Loop quantum cosmology: an overview

Abhay Ashtekar

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Abstract A brief overview of loop quantum cosmology of homogeneous isotropic models is presented with emphasis on the origin of and subtleties associated with the resolution of big bang and big crunch singularities. These results bear out the remarkable intuition that John Wheeler had. Discussion is organized at two levels. The main text provides a bird’s eye view of the subject that should be accessible to non-experts. Appendices address conceptual and technical issues that are often raised by experts in loop quantum gravity and string theory.

Keywords Loop quantum cosmology · Singularity resolution · Planck scale physics · Quantum geometry

1 Introduction

In general relativity, the gravitational field is encoded in the very geometry of space–time. Geometry is no longer an inert backdrop providing just a stage for physical happenings; it is a physical entity that interacts with matter. As we all know, this deep paradigm shift lies at the heart of the most profound predictions of the theory: the big bang, the black holes and the gravitational waves. However, the encoding of gravity in geometry also implies that space–time itself must end when the gravitational field becomes singular, and all of physics must come to an abrupt halt. This is why in popular articles relativists and cosmologists like to say that the universe was born with a big bang some 14 billion years ago and it is meaningless to ask what was there before. In more technical articles they point out that this finite beginning leads
to the ‘horizon problem.’ But we know that general relativity is incomplete because it ignores quantum physics. If we go back in time using general relativity, we encounter huge matter densities and curvatures at which quantum effects should in fact dominate physics. This is the regime where we can no longer trust general relativity. Thus, the big bang is a prediction of general relativity precisely in a domain where it is inapplicable. Although in the framework of general relativity the universe did begin with a big-bang, there is no reason to believe that the real, physical universe did.

To know what really happened, one needs a quantum theory of gravity. John Wheeler recognized this early and drew on various analogies to argue that quantum fluctuations of geometry would intervene and resolve classical singularities. Already in his 1967 lectures in Battelle Rencontres, he wrote [1]:

*In all applications of quantum geometrodynamics, none would seem more immediate than gravitational collapse Here, according to classical general relativity, the dimensions of collapsing system are driven down to indefinitely small values. ... In a finite proper time the calculated curvature rises to infinity. At this point the classical theory becomes incapable of further prediction. In actuality, classical predictions go wrong before this point. A prediction of infinity is not a prediction. The wave packet in superspace does not and cannot follow the classical history when the geometry becomes smaller in scale than the quantum mechanical spread of the wave packet.... The semiclassical treatment of propagation is appropriate in most of the domain of superspace of interest to gravitational collapse. Not so in the decisive region.*

Wheeler focused on the gravitational collapse but his comments are equally applicable to the big-bang—the time reverse of the collapse. This point was made explicit in Misner’s articles on quantum cosmology [2], particularly in his contribution to the Wheeler Festschrift.

However, It turned out that within the framework of quantum geometrodynamics (QGD) that Wheeler, Misner and DeWitt used, without additional inputs the big bang singularity could not be resolved generically, at least in the precise, physical sense spelled out in Sect. 4. The subject had therefore remained rather dormant for over two decades. Over the last 6–7 years, the issue was revived in the context of loop quantum cosmology (LQC) [3,4]—the application of loop quantum gravity (LQG) [5–7] to cosmological models. The LQG program is rather similar to that envisaged by Wheeler: both are canonical approaches, both follow pioneering ideas of Bergmann and Dirac, and in both cases dynamics has to be teased out of the quantum Hamiltonian constraint. There is however, a key difference: LQG is based on a specific quantum theory of Riemannian geometry. As a result, geometric observables display a fundamental discreteness [8–11]. It turns out that this discreteness plays a key role in quantum dynamics: While predictions of LQC are very close to those of QGD away from the Planck regime, there is a dramatic difference once densities and curvatures enter the Planck scale. In LQC the big bang is replaced by a quantum bounce. Moreover, thanks to the introduction of new analytical and numerical methods over the past two years, it is now possible to probe the Planck scale physics in detail.