Gravitational waves may oscillate, just like neutrinos

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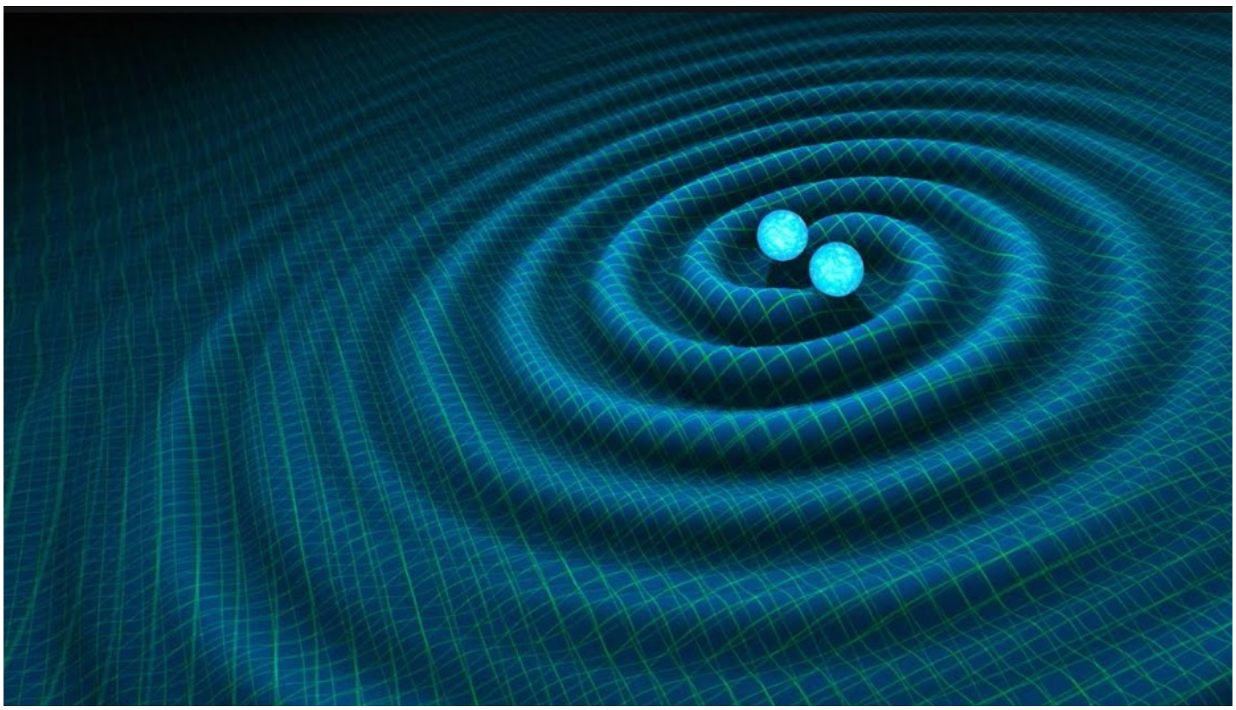

This illustration shows two merging black holes generating gravitational waves. At large distances from the black hole merger, spacetime may be described by superpositions of two grid sets, depicting the two metrics in the bigravity framework. Credit: Max, Platscher, and Smirnov, based on an image by R. Hurt at Caltech-JPL.

(Phys.org)—Using data from the first-ever gravitational waves detected last year, along with a theoretical analysis, physicists have shown that gravitational waves may oscillate between two different forms called "g" and "f"-type gravitational waves. The physicists explain that this phenomenon is analogous to the way that neutrinos oscillate between three distinct flavors—electron, muon, and tau. The oscillating gravitational waves arise in a modified theory of gravity called bimetric gravity, or "bigravity," and the physicists show that the oscillations may be detectable in future experiments.

The researchers, Kevin Max, a PhD student at Scuola Normale Superiore di Pisa and INFN Pisa, Italy; Moritz Platscher, a PhD student at the Max Planck Institute for Nuclear Physics, Germany; and Juri Smirnov, a postdoc at the University of Florence, Italy, have published a paper on their analysis of gravitational wave oscillations in a recent issue of *Physical Review Letters*.

As the physicists explain, the work may help answer the question of what "the other 95%" of the universe is made of, by suggesting that the answer may lie in modifications to gravity rather than new particles.

"Only 5% of matter is of a type we think to understand properly," Smirnov told *Phys.org*. "To address the question of what our universe is made of ('dark matter' and 'dark energy'), most authors discuss alternative particle physics models with new particles. However, experiments such as the ones at the LHC [Large Hadron Collider] haven't detected any exotic particles, yet. This raises the question if maybe the gravitational side needs to be modified.

