An Astrophysical Metric for LIGO Open Data Release
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We describe a quantitative criterion, based on the astrophysical predictions for binary neutron star (BNS) coalescence rates, for deciding when to release the data from Advanced LIGO gravitational-wave detectors to the broader scientific community. We find that an observable space-time volume for BNS systems of 3×10^7 Mpc^3 yr, corresponding to an observation time of slightly less than one year at design sensitivity for two Advanced LIGO detectors, would give a "reasonable chance" of detecting gravitational waves from BNS mergers, and is a well-motivated astrophysical criterion for defining the beginning of the LIGO open data era.

I. THRESHOLD FOR A REASONABLE CHANCE OF DETECTION

The LIGO Laboratory and the LSC intend to release data from the advanced LIGO detectors some fixed period of time after there is a "reasonable chance" of detecting gravitational waves. The purpose of this note is to establish a quantitative criterion, based on astrophysical considerations, for a threshold past which a reasonable chance of detection can be expected. The specific details of the data release (such as cadence, specific data products, etc.) as well as data release policies are not covered in this note.

Given the significant uncertainties in the rates and strengths of astrophysical sources, it is possible that no gravitational waves will be detected even when this criterion is met. Nevertheless, it is reasonable to guide our decision on when to release data by considering plausible astrophysical scenarios.

In developing these criteria, we are guided by the qualitative and quantitative considerations listed in the bullets below.

We find that an observable space-time volume for BNS systems of 3×10^7 Mpc^3 yr, corresponding to an observation time of 0.9 years at design sensitivity for two Advanced LIGO detectors, would give a "reasonable chance" of detecting gravitational waves from BNS mergers, and is a well-motivated astrophysical criterion for defining the beginning of the LIGO open data era.

A. Considerations for setting a threshold for a reasonable chance of detection

- Binary neutron stars. There are numerous plausible astrophysical sources of gravitational waves searched for with LIGO data [1]. However, only one source is at all constrained by direct astrophysical observation: the merger (coalescence) of binary neutron stars (BNS). Several binary neutron star systems in our Galaxy are known to be within 1 Gyr of merger [2]; most notably, the double pulsar system PSR J0737-3039 which will merge in $\sim$ 85 Myr. From these (with the aid of detailed modeling, see for example [3, 4] and references in [2, 5]), we can predict a merger rate per Milky Way Equivalent Galaxy (MWEG) [5], albeit with large uncertainties.

- Rate per unit volume. The rate of BNS mergers in our Galaxy is far too low for observation [5], but the LIGO and Virgo detector network can detect signals from distant galaxies, to sufficient distance that the density of source galaxies is essentially uniform. It is conventional to assume (crudely) that the merger rate is proportional to the star formation rate in a galaxy, for which blue light is a proxy [6]; this neglects (uncertain) contributions from older galaxies with little star formation [7]. The Milky Way is estimated to have a blue light luminosity of $\sim 1.7 \times 10^{10}\ L_\odot = 1.7 L_{10}$, where $L_\odot$ is the Solar blue light luminosity and L_{10} is $10^{10} L_\odot$ [8]. The density of galaxies emitting blue light within $\sim$ 1 Gpc of us is estimated to be 0.02 L_{10}/Mpc^3 [8]. Thus, a merger rate per MWEG can be converted to a merger rate per Mpc^3.

- Number of detected events. We can establish a "SenseMon distance" D_S (defined below) out to which a network of detectors can reliably detect BNS mergers. This corresponds to a detection volume of $V_S = 4\pi D_S^3/3$. An observation over a time T at that sensitivity corresponds to a four-dimensional (space-time) volume VT. If the rate of BNS mergers per unit volume is R_{BNS}, then the number of expected detections is a Poisson process with mean $\bar{N}_{BNS} = R_{BNS} VT$.

- Requirement on the expected number of detections. Since BNS mergers are a Poisson process, we require the mean $\bar{N}_{BNS}$ to be large enough that at least one or two events would be observed. We will require a threshold of $\bar{N}_{BNS} = \bar{N}_{thr} = 3$, corresponding to a probability of 1 or more detections of 95%, and a probability of 2 or more detections of 80%. The corresponding space-time volume threshold is $VT_{thr} = \bar{N}_{thr}/R_{BNS}$ in units of Mpc^3 yr.

