

# The Astrophysical Multimessenger Observatory Network



## AMON – TRANSITION TO REALTIME OPERATIONS

Gordana Tešić  
(for the AMON team)  
4<sup>th</sup> AMON Workshop  
Dec 3, 2015, Penn State, PA, USA

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

## AMON development and advisory team

### Penn State

A. Ashtekar<sup>1,3</sup>, S. Coutu<sup>1,2,3</sup>, D. Cowen<sup>1,2,3</sup>, J. DeLaunay<sup>1</sup>, A. Falcone<sup>2,3</sup>,  
 D. Fox<sup>2,3</sup>, A. Keivani<sup>1,3</sup>, P. Mészáros<sup>1,2,3</sup>, C. Messick<sup>1</sup>, M. Mostafá<sup>1,3</sup>,  
 K. Muraze<sup>1,3</sup>, C. Hanna<sup>1,3</sup>, F. Oikonomou<sup>1,3</sup>, P. Raghavan<sup>4,5</sup>, P. Sommers,  
 G. Tešić<sup>1,3</sup>, M. Toomey<sup>1,2</sup>, C. Turley<sup>2</sup>, A. Weinrich<sup>1,4</sup>

<sup>1</sup>Department of Physics

<sup>2</sup>Department of Astronomy and Astrophysics

<sup>3</sup>Institute for Gravitation and the Cosmos

<sup>4</sup>Computer Science and Engineering

<sup>5</sup>Institute for CyberScience

### Others

S. Barthelmy<sup>1</sup>, I. Bartos<sup>2</sup>, F. Feroz<sup>3</sup>, M. Smith<sup>4</sup>, I. Taboada<sup>5</sup>

<sup>1</sup>NASA GSFC

<sup>2</sup>Columbia University, Dept of Physics

<sup>3</sup>Cambridge University

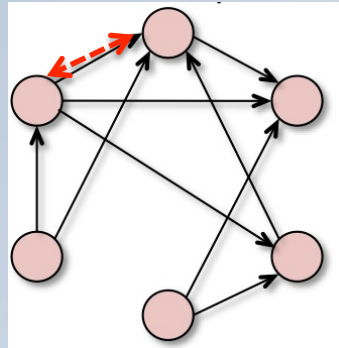
<sup>4</sup>NASA JPL

<sup>5</sup>Georgia Institute of Technology

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

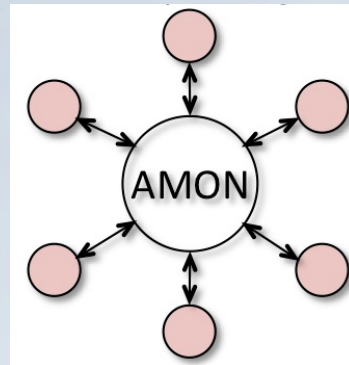


- **Long standing questions:** - origin of cosmic rays (CR) and neutrinos  
- existence of gravitational waves (gw)
- **Multiple searches for high-energy astrophysical multimessenger sources:**



- no discovery of yet
- sensitivities of non-EM observatories are limited (e.g.  $\sim 10$  per year for the IceCube HESE neutrinos)
- bilateral and mostly unidirectional searches
- near signal threshold required

- **Solution – generalize and unify existing multimessenger efforts:**



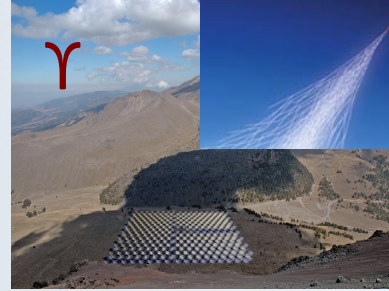
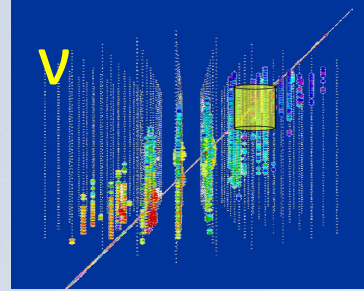
- lower the coincidence signal threshold (e.g., use single TeV  $\nu_\mu$  from IceCube, not just doublets or triplets)
- enable fast alerts for follow-up
- multilateral and omnidirectional
- reduces background and maximizes chances for discovery

# The AMON Idea

Use messenger particles of all four fundamental forces

## Triggering observatories

- Provide **sub-threshold** candidate events (VOEvents) to AMON in real time



## AMON



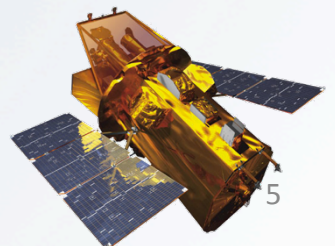
- Seeks **coincidences** in time and space
- Generates **alerts (VOEvents)** - broadcast and archived
- Enables archival analyses

