A SYSTEMATIC SEARCH FOR GAMMA-RAY TRANSIENTS ASSOCIATED WITH GRAVITATIONAL-WAVE EVENTS IN THE O3 RUN

The gravitational wave (GW) events that the LIGO and Virgo detectors have captured so far have all been "compact binary coalescence" events, also called "mergers". Each GW signal detected tells a short story of two massive objects, either black holes or neutron stars, which orbited each other ever more closely and rapidly until they finally spiraled together and merged into one. An enormous amount of energy was released in the form of gravitational waves as the objects finally fell together under their powerful gravitational pull, which is why our GW detectors have been able to detect them even though most occurred billions of light years away.

LIGO/Virgo/KAGRA (LVK) scientists and many other astronomers and astrophysicists are eager to learn if any of the GW events we're finding are also detectable by other telescopes or instruments. This "multi-messenger astronomy" effort involves observations by many different groups and had a spectacular success in 2017 with the detection of GW170817: a comparatively nearby (at 130 million light years!) merger of two neutron stars. Besides its distinctive GW signal, the source of GW170817 also generated a burst of gamma rays (the highest-energy form of light) about 2 seconds later, followed by emission of other kinds of light across the electromagnetic spectrum, from X-ray to radio. A great deal was learned from that one event, which so far is the only one of its kind to have been observed; in spite of a few reports of potential associations, no other GW event has had an unambiguous electromagnetic counterpart. But the LIGO-Virgo O3 observing run, which spanned April 2019 to March 2020, yielded about 8 times as many detected events as LIGO's and Virgo's earlier runs combined, providing many more GW events to study.

FIGURES FROM THE PUBLICATION

For more information on these figures and how they were produced, read the freely available preprint.

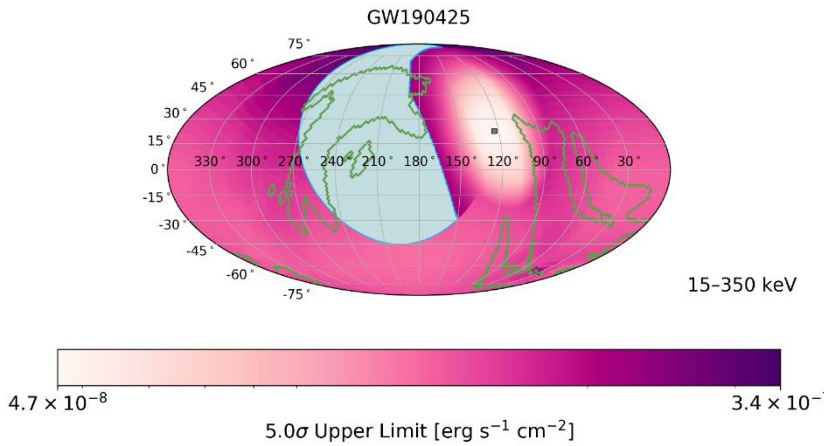

Figure 1 (from figure 6 of the paper): Upper limit sky map in energy flux for event GW190425, a binary neutron star merger detected in the LIGO and Virgo detectors. No electromagnetic counterpart has previously been reported for this event (unlike GW170817, another binary neutron star merger) and none is found in this analysis either. The large oval represents the full sky in all directions and the numbers in degrees are right ascension and declination coordinates. The light blue region is the range of directions blocked (occulted) by the Earth from *Fermi*'s viewpoint and outside the field of view of the *Swift*-BAT instrument. The green contours show the sky regions found to be likely (at the 90% confidence level) to contain the true sky location of the GW signal. Thus, *Fermi*-GBM and *Swift*-BAT data are able to constrain the flux over most of the sky, but only over part of the region identified by the GW detectors for this event.

