Quantum foam (also referred to as space-time foam) is a concept in quantum mechanics devised by John Wheeler in 1955. The foam is supposed to be conceptualized as the foundation of the fabric of the universe. Additionally, quantum foam can be used as a qualitative description of subatomic space-time turbulence at extremely small distances (on the order of the Planck length). At such small scales of time and space, the Heisenberg uncertainty principle allows energy to briefly decay into particles and antiparticles and then annihilate without violating physical conservation laws. As the scale of time and space being discussed shrinks, the energy of the virtual particles increases. According to Einstein's theory of general relativity, energy curves space-time. This suggests that—at sufficiently small scales—the energy of these fluctuations would be large enough to cause significant departures from the smooth space-time seen at larger scales, giving space-time a "foamy" character.

With an incomplete theory of quantum gravity, it is impossible to be certain what space-time would look like at these small scales, because existing theories of gravity do not give accurate predictions in that realm. Therefore, any of the developing theories of quantum gravity may improve our understanding of quantum foam as they are tested. However, observations of radiation from nearby quasars by Floyd Stecker of NASA's Goddard Space Flight Center have placed strong experimental limits on the possible violations of Einstein's special theory of relativity implied by the existence of quantum foam. Thus experimental evidence so far has given a range of values in which scientists can test for quantum foam.

The MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) telescopes have detected that among gamma-ray photons arriving from the blazar Markarian 501, some photons at different energy levels arrived at different times, suggesting that some of the photons had moved more slowly and thus contradicting the theory of general relativity's notion of the speed of light being constant, a discrepancy which could be explained by the irregularity of quantum foam. More recent experiments were however unable to confirm the supposed variation on the speed of light due to graininess of space. Other experiments involving the polarization of light from distant gamma ray bursts have also produced contradictory results. More Earth-based experiments are ongoing or proposed.

X-ray and gamma-ray observations of quasars used data from NASA's Chandra X-ray Observatory, the Fermi Gamma-ray Space Telescope and ground-based gamma-ray observations from the Very Energetic Radiation Imaging Telescope Array (VERITAS) show that space-time is uniform down to distances 1000 times smaller than the nucleus of a hydrogen atom.

Quantum mechanics predicts that space-time is not smooth, instead space-time would have a foamy, jittery nature and would consist of many small, ever-changing, regions in which space and time are not definite, but fluctuate.

The predicted scale of space-time foam is about ten times a billionth of the diameter of a hydrogen atom's nucleus, which cannot be measured directly. A foamy space-time would have limits on the accuracy with which distances can be measured because the size of the many quantum bubbles

through which light travels will fluctuate. Depending on the space-time model used, the space-time uncertainties accumulate at different rates as light travels through the vast distances.

Chandra's X-ray detection of quasars at distances of billions of light years rules out the model where photons diffuse randomly through space-time foam, similar to light diffusing passing through fog.

Measurements of quasars at shorter, gamma-ray wavelengths with Fermi; and, shorter wavelengths with VERITAS rule out a second model, called a holographic model with less diffusion.

Quantum foam is theorized to be the 'fabric' of the Universe, but cannot be observed yet because it is too small. Also, quantum foam is theorized to be created by virtual particles of very high energy. Virtual particles appear in quantum field theory, arising briefly and then annihilating during particle interactions in such a way that they affect the measured outputs of the interaction, even though the virtual particles are themselves space. These "vacuum fluctuations" affect the properties of the vacuum, giving it a nonzero energy known as vacuum energy, itself a type of zero-point energy. However, physicists are uncertain about the magnitude of this form of energy.

The Casimir effect can also be understood in terms of the behavior of virtual particles in the empty space between two parallel plates. Ordinarily, quantum field theory does not deal with virtual particles of sufficient energy to curve spacetime significantly, so quantum foam is a speculative extension of these concepts which imagines the consequences of such high-energy virtual particles at very short distances and times. Spin foam theory is a modern attempt to make Wheeler's idea quantitative.

In particle physics and physical cosmology, the **Planck scale** (named after Max Planck) is an energy scale around $1.22 \times 1019$ GeV (the Planck energy, corresponding to the mass-energy equivalence of the Planck mass, $2.17645 \times 10-8$ kg) at which quantum effects of gravity become strong. At this scale, present descriptions and theories of sub-atomic particle interactions in terms of quantum field theory break down and become inadequate, due to the impact of the apparent non-renormalizability of gravity within current theories.

