AMON

Astrophysical Multimessenger Observatory Network

The Astrophysical Multimessenger Observatory Network (AMON)

Azadeh Keivani

(For the AMON Team)

The Pennsylvania State University

American Museum of Natural History

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PennState

Multimessenger Astrophysics

- Cosmic Messengers:
  - Cosmic rays
  - Gamma rays
  - Neutrinos
  - Gravitational waves

- Use the messenger particles of all four of nature's fundamental forces

- Explore the most violent phenomena in the universe

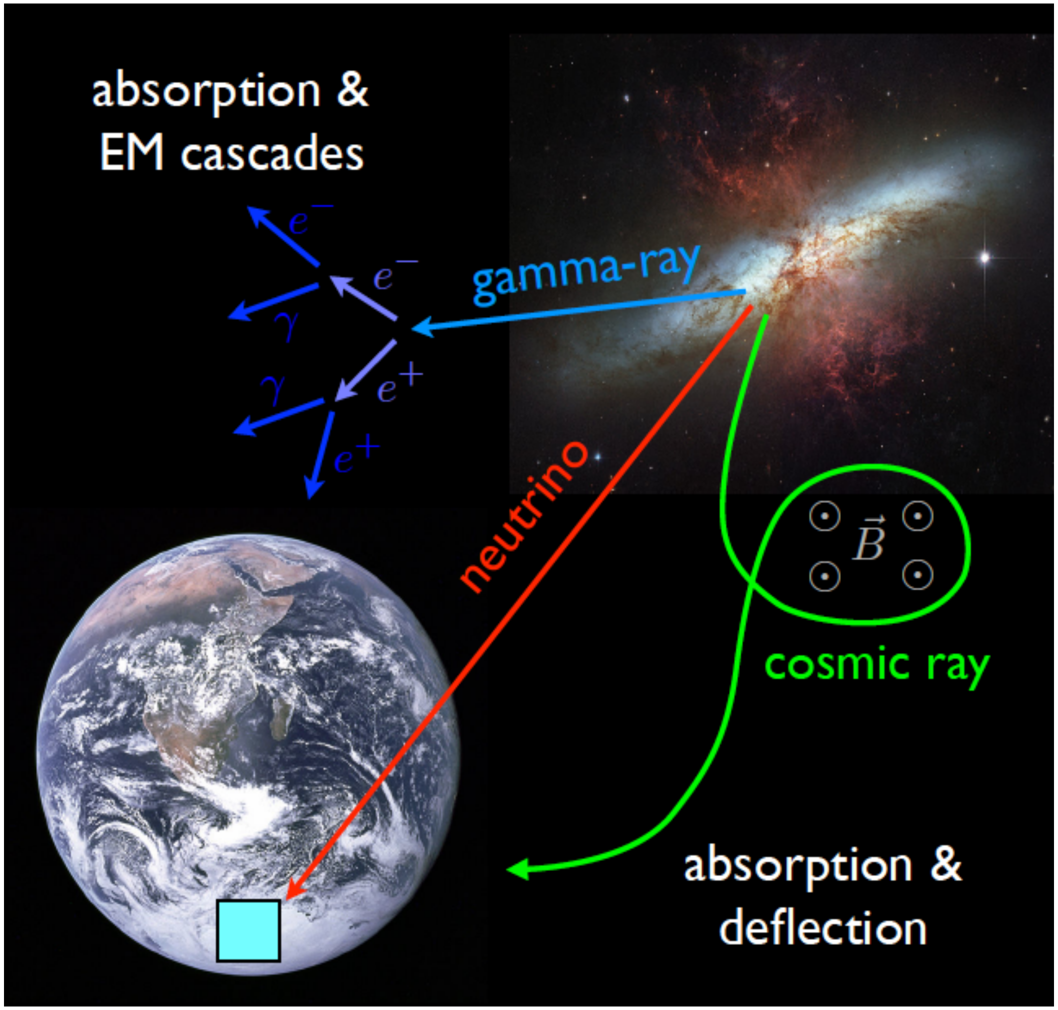


Image credit: M. Ahlers

Multimessenger Transient Source Candidates

- High-Luminosity Gamma-Ray Bursts:
  - long duration
  - high luminosity
  - seconds to minutes γ-radiation
  - $z > 1$
  - relativistic jet
- Low-luminosity Gamma-Ray Bursts:
  - long duration
  - under-luminous
  - $z < 0.5$
- Short-Hard Gamma-Ray Bursts
  - similar to HL-GRBs
  - shorter duration
  - harder spectra

- Chocked jet supernova
- Core collapse supernova
- Blazars
- Ultra-luminous star-forming galaxies
- Primordial black holes
- Other exotica

Potential Sources

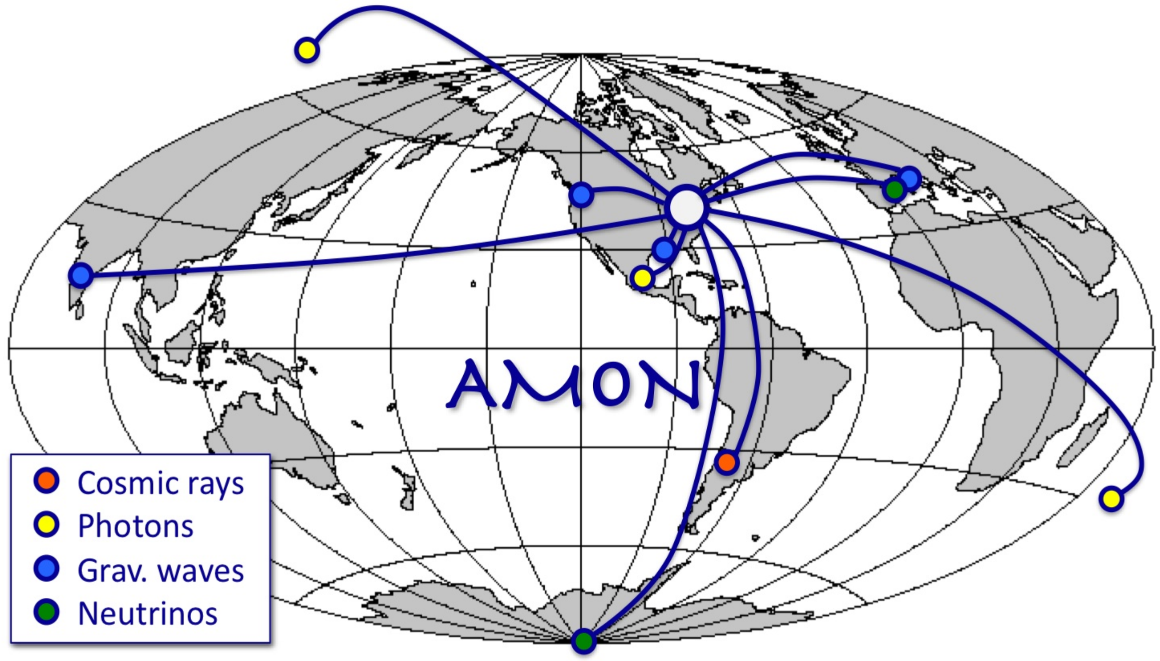
	Prompt				Delayed		
Event class	γ	ν	n	gw	x	IR/O/ UV	Radio
High-luminosity GRBs (HL-GRB)	✔	✔		✔	✔	✔	✔
Low-luminosity GRBs (LL-GRBs)	✔	✔		✔	✔	✔	✔
Short-hard GRBs (SHBs)	✔	✔		✔	✔	✔	✔
Choked jet SN		✔		✔	✔	✔	✔
Core-collapse SN		✔	✔		✔	✔	
Blazars	✔	✔			✔	✔	✔
Primordial black holes (PBHs)	✔	✔	✔				
Other exotica	✔	✔	✔	✔			

Astrophysical Multimessenger Observatory Network

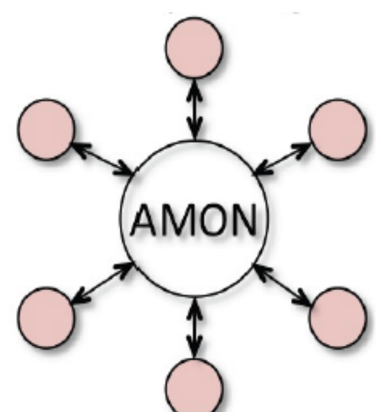
AMON links high-energy astrophysical observatories into a single virtual system.

AMON framework enables:

- Real-time and near real-time sharing of sub-threshold data between multimessenger observatories
- Real-time and archival searches for coincident signals
- Prompt distribution of electronic alerts for follow-up observations



http://sites.psu.edu/amon



Astroparticle Physics Vol. 45, 56–70, 2013

AMON Core Team

- Founded and Hosted at Penn State
- Current AMON Development and Advisory Team at Penn State:
  - Doug Cowen, Miguel Mostafa, Derek Fox,
    Stephane Coutu, Kohta Murase, Chad Hanna,
    B. S. Sathyaprakash, Peter Meszaros,
    Abhay Ashtekar, Abe Falcone
  - Azadeh Keivani, Jimmy DeLaunay,
    Colin Turley, George Filippatos, Cody Messick

AMON Network

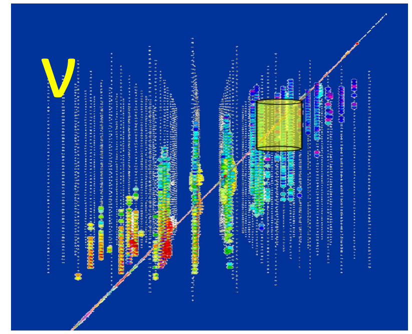
Use messenger particles of all four fundamental forces!

