

Article

AMON Multimessenger Alerts: Past and Future

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Abstract: The Astrophysical Multimessenger Observatory Network (AMON) was founded to tie the world's high-energy and multimessenger observatories into a single network, with the purpose to enable the discovering of multimessenger sources, to exploit these sources for purposes of astrophysics, fundamental physics, and cosmology, and to explore archival datasets for evidence of multimessenger source populations. Contributions of AMON to date include the GCN prompt alerts for likely-cosmic neutrinos, multiple follow-up campaigns for likely-cosmic neutrinos including the IceCube-170922A event, and several archival searches for transient and flaring $\gamma + \nu$ and $\nu + \text{CR}$ multimessenger sources. Given the new dawn of multimessenger astronomy recently realized with the detection of the neutron binary star merger and the possible $\gamma + \nu$ coincidence detection from the blazar TXS0506+056, in 2019, we are planning to commission several multimessenger alert streams, including GW + γ and high-energy $\gamma + \nu$ coincidence alerts. We will briefly summarize the current status of AMON and review our monitoring plans for high-energy and multimessenger AMON alerts during what promises to be a very exciting year for multimessenger astrophysics.

Keywords: monitoring; multimessenger; data analysis and processing

1. Introduction

Multimessenger astrophysics centers on the understanding of astrophysical phenomena by looking at the properties of the different messengers of the forces of nature. These messengers are electromagnetic (EM) radiation, cosmic rays (CR¹), neutrinos and gravitational waves (GWs). The combination of this information can help us in the understanding of some of the most powerful events that occur in the universe.

The first multimessenger examples occurred with the joint observation of photons and neutrinos. These were the observations of the Sun [1] and the discovery of the supernova SN1987A [2] in 1987. Models of the evolution of collapsing stars improved after the observation of the supernova, while confirmation of stellar fusion and deeper knowledge of fundamental properties of neutrinos were obtained with the Sun studies.

A more recent result that also involves measurements of a neutrino and EM radiation is the observation of the blazar TXS0506+056. A neutrino event was detected by IceCube (cataloged as event 170922A) close to the region of the blazar, which was found to be flaring around the same time by observations from the gamma-ray telescopes MAGIC and *Fermi* [3].

With the detection of the first GW by the LIGO observatory [4], new possibilities of multimessenger detection have emerged. In 2017, the first detection of EM radiation and GWs was made when a binary neutron star merger was observed. This event was first observed by the LIGO observatory, together with the INTEGRAL and the *Fermi* Gamma-ray Burst Monitoring telescopes. More observatories joined afterwards for follow-up observations. Binary neutron star mergers were found to be one of the sources to produce short gamma-ray bursts [5].

¹ The acronym will refer to ultra-high energy cosmic rays, since the data is obtained from the Pierre Auger Observatory.

2. The Astrophysical Multimessenger Observatory Network—AMON

AMON is a network that was conceived with the main purpose of enabling coincidence analysis between different detectors and observatories to study astrophysical multimessenger sources. An important point is that AMON will enable these searches using sub-threshold data—events that are statistically identical to background events (e.g., IceCube singlet events which consists mainly of atmospherical neutrinos or *hotspots* with $>2.75\sigma$ from the High Altitude Water Cherenkov Detector or HAWC)—that are received in real time. These events can acquire a high statistical significance (e.g., $>5\sigma$ detection, or a low false alarm rate of <1 per year) if there is a coincident event in another detector [6].

AMON provides a framework with which to study the most violent phenomena in the universe. Some of the main topics that are pursued are:

- Search for the sources of ultra high-energy cosmic rays,
- Identification of the sources of high-energy neutrinos,
- Search for non-standard or new exotic phenomena such as primary black holes
- Study of compact binary mergers,
- Study of core-collapse supernovae, main candidates for multimessenger transient phenomena,
- Study of soft gamma-ray emitters, objects that emit bursts of low-energy gamma rays and X-rays,
- Study of active galactic nuclei, galaxies with supermassive black holes in their centers, capable of converting gravitational energy into powerful jets, where particle acceleration occurs.

2.1. The AMON Network

AMON is a cyber-infrastructure and a network of astrophysical detectors and observatories. Under control of its participating observatories, it collects, analyses and distributes multimessenger data in real time for follow-up observations [7].

