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Neighboring Valley in the String Landscape A Phase Transition to Exact Susy *

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Abstract

The observation in the universe of a small but positive vacuum energy strongly suggests, in the string landscape picture, that there will ultimately be a phase transition to an exactly supersymmetric universe. This ground state or "true vacuum" of the universe could be similar to the minimal supersymmetric standard model with all the susy breaking parameters set to zero. Alternatively, it might be similar to the prominent superstring theories with nine flat space dimensions or to the supersymmetric anti-deSitter model that seems to be equivalent to a conformal field theory. We propose that the dominant phenomenological feature of these potential future universes is the weakening of the Pauli principle due to Fermi-Bose degeneracy. Providing the phase transition occurs in the cosmologically near future, an exact supersymmetry could extend the life expectancy of intelligent civilizations far beyond what would be possible in the broken susy universe.

1 Introduction

Several recent observations have made it increasingly likely that the expansion of the universe is accelerating in a way consistent with an interpretation in terms of a positive vacuum energy

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density of approximate magnitude

$$\epsilon_{now} = 3560 MeV/m^3 = (.0023eV)^4 \quad . \tag{1.1}$$

This is some 124 orders of magnitude greater than the natural value that might have been expected for this quantity:

$$M^4_{Planck} = 10^{127} MeV/m^3 \quad . \tag{1.2}$$

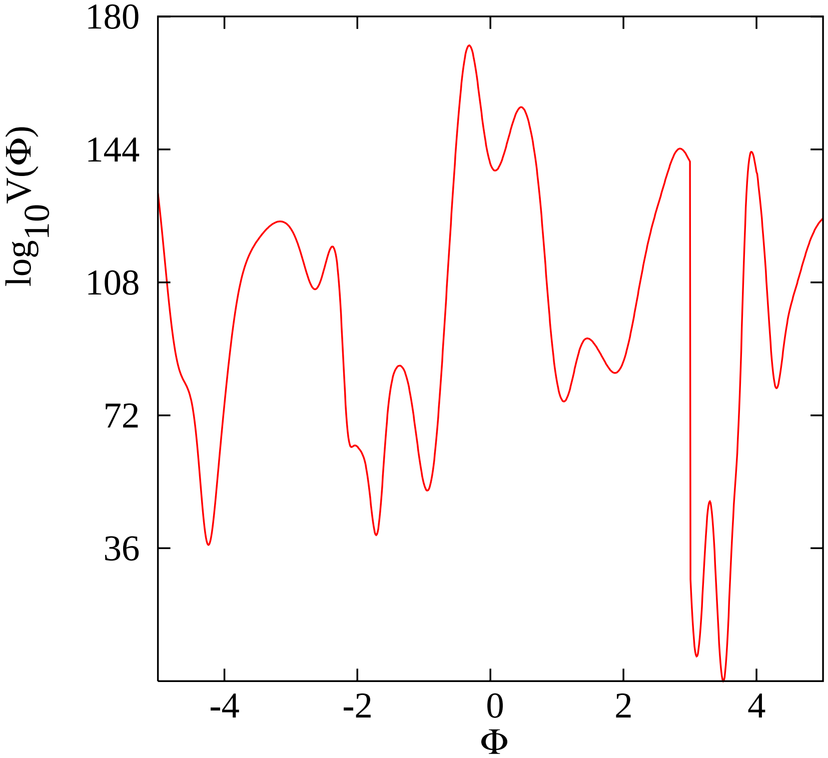

Figure 1: A schematic representation of the effective potential in the string landscape picture. The potential measured in units of MeV/m^3 is not drawn to scale. The y axis has a broken scale taken to be linear in V at low values of the potential. Our world with a small vacuum energy is shown together with the neighboring exact susy phase with zero vacuum energy.

