The Dawn of Multimessenger Astronomy

Doug Cowen

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Multimessenger Astrophysics

- Definition
- Motivations
- Candidate astrophysical sources
- The *status quo*
  - Messengers & Detectors
  - Discoveries
  - What's still hidden
- Discovery accelerants
  - New/Upgraded detectors
  - Virtual observatories: AMON and ASTERICS

What is Multimessenger Astrophysics?

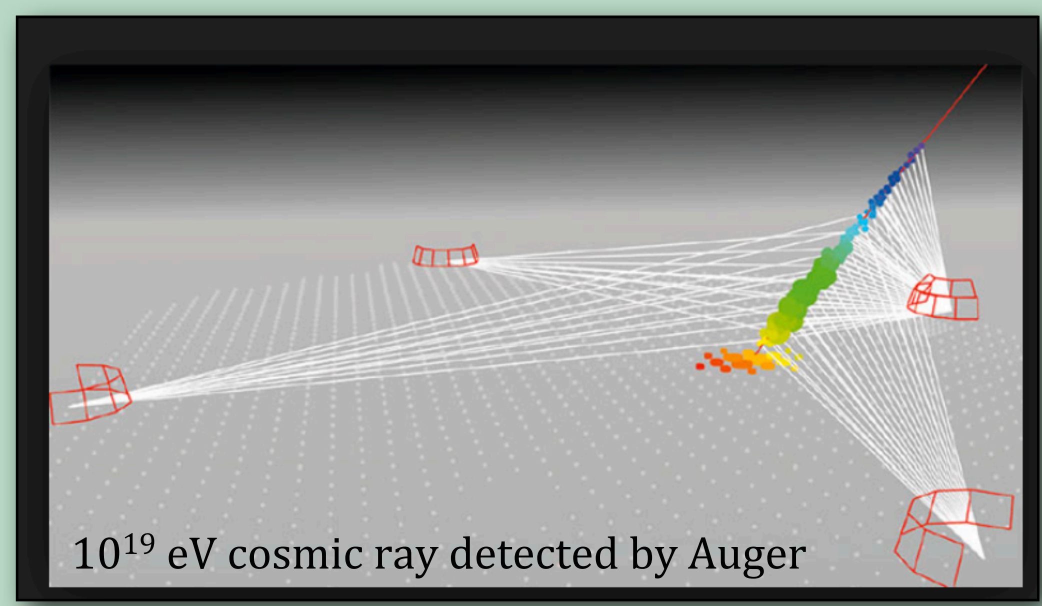
Def^{n}: The observation of a single source producing distinct signals associated with two or more of the four fundamental forces:

Force	Messenger	Messenger Detected?	Source ID'd?	Multi-messenger?
EM	γ	✓	Loads	Sun, SN1987A
Weak	ν	✓	Twice	
Strong	p, nuclei	✓	No	No
Gravity	Grav. Waves	✓	No	No

In this talk we focus on high energies

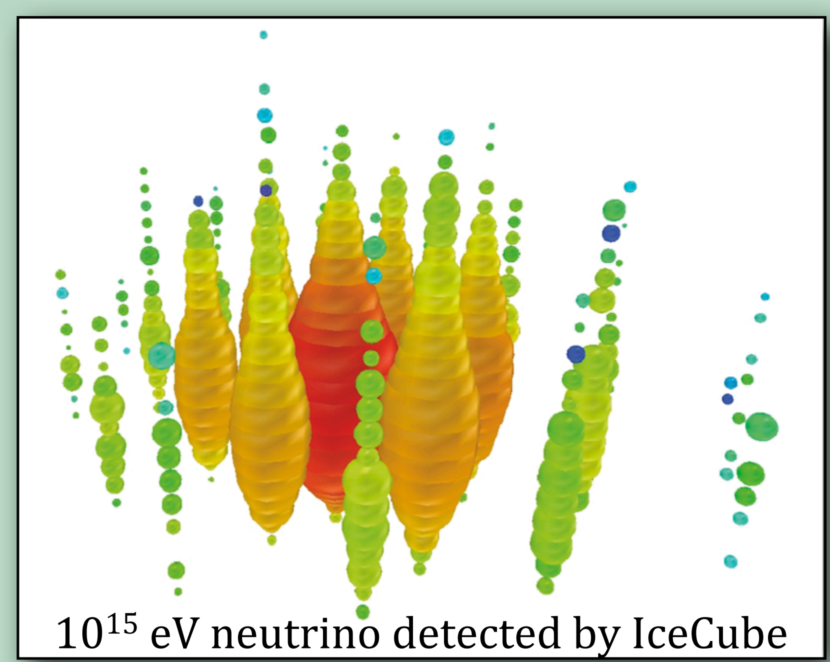
Motivations

What makes these?

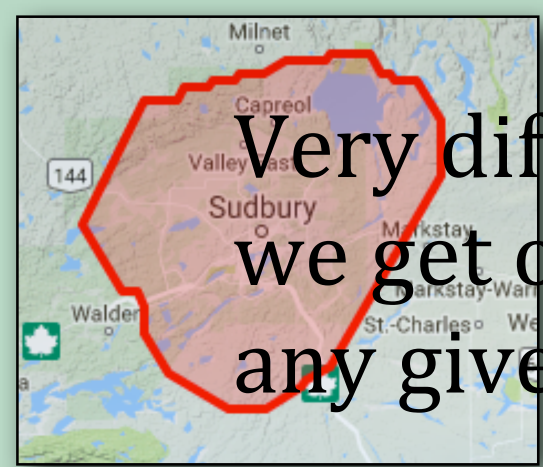


10^{19} eV cosmic ray detected by Auger

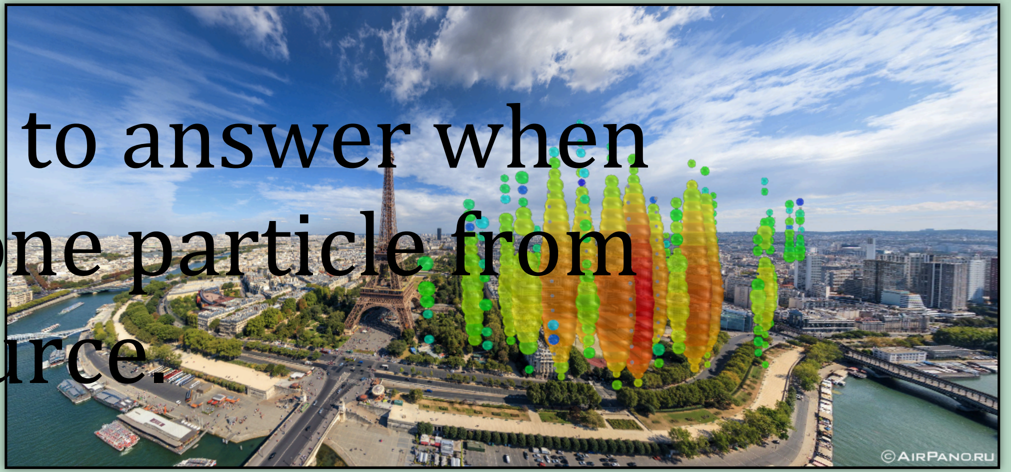
And these?



10^{15} eV neutrino detected by IceCube



Auger superimposed on Sudbury



IceCube event visiting Paris

Very difficult to answer when we get only one particle from any given source.

More Motivations

- Consider bonanza from low-energy multimessenger sources:
  - Sun: Used solar EM output to estimate ν production.
    - Measurements fell short → "solar ν problem"
    - Solved right here in Sudbury, deepening understanding of ν's (and confirming stars' fusion power source)
  - SN1987A: Coincident ν detection gave
    - Unprecedented insight into SN explosion mechanism
    - Enabled new measurements of fundamental ν properties
    - Generated hundreds of papers

More Motivations

- If we could detect *high*-energy multimessenger source(s):
  - We'd focus modern EM-based observatories on them, and similarly dramatic advances could ensue:
    - Acceleration mechanism revealed?
    - Source(s) of UHECRs unveiled?
    - Localization (and redshift) of GW emitters determined?
    - Additional fundamental particle properties discovered?

