The Astrophysical Multimessenger Observatory Network

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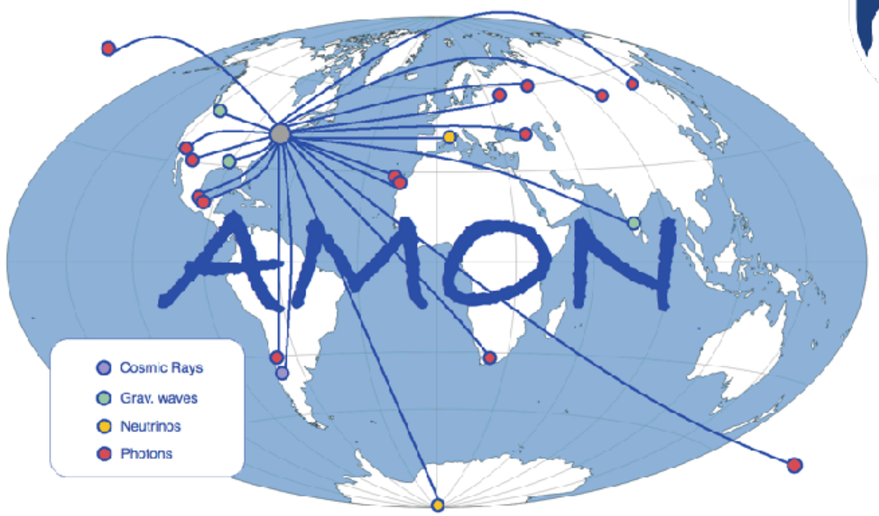
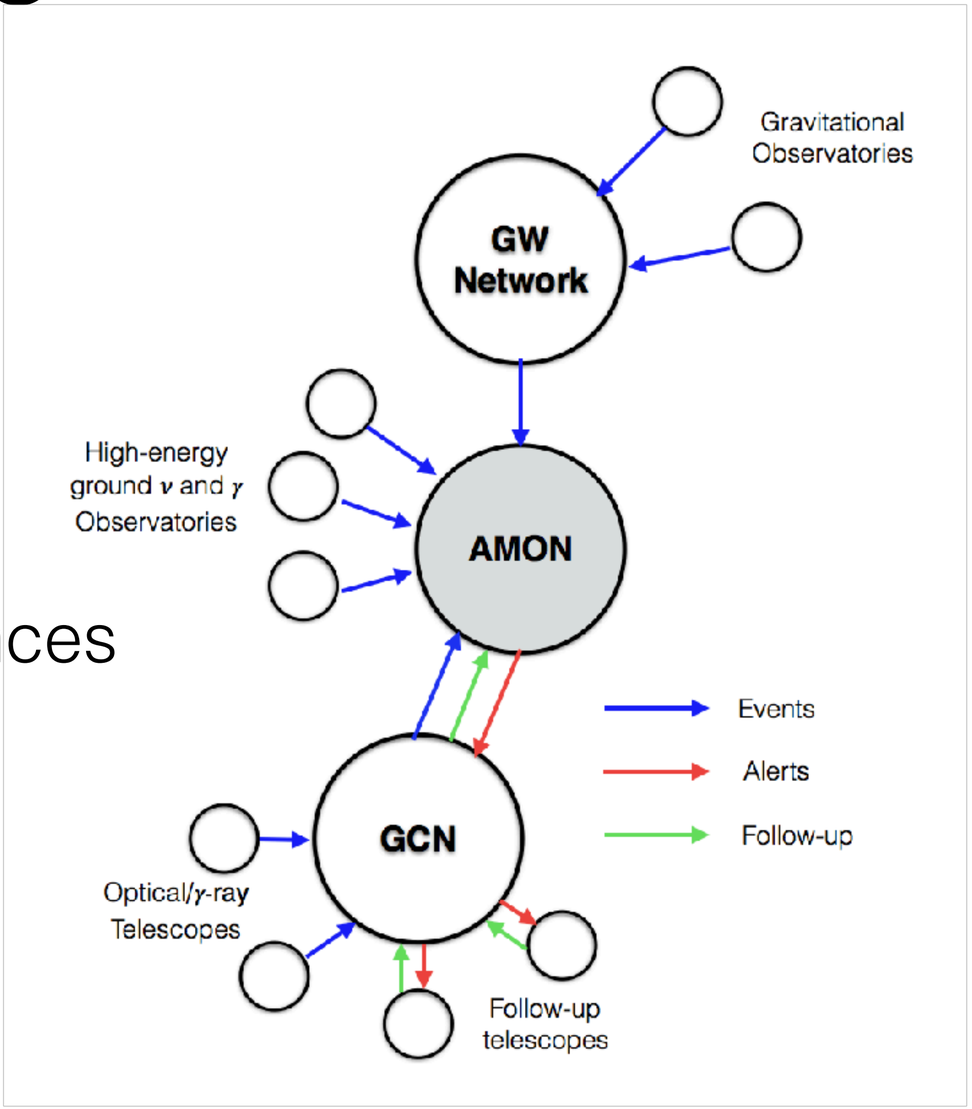


CRIS 2018 - Portopalo di Capo Passero, Italy

Outline

- The AMON concept
- Network status
- Notices, alerts, and real-time coincidences
- Outlook



The Astrophysical Multimessenger Observatory Network

The AMON concept

AMON provides the **framework** for:

- **Real-time** and near real-time sharing of *subthreshold* data among *multimessenger* observatories
- Real-time and archival searches for any **coincident** (in time and space) signals.
- Prompt distribution of **alerts** for follow-up observations

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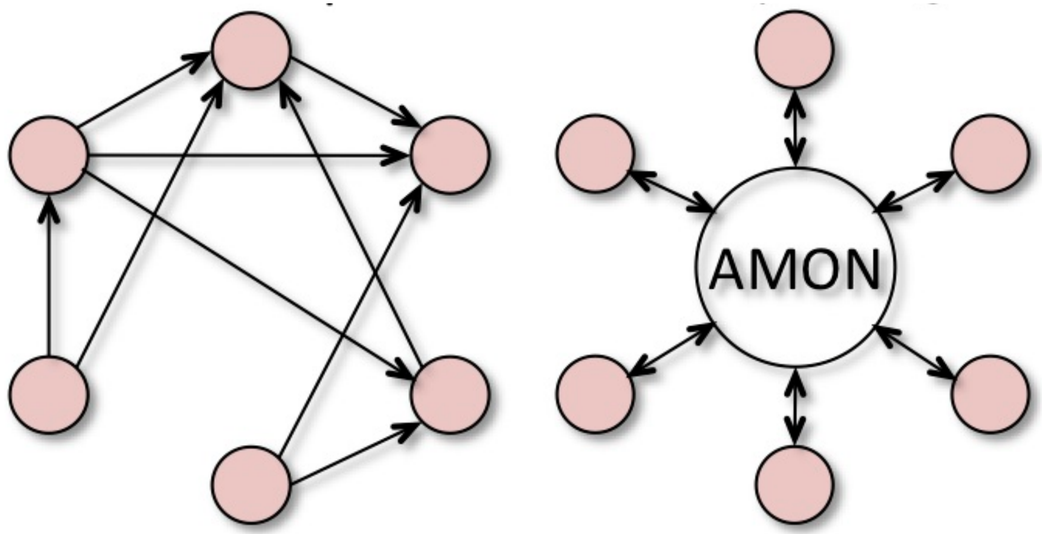
AMON unifies and simplifies existing *multimessenger* efforts:



Astrop.Phys. Vol. 45, 56–70, 2013

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

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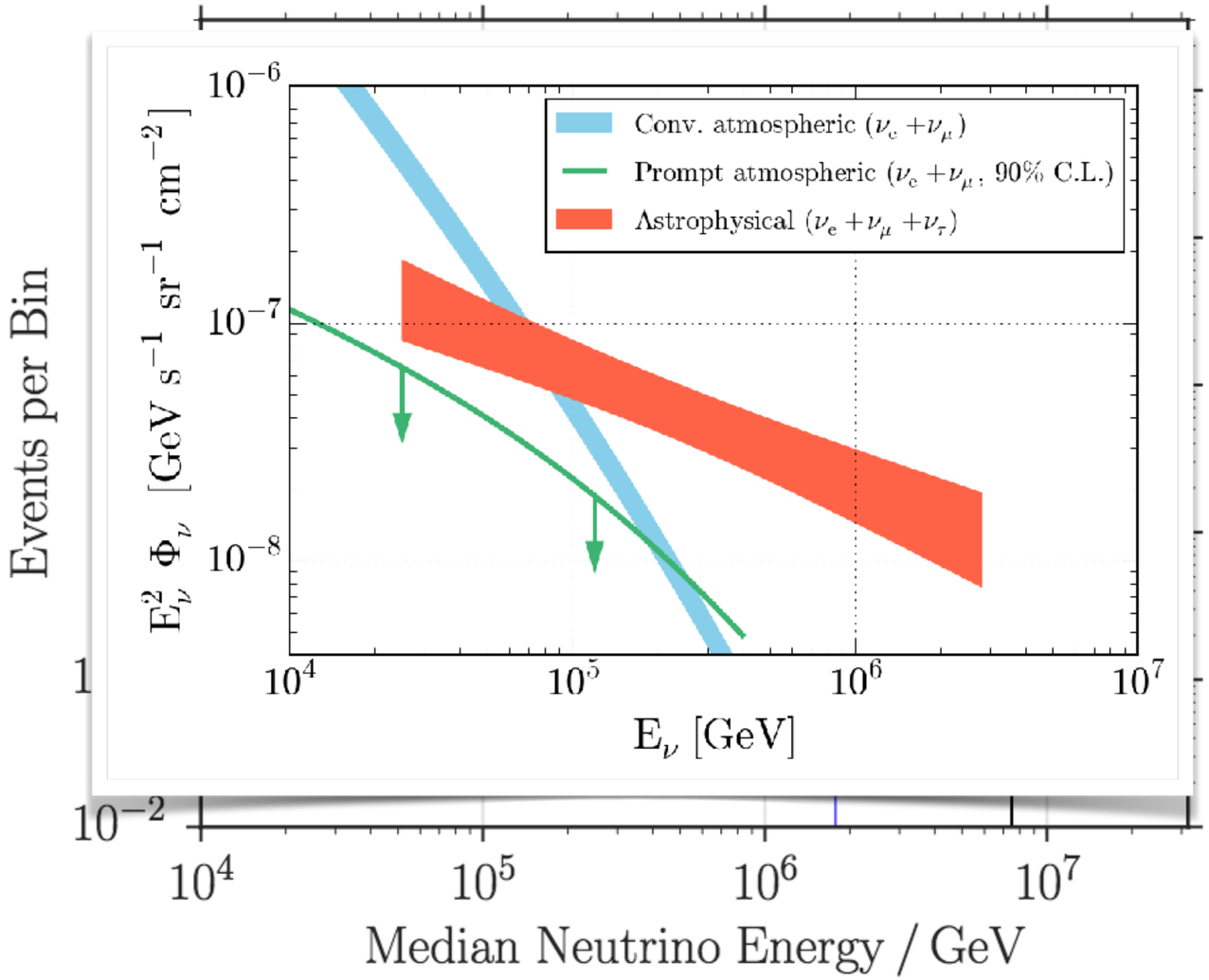
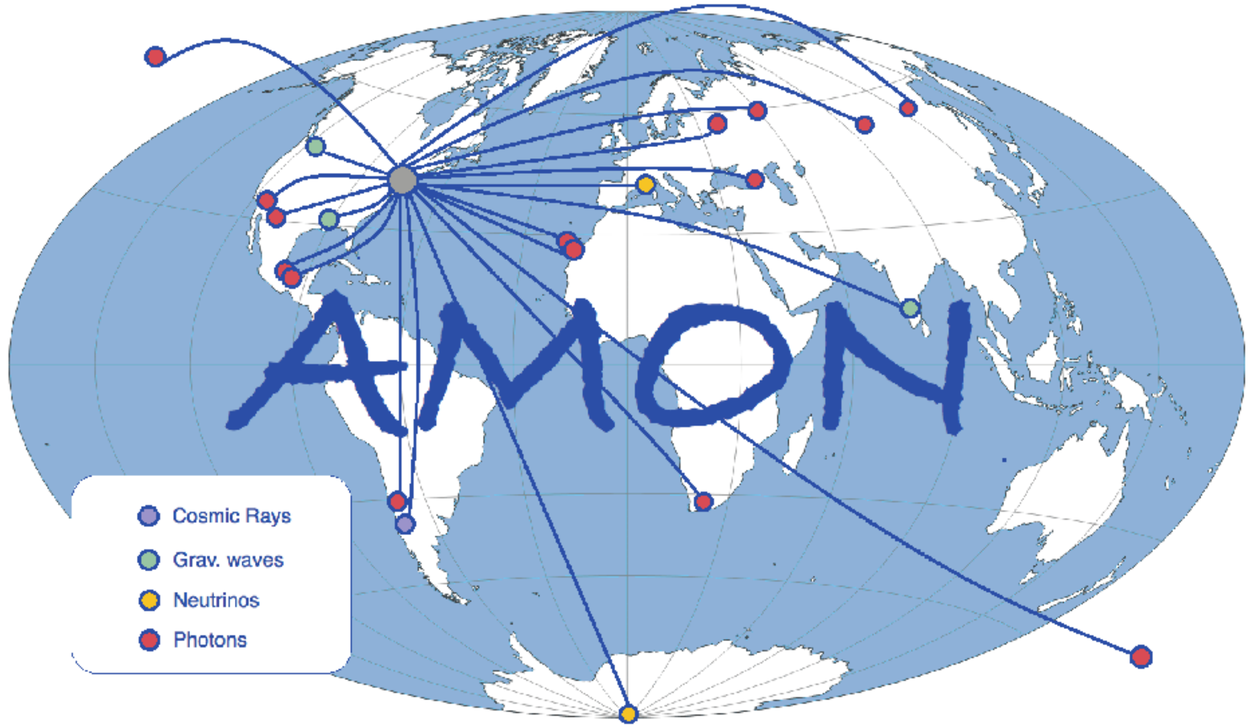


