

The Astrophysical Multimessenger Observatory Network



AMON: REAL-TIME OPERATIONS

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(for the AMON team)
HAP Workshop
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- 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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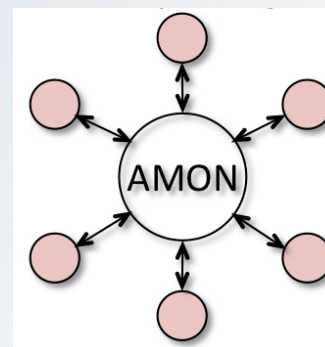
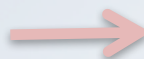
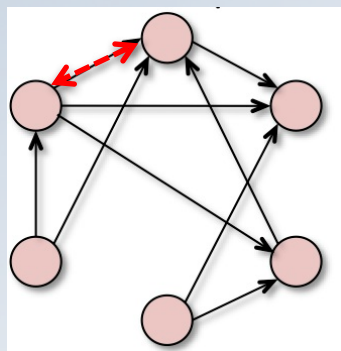
⁵Georgia Institute of Technology



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

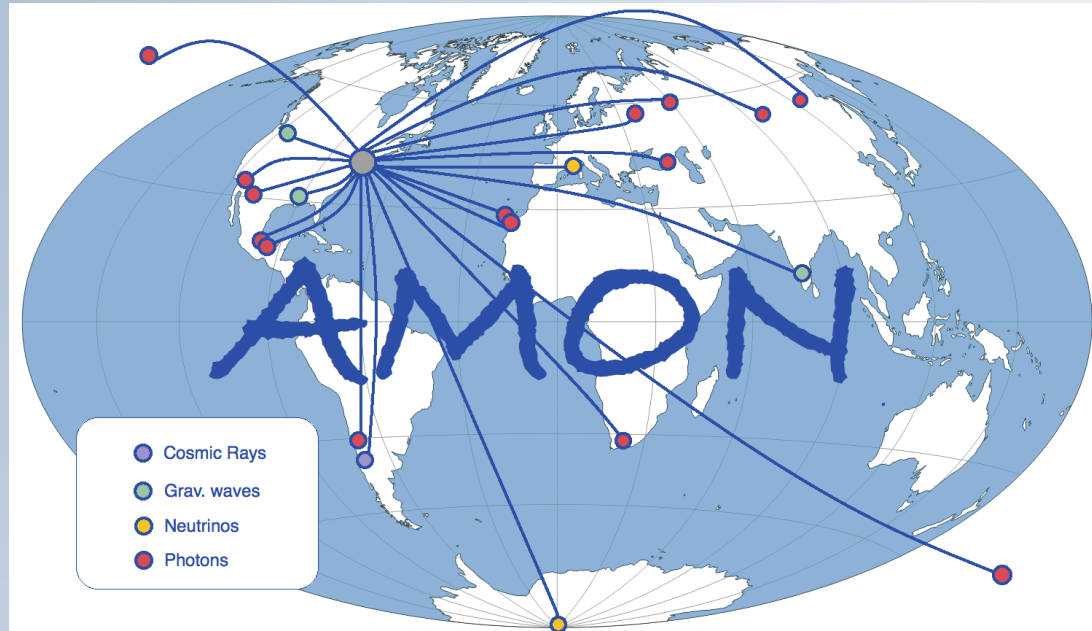


- AMON provides framework for:
 - Realtime and near realtime sharing of subthreshold data between multimessenger observatories
 - Realtime and archival searches for any coincident (in time and space) signals.
 - Prompt distribution of electronic alerts for follow-up observation
- AMON unifies and simplifies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



<http://amon.gravity.psu.edu/>

Astrop.Phys. Vol. 45, 56–70, 2013



Astrop.Phys. Vol. 45, 56–70, 2013

Triggering: IceCube, ANTARES, Auger, HAWC, VERITAS, FACT, Swift BAT

Follow-up: Swift XRT & UVOT, VERITAS, FACT, MASTER, LCOGT

Pending: LIGO, MAGIC, H.E.S.S., PTF, TA...

