LSC LIGO Scientific Collaboration
VIRGO

A SEARCH FOR SUB-SOLAR MASS BLACK HOLES

During their lifetime, stars shine by generating energy through **nuclear fusion**. This release of energy creates an outwards pressure that counterbalances the inward force due to gravity. The two forces cancel each other out, and the star stays in this equilibrium for millions or billions of years, depending on its initial mass. Heavier stars shine brighter and use up their fuel quickly, living for a shorter period.

Once the star has burned all of its fuel, nuclear fusion process is no longer able to counterbalance the gravitational force. This leads to stellar collapse and a new battle emerges: one between gravity and another type of force due to the **electron degeneracy pressure**. If the star is massive enough, gravity eventually wins, and a **neutron star** or a **black hole** is formed. Some of these very compact bodies happen to exist in pairs as binary star systems orbiting around each other, bound by gravity. As time passes, the system continuously loses energy which brings the two star remnants closer and closer to each other until they merge to form a single black hole or neutron star. When this happens, a very large amount of energy is liberated through gravitational waves, which can be observed by the LIGO detectors.

The star needs to be heavy enough to form neutron stars, and even more for black holes. Current theories explaining star formation predict that the stars can end up as a black hole only if their mass is larger than a certain threshold. In particular, we do not expect to observe neutron stars or black holes with less than the Sun's mass. A LIGO detection of a compact object with mass below one solar mass would be extremely interesting, as it would indicate that there are other yet to be discovered ways to form black holes. This would have profound implications for our understanding of the history and evolution of our universe.

FIGURES FROM THE PUBLICATION

For more information on these figures, see the preprint at https://arxiv.org/pdf/1808.04771.pdf

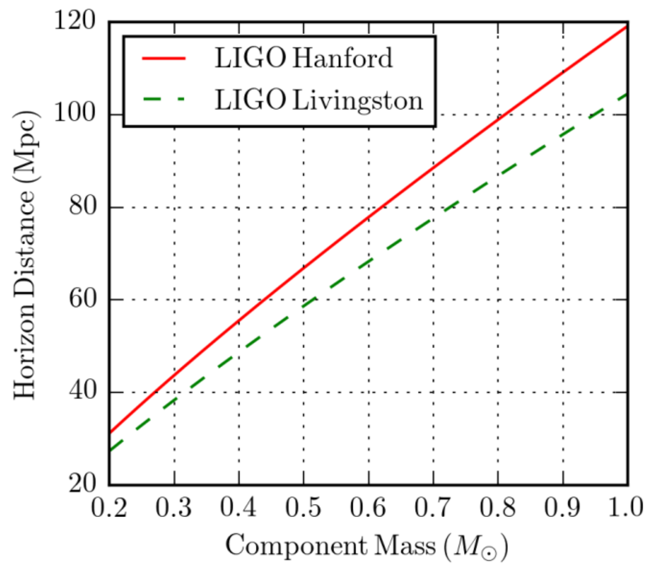

Figure 1: *The maximum distance to which LIGO could observe an optimally located and oriented binary.*

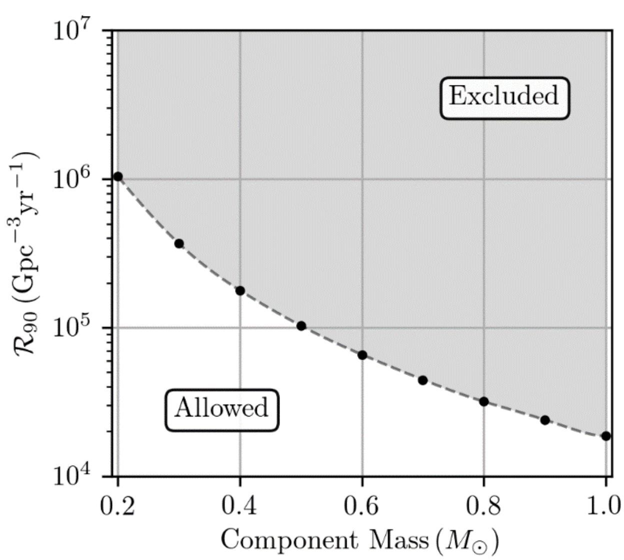

Figure 2*: The upper limits on the merger rates of equal mass binaries of sub-solar mass.*

Some theories suggest that black holes were created when the universe was young. At that time, the universe was extremely hot and dense, since the energy of today's universe was confined to a much smaller space. We also know that there were small fluctuations in density; some places in the universe were slightly more dense than others, and some were slightly less dense.