- Merger rates. For astrophysical merger rates, we use the predictions described in the CBC (Compact Binary Coalescence) rates paper [5]. These include predictions for three binary source types: neutron star – neutron star (BNS), neutron star – black hole (NS-BH) and black hole – black hole (BH-BH). For each binary type, three values are quoted: plausible pessimistic, realistic (i.e., most likely), and plausible optimistic rates. For systems involving black holes, there are no direct observational constraints, so the predictions are based on models. For BNS, extrapolations from observed Galactic binary pulsars and observationally constrained models yield a realistic rate of ~ 100 mergers per MWEG per Myr, with a plausible range between ~ 1 and ~ 1000 per MWEG per Myr (Table 2 of [5]). Most of the models in the literature [9] yield rates above 10 BNS mergers per MWEG per Myr, or $R_{BNS} \approx 1 \times 10^{-7}$ / Mpc^3 / yr. We choose to use this rate, which is 10 times lower than our most likely estimate, as a *reasonable conservative rate prediction.*

- VT Threshold. A "reasonable conservative rate prediction" of $R_{BNS} = 1 \times 10^{-7}$ / Mpc^3 / yr corresponds to a space-time volume threshold of $VT_{thr} = \bar{N}_{thr}/R_{BNS} = 3 \times 10^7$ Mpc^3 yr. Given the significant uncertainties in the BNS merger rates, it is possible that no gravitational waves will be detected even when this criterion is met. Nevertheless, it is reasonable to guide our decision on when to release data by considering this plausible astrophysical scenario.

- SenseMon distance. The SenseMon distance D_S [10, 11] (also known as the BNS range) is defined such that the search volume $V_S = (4\pi/3)D_S^3$ is the sky location- and orientation-averaged volume in which a detector has an SNR ≥ 8 for binary neutron star merger signals. It is easily computed from the strain-equivalent noise power spectral density of a detector (which, for the initial LIGO runs, was computed once per minute). For reference, the "horizon distance" used by the CBC group is the distance to which an *optimally* located and oriented system can be detected with $SNR = 8$; it is $D_h \approx 2.26 D_S$.

- BNS Search volume. Due to the presence of non-Gaussian noise fluctuations, the LSC-Virgo BNS searches require coincident signals from at least two detectors (detectors from at least three sites are required to locate the source on the sky). Thus, only periods when at least two detectors are simultaneously operating contribute to the four-dimensional search volume, and the effective search volume depends on the SenseMon distance of the *second most sensitive* detector in the network (different network-SNR thresholds are possible, but we'll stick with this simple definition of effective search volume here). In the initial LIGO and Virgo science runs, it was found [11, 12] that a (simulated) BNS signal with single-detector SNR ≥ 8 was sufficiently far above the (non-Gaussian) coincident noise trigger rate to be considered a reliable detection in double or triple coincidence. This may or may not be true also in the advanced detector era, depending on their glitchiness; with no further information, we take it to be so here. Thus, we take the search volume to be given by $V_S = (4\pi/3)D_S^3$, where D_S is the (SNR=8) SenseMon distance of the second most sensitive detector in the network.

- The space-time counter. During scientific observations we can compute D_{Si} for interval T_i (in the LIGO and Virgo science runs, this was done minute-by-minute) and accumulate $VT = \sum_i (4\pi/3) D_{Si}^3 T_i$, as a measure of our progress towards the threshold of $VT_{thr} = \bar{N}_{BNS}/R_{BNS} = 3 \times 10^7$ Mpc^3 yr.

- Estimated time to reach the VT threshold. The first Advanced LIGO detectors will come online in 2015, and it may take some time for them to reach design sensitivity. There are several possible Advanced LIGO configurations, as described in [13]. Here (as in the CBC rates document) we assume the "Mode 1b", high power broadband RSE configuration, which gives a BNS SenseMon distance of ∼200 Mpc. Assuming this to be the SenseMon distance of the second most sensitive detector in the network, we get an observation time of $T_{thr} = N_{thr}/R_{BNS}/V_S = 0.9$ years. Thus, an observation time of approximately one year at design sensitivity for two Advanced LIGO detectors would give a "reasonable chance" of detecting gravitational waves from BNS mergers.

More details and plots are provided in the Appendix below.

II. APPENDIX

In order to estimate the detection rate for BNS mergers, we need to estimate the SenseMon distance: the distance D_S such that the search volume $V_S = (4\pi/3)D_S^3$ is the sky location- and orientation-averaged volume in which a detector has an SNR ≥ 8 for binary neutron star merger signals. It is easily computed from the strain-equivalent noise power spectral density of a detector [5].