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

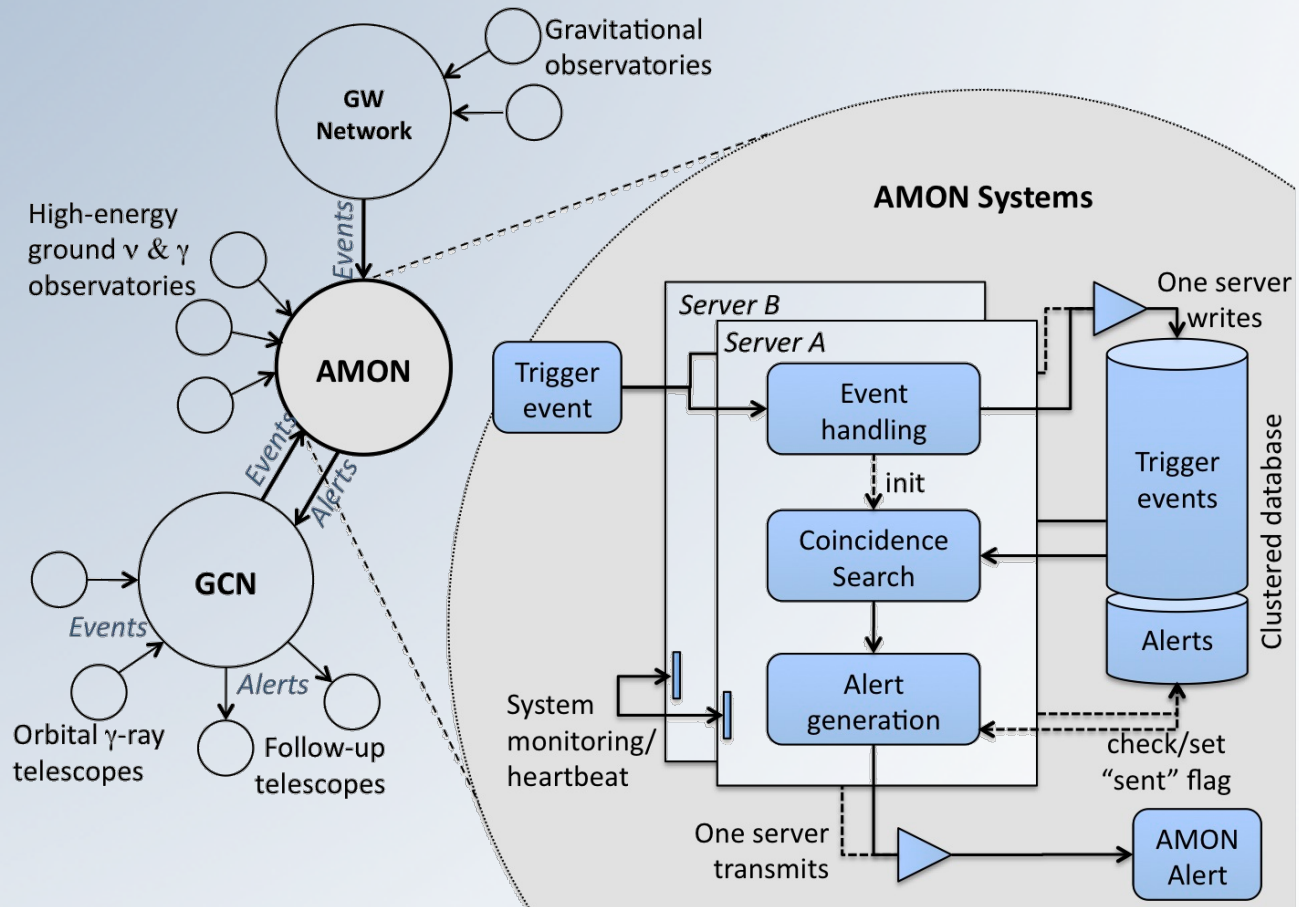
See AMON Memorandum of understanding (MOU)