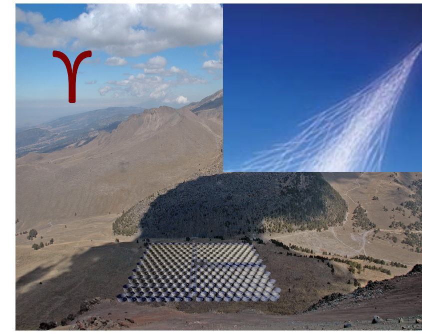
✧ Triggering observatories:

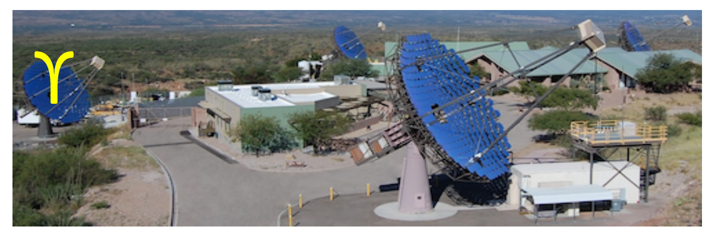
- Provide “sub-threshold” candidate events to AMON in real-time
- IceCube, ANTARES, Auger, HAWC, VERITAS, FACT, Swift BAT, Fermi LAT

✧ Follow-up Observatories:

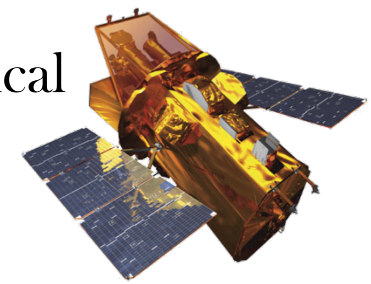
- Respond to AMON alerts
- Provide optical feedback on potential multimessenger transients
- Swift XRT & UVOT, VERITAS, FACT, MASTER, LCOGT





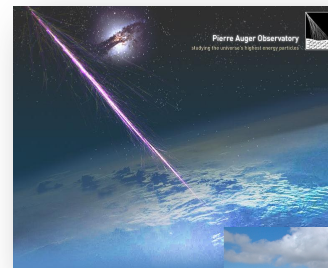


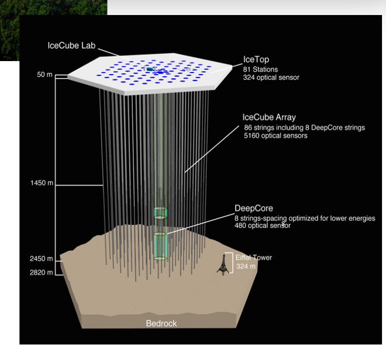
X, UV, Optical



AMON Functionality

- **Archival Searches**
  - ❑ AMON Stores events from participating observatories in the database
  - ❑ AMON searches through this database for temporal and spatial coincidences
- **Pass-Through**
  - ❑ AMON receives events and broadcasts them immediately via Gamma-ray Coordinate Network (GCN) to astronomical community for follow-up
    - ❑ E.g. IceCube high-energy neutrinos
- **Real-time Coincidences**
  - ❑ AMON receives "sub-threshold" events from multiple triggering observatories and searches in real-time for coincidences in direction and time
    - ❑ E.g. a single muon neutrino in coincidence with ≈15 photons from HAWC
  - ❑ AMON issues GCN alerts for follow-up



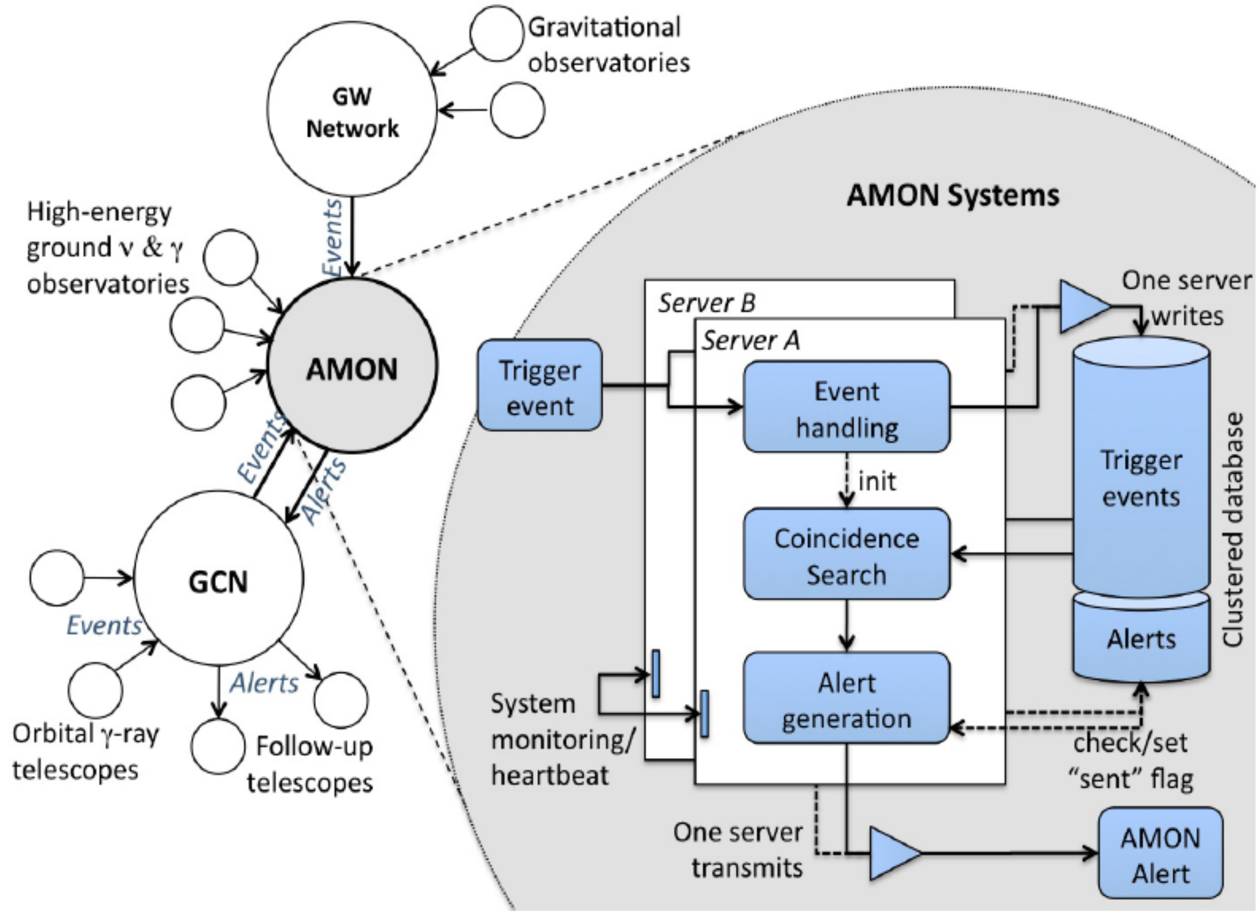


Data Flow

- Sub-threshold data from triggering observatories:
  - sent in a standard VOEvent format
  - store in a secure database

- VOEvents from satellite experiments via GCN

- Use GCN to distribute AMON alerts to the follow-up observatories as VOEvents



AMON Status: Participation

Observatories with AMON MoU	Stream content and 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	✓	✓	In progress		
Pierre Auger	✓	✓	✓	✓	In progress
HAWC	✓	In progress			
VERITAS	In progress				
FACT	✓	✓	✓	In progress	In progress
Swift BAT	✓	Not needed	Not needed	Not needed	✓
Fermi LAT	✓	Not needed	Not needed	Not needed	✓

AMON Status: Infrastructure

AMON event database

- Designed and implemented
- Contents:
  - Inserted: IceCube40/59 and year 1 of 86, Swift, Fermi (public)
  - Inserted: ANTARES 2008, Auger (private)
  - In progress: LIGO S5 and S6 (public)
  - Awaiting approval: IceCube, HAWC, VERITAS, ANTARES (private)

AMON application server

- Running stably since August 2014
  - Python/Twisted, asynchronous, tested with simulated and real clients
  - Accepts HTTP POST requests
  - Open for authorized connections using TLS certificates
- Started issuing public AMON alerts using VOEvent format/protocol in April 2016

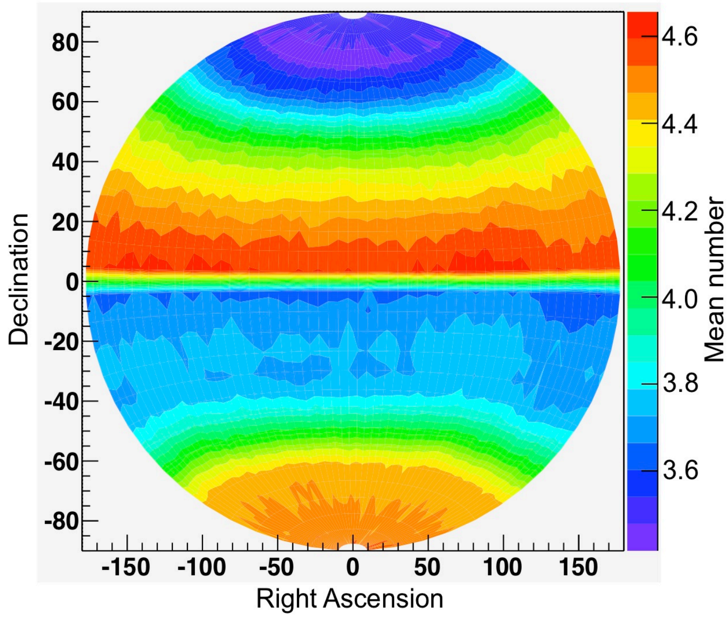
AMON hardware

- Two new high-uptime servers
  - Now deployed at Penn State
  - Physically and cyber secure; fully redundant systems

