Einstein's Legacy and Songs from the Stellar Graveyard

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In November1915, Albert Einstein published his theory of gravitation, the theory of general relativity (GR), which predicts that gravity arises as a consequence of the interaction between the geometry of space time and its matter-energycontent.This dynamic relationship is perhaps best expressed through John Wheeler's famous quote: "Space time tells matter how to move; matter tells space time how to curve". A 100 years on, GR firmly stands (along with quantum mechanics) as one of the twin pillars of modern physics.

The theory and its predictions have been tested thoroughly and extensively in the last century, and have passed all experimental verifications with flying colours. Such tests include the classical solar system tests and subsequent precision tests in terrestrial laboratories and in space (using spacecrafts like Cassini and Gravity Probe B) which have helped test predictions of GR to unprecedented accuracies.However, almost all these tests of GR are "weak-field" tests, i.e., they test the predictions of the theory in regions where the effects of gravity is extremely weak, and spacetime can be assumed"almost" flat. In fact, before 2015, GR had never been tested in strong-field regimes of gravity and there was no reason to believe *a priori* that it indeed was the correct theory to describe highly curved spacetime.

Where in the Universe is one most likely to find such highly curved spacetime? The answer lies in one of the most interesting predictions of GR: black holes. Black holes are the predicted end-points of the life cycle of a star at least about 15 times as massive as our Sun. When such

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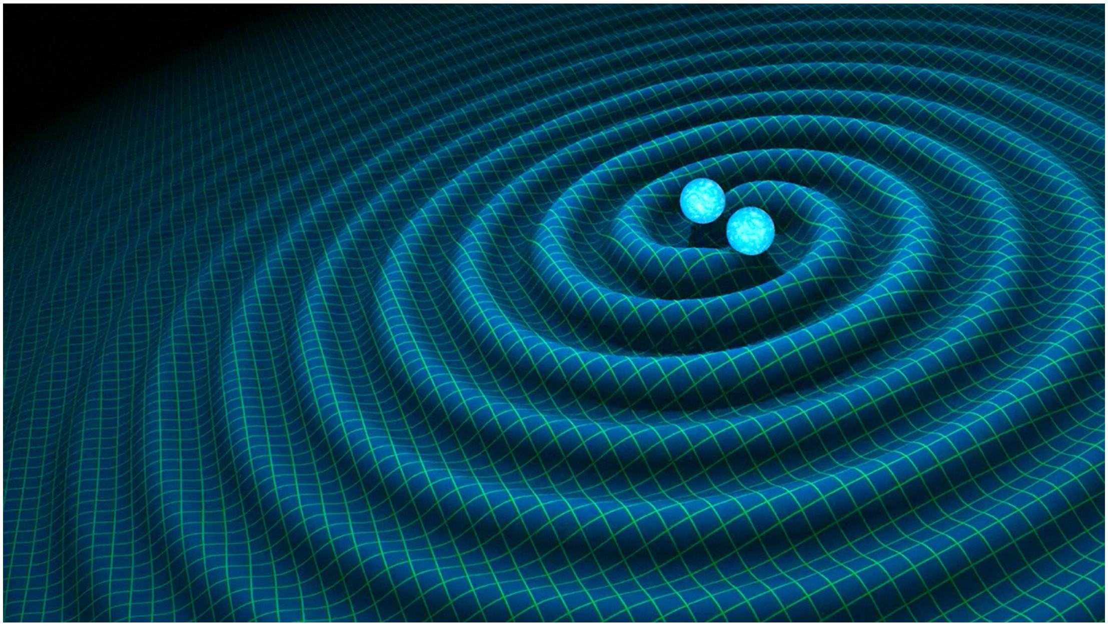

a star exhausts all the fuel for nuclear fusion in them, it collapses under the force of its own gravity to produce a region of spacetime so dense and gravitationally strong, that not even light (or electromagnetic radiation) can escape from it (thus the name "black hole"). Some of the most dynamical spacetimes in the Universe can be found around black holes, specifically, black holes in a binary system, making them ideal environments to test the strong-field effects of gravity.

Another remarkable prediction of GR is the existence of gravitational waves (GWs). According to GR, a change in the matter-energy distribution in spacetime causes a change in the geometry/curvature of spacetime. GWs are these propagating changes, or ripples in the geometry of spacetime that carry energy and angular momentum away from the source. The resulting distortions of spacetime, as the wave passes by, can be measured using advanced Michelson interferometric setups, like the ones present in the Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors in the United States. LIGO is a 4 km long Michelson interferometer that records relative changes in length between its two perpendicular arms produced by the passage of a GW. It is the most precise measuring device ever built, capable of detecting changes in length 1/1000th of the diameter of an atomic nucleus, roughly the displacements expected when the strongest GWs pass through Earth.

