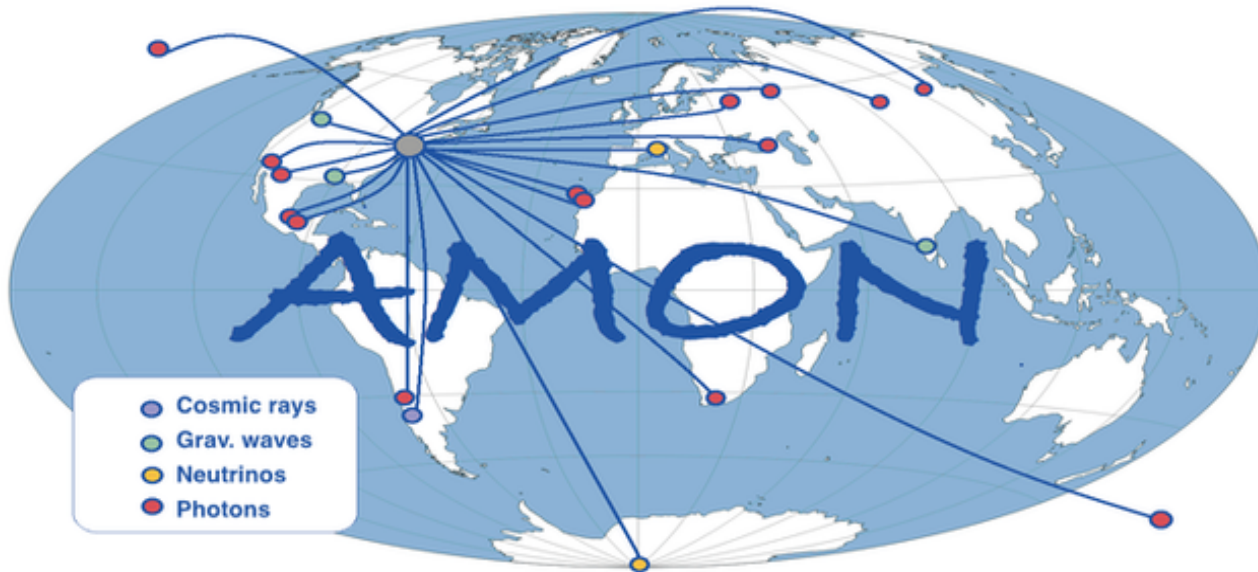


# AMON : Realtime Multi-Messenger Alerts / Analyses ?



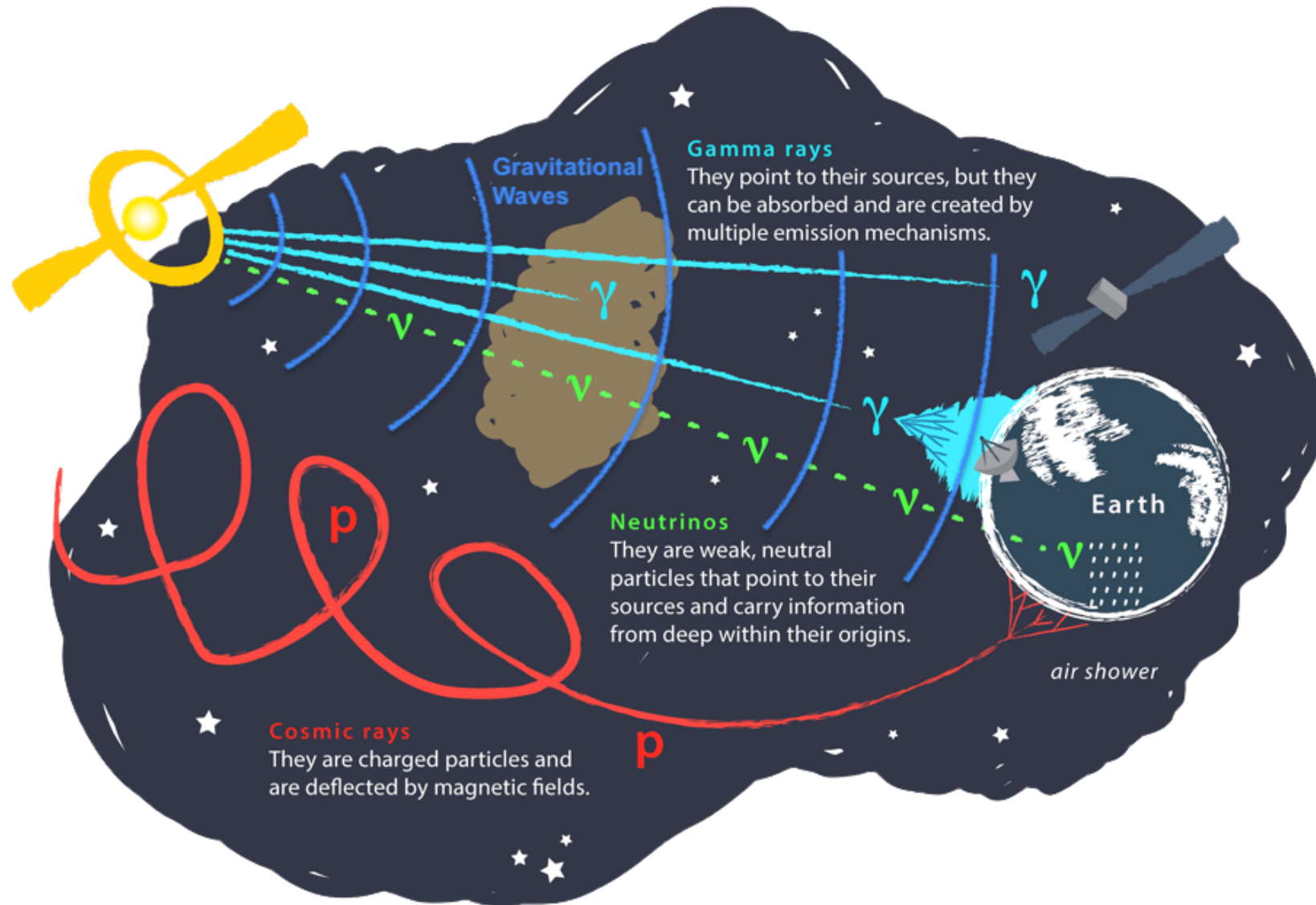
AMON  
Astrophysical Multimessenger Observatory Network



Thierry PRADIER  
IPHC (Strasbourg)

