PROCEEDINGS OF SCIENCE

Probing neutrino emission at GeV energies from compact binary mergers detected during O1-O4a with the IceCube Neutrino Observatory

The IceCube Collaboration

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Compact binary mergers, detected in gravitational waves since 2015, are candidate sources for astrophysical neutrinos in the GeV regime from proton-proton and proton-neutron collisions. This contribution presents the results of the search for such a signal using mergers detected during the fourth observing run of the LIGO, Virgo, and KAGRA interferometers. We use the dense infill array at the center of the IceCube detector, IceCube-DeepCore, to select neutrino candidates in the 0.5-–5 GeV energy range. The search for a statistically significant excess associated with an astrophysical signal is performed in a ±500 s window around the gravitational wave detection time. We do not observe any statistically significant excess in the neutrino data, and set upper limits on the neutrino emission from these objects. Additionally, we search for subpopulations of neutrino-emitting sources, including merger events detected in previous observing runs; no significant signal has been identified yet.

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Introduction Compact binary mergers, especially those involving at least one neutron star, are candidate neutrino emitters, especially in the GeV energy range [1, 2]. Searches performed so far in this regime have been inconclusive [3–5], reporting upper limits on the flux normalisation.

We report on the search for GeV neutrinos using the "Extremely-LOW-ENergy" (ELOWEN) sample, an event selection focusing on clusters of hits identified in DeepCore [6], the inner and denser sub-volume component of the IceCube Neutrino Observatory [7]. The ELOWEN selection has a background rate of about $20 - 25$ mHz and is mostly sensitive to neutrinos in the $0.5 - 5$ GeV energy range.

More details on the motivation, context, methods, and results of the presented analysis can be found in the related publication [8].

Analysis We focus on compact binary mergers detected in gravitational waves by LIGO-Virgo-KAGRA [9–12] between the first observing run (O1, September 2015) and the first part of the fourth observing run (O4a, January 2024). For each gravitational wave event, we search for an excess of ELOWEN events in a ± 500 s time window centered on the gravitational wave detection time $t_{\rm GW}$. For mergers involving at least one neutron star, we also investigate a shorter time window $[t_{\rm GW}, t_{\rm GW} + 3\,{\rm s}]$, as motivated notably by the observed time delay between the detection of the binary neutron star (BNS) merger GW170817 and the onset of the associated gamma-ray burst, GRB 170817A [13].

The analysis was performed for 178 sources, including 167 binary black hole (BBH) mergers, 9 neutron star – black hole candidates (including the marginal candidate GW200105_162426), and 2 BNS candidates. For each source, we compute the pre-trial p-value, and the best one is found to be 0.25% for S230707ai. However, this corresponds to a 40% post-trial p-value, therefore not significant.

In the absence of any excess, we compute upper limits on the all-flavour neutrino flux at Earth at 90% credible level, assuming an $E^{-\gamma}$ spectrum, with $\gamma = 2, 2.5, 3$. Figure 1 summarises the limits for $\gamma = 2$, compared to the results from the GRECO Astronomy [3] and the Gamma-ray Follow-up (GFU, [14]) datasets, which focus on GeV–TeV neutrinos and TeV–PeV track-like events, respectively.

Additionally, we perform a binomial test to search for evidence of subpopulations of neutrino emitters among the analysed mergers. We obtain a post-trial p-value of 81%, fully consistent with the background hypothesis.

Conclusion Despite not being able to claim any significant detection, the presented analysis shows several promising prospects. First, as illustrated in Figure 1, the different IceCube event selections probe complementary energy ranges, therefore maximising the chances to eventually identify the underlying neutrino production mechanisms. The plot also highlights how joint analyses, combining different datasets, could strengthen constraints on the neutrino energy distribution. This approach could be extended in the future to include multiple neutrino telescopes, further improving source characterization.

Second, the limits will be significantly enhanced by new developments in the ELOWEN selection, which will improve the noise rejection and incorporate a limited direction reconstruction [15]. Other approaches are currently under investigation to reduce the energy threshold even further.

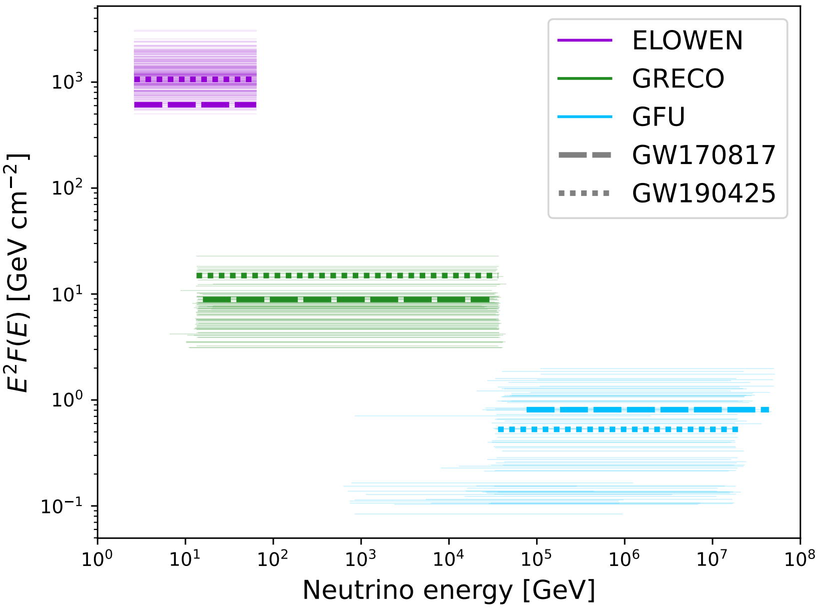

Figure 1: Summary of 90% upper limits on the all-flavour time-integrated energy-squared flux $E^2 F^{\nu+\bar{\nu}}_{\mathrm{all-flavour}}(E)$ assuming a power-law spectrum $F^{\nu+\bar{\nu}}_{\mathrm{all-flavour}}(E) = \phi(E/\mathrm{GeV})^{-2}$. The different colours correspond to different IceCube samples: ELOWEN (this work), GRECO [3], and GFU [14]. The spans in the horizontal axis correspond to the central 90% sensitive energy range for each GW event and sample. The thicker dashed and dotted lines are the limits corresponding to the two confirmed BNS mergers, GW170817 and GW190425.

Finally, the upcoming deployment of the IceCube Upgrade [16], notably including multi-PMT optical modules, will significantly improve the direction reconstruction capability and the effective area in the GeV range, pushing further the sensitivity of future searches.

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