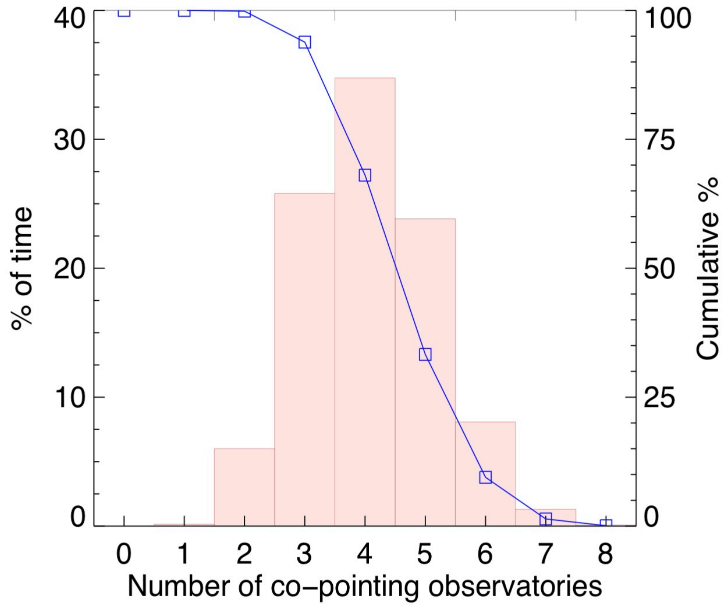
Field of View

1-year simulation for IceCube, ANTARES, HAWC, Swift BAT, Pierre 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 4π sr-yr is within the FoV of 3 or more observatories
- 2+ observatories are viewing any given part of the sky simultaneously

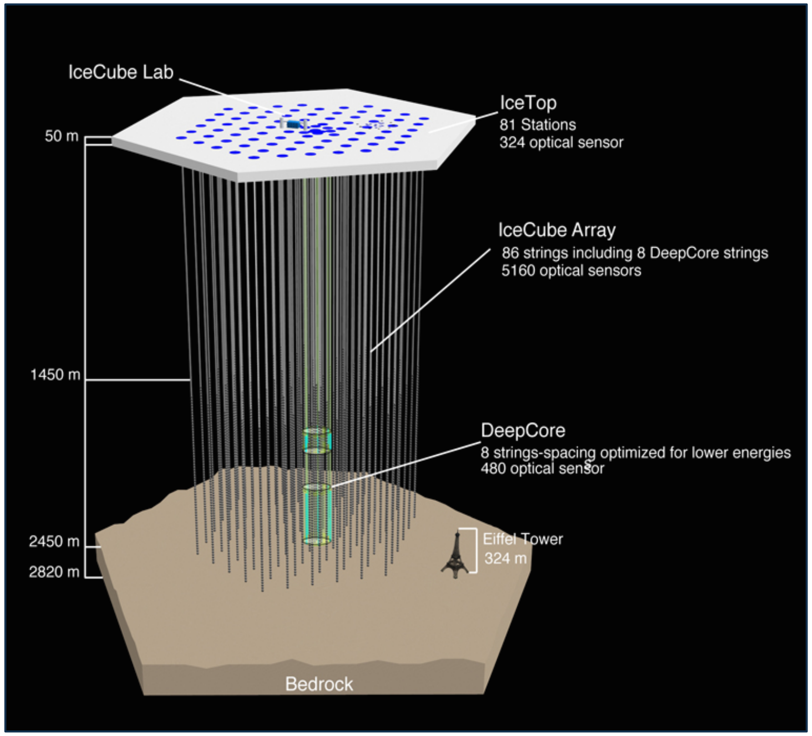
AMON Analyses

- Archival analyses:
  - Fermi LAT – IC40 (AK et al, PoS(ICRC2015)786 (2015))
  - Fermi LAT – IC40/59 (C. F. Turley et al., in preparation)
  - Primordial black holes (G. Tešić, PoS(ICRC2015)328 (2015))
  - VERITAS blazars – IC40 (C. F. Turley et al., APJ 833, 117 (2016))

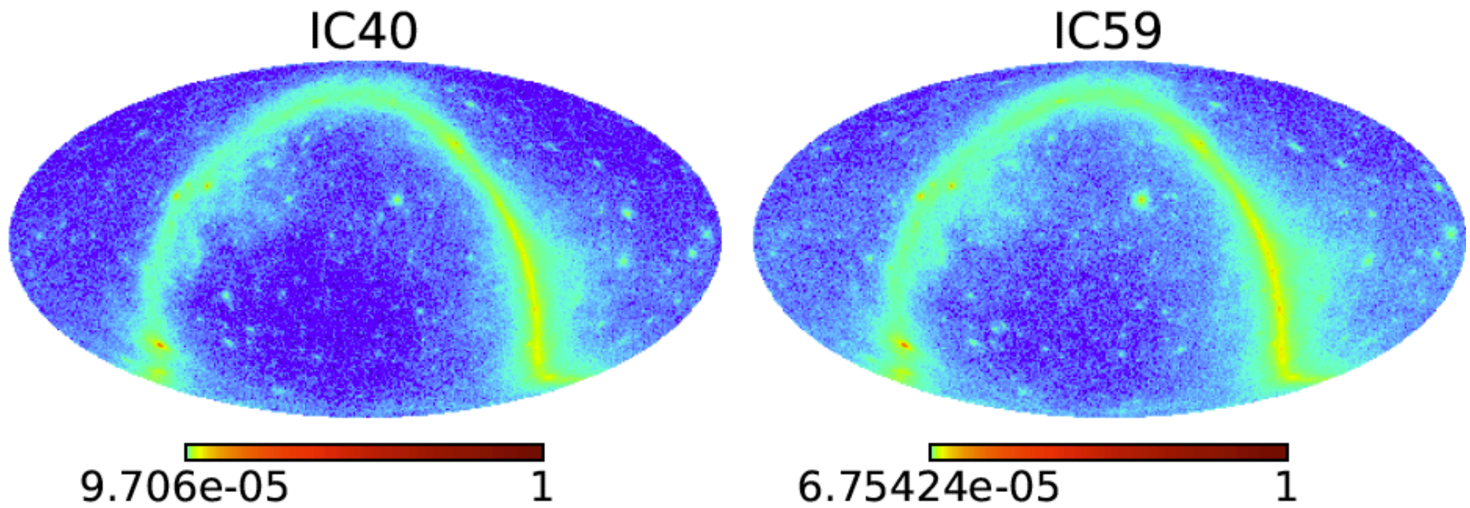
- Realtime analyses:
  - Swift XRT/UVOT – IceCube HESE (AK et al, in preparation)
  - IceCube Triplet follow-up (submitted to A&A)
  - Swift BAT – IceCube subthreshold neutrinos (Jimmy DeLaunay)
  - HAWC – IceCube subthreshold neutrinos (AK)
  - Pierre Auger – IceCube subthreshold neutrinos (George Filippatos)

Analysis I

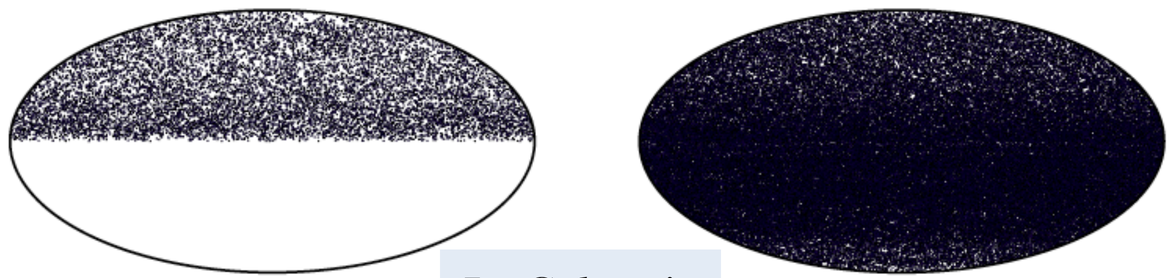
Searches for coincident signals between IceCube public data (40- and 59-string configuration) and Fermi LAT data



Analysis I: IceCube-Fermi LAT I



Fermi-LAT exposure corrected map



IceCube ν's

IC40-LAT:
- ✧ ≈ 15M photon events
- ✧ ≈ 13k neutrino events
- ✧ LAT weeks 9-50

Clustering of the events:
- ✧ Spatial: $\Delta\theta < 5^\circ$
- ✧ Temporal: $\Delta t = t_0 \pm 50$ s

IC59-LAT:
- ✧ ≈ 18M photon events
- ✧ ≈ 108k neutrino events
- ✧ LAT weeks 50-104

AK et al., PoS(ICRC2015)786 (2015) (using pass 7)
C. F. Turley et al., in preparation (using pass 8)

Analysis I: IceCube-Fermi LAT II

Study background:

- Scramble IceCube data
- Only scramble IceCube neutrinos: gamma event stream is more complicated due to LAT motion
- Keep neutrino's energy, position reconstructed uncertainties and declinations
- Scramble time and right ascension
- To test the analysis's effectiveness, a series of 10,000 scrambled data tests and a series of signal tests were performed

