TOPIC XI

SUMMARY AND NEW FRONTIERS

Lecture notes 1

Cosmology

Classical general relativity fails when the metric develops a curvature singularity. One such singularity occurs at the center of the classical black hole. But a curvature singularity also occurs in another interesting situation: at the initial singularity of the Universe; i.e., at the big bang.

For the case of the black hole, new difficulties arise when we add in the effects of quantum mechanics. Now problems arise not just at the singularity, but also because of the existence of a *horizon*. Entangled pairs are created at the horizon, leading to conceptual difficulties at the endpoint of evaporation.

It is natural to assume that quantum gravity effects will modify a planck size region around he curvature singularity. But this will not affect the physics at the horizon, and thus cannot resolve the problem. We have seen that the fuzzball paradigm resolves the problem in string theory, by modifying the entire structure of the black hole – there is no horizon, and thus no region interior to the horizon and no central singularity.

What about the big bang singularity? It is natural to expect that quantum gravity effects will modify this singularity for times $t \lesssim t_p$. But given what we have learnt from black holes, we can wonder if quantum gravity generates much larger changes to the physics of the early Universe. In both the black hole and in the early Universe we have large collections of matter, that – at least in the classical theory – are being compressed inexorably to a point. The classical metric in Cosmology has a horizon, though this is a somewhat different kind of horizon than the horizon of a black hole. Could it be that quantum gravity effects alter physics at the scale of this Cosmological horizon?

It might seem that since we have understood the physics of black holes in string theory, we can also immediately understand the physics of the early Universe in this theory. But things are not so simple, since the early Universe brings in a new set of issues, related to the question of *initial conditions*.

For the black hole, we have a well posed initial value problem. We can start with flat spacetime, containing a set of well separated quanta. We then send these quanta towards each other, so that they collide and to make a black hole. We then ask for the resulting wavefunctional, which can in principle be computed by a large computer containing all the rules of string theory. We have argued that the resulting wavefunctional will describe fuzzball solutions, rather than a black hole with the traditional vacuum horizon, and that this resolves all puzzles with black holes.

For Cosmology, on the other hand, it is not clear what initial condition we should choose. In any quantum theory we can determine the wavefunctional $|\psi(t)\rangle$ if we are given the initial wavefunctional $|\psi(0)\rangle$. But we then have to ask what principle will determine $|\psi(0)\rangle$:

(a) Is there a unique choice for this initial condition, similar to the 'no-boundary initial condition' suggested by Hartle and Hawking?

(b) Is it the case that all initial conditions are allowed, and some anthropic arguments determine which one is most likely to be chosen for our present Universe?

(c) Is it the case that all generic initial conditions give rise to similar evolutions, and lead to the kind of Universe that we observe?

The problem of initial conditions is not the only issue we face. We also have to understand what sets the value of the Cosmological constant Λ, since this value determines the evolution of the Cosmology. If we cutoff the energy of vacuum fluctuations at the planck scale, the we get

$$\Lambda \sim m_p^4 \tag{1.1}$$

which would make the universe have a curvature of order the planck scale. Supersymmetry can cancel the vacuum energies of bosons and fermions and give $\Lambda = 0$, but supersymmetry is clearly broken at the TeV scale or above, and it is unclear why we do not have a cosmological constant of order

$$\Lambda \gtrsim (1\, TeV)^4 \tag{1.2}$$

The current value of Λ is of the order of the closure density of the universe

$$\Lambda \sim \frac{H^2}{G} \tag{1.3}$$

where H is the Hubble constant. One might look for a theory where such is always the case, but observations suggest that Λ is a constant, and thus independent of current value of H. We then face a new issue – the coincidence problem: why is Λ of the order (1.3) today?

A third set of issues surround the idea of inflation. Observations appear to support the idea that the Universe underwent a period of rapid expansion, by around 60 e-folds or more. It is typically assumed that inflation starts when the temperature is order the GUTS scale, but there is no struct reason for this; it could start at the planck scale or at energies below the GUTS scale. The precise mechanism for inflation is however not very clear; we do not know which field would serve as the inflaton field, and the properties required of this field also appear to require fine-tuning in most models.

We are interested in the role of quantum gravity in the early Universe. In this context there are two possibilities:

(a) Inflation is a phenomenon governed by GUTS scale physics, or more generally, the low energy particle physics that emerges from the full theory of quantum gravity. In this case the details of planck scale physics become essentially irrelevant to inflation. It is natural to expect that these details get washed away during inflation, an dare therefore unlikely to leave an observable signature today.

(b) The mechanism of inflation is fundamentally rooted in the theory of quantum gravity. In this case we would expect that inflation, or something with similar consequences, emerges naturally from the quantum gravity theory. It is possible that observations today would then give a window into planck scale physics.

In addition to the above basic questions, we will encounter several more issues when we try to relate early Universe physics to the physics of black holes. Black holes have an entropy given by their horizon area. During inflation, the Cosmology has a de-Sitter metric, which also possesses a kind of horizon. Should the area of the de-Sitter horizon also define an entropy? If so, what is this entropy counting?

Bibliography