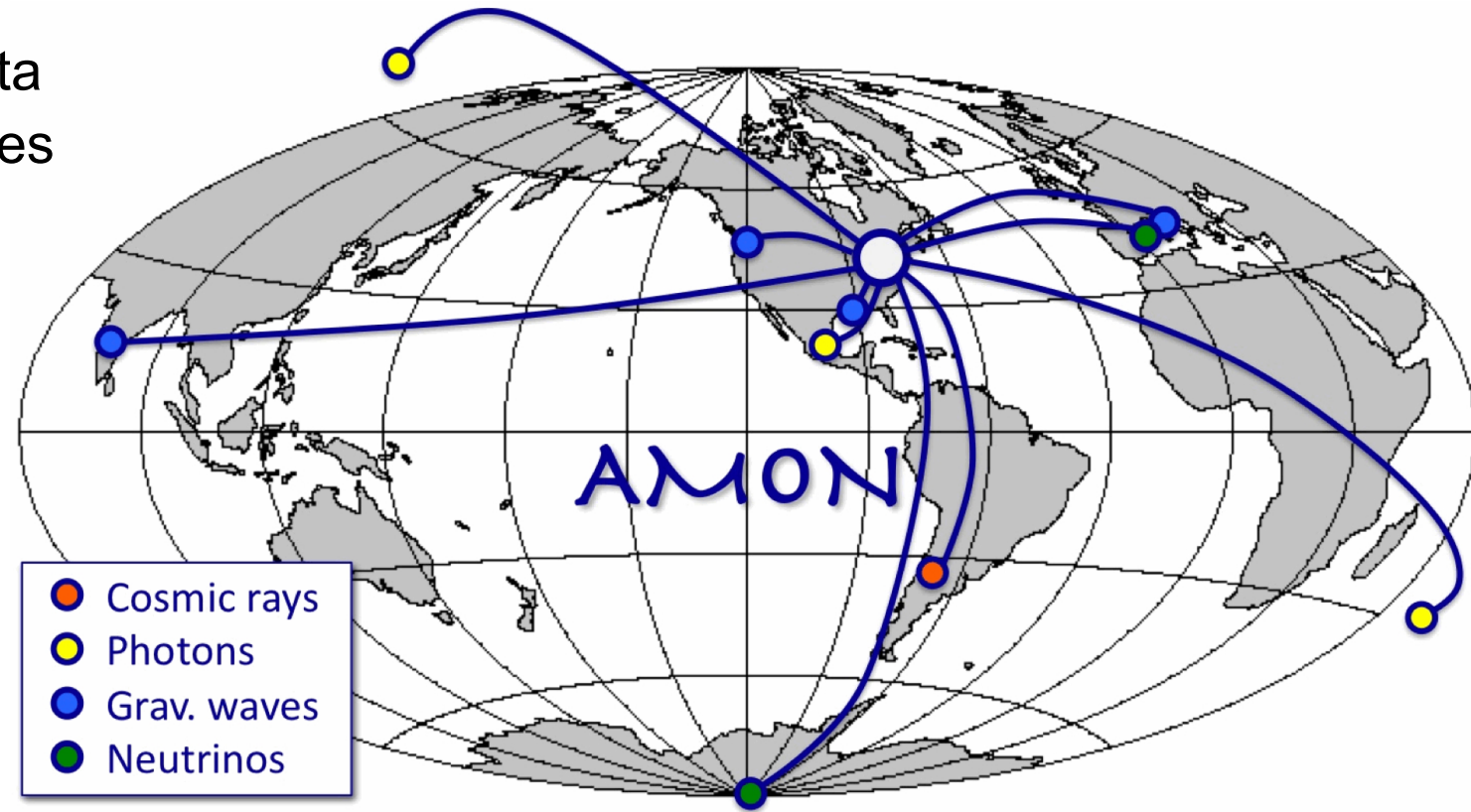


# Astrophysical Multi-messenger Observatory Network



# Astrophysical Multi-messenger Observatory Network

- AMON links high-energy astrophysical observatories into a single virtual system
- AMON framework enables:
  - Real-time sharing of sub-threshold data between multi-messenger observatories
  - Real-time and archival searches for coincident signals
  - Prompt distribution of electronic alerts for follow-up observations



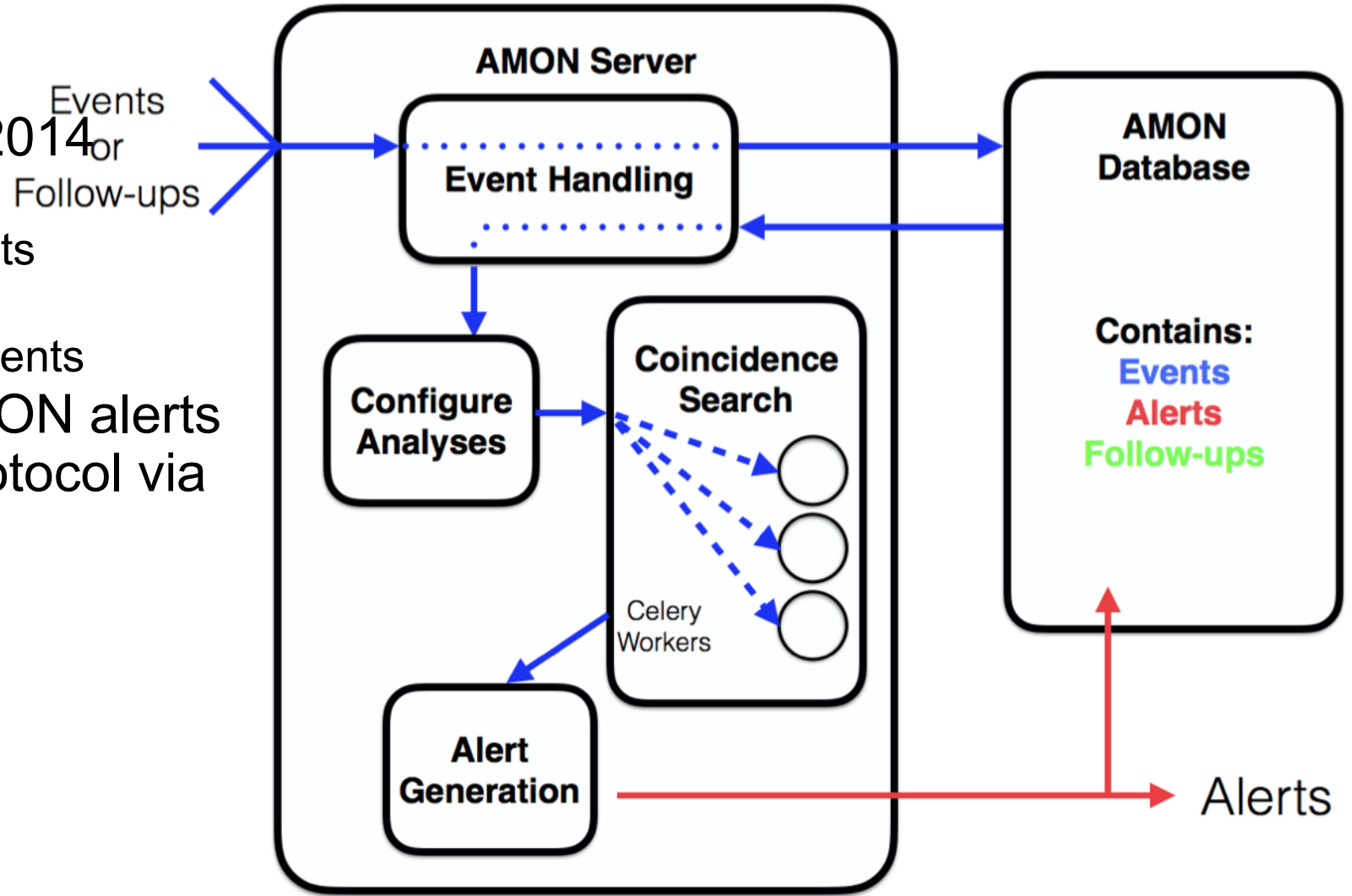
# AMON Infrastructure

## Application server

- Running stably since 08/2014<sup>or</sup>
- Python/Twisted
- Accepts HTTP POST requests
- connections using TLS
- Tested with simulated/real clients
- Started issuing public AMON alerts using VOEvent format/protocol via GCN in April 2016

## Hardware

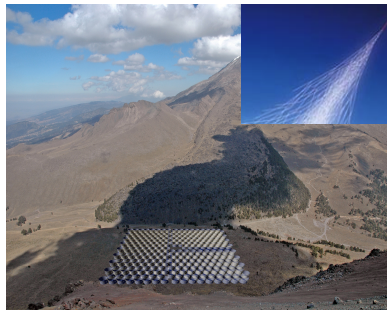
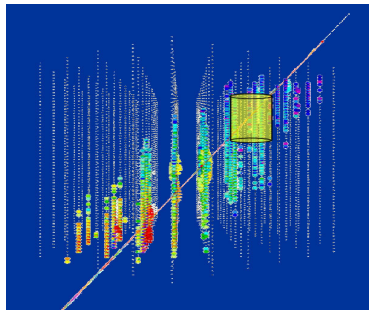
- Two high-uptime servers
- Deployed at Penn State
- Physically and cyber secure
- Fully redundant systems



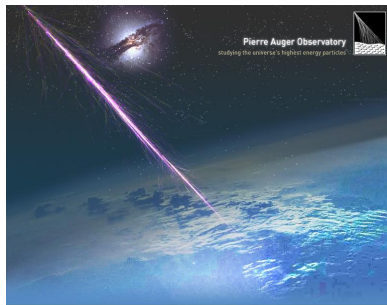
# Network: Triggering and Follow-up

## Triggering Observatories:

- Provide sub-threshold candidate events to AMON in realtime
- Have large FOV and high duty cycles



