

2001

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## Recommended Citation

Donoghue, JF, "Random values of the physical parameters" (2001). *INTERNATIONAL JOURNAL OF MODERN PHYSICS A*. 109.  
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## RANDOM VALUES OF THE PHYSICAL PARAMETERS

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I briefly describe two motivations, two mechanisms and two possible tests of the hypothesis that the physical parameters of the ground state of a theory can vary in different regions of the universe.

### 1. Introduction

The Standard Model has a unique ground state (modulo  $SU(2)_L$  rotations) and the 19 parameters of the model are uniquely fixed. However, when considering theories beyond the Standard Model, we have no evidence that this uniqueness will be preserved. In particular, string theory has continuous families of ground states, each with different values of the physical parameters, and we presently do not know the mechanism that distinguishes among them. Is the unique ground state of string theory that one with  $SU(3) \times SU(2) \times U(1)$  and  $m_u = 3$  MeV,  $m_d = 6$  MeV etc.? An alternative is that many, perhaps all, of the ground states can be realized in different regions of the universe, depending in some way on the past history of that region. At present we have no reason to rule out this possibility. However, if this is the case, we need to approach the theory in fundamentally different ways. This talk is devoted to some preliminary work in the context of random physical parameters<sup>1</sup>.

### 2. Two Motivations

Theories with variable parameters must involve anthropic constraints. In the space of all possible parameters, most domains involve combinations of parameters which are not suitable for life of any form. While many physicists have a negative reaction to anthropic ideas, they are a natural outcome of having domains with different parameters in the universe.

The strongest motivation for variable parameters and anthropic constraints comes from the cosmological constant  $\Lambda$ . The natural scale of this parameter is so large that the anthropically allowed region is an extremely tiny portion of parameter space. Most other values of  $\Lambda$  would not allow matter to clump into galaxies, or would make the universe extremely short lived. Unless we are able to uncover a generic mechanism to produce a small non-zero value of  $\Lambda$ , it would be remarkably lucky if the unique ground state of the ultimate theory just happened to fall in the anthropically allowed range. It seems more plausible that in a large ensemble of domains with various parameters, a few of those domains have parameters which happened to fall in the allowed range. We could only find ourselves in such

a domain.

A second motivation concerns the Higgs vacuum expectation value. If the Higgs vev was much larger (with the other parameters fixed) none of the complex elements would exist since the mass differences of quarks would exceed the 10 MeV per nucleon binding energy of nuclei, allowing decay of all quarks down to the lightest quark. A world of hydrogen alone likely does not have the complexity needed for life. This suggests that an anthropic constraint may also be at work to require that the weak scale be close to the QCD scale.

Note that anthropic constraints do not “solve” the cosmological constant or the Higgs vev problems. Instead they suggest the possibility that these are accidents of history, not really problems to be solved. The real function of these considerations is to motivate a search for theories with variable parameters.

### 3. Two Mechanisms

Scalar fields can be frozen at random values by the expansion of the universe if their potential is flat enough. This mechanism is used in inflationary theories to temporarily keep the scalar field from rolling down the potential. However, if the potential is yet flatter, compared to the Hubble expansion, the scalar field will be frozen longer<sup>1,2,3</sup>. If in the early history of the universe these scalar fields were initially fluctuating, they could get frozen at different values in different regions, influencing the cosmological constant in each region. For the present Hubble expansion  $H_o = 10^{-122} M_P^2$ , to freeze the scalar field requires a *very* flat potential. From this extreme flatness we can conclude that matter fields cannot couple to the scalar. (Otherwise loops of these other fields would generate a potential which would be too large unless there was extreme fine-tuning.) This implies that only the cosmological constant would be variable with this mechanism.

A more exotic mechanism involves four-form field strengths<sup>1,4</sup>. These are generalizations of electromagnetic fields such that the potential carries three antisymmetric Lorentz indices and the field strength carries four. In four dimensions these fields are non-dynamical - the field equations have only constant solutions. If these field strength values can settle down at any value, they can provide the random component.

Such four-forms do appear in string theory. In dimensions greater than four they are dynamical with plane wave solutions. This then gives a possible mechanism for producing them in a hot early universe with energies above the compactification scale. When the energy decreases through the scale of compactification, i.e. when the world becomes essentially four-dimensional, the four-form fields could take on different values in spatially disconnected regions. With subsequent inflation one of these regions could be the observable universe.

In string theory the values of the form fluxes are quantized, with the field strength being related to the size of the compact dimensions<sup>4</sup>. The impact of this constraint appears to depend on the history. In one extreme the moduli fields, governing the size and shape of the compact dimension, reach the minimum of their

zero-temperature potentials first. Then the form fields would only take on discrete values consistent with the quantization constraint. For anthropic considerations to apply, the discrete steps in the fields would need then need to be very tiny<sup>4</sup>. However, if the form fields are fixed first, before the moduli fields settle down to their absolute minima. they could potentially be at a continuous range of values. In this case, the quantization condition provides the constraint on the minimization of the moduli fields. The couplings between the form fields and the moduli imply that random values of the form fields will generate random contributions to vacuum selection and also imply random values of the other physical parameters.

#### 4. Two Possible Tests

The consideration of such theories is new enough that we do not fully understand their implications. Nevertheless, I can offer two modest possibilities that might be useful in revealing such dynamics.

One signal is observational. If the physical parameters vary, the cosmological constant will have the most dramatic variation. This is because the cancellation required to obtain the observed value of  $\Lambda$  is enormous, and a tiny change in any parameter upsets this cancellation. Therefore  $\Lambda$  is most sensitive to possible variation. If  $\Lambda$  varies continuously it is possible that it would have a small residual variation across our observed universe. In effect, a variation from one side of the universe to the other would signal that the parameter is not uniform and would hence favor this type of theory. Unfortunately, we don't have firm predictions for the size of the effect. A large amount of inflation could wash out a gradient in the parameters leaving a small residual. Nevertheless, it is eventually worth checking to see if there is any gradient in the cosmological constant.

Another test could come once we have a fundamental theory that has been shown to have multiple domains. This theory could not predict the specific quark masses, as these would not be unique. However, it could predict the distribution of quark masses. Empirically, the masses appear to be distributed as if with a weight that is close to scale invariant,  $\rho(m) \sim 1/m$ . This can serve as a test of the underlying theory.

#### References

1. Space limitations constrain me from giving a full set of references here. However, those that I would have cited appear in the reference section of my paper - J. F. Donoghue, "Random values of the cosmological constant," JHEP **0008**, 022 (2000) [hep-ph/0006088].
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