To conduct this analysis, an un-binned log-likelihood function is considered:

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

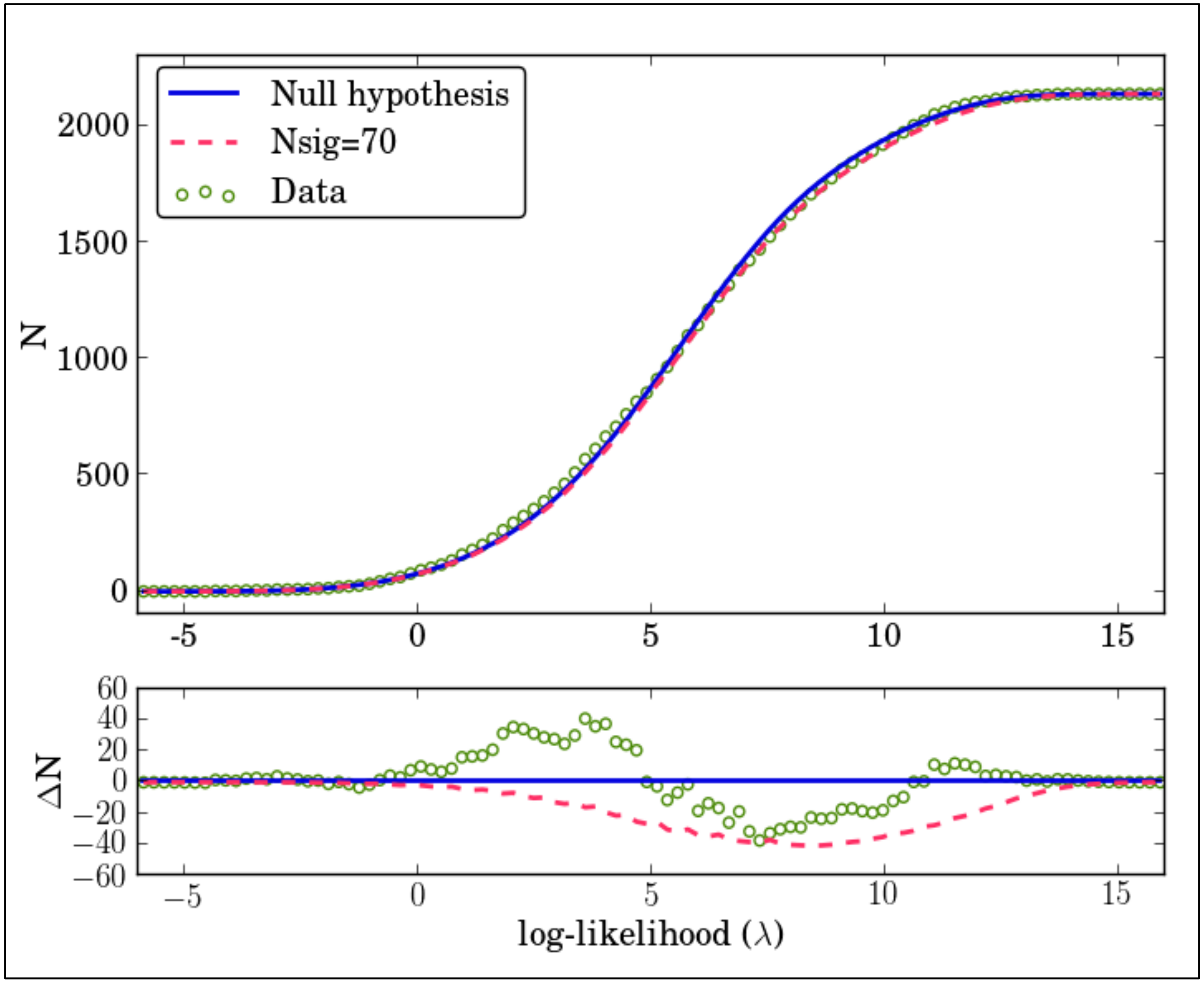
Analysis I: IceCube-Fermi LAT III

Un-blinding: Results from pass 7 Fermi LAT:

✧ IC40 – Fermi LAT:
Data: 2138 $\gamma + \nu$ pairs
BG: 2207±40 $\gamma + \nu$ pairs
p-value: 15%

✧ IC59 – Fermi LAT:
Data: 9025 $\gamma + \nu$ pairs
BG: 9077±153 $\gamma + \nu$ pairs
p-value: 9%

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

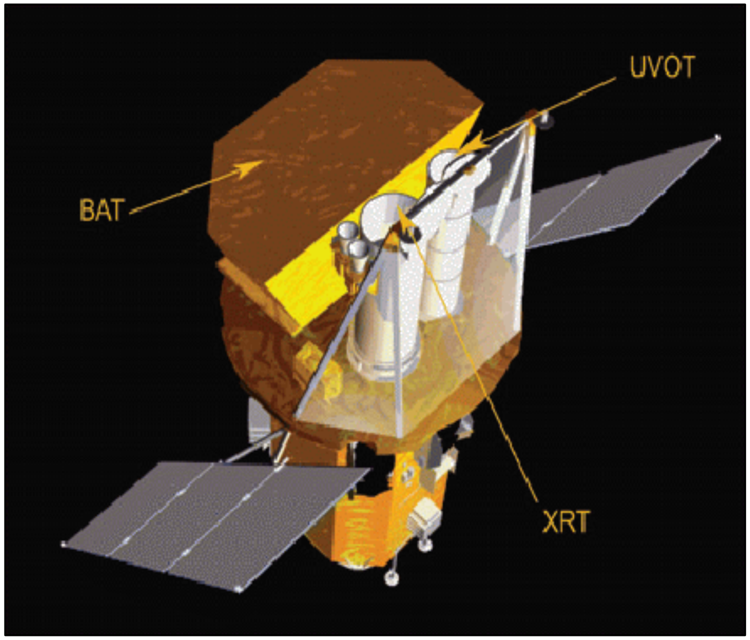


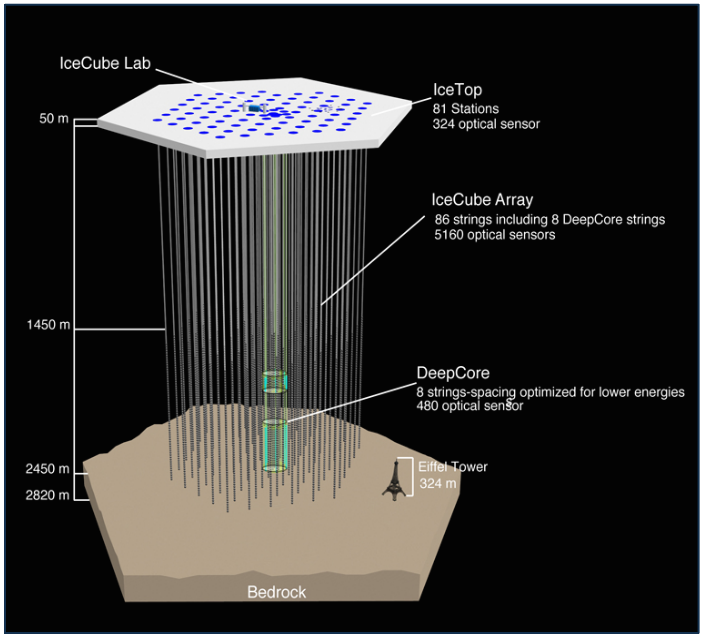
Results from pass 8 Fermi LAT in preparation

AK et al., ICRC, PoS(ICRC2015)786 (2015).

