The Astrophysical Multimessenger Observatory Network

AMON Network and Analyses

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MACROS 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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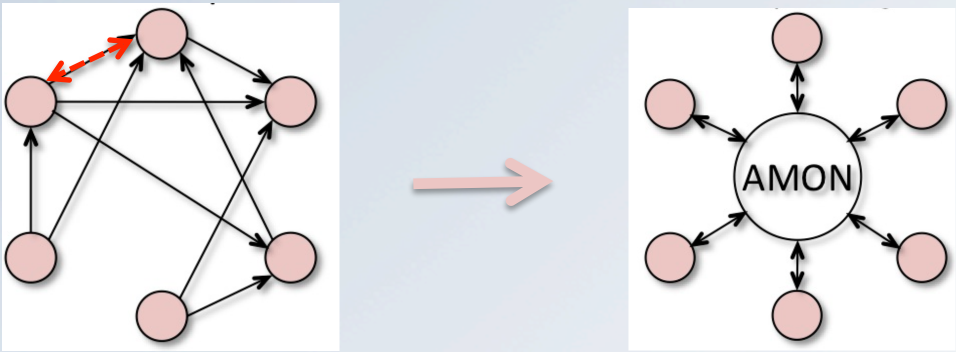
Introduction

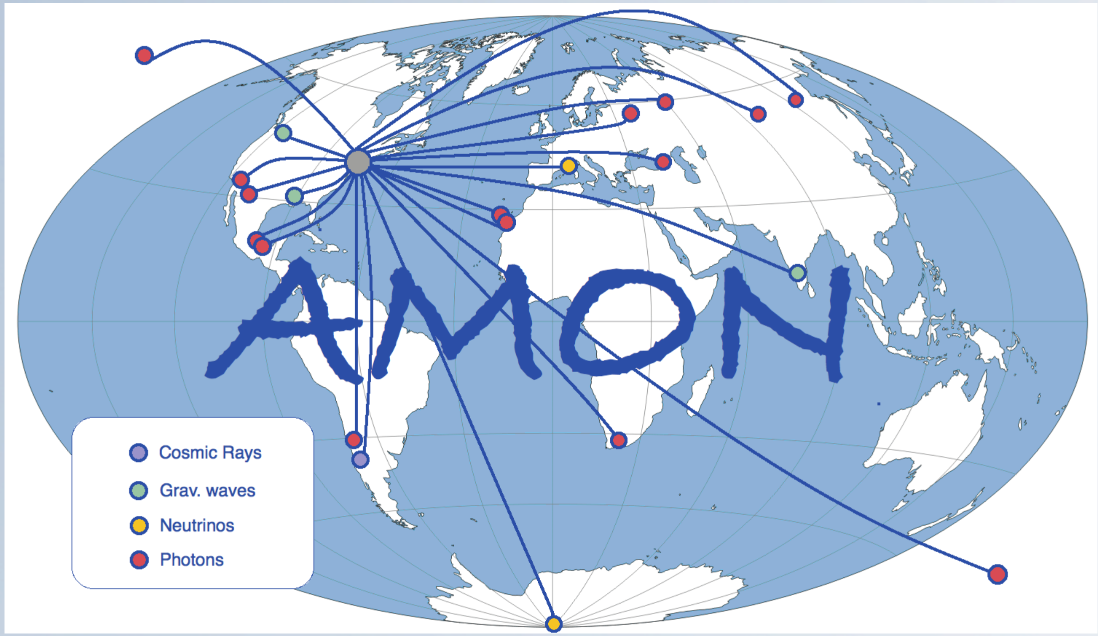
- AMON provides framework for:
  - Realtime and near realtime sharing of subthreshold data between multimessenger observatories
  - Realtime and archival searches for any coincident (in time and space) signals.
  - Prompt distribution of electronic alerts for follow-up observation
- AMON unifies and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

