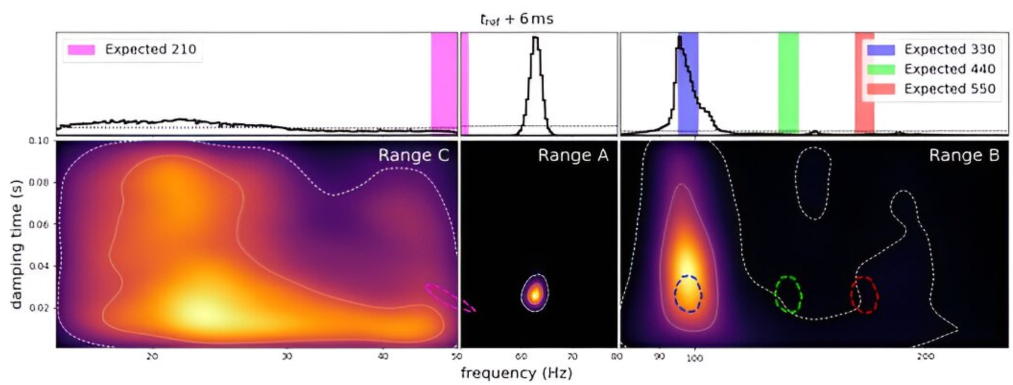
Using gravitational wave observations of a binary black hole merger to verify the no-hair theorem

November 30 2023



These plots show probability distributions for the frequency and damping times of ringdow modes for the remmant black hole formed in GW190521. The middle panel ("range A") is the dominant mode, while the right panel ("Range B") shows the newly discovered mode, in excellent agreement with the predictions of general relativity (shown as a dotted contour). The left panel ("Range C") is a low frequency range dominated by noise with no astrophysical signals. Credit: Radboud University

An international team of researchers including Prof. Badri Krishnan at Radboud University has verified an important property of black holes known as the no-hair theorem using gravitational wave observations. Their research is published in the journal *Physical Review Letters*.

It is a remarkable fact of nature that black holes are extremely simple objects. In fact, every black hole in our universe is completely described by just two numbers: its mass and angular momentum (or "spin"). This is not true for normal stars or planets which are made up of much more complex matter distributions.

Just like any other star, black holes have "quasi-normal modes." This will be familiar to most readers as the property of a bell: When struck by a hammer, the bell emits a spectrum of tones which slowly fade out over time. These tones are determined by many factors such as the shape of the bell, the particular material the bell is made up of, etc.

No-hair theorem

In a similar manner, a perturbed black hole emits a characteristic spectrum of gravitational wave signals which have specific frequencies and fade out over time. In light of the no-hair theorem, the quasi-normal mode spectrum for a black hole must be highly constrained since the entire spectrum must also be determined by just two numbers.

Thus, when we receive the gravitational wave signal from a star including at least two quasi-normal modes, we can use this property to determine whether it is in fact a black hole or not.

Surprise in the data

To verify this property of black holes, the team re-analyzed data from the gravitational wave signal from a binary black hole merger event known as GW190521. This event was detected by the LIGO and Virgo observatories in May 2019.

Using more sensitive techniques, they discovered a surprise hidden in the data: A second much weaker quasi-normal mode missed by earlier analyses. This was a major surprise since it was thought that such detections would require much more sensitive detectors which would be available only in the mid 2030s.

General relativity

"More than 20 years ago, we had proposed such observations as a means of testing the nature of black holes," says Badri Krishnan. "At the time we did not believe that the current LIGO and Virgo detectors would be able to observe multiple ringdown modes. Therefore these results are particularly gratifying for me.

"So far, we have found no deviations from the predictions of general relativity and Einstein continues to be right. Our analysis shows that the frequencies and damping times of the quasi-normal modes are consistent with the predictions of general relativity."

More information: Collin D. Capano et al, Multimode Quasinormal Spectrum from a Perturbed Black Hole, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.131.221402

Provided by Radboud University