Graviton

Let me write down first an equation that is Einstein's crowning achievement (and no, it's not $E=mc2$

):

$R\mu\nu-12g\mu\nu R=8\pi GT\mu\nu$.

Without going into details, the essence of this equation is that the geometry of spacetime, represented by the left-hand side, is determined by the stress-energy-momentum of matter, represented by the right-hand side and vice versa. As Wheeler once said, "spacetime tells matter how to move; matter tells spacetime how to curve."

Enter quantum mechanics, or rather, quantum field theory in the form of the Standard Model of particle physics: A theory of all matter and all interactions, except for gravity. (I.e., a theory of almost everything.) It changes the preceding equation in a very subtle way:

$R\mu\nu-12g\mu\nu R=8\pi GT\hat{}\mu\nu$.

Note the difference: that little hat on top of the T on the right-hand side.

What it means is that stress-energy-momentum is no longer represented by a number, as in classical physics. It is now represented by a quantum-mechanical operator (or, as Dirac called these quantities, a q-number.) In short, our equation now reads

number = non-number.

This clearly cannot be. It's like asking how many apples equal one orange.

The generally accepted wisdom is that the problem with this equation is on the left-hand side. That is, the problem is that we use numbers to represent spacetime geometry, instead of developing a proper quantum theory of spacetime, i.e., quantum gravity. But we have failed this task miserably: many tried, but no one really succeeded creating a mathematically self-consistent, working quantum theory of gravity.

Mind you, there is another way. Here is another version of Einstein's field equation:

$R\mu\nu-12g\mu\nu R=8\pi G\langle T\mu\nu\rangle$.

The angle brackets on the right-hand side represent the so-called expectation value of a quantum mechanical operator. This expectation value is a number, so all is well: now that there are ordinary numbers on both sides of the equation, we can go ahead solving it. This variation has a name: it is called semiclassical gravity.

And guess what: It works. That is to say, with the exception of the extreme early universe and the immediate vicinity of the singularity deep inside the event horizon of a black hole, semiclassical gravity is more than sufficient to describe Nature.

So why bother with quantum gravity, then? For starters, semiclassical gravity is deeply unsatisfactory to most theorists: the angle brackets are put in “by hand” with no theoretical justification other than the fact that “it works and we are too dumb to do any better”. It is also conceptually problematic: it basically says that even though we don’t know, say, the actual location of an electron, somehow the electron’s gravitational field does anyway, by acting as though the electron’s location was its expectation value.

Nonetheless, the idea that gravity may after all be classical hasn’t been abandoned. A good example is entropic gravity, which views gravity as an emergent, fundamentally classical phenomenon related to thermodynamics and statistical physics.