At the Planck scale, the strength of gravity is expected to become comparable with the other forces, and it is theorized that all the fundamental forces are unified at that scale, but the exact mechanism of this unification remains unknown. The Planck scale is therefore the point where the effects of quantum gravity can no longer be ignored in other fundamental interactions, and where current calculations and approaches begin to break down, and a means to take account of its impact is required.

While physicists have a fairly good understanding of the other fundamental interactions of forces on the quantum level, gravity is problematic, and cannot be integrated with quantum mechanics at very high energies using the usual framework of quantum field theory. At lesser energy levels it is usually ignored, while for energies approaching or exceeding the Planck scale, a new theory of quantum gravity is required. Other approaches to this problem include string theory and M-theory, loop quantum gravity, noncommutative geometry, scale relativity, causal set theory and p-adic mathematical physics.

The term Planck scale can also refer to a length scale or time scale.

| Quantity | SI equivalent |
| --- | --- |
| Planck time | 5.39121 × 10—44 s |
| Planck mass | 2.17645 × 10—8 kg |
| <span style="color:red">Planck length (ℓP)</span> | <span style="color:red">1.616252×10—35 m</span> |



The Planck length is related to Planck energy by the uncertainty principle. At this scale, the concepts of size and distance break down, as quantum indeterminacy becomes virtually absolute. Because the Schwarzschild radius of a black hole is roughly equal to the Compton wavelength at the Planck scale, a photon with sufficient energy to probe this realm would yield no information whatsoever. Any photon energetic enough to precisely measure a Planck-sized object could actually create a particle of that dimension, but it would be massive enough to immediately become a black hole (a.k.a. Planck particle), thus completely distorting that region of space, and swallowing the photon. This is the most extreme example possible of the uncertainty principle, and explains why only a quantum gravity theory reconciling general relativity with quantum mechanics will allow us to understand the dynamics of space-time at this scale. Planck scale dynamics are important for cosmology because if we trace the evolution of the cosmos back to the very beginning, at some very early stage the universe should have been so hot that processes involving energies as high as the Planck energy (corresponding to distances as short as the Planck length) may have occurred. This period is therefore called the Planck era or Planck epoch.The nature of reality at the Planck scale is the subject of much debate in the world of physics, as it relates to a surprisingly broad range of topics. It may, in fact, be a fundamental aspect of the

universe. In terms of size, the Planck scale is extremely small (many orders of magnitude smaller than a proton). In terms of energy, it is extremely 'hot' and energetic. The wavelength of a photon (and therefore its size) decreases as its frequency or energy increases. The fundamental limit for a photon's energy is the Planck energy, for the reasons cited above. This makes the Planck scale a fascinating realm for speculation by theoretical physicists from various schools of thought. Is the Planck scale domain a seething mass of virtual black holes?[citation needed] Is it a fabric of unimaginably fine loops or a spin foam network?[citation needed] Maybe at this fundamental level all that remains of space-time is the causal order? Is it interpenetrated by innumerable Calabi-Yau manifolds,[2] which connect our 3-dimensional universe with a higher-dimensional space? Perhaps our 3-D universe is 'sitting' on a 'brane'[3] which separates it from a 2, 5, or 10-dimensional universe and this accounts for the apparent 'weakness' of gravity in ours. These approaches, among several others, are being considered to gain insight into Planck scale dynamics. This would allow physicists to create a unified description of all the fundamental forces.

Experimental evidence of Planck scale dynamics is difficult to obtain, and until quite recently was scant to non-existent. Although it remains impossible to probe this realm directly, as those energies are well beyond the capability of any current or planned particle accelerator, there possibly was a time when the universe itself achieved Planck scale energies, and we have measured the afterglow of that era with instruments such as the WMAP probe, which recently accumulated sufficient data to allow scientists to probe back to the first trillionth of a second after the Big Bang, near the electroweak phase transition. This is still several orders of magnitude away from the Planck epoch, when the universe was at the Planck scale, but planned probes such as Planck Surveyor and

related experiments such as IceCube expect to greatly improve on current astrophysical measurements.

No experiment current or planned will allow the precise probing or complete understanding of the Planck scale. Nonetheless, enough data has already been accumulated to narrow the field of workable inflationary universe theories, and to eliminate some theorized extensions to the Standard Model.

The current understanding of gravity is based on Albert Einstein's general theory of relativity, which is formulated within the framework of classical physics. On the other hand, the non-gravitational forces are described within the framework of quantum mechanics, a radically different formalism for describing physical phenomena based on probability. The necessity of a quantum mechanical description of gravity follows from the fact that one cannot consistently couple a classical system to a quantum one.