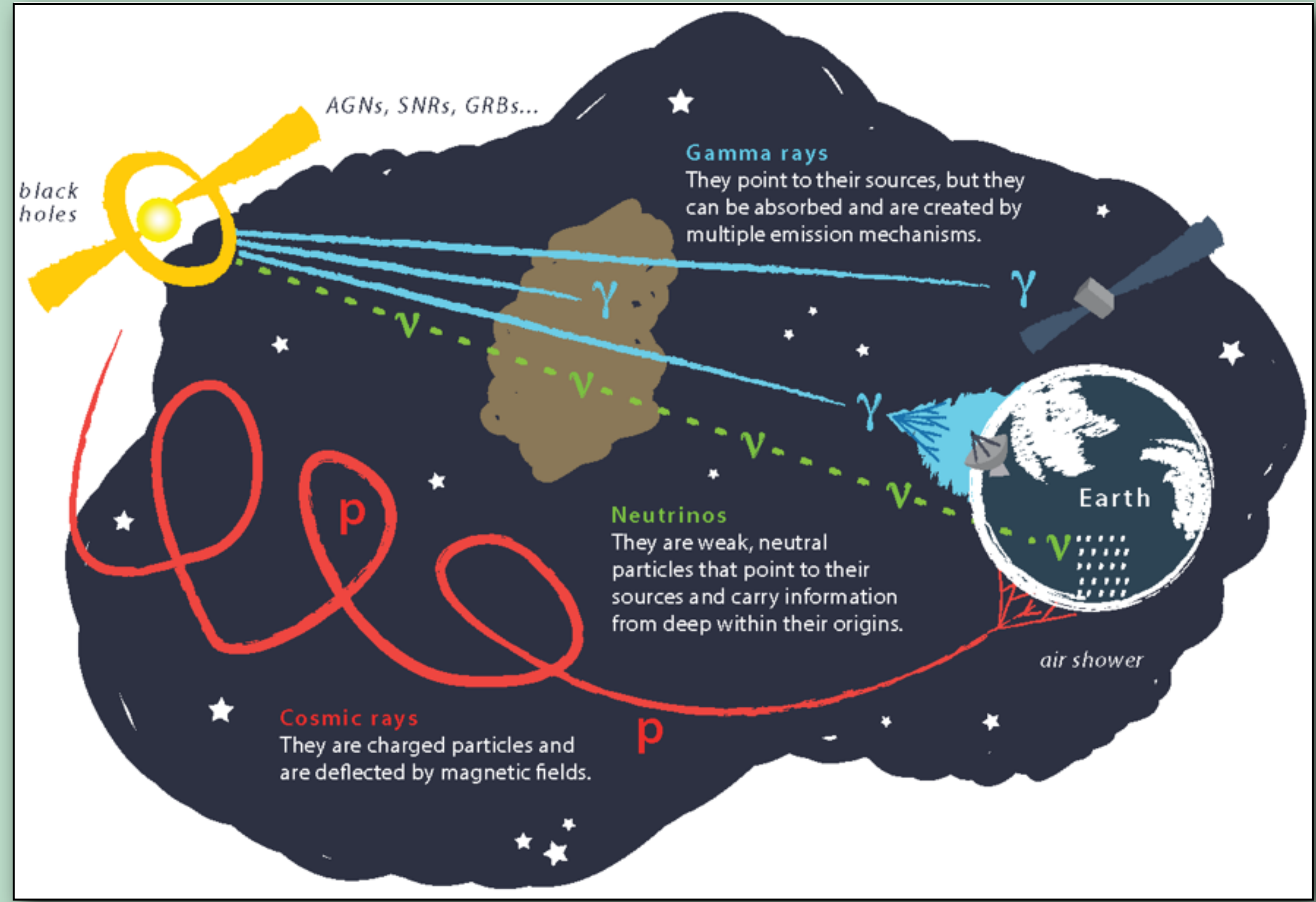
Candidate Astrophysical Sources

- Gamma Ray Bursts
  - Top candidate (but IceCube rules out some models)
- Active Galactic Nuclei; Blazars
  - Continuous sources (but not the most energetic)
- Supernovae
  - Have to play the waiting game for one in Milky Way
- NS-NS mergers, NS-BH mergers
  - BH-BH mergers may "only" produce GWs
- "Top-down": WIMPs, supermassive GUT relic particles, evaporating primordial BHs,...
  - Very important area of research, but not covered here

Figure from *Chandra/Harvard* webpage

High-Energy Astrophysical Messengers

Relative advantages and disadvantages:



High-Energy Astrophysical Messengers

Relative advantages and disadvantages:

Messenger	Sample size	Straight trajectory	Pointing resolution	Penetrat-ing
γ			$\ll 1^\circ$	$E_\gamma < 50$ TeV ($\gamma+\gamma_{IR}\rightarrow e^+e^-$)
ν	$\sigma_{\nu,matter} \ll 1$		$\sim 1^\circ$	
p, nuclei		***B*** fields	$\sim 1^\circ$	$E_p < 30$ EeV (GZK cutoff)
Grav. waves			$\sim 1000\ (^\circ)^2$ (only 2 detectors)	

What Has the High-E Universe Given Us So Far?

- GeV-TeV γ rays
  - satellites
  - IACTs
  - air shower arrays
- EeV-scale protons, nuclei
  - air shower arrays
- PeV-scale neutrinos
  - IceCube
- Grav. Waves
  - a-LIGO

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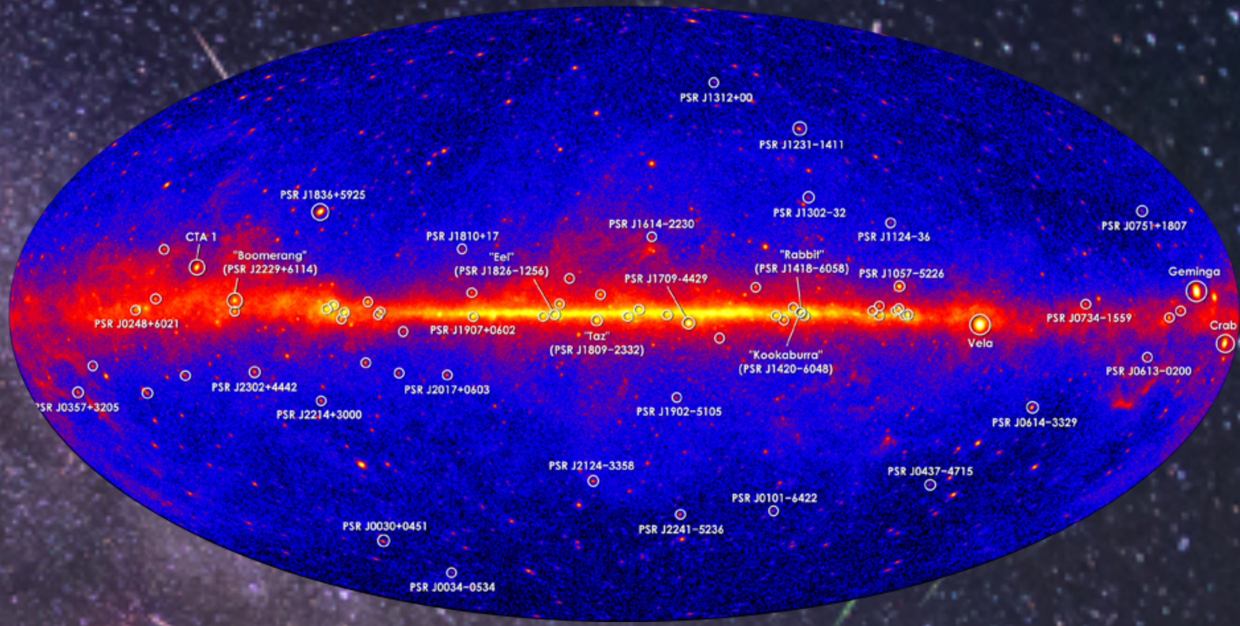

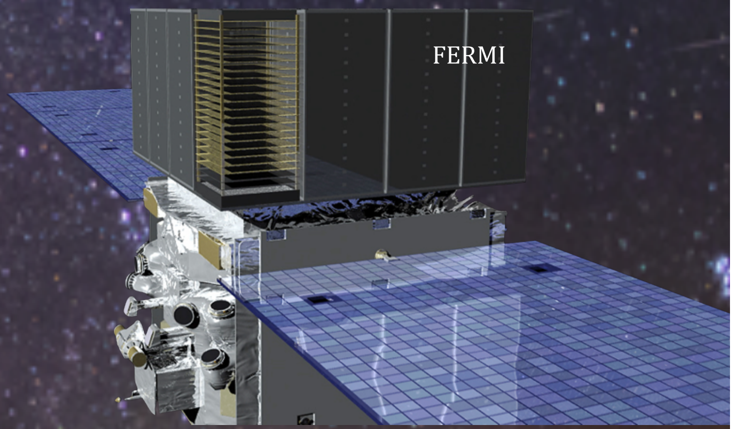

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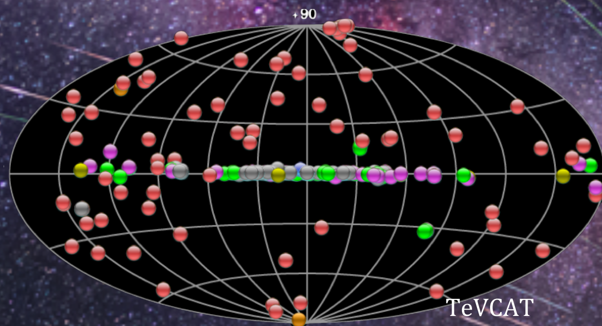

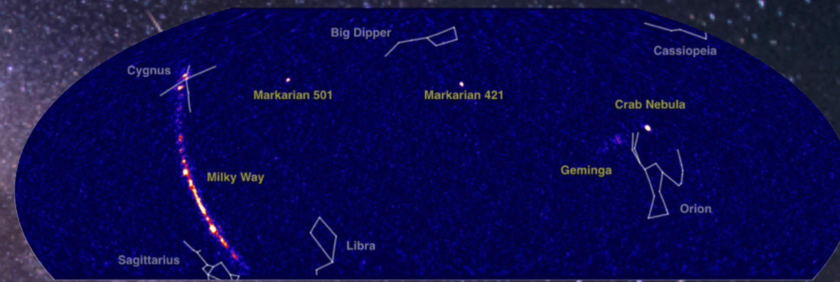

Daniel López

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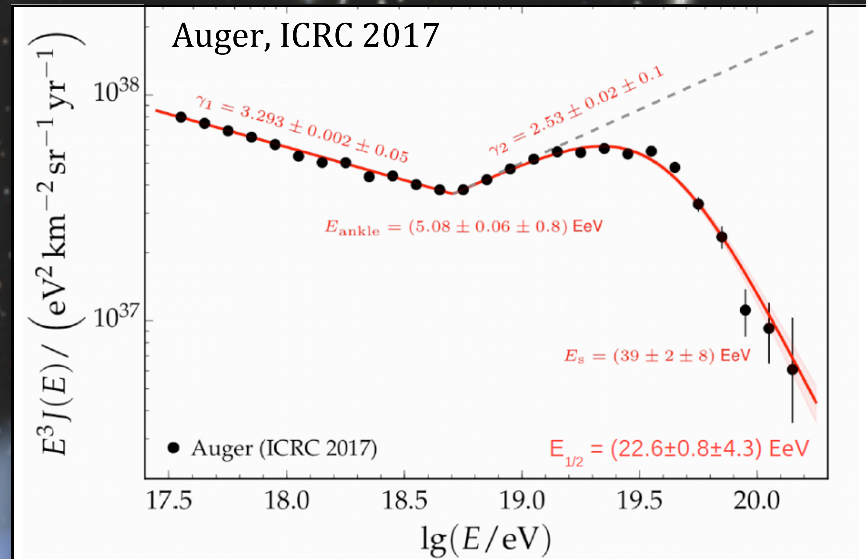

Pierre Auger, HiRes, AGASA, TA et al.

