comment

Lessons from counterpart searches in LIGO and Virgo's third observing campaign

No confirmed counterparts during LIGO and Virgo's third observing run bring more questions than answers to the active multi-messenger community, which is adapting collaboratively and technically as expectations evolve and more data are taken.

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The second portion of the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo's third observing run (O3) was suspended a month ahead of schedule, on 27 March 2020, as part of a wave of observatory facilities closing due to COVID-19. It signalled the end of a nearly year-long marathon not only for those actively involved in searches for gravitational waves (GWs), whose work mining the data for faint signals will no doubt continue well into the rest of the year, but also for hundreds of astronomers worldwide searching for electromagnetic and neutrino counterparts to GW messengers. The run started with optimism brought by GW170817[1], the first binary neutron star (BNS) merger observed by LIGO and Virgo with its associated electromagnetic counterpart, along with the development of tools and techniques after the lessons of the second observing run (O2).

There are many differences between the GW observations taken during O2 and O3. After debugging during the first two months of O3, detected events became public within minutes of discovery. But perhaps more importantly, until the detection of GW170817, the level of uncertainty as to what might be observed in electromagnetic wavelengths was quite high. While there was an impressive body of theoretical work about what might be produced by the merger of BNSs or neutron-star–black-holes (NSBHs) going into that run[2], in general observational strategies were not being strongly built around them. This story changed with the success of theoretical models in describing the observational data. It also spurred a resurgence of transient modelling that reminds us just how broad the parameter space for these counterparts might be[3], and that certain mergers, including NSBHs with high mass ratios, are not expected to have counterparts at all.

The first half of O3 quickly brought the detection of a second BNS merger, GW190425[4]. This event was exceptional

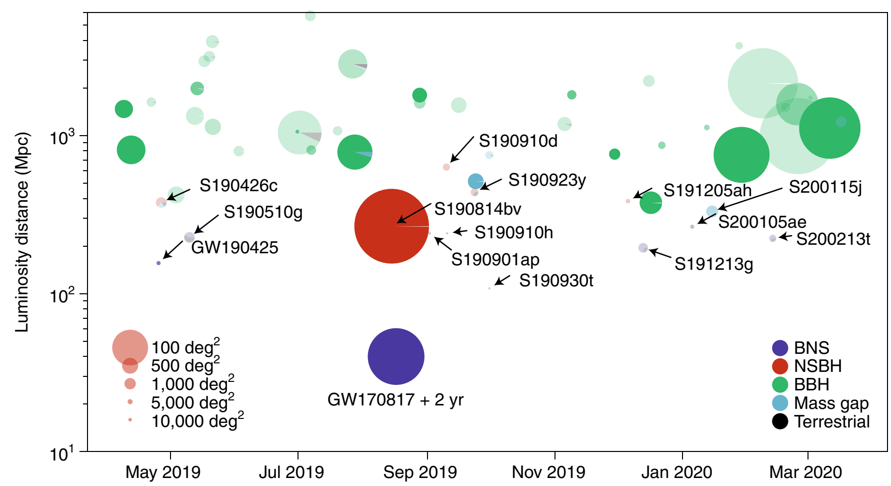

Fig. 1 | Public O3 alerts, including BNS, NSBH and binary black hole (BBH) candidates. The size of the circle is inversely proportional to the area, and so bigger circles indicate easier objects for follow-up. The transparency is related to the candidate's false-alarm rate, with a higher opacity indicating a greater significance.

for its significantly higher pair of neutron star masses than those of GW170817, with a total mass of 3.4 $M_{\odot}$ compared to 2.7 $M_{\odot}$ for the latter; pairs of neutron stars with individual masses higher than 1.4 $M_{\odot}$ are not readily predicted by theorists. It also led to broadly consistent inferred BNS merger rates. With GW190425, a wild swing of emotions ensued as potential counterparts were found and later rejected; dozens of groups participated, with more than 100 γ-ray burst coordinates network (GCN) notices shared over the following few days. This GW counterpart search was a very different beast to that of GW170817, which was localized to ~30 deg^2, instead covering nearly 10,000 deg^2 on the sky. With a probable distance about four times larger than that of GW170817, astronomers quickly realized that this was a completely different game. Thousands of square degrees were covered in the search as many follow-up campaigns characterized the ~30 counterpart candidates. With a combination of photometric and spectroscopic follow-up using more than a dozen telescopes, all of the possible counterparts were ruled out.

While the follow-up of GW190425 was extensive due to the sky-map's intersection with the Galactic plane and the location of the Sun, less than half of that localization was collectively covered by optical, wide field-of-view systems, which made it difficult to set kilonova limits. If the counterpart location was covered, the limits on properties of these counterparts and the merger components that yield them could be very constraining[5], but it is also possible we had simply not imaged the correct location. To go after more marginal signals, the signal-to-noise ratio threshold for public alerts was lower than that used for O2, so sky localizations were large (see Fig. 1), and therefore a large fraction of events would have localizations hidden by the Sun and/or intersect with the Galactic plane.

