AMON: Transition to Real-Time Operations

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Rome, Italy
September 2015

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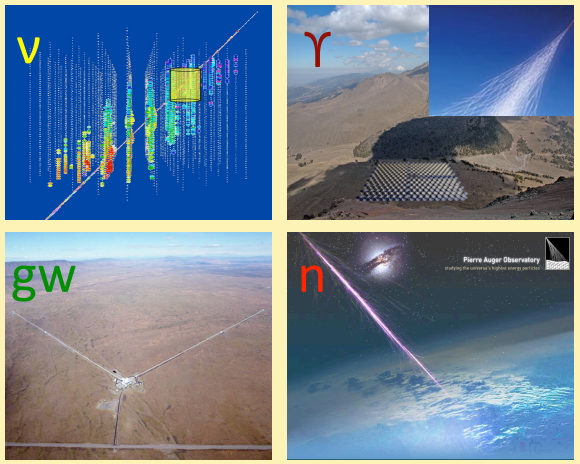
Motivation

- Numerous searches for high energy astrophysical multimessenger sources have been performed: No luck so far.
  - All searches have been bilateral, uni-directional
    - Two observatories, one triggers the other (e.g., ANTARES triggers TAROT)
  - All have required triggering detector to have signal near or above standalone discovery level
    - E.g., IceCube standalone discovery level is a “triplet” but sends “doublets” to Swift
      - triplet: 3 neutrinos in temporal and spatial coincidence, unlikely to be atm. ν pileup
      - doublet: 2 neutrinos, expect several/month from atm. ν pileup
- Lessons:
  - Non-optical signals are tiny; desire thresholds as low as possible
    - Need to be able to dig deeper into data without drowning in background
  - Tying together multiple observatories into one system to search for multimessenger coincidences reduces bkgd & maximizes chances of discovery
    - Also unifies MoUs, connection protocols, data formats, etc. to maximize efficiency

The AMON Idea

AMON enables searches for multimessenger coincidences using particles representing the four fundamental forces.



Triggering observatories:

- Transmit "sub-threshold" candidate events to AMON in real time.

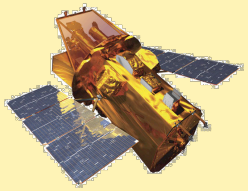
AMON:

- Provides framework for real-time coincidence searches of data in direction & time.
- Broadcasts real time alerts (via VOEvent & GCN).
- Enables archival analysis of sub-threshold data.

Follow-up observatories:

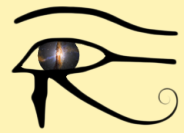
- Respond to AMON alerts.
- Provide optical feedback on potential multimessenger transients.