The Network

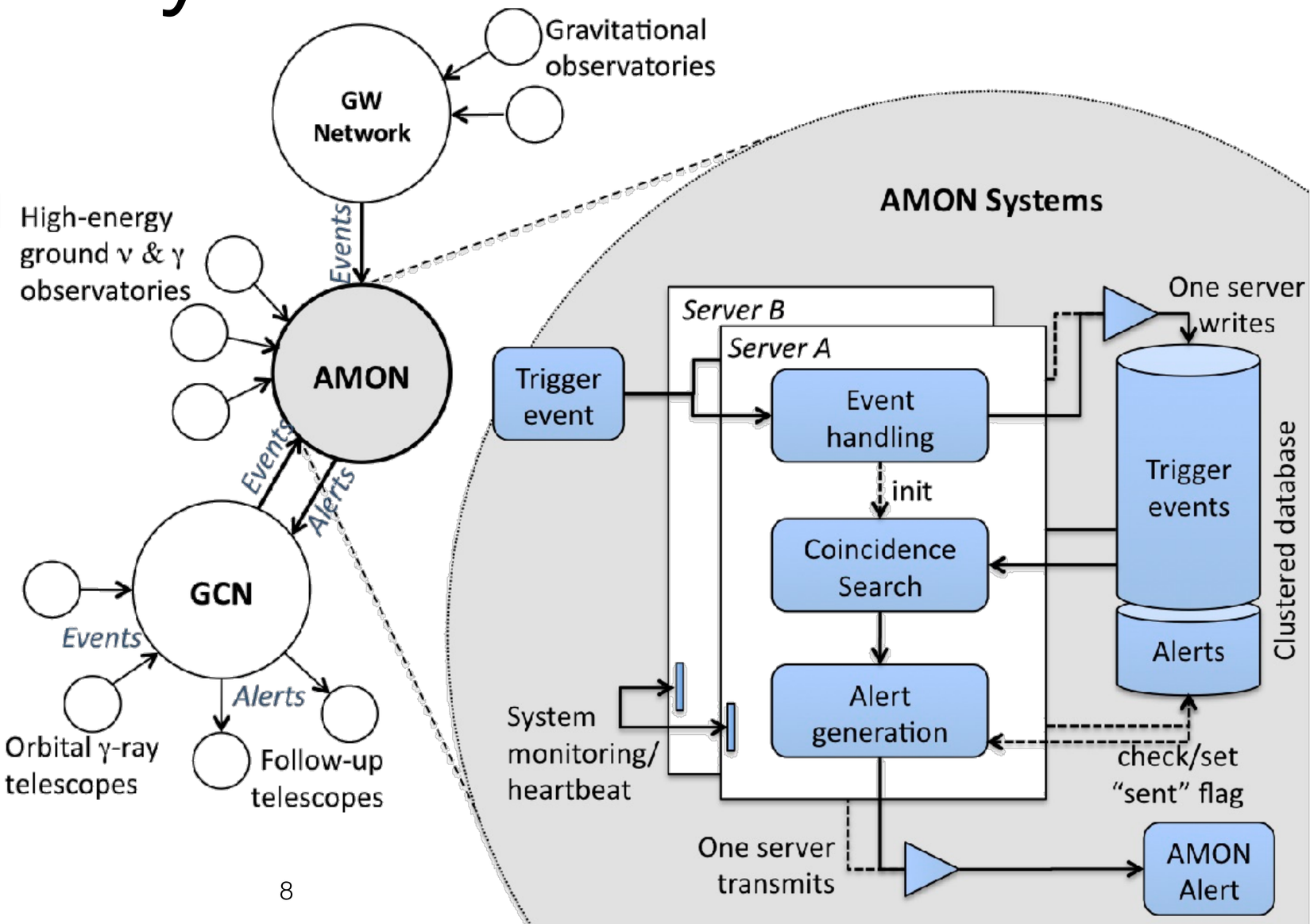
- **Triggering:** IceCube, ANTARES, Auger, HAWC, VERITAS, FACT, Swift-BAT, MAGIC, HESS
- **Follow-up:** Swift-XRT & UVOT, VERITAS, FACT, MASTER, LCOGT, MAGIC, HESS
- **Pending:** LIGO, PTF, TA, …



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

The 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



The network status - database

First full version of the **AMON database** designed and implemented. Now being used and tested!

- Data from **triggering** observatories implemented:
  - public completed: IC-40, IC59, Swift, Fermi
  - private completed: ANTARES, Auger
  - in progress: IceCube, HAWC, VERITAS, ANTARES, LIGO S5 & S6
- **Real-time tests** with simulated and real (IC) data constantly being performed

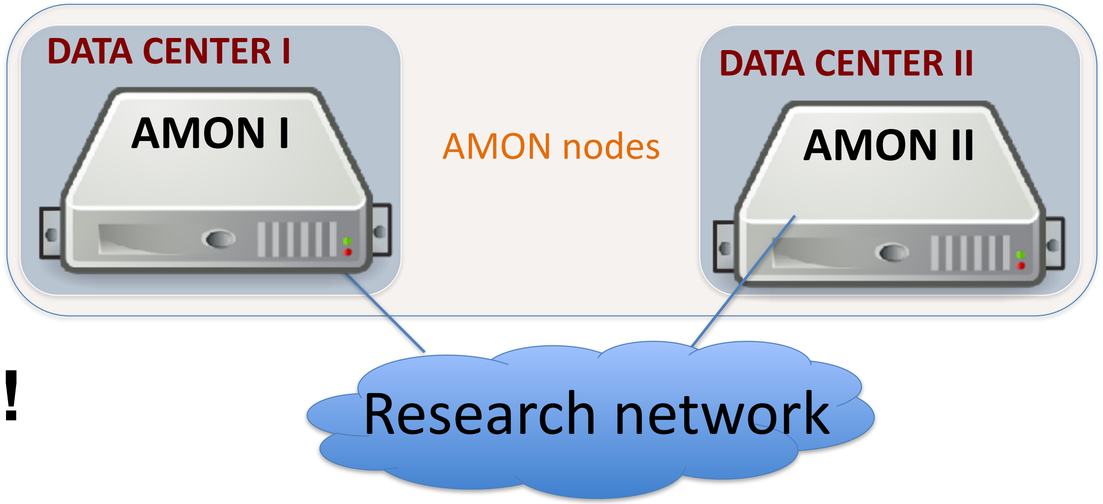
The network status - application server

The AMON application server has been up and running since **August 2014!**

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

The network status - 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!**



nalyses

The Astrophysical Journal, 833:117 (8pp), 2016 December 10 doi:10.3847/1538-4357/833/1/117

SEARCH FOR BLAZAR FLUX-CORRELATED TEV NEUTRINOS IN ICECUBE 40-STRING DATA

C. F. Turley[1,2], D. B. Fox[2,3,4], K. Murase[1,2,3,4], A. Falcone[2,3], M. Barnaba[3], S. Coutu[1,2], D. F. Cowen[1,2,3], G. Filippatos[1,2], C. Hanna[1,2,3], A. Keivani[1,2], C. Messick[1,2], P. Mészáros[1,2,3,4], M. Mostafá[1,2,3], F. Oikonomou[1,2], I. Shoemaker[1,2], M. Toomey[1,2], and G. Tešić[1,2]
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[2] Center for Particle & Gravitational Astrophysics, Institute for Gravitation and the Cosmos, Pennsylvania State University, University Park, PA 16802, USA
[3] Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
[4] Center for Theoretical & Observational Cosmology, Institute for Gravitation and the Cosmos, Pennsylvania State University, University Park, PA 16802, USA
Received 2016 August 30; revised 2016 October 2; accepted 2016 October 5; published 2016 December 12

ABSTRACT

We present a targeted search for blazar flux-correlated high-energy ($\varepsilon_\nu \gtrsim 1$ TeV) neutrinos from six bright northern blazars, using the public database of northern hemisphere neutrinos detected during "IC40" 40-string operations of

-
  - IC40/59 and Swift-BAT sub-threshold (in progress)
  - IC40 and VERITAS blazar TeV flares: Astrophys. J. **833** (2016) 117
- γ rays + gravitational waves
  - HAWC/Swift and LIGO (in progress)
- ν's + γ rays + cosmic rays
  - PBH evaporation searches, G. Tešić, PoS (ICRC'15) 328 (2015)
- others… FRB + Swift: ApJL **832** (2016) L1