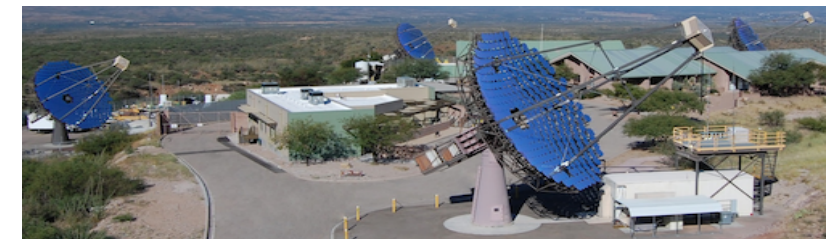
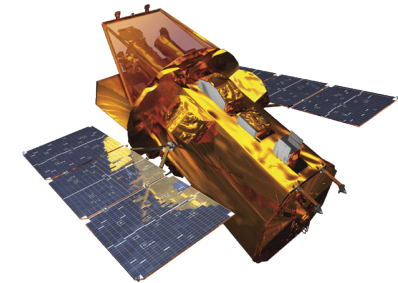
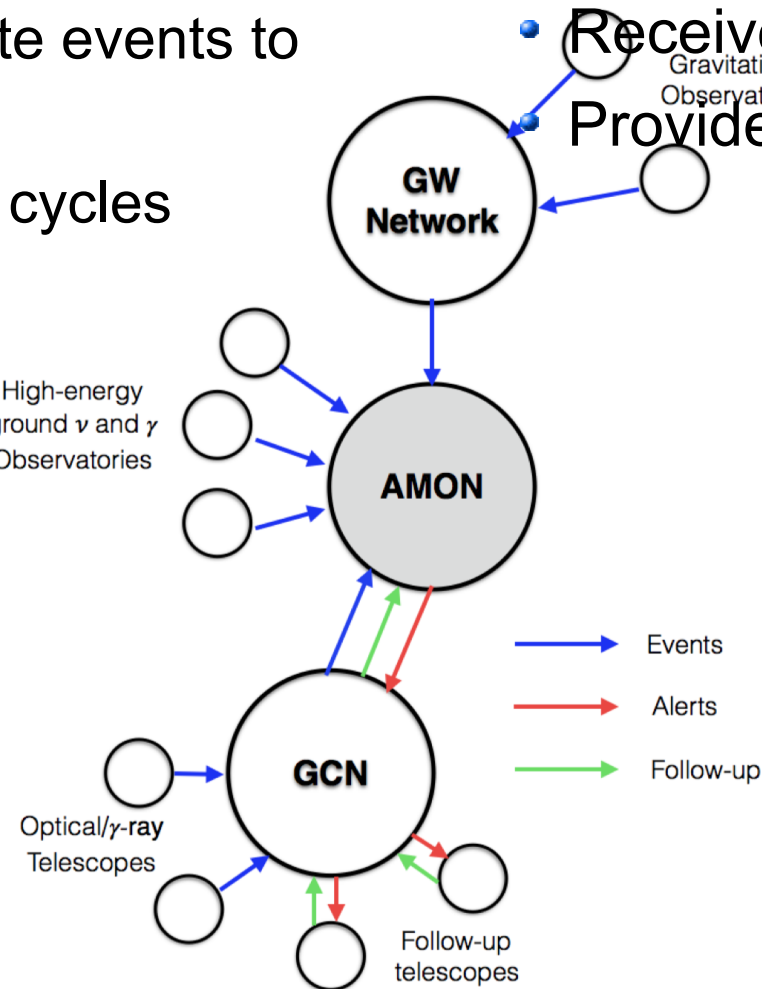
High-energy ground  $\nu$  and  $\gamma$  Observatories



Pierre Auger Observatory  
observing the universe's highest energy particles

## Follow-up Observatories:

- Receive and respond to AMON alerts
- Provide afterglow or delayed feedback



# Partner Observatories

Partner observatories	Stream content/format	TLS certificate	Test stream (fake data)	Test stream (real data scrambled)	Real data stream
IceCube singlet	✓	✓	✓	✓	In progress
IceCube HESE	✓	✓	✓	✓	✓
IceCube EHE	✓	✓	✓	✓	✓
IceCube OFU	✓	✓	✓	✓	✓
ANTARES	✓	✓	✓	✓	✓
Pierre Auger	✓	✓	✓	✓	✓
FACT	✓	✓	✓	✓	✓
HAWC	✓	✓	✓	✓	✓
VERITAS	In progress				
Swift BAT	✓	Not needed	Not needed	Not needed	✓
Fermi LAT	✓	Not needed	Not needed	Not needed	✓

# Current Realtime Alerts

Started issuing “pass-through” alerts of significant IceCube track-like events in April 2016

- Sent via connection to GCN
- Public Alerts (receivable by all)
  - High Energy Starting Events (HESE)
  - Extremely High Energy (EHE)
- AMON GCN page
- <https://gcn.gsfc.nasa.gov/gcn/amon.html>

Stream	HESE	EHE	Multiplets
Description	Starting tracks	Very high energy through-going tracks	~1TeV multiple tracks
Angular Error	> 0.4°	> 0.2°	~0.5°
Rate	~ 4/year	~ 4 - 6 / year	~ 2-6 / year

“The IceCube Realtime Alert System”, *Astroparticle Physics*, 92, 30-41 (2017)

# Follow-up Campaigns

Follow-up campaigns of some of the IceCube high-energy  $\nu$ 's performed in 2016:

Alert name/type	161103/HESE	160814A/HESE	160806A/EHE	160731A/HESE	160731A/EHE	160427A/HESE
RA/DEC (rev1) RA/DEC (rev2)	[40.87°, 12.62°] [40.83°, 12.56°]	[199.31°, -32.02°] [200.25°, -32.35°]	[122.80°, -0.73°] [122.81°, -0.81°]	[215.11°, -0.46°] [214.54°, -0.33°]	[215.09°, -0.42°] [214.54°, -0.33°]	[239.66°, +6.85°] [240.57°, +9.34°]
Resolution	0.42° (50%), 1.23° (90%) 0.65° (50%), 1.10° (90%)	0.48° (50%), 1.49° (90%)	0.11° (50%)	0.42° (50%), 1.23° (90%) 0.35° (50%), 0.75° (90%)	0.17° (50%), 0.8° (90%) 0.35° (50%), 0.75° (90%)	1.6° (50%), 8.9° (90%) 0.6° (90%)
ST or Signalness	0.30	0.12	0.28	0.91	0.85	0.92
Latency: Event t0 to GCN alert sending	40 s	42 s	37 s	41 s	54 s	81 s
Followups						



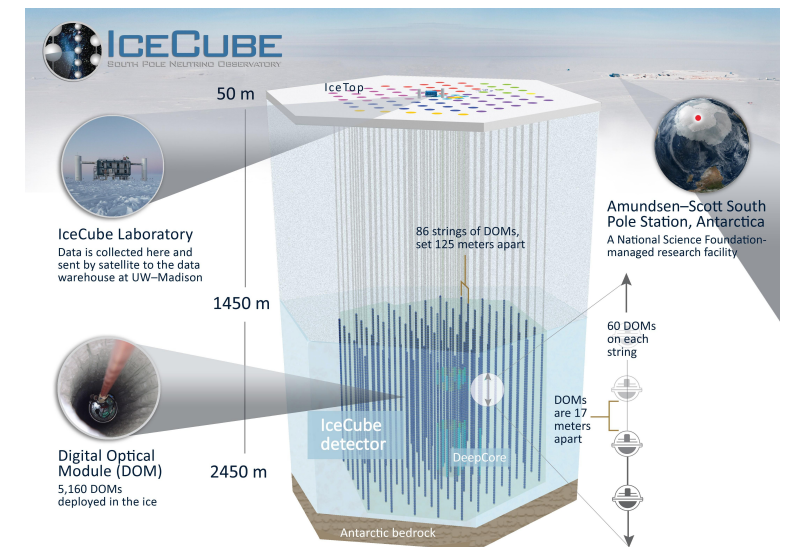
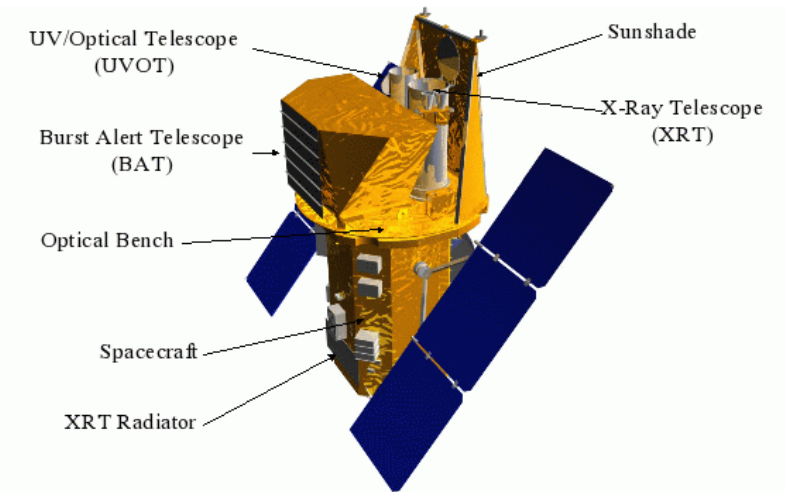