Although a quantum theory of gravity is needed in order to reconcile general relativity with the principles of quantum mechanics, difficulties arise when one attempts to apply the usual prescriptions of quantum field theory to the force of gravity. From a technical point of view, the problem is that the theory one gets in this way is not renormalizable and therefore cannot be used to make meaningful physical predictions. As a result, theorists have taken up more radical approaches to the problem of quantum gravity, the most popular approaches being string theory and loop quantum gravity.[4] A recent development is the theory of causal fermion systems which gives quantum mechanics, general relativity, and quantum field theory as limiting cases.

Strictly speaking, the aim of quantum gravity is only to describe the quantum behavior of the gravitational field and should not be confused with the objective of unifying all fundamental interactions into a single mathematical framework. While any substantial improvement into the present understanding of gravity would aid further work towards unification, study of quantum gravity is a field in its own right with various branches having different approaches to unification.

Although some quantum gravity theories, such as string theory, try to unify gravity with the other fundamental forces, others, such as loop quantum gravity, make no such attempt; instead, they make an effort to quantize the gravitational field while it is kept separate from the other forces. A theory of quantum gravity that is also a grand unification of all known interactions is sometimes referred to as a theory of everything (TOE).

One of the difficulties of quantum gravity is that quantum gravitational effects are only expected to become apparent near the Planck scale, a scale far smaller in distance (equivalently, far larger in energy) than what is currently accessible at high energy particle accelerators. As a result, quantum gravity is a mainly theoretical enterprise, although there are speculations about how quantum gravity effects might be observed in existing experiments.

Much of the difficulty in meshing these theories at all energy scales comes from the different assumptions that these theories make on how the universe works. Quantum field theory depends on particle fields embedded in the flat space-time of special relativity. General relativity models gravity as a curvature within space-time that changes as a gravitational mass moves. Historically, the most obvious way of combining the two (such as treating gravity as simply another particle field) ran quickly into what is known as the renormalization problem. In the old-fashioned understanding of renormalization, gravity particles would attract each other and adding together all of the interactions results in many infinite values which cannot easily be cancelled out mathematically to yield sensible, finite results. This is in contrast with quantum electrodynamics where, given that the series still do not converge, the interactions sometimes evaluate to infinite results, but those are few enough in number to be removable via renormalization.

*Quantum gravity* can be treated as an effective field theory. Effective quantum field theories come with some high-energy cutoff, beyond which we do not expect that the theory provides a good description of nature. The "infinities" then become large but finite quantities depending on this finite cutoff scale, and correspond to processes that involve very high energies near the fundamental cutoff. These quantities can then be absorbed into an infinite collection of coupling constants, and at energies well below the fundamental cutoff of the theory, to any desired precision; only a finite number of these coupling constants need to be measured in order to make legitimate quantum-mechanical predictions. This same logic works just as well for the highly successful *theory of low-energy pions* as for quantum gravity. Indeed, the first quantum-mechanical corrections to graviton-scattering and Newton's law of gravitation have been explicitly computed (although they are so infinitesimally small that we may never be able to measure them). In fact, gravity is in many ways a much better quantum field theory than the Standard Model, since it appears to be valid all the way up to its cutoff at the Planck scale.

While confirming that quantum mechanics and gravity are indeed consistent at reasonable energies, it is clear that near or above the fundamental cutoff of our effective quantum theory of gravity (the cutoff is generally assumed to be of the order of the Planck scale), a new model of nature will be needed. Specifically, the problem of combining quantum mechanics and gravity becomes an issue only at very high energies, and may well require a totally new kind of model.

The general approach to deriving a quantum gravity theory that is valid at even the highest energy scales is to assume that such a theory will be simple and elegant and, accordingly, to study symmetries and other clues offered by current theories that might suggest ways to combine them into a comprehensive, unified theory. One problem with this approach is that it is unknown whether quantum gravity will actually conform to a simple and elegant theory, as it should resolve the dual

