Gravity as an Effective Medium

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1 Overview of the Field

Our working group focused on problems related to how gravity, in the form of a non-trivial space-time, would modify the behavior of quantum field theories. This area has been of interest to physicists for years for a number of reasons. Two of the main ones have to do with the inflationary universe paradigm as well as with the black hole information problem.

Current cosmological observations are consistent with the idea that very likely something like inflation, where the Universe undergoes a phase of accelerated expansion, did occur. Even more interestingly, and the reason we believe that inflation may have occurred is that measurements of the statistics of structure we see in the Universe, as quantified by the power spectrum (2-point correlation function) of both the temperature of the residual cosmic microwave background radiation (CMBR) as well as the matter density power spectrum, are well fitted by the same quantities as calculated via the quantum fluctuations of the field whose energy density drove this inflationary phase. What we now need to understand is to what extent these observations can take us from the *paradigm* of inflation to a specific *model* that realizes this paradigm in a way that is consistent with other known physical theories.

The space-time describing an inflationary universe is a dynamical one and the standard ideas of a fixed vacuum state for the quantum field theory are not as tenable as they would be in a non-expanding space-time. New techniques need to be developed to deal with this situation.

Similar, though arguably more serious, issues arise in black hole spacetimes. Hawking's [1] seminal calculation of the radiation of particles by black holes inevitably leads one to the potential breakdown of quantum mechanics in this process. Due to the apparent thermal nature of the Hawking radiation coming from a black hole, one can seemingly construct situations where a pure state (described by a single vector in the Hilbert space of states) can be converted into a mixed state, described by a density matrix. The unitary nature of time evolution in quantum mechanics should preclude this possibility, thus apparently generating a paradox, since the original calculation was a quantum mechanical one, albeit in a non-trivial spacetime. Resolving this paradox is one of the most pressing issues currently in fundamental physics.

2 Recent Developments and Open Problems

2.1 Inflation

The ideas of effective field theory[2] that have had a major impact in such diverse areas of physics as: high energy physics, condensed matter physics, gravity waves and more recently fluid dynamics, have been applied to inflation[3]. The field that gives rise to the various power spectra can be interpreted as the so-called Goldstone mode of spontaneously broken time translation invariance, where the background time-evolving fields induce a preferred arrow of time. Applying the technology of effective field theories to this viewpoint then allows us to have a more global picture of what the generic predictions of inflation (at least in its simplest form) might be. The work we did at BIRS bears directly on how to calculate reliably within this effective field theory.

2.2 Black Hole Information

The black hole information problem was made sharper recently with the development of the so-called firewall[4] idea. The particles emitted by the black hole come out in entangled pairs one of which escapes while the other falls back into the black hole. The problem arises with the idea that, by the time about half the available mass of the black hole has been emitted, particles emitted after this time must be entangled with *all* the particles that have been emitted before. This gives rise to a paradox due to the "monogamy of entanglement" theorem in quantum mechanics; the outgoing particle cannot be entangled with different sets of particles at the same time. Almheiri et al[4] posit that a "firewall" appears somewhere before the event horizon of the black hole with sufficient energies to break the entanglement. Where this firewall appears from is as yet an unresolved problem and there are a number of competing ideas of how the entanglement might be lost.

Part of what leads us to the firewall picture is the idea that standard local quantum field theory still applies in the vicinity of the horizon. The work we did at BIRS on the black hole information paradox focuses on this part of the problem.

3 Scientific Progress Made

During our visit to BIRS our working made significant progress on a number of fronts. First, we were able to construct the diagnostic tool that allows us to tell when the perturbative expansion used to compute cosmological observables in inflation is valid. We are now able to tell when a so-called semiclassical expansion is valid (technically, keeping only the tree level Feynman graphs in the calculation) and when this breaks down. In particular we can explore interesting parts of the parameter space, the regime of small sound speeds of fluctuations and the eternal inflation regime in which quantum fluctuations can push the background up its potential hill and keep inflation going. For the black hole problem, we are exploring the possible breakdown of the effective quantum theory used in the vicinity of the black hole due to infrared divergences of the type that occur in flat space thermal theories. We decided to use a toy model, the so-called Rindler spacetime which is what an accelerating observer would see the flat space vacuum as to model what we think are the essential features of the black hole problem.

4 Outcome of the Meeting

We are in the process of finishing the paper on our inflation work above and have started in on the Rindler calculation; we expect that this will be done shortly. We have also embarked on the task of deriving the relevant Fokker-Planck equation for the probability distribution of the fields that drive the quantum fields that drive the fluctuations during inflation directly from the relevant quantum field theory. The work on the control of cosmological perturbation theory discussed above was a necessary preamble to this calculation, since we need to be able to evaluate the errors involved in the various truncations of the full theory.

References

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