LSC LIGO Scientific Collaboration VIRGO

SEARCHING FOR MERGERS OF INTERMEDIATE-MASS BLACK HOLES

WHAT IS AN INTERMEDIATE-MASS BLACK HOLE?

On September 14, 2015, LIGO made the first detection of gravitational waves, a signal known as GW150914. This signal was generated by two black holes, with masses 36 and 29 times the mass of the sun, which orbited each other and then merged into a single black hole with mass 62 times the mass of the sun.

Black holes with masses like these are categorized as stellar-mass black holes. Before the discovery of GW150914, astronomers had used x-ray measurements to determine the masses of about 20 stellar-mass black holes. All of these black holes have masses less than 20 times the mass of the sun, a figure surpassed by the black holes which generated GW150914. The detection of GW150914 was thus important not just for the historic detection of the gravitational waves themselves, but also because it provided evidence for the existence of relatively heavy stellar-mass black holes. A second gravitational-wave signal, detected in December 2015, and a likely third detected that October, were also generated by the merger of two stellar-mass black holes. In these cases, the merging holes were not as massive as those which generated GW150914, but they still provided important information about the stellar-mass black hole population.

A second type of black hole is also known to exist. Supermassive black holes, which have masses millions or billions times that of the sun, are found in the centers of nearly all large galaxies. Our own Milky Way contains a relatively light one, at 4 million times the mass of the sun. We believe that when galaxies merge, the black holes at their centers will come together and also merge, emitting gravitational waves. Unfortunately, these waves oscillate too slowly to be detected by LIGO. A future gravitational-wave detector in space, called LISA, will detect these systems.

A logical question to ask is: If there are stellar-mass black holes which can be as massive as 62 times the mass of the sun, and supermassive black holes with mass millions or billions times that of the sun, should we expect there to be black holes with masses in between? These theorized objects, known as intermediate-mass black holes, would have masses from about 100 to 10,000 times the mass of the sun. Several observations have hinted at the presence of these intermediate-mass holes, including so-called ultraluminous x-ray sources. They may be present in the center of globular clusters, tightly bound groups of old stars. Theoretical astrophysicists have devised several models by which intermediate-mass black holes could be formed. However, there has been no unambiguous detection of an intermediate-mass black hole, nor is there one preferred theory for how they might form—if they form at all!

FIGURES FROM THE PUBLICATION

For more information on these figures and their meaning, see the freely available preprint on the arXiv.

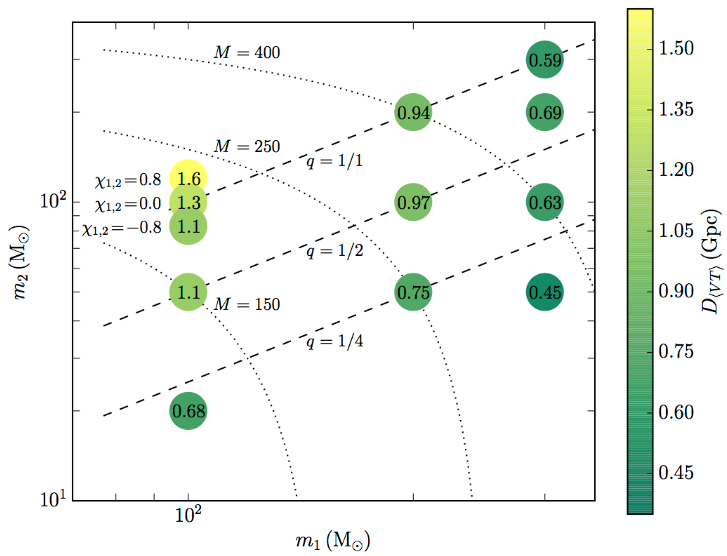

Figure 1: Distance to which Advanced LIGO was sensitive to intermediate-mass black hole mergers during the first observing run. The distance is given in Gpc (gigaparsecs), where 1 Gpc = 3.26 $\times$ 10^9 light years = 3.09 $\times$ 10^{22} km. It is computed for ten different mass combinations and, in the case of both black holes having 100 times the mass of the sun, three different combinations of black hole spin. The distance is given both as a number in each circle and as a color in order to see trends at a glance. The plot also shows lines of constant total mass $M = m_1+m_2$ (dotted) and mass ratio $q = m_2/m_1$ (dashed) for easy comparison. The systems with both black holes having 100 times the mass of the sun can be seen to the largest distance (1.6 Gpc, 1.3 Gpc, and 1.1 Gpc, depending on the spin).