Now, a team of astronomers collaborating with LVK scientists has used data from two major NASA missions to search systematically for other gamma-ray signals which could be associated with the GW events found in the LIGO-Virgo O3 observing run. NASA's *Fermi* and *Swift* spacecraft are both in orbit around the Earth, where even the high-energy forms of light (gamma and X-rays, arriving as individual "particles" of light called photons) from deep space can reach them without being absorbed by Earth's atmosphere. Both missions have instruments which continuously monitor large areas of the sky for gamma-ray bursts: the Gamma-ray Burst Monitor (GBM) on *Fermi* and the Burst Alert Telescope (BAT) on *Swift*. They routinely detect and report gamma-ray bursts (GRBs) from on-board and on-the-ground analysis of their data using certain criteria to be very confident in their detections. LVK scientists had previously checked carefully for any notable GW signals occurring around the times of reported GRBs during O3 (see "Searching for quiet gravitational waves produced by gamma-ray bursts in O3b") as well as during earlier observing runs. The new analysis is a comprehensive check for gamma-ray signals which could have been missed because they were too weak or ambiguous to satisfy the usual criteria for GRBs, but would be more interesting if connected with a GW event. These potential signals are referred to as "gamma-ray transients", although they may include photons in both the gamma-ray and X-ray energy ranges.

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The target sample of GW candidates for this analysis consisted of 79 likely events from the O3 run, defined as candidates with estimated probability of having a true astrophysical origin (as opposed to a detector noise fluctuation) of greater than 50%. The properties of these events were published jointly by the LIGO, Virgo, and KAGRA collaborations in two "catalog" updates, which are summarized online in "GWTC-2.1: Extended catalog of binary mergers observed by LIGO and Virgo during the first half of the third observing run" and "GWTC-3, a third catalog of gravitational wave detections". Six marginal GW candidates were examined too. Only a handful of the mergers involved low-mass objects believed to be neutron stars, which are promising sources of gamma rays if a single or a pair of neutron stars are disrupted by tidal forces before and during the merger, as in the case of GW170817. All of the other events are likely binary black hole mergers, which theorists believe are unlikely to produce gamma-ray transients except in certain uncommon environments. While the specific properties of the gamma-ray transients could be different for the different types of mergers, all GW events were treated the same in this analysis.

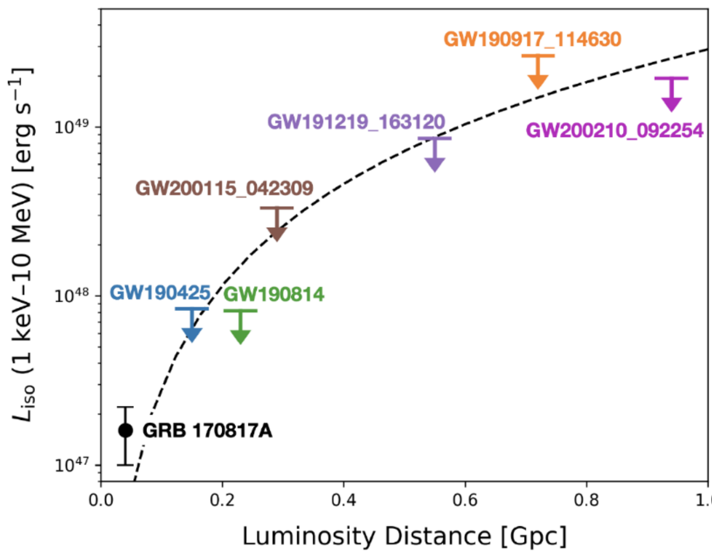

Figure 2 (figure 5 of the paper): The short horizontal lines with downward-pointing arrows represent upper limits on energy emission in the X-ray and gamma-ray energy range for six gravitational-wave events. These six GW events are of particular interest because in these cases the binary which merged may have had either one or two neutron stars. The vertical axis measures "luminosity", which is energy emitted per second by the source, under the simplifying assumption that equal energy was emitted in all directions. The energy flux upper limits determined directly from the *Fermi*-GBM and *Swift*-BAT data have been converted to luminosity upper limits using the estimated distances to the sources of each of these GW events, which are shown on the horizontal axis in units of gigaparsecs. (One gigaparsec is about 3.26 billion light years.) The dashed line is an approximate model for the sensitivity of *Fermi*-GBM, rising in the plot because its on-board gamma-ray detectors capture a smaller fraction of the energy from distant sources. For comparison, the gamma-ray burst detected in 2017 together with the binary neutron star merger GW170817 is shown as a dot with error bars. GW170817 was much closer, so the other six GW events shown here would have been detectable only if their luminosities had been much larger than what was measured for GRB 170817A.

