The Astrophysical Multimessenger Observatory Network

# Status of the AMON Network

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(for the AMON team)
AMON Workshop
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AMON project

- Founded and hosted at Penn State
- Internal initial funding
- Official NSF funded project as of 2014

# AMON development and advisory team


## Penn State

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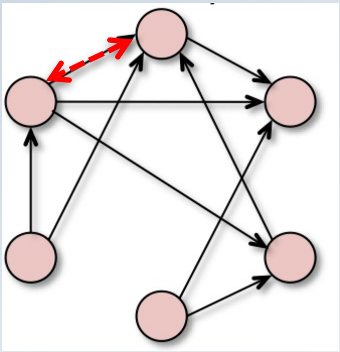
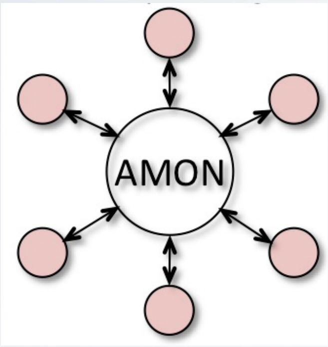
Outline

- Overview of AMON
- Status of the network:
  - database and servers
  - realtime streams
  - alert reporting and GCN
- AMON analyses
- Conclusions

Introduction

- AMON provides framework for:
  - Realtime and near realtime sharing of subthreshold data between multimessenger observatories
  - Realtime and archival searches for any coincident (in time and space) signals.
  - Prompt distribution of electronic alerts for follow-up observation
- AMON unifies and simplifies existing multimessenger efforts

