August 28, 2020

Earth & Space

Black holes ring like Einstein predicted

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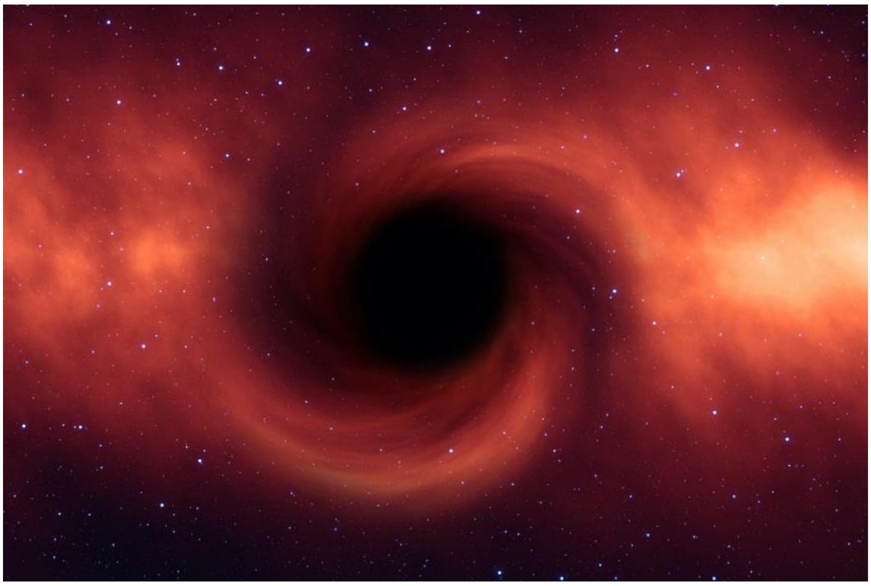
This Break was edited by Beata Kusmider, *Scientific Editor* - TheScienceBreaker

ABSTRACT

Black holes lie at the center of some of the deepest questions in fundamental physics. Yet, according to Einstein's theory of gravity, black holes should also be remarkably simple. Using gravitational waves to check that this is the case could yield invaluable clues about the true nature of gravity, space and time.



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In their inscrutable depths, black holes hold the keys to some of the deepest mysteries of our Universe. Woven out of nothing more than pure space and time, black holes are regions so dense that nothing may escape their gravitational pull. At their center lies a *singularity*: a point at which time itself seems to come to an end—indicating that Einstein's theory of general relativity, our best theory of gravity, ceases to apply. Studying black holes experimentally could provide invaluable clues towards a deeper understanding of the most basic components of our Universe. By analyzing gravitational waves from a vibrating black hole, we have now gotten a new clue that these mysterious objects ring like Einstein predicted.

In spite of their curious properties, black holes in general relativity are extremely simple. To fully describe such an object, one needs only to specify three numbers: its mass, its electric charge, and its rotation speed (spin). In fact, we expect electric charge to be negligible for actual black holes, so only two numbers would suffice. This is unlike most commonplace objects, which have an abundance of independent characteristics: shape, color, roughness, smell, etc. The striking simplicity of black holes is known to physicists as the *no-hair theorem*, referring to the holes' lack of additional attributes, or "hair". Evidence of any black-hole hair (a property other than mass or spin) would be a revolutionary smoking gun for new physics.

An ideal way to check whether black holes are indeed bald would be to record their ringing. Much like a struck bell, a disturbed black hole rings at characteristic tones that quickly fade away as the hole settles. Instead of sound waves, however, black holes ring in gravitational waves—gravitational changes that propagate across the Universe at the speed of light. Because of the no-hair theorem, Einstein's theory predicts that the pitch and decay rate of these vibrations are uniquely set by the hole's mass and spin—just like the sound of a bell depends on its shape and material. Therefore, if we could record the gravitational ringing from a disturbed black hole, we could put the no-hair theorem to the test.

Although we do not have access to a nearby black hole to jiggle, we can instead attempt to study black holes as they are born in far away galaxies. Since 2015, this has been possible thanks to gravitational-wave detectors, like LIGO in the United States, which can detect the gravitational echoes from black holes colliding throughout the Universe. When two black holes merge, the crash produces an incredible burst of gravitational waves (more powerful than all the light from all stars in the Universe combined!), which eventually washes over Earth and can be detected by our exquisitely sensitive instruments. The final portion of this signal carries information about the newly-formed black hole. This *ringdown* should be nothing more than a superposition of tones corresponding to the new hole's mass and spin, in agreement with the no-hair theorem.

In our work, we have demonstrated that current detectors already have enough sensitivity to start doing some of these measurements. By reanalyzing data from the first gravitational waves ever detected, we identified two ringdown tones emitted by the newly born black hole. We then confirmed that their pitch and duration are in agreement with Einstein's theory and the expectation that black holes have no hair. This test comes earlier than expected, as current instruments were thought to be insufficient to detect multiple black-hole tones. Our advance was made possible by considering a type of tone ("overtones") that had been previously believed too faint. To the contrary, we have found that these overtones dominate the gravitational-wave signal at its loudest point, allowing us to tease them out of the instrumental noise.

Observationally, it still remains quite possible that black holes are not the simple objects we expect from Einstein's theory. As our instruments continue to observe gravitational waves with improved sensitivity, tests like ours will become more and more precise, probing the black-hole paradigm in ever richer and more stringent ways. It is now commonplace for the LIGO and Virgo gravitational-wave detectors to observe around one black-hole collision per week. Our opportunities for discovery grow every day: little by little, black holes will shed their mysteries, revolutionizing our understanding of gravity, space and time.