IceCube High-Energy Neutrino Track Alerts

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1 Motivation

The IceCube Neutrino Observatory [1] has observed a high-energy flux of astrophysical neutrinos [2, 3, 4] at high statistical significance above the known atmospheric backgrounds. To date, IceCube searches for individual sources [5] or source classes [6, 7, 8] have yet to reveal the source. A multi-messenger search that combines observations in photons and neutrinos will increase the sensitivity to sources over observations in neutrinos alone.

To achieve these multi-messenger observations, the IceCube collaboration began issuing prompt alerts to the broader multi-messenger observational community in April 2016 that encourage rapid follow-up observations following the detection of neutrino events that are likely of astrophysical origin [9]. These alerts focused on track-like neutrino candidates, which offer the most precise angular localizations of all IceCube neutrino detections. Through October 2018, a total of 15 public alerts have been issued, each receiving follow-up observations across multiple wavelength bands. One alert in particular, IceCube-170922A [10], was found across a broad range of electromagnetic (EM) emissions to be associated with a flaring blazar, TXS 0506+056 [11]. To date, this was the first and only 3σ association of a high-energy neutrino to an EM astrophysical source, and was enabled by the rapid distribution of the neutrino alert and prompt multi-wavelengths follow-up observations. Further searches within the IceCube archival data also show evidence of time-dependent neutrino emission from the position of TXS 0506+056 [12].

The IceCube collaboration has improved the existing prompt IceCube high-energy track alerts program. This work has resulted in a new set of alert streams, which will replace the original set, and are presented in detail here. These revisions target the following goals:

- Increase the number of alerts available to the community for follow-up, while keeping the signal purity high and removing mis-characterized events. Generally, IceCube high-energy neutrino track alerts should be at least ∼50% likely to be of astrophysical origin (Gold events).
- Improve the clarity of our alert information and provide more directly relevant information about each neutrino alert to the follow-up community.
- Introduce a new set of alert track events with higher rate but reduced signal purity, the Bronze events.

To increase the rate of available alerts, improvements made to astrophysical neutrino searches developed in offline studies are now made available for realtime events. These new tools offer larger numbers of astrophysical event candidates with the same high level of purity.

The alert information transmitted has also been improved with this update. Specifically, IceCube is no longer including information that is used internally to classify events, as this caused some confusion within the community. Additionally, the details of the individual event selections are no longer used to separate alerts into different classes ("EHE" vs. "HESE"), now all alerts are transmitted on a single alert channel. We also focus on clear presentation of the neutrino-candidate events, including the direction with 50% and 90% error uncertainties, our best estimate of the likely neutrino energy that could have generated this alert, a likelihood estimate that the event is an astrophysical neutrino based on the observed characteristics (called "signalness"), and a false-alarm rate (FAR). See Section 3 for more details on and limitations of these values.

In response to requests from several observatories for an increased rate of alerts, a second alert classification has been created, the so-called Bronze alerts. These alerts consist of well-reconstructed track-like neutrino events, but fall short of the 50% likelihood of being of astrophysical origin. With a threshold of ∼30% likely astrophysical origin, the total number of alerts is ∼3

times larger than the alert candidates previously provided. While a subset of the Bronze alerts also pass the Gold alert criteria, these events are **not** sent on both alert channels to avoid confusion.

2 Description of event selections

The IceCube alerts are distributed as Gamma-ray Coordination Network (GCN) notices. Originally two GCN streams, HESE and EHE, were provided. Those are now replaced by two new GCN streams, the Gold and Bronze streams. These two GCN Notices are now available using a combination of high-energy neutrino track candidate selections within IceCube, providing an astrophysical neutrino rich sample of tracks to the astrophysical community. These selections classify events based on observed quantities derived in the online reconstruction (deposited energy and charge in the instrumented volume, direction, etc.) and classify each event based on how likely it is to be of astrophysical origin. The signalness, defined as:

$$\text{Signalness} = \frac{N_{signal}}{N_{signal} + N_{background}} \tag{1}$$

where N_{signal} and $N_{background}$ are the number of signal and total background (both atmospheric neutrinos and muons) above the selection cut value. Based on this signalness value, two classes of alerts are made:

- Gold alerts - A high-energy neutrino track event selection that provide astrophysical neutrino candidates that have a signalness of at least 50%.
- Bronze alerts - A high-energy neutrino track event selection that provide astrophysical neutrino candidates that have a signalness of at least 30%.

