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Prospects for gravitational wave triggered high energy neutrino searches from binary neutron star mergers

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The next generation gravitational wave (GW) detectors - Einstein Telescope (ET) and Cosmic Explorer (CE), will have distance horizons up to $\mathcal{O}(10)$ Gpc for detecting binary neutron star (BNS) mergers. This makes them ideal to be used as triggers for neutrino searches from BNS mergers at the next generation neutrino detectors like IceCube-Gen2 and KM3NeT. We calculate the distance limits up to which meaningful triggers from the GW detectors can be used to minimize backgrounds and collect a good sample of neutrino events at the neutrino detectors, using the sky localization capabilities of the GW detectors. We then discuss the prospects of the next generation detectors to work in synergy to facilitate coincident neutrino detections or to constrain the parameter space in the case of non-detection of neutrinos. We find that for a typical scenario while CE and ET can provide with such detections or constraints over a timescale of $10-20$ years, the combination of ET+CE, owing to its good localization capabilities can lead to coincident detections or constraints at the 3σ level within 20 years even for the most conservative parameter choices.

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[*] Speaker

1. Introduction

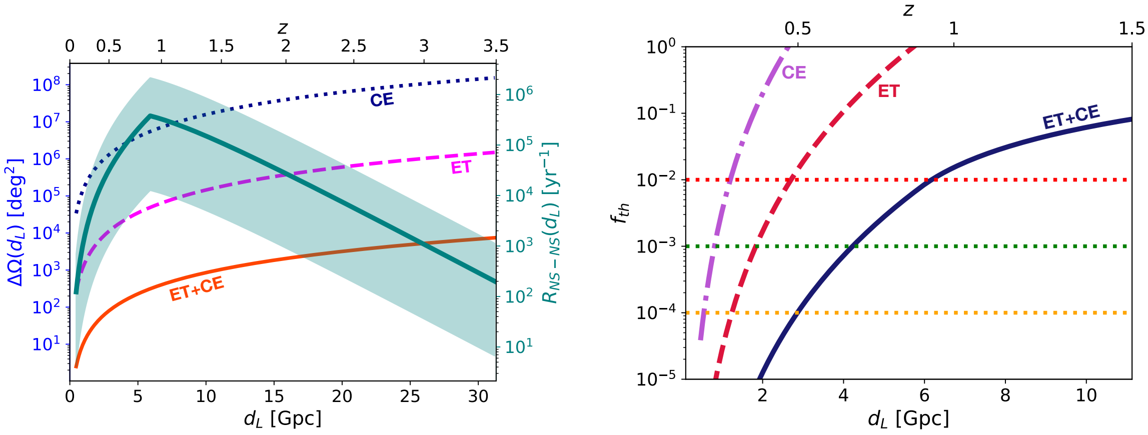
The ongoing era of multi-messenger astronomy will further advance with the next generation of gravitational wave (GW) and neutrino detectors which are capable of probing very large distances. This will naturally open up the possibility of using the joint capabilities of the detectors in regards to their respective messengers from various astrophysical sources in order to maximize our understanding about these sources through observational insights. Using GW or neutrino-triggered searches have been discussed in the literature depending on the distance horizon of the corresponding detectors in a particular scenario [1–3]. In this work we focus on the synergy between next generation GW detectors like the Einstein Telescope (ET) [4], Cosmic Explorer (CE) [5], and a combination of the two ET+CE, to provide triggers for neutrino searches at upcoming IceCube-Gen2 [6].

Although the main question to answer would be, what distance horizons are useful to give a relatively clean IceCube-Gen2 data sample of high energy neutrino events from a generic astrophysical source, in this work we focus on the case of binary neutron star (BNS) mergers. The combination of triggered searches along with distance limits, although less rigorous, can be complementary to likelihood searches.

2. Strategy

In this section we focus on the generic strategy to collect a low background neutrino sample from generic astrophysical sources in particular compact object mergers. A generic high-energy astrophysical phenomenon leads to radiation in various multi-messenger channels. Assuming the total energy radiated to be $E^{\rm tot}$, we have, $E^{\rm tot} = E_{\rm GW} + E_\nu^{\rm HE} + E^{\rm Misc}$, where, $E_{\rm GW}$ is the energy emitted in GWs, $E_\nu^{\rm HE}$ is tht energy emitted in high-energy neutrinos, and $E^{\rm misc}$ involves the energy emitted in all other (including exotic if applicable) channels. Next generation GW detectors have very large distance horizons of upto $z \sim 10$ for BNS mergers. At such large distances, the number of triggers provided by the next-generation GW detectors for the neutrino detectors would be very large owing to the rate of BNS mergers. Thus, it then becomes crucial to quantify what distances are useful to use the GW triggers from, such that the background events in the neutrino detector are minimum. We use the sky localization capabilities of the GW detectors to estimate a critical distance up to which the GW triggers can be useful.