This network is comprised by triggering and follow-up observatories:

- Triggering observatories have monitoring capabilities due to their high-duty cycles and large fields of view. Observatories in this category that have a memorandum of understanding with AMON are: IceCube [8], HAWC [9], *Fermi*-LAT [10], *Fermi*-GBM [11], ANTARES [12], FACT [13], Pierre Auger Observatory [14] and *Swift*-BAT [15]. Negotiations are on-going with LIGO [16] and Virgo [17].
- Follow-up observatories are usually pointing telescopes, with narrower fields of view but with the advantage of having better sensitivity in less time compared with some of the triggering observatories (as is the case of imaging air Cerenkov telescopes versus water Cerenkov detectors). Follow-up observatories receive alerts through the Gamma-Ray Coordinate Network/Transient Astronomy Network (GCN/TAN) [18]. In some cases, follow-up observatories can trigger on a relevant event, which can then be sent to AMON for coincidence analysis. Detectors in this category that have an MoU with AMON are: MAGIC [19], HESS [20], VERITAS [21], MASTER [22], *Swift*-XRT [15], LMT [23], LCOGT [24] and ZTF [25].

Figure 1 shows a simple diagram on how the connection between triggering and follow-up observatories occurs with AMON. More information of what a follow-up entails will be given in Section 2.2.

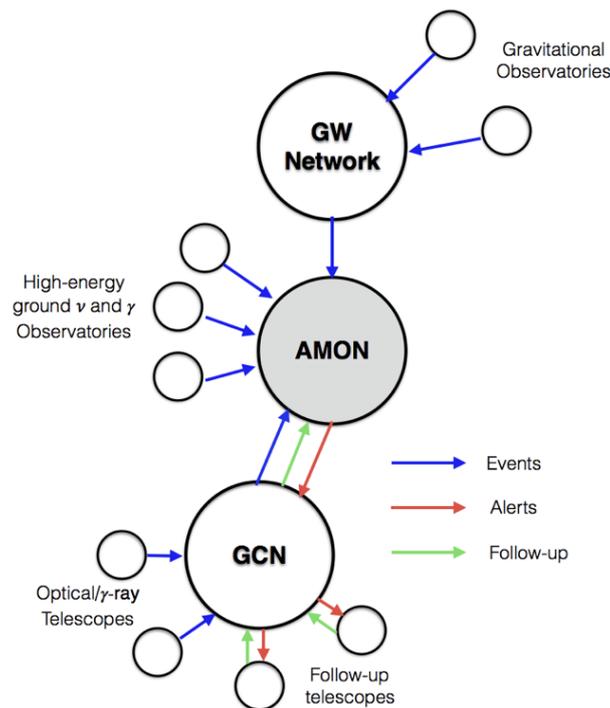


Figure 1. The AMON network. AMON receives information from triggering observatories. This observatories can be ground-based or space-based. Most of the space-based send their alerts through GCN, which AMON is subscribed to. Any alerts produced by AMON are sent to GCN for follow-up observations. Interesting followed-up observations are sent back to AMON for archival purposes (see Section 2.2).

2.2. Monitoring Capabilities: Hardware and Software

AMON uses two servers that are located at the Pennsylvania State University. The two servers have a high duty cycle with an up-time of 99.99%, i.e., less than one hour of down-time per year, which is an important feature in order to monitor the sky for extended periods of time. The machines are DELL Model PowerEdge R630 hosted by Penn State’s Institute for Cyber-Science at the University Park Campus in State College, PA, USA.

One server is used as a development machine, while the second one is used as the production machine. This second machine runs the real-time system, stores events in the AMON database and computes the coincidence analyses. This server is the one connected to GCN/TAN.

The AMON servers are able to hold a terabyte-scale database. We use MySQL (<https://dev.mysql.com/doc>) as the management system and we use the Python package *PyMySQL* to interact with the databases.

AmonPy is the software that has been developed by AMON members. The software has the ability to act as a server to receive events and also works as the main platform for the coincidence analyses. *AmonPy* software is written in Python 2.7. The software relies on the Python packages *NumPy* (<http://www.numpy.org>), *SciPy* (<http://www.scipy.org>) and *AstroPy* (<http://www.astropy.org>). For the server application, we rely on the Python packages *Twisted* (<https://twistedmatrix.com/trac>) and *Celery* (<http://www.celeryproject.org>), which are packages that can handle asynchronous operations. With *Twisted*, we can receive events from the different observatories, while *Celery* creates the specific workers that are in charge of doing the coincidence analyses. We use the *RabbitMQ* (<https://www.rabbitmq.com>) broker for the communication between the server and the *Celery* workers. The software is tested in the development machine and once it has been confirmed to be running correctly (e.g., alert rates are consistent with simulation studies; no errors in messages sent to GCN; etc.), it is deployed in

the production machine. Since new detectors can be added to the AMON network, new detector combinations can be conceived making the development of the software very dynamic.

Figure 2 is a simple representation of how the AMON server works. Each detector or observatory sends AMON events depending on a criteria that they select (For example, IceCube sends to AMON a stream designed as singlets, which are composed mostly of atmospheric neutrinos).

