Mind the [Mass] Gap

Copied verbatim from my article published in the Scientific American *Observations* blog (October 2019): https://blogs.scientificamerican.com/observations/mind-the-mass-gap/

“Now that LIGO has detected gravitational waves, what will you do next?” was a question I got from a surprising number of people. It was February, 2016, and LIGO (the Laser Interferometer Gravitational-wave Observatory) had announced their first detection: gravitational waves emitted from a pair of black holes as they spiraled in and smashed into one another. As a masters’ student, I had just started research in this field. My highly optimistic response: “This is just the beginning. LIGO is going to routinely make new scientific discoveries that will give us researchers a lot of sleepless nights.”

Three years later, LIGO and its European counterpart, Virgo, have lived up to that promise: so far, they’ve found 21 mergers of binary black holes and three mergers involving binary neutron stars. And in the wee hours of September 24th of this year, the “sleepless nights” prediction came true: my phone woke me up with a message from a new LIGO-Virgo public notification system that alerts subscribers within minutes of a new detection.

I’m someone who enjoys a sound sleep more than anything else, but I never complain when the universe calls—and this particular alert was especially worth waking up for. The reason: not only had LIGO-Virgo made a new detection, but I could immediately see what kind of event had triggered this blast of gravitational waves. It was almost certainly a collision between two objects in a mysterious gray area known as the “mass gap”

To understand what that means, we need to delve deeper into the kinds of objects LIGO-Virgo studies. I have always been fascinated by matter at the most extreme densities. Objects like neutron stars and stellar-mass black holes weigh as much as a star but have a diameter only about the size of a large city. They form when very big stars, weighing more than eight times the mass of the sun, run out of their nuclear fuel and explode as supernovas.

What’s left depends on how much of the star’s core remains. The lighter ones tend to form neutron stars, while the heavier ones tend to collapse uncontrollably under their own gravity and turn into black holes.

But things get fuzzy at this point: we can’t say precisely where the line between “lighter” and “heavier” falls. Theoretically, the heaviest a neutron star can be is about three times the mass of the sun—but we’ve never been able to adequately test that theory with observations. The heaviest neutron star ever observed, weighing in at about 2.14 solar masses, was announced recently in the journal *Nature Astronomy.* And the lightest black holes we’ve seen weigh around five solar masses. We’ve never seen anything in the space between three and five—a range we call the mass gap.

The closest we have come to observing something was when LIGO-Virgo detected the first merger of binary neutron stars in August 2017. The result of their collision is an object estimated to weigh around 2.8 solar masses, tantalizingly close to the lower bound of our mass-gap. Whether it is a neutron star or a black hole remains unresolved to this day.

It may sound like an obscure question to worry about, but for physicists like me, this uncertainty is a really big deal. If the mass gap is real—if there’s truly nothing to be found in that range—it will force theorists to go back to their blackboards to review their ideas of the physics of supernovae. And if there is no gap, and there is actually a sharp dividing line, we need to figure out why we haven't seen objects in that intermediate range.

That is why all eyes, including mine, immediately focused on the September alert. The pattern of gravitational waves emitted when pairs of compact objects revolve around one another gives us a totally new method of estimating the mass of each body. If a mass-gap object underwent such a collision with another compact object, LIGO-Virgo would definitely catch the distinctive ripples that emerge.

In fact, the September event was not the first time a public alert has been issued for a mass gap object. A few months earlier, LIGO-Virgo sent out a similar alert. But less than 12 hours later, they released updated probabilities, which downgraded the likelihood of it being a mass gap object to under one percent.

Despite the crushed hopes of having our first mass gap detection, that event gave us plenty of reason to remain jubilant; it holds the promise of being the first time we have seen the merger of a neutron star and a black hole.

As for the most recent detection that woke me up, researchers at LIGO-Virgo are now hard at work churning data analysis codes to confirm whether it really contains an object that fills into the existing void. It would help us finally determine what the nature of these objects is. Most researchers, myself included, would bet on them being “missing” lightweight black holes that we just had not been able to see with previous methods. But alternative theories also suggest that this void may be filled with exotic objects like stars made entirely of quarks.

Whatever the outcome, the current LIGO-Virgo observing run encapsulates the excitement of cutting-edge research that hooked me into this field in the first place. What’s even better is that you can share in the fun. Anyone can subscribe to the public alerts that woke me that night in September. There’s even an app for that. So, keep your phone handy, and you too can get a message from the universe.