The puzzle of the spins of stellar-mass black holes

Despite being exotic objects, black holes are truly the simplest entities in the Universe, fully described by only three fundamental parameters: their mass, spin (the rate at which they rotate), and electric charge. However, in astrophysical environments, black holes neutralize quickly through interactions with their surroundings, leaving mass and spin as their sole defining properties. We observe two kinds of black holes in the Universe: very massive ones with masses of millions to billions of solar masses residing in the centers of galaxies (also in the center of the Milky Way), and those stellar-like, being the end stage of evolution of massive stars (with a mass of at least several tens of solar masses). This stage is reached after a massive star exhausts all of its nuclear fuel. At this moment, the force of gravity causes it to collapse into an object with an escape velocity higher than the speed of light. Such an object is thus invisible, and we call it a black hole. The innermost radius from which light can still escape is called the horizon radius. It is proportional to the black-hole mass, and it decreases with increasing spin. For a nonrotating black hole with a mass of 10 solar masses, the horizon radius equals 30 km. The rotation of a black hole cannot be arbitrarily fast. Its maximum spin (denoted as $a = 1$) is analogous to the maximum spin of a normal star, at which it would disintegrate. The horizon radius at the maximum spin is 15 km at 10 solar masses.

Black-hole masses can be measured using Newton's laws (reformulated for stars by Kepler), and such measurements have found them to be in the approximate range of 4 to 20 solar masses. However, measuring the spin is elusive. Since black holes are invisible, a good way to do it is by studying them when accompanied by a normal star. Then, matter from the normal star can flow onto the black hole (the process called accretion) and radiate in the process. Such systems are called X-ray binaries because most of the emitted photons are X-rays. For many years, the only way to do it was by estimating the strength of gravity near black holes. Gravity reduces the energy of X-rays observed at large distances with respect to that emitted. The spins measured in that way were mostly **close to maximal** ($a = 1$). These values have important consequences for the proper understanding of the evolution of massive stars, for example, the determination of the stellar spin just before a gravitational collapse. Also, the matter falling onto the black hole in a binary system has angular momentum, which spins up the black hole. To spin up a nonrotating black hole to $a = 1$, we need to increase its mass by a large factor of approximately 2.5. Spin measurements are then critically important for understanding the evolution of binary systems containing black holes, since the donor star needs to be sufficiently massive at the onset of mass transfer onto the black hole (which is not the case in standard models). Furthermore, the efficiency of energy extraction from an accreting black hole increases rapidly with increasing spin, which is crucial for understanding the formation of bipolar outflows (jets), commonly observed in X-ray binaries.

The discovery of gravitational waves from merging binary black holes by the LIGO/Virgo collaboration in 2015 (announced in 2016) gave us a completely new way to measure their masses and spins. (Binary black holes are systems in which both of the stars evolved to become black holes.) The measured masses covered those measured in X-ray binaries, but their range increased to above 100 solar masses. Two effects can explain the presence of high masses. LIGO/Virgo detects binaries from a much larger volume than that available to X-ray binaries and samples a much wider range of systems. Next, heavy elements are synthesized in the process of cosmic evolution, which means much less of them were present in early stars, allowing them to be more massive in turn.

The spins measured by LIGO/Virgo were found to be very small, with the typical spin value of $a \approx 0.1$. Since accretion increases the spin, this means that black holes are born with a small spin. In this case, the high spins measured in X-ray binaries require that they were spun up by accretion. This, however, is not compatible with standard stellar evolutionary scenarios, in which only a small mass is transferred. This discrepancy presents us with a fundamental challenge. In this project, we intend to resolve it. There is a consensus in the astrophysical community that the average spins measured by LIGO/Virgo are reliable, which we will also assume. In one part of our study, we will investigate scenarios with efficient accretion spin-up in XRBs. In the other, we will study improved methods of measuring XRB spin, investigating the possibility that XRB spins are, in reality, low on average, and most of the previous measurements suffered from some systematic errors.