http://amon.gravity.psu.edu/mou_may2015.shtml





- 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





NETWORK STATUS

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



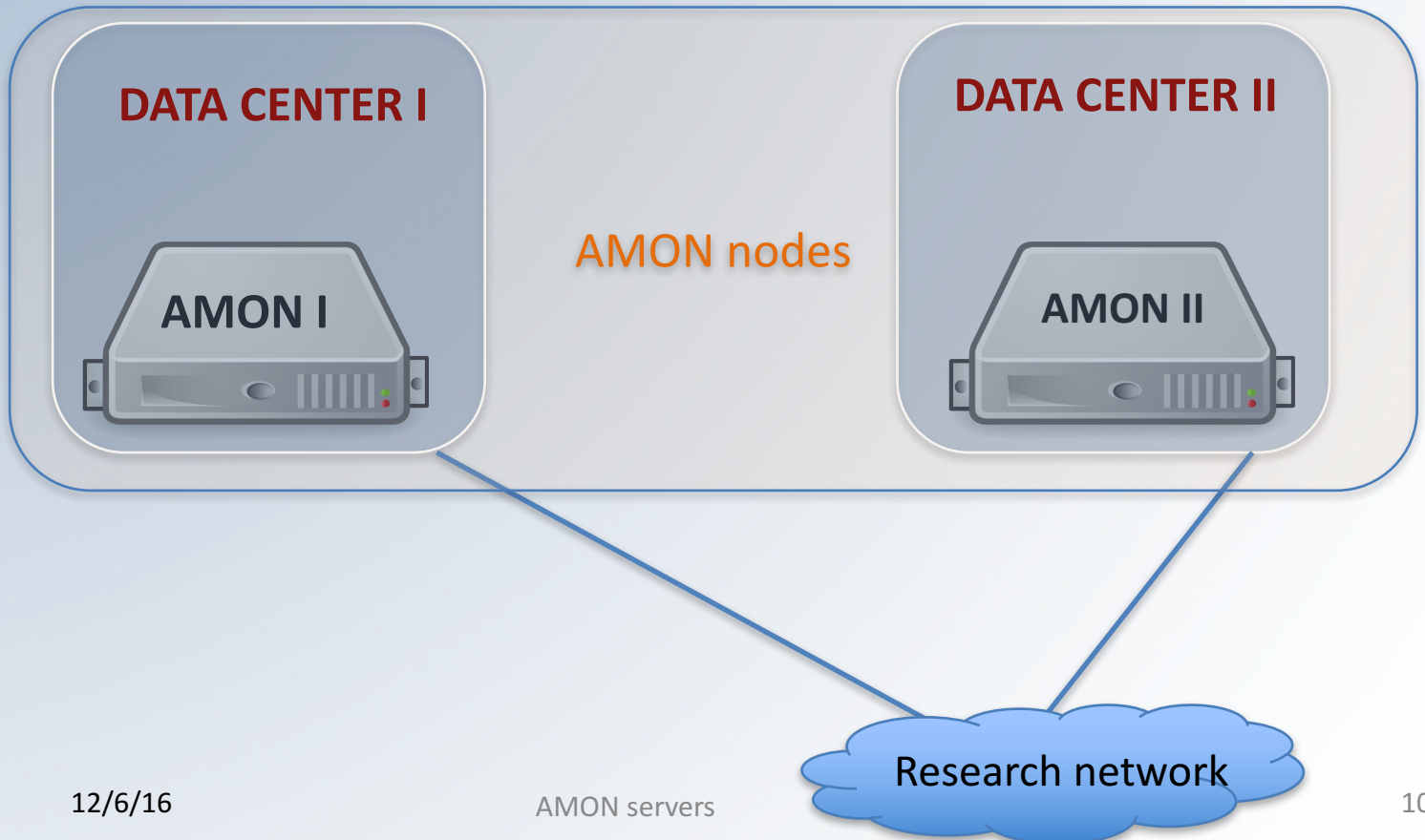
AMON application server is up and running since August 2014