The total energy emitted in high energy neutrinos can be written as, $E_\nu^{\rm HE} = f_\nu^{\rm HE} f_{\rm bm} E_{\rm GW} = f_\nu E_{\rm GW}$. For a BNS merger, $E_{\rm GW} = \alpha E^{\rm tot}$, where $\alpha \sim 1\%$ is the fraction of total energy emitted in GWs. The fraction of GW energy emitted in neutrinos is given by $f_\nu^{\rm HE}$. However, not all sources have a jet directed towards us (which is assumed to be a typical case for neutrino production). This is accounted for by considering a factor $f_{\rm bm}$. For example, in [7], where a scenario of neutrino emission from BNS merger was studied, the authors found $f_\nu^{\rm HE} \sim 0.1\%$ and $f_{\rm bm} \sim 0.1\%$. Combining the two factors we define an effective parameter f_ν which gives the total fraction of GW energy that is emitted in high-energy neutrinos. This will be an important parameter for our work.



(a) (b)

Figure 1: (a) The right axis shows the the size of the localization area in the sky for a single BNS merger event ($\Delta\Omega$) as a function of the luminosity distance d_L for CE (dashed dark blue line), ET (dashed pink line), and ET+CE (solid orange line). The left axis shows the BNS merger rate $R(z)$. The fiducial rate is shown as a solid teal line and the area between the upper and the lower limits of $R(z = 0)$ is shaded. (b) The fraction of sky area covered $f_{\rm th}$ as a function of d_L for CE (dot-dashed purple line), ET (dashed orange line), and ET+CE (solid dark blue line). The $f_{\rm th}$ corresponding to 10^{-2}, 10^{-3}, and 10^4 are also shown.

2.1 Sky localization for GW detectors

The total fraction of the sky area covered as a result BNS merger event detections in a given time period by the GW detector can be given by,

$$\left(\frac{\Delta\Omega\big(d_L(z)\big)}{4\pi} N_{\rm BNS}(z)\right) = f_{\rm th}\,, \tag{1}$$

where, $f_{\rm th}$ is the fraction of the sky area covered which we use as a threshold and hence a free parameter, $d_{\rm L}$ is the luminosity distance which is a function of the redshift z, $\Delta\Omega$ is the size of the localization area in the sky for a single BNS merger event for a given GW detector, $N_{\rm BNS}$ is the total number of BNS merger events at a given redshift z in a given time period.

Given the properties of the GW detector, the size of the localization area $\Delta\Omega$ depends on the distance to the source [8]. In Fig. 1a we show $\Delta\Omega$ as a function of the luminosity distance d_L for ET (dashed pink), CE (dotted dark-blue) and ET+CE (solid orange). As the distance to the source increases as expected the localization area becomes larger. It is interesting to note that although CE has a longer arm and hence is sensitive to higher distances for BNS mergers, it has a comparatively poor sky localization capability owing to a single arm as compared to the ET which can use triangulation techniques to have a much better (around an order of magnitude) sky localization capability. The combination of ET+CE is the most effective and has a localization capability which is an order of magnitude better than that of ET.

2.2 BNS merger rates

In this section we discuss the rate of BNS mergers which then helps calculate $N_{\rm BNS}$ in Eq. (1). The redshift dependence of the rate is adapted from that of short GRBs [9]. This is a reasonable assumption given that short GRBs might primarily originate from NS-NS mergers. The redshift dependent rate of compact binary mergers is given as [9],

$$R(z) \equiv \mathcal{N} R(z=0) \begin{cases} \mathrm{Exp}\big((z-0.9)/0.39\big)\,, z \leq 0.9\,, \\ \mathrm{Exp}\big(-(z-0.9)/0.26\big)\,, z > 0.9\,, \end{cases} \tag{2}$$

