IMPLICATIONS OF GW RELATED SEARCHES FOR ICECUBE

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At the beginning of 2016, LIGO reported the first ever direct detection of gravitational waves. The measured signal was compatible with the merger of two black holes of about 30 solar masses, releasing about 3 solar masses of energy in gravitational waves. We consider the possible neutrino emission from a binary black hole merger relative to the energy released in gravitational waves and investigate the constraints coming from the non-detection of counterpart neutrinos, focussing on IceCube and its energy range. The information from searches for counterpart neutrinos is combined with the diffuse astrophysical neutrino flux in order to put bounds on neutrino emission from binary black hole mergers. Prospects for future LIGO observation runs are shown and compared with model predictions.

1 Introduction

At the end of 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) observed for the first time a gravitational wave signal, GW150914.\textsuperscript{1} The measured signal is compatible with what is predicted for a binary black hole (BBH) merger. In this event, two black holes with masses $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$ merged to form a black hole of $62^{+4}_{-4} M_\odot$, in the process releasing $3^{+0.5}_{-0.3} M_\odot$ of energy into gravitational waves, from a distance of $410^{+160}_{-180} Mpc$ from Earth.

In the standard picture of binary black hole mergers, such environments are devoid of matter by the time of the merger.\textsuperscript{2} Therefore, this type of event is expected to be visible only in gravitational waves. Still, now that binary black hole mergers are observable,\textsuperscript{a} it is interesting to test whether they do emit other particles or not. Indeed, the detection of GW150914 triggered several follow-up searches, both in electromagnetic waves\textsuperscript{4} and in neutrinos.\textsuperscript{5,6,7}

In this work,\textsuperscript{8} constraints on high energy neutrino emission from binary black hole mergers are investigated. These constraints come from two sources. Firstly, there are the constraints from direct searches for counterpart neutrinos coincident with the LIGO event. Secondly, given

\textsuperscript{a}Indeed, in addition to GW150914, an additional binary black hole merger has been detected, as well as a candidate event.\textsuperscript{3}
that binary black hole mergers happen throughout the history of the universe, the emission is constrained from the observation of the diffuse astrophysical neutrino flux by IceCube.

## 2 Neutrino emission from BBH mergers

The neutrino emission can be characterized by the following parameter

$$f_{\nu}^{\text{BBH}} = \frac{E_{\nu}}{E_{\text{GW}}}.$$  \hspace{2cm} (1)

The experimental constraints from follow-up searches for counterpart neutrinos can be immediately translated to a bound on this parameter.

Under the assumption that BBH mergers do emit neutrinos, the mergers that have happened throughout the history of the universe give rise to a diffuse flux of neutrinos. According to LIGO, the rate of such merger is between $9 \times 10^{-2} - 240 \text{ Gpc}^{-3}\text{yr}^{-1}$ in the local universe. Following the standard approach, one finds that the resulting flux equals

$$E^2 \frac{dN_{\nu}}{dE_{\nu}}|_{\text{obs}} = \left( f_{\nu}^{\text{BBH}} \frac{c}{4\pi} \xi_z \right) E^2 \frac{dN_{\nu}}{dE_{\nu}}|_{\text{inj},f_{\nu}^{\text{BBH}}=1}.$$  \hspace{2cm} (2)

The injection spectrum and rate is contained in $\frac{dN_{\nu}}{dE_{\nu}}|_{\text{inj},f_{\nu}^{\text{BBH}}=1}$. Here, it is assumed that the BBH mergers emit neutrinos with an $E^{-2}$-spectrum between $100 \text{ GeV}$ and $10^8 \text{ GeV}$, in order to explain (part of) the observed diffuse astrophysical neutrinos flux. The factor $\xi_z$ captures the cosmic evolution of the sources and the redshift effect on the spectrum. For power law spectra, this $\xi_z$ is $z$-independent. In the following, it will be assumed that BBH mergers follow the star evolution and set $\xi_z = 3$.

The resulting flux can then be compared with the diffuse neutrino flux observed by IceCube

$$E^2 \Phi(E) = 0.84 \pm 0.3 \times 10^{-8} \text{ GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}.$$  \hspace{2cm} (3)

One gets a bound on $f_{\nu}^{\text{BBH}}$ when the fluxes in Eq. 2 and Eq. 3 are equal. If one would find $f_{\nu}^{\text{BBH}}$ higher than this bound from direct observation of BBH mergers, one of the assumptions that went into the calculation must be wrong. This would mean that either $f_{\nu}^{\text{BBH}}$ is not universal, or that BBH mergers do not follow star formation, resulting in bounds on these two cases.

