Experimental Signatures of Quantum Gravity

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ABSTRACT

I review several different calculations, coming from string theory, nonperturbative quantum gravity and analyses of black holes that lead to predictions of phenomena that would uniquely be signatures of quantum gravitational effects. These include: 1) deviations from a thermal spectra for evaporating black holes, 2) upper limits on the entropy and energy content of bounded regions, 3) suppression of ultra-high energy scattering amplitudes, consistent with a modified uncertainty principle, 4) physical volumes and areas have discrete spectra, 5) violations of CPT and universal violations of CP, 6) otherwise inexplicable conditions on the initial state of the universe or otherwise inexplicable correlations between cosmological and microscopic parameters. Consideration of all of these together suggests the possibility of connections between perturbative and nonperturbative approaches to quantum gravity.

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Introduction

It is unfortunately true that we do not yet have a completely satisfactory quantum theory of gravity. At the same time, there has been a great deal of progress in recent years in more than one approach to quantum gravity. One measure of this progress is that we now know how to do several different kinds of calculations which describe what might be called characteristic quantum gravitational phenomena. These are conjectured phenomena that share the following features,

1) They seem to be follow necessarily from rather general assumptions about how to extend the basic principles of relativity, quantum theory and quantum field theory.

2) They would be impossible in a world described either by classical general relativity or by quantum field theory on a fixed spacetime background.

3) In spite of the incompleteness of our present understanding of quantum gravity, we are able to make specific predictions concerning them which could be tested experimentally, subject only to the technical feasibility of Planck scale experiments.

It is significant that these developments describe different kinds of phenomena, and arise in the framework of different approaches to quantum gravity. However, I do not think this should necessarily imply that they could not all be simultaneously true. While there is as yet no complete theory of quantum gravity, it is possible that the different approaches that to some partial extent succeed are complementary rather than contradictory, in that they explore different physical domains. For example, most calculations in string theory that bear on quantum gravity are perturbative and describe small deviations from a classical background, while most interesting results in the loop representation approach to quantum gravity are non-perturbative. Furthermore, in each case the striking results seem to rely more on general principles, and less on specifics such as dynamics or matter content. In the case of string theory, predictions about hyper-Planck scale physics[1, 2, 3] follow rather directly when one assumes that perturbative finiteness can be accomplished without breaking Lorentz invariance[4, 5]. In the case of the loop representation approach[6, 7, 8], certain effects seem to follow rather directly from the assumption that the representation and regularization procedures are compatible with diffeomorphism invariance[9, 10]. In neither case are detailed dynamical assumptions involved. Thus, it is possible to imagine that at least some of the effects predicted by string theory are characteristic of the perturbative domain of any consistent quantum theory of gravity.
gravity, while some of the effects found in the loop representation approach
are characteristic of any successful approach to the non-perturbative domain.

In addition, other calculations, such as those showing violations in the
thermal spectra of black holes [11, 12, 13, 14], seem to rely only on rather
general assumptions about the Planck scale, without making detailed as-
sumptions about the dynamics.

For this reason I would like to suggest that we try to see if we can learn
anything if we take the point of view that these different approaches are
complementary, rather than competing. To this end, it may be interest-
ing to list together some of the different experimental predictions that have
emerged out of these different approaches, and to ask whether, taken to-
gether, they might make a kind of a picture of physics at the Planck scale. I
thus describe in the following six sections six different kinds of results which
may be taken to describe signatures of quantum gravitational physics.

Unfortunately, due to limitations of space, I cannot attempt to give a
complete survey of all the experimental predictions that have come from
attempts at quantum gravity, nor do I give a complete list of references in
the cases I do describe. The discussions are abbreviated, but details may be
found in the cited references. Also, I apologise if more space is given to work
with which I am more familiar; this is only because my ignorance of some
topics does not permit me to discuss them in the same depth as the others.

1 Corrections to the spectra of evaporating black
holes

In the semiclassical approximation, black holes have thermal spectra [10]. As
has been pointed out by many people, it is quite likely that in a full quantum
theory of gravity there must be corrections to the thermal spectra of black
holes. These corrections are quite likely necessary to resolve the questions,
such as the information loss paradox, raised by the semiclassical claculations;
to this extent experimental observations may in principle decide between
different proposals about how these puzzles are to be resolved [17]. Motivated
primarily by these, at least three kinds of corrections to the thermal Hawking
spectra, coming from quantum gravity effects, have been investigated.

