Breaking SUSY on the Horizon

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Abstract: I present a heuristic calculation of the critical exponent relating the gravitino mass to the cosmological constant in a de Sitter universe. The ingredients for the calculation are the area law for entropy, an R symmetry of the low energy effective Lagrangian, and a crude picture of the degenerate levels of the cosmological horizon.

Keywords: de Sitter space, SUSY breaking.

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1. Introduction

In [1] I proposed that the breaking of Supersymmetry (SUSY) in the world we observe is correlated with a nonzero value of the cosmological constant. Crucial elements of this conjecture were the claim that Poincare invariant theories of gravity had to be exactly supersymmetric, and the claim that the cosmological constant is an input parameter, determined by the finite number of quantum states necessary to describe the universe. It follows that the gravitino mass is a function of Λ, vanishing as Λ → 0 and the number of states goes to infinity. As in any critical phenomenon, one may expect that classical estimates of the critical exponents are not correct. Thus I proposed that the classical formula $m_{3/2} \sim Λ^{(1/2)}$ (in Planck units) might be replaced by $m_{3/2} \sim Λ^{(1/4)}$ in a correct quantum mechanical calculation. The latter formula has been known for years to predict TeV scale superpartners when the cosmological constant is near the current observational bounds.

Unfortunately, I was not able to come up with even a crude argument for the validity of this conjecture. Indeed, in a recent note on the phenomenology of cosmological SUSY breaking (CSB) [2], I entertained the hypothesis that various terms in the low energy effective Lagrangian scaled with different powers of Λ. I am happy to report that

One can play with the idea of a meta-theory in which universes with different numbers of states are generated by some random or deterministic process, and the number characterizing our world is picked out by anthropic or number theoretic criteria. Such a theory could never be subjected to experimental test, and so appears somewhat futile.
this state of affairs has changed. Where there was nothing, there is now a waving hand. That is, there is a set of plausible sounding arguments about the interaction of particles with the cosmological horizon that reproduces the critical exponent $1/4$ for the gravitino mass. I do not pretend that these arguments are definitive, but I do hope that they are approximately correct.

In my initial thinking about this problem, I suggested that "Feynman Diagrams" describing virtual black hole production and decay were responsible for the anomalous relation between the gravitino mass and the cosmological constant. I soon realized that this was unlikely to make sense. Although production of black holes by high energy few particle collisions has probability of order one, the probability that the decay products of a large black hole will reassemble themselves in spacetime so that they can be absorbed by the particle that emitted the high energy virtual lines, and contribute to its mass renormalization, is infinitesimally small. While this argument involves an extrapolation between onshell and offshell processes, it convinced me that black holes were not the answer. Simultaneously, I realized that most of the states in dS space, could not be described as black holes in a single observer’s horizon volume. Rather they should be thought of as black holes sprinkled among many different static horizon volumes, causally disconnected from each other. According to cosmological complementarity [6], a single observer sees these as states near his cosmological horizon. This observation led to the paper which follows.

The calculation I will present is very heuristic and unconventional and one might be led to ask why more conventional methods of quantum field theory in curved spacetime do not lead to hints of this behavior. In fact, no calculations have been done in the conventional framework, and there are many indications that any such calculation would suffer from a variety of divergences. I will outline some of the problems in an appendix.