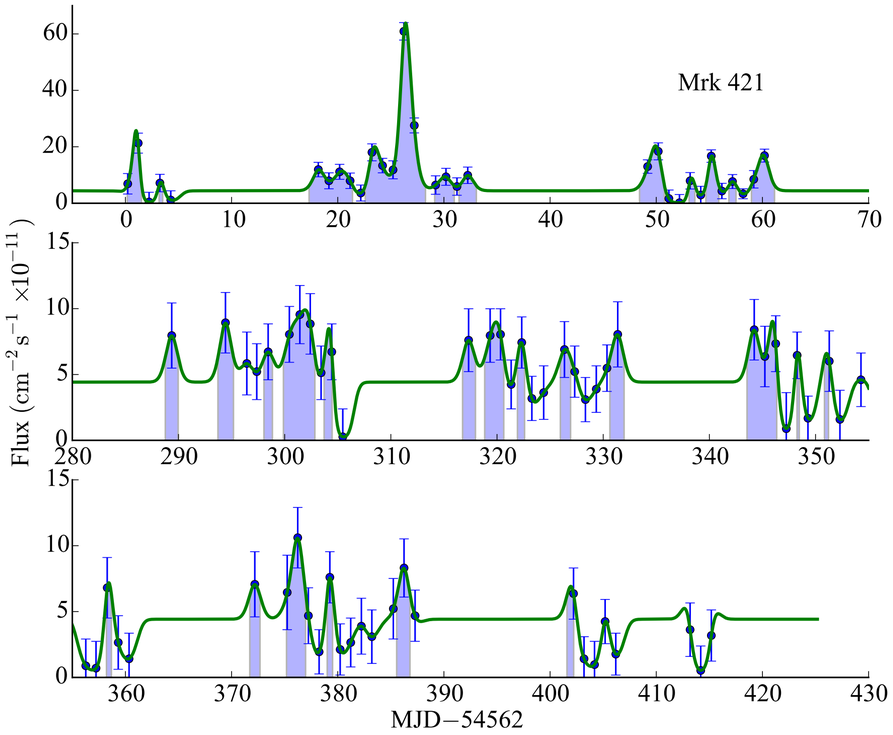

Fig. 2.— Times of interest for Markarian 421. These times were selected in our initial optimization as the most sensitive search for associated neutrinos (Sec 2.3). The selection includes 45.6 days with a total γ-ray fluence of $4.1 \times 10^{-4}\,\mathrm{cm}^{-2}$ and yields an expected background of 1.03 neutrinos.

First archival analyses

- ν's + γ rays
  - IC40 and Fermi-LAT, A. Keivani et al., PoS (ICRC'15) 786 (2015)
  - IC40/59 and Fermi-LAT (final stage, submitted)
  - IC40/59 and Swift-BAT sub-threshold (in progress)
- 2
- 1
- others… FRB + Swift: ApJL **832** (2016) L1

The Astrophysical Journal Letters, 832:L1 (9pp), 2016 November 20 doi:10.3847/2041-8205/832/1/L1

CrossMark

DISCOVERY OF A TRANSIENT GAMMA-RAY COUNTERPART TO FRB 131104

J. J. DeLaunay[1,3], D. B. Fox[2,3,4], K. Murase[1,2,3,4], P. Mészáros[1,2,3,4], A. Keivani[1,3], C. Messick[1,3], M. A. Mostafá[1,3], F. Oikonomou[1,3], G. Tešić[1,3], and C. F. Turley[1,3]
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Received 2016 September 26; accepted 2016 September 29; published 2016 November 11

ABSTRACT

We report our discovery in *Swift* satellite data of a transient gamma-ray counterpart (3.2σ confidence) to the fast radio burst (FRB) FRB 131104, the first such counterpart to any FRB. The transient has a duration $T_{90} \gtrsim 100$ s and a fluence $S_\gamma \approx 4 \times 10^{-6}$ erg cm^{-2}, increasing the energy budget for this event by more than a billion times; at the nominal $z \approx 0.55$ redshift implied by its dispersion measure, the burst's gamma-ray energy output is $E_\gamma \approx 5 \times 10^{51}$ erg. The observed radio to gamma-ray fluence ratio for FRB 131104 is consistent with a lower

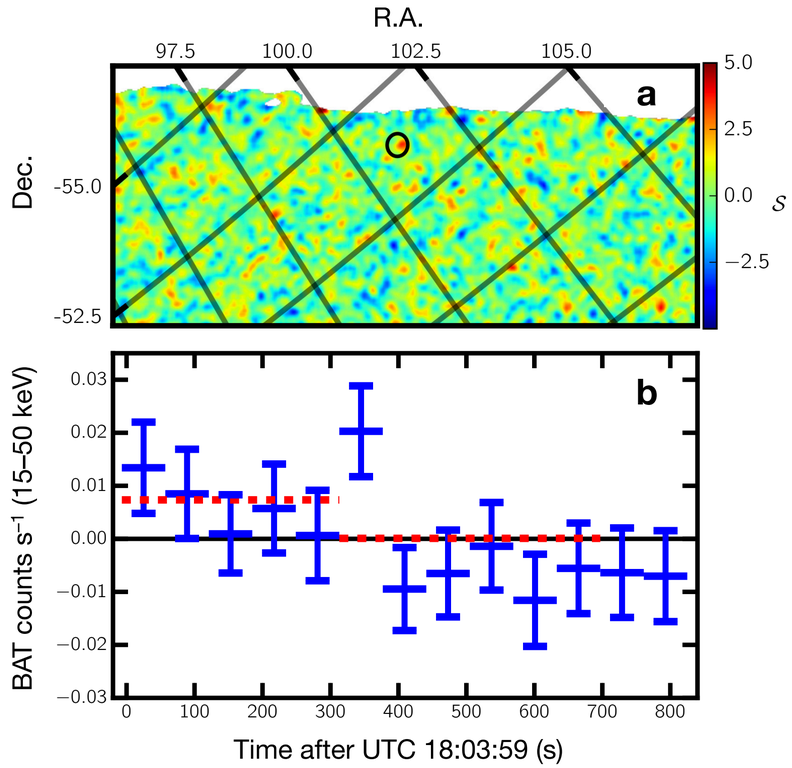


Figure 1. Swift BAT discovery image and light curve for the transient gamma-ray counterpart to FRB 131104, Swift J0644.5−5111. (a) Swift J0644.5−5111 discovery image (15–150 keV; UTC 18:03:52 start; 300 s exposure), showing a small portion of the BAT field of view in tangent plane projection. The search region for FRB 131104 (black circle) is shown; regions with <1% coding are masked. The point-like excess associated with the gamma-ray transient peaks at signal-to-noise $\mathcal{S} = 4.2\sigma$. (b) Soft-band (15–50 keV) light curve for Swift J0644.5−5111. Time is measured from the FRB detection, UTC 18:03:59. Both 64 s (blue) and 320 s (red dashed) flux measurements are shown; error bars are $\pm 1\sigma$.

Online analyses & proposals

- Real-time ν notices
  - **HESE** GCN notices went live in **April 2016**
  - **EHE** notices followed in **July 2016**
  - HE ν from flaring blazar
- Swift proposals
  - X-ray and UV/optical counterparts to HE ν's
  - X-ray and UV/optical counterparts to ν's + X- and γ-ray coincidences

Recent Notice example

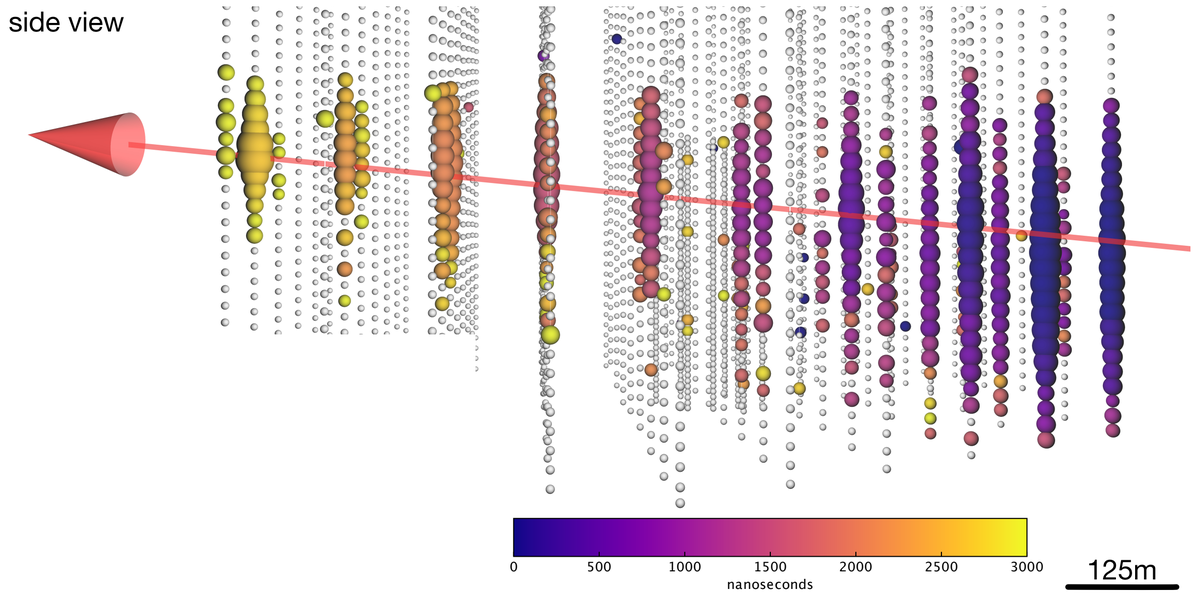
To take advantage of multi-messenger opportunities, the IceCube neutrino observatory (13) has established a system of real-time alerts that rapidly notify the astronomical community of the direction of astrophysical neutrino candidates (14). From the start of the program in April 2016 through October 2017, 10 public alerts have been issued for high-energy neutrino candidate events with well-reconstructed directions (15).

