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Searching for joint neutrino and gravitational wave emission from the environment of Active Galactic Nuclei

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With the observation of gravitational waves from merging compact binary systems, a new observing window of the universe has been opened. Most of the gravitational wave events currently detected are due to the merger of binary black hole systems. One way to better investigate such systems is to look for coincident emission in electromagnetic waves or neutrinos. For typical models of isolated binaries, no such emission is expected. However, one promising class of mergers is that of binary black holes in the accretion disk of active galactic nuclei. Such mergers potentially occur at high rates, since these environments naturally have high numbers of black holes, which can efficiently form binaries, merge rapidly, and potentially accrete matter fast due to the surrounding gas. Here, we propose a method to search for coincident gravitational wave and neutrino emission from the location of known AGN, using an unbinned maximum likelihood analysis, and apply it to currently available public data.

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1. Introduction

Gravitational waves were observed directly for the first time in 2015 by LIGO-Virgo-KAGRA (LVK). Since then, almost one hundred such gravitational wave events have been detected. Most gravitational wave events are the result of the merger of a binary black hole (BBH) system, while a few of them are from a neutron star-black hole (NSBH) or binary neutron star (BNS) system [1]. This dominance by BBH events, as well as their high masses, was unexpected.

For each of the gravitational wave events, there are also accompanying searches for electromagnetic or neutrino emission by other experiments. For example, there exist several searches for coincident emission of high-energy neutrinos [2, 3]. Such a (high-energy) multi-messenger signal is typically only expected for mergers involving a neutron star, since they can supply the accreting matter necessary for particle acceleration and subsequent interaction and emission to occur.

However, tentative detections of possible coincident electromagnetic (EM) signals have inspired models where such emission is possible for BBH mergers [4, 5]. One class of such models is of binary black holes merging in the accretion disk of active galactic nuclei (AGN) [6]. This region is expected to contain many black holes, which can efficiently form binaries and merge rapidly due to the surrounding gas. This also allows for hierarchical mergers, where black holes undergo multiple mergers, possibly explaining the high black-hole masses seen by LVK. Moreover, the gas-rich environment allows for rapid accretion of gas and possible emission of an electromagnetic and/or neutrino signal. Several realizations of this scenario have been proposed to explain multi-messenger emission, see e.g. [5, 7]. The rate at which BBH mergers in AGN accretion disks occur is currently unknown, since there are many modeling uncertainties. Estimates vary from less than a percent of the observed BBH merger rate, to more than 50% of the observed rate [8–11].

Establishing how frequently this scenario really occurs is possible in several ways. Using localization alone, it is already possible to show a coincidence between the location of BBH mergers and AGN after less than a hundred BBH mergers at low redshifts [12, 13]. As of observing run O3 of LVK, it can already be shown that the most luminous AGN most likely do not produce the majority of BBH mergers [14]. However, this does not significantly constrain the total rate of BBH mergers in AGN.

In these proceedings, we aim to test whether BBH mergers occur in AGN accretion disks and whether such mergers result in neutrino emission. We propose a method, based on an unbinned maximum likelihood analysis, to search for coincident emission of gravitational waves and neutrinos from the location of known AGN. In order to demonstrate our method, we apply it to currently available public data from IceCube [15], ANTARES [16, 17], and LVK [18].

2. Analysis

2.1 Data

Since our analysis aims to find a correlation between gravitational wave events, neutrinos, and active galactic nuclei, we need catalogs for all three of these. For the neutrino data, we use the public IceCube all-sky point-source dataset (2008–2018) [19] and ANTARES point-source dataset (2007–2017) [16, 17]. Both of these contain track events, which possess excellent pointing as needed for a point-source search. For the gravitational wave data, we use the gravitational wave transient catalog

(GWTC). Since the neutrino data we use only spans until 2018, we restrict ourselves to gravitational wave events in GWTC-1 [18]. For every gravitational wave, LVK supplies a skymap that contains, for each pixel, the probability $p\left(\Omega\,|\mathrm{GW}\right)$ that the gravitational wave comes from that direction and the probability $p\left(d\,|\mathrm{GW}\right)$ that the gravitational wave comes from a source at distance d if it comes from the direction Ω. In practice, the distance distribution is given by a Gaussian parametrized by a mean and standard deviation $d_{\mathrm{GW}}\left(\Omega\right)$ and $\sigma_{\mathrm{GW}}\left(\Omega\right)$.

