

Follow-up of GWTC-2 gravitational wave events with neutrinos from the Super-Kamiokande detector

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Super-Kamiokande (SK) is a 50-kt water Cherenkov detector, instrumented with $\sim 13\text{k}$ photomultipliers and running since 1996. It is sensitive to neutrinos with energies ranging from 4.5 MeV to several TeV. A new framework has been developed for the follow-up of gravitational wave (GW) alerts issued by the LIGO-Virgo collaboration (LVC). Neutrinos are searched for, using a 1000-second time window centered on the alert time and in both SK low-energy and high-energy samples. Such observation can then be used to constrain the neutrino emission from the GW source. The significance of potential signals has been obtained by comparing neutrino direction with the localization of the GW. The computation of limits on incoming neutrino flux and on the total energy emitted in neutrinos by the source has been performed for the different neutrino flavors. The results using the LVC GWTC-2 catalog (covering O3a period) are presented, as well as the outlooks for the future real-time public release of follow-ups for the O4 period (in 2022) and beyond.

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1. Introduction

The LIGO/Virgo collaboration (LVC) has released GWTC-2, their new catalog of gravitational waves (GW) objects, detected during the first half of the third observing run (O3a) from April to September 2019 [1]. The detection of neutrinos in time and spatial coincidence with any of these objects would be the first hint for a joint source emitting both messengers and it would greatly help to understand the underlying mechanisms.

Super-Kamiokande [2] is a Cherenkov detector located in the Mozumi mine in Japan. It consists in a tank of 50 kt of water, separated into an inner detector (32 kt) equipped with $\sim 11,000$ PMTs and an outer detector used mainly as veto. The data can be broadly divided into four sub-samples:

- low-energy neutrinos (LE- ν , $7 \text{ MeV} < E_\nu < 100 \text{ MeV}$),
- high-energy fully-contained events (HE- ν /FC, $0.1 \text{ GeV} < E_\nu \lesssim 10 \text{ GeV}$),
- high-energy partially-contained events (HE- ν /PC, $0.1 \text{ GeV} < E_\nu \gtrsim 100 \text{ GeV}$),
- and high-energy upgoing muons (HE- ν /UPMU, $E_\nu \sim O(\text{GeV} - \text{TeV})$).

The former is mainly sensitive to electron anti-neutrinos from inverse beta decay and other flavors contribute through elastic scatterings. The FC and PC samples are sensitive to ν_μ , $\bar{\nu}_\mu$, ν_e , and $\bar{\nu}_e$, while the UPMU sample is focusing on muon (anti-)neutrinos originating below the SK horizon (downgoing events are not selected due to large atmospheric muon background).

The data from the detector have been used to search for neutrinos in time coincidence with GW objects, using a 1000 s time window centered on each trigger. For the three high-energy samples, the spatial correlation between the reconstructed neutrino direction and the GW localization is used to assign p-values to the observations and upper limits on the emitted neutrino flux have been computed. Detailed methods and results are presented in [3] and the data release [4] contains the full list of observations and flux limits for the 39 GW in the GWTC-2 catalog.

The [section 2](#) presents an overview of the event-by-event results of the 39 GW follow-ups while the [section 3](#) focuses on the joint analysis of binary mergers in order to constrain their population. Lastly, the [section 4](#) highlights the important results and the prospects for future observations.

2. SK observations

Neutrinos have been searched for in 1000 s time window centered on each GW events from the GWTC-2 catalog. Out of the 39 GWs, the follow-up was possible for 36 of them (35 for low-energy energy neutrinos), as the detector data are not available for 3 of them, due to calibration periods. The number of observed events is compared to the expectation that is based on the average background rate for each sample and on the detector livetime over the time window. The expected backgrounds from solar and atmospheric neutrinos in 1000 s are 0.729, 0.129, 0.007, and 0.015 for LE- ν , HE- ν /FC, HE- ν /PC, and HE- ν /UPMU samples, respectively.

The [Figure 1](#) summarizes the follow-up of all events. No significant excess was observed in any of the four samples: $N_{\text{obs}} = 24, 8, 0, 2$ observed events respectively with the same order as above, compared to $N_{\text{exp}} = 25.0, 4.0, 0.3, 0.6$ expected background events summing over the full list.

