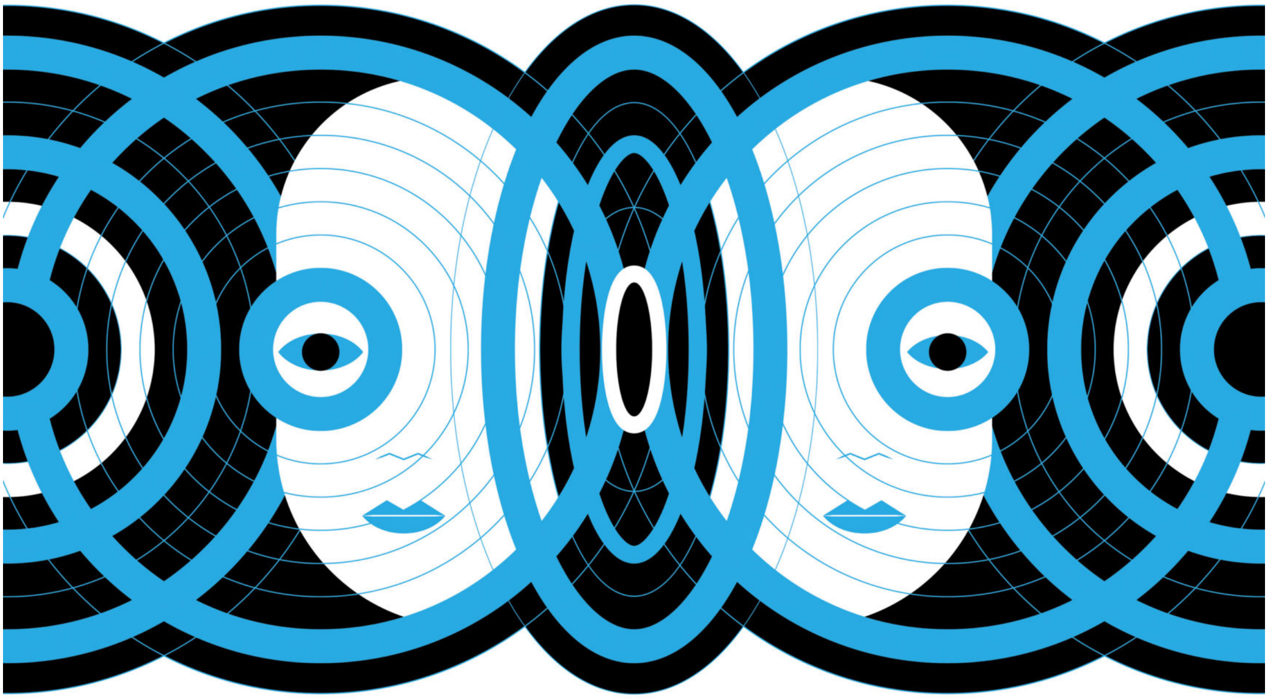
Black Hole Echoes Would Reveal Break With Einstein's Theory

Gravitational waves have opened up new ways to test the properties of black holes — and Einstein's theory of gravity along with them.

By Sabine Hossenfelder



James O'Brien for Quanta Magazine

We all dream the same dream, here in theoretical physics. We dream of the day when one of our equations will be plotted against data and fit spot on. It's rare for this dream to come true. Even if it does, some don't live to see it.

Take, for example, Albert Einstein, who passed away in 1955, 60 years before his equations' most stunning consequence was confirmed: Space-time has periodic ripples — gravitational waves — that can carry energy across billions of light-years.

Since that September 2015 black hole collision, the Laser Interferometer Gravitational-Wave Observatory (LIGO) team has reported five more events (a sixth fell just short of the standard of significance). But the LIGO data is still virgin territory. It is an entirely new way of decoding the universe, and physicists must develop methods of data analysis along with the measurements.