The first kind follows from the hypothesis that information is not actually
lost in black hole evaporation. If this is the case there must be corrections
to the spectra coming from correlations between quanta emitted from the
black hole at different times [18].
The second source of corrections to the Hawking radiation comes from the peculiar fact that the modes that dominate the Hawking radiation at times long after the formation of the black hole are extraordinarily blue shifted when they propagate near the horizon\cite{16}. Thus, the derivation makes it seem as if effects at scales much shorter than the Planck length are involved in the Hawking radiation.

On the other hand, all of the approaches to quantum gravity that have been at least partially successful require strong modifications in the physics below the Planck length, which introduces some truncation or diminuation in the number of degrees of freedom at such scales\cite{20}. For example, one such modification might be the presence of a discrete spacetime structure at the Planck scale. Another might be a modification in the energy-momentum dispersion relationship at hyperplanck scales. It is then very important to investigate whether such changes from the naive free field behavior might lead to modifications in the thermal spectra predicted by the semiclassical theory.

This question was investigated from different points of view by Jacobson\cite{11} and Unruh\cite{12}. A key question that arises in this work is whether there the existence of a discrete spacetime structure can be consistent with Lorentz invariance. If not, there must in some circumstances be preferred observers who see the violations from the free field behavior to happen at a particular scale. Jacobson hypothesizes that the answer is yes, and imposes a cutoff in the frame of an observer freely falling into the black hole. The result is that there are small modifications away from a thermal spectra for evaporating black holes\cite{11}. However, even drastic changes in Planck scale physics do not lead to a suppression of the Hawking radiation for larger than Planck scale black holes.

The work of Unruh was based on numerical studies of his model of sonic black holes, or dumb holes, in which horizons appear in supersonic fluid flows\cite{12}. He investigated whether modifications in the dispersion relation of sound waves at high frequencies lead to modifications in the “Hawking” radiation coming from the hole. He found that the radiation is still thermal. However his results do not rule out the possibility that there are small modifications in the spectra due to the short distance effects.

These results suggest that the corrections to the spectra of evaporating black holes are of the order of $m_{Pl}/M_{bh}$. However there is a very interesting suggestion that this may be too pessimistic, and that quantum gravity may actually induce corrections in the predictions for the spectra of evaporating black holes which are of order unity, no matter how large the mass of the
black hole is. In a very provocative paper, Bekenstein and Mukhanov show that the simple hypothesis that the area of the event horizon of the black hole is quantized in discrete Planck scale units results in a rather different spectra than that predicted by Hawking.

The argument for this is quite simple. Let us make the simplest possible assumption for the quantization of area, which is that the area of the horizon must take one of the values,

$$A_h = n \alpha l_P^2$$  \hspace{1cm} (1)

where $\alpha$ is a dimensionless constant of order one and $n$ is an integer. It follows that there is a discrete spectrum of neutral non-rotating black holes with masses,

$$M_{bh} = m_P \frac{1}{4} \sqrt{\frac{\alpha}{\pi n}}$$  \hspace{1cm} (2)

It follows from this that an evaporating spherical black hole may only radiate in integer multiples of a characteristic frequency

$$\omega_0 = \frac{\alpha}{16\pi} \frac{1}{2GM}$$  \hspace{1cm} (3)

as long as it only makes transitions to other non-rotating black holes. There will, of course, be fine structure in the spectra of black holes, due to the quantized angular momentum. The general expression for a quantized Kerr black hole with quantized horizon area and angular momentum is, using the formula of Christodolou and Ruffini

$$\frac{M^2}{m_P^2} = \frac{\alpha}{16\pi} \frac{1}{n} + \frac{4\pi \ell (\ell + 1)}{\alpha n}$$  \hspace{1cm} (4)

As long as the angular momentum is small compared to the irreducible mass squared (in units $G = c = 1$), the result will be a fine structure of the lines coming from the black holes making transitions in both spin and area. However, the resulting broadening of the of the lines will be small compared to the spacing given by (3) as long as $J/M_{irr}^2$ is small. Thus, except for the case of near-extremal black holes, the broadening due to angular momentum cannot be responsible for spreading out the lines sufficiently to recover the continuous thermal spectra predicted by the semiclassical calculation.

