

# Quantum gravity faces reality

Lee Smolin

**String theory is only one of many approaches to quantizing general relativity. Increasingly, all those approaches will be judged by how well they accord with experimental data.**

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The discoveries of general relativity and quantum mechanics began a revolution in physics. But the problem remains of completing the revolution with a theory of quantum gravity that joins those two pillars of modern physics. To have a chance to succeed, the new theory must not only make sense, it must make new predictions that can be tested by doable experiments. Physicists have made a great deal of progress in achieving the synthesis and have even proposed new experiments. That progress is the subject of this article.

The need for a quantum theory of gravity was first mentioned by Albert Einstein in 1915, in his initial paper about gravitational waves. The first PhD thesis on the subject, by Matvei Petrovich Bronstein, appeared in 1935. Still, the subject needed a long time to develop into a real branch of physics. Only in the past 20 years has the physics community seen real, cumulative progress that has led to proposals for new experiments, some of which are being done now.

## Small effects at large energies

Quantum theories of gravity are already confronting experiment in two distinct domains and have a realistic possibility of soon doing so in a third area.

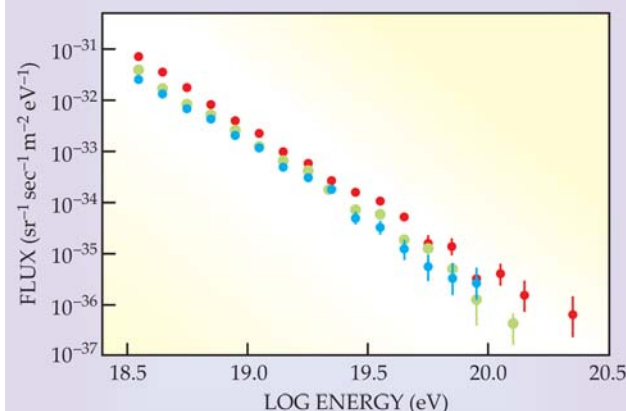
The first concerns the Poincaré invariance—Lorentz invariance plus spacetime translations—of ordinary quantum field theory. Quantum theories of gravity might break or modify that symmetry; the reason is that quantum geometry is dynamical, so moving particles see a fluctuating geometry, not a fixed spacetime. As a result, energy–momentum relations or conservation laws might be modified at energies on the order of the Planck energy  $E_{\text{pl}} = (\hbar c^5/G)^{1/2} = 1.2 \times 10^{19}$  GeV, the energy scale determined by Planck's and Newton's constants and the speed of light. Lorentz invariance may simply be broken by the existence of a preferred reference frame. But it may also be that Poincaré invariance is modified, not broken, so that special relativity need be corrected with terms involving the Planck energy.

The latter possibility is motivated by a simple question: If the Planck length,  $l_{\text{pl}} = \hbar c/E_{\text{pl}} = 1.6 \times 10^{-35}$  m, is a threshold for a transition to a new formulation of spacetime geometry—quantum geometry—shouldn't it be observer independent? In ordinary special relativity, lengths and energies transform under boosts. But one can alter the Lorentz transformations to keep invariant both a speed—the speed of light in the limit of zero photon energy—and a specified length or energy. The resulting class of models, which describes the propagation of particles and fields, is called doubly, or deformed, special relativity (DSR).<sup>1</sup>

Of course, it may be that Poincaré invariance is neither

modified nor broken. The important news is that the different possibilities for the symmetry of spacetime may be probed by several recent and upcoming experiments. Several atomic and nuclear physics experiments and astrophysical observations have already ruled out first-order effects in  $E/E_{\text{pl}}$  that arise from a preferred reference frame (see reference 2 and the article by Maxim Pospelov and Michael Romalis, PHYSICS TODAY, July 2004, page 40).