It's not a simple task. Measuring gravitational waves is not the kind of discovery you make by accident. But now that they have the data, physicists have been able to extract insights about the astrophysics of black holes and neutron stars, including their location, composition and masses. They've measured the expansion of the universe and made new precision tests of Einstein's general theory of relativity. The theory has passed all tests — so far.

But the same measurements that have so spectacularly confirmed Einstein's theory could also, perhaps, reveal where it goes wrong.

Physicists know that general relativity breaks down close to a black hole's center. Yet the center of a black hole is, famously, a place where we can never look. It's protected by the black hole's horizon — the surface surrounding the black hole from which light can never escape. In general relativity, the black hole horizon has no substance; it poses no obstacle. The black hole simply swallows whatever dares to pass the horizon.

Most physicists believe that general relativity correctly describes the horizons of black holes. Yet some have argued that contradictions between general relativity and quantum theory mean that something else could be going on. In particular, the claim that black holes are surrounded by a "firewall," though controversial, has spurred work on alternative descriptions of the horizon.

If the horizon of a black hole is obstructed by something like a firewall, then the horizon could potentially reflect gravitational waves. If that was so, then LIGO should see evidence for these modifications. In particular, a collision between two black holes should produce an echo.

That's the basic idea put forward by two independent groups of physicists, one led by Vítor Cardoso and the other by Niayesh Afshordi. Using simple models for a horizon with substance, the researchers showed that some of the gravitational waves emitted by a black hole collision should reflect back toward the black hole's center. The waves would then reflect outwards again, where some would then once again be reflected at the horizon. The black hole would act like a resonant cavity with a semitransparent mirror at one end. It would emit periodic signals with decreasing amplitude. It would echo.

So much for the theory. What about the data? In late 2016, Afshordi and collaborators applied a custom-designed analysis to the publicly available LIGO data and looked for evidence of echoes. Amazingly enough, they found echoes just where they sought them. The signal was not highly significant — the researchers estimated a 1 in 100 chance that the signal was just noise — but a signal nevertheless.

Theirs was a big claim, a daring claim. If correct, it would be evidence for the failure of Einstein's theory.

A few weeks after Afshordi's group published their paper, members of the LIGO collaboration put out a reply, raising concerns about Afshordi's analysis. The LIGO team then set out to do their own study. But large collaborations work slowly, and so it took more than a year until they were able to finish the analysis and get the collaboration's approval to publish the work.

The LIGO analysis is now available. The researchers found the echo, but at a lower statistical significance than before. They concluded that there's a 1 in 50 chance that the echo is merely noise.

Moreover, the study found the strongest evidence for an echo in one particular event — the event that itself has the lowest significance. When they remove this event from the sample, the probability that the echo isn't real goes up to almost 20 percent.

For this data analysis to be doable at all, the physicists must make assumptions about the signal that they search for. Inspired by Afshordi's model, researchers assumed that the echoes should come at regular intervals, that they decay exponentially, and that they remain unmodified (aside from the decrease of amplitude). In many regards, they're searching for the simplest possible echo.

The theorists could now review the data analysis and develop hypotheses that fit the data better. But reanalyzing the same data over and over again carries a big risk: Instead of developing a better theory, they could merely find a way to better amplify noise.

The more types of echoes they look for, the more likely they are to find something. But these repeated attempts will render measures of statistical significance unreliable.

The only way to overcome this impasse is fresh data. It will take many more iterations of this exchange between theory and experiment before the case can be settled.

So far, both the experimentalists and the theorists have found the exchange fruitful. "We are going ahead full force with modeling the echoes theoretically, and finding better ways to search for them," said Afshordi, the author of the original study. He also pointed out that another group has found evidence for echoes in the LIGO data, claiming a less than 1 percent risk of a false positive.

Meanwhile Ofek Birnholtz, a researcher with the LIGO collaboration, said that "there have certainly been tensions," but the idea that black holes echo is "without a doubt worth looking further into." A search for black hole echoes has become one of the official goals of the LIGO Scientific Collaboration.

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