- 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

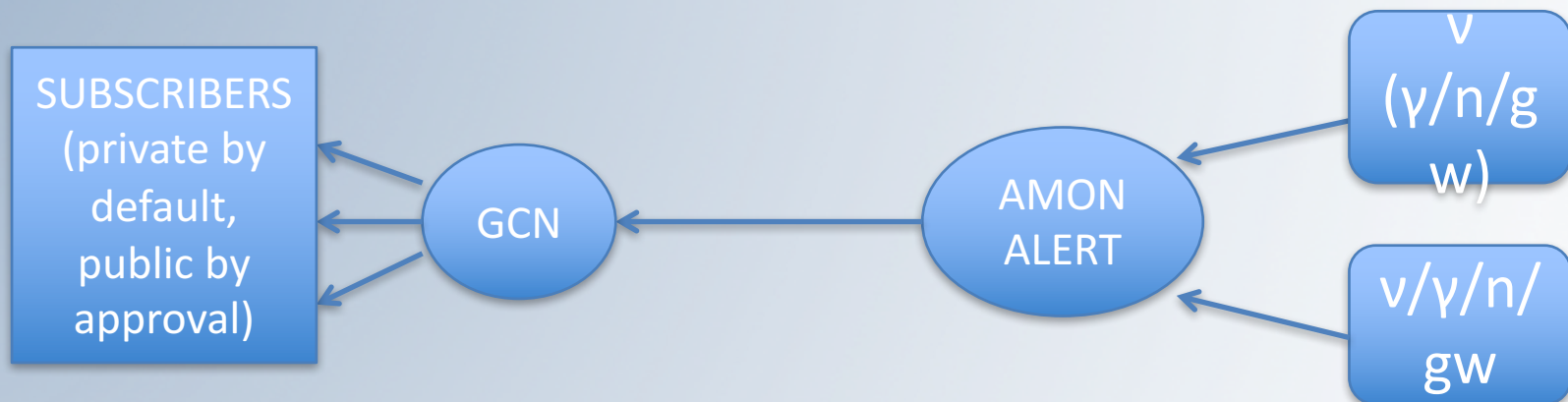
AMON application
server



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



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	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	✓



- Only track-like High Energy Starting Event (HESE) that are likely astrophysical
- 4 alerts per year: $\sim$ 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.)



- Only track-like Extremely High Energy (EHE) neutrinos ($E > 100$ s 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.)

 AGILE
  Fermi LAT
  IPN
  MASTER
  Swift

 ANTARES
  HAWC
  Konus-Wind
  Maxi/GSC
  VERITAS

 FACT
  H.E.S.S.
  LCOGT
  Pan-STARRS

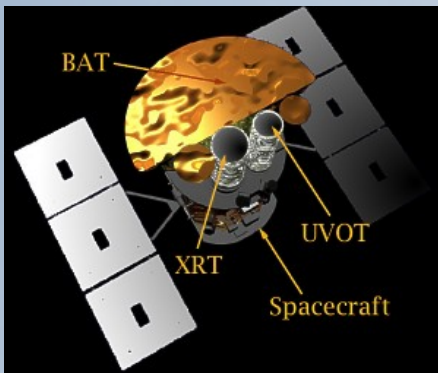
 Fermi GBM
  INTEGRAL
  MAGIC
  PTF



- 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

Swift BAT



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

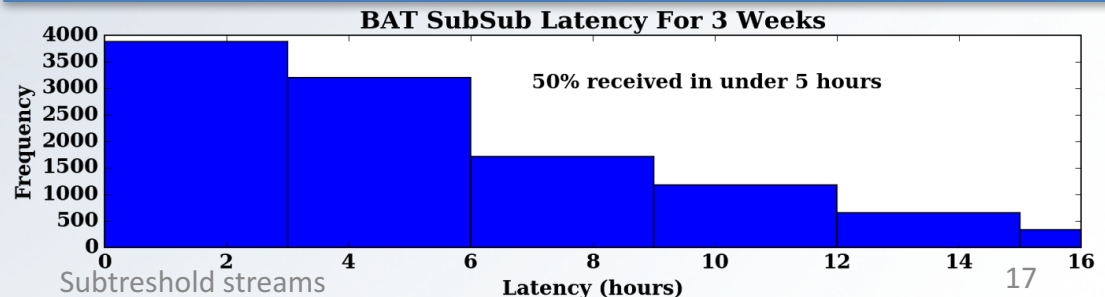
Watching the hard X-ray sky for sudden rate increases
Rate trigger