Here, we use the same high laser power, zero detuning configuration [13] that was used in the rates document [5]. Of course, we anticipate the actual sensitivity of the advanced detectors to differ from the sensitivity assumed here. Indeed, the sensitivity will change as the instrument is commissioned, gradually improving over time.

During scientific observations we will compute D_{Si} for interval T_i (in the LIGO and Virgo science runs, this was done minute-by-minute) and accumulate $VT = \sum_i (4\pi/3) D_{Si}^3 T_i$, as a measure of our progress towards the threshold of $VT_{thr} = \bar{N}_{BNS}/R_{BNS}$.

Fig. 1 shows the expected number of detections with the Advanced-detector network as a function of observation time. The blue, green, and red curves correspond to NS-NS (BNS), NS-BH, and BH-BH binaries, respectively. The dashed, solid, and dotted curves correspond to the plausible optimistic, realistic, and plausible pessimistic rates from the rates paper, respectively. In addition, the thick magenta curve represents the "reasonable conservative rate" for BNS systems adopted in this note.

Two black lines are added to guide the eye. The vertical line corresponds to an observation time of 1 year. The horizontal line corresponds to $N_{thr} = 3$ expected detections. Via Poisson statistics, this is the expected number of detections that yields a 95% confidence level that at least one detection will be made if the relevant rate is correct. Conversely, if no detections are made when 3 detections are expected, the given model can be ruled out with a 95% confidence limit.

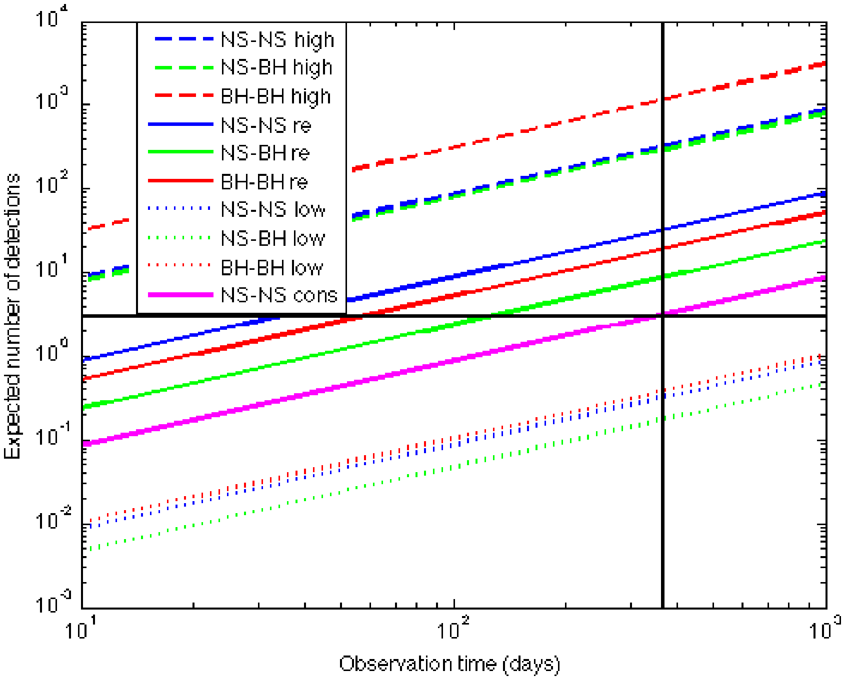

FIG. 1: Expected number of detections in the Advanced LIGO detectors as a function of observation time. Blue, green, and red curves correspond to NS-NS, NS-BH, and BH-BH binaries, respectively. High (dashed lines), realistic (solid lines) and low (dotted lines) merger rate estimates are found in Table 4 of [5]. The "NS-NS cons" (thick magenta) line is the "BNS reasonable conservative rate" adopted in this note. The vertical black line corresponds to an observation time of 1 year. The horizontal black line corresponds to 3 expected detections.

For example, looking at the intersection of the optimistic ("high") predictions with this horizontal level, we see that even a single day of running at the advanced-detector sensitivity would allow us to impose non-trivial constraints on astrophysical models via BH-BH predictions, which means that we will already have an astrophysically interesting result. Tens to ~ 100 of days of running should be sufficient to ensure a detection for all source types in the advanced-detector era if the realistic rate estimates are correct. However, if the plausible pessimistic ("low") rate estimates are correct, even 3 years of running at the model sensitivity of Advanced LIGO will not be sufficient to guarantee a detection at the 95% confidence level. This suggests that it may be impractical to demand that a guaranteed detection is made before data can be released publicly.