We assume that, in addition to our broken susy universe, there is a neighboring valley in the string landscape described by a perfect supersymmetry (susy) [1] and, most likely, a vanishing cosmological constant as pictured in figure 1. For our current purposes it matters little whether the susy minimum has four or more dimensions or whether the space is flat, deSitter, or anti-deSitter as long as the cosmological constant is not much greater in absolute value than our current one. We postulate that this susy minimum is the true vacuum and, therefore, the final phase of the universe. At CERN, the broken susy phase has been referred to as "Susonia" and we have correspondingly suggested the future exact susy phase be called "Susyria".

In this talk we discuss the properties of this end-phase and address the four basic questions that were raised in [1]. While our primary interest, at present, is in the final transition from our broken susy world to the exact susy universe, it is thought that the inflationary phase in the very early universe corresponded to a sequence of similar phase transitions to progressively lower vacuum energies. Many such scenarios have been considered recently by Susskind and collaborators [2] as well as by others. We do not consider here the disfavored possibility of quantum jumps back to higher local minima. Some, presumably for philosophical reasons, have pursued the idea of an "eternal inflation" continually throwing off bubble universes in some of which the cosmological constant is small enough to support the evolution of life. Others, for similar reasons, have embraced the idea of a cyclical universe with repeated big crunches alternating with big bangs. These alternative philosophies envision an infinite number of life-supporting universes existing elsewhere in space time causally disconnected from our world. They therefore seem uneconomical in the extreme although this might depend on one's philosophical presuppositions. As, possibly, the most economical interpretation of the big bang data we prefer an absolute beginning of the multiverse at a finite time in the past in a state near the peak of the vacuum energy distribution although this is not crucial to the current discussion. We do assume that immediately after the big bang the universe was in a local minimum of vacuum energy density near M_P^4 and was, therefore, inflating rapidly. We assume that the distribution of string minima in vacuum energy density is strongly peaked at this natural value M_P^4 as, for example, in a Gaussian distribution:

$$N(\epsilon) = N_0 exp^{-k(\epsilon - M_P^4)^2/M_P^8} \quad . \tag{1.3}$$

If k is large enough, the vast majority of local minima are of order M_P^4 but if the total number of minima proportional to N_0 is also very large, a few of the minima will have vacuum energy density values ϵ below the maximum at which life could evolve. This maximum is about two orders of magnitude higher than our observed vacuum energy density [3]. The existence of such a mildly accelerating universe is the first prerequisite for the study of physics by intelligent beings. String theory suggests that the distribution of eq. 1.3 integrates up to a total number of local minima above 10^{100}. However, it is not enough to have a local minimum with a small enough vacuum energy. It is also crucial for the rise of life that the transition to our minimum ϵ_{now} happen in a time that is neither too short nor too long. If the transition takes too long the universe would be too dilute to form galaxies, planets, and life. If the transition takes place too rapidly, there would be too sudden an entropy growth and too much overheating of the nascent universe. Susskind and collaborators [2] have investigated many scenarios for the emergence from the inflationary era into the present mildly accelerating universe.

From Coleman and collaborators [4], we adopt the simplest vacuum decay probability per unit time per unit volume from a minimum of initial energy density ϵ_0 to a lower minimum of energy density ϵ. Multiplying this by eq. 1.3, the number of minima near ϵ, gives us the transition rate per unit volume

$$\frac{d^2P}{dtdV} = N(\epsilon) A e^{-13.5\pi^2 S^4/(\epsilon_0 - \epsilon)^3} \quad . \tag{1.4}$$