Make image, search for unknown sources

$\text{snr} > 6.5\sigma$

$\text{snr} > 3.8\sigma$

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





- 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

AMON Sub-Threshold Stream of LAT data

- All single photons $E > 100$ MeV
- Very high rate, ~ 25 per minute ($\sim 10^7$ per year)
- Angular Resolution (68% containment of PSF)
 - 100 MeV, $2^\circ - 9^\circ$
 - 1 GeV, $0.5^\circ - 2^\circ$
 - > 10 GeV, $< .4^\circ$
 - 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



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) 4π sr (up+downgoing)	~ 2 sr	2π sr
Expected Rate	~ 12 per hour	Very high, ~ 100 per hour	Low, couple per month
Latency	$\sim$ minute	?	$\sim$ seconds - minute
Angular Resolution	$0.1^\circ - 3^\circ$	$\sim 0.1^\circ - 1^\circ$	$\sim 0.3^\circ - < 1^\circ$
Status	• Stream content done • Connection made • Scrambled real-time data sent • Working on coincidence analysis and permission to unscramble	• Stream content done • Fake/Scrambled archival data sent • Working on coincidence analysis and permission to unscramble	• Stream content done • Certificate created • Connection to AMON made • Testing real-time data transmission



AMON



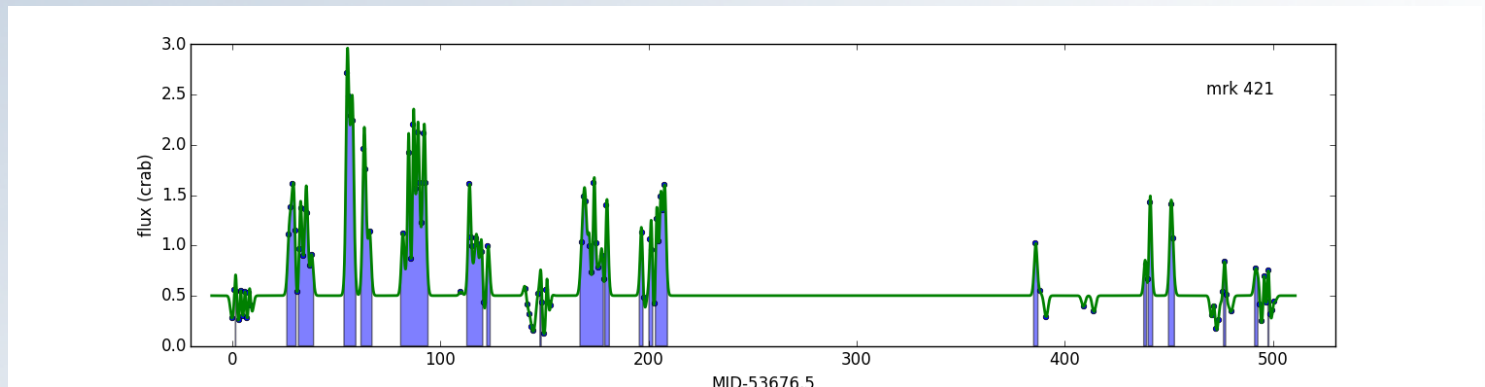
ANALYSES

Archival analyses:

- v+ γ -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)
- γ -ray + gravitational waves (gw):
 - Swift and LIGO S5 (in progress)
- v+ γ -ray + cosmic ray (CR):
 - Primordial Black Hole (PBH) evaporation searches ([G. Tešić, PoS\(ICRC2015\)328 \(2015\)](#))