## 3 Prospects

The bounds on $f_{\nu}^{\text{BBH}}$ from the diffuse astrophysical neutrino flux will be compared to those from direct searches as more BBH mergers are accumulated. All BBH mergers are assumed to be similar to GW150914, emitting 3 M$_\odot$ of energy in gravitational waves from a distance of 410 Mpc, from random locations in the sky. The IceCube follow-up analysis of GW150914 is replicated, using the respective effective area, averaged over the full sky. A background of atmospheric neutrinos is included, integrated over a time window of 1000 s and over a sky patch of 600 deg$^2$, 100 deg$^2$ and 20 deg$^2$, corresponding to the current localization uncertainty given by LIGO.

Fig. 1 shows the results of this analysis, for various significances with which one could detect a neutrino signal. The astrophysical bounds are at $f_{\nu}^{\text{BBH}} \approx 1.58 \times 10^{-3}$ and $f_{\nu}^{\text{BBH}} \approx 5.93 \times 10^{-5}$. This value is reached by direct searches, at $S/\sqrt{S+B} = 1$, after about 10 mergers have been detected. By the end of LIGO run O2, it is expected that between 10 and 35 BBH mergers (90% credible interval) have been seen. In case one would see 35 events, this means that a counterpart neutrino emission could be detected with $S/\sqrt{S+B} = 1$ for $f_{\nu}^{\text{BBH}} \approx 5 \times 10^{-4}$. 
Figure 1 – The sensitivity of $f_{\nu \text{BBH}}$ expected at various significance requirements (from top to bottom $S/\sqrt{S+B} = 5, 3, 1$) as a function of number of 3 M$_\odot$ BBH mergers observed in gravitational waves. The results are shown for different sky patch sizes, corresponding to current and future LIGO pointing accuracy ($600 \deg^2$, $100 \deg^2$ and $20 \deg^2$ uncertainty for the full, dashed and dashed-dotted lines respectively). The green hatched lines show the upper bounds from the astrophysical neutrino flux for the upper and lower limit of the BBH merger rate for the case discussed in the text. The vertical band shows the expected number of BBH mergers seen in LIGO run O2.

4 Model dependent interpretation

The general bound on $f_{\nu \text{BBH}}$ from the previous section can be interpreted in specific models. Assuming now that the neutrino emission originates from matter present around the black hole, $f_{\nu \text{BBH}}$ can be decomposed in the following way

$$f_{\nu \text{BBH}} = f_{\text{matter}} \times f_{\text{engine}} \times \epsilon_{p,\text{acc}} \times \epsilon_{\nu}. \quad (4)$$

In here, $f_{\text{matter}}$ is a fraction expressing the amount of matter present, relative to $E_{\text{GW}}$. The second part, $f_{\text{engine}} \times \epsilon_{p,\text{acc}} \times \epsilon_{\nu}$ represents the amount of energy that forms an acceleration engine, the amount of energy going into protons and the amount of proton energy going to neutrinos respectively. In the case of a gamma-ray burst fireball model,\textsuperscript{19} this last part is equal to $1/10 \times 1/10 \times 1/20$. A bound on $f_{\nu \text{BBH}}$ can then be immediately translated into a bound on $f_{\text{matter}}$ within the fireball model. One can turn this around and estimate possible values of $f_{\nu \text{BBH}}$, using specific matter models. In the dead disk model,\textsuperscript{2} one finds that approximately $10^{-4} - 10^{-5}$ M$_\odot$ of matter is present, which can be reactivated upon the merger. This then leads to $f_{\nu \text{BBH}} \approx 10^{-7}$, still below the reach estimated in Fig.1.