In Fig. 2, we show the number of days required to achieve a detection with a 95% confidence level as a function of the horizon distance *for the given binary type.*

One should be careful when interpreting this figure, where the time necessary to achieve an expected 3 detections of binaries of a given type is plotted against the horizon distance for that binary type. It would appear from the plot that NS-NS binaries require the least time to detect, while BH-BH binaries require the most time to detect, because the rates per unit volume per unit time are lower for BH-BH binaries than for NS-NS binaries. However, a reasonable detector configuration will have a much higher horizon distance for BH-BH binaries than for NS-NS binaries, so for a given configuration, the times to detection are typically comparable for the various source types.

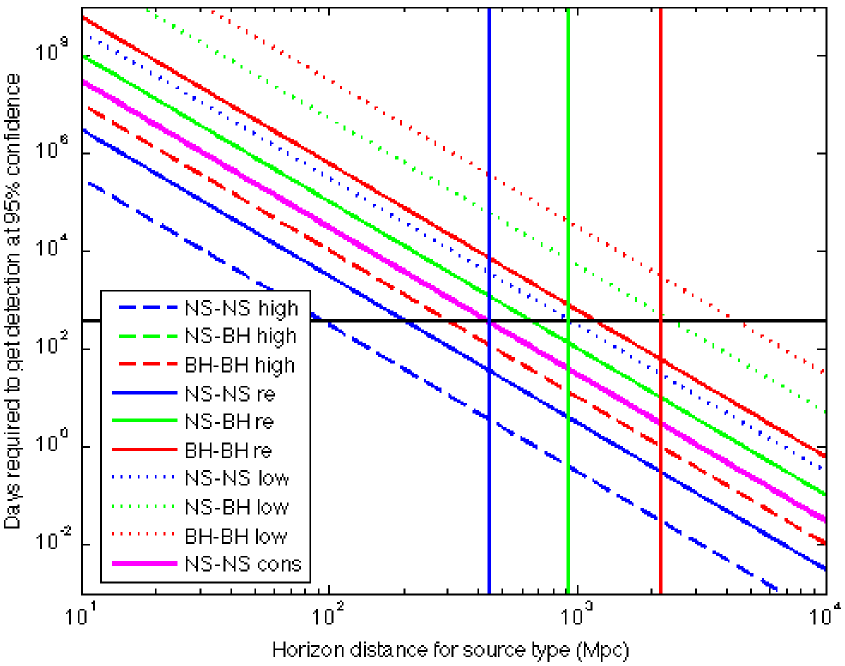

FIG. 2: The number of days required to achieve at least one detection with a 95% confidence level (i.e., 3 expected detections) as a function of the horizon distance *for the given binary type*. The line colors and styles mean the same as they do in Fig. 1. The "NS-NS cons" (thick magenta) line is the "BNS reasonable conservative rate" adopted in this note. The black horizontal line denotes an observation time of 1 year. The colored vertical lines denote the horizon distance for that source binary type for the nominal Advanced LIGO sensitivity.

In Fig. 3, we show the expected number of detections as a function of the four-dimensional detection volume: the volume multiplied by the observation time. The volume is averaged over sky location and orientation; e.g., for binary neutron stars, it is the volume of a sphere whose radius is the *Sensemon* distance. Note that, as in the previous figure, the volume is computed separately for each binary type; a reasonable detector configuration will have a much higher volume for BH-BH binaries than for NS-NS binaries. The black horizontal line denotes 3 expected detections.

Finally, in Fig. 4, we show the expected number of detections as a function of the four-dimensional *Sensemon* volume: the BNS sensitivity volume (averaged over sky location and orientation) multiplied by the observation time. To create this figure, we have assumed that for relatively low-mass systems, the volume for a particular type of mergers scales as $M_c^{15/6}$, where M_c is the chirp mass. We further assumed, as we did in the CBC rates paper, that all neutron stars weigh in at 1.4 solar masses and all black holes at 10 solar masses.

Fig. 4 suggests that a relevant figure of merit for open data release could be the average four-dimensional volume for binary neutron star mergers. A relevant value could be in the range of 3×10^7 Mpc^3 $\times$ yr. This observed volume should be reached in slightly less than one year of observation in the high laser power, zero detuning configuration. Observing this volume will guarantee detections of NS-NS binaries at a 95% confidence level if the actual merger rate is equal to the "reasonable conservative rate" (i.e., 10 times lower than the likely rate). In fact, all three source types should be detected if the actual rates are a few times lower than the current likely predictions. Serendipitous detections may be possible, though by no means guaranteed, even if the actual rates are near the lower end of the range. Even in the absence of detections, the LSC+Virgo network will be able to make very interesting astrophysical statements on the basis of upper limits, since most of the model parameter space will be ruled out, allowing significant constraints to be placed on uncertain astrophysical parameters.