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

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

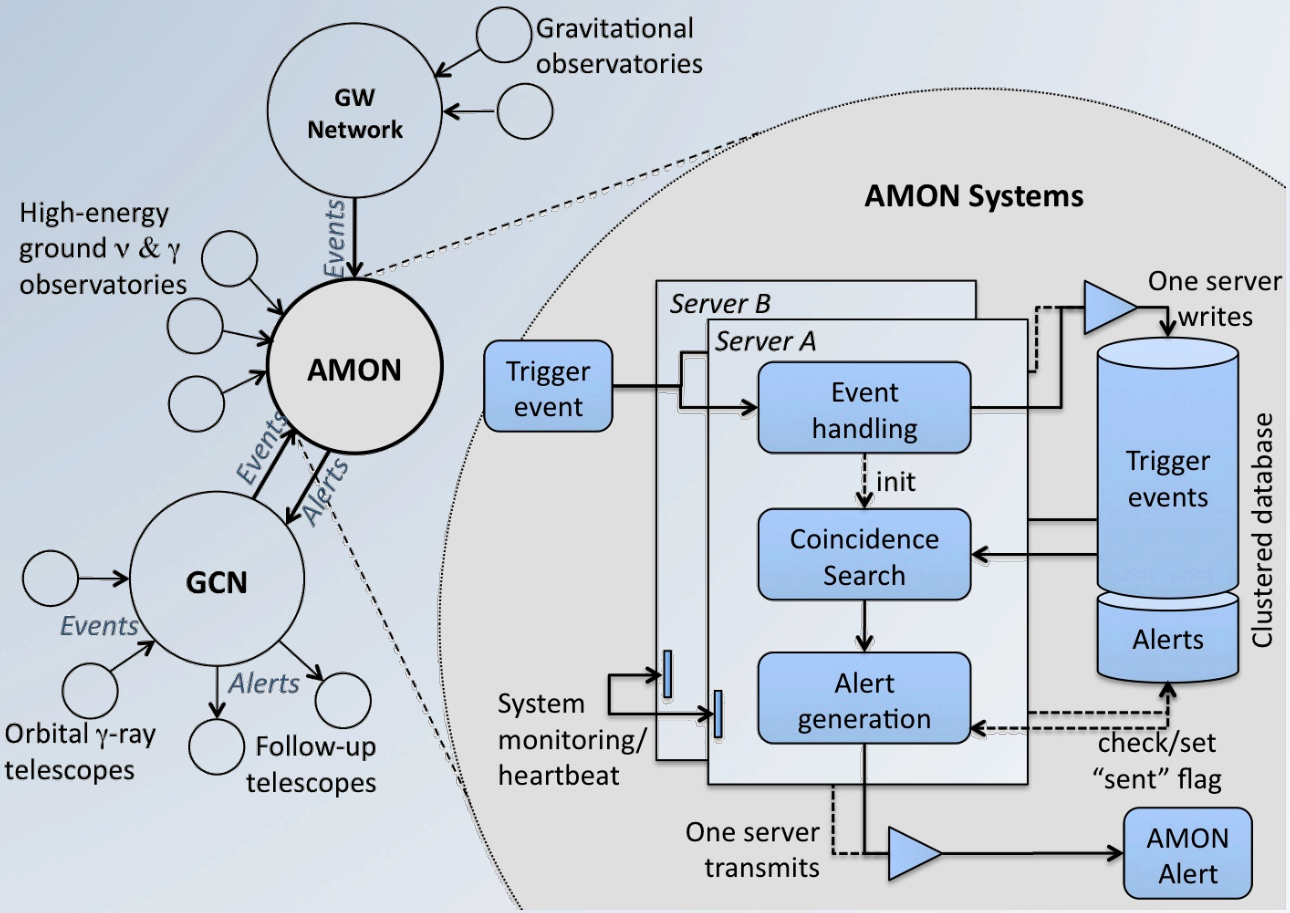
Pending: LIGO, MAGIC, H.E.S.S., PTF, TA…

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

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



Network Status

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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