"In our work, we ask what signals we could expect from a modification of gravity, and it turns out that bigravity features a unique such signal and can therefore be discriminated from other theories. The recent detection of gravitational waves by LIGO [Laser Interferometer Gravitational-Wave Observatory] has opened a new window on the dark sectors of the universe for us. Whether Nature has chosen general relativity, bigravity, or any other theory is a different question in the end. We can only study possible signals for experimentalists to look for."

Two gravitons instead of one

Currently, the best theory of gravity is Einstein's theory of general relativity, which uses a single metric to describe spacetime. As a result, gravitational interactions are mediated by a single hypothetical particle called a graviton, which is massless and so travels at the speed of light.

The main difference between general relativity and bigravity is that bigravity uses two metrics, g and f. Whereas g is a physical metric and couples to matter, f is a sterile metric and does not couple to matter. In bigravity, gravitational interactions are mediated by two gravitons, one of which has mass and the other of which is massless. The two gravitons are composed of different combinations (or superpositions) of the g and f metrics, and so they couple to the surrounding matter in different ways. The existence of two metrics (and two gravitons) in the bigravity framework eventually leads to the oscillation phenomenon.

As the physicists explain, the idea that there might exist a graviton with mass has been around since almost as long general relativity itself.

"Einstein's theory of general relativity predicts one mediator (the 'graviton') of the gravitational interactions, which travels at the speed of light, i.e., which is massless," Max said. "Back in the late 1930s, people were already trying to find a theory containing a mediator that has a mass, and thus travels at a speed less than the speed of light. This turned out to be a very difficult task and was only recently accomplished in 2010. Bigravity is a variation of this 2010 framework, which features not one, but two dynamical metrics. Only one of them couples to matter while the other doesn't; and a linear combination of them becomes massive (slower than the speed of light) while the other is massless (speed of light)."

Oscillations

The physicists show that, in the framework of bigravity, as gravitational waves are produced and propagate through space, they oscillate between the g- and f-types—though only the g-type can be detected. Although previous research has suggested that these oscillations might exist, it appeared to lead to unphysical results, such as a violation of energy conservation. The new study shows that the oscillations can theoretically emerge in a realistic physical scenario when considering graviton masses that are large enough to be detected by current astrophysical tests.

In order to understand these oscillations, the scientists explain that in many ways they resemble neutrino oscillations. Although neutrinos come in three flavors (electron, muon, and tau), typically the neutrinos produces in nuclear reactions are electron neutrinos (or electron anti-neutrinos) because the others are too heavy to form stable matter. In a similar way, in bigravity only the g metric couples to matter, so the gravitational waves produced by astrophysical events, such as black hole mergers, are g-type since f-type gravitational waves do not couple to matter.

"The key to understanding the oscillation phenomenon is that electron neutrinos do not have a definite mass: they are a superposition of the three neutrino mass eigenstates," Platscher explained. "More mathematically speaking, the mass matrix is not diagonal in the flavor (electron-muon-tau) basis. Therefore, the wave equation that describes how they move through space will mix them up and therefore they 'oscillate.'

"The same is true in bigravity: g is a mixture of the massive and the massless graviton, and therefore as the gravitational wave travels through the Universe, it will oscillate between g- and f-type gravitational waves. However, we can only measure the former with our detectors (which are made of matter), while the latter would pass through us unseen! This would, if bigravity is a correct description of Nature, leave an important imprint in the gravitational wave signal, as we have shown."

As the physicists note, the similarity between neutrinos and gravitational waves holds even though neutrino oscillation is a quantum mechanical phenomenon that is described by the Schrödinger wave equation, whereas gravitational wave oscillation is not a quantum effect and instead is described by a classical wave equation.

One particular effect that the physicists predict is that gravitational wave oscillations lead to larger strain modulations compared to those predicted by general relativity. These results suggest a path toward experimentally detecting gravitational wave oscillations and finding support for bigravity.

"Since bigravity is a very young theory, there is still a lot to be done, and its potential to address our theories' shortcomings needs to be explored," Smirnov said. "There has been some work along these lines, but certainly a lot is yet to be done and we hope to contribute in the future as well!"

More information: Kevin Max, Moritz Platscher, and Juri Smirnov. "Gravitational Wave Oscillations in Bigravity." *Physical Review Letters*. DOI: 10.1103/PhysRevLett.119.111101. Also at arXiv:1703.07785 [gr-qc]