To generate alerts, several neutrino candidate selections have been developed, each targeting different types of events, and the resulting samples combined to make the Gold and Bronze alerts. These are based on existing IceCube neutrino analyses and have been moved to the fast, online alert system as dedicated filters. These selections include:

- GFU track selection - The Gamma-ray Follow-Up (GFU) track selection serves as a realtime point-source sample that is used in rapid point-source searches [13]. For this selection, a pre-trained machine learning algorithm identifies likely neutrino-induced through-going track events from all directions [9]. In addition to serving the online point source searches, the GFU track selection can identify single astrophysical neutrino candidates. By selecting events with the highest muon energy (Northern sky) or deposited charge (Southern sky), atmospheric backgrounds are suppressed, leaving events likely to be of astrophysical origin. For the Gold and Bronze selection, these tight cuts on muon energy/charge are used to obtain 50% or 30% astrophysical purity.
- HESE starting track selection - The High Energy Starting (HESE) selection targets high-energy neutrino events where the interaction vertex occurs well within the IceCube instrumented volume [2]. The updated alert selection has been simplified from [9], and now only require a track-like hypothesis be preferred to the shower hypothesis, and a measured track length of at least 200 m. To generate the Gold and Bronze class events, the deposited charge required at each declination is varied to obtain 50% or 30% astrophysical purity.
- EHE track selection - The online Extremely High Energy (EHE) alert selection is a modification of the diffuse EHE neutrino search [7] that yielded the first observed PeV neutrino events. The analysis was modified to increase the purity of track-like neutrino candidates and to increase the sensitivity for PeV neutrinos by tightening the requirement on the fit quality and re-optimizing the two-dimensional cut on declination and total charge observed in the event. This selection remains unchanged from the first version of the alert system [9], and only contributes to the Gold alert sample (50% astrophysical purity).

Each alert selection determines the values to report in the GCN Notice issued (signalness, FAR and likely neutrino energy) based on the parameters used in candidate event identification. In the case where an event is identified by multiple selections, a single GCN notice will is issued and a hierarchical rule will be used to decide which selection's information is used in the report. This

ordering was chosen based on astrophysical signal purity and angular resolution studies. For Gold events, GFU selection information will be preferentially used, then EHE information, and finally HESE information. The Bronze events follow the same hierarchy, but because there is no EHE selection in the Bronze category, GFU information is preferred followed by HESE information. Note: events that pass the Gold event selection are **not** also sent on the Bronze alert channel to avoid confusion from multiple alerts on the same event.

When combined, these selections provide a robust astrophysical neutrino alert sample that is sensitive to neutrino track events, predominantly arising from muon neutrino charge current neutrino interactions. The neutrino effective areas for these combined selections for through-going and starting event selections are shown in Figure 1. Astrophysical neutrino generated tracks selected by these selections are expected to have very good angular resolution. The median angular resolution for these events as a function of energy is shown in Figure 2, and the expected alert declination distribution is shown in Figure 3.

3 Description of event contents

Each GCN Notice will contain several values to help follow-up observers understand the details and significance of each astrophysical neutrino candidate. At the time of detection, there is no method to clearly know if an event is truly astrophysical in nature, only probabilities based on measured properties for signal and background event classes. These values are calculated based on event samples and analyses derived from historical IceCube observations.

For both Gold and Bronze alerts, IceCube will report:

- Time and date in Univeral Time to 0.01 sec precision.
- The IceCube Run number and event number - used as a unique ID within the IceCube collaboration.
- Direction (Right Ascension and Declination) in several epochs (J2000, current and 1950) with 50% and 90% containment angular error radii.
- “Signalness” - probability this is an astrophysical signal relative to backgrounds, as defined above.
- "False Alarm Rate" - rate of background events expected that are “like this alert” that would be seen by IceCube per year.
- Likely neutrino energy - The most probable neutrino energy that would have produced an event with these observed parameters under an astrophysical neutrino signal hypothesis, assuming the best-fit diffuse muon neutrino astrophysical power-law flux ($E^{-2.19}$) [13].