2. The Low Energy Effective Lagrangian

According to the conjecture of [1][3], Asymptotically dS (AsdS) spaces have a finite number of quantum states. In a universe with a finite number of states, there can never be precisely defined observables, because any exact measurement presupposes the existence of an infinite classical measuring apparatus. With a finite number of states (all of which have at least mutual gravitational interactions) there is no way to make a precise separation between observed system and measuring apparatus, nor any possibility of exactly neglecting the quantum nature of the measuring apparatus. Thus there should be no mathematically defined observables in dS spacetime.
Nonetheless, we know (though we do not yet know why or how) that when the cosmological constant is small, there should be an approximate notion of scattering matrix and (at low enough energy) of an effective Lagrangian. The hypotheses of [1] make this more precise. The cosmological constant is a tunable parameter, and in the limit that it vanishes there is a SUSic theory of quantum gravity in asymptotically flat spacetime. This theory has a well defined S-matrix. There should be an object for finite \( \Lambda \) which converges to this S-matrix. Indeed, by analogy to critical phenomena, one might expect that there are a plethora of different unitary operators in the finite \( \Lambda \) Hilbert space, which all converge to the same S-matrix. However, again by analogy to critical phenomena, we might expect that several terms in the asymptotic expansion of the S matrix around \( \Lambda = 0 \) are universal. I believe that it is in these universal terms that the "physics of AsdS space" lies. Everything else will be ambiguous.

I expect that the validity of this asymptotic expansion is highly nonuniform, both in energy and particle number. This is a consequence of the postulated finite number of states of the AsdS universe. The best convergence is to be expected for low energy, localizable processes, which do not explore most of the spacetime. These are the processes described by the low energy effective Lagrangian. The gravitino mass is the coefficient of a term in this Lagrangian, and has no more exact definition.

In the \( \Lambda \to 0 \) limit the effective Lagrangian should become SUSic and of course have vanishing cosmological constant. This indicates [2] that a complex (discrete) R symmetry is also restored in this limit. In [2] I argued that the limiting theory had to be a four dimensional \( N = 1 \) SUGRA with a massless chiral or vector multiplet which will be eaten by the gravitino when \( \Lambda \) is turned on. From the point of view of the effective Lagrangian, SUSY breaking should be spontaneous and triggered by explicit R breaking terms, all of which vanish as some power of \( \Lambda \). Among these is a constant in the superpotential, which guarantees that the cosmological constant take on its fixed input value. From the low energy point of view this looks like fine tuning. From a fundamental point of view it is merely a device for assuring that the low energy theory describes a system with the correct number of states (once one implements the Bekenstein-Hawking bound).

The reason that R breaking is explicit while SUSY breaking must be spontaneous is that the R symmetry is discrete, while SUSY is an infinitesimal local gauge symmetry. Explicit SUSY breaking can be made to look spontaneous by doing a local SUSY transformation and declaring that the local SUSY parameter is a Goldstino field. The possibility of restoring SUSY by tuning the cosmological constant to zero implies that the Goldstino must come from a standard linearly realized SUSY multiplet, which appears in the low energy Lagrangian. No such arguments are available for the discrete R symmetry. The picture of low energy SUSY breaking which thus emerges consists of
a SUSic, R symmetric theory, in which SUSY is spontaneously broken once R violating terms are added to the Lagrangian. The R violation should be attributed to interaction of the local degrees of freedom with the cosmological horizon.

The purpose of this paper is to estimate the size of the R breaking terms in the low energy effective Lagrangian. In [2] I also had to invoke Fayet-Iliopoulos (FI) D terms for some U(1) groups. I have since learned from Ann Nelson that such terms can be generated by nonperturbative physics in low energy gauge theory[4]. This physics in turn depends on the existence of certain terms in the superpotential; terms which could be forbidden by an R symmetry. In addition, I have found models not considered in [2], where dynamical SUSY breaking is triggered by the addition of R violating terms to an otherwise SUSic theory. I will therefore assume that our task is just to estimate the breaking of R symmetry by the horizon. As we will see, this is dominated by the lightest R-charged particle in the bulk. In many models of low energy physics, this will be the gravitino, and I will assume that this is the case.

3. Horizontal Breaking of R Symmetry

The basic process by which the horizon can effect the low energy effective Lagrangian is described by Feynman diagrams like that of Fig. 1. A gravitino line emerges from a vertex localized near the origin of some static coordinate in dS space, propagates to the horizon, and after interacting with the degrees of freedom there, returns to the vertex. The dominance of diagrams with gravitinos is a consequence of our attempt to calculate R violating vertices and our assumption that the gravitino is the lightest R charged particle. The dominance of diagrams with a single gravitino propagating to the horizon will become evident below.

