Quantum theories of gravity

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According to the arguments we have developed, quantum theories of gravity are holographic in nature: they are not specified in terms of local degrees of freedom in the spacetime where gravity lives. Instead they are defined by quantum theories that live in the boundary of spacetime.

Then, it does not seem appropriate to talk about 'the theory of quantum gravity' as if this were a unique theory that characterizes the microscopic gravitational degrees of freedom and their interactions, once and for all, independently of what the state of the field is at long distances. Instead, spacetimes with different asymptotics will correspond to different quantum theories of gravity, with microscopic degrees of freedom that may be completely different in each case. The picture is one in which gravity 'emerges' as a semiclassical description of the dynamics of certain classes of quantum theories. Many different quantum theories may admit such dual gravitational descriptions, so we speak of 'quantum theories (or models) of gravity'.

In this picture gravity is definitely not a fundamental interaction. Gravitons appear only as collective excitations valid for describing quantum perturbations of the effective geometry with wavelength $\gg L_{Planck}$.

In some regimes, *e.g.*, near the end of black hole evaporation, or close to singularities, the gravitational description will break down, but then the dual quantum theory should provide the correct physics. It is a big challenge to answer these questions, but at least the explicit realizations of AdS/CFT give a framework where, in principle, they can be posed.

Our examples of holographic theories are for the most part based on local quantum field theories, since these are the quantum theories that we understand best. In this case, the QFTs are controlled by the CFTs at the UV fixed-points, and the gravitational duals are necessarily asymptotic to AdS. We do not have a general understanding of what other asymptotics admit a good quantum holographic dual.

In the case of flat asymptotics, it seems that, if there is a holographic description, the theory cannot straightforwardly be a local QFT. It might be that the arguments can be evaded by having the hologram on a null boundary instead of a timelike one, but this is unclear. Our arguments above also indicate that, given the absence of a cosmological constant, now the microscopic theory must include a length scale, which would seem to preclude that it is a conformal theory: its central charge should be zero or infinity, but not any finite number.[34]

We can obtain asymptotically flat spaces as limits of AdS in which $L_{AdS} \to \infty$, *i.e.*, when we focus on physics occurring at scales much shorter than the AdS radius. However, it is unclear whether one can take this limit in the CFT and recover a sensible quantum theory. In this limit, the central charge would seem to diverge.

Local quantum (field) theory wisdom:

Short distances = definition of theory
"fundamental"

Asymptotics = properties of states (solutions)
"not fundamental"

In Quantum Gravity

Long distance asymptotics is fundamental

Different asymptotics
⇒ different theory
⇒ different fundamental degrees of freedom

Quantum is fundamental

Gravity emerges

Not a unique theory, but a paradigm for them

Space emerges out of quantum

Energy scale becomes one more space dimension

More deeply:
space out of quantum entanglement