conundrums of special relativity with regard to the uniformity of acceleration and gravity, and general relativity with regard to <span style="color:red">spacetime curvature</span>.
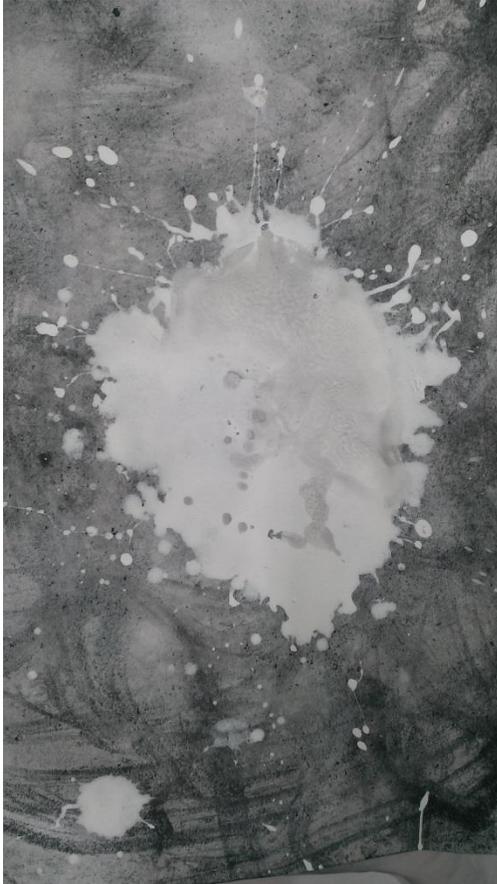


Such a theory is required in order to understand problems involving the combination of very high energy and very small dimensions of space, such as the behavior of black holes, and the origin of the universe.

At present, one of the deepest problems in theoretical physics is harmonizing the theory of general relativity, which describes gravitation, and applications to large-scale structures (stars, planets, galaxies), with quantum mechanics, which describes the other three fundamental forces acting on the atomic scale. This problem must be put in the proper context, however. In particular, contrary to the popular claim that quantum mechanics and general relativity are fundamentally incompatible, one can demonstrate that the structure of general relativity essentially follows inevitably from the quantum mechanics of interacting theoretical spin-2 massless particles (called gravitons).

While there is no concrete proof of the existence of gravitons, quantized theories of matter may necessitate their existence. [citation needed] Supporting this theory is the observation that all fundamental forces except gravity have one or more known messenger particles, leading researchers to believe that at least one most likely does exist; they have dubbed this hypothetical particle the graviton. The predicted find would result in the classification of the graviton as a "force particle" similar to the photon of the electromagnetic field. Many of the accepted notions of a unified theory of physics since the 1970s assume, and to some degree depend upon, the existence of the graviton.

These include string theory, superstring theory, M-theory, and loop quantum gravity. Detection of gravitons is thus vital to the validation of various lines of research to unify quantum mechanics and relativity theory.



The dilaton made its first appearance in Kaluza-Klein theory, a five-dimensional theory that combined gravitation and electromagnetism. Generally, it appears in string theory. More recently, however, it's become central to the lower-dimensional many-bodied gravity problem based on the field theoretic approach of Roman Jackiw. The impetus arose from the fact that complete analytical solutions for the metric of a covariant N-body system have proven elusive in general relativity. To simplify the problem, the number of dimensions was lowered to (1+1), i.e., one spatial dimension and one temporal dimension. This model problem, known as R=T theory (as opposed to the general G=T theory) was amenable to exact solutions in terms of a generalization of the Lambert W function. It was also found that the field equation governing the dilaton (derived from differential geometry) was the Schrödinger equation and consequently amenable to quantization.

Thus, one had a theory which combined gravity, quantization, and even the electromagnetic interaction, promising ingredients of a fundamental physical theory. It is worth noting that this outcome revealed a previously unknown and already existing natural link between general relativity and quantum mechanics. However, this theory lacks generalization to the (2+1) or (3+1) dimensions. In principle, the field equations are amenable to such generalization (as shown with the inclusion of a one-graviton process) and yield the correct Newtonian limit in d dimensions but only if a dilaton is included. Furthermore, it is not yet clear what the fully generalized field equation governing the dilaton in (3+1) dimensions should be. The fact that gravitons can propagate in

(3+1) dimensions implies that gravitons and dilatons do exist in the real world. Nonetheless, detection of the dilaton is expected to be even more elusive than the graviton. But since this simplified approach combines gravitational, electromagnetic and quantum effects, their coupling could potentially lead to a means of vindicating the theory, through cosmology and even, perhaps, experimentally.



General relativity, like electromagnetism, is a classical field theory. One might expect that, as with electromagnetism, the gravitational force should also have a corresponding quantum field theory.

However, gravity is *perturbatively nonrenormalizable*. For a quantum field theory to be well-defined according to this understanding of the subject, it must be asymptotically free or asymptotically safe. The theory must be characterized by a choice of finitely many parameters, which could, in principle, be set by experiment. For example, in quantum electrodynamics these parameters are the charge and mass of the electron, as measured at a particular energy scale.