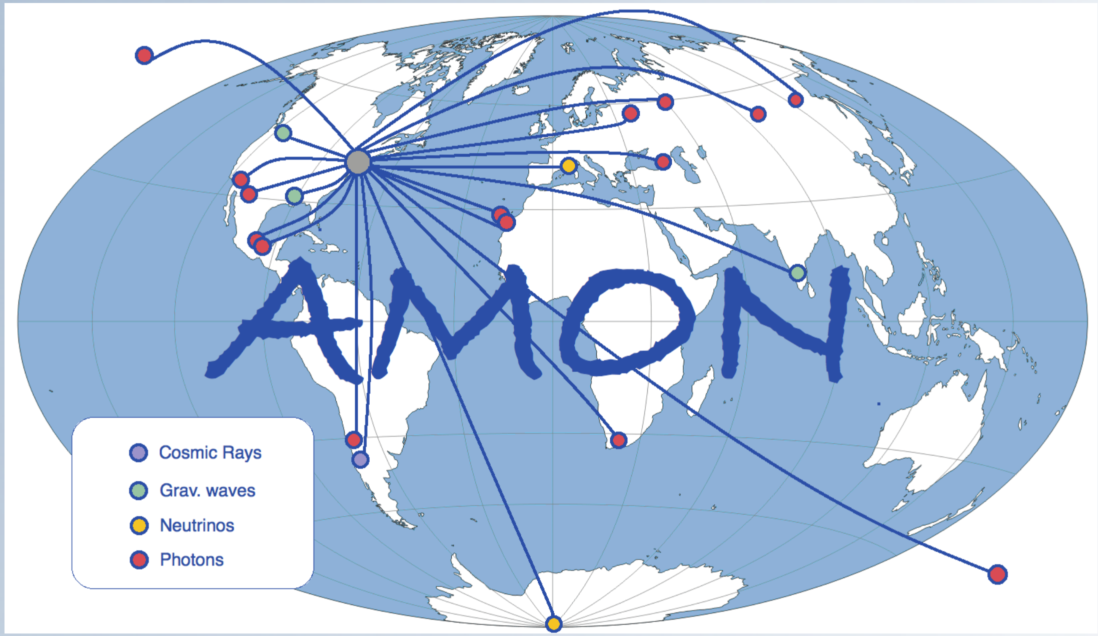





**http://amon.gravity.psu.edu/**

**Astrop.Phys. Vol. 45, 56–70, 2013**

# AMON Network




**Astrop.Phys. Vol. 45, 56–70, 2013**

**<u>Triggering</u>: IceCube, ANTARES, Auger, HAWC, VERITAS, FACT, Swift BAT**

**<u>Follow-up</u>: Swift XRT &UVOT, VERITAS, FACT, MASTER, LCOGT**

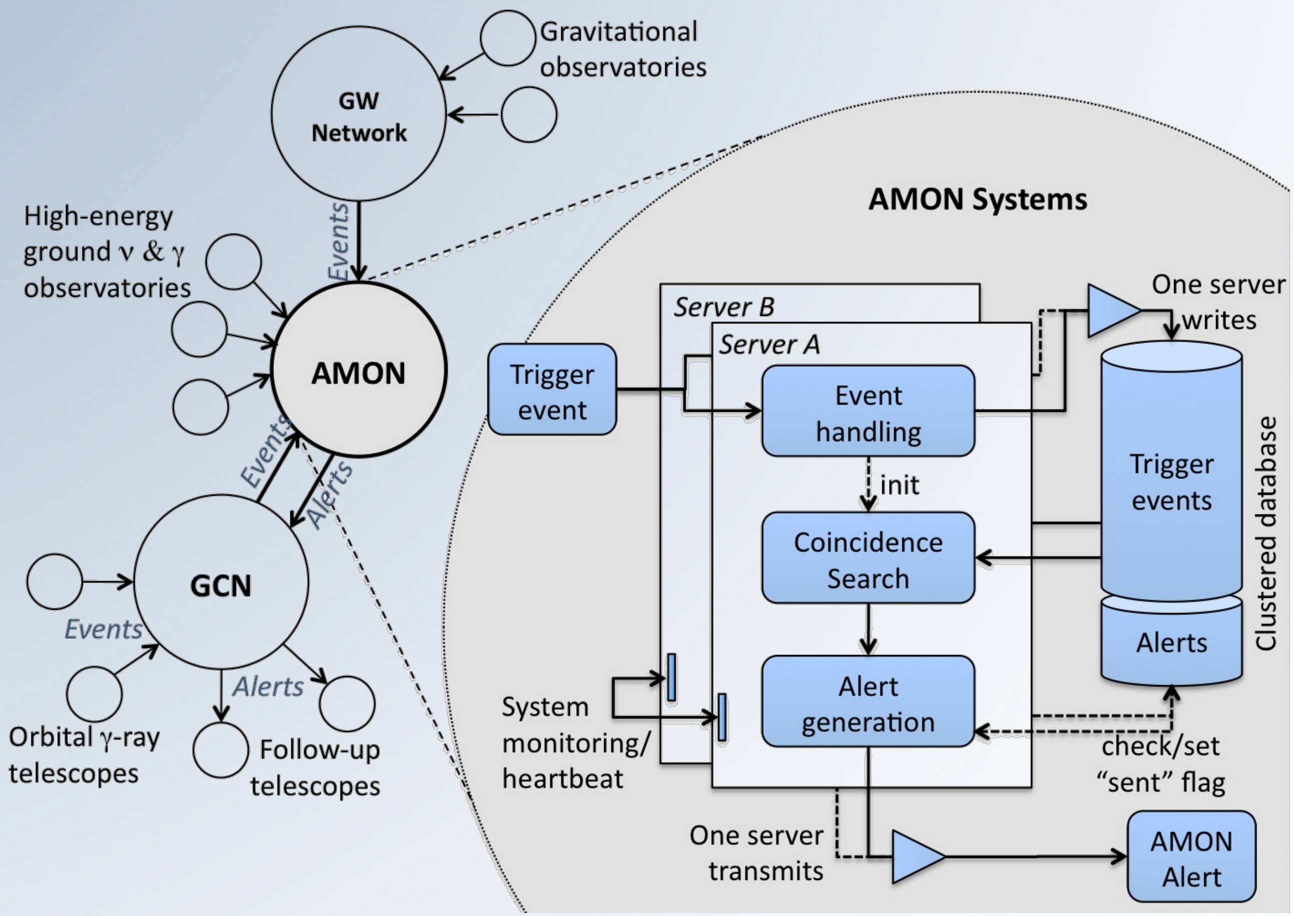
**<u>Pending</u>: LIGO, MAGIC, H.E.S.S., PTF, TA…**

Decisions about data sharing and analysis are made by the participating collaborations.

See AMON Memorandum of understanding (MOU)
http://amon.gravity.psu.edu/mou_may2015.shtml

# AMON system- data flow

- Subthreshold data from triggering observatories are sent in a VOEvent format and stored in a secure database
- VOEvents from satellite experiments are received via the Gamma-ray Coordinates Network (GCN)
- AMON alerts are distributed as VOEvents to follow-up observatories via GCN



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# Network Status

Database

First full version of AMON database designed and implemented, now being used and tested:

- Data from triggering observatories inserted
  - -done: IC-40, IC-59, Swift, Fermi [public]
  - -done: ANTARES 2008 [private], Auger [private]
  - -in progress: IceCube, HAWC, VERITAS, ANTARES [private – pending permissions], LIGO S5 and S6 [public]
- Real-time test with fake and real (IC) data performed

