LSC LIGO Scientific Collaboration VIRGO

A SEARCH FOR SUBSOLAR-MASS BLACK HOLES

Gravitational Waves from Small Black Holes

LIGO and Virgo have now detected many pairs of large **black holes** (BHs) from the gravitational waves generated as they spiral together and merge, but can we also see very small black holes this way?

Using LIGO and Virgo data from 1 April to 1 October 2019 we searched for BHs as light as one fifth of the Sun's mass, employing 3 different **matched-filter** based pipelines. This search covers a larger mass and **spin** range for the BHs than the previous analysis. We did not find any valid candidate signal for compact objects under one solar mass.

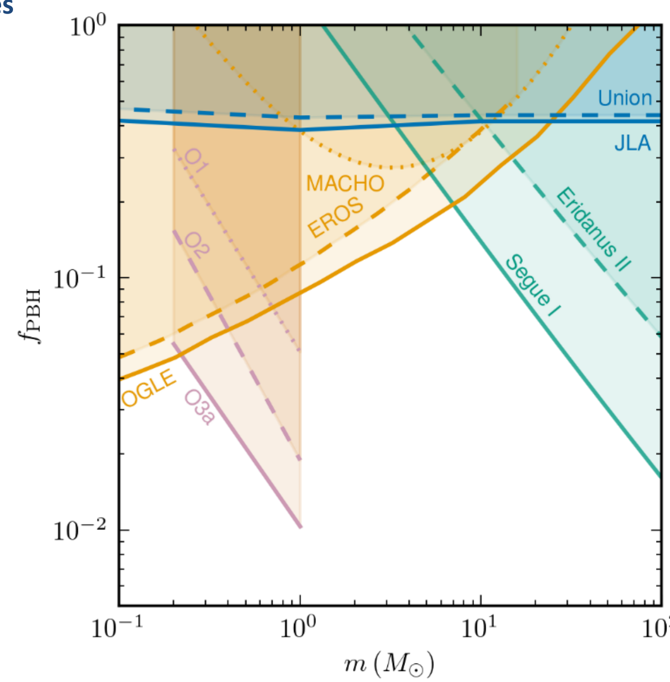

Figure 1: *Constraints on the fraction of dark matter in primordial black holes. The horizontal axis shows the mass of the black hole, the vertical axis shows the upper limit on the fraction of the dark matter that those black holes can account for. See the main text for the meaning of the coloured regions.*

The non-detection of these signals allows us to set new upper limits on the **merger rate density** of subsolar-mass BHs. These limits can be recast into limits on the physical parameters of any astrophysical model that could generate subsolar-mass binaries. In **Figure 1** we show the constraints on the abundance of **primordial black holes** as a **dark matter** component. We consider a population of equal-mass BHs; the horizontal axis shows the mass of the BH in each model and the vertical axis shows the constraints on the fraction of dark matter in primordial BHs (fPBH). The different coloured lines in the figure represent constraints set by different experiments: the orange lines are constraints from **microlensing experiments**; the green lines are from observations on the dynamics of the dwarf galaxies Segue I and Eridanus II; the blue lines are from **supernova lensing**; finally the violet lines are the LIGO-Virgo-KAGRA (LVK) results from the first and second observing runs (O1 and O2), and the new constraints we set with this analysis from the first part of the third observing run (O3a). Our new results significantly improve microlensing and supernova lensing constraints in the same mass region, as well as our previous constraints from O1 and O2; we have obtained an upper limit on the abundance of these BHs as a function of their mass at formation, with $f_{PBH} \lesssim 5\%$. In **Figure 2** we show the same constraints for BHs formed from the collapse of particle **dark matter halos** (DBH). The lowest upper limit is found at one solar mass, where $f_{PBH} \lesssim 0.002\%$.

If LIGO-Virgo detectors observe gravitational waves from a binary system of two compact objects where at least one of the two component masses is subsolar, this result will challenge our understanding of **stellar evolution** or possibly hint at new physics.

Life and turbulent death of stars

Stars spend most of their life in an equilibrium state, where the outward pressure generated by **nuclear fusion** reactions sustains the matter against the inward gravitational force. Depending on the mass of the star, the nuclear reactions can last millions or even billions of years. Heavier stars shine brighter and consume their fuel faster, living a shorter life.

The nuclear fuel for young stars like our Sun is mainly hydrogen. When a star has converted all the hydrogen in its core into helium, nuclear reactions can no longer sustain the matter against the gravitational force, and the star starts to collapse. The contracting star reaches higher temperature in its innermost regions and, if the mass is sufficiently large, the star can start new nuclear fusions involving helium, or even heavier elements. The star passes through different equilibrium phases, until eventually the conditions for igniting further nuclear reactions are no longer satisfied. At this point the star will start to collapse, and **stellar evolution models** predict different final fates for the star, depending again on its initial mass. For light stars with roughly less than 10 solar masses, the electron **degeneracy pressure** is high enough to halt the gravitational collapse and they become white dwarfs. In contrast, heavier stars become **neutron stars** and very massive stars, with initial mass larger than roughly 25 solar masses, turn into BHs.