…

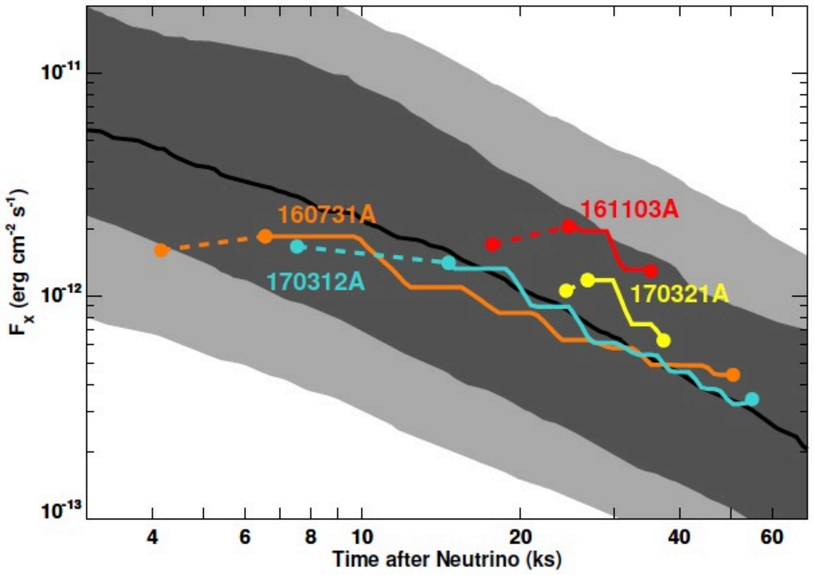
The neutrino alert

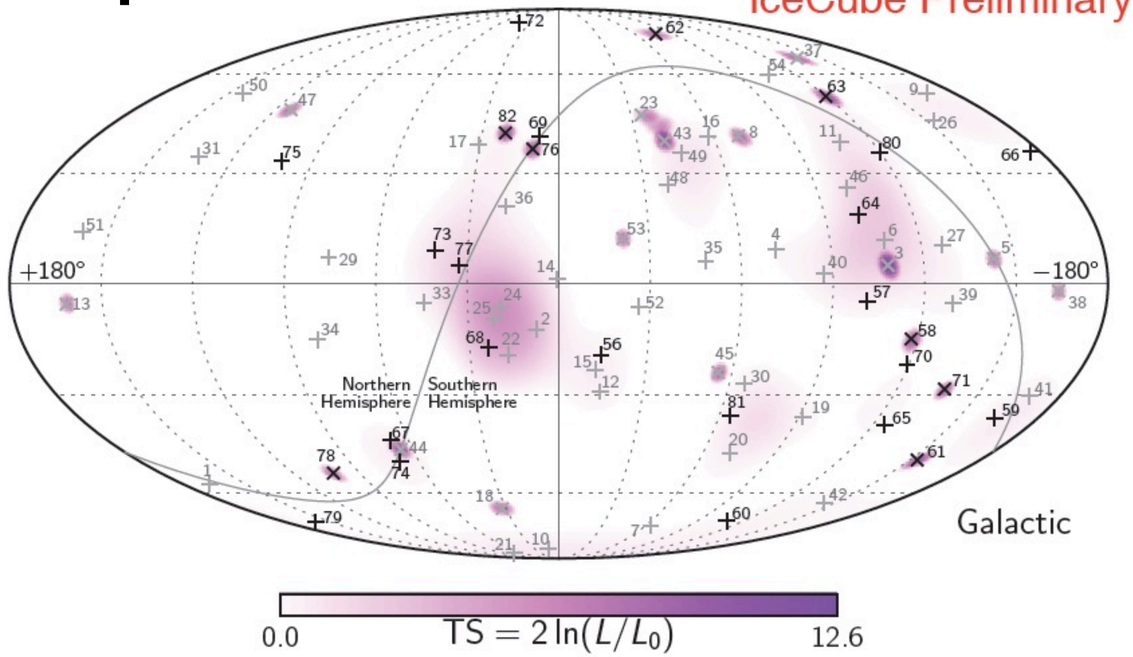
IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths between 1450 m and 2450 m. When a high-energy muon-neutrino interacts with an atomic nucleus in or close to the detector array, a muon is produced mov- ing through the ice at superluminal speed and creating Cherenkov radiation detected by the DOMs. On 22 September 2017 at 20:54:30.43 Coordinated Universal Time (UTC), a high-energy neutrino-induced muon track event was detected in an automated analysis that is part of IceCube's real-time alert system. An automated alert was distributed (*17*) to observers 43 seconds later, providing an initial estimate of the direction and energy of the event. A sequence of refined reconstruction algorithms was automatically started at the same time, using the full event information. A representation of this neutrino event with the best-fitting reconstructed direction is shown in Figure 1. Monitoring data from IceCube indicate that the observatory was functioning normally at the time of the event.

17. IceCube Collaboration, *GRB Coordinates Network/AMON Notices* **50579430_130033** (2017).



Swift proposals





ν	γ	r_{90}	Average Latency	Potential Sources
ANTARES	*Fermi*-LAT	~0.3°	~5 hrs	AGNs, GRBs
IceCube	HAWC	~0.1°	~7 hrs	
IceCube	*Fermi*-LAT	~0.3°	~5 hrs	
IceCube	*Swift* BAT	~4'	~8 hrs	