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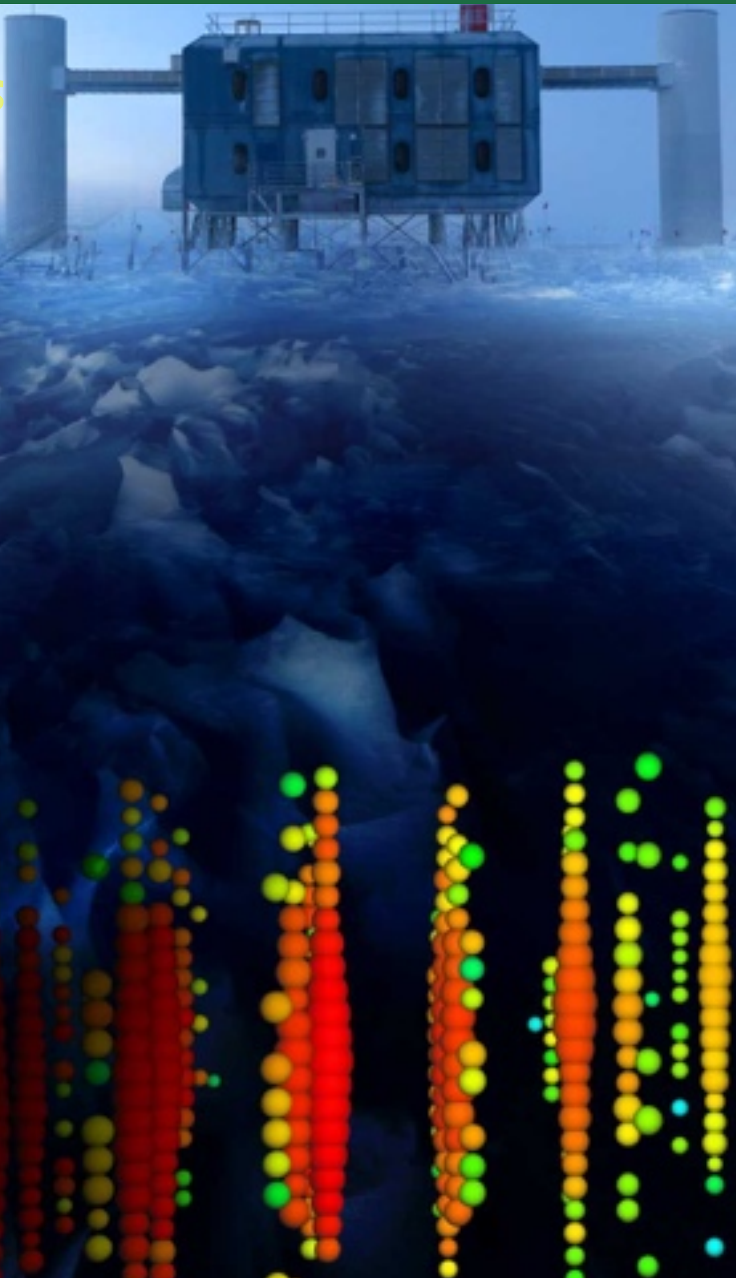

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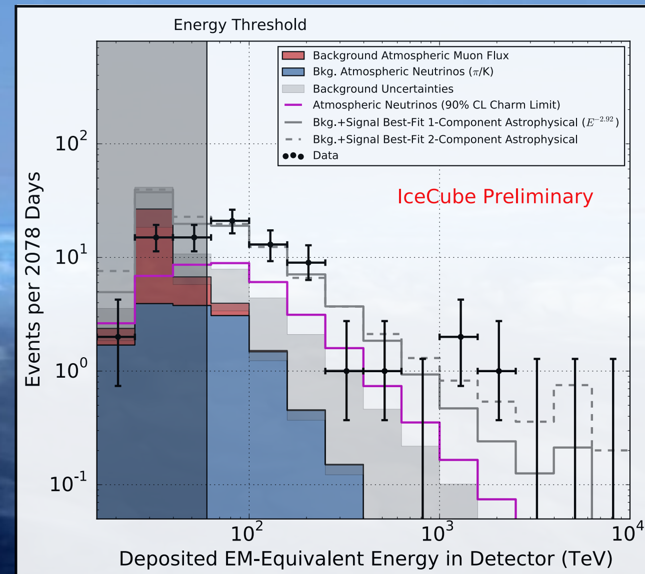

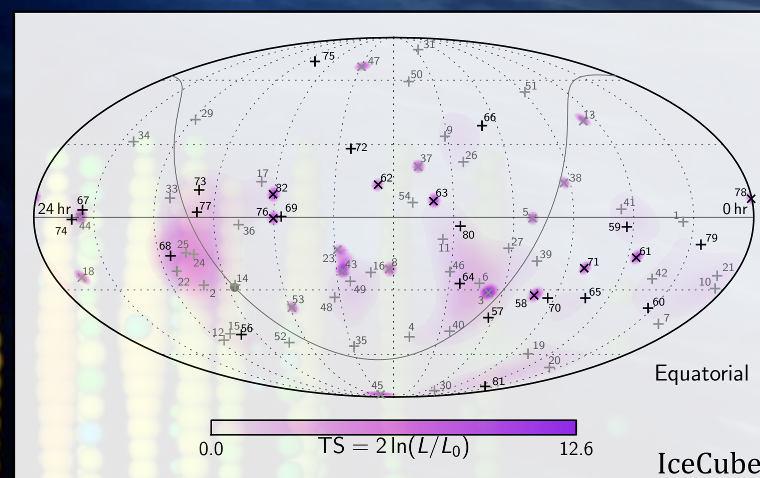

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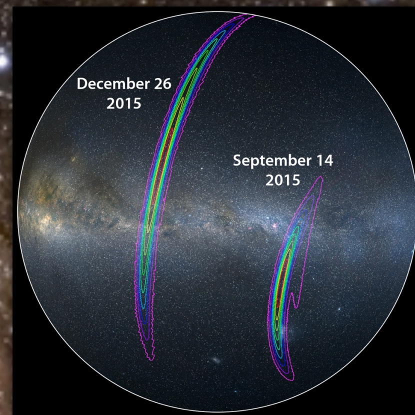
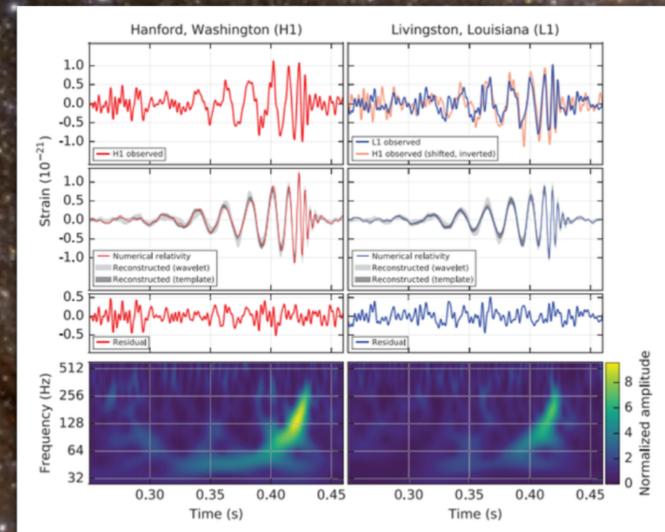
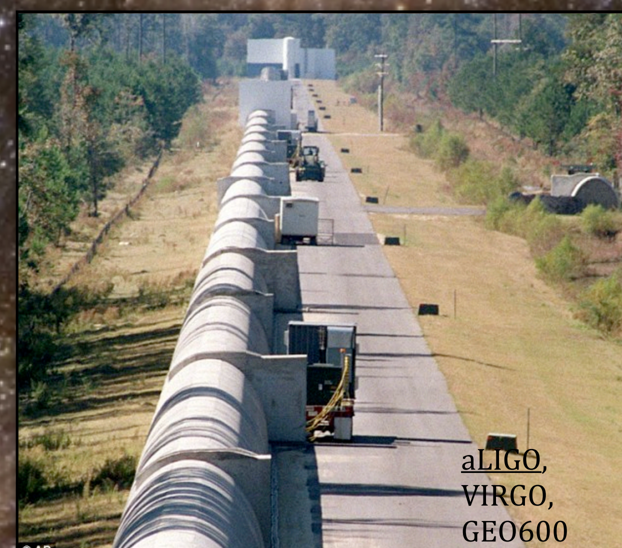
  - **aLIGO**







aLIGO, VIRGO, GEO600

Exciting Times for Particle Astrophysics!

- Thunderous gravitational waves
  - Discovered and studied, but no counterparts seen
- Elusive cosmic neutrinos unveiled
  - Discovered but no sources identified yet
- Persistently inscrutable cosmic rays
  - Discovered decades ago, provenance still unknown

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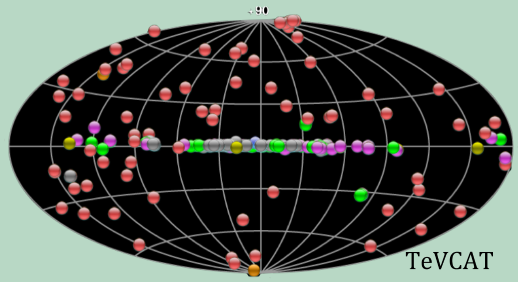
At high energies, why have we only been able to associate γ-rays with astrophysical sources?



Why Only γ-ray Sources So Far?

