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Improvement of the follow-up observations of IceCube neutrinos by CTA LST

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A decade has passed since high-energy astrophysical neutrinos have been discovered by IceCube, however the corresponding sources have not been fully identified yet. The reported coincidence of the high-energy IceCube-170922A with the gamma-ray blazar TXS 0506+056 is not enough to claim that blazars are the dominant high-energy neutrino emitters in the Universe. In fact, recently IceCube announced a second correlation with NGC 1068, a nearby Seyfert galaxy, which is significantly different from a gamma-emitting blazars. The hunt for counterparts of the IceCube neutrinos using gamma-ray telescopes started in 2012. Nonetheless, these efforts will continue with the next-generation gamma-ray telescopes, such as the CTA Large Size Telescopes (LSTs) and other telescopes, by means of an improved and revised observation strategy. These new observations will allow us to detect enough sources in order to elucidate the mystery of the neutrino emitters. In this contribution, we introduces the efforts made thus far in the search for gamma-ray counterpart of high-energy IceCube events using the current generation IACTs, focusing on alerts made of multiple neutrinos events, and present an idea to improve in the observational strategies with the CTA LSTs that will become operational in the coming decade. We will discuss how to reduce the bias to gamma-ray emitters in order to search for possible neutrino counterparts.

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1. Introduction

Astrophysical neutrinos with high energies above PeV have been discovered by IceCube experiment in 2013 [1]. Since then effort has started to look for possible counterparts of the IceCube high energy neutrino events with multi-wavelength/-messenger instruments[1]. The effort became successful after four years when a flaring blazar TXS 0506+056 was found coinciding both spatially and temporally with an IceCube event IC170922A [3]. However, there is a general difficulty in explaining the single high energy neutrino event with simple blazar models. Furthermore, even more surprisingly, enough amount of such blazars could not be found to explain the diffuse neutrinos measured by IceCube. A general consensus in 2020's is that, the blazar, which is the dominant GeV gamma-ray emitters in the sky, is not a dominant source of high energy neutrinos. In 2022, IceCube reported the second clear coincidence between the neutrino events and a gamma-ray emitter, NGC 1068 [4]. This object is indeed not a blazar, but a nearby Seyfert galaxy with a starburst activity, which strengthens the need of further searches for the emitters of high-energy neutrinos other than the blazars.

The hunt for counterparts using the imaging atmospheric Cherenkov telescopes (IACTs) has started in 2012, including the success of the detection of flaring states of blazar TXS 0506+056 by MAGIC telescopes. There are a few possible channels for follow-up observations by IACTs [5]:

1. Single high-energy ($>$ 100 TeV) track events (singlet), localization error of typ. 0.3 deg, classified into Gold/Bronze with the signal quality. This alert is open to the community via GCN[2], since 2015 (started with a different classification such as EHE and HESE).
2. Multiple events (multiplet) within a variable duration, spatially correlated with a known gamma-ray emitter. No localization error is given, but the angular resolution of events affects the significance. This alert is private under MoUs with IACTs, started since 2012.
3. Multiple events selected with the same criteria as above, but without taking any correlation with known sources. This is also a private channel under MoU, called "all-sky" alerts, with a low rate of ~ 0.5 yr^{-1}.
4. Single cascade event mainly from electron neutrinos, with a large localization error of typ. $>$ 10 deg. This alert is open to the community via GCN, since 2021.

The observation of TXS 0506+056 was triggered by a single event EHE-170922A, under the (previous version of) channel 1. The main purpose to follow up the channel 1 by IACTs is to identify possible EM counterparts, which so far provide us with the single success after 10 years. This would suggest that such a search for counterparts of energetic events would require a modification of the strategy, together with the other search for counterparts of cascade events.