It should be made clear that no reporting of potential errors on these values is done in the GCN notice, but uncertainties in these values do exist. The information reported in the alerts are provided to help observers prioritize follow-up observations, not perform detailed analyses. For example, a different choice of the neutrino astrophysical power-law flux would yield different values for the signalness and likely neutrino energy. Additionally, the likely neutrino energy is highly uncertain, as for track-like events an unknown fraction of the muon’s energy is deposited outside the IceCube instrumented volume, yielding energy uncertainties that can be as large as a factor of 10.

4 Expected alert rates

Expected annual alert rates are calculated based on our best fit astrophysical neutrino flux measurements [4, 14] and our measured rate of background-like events. These predicted rates are also compared with observed rates of alert-qualifying events that are observed in the 7 year archival IceCube data sample. These all-sky rates for Gold and Bronze alert thresholds are presented in Table 1.

It should be noted that these alerts are not expected uniformly in declination. The zenith-angle dependence of IceCube backgrounds, and absorption of high-energy neutrinos passing through the

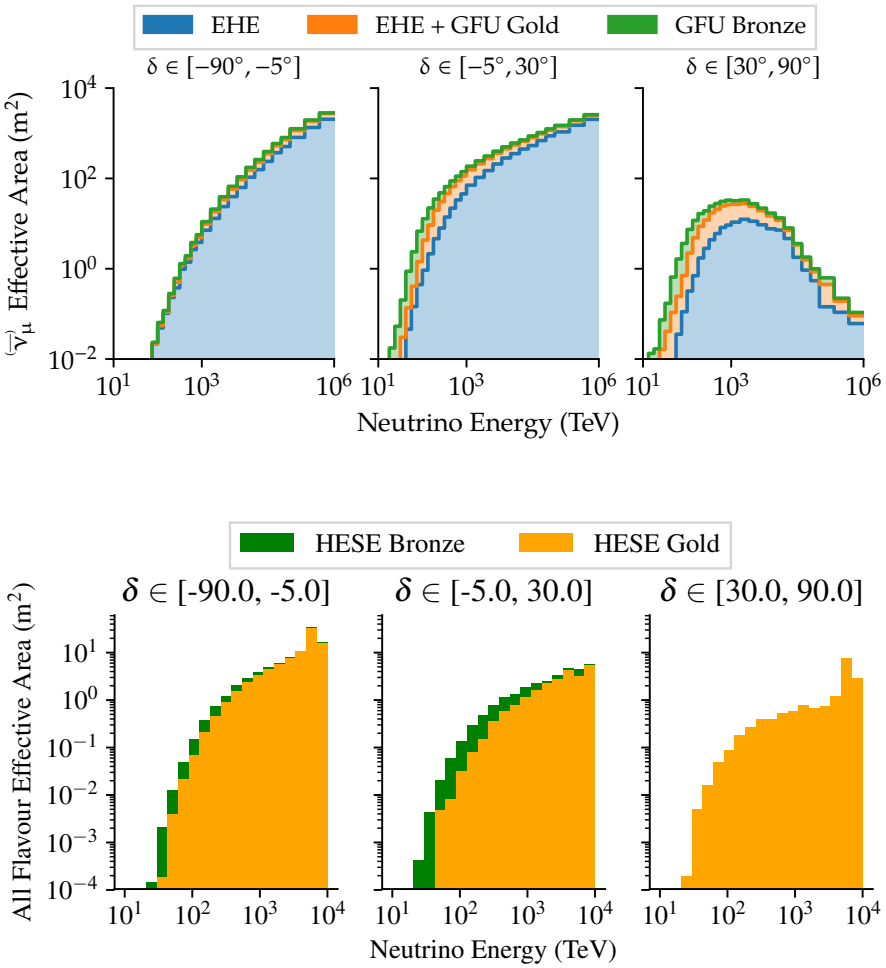

Figure 1: IceCube realtime astrophysical neutrino alert effective areas as a function of neutrino energy. The upper row presents the muon neutrino effective area for through-going neutrino selections (EHE + GFU Gold and GFU Bronze) in 3 declination bands. The older EHE selection from previous alert version is also shown (EHE). Small contributions from other neutrino flavors are not shown. The lower row presents the effective area for the HESE starting track selection for all neutrino flavors in 3 declination bands. Alerts at the Gold and Bronze levels are issued based on these selections. In these figures, the Bronze alerts shown also include events selected by the Gold alerts.