5 Conclusions

The current and expected future bounds on high energy neutrino emission from binary black hole mergers have been investigated, in terms of a parameter $f_{\nu \text{BBH}}$. This was done by combining the information from coincident searches for counterpart neutrinos, together with the already observed diffuse astrophysical neutrino flux. This latter one results in a bound between $f_{\nu \text{BBH}} \approx 1.58 \times 10^{-3} - 5.93 \times 10^{-5}$. It is found that after about 10 binary black hole mergers detected using gravitational waves, it will be possible to probe the neutrino emission down to the upper value of that range. This number of events coincides with the lower value of the 90% credible interval for expected number of events in LIGO run O2. Finally, when comparing this expected bound with estimates from realistic models of neutrino emission, it is found that such models predict a neutrino emission of $f_{\nu \text{BBH}} \approx 10^{-7}$, which is below this expected bound in run O2.
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References

1. B. P. Abbott et al. Observation of Gravitational Waves from a Binary Black Hole Merger. *Phys. Rev. Lett.*, 116(6):061102, 2016.
2. Rosalba Perna, Davide Lazzati, and Bruno Giacomazzo. Short Gamma-Ray Bursts from the Merger of Two Black Holes. *Astrophys. J.*, 821(1):L18, 2016.
3. B. P. Abbott et al. Binary Black Hole Mergers in the first Advanced LIGO Observing Run. *Phys. Rev.*, X6(4):041015, 2016.
4. B. P. Abbott et al. Localization and broadband follow-up of the gravitational-wave transient GW150914. *Astrophys. J.*, 826(1):L13, 2016.
5. S. Adrian-Martínez et al. High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube. *Phys. Rev.*, D93(12):122010, 2016.
6. K. Abe et al. Search for Neutrinos in Super-Kamiokande associated with Gravitational Wave Events GW150914 and GW151226. *Astrophys. J.*, 830(1):L11, 2016.
7. Alexander Aab et al. Ultrahigh-energy neutrino follow-up of Gravitational Wave events GW150914 and GW151226 with the Pierre Auger Observatory. *Submitted to: Phys. Rev. D*, 2016.
8. Krijn D. de Vries, Gwenhal de Wasseige, Jean-Marie Frre, and Matthias Vereecken. Constraints and prospects on GW and neutrino emissions using GW150914. 2016.
9. Marek Kowalski. Status of High-Energy Neutrino Astronomy. *J. Phys. Conf. Ser.*, 632(1):012039, 2015.
10. Markus Ahlers and Francis Halzen. Pinpointing Extragalactic Neutrino Sources in Light of Recent IceCube Observations. *Phys. Rev.*, D90(4):043005, 2014.
11. Eli Waxman and John N. Bahcall. High-energy neutrinos from astrophysical sources: An Upper bound. *Phys. Rev.*, D59:023002, 1999.
12. Andrew M. Hopkins and John F. Beacom. On the normalisation of the cosmic star formation history. *Astrophys. J.*, 651:142–154, 2006.
13. Hasan Yuksel, Matthew D. Kistler, John F. Beacom, and Andrew M. Hopkins. Revealing the High-Redshift Star Formation Rate with Gamma-Ray Bursts. *Astrophys. J.*, 683:L5–L8, 2008.
14. M. G. Aartsen et al. The IceCube Neutrino Observatory - Contributions to ICRC 2015 Part II: Atmospheric and Astrophysical Diffuse Neutrino Searches of All Flavors. In *Proceedings, 34th International Cosmic Ray Conference (ICRC 2015): The Hague, The Netherlands, July 30-August 6, 2015*, 2015.
15. M. G. Aartsen et al. Searches for Extended and Point-like Neutrino Sources with Four Years of IceCube Data. *Astrophys. J.*, 796(2):109, 2014.
16. T. S. Singewald, E. V. Ogorodnikova, and S. I. Singewald. High-energy fluxes of atmospheric neutrinos. In *Proceedings, 33rd International Cosmic Ray Conference (ICRC2013): Rio de Janeiro, Brazil, July 2-9, 2013*, page 0040, 2013.
17. Neil Gehrels, John K. Cannizzo, Jonah Kanner, Mansi M. Kasliwal, Samaya Nissanke, and Leo P. Singer. Galaxy Strategy for LIGO-Virgo Gravitational Wave Counterpart Searches. *Astrophys. J.*, 820(2):136, 2016.
18. B. P. Abbott et al. The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914. *Astrophys. J.*, 833:1, 2016.
19. Eli Waxman and John N. Bahcall. High-energy neutrinos from cosmological gamma-ray burst fireballs. *Phys. Rev. Lett.*, 78:2292–2295, 1997.