The smallest frequency of the spectra (3) is near the peak of the thermal radiation. This means that if radiation could be seen from any evaporating
black hole, there would, according to the hypothesis of quantized area, be a stark difference from Hawking’s prediction of a continuous thermal spectra. Bekenstein made the hypothesis that the area of black hole horizons should be quantized some time ago[14]. More recently, the quantization of the areas of physically distinguished surfaces has been shown to be a consequence of the loop representation approach to non-perturbative quantum gravity, as I will describe in section 6 below. Although the predictions of the spectra differs to some extent from equation (1), it is possible then that line emission of the sort described by (3), rather than the continuous thermal spectra of Hawking, must in fact be a general prediction of a nonperturbative quantum theory of gravity.

Finally, one expects corrections to the thermal radiation in any quantum theory of gravity coming from the fact that the metric itself is quantized. Kraus and Wilczek have been able to compute such corrections, in the model in which the gravitational field is taken to be spherically symmetric[15]. Because quantum gravity is expressed in terms of constraints, the physical, gauge invariant perturbations of a black hole involve necessarily functions of both the matter fields and gravitational fields. One cannot in a gauge invariant way separate them from each other. Kraus and Wilczek are able to compute Hawking radiation in a model in which gravity is coupled to matter fields, but spherical symmetry is imposed. They find that there is Hawking radiation in the physical, coupled gravity/matter modes. However, there are corrections to the Hawking formula coming from the fact that the metric is correctly included as part of the quantum modes. This is a highly significant result, and should be quite independent of which theory correctly describes Planck scale physics.

2 Violations of CPT and CP

The CPT theorem depends on assumptions about the geometry of Minkowski spacetime. Furthermore, we do not expect local causality to hold in a quantum theory of gravity, because there is no fixed background metric within which the fields propagate. It then may be expected that CPT could be violated in a quantum theory of gravity.

More specific reasons for expecting such a violation have come from two directions. First, Hawking proposed that CPT must be violated if information is lost in black hole evaporation[13]. To discuss this work we must separate two claims made by Hawking, the first, that CPT is violated
in the evaporation of real black holes, and the second, that it is also violated to some extent in all processes due to contributions from virtual black holes. While the first may imply the second, given certain assumptions, it is also possible to imagine that in quantum gravity structures such as black holes do not contribute to virtual processes in the same way that field theory quanta do.

That \textit{CPT} is violated universally due to virtual processes involving information lost in black holes is problematic as it may, under certain assumptions, lead to large violations of energy\cite{22}. (But, for a criticism of this view, see a recent paper by Unruh and Wald\cite{23}.) But these arguments do not necessarily bear against the possibility of \textit{CPT} violation in the evaporation of real black holes.

A different argument that quantum gravity may violate both \textit{CP} and \textit{CPT} has been given by Chang and Soo\cite{24, 25, 26}. Their results are based on the Ashtekar formulation of quantum gravity\cite{7}, treated in a path integral formulation. While the Ashtekar formulation is classically equivalent to general relativity, they find that the two theories may differ quantum mechanically due to the different ways they couple the spacetime connection to chiral fermions. In the Ashtekar formalism, the total action, taken in the Jacobson-Samuels-Smolin form\cite{27}, fails to be \textit{CPT} and \textit{CP} invariant when boundary terms are included. The change of the action under \textit{CP} and \textit{CPT} is given by a chiral anomaly, coming from the coupling of the left handed $SU(2)$ spin connection to the chiral fermions. In the presence of gravitational instantons, then the full action is then not hermitian, and violations of \textit{CP} and \textit{CPT} are expected.

The possibility of \textit{CP} violation in quantum gravity was also studied using the Hamiltonian formulation by Ashtekar, Balachandran and Jo\cite{28}. They showed that quantum gravity may naturally violate \textit{CP} through the appearance of $\theta$ vacua, with the left-handed spin connection playing the role of the gauge field. We may note that as the effect comes from the coupling of the spacetime connection to fermions, any such gravitational violations of \textit{CP} will be universal. This universality might be used to distinguish quantum gravitational \textit{CP} violating effects from other \textit{CP} violating effects.

\footnote{One reason for this, recently pointed out by Martinec\cite{21}, is that if there is a bounce at Planck scales such that black hole singularities are replaced by new, expanding regions of spacetime that grow large (as in section 7, below) the quantum amplitude for creation of a black hole is strongly suppressed.}
3 Limitations on the spectrum of fermions

When there are an unequal number of left and right handed fermion modes, as does appear to be the case in nature, the coupling of the fermions to the spacetime connection need not be invariant under a chiral, or parity, transformation that exchanges the left and right handed spacetime connections. This is the case in the Ashtekar formulation. The result is that there can be a global $SU(2)$ anomaly in the theory, coming from the $SU(2)$ left handed spacetime connection. This anomaly will lead to contradictions if the path integral for quantum gravity coupled to the fermions must receive contributions from manifolds with arbitrary topology.