In field theory, the effective Lagrangian induced by a diagram like Fig. 1 will have a factor\(^2\)

\[
\delta L \sim e^{-2m_{3/2} R} R^{-4},
\]

where \(R\) is the spacelike distance to the horizon. This factor comes from the two propagators and an integral over the point where the gravitino lines touch the horizon. The gravitino is assumed massive because we know that SUSY is broken in dS space.

\(^2\)All of the calculations of this section are done in four dimensions.
Our hope to overcome this field theoretic suppression comes from the fact that the horizon has $e^{\frac{(RMP)^2}{4}}$ states. We thus want to estimate how many of these states the gravitino line interacts with. Since the entropy of the horizon is extensive, this is, crudely, the amount of horizon area the gravitino sees. The thermal nature of Hawking radiation from the horizon suggests that the gravitino interacts in much the same way, with most of the horizon states it comes in contact with. Since the gravitino is massive and the horizon a null surface, it can only propagate along the null surface for a proper time of order $1/m^{3/2}$.

During its contact with the horizon the gravitino is interacting with a Planck density of degrees of freedom. Rather than free propagation, we should imagine that it performs a random walk with Planck length step over the surface of the horizon, covering a distance of order $m^{-\frac{1}{2}}$ and an area of order $1/m^{3/2}$.

We now make our major assumption, which is that the diagram of Fig. 1 gets a coherent contribution from a number of states of order $e^{m^{3/2}}$ that the gravitino encounters as it wanders over the horizon. For small gravitino mass, this might be an extremely tiny fraction of the total number of states localized in the area of the horizon explored by the gravitino. Thus, to exponential accuracy, the contributions to the $R$ breaking part of the low energy effective Lagrangian are of order

$$\delta\mathcal{L} \sim e^{-2m^{3/2}R + \frac{aMP}{m^{3/2}}}$$

We imagine the calculation of this diagram to be part of a self consistent calculation of the gravitino mass, in the spirit of Nambu and Jona-Lasinio [5]. That is, the interaction with the horizon of a gravitino of a certain mass causes $R$ breaking,
which gives rise to SUSY breaking and a gravitino mass. If $m_{3/2}/M_P > (\frac{2RM_P}{a})^{-\frac{1}{2}}$ then our calculation gives an $R$ breaking effective Lagrangian which falls exponentially with $RM_P$. Thus, the horizon contribution is totally negligible. On the other hand, we know of no other contribution to the mass which is this large, for large $RM_P$. Thus masses in Planck units greater than $(\frac{2RM_P}{a})^{-\frac{1}{2}}$ are not self consistent.

If $m_{3/2}/M_P < (\frac{2RM_P}{a})^{-\frac{1}{2}}$, the equation predicts an exponentially growing breaking of $R$ symmetry, and a correspondingly huge gravitino mass, so again the assumption is inconsistent. Notice that this, in particular, rules out the classical formula, $m_{3/2} \sim R^{-1}$. The only self consistent formula, to leading order in $RM_P$, is $m_{3/2} = M_P(\frac{2RM_P}{a})^{-\frac{1}{2}}$. Taking $R$ of order the Hubble radius of the observable universe, we get a gravitino mass of order $10^{-11.5} \text{GeV}$. This corresponds to a scale for the splitting in nongravitational SUSY multiplets of order $5 - 6 \text{TeV}$. This is the scaling of the gravitino mass conjectured in [1].