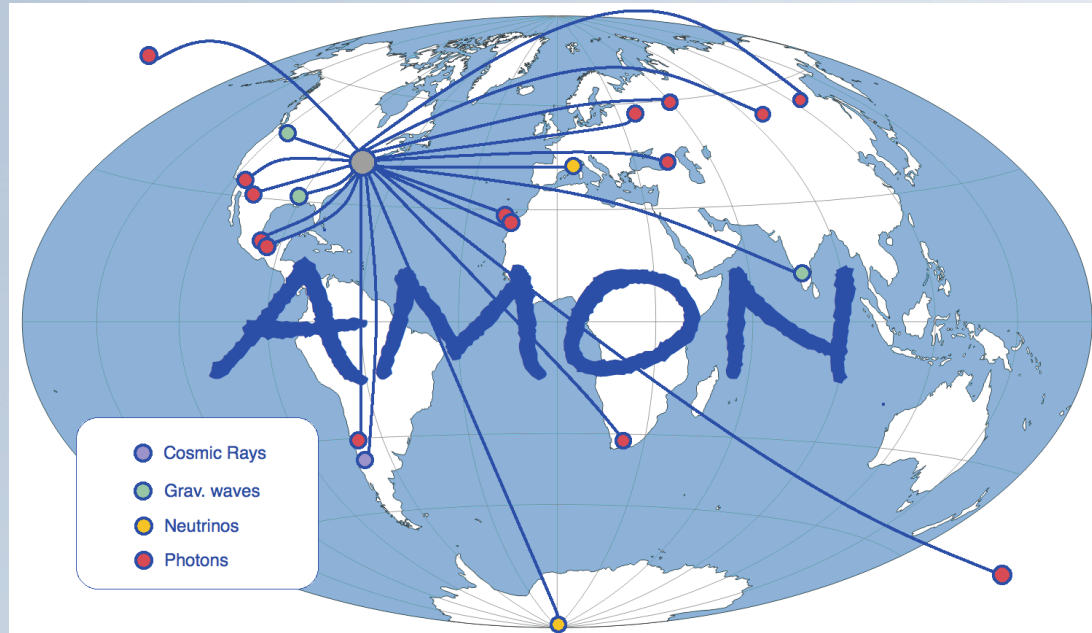
## Follow-up observatories

- respond to AMON alerts
- provide optical feedback on potential multimessenger transients



x, UV, optical





**Astrop.Phys. Vol. 45, 56–70, 2013**

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

**Follow-up: Swift XRT & UVOT, VERITAS**

**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)

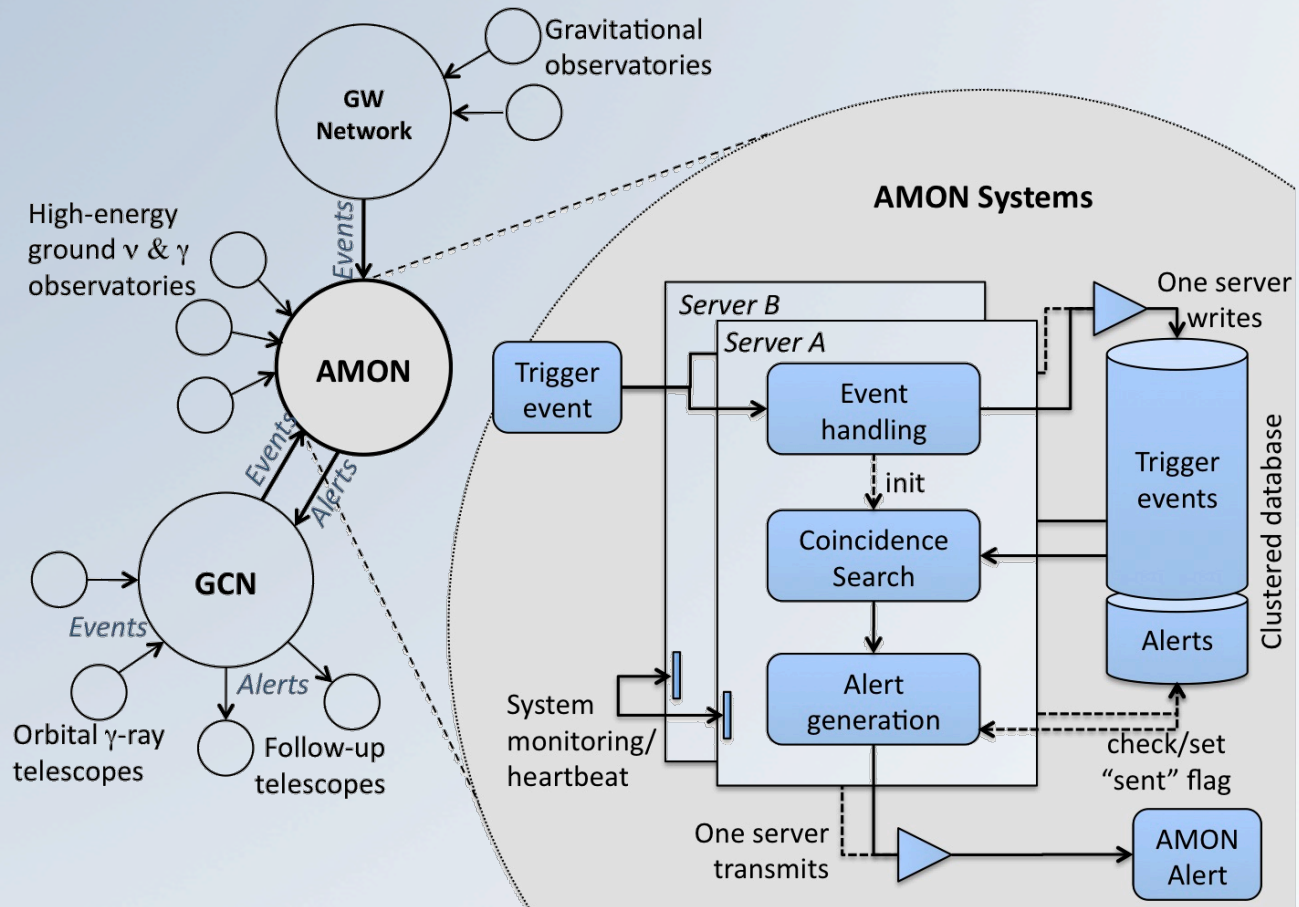
[http://amon.gravity.psu.edu/mou\\_may2015.shtml](http://amon.gravity.psu.edu/mou_may2015.shtml)