This problem was studied by Chang and Soo [25], who found that if manifolds with arbitrary spacetime topology are to appear in the Euclidean continuation of the path integral, there must be restrictions on the fermion content of the theory. Both the standard model with $SU(3) \times SU(2) \times U(1)$ and the minimal $SU(5)$ grand unified model are ruled out. The simplest grand unified model that is allowed is $SO(10)$ with one 16 dimensional multiplet of Weyl fermions per generation.

Of course, it is not obvious that the correct theory of quantum gravity will have amplitudes that are representable by a Euclidean path integral in which arbitrary topologies are included. One thing we learn from this analysis is that, if experiments confirm that the correct description of matter is a grand unified theory which is inconsistent with these conditions, any theory of quantum gravity that is representable in terms of such a Euclidean path integral with a sum over topologies and a chiral gravitational connection is ruled out. In this sense experiments in elementary particle physics test hypotheses about quantum gravity.

4 Scattering at transplankian energies

String theory has provided us with the only consistent semiclassical perturbation theory we have so far that can incorporate gravitation. This does not necessarily mean that the final theory of quantum gravity is a string theory, but it may mean that in any consistent non-perturbative formulation of quantum gravity, whether that be a string theory or not, the spectra of small oscillations around a semiclassical ground state must resemble that of a string theory. It is then extremely interesting that rather general arguments suggest that in string theory there is a cutoff scale above which many
fewer degrees of freedom are excited than would be the case in a naive field theory. These arguments are based on several different analyses of physics at ultrahigh energies\[1, 2, 3\]. The same kinds of arguments have also been used to suggest a universal modification of the uncertainty principle, of the form,

$$\Delta x > \frac{\hbar}{\Delta p} + \ell^2_{\text{Planck}} \Delta p$$  \hspace{1cm} (5)

If such a relation holds then it is impossible to resolve any structure on lengths shorter than the Planck scale.

A key issue which is probed in these experiments is the one I raised above: whether the existence of a cutoff scale at Planck energies, or a modification of spacetime structure, such that there are many fewer degrees of freedom than in a conventional field theory below the Planck scale, can be consistent with Lorentz invariance. It seems that in string theory this is achieved in a very interesting way, which leads to the modified uncertainty relation (1). Very interesting discussions of this issue are found in the papers of Susskind and collaborators\[5\], who show why in a string theory Lorentz invariance can be compatible with the existence of a finite cutoff scale. It may, indeed, be exactly because of this that string theory succeeds in giving a consistent perturbative description of quantum gravitational interactions.

5 Limitations on the information and energy content of finite regions of space

Another characteristic limitation on the numbers of degrees of freedom that can be excited in a finite region comes from the existence of black holes. If more energy than $\sqrt{A}$ (in Planck units) is put in a region surrounded by a boundary of area $A$, we may expect that a black hole will form. This has several implications that would lead to characteristic tests of quantum gravity. First, we may conjecture that there is an upper bound for the energy that can be contained in any region, which is given by $\sqrt{A}$. We may note that this may be shown for the spherically symmetric case, assuming only the positive energy conditions\[29\], and it may be conjectured to hold in general.

We may also conjecture that as a result of this upper limit on the energy, the Hilbert space for quantum theory for any finite region will be finite dimensional, because there is then present both a low and high frequency cutoff. Related to this conjecture is the Beckenstein conjecture that the
information that can be contained within any finite region is bounded by
its area, in Planck units\[30\]. We may note that if this is the case then, as
proposed by 't Hooft\[31\] and Susskind\[5\], the physical state describing any
bounded region of space should be describable in terms of a finite field theory
on the surface of that region. They call this the \textit{holographic hypothesis}.

Completely independent arguments that in quantum gravity the quantum
state describing a region is actually a quantum state of a field theory
on its boundary have been given by Crane, in the context of an analysis of
the role of diffeomorphism invariance on the interpretation of any quantum
theory of gravity\[32\]. These arguments have been strengthened recently by
progress in the construction of four dimensional topological quantum field
theories\[33\], based on this picture. Additionally, evidence that some, and
perhaps all of the information contained in a quantum state of in general
relativity in a region bounded by a finite boundary has been found by the
author, at least in the Euclidean case and only for a particular choice of
boundary conditions\[34\].

