SCIENCE SUMMARY

On 14 September 2015, two Advanced LIGO detectors made the first direct detection of gravitational waves (GW) from two merging black holes. This discovery not only confirms the prediction of Einstein's general theory of relativity, but also provides us, for the first time, a probe into strong gravity physics and highly warped spacetime, which was inaccessible to us before. It marks the dawn of GW astronomy and opens an entirely new window into the universe, complementary to observations using electromagnetic waves and neutrinos.

The core of Advanced LIGO is a Michelson laser interferometer with 4km arm length, which measures tiny displacements of mirror-endowed test masses induced by GWs as shown schematically in Figure 1. The peak amplitude of the event GW150914 that we detected, in terms of strain, is of the order of 10^{-21}, with the corresponding displacement of the test masses being 10^{-19} meter. Such a high sensitivity is achieved by using the state-of-the-art techniques to reduce various noises---disturbances that mimic GW signals. Figure 1 also shows the design sensitivity of Advanced LIGO that is around factor of three better than the one we have at the current stage. Different curves in the figure show the strength of various major noises as a function of frequency. The seismic noise and the Newtonian noise come from random motion of the ground. The suspension thermal noise and the coating Brownian noise originate from the thermal motion of the suspension wire and the mirror coating surface, respectively. In addition to these so-called 'classical noises', there is also quantum noise that arises from quantum nature of light and intrinsic quantum mechanical uncertainty. It limits the detector sensitivity from intermediate frequencies up to high frequencies.

The fact that advanced GW detectors are quantum-limited has two implications: (i) we have to manipulate quantum coherence to further improve the detector sensitivity, and (ii) advanced GW detectors will achieve sensitivity sufficient for probing the quantum dynamics of macroscopic test masses. These are the topics studied by Prof. Andreas Freise and Dr. Haixing Miao during this project. In particular, they have explored different approaches for reducing the quantum noise with both numerical modelling and analytical study, e.g., using the interaction between light and mechanical oscillator (or atomic gain medium) to create active optical filters that can enhance the detector response to GW signals. They also applied quantum measurement theory to investigate the general principle behind and studied the fundamental quantum limitation to GW detection, which leads to new ideas for designing the next-generation GW detectors that can probe further into the distant universe and unveil new astrophysical objects.

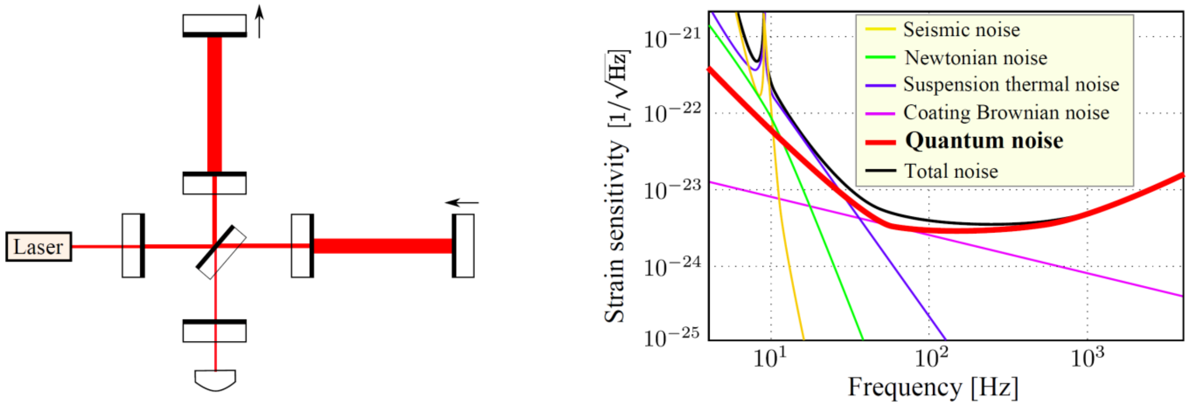

Figure 1. The schematic shows the configuration of advanced GW detectors. It is a Michelson interferometer ideal for measuring GW induced differential motions of mirror-endowed test masses. The plot on the right shows the design sensitivity of Advanced LIGO with major noises.