The other two private channels have been in even 'less fruitful' situations. The private alert by channel 2 aims at a change of state (flares) of known gamma-ray emitters, which should have contained the blazars like TXS 0506+056. However, it was not, due to the lack of redshift information then. It means that the pre-selected list of gamma-ray emitters should contain those

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[1] The gamma-ray followup of neutrinos started with a dedicated joint effort by AMANDA and MAGIC [2]

[2] https://gcn.nasa.gov/

without any known redshift in some way. About the channel 3, such searches with less bias to gamma-ray emission have become more important than before, as we know now that the blazars are not dominant neutrino sources. The current rate of $\sim 0.5\ \mathrm{yr}^{-1}$ is far less than what would be needed. The channel should be modified to enlarge its scope with a higher rate, or another channel should be developed to provide much more of gamma-unbiased alerts.

In order to tackle the above situations, gamma-ray telescopes (IACTs, in particular) and neutrino experiment (IceCube) should collaborate. However, the work under MoU has a big inertia in general, and, on top of that, there were practical constraints among the players. LST decided to start autonomously a study of possible revisions of the strategies, and then to propose them to IceCube. This contribution is mostly based on this phase of activities, i.e., before proposing to IceCube. Note that, the proposals described below in Section 2 and Secion 3 have been sent officially to IceCube in Jan 2023, and a collaborative work started since then. This contribution does not cover most of the activities after Jan 2023, except for the ongoing strategical changes briefly mentioned in Sec. 4.

2. Methods

The strategical change for the open alerts would be simple, in the sense that it requires only activities from the IACT side. The Gold/Bronze classification (channel 1) is now openly done by a single parameter called ‘signalness’ (probability of being an astrophysical neutrino event), thus the IACT side can easily adjust what to observe depending on physics and practical conditions in each IACT teams. The cascade event (channel 4.) is special in that the localization error is typically larger than the IACT field of view, and IACT needs to point to multiple directions spending a large amount of observation time. How much observation time can be spent for the cascade events is rather various among the policies of IACT teams, depending also on how much time will be used for the other three channels, thus it is left aside. Consequently, the main topic in this contribution is the revisions of the private alerts via channel 2 and 3.

2.1 Multiplet correlating with a gamma-ray emitter

The channel 2 has been called Gamma-ray Follow-Up (GFU[3]) program, which is the oldest program with IACTs started since 2012 with MAGIC and VERITAS, followed by H.E.S.S. since 2015. The details of the program is seen in [5], and based on it we discuss here potential revisions as below. The list of the gamma-ray objects monitored for neutrino multiplet is composed of two parts, one with GeV gamma catalogs, by Fermi-LAT, and the other with a TeV gamma catalog.

2.1.1 GeV part

About the Fermi-LAT part, the current list was based on 3FGL [6] or 3FHL [7] catalog, while now the next catalog 4FGL [8] is available. Then, extragalactic sources with known redshift were selected, with a cut by the redshift $z \leq 1$. However, as mentioned in Section 1, this cut removed TXS 0506+056 off the list, which should be debated for the possible improvement. Another cut was applied using variability, assuming that the neutrino emitter is variable in gamma-rays. This

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[3] The word GFU is originated from the follow-up observations by gamma-ray telescopes, as it stands for, but GFU in IceCube is more than it, and is a particular set of event selection. The GFU selection is indeed used now for the channel 1, which is not necessarily for gamma-ray observations. The fraction of GFU events is more than the rest of channels.

assumption is now questionable, and we should avoid such an assumption after knowing that blazars are not the dominant neutrino emitters. Finally, the GeV-gamma flux in the Fermi-LAT catalog was extrapolated to the IACT energy range (100 GeV), and multiplied by a factor of 10, mimicking a flaring activity / high state. This fudge factor would be somehow duplication of the variability cut, but without any assumption of the time scale of the high state, the fudge factor would be more reasonable than the variability cut. However, the EBL attenuation was not taken into account in the extrapolation, so the meaning of the factor 10 is different among the sources, which should be regarded as another room for an improvement. After all the above criteria were applied about the source properties, the flux was compared with the 5-sigma sensitivity of each IACTs (for 2.5-5 hours). The sources exceeding the sensitivity threshold were listed if they are visible from each IACT site (with the zenith angle less than typ. 45 deg).

As a summary for the Fermi-LAT part, we have proposed the following improvements in the criteria: we use 4FGL, selecting extragalactic sources. No cut is applied by variability. The EBL attenuation is applied in the extrapolation to 100 GeV. If redshift is known, the known value is used. If redshift is unknown, the source is cut for the first trial, but then (after discussions) $z = 0.3$ is assumed for the second trial.