Here A is an undetermined normalization and S, the surface tension of the bubble of vacuum ϵ, is a function of the initial and subsequent vacuum energies. If S is sufficiently small and/or k is sufficiently large, the peak of the transition probability as a function of ϵ is to values of ϵ very near ϵ_0. This leads to a "slow roll" of the effective scalar field Φ down to our universe. If we re-order the minima in fig. 1 the picture suggested is as appears in fig. 2 where our universe with a broken susy and a residual vacuum energy is shown together with the ultimate exact susy true vacuum. If the true vacuum is a deSitter space with negative vacuum energy density many of our considerations will remain true although the universe will ultimately collapse in a big crunch. If string theory is a guide [5], a future transition to some such universe is essentially inevitable. Since the particle masses , as well as other properties of the theory, are different in each of the meta-stable intermediate universes, the entropy release is not necessarily as severe a problem as in the conventional theory. In the exact susy true vacuum susy particles will be degenerate with their standard model (SM) counterparts. We will assume the common masses are those of the SM particles in our broken susy world. For simplicity we can think of the minimal supersymmetric standard model (MSSM) with all of the susy breaking parameters put to zero. Also, at the current stage of investigation, we assume the future topology of space time is as in the broken susy world.

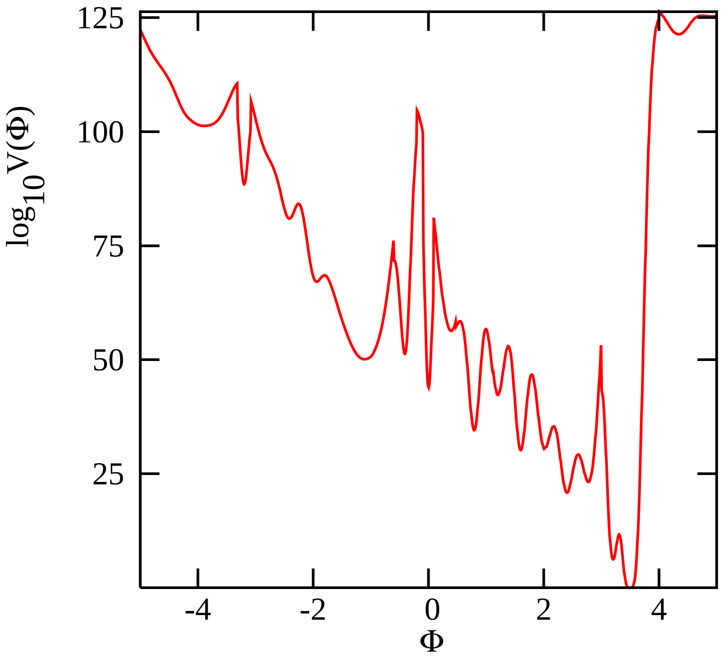

Figure 2: A schematic representation of the effective potential in the string landscape picture with re-ordered minima to reflect the slow roll of the effective field down to the current broken susy minima and showing the neighboring exact susy true vacuum.

We have proposed [1] that the primary distinguishing property of matter in the exact susy phase relative to our universe is an effective weakening of the Pauli Principle. This is due to the fact that, in the broken susy world, every atom above Helium is characterized by energy permanently stored in a Pauli tower of electrons and in a separate tower of nucleons in the atomic nucleus. In exact susy, conversion of Fermion pairs to degenerate scalar pairs not governed by the Pauli principle allows the release of this energy.

$$ff \to \tilde{f}\tilde{f} \tag{1.5}$$

This process [6] occurs in every susy model with or without R parity violation. For electrons the pair conversion process is mediated by photino exchange while for quarks it is mediated also by gluino exchange. Thus, following a phase transition to exact susy, fermions in excited states will convert in pairs to bosons which can then drop into the ground state as indicated in fig. 3.

Susy atoms in their ground state will therefore consist of zero, one, or two fermionic electrons with the rest of the leptonic cloud consisting of selectrons in the ground state. Similarly, all the particles in the nucleus will occupy the ground state wave function with as many as necessary being scalars. There will be no orbital angular momentum in ground state susy nuclei or leptonic clouds and therefore greatly restricted magnetic moments.