Thus, completely independent lines of argument lead to the conclusion
that in quantum gravity the number of degrees of freedom which may be
observed inside a region bounded by a surface of finite area must be finite
and bounded. One important effect of this hypothesis will be on the ther-
modynamics of the quantum gravitational field, coming from bounds on the
entropy and energy of the contents of such bounded regions. These implies
that the very high temperature thermodynamic behaviour of any finite region
will be very different than would be expected in conventional quantum field
theory. Thus, we may expect that, were it possible to heat an oven up to
temperatures on the order of the square root of its area, (in Planck units)
quite spectacular results would be achieved\[2\].

Finally, we may note that, as far as we know, the region of the universe
within our present horizon was at one time contained in a region bounded
by a very small area. Perhaps this is the real explanation for the hori-
zon and flatness problem, or, in other words, for Penrose’s \textit{Weyl curvature
hypothesis}\[36\] according to which the big bang singularity is characterized
by very low entropy. For if Beckenstein’s bound is true, then the state space
that describes the possible initial conditions of a region of the universe that
is initially only the Planck scale is very small.

\footnote{One caution about such experiments that must be mentioned is the impossibility of constructing an oven that would contain gravitational radiation\[35\].}
6 Discreteness of area and volume

A major theme of work in quantum gravity from the beginning has been the hypothesis that the combination of the principles of general relativity and quantum theory leads to a discreteness of the geometry of space or spacetime at Planck scales. The many different directions from which this conclusion has been reached are described in a recent article, which is recommended to the reader[20]. Here I would like to describe one set of predictions concerning such a discrete structure that have recently been obtained[10, 8], which is based on the loop representation formulation of quantum gravity[37, 38].

What is found here is that given certain general assumptions about the quantum theory of gravity, it is not possible to define operators that measure local quantities in the theory, such as the components of the metric or the curvature tensor at a point[8]. Instead, physical meaning can only be given to certain non-local operators. Furthermore, in at least two cases, these non-local observables, which have continuous spectra in classical general relativity turn out to have discrete spectra in the quantum theory[9, 10]. Moreover, given only rather general kinematical assumptions, these spectra may be computed.

The two cases for which this has been so far worked out are the area of any physical two dimensional surface and the volume of any physical three dimensional region. Here what I mean by a physical surface or region is one defined by the values of some physical fields. The particular three dimensional surface in spacetime within which these surfaces and regions are defined may be picked out by some physical field such as a scalar field[39], after which a two surface may be picked out by the value of a second field[40, 41]. The physically meaningful areas is then the area of that two dimensional surface or the volume of that three dimensional region.

Thus, the observables we are discussing are composite operators, that involve measuring simulatanously matter and gravitational fields. As such they are not defined naively and must be defined through a regularization procedure.

As a result of the necessity of regularization, a key requirement of the quantum theory of gravity emerges as greatly restricting the framework of the theory. This is diffeomorphism invariance. This appears to place several limitations on the quantum field theory which is being used.

First of all, diffeomorphism invariance places limitations on the representation of the observable algebra on which the quantum theory is based[5, 12]. The representation must be one that allows us to construct nonanomolous
generators of the three dimensional spacial diffeomorphism group. At present, only one kind of representation is known to have this property, which is the loop representation, with a discrete norm of the type described in [44], and developed rigorously by [42]. Although there is not yet a theorem that these are the only representations of the observable algebra of quantum gravity that will allow imposition of the generators of diffeomorphisms, it is quite possible that this is the case. In particular, Fock spaces based on a fixed spacetime metric do not have this property. For this reason, we work with these representations.

The second limitation is that the composite operators that represent observables such as we have been discussing must be constructed through a regularization procedure that does not violate the diffeomorphism invariance of the representation used to construct the quantum field theory. As we are describing only kinematical observables that do not involve the dynamics, what needs to be done at this stage is something analogous to the normal ordering of conventional Fock space quantum field theory. We may recall that, in the case of Fock space, normal ordering reveals the physical content of the theory, which in the case of free field theory is the spectra of quanta. In the case of quantum gravity, we do not have a systematic account of possible regularization procedures, but so far only one kind of procedure has been found which does not violate diffeomorphism invariance [3]. This leads to definite predictions, which is that the areas of physical surfaces and the volumes of discrete regions come in certain discrete spectra [3, 4]. To understand these, it is necessary to know that the spectra of states which arises from the diagonalization of these operators are in one to one correspondence with certain graphs, which are called spin networks [10, 45]. These are graphs in which the edges are labeled by integers, that label $SU(2)$ representations. For the case of the area of a surface, the spectra is then [10]

$$A = l_P^2 \sum_l \sqrt{j_l(j_l + 1)}$$

(6)

where the sum is over the intersections of the edges of the graph with the surface and $j_l$ is the spin of the $l$'th edge when it intersects the surface.