Another test follows from the expectation that the universe should be opaque to cosmic rays with energies greater than  $3 \times 10^{19}$  eV; at such high energies, the photons scatter from the cosmic microwave background (CMB). The result is a cutoff—the GZK (Greisen-Zatsepin-Kuzmin) cutoff—in the cosmic-ray spectrum. The High Resolution Fly's Eye (HiRes) collaboration reported a suppression in cosmic-ray flux above the GZK threshold, but the Akeno Giant Air Shower Array experiment did not. AGASA's null result may indicate a breaking or modifying of Poincaré invariance, but numer-



**Figure 1. Extremely high-energy cosmic rays**, according to conventional theory, should scatter from the cosmic microwave background. Thus, the spectrum should be suppressed at energies above about  $3 \times 10^{19}$  eV. The AGASA experiment (red) did not see any suppression, but the HiRes collaboration (green) did. In time, an experiment currently being run at the Pierre Auger Observatory should resolve the conflict. The plot also shows preliminary data (blue) from Auger. (Adapted from ref. 3.)

ous other theoretical or systemic possibilities can also explain it. The Pierre Auger Observatory is now measuring the high-energy cosmic-ray spectrum (see figure 1) with much better statistics; it should be able to establish whether there is a GZK cutoff and address some of the ideas posed to explain the AGASA result.<sup>3</sup>

Another indication of the breaking or deforming of special relativity would be an energy dependence in the speed of light. Lorentz symmetry breaking would give rise to a polarization-dependent variation, but observations of polarized radio galaxies already provide good evidence against such a change at order  $E/E_{\text{pl}}$ . On the other hand, DSR predicts a polarization-independent effect, which has not yet been ruled out at first order. But it could be soon, by *GLAST*, a gamma-ray burst observer due for launch next year.

A second class of experiments relevant for quantum gravity looks for modifications of the CMB spectrum. As I discuss later, the *Planck* satellite, scheduled for launch in early 2007, may be able to see effects of order  $E/E_{\text{pl}}$ , where the numerator denotes the energy scale at which fluctuations are imprinted on the CMB.

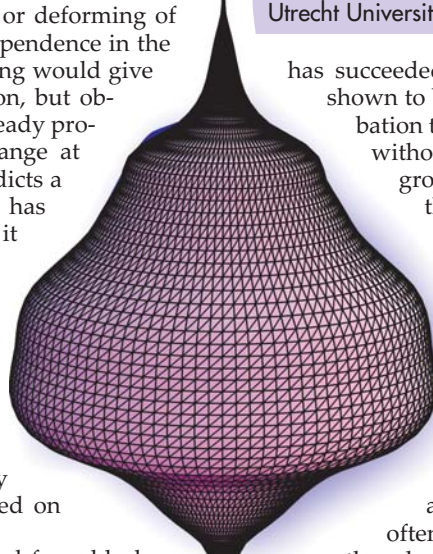
Observations of the radiation emitted from black holes may also be relevant, provided that enough primordial black holes were created in the early universe. Such radiation acts like a microscope, and some models of the black-hole horizon predict that Planck-scale features are blown up and revealed in a spectrum whose discrete features easily distinguish it from the thermal spectrum predicted by Stephen Hawking. In those cases spectral details could then be used to test quantum-gravity theories.

## Geometry in flux

The basic lesson of Einstein's general theory of relativity is that the geometry of spacetime is dynamical. Nature exhibits no fixed or preferred geometry; instead, the geometry of space and time evolves just as other fields such as the electromagnetic field do. That dynamism makes it difficult to study quantum gravity with the tools of ordinary quantum field theory, which assumes a fixed, nondynamical background geometry of spacetime—usually the featureless Minkowski spacetime of special relativity. Theorists need to develop new ideas and calculational methods to define and study quantum field theories in which the degrees of freedom of the geometry evolve quantum mechanically, on an equal footing with other fields, and in which the spacetime consequently possesses no global symmetries. Such new methods have been developed and are the key to recent progress, including the formulation of testable predictions about Planck-scale phenomena.

Those methods are said to be manifestly background independent. Before describing them, however, I note that some theorists have pursued contrasting background-dependent approaches to quantum gravity. In those approaches, one studies fields or degrees of freedom defined as small fluctuations on fixed classical spacetime geometries. The most successful of them have been semiclassical methods, which were used by Jacob Bekenstein, Hawking, and others in the 1970s to predict that black holes have entropy and radiate thermally. Semiclassical methods were also the basis for the predictions of inflationary cosmological models. String theory represents much of the work that has gone into background-dependent approaches to quantum gravity. It

**Figure 2.** A typical contribution to the path integral calculated in the method of causal dynamical triangulations. Time proceeds vertically by discrete steps, and each spatial slice is constructed from discrete tetrahedral units. Together, the evolving spatial slices define a universe with four spacetime dimensions. (Courtesy of Renate Loll, Utrecht University.)



has succeeded to the extent that infinities have been shown to be absent through second order in perturbation theory. Theorists have also explored, so far without definitive progress, manifestly background-independent formulations of string theory.