Finally, for the active galactic nuclei we test, we use the Véron-Cetty AGN catalog [20]. While this catalog does not contain data from the most recent surveys, it is still a reliable source of AGN data. The catalog contains 168 940 AGN, spread out over redshift, of which 95 075 are at a redshift smaller than 1.5, relevant for gravitational wave coincidences. As with any AGN catalog, the biggest challenge is the completeness of the catalog. In particular, some directions in the sky have been surveyed far deeper than others. The effect of this is especially visible at southern declinations, where the number of AGN in the catalog is small.

2.2 Method

In order to test our model, we propose a modified version of the unbinned maximum likelihood method used in one of the combined gravitational wave-neutrino searches by IceCube [2, 21]. At its core, we perform a neutrino point-source search at the location of each AGN in our AGN catalog within the 90% probability contour region as inferred by LVK. We consider neutrinos observed by IceCube and ANTARES within a time window of 2 days centered on the observed arrival time of the gravitational wave event. To this neutrino point-source search, we add a prior based on the inferred gravitational wave direction and distance. Concretely, we construct the quantity

$$\tilde{\mathcal{L}}_{\mathrm{AGN}}^{\mathrm{post}} = \mathcal{L}_{\nu,\mathrm{S+B}}\left(n_S\right) \times p\left(\Omega_{\mathrm{AGN}}\,|\mathrm{GW}\right) \times p\left(d_{\mathrm{AGN}}\,|\mathrm{GW}\right), \tag{1}$$

which can be interpreted as a sort of posterior likelihood. Our method differs from the one in [2, 21] through the added distance factor and by testing individual AGN in a catalog instead of performing a sky scan.

The first part of $\tilde{\mathcal{L}}_{\mathrm{AGN}}^{\mathrm{post}}$ represents the neutrino point-source likelihood. It is given by

$$\mathcal{L}_{\nu,S+B}\left(n_S\right) = \prod_i^{N_\nu} \frac{n_S}{N_\nu}\mathcal{S}_i + \left(1 - \frac{n_S}{N_\nu}\right)\mathcal{B}_i, \tag{2}$$

with N_ν the total number of neutrinos in the 2-day time window, n_S the expected number of signal neutrinos, $\mathcal{S}_i$ the signal probability distribution function, and $\mathcal{B}_i$ the background probability distribution function. For this first analysis, we only use a spatial likelihood. For each observed neutrino in the time window, it consists of a signal term and a background term. The signal likelihood gives the probability of measuring a neutrino direction $\vec{x}_{\mathrm{obs}}$ from a true direction $\vec{x}_{\mathrm{true}}$, and is described by the Von Mises-Fisher distribution, which is the generalization of a Gaussian on a sphere. For computational reasons, this distribution is approximated by a Gaussian if the neutrino is well-localized (angular error below 7°). The background distribution is derived directly from the neutrino data and depends only on declination. This neutrino likelihood depends on n_S. Higher values of n_S at the tested position are preferred if the spatial distribution of observed neutrinos prefers a point source at that position instead of a distribution compatible with background. Thus, for each AGN in our catalog within the gravitational wave localization contour, we maximise the neutrino likelihood $\mathcal{L}_{\nu,S+B}(n_S)$ in order to obtain the best-fit number of signal neutrinos n_S for that AGN.

The second factor in $\tilde{\mathcal{L}}^{\text{post}}_{\text{AGN}}$ is $p(\Omega_{\text{AGN}}|\text{GW})$, the probability that the gravitational wave comes from the direction of the AGN, as given by the gravitational-wave localization skymap. Finally, the third factor in $\tilde{\mathcal{L}}^{\text{post}}_{\text{AGN}}$ is $p(d_{\text{AGN}}|\text{GW})$, the probability that the gravitational wave source is located at the same distance as the AGN, if it comes from the direction of the AGN. This probability is given by

$$p(d_{\text{AGN}}|\text{GW}) = \frac{1}{\sqrt{2\pi}\sigma_{\text{GW}}}\exp\left(-\frac{(d_{\text{AGN}} - d_{\text{GW}})^2}{2\sigma^2_{\text{GW}}}\right). \tag{3}$$