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AMON application server

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

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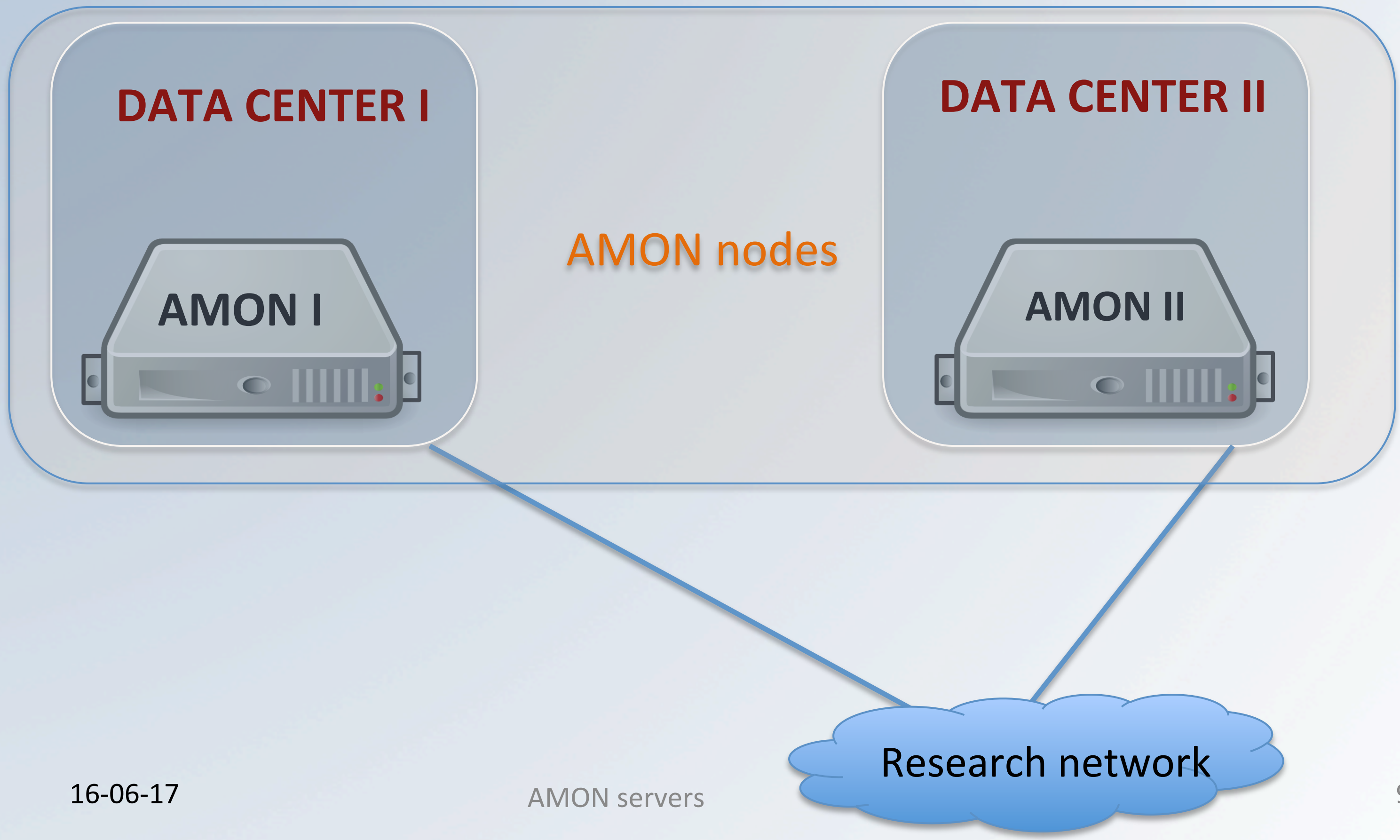
AMON new hardware

