LSC LIGO Scientific Collaboration VIRGO

MAKING GW170817: NEUTRON STARS, SUPERNOVAE AND TRICK SHOTS

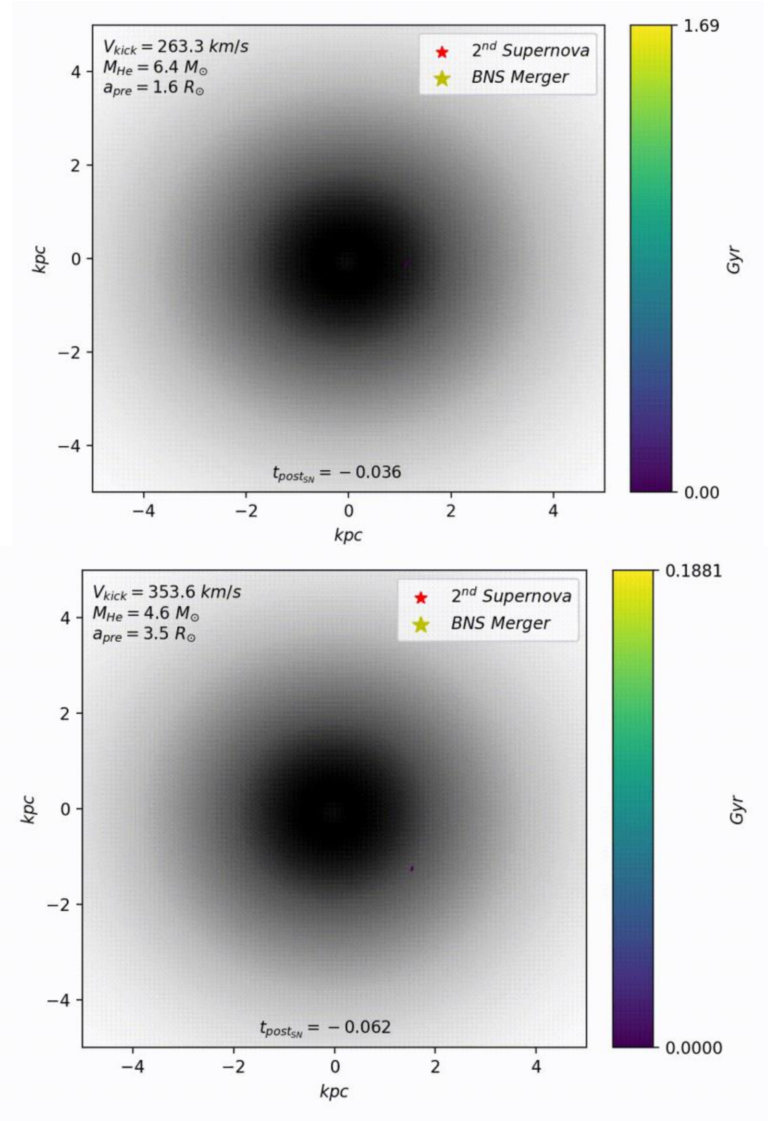
On 17 August 2017, Advanced LIGO and Advanced Virgo detected a gravitational-wave signal, called GW170817, matching the insprial of two neutron stars. Subsequent observations by astronomers from around the world revealed an electromagnetic counterpart, allowing us to pinpoint the source of the signal. The home of our binary of neutron stars is the galaxy NGC 4993. Using our observations of the source, we can try to figure out how the neutron stars formed; it seems they are probably similar to those we know in our own Galaxy.

We know that GW170817 ended with a bang. Our two neutrons stars inspiralled together, eventually merging, resulting in some celestial fireworks. But how was the binary formed?

Neutron stars are the remains of exhausted stars. When stars have burnt through their supply of fuel, they no longer have the energy to keep themselves puffy, and they start to collapse under their own weight. The central core of the star gets squeezed down, releasing energy which can blast away the outer layers of the star. Neutron stars are formed when the core is too massive to end up as a white dwarf (as our Sun will), but not big enough to end up as a black hole. Large amounts of energy are released as a star's core forms a neutron star, resulting in a bright explosion called a supernova. Our neutron star binary started with *two* bangs, one for the birth of each of the neutron stars.

During a supernova, material might not explode outwards in all directions equally. This results in the newly formed neutron star getting a kick. It can be propelled by the blast at speeds of several hundred kilometres per second (equivalent to millions of miles per hour). We worked backwards from the collected observation of GW170817 to try to figure out how big a kick it could have received.

ASSOCIATED FIGURES



Example trajectories of simulated binaries neutron stars around a simulated galaxy, which would match our observations of GW170817.The line shows the path of the binary in the galaxy, the color coding is time until merger measured in gigayears; the red star marks the second supernova, the arrow shows the kick direction, and the yellow star marks the spot of the merger. Some trajectories are simple (like straight pots of a pool ball), others are more complicated (like bouncing the ball off several cushions before it reaches the pocket). See Figure 4 of the paper for more.