2.1.2 TeV part

There is only one complete catalog for TeV-gamma sources, called TeVCat [9], which is an online table updated regularly. The selection for the current list was done as written as ‘all extragalactic sources detected by IACTs, the Galaxy Center, and the Crab Nebula’ [5]. It was not clear if the selection was using TeVCat (probably so, but it was not explicitly written). Possible improvements would be to use newest TeVCat entries (and write down explicitly the time when it was done), and to include more Galactic sources. Note that, a detection in TeV range already should work as a filter with the EBL attenuation, so there is no need for additional cut by redshift, flux, and so on. We have started from the catalog taken in Oct 2022, cutting sources with Galactic latitude $|b| > 2.5$ deg, removing non-repeating transients such as GRBs, and removing the double counts with GeV part and duplication within TeVCat. In the end, there are several unID sources and Galactic sources left, which we removed.

2.2 Multiplet without correlating with a gamma-ray emitter

In order to get more of alerts with less bias to gamma-ray emitter, eventually the best way would be to develop a new channel without any bias to known sources. However, it is rather a work inside IceCube collaboration, and is out of scope of this contribution. In the context of the multiplet alerts made with the pre-selected source list, one possible easier way is to prepare another set of sources that are not (necessarily) the gamma-emitters. If we assume that the neutrino counterparts are the astronomical objects, they should be located inside a galaxy. The numbers of galaxies inside the localization error region is rather large. However, the multiplet alert has intrinsically lower redshift than the singlet alert, as the source should have a larger flux and the probability of having a counterpart in a closer galaxy is higher than in a farther galaxy. Thus, a cross-match with a list of nearby galaxies is required. To this end, we have used the GLADE+ catalog [10], a dedicated catalog developed specifically for multi-messenger searches and extensively used in gravitational wave counterpart search.

The main point in this part is how distant galaxies we can select. The multiplet alerts have a sharp peak of the distribution below $z = 0.1$ (about 400 Mpc) even if one allows multiple events during a period of up to 30 days [11]. We can safely use an upper bound of the distance of a few 100 Mpc or lower. We changed the distance limit and tried to find a realistic distance bound for a predefined list.

3. Results

Before testing our method, we tried to reproduce the results reported in [5] where a list of 120-180 sources were selected for each IACT. LST cannot use the contents of the list for MAGIC, which is under MoU between MAGIC and IceCube, thus we tried to reproduce it only by the number of the sources to be roughly 180. LST is sharing the site with MAGIC (ORM, La Palma, Canaries, Spain), so only by using the sensitivity curve of MAGIC instead of LST, one can in principle reproduce the contents of the list, even starting from 4FGL. However, due to the fact that now more sources have known redshift than in 2012, the cut by redshift removed much more and the number of sources became about 100, ∼ 54% of the target. We understood the situation, gave up to reproduce the MAGIC list, and decided to go to the improved list as described in Section 2.

The result is summarized in Tables 1 and 2. For the GeV part (Table 1), the number of sources are reduced to ∼ 55% after applying the cuts by visibility (zenith distance lower than 50 degrees from La Palma), and ∼ 10% after applying the extrapolation to 100 GeV with the enhancement of a factor 10. Then, in the first trial, the sources with a known redshift (so extragalactic ones) were selected, to be 398, which became 110 after the EBL attenuation. In the second trial, we keep also the rest 298 sources without known redshift, and applied the EBL attenuation by assuming $z = 0.3$, which gave us 69 survived sources. They still include Galactic sources, which should not get EBL-attenuated, thus we have applied an additional cut by requiring Galactic latitude $|b| > 2.5$ deg, to be 42 sources in the end.

One possibility here is not to apply the cut by $|b|$ to remove 27 Galactic sources, but instead to keep these Galactic sources but without the enhancement of the factor 10. This will add ∼10 of known bright Galactic sources, which has a large overlap with the TeV sources.

