THE QUEST FOR BLACK HOLES LIGHTER THAN OUR SUN

WHY DISCOVERING "LIGHT" BLACK HOLES WOULD REVOLUTIONIZE PHYSICS

Advanced LIGO and Advanced Virgo have found a plethora of signals that are likely produced by the gravitational waves emitted during the coalescence of binaries of compact objects (black holes and neutron stars). Most of the black holes routinely observed in this way are usually between ten and one hundred times the mass of our Sun. However, the LIGO–Virgo–KAGRA Collaboration also looks for less massive compact objects. In this publication, we present such an endeavor, using data collected by the interferometers from 1 November 2019 to 27 March 2020 spanning the second half of the third observing run (O3b).

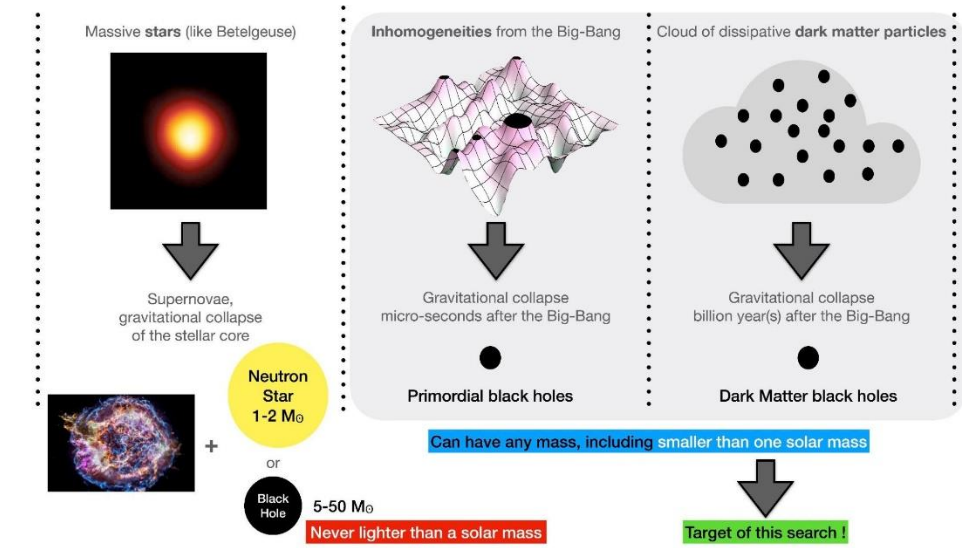

Figure 1: Sketch of the different pathways to form the compact objects that can be observed by LIGO-Virgo-KAGRA. Besides neutron stars and black holes formed by stellar evolution, there are hypothetical primordial or dark matter black holes that could exist in the Universe and be less massive than our Sun.

Detecting even a single black hole less massive than the Sun would have groundbreaking implications for our understanding of the Universe. The reason is the following: no known astrophysical process could make the core of a star collapse into a black hole with a mass below one solar mass (the mass of our Sun). Furthermore, there is also no firm observation of neutron stars lighter than the Sun (neutron stars could possibly be confused with black holes in gravitational-wave signals). Such black holes, which we call subsolar mass black holes, would therefore be the result of a novel phenomenon in the Universe.

HOW TO DETECT LIGHT BLACK HOLES WITH GRAVITATIONAL-WAVE OBSERVATORIES

As in the standard gravitational-wave searches on which the GWTC-3 is based, several matched-filter analysis pipelines are employed to identify subsolar mass candidates. Specifically, the three pipelines participating in this search make use of templates that represent our best description of the inspiral part of a binary black hole coalescence. These are compared to the signal in the detectors, enabling us to find gravitational waves buried in the noise. Using three pipelines allowed us to cross-check and validate the obtained results. The main difference with the GWTC-3 search lies in the parameter space probed. In this subsolar search, the mass of the smallest black hole in the binary goes from 0.2 to 1 solar mass, while the mass of the largest black hole can range from 0.2 to 10 solar masses. Typically their signal is longer and fainter than the one of other observed, more massive, black hole coalescences. For instance, a binary black hole signal with both masses equal to that of our Sun lasts 280 seconds in the detectors' sensitive band. Comparing this to the 0.2 second signal of the first observed black hole coalescence, GW150914, gives an idea of the much larger computing resources needed for their search!

DID WE DISCOVER SOMETHING?

To quantify the significance of a match between a template and the data, the aforementioned pipelines estimate how many times per year, on average, the detector noise is expected to mimic something as signal-like as what is observed. This is called the false alarm rate (FAR). We find that no candidate is significant enough to be considered a discovery, the best one has a FAR of 1 per 5 years. For comparison, GW150914, which was used to claim the first direct detection of gravitational waves, had a FAR of less than 1 per 200000 years.

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INJECTIONS & CONSTRAINTS

In Science, much information can be extracted even if we do not make a detection. Considering the astrophysical range of the detectors and the duration of observations, the absence of any firm detection can be used to put upper limits on the merger rate density of subsolar mass objects. Since the search sensitivity is primarily a function of chirp mass, we show in Figure 2, as a function of this parameter, the values of the merger rate density excluded by the absence of detections. The constraints were derived using the whole O3 run, getting a result twice as strict when compared to previous searches. As we can see, the limit on the maximum merger rate allowed is consistent amongst search pipelines. For example, if we look at the binaries with a chirp mass of about 1.5 solar masses, we determine that there have to be less than 300 mergers per cubic gigaparsec per year. This is still about 10 times larger than the merger rate as measured from the binary black holes of GWTC-3, which are heavier than a solar mass.