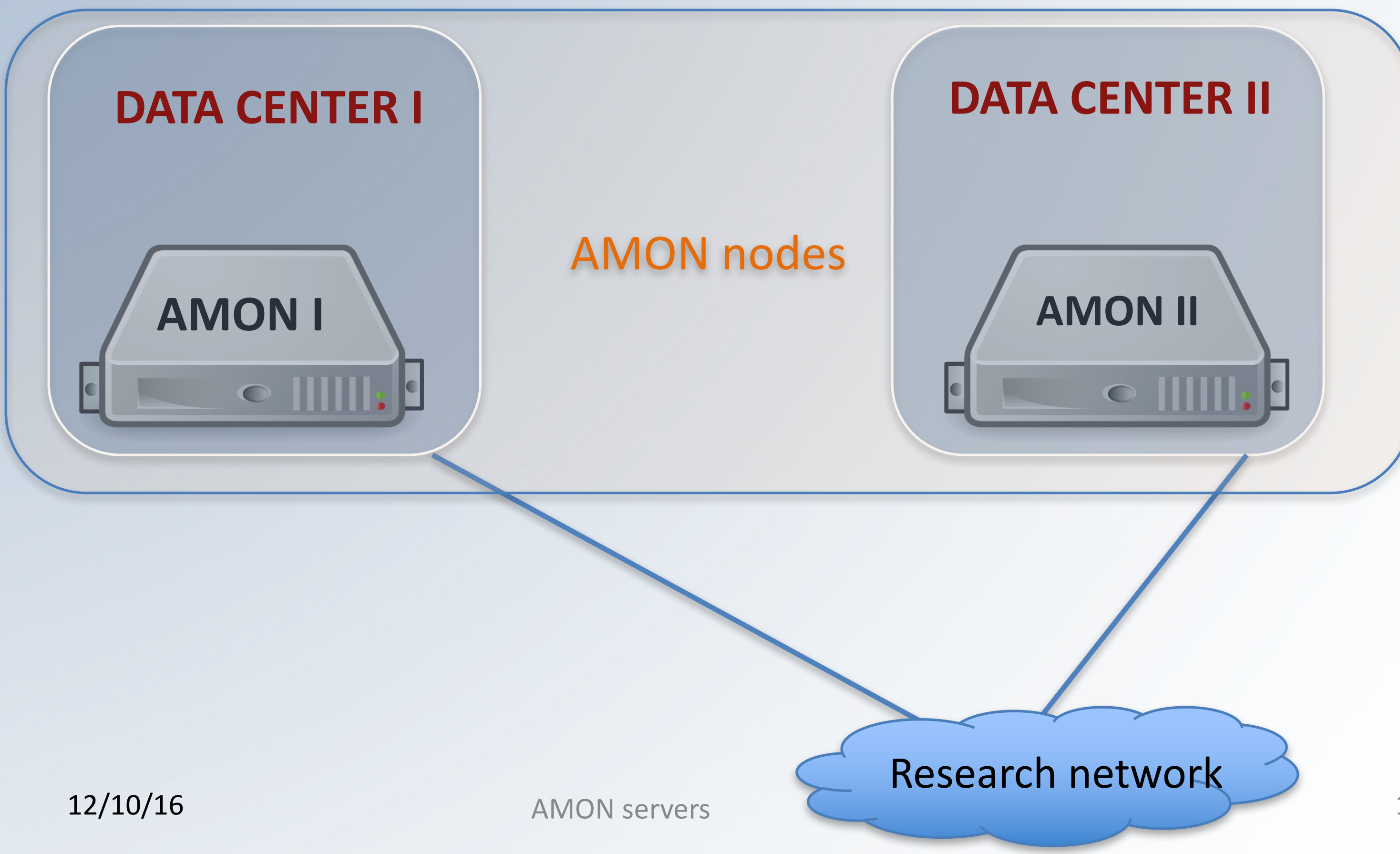
# AMON application server is up and running since August 2014

- built using Python/Twisted, asynchronous, tested with several simulated and real clients
- Accepts HTTPS POST requests (Twisted client available, but accepts other clients)
- Open for authorized connections (TLS certificates)
- Started issuing alerts from scrambled real-time data (VOEvents) via GCN in May 2015

AMON application server

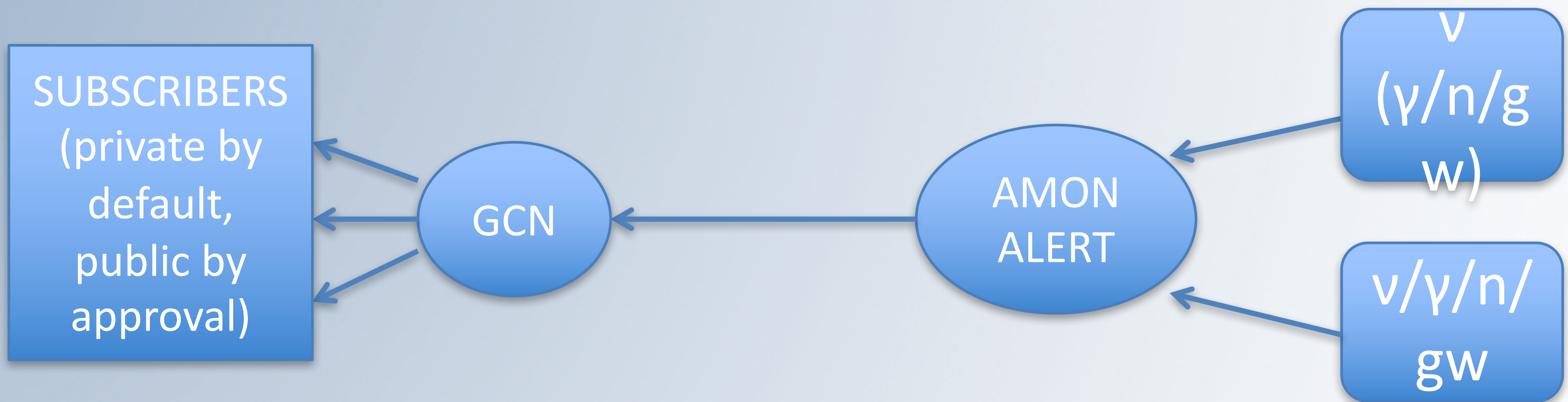
# AMON new hardware

- Deployed two new high-uptime servers
  - systems are physically and cyber secure
  - hardware and power redundant
  - memory mirroring
- Fully operational since February 2016



# Event and alert reporting - GCN

Subthreshold streams – used in AMON coincidence analysis
Above threshold events – distributed by AMON via GCN




- Subscribers can choose to get original AMON VOEvent format or any other standard GCN formats (e.g. email & socket-based)
- AMON receiver program is built by GCN (S. Barthelmy)
- Connection is running since May 2015
- Real time alerts for testing to collaborators since August 2015 (e.g., VERITAS & MASTER)
- First public stream as of April 2016 – IceCube HESE alerts