Background-dependent approaches—at least the ones that have achieved some success—assume that the background geometry is Poincaré invariant. They thus predict that no breaking of the invariance will be found in experiments that test spacetime symmetry.

Most nonstringy approaches to quantum gravity presently under study are background independent. They can often be characterized by their approach to three key issues: discreteness, causality, and emergence. Specifically, they address the following questions: Does the geometry of space or spacetime have a discrete structure at the Planck scale? How should one talk about events and their causal relations? How does a classical spacetime geometry that satisfies Einstein's equations emerge from the more fundamental quantum description?

Physicists with experience in condensed matter and other disciplines will quickly understand that the final question about emergence represents the main challenge. Remarkably, the past few years have seen substantial progress in meeting that challenge, most notably in an approach called causal dynamical triangulations.<sup>4</sup>

Invented by Renate Loll, Jan Ambjorn, and collaborators, CDT can be regarded as the Ising model of quantum spacetime. The researchers' approach expresses quantum spacetime as a continuum limit of geometries composed of discrete elements. In the discrete, regulated description, the geometry of a spatial surface is represented by a bunch of identical tetrahedra stuck together.

The quantum spacetime dynamics is studied by a path integral, in which each spatial surface gives rise to the next one by what can be understood as elementary causal processes. Figure 2 shows a typical contribution. The path-integral action is a discrete approximation to the action of Einstein's general theory of relativity.

Loll, Ambjorn, and their collaborators first studied models in which the discrete elements from which space is built have a single dimension. Those models can be solved exactly in the absence of matter degrees of freedom and numerically when matter is added. In the past two years, the researchers extended the model to three spatial dimensions and found strong numerical evidence for a phase in which classical spacetime geometry emerges. By measuring various observables such as the surface-to-volume ratio, they could estimate the dimension of the geometry that a low-energy particle would experience—and they got three to good approximation. Interestingly, high-energy particles would see only one spatial dimension. But there is much left to do within the framework of CDT. For example, no one has determined to what extent, if at all, Einstein's equations are satisfied.

As in the study of spin systems in condensed matter physics, one wants to know if the good properties of simple models are generic, and if so, which assumptions are essential for reproducing the observations. CDT assumes that the discrete quantum spacetime geometries can be seen as a succession of discrete spatial geometries. One can test that assumption by removing it. In the resulting, simpler “causal set” models, studied by Raphael Sorkin, Fay Dowker, and collaborators, quantum spacetime consists of nothing but a set of discrete events whose only properties are their causal relations.<sup>5</sup> Those discrete causal relations, depicted in figure 3, abstract the relations that two events can have in relativity.

In causal set models, one assumes a single event per Planck spacetime volume. The challenges are to define a path integral and action solely in terms of the causal sets and to find dynamics for which classical spacetime emerges in the limit of a universe with many discrete events. That challenge has not been realized, but the models have achieved one notable result: If classical spacetime can be shown to emerge, the cosmological constant will automatically be nonzero and of roughly the experimentally observed magnitude.

### Derived discreteness

The discrete nature of spatial and spacetime geometry is assumed a priori in causal set models. If the approach succeeds, such an assumption cannot be objectionable, since quantum gravity should be a more fundamental theory than classical general relativity. Still, one might ask if the discreteness of quantum geometry can be derived from an application of quantum mechanics to general relativity. The answer is yes.