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The [Advanced LIGO](#) detectors are extremely sensitive to the mergers of black holes with a total system mass ranging from one hundred to several hundred times the mass of the sun. If LIGO were to detect two merging intermediate-mass black holes (or an intermediate-mass hole merging with a somewhat smaller one), it would be the first unambiguous evidence for the existence of intermediate-mass holes and provide the first clue to the mystery of how these objects form. We have therefore performed a thorough search of LIGO data for gravitational-wave signals from intermediate-mass black hole systems.

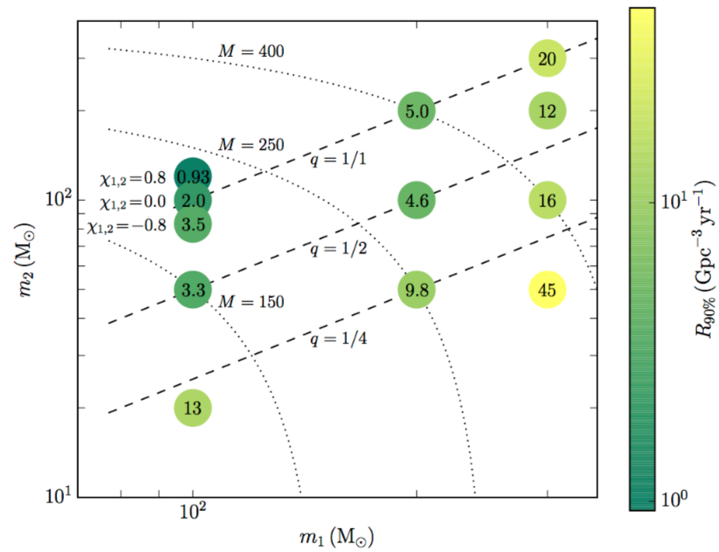

Figure 2: Rate upper limits (at 90% confidence) for twelve different intermediate-mass black hole systems. The rate is given in number of mergers per cubic gigaparsec per year. Otherwise, the format is similar to Fig. 1. The systems with both black holes having 100 times the mass of the sun have the tightest upper limits: Because we can see them the farthest (see Fig. 1), and yet none were detected, we have learned more about their rate than for the other systems.

HOW DOES THE SEARCH WORK?

This search is distinct from the one which initially detected GW150914 and the other two gravitational-wave events. It combines two different techniques. The first relies on very accurate theoretical models of the gravitational waveform produced by two merging black holes. Since we don't know in advance the properties of any black holes we might detect, we generate a series of these models covering the entire range of possible systems. For this search, we use models with a total mass ranging from 50 to 600 times the mass of the sun and a ratio of masses ranging from 1:1 to 1:10. We also consider different values for the black holes' rotation speed, known as their *spin*. We then compare the data to all these different models and check to see if any are a good match.

The second technique does not rely on theoretical models of the waveform. Instead, it looks for times when both LIGO detectors exhibit excess power over what is observed in the usual case of background noise. This technique is often referred to as a "burst search" because it is ideally suited to detecting very short-lived but strong gravitational-wave events, like the merger of two intermediate-mass black holes. In fact, burst searches have historically been the primary technique used to search for intermediate-mass black holes. In our new search, however, we combine both techniques, modeled and unmodeled, in order to take advantage of their individual strengths.

WHAT ARE THE RESULTS?

Unfortunately, this search did not detect any gravitational waves from intermediate-mass black hole mergers. However, we can still make interesting statements about our sensitivity to these events and how often they occur in the universe. We do so by performing extensive simulations. We generate artificial waveforms (based on the theoretical models) for mergers at different distances from the earth and insert them into the real data from our detectors. We then run our search procedure again and see how many of these signals we can recover. We performed simulations for ten different choices of the black hole masses. In one of these cases, we also studied three different values of black hole spin. Figure 1 shows the distance to which the LIGO detectors were sensitive to each of these types of sources. Figure 2 then shows the rate upper limit. This is the answer to the question: What is the maximum number of *mergers per volume per year* that is consistent with the fact that we didn't detect any in these particular data? The systems that we can see farthest away are the ones in which both black holes have mass 100 times the mass of the sun. This means that we can place the strongest (i.e., smallest) rate upper limit on these systems. The fact that they were *not* detected, despite being the ones LIGO is most sensitive to, tells us a great deal of information about their true rate.

WHAT'S NEXT?

This search used data from the first observing run of Advanced LIGO, which ran from September 2015 to January 2016. Thanks to the improvement in detector performance, the upper limits shown in Fig. 1 are about 100 times better than those obtained using older data from the initial LIGO runs (2010 and earlier). Future increases in detector performance will tighten these upper limits further, as well as increase the chances of actually detecting an intermediate-mass black hole merger. LIGO data analysts are also hard at work improving the search techniques and waveform models in order to be more sensitive to these systems. With any luck, it will not be long before the first detection of an intermediate-mass black hole!

READ MORE

The publication (preprint on arXiv.org)