where, the normalization $\mathcal{N}$ is chosen such that the rate at $z = 0$ is given by the fiducial rate, $R(z = 0) = 300\ \mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$. We choose a conservative value for the fiducial case. However, this rate has associated uncertainties and can vary over a wide range between $10\ \mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$ and $1700\ \mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$ [10]. In Fig. 1a, we show the $R(z)$ as a function of d_L, where the fiducial rate ($R(z = 0) = 300\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$) is shown as a thick solid line and the area between the upper and lower limits are shaded with teal. We see the break at $z = 0.9$ as the peak according to Eq. (2). The cumulative rate is given by, $R_{\mathrm{BNS}}(z) = \int_0^z dz'\ R(z')$. We note that given that the rate decreases post $z = 0.9$, it implies that the cumulative rate becomes approximately constant for $z \gtrsim 0.9$.

2.3 Fraction of sky area covered

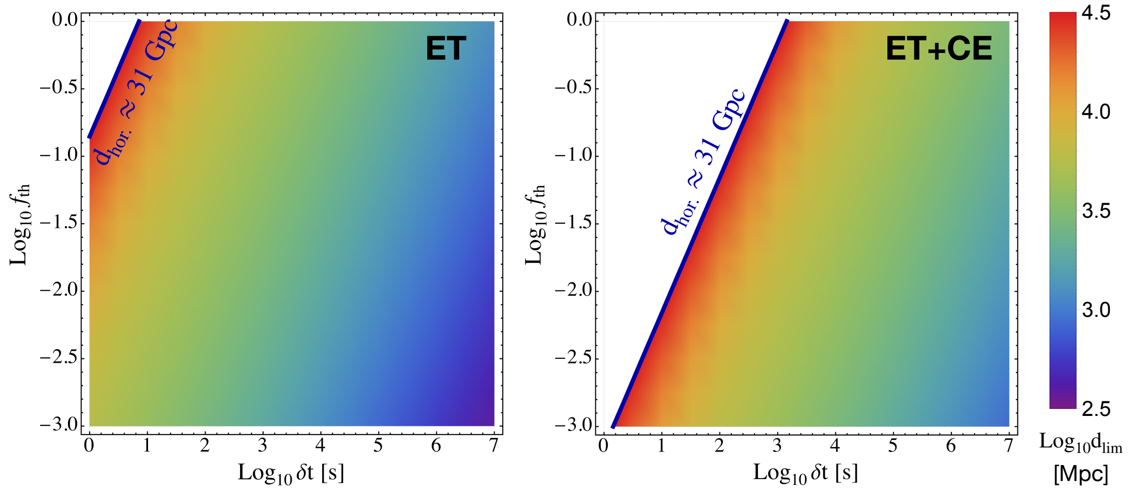


Figure 2: Density plot showing the limiting distance ($d_{\mathrm{GW}}^{\mathrm{lim}}$) for ET (*left*) and ET+CE (*right*) on the δt - f_{th} plane. The maximum distance horizon ($d_{\mathrm{GW}}^{\mathrm{max}} \approx 31\mathrm{Gpc}, z = 3.5$) is shown as a solid dark blue line. We do not show our results beyond this distance (the white space).

We now have all the ingredients to evaluate Eq. (1). The total number of BNS merger events at a given redshift z in a given time period δt can be given by,

$$N_{\mathrm{BNS}}(z) = \delta t\ R_{\mathrm{BNS}}(z) \left(\frac{4}{3}\pi d_{\mathrm{com}}(z)^3\right), \tag{3}$$

where, d_{com} denotes the comoving distance and the term in the paranthesis gives the comoving volume. The time interval δt is an important quantity and is given by the neutrino emission duration from the time of the GW trigger. The lesser the value of δt the better chances we have to use triggers from larger distances. This is because a larger value of δt would lead to more number of triggers and hence higher backgrounds. Assuming a typical $\delta t \sim 1000$s in Fig. 1b we show the fraction of sky area covered by CE (dot-dashed purple), ET (dashed red), and ET+CE (solid dark blue) with the luminosity distance. Depending on the chosen value of $f_{\rm th}$, one can estimate the distance limit for a given GW detector from which triggers can be used to have reduced backgrounds. Similar to the localization capabilities we have the ET+CE combination to be the most effective followed by ET and CE. For CE the fraction of sky area covered needs to be relatively larger than ET and the combination. For $f_{\rm th} \sim 1\%$. of the total sky area CE is limited to $\sim$ 1 Gpc. The case can be improved for ET where choosing a threshold of $f_{\rm th} \sim 0.1\%$ of the total sky area puts the distance limit at $\sim$ 2 Gpc and the combination of ET+CE can have a limit at $\sim$ 2.5 Gpc where the $f_{\rm th}$ has a very small value of $f_{\rm th} \sim 0.01\%$ of the total sky area.