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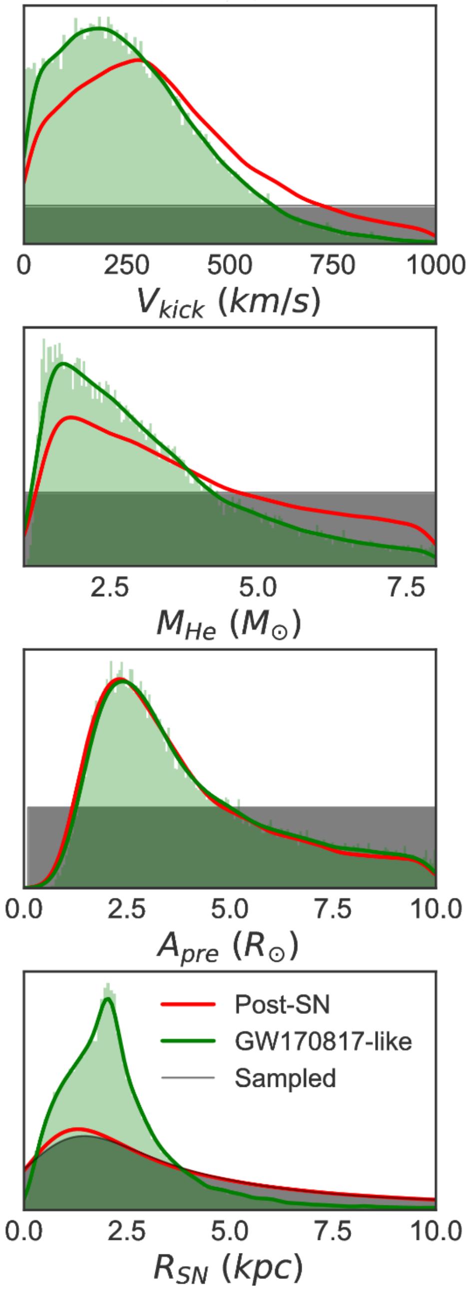
This calculation is kind of like trying to figure out how hard a pool ball was hit, given that we know it ends up in the corner pocket. It could have been cued softly, if it started close to the pocket, or hit really hard and bounced off several cushions. We can try a number of shots, from different starting positions, and see what works out. For GW170817, we simulated a large number of binaries, starting from different points in the galaxy, and given different kicks, and saw which ones ended up merging at a distance from the center of the galaxy that matches the observed position of the counterpart. The binary could have started close by and got a really small kick, but there are fewer stars formed in the outer parts of the galaxy than further away in the center; it could have formed further away and got a big kick, but if the kick is too big the two neutron stars will fly apart and never merge; it could have got a small kick and travelled a long way slowly, but then the neutron stars must not start too close to merging or they would do so before arriving at their final position. Folding together all the possibilities, we can work about the probabilities for having different kicks and starting configurations.

The results of our simulations is a set of Goldilocks parameters that are just right to explain our observations. At the time of the second supernova, the binary had an orbital size of around twice the radius of our Sun(which is pretty close for stars): smaller separations would mean that the binary merged too quickly, larger separations mean that the binary doesn't merge at all. At the time of the second supernova, the binary was about two kiloparsec (7 thousand light-years or 100 billion times the radius of our Sun) from the center of the its home galaxy: more stars are formed closer to the center, but it's also harder to escape from there out to where the counterpart was seen. The kick of the second supernova was around 300 kilometres per second: faster kicks are unlikely because they rip apart the binary. Finally, to give the right kick and the necessary change in the orbital separation, we second supernova probably came from a star that was around 3 times the mass of our Sun. These are our first results from a binary neutron star merger, as we collect more, we'll be able to learn more how neutron stars are made, and exactly what happens during a supernova explosion.



Inferred properties of the second supernova and the binary: the supernova kick velocity (top), the mass of the star pre-collapse, the orbital separation before the supernova, and the distance of the binary from the center of the galaxy (bottom). The solid band grey shows distribution of all the binaries we simulated (all the balls we hit). The red line shows the distribution of the all the binaries which go on to merge after the supernova (all the balls which go in a pocket). The green line shows the distribution for all the binaries that merge in a similar spot to GW170817 (all the balls which go in the right pocket). See Figure 5 of the paper for more details.

GLOSSARY

- **Gravitational waves:** Ripples in space-time, a stretching and squashing, created by accelerating massive objects. They are a prediction of Einstein's theory of general relativity. Like electromagnetic radiation, they travel at the speed of light. If you've not heard of a gravitational wave before, you have come to the right place! If you would like to know more, try looking at our other pages on gravitational-wave science. We have observed a number of gravitational waves, our detections are named GW (for gravitational wave) followed by the date of observation.
- **Electromagnetic waves:** Ripples in electric and magnetic fields. They are a prediction of Maxwell's theory of electromagnetism. Like gravitational waves, they can be used to do astronomy. Electromagnetic waves are most commonly known as light. Visible light stretches from red to violet, but outside this rainbow, there are other forms of electromagnetic waves. Beyond red light there is infra-red, microwaves and radio waves, and beyond violet there is ultraviolet, X rays and gamma rays. Each part of the spectrum of electromagnetic radiation gives a different insight into parts of our Universe. LIGO and Virgo planned sharing detections with electromagnetic astronomers so we could get a more complete understanding of the sources of our signals.
- **Neutron star:** The dense remains of a collapsed star. We think neutron stars have masses roughly between that of our Sun and three times the mass of our Sun, we're not exactly sure of the boundaries yet, but hope to learn this from collecting more gravitational-wave observations. The maximum mass of a neutron star is set by the properties of the material it is made from. This is a strange form of matter, similar to the stuff which makes up the nuclei of atoms but scaled up enormously—neutron stars are about the size of a city.
- **Supernova:** A violent explosion, often spotted a rapidly appearing bright object in the sky, which then fades away. A supernova may outshine the rest of its galaxy. There are a variety of different supernovae. Some come from the collapse of massive stars, others may come from the collision of two white dwarfs. A supernova in our Galaxy was observed by ancient astronomers in 1054. This was the collapse of a massive star: its outer layers were blasted off to from the Crab Nebula, and its core collapsed down to form the Crab Pulsar, a neutron star.

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