On the other hand, in quantizing gravity there are infinitely many independent parameters (counterterm coefficients) needed to define the theory. For a given choice of those parameters, one could make sense of the theory, but since it's impossible to conduct infinite experiments to fix the values of every parameter, we do not have a meaningful physical theory:

At low energies, the logic of the renormalization group tells us that, despite the unknown choices of these infinitely many parameters, quantum gravity will reduce to the usual Einstein theory of general relativity.

On the other hand, if we could probe very high energies where quantum effects take over, then every one of the infinitely many unknown parameters would begin to matter, and we could make no predictions at all.

If we treat QG as an effective field theory, there is a way around this problem.

That is, the meaningful theory of quantum gravity (that makes sense and is predictive at all energy levels) inherently implies some deep principle that reduces the infinitely many unknown parameters to a finite number that can then be measured:

One possibility is that normal perturbation theory is not a reliable guide to the renormalizability of the theory, and that there really is a UV fixed point for gravity. Since this is a question of non-perturbative quantum field theory, it is difficult to find a reliable answer, but some people still pursue this option.

Another possibility is that there are new unfound symmetry principles that constrain the parameters and reduce them to a finite set. This is the route taken by string theory, where all of the excitations of the string essentially manifest themselves as new symmetries.

In an effective field theory, all but the first few of the infinite set of parameters in a non-renormalizable theory are suppressed by huge energy scales and hence can be neglected when computing low-energy effects. Thus, at least in the low-energy regime, the model is indeed a predictive quantum field theory. (A very similar situation occurs for the very similar effective field theory of low-energy pions.) Furthermore, many theorists agree that even the Standard Model should really be regarded as an effective field theory as well, with "nonrenormalizable" interactions suppressed by large energy scales and whose effects have consequently not been

observed experimentally.



Recent work has shown that by treating general relativity as an effective field theory, one can actually make legitimate predictions for quantum gravity, at least for low-energy phenomena. An example is the well-known calculation of the tiny first-order quantum-mechanical correction to the classical Newtonian gravitational potential between two masses.

A fundamental lesson of general relativity is that there is no fixed spacetime background, as found in Newtonian mechanics and special relativity; the spacetime geometry is dynamic. While easy to grasp in principle, this is the hardest idea to understand about general relativity, and its consequences are profound and not fully explored, even at the classical level. To a certain extent, general relativity can be seen to be a relational theory, in which the only physically relevant information is the relationship between different events in space-time.

On the other hand, quantum mechanics has depended since its inception on a fixed background (non-dynamic) structure. In the case of quantum mechanics, it is time that is given and not dynamic, just as in Newtonian classical mechanics. In relativistic quantum field theory, just as in classical field theory, Minkowski spacetime is the fixed background of the theory.

String theory can be seen as a generalization of quantum field theory where instead of point particles, string-like objects propagate in a fixed spacetime background, although the interactions among closed strings give rise to space-time in a dynamical way. Although string theory had its

origins in the study of quark confinement and not of quantum gravity, it was soon discovered that the string spectrum contains the graviton, and that "condensation" of certain vibration modes of strings is equivalent to a modification of the original background. In this sense, string perturbation theory exhibits exactly the features one would expect of a perturbation theory that may exhibit a strong dependence on <span style="color:red">asymptotics</span> (as seen, for example, in the <span style="color:red">AdS/CFT</span> correspondence) which is a weak form of background dependence.

$$\frac{f_o}{f_s} = \frac{1 - \frac{v_s}{c}\cos(\theta_{os})}{1 - \frac{v_s}{c}\cos\theta}\sqrt{\frac{1-(v_s/c)^2}{1-(v_o/c)^2}}$$

$$\frac{\frac{u'}{c}+v}{1+\frac{v}{c}\frac{u'}{c}}$$

$$\gamma(x' + \beta ct')$$

$$\Delta_0 = 2\left(\frac{L}{\sqrt{1-\frac{v^2}{c^2}}} - \frac{L}{1-\frac{v^2}{c^2}}\right)$$

$$= \frac{2L}{c}\frac{1}{1-\frac{v^2}{c^2}}$$

$$t = \frac{\lambda}{c-v} = \frac{c}{(c-v)f_s} = \frac{1}{(1-\beta)f_s},$$

$$n = \frac{\Delta_1 - \Delta_0}{\lambda} \approx \frac{2Lv^2}{\lambda c^2}$$

$$\approx \frac{2L}{c}\left(1+\frac{v^2}{c^2}\right)$$

$$T_1 - T_i = 2\left(\frac{L}{1-\frac{v^2}{c^2}} - \frac{L}{\sqrt{1-\frac{v^2}{c^2}}}\right)$$

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$\Delta_1 = 2\left(\frac{L}{1-\frac{v^2}{c^2}} - \frac{L}{\sqrt{1-\frac{v^2}{c^2}}}\right)$$

$$T_1 = \frac{2L}{\sqrt{c^2-v^2}} = \frac{2L}{c}\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \approx \frac{2L}{c}\left(1+\frac{v^2}{2c^2}\right)$$

$$T_i = \frac{L}{c-v} + \frac{L}{c+v}$$

$$x' = \gamma(x-vt),\ y' = y,\ z' = z,\ t' = \gamma\left(t-\frac{vx}{c^2}\right)$$

Loop quantum gravity is the fruit of an effort to formulate a background-independent quantum theory.