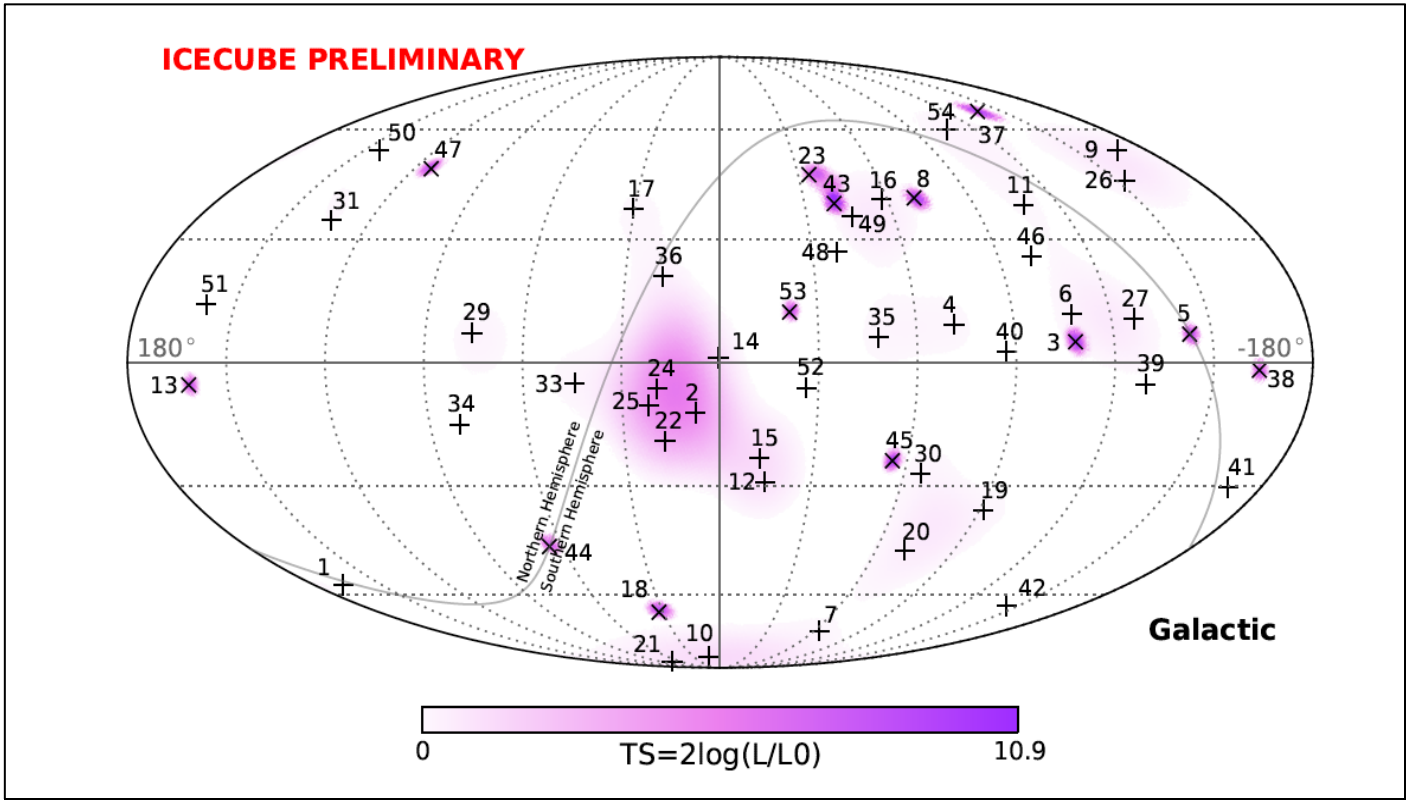
Analysis II

Seeking sources of IceCube high-energy neutrinos with Swift





Analysis II:
IceCube Detection of High-Energy Neutrinos

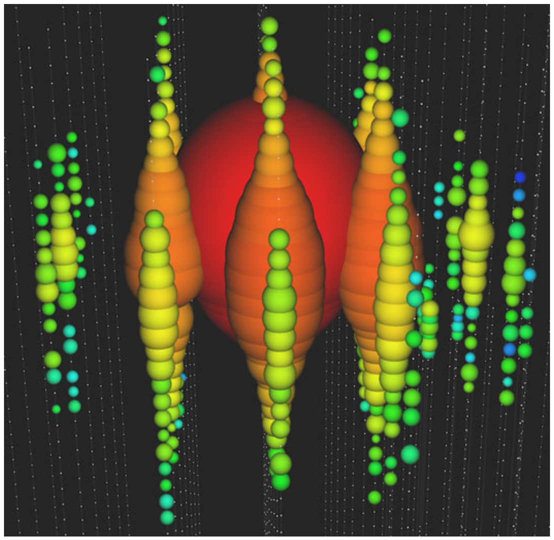


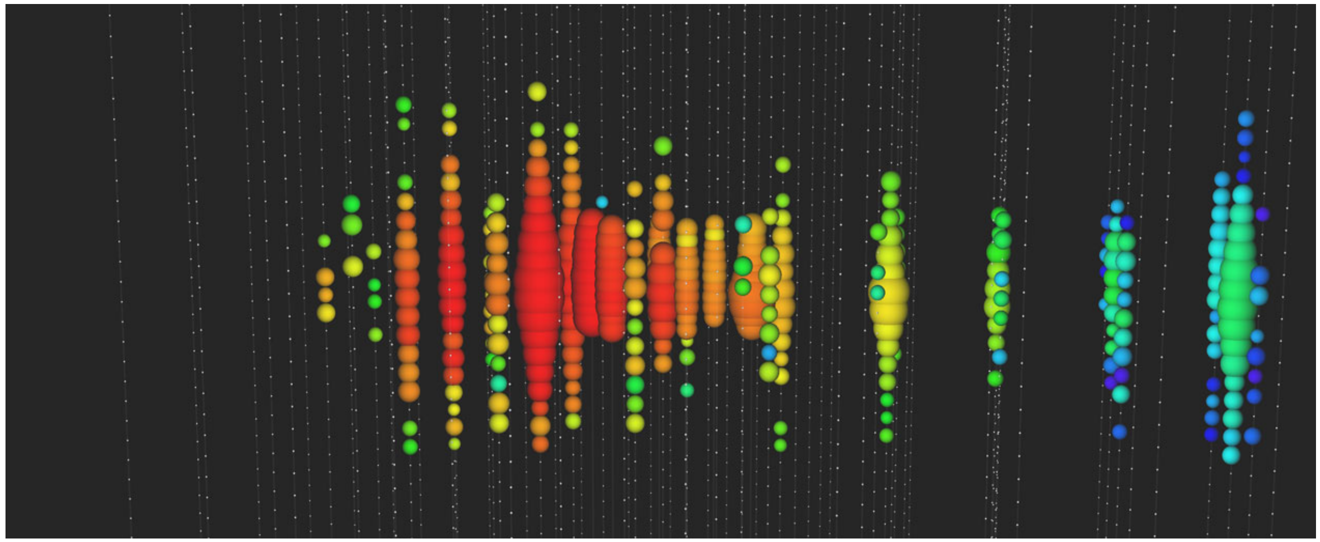
54 High-Energy Starting Events (HESE) in 4 years of data:

- Outer strings of the facility as a veto layer
- Large deposited energy in a restricted fiducial volume

→ Contamination by muons and atmospheric neutrinos reduced

Analysis II:
HESE Topology





Cascade-like event
Average angular error 15°

Track-like event
Average angular error 1°

Track-like events resulting from charged-current interactions of muon neutrinos:

- better localization
- suitable for *Swift*

Analysis II: A Powerful Approach to Source Identification

- Neutrino localizations are too uncertain
- Better approach to source identification:
  - Identify neutrino localization in realtime
  - Carry out a prompt search for its electromagnetic counterpart

- HESE sample: high probability of being astrophysical
- Most proposed source populations: X-ray and optical emission

Analysis II: IceCube HESE Real-time 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
- Many subscribers (50+ including VERITAS, MASTER, Swift XRT/UVOT, ANTARES, XMM-Newton, etc.)

Analysis II: IceCube EHE Real-time Stream

- Only track-like Extremely High Energy (EHE) neutrinos (E>100s TeV) that are likely astrophysical
- 4 alerts per year: 4-6 signal-like and 2 background like
- Fast alerts (median time delay 40 seconds)
- Distribute timestamps, RA/Dec, angular error, charge deposited and probability of an event being astrophysical
- Public since July 16, 2016 at AMON/GCN stream
- More into: http://gcn.gsfc.nasa.gov/amon.html
- Many subscribers (45+ including VERITAS, MASTER, Swift XRT/UVOT, ANTARES, XMM-Newton, etc.)

Analysis II:
Public IceCube Real-time HESE/EHE

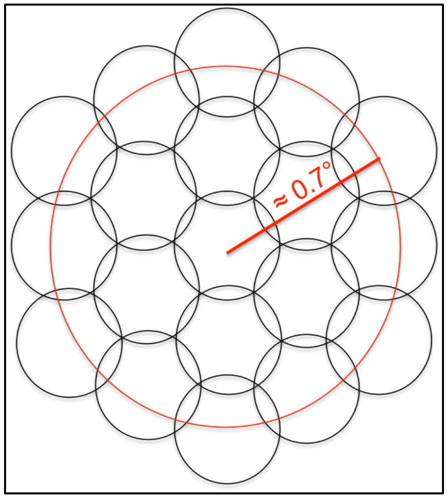
Alert name/type	161103/HESE	160814A/HESE	160806A/EHE	160731A/HESE	160731A/EHE	160427A/HESE
RA/DEC (rev1) RA/DEC (rev2)	[40.87°, 12.62°] [40.83°, 12.56°]	[199.31°, -32.02°] [200.25°, -32.35°]	[122.80°, -0.73°] [122.81°, -0.81°]	[215.11°, -0.46°] [214.54°, -0.33°]	[215.09°, -0.42°] [214.54°, -0.33°]	[239.66°, +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						

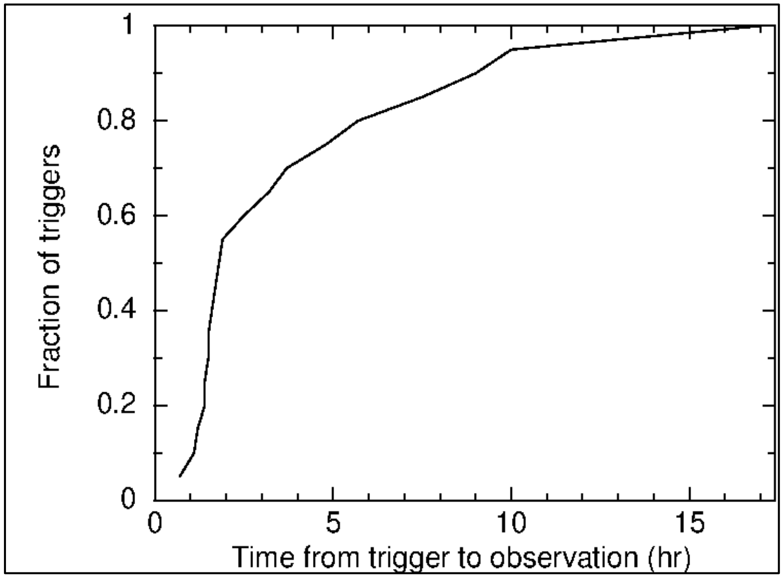
AGILE
ANTARES
FACT
Fermi GBM
Fermi LAT
HAWC
H.E.S.S
INTEGRAL
IPN
Konus-Wind
LCOGT
MAGIC
MASTER
Maxi/GSC
Pan-STARRS
PTF
Swift
VERITAS
CALET