For each gravitational-wave event, we then perform a hypothesis test of our model against a background-only neutrino likelihood (Eq. 2 with $n_S = 0$). We construct a test statistic for each AGN compatible with the gravitational wave event; it is given by

$$\Lambda_{\text{AGN}} = 2\ln\left(\frac{\tilde{\mathcal{L}}^{\text{post}}_{\text{AGN}}}{\mathcal{L}_{\nu,\text{B}}}\right). \tag{4}$$

The AGN with the highest value of the test statistic Λ_{AGN} is considered as the best-fit AGN for that particular gravitational-wave event.

In order to obtain the significance of the best-fit result, we repeat the analysis above for 10 000 trials with randomized neutrino skymaps. These randomized neutrino skymaps are obtained by scrambling the neutrinos in the IceCube and ANTARES catalogs in time, and reselecting the neutrinos in the time window of the gravitational wave event. In this way, we can estimate the p-value, i.e. the chance that a background-only neutrino skymap produces a best-fit result with a test statistic equal to or higher than the one observed.

3. Results

Our results are shown in Table 1. None of the gravitational wave events in GWTC-1 show a significant excess of neutrinos at the location of an AGN in the Véron-Cetty catalog. The completeness of the AGN catalog strongly influences the results. Indeed, when a gravitational-wave localization contour only contains a few AGN in the catalog, the best-fit number of neutrinos is often equal to zero. The only exception is GW170818, which only has one coincident AGN but has the lowest p-value. However, since the p-value is still high and this region is poorly surveyed by the AGN catalog, we do not consider this result as significant. Likewise, the gravitational-wave localization also has a strong effect on our analysis, since large localisations imply a high number of AGN to test which increases the chance of an accidental coincidence with a clustering of background neutrinos, which in turn decreases the sensitivity of the analysis.

4. Discussion

The current analysis serves as a demonstration of the method we propose to search for a coincidence between neutrinos, gravitational waves, and AGN. The three ingredients to our analysis

GW event	Area (deg^2)	N_ν	N_{AGN}	best-fit AGN	n_S	p-value
GW150914	182	785	2	IRAS 03230-5800	0.00	1.00
GW151012	1523	733	257	MARK 1187	1.31	0.96
GW151226	1033	767	282	SDSS J12548-0010	0.90	0.63
GW170104	921	745	1096	2MASS J08191+3419	1.00	0.75
GW170608	392	684	213	3C 192	0.00	1.00
GW170729	1041	722	151	SDSS J12254+4901	1.40	0.27
GW170809	308	710	58	Q 0052-2956	0.00	1.00
GW170814	87	699	7	RXS J03149-4241	0.00	1.00
GW170818	39	707	1	MARK 308	0.53	0.20
GW170823	1666	692	357	MS 07199+7100	1.60	0.47

Table 1: Results of our analysis, showing for each gravitational wave event its localization, the number of neutrinos in a 2-day time window, the number of AGN in the Véron-Cetty catalog within the 90% contour region, the best-fit AGN, the number of fitted signal neutrinos, and the significance (p-value) of the best fit.

each add their own information: gravitational waves contain some distance information but are badly localized, neutrinos have no distance information but improved pointing, while AGN have accurate position and distance. In this way, this method can test whether binary black hole mergers occur regularly in AGN accretion disks and whether this results in neutrino emission.

However, the current analysis can be improved in several ways. First, in order to demonstrate the analysis, we only included spatial information in the neutrino likelihood. A full analysis should also make use of the energy distribution and the number of observed neutrinos compared to the expected background rate.

More critically, the incompleteness of the AGN catalog needs to be addressed (see also [14]). This aspect can be improved in multiple ways: using more recent/complete surveys, combining different AGN catalogs, testing only AGN with high luminosity (assuming that they also have more binary black hole mergers and/or gas powering neutrino emission, and more likely to be complete in catalogs), and considering gravitational wave events only up to a certain redshift, with good localization, or in regions of the sky where catalogs are sufficiently complete.

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