Following HE ν's

```
////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
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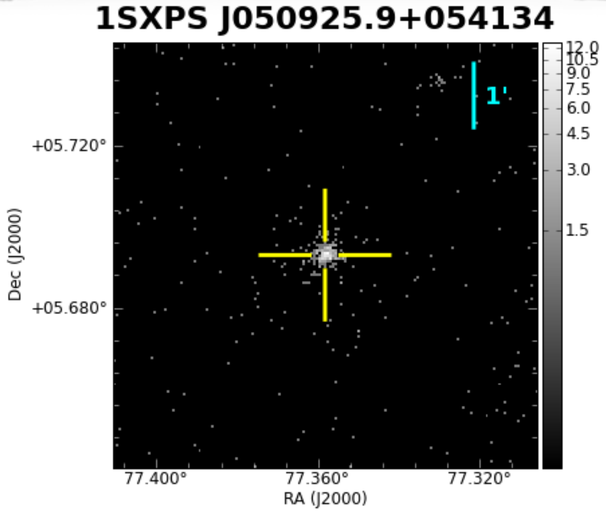
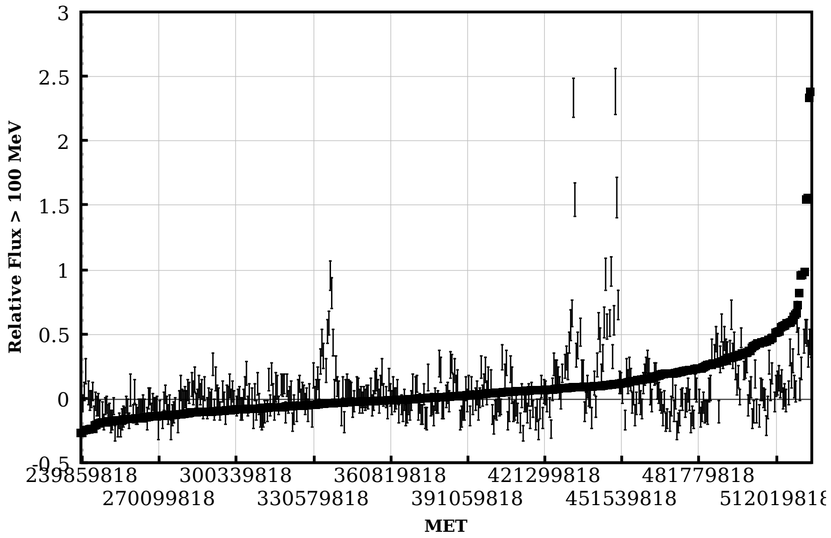
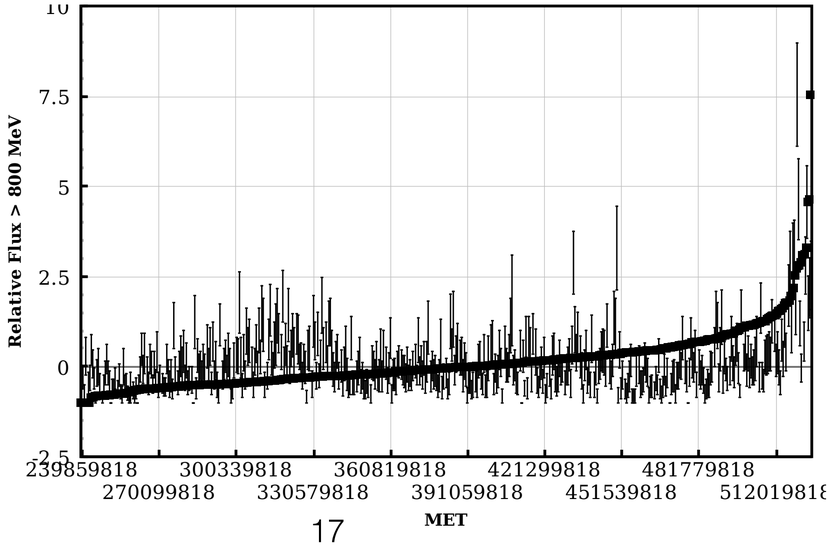
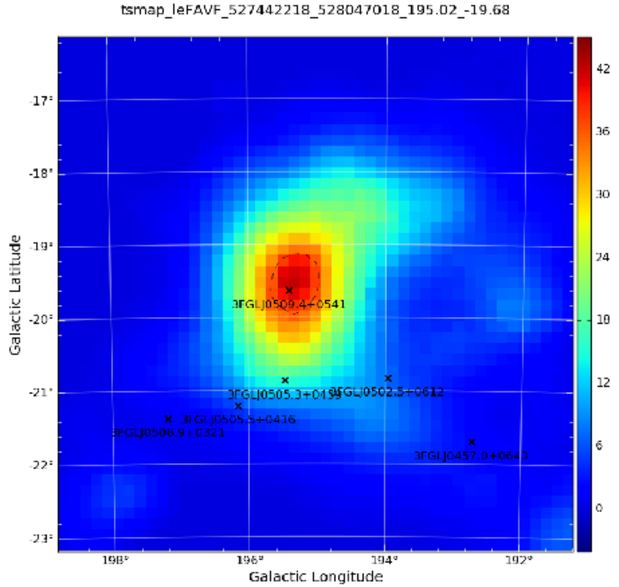
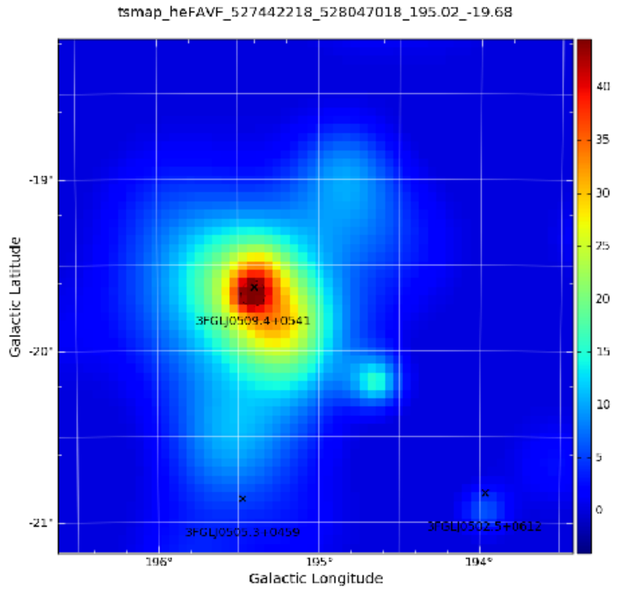


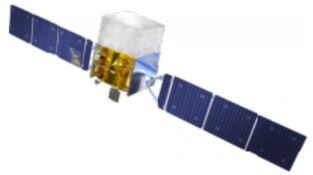








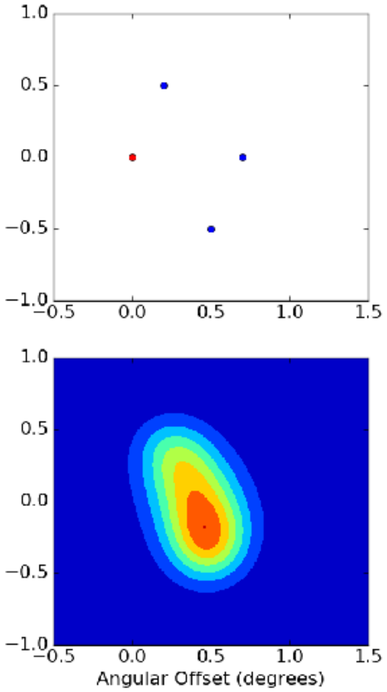
Archival analysis



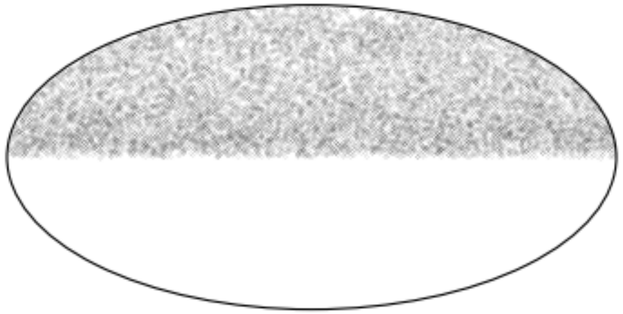
Coincidence parameters

$$\Delta t = \pm 100 \text{ s}$$

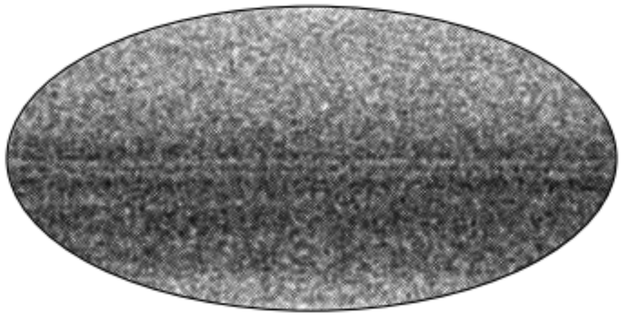
$$\Delta\theta < 5^\circ$$



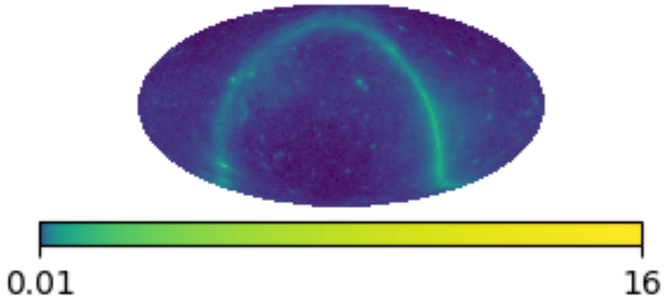
A: IC40



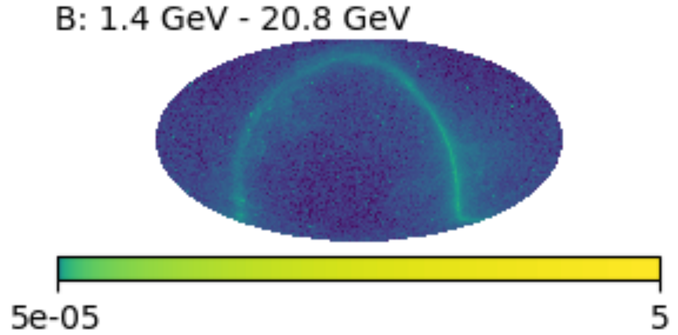
B: IC59



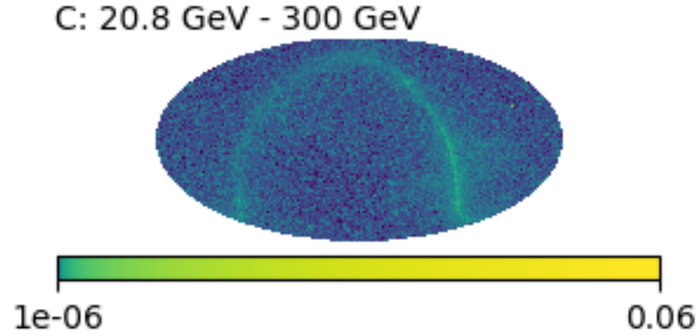
A: 100 MeV - 1.4 GeV



B: 1.4 GeV - 20.8 GeV



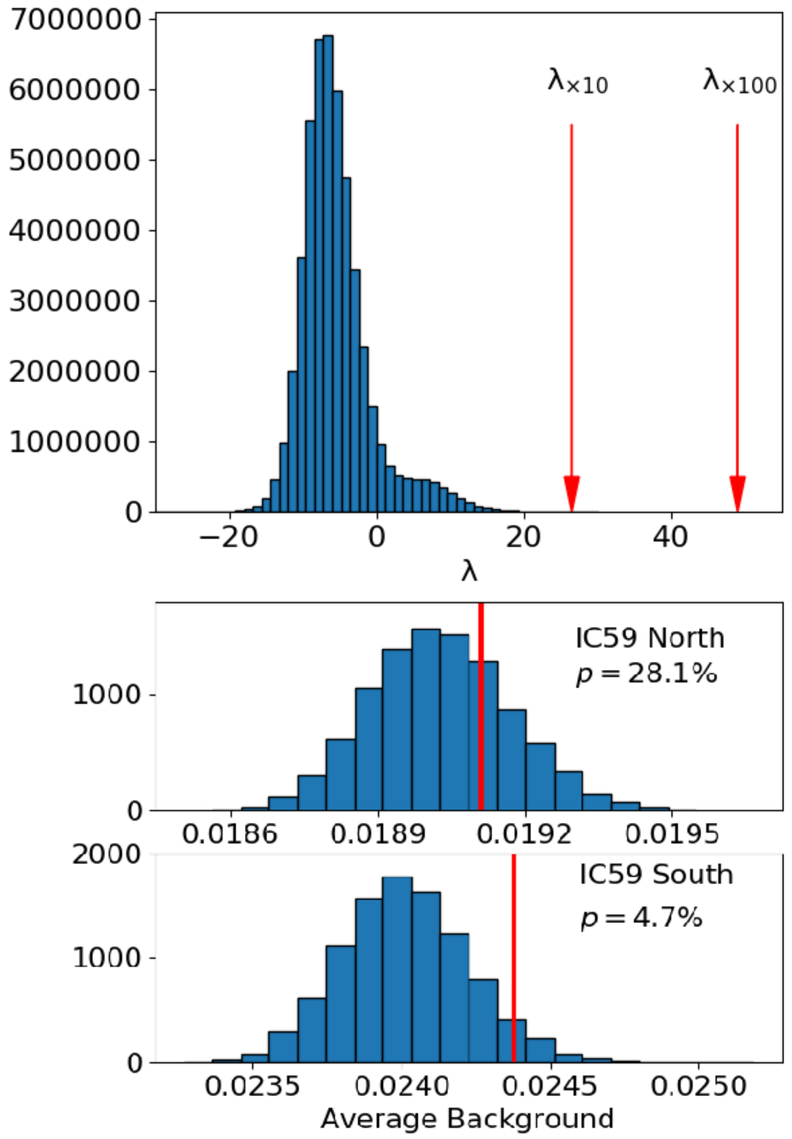
C: 20.8 GeV - 300 GeV



- Localize coincidence by max overlap of PSFs
- Rank coincidences by a log-likelihood statistic

Archival analysis: IC+Fermi

- Two ways to identify a coincidence signal:
  - Look for excess of events with high log-likelihood values (real time search)
  - Comparison of real and null distributions with the Anderson-Darling test



Archival analysis: IC+Fermi

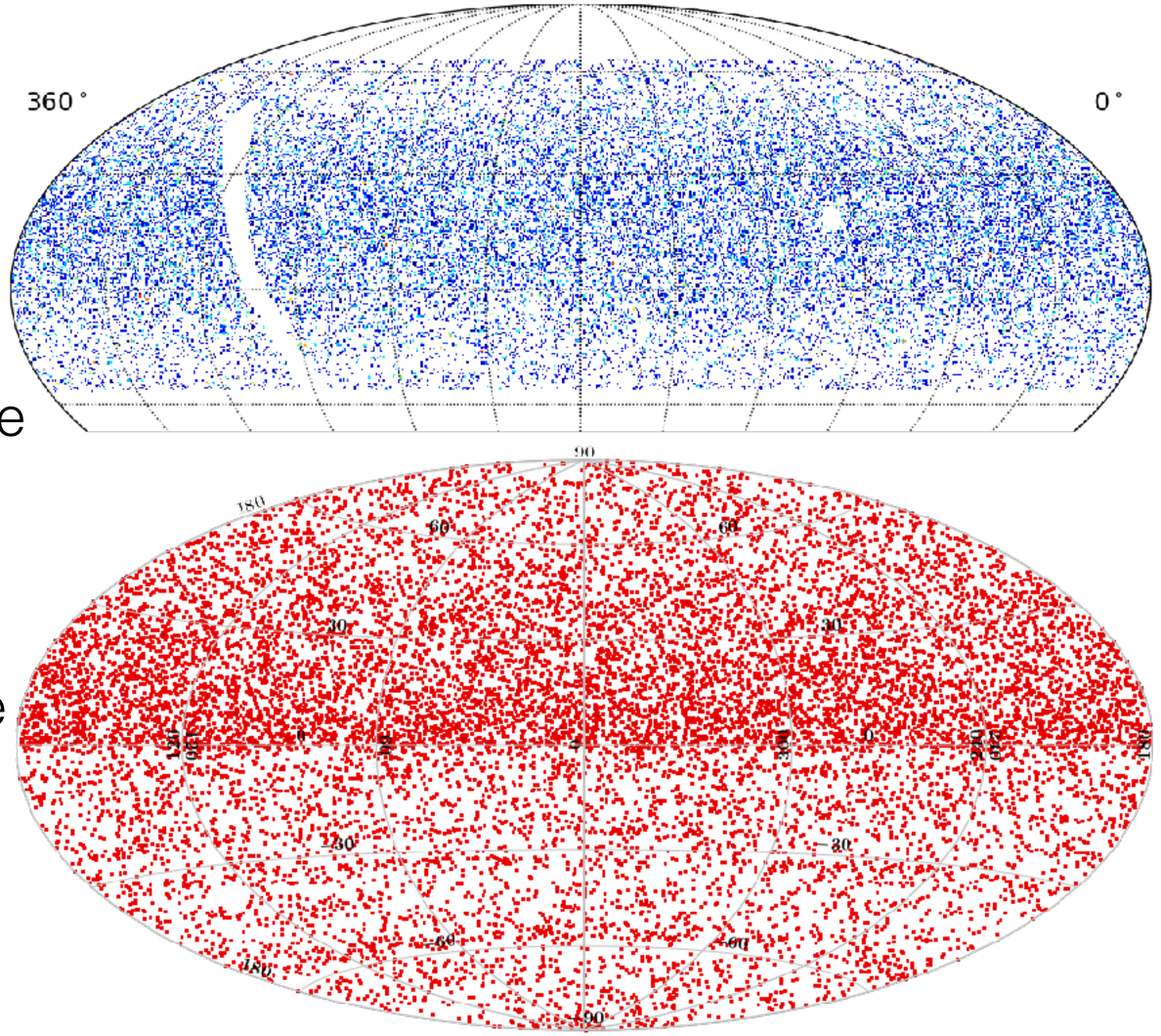
- Developed a **time sensitive** coincident analysis for IceCube and Fermi data
- Methods sensitive to
  - rare high-multiplicity events; e.g., GRBs
  - a population of cosmic signals

Details at arXiv:1802.08165

- Found a potentially interesting ($p = 4.7\%$) correlation between photon and neutrino populations
- Analysis will be extended to
  - cover all archival Fermi and IceCube data