- In their first data runs, (ν, p, GW) detectors aimed first for standalone source discoveries
  - Successfully detecting rare events (~1/month) but no astrophysical sources identified
- Next step: send out strong individual detections for (mostly EM) follow-up
  - $\mathcal{O}(100)$ follow-ups have been performed: nothing found yet
- Standalone and follow-up searches have been ongoing for nearly a decade
  - Clearly must keep looking, but perhaps new strategies are needed

New Strategy: Medium→Long-Term

- Augment sensitivity of existing detectors, or add new detectors
  - Approved:
    - GW: aLIGO upgrades, VIRGO, GEO600, KAGRA, LIGO-India
    - p, nuclei: Telescope Array
  - Proposed:
    - p, nuclei: AugerPrime
    - ν: IceCube-Gen2/Phase 1
- Build larger, more sensitive detectors
  - Under construction:
    - γ-rays: CTA
    - ν: KM3NeT (partial)
  - Proposed:
    - ν: IceCube-Gen2

New Strategy: Medium→Long-Term

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    - p, nuclei: Au…
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- Bui… …e sensitive detectors
  - U… …nstruction:
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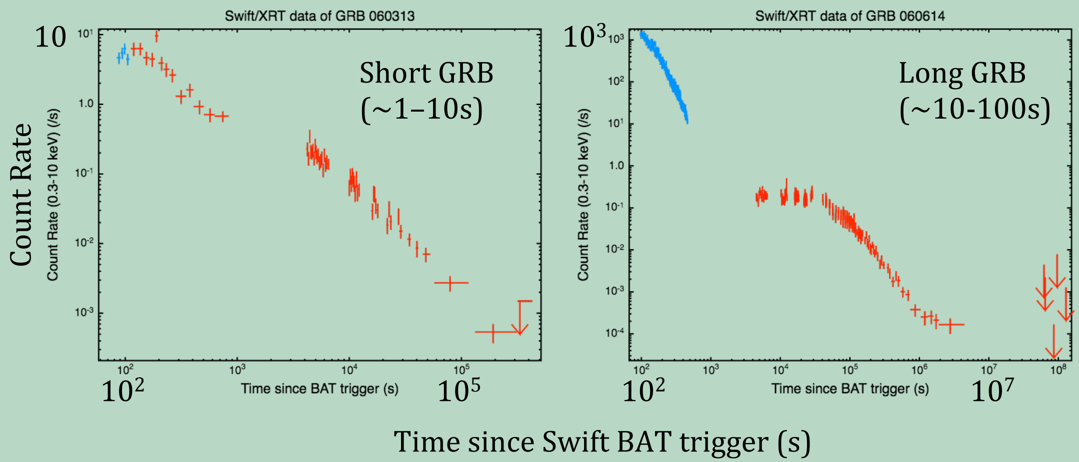
Waiting time: years

New Strategy: Short-Term

- Overcome rareness by lowering thresholds; exploit otherwise "unusable" data
  - Examples:
    - IceCube single muon neutrinos at lower energies
    - Single-interferometer LIGO data
  - Can we get S/N large enough to be useful?
- Emphasize transient sources: lower EM background
  - In any smallish region of space, there's always a few known sources
  - Can we gather (ν, p, GW) signals in real-time and trigger EM follow-up at sufficient low latency?



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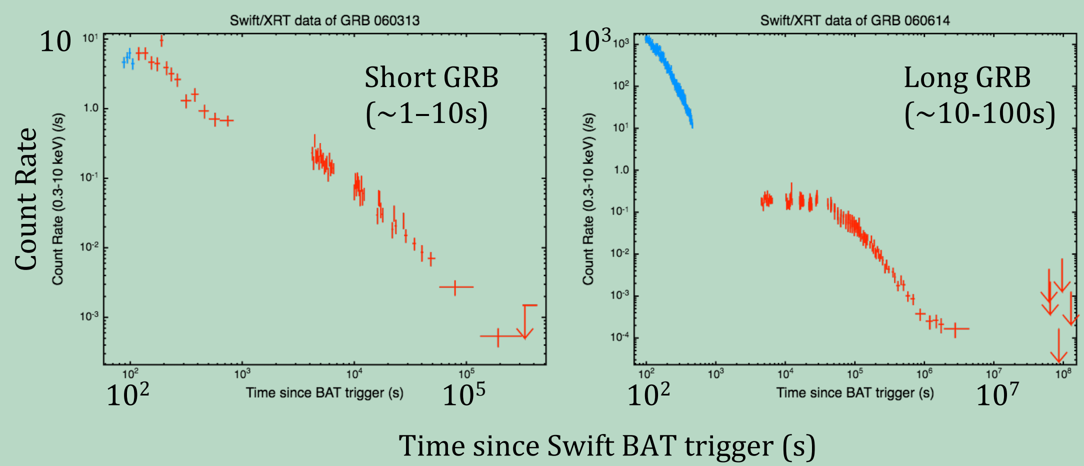
- Yes and yes.

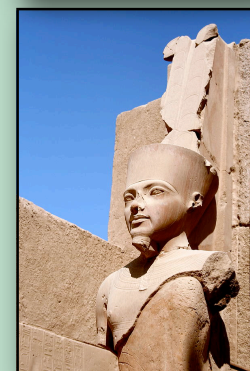


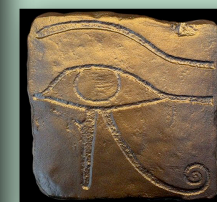
New Strategy: Short-Term

- Can do so by building a *multimessenger, real-time virtual observatory*
  - Pull together signals from disparate "triggering" detectors
    - E.g., IceCube(ν) + HAWC(γ)
  - Find coincidences in time and direction in real-time (& archivally)
  - Issue alerts for fast EM follow-up: catch fading transients & study them
- Benefits:
  - Powerful combination of
    - Wide field-of-view (FoV), 24/7 coverage of triggering observatories
    - High resolution of EM follow-up observatories
  - Can use "sub-threshold" data from triggering observatories
    - Otherwise low-significance data can rise in significance *if in coincidence with other data*
    - Note: This idea generalizes previous efforts, e.g. SNEWS for SNe ν
  - Supports higher than just pair-wise coincidence searches

Multimessenger Virtual Observatories

- Two efforts are now underway:
  - AMON (link)
    - Astrophysical Multimessenger Observatory Network (started ~6 years ago)
      - See *Astroparticle Physics* Vol. 45, 56-70 (2013)
  - ASTERICS (link)
    - Astronomy ESFRI* and Research Infrastructure Cluster (started ~2 years ago)
- Similar ideas and goals
  - Focus here on AMON



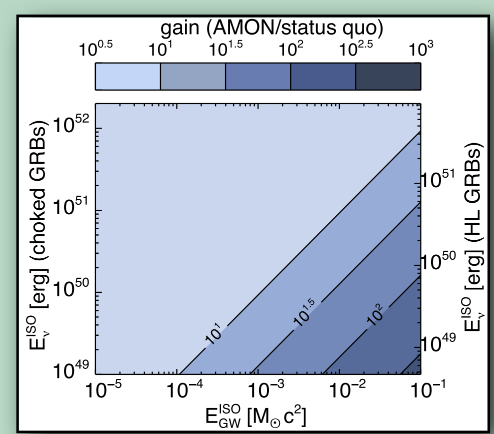


*European Strategy Forum on Research Infrastructures

AMON

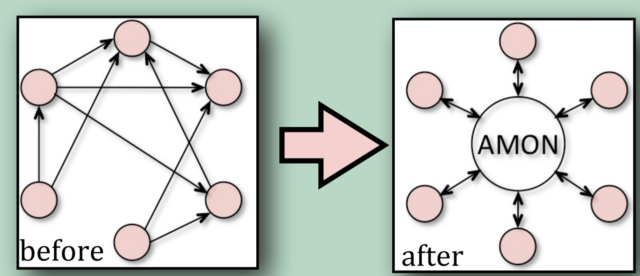
- Allows multiple particle astrophysics experiments to work in concert & share data to increase sensitivity to multimessenger transients
  - Provides low-latency, real-time system to
    - gather data
    - search for coincident multimessenger signals
    - issue alerts for rapid follow-up
  - Enables use of sub-threshold data
    - in real-time and archivally

Predicted sensitivity gain in sub-threshold GW-ν searches with AMON:



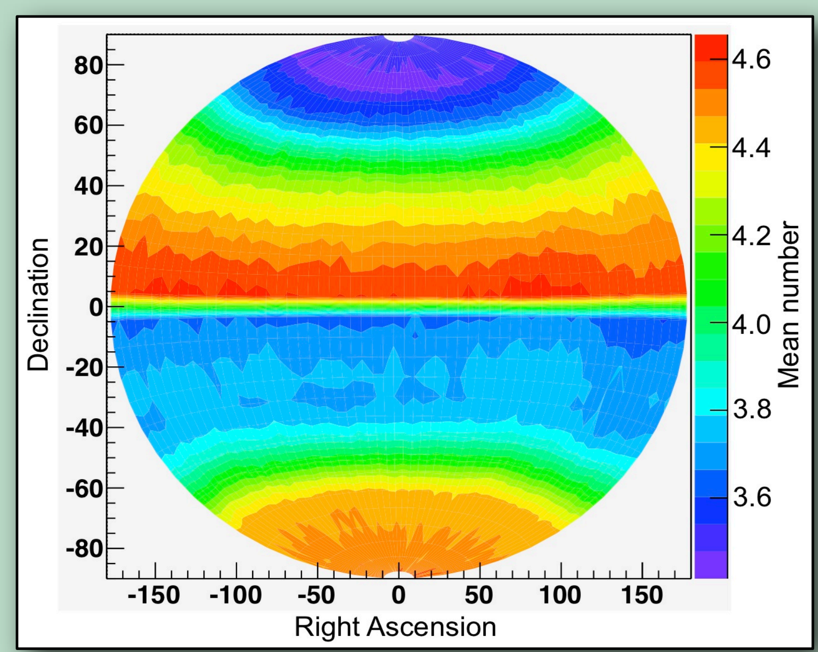
Astroparticle Physics Vol. 45, 56-70 (2013)

- Simplifies interfaces
  - Straightforward connection to GCN (γ-ray Coord. Network)
  - Standardized event transmission
  - Cleaner interconnect topology
  - Single MoU



Important Questions for AMON et al.