It may appear that our solution for $m_{3/2}$ is not consistent at the power law order in $RM_P$. That is to say, if the $R$ dependence of $\delta L$ is given by the above equation, it does not give rise to a gravitino mass of order $\Lambda^{1/4} = R^{\frac{1}{2}}$. However, corrections to the parameter $a$ of the form $\delta a \sim b \ln(RM_P)/(RM_P)^{1/2}$ can remedy this difficulty. Alternatively, (or in addition) nonleading, logarithmic terms in the self consistent formula for $m_{3/2}$ for fixed $a$ can have the same effect. Notice that although at present we have no way of estimating such corrections, self consistency requires them to be present in precisely the right amounts. The dominant exponential terms in the gravitino mass relation are self consistent only for $m_{3/2} \sim \Lambda^{1/4}$.

It should now also be clear why diagrams with more than one gravitino line propagating to the horizon, or with any heavier particle replacing the gravitino, are subdominant. These have a larger negative term in the exponential, but no larger enhancement from the number of states.

Our calculation clearly rests squarely on the assumption that we can get a contribution of order $e^A$ from interacting with an area $A$ of a system. This sounds peculiar when heard with the ears of local field theory. If, in the spirit of the Membrane paradigm, we modeled the physics of the horizon by a cutoff field theory we would again find $e^{A\sigma}$ states in an area $A$, where $\sigma$ is the entropy density of the field theory. Yet the interactions of a probe concentrated in an area $A$ would be expected to renormalize the effective action of the probe by terms of order $A$. This follows from general clustering and locality arguments in field theory.

However, there is another way that such a field theoretic model fails to capture the physics of horizons. Consider the case of a black hole. A field theory model would predict an energy density as well as an entropy density. The total energy of the black hole would then be of order its area, much larger than its mass.
A somewhat better model of a horizon may be obtained by considering a system of fermions on a two sphere, coupled to an external $U(1)$ gauge field. The field configuration on the sphere is that produced by a magnetic monopole of very large charge. All fermions are in the lowest Landau level and we tune the magnetic charge so that this is completely full. We can choose linear combinations of the single particle wave functions so that each fermion is localized in a quantum of area on the sphere. Now imagine giving each fermion a two valued "isospin" quantum number, on which neither the horizon’s Hamiltonian nor its coupling to the external probe depend. The probe is coupled to the position coordinates of the fermions, in a local manner. The system has $2^A$ degenerate states in area $A$ and the probes effective action will be renormalized by an amount $\propto 2^A$.

4. Discussion

The handwaving nature of the arguments I have presented is probably unavoidable at this stage of our understanding of quantum gravity in de Sitter space. To do better, we must first construct a complete quantum model of de Sitter space, presumably a quantum system with a finite number of states. This construction must recognize the approximate nature of any theory in dS space. There should not be precisely defined, gauge invariant observables, corresponding to the fact that no precise self-measurements can be carried out in a quantum system with a finite number of states. Rather we should look for approximations to the Super Poincare Generators and S-matrix. We should then understand how to identify an approximate notion of low energy effective Lagrangian, which describes some of the physics of the full quantum S-matrix. The latter in particular is a difficult task. Even in Matrix Theory, and AdS/CFT, where there is a precisely defined quantum theory, we can only find the low energy effective Lagrangian by computing the S-matrix and taking limits.

Further development of the kind of mongrel argument used in this note, in which properties of the low energy effective Lagrangian and the horizon, are used as separate constructs which have to fit into a self consistent picture, depends on refinement of our understanding of horizons. It may be that this can be achieved by studying Schwarchild black holes, and assuming that the local properties of dS horizons are similar. Black holes are objects in asymptotically flat space and precise mathematical questions about their properties can be formulated. It is intriguing that we have already found that a picture of horizon dynamics in terms of a cutoff local quantum field

\footnote{I would like to thank O. Narayan for discussions about quantum Hall systems.}

\footnote{In perturbative string theory we can also derive the Lagrangian from the world sheet renormalization group, an intriguing hint, which has not had any echoes in nonperturbative physics.}
theory on the horizon is inconsistent both with the large breaking of SUSY conjectured in [1] and with the entropy/mass relation of the black hole. In this context, it is worth pointing out that for those near extremal black holes where a field theoretic counting of entropy is successful, the field theory does not live on the horizon, and some of the horizon coordinates are quantum operators. This suggests, as does the Landau level model of the last section, that horizons are described by a noncommutative geometry.

