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Supersymmetry, the Cosmological Constant, and A Theory of Quantum Gravity in Our Universe

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ABSTRACT: There are many theories of quantum gravity, depending on asymptotic boundary conditions, and the amount of supersymmetry. The cosmological constant is one of the fundamental parameters that characterizes different theories. If it is positive, supersymmetry must be broken. A heuristic calculation shows that a cosmological constant of the observed size predicts superpartners in the TeV range. This mechanism for SUSY breaking also puts important constraints on low energy particle physics models.

KEYWORDS: .

Superstring Theory (ST) is our most successful attempt at constructing a quantum theory of gravitation. The advances of the Duality Revolution[1] gave us detailed mathematical evidence for the nonperturbative existence and consistency of the theory. Ironically, they also told us that its name is misleading because it emphasizes particular asymptotic regions of a collection of continuous moduli spaces of theories. A better name would be *Supersymmetric Quantum Theories of Gravity (SQUIGITS).*

Indeed, the most cogent statement of the results of the Duality Revolution is that the principles of supersymmetry (SUSY) and quantum mechanics imply the existence of these moduli spaces of theories and of certain extended objects in them, whose tension can be calculated exactly. One then sees that in certain limiting regions of moduli space, strings of tension much less than the Planck scale exist, and one is led to expect a perturbative theory of strings. The existing formalism of perturbative superstring theory is a brilliant confirmation of these general arguments. Almost all known perturbative string expansions can be derived from arguments of this sort. The perturbation expansions allow us to calculate many quantities whose value does not follow from SUSY. More remarkably, in many cases, they can be used to obtain a completely nonperturbative formulation of the theory. The latter examples go under the names of Matrix Theory[2] and the AdS/CFT correspondence[3].

Two points on a connected moduli space of such theories can be considered part of the same system because any physical observable of one can be recovered with arbitrary accuracy in terms of measurements done in the other. But this is no longer true if we try to compare theories on different moduli spaces[5]. We seem to be presented with a plethora of different consistent theories of quantum gravity, all of which are exactly supersymmetric and none of which describe the real world. It behooves us to search for criteria that would help us to understand how to construct a theory of the world, and to explain why our world is not described by a point on one of these moduli spaces of consistent theories.

An important general principle that emerges[1] from our rigorous understanding of supersymmetric theories of quantum gravity is the principle of Asymptotic Darkness: *The high energy spectrum of a theory of quantum gravity is dominated by black holes[8]. All scattering amplitudes at sufficiently large values of the kinematic invariants are dominated by black hole production[10].* The famed UV/IR connection follows from this principle[2] : high energy states take up large regions in space, and have low curvature

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[1] This principle could have been declared earlier, on the basis of black hole physics. However, only the mathematically rigorous formulation of the SUSic theories, particularly the AdS/CFT correspondence, gives us confidence that it is correct.

[2] as does the even more famous Holographic Principle. One can attempt to probe short distances in order to demonstrate the volume extensive density of states we expect from quantum field theory

external gravitational fields. This connection is the key to understanding that isolated vacuum states or theories with different values of the cosmological constant are not connected. The traditional notion of vacuum state in QFT is an infrared notion. Two vacua of the same QFT have identical high energy behavior, but this is false for states with different values of the cosmological constant.

For negative cosmological constant, the evidence for this statement comes from AdS/CFT. In these systems, the value of the cosmological constant in Planck units is determined by an integer N. N determines the number of degrees of freedom of the conformal field theory whose boundary dynamics defines quantum gravity in the bulk of AdS space. For 5 dimensional AdS spaces the relevant theories are conformally invariant supersymmetric gauge theories and N is the rank of the gauge group. Large N corresponds to small cosmological constant, Λ. *AdS/CFT shows us that the value of Λ is a discrete choice that we make in defining the theory, rather than a computable quantity in the low energy effective action.* Λ determines the density of *high* energy states of the theory.

For positive Λ the evidence is less compelling since we do not yet have a mathematical quantum theory of de Sitter (dS) space. Fischler[6] and the author[4] suggested that the Bekenstein-Gibbons-Hawking entropy of dS space be interpreted as the logarithm of the number of quantum states in the Hilbert space defining quantum dS gravity. Evidently, Λ is then a discrete parameter chosen by the theorist, just as it is in the AdS systems. The existence of a maximal size black hole with entropy less than the dS entropy, together with the Bekenstein bound on the entropy of general localized systems by the entropy of black holes, then implies that a finite number of states suffices to describe any conceivable measurement in dS space.

The new role of Λ as a fundamental parameter, suggests that we give up the attempt to explain its value by other than anthropic means. Rather, we should attempt to calculate everything else in the theory, as a function of Λ, in Planck units, and use one experiment to determine that pure number. The opportunity to explain the conundrum of vacuum selection now presents itself. A unitary quantum theory of dS space cannot be SUSic. Thus, the choice of a finite dimensional Hilbert space for the quantum theory, breaks SUSY. The question is by how much. Low energy field theory suggests a gravitino mass that scales like $\Lambda^{1/2}$ in Planck units. I have presented a quantum calculation that suggests an enhancement to[7]

$$m_{3/2} \sim \Lambda^{1/4}. \tag{1}$$

(QFT). The production of black holes prevents us from doing this, and instead presents us with an area extensive spectrum of states.

The key to the calculation is the fact that the $\Lambda \rightarrow 0$ limit of the dS theory is a SUSic, R-symmetric theory[4]. R symmetry violating terms are induced in the low energy effective Lagrangian by the dS background. These then lead to spontaneous violation of SUSY, and a gravitino mass. The leading contribution to these R violating terms comes from Feynman diagrams where a single gravitino line propagates out to the horizon and interacts with the large number of degenerate quantum states that a static observer sees there. The graph is suppressed by $e^{-cm_{3/2}R}$ from the gravitino propagator, where $R = \Lambda^{\frac{-1}{2}}$ is the radius of the horizon. I argued that there was a compensating factor $e^{\frac{b}{m_{3/2}}}$ from the interaction with the large set of degenerate states on the horizon. Self consistency then leads to the scaling law 1. If the two exponential terms don't exactly cancel, leading to power law corrections, then the assumption of a small gravitino mass leads to a very large mass and vice versa. Of course, we really need a complete mathematical theory of the dS horizon to construct a reliable version of this argument.

The phenomenological consequences of the calculation are significant. The consistent SUSY vacua are banished from the theory of the world by the assumption that the theory has a finite number of states. The dimension of the dS space is probably fixed to be 4 because this is the only dimension in which SQUIGITS can have a low energy Lagrangian with small deformation that supports a dS solution. The limiting SUSY theory cannot have any moduli. The value of superpartner masses that solves the Standard Model hierarchy problem is predicted in terms of the cosmological constant. There are also more detailed constraints on the possible forms of the low energy supersymmetric Lagrangian[9].

One problem that remains to be solved is the construction of machinery for finding all possible isolated Super Poincare invariant theories of quantum gravity in four dimensions. A second is the development of a mathematical theory of horizon dynamics, which will provide a firm foundation for the calculation of supersymmetric mass splittings in terms the cosmological constant.

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