- 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

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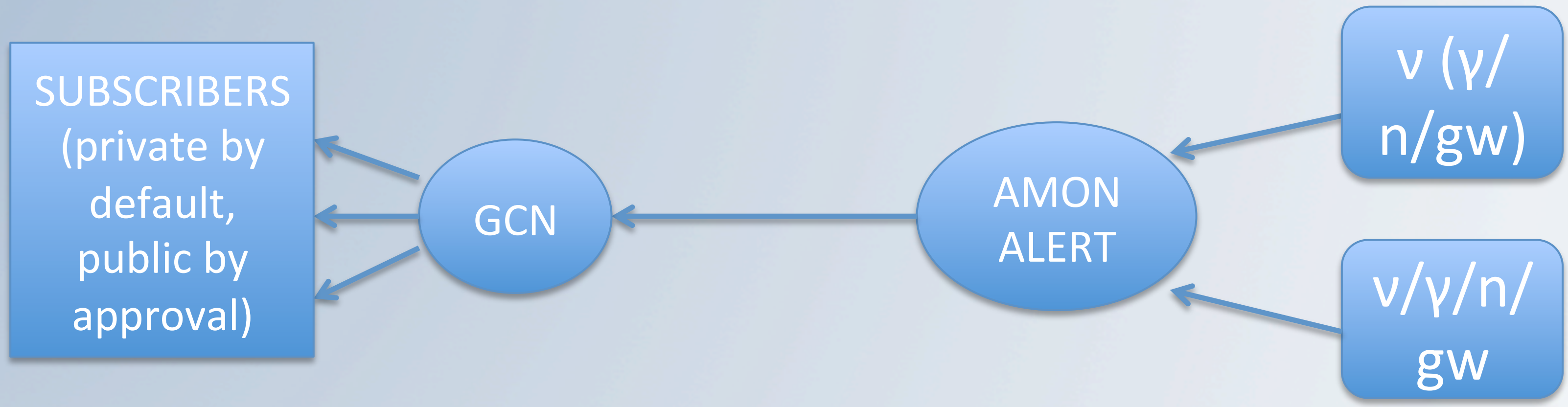
<u>Subthreshold streams</u> – used in AMON coincidence analysis

<u>Above threshold events</u> – 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 steam (real data scrambled)	Real data stream
IC Singlet	✔	✔	✔	✔	In progress
IC HESE	✔	✔	✔	✔	✔
IC EHE	✔	✔	✔	✔	In progress
IC OFU	✔	✔	✔	✔	In progress
ANTARES	✔	In progress			
Auger	✔	✔	✔	In progress	
HAWC	In progress				
VERITAS	In progress				
FACT	In progress				
Swift BAT	✔	Not needed	Not needed	Not needed	In progress
Fermi LAT	✔	Not needed	Not needed	Not needed	In progress

AMON/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
- 26+ subscribers so far (VERITAS, MASTER, Swift XRT/UVOT, XMM-Newton etc.)

Analyses

Current status– Analyses

Archival analyses:

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

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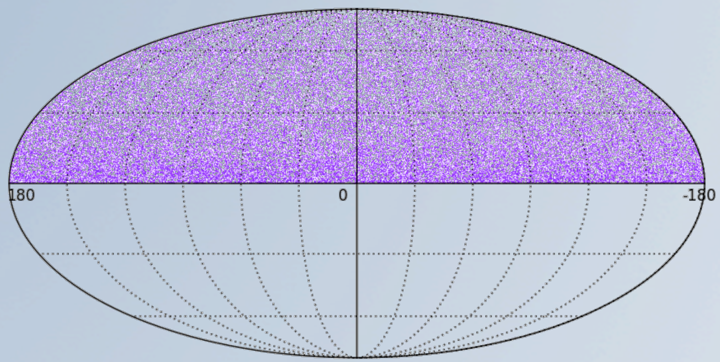
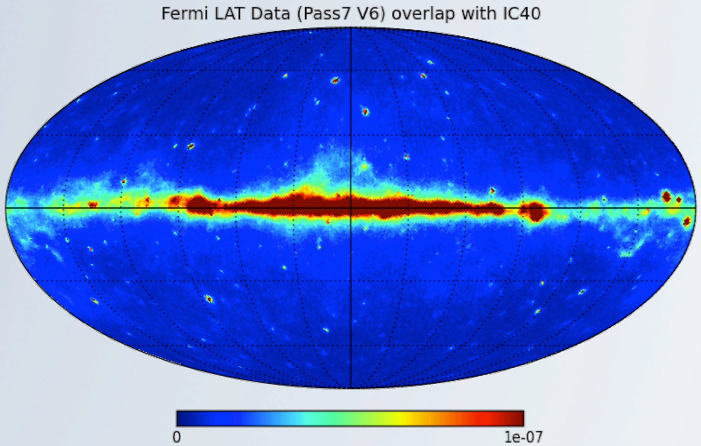
AMON enabled γ−ray + ν search

IceCube + Fermi LAT (public data)





<u>IC40 run period (done)</u>:

