Observational Constraints on Multimessenger Sources of Gravitational Waves and High-Energy Neutrinos

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Many astronomical sources of intense bursts of photons are also predicted to be strong emitters of gravitational waves (GWs) and high-energy neutrinos (HENs). Moreover some suspected classes, e.g., choked gamma-ray bursts, may only be identifiable via nonphoton messengers. Here we explore the reach of current and planned experiments to address this question. We derive constraints on the rate of GW and HEN bursts based on independent observations by the initial LIGO and Virgo GW detectors and the partially completed IceCube (40-string) HEN detector. We then estimate the reach of joint GW + HEN searches using advanced GW detectors and the completed km^3 IceCube detector to probe the joint parameter space. We show that searches undertaken by advanced detectors will be capable of detecting, constraining, or excluding, several existing models with 1 yr of observation.

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Gravitational-wave (GW) astronomy, as well as high-energy neutrino (HEN) observations are entering a new and promising era with newly constructed detectors, providing unprecedented opportunities to observe these astrophysical messengers, opening new windows onto the universe. GW observatories [1–4] are being built and upgraded to second generation detectors. Several HEN detectors [5,6] have reached their design sensitivities and will be further upgraded in the near future [7].

GWs and HENs can originate from a number of common sources. Plausible sources include gamma-ray bursts (GRBs), core-collapse supernovae (CCSNe), soft gamma repeaters as well as microquasars [8]. For a joint GW + HEN analysis, the most interesting sources are those which have no detected electromagnetic (EM) emission. With the near completion of the first searches for multimessenger GW + HEN sources [9], it is important to examine the projected science reach of such searches, as well as how it relates to independent GW and HEN measurements. This can support and guide the theoretical work necessary to gain a better understanding of future observational results.

In this Letter we interpret and combine previously published and independent GW and HEN observational results, to derive the first joint constraints on the rates of GW + HEN sources. We first discuss constraints from individual HEN and GW searches, and then combine these to derive upper limits on GW + HEN sources. We finally estimate projected constraints on GW + HEN sources with future detectors and joint GW + HEN searches.

Upper limits from neutrino observations.—Abbasi *et al.* [10] searched for transient point sources with the partially constructed IceCube detector in its 40-string configuration (hereafter IceCube-40) for over 1 yr. The search covered the northern sky with various emission time-scales; no evidence for transient sources was found. With a conservative time window of 500 s for HEN emission from GRBs [11], three spatially coincident neutrinos in this analysis would have been sufficient for a (5σ) discovery (even with the higher event rate of IceCube-86, three coincident neutrinos will remain a highly unlikely outcome from the background). We therefore estimate the source population upper limit as the maximum source rate that has $\lesssim 90\%$ probability to result in at least one occurrence of ≥ 3 coincident neutrinos in a time window of 500 s during a 1-yr measurement.

We model the source population as following the blue-luminosity distribution of galaxies [12]: (i) for up to 40 Mpc, we take the blue-luminosity distribution given in the Gravitational Wave Galaxy Catalog [13] (we note that any incompleteness in the galaxy catalog makes our upper limits conservative.); (ii) for larger distances (up to 1 Gpc) we adopt the homogenous blue-luminosity density from Blanton *et al.* [14]; (iii) we assume that IceCube is uniformly sensitive to sources in the northern sky only, which is a reasonable approximation of the detector's directional sensitivity [10]. Our upper-limits are calculated as a function of n_{HEN}, defined as the average number of detected HENs from a source at 10 Mpc (e.g., [15]). This representation is independent of specific neutrino emission models or detectors; however, its conversion to isotropic-equivalent neutrino luminosity L_ν^{iso} depends on the neutrino spectrum, duration of emission (t_0), and detector sensitivity. Writing $L_\nu^{\mathrm{iso}} = \kappa n_{\mathrm{HEN}} t_0^{-1}$, we estimate the conversion factor for IceCube-40 [10,16] as $\kappa \approx 1.5 \times 10^{49}$ erg for high-luminosity (HL) GRBs [differential spectrum $n(\epsilon_\nu) \sim \epsilon_\nu^{-2}$, 4 TeV $< \epsilon_\nu <$ 2 PeV], and $\kappa \approx 8 \times 10^{49}$ erg for choked GRBs [$n(\epsilon_\nu) \sim \epsilon_\nu^{-2} e^{-\epsilon_\nu/3\ \mathrm{TeV}}$, 300 GeV $< \epsilon_\nu <$ 4 TeV]. The conversion assumes that the detectable ν_μ flux represents 1/3 of the total ν flux (after oscillations). For IceCube-86, κ differs by an estimated $\times 0.5$ (HL; [16]) to $\times 0.2$ (choked; [17]).

