The Astrophysical Multimessenger Observatory Network: Science, Infrastructure, and Status

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Multimessenger Astrophysics

✧ Cosmic Messengers:
  • Cosmic rays
  • Gamma rays
  • Neutrinos
  • Gravitational waves

✧ Use the messenger particles of all four of nature’s fundamental forces

✧ Explore the most violent phenomena in the universe

Image credit: M. Ahlers
Multimessenger Transient Source Candidates

- **High-Luminosity Gamma-Ray Bursts:**
  - long duration
  - high luminosity
  - seconds to minutes $\gamma$-radiation
  - $z > 1$
  - relativistic jet

- **Low-luminosity Gamma-Ray Bursts:**
  - long duration
  - under-luminous
  - $z < 0.5$

- **Short-Hard Gamma-Ray Bursts**
  - similar to HL-GRBs
  - shorter duration
  - harder spectra

- **Chocked jet supernova**
- **Core Collapse supernova**
- **Blazars**
- **Primordial Black holes**
- **Other exotica**
## Potential Sources

<table>
<thead>
<tr>
<th>Event class</th>
<th>Prompt</th>
<th>Delayed</th>
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</thead>
<tbody>
<tr>
<td>High-luminosity GRBs (HL-GRB)</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Low-luminosity GRBs (LL-GRBs)</td>
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<td>✓</td>
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<tr>
<td>Short-hard GRBs (SHBs)</td>
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<td>✓</td>
</tr>
<tr>
<td>Choked jet SN</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Core-collapse SN</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Blazars</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Primordial black holes (PBHs)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Other exotica</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
AMON links high-energy astrophysical observatories into a single virtual system.

AMON framework enables:

- Real-time and near real-time sharing of sub-threshold data between multimessenger observatories
- Real-time and archival searches for coincident signals
- Prompt distribution of electronic alerts for follow-up observations

http://sites.psu.edu/amon

Astroparticle Physics Vol. 45, 56–70, 2013
AMON Core Team

- Founded and Hosted at Penn State
- Current AMON Development and Advisory Team at Penn State:
  - Doug Cowen, Miguel Mostafa, Derek Fox,
    Stephane Coutu, Kohta Murase, Chad Hanna,
    B. S. Sathyaprakash, Peter Meszaros,
    Abhay Ashtekar, Abe Falcone
  - Azadeh Keivani, Jimmy DeLaunay,
    Colin Turley, George Filippatos, Cody Messick
AMON Network

Use messenger particles of all four fundamental forces!

✧ Triggering observatories:
  o Provide “sub-threshold” candidate events to AMON in real-time
  o IceCube, ANTARES, Auger, HAWC, VERITAS, FACT, Swift BAT, Fermi LAT

✧ Follow-up Observatories:
  o Respond to AMON alerts
  o Provide optical feedback on potential multimessenger transients
  o Swift XRT & UVOT, VERITAS, FACT, MASTER, LCOGT
AMON Functionality

• Archival Searches
  - AMON Stores events from participating observatories in the database
  - AMON searches through this database for temporal and spatial coincidences

• Pass-Through
  - AMON receives events and broadcasts them immediately via Gamma-ray Coordinate Network (GCN) to astronomical community for follow-up
    - E.g. IceCube high-energy neutrinos

• Real-time Coincidences
  - AMON receives “sub-threshold” events from multiple triggering observatories and searches in real-time for coincidences in direction and time
    - E.g. a single muon neutrino in coincidence with ≈15 photons from HAWC
  - AMON issues GCN alerts for follow-up
Data Flow

✧ Sub-threshold data from triggering observatories:
  • sent in a standard VOEvent format
  • store in a secure database

✧ VOEvents from satellite experiments via GCN

✧ Use GCN to distribute AMON alerts to the follow-up observatories as VOEvents
## AMON Status: Participation

<table>
<thead>
<tr>
<th>Observatories with AMON MoU</th>
<th>Stream content and format</th>
<th>TLS certificate</th>
<th>Test stream (fake data)</th>
<th>Test stream (real data scrambled)</th>
<th>Real data stream</th>
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<tbody>
<tr>
<td>IceCube singlet</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>In progress</td>
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<tr>
<td>IceCube HESE</td>
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<td>ANTARES</td>
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<td>In progress</td>
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<tr>
<td>Pierre Auger</td>
<td>✓</td>
<td>✓</td>
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</tr>
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<td>HAWC</td>
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<td>VERITAS</td>
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<td>In progress</td>
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<td>Swift BAT</td>
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<td>Not needed</td>
<td>✓</td>
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<td>Fermi LAT</td>
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<td>Not needed</td>
<td>Not needed</td>
<td>Not needed</td>
<td>✓</td>
</tr>
</tbody>
</table>