# 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



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

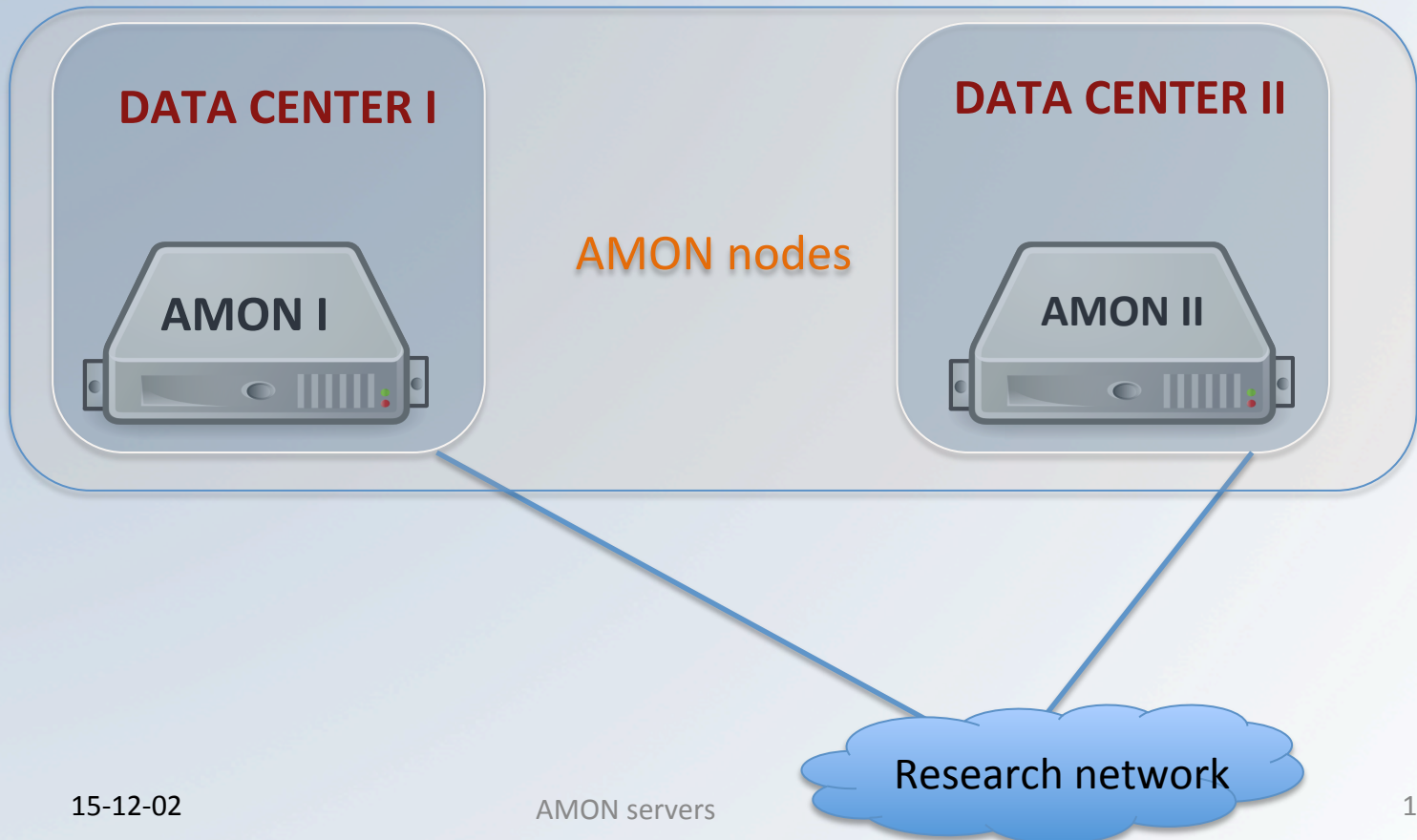
- Data from triggering observatories inserted
  - done: **IC-40, IC-59, Swift, Fermi** [public]
  - done: **ANTARES 2008** [private], **Auger** [private]
  - in progress: **IceCube, HAWC, VERITAS, ANTARES** [private – pending permissions], **LIGO S5 and S6** [public]
- Real-time test with fake and real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