# Steps needed for participations of the triggering observatories

Observatory links to AMON

| Observatory | Stream content & format | TLS certificate | Test stream (fake data) | Test stream (real data scrambled) | Real data stream |
|---|---|---|---|---|---|
| IC Singlet | ✔ | ✔ | ✔ | ✔ | In progress |
| **IC HESE** | ✔ | ✔ | ✔ | ✔ | ✔ |
| **IC EHE** | ✔ | ✔ | ✔ | ✔ | ✔ |
| **IC OFU** | ✔ | ✔ | ✔ | ✔ | ✔ |
| ANTARES | ✔ | ✔ | In progress | | |
| Auger | ✔ | ✔ | ✔ | ✔ | In progress |
| HAWC | ✔ | In progress | | | |
| VERITAS | In progress | | | | |
| FACT | In progress | | | | |
| **Swift BAT** | ✔ | Not needed | Not needed | Not needed | ✔ |
| **Fermi LAT** | ✔ | Not needed | Not needed | Not needed | ✔ |

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# AMON/IceCube HESE public 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
- 50+ subscribers so far (VERITAS, MASTER, Swift XRT/UVOT, ANTARES, XMM-Newton etc.)

# AMON/IceCube EHE stream

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- Only track-like Extremely High Energy (EHE) neutrinos (E>100s TeV) that are likely astrophysical
- 6 alerts per year: ~ 4 signal-like and 2 background like
- Fast alerts (median time delay 40 seconds)
- Distribute timestamps, RA/Dec, angular error, charge deposited, lower energy bound, 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
- 45+ subscribers so far (VERITAS, MASTER, Swift XRT/UVOT, ANTARES, XMM-Newton etc.)

# Follow-ups of HESE/EHE

| Alert name/type | 161103/HESE | 160814A/HESE | 160806A/EHE | 160731A/HESE | 160731A/EHE | 160427A/HESE |
|---|---|---|---|---|---|---|
| RA/DEC (rev1)<br>RA/DEC (rev2) | [40.87°, 12.62°]<br>[40.83°, 12.56°] | [199.31°, -32.02°]<br>[200.25°, -32.35°] | [122.80°, -0.73°]<br>[122.81°, -0.81°] | [215.11°, -0.46°]<br>[214.54°, -0.33°] | [215.09°, -0.42°]<br>[214.54°, -0.33°] | [239.66°, +6.85°]<br>[240.57°, +9.34°] |
| Resolution | 0.42° (50%), 1.23°(90%)<br>0.65° (50%), 1.10°(90%) | 0.48° (50%), 1.49(90%) | 0.11° (50%) | 0.42° (50%), 1.23°(90%)<br>0.35° (50%), 0.75°(90%) | 0.17° (50%), 0.8°(90%)<br>0.35°(50%), 0.75°(90%) | 1.6° (50%), 8.9° (90%)<br>0.6° (90%) |
| ST or Signalness | 0.30 | 0.12 | 0.28 | 0.91 | 0.85 | 0.92 |
| Latency: Event t0 to GCN alert sending | 40 s | 42 s | 37 s | 41 s | 54 s | 81 s |
| Followups | | | | | | |

AGILE, ANTARES, FACT, Fermi GBM, Fermi LAT, HAWC, H.E.S.S, INTEGRAL, IPN, Konus-Wind, LCOGT, MAGIC, MASTER, Maxi/GSC, Pan-STARRS, PTF, Swift, VERITAS, CALET

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# Subtreshold streams

- Streams that are up and running:
  - Swift BAT (hard x-ray), publicly available
  - Fermi LAT (gamma-ray), publicly available
- Streams that are almost ready:
  - IceCube singlets (neutrinos), private – scrambled data since Feb 2015
  - ANTARES (neutrinos), private – tests started in Nov 2016
  - HAWC (gamma-ray), private – defined

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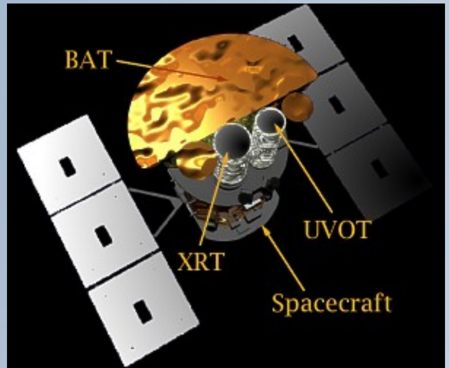
# Swift BAT




Watching the hard X-ray sky for for sudden rate increases

Rate trigger

64 s pass by

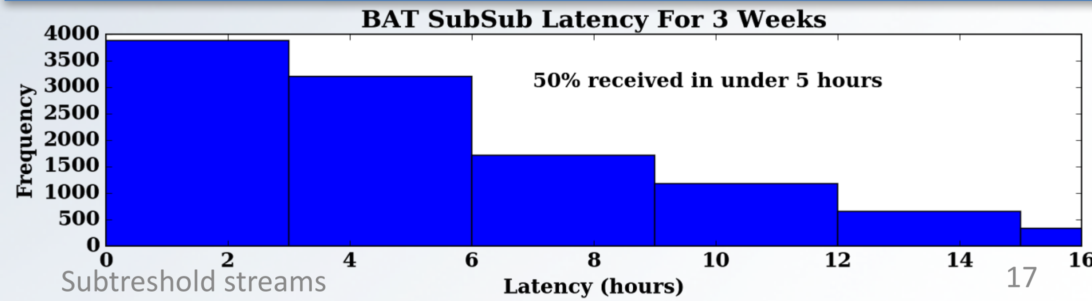
Make image, search for unknown sources

snr > 6.5σ

snr > 3.8σ

- FOV ~2 sr
- 15 - 350 keV
- Coded Imager
  - Performs FFT to create image
- Archival data available from end of 2004

| Trigger Type | Above-Threshold | SubSub-Threshold |
|---|---|---|
| Rate | ~100 per year | ~500/day (~$10^5$/year) |
| Time from event to GCN transmission | seconds | hours |
| 90% containment | 1 - 3 arcmin | 4 arcmin |