Azadeh Keivani (Penn State) | NASA’s Goddard Space Flight Center
AMON Status: Infrastructure

AMON event database

- Designed and implemented
- Contents:
  - Inserted: IceCube40/59 and year 1 of 86, Swift, Fermi (public)
  - Inserted: ANTARES 2008, Auger (private)
  - In progress: LIGO S5 and S6 (public)
  - Awaiting approval: IceCube, HAWC, VERITAS, ANTARES (private)

AMON application server

- Running stably since August 2014
  - Python/Twisted, asynchronous, tested with simulated and real clients
  - Accepts HTTP POST requests
  - Open for authorized connections using TLS certificates
- Started issuing public AMON alerts using VOEvent format/protocol in April 2016

AMON hardware

- Two new high-uptime servers
  - Now deployed at Penn State
  - Physically and cyber secure; fully redundant systems
Field of View

1-year simulation for IceCube, ANTARES, HAWC, Swift BAT, Pierre Auger, Fermi LAT, and LIGO-Virgo

- Average number of observatories viewing a source simultaneously
- Number of triggering facilities observing a source (averaged over time and sky location)

- 94% of $4\pi$ sr-yr is within the FoV of 3 or more observatories
- 2+ observatories are viewing any given part of the sky simultaneously
AMON Analyses

• **Archival analyses:**
  - Fermi LAT – IC40/59 (C. F. Turley et al., in preparation)
  - Primordial black holes (G. Tešić, PoS(ICRC2015)328 (2015))
  - VERITAS blazars – IC40 (C. F. Turley et al., APJ 833, 117 (2016))

• **Realtime analyses:**
  - Swift XRT/UVOT – IceCube HESE (AK et al, in preparation)
  - Swift BAT – IceCube subthreshold neutrinos (Jimmy DeLaunay)
  - HAWC – IceCube subthreshold neutrinos (AK)
  - Pierre Auger – IceCube subthreshold neutrinos (George Filippatos)
IceCube-Fermi LAT Analysis I

Fermi-LAT exposure corrected map

IC40-LAT:
★ ≈ 15M photon events
★ ≈ 13k neutrino events
★ LAT weeks 9-50

Clustering of the events:
★ Spatial: Δθ < 5°
★ Temporal: Δt = t_0 ± 50 s

IC59-LAT:
★ ≈ 18M photon events
★ ≈ 108k neutrino events
★ LAT weeks 50-104

C. F. Turley et al., in preparation (using pass 8)
Study background:

- Scramble IceCube data
- Only scramble IceCube neutrinos: gamma event stream is more complicated due to LAT motion
- Keep neutrino’s energy, position reconstructed uncertainties and declinations
- Scramble time and right ascension
- To test the analysis’s effectiveness, a series of 10,000 scrambled data tests and a series of signal tests were performed

To conduct this analysis, an un-binned log-likelihood function is considered:

\[
\lambda = 2 \ln(P_{LAT}(|\hat{x} \gamma|)P_{IC}(|\hat{x} \nu|)) - 2 \ln(B(\hat{x} \gamma))
\]
Un-blinding: Results from pass 7 Fermi LAT:

✧ IC40 – Fermi LAT:
  Data: 2138 $\gamma + \nu$ pairs
  BG: 2207±40 $\gamma + \nu$ pairs
  p-value: 15%

✧ IC59 – Fermi LAT:
  Data: 9025 $\gamma + \nu$ pairs
  BG: 9077±153 $\gamma + \nu$ pairs
  p-value: 9%

In addition, clustering of detected pairs, time distribution and multiplicity are consistent with background expectation

AMON Realtime: IceCube HESE Stream

- Only track-like High Energy Starting Event (HESE) that are likely astrophysical
- 4 alerts per year: 1 signal-like and 3 background like
- Fast alerts (median time delay 40 seconds)
- Distribute timestamps, RA/Dec, angular error, charge deposited and probability of an event being signal-like and track-like
- Public since April 6, 2016 at AMON/GCN stream
- More into: http://gcn.gsfc.nasa.gov/amon.html
- Many subscribers (50+ including VERITAS, MASTER, Swift XRT/UVOT, ANTARES, XMM-Newton, etc.)
AMON Realtime: IceCube EHE Stream

- Only track-like Extremely High Energy (EHE) neutrinos (E>100s TeV) that are likely astrophysical