On a more phenomenological note, the present calculation sheds some light on a possibility that I raised in [2]. I suggested that different R breaking terms in the low energy effect Lagrangian might scale with different powers of the cosmological constant. There is no hint of that possibility in the calculation I presented. That is, the powers of the dS radius do not depend at all on the external legs of the Feynman diagram, which would distinguish between different R breaking operators. On the other hand, if the FI D term is generated, as in [4] from low energy dynamics, which is itself triggered by the existence of R breaking terms, the FI D term might depend on both the explicit R breaking scale and the dynamical scale of a low energy SUSY gauge theory. I will leave the exploration of the latter question, as well as of alternative models of low energy physics, to another paper.

It is worth pointing out that large effects of the type I have calculated would not occur in FRW cosmologies which asymptote to SUSic universes, at least if one follows the rules that I have advocated here. The holographic screen, analogous to the cosmological horizon, for such a universe is future null infinity. It is an infinite spacelike distance away from any finite point on the worldline of a timelike observer. The effect I have calculated is larger than any which might have been found in local physics, but it still vanishes as the spacelike distance to the holographic screen goes to infinity. SUSY breaking in such spacetimes will be dominated by local physics.

A somewhat more puzzling situation is presented by a hypothetical universe which stays in a dS phase for a very long time (60 gazillion years, to use technical language) but then asymptotes to a SUSic state. One can easily invent (fine tuned) models of quintessence which have this property. I think the answer here is that the effective Lagrangian of a local timelike observer in such a universe is time dependent. It will initially exhibit larger than normal SUSY breaking, and then become rapidly SUSic. The puzzle that remains is how the transition is made and what a convenient set of holographic screens for such a spacetime might be.

Finally, I want to respond to a question I have been asked many times in the context of lectures on [1]: why doesn’t CSB also imply large corrections to other calculations in low energy effective field theory? The answer has been given before and does not really depend on the calculation in this paper, but perhaps it obtains new force from that calculation. The basic idea of CSB is that Λ is a variable parameter and that the
Λ = 0 theory has a SUSic, R symmetric low energy effective Lagrangian. All terms in this Lagrangian obviously have a finite Λ → 0 limit. CSB is the theory of how the R violating terms (and perhaps an FI D term that is induced by them) depend on Λ in the flat space limit. It is calculating quantities that are parametrically smaller than the SUSic, R symmetric terms in the Lagrangian. Our calculation did not lead to any terms, which diverge in the limit. Such behavior is not compatible with the self consistency of the induced gravitino mass. Thus, any corrections to the preexisting terms in the Lagrangian take the form of small (suppressed by a positive power of the cosmological constant) corrections to their finite, SUSic, values.

5. Appendix

In order to discuss the question of SUSY breaking in dS space we first have to realize dS space as a solution of a SUGRA Lagrangian. This restricts us to minimal supergravity in 4 dimensions. The simplest Lagrangian with a dS solution contains one chiral supermultiplet in addition to the SUGRA multiplet, and is characterized by a holomorphic superpotential \( W(Z) \) and a Kahler Potential \( K(Z, Z^*) \). In fact, away from zeroes and singularities of \( W \), these can be combined into a single function. We will not make this combination because we start out from the assumption of an R symmetric minimum where \( W \) vanishes. The quantum field theory associated with this Lagrangian is not renormalizable and must be supplemented with a cutoff procedure, with a cutoff of order the Planck scale. Ensuring that the cutoff procedure is invariant under superdiffeomorphisms is a complicated technical problem to which there is no known solution. I will assume that this can be solved.