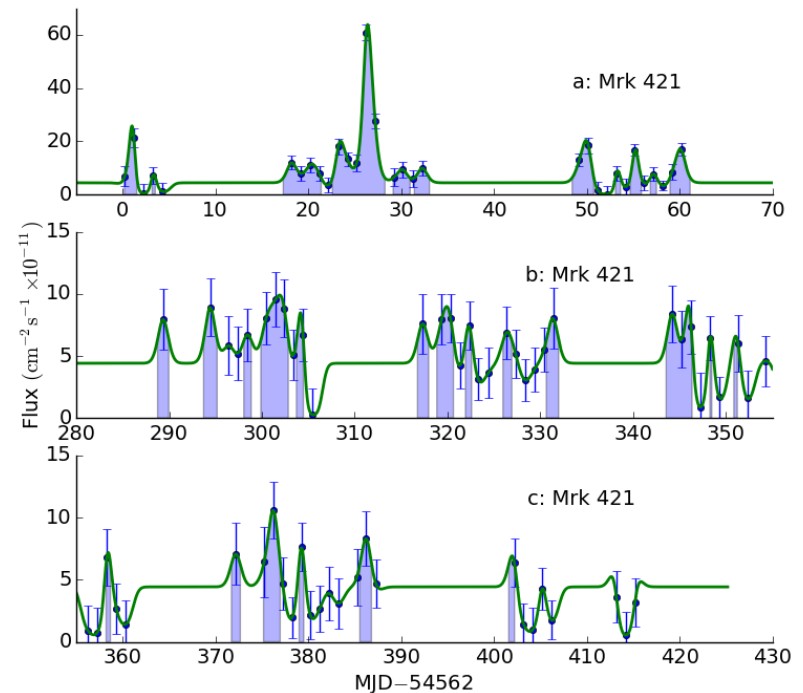
Search for Blazar Flux-Correlated TeV Neutrinos in IceCube 40-String Data (C. F. Turley, D. B. Fox et al., arXiv:1608.08983)

- 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



Method

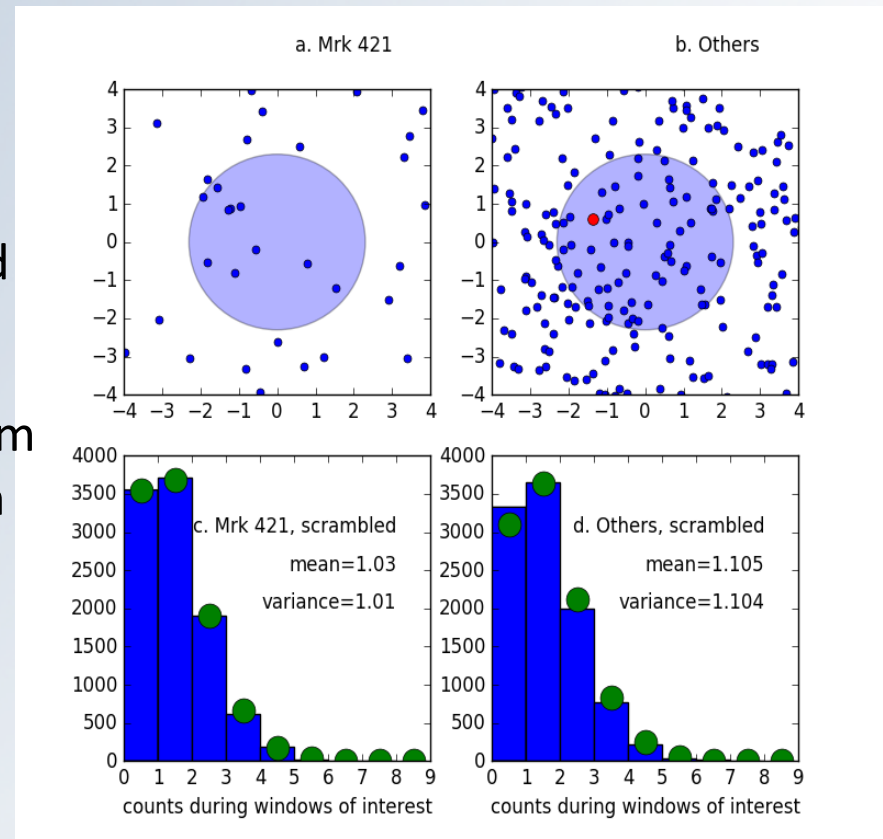
- Define temporal periods of interest for each blazar
- Maximize ratio of TeV fluence to number of ν needed to give a 3σ excess over atmospheric BG
- Markarian 421 bright intervals dominate the optimization; thus carry out 2 analyses:
 - Mrk 421 bright intervals only
 - All other blazar bright intervals



