Electromagnetic Follow-up: What do the estimates provided about the nature of the source mean, and how should you use them?

The LIGO Scientific Collaboration and the Virgo Collaboration

Contents

I. EXECUTIVE SUMMARY

Upon identification of a gravitational-wave transient candidate, two probability estimates are computed and distributed within the VOEvent notices sent to electromagnetic (EM) observing partners:

- `ProbHasNS`: an estimate of probability that at least one object in the binary is less than 3 solar masses, and
- `ProbHasRemnant`: an estimate of probability that there is matter in the surroundings of the central object. This uses a simple and conservative estimate [8] of the post-merger accretion disk mass that depends on the masses and spins of the merging binary system.

We recommend follow-up of any event for which either reported `ProbHasNS` or `ProbHasRemnant` are non-zero. Observers may wish to follow a somewhat more refined approach if resources are constrained. In particular:

- We **advise follow-up** of any event for which `ProbHasNS` is non-zero.
- We **strongly advise follow-up** of any event for which `ProbHasRemnant` is non-zero.

Estimates of these two numbers may be revised using better parameter estimation as it becomes available. Such updates will be distributed via GCN as described on the LV-EM wiki [9]. Finally, we emphasize that our calculations do not factor in prior information from previous detections or upper limits.

II. WHAT DO WE REPORT ABOUT THE SOURCE AND WHY?

Principles: LIGO will continue to detect binary black holes at a high rate [1], most likely at a higher rate than events with an associated EM counterpart [2]. Additionally LIGO's search parameter space simply includes more prior volume associated with binary black holes. To assist with scheduling telescopes to follow-up events most likely to produce an EM counterpart, we provide two quantitative estimates designed to winnow away events of less interest.

We report an estimate of probability that at least one object in the binary has mass less than $3\,M_\odot$ (but see [11]). Gravitational-wave observations do not cleanly distinguish all binary-black-hole events from candidate events which could contain neutron stars. Inferences about component masses can be highly degenerate extending to high mass ratios thus allowing binary black holes to masquerade as neutron-star/black-hole (NS-BH) candidates and vice-versa. These high-mass-ratio binaries involve large black holes which may swallow a neutron star whole. We therefore also report the probability that a neutron star would have tidally disrupted before being swallowed, assuming a very conservative equation of state (i.e., one that yields large neutron star radii, as detailed below), and using an expression for the tidal disruption condition that includes basic relativistic effects (e.g., the size of the innermost stable circular orbit as a function of black hole spin) and that was calibrated to results of numerical-relativity simulations of tidal disruption [8].

In the interests of speed, the probabilities we report in the preliminary notice are *rapid estimates.* Full parameter estimation studies will change the quantitative estimates for some candidates. The rapid estimates and associated recommendations in this document are designed to preferentially follow-up almost all events that could have an EM counterpart.

- `ProbHasNS`: **Is an object $< 3\,M_\odot$ ("neutron star") present?**: The first probability quantifies the chances that **at least one of the two masses** m_1 **and** m_2 **is smaller than** $3\,M_\odot$, if one adopts a uniform prior in the two masses. The rationale is that $3\,M_\odot$ represents a safe upper limit on the maximum possible neutron star mass.
- `ProbHasRemnant`: **Would a neutron star tidally disrupt prior to merger [or is the source a binary neutron star system]?**: The second estimate quantifies the chances the binary is a double neutron star, or an NS-BH system that tidally disrupts prior to merger. For this purpose, binary neutron star systems have both $m_1, m_2 \leq 3\,M_\odot$, and an NS-BH binary that tidally disrupts prior to merger means a central black hole forms and a non-vanishing amount of matter is liberated by the neutron star tidal disruption, a few milliseconds after the merger. This matter includes the accretion disk mass, the mass of the tidal tail, and the mass of potential ejecta. To identify the tidal disruption condition, we use the formulae for the remnant liberated mass provided in [8] (an application of the interpretation suggested by the phenomenological model introduced in [17]): any NS-BH binary that liberates a non-vanishing amount of neutron star matter is assumed to be a potential EM-bright candidate. [Because we assume the spin and orbit are aligned, we do not generalize this expression to precessing spins, as in [13, 20].]

How do these rapid estimates differ from a slower but more accurate estimate?: The rapid procedures reported in the initial alert currently use information provided by the search code to generate an error ellipsoid (centered on the search-provided point estimate and covering the 90% confidence region; see Sec. III for further technical details). The probabilities we report are the fraction of the volume of this ellipsoid that intersects the parameter space region of interest (e.g., $m_2 \leq 3\,M_\odot$). We specifically note that the fraction of volume is not equivalent to the posterior weight within that region and only serves as an approximation. As noted below, these calculations assume that spin and orbital angular momentum vectors are parallel.

By contrast, full Bayesian parameter estimates generally account for generic spin precession, provide a robust estimate of the posterior distribution, and include estimates for all source parameters, including source orientation relative to the line of sight. We expect to revise our estimate for these two probabilities using these more comprehensive calculations.