In the case of the volume, the spin network states still provide a basis with diagonalizes the volume operators. In a few cases the eigenvalues of the volume have been computed explicitly. It turns out that the volume contributed by any trivalent vertex is zero [46]. The eigenvalues associated

\[3\] This corrects a sign error in the original calculation [10].
with some higher valence vertices have been computed\[46, 48\]. Calculations underway now, but presently incomplete, are expected to lead to a general expression form the spectrum of the volume operator.

We may note that as we are describing observables that measure the properties of the geometry of a given three surface, no dynamics is involved. Thus no assumption is made about the field equations or the constraints that describe the evolution of the fields in time. Thus, these predictions must hold in any field theory describing gravity that may be expressed in terms of framefield and connection variables. In particular, these spectra stand as much as predictions of supergravity, higher derivative quantum theories or dilaton theories as they are of conventional general relativity, and they are independent of what matter fields are coupled to the theory.

Several recent results also attest to the robustness of the predictions of the discreteness of area and volume observables in non-perturbative quantum gravity. Ashtekar and collaborators have found similar, if not identical, results for the quantization of the area in the context of a mathematically rigorous formulation of quantum general relativity based on the connection representation\[47\]. Renata Loll has found that the volume is quantized also in a lattice formulation of quantum gravity\[46\]. Finally, it has been found recently that the whole formulation of quantum gravity in terms of spin networks\[45\] extends naturally to a $q$ deformed representation\[48\] in which the deformation parameter is $q = e^{i\pi/(k+2)}$, where $k = 6\pi/G^2\Lambda$.

7 Predictions about the parameters of the standard model of particle physics

One of the things that we would like a quantum theory of gravity to do for us is to tell us what happens to the singularities that are predicted by classical general relativity. There are, roughly speaking, three possibilities as to what happens when quantum physics is taken into account at both black holes and cosmological singularities. 1) The singularity is removed and time continues without bound. 2) The singularity persists, even in the quantum theory. 3) Something new and unexpected happens to time, for example time simply becomes ill defined in such regions, as in the proposal of Barbour\[49\].

It is interesting to note that in the first case, we can make hypothesis which can lead to predictions that are testable by means of astrophysical observations and theory. This is because of the possibility that in our past
there lies a succession of events in which a region of the universe collapsed almost to singularity and then expanded again.

Unfortunately, it is still not the case that we have a theory that can tell us what happens to singularities in our real, four dimensional spacetime. But, two simple hypotheses about the fate of singularities may be stated that do have testable consequences[5, 6]. These are

1) The bounce hypothesis: Quantum effects cause collapsing matter to begin again to reexpand whenever the density of matter approaches the Planck density.

2) The mutation hypothesis: Whenever a region of spacetime reaches a density or temperature near the Planck scale, the dimensionless parameters that characterize low energy physics change by small random amounts. The new values hold for the future of that region.

To see how these leads to observable consequences, we may note that the first hypothesis means that to the future of every surface that, according to classical general relativity, would be a black hole singularity, there develops a new expanding region of the cosmos. This region is protected from view by observers in the region where the black hole formed by the event horizon of the black hole, for time scales less than the black hole evaporation time. (We may note that for astrophysical black holes this is enormously greater than the age of the universe.) Conversely, our expanding universe might, according to this hypothesis, be one such region, expanding to the future of another region in which a black hole formed. Thus, the universe consists of many regions, each separated from the other by the event horizons of the black holes which lead from one to the other.

We may note that while such a scenario has been conjectured for some time, a recent calculation that suggests that it is actually a consequence of string theory[21]. Other proposals have been made concerning the short distance behavior of quantum gravity which also results in the bounce hypothesis[5].