# Swift Follow-up of High-Energy Neutrinos

- **Swift follow-up campaigns:**

- Powerful approach to search for luminous EM counterparts to high-energy cosmic neutrinos
- Set useful constraints on associated transients
- Use XRT and UVOT telescopes

Under NASA *Swift* Cycle 12 Guest Investigator program

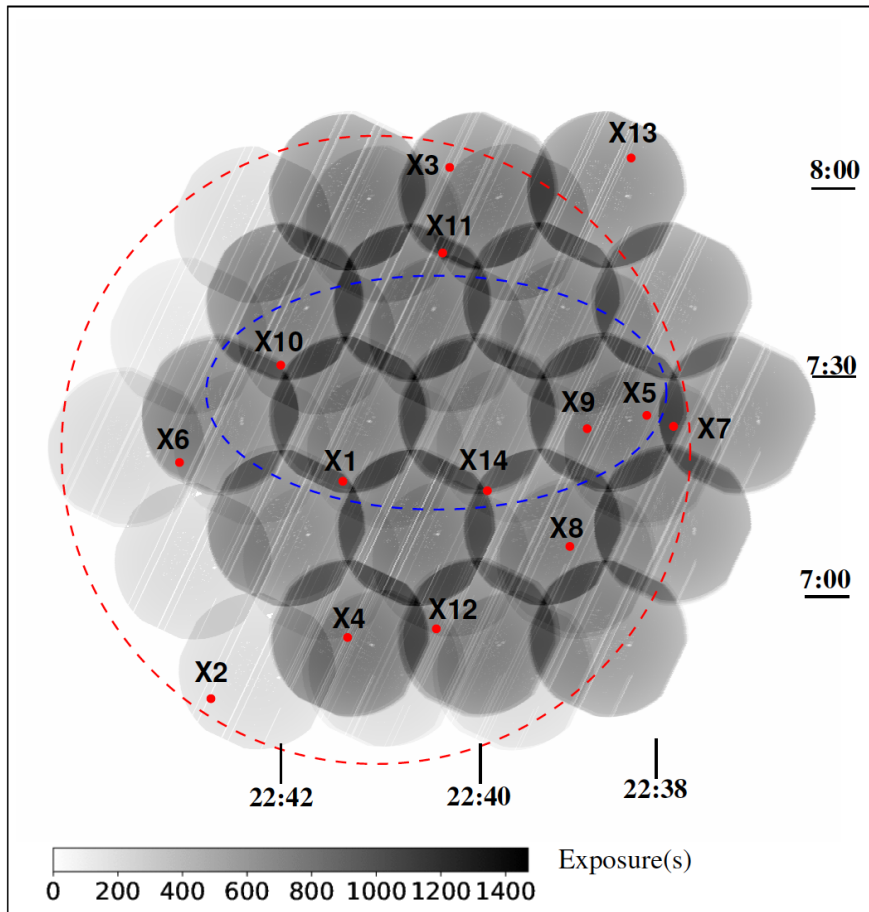


# Swift Follow-up of High-Energy Neutrinos

Events	Stream	Charge (p.e.)	Signalness*	R <sub>50</sub> Rev0	R <sub>90</sub> Rev0	R <sub>50</sub> Rev1	R <sub>90</sub> Rev1
IceCube-160731A	HESE/EHE	15814	0.91	0.42° (HESE) 0.17° (EHE)	1.23° (HESE)	0.35°	0.75°
IceCube-161103A	HESE	7546	0.30	0.42°	1.23°	0.65°	1.1°
IceCube-170312A	HESE	8858	0.78	0.42°	1.23°	-	< 0.5°
IceCube-170321A	EHE	6214	0.28	0.32°	-	-	1.2°
IceCube-170922A	EHE	5785	0.56	0.25	-	-	-0.8°+1.3°, -0.4°+0.7°
IceCube-171106A	EHE	15456	0.75	0.25	-	-	-0.5°+0.7°, -0.25°+0.35°

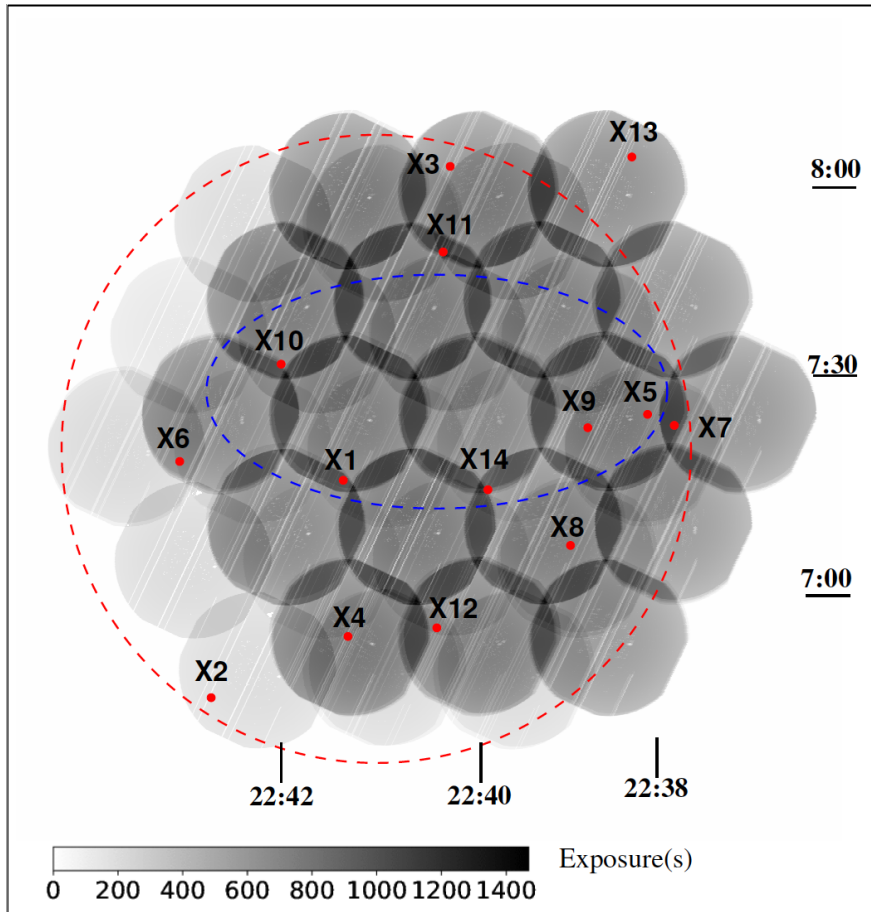
\* Signalness for EHE is an estimate probability that the event is due to an astrophysical neutrino. It is called "signal\_trackness" for HESE reflecting the likelihood for the neutrino to be signal-like/track-like.

# Swift Observations of IceCube-171106A



- Observations taken 11.5 to 62.0 ks after the neutrino trigger
- Covered 2.1 deg<sup>2</sup>
- Covered the neutrino revised  $r_{90}$  error region
- Collected ~750 s per field of PC mode data per tile
- 14 X-ray sources were detected
  - 5 inside the refined neutrino localization

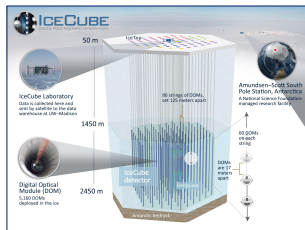
# Swift Observations of IceCube-171106A



- X5 matches to 87GB 223537.9+070825 (5BZQJ2238+0724 in BZcat), which is a flat-spectrum radio quasar and known blazar, not previously reported to emit in X-rays
- X9 has no X-ray counterpart
- X14 has position consistent with ROSAT Faint Source Catalog Object 1RXS J223951.8+071132
- More observations requested