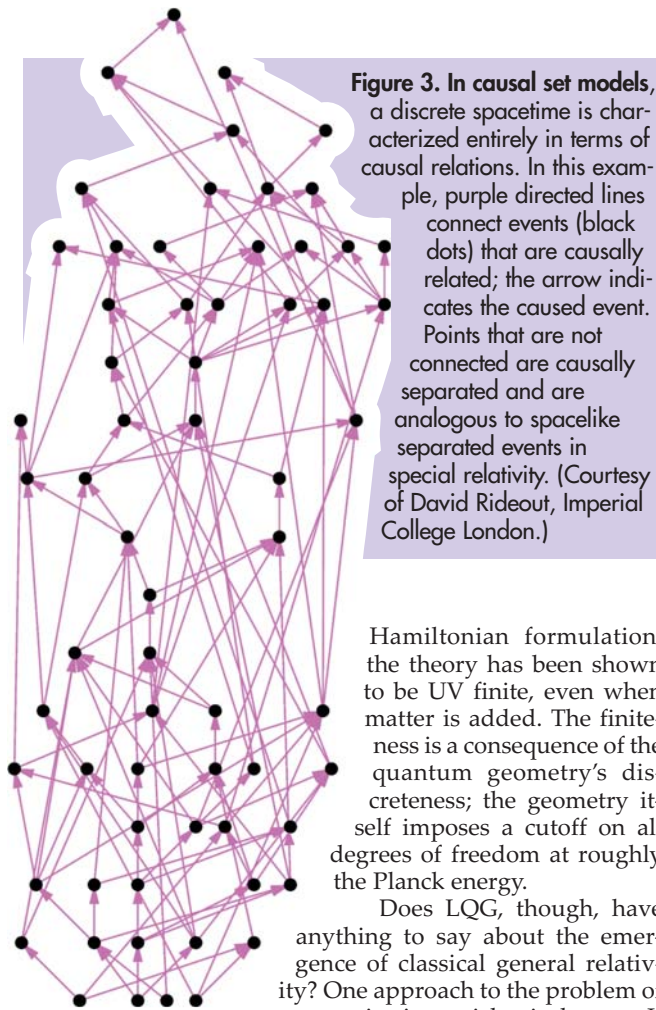
Key to the derivation is a remarkable fact discovered by Abhay Ashtekar in 1986. Ashtekar realized that he could express the dynamics of Einstein’s general theory of relativity in a language in which the coordinate is a gauge field analogous to those of the standard model. Further, the momentum conjugate to the gauge field is a kind of electric field. In Ashtekar’s reformulation, the metric that gives spacetime geometry is described in terms of such an electric field.

A quantum field theory constructed from Ashtekar’s reformulation would necessarily be background independent. Often the most challenging part of constructing quantum field theories is to preserve all the gauge invariances, including general covariance. In this case the quantization program has been carried out. The resulting approach to quantum gravity is called loop quantum gravity.

The key physical idea behind LQG is that the quantum gauge theory may be described in terms of quantized field lines of electric flux; the so-called dual superconductor picture of the quantum-chromodynamics vacuum is a related description. The resulting space of states in LQG has a basis that is easy to visualize—graphs, called spin networks, labeled by units of quantized electric flux. Figure 4 shows a representative graph, which is embedded in a space with topology but no metric.

Loop quantum gravity has been well studied during the past 20 years. Although many open problems remain, those investigations have produced results that address all the major issues related to quantum gravity.<sup>6</sup> Among the key results are that the areas of surfaces and volumes are quantized and that the spectra of the corresponding operators can be predicted.

Theorists have studied the dynamics of quantum geometry in both Hamiltonian and path-integral, or spin-foam, formulations. Both cases have yielded closed-form expressions acting on spin network states. And in both cases, the dynamics avoids high-energy “ultraviolet” infinities. In the



**Figure 3.** In causal set models, a discrete spacetime is characterized entirely in terms of causal relations. In this example, purple directed lines connect events (black dots) that are causally related; the arrow indicates the caused event. Points that are not connected are causally separated and are analogous to spacelike separated events in special relativity. (Courtesy of David Rideout, Imperial College London.)

Hamiltonian formulation, the theory has been shown to be UV finite, even when matter is added. The finiteness is a consequence of the quantum geometry’s discreteness; the geometry itself imposes a cutoff on all degrees of freedom at roughly the Planck energy.