The idea that the laws of physics might change at such bounces is not a new one, in the context of bounces of the cosmological singularity it has been called by John Wheeler “the reprocessing of the universe.” We may note that in the black hole case, some form of cosmic censorship is required if the futures of the almost singular region where the couplings change are not to overlap. We might note that this hypothesis is also consistent with the present state of knowledge of string theory, which is that we have a very large number of apparently equally consistent perturbative string theories, apparently describing small perturbations around different vacuum states, characterized by different dimensions and low energy matter content. The
new suggestion is then that all of these may be realized in nature and that the principle that realizes which of these is realized in our universe is statistical and reflects contingent factors about the past of the interior of our horizon.

What is interesting is that, as I shall now describe, if we restrict how the laws of physics can change at the bounces to small variations in the parameters of the standard model of particle physics (expressed in terms of dimensionless ratios) we find there are testable consequences.

These consequences follow because we can now make statistical predictions about the regions\(^{[50, 51]}\). This is because it follows from these assumptions that after a large but finite number of iterations almost every region has a particular property, which is that its parameters are near to those that externalize a certain quantity, which is the average number of black holes produced by a region with those values of the parameters. This is testable because it is natural to assume that our region of the universe is typical, in which case any property held by a typical region must be a property of our observable universe.

To test this we have to combine astrophysical observation and theory, and ask whether increases or decreases of the parameters of the standard model lead in almost every case to a decrease in the number of black holes produced. This hypothesis has been examined, and a significant amount of evidence found in its favor. For details the reader is referred to \([50, 51, 52]\). A partial list of those changes that decrease the number of black holes formed is 1) increasing the proton-neutron mass difference, 2) decreasing \(\alpha_{\text{QCD}}\), 3) increasing \(\alpha\), 3) increasing \(m_{\text{electron}}\), 4) increasing \(m_{\nu_e}\), 5) increasing or decreasing \(G_{\text{Fermi}}\) 6) making \(m_{\text{proton}} > m_{\text{neutron}}\), 7) increasing \(\Lambda_{\text{cosmological}}\).

A very interesting test is being examined at the present time, in which the parameter varied is the mass of the strange quark. According to a recently proposed theory of neutron star matter of Bethe and Brown\(^{[54]}\), an increase in the kaon mass above its present value would increase the upper mass limit for neutron stars, which would greatly decrease the number of black holes produced. We are investigating at present whether decreases in the kaon mass would not significantly increase the number of black holes. If this is the case it would stand as a strong confirmation of the hypothesis.

However, whether or not this scenario turns out to be true, the fact remains that because the universe itself passes through Planck scale regions, hypotheses about quantum gravity can have cosmological and astrophysical implications. What I have described here is only one way that natural assumptions about what happens at the Planck scale might lead to testable predictions about astronomical observations.
8 Conclusions

The list of experimental consequences of theories of quantum gravity I have given here is incomplete, but even so I hope that it makes the point. We know quite a lot about what we might reasonably expect the characteristic experimental signatures of quantum gravity to be. Experimental observation of any of the following phenomena would likely be useful as tests of a quantum theory of gravity: 1) deviations from a thermal spectra for evaporating black holes, 2) upper limits on the entropy and energy content of bounded regions 3) suppression of ultra-high energy scattering amplitudes, consistent with the modified uncertainty principle (1) 4) the discovery that observables that measure aspects of the spacetime geometry, such as physical volumes or the areas, have discrete spectra 5) violations of CPT or universal violations of CP. 6) Otherwise inexplicable conditions on the initial state of the universe or otherwise inexplicable correlations between cosmological and microscopic properties, such as discussed in the previous section.

Further, while these predictions come from different theoretical programs, in each case the predicted phenomena are rather robust, and come from the most general assumptions about quantum gravity, and not from detailed assumptions about the form of the dynamics or the matter content of the theory. Nor do they for the most part depend on the very difficult foundational problems associated with quantum cosmology. Thus, I would venture to make the optimistic statement that the present situation in quantum gravity is perhaps analogous to the quantum theory of about 1918, when physicists knew of a number of different characteristic quantum effects, in atomic physics, thermal radiation and low temperature physics, without having yet a complete theory.