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

Validating background model (scrambled data):

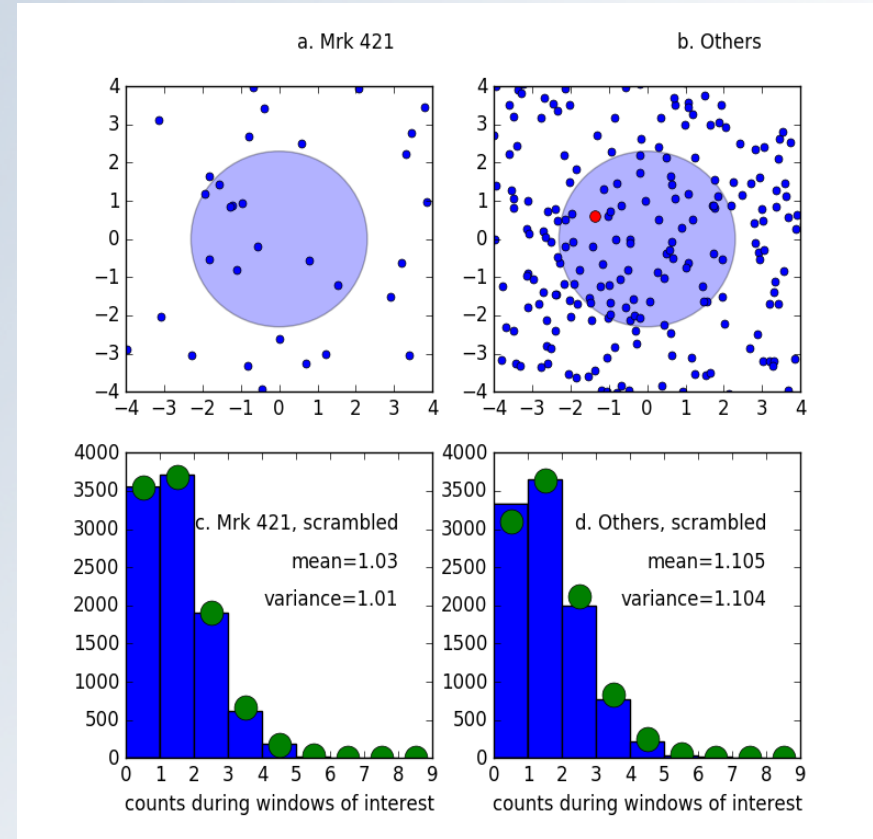
- Distribution of neutrinos found during times of interest from the 10000 scrambled runs (bottom plots)
- Each region of interest expects 0.023 neutrinos per day (1 per 44 days)
- Confirm expected background rate + Poisson behavior
- Need 5 or more neutrinos from Markarian 421 for a detection ($t_{\text{exp}}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



Results – Mrk 421:

v+TeV Blazar flares

- No neutrinos detected
- 90% CL upper limit of $N_{\text{obs}} < 1.27$ ($N_{\text{exp}} = 0.79$)
- 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)