<span style="color:red">Topological quantum field theory</span> provided an example of background-independent quantum theory, but with no local degrees of freedom, and only finitely many degrees of freedom globally. This is inadequate to describe gravity in 3+1 dimensions, which has local degrees of freedom according to general relativity. In 2+1 dimensions, however, gravity is a topological field theory, and it has been successfully quantized in several different ways, including spin networks.

Quantum field theory on curved (non-Minkowskian) backgrounds, while not a full quantum theory of gravity, has shown many promising early results. In an analogous way to the development of quantum electrodynamics in the early part of the 20th century (when physicists considered quantum mechanics in classical electromagnetic fields), the consideration of quantum field theory on a curved background has led to predictions such as black hole radiation.

Phenomena such as the Unruh effect, in which particles exist in certain accelerating frames but not in stationary ones, do not pose any difficulty when considered on a curved background (the Unruh effect occurs even in flat Minkowskian backgrounds). The vacuum state is the state with the least energy (and may or may not contain particles). See Quantum field theory in curved spacetime for a

more complete discussion. There are other points of tension between quantum mechanics and general relativity.



First, classical general relativity breaks down at singularities, and quantum mechanics becomes inconsistent with general relativity in the neighborhood of singularities (however, no one is certain that classical general relativity applies near singularities in the first place).

Second, it is not clear how to determine the gravitational field of a particle, since under the Heisenberg uncertainty principle of quantum mechanics its location and velocity cannot be known with certainty. The resolution of these points may come from a better understanding of general relativity.

Third, there is the problem of time in quantum gravity. Time has a different meaning in quantum mechanics and general relativity and hence there are subtle issues to resolve when trying to formulate a theory which combines the two.

There are a number of proposed quantum gravity theories. Currently, there is still no complete and consistent quantum theory of gravity, and the candidate models still need to overcome major formal and conceptual problems. They also face the common problem that, as yet, there is no way to put quantum gravity predictions to experimental tests, although there is hope for this to change as future data from cosmological observations and particle physics experiments becomes available.

One suggested starting point is ordinary quantum field theories which, after all, are successful in describing the other three basic fundamental forces in the context of the standard model of elementary particle physics. However, while this leads to an acceptable effective (quantum) field

theory of gravity at low energies, gravity turns out to be much more problematic at higher energies. For ordinary field theories such as quantum electrodynamics, a technique known as renormalization is an integral part of deriving predictions which take into account higher-energy contributions, but gravity turns out to be nonrenormalizable: at high energies, applying the recipes of ordinary quantum field theory yields models that are devoid of all predictive power.
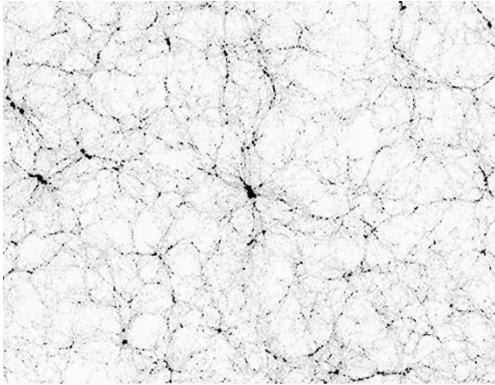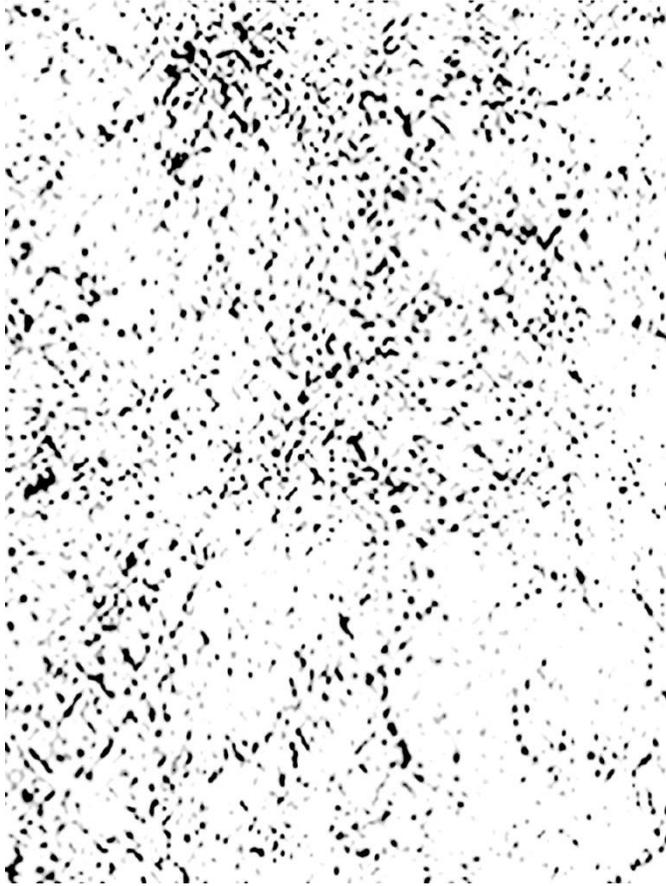