≈14 000 neutrinos
≈4.1 x 10^6 photons

<u>IC59 run period (final stage)</u>:

≈43 000 neutrinos
≈5.5 x 10^6 photons

<u>Coincidence requirement</u>:

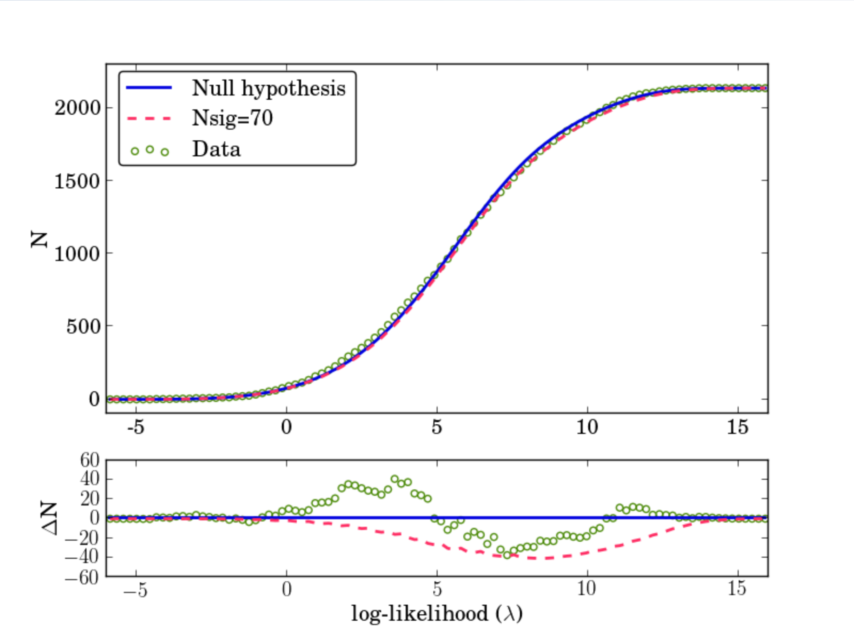
Temporal: $\Delta t = \pm$ 50 s
Spatial: $\Delta\theta < 10°$

A.Keivani et al., ICRC, PoS(ICRC2015)786 (2015).

AMON enabled γ–ray + ν search

Results:

IC40



IC40 run period:

Data – 2138 γ+ν pairs
BG – 2207±40 γ+ν pairs
p-value: 15%

IC59 run period :

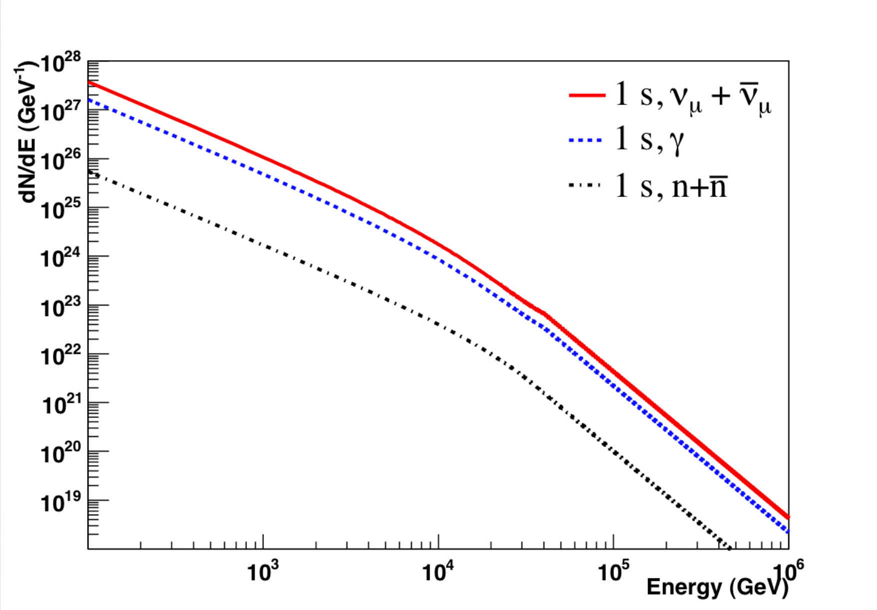
Data – 9025 γ+ν pairs
BG – 9077±153 γ+ν pairs
p-value: 9%

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

PBH evaporation signal

- Primordial Black Hole (PBHs) could produce appealing signature for AMON

- Explode violently during the last few seconds of their lives, producing a burst of high energy particles (ν, γ and CR).