x, UV, optical



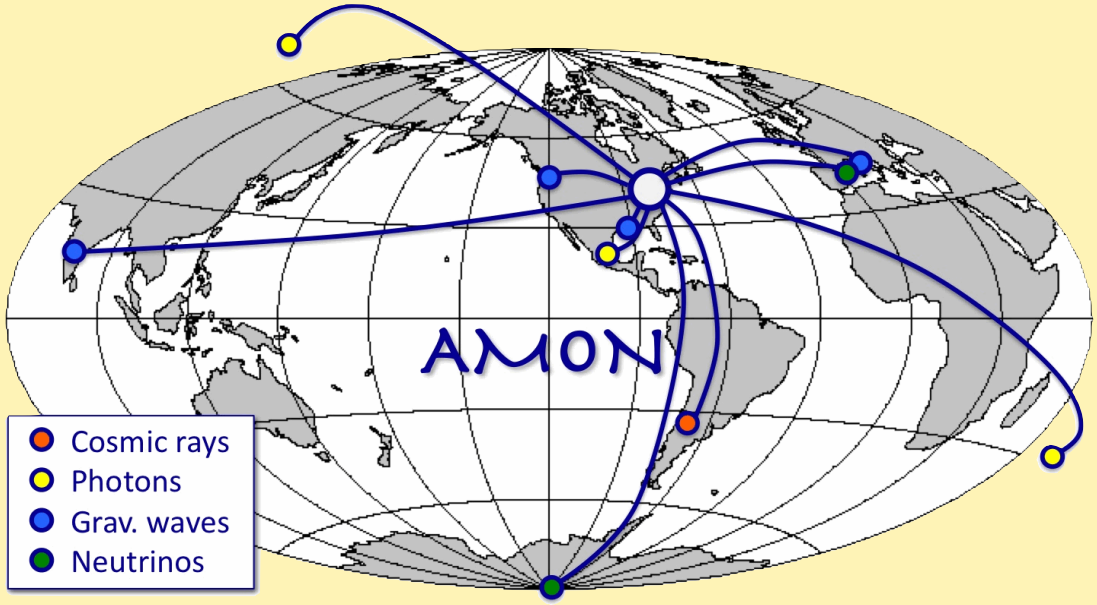
http://amon.gravity.psu.edu/index.shtml

AMON Functionality in a Nutshell



- Archival searches
  - AMON database stores summarized event information from all participating observatories
  - AMON provides framework for searching through this database for temporal and spatial coincidences
- Pass-through
  - AMON receives events and broadcasts them immediately via GCN to astronomical community for follow-up
    - E.g., future IceCube HESE events
- Real-time coincidences
  - AMON receives "sub-threshold" events from multiple triggering observatories and searches in real time for coincidences in ($\mathbf{r}$,t)
    - E.g., a single IceCubes ν_μ in coincidence with ~15γ's from HAWC
  - AMON issues GCN alerts for follow-up (mainly optical)

AMON Status: Participation



Astrop.Phys. Vol. 45, 56–70, 2013

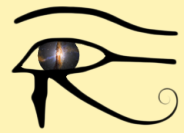
AMON MoU signed	*Triggering*	IceCube	ANTARES	Auger	HAWC	VERITAS	Swift BAT	Fermi
	Follow-up	Swift XRT/ UVOT	VERITAS	MASTER	FACT			
Pending		LIGO	TA	PTF	HESS	MAGIC		

Under AMON MoU, non-public data are protected and only released with explicit permission of the source observatory.
Coincident analyses using private data are done by members of participating observatories working together, with explicit agreement of their collaborations.

AMON Status: Participation

Observatories with AMON MoU	Stream content & format	TLS certificate	Test stream (fake data)	Test steam (real data scrambled)	Real data stream
IceCube Singlet	✔	✔	✔	✔	In progress
IceCube HESE	✔	✔	✔	✔	In progress
IceCube EHE	✔	✔	In progress		
ANTARES	✔	In progress			
Auger	✔	✔	In progress		
HAWC	In progress				
VERITAS	In progress				
MASTER	In progress				
FACT	In progress				
Swift BAT	✔	Not needed	Not needed	Not needed	In progress
Fermi	✔	Not needed	Not needed	Not needed	In progress