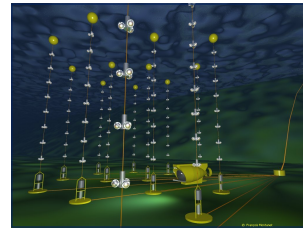
# New Realtime Alerts: Coming Soon

## Realtime - coincident alerts

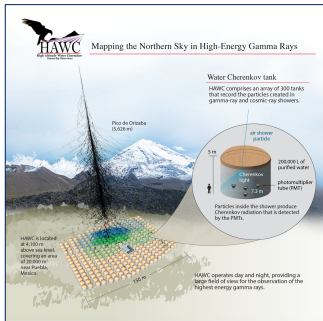


IceCube

Neutrinos  
GeV - PeV



ANTARES



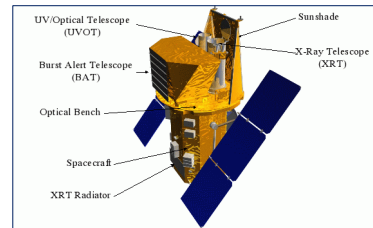
HAWC  
TeV



FACT  
100 GeV - 10 TeV



Fermi  
MeV - GeV



Swift BAT  
15 - 150 KeV

- AMON infrastructure ready to go
  - “Pass-through” alerts successfully brokered
  - Preliminary analyses running in realtime on scrambled/fake data
- What needs to happen
  - Cross-collaboration tuning and approval of analyses

# IceCube Sub-Threshold Data

Data proposed for AMON	Through-Going Tracks
FOV	All Sky
Position Error	$\sim 1^\circ$
Rate	100's/day
Latency	$\sim 1$ min

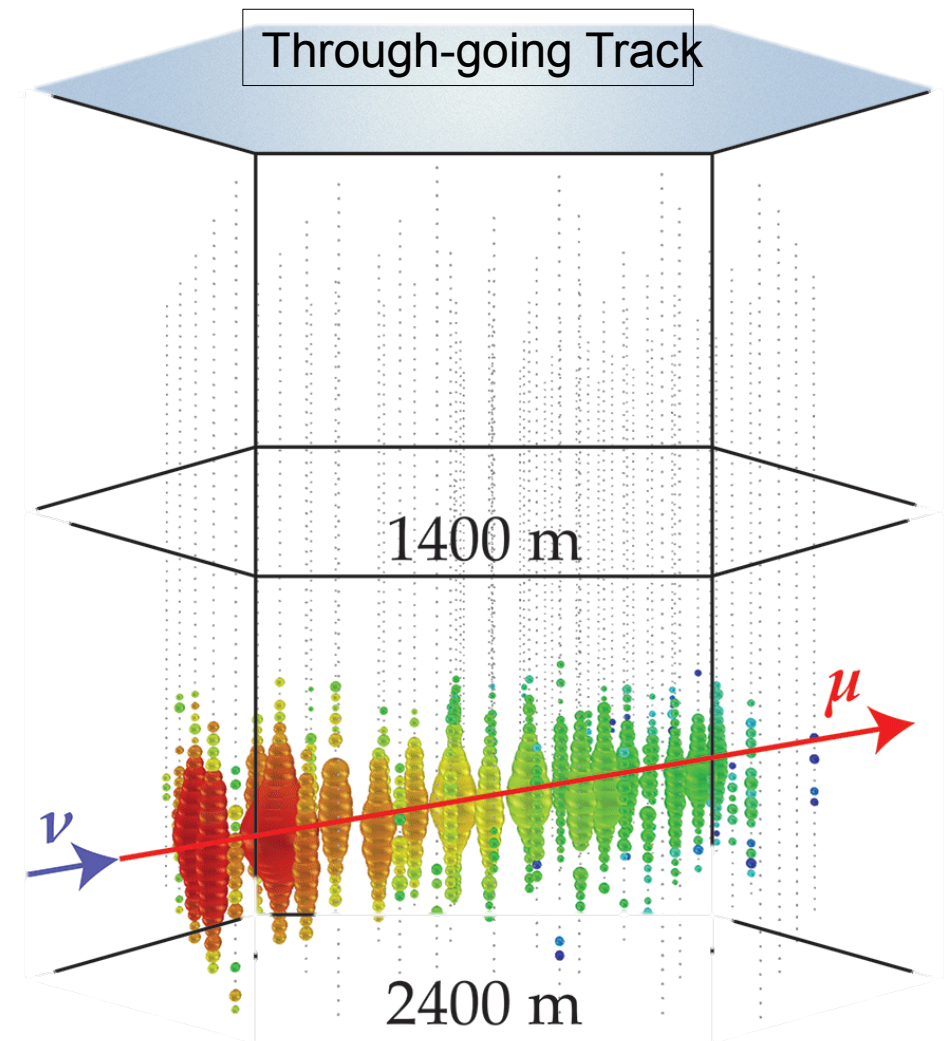
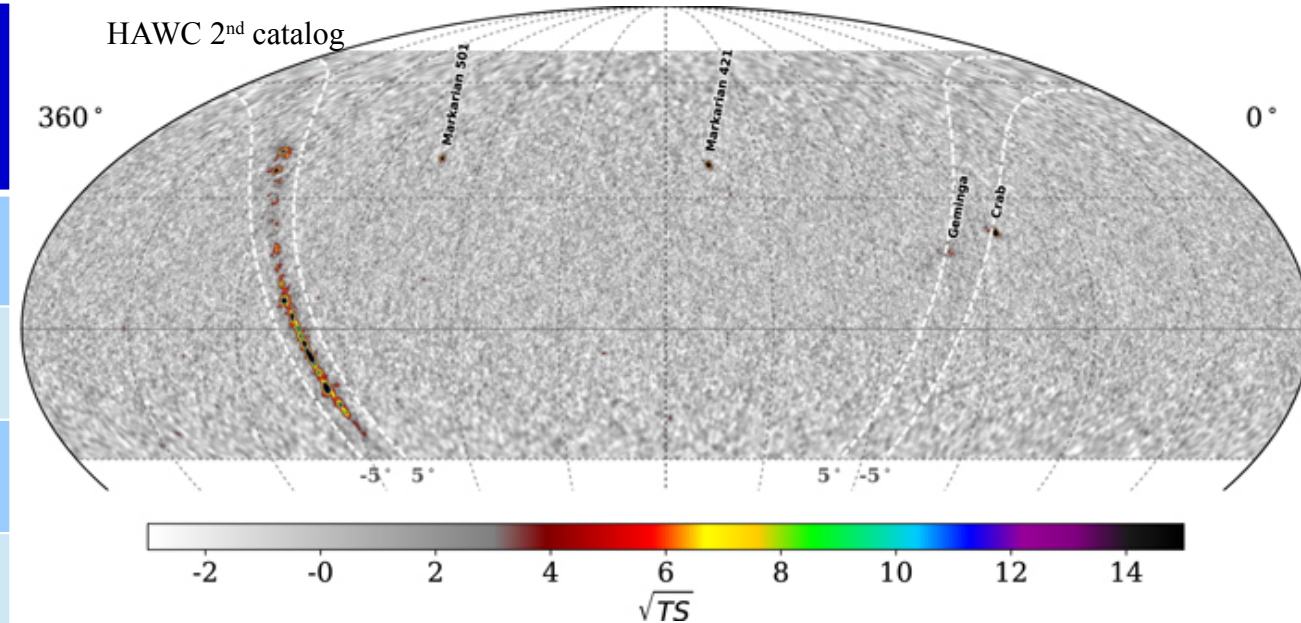


Illustration: APS/Joan Tycko; Neutrino event: IceCube

# HAWC Hotspots

Data proposed for AMON	Sub-threshold signals in daily maps of TeV $\gamma$ 's
FOV	~15% sky
Position Error	~ 0.1°
Rate	100's/day
Latency	hours



[AstrophysJ. 843 \(2017\) 1, 40](#)