A few months later, another exceptional candidate, S190814bv, would change that story. It is currently classified as potentially the first NSBH merger[6], and we have seen more examples of this potentially new source class since[7,8]. Reminiscent of GW170817, its 90% credible region was 23 deg^2 with a location in the Southern Hemisphere, albeit at a much farther distance of 276 ± 56 Mpc. Covered extensively by many optical facilities, S190814bv yielded a number of moments where the heart skipped a beat, with examples of candidate photometric evolution consistent with kilonovae that required a spectrum to eventually rule out, for example, DG19wxnjc[9]. In this event as well, no viable counterpart candidates remained, leading to significant limits on ejecta properties.

Over the course of O3, LIGO and Virgo released eight NSBH and six BNS candidate events, with localization regions spanning a few tens to several thousands of square degrees, and median distances in the range ~108–630 Mpc. Based on these events, 1,558 GCN circulars were published to report searches related to electromagnetic counterparts to GW triggers. Sixty-three observatories participated in the optical follow-ups, yielding around 388 candidate counterparts.

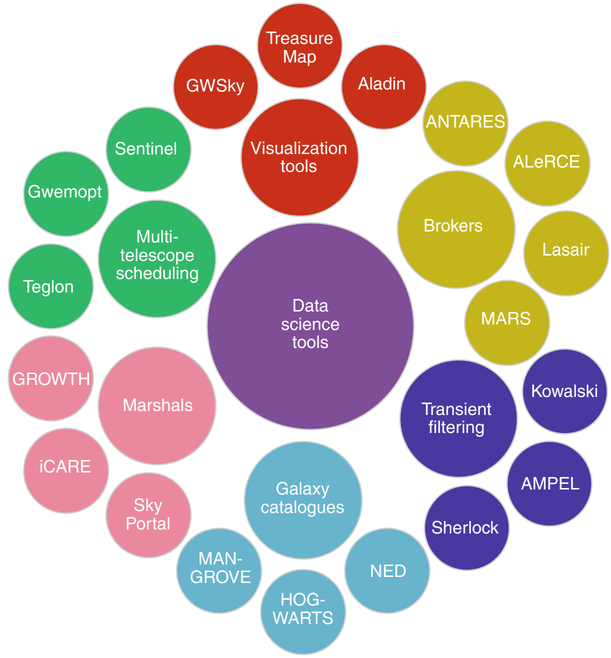

Fig. 2 | Example data science tools employed during O3. Telescope scheduling marshals and infrastructure (such as GROWTH's target of opportunity marshal[16], GRANDMA's iCARE pipeline[10], GOTO's sentinel[17], and Swope's teglon), galaxy targeting focused toolkits (such as MANGROVE[18] or HOGWARTS[19]), modules for light-curve filtering (for example, Kowalski[20], AMPEL[21] and Sherlock), visualization tools (like TreasureMap[22] and Aladin[23]), and alert brokers (such as Lasair[24] and ANTARES[25]) are part of the ecosystem of data science tools supporting this science.

Worldwide collaborations

The first of many lessons from O3 relate to maintaining the enthusiasm for follow-up that persisted for a year despite the lack of identified counterparts. This situation is fundamentally different from GW170817, when just about anyone with a small aperture telescope and a galaxy catalogue could have found the counterpart. Some teams would directly assign 'shifts' where on-duty astronomers would coordinate observations as events came in; this was the choice of collaborations such as the Global Rapid Advanced Network Devoted to the Multi-messenger Addicts (GRANDMA)[10] and Electromagnetic Counterparts of Gravitational Wave sources at the Very Large Telescope (ENGRAVE)[11], among others. Other teams, such as the Global Relay of Observatories Watching Transients Happen (GROWTH)[12] and the Gravitational-wave Optical Transient Observer (GOTO)[13], had vibrant teams of members getting calls with each alert; it is nice when the Sun never sets (or maybe better, never rises) on the teams. Following alerts, some of us performed double duty, first attending the LIGO and Virgo meetings to perform data quality checks, before running off to support the telescope coordination for events that survive initial scrutiny. This well-honed routine involved dedicated human organization, data analysis and protocol communication to manage GW follow-up observations, with more than 50 optical and near-infrared telescopes contributing significantly.

Search and follow-up coordination

Coordinated synoptic searches using a network of telescopes placed strategically around the globe could address these large sky localizations by obtaining observations of different portions of the sky maps or cadenced epochs of the same region to increase the probability of detecting a counterpart. Using an iterative strategy, one telescope could cover regions of the sky map that were not observed by another telescope of comparable sensitivity[14]. In addition, using common online platforms in which observed candidates are ingested, astronomers could directly trigger accessible photometric and spectroscopic facilities all over the world to expedite the counterpart discovery process. This vision has been supported by the rapid, public release of candidates in GCNs and on the Transient Name Server (TNS), and public access to data such as that from the Dark Energy Camera (DECam)[9] or the Canada–France–Hawaii Telescope (CFHT)[10], which has allowed for more science to be accomplished by the astronomy community, but there is further to go.