How are we then to go ahead and construct that complete theory? The strongest thing that emerges from this list of quantum gravitational predictions is that they all indicate in one way or another that the beast we are after cannot be a conventional quantum field theory, if by that we mean that there are an infinite number of degrees of freedom within every physical volume. What is striking is also the way in which the results of these calculations are often simpler than the machinery one has to employ to derive them from the formalisms we have. Certainly some of the steps of these calculations, such as the way diffeomorphism invariant states and operators are built out of unphysical and infinite dimensional structures, or the way that calculations in string theory are so far limited to expansions around vacuum states associated with classical geometries, reflects more our present stage
of ignorance than they actually mirror anything in nature. But more than this, classical field theory, with its infinite degrees of freedom, and enormous redundancy of degrees of freedom due to diffeomorphism and gauge invariance, must be an approximation to reality and not a starting point for the construction of the right theory. Instead, in different ways the results of string theory, topological field theory and nonperturbative quantum gravity suggest that the right mathematics to construct quantum gravity is some combination of algebra, representation theory, combinatorics and category theory.

At some point we may have to take a leap and attempt to build the theory of quantum gravity up from some simple structure we posit as a first principle. What general conclusions can we draw about the Planck scale that may then be clues for the construction of such a theory? I would venture the following remarks:

1) The physical fields must create non-local structures, most likely one dimensional. This is the conclusion of both string theory and non-perturbative quantum gravity. Susskind’s analysis explains to us why this is necessary if a perturbative is to have a finite cutoff and at the same time not break lorentz invariance\footnote{5}. On the other hand, non-perturbative quantum gravity explains why this is necessary if we are to have a quantum field theory based on a connection that does not break diffeomorphism invariance. This is an important example of the way in which string theory tells us how a quantum theory of gravity must work in the perturbative domain, while the loop representation approach tells us how it must work non-perturbatively. There is something important yet to be understood in the fact that both points of view lead to the conclusion that the physical excitations of the quantum gravitational field must be one dimensional.

2) There are not an infinite number of degrees of freedom in any volume. There are instead a finite number of degrees of freedom in every bounded region. Again, it is striking that string theory reaches this conclusion from requiring the consistency of the perturbative description, while the loop representation reaches the same conclusion from the requirement of the consistency of the non-perturbative description. While the resulting pictures are apparently quite different, it seems quite possible there is a connection between them. Moreover, several arguments discussed above suggest that there are actually only a fixed number of degrees of freedom per unit area of the boundary of any region (expressed in Planck units.)

3) In both string theory and the loop representation, constructed as in \footnote{8, 10}, physical quantities are “automatically” ultraviolet, finite but there
are dangers of infrared divergences. In both cases the finiteness comes from the existence of a finite number of degrees of freedom below the Planck scale.

The danger of infrared divergences seems to have a rather different origin in string theory and non-perturbative quantum gravity. However, given the relationship between the infrared divergences in bosonic string theory and the danger of forming “spikes” in random surface theory they may in the end be related. In both of these cases the problem is that finite Planck scale quantum geometries do not normally correspond to slowly varying classical geometries. To do so special conditions must be met.

We may note that a similar situation was found in the Monte Carlo approaches to four dimensional quantum gravity within the framework of dynamical triangulations. For most values of the gravitational and cosmological constants the theory does not seem to have a critical behaviour that would result in correlation functions behaving as if they live in a four dimensional classical geometry. To achieve this the theory must be tuned to a critical point. The fact that this problem is found also in the other non-perturbative approaches suggests that it is generic. It is possible that the solution is also generic. This would imply that in a non-perturbative quantum theory of gravity the classical limit, when it exists, must be a critical phenomena.

At the perturbative level, string theory finds a different solution to the problem of the infrared divergences, which is by the addition of supersymmetry, which removes the tachyonic divergences. This suggests that it could be very important to explore the implications of supersymmetry in the non-perturbative, loop representation, approach. There are, it might be added, important results from supersymmetric Yang-Mills theory that show how supersymmetry can control the infrared behavior of strongly coupled theories.

But, beyond this, it is striking that in all the non-perturbative formulations of quantum gravity, the problem of the classical limit seems to be a problem of a critical phenomena. The theory must find or be tuned to a critical point for there to be a classical world at all. In this sense the existence of classical spacetime arises from a limit which has much in common with the thermodynamic limit. Perhaps in this circumstance is to be found the connection between spacetime and thermodynamic that is suggested by the results on black hole evaporation.

Finally, in closing it must be said that, unlike the case of atomic physics

\[\text{There is an extension to supergravity which deserves more attention.}\]
in the 1920’s, the major impediment to progress in quantum gravity remains
the difficulty of doing experiments to check predictions like those described
here. But it can no longer be said that theorists have been unable to make
experimental predictions about quantum gravity. Perhaps it is beginning to
be time to wonder whether there might not be unforeseen ways to test for
the presence of these characteristic quantum gravitational phenomena.

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