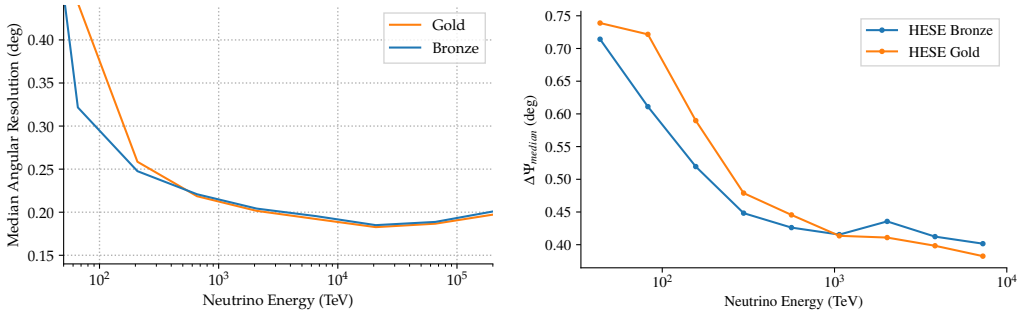

Figure 2: IceCube realtime astrophysical neutrino alert angular resolution as a function of neutrino energy. The left panel presents the angular resolution for through-going neutrino selections (GFU and EHE) and the right panel presents the angular resolution for the HESE starting track selection. Alerts at the Gold and Bronze levels are issued based on these selections, with a minimum reported angular resolution for automated alerts of 0.2 degress reported. In these figures, the Bronze alerts shown also include events selected by the Gold alerts.

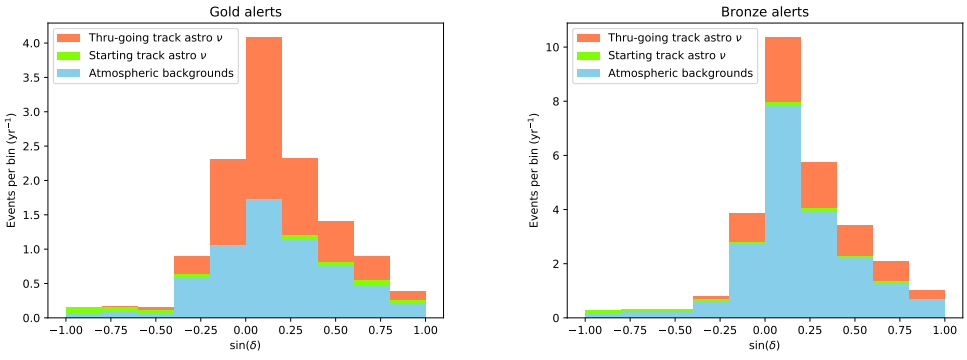

Figure 3: IceCube realtime astrophysical neutrino alert declination distribution for Gold (left) and Bronze (right) alert levels. For each figure, the expected astrophysical neutrinos ($E^{-2.19}$ spectrum assumed) and atmospheric neutrino components are shown in a stacked histogram. In these figures, the Bronze selections shown also include events selected by the Gold selection.