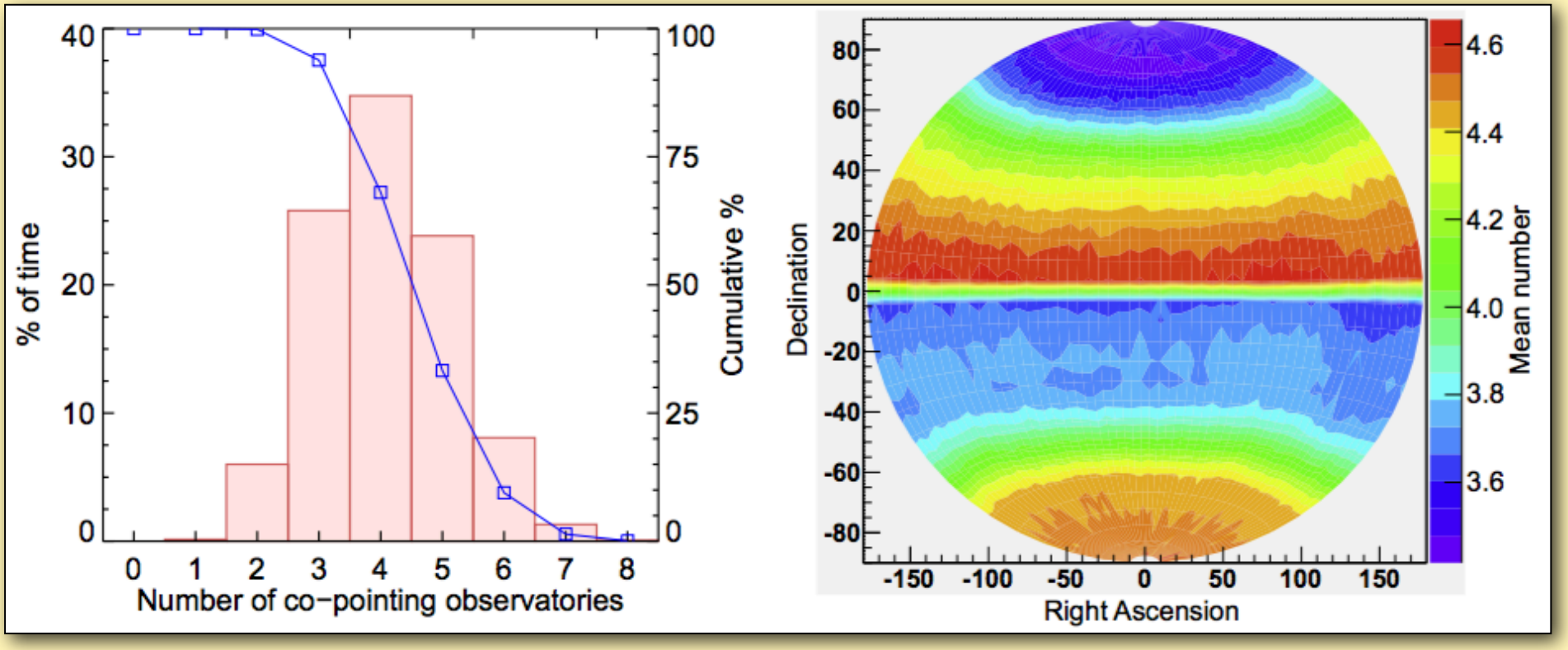
AMON Status: Infrastructure



- AMON event database
  - Designed & implemented, now being used & tested
  - Contents:
    - Inserted: IceCube IC40 & IC59, Swift, Fermi (public)
    - Inserted: ANTARES 2008, Auger (private)
    - In progress: LIGO S5 (public)
    - Awaiting approval: IceCube, HAWC, VERITAS, ANTARES (private)
- AMON application server
  - Running stably for about a year already
    - Python/Twisted, asynchronous, tested with multiple simulated clients
    - Accepts HTTP POST requests
    - Open for authorized connections using TLS certificates
  - GCN connection fully tested and running (using scrambled data)
  - Can soon start issuing AMON alerts using VOEvent format/protocol
- AMON hardware
  - Two new low-downtime (<1hr/yr) servers now deployed at Penn State
  - Physically & cyber secure; fully redundant systems

G. Tešic and A. Keivani, ICRC, PoS(ICRC2015)329 , 2015.

AMON Sensitivity



Astropart. Phys. 45 (2013) 56–70

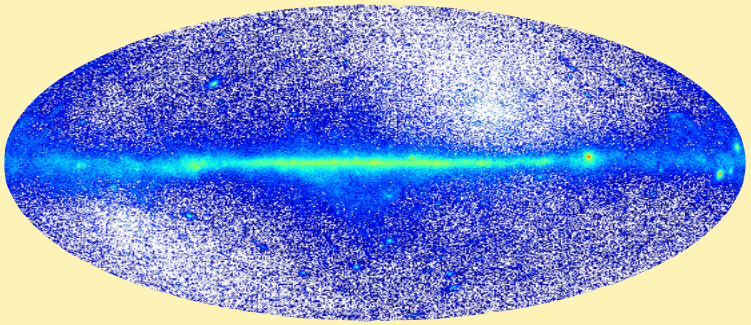
Distribution of the total number of trigger facilities observing a cosmological source, averaged over time and sky location.