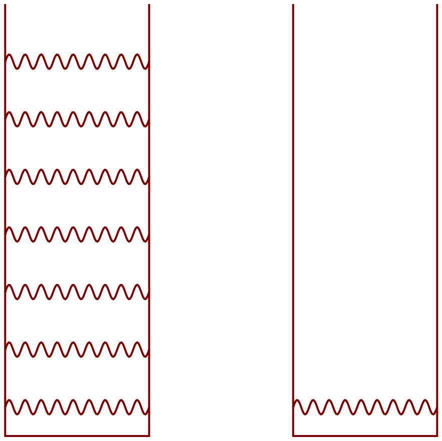

Figure 3: A Fermi degenerate system in the broken susy phase (on left) and after a phase transition to exact susy (on right).

A phase transition in vacuum will begin with the nucleation of a bubble of true vacuum with radius greater than a critical radius

$$R_c = \frac{3S}{\epsilon_{now}} \quad . \tag{1.6}$$

Although he did not specifically consider a supersymmetric true vacuum, the work of [4] generically predicts that such a bubble will expand in the vacuum at the speed of light converting all the matter in its path to the new phase. As such, the bubble wall will strike each planet without the possibility of advance warning. An artist's depiction of such a bubble striking the earth might be as in fig. 4. Although there can be no advance warning of the arrival time of a susy bubble nucleated in the vacuum, the inevitability of such a phase change is implied if gamma ray bursts or other violent astrophysical events are due [7] to density stimulated susy phase transitions in degenerate stars (for a review see ref. [8]). Stimulated phase transitions are confined to the region of high density although photons, light in both phases, can escape. After such transitions, the absence of an outward degeneracy pressure will lead to gravitational collapse to a susy black hole.

Figure 4:

The four basic questions posed in ref. [1] are

1. **Could life have arisen if there had been a phase transition directly from the inflationary era to the exact susy minimum?**

   Only if other low lying minima in the string landscape are few in number or are unsuitable for the evolution of life does observer bias or the anthropic principle provide some understanding of why the universe is as it is. The likelihood that exact susy minima exist in string theory forces one to examine the possibility of life arising after a transition from the inflationary era direct to an exact susy minimum. There are several weak hints arguing that no such possibility exists. First of all, one could note that galactic evolution seems to rely on a large dark matter component to provide the gravitational well within which normal matter can condense into galaxies. In the broken susy world, this role is played by the stable lightest supersymmetric particle (LSP) which is thought to have a mass in the 100 GeV region. In the exact susy phase, the LSP's are massless partners of the photon and graviton and there is no heavy stable particle to provide dark matter. Of course one could investigate whether other non-susy particles such as heavy neutrinos or axions could plausibly provide the dark matter in the exact susy phase without otherwise hindering the evolution of life. Other possible problems with production and distribution of heavy elements following a transition directly from the inflationary era to the exact susy phase have been noted in ref. [1].

Thus it is possible that the existence of life in a susy universe might require the prior generation of heavy elements in a broken susy phase.

2. **Could life survive, or re-establish itself, following a transition from our broken susy world to the exact susy world?**

   It is easy to find possible impediments, such as the one discussed in point 1 above, to the evolution of life in an exact susy universe following a direct transition from an inflationary era. If it is confirmed that these are incurable, one could still ask whether an exact susy universe could support life if there was an intermediate broken susy phase. Like the time critical property of the transition from the inflationary era to our calm broken susy universe, the transition to exact susy might also be time critical. If the current accelerating phase lasts too long, most stars will consist of white dwarfs out of causal contact with each other. At that point it is unlikely that life could be revived through a susy phase transition. The energy release in the conversion of fermions to bosons would be primarily in the form of gamma radiation and would not efficiently redistribute heavy nuclei through the universe. On the other hand, if the transition takes place while there are still earth-like planets orbiting burning stars, it is conceivable that life could re-establish itself. Although the radiation released from the Pauli towers would totally sterilise planets, it is not sufficiently energetic to totally dissociate nuclei. Leptons would eventually condense on heavy nuclei and it is plausible that molecular binding qualitatively similar to that of our world would occur. Afterwards, as we discuss in point 3 below, heavy elements would beta decay down to susy nuclei near Oxygen. Since all the elements needed to form DNA and 96% by weight of animal species are no heavier than Oxygen, evolution would be expected to recur leading to the re-emergence of species qualitatively similar to many of those in the broken susy world and defined by the same genetic codes.