While these differences in density were tiny, some of these fluctuations could have been large enough to undergo gravitational collapse and form black holes. We call these black holes primordial, as they were formed when the universe was very young. According to this model, the mass of the black hole is determined by the size of the density fluctuation. As fluctuations could come in any size, black holes as light as an asteroid or as heavy as a galaxy could have formed! If LIGO saw a compact object with mass below one solar mass, this could provide evidence for the existence of primordial black holes.

Primordial black holes are especially interesting because they have been considered as a potential form of **dark matter**. Dark matter is a form of matter that makes up most of the mass in our universe, but does not emit any light which makes it very difficult to study. Its origin and composition still elude us today. Primordial black holes could be a possible explanation as they interact gravitationally but do not emit any light. Several collaborations have looked for primordial black holes in the past to find clues of their existence - either by studying the motion of stars in distant star clusters or by looking for the expected bending of light passing close to a hypothetical primordial black hole. So far no compact objects have been observed, allowing scientists to constrain the number of such hypothetical objects in the universe. However, LIGO has access to a new way of observing these objects and provides a new, independent way to learn about them.

Although detecting such ‘ light ’ objects is a challenge on many levels, LIGO's sensitivity to faint signals makes it possible. Using LIGO data from 2015 and 2016, we searched for black holes as light as one fifth the mass of our sun. We didn't find any candidate signals for primordial black holes, but we were able to place new limits on how much of the dark matter they can make up.

LIGO is still getting more sensitive, so in future sub-solar mass searches we will be able to probe an even bigger part of the universe. This will let us search for lighter black holes, and for even weaker signals. Once we reach the maximum sensitivity of the detectors, we will either see a primordial black hole, or put extremely tight constraints on the possible mass and amount of such black holes in our universe!

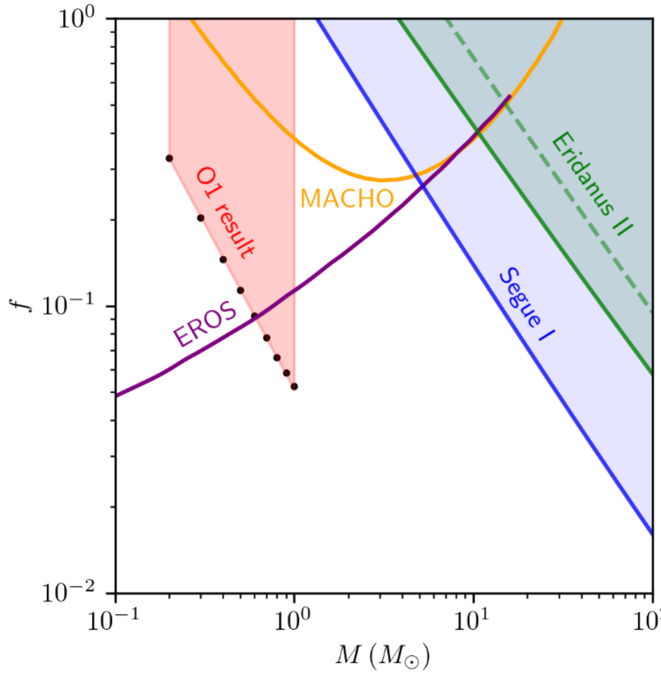

Figure 3: *Constraints on the abundance of primordial black holes as a component of the dark matter. The x-axis shows the mass of the black hole while the y-axis shows the upper limit on the fraction of the dark matter that those black holes can account for.*

GLOSSARY

Nuclear fusion: **Nuclear fusion** occurs when two nuclei 'fuse' together into a single nucleon. This represents a transition to a lower energy state, and an enormous quantity of energy is released.

Black hole: A region of space-time caused by an extremely compact mass where the gravity is so intense it prevents anything, including light, from leaving.

Neutron star: An extremely dense remnant from the collapse of more massive stars.

Electron degeneracy pressure: **Electron degeneracy pressure** arises from the Pauli exclusion principle, which states that no two electrons can share identical quantum states. This means that even under extreme gravitational forces, such as at the heart of stars, there is a limit to how compressed electrons can become.

Primordial black holes: A theoretical type of black hole formed in the early universe. Fluctuations in the energy density of the universe could have led to regions of space that were so dense that they spontaneously collapsed to form a black hole. Since they are not formed via the collapse of massive stars, primordial black holes could conceivably exist below one solar mass.

Dark matter: This mysterious form of matter makes up about 85% of the mass in the universe. It is 'dark' because it doesn't emit light or interact electromagnetically. Many theories of **dark matter** predict that it is some type of fundamental particle, but it is also interesting to consider the possibility that the darkest objects we know of (black holes!) could be a component of dark matter.

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