- 4 alerts per year: 4-6 signal-like and 2 background like

- Fast alerts (median time delay 40 seconds)

- Distribute timestamps, RA/Dec, angular error, charge deposited and probability of an event being astrophysical

- Public since July 16, 2016 at AMON/GCN stream

- More into: http://gcn.gsfc.nasa.gov/amon.html

- Many subscribers (45+ including VERITAS, MASTER, Swift XRT/UVOT, ANTARES, XMM-Newton, etc.)
<table>
<thead>
<tr>
<th>Alert name/type</th>
<th>161103/HESE</th>
<th>160814A/HESE</th>
<th>160806A/EHE</th>
<th>160731A/HESE</th>
<th>160731A/EHE</th>
<th>160427A/HESE</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA/DEC (rev1)</td>
<td>[40.87°, 12.62°]</td>
<td>[40.83°, 12.56°]</td>
<td>[199.31°, -32.02°]</td>
<td>[122.80°, -0.73°]</td>
<td>[215.11°, -0.46°]</td>
<td>[215.09°, -0.42°]</td>
</tr>
<tr>
<td>RA/DEC (rev2)</td>
<td>[40.83°, 12.56°]</td>
<td>[200.25°, -32.35°]</td>
<td>[122.81°, -0.81°]</td>
<td>[214.54°, -0.33°]</td>
<td>[214.54°, -0.33°]</td>
<td>[240.57°, +9.34°]</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.42° (50%), 1.23°(90%)</td>
<td>0.48° (50%), 1.49°(90%)</td>
<td>0.11° (50%)</td>
<td>0.42° (50%), 1.23°(90%)</td>
<td>0.35° (50%), 0.75°(90%)</td>
<td>0.17° (50%), 0.8°(90%)</td>
</tr>
<tr>
<td>ST or Signalness</td>
<td>0.30</td>
<td>0.12</td>
<td>0.28</td>
<td>0.91</td>
<td>0.85</td>
<td>0.92</td>
</tr>
<tr>
<td>Latency: Event t0 to GCN alert sending</td>
<td>40 s</td>
<td>42 s</td>
<td>37 s</td>
<td>41 s</td>
<td>54 s</td>
<td>81 s</td>
</tr>
<tr>
<td>Followups</td>
<td>![Followups]</td>
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<td>![Followups]</td>
<td>![Followups]</td>
<td>![Followups]</td>
<td>![Followups]</td>
</tr>
</tbody>
</table>

- AGILE
- ANTARES
- FACT
- Fermi GBM
- Fermi LAT
- HAWC
- H.E.S.S.
- IPN
- Konus-Wind
- LCOGT
- MAGIC
- MASTER
- Maxi/GSC
- Pan-STARRS
- PTF
- Swift
- VERITAS
- CALET
Swift follow-up of IceCube HESE/EHE

Searching the sources of high energy neutrinos with Swift
IceCube Detection of High-Energy Neutrinos

54 High-Energy Starting Events (HESE) in 4 years of data:
• Outer strings of the facility as a veto layer
• Large deposited energy in a restricted fiducial volume
→ Contamination by muons and atmospheric neutrinos reduced
HESE Topology

Cascade-like event
Average angular error 15°

Track-like event
Average angular error 1°

Track-like events resulting from charged-current interactions of muon neutrinos:
• better localization
• suitable for Swift
Neutrino Source Candidates

- The origin of HESE cosmic neutrinos is unknown.
- Candidate source populations include:
  - Gamma-ray bursts
  - Blazars and other types of AGN
  - Ultra-luminous star-forming galaxies
  - Hupernovae
  - Other types of supernovae, including “quenched jet” GRBs.

Credit: NASA/Swift/Cruz deWilde
A powerful approach to Source Identification

- Neutrino localizations are too uncertain
- Better approach to source identification:
  - Identify neutrino localization in realtime
  - Carry out a prompt search for its electromagnetic counterpart

- HESE sample: high probability of being astrophysical
- Most proposed source populations: X-ray and optical emission
Our proposal:
• 50% confidence error region of high-confidence ($p_{\text{cosmic}} > 80\%$) HSE neutrinos
• Observe with Swift in 19-tile pattern


• Within 16 hours of the neutrino detection
• Automatic process
• XRT and UVOT
Follow-up Plan

• Cycle 12 approved and funded
• April 2016 – March 2017
• Three approved triggers: priority I TOO
• IceCube HESE realtime analysis:
  ➢ Identified and localized at the South Pole
  ➢ Telemetered via Wisconsin to AMON at Penn State (median latency ≈ 40 s)
  ➢ Convert into GCN notices
  ➢ Notices are publicly available (http://gcn.gsfc.nasa.gov/amon.html)
  ➢ Swift follows up track-like HESE with flux of >7000 p.e.
• Recovers >50% of Swift GRB afterglows
Follow-up Plan - Continued

- Automated analysis of the XRT data: University of Leicester (Phil Evans)

- Sources selected for subsequent monitoring:
  - Bright and previously uncatalogued X-ray source
  - Variability over the course of the tiling observations

- Search UVOT data for new and interesting/variable sources to submit for follow-up.