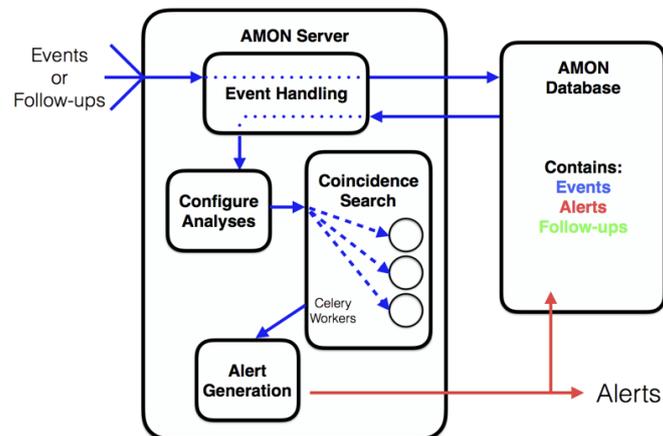


Figure 2. The AMON server. After receiving the events, these are written into the database. Then, they are sent to the *Celery* workers that are in charge of the coincidence analyses. If a coincidence has high significance, meaning a low false alarm rate (e.g., <1 per year), an alert is generated and sent to GCN.

After events have been received, they are written into the database. The events are then sent to specific analyses, defined by the configuration of the analyses, which contains information of the observatories that are part of the specific analysis. The analysis are performed by the *celery* workers. Depending on the information given by the detectors or observatories, different criteria for defining a coincidence can exist. For example, from the archival study of $\gamma + \nu$ coincidences of *Fermi* and IceCube events done in [26], the analysis selects all photons within angular separation of 5° and ± 100 s arrival time from a neutrino. Another example is an analysis of HAWC and IceCube events, which is under development. It selects neutrinos with angular separation of 3.5° around a HAWC *hotspot* (an event with $>2.75\sigma$ significance during 1 transit above the HAWC detector) and that fall inside the time window of the HAWC hotspot transit above the detector.

The analyses will produce false alarm rates based on test statistics such as a log-likelihood ratio as in the work done in [26]. If a false alarm rate (FAR) is low enough, i.e., <1 per year, this will be sent to GCN for follow-up observations. It is also possible to increase the threshold for the FAR and let the follow-up observatories decide what to pursue. If any follow-up observatories detect new sources or sources in flaring state, they are encouraged to be sent back the event to AMON for archival purposes.

The time response of follow-up observatories will vary depending first if the event is in the field of view of the telescopes or ground-based observatories, or slewing capabilities of space telescopes, etc. As an example, the IceCube event 170922A triggered the *Swift* Observatory via the AMON network. The telescope started taking data 3.25 h after the detection of the neutrino [27]. In Ref. [28], *Swift* response-times varied between 1 h and 6 h after the alerts from IceCube were sent. We expect similar time-scales for responses for coincidence alerts, once these are in place.

3. AMON Streams

Different alert streams, depending on the type of messengers that can be combined, are being developed. Currently, the stream channels created are $\gamma + \nu$, $\gamma + \nu + CR$, and $\gamma + GW$.

There are cases in which a trigger (or follow-up) observatory detects a significant event by itself (above detection threshold by the observatory standards). In these instances, AMON can act as a pass-through, sending these events directly to GCN so that they can be followed up faster.

We have summarized these channels in Table 1.

Table 1. Characteristics of different AMON alerts that are in development. Facilities include the detectors used for a specific analysis. Estimated latency considers the time of the generation of the event from the specific observatories. Potential sources show which sources can be monitored (see abbreviations in the Abbreviations section).

Channel	Facilities	Estimated Latency (hours)	Potential Sources
$\gamma + \nu$	ANTARES- <i>Fermi</i> LAT	1–12	GRBs
	IceCube- HAWC	3–8	AGNs, GRBs
	IceCube- <i>Fermi</i> LAT	1–12	GRBs
	IceCube- <i>Swift</i> BAT	1–8	AGNs, GRBs TDEs, SGRs
$\gamma + \nu + \text{CR}$	IceCube-HAWC-Pierre Auger	1–12	PBHs
$\gamma + \text{GW}$	LIGO/Virgo-HAWC	3–8	GRBs
	LIGO/Virgo- <i>Fermi</i> LAT	1–12	GRBs
	LIGO/Virgo- <i>Swift</i> BAT	1–8	GRBs TDEs, SGRs
Pass-through γ	HAWC	0.5	GRBs
	FACT	0.3	AGNs, GRBs TDEs, SGRs
Pass-through ν	IceCube	30 s	AGNs, GRBs TDEs, SGRs

As a brief comment about the uncertainty in the location of the alerts, we expect these values to be closer to the uncertainty region from the detector with the smaller value. This can be seen in the case of a log-likelihood analysis, where the spatial component is characterized by multiplying the point spread functions of each detector (see [26], as an example). In general, the uncertainties are of the order of $\sim 0.1^\circ$ for detectors such as HAWC or *Fermi*, for example.