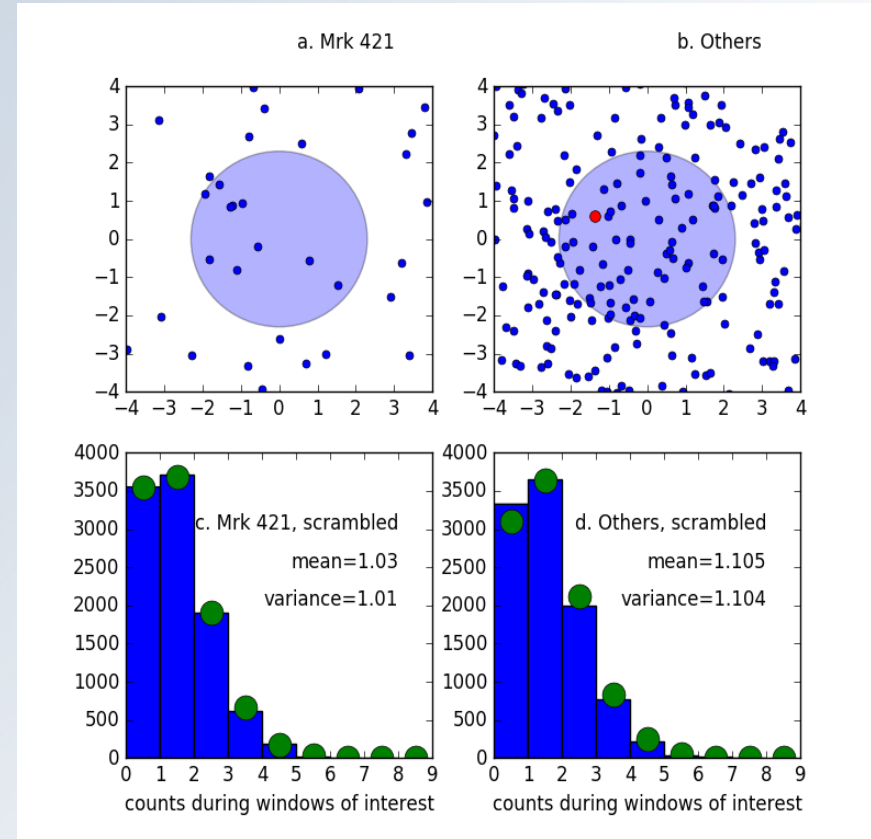
C. F. Turley, D. B. Fox et al., [arXiv:1608.08983](https://arxiv.org/abs/1608.08983)



Results – other blazars:

v+TeV Blazar flares

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

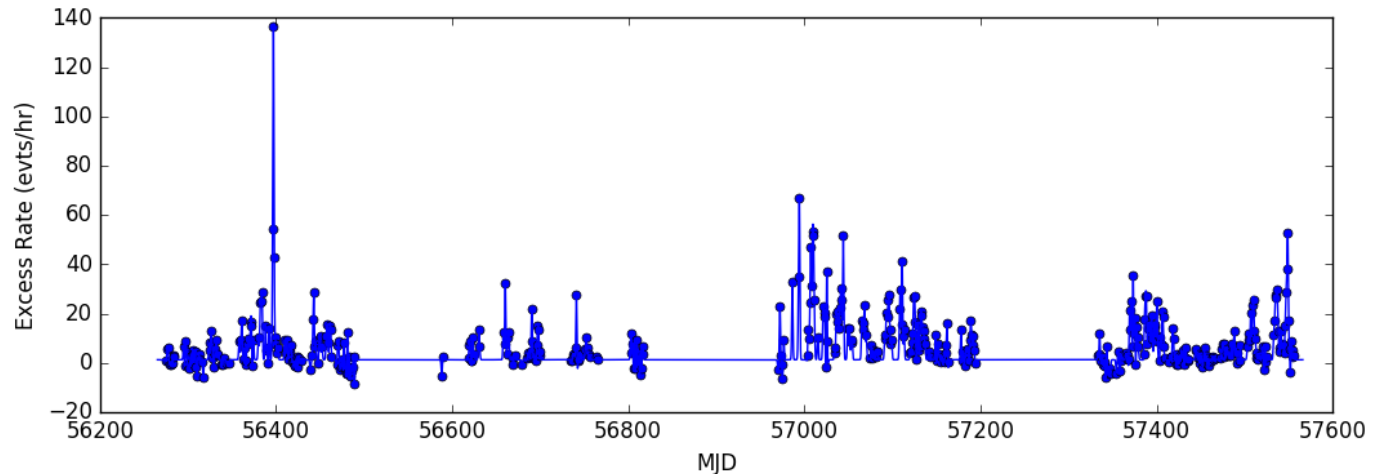


C. F. Turley, D. B. Fox et al., [arXiv:1608.08983](https://arxiv.org/abs/1608.08983)



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



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





EXTRA SLIDES





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.*)



AMON Alert content:

stream number

id number

revision number

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



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)