# AMON application server is up and running since August 2014!

- built using Python/Twisted, asynchronous, tested with several simulated 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

- Deployment of the two new high-uptime servers [in progress]
  - systems are physically and cyber secure
  - hardware and power redundant
  - memory mirroring
- To be fully operational soon



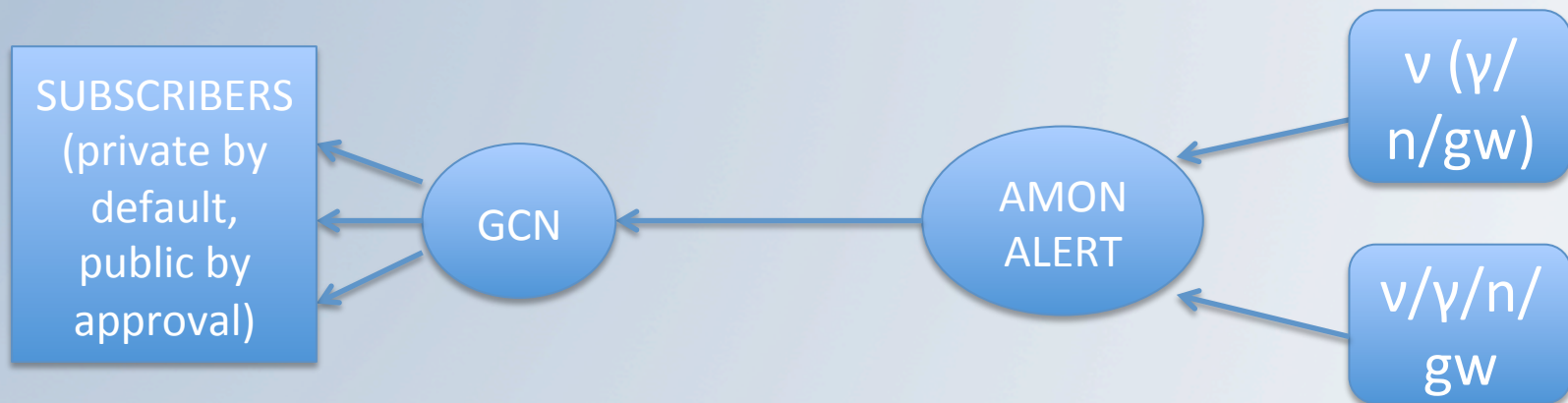


## Several efforts toward real-time analysis:

- IceCube  $\nu_\mu$  singlet stream – **done**
- IceCube high-energy starting events (HESE) – **done**
- IC extremely high-energy (EHE) events – **underway**
- Auger events – **underway**
- Ongoing efforts with other member collaborations on getting their real-time subthreshold streams (e.g., ANTARES, HAWC, FACT)



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



- GCN client directly connects to AMON by using vTCP protocol and gets AMON alerts
- Subscribers can choose to get original AMON VOEvent format or any other standard GCN formats (e.g. email)
- AMON receiver program is built by GCN (see talk by S. Barthelmy)
- Connection is running since May 2015
- Available to the AMON network members

# Steps needed for participations of the triggering observatories

Observatory	Stream content & format	TLS certificate	Test stream (fake data)	Test steam (real data scrambled)	Real data stream
IC Singlet	✓	✓	✓	✓	In progress
IC HESE	✓	✓	✓	✓	In progress
IC EHE	✓	✓	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