The presumed stationary point of \( W \), with \( W = 0 \) gives a Minkowski spacetime in which can compute a gauge invariant S-matrix, and extract from it, order by order in perturbation theory, a gauge invariant effective action. If we perturb the superpotential by small explicit R breaking terms that lead to a dS minimum with small cosmological constant, we would hope that, at least to some order in the perturbation, the gauge invariant effective action is still a valid physical quantity. Indeed, apart from the problem of superdiffeomorphism invariant regulators, the standard background field action of DeWitt seems to provide us with the required perturbatively gauge invariant quantity, even for a dS background. When I refer to particle masses, I mean coefficients in this gauge invariant action. Note that the action is globally dS invariant, so that even if one insists that the global isometries are gauge transformations, the effective action should still be meaningful. In order to tune the cosmological constant to be much smaller than the SUSY breaking scale, \( F = |DW| \) we must, generally, add an explicit R breaking constant to \( W \).
Now consider loop corrections to the effective action. These are logarithmically UV divergent at one loop\(^5\). Higher loop calculations will have higher powers of the logarithm, and there is no small expansion parameter. In previous discussions of this problem, I have argued that this shows UV sensitivity of the calculation of UV effects, and then invoked the UV/IR connection to claim that physics above the Planck scale will renormalize the gravitino mass by amounts that depend on the cosmological constant.

It now appears more probable that the signal for large breaking of SUSY, within the framework of field theory, is the infamous IR divergence problem of dS space\(^7\). The transverse, traceless part of the graviton propagator grows logarithmically at large distances. In an initial version of [1] I considered the possibility that these divergences might be the mechanism responsible for the anomalous scaling behavior of the gravitino mass. I rejected this mechanism because there was confusion in the literature as to whether the IR divergences could appear in gauge invariant physical quantities. It was only later that I came to the conclusion that there were no mathematically precise, gauge invariant quantities in dS space. IR divergences have certainly been shown to appear in quantities that appear to be perturbatively gauge invariant. I would speculate that the calculation of the gravitino mass renormalization will similarly have IR problems.

It is not at all clear that any kind of resummation of these divergences should give a finite answer, much less an answer that agrees with the calculation of this paper. Our calculation had an explicit cutoff on the number of states, that is absent in QFT in dS space. So the IR divergence of the naive low energy theory may just be an indication that the true quantum theory of dS space is not well approximated by field theory. At issue here is whether there is a sort of duality between the description by a single static observer, of UV processes localized near his cosmological horizon (this is the description used in the foregoing paper), and an IR description of the same physics using quantum field theory in the global dS space time. None of our experience with black hole physics gives us guidance here, since we do not yet have an adequate description of the physics of an infalling observer.

If one believes in such a duality, he would be motivated to recover our result by calculations in quantum field theory, that is, by trying to resum the IR divergences that I believe would appear in a global computation of the gravitino mass. On the other

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\(^5\)It is often said that in minimal four dimensional SUSY, the cosmological constant is quadratically divergent. It is hard to understand how this could be compatible with the general structure of SUSic effective Lagrangians for positive cosmological constant. The positive term in the effective potential is proportional to the square of the gravitino mass. Thus, a divergent positive cosmological constant would imply a divergent gravitino mass. S.Thomas has informed me that if the calculation is done with SUSic Pauli-Villars regulators, the one loop vacuum energy is only logarithmically divergent.
hand, for a given observer, it may be that only the description of low energy processes localized far from his/her cosmological horizon is well approximated by quantum field theory. At the moment, I do not know which of these two points of view is correct, though the lack of a natural IR cutoff in the field theory calculation suggests that one is unlikely to reproduce the correct physics by simply resumming field theory diagrams. Unfortunately, the calculation of loop corrections to the gravitino mass in the perturbative approach to quantum gravity in dS space, is a daunting exercise. One may hope to compute the one loop contribution, but a systematic analysis to all orders in perturbation theory, seems difficult.

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