One attempt to overcome these limitations is to replace ordinary quantum field theory, which is based on the classical concept of a point particle, with a quantum theory of one-dimensional extended objects: string theory. At the energies reached in current experiments, these strings are indistinguishable from point-like particles, but, crucially, different modes of oscillation of one and the same type of fundamental string appear as particles with different (electric and other) charges. In this way, string theory promises to be a unified description of all particles and interactions. The theory is successful in that one mode will always correspond to a graviton, the messenger particle of gravity; however, the price of this success are unusual features such as six extra dimensions of space in addition to the usual three for space and one for time.

In what is called the second superstring revolution, it was conjectured that both string theory and a unification of general relativity and supersymmetry known as supergravity form part of a hypothesized eleven-dimensional model known as M-theory, which would constitute a uniquely defined and consistent theory of quantum gravity. As presently understood, however, string theory admits a very large number (10500 by some estimates) of consistent vacua, comprising the so-called "string landscape". Sorting through this large family of solutions remains a major challenge.

Loop quantum gravity seriously considers general relativity's insight that spacetime is a dynamical field and is therefore a quantum object. Its second idea is that the quantum discreteness that

determines the particle-like behavior of other field theories (for instance, the photons of the electromagnetic field) also affects the structure of space.

The main result of loop quantum gravity is the derivation of a granular structure of space at the Planck length. This is derived from following considerations: In the case of electromagnetism, the quantum operator representing the energy of each frequency of the field has a discrete spectrum. Thus the energy of each frequency is quantized, and the quanta are the photons. In the case of gravity, the operators representing the area and the volume of each surface or space region likewise have discrete spectrum. Thus area and volume of any portion of space are also quantized, where the quanta are elementary quanta of space. It follows, then, that spacetime has an elementary quantum granular structure at the Planck scale, which cuts off the ultraviolet infinities of quantum field theory.

The quantum state of spacetime is described in the theory by means of a mathematical structure called spin networks. Spin networks were initially introduced by Roger Penrose in abstract form, and later shown by Carlo Rovelli and Lee Smolin to derive naturally from a non-perturbative quantization of general relativity. Spin networks do not represent quantum states of a field in spacetime: they represent directly quantum states of spacetime.

The theory is based on the reformulation of general relativity known as <span style="color:red">Ashtekar variables</span>, which represent geometric gravity using mathematical analogues of electric and magnetic fields. In the quantum theory, space is represented by a network structure called a spin network, evolving over time in discrete steps.



The dynamics of the theory is today constructed in several versions. One version starts with the canonical quantization of general relativity. The analogue of the Schrödinger equation is a <span style="color:red">Wheeler–DeWitt equation</span>, which can be defined within the theory. In the covariant, or <span style="color:red">spinfoam formulation</span> of the theory, the quantum dynamics is obtained via a sum over discrete versions of spacetime, called spinfoams. These represent histories of spin networks.