The results provided here assume that each source has the same intrinsic neutrino brightness (limits based on a fixed average brightness are conservative compared to those using any other brightness distribution), and account for beaming of the HEN emission. For a source with intrinsic brightness n_{HEN} at distance r, the probability that ≥ 3 neutrinos will be detected from it is

$$p(n \geq 3 | r, n_{\mathrm{HEN}}) = 1 - F(2|(10\ \mathrm{Mpc}/r)^2 n_{\mathrm{HEN}}), \quad (1)$$

where r is the source distance, F is the Poisson cumulative distribution function, and n is the number of detected neutrinos from the source. Therefore, for galaxy i with blue luminosity $L_{\mathrm{B}}^{(i)}$ at a distance r_i, the average number $\hat{N}_i$ of sources which are discovered (i.e., have ≥ 3 detected neutrinos) will be

$$\hat{N}_i(R, T) = p(n \geq 3 | r_i, n_{\mathrm{HEN}}) R / f_b T L_{\mathrm{B}}^{(i)} / L_{\mathrm{B}}^{\mathrm{MW}}, \quad (2)$$

where R is the source rate [number of sources per year per Milky Way equivalent (MWE) galaxy (with respect to blue luminosity)], f_b is the HEN beaming factor of the source, T is the duration of the measurement (≈ 1 yr [10]), and $L_{\mathrm{B}}^{\mathrm{MW}}$ is the blue luminosity of the Milky Way. The 90% confidence source population upper limit R^{UL} will be the upper limit that satisfies $2.3 \geq \sum_i \hat{N}_i(R^{\mathrm{UL}}, T)$, i.e.,

$$R^{\mathrm{UL}}(n_{\mathrm{HEN}}) = \frac{2.3 f_b L_{\mathrm{B}}^{\mathrm{MW}}}{T \sum_{\delta_i \geq 0} p(n \geq 3 | r_i, n_{\mathrm{HEN}}) L_{\mathrm{B}}^{(i)}}, \quad (3)$$

where the sum is over all galaxies with declination $\delta_i \geq 0$. For $r > 40$ Mpc where we consider a homogeneous matter distribution, the summation is substituted with an integral. Figure 1 (top) shows the fraction of HEN sources as a function of n_{HEN}. In the lower plot, population upper limits for HEN sources are shown, taking into account the sources' HEN beaming factor f_b. As mildly relativistic jets from CCSNe and low-luminosity (LL) GRBs are expected to make up a significant portion of HEN sources of interest [8,15,18], we adopt $f_b = 14$ corresponding to the LL-GRB beaming factor obtained in [19].

Upper limits from gravitational-wave observations.—We use the limits obtained by the latest GW all-sky burst search by Abadie *et al.* [20]. We consider their result for sine-Gaussian GW waveform in the sensitive band of the GW detectors (LIGO band, ~150 Hz). Abadie *et al.* report no detection using the initial LIGO-GEO-Virgo detectors [1–3], and set a frequentist 90% confidence upper limit of $R_{\mathrm{Abadie}} \approx 0.5(10^{-2} M_\odot c^2 / E_{\mathrm{GW}}^{\mathrm{iso}})^{3/2}\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$, or 2.0 detectable events per year, on the population of the considered GW bursts. Here we interpret this result through

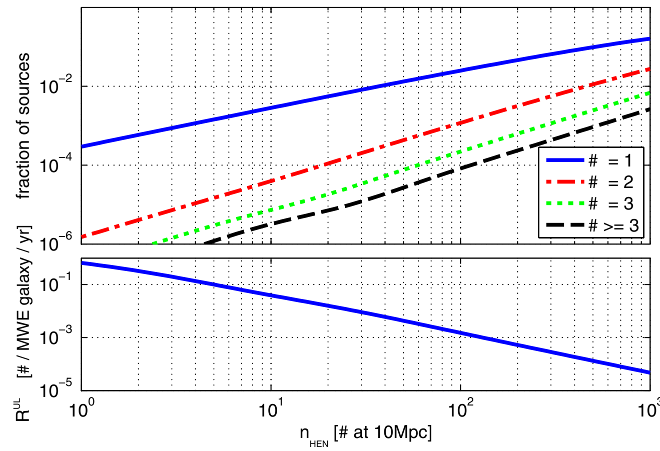

FIG. 1 (color online). Top: fraction of neutrino-emitting sources within 1 Gpc which would be detected with 1, 2, 3, or ≥ 3 neutrinos, as a function of n_{HEN} (the mean number of detected neutrinos from a source at 10 Mpc) for a detector with northern sky coverage (e.g., IceCube). Only sources are considered that emit neutrinos towards the Earth. Bottom: source population upper limit R^{UL} as a function of n_{HEN}, assuming a beaming factor of $f_b = 14$, and considering only the northern sky.