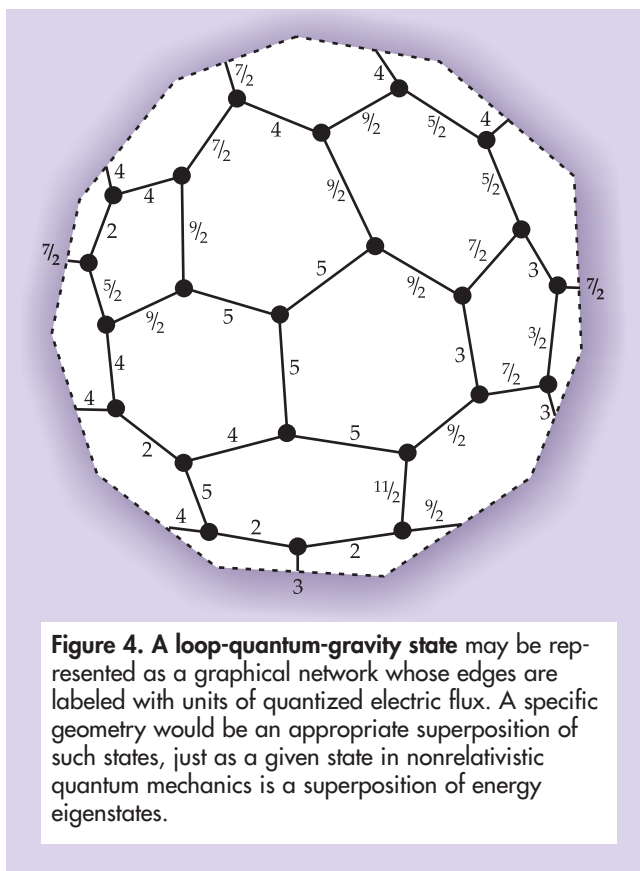
Does LQG, though, have anything to say about the emergence of classical general relativity? One approach to the problem of emergence is via semiclassical states. It is not difficult to write down such states, nor is it difficult to study their excitations and show that, at wavelengths long compared to  $l_{\text{pl}}$ , the spectrum includes massless spin-2 gravitons. When matter is included, one can show, also at long wavelengths, that an appropriate matter quantum field theory emerges. In the past few years, some work has gone beyond the semiclassical approximation. Using the path-integral formulation of the dynamics, Carlo Rovelli and collaborators have been able to carefully define and compute the graviton propagator.<sup>7</sup> Their result, in the long-wavelength limit, is consistent with general relativity.

### Connections with other fields

In CDT, causal sets, and LQG, a quantum spacetime is defined either as a discrete quantum system or in terms of a limit of such systems. Discrete quantum systems are nothing new; condensed matter physicists often use them. Thus, it is not surprising that several researchers have proposed that ideas and techniques from condensed matter physics could be applied to problems in quantum gravity.

Might special relativity emerge, they ask, as a low-energy description of the excitations of some discrete quantum system analogous to those common in condensed matter physics? And might those excitations behave at long wavelengths like gauge fields, chiral fermions, and even gravitons? Recent results suggest that the answer is yes,<sup>8</sup> and even hint that the cosmological-constant problem is solved in such theories.<sup>9</sup>

Such results represent substantial progress toward showing how conventional physics could be emergent, but



they are based on fixed lattices, and hence do not incorporate Einstein's insight that the geometry of spacetime is dynamical. The next step is to understand whether similar results can emerge from the study of excitations of dynamical lattices, for which there is no natural notion of locality. Thus, part of the challenge is to use quantum dynamics to define local excitations in an evolving quantum geometry.

A new approach to the emergence of particles and symmetries in quantum spacetimes builds on techniques applied to quantum computers. Fotini Markopoulou and colleagues, the pioneers of the approach, begin by asking how photons and electrons can be protected from decohering into the quantum fluctuations of the spacetime geometry, with which the particles are constantly interacting. They point out that the particle-protection question is analogous to the question of how a qubit of quantum information can be protected from decoherence given that it constantly interacts with noise as it travels through a circuit in a quantum computer. In the context of quantum computation, theorists understand that effective symmetries can arise that protect quantum information from decoherence. Those noiseless or decoherence-free subsystems are the key to some designs for quantum computers, and, argues Markopoulou, they also should be the key to understanding how particles and symmetries arise.<sup>10</sup> Seth Lloyd has also approached gravity from a quantum-computational point of view and has proposed a way to express the Einstein equations directly in the language of quantum information theory.<sup>11</sup> The new developments coming from condensed matter physics and quantum information theory raise many issues, but clearly those fields are having an impact on the study of quantum spacetimes.