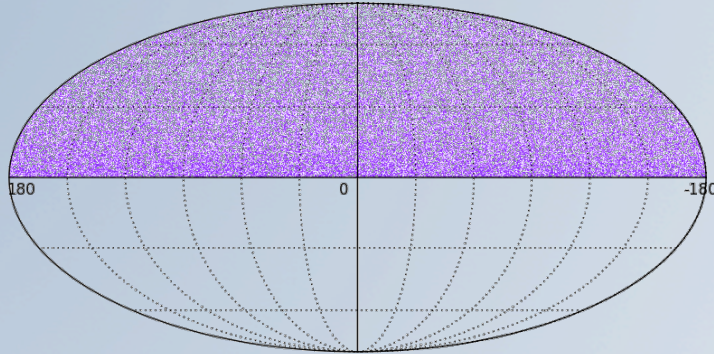
Observatory links to AMON



# Archival analyses:

- $\nu + \gamma$ -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 (see talk by C. Turley)
- $\gamma$ -ray + gravitational waves (gw):
  - Swift and LIGO S5 (in progress)
- $\nu + \gamma$ -ray + cosmic ray (CR):
  - Primordial Black Hole (PBH) evaporation searches (G. Tešić, PoS(ICRC2015)328 (2015))

# IceCube + Fermi LAT (public data)



IC40 run period (done):

$\approx 14\,000$  neutrinos

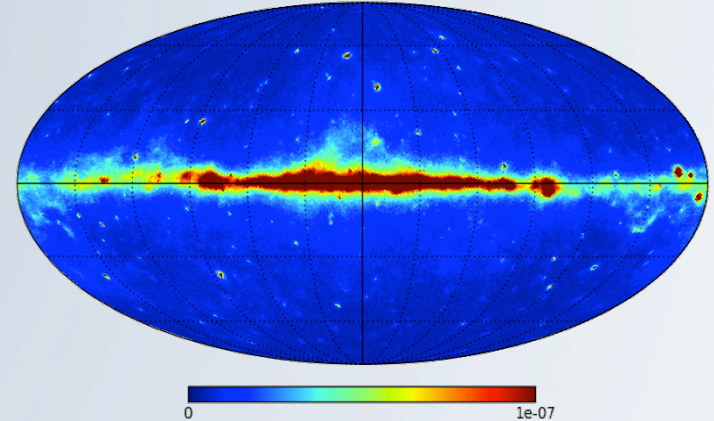
$\approx 4.1 \times 10^6$  photons

IC59 run period (in progress):

$\approx 43\,000$  neutrinos

$\approx 5.5 \times 10^6$  photons

Fermi LAT Data (Pass7 V6) overlap with IC40



Coincidence requirement:

Temporal:  $\Delta t = \pm 50$  s

Spatial:  $\Delta\theta < 10^\circ$

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

## Method:

- Likelihood:

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

Energy dependent  
point spread functions  
(PSF)