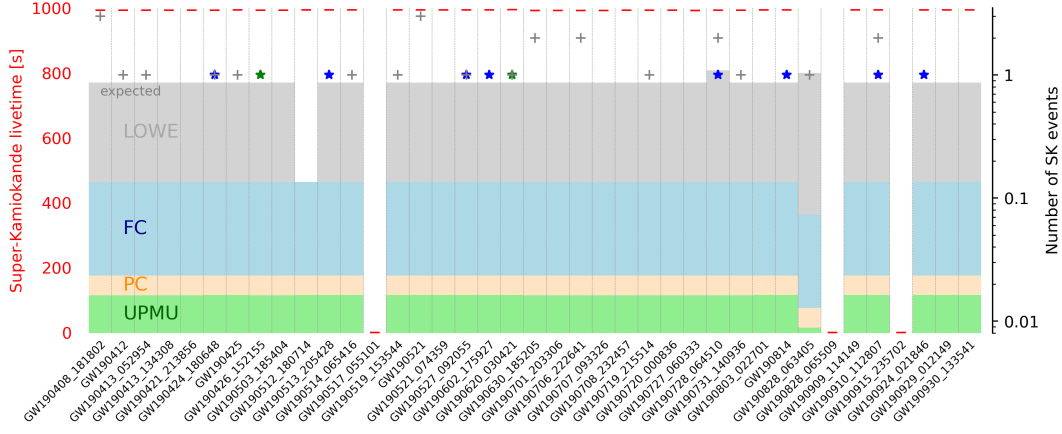


Figure 1: Summary of the follow-up of GWTC-2 events. The red plot shows the Super-Kamiokande livetime over the selected 1000 s window for each trigger. The light color stacked bars indicate the expected number of events and the markers give the observed number of events for the four samples.

For the ten observed events in the HE- ν /FC and HE- ν /UPMU samples, it is possible to use the reconstructed neutrino direction in order to better quantify the “signalness” of the observations (the skymaps are available e.g. in [4]). The method, detailed in [3], consists in defining a test statistic TS to discriminate between background events (covering the full sky and following atmospheric neutrino spectrum) and signal events (point source consistent with GW localization, $E^{-\gamma}$ spectrum).

The final p-value can be dissociated into $p = p_{\text{time}} \times p_{\text{space}}$ where p_{time} is the Poisson p-value associated to the observation of at least one event given the expected background (for $N_{\text{exp}} = N_{\text{exp,FC}} + N_{\text{exp,PC}} + N_{\text{exp,UPMU}} = 0.13$, we get $p_{\text{time}} = 12.6\%$) and p_{space} is obtained comparing observed value of TS to the expected background distribution obtained from MC simulations (with at least one neutrino event).

The Figure 2 illustrates the obtained p-values. The most significant observation is associated to GW190602_175927 with a pre-trial p-value of 0.22%. However, it is needed to take into account the corresponding trial factor (as the analysis was repeated 36 times, for the 36 follow-ups) and the final post-trial p-value is 7.8% (equivalent to 1.4σ), hence being fully compatible with the background-only hypothesis.

Upper limits on the incoming neutrino flux have been computed for each GW and full results are available in [4]. For the LE- ν sample, limits were obtained with the assumption of a Fermi-Dirac spectrum and typical limits are of the order of 10^8 cm^{-2} for the $\bar{\nu}_e$ fluence at 90% C.L. ($10^9 - 10^{10} \text{ cm}^{-2}$ for other flavors). For the three HE- ν samples, limits were computed assuming E^{-2} spectrum, first independently for each sample but also by combining them. As the UPMU sample is only sensitive to events below the horizon, high-energy limits feature two different behaviors: for GW mainly located below the horizon, the UPMU sample is effectively used and we get $E^2 \frac{dn}{dE} < 40 \text{ GeV cm}^{-2}$ (90% C.L.); otherwise, only FC and PC are contributing and $E^2 \frac{dn}{dE} < 2 \times 10^3 \text{ GeV cm}^{-2}$.

Detailed results for low-energy and high-energy samples are presented in [4].

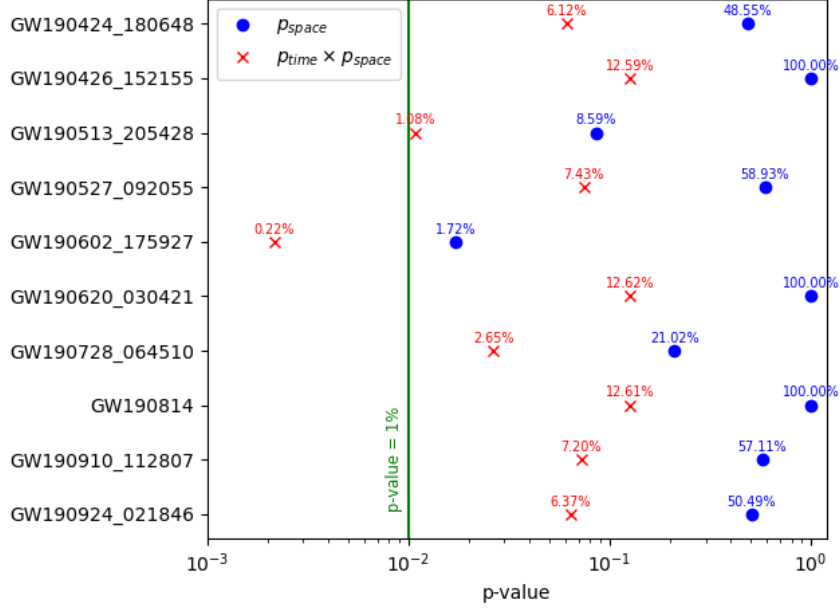


Figure 2: Obtained p-values for the ten observed events in the HE- ν samples. The p_{space} values are reported with blue markers while the total p-values are shown in red.