Analysis II:
Swift an Ideal Follow-up Facility

Our proposal:

- 50% confidence error region of high-confidence (p_cosmic > 80%) HESE neutrinos
- Observe with Swift in 19-tile pattern



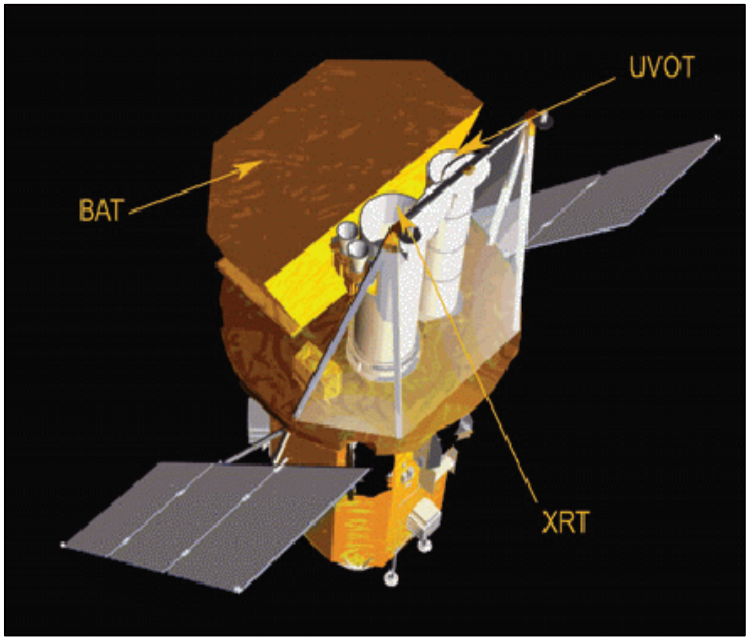


Evans, P. A. et al, 2015 MNRAS, 448, 3.

- Within 16 hours of the neutrino detection
- Automatic process
- XRT and UVOT

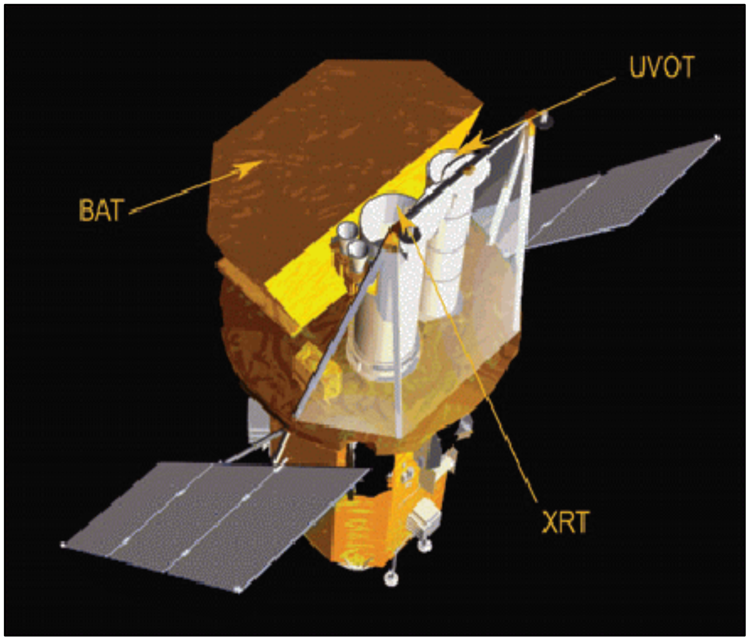
Analysis II: Follow-up Plan I

- Cycle 12 approved and funded
- April 2016 – March 2017
- Three approved triggers: priority I ToO
- IceCube HESE realtime analysis:
  - Identified and localized at the South Pole
  - Telemetered via Wisconsin to AMON at Penn State (median latency ≈ 40 s)
  - Convert into GCN notices
  - Notices are publicly available (http://gcn.gsfc.nasa.gov/amon.html)
  - Swift follows up track-like HESE with flux of >6000 p.e.
- Recovers >50% of Swift GRB afterglows



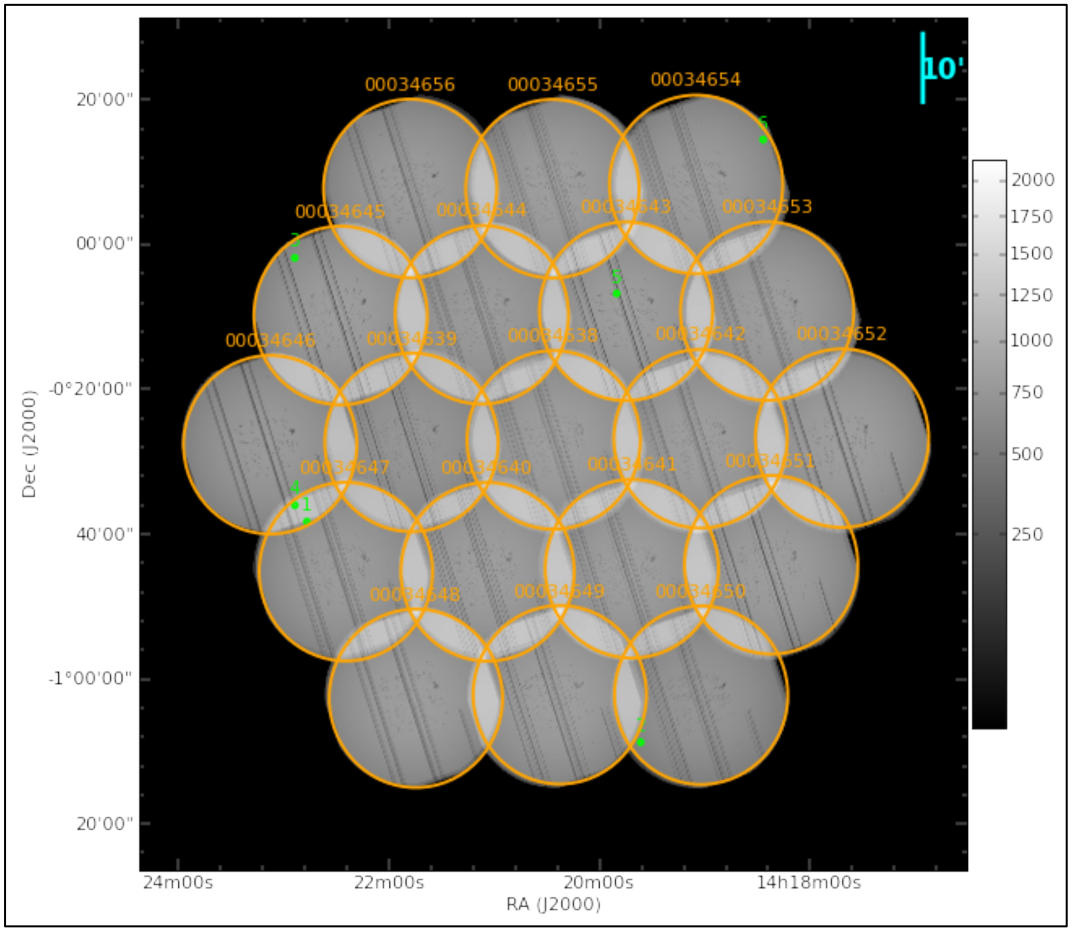
Analysis II:
Follow-up Plan II

- Automated analysis of the XRT data:
  University of Leicester (Phil Evans)
- Sources selected for subsequent monitoring:
  - ➢ Bright and previously uncatalogued X-ray source
  - ➢ Variability over the course of the tiling observations
- Search UVOT data for new and interesting/ variable sources to submit for follow-up
- New and variable sources (≈ 2) with subsequent follow-up observations:
  - ➢ Three daily epochs
  - ➢ Two Swift pointing
  - ➢ 1 ks per pointing
- Total observing request is
  - ➢ 31 ks (i.e. 19+2*3*2) per HESE or
  - ➢ 93 ks total



