thus screen the cosmological constant today.

Ward<sup>94,95</sup> considers the cosmological constant in a model of resummed quantum gravity with an asymptotically safe ultraviolet fixed point.<sup>91</sup> He finds a value of the cosmological constant close to the measured value with theoretical error of a factor of  $10^4$ .

In the causal dynamical triangulation approach to quantum gravity Ambjorn et al.<sup>96</sup> start with the gravitational path integral

$$Z(G, \Lambda) = \int \mathcal{D}g e^{iS_{G,\Lambda}[g]} \quad (18)$$

before coupling to matter and taking as inputs causality and locality plus Newton's constant and the cosmological constant as parameters. Curved space-time at early intermediate stages in the time evolution is approximated by triangulations. This approach generates de Sitter space with an emergent 4 dimensions of space-time (starting from 2 dimensions near the Planck mass).

In a different approach where the Planck mass also plays a vital role, McLerran et al<sup>97</sup> assume that the sum of baryon and lepton number might not be conserved at a very high scale near the Planck mass through electroweak axion coupling to the topological charge of the electroweak gauge theory and instantons. The electroweak axion might then generate a dark energy contribution close to the measured value if there is no new physics between the electroweak and Planck scales.

## 5. Conclusions

The cosmological constant puzzle continues to fascinate. Why is it finite, positive and so very small? What suppresses the very large vacuum energy contributions expected from particle physics? Is the accelerating expansion of the Universe really driven by a time independent cosmological constant or by new possibly time dependent dynamics? Experiments will push the high-energy and precision frontiers of subatomic particle physics. Is new physics “around the corner” or might the Standard Model work up to a very large scale, perhaps close to the Planck mass and perhaps hinting at critical new phenomena in the ultraviolet? Understanding the accelerating expansion of the Universe and the cosmological constant vacuum energy puzzle promises to teach us a great deal about the intersection of subatomic physics and dynamical symmetry breaking on the one hand, and gravitation on the other.

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