Among the various sources of GWs, mergers of black holes in a binary system (mentioned above), are the most promising for these detectors because, 1) such sources are extremely powerful, allowing us to observe them far out in the Universe, 2) they are expected to be quite frequent (about a few hundred per year when the detectors reach their maximum sensitivities) and 3) such sources are well described in GR. A binary black hole coalescence evolves over three phases: an

inspiral, where the two black holes move around each other and spiral in dueto the emission of GWs, the **merger** when the two black holes coalesce into a single object, and **ringdown** when the recently merged object radiates away its asymmetries through a spectrum of exponentially damped sinusoidal GWs and settles down to a single stable rotating remnant black hole. While there are analytical descriptions for the inspiral and ring down stages of a binary black hole merger, an accurate description of the highly non-linear merger regime requires us to numerically solve Einstein's equations on a supercomputer. This also allows us to predict the final mass and spin of the remnant object accurately starting from an initial binary black hole system. Using the above information that a binary black hole merger is completely described in GR, the astrophysical relativity at the International Centre for Theoretical Sciences in Bangalore (which includes the author), formulated and implemented a strong-field test of GR called the "inspiral-merger-ringdown (IMR) consistency test", and demonstrated it on actual GWs from binary black hole mergers observed by LIGO.

Given a GW signal observed by LIGO, it is possible to infer the properties of the source that produced it, for example, the masses and spins of the initial binary black hole system. The IMR consistency test is based on inferring the mass and spin of the remnant black hole from the initial part of the signal produced by the inspiral of the two black holes, and then comparing them to the same two quantities estimated independently from the final merger-ring down parts of the signal. If the underlying theory of gravity is different from GR, then a discrepancy from the predictions of GR is most likely to arise during the merger regime where gravity is the strongest and most non-linear. This would then show up as aninconsistency between the two independent estimates of the mass and spin of the final black hole. We demonstrated the robustness of the method by performing the test on a simulated population of binary black hole merger events across the Universe, and concluded that the test is most sensitive for some "golden events" where all three phases of evolution the inspiral, merger and ringdown, are observed with appreciable loudness; and that the strongest constraints on possible deviations from the predictions of GR can be obtained by combining information from multiple events. Finally we were able to show that the test is even able to distinguish cases where the energy and angular momentum emitted into GWs from a binary black hole merger is different from the predictions of GR, thus allowing for a theory-agnostic formalism to test deviations from GR from various theories of gravity.

Real Gravitational Wave Observations: On September 14, 2015, GWs produced by the inspiral and merger of two black holes (each around 30 times the mass of our Sun) passed through Earth and were observed by the twin detectors of the Advanced LIGO, opening the new window of GW astronomy onto the Universe, and allowing scientists to test GR in the strong-field regime for the first time. **The IMR consistency test was among the handful of tests used for this purpose, and through the absence of any deviations from the predictions of GR, helped establish the consistency of the first LIGO event, GW150914, with a binary black hole merger described in GR.** Since then, the test has been demonstrated on two subsequent detections: GW170104 and GW170814. We also showed that one can indeed obtain tighter bounds on possible deviations from GR by combining information from multiple events. As further proof of the robustness of the test on real data, it was demonstrated on software injections, i.e., simulated GW signals injected in real LIGO instrumental noise as well as hardware injections, i.e., when the passage of a GW is mimicked by displacing the actual hardware of the interferometers!

The future: The IMR consistency will continue to be demonstrated on GW observations of binary black holes mergers by current as well as future GW detectors. The current second-generation of detectors are expected to be followed by a thirdgeneration of ground-based interferometric detectors, like the EinsteinTelescope and CosmicExplorer (with almost 10 times more sensitivity), well as space-based detectors like the Laser Interferometer Space Antenna (LISA). With the detection of seven GW events by the current detectors so far, we have firmly begun an exciting era of GW astronomy. The upcoming years will be a period of active research which will help us address long-standing questions in theoretical physics, astrophysics and cosmology usinginformationfrom GWs. It will also perhaps lead us into the unknown, revealing new mysteries about our Universe. The future of the field, in general, and the IMR consistency test, in particular, is truly exciting. Stay 'gravitationally' tuned!