Closely related literature: Pannarale et al [16] introduced the idea of targeting certain gravitational-wave triggers for EM follow-up, based on a ellipsoid-based estimate of whether their parameters were consistent with a tidal disruption condition. Miller et al [13] demonstrated how to use full parameter estimation to evaluate an EM-bright probability, to quantify whether a candidate event merited follow-up.

III. SUPPLEMENTARY INFORMATION

Where this information appears in alerts: Authoritative information about where to find these parameters is available on the LV-EM wiki [9]. Sample events are provided from the "first2years" study.

- *GCN*: GCN notices for LIGO will include this information as `ProbHasNS` and `ProbHasRemnant`.
- *VOEvent*: LIGO VOEvents [7] will include `ProbHasNS` and `ProbHasRemnant`; see examples on the LV-EM wiki page.
- *GraceDB*: In GraceDB, information about EM classification will be provided in two formats, both tagged `lvem`. The first is a human-readable message:

  ```
  EM-Bright probabilities computed from detection pipeline: The probability of second
  object being a neutron star = 100.0% The probability of remnant mass outside the black
  hole in excess of 0.0 M_sun = 100.0%
  ```

  The second is a .json file

  ```
  {"Prob NS2": 100.0, "Prob EMbright": 100.0}
  ```

  VOEvent files are also archived in GraceDB.

Caveats: What our rapid estimates do not account for: We adopt simple and rapid estimates in the quantities provided above. We therefore omit many possible factors, necessary to provide the best possible Bayesian inference about whether the objects are neutron stars and/or could produce an associated EM counterpart:

- *Direct identification of matter from gravitational waves*: We do not use subtle features of the signal to identify the unique signatures of matter on the gravitational wave signal (e.g., tidal deformability, multipole moments, modified termination frequency).
- *Central engine: what makes a binary EM bright?*: Except for the requirement that matter exist outside the remnant central object, we (conservatively) apply no constraints to restrict whether a binary is EM bright or not. In particular, we do not account for source orientation, potentially important if a central engine model is tightly beamed. Since we do not know the relative event rate or parameter distribution of EM-bright and EM-dark events, we also do not prioritize follow-up in any region of parameter space — and, in particular, we can and do treat follow-up towards high mass, high-spin binary black holes with neutron stars equally with an NS-BH binary with a black hole in the mass gap.
- *Astrophysical priors and no precession*: We assume all masses and component compact object spins are equally likely to occur, even for binary neutron stars. We assume the binary's spins are aligned with the orbital angular momentum — often a good first approximation for detected sources, particularly given degeneracies [12], but not necessarily true, particularly given strong supernova kicks on neutron stars in NS-BH binaries.
- *Neutron star equation of state*: We adopt a conservative equation of state. The tidal disruption condition depends on neutron star compactness [8].

  We pick an equation of state that yields neutron stars with a $\sim 15\,\mathrm{km}$ radius and a maximum neutron star mass of $2.8\,M_\odot$. Both choices enhance the possibility of having matter in the aftermath of an NS-BH merger. This equation of state – namely the 2H 2-piecewise polytrope, e.g., [10] – represents a conservative upper limit on equations of state supported by current astrophysical observations and by nuclear physics calculations, e.g., [19].
- *Waveform systematics*: Einstein's equations have not been completely solved; even our best inferences rely on assumptions and approximations. These assumptions break down for moderate to high mass ratio and spin, as well as near merger. These approximate models also often neglect the impact of higher harmonics. While some preliminary studies suggest some of these omissions may have modest impact on pertinent observables [6, 13, 14], considerably more study is needed to assess their impact here.
- *Detailed parameter estimation*: Our rapid estimate assumes a loud signal and hence an ellipsoidal ambiguity region around the parameters reported by the search. More detailed parameter estimation may result in posterior distributions that are not necessarily ellipsoidal. Further, they may yield final estimates with support in the mass space that exceeds the $3\,M_\odot$ upper limit used in the rapid estimate approach.

Rapid estimate: further technical details: Three parameters that characterize a given trigger are of interest for our purposes: the two masses, and the black hole dimensionless spin parameter $(m_1, m_2, \chi_{1,z})$. These quantities influence the gravitational-wave signal in certain combinations, most strongly through chirp mass $[(m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}]$; as a result, gravitational-wave measurements (which naturally constrain these correlated combinations) lead to strongly-correlated constraints on the astrophysically relevant parameters [18]. We use the *effective Fisher matrix method* [6] to model the ambiguity region — assumed to be an ambiguity ellipsoid — around the trigger point in the parameter space. We use the code provided in [15] to construct these ellipsoids that (approximately) cover the 90% confidence region, using a point-particle inspiral-merger waveform model (SEOBNRv4, [4]), transitioning to a post-Newtonian model at low masses.

LIGO policy documents for O2: For reference for LVC members seeking up-to-date policy documents related to this document's description, we provide a brief summary of the most pertinent and current documents. The EM follow-up communication plan for O2 is outlined in LIGO-M1600034 [5]. Before automated alerts become active, the decision process procedures for releasing a trigger are described in LIGO-L1600157 [3].

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