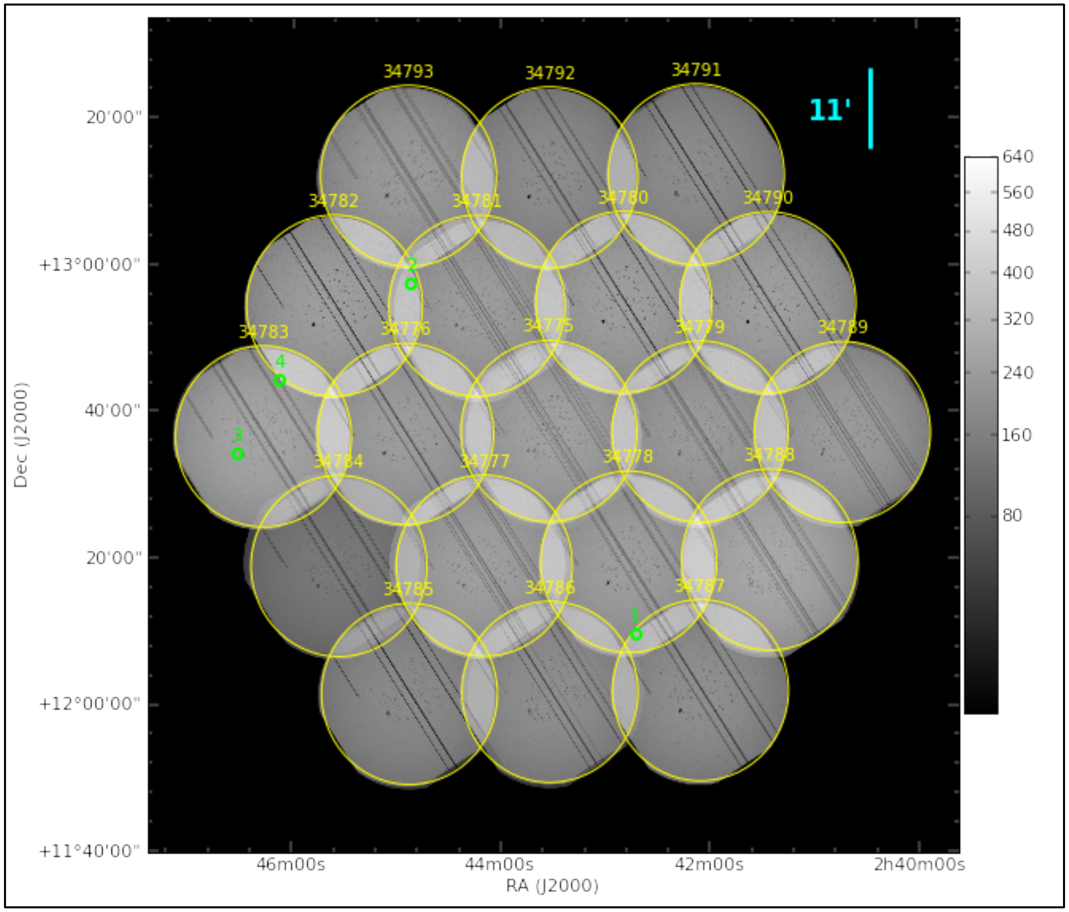
Analysis II: First Swift Follow-up of a HESE Alert

- IceCube-160731A:
  - 2016 July 31
  - (RA, Dec) = (215.109°, -0.458°)
  - Error 1.2°
- Swift followed up this event within about an hour
- Radius of 0.8°
- Observations:
  03:00:46 – 14:51:52 UT
- Covered 2.1 deg^2
- XRT collected ≈ 800 s of PC mode data per tile
- Six X-ray sources → all known
- No transients in XRT/UVOT data



Analysis II:
Second Swift Follow-up of a HESE Alert

- IceCube-161103A:
  - ➢ 2016 November 3
  - ➢ (RA, Dec) = (40.874°, +12.616°)
  - ➢ Error 1.2°
- Swift followed up this event within about five hours
- XRT radiator pointed towards Sun made XRT very hot
- Radius of 0.8°
- Observations: 13:58:30 – 18:55:15 UT
- Covered 2.1 deg^2
- XRT collected between 150 and 250 s of PC mode data per tile
- Four X-ray sources, unknown but faint



Analysis II: Swift-IceCube GCN Circulars

Swift has followed up four IceCube high-energy events so far

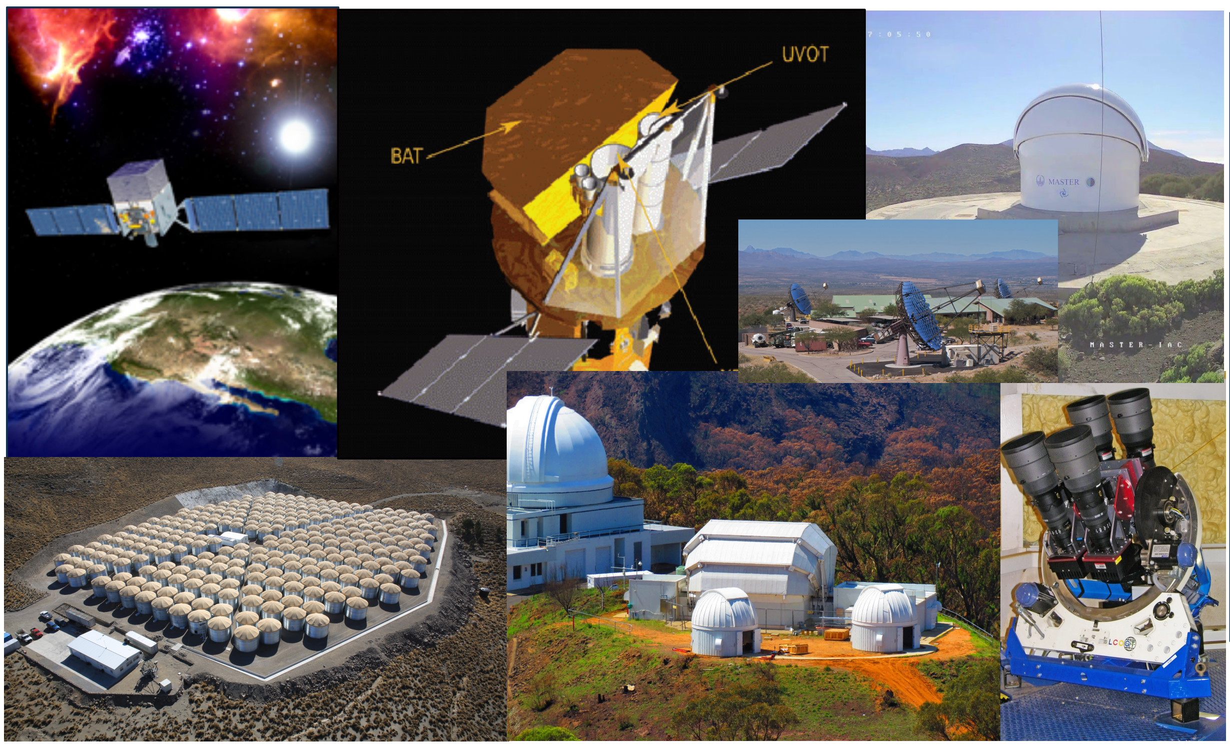
- IceCube-170321A: https://gcn.gsfc.nasa.gov/gcn3/20964.gcn3
- IceCube-170312A: https://gcn.gsfc.nasa.gov/gcn3/20890.gcn3
- IceCube-161103A: https://gcn.gsfc.nasa.gov/gcn3/20125.gcn3
- IceCube-160731A: https://gcn.gsfc.nasa.gov/gcn3/19747.gcn3

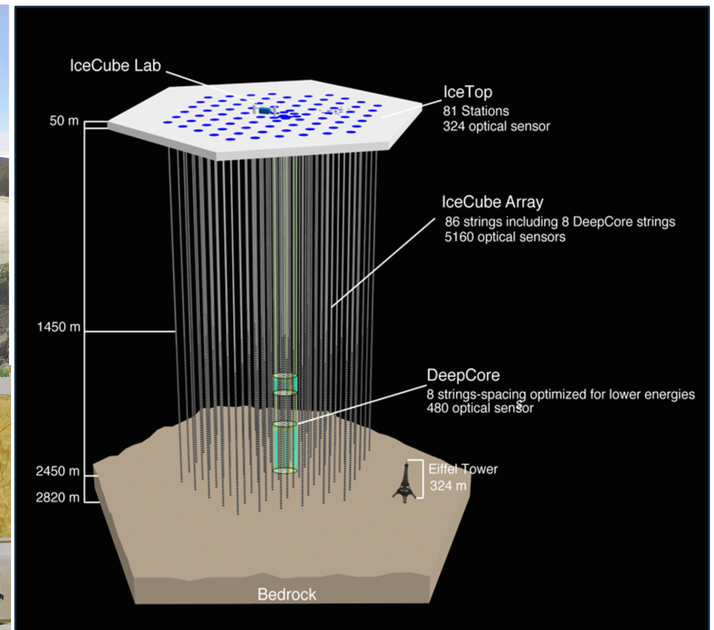
No significant counterpart has been discovered

Analysis II:
Current Plan

- Add Extremely High-Energy (EHE) events:
  - high-energy through-going tracks
  - energies exceeding several hundreds TeV
  - better resolution (≈ 0.2°)
  - expected rate 4 to 6 (2 background)
  - 7-pointing mosaic
  - completion of tiling pattern within 10 hours
  - recover >79% of Swift GRB afterglows
- Rapid follow-up of a few high-energy events
- Example of 2 HESE and 4 EHE per year:
  - 1 ks per pointing
  - new pointings for object of interest
  - two daily epochs at 2 ks per epoch
  - 27 ks per HESE, 11 ks per EHE (total of 98 ks)