introducing a GW horizon distance $D^{\mathrm{GW}}(E_{\mathrm{GW}}^{\mathrm{iso}})$, within which any GW bursts with $E_{\mathrm{GW}}^{\mathrm{iso}}$ energy would have been greater than the loudest background event of the measurement, such that $\frac{4}{3}\pi (D^{\mathrm{GW}})^3 R_{\mathrm{Abadie}} \times (1\ \mathrm{yr}) \simeq 2.0$. This gives $D^{\mathrm{GW}}(E_{\mathrm{GW}}^{\mathrm{iso}}) = 7.8(E_{\mathrm{GW}}^{\mathrm{iso}}/10^{-2} M_\odot c^2)^{1/2}$ Mpc. Using D^{GW} is a reasonable approximation of the detection efficiency of [20]. We conservatively assume isotropic GW emission since GW beaming is expected to be small (e.g., [21]). We thus derive a galaxy-based GW source population upper limit as a function of $E_{\mathrm{GW}}^{\mathrm{iso}}$, using the blue-luminosity-weighted distribution of galaxies as described in (i)–(ii) above:

$$R^{\mathrm{UL}}(E_{\mathrm{GW}}^{\mathrm{iso}}) = \frac{2.0 L_{\mathrm{B}}^{\mathrm{MW}}}{\sum_{r_i \leq D^{\mathrm{GW}}} L_{\mathrm{B}}^{(i)}} \mathrm{yr}^{-1}. \quad (4)$$

Here, we assumed that each GW source emits the same amount of GW energy. We estimate the achievable population upper limit for the advanced LIGO-Virgo GW detector network by assuming a ~10× increase in sensitivity compared to initial detectors, with similar measurement duration. Results are shown in Fig. 2.

Joint GW + HEN *population upper limits.*—Individual GW and HEN observations can be combined to determine a GW + HEN source population upper limit in the $E_{\mathrm{GW}}^{\mathrm{iso}} - n_{\mathrm{HEN}}$ parameter space. In Fig. 3 (top) we provide GW + HEN population upper limits based on the statistical combination of current observational results from *independent* GW and HEN measurements. We obtain a joint observational upper limit by considering that, on average, less than 2.3 GW + HEN bursts occur within D^{GW} or have ≥ 3 detected HENs per year (this is a >90% confidence upper limit, since the GW and HEN measurements were longer than 1 yr). The observational GW + HEN upper limit for a source population proportional to the blue-luminosity-weighted galaxy distribution will therefore be

$$R^{\mathrm{UL}}(E_{\mathrm{GW}}^{\mathrm{iso}}, n_{\mathrm{HEN}}) = \frac{2.3 L_{\mathrm{B}}^{\mathrm{MW}} \mathrm{yr}^{-1}}{\frac{1}{f_b} \sum_{\{r_i > D^{\mathrm{GW}}, \delta_i \geq 0\}} p(n \geq 3 | r_i, n_{\mathrm{HEN}}) L_{\mathrm{B}}^{(i)} + \sum_{\{r_i \leq D^{\mathrm{GW}}\}} L_{\mathrm{B}}^{(i)}}. \quad (5)$$

Note that the first sum in the equation runs over sources farther than D^{GW}. This is to ensure that sources detectable by both GW and HEN detectors are not counted twice in the statistics. As the theoretical estimates [18,22] shown in Fig. 5 are provided for km^3 scale detectors, for Fig. 5(top) we convert them to estimates for IceCube-40 using the factors 0.5 (hard) and 0.2 (soft) for the difference in sensitivity between IceCube-86 and IceCube-40.

Similarly to the above observational results, we also calculate the projected GW + HEN population upper limits based on the statistical combination of projected results from independent, 1 yr long measurements with advanced LIGO-GEO-Virgo and IceCube-86. Results are shown in Fig. 3 (bottom).

