Summary

The elusive theory of quantum gravity is often called "the holy grail of theoretical physics". Of all the attempts to quantize gravity, string theory is the best developed theory, but it is still poorly understood and poorly supported by experiment. Thus, it is prudent to consider simpler approaches to quantum gravity, where results can be expected on a reasonable time-scale. Lower-dimensional models of gravity provide such an approach. In the past 20 years studies of 2-dimensional gravity led to numerous exciting results for classical and quantum black holes. However, the simplicity of these black hole models eliminates two important features of higher-dimensional gravity: they do not contain gravitons, and they lack a good analogue for the horizon area of black holes. Both these deficiencies can be remedied by considering a suitable model of gravity in three dimensions. The construction of a consistent theory of quantum gravity in three dimensions was the main goal of the project. The key guideline was the holographic principle.

The holographic principle predicts that the number of dimensions is a matter of perspective: we can choose to describe Nature as obeying one set of laws, including gravity, in three spatial dimensions or, equivalently, obeying a different set of laws, excluding gravity, in two spatial dimensions. Despite the radically different descriptions, we have no way to determine which of these formulations is "really" true. An analogous phenomenon occurs in everyday life. A hologram is a 2-dimensional object, but it looks like a fully 3-dimensional image. According to the holographic principle the entire Universe could be a kind of hologram.

For typical gravity models we found it impossible to obtain a consistent quantum description: the theory is sick and has so-called ghosts or excitations with negative energy, which destabilize the system. Only for certain fine-tuning of parameters the ghosts can be exorcized. However, precisely for these fine-tunings another kind of instability emerges, so-called "log modes". The appearance of the log modes led to unexpected holographic relations to log conformal field theories (CFTs), where this instability is not a problem, but rather a distinguishing property of the model. (These theories are used to describe non-unitary quantum systems with "quenched disorder".) Checking the holographic correspondence between critical gravity theories and log CFTs was one of the key achievements of the project and led to a fruitful exchange with the log CFT community, as well as to several spin-offs on the gravity side, like new exact solutions.

The quest for a consistent theory of quantum gravity eventually required to think outside the box. We investigated a particularly promising looking gravity model – conformal Chern-Simons gravity – and pioneered its holographic description. We discovered flat space boundary conditions that made the theory consistent and, for a special value of the Newton constant, allowed us to uniquely identify the dual CFT. It turned out to be the so-called "Monster CFT" that was conjectured to play a significant role in 3-dimensional quantum gravity in 2007 by Witten and in 2008 by Li, Song and Strominger. Finally, we considered more general gravity theories with higher spin fields and discovered a particular model that appears to be a consistent quantum gravity theory not only for one value of the Newton constant, but for arbitrarily many values. Thus, we are now a bit closer to the "holy grail", though the quest is not completed yet.