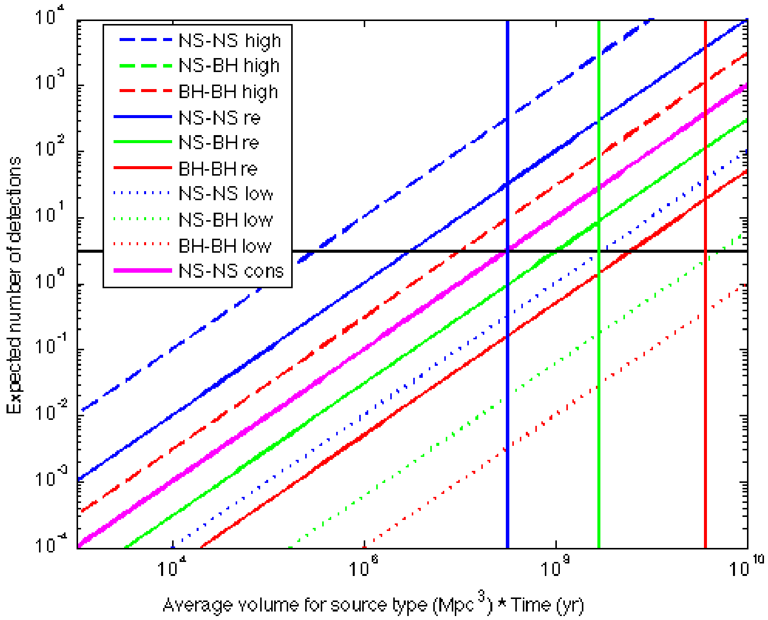

FIG. 3: The expected number of detections as a function of the four-dimensional volume (volume times time, VT) *for the given source binary type*. The line colors and styles mean the same as they do in Fig. 1. The "NS-NS cons" (thick magenta) line is the "BNS reasonable conservative rate" adopted in this note. The black horizontal line denotes an average of 3 detections. The colored vertical lines denote the VT for that source binary type for one year of observation at the nominal Advanced LIGO sensitivity.

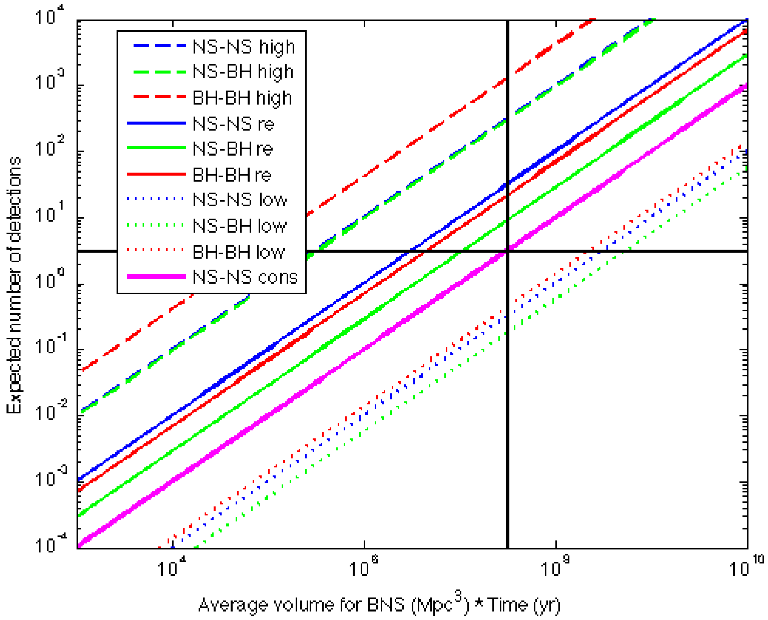

FIG. 4: The expected number of detections as a function of the four-dimensional volume (volume times time, VT) computed for neutron star binaries. The line colors and styles mean the same as they do in Fig. 1. The "NS-NS cons" (thick magenta) line is the "BNS reasonable conservative rate" adopted in this note. The black horizontal line denotes an average of 3 detections. The black vertical line denotes the VT for BNSs for one year of observation at the nominal Advanced LIGO sensitivity.

III. REFERENCES

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