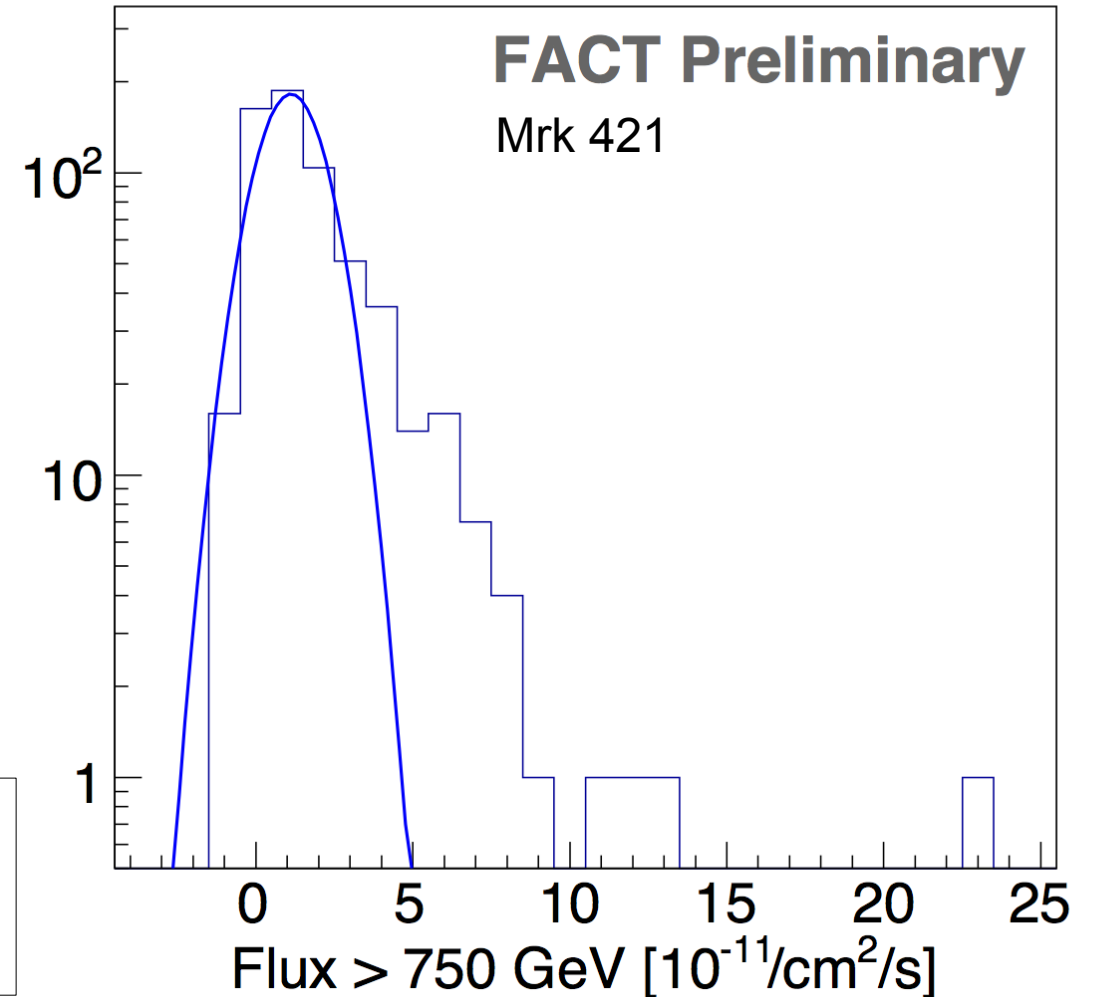
HAWC daily maps  
Duration 6-7 hours

# FACT Flares

Data proposed for AMON	Tev -flares from a few bright sources in 20 minute bins
FOV	Small
Position Error	Known locations
Rate	?
Latency	~ hour

## Define a flare

Excess Flux seen above “normal” flux in 20 minute bins  
Right of the Gaussian curve is considered a flare



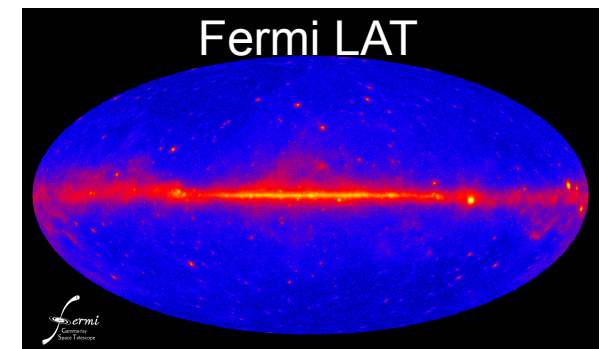
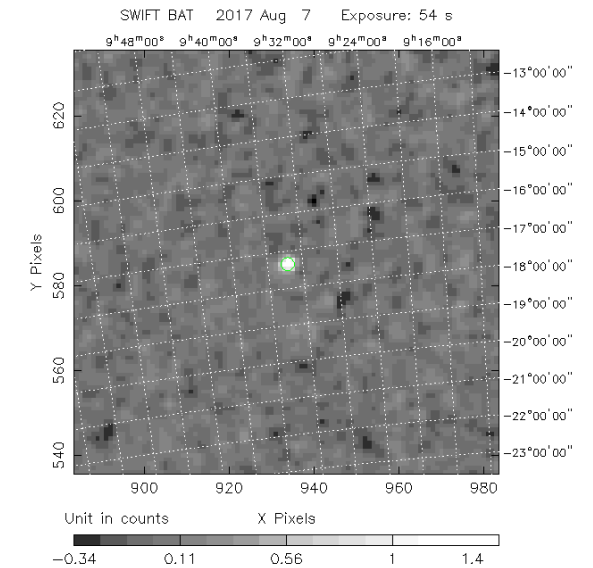
Credit: Daniela Dorner



# Swift BAT – Fermi LAT

	Swift BAT	Fermi
Data proposed for AMON	Low significance peaks found in onboard created images	>100 MeV single $\gamma$ 's
FOV	~15% sky	~15% sky
Position Error	~ 4 arcminutes	~ 0.1° - few°
Rate	100's/day	~ 10 <sup>4</sup> / day
Latency	hours	hours

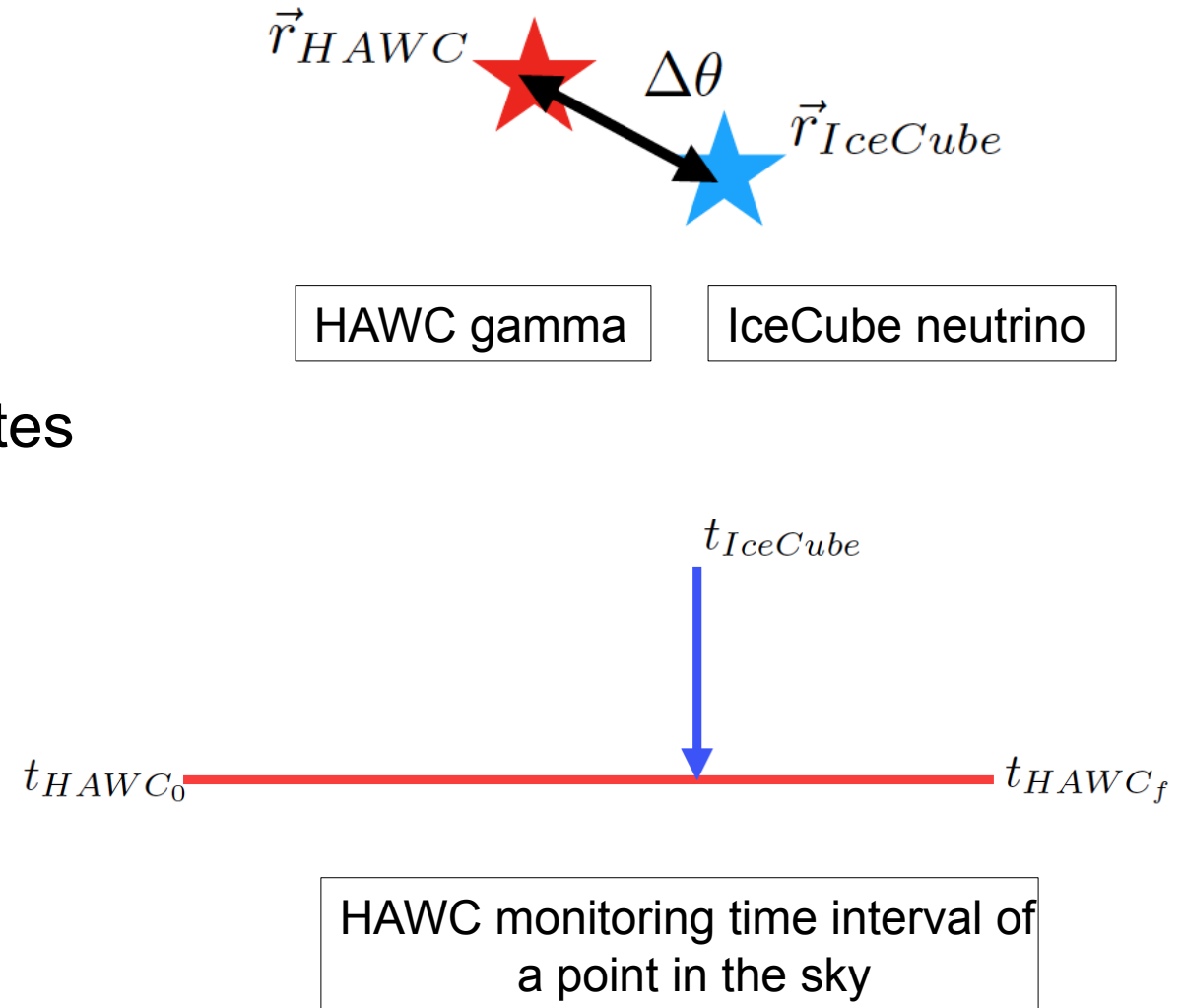
## GRB 170807A



[https://gcn.gsfc.nasa.gov/notices\\_s/1766821/BAL](https://gcn.gsfc.nasa.gov/notices_s/1766821/BAL)