Subtreshold streams

Fermi LAT

# AMON Sub-Threshold Stream of LAT data

- Pair-production high energy photon detector
- 20 MeV - >300 GeV
- FOV 2.4 sr
- Angular Resolution (on-axis)
  - < 3.5° (100 MeV)
  - < 0.15° (>10 GeV)
- Taking data since 2008

- All single photons E>100 MeV
- Very high rate, ~25 per minute (~$10^7$ per year)
- Angular Resolution (68% containment of PSF)
  - 100 MeV, 2° - 9°
  - 1 GeV, 0.5° - 2°
  - >10 GeV, < .4°
  - Calculated from King Function PSF as a function of incoming angle and energy
- Latency
  - Data processing takes ~10 hours
  - Data dumped 6-8 times a day

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# Upcoming streams

| Detector | IceCube | HAWC | ANTARES |
|---|---|---|---|
| Messenger | Track-like muon neutrinos | High energy gamma-rays >100 GeV | Track-like upgoing muon neutrinos |
| FOV | 2π sr (upgoing)<br>4π sr (up+downgoing) | ~ 2 sr | 2π sr |
| Expected Rate | ~ 12 per hour | Very high, ~100 per hour | Low, couple per month |
| Latency | ~ minute | ? | ~ seconds - minute |
| Angular Resolution | 0.1° - 3° | ~ 0.1° - 1° | ~ 0.3° - < 1° |
| Status | • Stream content done<br>• Connection made<br>• Scrambled real-time data sent<br>• Working on coincidence analysis and permission to unscramble | • Stream content done<br>• Fake/Scrambled archival data sent<br>•Working on coincidence analysis and permission to unscramble | • Stream content done<br>• Certificate created<br>• Connection to AMON made<br>• Testing real-time data transmission |

# ANALYSES

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Current status- Analyses

# Archival analyses:

- ν+ϒ-ray:
  - IC40 and Fermi LAT (A. Keivani et al., PoS(ICRC2015) 786 (2015))
  - IC40/59 and Fermi LAT (final stage)
  - IC40/59 and Swift BAT sub threshold (in progress)
  - IC40 and VERITAS Blazar TeV flares (awaiting publication)
  - IceCube + HAWC (in progress)
- ϒ-ray + gravitational waves (gw):
  - Swift and LIGO S5 (in progress)
- ν+ϒ-ray + cosmic ray (CR):
  - Primordial Black Hole (PBH) evaporation searches (G. Tešić, PoS(ICRC2015)328 (2015))

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ν+TeV Blazar flares

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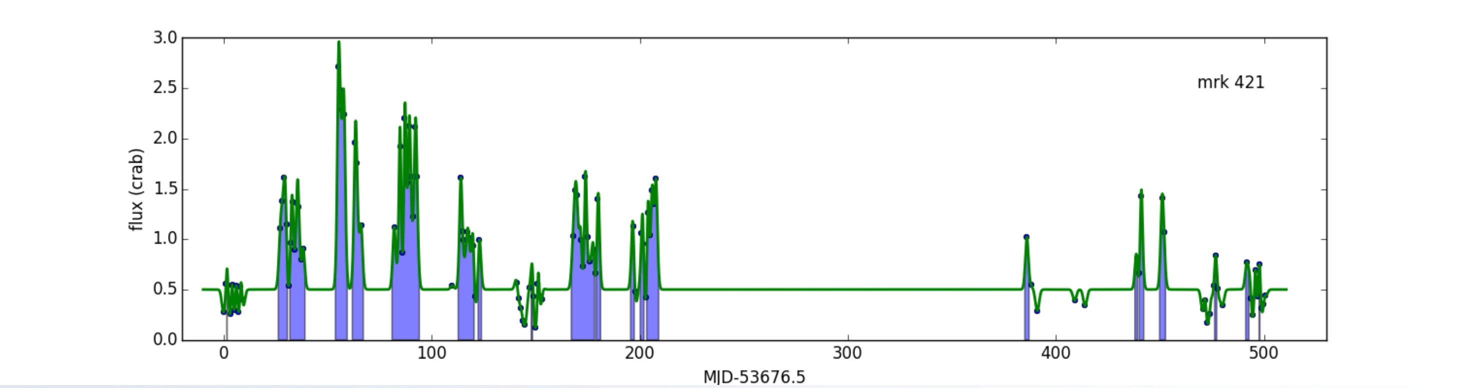
## **Search for Blazar Flux-Correlated TeV Neutrinos in IceCube 40-String Data** (C. F. Turley, D. B. Fox et al., **arXiv:1608.08983**)