- Is someone else going to analyze my collaboration's data?
  - Each observatory retains full rights over use of its data (see AMON MoU)
  - All coincidence analyses require explicit permission of each participating collaboration
- Is the trigger latency small enough?
  - IceCube → Swift: $\mathcal{O}$(mins)
- Is the aggregate data rate manageable?
  - Individual datum: direction, time, quality parameters
  - Adjustable rates, aim for few/hr/observatory
    - Cf.: ~1/month for high significance events
  - Anticipate ~1 TB/yr of data
- Is the system on 24/7?
  - AMON uses two robust servers in separate physical locations, a clustered database,...
  - Achieved downtime of < 1 hr/yr
- Is there adequate sky coverage?
  - 94% of 4π sr-yr in FoV of 3 or more obs.
  - 2+ obs. view any given part of sky at same time



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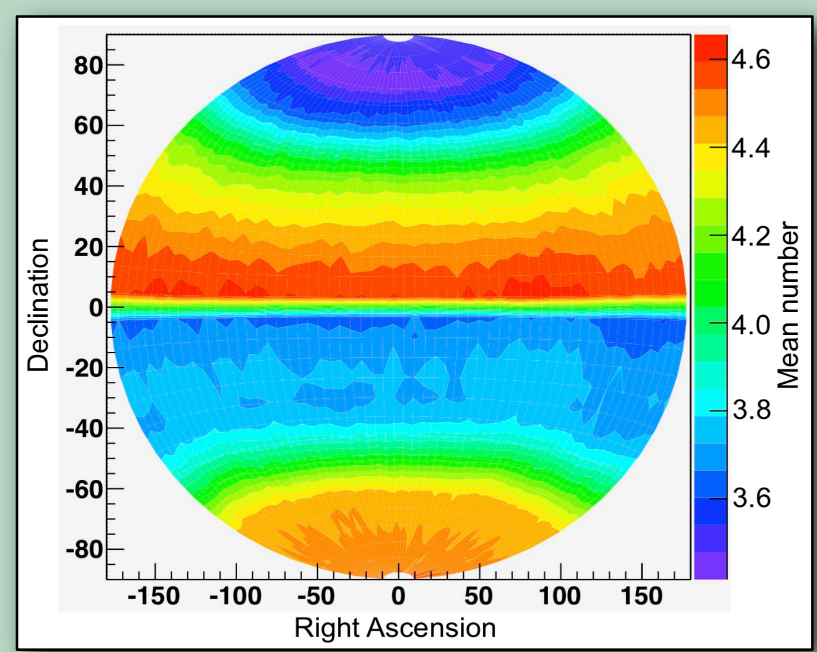
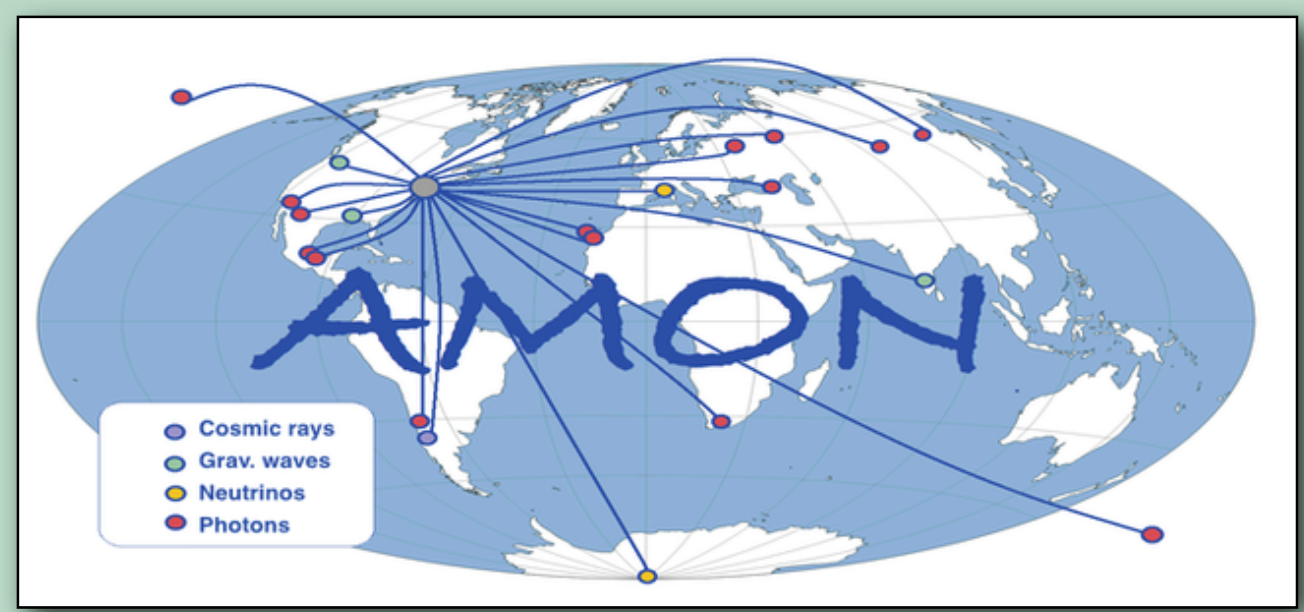


AMON

- Multiple *triggering* observatories have joined AMON:
  - ANTARES, Auger, FACT, Fermi, HAWC, IceCube, Swift BAT, LIGO/VIRGO
  - Are now, or will be, sharing sub-threshold data in real time
  - Many are wide–FoV, 24/7 instruments



- Multiple *follow-up* observatories have also joined:
  - FACT, MASTER, Swift XRT & UVOT, VERITAS
  - Have already started performing follow-up observations of AMON-brokered alerts

Results

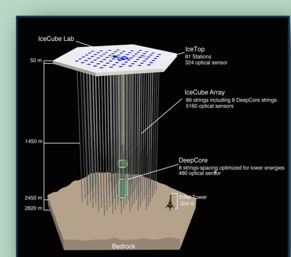
- Initially enabling archival analyses (“walk before we run”):
  - Fermi LAT + IC40 (A. Keivani et al., PoS(ICRC2015)786 (2015))
  - Fermi LAT + IC40/59 (C. F. Turley et al., in preparation)
  - Primordial black hole search (G. Tešić, PoS(ICRC2015)328 (2015))
  - VERITAS Blazars + IC40 (C. F. Turley et al., ApJ 833, 117 (2016))

- Now starting to enable real-time analyses:
  - Swift XRT/UVOT + IceCube HESE (A. Keivani et al., in preparation)
  - Swift BAT + IceCube sub-threshold ν’s (analysis starting)
  - HAWC sub-threshold + IceCube sub-threshold ν’s (starting)
  - Auger + IceCube sub-threshold ν’s (starting)
  - IceCube Triplet ν follow-up (IceCube Collab., submitted to A&A)

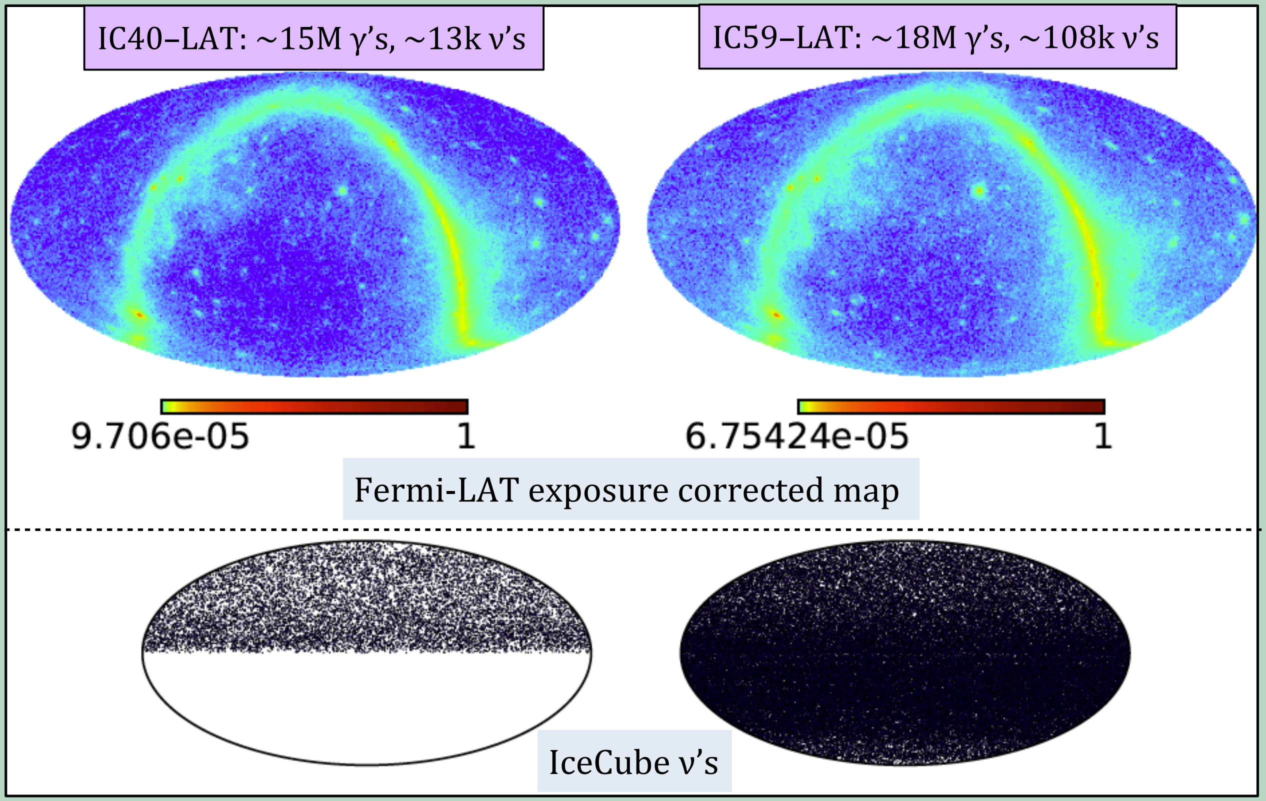
- For these efforts, AMON provides/provided (since April 2016)
  - a software framework for real-time coincidence analyses & alert emission
  - a database populated with private and public data from numerous observatories
  - a “pass-through” service for sending out alerts via GCN
    - E.g., IceCube’s High-Energy Starting Event (“HESE”) data

Example AMON-Enabled ν+γ Analysis

Event clustering: $\Delta\theta < 5°$ and $\Delta t = t_0 \pm 50$ s



(IC40, IC59)



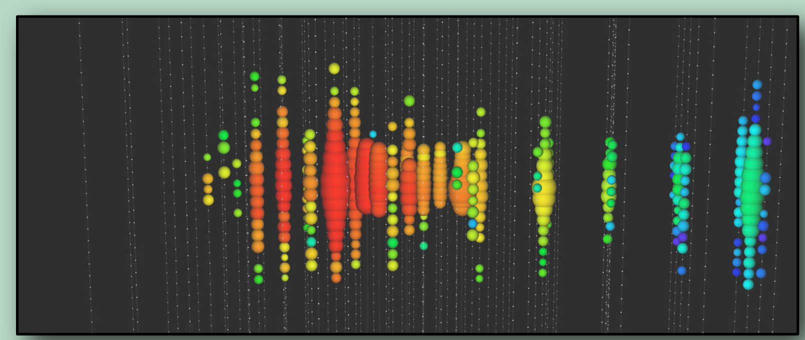
IC40–LAT:
Data: 2138 γ+ν pairs
BG: 2207±40 γ+ν pairs
p-value: 15%