3. Population constraints with HE- ν samples

As for the neutrino flux, upper limits on the total energy E_{iso} emitted in neutrinos by the source (assuming isotropic emission) can be obtained by taking into account the source luminosity distance d . However, its correlation with the localization has to be considered by using the 3D skymaps (in right ascension, declination and distance) from the GWTC-2 catalog. The full method is described in [3].

The Figure 3 shows the obtained limits on all-flavor E_{iso} for E^{-2} spectrum assuming the flux at Earth is equally distributed between the neutrino flavors ($\nu_e/\bar{\nu}_e$, $\nu_\mu/\bar{\nu}_\mu$, $\nu_\tau/\bar{\nu}_\tau$, where the contribution of the latter in SK samples is neglected in this analysis). This hypothesis of equipartition originates from the most common source scenario where the produced flavor ratio is $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ which becomes $1 : 1 : 1$ after oscillations on astronomical distance. The two-tiers behavior introduced in the last section is clearly visible, with the limits being distributed along two lines depending whether the UPMU contribution is significant or not.

The list of GWTC-2 objects followed by SK is populated with 33 binary black hole mergers (BBH), making it a very good sample to constrain the neutrino emission from these objects. Individual upper limits presented in Figure 3 can thus be combined under the assumption that either (a) all BBH emits the same total energy E_{iso} in neutrinos or (b) E_{iso} is proportional to the total mass of the binary system: $E_{\text{iso}} = f_\nu \times \mathcal{M}_{\text{tot}}$ (where \mathcal{M}_{tot} is obtained from the GWTC-2 catalog). These two hypotheses were investigated and the following limits were obtained:

- (a) $E_{\text{iso}}^{\text{per BBH}} < 4.16 \times 10^{55} \text{ erg}$
- (b) $f_\nu < 1.06 \times 10^{54} \text{ erg}/M_\odot = 66\%$

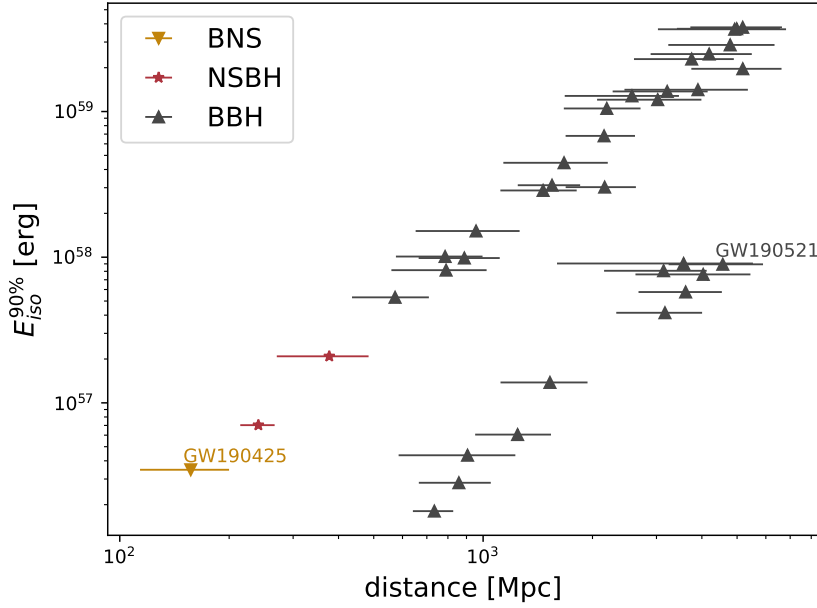


Figure 3: Upper limits on E_{iso} for the 36 GW triggers followed up by SK, as a function of source mean distance, assuming equipartition between all neutrino flavors.

4. Discussion and conclusion

The results presented in the previous sections yield no significant observations and upper limits have been computed. The final results are the 90% upper limits on E_{iso} for each trigger and from the joint study for BBH objects. One can notice that the obtained limits for E^{-2} spectrum are barely covering the unrealistic region where most than half of the initial mass of the binary system is converted to neutrinos, but the situation may greatly change if the assumed spectrum is different (e.g. E^{-2} spectrum with a cut-off or softer spectrum).

Moreover, the GWTC-2 catalog only contains three mergers where neutron stars are likely involved and all these events were located above the SK horizon. The follow-up of mergers during the next GW observation periods are very promising, in particular in the case of binary neutron star mergers (where large neutrino emission is expected [5]) below the SK horizon (where the UPMU sample is expected to contribute). In this context, the possibility to perform real-time follow-up of public alerts with Super-Kamiokande may contribute to the discovery of a joint GW+ ν source, that would complete the triangle of real-time multimessenger observations between neutrinos, electromagnetic and gravitational waves (TXS 0506+056 being the foremost example of coincidence between the two former, and GW170817 for the two latter).

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