best fit  
positions

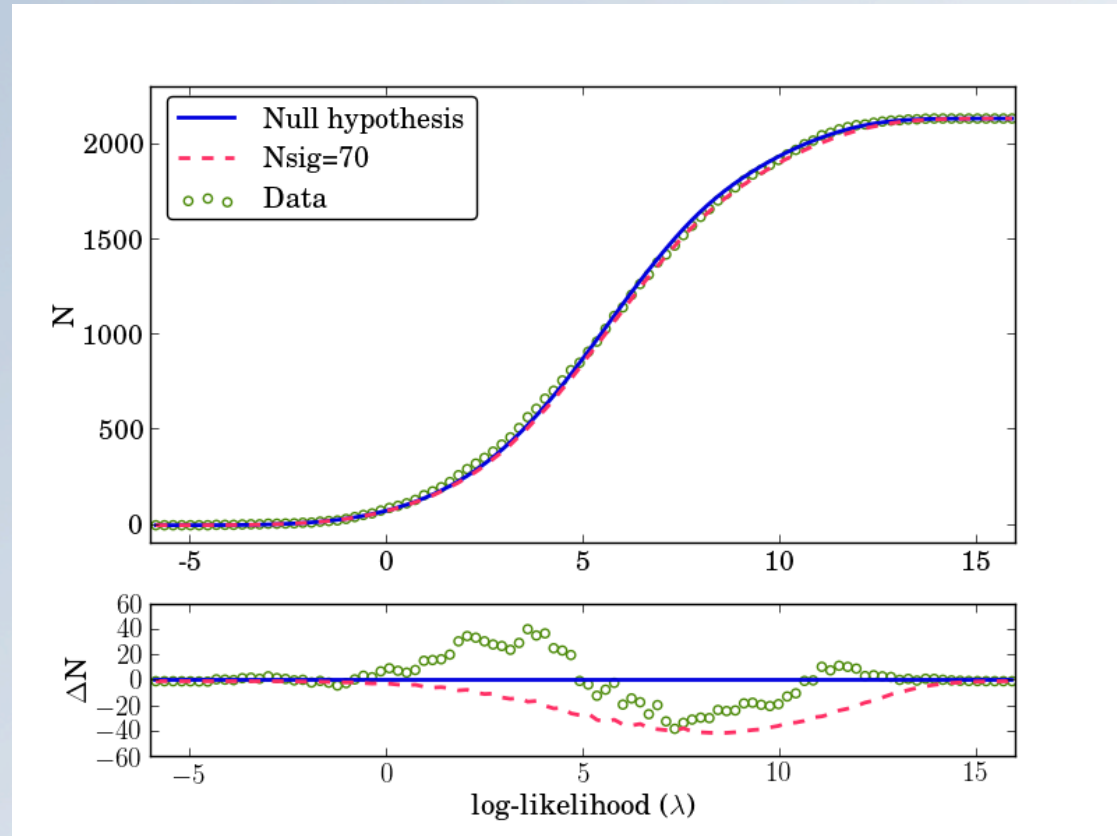
arrival  
directions

$\gamma$  background  
rejection term

- $\lambda_{\text{null}}$  from  $10^4$  scrambled data sets:  $2207 \pm 40$  (IC40) and  $9077 \pm 153$  (IC50)  $\nu + \gamma$  pairs
- $\lambda$  distribution for data: 2138 (IC40) and 9025 (IC59)  $\nu + \gamma$  pairs
- $\lambda_{\text{signal}}$ :  $10^4$  signal tests by injecting forced coincidences into the null distribution

## Results:

- Applied the Anderson-Darling (AD) test statistics:
  - p-value: 15% (IC40, used to be 4% or  $N_{\text{signal}}=70$ ) and 9% (IC59)



- Data are different than background distribution, but also they are different than signal hypothesis

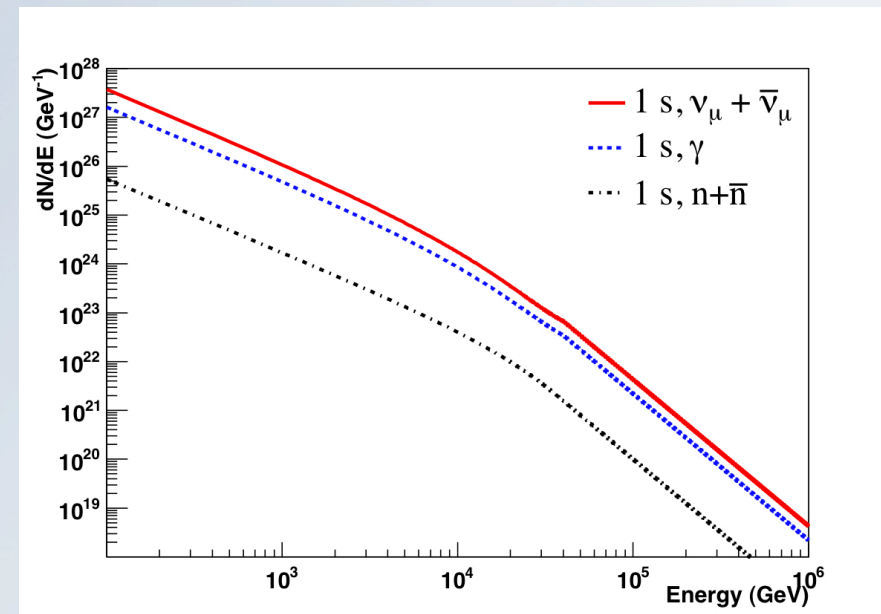
## Results:

- Further tests to see if there are real cosmic  $\nu+\gamma$  pairs are present (use only high  $\lambda$  ( $>11$ ) values – more likely a signal):
  1. mean number of photons in coincidence with each single neutrino
    - $\langle N \rangle_{\text{data}} = 2.17$  vs.  $\langle N \rangle_{\text{null}} = 2.08 \pm 0.15$  (IC40 + LAT)
    - $\langle N \rangle_{\text{data}} = 2.69$  vs.  $\langle N \rangle_{\text{null}} = 2.67 \pm 0.05$  (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  $\nu+\gamma$  pairs lie within  $2^\circ$  of one another
    - null dist. : 12.9  $\nu+\gamma$  pairs lie within  $2^\circ$  of one another
- In all three test the consistency with background was found
- Next step is full archival analysis with the private IceCube data