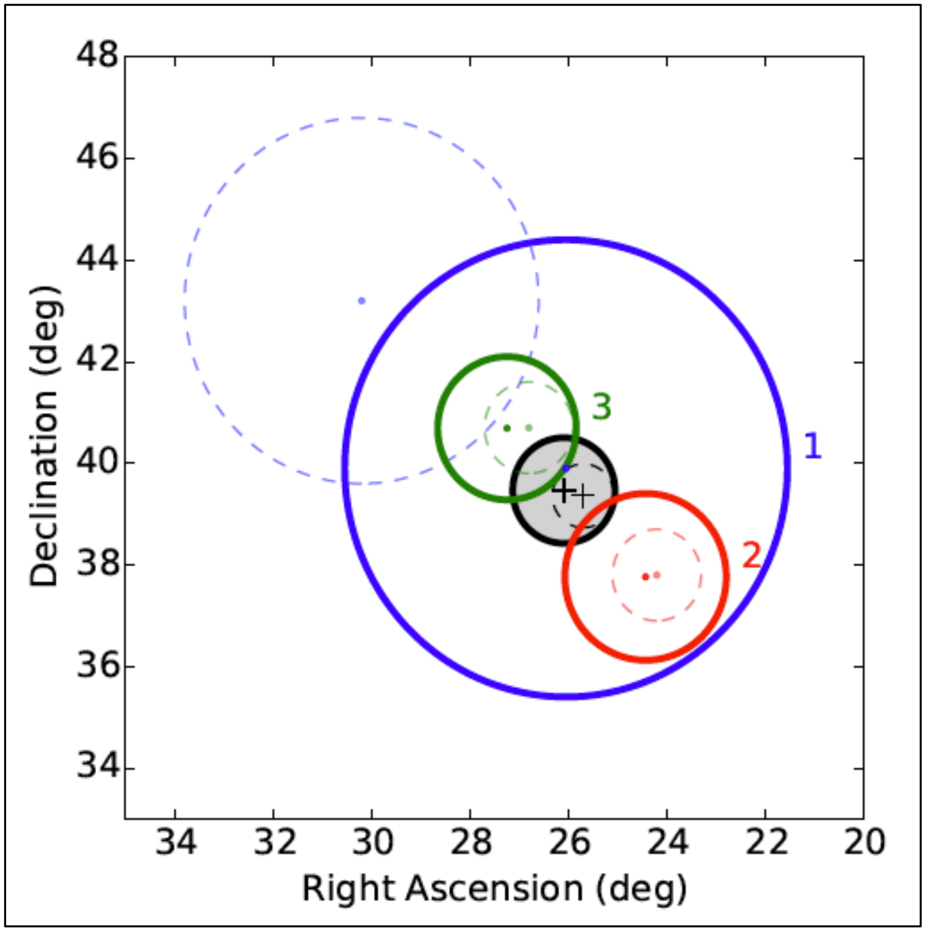
Multiwavelength follow-up of a rare IceCube neutrino multiplet





Analysis III: IceCube Neutrino Multiplet

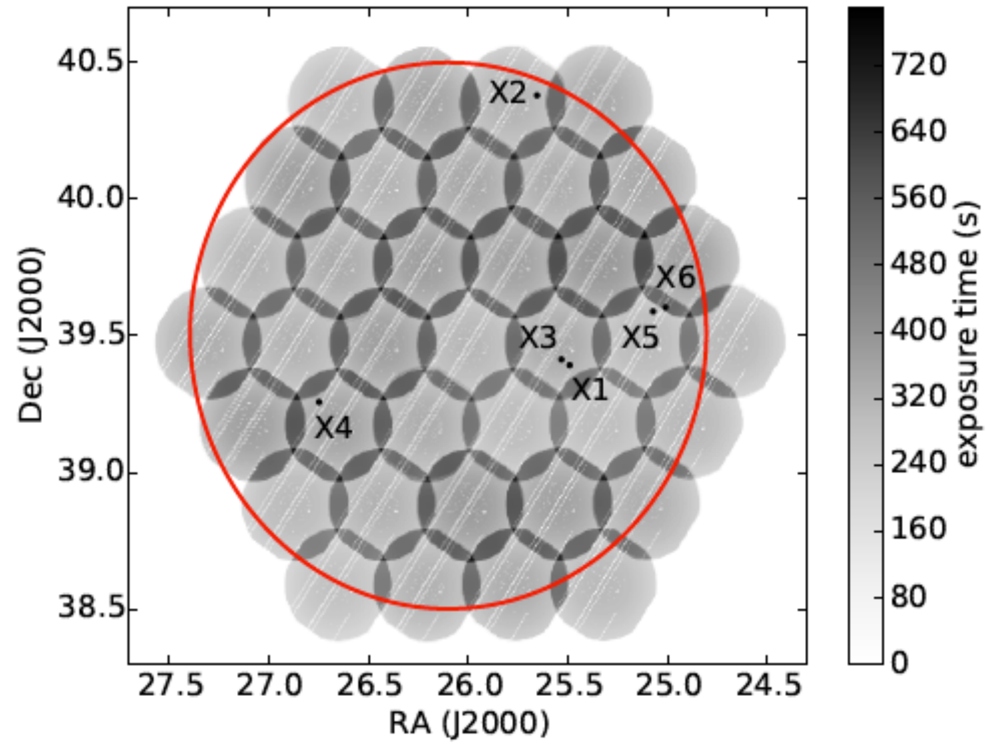
- Triplet every 13.7 years
- Two neutrino doublets:
  - 2016-02-17 19:21:31.65
  - $\Delta T = 100$ s
  - $\Delta\theta_{23} = 3.6°$
  - (RA, Dec) = (26.1°, 39.5°)
  - $\sigma_{50} = 1°$
  - $\sigma_{90} = 3.6°$
- Follow up observations after 22 hrs:
  - Swift XRT
  - ASAS-SN
  - LCO
  - MASTER
  - VERITAS
- Analyze data:
  - Swift BAT
  - Fermi LAT
  - HAWC



Analysis III: IceCube Neutrino Multiplet – Swift Searches

- Swift XRT:
  - 37 pointings
  - 320 s per tiling
  - 0.3-10 keV
  - Search for GRB afterglows,
    AGN flares,
    other X-ray transients
  - Six X-ray sources identified
  - One highly variable but faint source

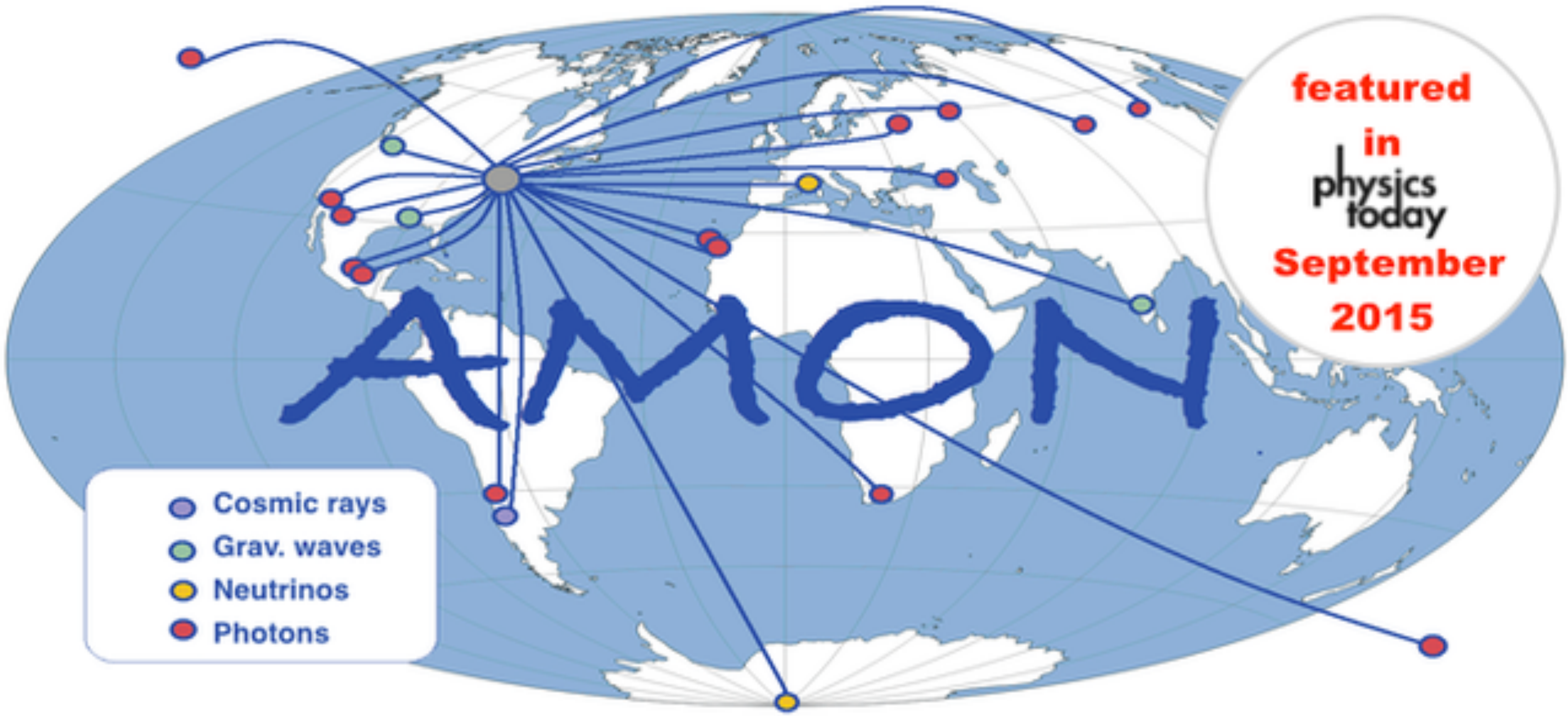
- Swift BAT:
  - By chances BAT observed the position within 1 min after the neutrino detection
  - Hard X-rays: 15-150 keV
  - Detection with single-trial significance 4.6σ
  - P-value of 9.9%
  - Random fluctuation
  - 4σ upper limit of 3.9×10^{-9} erg cm^{-2} s^{-1}



Summary

- AMON expands discovery space in new ways
  - Unleashes sub-threshold data for multimessenger searches in real-time
  - Creates bidirectional, multilateral connections between triggering and follow-up observatory partners
  - Enables complex real-time and archival searches
- AMON greatly simplifies multimessenger searches
  - Common transfer protocol, data format, event database, MoUs
- AMON has made a significant progress towards real-time and archival analysis
- AMON server is up and running: open for authorized connections!
- AMON started issuing alerts in April 2016!
- New participants are always welcome!

Thanks



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