- New and variable sources (≈ 2) with subsequent follow-up observations:
  - Three daily epochs
  - Two Swift pointing
  - 1 ks per pointing

- Total observing request is
  - 31 ks (i.e. 19+2*3*2) per HESE or
  - 93 ks total.
First Swift follow-up of a HESE alert

- **IceCube-160731A:**
  - 2016 July 31
  - (RA, Dec) = (215.109°, -0.458°)
  - Error 1.2°
- Swift followed up this event within about an hour
- Radius of 0.8°
- Observations: 03:00:46 – 14:51:52 UT
- Covered 2.1 deg²
- XRT collected ≈ 800 s of PC mode data per tile
- Six X-ray sources → all known
- No transients in XRT or UVOT data
Second Swift follow-up of a HESE alert

- IceCube-161103A:
  - 2016 November 3
  - (RA, Dec) = (40.874°, +12.616°)
  - Error 1.2°
- Swift followed up this event within about five hours
- XRT radiator pointed towards Sun, made XRT very hot
- Radius of 0.8°
- Covered 2.1 deg²
- XRT collected between 150 and 250 s of PC mode data per tile
- Four X-ray sources → unknown but faint
Swift has followed up four IceCube high-energy events so far


No significant counterpart has been discovered
Current Plan

• Add Extremely High-Energy (EHE) events:
  ➢ high-energy through-going tracks
  ➢ energies exceeding several hundreds TeV
  ➢ Better resolution (≈ 0.2°)
  ➢ Expected rate 4 to 6 (2 background)
  ➢ 7-pointing mosaic
  ➢ Completion of tiling pattern within 10 hours
  ➢ Recover >79% of Swift GRB afterglows

• Rapid follow-up of a few high-energy events
• Example of 2 HESE and 4 EHE per year:
  ➢ 1 ks per pointing
  ➢ new pointings for object of interest
  ➢ two daily epochs at 2 ks per epoch
  ➢ 27 ks per HESE, 11 ks per EHE (total of 98 ks)
AMON expands discovery space in new ways
- Unleashes sub-threshold data for multimessenger searches in real-time
- Creates bidirectional, multilateral connections between triggering and follow-up observatory partners
- Enables complex real-time and archival searches

AMON greatly simplifies multimessenger searches
- Common transfer protocol, data format, event database, MoUs

AMON has made a significant progress towards real-time and archival analysis

AMON server is up and running: open for authorized connections!

AMON started issuing alerts in April 2016!

New participants are always welcome!
Thanks
IceCube triplet analysis
IceCube Neutrino Multiplet

- Triplet every 13.7 years
- Two neutrino doublets:
  - $\Delta T = 100$ s
  - $\Delta \theta_{23} = 3.6^\circ$
  - $(\text{RA}, \text{Dec}) = (26.1^\circ, 39.5^\circ)$
  - $\sigma_{50} = 1^\circ$
  - $\sigma_{90} = 3.6^\circ$
- Follow up observations after 22 hrs:
  - Swift XRT
  - ASAS-SN
  - LCO
  - MASTER
  - VERITAS
- Analyze data:
  - Swift BAT
  - Fermi LAT
  - HAWC
IceCube Neutrino Multiplet Swift

- **Swift XRT:**
  - 37 pointings
  - 320 s per tiling
  - 0.3-10 keV
  - Search for GRB afterglows, AGN flares, other X-ray transients
  - Six X-ray sources identified
  - No significant source

- **Swift BAT:**
  - By chances BAT observed the position within 1 min after the neutrino detection
  - Hard X-rays: 15-150 keV
  - Detection with single-trial $S=4.5\sigma$
  - P-value of 9.9%
  - Random fluctuation
  - $4\sigma$ upper limit of $3.9 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$
Fermi LAT likelihood ratio TS

Fermi LAT 95% upper limits on the flux:
100 MeV-100 GeV