IC59–LAT:
Data: 9025 γ+ν pairs
BG: 9077±153 γ+ν pairs
p-value: 9%

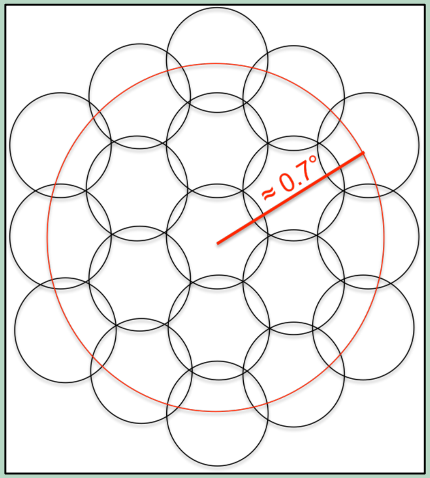
A. Keivani et al., PoS(ICRC2015)786 (2015) (w/pass 7)
C. F. Turley et al., in preparation (w/pass 8)

Example AMON-Enabled Real-Time Analysis

- IceCube track-like HESE alerts
  - Sent to AMON (~12/yr) in real time
    - Broadcast via GCN to ~50 subscribers
    - See GCN AMON page for details
  - AMON-based code down-selects ~4/yr
    - Swift time is valuable!
- Swift performs follow-up, auto-tiling sky around reported ν_μ direction
  - Total observing request ~90ks



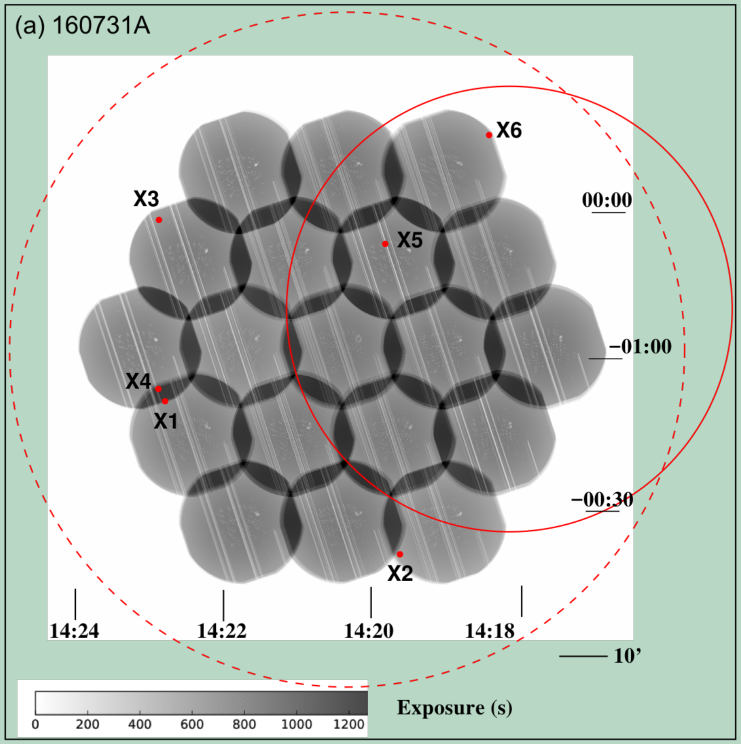
Example track-like HESE: ~1° pointing resolution.



Swift tiling pattern

Example AMON-Enabled Real-Time Analysis

- Swift images are then automatically analyzed for new or fading UV or x-ray sources
  - Swift then performs follow-up of ~2 possible sources
- IceCube-160731A:
  - Swift slewed within ~1 hr
  - Covered ~2.1 deg^2
  - Saw 6 x-ray sources:
    - all known
  - Saw no transients



Summary of AMON-Brokered Public IceCube Real-time HESE/EHE 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						

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

Conclusions

- Fantastic new particle astrophysics detectors have put high-energy multimessenger astronomy at our fingertips
  - All we need are some source detections!
- No luck so far under current paradigms (standalone, or bilateral & unidirectional)
- AMON (and ASTERICS) expand multimessenger discovery space
  - Establish bidirectional, multilateral connections in real-time (and archivally)
  - Unleash sub-threshold data
    - HAWC+IceCube (γ+ν) real-time sub-threshold coincidence analysis ready
  - Simplify multimessenger effort via common xfer protocol, data format, event database and MoU
  - The world's particle astrophysics detectors are an aggregate investment of ~$\$10^9$, so even a small increase in sensitivity is a worth it
  - New partners welcome

Conclusions

- Fantastic new particle astrophysics detectors have put high-energy multimessenger astronomy at our fingertips
  - All we need are some source detections!
- No luck so far under current paradigms (standalone, or bilateral & unidirectional)
- AMON (and ASTERICS) expand multimessenger discovery space
  - Establish bidirectional, multilateral connections in real-time (and archivally)
  - Unleash sub-threshold data
    - HAWC+IceCube ($\gamma+\nu$) real-time sub-threshold coincidence analysis ready
  - Simplify multimessenger effort via common xfer protocol, data format, event database and MoU
  - The world's particle astrophysics detectors are an aggregate investment of ~$\$10^9$, so even a small increase in sensitivity is a worth it
  - New partners welcome
- *Every time we look at the heavens in a new way, discoveries usually ensue!*

Backup

Potential Sources

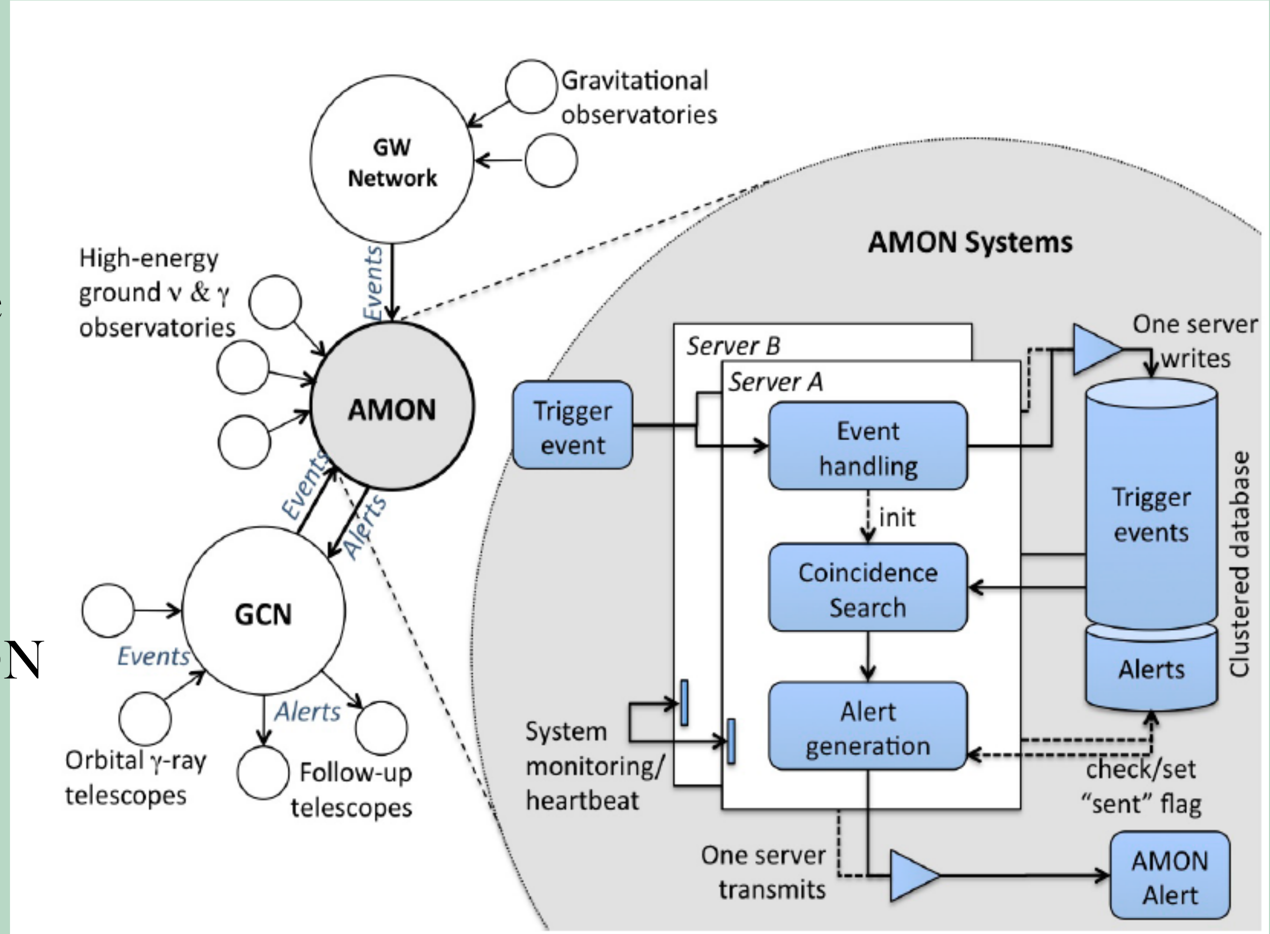
	Prompt				Delayed		
Event class	γ	ν	n	gw	x	IR/O/UV	Radio
High-luminosity GRBs (HL-GRB)	✔	✔		✔	✔	✔	✔
Low-luminosity GRBs (LL-GRBs)	✔	✔		✔	✔	✔	✔
Short-hard GRBs (SHBs)	✔	✔		✔	✔	✔	✔
Choked jet SN		✔		✔	✔	✔	✔
Core-collapse SN		✔	✔		✔	✔	
Blazars	✔	✔			✔	✔	✔
Primordial black holes (PBHs)	✔	✔	✔				
Other exotica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

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
Swift BAT	✓	Not needed	Not needed	Not needed	✓
Fermi LAT	✓	Not needed	Not needed	Not needed	✓