## Nailing down predictions

The condensed matter models that yield relativistic fermions, gauge fields, and gravitons predict a breakdown of special

relativity at Planck scales: At those small lengths, the underlying lattice will be revealed. As mentioned earlier, experimental tests of Lorentz invariance have failed to see evidence of a preferred frame at order  $E/E_{\text{pl}}$ .

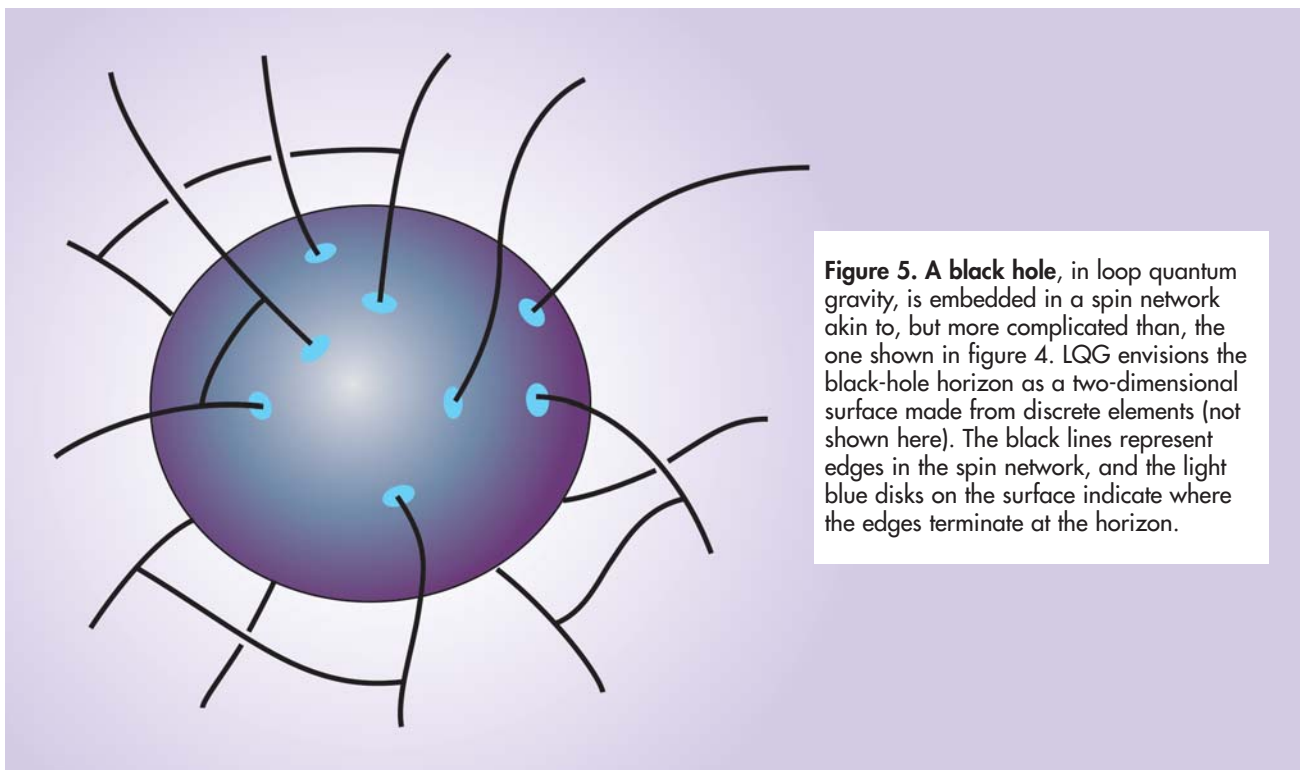
Effects predicted by DSR are neither confirmed nor ruled out, but they may be in the next few years. Do theories of quantum gravity predict that DSR is the symmetry of spacetime? The question has been answered for the so-called 2 + 1 quantum gravity model in which space has two dimensions. In the absence of matter, the system is exactly solvable, as shown by Edward Witten in 1989. Once matter is added, however, the system is much more difficult to analyze. It was first studied by Stanley Deser, Roman Jackiw and Gerard 't Hooft in 1983, and theorists have made significant progress in the past few years. Indeed, in work published this year, Laurent Freidel and Etera Livine definitively show that DSR is the correct symmetry of spacetime in 2 + 1 quantum gravity with matter: They solve the emergence problem cleanly and derive the effective theory that governs matter propagating through the quantum spacetime.<sup>12</sup>

One focus of current work is quantum gravity in 3 + 1 dimensions. My own work indicates, but does not yet prove, that DSR is the right low-energy symmetry.<sup>13</sup> Hopefully, a clear answer will emerge before the *GLAST* team reports their results.