From Eqns. (1) and (3) it is evident that the combination of $f_{\rm th}$ and δt plays an important role in deciding the distance limits for the GW detectors to consider triggers from. In Fig. 2 we show the distance limits for ET (left) and the combination ET+CE (right) on the $f_{\rm th} - \delta t$ plane. For both the detectors we only consider luminosity distances upto $d_L \sim 31$ Gpc ($z \sim 3.5$). This is shown by the solid blue line on the plane, beyond which we do not show the results. We note for short values of $\delta t \sim 2$s corresponding to neutrino emission as was the case in [7], we find very large distance limits for ET and the combination ET+CE. However for neutrino emission scenarios where $\delta t \sim 10^6$s like in magnetars we are limited to less than 1 Gpc.

3. Results

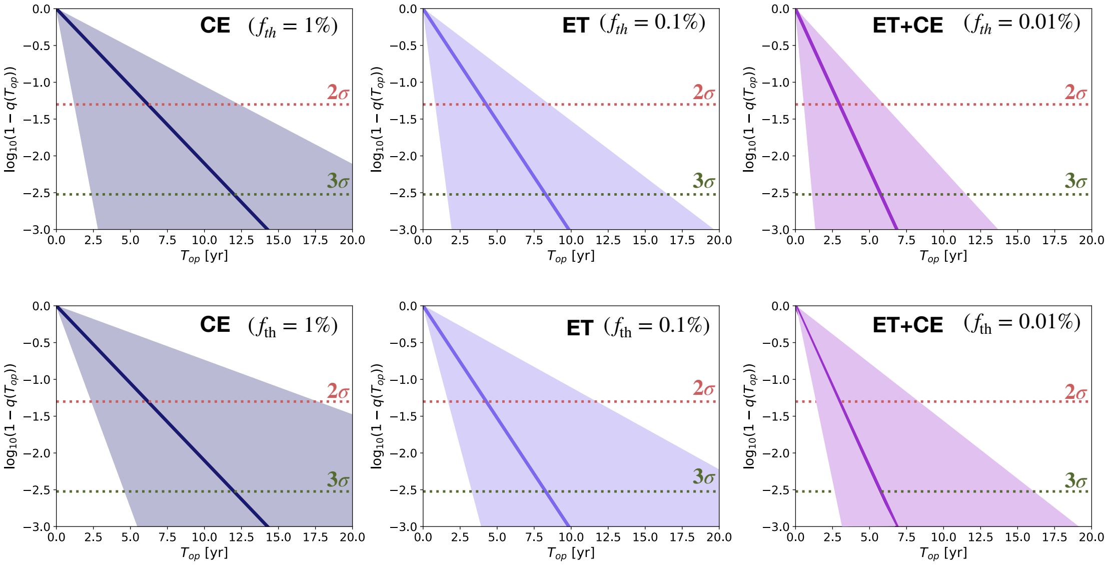


Figure 3: The probability of neutrino detection (q) with the operation time T_{op} for a range of f_ν (*top row*) and δt (*bottom row*) for the different GW detectors. The fiducial case for each panel is shown as a solid line. The 2σ and 3σ C.L.s are also shown with dashed lines. See the text for details on parameters.

In this section we discuss the prospects for next generation GW detectors to trigger searches in neutrino detectors to find coincident events or constrain the physical parameter space at a particular confidence level (C.L.). The probability to detect more than one neutrino associated with a GW signal is given by [11], $q(z^{\rm GW}_{\rm lim}, T_{op}) = 1 - {\rm Exp}\big(-T_{op} I(z^{\rm GW}_{\rm lim})\big)$ where, T_{op} is the operation time of the GW detector, $z_{\rm lim}^{\rm GW}$ is the distance limit given a particular value of threshold obtained from Sec. 2. The quantity I is defined as,