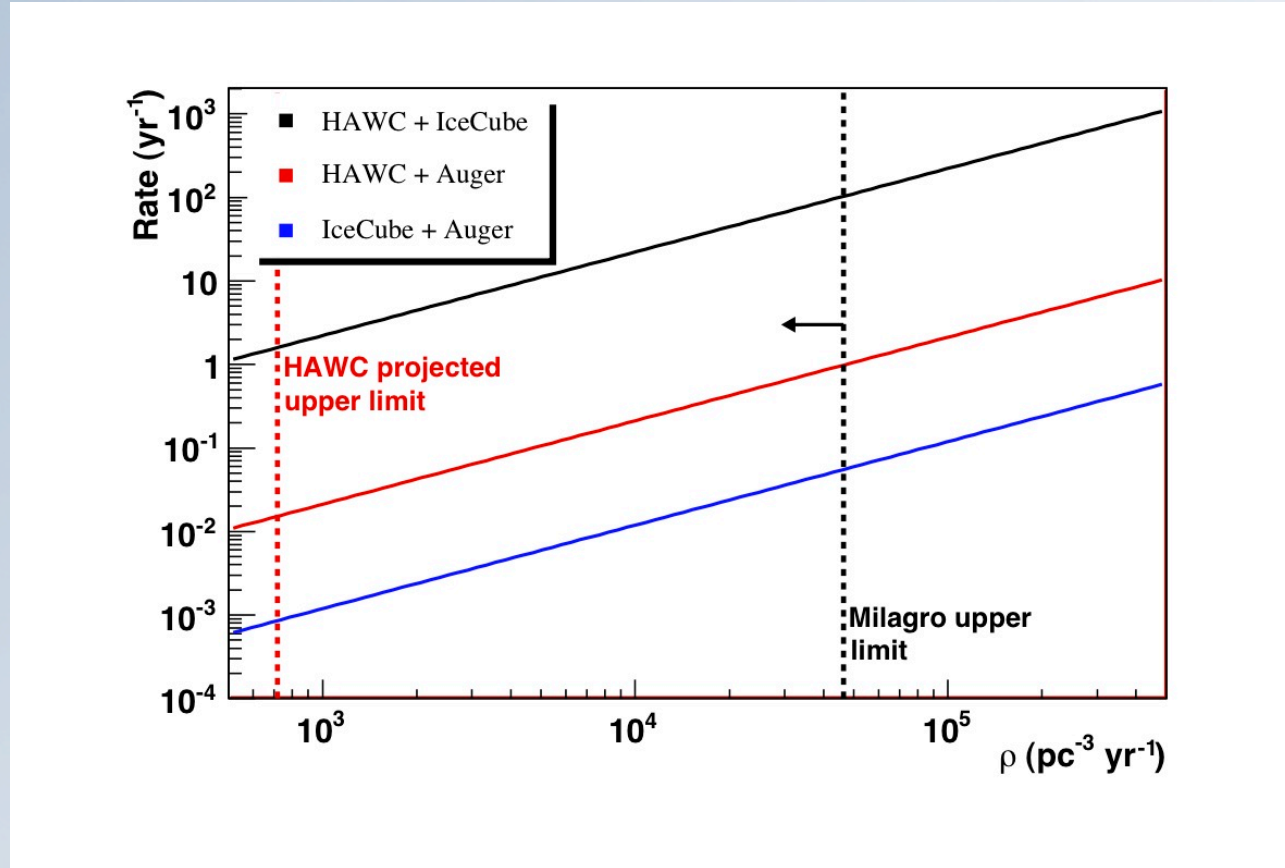
- Primordial Black Hole (PBHs) could produce appealing signature for AMON
- Hawking 1974 - black holes emit black body radiation with a temperature:  $T_H = M_{Planck}^2 / [8\pi M]$
- PBH loses its mass due to Hawking radiation:  

$$dM / dt \propto -\alpha(M) / M^2$$
- Explode violently during the last few seconds of their lives, producing a burst of high energy particles ( $\nu$ ,  $\gamma$  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).

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



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

# Conclusions

- AMON has made a significant progress toward real-time and archival analysis
- AMON application server is online - open for authorized connections
- New high-uptime dual hardware to be fully operational soon
- Ongoing realtime streams with the scrambled neutrino singlet and HESE events from IceCube
- Expecting soon new realtime streams
- AMON has started distributing test alerts via GCN (private streams by default, public if approved)
- AMON will start issuing electronic alerts via GCN in Winter 2015/16