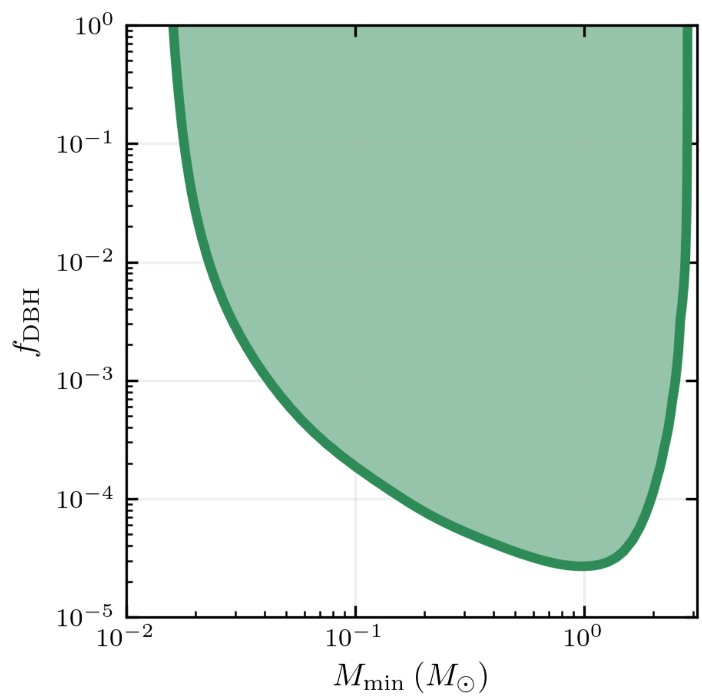

Figure 2: *Constraints on the fraction of dark matter in black holes formed from the gravitational collapse of dark matter halos. The horizontal axis shows the minimum possible mass of black holes formed from this mechanism.*

Stellar evolution models predict that neither BHs nor neutron stars can be **subsolar-mass compact objects**. As a matter of fact, the lightest neutron star observed so far has a mass slightly higher than one solar mass, while BHs arising from stellar evolution are heavier objects.

What might subsolar-mass compact objects be?

Several models relate subsolar-mass compact objects to **dark matter**. Dark matter is a hypothetical form of matter that does not emit any light, making it difficult to detect. It is dark in a similar way as BHs, and it can be perceived only through gravitational effects.

We do not know what the building blocks of dark matter are, but the latter is thought to account for the majority of the matter in the Universe. Among the proposed candidates for dark matter, an appealing possibility is that it could comprise new types of

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fundamental particles that primarily interact through gravity. In this context, theorists predict that dense regions of particle dark matter can collapse to BHs of masses that cannot be explained with the known astrophysical processes. Alternatively, ultralight particles can clump together and form very low-mass compact objects known as boson stars. Furthermore, dark matter particles can gravitationally interact with neutron stars and trigger their collapse to BHs, and eventually form a subsolar-mass compact object. All these possibilities are currently under investigation.

Another possibility is that dark matter is composed not only of particles, but of BHs formed in the early stages of the Universe, through the gravitational collapse of overdense regions. These are known as primordial BHs, which can have masses below one solar mass.

Analysis of the second portion of O3 (called O3b) is currently in progress and might eventually unveil a subsolar-mass merger event, or further improve the constraints on the abundance of these objects in the Universe. Furthermore, Advanced LIGO, Advanced Virgo and KAGRA are going to enter a new observing run in 2022, with more sensitivity than ever!

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GLOSSARY

Black hole: A region of spacetime where the gravity is so intense it prevents anything, including light, from leaving.

Matched filtering: Data analysis method consisting of correlating the data against a simulated waveform in order to try to identify that signal hidden in the detector noise.

Spin: Quantity that measures how fast an object rotates around itself.

Merger rate density: The number of compact-object binaries that are expected to merge per unit volume of space, per year.

Primordial BH: A theoretical type of BH 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 BHs. Since they are not formed via the collapse of massive stars, primordial BHs 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 does not 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 (BHs!) could be a component of dark matter.

Microlensing experiments: Gravitational lensing is an optical effect that occurs when a distribution of matter (such as a cluster of galaxies) sits between a distant source of light and the observer on Earth; the gravitational effect of this matter bends the light's path, like a lens. If the lens is smaller than a galaxy (for example a star), the effect is known as 'microlensing' and is seen as a change in brightness of the source.

Supernova lensing: Gravitational lensing caused by compact objects along the line of sight between Earth and a Type I supernova can magnify the brightness of the supernova. This effect depends on primordial BH models and can be used to set constraints on their population.

Dark matter halo: A dark matter halo is the inferred halo of dark matter that permeates and surrounds individual galaxies.

Stellar evolution models: These are mathematical models which are used to study how the physical parameters of a star evolve with time, from the moment when it is born until it becomes a stellar remnant.

Nuclear fusion: Nuclear fusion occurs when two nuclei merge together into a single nucleus. For elements lighter than iron, this results in a release of energy. This energy powers stars.

Degeneracy pressure: Degeneracy pressure is a quantum effect that arises when identical particles (such as electrons or neutrons) cannot share the same quantum state. This results in a quantum pressure that can be sufficient to prevent the gravitational collapse of a star, even after all its fuel has been exhausted.

Neutron star: An extremely dense remnant from the collapse of a massive star, supported by neutron degeneracy pressure.

Subsolar-mass object: An astrophysical object is considered to be a subsolar-mass object if its mass is lower than that of the Sun, which is denoted by the symbol $M_{\odot}$.