We now estimate the projected population upper limits for GW + HEN sources obtainable with a *joint* GW + HEN search, considering a 1-yr measurement with the advanced LIGO-Virgo and IceCube-86 detectors. We consider an event candidate to be the coincidence of 1 GW trigger and 1 HEN. While we might detect more than 1 HEN from some sources, the fraction of such sources is small (see Fig. 1); therefore, we conservatively omit multi-HEN sources. For the joint search we define a horizon distance $D^{\mathrm{GWHEN}}(E_{\mathrm{GW}}^{\mathrm{iso}})$, such that a joint GW + HEN event with 1 detected HEN and GW energy $E_{\mathrm{GW}}^{\mathrm{iso}}$, within D^{GWHEN} would be more significant than the (anticipated) loudest background event. We estimate D^{GWHEN} to be the same as the exclusion distance of the externally triggered search for GW bursts by Abbott *et al.* [23], who obtained a median exclusion distance of $D \sim 12$ Mpc $(E_{\mathrm{GW}}^{\mathrm{iso}}/10^{-2} M_{\odot} c^2)^{1/2}$ with GW emission in the LIGO band. Such comparison to externally triggered GW searches is a reasonable approximation if the joint search has $O(1)$ chance overlaps of background GW and HEN events (which can be controlled by adjusting the event selection threshold). For the joint GW + HEN search the estimated source population upper limit R^{UL} will be

$$R^{\mathrm{UL}}(E_{\mathrm{GW}}^{\mathrm{iso}}, n_{\mathrm{HEN}}) = \frac{2.3 f_b L_{\mathrm{B}}^{\mathrm{MW}}}{T \sum_{\{r_i \leq D^{\mathrm{GWHEN}}, \delta_i \geq 0\}} p(n \geq 1 | r_i, n_{\mathrm{HEN}}) L_{\mathrm{B}}^{(i)}}. \quad (6)$$

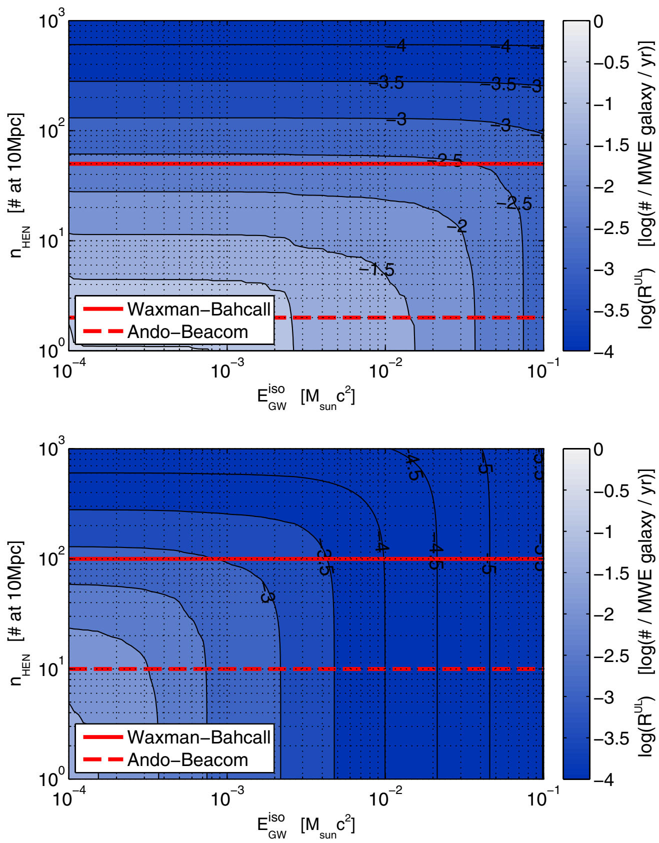

FIG. 3 (color online). GW + HEN source population upper limits based on the statistical combination of independent GW and HEN measurements. Top: observational results for measurements with the initial LIGO-GEO-Virgo GW detectors [20] and the IceCube-40 HEN detector [10]. Bottom: projected results for 1-year observations with advanced LIGO-Virgo and IceCube-86. The limits shown assume a HEN beaming factor of 14. Horizontal lines: expected HEN rate from the Waxman-Bahcall [22] (solid) and Ando-Beacom [18] (dashed line) models, scaled to the IceCube-40 (top) and IceCube-86 (bottom) detector configurations.