In quantum field theory, the <span style="color:red">Weinberg–Witten</span> theorem places some constraints on theories of composite gravity/emergent gravity. However, recent developments attempt to show that if locality is only approximate and the holographic principle is correct, the Weinberg–Witten theorem would not be valid

As was emphasized above, quantum gravitational effects are extremely weak and therefore difficult to test. For this reason, the possibility of experimentally testing quantum gravity had not received much attention prior to the late 1990s. However, in the past decade, physicists have realized that evidence for quantum gravitational effects can guide the development of the theory. Since theoretical development has been slow, the field of phenomenological quantum gravity, which studies the possibility of experimental tests, has obtained increased attention.
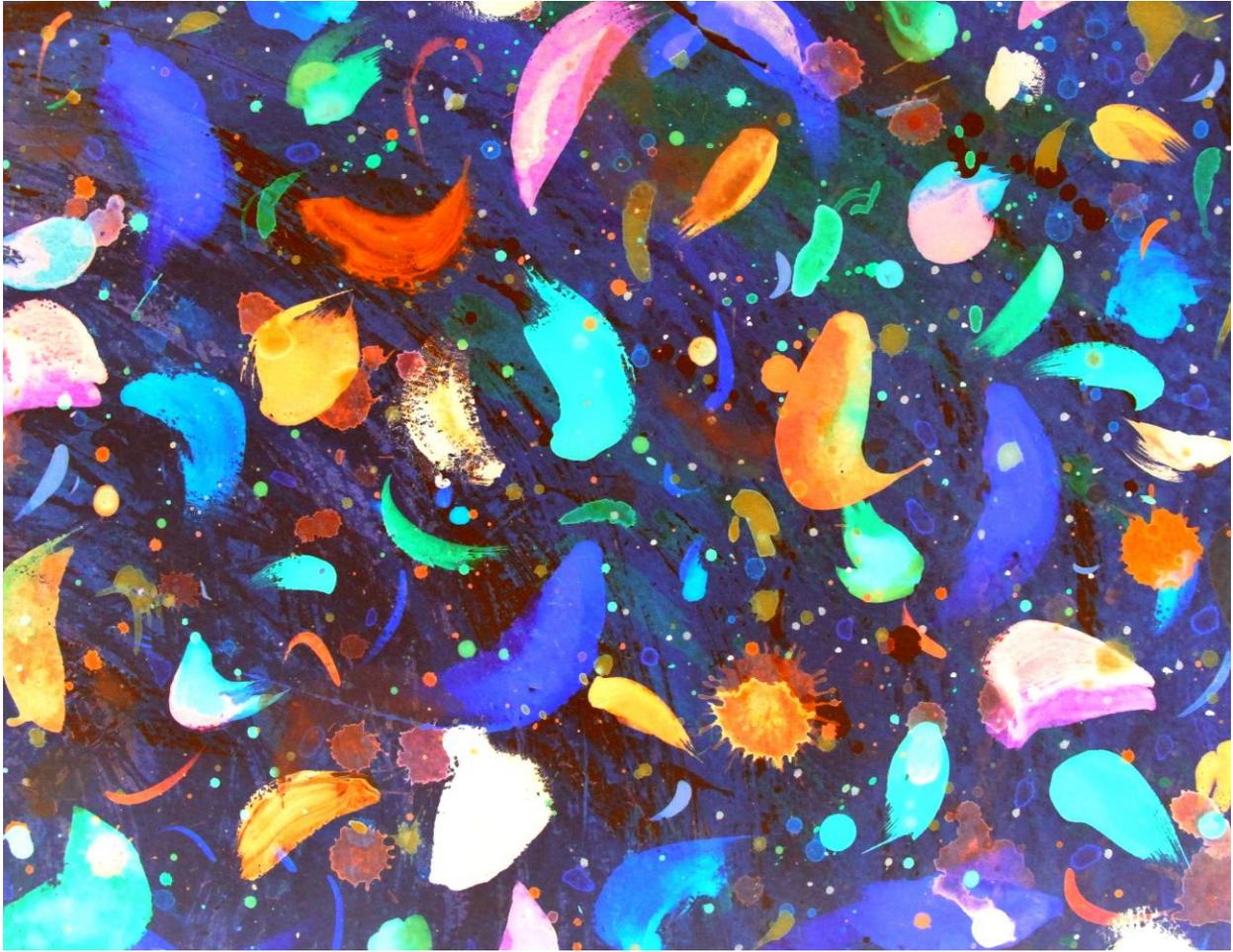
The most widely pursued possibilities for quantum gravity phenomenology include violations of Lorentz invariance, imprints of quantum gravitational effects in the cosmic microwave background (in particular its polarization), and decoherence induced by fluctuations in the space-time foam.

The BICEP2 experiment detected what was initially thought to be primordial B-mode polarization caused by gravitational waves in the early universe. If truly primordial, these waves were born as quantum fluctuations in gravity itself. Cosmologist Ken Olum (Tufts University) stated: "I think this is the only observational evidence that we have that actually shows that gravity is quantized....It's probably the only evidence of this that we will ever have."