During the past five years, many theorists have developed models of the early universe by applying the methods of LQG.<sup>14</sup> In those simplified models, the quantum spacetimes are highly symmetric so that the dynamics can be reduced to just a few variables. Such models had been studied previously at the semiclassical level, but new techniques now allow them to be precisely defined and exactly solved. The key innovation is a quantization of geometry that follows from the quantization of electric flux. As a result, the Big Bang singularity is eliminated and replaced by a "bounce." One can thus follow the history of the universe to times before the Big Bang.

Does the bounce occur in the full theory? That question is presently under study. Meanwhile, investigators have shown that to the quantum-cosmology models one can add degrees of freedom that represent inhomogeneities in the geometry and matter and then see how quantum effects are imprinted on the cosmic microwave radiation. Recent studies indicate effects of order  $E/E_{\text{pl}}$  that will potentially be observable by the *Planck* satellite. In particular, they show an anomalous suppression in the power spectrum for low multipole modes. That is a noteworthy result, because the *Wilkinson Microwave Anisotropy Probe* and *BOOMERANG* have seen hints of such a suppression. Stephon Alexander has suggested that parity-breaking effects in quantum gravity, which are natural in the Ashtekar formulation, could explain anomalies observed in the CMB spectrum.<sup>15</sup> It is too soon to put much stock in the observed anomalies, but it is realistic to believe that data obtained over the next few years will enable detailed comparisons of observations with predictions of quantum-cosmology models.

The methods developed from the study of the cosmological singularity have been applied, in simplified models, to black-hole singularities. The conclusion is the same: Quantum effects eliminate the singularities, and one can follow the history of a black hole beyond its would-be singularity. The elimination of the singularity, if it is a feature of the full theories, resolves the famous black-hole information paradox noted by Hawking in 1975. Information is not lost in a black hole; it continues to exist in the spacetime to the future of the singularity.



**Figure 5.** A black hole, in loop quantum gravity, is embedded in a spin network akin to, but more complicated than, the one shown in figure 4. LQG envisions the black-hole horizon as a two-dimensional surface made from discrete elements (not shown here). The black lines represent edges in the spin network, and the light blue disks on the surface indicate where the edges terminate at the horizon.

Theorists working with LQG have made detailed studies of the quantum geometry of black-hole and other horizons (see figure 5). Their work has reproduced the result for black-hole entropy originally discovered by Bekenstein and Hawking. Further, it led to the computation of quantum-gravity corrections to the entropy and radiation of black holes. One study, by Mohammad Ansari, finds derivations from the Hawking spectrum that would be observable were x rays from Hawking radiation of evaporating primordial black holes to be observed.<sup>16</sup>

Work in nonstringy approaches to gravity is growing rapidly; I have only given a snapshot of progress in the field. For historical reasons, the field is mainly developing outside the US (see my opinion piece in *PHYSICS TODAY*, June 2005, page 56). But progress worldwide has been rapid; recent meetings have attracted some 150 participants.

Experiments planned for the near future may provide direct evidence for a preferred reference frame or may establish that DSR is the proper symmetry of a spacetime that has no preferred frame. The possibly observed anomalies for the low multipoles in the CMB spectrum may persist and may have an explanation in terms of quantum-gravity effects and a bounce that replaces the initial Big Bang singularity.

History shows, however, that new theories triumph as often by the surprises they lead to as by expected results. One possibility for a quantum gravity surprise is in quantum theory itself: Roger Penrose and others, for example, have speculated that quantum gravity may involve nonlinear effects that could be seen in near-future experiments.<sup>17</sup> The holographic principle of 't Hooft suggests that quantum gravity may be solved only with radical reformulation of quantum theory.<sup>18</sup>

Whether the detection of quantum-gravity effects comes from planned experiments or unplanned surprises, one thing is clear: The field of quantum gravity has matured to the point that it makes contact with experiment. Several relevant experiments are in progress and at any time may yield results

that would require a quantum theory of gravity for their interpretation. Stay tuned.

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