- Hadronic models predict associated TeV neutrinos (proportional to TeV flux)
- AMANDA-II detected a neutrino from the vicinity of 1ES 1959+650 during a TeV orphan flare, though no association claimed, significance not quantifiable
- Kadler et al. (2016) suggested the 9.5 month outburst from PKS B1424−418 may be the source of the 2 PeV HESE 35 event
- VERITAS TeV blazar monitoring over IC40

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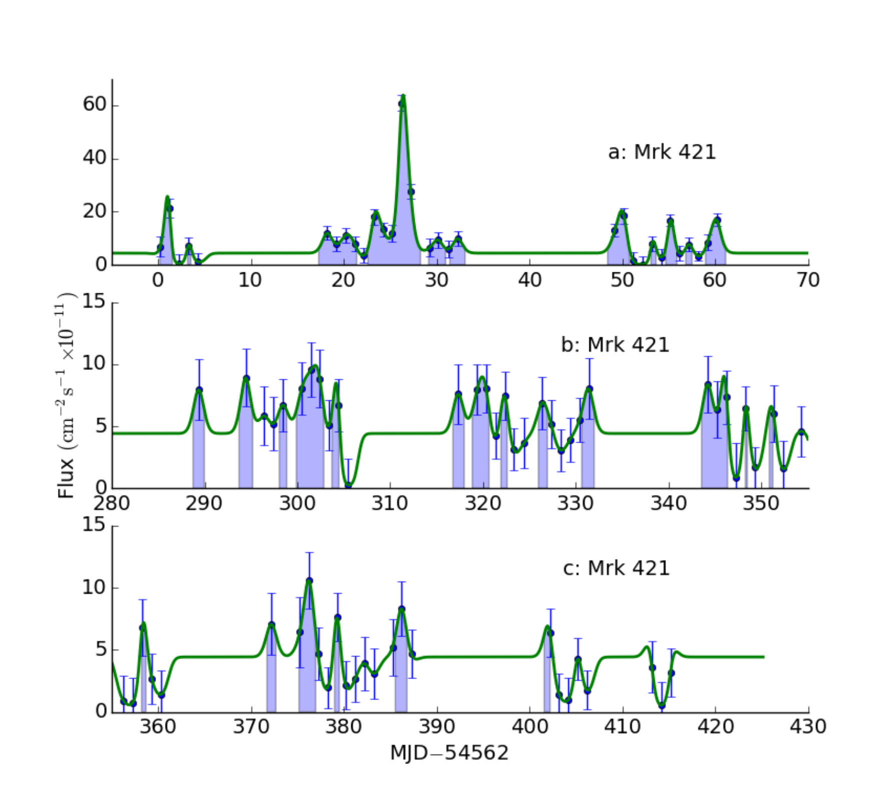
# Method

- Define temporal periods of interest for each blazar
- Maximize ratio of TeV fluence to number of ν needed to give a 3σ excess over atmospheric BG
- Markarian 421 bright intervals dominate the optimization; thus carry out 2 analyses:
  - Mrk 421 bright intervals only
  - All other blazar bright intervals




Times of interest for Mrk 421 during the IceCube 40-string search, totaling 45.6 days.

ν+TeV Blazar flares

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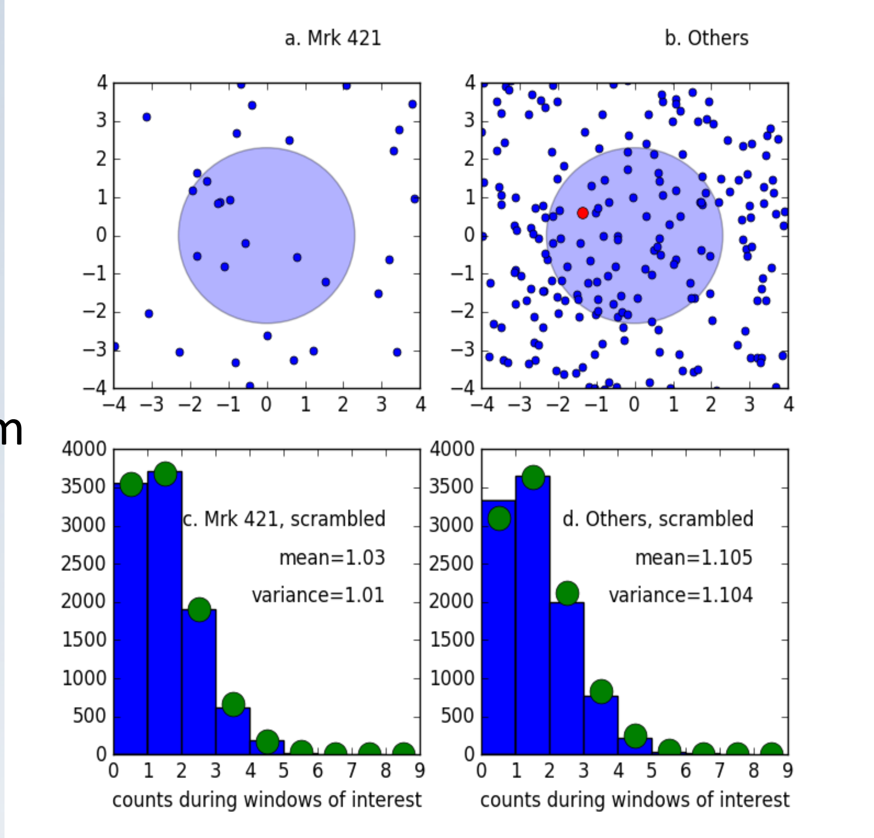
ν+TeV Blazar flares