# Example Correlation Analysis: IceCube-HAWC

- Spatial correlation: e. g.  $\Delta < 3.5^\circ$
- Temporal correlation:  $t_i < t_{\text{IceCube}} < t_f$
- Define test statistic
- Study background and false positive rates
- Define threshold



# IceCube-HAWC: Test Statistic (example)

- Maximize to find best fit position of the coincidence:

- $PSF$  PDF of the messenger source direction
- $B_i$  Background Term
- $\Delta T_{ij}$  Time difference between neutrinos
- $T_{HAWC}$  Duration of the HAWC event transit

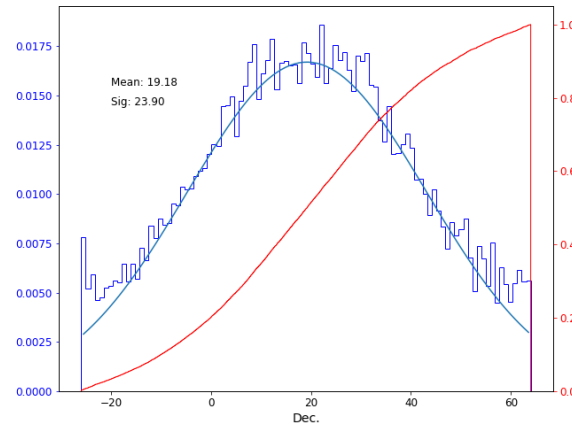
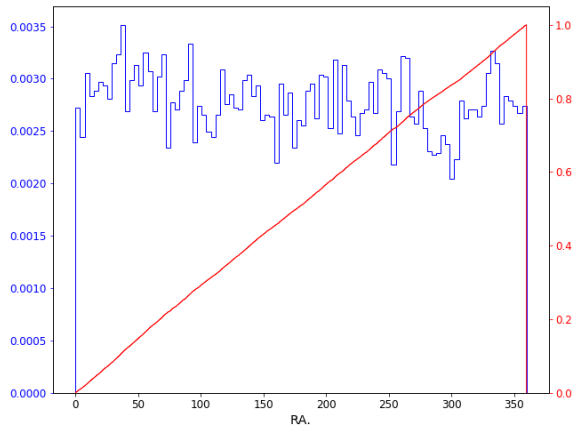
$$\Lambda = \begin{cases} 1\gamma + 1\nu & : \sum_{i=1}^2 \ln \frac{PSF_i}{B_i} \\ 1\gamma + > 1\nu & : \sum_{i=1}^N \ln \frac{PSF_i}{B_i} + \sum_{i=2}^{N-1} \sum_{j=i+1}^N \ln \frac{T_{HAWC}}{|\Delta T_{ij}|} \end{cases}$$

- Combine p-values using Fisher's method:  $\chi^2 = -2 \ln (p_\Lambda p_{HAWC} p_{cluster} p_{IC})$

# Test Statistic: Background Terms

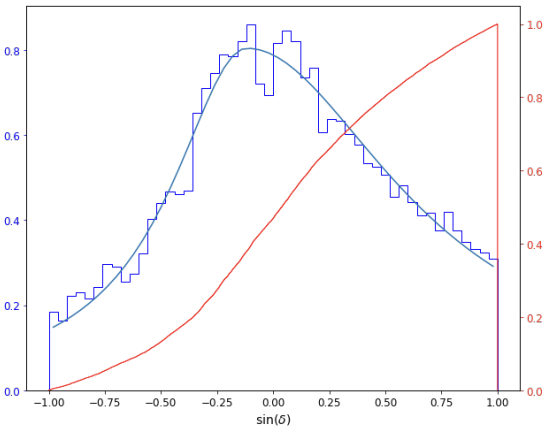
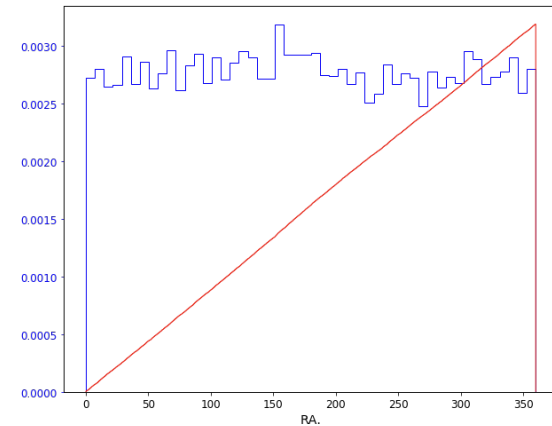
## HAWC event distribution

$$B_{\text{HAWC}} = f(\delta)g(\alpha)$$
$$g(\alpha) = \text{constant}$$
$$f(\delta) \approx \text{Gaussian}$$



## IceCube event distribution

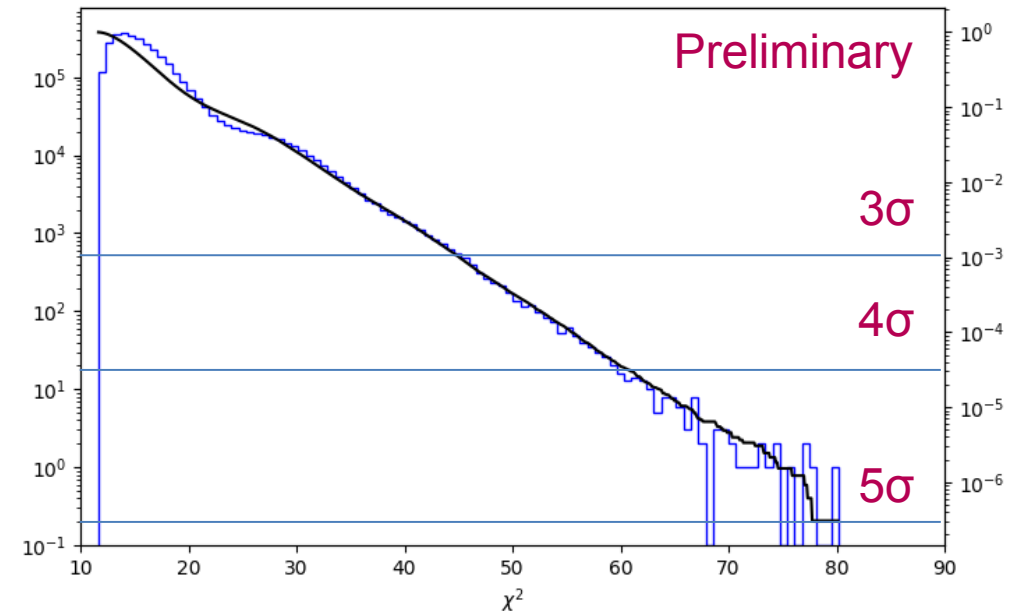
$$B_{\text{IC}} = f(\alpha)g(\sin \delta)$$
$$f(\alpha) = \text{constant}$$
$$g(\sin \delta) = \text{complicated...}$$



# Alert Significance

- Terms in the chi-square:
  - $P_{\Delta}$ : p-value from likelihood distribution
  - $P_{\text{HWC}}$ : HAWC event significance
  - $P_{\text{cluster}}$ : probability of getting  $N (>1)$  neutrinos
  - $P_{\text{IC}}$ : ratio of signal acceptance to false positive rate density
    - Under revision.
- Estimate false alarm rate