  - run on ANTARES data
- Code for **real-time analysis** on the AMON servers is ready pending collaboration approval

Coincidence alert: IC+HAWC

- Proof-of-concept dataset (**1 month**)
  - HAWC daily *sub-threshold* **hotspots**
    Parameters: position, error in position, significance (>2.75), start time of transit, end time of transit
  - IC **track-like** events
    Parameters: position, time of event, false positive rate density (FPRD), signal acceptance, PSF



Coincidence alert: IC+HAWC

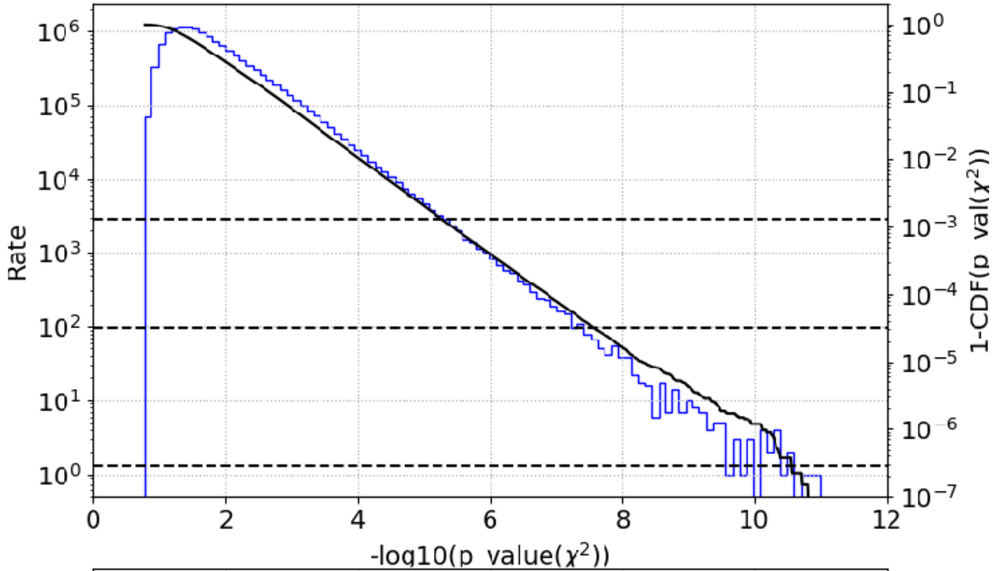
- Temporal and spatial coincidence
- Best position of the coincidence

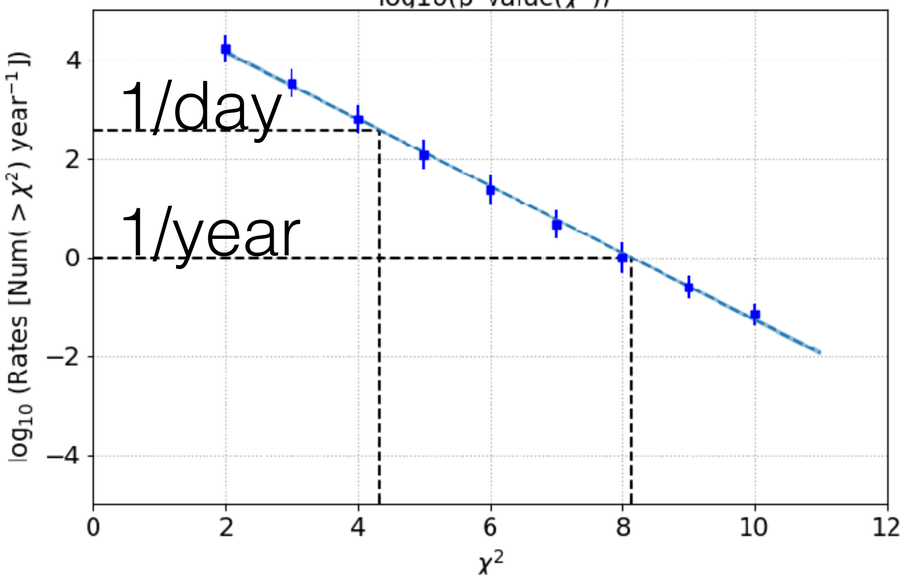
$$\lambda(\vec{x}) = \begin{cases} \sum_{i=1}^{2} (\ln(\mathcal{S}_i(\vec{x})) - \ln(\mathcal{B}_i)) & 1\gamma, 1\nu \\ \sum_{i=1}^{N} (\ln(\mathcal{S}_i(\vec{x})) - \ln(\mathcal{B}_i)) + \sum_{i=2}^{N-1} \sum_{j=i+1}^{N} \ln T_{HWC} - \ln|\Delta T_{ij}| & 1\gamma, > 1\nu. \end{cases}$$

- Combine p values using Fisher's method

$$\chi^2 = -2 \ln[p_\lambda \, p_{HWC} \, p_{cluster} \prod_{i}^{n_\nu} p_{i_{IC}}]$$

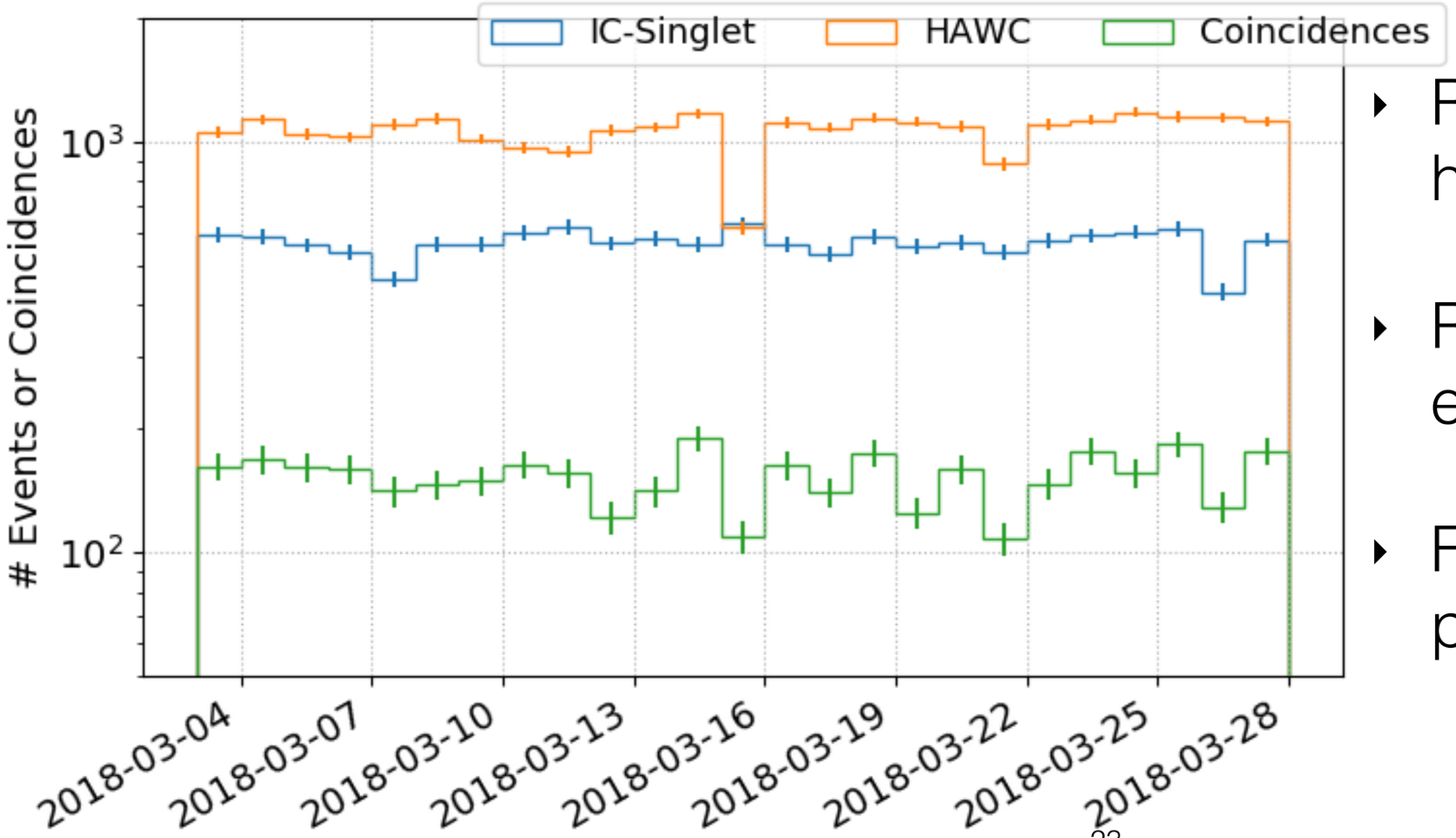
- Account for different DoF for different multiplicities, and use -log[$p(\chi^2 > \chi^2_{obs})$] to rank coincidences





Coincidence alert: IC+HAWC

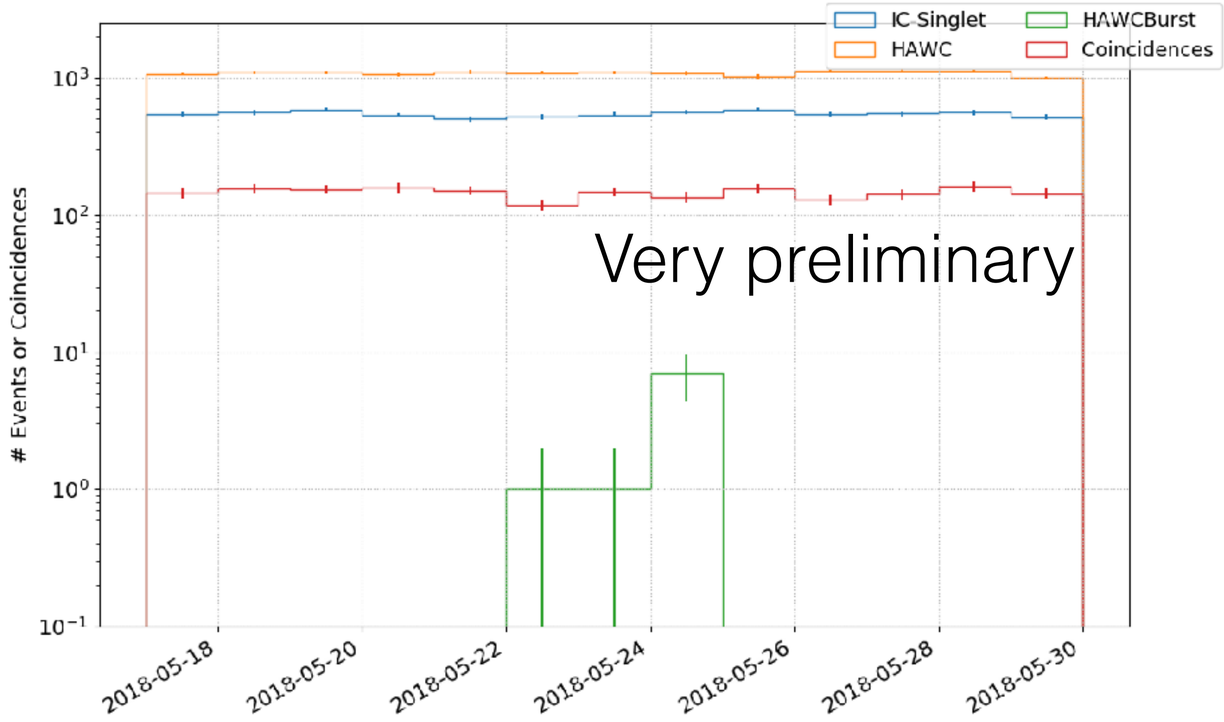
- Moving to **real-time** analysis!



- Receiving ~1000 HAWC daily hotspot per day
- Receiving ~600 IC track-like events per day
- Finding ~150 coincidences per day

VHE γ Notices

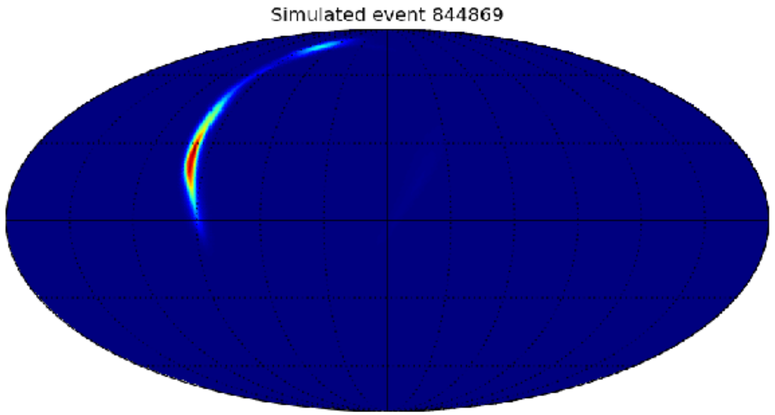
- Add HAWC's own GRB *sub-threshold* triggers
- studying FARs
  - internal a few/day
  - send to GCN the 1/year events