Multimessenger Transient Source Candidates

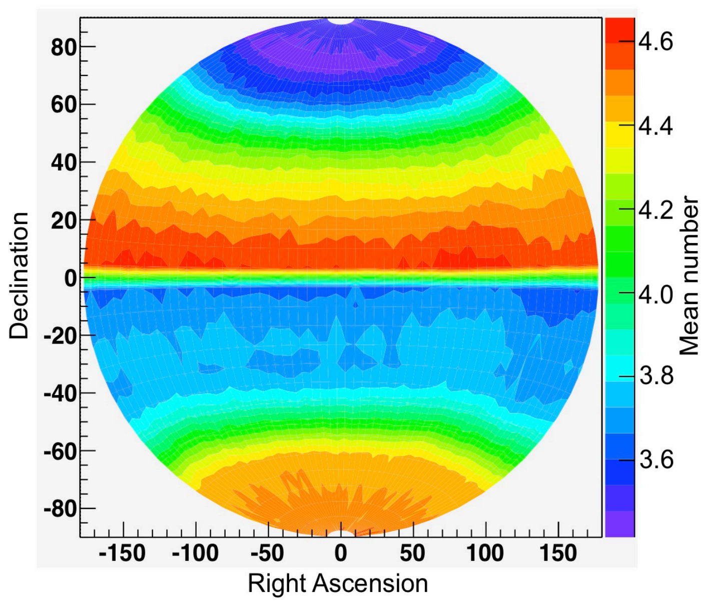
- High-Luminosity Gamma-Ray Bursts:
  - long duration
  - high luminosity
  - seconds to minutes γ-radiation
  - $z > 1$
  - relativistic jet
- Low-luminosity Gamma-Ray Bursts:
  - long duration
  - under-luminous
  - $z < 0.5$
- Short-Hard Gamma-Ray Bursts
  - similar to HL-GRBs
  - shorter duration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

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

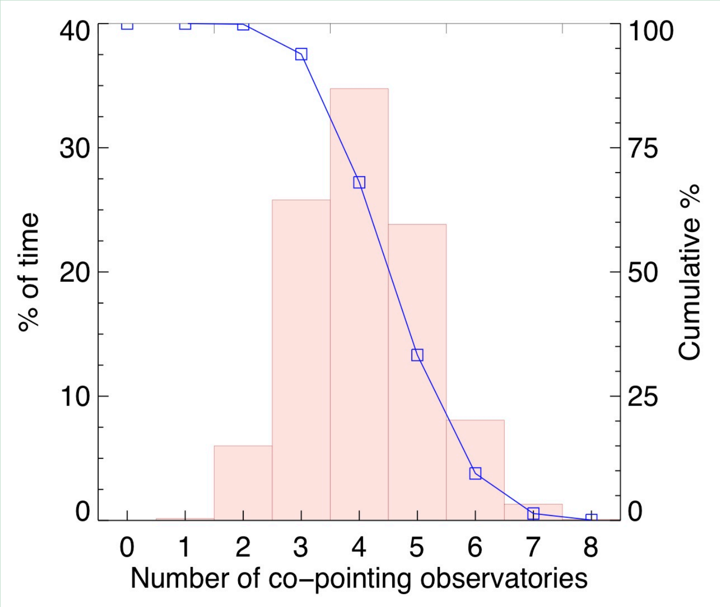
Field of View

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

AugerPrime

The upgrade will consist of
● enhanced surface detector stations (SSD),
● faster electronics,
● dedicated underground muon detectors and
● optimized operations for the fluorescence telescopes.

Ten more years of operation is planned to double the data set and to particularly study:

• The origin of the flux suppression at ultra-high energy,
• The proton contribution at highest energies (E > 6.10^{19} eV), leading to a so-called "particle astronomy"
• New particle physics beyond the reach of the LHC

Archival vs. Realtime Analysis

	Pros	Cons
Archival studies	• Precise event properties: position, localization, false positive rate • Construct statistical tools/ methods (needed for realtime analyses)	• Too late to do additional observations in case of a significant signal
Realtime studies	• Rapid followup of events and alerts • Discovery potential of transient sources and extended followup observation	• Use only fast online tools • Larger uncertainties • Harder to reject background events

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, IceCube (private)
  - In progress: LIGO S5 and S6 (public)
  - Awaiting approval: 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

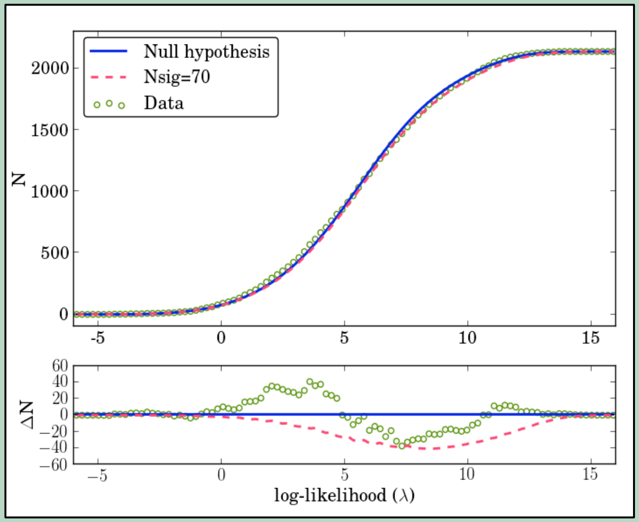
AMON hardware

- Two new high-uptime servers
  - Now deployed at Penn State; < 1 hr/yr downtime
  - Physically and cyber secure; fully redundant systems

Analysis I: IceCube-Fermi LAT II

- Scramble IceCube data in time and right ascension to study background:
  - Only scramble IceCube neutrinos: gamma event stream is more complicated due to LAT motion
  - Keep neutrino's energy, position reconstructed uncertainties and declinations
  - Use 10,000 scrambled data sets plus a series of signal tests
- Test statistic: Unbinned log-likelihood function

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



- Result:
  - IC40 – Fermi LAT:
    - Data: 2138 γ+ν pairs
      BG: 2207±40 γ+ν pairs
      p-value: 15%
  - IC59 – Fermi LAT:
    - Data: 9025 γ+ν pairs
      BG: 9077±153 γ+ν pairs
      p-value: 9%
  - Clustering of detected pairs, time distribution and multiplicity are consistent with background expectation

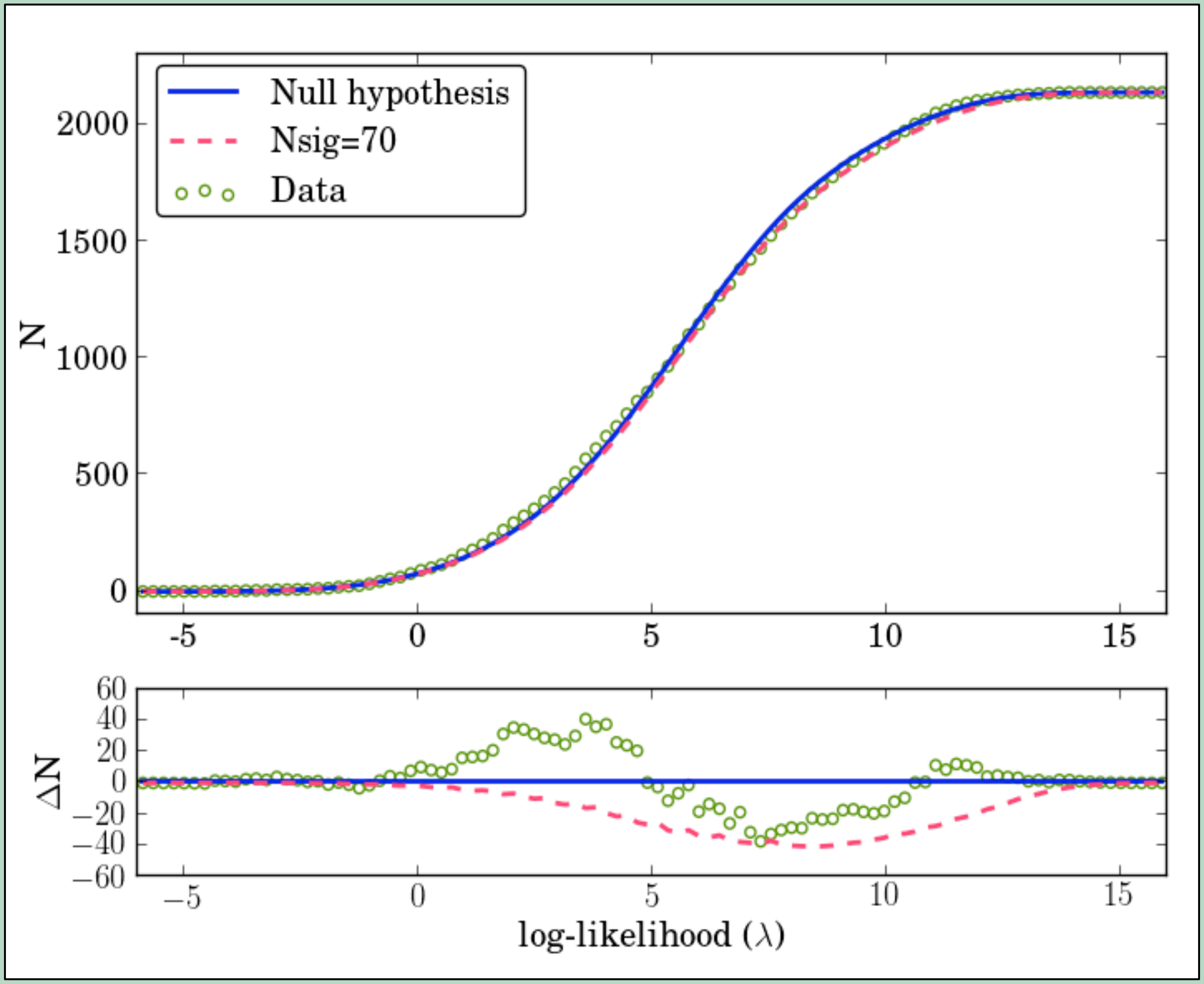
Analysis I: IceCube-Fermi LAT III

Un-blinding: Results from pass 7 Fermi LAT:

- IC40 – Fermi LAT:
  Data: 2138 γ+ν pairs
  BG: 2207±40 γ+ν pairs
  p-value: 15%

- IC59 – Fermi LAT:
  Data: 9025 γ+ν pairs
  BG: 9077±153 γ+ν pairs
  p-value: 9%