Average number of observatories simultaneously viewing a source, as a function of location. Spatial variance is caused by the limited field-of-view of some observatories and the movement of orbital telescopes.

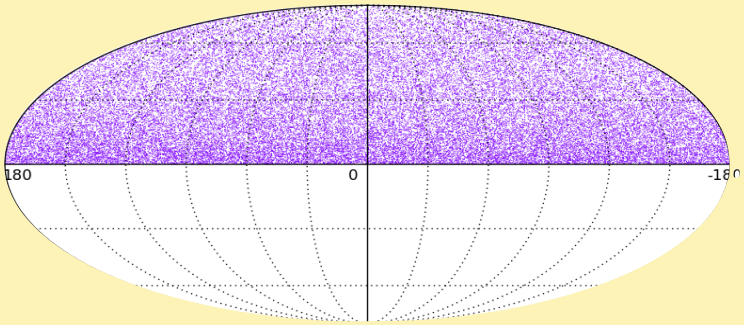
Example AMON-Enabled ν+γ Search

- IceCube and Fermi/LAT
  - Archival search using public data & full AMON framework

Fermi-LAT exposure corrected map



IC40-IC59 neutrinos in northern hemisphere



Coincidence Requirement:
Spatial: $\Delta\theta < 10°$
Temporal: $\Delta t = t_0 \pm 50$ s

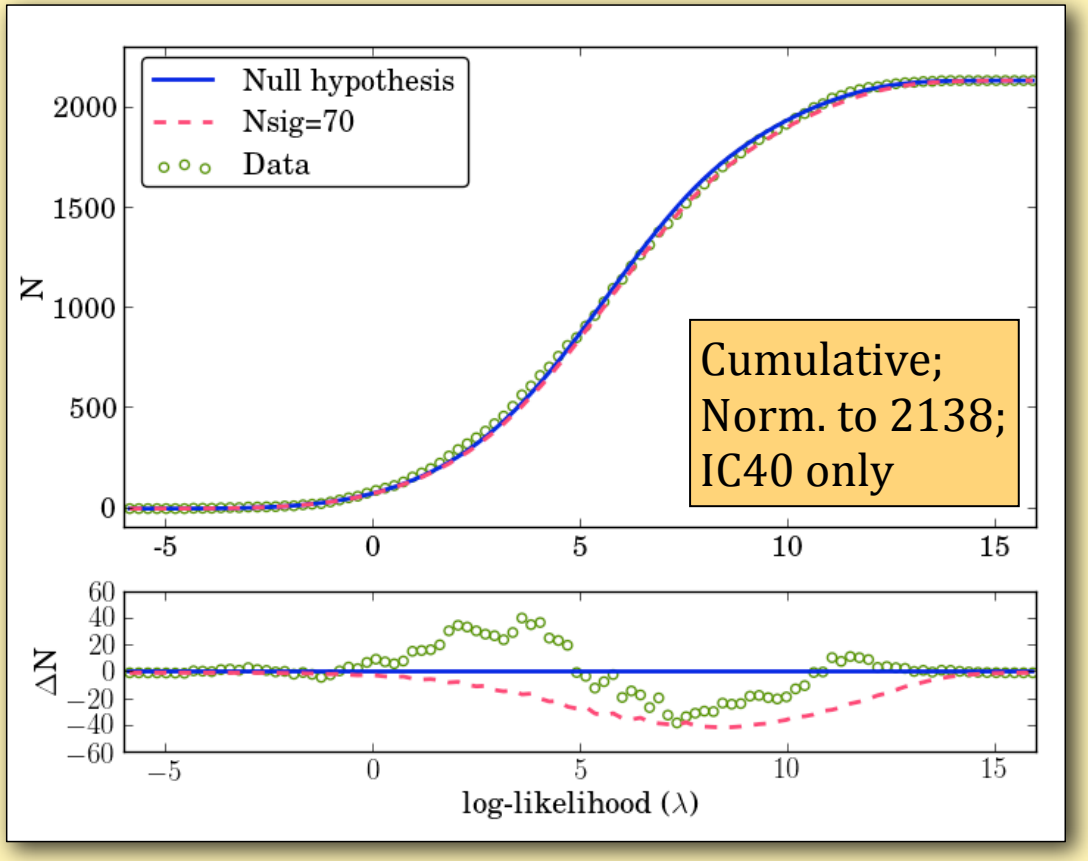
IC40 run period:
$\approx 4.1 \times 10^6$ photon events
≈ 14,000 neutrino events