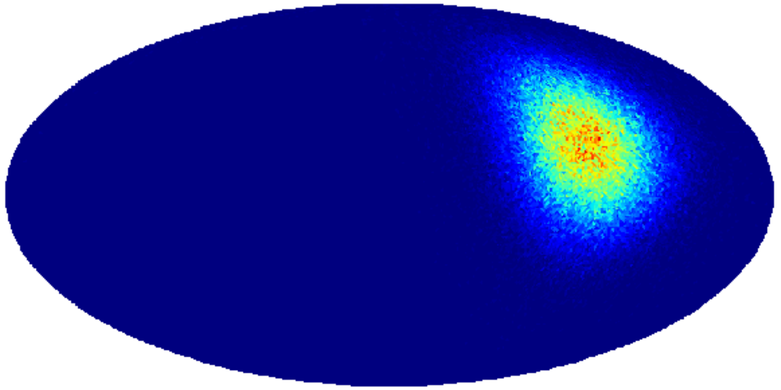
Outlook

- New GCN channel for **IceCube-HAWC alerts**
- New (separate) GCN channel for **HAWC GRB-like notices** (similar to the HESE or EHE IceCube notices)

Coincidence alert: γ+GW



⊗



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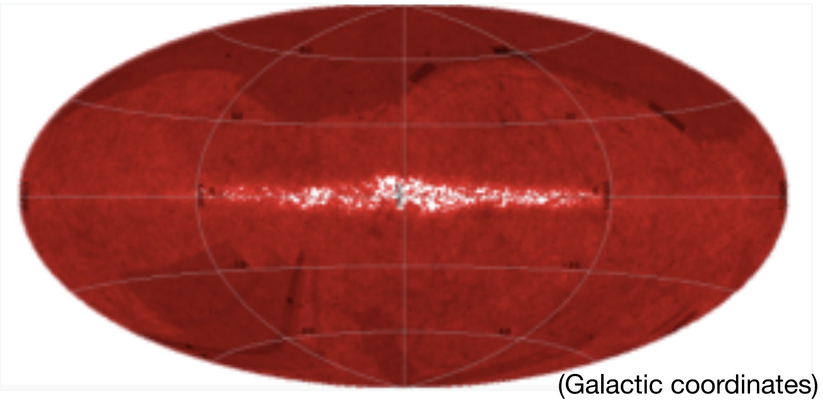


(Galactic coordinates)

LIGO simulated event | **HAWC exposure per 4 min** | **GLADE galaxy catalog**

http://aquarius.elte.hu/glade/

- Joint likelihood ratio as a ranking statistics

$$\lambda(\vec{x}_S) = \frac{H_1^{GW}(\vec{x}_S) \cdot H_1^{Gal}(\vec{x}_S) \cdot \prod_j H_1^{\gamma_j}(\vec{x}_S)}{H_0^{GW} \cdot H_0^{Gal} \cdot H_0^{\gamma}} \quad \longrightarrow \quad p_{spatial} = \int_{\lambda}^{\infty} P_{BG}(\lambda')d\lambda'$$

- Fisher's method to combine p-values

$$\chi^2 = -2 \cdot ln(p_{spatial} \cdot p_{gw} \cdot p_{\gamma}) \quad \longrightarrow \quad \boxed{p_{GW\gamma} = \int_{\chi^2}^{\infty} P_{BG}(\chi'^2)d\chi'^2}$$

Coincidence alert: γ+GW

Proposed scheme

HAWC TRIGGER

- Real-time GRB search
- 0.2,1,10,100s

GW TRIGGER

GALAXY CATALOGUE

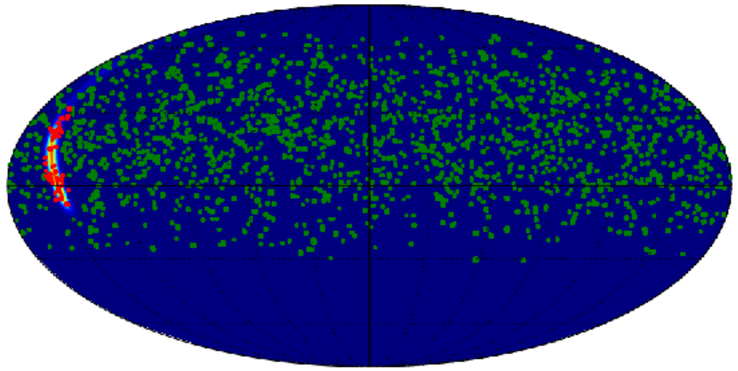
TEMPORAL COINCIDENCE (500s WINDOW)

SPATIAL COINCIDENCE

HAWC candidate is in the 90% GW area?

LIKELIHOOD COMPUTATION

P-VALUE OF THE DETECTION

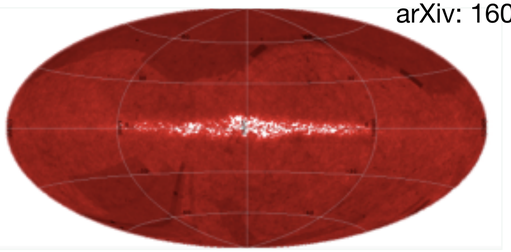


$$\lambda(\vec{x}_S) = \frac{H_1^{GW}(\vec{x}_S) \cdot H_1^{Gal}(\vec{x}_S) \cdot H_1^{\gamma_j}(\vec{x}_S)}{H_0^{GW} \cdot H_0^{Gal} \cdot H_0^{\gamma}}$$

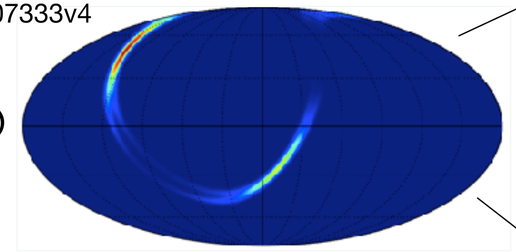
$$\chi^2 = -2 \cdot ln(p_{spatial} \cdot p_{gw} \cdot p_{\gamma})$$

$$p_{GW\gamma} = \int_{\chi^2}^{\infty} P_{BG}(\chi'^2) d\chi'^2$$