	Gold events	Bronze Events
Signal ($E^{-2.19}$)	6.6 (Total) 5.1 (GFU) 0.5 (HESE) 2.1 (EHE)	8.4 (Total) 7.6 (GFU) 0.8 (HESE)
Atmospheric Backgrounds	6.1 (Total) 4.7 (GFU) 0.4 (HESE) 1.9 (EHE)	19.8 (Total) 18.5 (GFU) 1.3 (HESE)
Observed historical rate	9.9 (Total) 7.8 (GFU) 1.1 (HESE) 4.3 (EHE)	28.2 (Total) 26.2 (GFU) 2.0 (HESE)

Table 1: Expected alert rates for Gold and Bronze selections, all values shown are per year. Presented are expected signal event assuming an $E^{-2.19}$ neutrino spectrum [14], anticipated atmospheric background (both atmospheric neutrinos and muons), and the total observed hitorical rate. Totals are further dividied into per-event selection values. Please note that the Bronze event rates shown here also include the events that also pass the Gold event selection. However, only a Gold or a Bronze alert is issued for a single event, not both.

Earth's core yields non-uniform astrophysical neutrino distributions. The expected alert distribution is shown above in Figure 3, with the majority of alerts expected from the Northern hemisphere in the region just above the equator.

5 Example alert messages

An example gold alert GCN Notice is listed below:

```
////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Tue 16 Apr 19 15:22:51 UT
NOTICE_TYPE:      GOLD ICECUBE ASTROPHYSICAL
RUN_NUM:          132446
EVENT_NUM:        59759967
SRC_RA:           239.2334d {+15h 56m 56s} (J2000),
                  241.7055d {+16h 06m 49s} (current),
                  233.3180d {+15h 33m 16s} (1950)
SRC_DEC:          -87.5694d {-87d 34' 09"} (J2000),
                  -87.6224d {-87d 37' 20"} (current),
                  -87.4141d {-87d 24' 50"} (1950)
SRC_ERROR90:      36.55 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      14.24 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18589 TJD;   106 DOY;   19/04/16 (yy/mm/dd)
DISCOVERY_TIME:   55341 SOD {15:22:21.08} UT
REVISION:         0
ENERGY:           1.8867e+03 [TeV]
SIGNALNESS:       0.5643 [dn]
FAR:              2.5605 [yr^-1]
STREAM:           24
SUN_POSTN:         24.45d {+01h 37m 47s}  +10.17d {+10d 10' 11"}
SUN_DIST:         102.06 [deg]   Sun_angle= 9.5 [hr] (West of Sun)
MOON_POSTN:       170.58d {+11h 22m 19s}   +8.65d {+08d 39' 06"}
MOON_DIST:         97.88 [deg]
GAL_COORDS:       304.88,-25.44 [deg] galactic lon,lat of the event
ECL_COORDS:       267.12,-64.44 [deg] ecliptic lon,lat of the event
COMMENTS:         IceCube Gold Event.
```

An example bronze alert GCN Notice is listed below:

```
////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Tue 16 Apr 19 11:05:37 UT
NOTICE_TYPE:      BRONZE ICECUBE ASTROPHYSICAL
STREAM:           25
RUN_NUM:          132446
EVENT_NUM:        18028384
SRC_RA:           282.4984d {+18h 50m 00s} (J2000),
                  282.6935d {+18h 50m 46s} (current),
                  281.9928d {+18h 47m 58s} (1950)
SRC_DEC:          +26.4057d {+26d 24' 21"} (J2000),
                  +26.4291d {+26d 25' 45"} (current),
                  +26.3466d {+26d 20' 48"} (1950)
SRC_ERROR90:      45.56 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      17.75 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18589 TJD;   106 DOY;   19/04/16 (yy/mm/dd)
DISCOVERY_TIME:   39909 SOD {11:05:09.34} UT
REVISION:         0
ENERGY:           2.2131e+04 [TeV]
SIGNALNESS:       0.3344 [dn]
FAR:              14.8404 [yr^-1]
SUN_POSTN:         24.28d {+01h 37m 07s}  +10.11d {+10d 06' 23"}
SUN_DIST:          95.68 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       168.09d {+11h 12m 22s}   +9.56d {+09d 33' 45"}
MOON_DIST:        107.08 [deg]
GAL_COORDS:        56.64, 11.99 [deg] galactic lon,lat of the event
ECL_COORDS:       287.22, 49.10 [deg] ecliptic lon,lat of the event
COMMENTS:         IceCube Bronze Event.
```

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