# Validating background model (scrambled data):

- Distribution of neutrinos found during times of interest from the 10000 scrambled runs (bottom plots)
- Each region of interest expects 0.023 neutrinos per day (1 per 44 days)
- Confirm expected background rate + Poisson behavior
- Need 5 or more neutrinos from Markarian 421 for a detection ($t_{exp}$ = 46 days)
- Need 6 or more neutrinos from the other blazars for a detection ($t_{exp}$ = 52 days)



# Results – Mrk 421:

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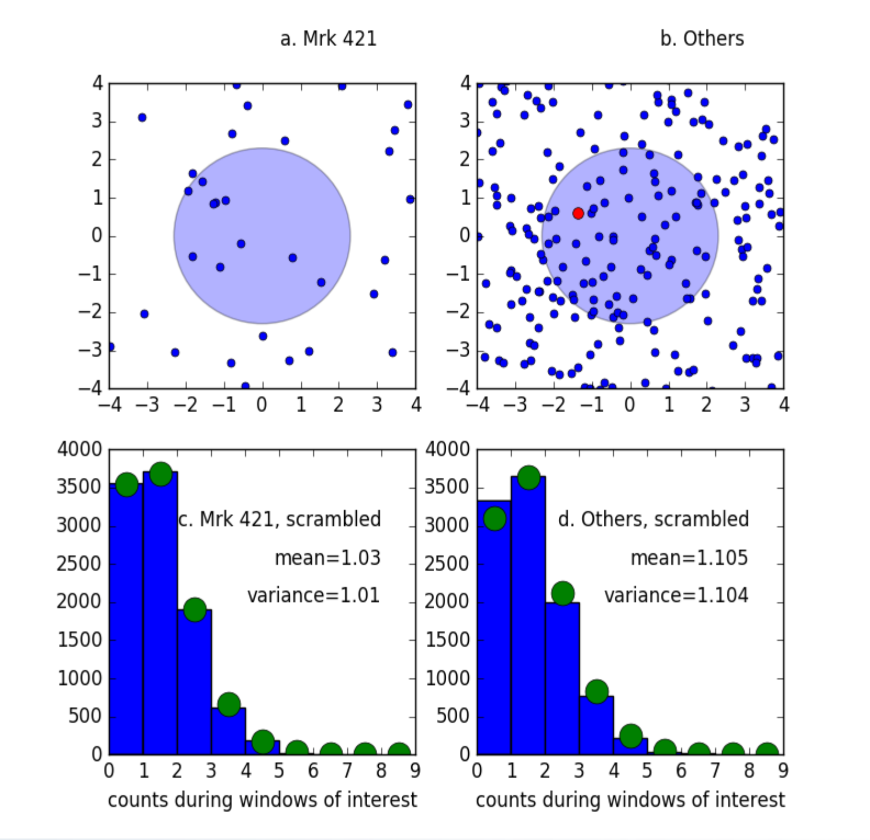
ν+TeV Blazar flares

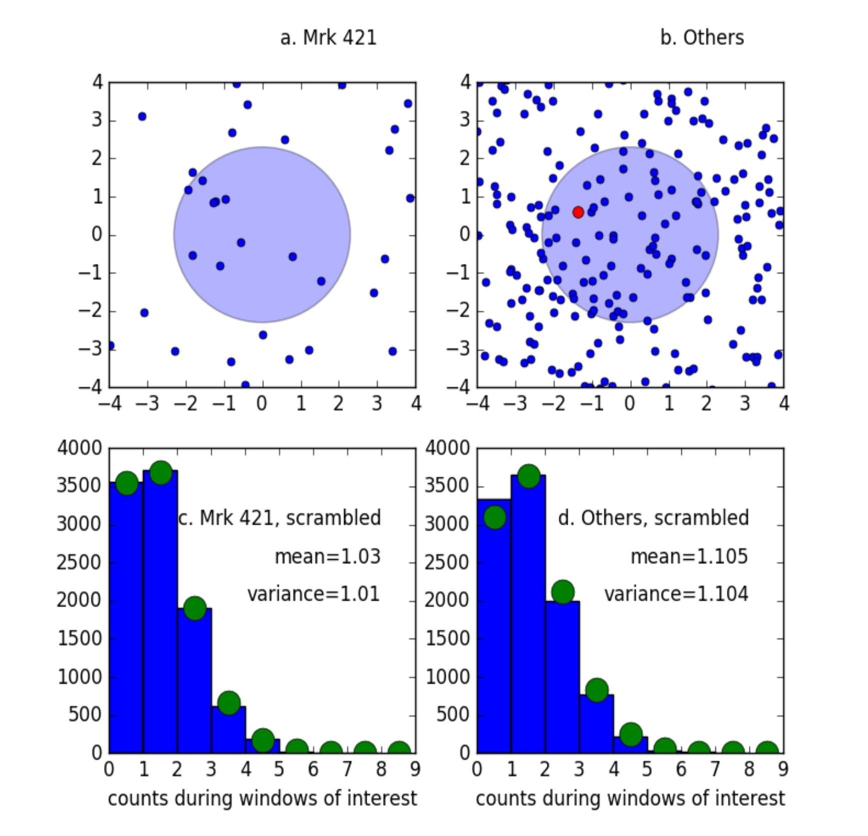
- No neutrinos detected
- 90% CL upper limit of $N_{obs}$<1.27 ($N_{exp}$=0.79)
- Within a factor of 2 from constraining the hadronic model for Mrk 421
- IceCube's 7 further years of data should yield physically constraining limit (3.8x improvement in figure of merit expected)