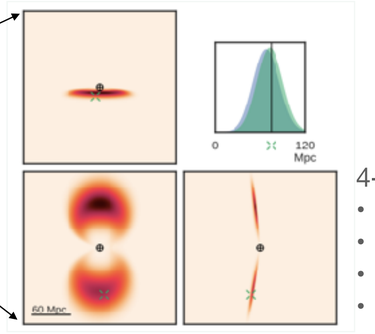
arXiv: 1603.07333v4



GLADE: galaxy distribution



LIGO-Virgo map

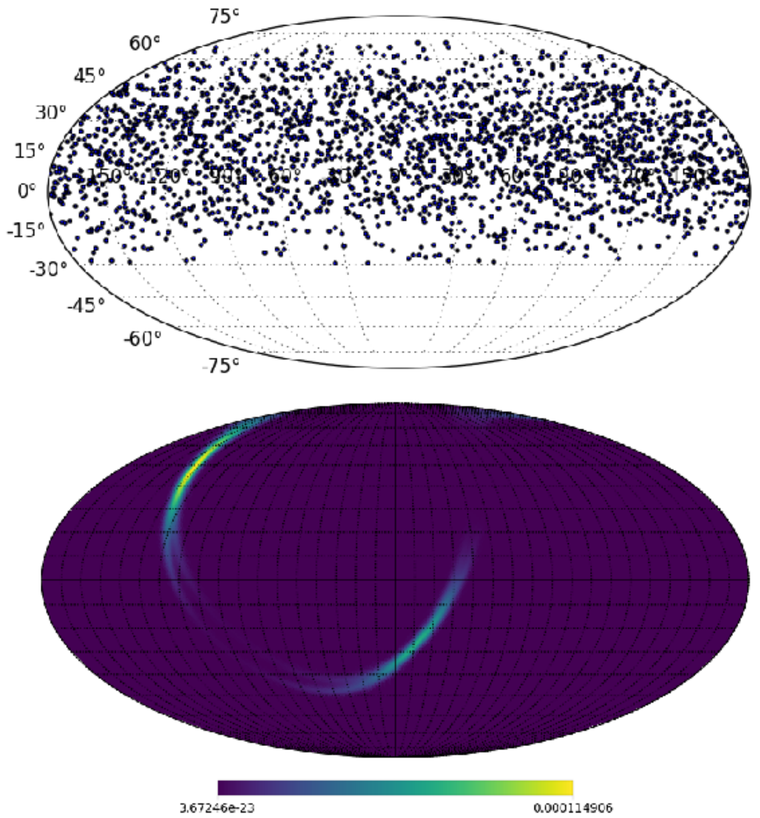


4-layers information:

- the posterior probability ρ
- Distance estimate
- Dispersion
- Normalization

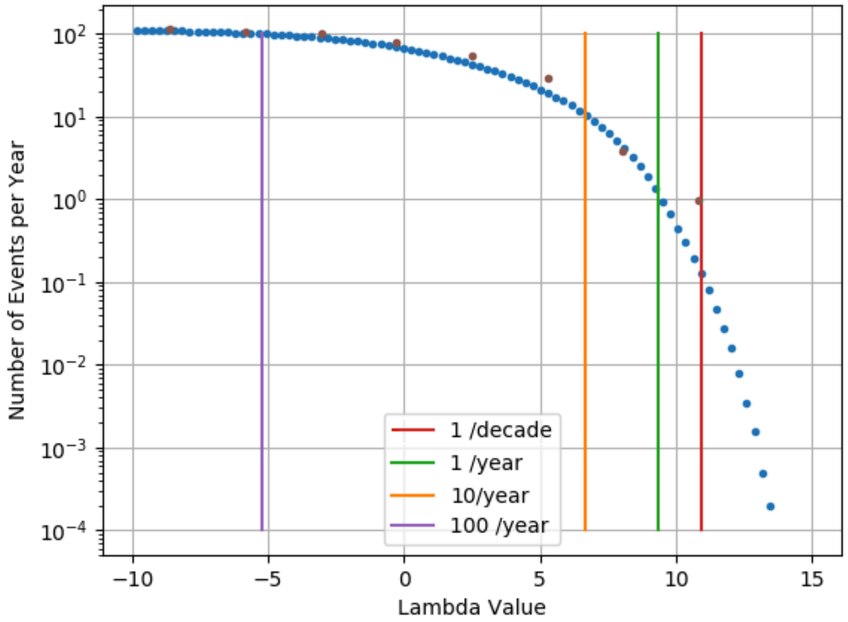
Outlook

- Running on:
  - HAWC GRB-like *sub-threshold* triggers & HAWC *hotspots*
  - LIGO-Virgo simulations of NS mergers for O2
- Writing two proposals:
  - Run over O1 and O2 archival data
  - Real-time analysis for O3
- Analyzing GW+(Swift *sub-sub-threshold*) coincidences

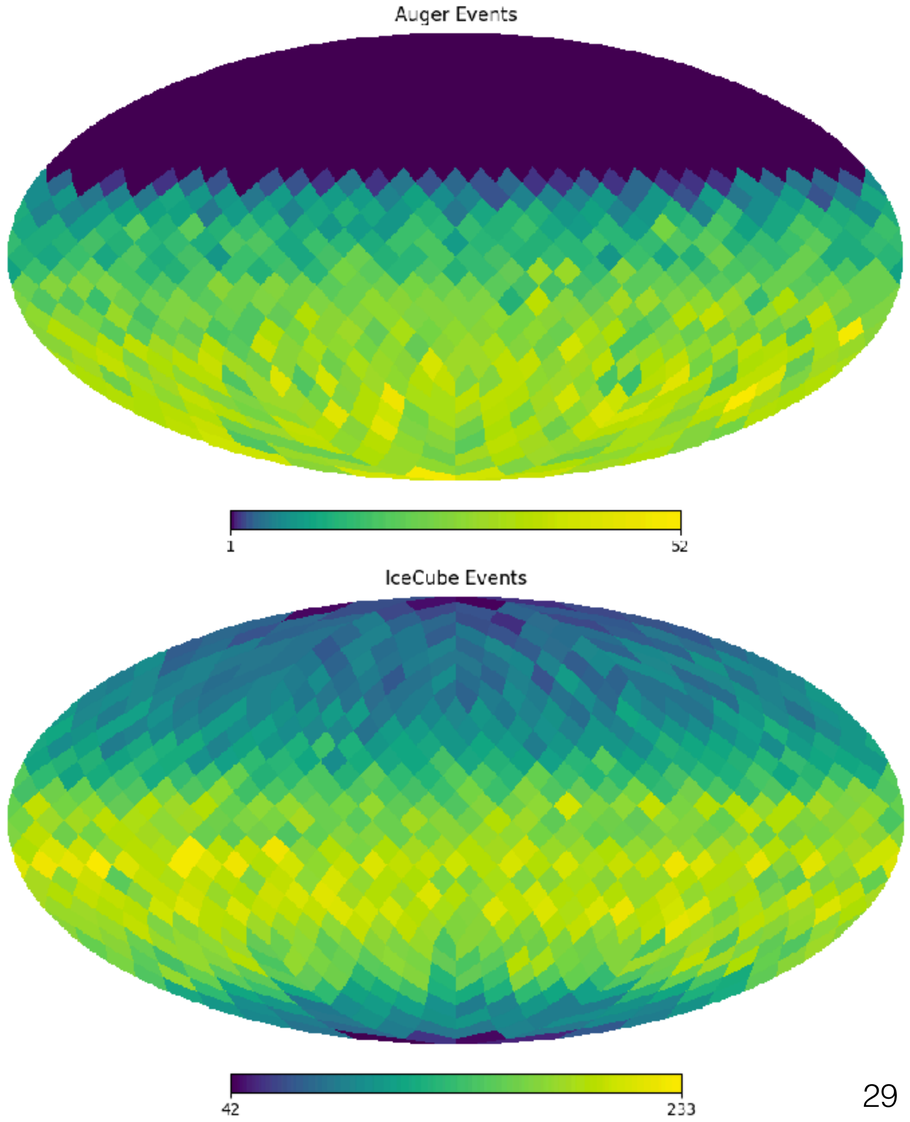


Coincidence alert: IC+Auger

- Analysis of sub-threshold archival data:
  - Auger: vertical (i.e., 60°) CRs above 3 EeV
  - IC: public IC-40 and IC-59



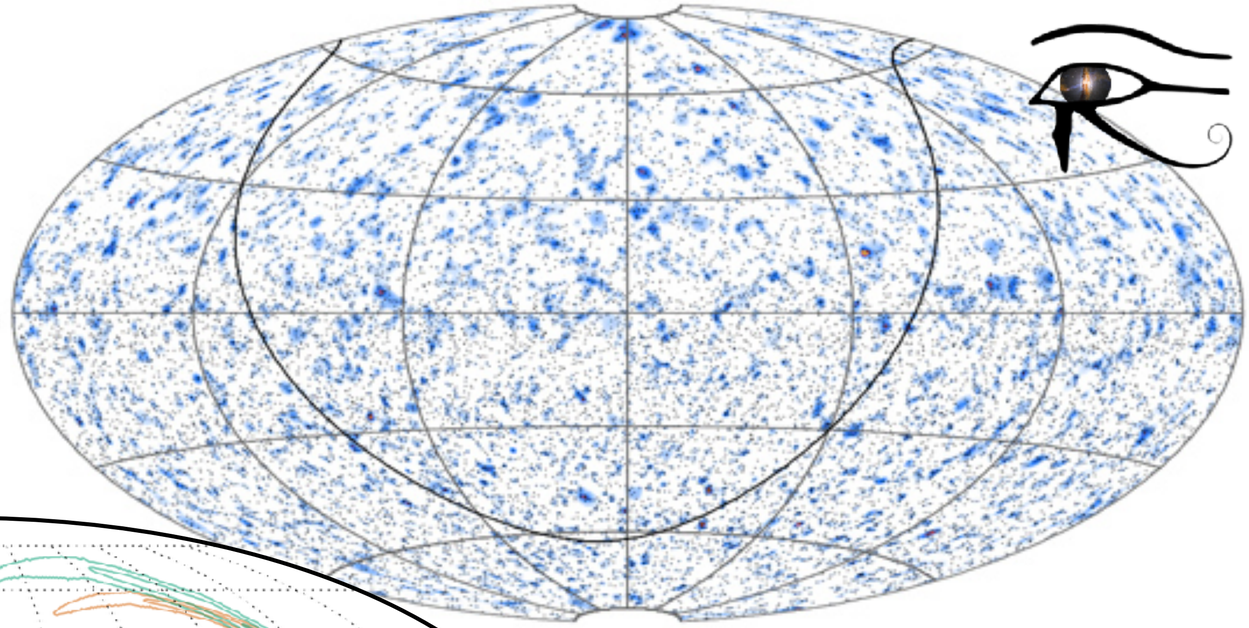
- Outlook: implement the analysis in real-time

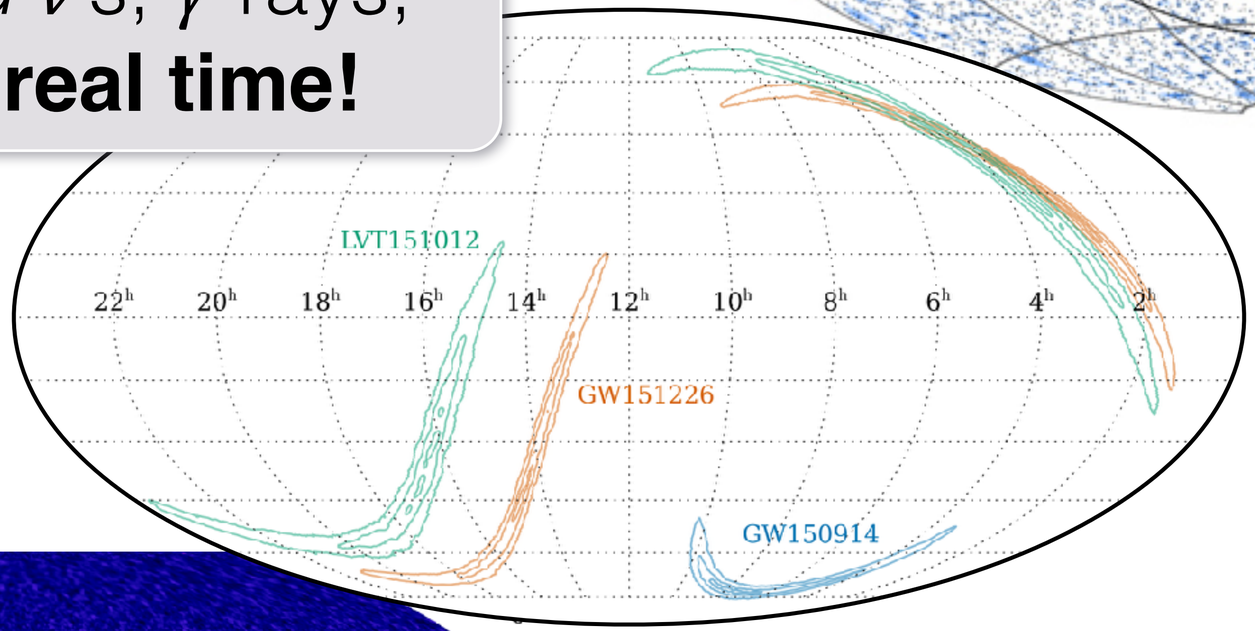


Prospects

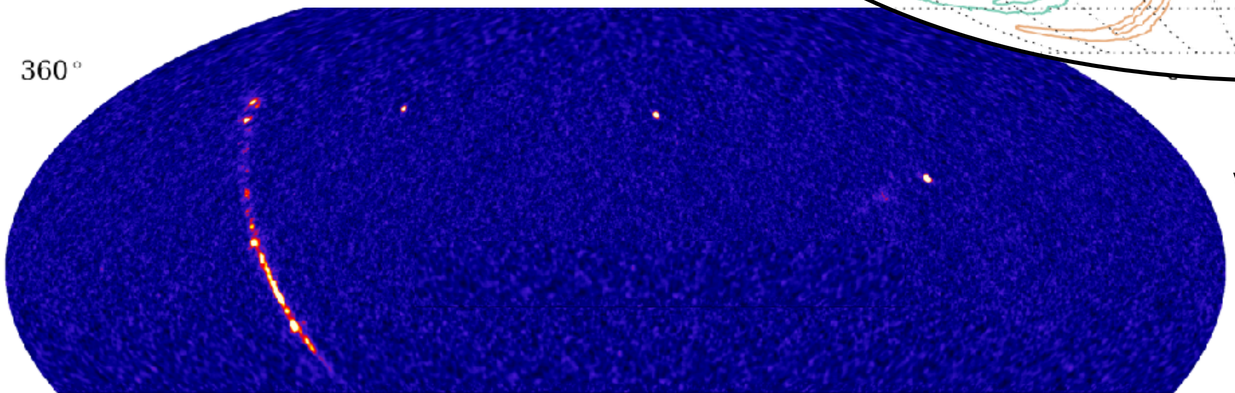
Sub-threshold ν's, γ rays, and GWs in **real time!**

HE ν's





GW



VHE γ rays

AMON progress

- AMON has made a significant progress toward **real-time** and archival analyses
- AMON server is online
- New high-uptime dual hardware is **fully operational**
- Ongoing real-time streams from IceCube
- IceCube's HESE and EHE **notices** distributed via GCN (public!)
- More real-time electronic **alerts** via AMON/GCN (e.g., IceCube's EHE, OFU) and incoming event streams (e.g., Auger and HAWC)

Conclusions

- Current generation detectors are fantastic!
- Next generation detectors will be yuuge!
- **Multimessenger** is the best way to make progress toward understanding the messages!

Thank you!

Image by Fabian Schüssler