$$I(z_{\rm lim}^{\rm GW}) = 4\pi \int_0^{d_{\rm com}^{\rm UL}} d(d_{\rm com}) \frac{T_{op}}{\left(1+z(d_{\rm com})\right)} R\left(z(d_{\rm com})\right) d_{\rm com}^2 P_{n\geq 1}\left((1+z(d_{\rm com}))d_{\rm com}\right) \tag{4}$$

where, the integral is performed over the comoving distance, the upper limit is chosen to be the minimum of the limiting distance ($d_{\rm hor}^{\rm GW}$) or the maximum distance considered ($z_{\rm lim}^{\rm GW}$) which is set to $z \sim 3.5$, that is, $d_{\rm com}^{\rm UL} = \min\left({\rm d_{hor}^{GW}}({\rm z_{lim}^{GW}}), {\rm z_{lim}^{GW}}\right)$, and $P_{n\geq 1}(r)$ is defined as the declination integrated (or total) probability to detect at least one neutrino as a function of distance, $P_{n\geq 1}(r) = (1/4\pi) \int d\Omega \; p_{n\geq 1}(\delta, r)$. The declination ($\delta$) dependent probabililty ($p_{n\geq 1}(\delta, r)$) to detect at least one neutrino is given by the Poissonian probability, $p_{n\geq 1}(\delta, r) = 1 - \exp\left(-{\rm N}_{\nu_\mu}(\delta, {\rm r})\right)$, where, $N_{\nu_\mu}(\delta, r)$ is the number of neutrino events from a source at distance r. The expected number of neutrino events at a given declination is given as, $N_{\nu_\mu}(\delta, r) = \int_{E_\nu^{\rm LL}}^{E_\nu^{\rm UL}} dE_{\nu_\mu} \phi_{\nu_\mu}(E_{\nu_\mu}, r) \mathcal{A}_{\rm eff}(E_{\nu_\mu}, \delta)$, where, $E_\nu^{\rm LL}$ and $E_\nu^{\rm UL}$ gives the lower and the upper limits of the integral and is decided based on the neutrino energy spectra from a particular source. For this work we choose, $E_{\rm LL} = 10^3$GeV and $E_{\rm UL} = 10^6$ GeV, ϕ_{ν_μ} gives the neutrino flux from a given source at some distance r, $\mathcal{A}_{\rm eff}$ is the IceCube effective area. For this work, we use the 10 years point source (PS) effective area from IceCube [12], scaled with a factor of $10^{2/3}$ in accordance with the estimates of IceCube-Gen2..

The neutrino flux given a total energy in high-energy neutrinos $E_\nu^{\rm HE}$ and assuming a E_ν^{-2} spectra is given as,

$$\phi_\nu(E_\nu^{\rm HE}, E_\nu, r) = \frac{1}{4\pi r^2} \frac{E_\nu^{\rm HE}}{\ln\left({\rm E_\nu^{UL}}/{\rm E_\nu^{LL}}\right)} E_\nu^{-2}\,, \tag{5}$$

and $\phi_{\nu_\mu}(E_\nu, r) = (1/3)\phi_\nu(E_\nu^{\rm HE}, E_\nu, r)$. It is important to note that this is a generic flux and the upper and the lower energy limits are chosen according to $p\gamma$ interactions, which is an optimistic case. These limits would change for pp interactions and might lead to not so optimistic results.

It is important to understand the time-scales over which the next generation GW detectors need to operate to either enable coincident neutrino detection or in case of non-detections, constrain the physical parameter space. We address this question in Fig. 3, where we plot the probability of neutrino detection at IceCube-Gen2 with T_{op} of the GW detectors, which serves as one of our main results. The two main parameters are f_ν and δt, while the former decides the total energy emitted in high energy neutrinos, the latter allows us to put a distance limit to reduce backgrounds to facilitate detections.