C. F. Turley, D. B. Fox et al., **arXiv:1608.08983**

# Results – other blazars:

- One neutrinos detected
- 90% CL upper limit of $N_{obs}$<2.79 ($N_{exp}$=0.023)
- Less constraining than Mrk 421




C. F. Turley, D. B. Fox et al., **arXiv:1608.08983**

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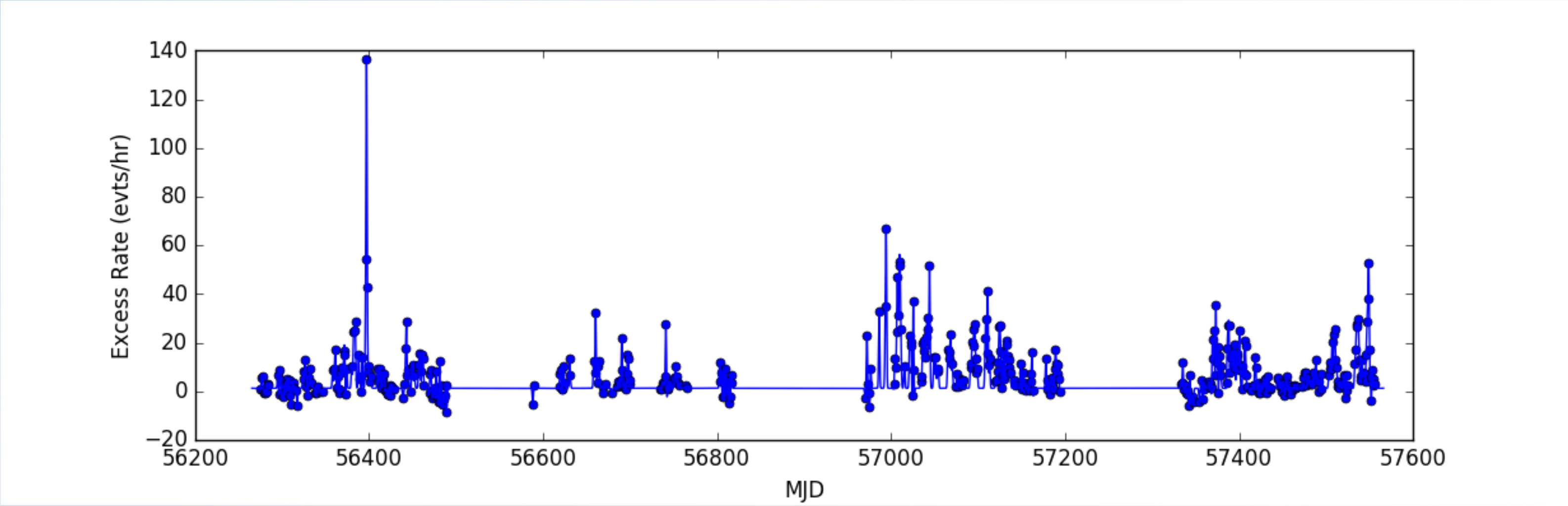
ν+TeV Blazar flares

# Future work

- Flux-sensitive point source search protocol has been defined and can be easily applied to all existing datasets
- Mrk 421 best candidate for flux-correlated neutrinos
- Regular monitoring of Mrk 421 in TeV gamma-rays from HAWC, FACT, VERITAS (plus Swift BAT as X-ray veto for orphan flare selection)
- To propose IceCube-AMON Mrk-421 project




Mrk 421 light curve from FACT

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# Conclusions

- AMON has made a significant progress toward real-time and archival analysis
- AMON server is online - open for authorized connections
- New high-uptime dual hardware is fully operational
- Ongoing realtime streams from IceCube, Swift BAT and Fermi LAT
- In 2016 AMON has started distributing IceCube's HESE and EHE (public), plus OFU (private) alerts via GCN
- More incoming event streams soon (e.g. ANTARES, HAWC & Pierre Auger) to be used in multimessenger coincidence analyses in real-time

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EXTRA SLIDES

Event content

**Event content common to each observatory :**

stream number,
id number,
revision number
trigger time
position
positional error
number of events
time window
error on time
false positive rate density
p-value
type of the event
pointing
observatory location
type of the PSF

**Event content specific to each observatory :**

parameter name: *(energy, SNR, etc)*.
value of the parameter
units (*TeV etc*.)

Alert content

# AMON Alert content:

<u>stream number</u>
<u>id number</u>
<u>revision number</u>
time
position of the best fit
positional error
number of events
time window
error on time
false positive rate density
experiments observing
experiments triggered
type of the alert
skymap

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Event/Alert Format

# AMON will receive events and send alerts in VOEvent format

- Standardized data packet format simplifies protocols for data handling (e.g. adding new observatory will not require new methods for injection of data into database and analysis stream)
- VOEvent is used by larger astronomical community i.e. became a standard for real-time event distribution (e.g. GCN notices, Swift, Fermi, LIGO, AMON etc.)
- Well structured in XML format with simple schema
- Easily interpreted by software, can be read by robotic telescopes (important for real-time analysis and near real-time follow-up)

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