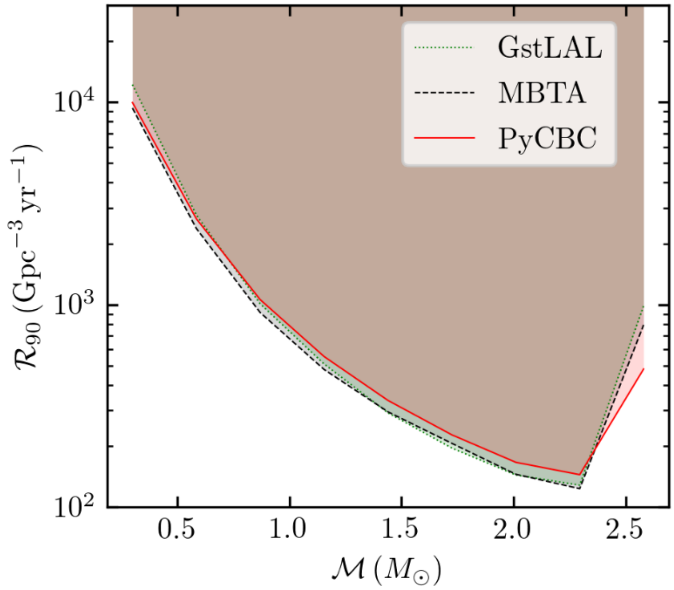

Figure 2: Merger rate upper limits (in units of the number of mergers per year per cubic gigaparsec) as a function of binary chirp mass for the three different search pipelines used in the analysis (GstLAL, MBTA and PyCBC). The lines represent the merger rate upper limits and the coloured zones mark the values of the merger rates that are excluded because our search did not make any detections.

These merger rate limits translate into constraints on any model's parameters that predict subsolar mass objects' mergers. Two scenarios have been considered: primordial black holes and black holes made of dark matter particles.

In the case of primordial black holes, we consider the simplest model in which all black holes have the same mass and are randomly distributed in space, with the binary formation happening in the very early universe, just after their formation. We include physical effects that were not considered in previous searches, like the breaking of binaries by other primordial black holes. In the range of masses to which our analysis is sensitive, between 0.2 and 1 solar masses, we are able to exclude for the first time that primordial black holes described by this model constitute all the dark matter in the Universe. However, we cannot significantly constrain models of dark matter made of primordial black holes with a wide distribution of masses.

We also obtained improved limits on the dark matter black holes. We find that no more than about a thousandth of a percent of all the dark matter could have collapsed into these objects.

PROSPECTS FOR O4

The LIGO and Virgo detectors are now offline for improvements before the upcoming fourth observing run, currently set to get underway in 2023. The KAGRA detector in Japan will also join the O4 run. The network's sensitivity will increase significantly, boosting the chances of detecting such an unprecedented event or further improving the constraints on their abundance.

GLOSSARY

Gravitational waves: Gravitational waves are disturbances or ripples in the curvature of spacetime, generated by accelerated masses, that propagate as waves outward from their source at the speed of light. (See gravitational waves on Wikipedia.)

Binary black hole: A system consisting of two black holes in close orbit around each other. (See binary black hole on Wikipedia.)

Neutron stars: A relic of a massive star. When a massive star has exhausted its nuclear fuel, it dies in a catastrophic way — a supernova — that may result in the formation of a neutron star: an object so massive and dense (though not as much as a black hole) that atoms cannot sustain their structure as we normally perceive them on Earth. These stars are about as massive as our sun, but with a radius of about ten kilometers.

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 black holes. Since they are not formed via the collapse of massive stars, primordial black holes could conceivably exist below one solar mass.

Dark matter: A hypothetical form of matter which accounts for approximately 85% of the matter in the universe. Dark matter is called "dark" because it does not appear to absorb, reflect, or emit light, and is, therefore, difficult to detect. The composition of dark matter is unknown, it could be made of fundamental particles, or black holes, among other candidates.

Standard Model: Theory describing three of the four known fundamental forces (electromagnetic, weak, and strong interactions) excluding gravity in the universe and classifying all known elementary particles. (See Standard Model on Wikipedia)

GWTC-3: The third Gravitational-wave Transient Catalog (GWTC-3) describes signals, most likely generated by gravitational waves, which were detected with Advanced LIGO and Advanced Virgo up to the end of their third observing run.

Matched filter: 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.

Template: In this context, a time or frequency domain representation of a gravitational-wave signal. Usually, they are generated with the help of computers based on a particular theoretical model and set of parameters.

Inspiral: The slow shrinking of the orbit of a binary due to the effect of gravitational wave emission. It's the first and longest phase in the coalescence of a binary.

Sensitive band: The range of frequencies in which a gravitational wave detector is sensitive to gravitational wave signals. For the LIGO-Virgo interferometers, this usually spans from ~20 Hz to ~1 kHz.

GW150914: The first confident direct observation of gravitational waves, which was made on 14 September 2015 by the LIGO Scientific and Virgo Collaborations.

Signal-to-noise ratio (SNR): A measure used in data analysis that compares the strength of the desired signal to the strength of background noise.

Detector noise: Fluctuation in the gravitational-wave measurement signal due to various instrumental and environmental effects. The sensitivity of a gravitational-wave detector is limited by different sources of noise.

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

Chirp mass: A mathematical combination of masses for each compact object in a binary (see Wikipedia for the formula). The chirp mass determines the leading-order orbital evolution of the system as a result of energy loss from emitting gravitational waves.

Gigaparsec: Unit of distance equal to 3262 million light years, or $3{,}0857\times10^{25}$ meters.

Network sensitivity: A description of a network of detectors' ability to detect a signal. A network composed of detectors with lower noise is able to detect weaker signals and therefore is said to have higher sensitivity.

Inhomogeneities from the Big Bang: Fluctuations in the density of the primordial plasma caused by the quantum fields dominating the Early Universe.