- Look for a short multimessenger signal with no afterglow

- Short temporal structure provides a very low false positive rate

G. Tešić, ICRC, PoS(ICRC2015)328 (2015).

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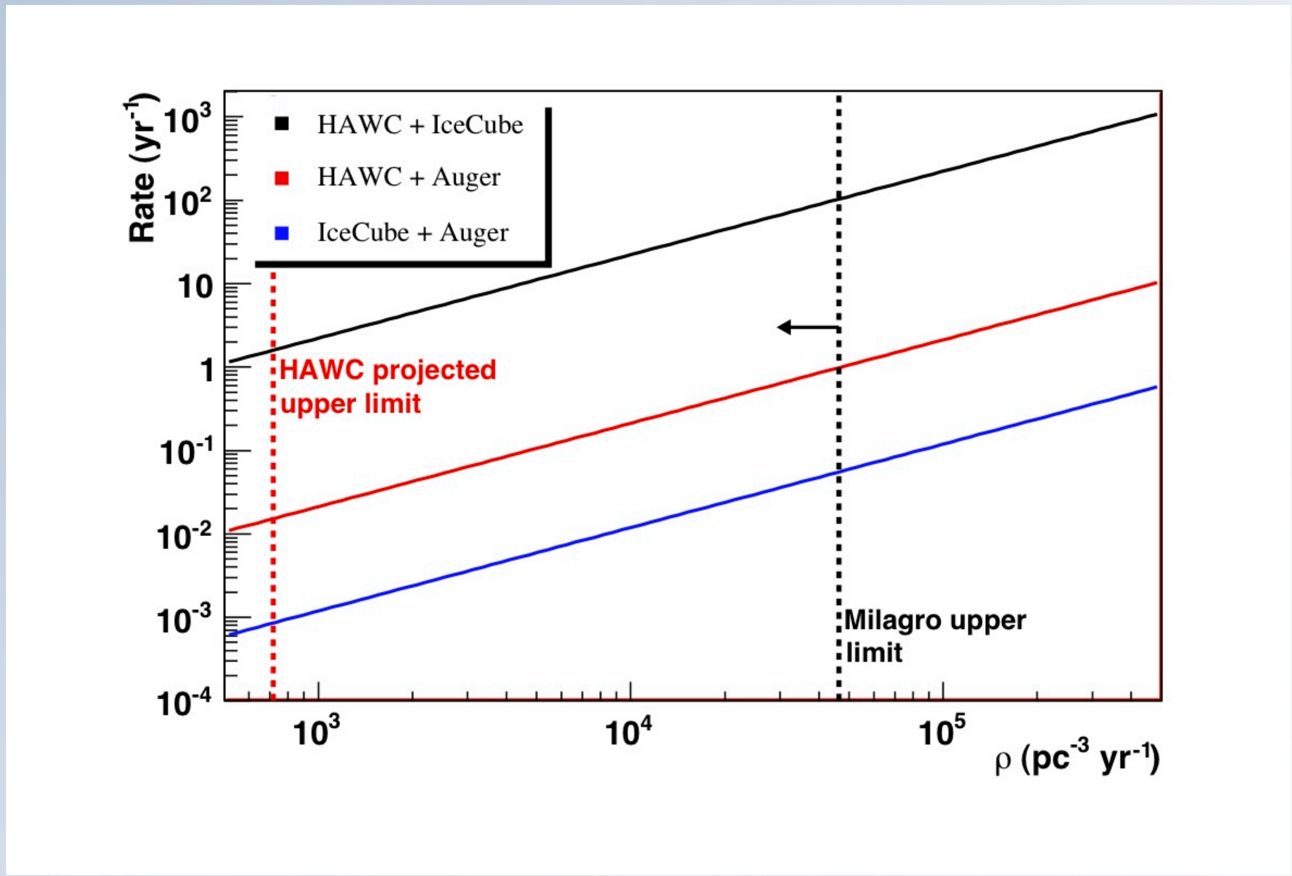
PBH evaporation signal

- At current Milagro limit, expect ~100 HAWC+IceCube detections/yr.
- At projected HAWC limit, expect ~1 HAWC+IceCube detection/yr.