Team members analyzed the available data from the *Fermi*-GBM and *Swift*-BAT instruments to search for transients associated with the target sample of GW events. *Fermi*-GBM data for individual gamma-ray photons are routinely transferred to the ground and archived. This data has now been analyzed using two search methods that are more sensitive than *Fermi's* on-board trigger algorithm. The "Untargeted Search" re-analyzes all of the data, with a wider range of assumptions about the photon energies and durations of possible gamma-ray transients, in order to identify an enlarged list of triggers. The "Targeted Search" performs a coherent analysis of the data from all 14 GBM scintillator detectors to check for a weak but consistent signal around the time of each GW event, considering durations from 0.064 to 8 seconds which are typical emission times for the "short" GRBs associated with binary mergers. The *Swift*-BAT instrument does not send down photon-by-photon data except at times when an on-board trigger is identified, or by special command. However, processed *Swift*-BAT data measuring photon detection rates in four energy ranges are sent to the ground and archived, and that data has been analyzed to search for any periods of elevated photon rate near the times of the GW events.

These searches did not reveal any gamma-ray transient that seems likely to be associated with a GW event in O3. Nevertheless, the absence of a gamma-ray signal is also a scientific finding. The analysis team went on to calculate upper limits on the gamma-ray energy flux for each GW event, that is, they evaluated how much gamma-ray energy could have been present without appearing as a signal in the analyses performed. These upper limits are a function of direction because both *Fermi*-GBM and *Swift*-BAT have direction-dependent sensitivities, depending on the orientation of the spacecraft at the time of the event and its location above the Earth, which occults (blocks) gamma rays which hit it. The upper limits are thus mapped out over the sky. In addition, marginalized upper limits have been calculated by taking a weighted average over the GW event's probability sky map to get the best estimate of the energy flux limit assuming that the gamma-ray emission really was associated with the GW event. These upper limits are also interpreted using different theoretical models of ways in which a binary black hole merger could produce gamma rays, such as by transferring energy from the angular momentum ("spin") of the black hole, from electric charges in the system, or from an intense outburst of neutrinos interacting with material around the black holes to produce high-energy photons.

Even for binary neutron star mergers, detecting a gamma-ray transient might be a rare occurrence since the brightness of the gamma rays probably depends on the distance to the system, the properties of the neutron stars, and the orientation of their orbit. In standard GRBs, the gamma rays are known to be concentrated in two beams and there is only a small chance that one of the beams will happen to point in the direction of Earth. For binary black hole mergers there is the added uncertainty about whether gamma rays will be produced at all, and if so, will be bright enough to be detected from very far away. Fortunately, the LIGO, Virgo, and KAGRA detectors will record many more binary mergers in future observing runs, providing many opportunities to capture a fleeting gamma-ray transient and to learn about these powerful, distant astrophysical events, as well as to test different models for their emission.