In the top row of Fig. 3 we vary f_ν, while the bottom row shows the variation in δt. The fiducial case in each case is given by $f_\nu = 0.001\%$, $\delta t = 1000$s, and $E^{\rm tot} = 5 \times 10^{54}$erg which is a typical value from BNS mergers [13]. We vary f_ν between 0.0005% and 0.005%. The shaded region shows the area between the upper and lower limits of f_ν. We note that a higher value of f_ν will lead to smaller operation times to detect coincident neutrinos or put constraints. This is because the flux emitted in neutrinos is higher owing to the larger value of $E_\nu^{\rm HE}$. We choose $f_{\rm th} = 10^{-2}, 10^{-3}, 10^{-4}$ for CE, ET and ET+CE respectively owing to the localization capabilities as discussed in Sec. 2. CE requires an operation time of $\sim$ 15 years to make a 3σ coincident neutrino observation or a constraint on the parameter space in case of a non-observation for the fiducial case. ET would take $\sim$ 10 years to arrive at a similar conclusion, but can reach the 3σ level over a timescale of $\sim$ 20 years even for the lowest value of f_ν. The combination ET+CE can reach the 3σ level in a timescale of $\lesssim 15$ years even for the most conservative choice of f_ν. The time of neutrino emission from the time of GW trigger δt is varied between 1s and 10^6s. In this case, a longer δt leads to less optimistic results which is seen for all three detectors. For small values of $\delta t \sim 1$s, a 3σ coincident detection or a constraint based on non-detection is possible within 5 years using any of the detectors and/or the combination. However, for large values of δt CE can only reach the 2σ level in ~ 20 years. While the combination of ET+CE can reach a 3σ level over 20 years, ET by itself would need ~ 30 years to reach the same level.

Although we reduce the background by a lot by performing GW triggered searches and implementing distance limits from the sky localization threshold, it is still important to quantify the level of *triggered* backgrounds ($N_{\rm trig}^{\rm bkg}$) from such a search. It is also important to note that in the presence of backgrounds, the operation time T_{op} and the threshold for the fraction of sky localization $f_{\rm th}$ are not independent parameters. We show an estimate of such triggered backgrounds in Fig. 4. We consider the backgrounds from the conventional, prompt [14] and diffuse astrophysical flux [15] at IceCube-Gen2. We see that for CE assuming a $f_{\rm th} \sim 1\%$, allows us to have $T_{op} \sim 10$ years before the triggered background starts to dominate over the signal events obtained from the GW triggers. For ET, an operation time of 10 years suggests that $f_{\rm th} \sim 0.03\%$ to have $N_{\rm tirg}^{\rm bkg} = 0.1$ which is an order of magnitude better than CE. Finally for the combination of ET+CE, 10 years of operation time dictates $f_{\rm th} \sim 0.004\%$ to obtain a sample where $N_{\rm trig}^{\rm bkg} = 0.01$. These values can be compared with those used in Fig. 3.

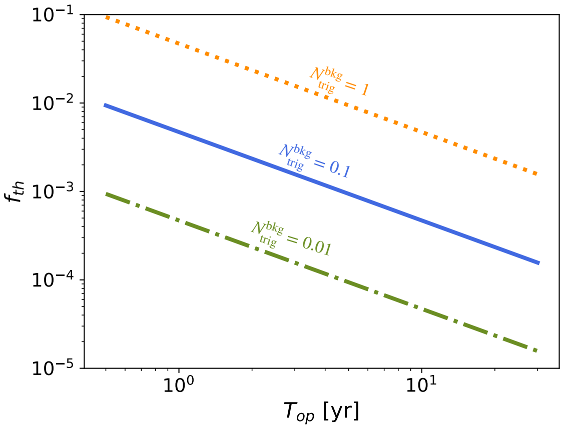


Figure 4: The fraction of sky area covered $f_{\rm th}$ with operation time T_{op} for different values of triggered background events $N_{\rm bkg}^{\rm trig}$ at IceCube-Gen2.

4. Conclusions and Discussion

In this work, we focused on analyzing the prospects of the next-generation GW detectors like ET, CE and a combination of ET+CE, in facilitating triggered searches for neutrinos from BNS mergers in the next generation neutrino detectors like IceCube-Gen2. We found that ET+CE can give coincident neutrino events or 3σ level constraints on the parameter space, due to extremely good sky localization capabilities over a timescale of ≤ 20 years even for the less optimistic scenarios. ET can lead to a similar outcome owing to its good sky localization capabilities over a time scale of $20 - 30$ years for the less optimistic cases. CE has comparatively poor sky localization and hence may be good for coincident detections or 2σ-level constraints over reasonable time scales. Our analysis can constrain f_ν for a population of BNS sources, which can then help in understanding emissions from BNS mergers. Model independent analysis can help constrain the BNS merger models in particular, neutrinos from choked jet scenarios and hence provide insights regarding GRB jets, neutrino emission sites and mechanisms.

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