IC59 run period:
$\approx 5.5 \times 10^6$ photon events
≈ 43,000 neutrino events

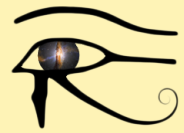
A. Keivani et al., ICRC, PoS(ICRC2015)786 (2015).

ν+γ Analysis Steps & Preliminary Result

- Define test statistic
  - $\lambda = 2\ln(P_{LAT}(\mathbf{x}|\mathbf{x}_\gamma)P_{IC}(\mathbf{x}|\mathbf{x}_\nu)) - 2\ln(B(\mathbf{x}_\gamma))$
- Plot λ distribution for data
  - 2138 ν+γ coincidences ($\Delta\theta < 10^o$, $\Delta t = \pm 50s$; all 1ν + Nγ, <N> = 2.17)
- Scramble neutrinos' (t, RA), plot λ_{null}
- Perform Anderson-Darling test on λ distributions
  - Find p-value of 4%
- Simulation says p=4% is consistent with N_{sig} = ~70 (and ~2200 bkgd)
- Compare simulated N_{sig} = 70 datasets with actual data
  - unblinded data looks different from null hypothesis...
  - ...but also looks different from signal hypothesis



ν+γ Search Consistency Checks and Outlook



- Consistency checks (using λ>11 events)
  - Average number of γ's per ν-γ coincidence: $\langle N \rangle_{data}$ = 2.17, $\langle N \rangle_{null}$ = 2.08±0.15
  - Distribution of time difference between each ν,γ
    - Flat: Consistent with absence of signal
  - Source map
    - 6 ν-γ pairs lie within 2° of one another
    - 12.9 ν-γ pairs lie within 2° of one another in scrambled datasets
- Will include IC59 and Swift in near future
- Will include later IceCube data (pending IceCube approval)
- Promising technique!

Conclusions

- AMON expands discovery space in new ways
  - Unleashes sub-threshold data for multimessenger source searches in real-time
    - leverages data that individual observatories cannot use for source searches on their own
  - Creates multilateral and bidirectional connections between triggering and follow-up observatory partners
  - Enables complex real-time and archival searches
    - Archival searches for ν + γ coincidences and primordial black holes already underway
- AMON greatly simplifies multimessenger searches
  - Common transfer protocol, data format, event database, MoUs
- AMON's "first light" will happen very soon!
  - New participants are always welcome
  - 4th AMON workshop Dec. 3-4 2015 at Penn State:
    - http://sites.psu.edu/amonworkshop/