## 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

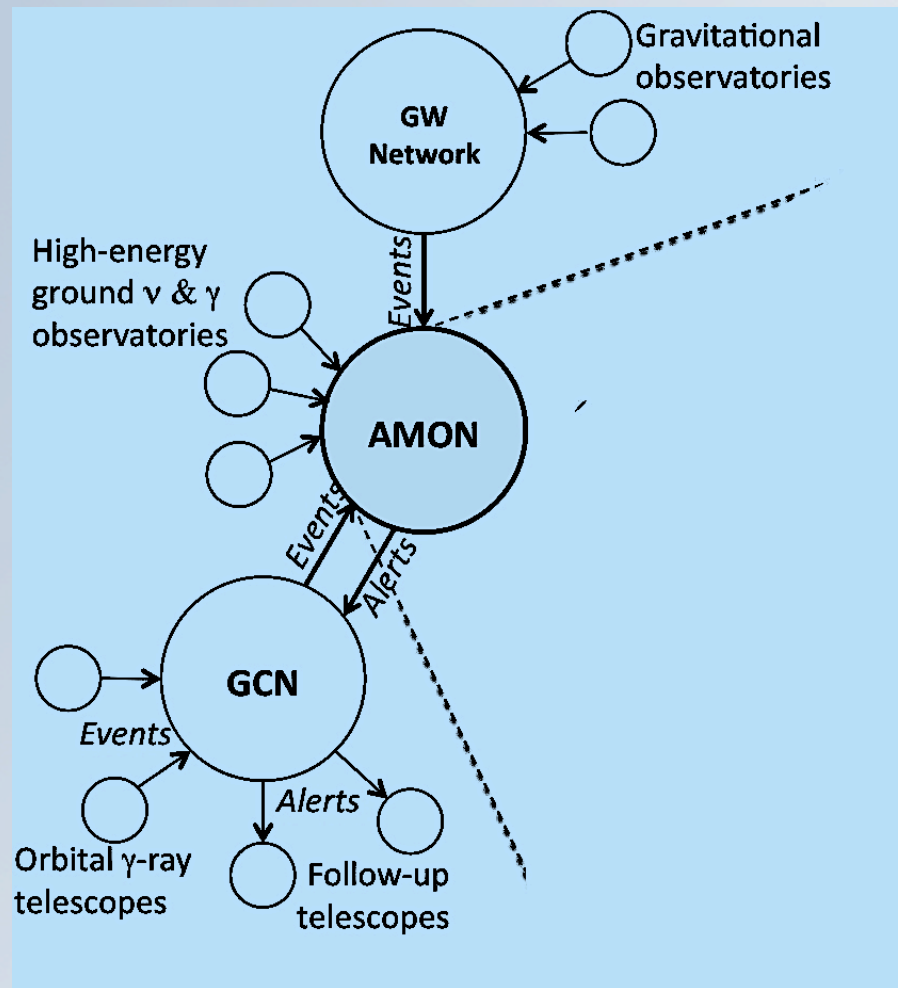


# AMON will receive events and send alerts in VOEvent format

- 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)



# AMON system - data flow

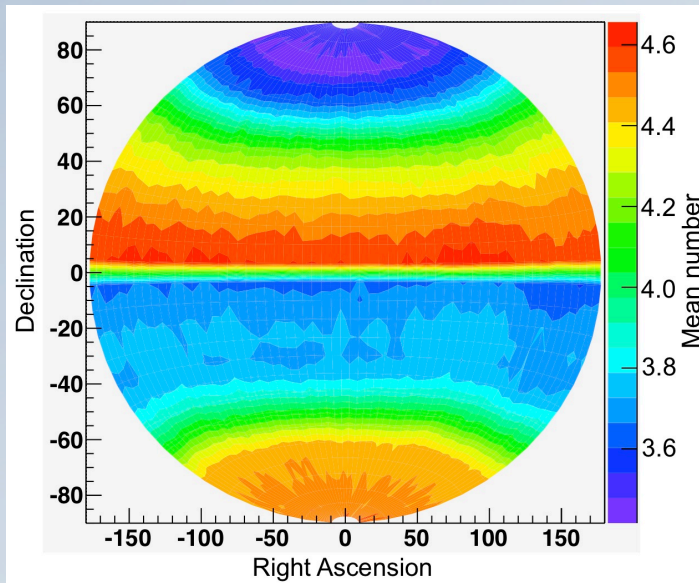


AMON will utilize existing:

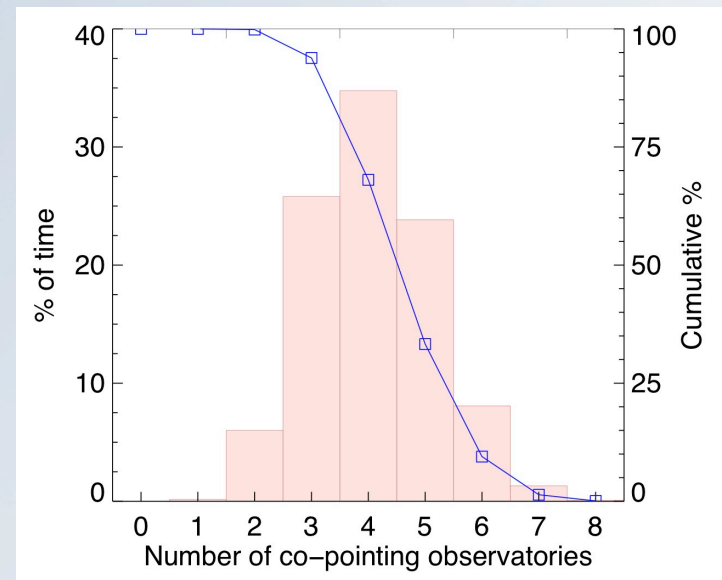
**Gamma-ray Coordinates Network (GCN)**  
**Gravitational Wave (GW) Network**  
 Open to other networks (e.g. SNEWS)

# 1-year simulation for IceCube, ANTARES, HAWC, Swift BAT, 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-y is within the FoV of 3 or more observatories
- 2+ observatories are viewing any given part of the sky simultaneously