   The properties of bulk susy matter are discussed in point 3 below and in point 4 we show that the expected time of the transition is close to the critical time discussed here for the re-establishment of life.

3. **What would be the primary characteristics of the physics (and biology, if any) of the exactly supersymmetric phase?**

The primary distinguishing features of bulk susy matter relative to matter in the broken susy phase are the greater numbers of states due to supersymmetry and the weakening of the Pauli Principle due to the possibility of pair conversion from Fermions to Bosons according to eq. 1.5. Whenever, in the broken susy phase, bound Fermions are forced into elevated energy levels, in the susy phase it will be advantageous for them to convert in pairs into their degenerate susy partners which, being Bosons, can drop into the ground state. Susy atoms will consist of zero, one, or two fermionic electrons. The remaining leptonic cloud will consist of selectrons. The entire leptonic cloud will be in the 1S state. This has the effect of making susy atoms much smaller in general than their broken susy counterparts although the effect is moderated by the increased self repulsion of the cloud. Smaller atoms in a solution will be expected to have slower reaction rates due to the decreased probability of collisions but might bind more tightly into molecules because of the smaller intra-molecular distances.

Susy nuclei would be expected to be sneutron rich since the increased binding with extra sneutrons would not be in competition with the Pauli exclusion principle which forces Fermionic neutrons into higher energy levels. Sprotons are also unaffected by the Pauli principle but their number is limited by Coulomb repulsion. In ref. [1] we have considered the beta decay constraints on snuclear stability:

$$\left(\frac{2a_c(Z-1/2)}{M_n - M_p + m_e}\right)^2 < A < \left(\frac{2a_c(Z+1/2)}{M_n - M_p - m_e}\right)^2 \tag{1.7}$$

where a_c is the coefficient of the Coulomb term in the semi-empirical mass formula for nuclei. We have assumed that the interaction strengths are similar to those in the broken susy world. Assuming degenerate susy multiplets have the same masses as the standard model particles in the broken susy world, the atomic weight of snuclei increases rapidly with atomic number so that stable elements above susy Oxygen must have atomic weights well above 238. Since in the broken susy world there are long-lived elements with atomic weights only up to this number, after a susy phase transition only elements up to susy Oxygen would be abundant. The elements with higher atomic number would beta decay down to Oxygen and below. A brief period of fusion burning might rebalance relative abundances of the light elements without leading to appreciable quantities of elements beyond Oxygen due to the requirement that higher elements have prohibitively large numbers of sneutrons.

As previewed in point 2, the constituents of life would then be available and, assuming molecular binding is cooperating, life forms similar to many of those we are familiar with would inevitably evolve given enough time. This assumes that the trace elements heavier than Oxygen found in living systems can be somehow dispensed with or replaced with lighter elements.

Fusion in susy phase stars will proceed beyond the iron limit of the broken susy phase because of the absence of a restrictive Pauli Principle. This means that susy stars will burn considerably longer than normal stars. Unless some new considerations come into play, they will, of course, eventually exhaust their fuel and collapse into black holes irrespective of their mass since there will be no degeneracy pressure to prevent collapse.

4. **Can we estimate the probable time remaining before our universe converts to a susy world?**

   The vacuum decay probability per unit time per unit volume as given in eq. 1.4 depends on the vacuum energy of the current phase, eq. 1.1. Thus the transition rate is proportional to the volume in which a phase change is possible. This volume is proportional to the cube of the scale factor in the Friedman-Robertson-Walker metric which, for positive cosmological constant, is exponentially growing at large times.