Table 1: GeV part

	original	visibility	extrapolation	redshift	EBL attenuation
First trial	6659	3690	696	398 (egal.)	110 (egal.)
Second trial	6659	3690	696	(696)	152 (egal.)

For the TeV part (Table 2), the number of sources are reduced to ∼ 64% after applying the cuts by visibility, which is larger than for GeV part due to the reasonable overlap between the distribution of the detected IACT sources and the visibility of MAGIC. Then, we have applied a cut with Galactic latitude $|b| > 2.5$ deg, followed by more cuts described in Section 2. Here again, if we need to keep more Galactic sources, we should not apply the $|b|$ cut at the early stage. The removed 81 sources would give ∼10-20 more sources in the end, which is corresponding to the above discussion in the GeV part.

Table 2: TeV part

	original	visibility	extragalactic	transients	double counts	unIDs etc.
First trial	280	179	98	91	39	29

Finally, on top of the above gamma-biased list, another subset based on GLADE+ is prepared. We need to reduce the total number to ∼ 100, in order to keep the total number of sources to maintain the false alarm rate as an acceptable value. We introduced a distance cut corresponding to the distance of NGC 4993, where GW170817/GRB 170817A was found [12]. Also, the BNS rate and Bmag entries are used to cut possibly farther galaxies. We started from all the galaxy entries with the BNS rate, and just cut by the distance of NGC 4993 (and its BNS rate and Bmag), it becomes 224. By cutting the sources that cannot be seen from La Palma, it went to less than a half. In the end, we cut also one of the two galaxies that are too close in the sky, in order to avoid that two similar alerts are sent in a short time scale.

Table 3: Nearby galaxies part

	original	distance	visibility	double counts
First trial	3.2e6	224	94	73

As the result, the list of the extragalactic gamma emitters consist of 152 extragalactic sources from GeV part and 29 extragalactic sources from TeV part, to be 181 in total. A possible addendum of ∼10 Galactic sources will be discussed later. The list of nearby galaxies has 73 sources in total. These 254 sources in the sky map are seen in Figure 1.

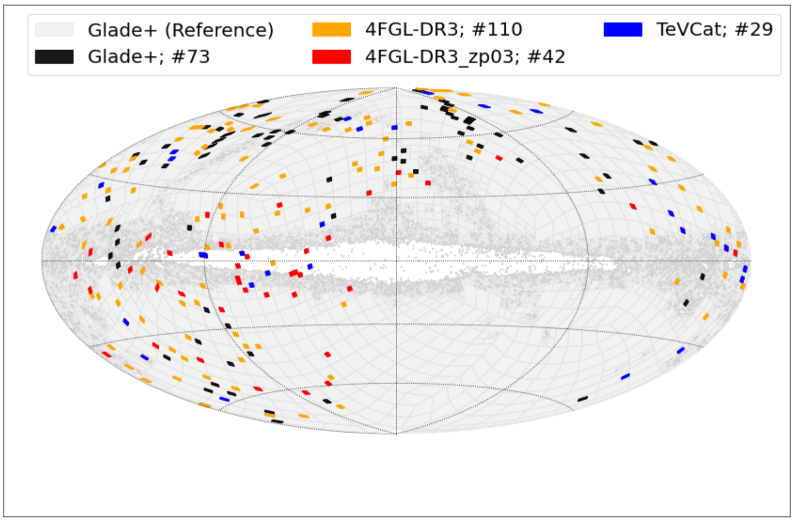

Figure 1: GFU map of sources.

4. Discussions

There are points for discussions. First would be how to include TeV (or higher) galactic sources. A correlation was found between the IceCube events and the galactic plane [13], thus it might make sense to keep steady Galactic sources such as pulsar wind nebulae and supernova remnants. Another point is for GLADE+ catalog. The cut by the distance is already cutting too much, but the number of galaxies will be too many if we allow farther ones. It would be more efficient if the multiplet alert is sent without any correlation, together with an attached list of (several) galaxies in the error region.

Such discussions started together with IceCube, including also other possibilities such as an unification of the lists of IACT teams, open multipet alerts, and integration with other activities. The following activities and the final list of sources will be the subject of a dedicated forthcoming publication as a collaborative work between LST and IceCube.

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