

The Trouble with Gravity Summary/Review

Lecture 7: Spring 2009 Compton Lecture Series:

From Quantum Mechanics to the String

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- Gravity is different from the other three forces
 - The “charge” that gravity reacts to is mass, for example the force on a particle of mass m in a gravitational field g is $F = mg$.
 - In addition, the mass determines how much an object accelerates under a given force. For a particle of mass m acted on by a force F , the acceleration a is given by $F = ma$.
 - This means that the acceleration is independent of the mass: $F = ma = mg$ implies $a = g$.
 - Because of this, the effects of acceleration are indistinguishable from those of a gravitational field. This means that we can interpret the gravitational effects as coming from a curvature of the background.
- Black holes are a prediction of the curved space interpretation (general relativity)
 - When space curves around a point mass, there is a singularity where the center is.
 - This singularity is hidden behind a horizon. Though locally a horizon isn’t necessarily different from any other region of space, objects can only go inward past the horizon, nothing (not even light) can come back out. No experiment can tell you what goes on behind the horizon.
 - A black hole (everything behind the horizon) is described by a few numbers: mass, charge, angular momentum.
 - Quantum mechanically pairs of virtual particles can be produced near the horizon. If one ends up inside and the other outside, they don’t end up annihilating again. Instead, the one outside carries off positive energy, and the mass of the black hole decreases to compensate. This is “Hawking radiation.”
 - Complicated objects fall into black holes, but the Hawking radiation coming off of it depends only on the few numbers describing the black hole. This process is *irreversible*, which is in conflict with the assumptions of quantum mechanics.
- Gravity affects the vacuum energy density
 - According to Newton, gravity affects anything with mass. But according to Einstein, mass is just one form of energy. It follows that gravity actually affects any form of energy.
 - Because of this, it is the only one of the fundamental forces that notices what the total energy of a system is, rather than just differences in energy.
 - The energy of the “vacuum” comes from a variety of sources, including things like the value of the background Higgs field and the quantum fluctuations of all particle fields.
 - This vacuum energy density affects the way the universe expands. Normal matter causes the expansion to decelerate because of gravitational attraction. The vacuum energy density can cause the expansion to either accelerate or decelerate depending on whether it is positive or negative.
 - A positive vacuum energy density is a negative cosmological constant $\Lambda < 0$, a negative vacuum energy density is a positive cosmological constant $\Lambda > 0$.
 - The observed acceleration of the expansion puts one constraint on the relationship between amount of normal matter and the amount of Λ .
 - Normal matter and the cosmological constant also cause space to curve: the observed curvature puts another constraint on the relationship between amount of normal matter and the amount of Λ .

- Direct measurements of the amount of dark and luminous matter imply one last constraint. Together, all three of these constraints imply a small, positive cosmological constant.
- We don't have a complete understanding of all the sources of the vacuum energy density, but if we look at the quantum fluctuations from any one field, it generates a energy density 120 orders of magnitude larger than the observed value. This implies that the various sources of Λ conspire to cancel each other out to 120 decimal places (and yet they don't cancel completely). This is either a very strange coincidence or evidence of something deeper. It is called the "cosmological constant problem."
- Quantum theories, in particular gravity, don't make sense at high energies. String theory solves this problem.
 - The idea that particles are pointlike eventually implies that a finite amount of mass, charge, etc is concentrated in an infinitesimal space. This creates a problem in all quantum theories at very high energies (short distances).
 - In most quantum theories, we can still make sense out of them at low energies because the observed objects are not the bare particles but rather the these particles together with their interactions with virtual particles in the vacuum, which are fine at low energies, though we assume that there is some form of correction at very high energies.
 - In the case of quantum gravity, there is no consistent way to separate the low energy behavior from the high energy behavior, which is what is generally meant when people say that they can't "quantize gravity."
 - The idea that the fundamental objects are not pointlike but instead are extended in one direction naturally solves this problem: there is no singular pointlike behavior because the strings have some length and everything (energy, charge, interactions) is spread out by at least this length scale.
- Strings provide a different way of unifying forces and particles into one system
 - Historically, patterns of "particles" have been explained when we have discovered that these objects were actually created from smaller constituents. For example, molecules are made up of atoms, atoms are made up of protons, neutrons, and electrons, and protons and neutrons are made up of quarks.
 - Suppose instead of smaller pointlike objects combining to form quarks and/or leptons, we assume that these are vibrating one-dimensional strings.
 - This creates a different way for internal structure to lead to a pattern of observed particles.
 - The amount of internal vibrations in a string increases the internal energy of the string, which is observed as a particle with greater mass.
 - The motions of the vibrations of the string also create internal angular momentum, which is observed as the spins of particles.
 - There is a closed string which corresponds to a massless spin-2 particle (a graviton) and an open string which corresponds to a massless spin-1 particle (a photon or a gluon). This creates a framework under which all four forces can be unified.
- Strings may eventually also solve the black hole information paradox and the cosmological constant problem.
 - The information paradox could be solved if the black hole actually contains more information than just its mass, charge, and angular momentum. Using string theory we hope to describe the black hole more completely. This has been done in some specialized cases, but a general understanding is still pending.

- One of the biggest problems with string theory is that it only works in a specific number of space-time dimensions (usually 10 or 11). We assume that all but the observed 4 are somehow wrapped up in loops, spheres, donut shapes, etc. (More about this next week!) There are many different ways of wrapping up extra dimensions, and each other these different ways leads to a different pattern of 4-dimensional physics (particles, forces, etc). In particular, it determines what the value of the cosmological constant will be. It is possible that some day we may understand our observed cosmological constant in this way.