   In the presence of a vacuum energy density, ϵ, the scale factor of general relativity will satisfy

$$\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(\rho_{vac} + 3p_{vac}) \quad . \tag{1.8}$$

   Putting $p_{vac} = -\rho_{vac} = -\epsilon$, where ϵ is our current vacuum energy, the ϵ_{now} of eq. 1.1, this has the solution

$$a(t) = e^{\gamma t/3} a(0) \left(1 + (\frac{3\dot{a}(0)}{\gamma a(0)} - 1) \frac{1 - e^{-2\gamma t/3}}{2} \right) \tag{1.9}$$

   where, in terms of Newton's constant, G_N,

$$\gamma = \sqrt{24\pi G_N \epsilon} \quad . \tag{1.10}$$

   Neglecting sub-leading terms, we may write the volume of the universe at time t in terms of its present volume $V(0)$ as

$$V(t) = V(0) e^{\gamma t} \quad . \tag{1.11}$$

   The natural time scale for the growth in volume of the universe is

$$\gamma^{-1} = 5.61 \cdot 10^9 yr \quad . \tag{1.12}$$

   This time is comparable to the current age of the sun and to its expected additional lifetime before becoming a red giant. The volume of the universe is at least as big as the Hubble volume

$$V(0) > V_H = 7.79 \cdot 10^{78} m^3 \quad . \tag{1.13}$$

   What is the probability that such a bubble will strike Earth or some other location in a given time from now? Once nucleated somewhere in the universe, the bubble will require some time to propagate to any particular location such as that of Earth.

   The probability per unit time for a susy bubble to arrive at any given location at local time t is the probability per unit time for a critically sized bubble to be nucleated at any position r' at the retarded time $t' = t - r'/c$

$$\frac{dP(0,t)}{dt} = \int d^3r' e^{\gamma t'} \frac{dP(r',t')}{dV'dt'} dt' \delta(t' - t + r') = e^{\gamma t} A e^{-B} \int d^3r' e^{-\gamma r'} \quad . \tag{1.14}$$

This can be written

$$\frac{dP(0,t)}{\gamma dt} = e^{(\gamma t - B + \ln(8\pi A/\gamma^4))} \quad . \tag{1.15}$$

An integrated probability over any time interval exceeding unity should be interpreted as the probable number of susy bubbles hitting the earth in that time interval. We know that this has not happened between the time of the big bang and now. Requiring that the integrated probability from the big bang to now ($t = 0$) be less than unity suggests

$$B > ln(8\pi A/\gamma^4) \quad . \tag{1.16}$$

If we allow ourselves to consider saturating the limit 1.16, there is a non-negligible probability that the Earth will be swallowed by a susy bubble in a time T from today that is smaller than $1/\gamma$. This can be seen by replacing the inequality of eq. 1.16 by an equality and integrating eq. 1.15 from 0 to T:

$$P(T) = e^{\gamma T} - 1 \quad . \tag{1.17}$$

This is only relevant while $P(T) < 1$ since the collision of multiple susy bubbles with Earth is overkill.

We find it somewhat amazing that the natural time scale defined by the observed vacuum energy eq. 1.12 is at the boundary between that at which the re-evolution of life is possible and that at which a susy phase transition would lead to a lifeless universe of isolated susy black holes as described in point 2 above.

2 Conclusions

The time γ^{-1} provides an approximate upper limit to the lifetime of intelligent species in our broken susy universe. At times significantly larger than this all earth-like planets will have been devoured by red giants or obliterated in supernovae. 99% of stars will be in the form of cold white dwarfs accelerating rapidly away from each other. The others will be in the form of neutron stars or black holes. This corresponds to the much-discussed heat death of the universe, an end in ice. Alternate cosmologies under consideration postulate a reversal of the current outward acceleration of the universe toward an ultimate "big crunch", an end in fire, or toward a recurring eternal sequence of big bangs followed by big crunches.

We have outlined a possible new end phase scenario, a phase transition to an exactly supersymmetric universe. Because of the outward acceleration of the universe, the transition probability per unit time is an exponentially increasing function of time. Providing the inevitable transition occurs before about γ^{-1} there is a possibility that supersymmetric life forms could evolve.

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