Backup Slides

ν+γ Analysis Steps & Preliminary Result

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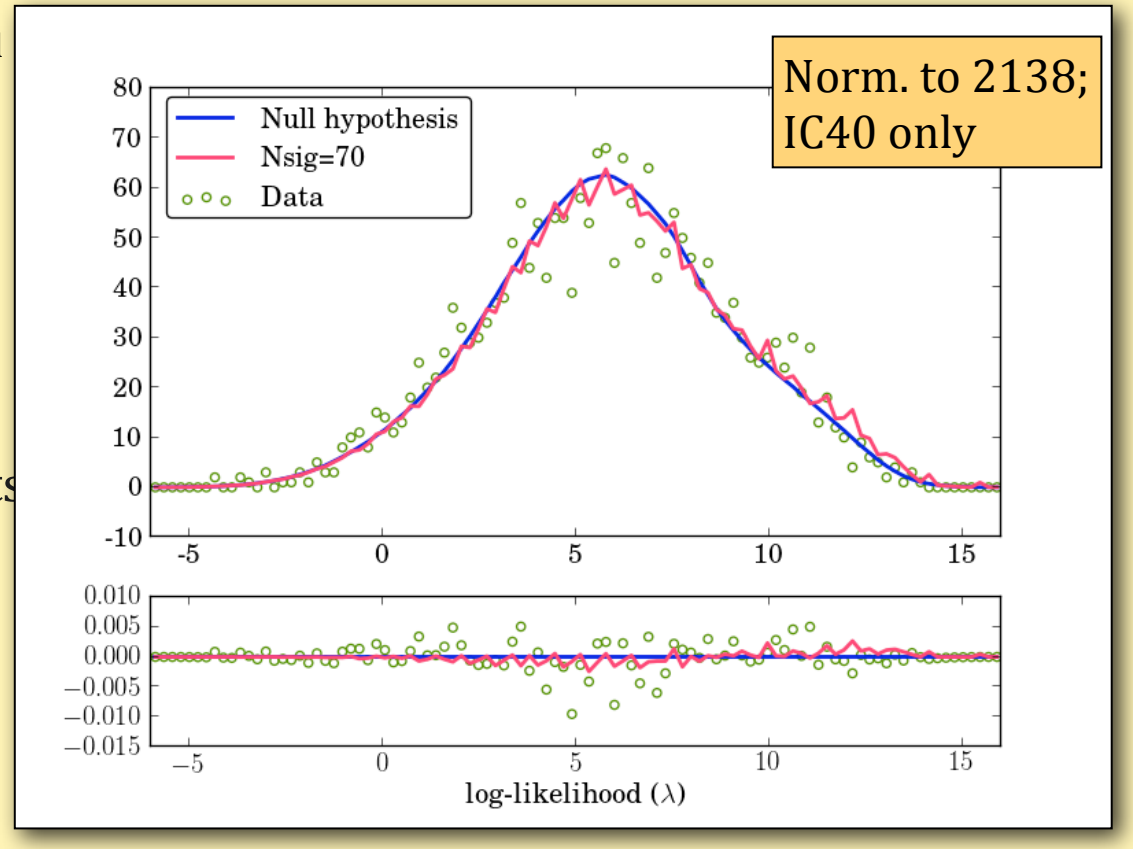
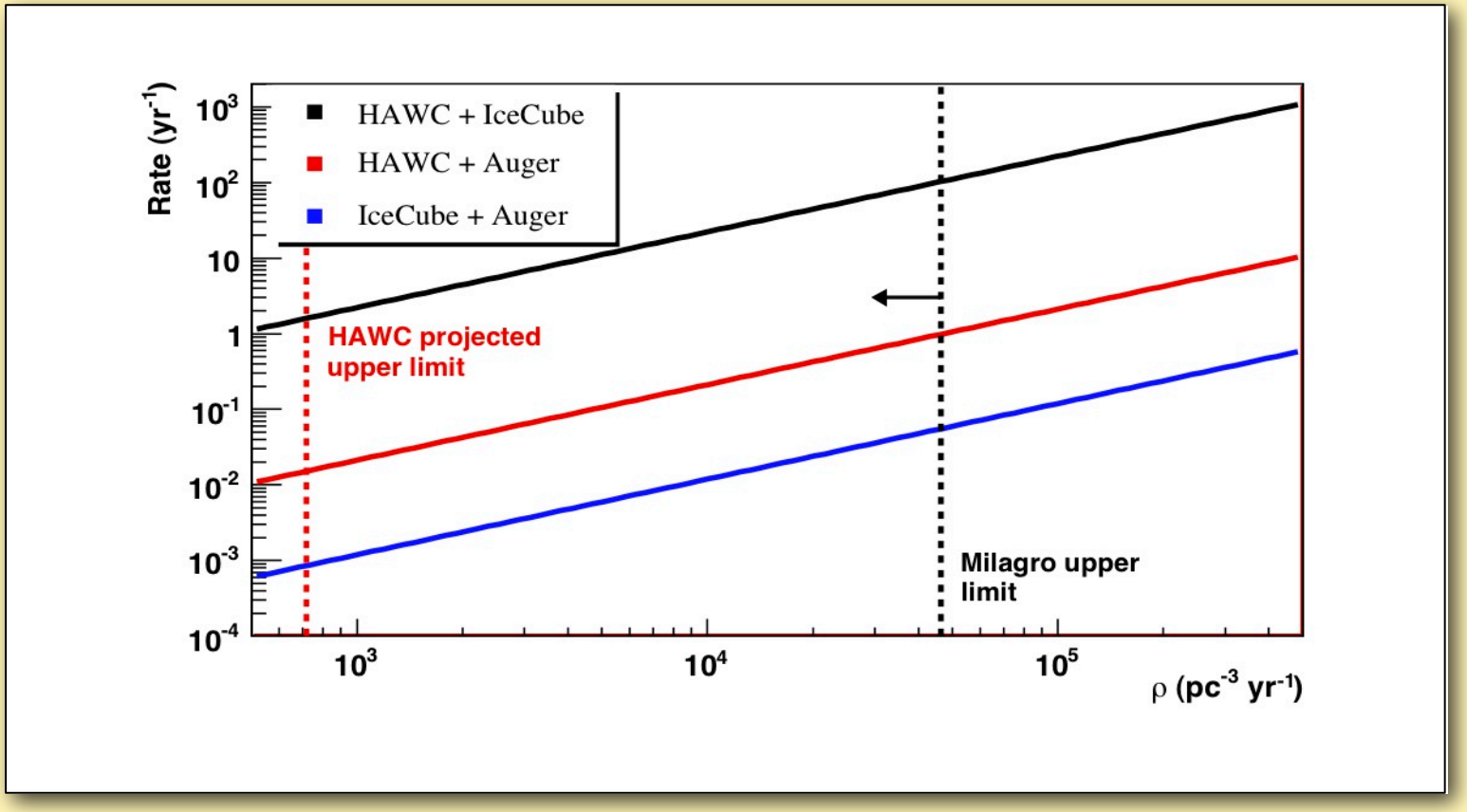