- Multimessenger approach is essential to distinguish between bursts due to PBHs and other possible sources, should a positive detection occur.

ν+TeV Blazar flares

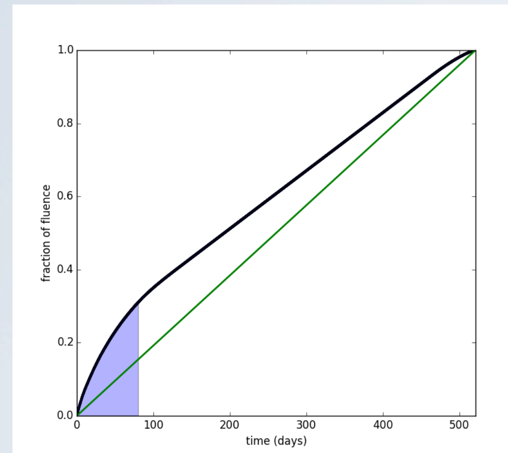
Search for Blazar Flux-Correlated TeV Neutrinos in IceCube 40-String Data (C. Turley and D. Fox)

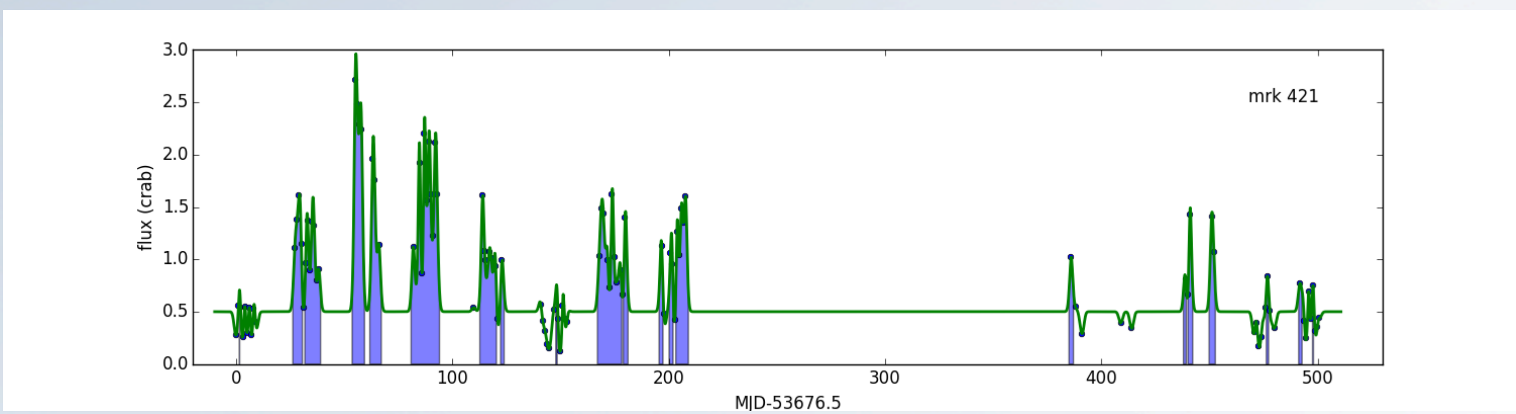
- Hadronic models predict associated TeV neutrinos (proportional to TeV flux)
- VERITAS TeV blazar monitoring (private data) over IC40