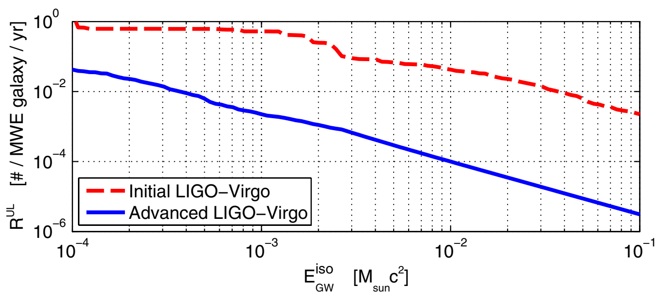

FIG. 2 (color online). Source population upper limits as functions of the sources' GW emission in isotropic-equivalent energy $E_{\mathrm{GW}}^{\mathrm{iso}}$. Dashed red line: observational limits with initial LIGO-GEO-Virgo [20]. Solid blue line: projected limits for the advanced LIGO-GEO-Virgo GW detectors in the event of nondetection.

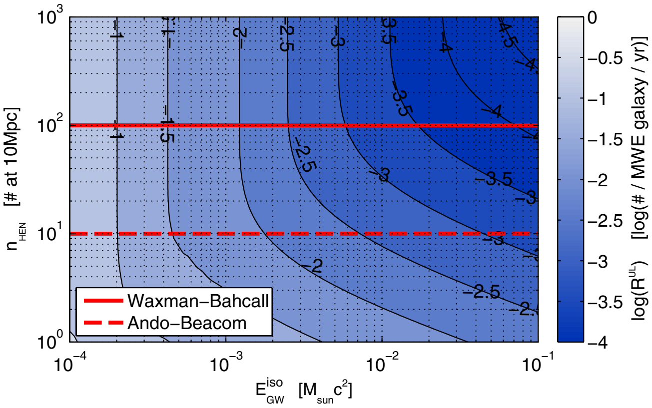

FIG. 4 (color online). Projected GW + HEN source population upper limits for a joint analysis of 1 yr of observations with advanced LIGO-Virgo and IceCube-86. Results are given as functions of source emission parameters $E_{\rm GW}^{\rm iso}$ (GW emission in isotropic-equivalent energy) and $n_{\rm HEN}$ (average number of detected neutrinos from a source at 10 Mpc). Horizontal lines: expected HEN rate from the Waxman-Bahcall [22] (solid) and Ando-Beacom [18] (dashed line) models. The limits shown assume a HEN beaming factor of 14.

The estimated population upper limits for a GW + HEN search are shown in Fig. 4 for advanced LIGO-Virgo and IceCube-86.

Discussion.—To compare our results to emission models, we consider SNe Ib/c with mildly relativistic jets as promising GW+HEN emitters, whose rate $R_{\rm SN}^{\rm jet}$ is $\lesssim 1\%$ [24] of the SN Ib/c rate $R_{\rm SN}$. This estimate is based on radio observations. It has been proposed, however, that mildly relativistic jets may be much more common, but completely choked (bright in neutrinos, dark in gamma rays and radio) [15,18]. The nearby CCSN rate is high enough to allow testing these models soon.

All-sky population upper limits with IceCube-86 are projected to exclude sources at rates $\geq R_{\rm SN}$ ($\lesssim 3\times 10^{-2}$/yr/MWE galaxy) for $n_{\rm HEN} \gtrsim 12$ and at rates $\geq R_{\rm SN}^{\rm jet}$ for $n_{\rm HEN} \gtrsim 300$ (Fig. 1). The former is comparable to the emission expected from SN jets by Ando & Beacom ($n_{\rm HEN} \approx 10$; [18]), or emission through reverse shocks in mildly relativistic jets ($n_{\rm HEN} \lesssim 7$; [15]). The latter is comparable to the Waxman-Bahcall flux, which estimates emission from HL-GRBs (which are, however, much rarer than SNe or LL-GRBs and have different spectra). Moreover, as evident from Fig. 2, advanced GW detectors are projected to exclude sources at rates $\geq R_{\rm SN}$ for $E_{\rm GW}^{\rm iso} \gtrsim 2\times 10^{-4} M_\odot c^2$, and at rates $\geq R_{\rm SN}^{\rm jet}$ for $E_{\rm GW}^{\rm iso} \gtrsim 5\times 10^{-3} M_\odot c^2$. Both of these limits would exclude the suspended accretion model in the LIGO band [25], and significantly constrain, e.g., the collapsar accretion disk fragmentation model [26].

We obtain projected population constraints with a joint GW + HEN search (Fig. 4) that can be more restrictive in some regions of the parameter space than individual searches if the GW horizon distance $D^{\rm GW}$ of the joint search is at least a factor 2.4 greater ($\sim f_b^{1/3}$ greater) than $D^{\rm GW}$ of individual searches.

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