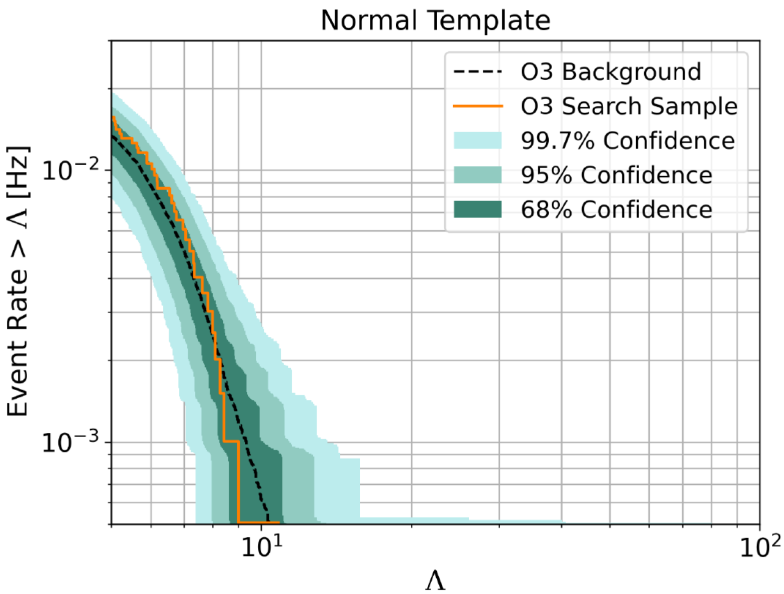

Figure 3 (from figure 2 of the paper): This type of data plot is designed to check whether a set of many events are all consistent with a hypothesis, or whether some subset stands out as being distinctly unusual. Here, a "lambda" (Λ) value has been calculated for each GW event which is a measure of how likely it is that the event has a real gamma-ray transient, versus being just a noise fluctuation in the gamma-ray instrument data. (A larger value of Λ means a higher probability of being real.) Because of statistical variations in signals and random noise, a wide range of lambda values is expected. The 79 values in the O3 search have been sorted and plotted in a cumulative fashion going from right to left as an orange stair-step line, with each step up occurring at the position of the next lambda value in the sorted list. (Because the vertical scale is logarithmic, the vertical steps appear to get smaller and smaller as they go up, but all the steps are actually equal in rate units.) The largest lambda value is greater than 10, which would be pretty significant except for the fact that the sorting highlights the largest out of 79 cases. The real test for significance is to compare the observed distribution to what it would be under the hypothesis that none of the GW events has a gamma-ray transient counterpart. This is traced out by the dashed line labeled "O3 Background", sorted in the same fashion (but with smaller vertical steps from using a larger number of samples), and the colored bands show the range of variations around the dashed line that can be expected to occur a given percentage of the time simply from random fluctuations. Because the orange stair-step does not stray far from the dashed line in this plot, even at the largest lambda values, we can conclude that the event sample is consistent with the background – that is, there is no convincing evidence here that any of the GW events has a gamma-ray transient counterpart.

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GLOSSARY

Photon: A particle of light which carries a certain amount of energy. In the early 1900s it became clear that light, which was previously thought of as a wave phenomenon, can act like a particle in certain ways. That was a key piece of evidence that led to the development of quantum mechanics (see, for example, History of quantum mechanics in Wikipedia). All light is composed of photons, with the amount of energy in a photon determining how it interacts with matter.

Gamma ray(s): Light with a very large amount of energy per photon. Despite the word "ray" in the name, gamma rays often behave like individual particles. Typically, a photon with an energy of 100 keV (kilo electron volts) or greater is considered a gamma-ray photon, although this is not a firm definition. Gamma rays can be produced in nuclear reactions or the collisions or radioactive decays of especially high-energy particles.

X-ray(s): Light with a large amount of energy per photon, but not as much as a gamma ray. Photons with energies between about 100 eV (electron volts) and 100 keV are generally considered X-ray photons, although there is a seamless transition between "hard" (high-energy) X-rays and gamma rays. X-rays can be produced in the collisions of high-energy particles, as well as by the decay of "excited" (temporarily elevated energy) states of electrons in atoms.

GRB: A gamma-ray burst (GRB) is an astronomical phenomenon in which a distant object suddenly emits a very powerful flash of gamma rays and X-rays, often followed by light at lower energies (ultraviolet, visible, infrared, and radio waves). While only a small amount of energy is captured by detectors near the Earth, the amount of energy released must be enormous since most GRBs occur billions of light years away and the energy has spread out. Most GRBs are believed to be produced by collapsing stars that are much more massive than our Sun or by mergers of neutron stars in binary systems.

Energy Flux: A measure of how much energy is reaching a detector per unit area per unit time. For example, energy flux can have units of ergs per square centimeter per second. This definition is useful when the detector is very far from the source because then the amount of energy gathered by a detector is proportional to its size (area) and to how long it waits. However, the energy flux may be present for only a fraction of a second in a transient astrophysical event such as a short GRB.

Neutrino: A fundamental particle produced in some radioactive decay processes and high-energy particle reactions. A distinctive property of neutrinos is that they can normally pass through other matter with very little chance of interacting with it, so they are sometimes called "ghost particles". Neutrinos are produced in huge numbers by the Sun, in supernovas, and possibly also in binary mergers.

Scintillator detector: A type of particle detector that produces a flash of light when an energetic particle enters it and is stopped or scattered. The light is collected, converted to an electrical signal by an optical sensor such as a photomultiplier tube, and measured to determine the amount of energy that was deposited in the detector.

Coherent analysis: A method for simultaneously analyzing data recorded by multiple detectors which requires them all to be consistent with a single physical signal. This approach can be significantly more effective than simply adding together the outputs from the detectors, especially when the pattern of signals in the different detectors depends on some factor like location in the sky.

Marginalize: A calculation method used in statistics to focus on a quantity of interest by averaging over the uncertain values of one or more other quantities that influence it. The averaging is typically done using likelihood or probability weighting so that the marginalized value represents a best estimate.