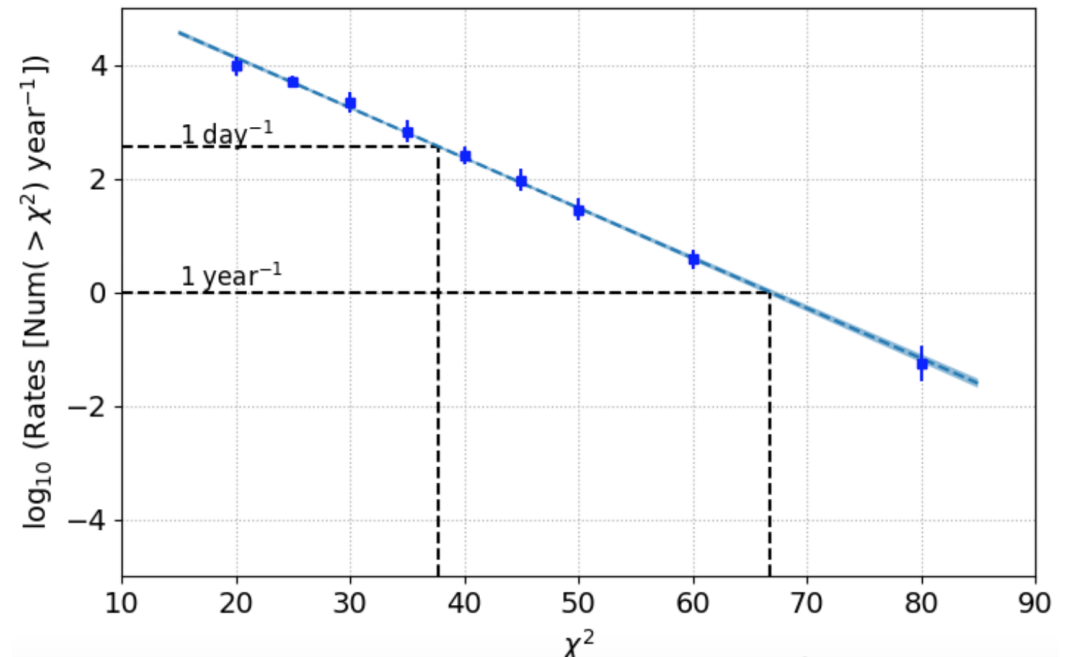
$$\chi^2 = -2 \ln (p_{\Delta} p_{\text{HAWC}} p_{\text{cluster}} p_{\text{IC}})$$
$$p_{\text{cluster}} = 1 - \sum_{i=0}^N \text{Poisson}(i, N)$$



# Alert Significance

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  - $P_{\Delta}$ : p-value from likelihood distribution
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$$p_{\text{cluster}} = 1 - \sum^N \text{Poisson}(i, N)$$



# AMON Prospects for Future Experiments

## Neutrino:

- AMON currently receives real-time data from ANTARES and IceCube
- Future experiments
  - **KM3NeT**
  - **IceCube-Gen2**
  - Better angular resolution
  - Broader energy range

## Gamma-Ray:

- AMON currently receives data from and will soon send alerts to IACT community
- Interested in more connections (ongoing MAGIC and H.E.S.S. membership negotiations)
- Future experiments
  - **CTA**
  - Join as both triggering and follow-up facility
  - Faster follow-up of AMON alerts (v- )
  - Larger FOV → suitable also for neutrino cascades

# AMON Prospects for Future Experiments

## Radio:

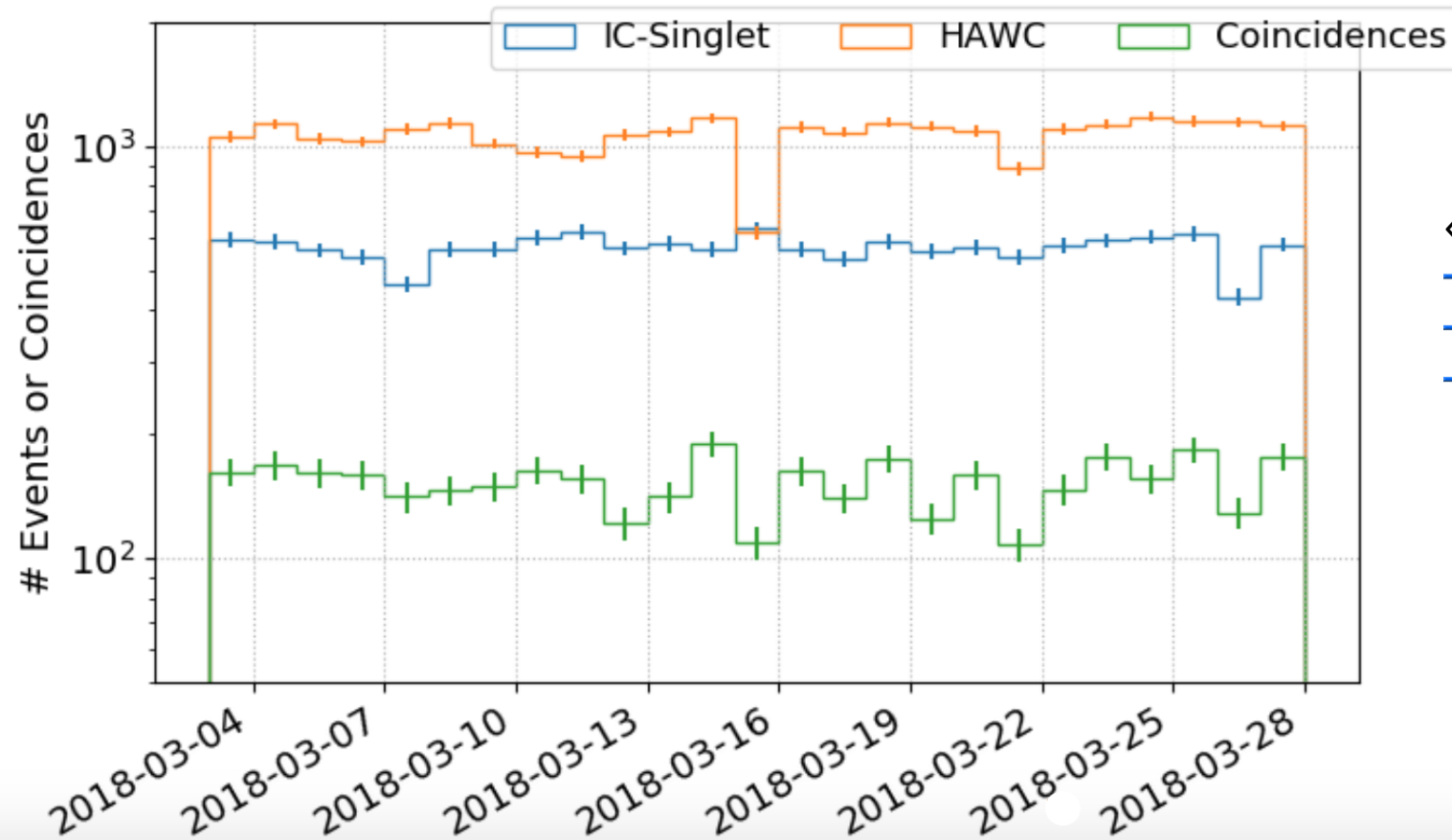
- Interested in receiving **LOFAR** transients alerts (ongoing negotiations)
- Use in subthreshold multimessenger coincidence searches
- Send alerts to LOFAR for follow-up

## Gravitational Waves:

- **LIGO** soon to be triggering facility for AMON
- Final approval from LSC committee
- AMON will be a follow-up partner by O3
- Pipeline + archival analysis undergoing



# ~ AMON ~



- « Scrambled » events in real-time:
- 1000 HAWC « hotspots »/day
- 600 IC track-like events/day
- 150 coincidences/day

AMON  
Astrophysical Multimessenger Observatory Network



<https://sites.psu.edu/amon>

## References (among others)

- *A coincidence search for cosmic neutrino and gamma-ray emitting sources using IceCube and Fermi LAT public data*, C.F. Turley et al., submitted to ApJ, 2018, arXiv:1802.08165
- *The Present and Future of Realtime Multi-Messenger Alerts from AMON* - A. Keivani, Columbia
- *Astrophysical Multimessenger Observatory Network (AMON): Science, Infrastructure, and Status*, A. Keivani et al., 35th International Cosmic Ray Conference (ICRC2017), PoS(ICRC2017)629 (2017), arXiv:1708.04724
- *Gravitational Wave and Multimessenger Searches with AMON* – J. Delaunay, APS April Meeting 2018
- *Multimessenger TeV Gamma and TeV Neutrino Coincidence Alerts from HAWC and IceCube* – H. Ayala, APS April Meeting 2018
- *Real-time search for coincidence of sub-threshold events between HAWC and LVC* – M. Seglar-Arroyo, APS April Meeting 2018



<https://sites.psu.edu/amon>