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

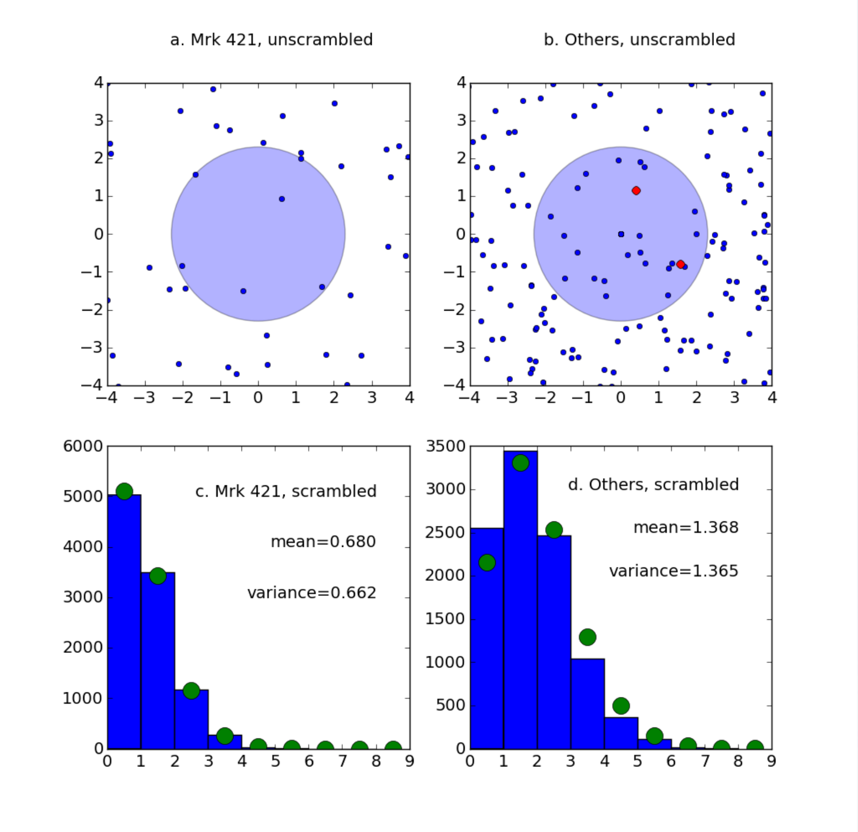
Fraction of fluence vs time





Results from scrambled data:

- distribution of neutrinos found during times of interest from the 10000 scrambled runs (bottom plots)



- 90% CL upper limits on neutrino arrival:
  - 2.30 for Mrk 421
  - 5.32 for other blazars

- Fluence to Neutrino ratio ($x10^{-11}$ erg cm^{-2} ν^{-1}):
  - 8.14 for Mrk 421
  - 1.59 for the others

- Method applicable for HAWC, FACT, Swift data

- To propose IceCube-AMON Mrk-421 project

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ν+TeV Blazar flares

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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
- AMON has started distributing IceCube's HESE alerts via GCN (public stream!)
- More real-time electronic alerts via AMON/GCN this summer (e.g. IceCube's EHE, OFU) and incoming event streams (e.g. Pierre Auger & HAWC)

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*.)

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Alert content

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

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)

AMON enabled γ-ray + ν search

Method:

- Likelihood:

$$\lambda = 2\ln\left(P_{LAT}\left(\vec{x} \mid \hat{x}_{\gamma}\right) P_{IC}\left(\vec{x} \mid \hat{x}_{\nu}\right)\right) - 2\ln(B(\hat{x}_{\gamma}))$$

Energy dependent point spread functions (PSF)

best fit positions

arrival directions

γ background rejection term

- λ_{null} from 10^4 scrambled data sets: 2207±40 (IC40) and 9077±153 (IC50) ν+γ pairs

- λ distribution for data: 2138 (IC40) and 9025 (IC59) ν+γ pairs

- λ_{signal}: 10^4 signal tests by injecting forced coincidences into the null distribution

Results:

AMON enabled γ–ray + ν search

- Further tests to see if there are real cosmic ν+γ pairs are present (use only high λ (>11) values – more likely a signal):

  1. mean number of photons in coincidence with each single neutrino
     $\langle N\rangle_{data}$=2.17 vs. $\langle N\rangle_{null}$=2.08 ± 0.15 (IC40 + LAT)
     $\langle N\rangle_{data}$=2.69 vs. $\langle N\rangle_{null}$=2.67 ± 0.05 (IC59 + LAT)

  2. the time difference between the photon event and the neutrino
     - flat, consistent with absence of cosmic signal

  3. the clustering of detected pairs
     data: 6 ν+ γ pairs lie within 2°of one another
     null dist. : 12.9 ν+ γ pairs lie within 2° of one another

- In all three test the consistency with background was found

- Next step is full archival analysis with the private IceCube data