4. Status of AMON

As of today, contributions of AMON include:

- IceCube neutrino alerts passed by AMON to GCN/TAN since April 2016.
- Active participation in multiple follow-up campaigns for likely-cosmic neutrinos including the IceCube-170922A event.
- Several archival searches for transient and flaring γ - ν and ν -CR multimessenger sources [26–28].

AMON expects to enable the emission of $\gamma + \nu$ coincidence alerts between HAWC-IceCube and *Fermi*-LAT-ANTARES as well as send HAWC alerts to GCN/TAN by the end of 2018/beginning of 2019.

AMON has also tested the real-time software, which determined that the servers can handle >3000 events per day based on the current streams that it is receiving from IceCube, HAWC, ANTARES, Auger and FACT. Figure 3 shows an example of a month of data showing some of the recent data streams that AMON has received. The figure shows events from:

- IceCube singlets: data from that contains mostly atmospheric neutrino events.
- HAWC: data from the daily monitoring analysis consisting mostly of *hotspots*, which were mentioned in Section 2.2.
- HAWCBurst: data from a GRB search monitoring system implemented by HAWC.
- HESE: the High Energy Starting Events from IceCube.
- EHE: the Extremely High Energy events from IceCube.
- Auger: data from ultra-high energy CRs from the Pierrer Auger Observatory.

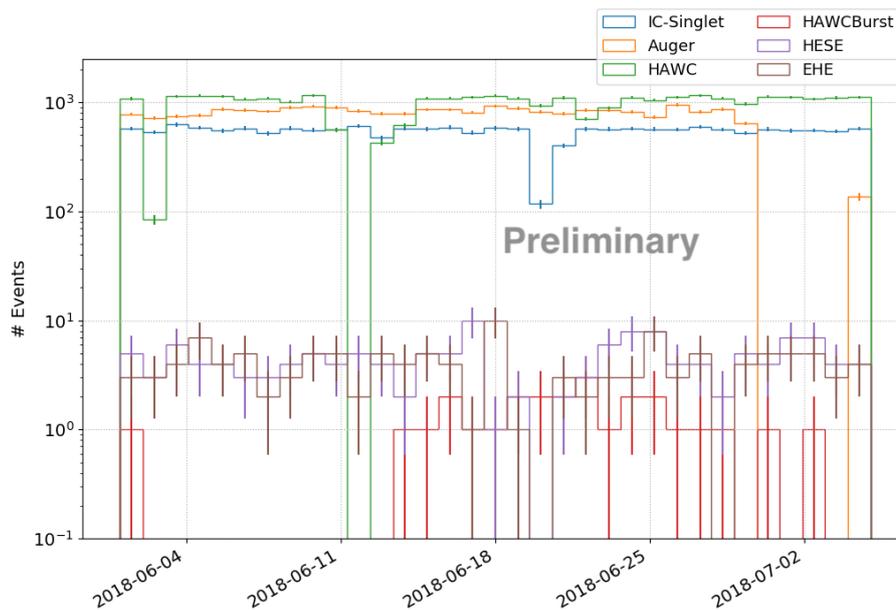


Figure 3. Rates of selected streams received by AMON. The plot shows the number of events per day received during the month of June 2018.

5. Conclusions

AMON is a cyber-infrastructure and network that facilitates a simple way for different observatories and instruments to cooperate with each other. It is well suited to do real-time and archival analyses, which are vital to advance the efforts of monitoring multimessenger sources. AMON is ready to distribute coincident alerts publicly or to private recipients per request of its partner observatories.

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Abbreviations

The following abbreviations are used in this manuscript:

AMON	Astrophysical Multimessenger Observatory Network
EM	Electromagnetic
GW	Gravitational Wave
GRB	Gamma-Ray Burst
SGR	Soft Gamma-Ray Repeater
TDE	Tidal Disruptive Event
AGN	Active Galactic Nuclei
PBH	Primordial Black Hole
CR	Cosmic Rays
GCN	Gamma-Ray Coordinate Network
TAN	Transient Astronomy Network

HESE	High Energy Starting Event
EHE	Extremely High Energy
HAWC	High Altitude Water Cherenkov
MAGIC	Major Atmospheric Gamma Imaging Cherenkov Telescopes
FACT	First G-APD Cherenkov Telescope
LIGO	Laser Interferometer Gravitational-Wave Observatory
GBM	Gamma-ray Burst Monitoring
LAT	Large Area Telescope
BAT	Burst Alert Telescope
ANTARES	Astronomy with a Neutrino Telescope and Abyss environmental RESearch project
LMT	Large Millimeter Telescope
LCOGT	Las Cumbres Observatory Global Telescope Network
VERITAS	Very Energetic Radiation Imaging Telescope Array System
MASTER	Mobile Astronomical System of Telescope-Robots
XRT	X-Ray Telescope
ZTF	Zwicky Transient Facility

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