Example AMON-Enabled PBH Search

- Primordial Black Holes (PBHs) could produce appealing signature for AMON
- Hawking radiation
  - $TH = (M_{Planck})^2/[8\pi M]$
  - $dM/dt \propto -\alpha(M)/M^2$
- At end of PBH life, as $M \rightarrow 0$
  - gets very hot
  - radiates energy in shorter & shorter time
- Look for short burst of high energy radiation

Example AMON-Enabled PBH Search

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



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

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

Event and Alert 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*.)

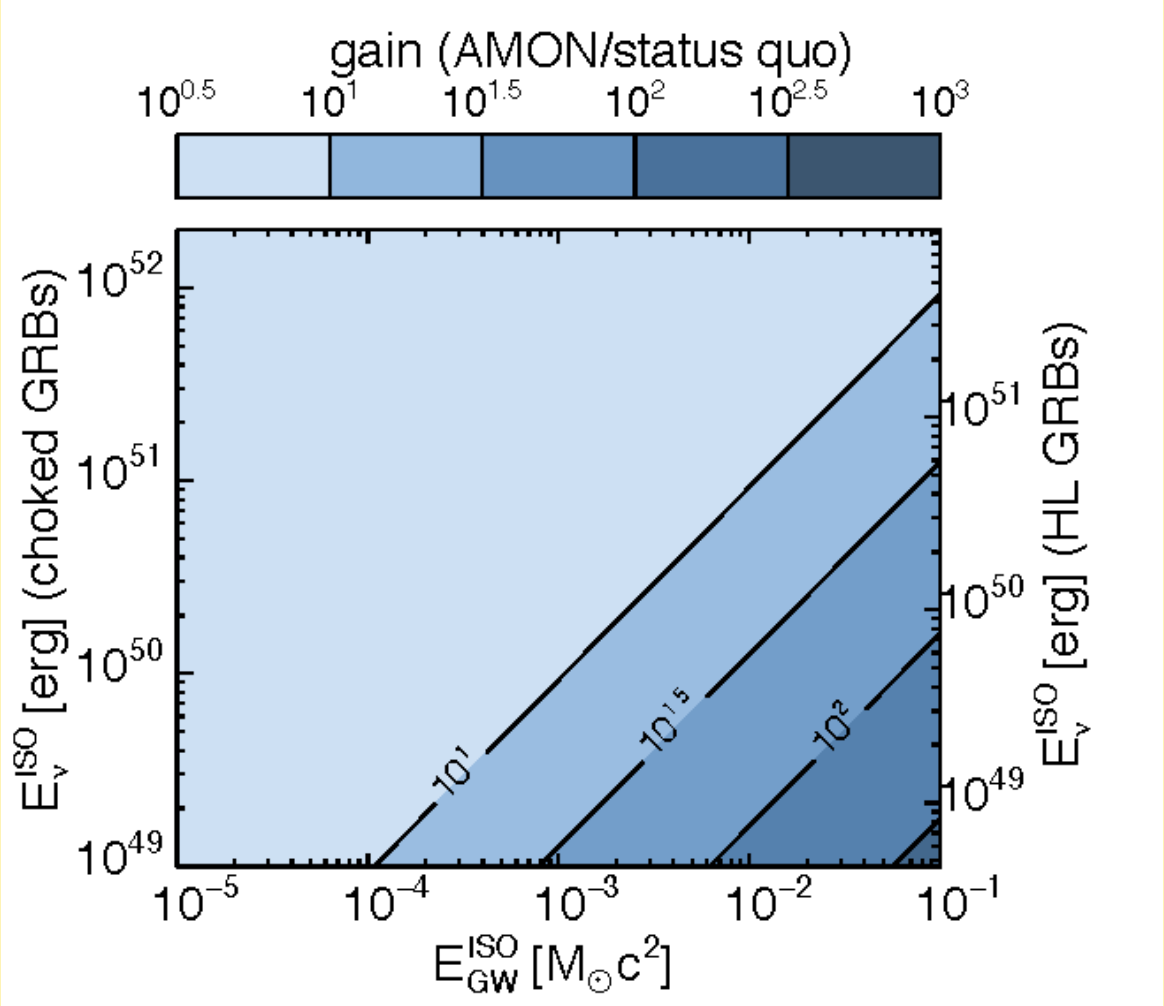
AMON Alert content:

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

VOEvent

- 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 Sensitivity Study



M.W.E. Smith et al., Astropart.Phys. 45 (2013) 56-70

Sensitivity ratio of AMON approach to *status quo* for detection of GW+CN source population with one-year A-LIGO/Virgo and IC86.

Fermi LAT Data

- Fermi LAT purest (i.e. lowest instrumental background) analysis class (Pass 7-V15 Ultraclean).
  - The photon events that are detected while the telescope is repositioning, or is in pointing mode, or pointing to the Sun are removed.
  - In addition, only photon events with spacecraft zenith angle smaller than 65º and energies above 200 MeV are accepted.
- Fermi: can keep events with spacecraft zenith angle smaller than 65º. Can also increase the energy threshold.
- Will update to Pass 8 at 90º above 100 MeV; will yield more data