Just in the case of the Zwicky Transient Facility[15], we have more than 100,000 objects changing brightness at detectable levels during a given night, and the goal is to find the one associated with the GW event. While observations within around the last three nights are especially desirable to strongly constrain explosion times, there are often still tens of transients to characterize. With changes in their brightness and colour occuring on the order of hours, it is essential to have photometric and spectroscopic observations every few hours to understand the event in detail, including the chemical elements synthesized and material surrounding the remnant. Given that half of the battle is classifying objects found by surveys, there should be more coordination between astronomers performing counterpart identification and those performing classification. Follow-ups to O3 have made it clear that robotic spectroscopic classification resources are incredibly useful for classifying many objects as quickly as possible; given that it is unlikely that such large time allocations will be awarded in future without more identified counterparts, medium-sized robotic systems devoted to spectroscopic follow-up will need to be the future.

Finding balance in the amount of data taken is crucial when their eventual significance is still unknown. Incentivizing coordination between those using more telescopes, including the sharing of information and credit, will simplify the process of splitting up the responsibilities of getting spectroscopic or long-term photometric follow-up. While high-cadence spectroscopy of the eventual kilonova counterpart is highly desirable, this would prevent, for example, the over-abundance of classifications for specific candidates such as ZTF19aarzaod[12], a potential counterpart to BNS candidate GW190425 with at least five spectra and more than twice as many photometric observations. It would also prevent other candidates from falling through the cracks, perhaps disfavoured for being relatively faint or not having a known host redshift. Isolated follow-up programmes on large aperture systems, without support from other resources, is simply not the most efficient use of time, and emphasizes the need for data reduction and dissemination of results as quickly as possible.

Data science tools

The multi-telescope networks described above motivated the development of systems for coordinated observations. A number of these tools now exist (see Fig. 2). The end goal for such follow-up tools, however, must be the ability to plan coordinated observations both for counterpart identification and for characterization. The community should continue to focus on particular joint-scheduling architectures to avoid reinventing the wheel, beginning with the Target and Observation Manager (TOM) toolkit developed with the Vera Rubin Observatory era in mind[26]. The same holds true for technical infrastructure to reduce the many variable objects. Techniques for candidate selection, light-curve filtering and visualization tools provide interfaces to assess these objects, including collating information from astronomical datasets. This information is essential for removing potential asteroids and other moving objects, probable nontransient point sources such as stars in our Galaxy and quasars, and focusing on transients within the GW localizations with first detections after the merger. These tools must also include information from the counterpart modelling community, which continues to make significant strides in terms of expected luminosities and colours. Continued efforts to synthesize the existing datasets for all events, such as was done for GW170817[27], will be essential to this effort. This work goes hand in hand with the development of 'brokers' to ingest the large data streams of alerts from the Vera Rubin Observatory[28], designed to help astronomers determine which of the millions of dynamical objects in the night sky they should care about. These brokers provide astronomers with the ability to create customized filters based on transient colour and luminosity evolution to rapidly point them to only those types of objects they may be interested in.

Given the large distances of O3 and looking ahead to O4 (where they may be even larger, especially for NSBHs), covering more volume rather than more area is key, motivating more coordination. We need to improve the variety of technical tools now under our belt, many of which were built to address challenges that arose during observations of these large sky maps. Machine-learning tools trained on the large photometric datasets produced during these last three runs are gaining in popularity within the community[29], but continued significant investment in technical and observational, particularly spectroscopic, resources will be required.

There are likely to be sociological challenges for the GW counterpart community while the detectors are upgraded. O3 provided a large number of exciting detections, and those analyses will continue for some time, but the lack of detection of a counterpart makes the downtime particularly difficult. GW170817 brought increased funding and telescope time awarded, a double-edged sword given the large number of postdocs and PhD students now tasked to do GW follow-up in an era without counterparts. If O4 does not begin until 2022, it could be more than five years between detection of GW counterparts, longer than some graduate school timescales. Indeed, in the five-year gap between Initial LIGO and Virgo and Advanced LIGO and Virgo, experience and expertise was lost. If the follow-up community is not vigilant and does not apply these scientific and technical lessons in the intervening time, including continuing the searches for counterparts to short γ-ray bursts and/or neutrinos, the experience of a generation of graduate students and post-doctoral fellows may simply fade.

Leadership and accommodation from the GW observatories could be one part of the solution. The GW community is taking a part in transforming how we do astronomy, in particular the sociology of how the counterpart community works together. Between O3 and O4, reopening observatories for short observational runs in between more moderate upgrades, supported by the instantaneous release of more information, such as the chirp mass[30], would help support the follow-up. Increased understanding of how GW observatories report their false-alarm rates for events will be crucial to sustaining a substantial follow-up. The impact of GW170817 would not have been the same without the associated multi-messenger detections (as evinced by the more than 3,600 citations currently connected with it), and I hope that decisions made at all levels will reflect the partnership between these communities. ❐

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