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

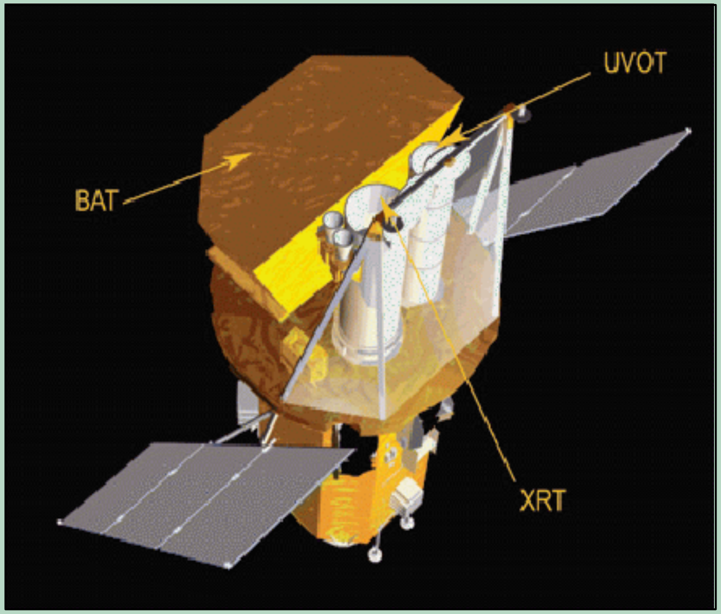


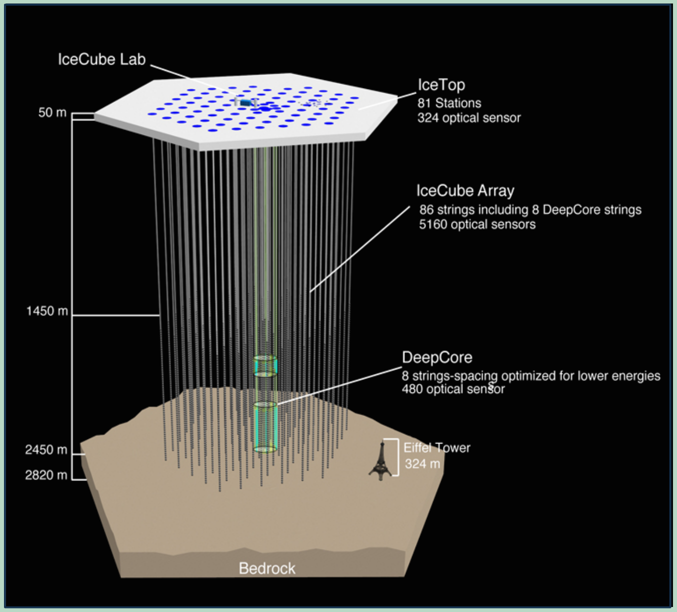
Results from pass 8 Fermi LAT in preparation

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

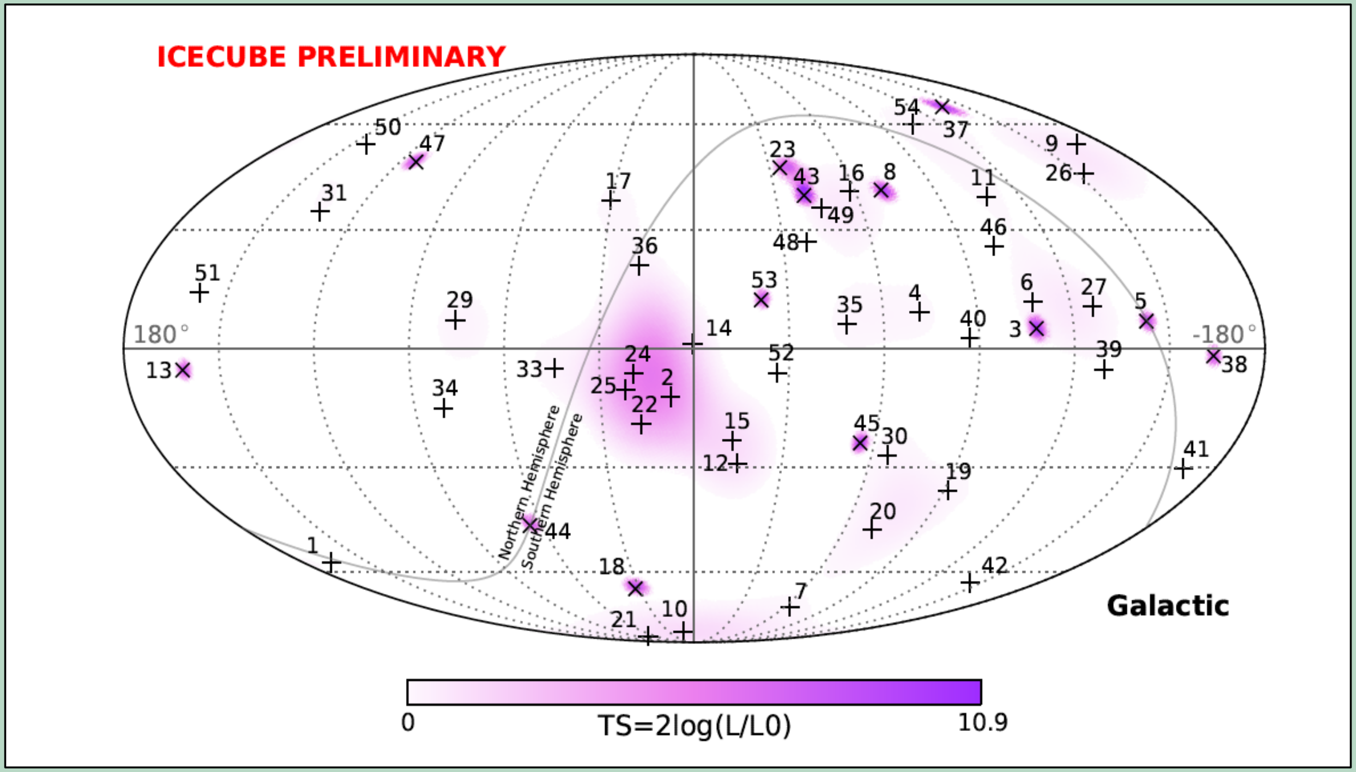
Analysis II

Seeking sources of IceCube high-energy neutrinos with Swift





Analysis II:
IceCube Detection of High-Energy Neutrinos

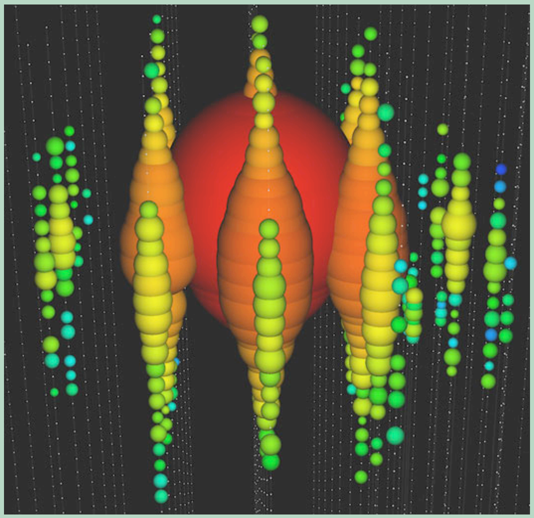


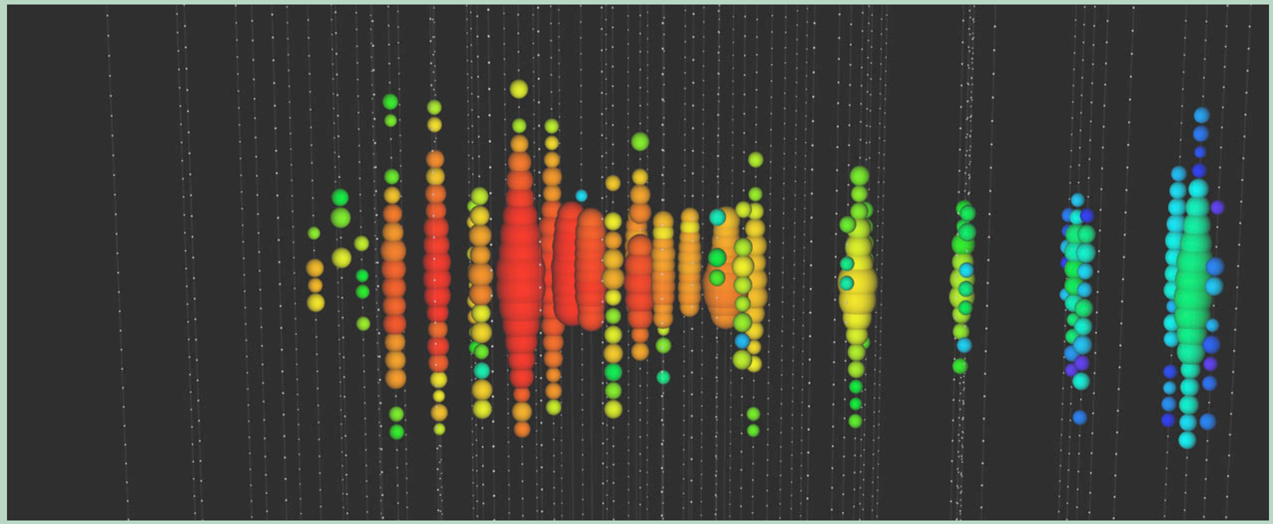
54 High-Energy Starting Events (HESE) in 4 years of data:

- 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

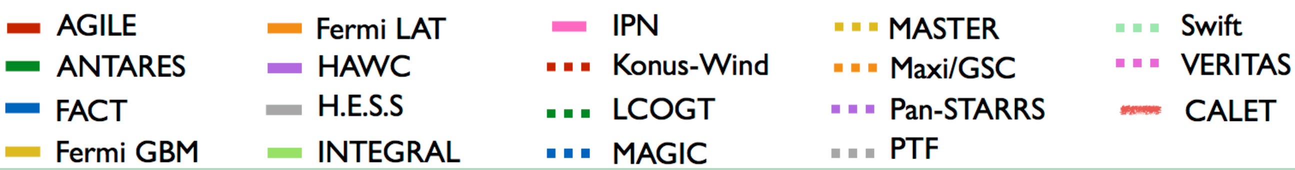
- Only track-like High Energy Starting Event (HESE) that are likely astrophysical
- 4 alerts per year: 1 signal-like and 3 background like
- Fast alerts (median time delay 40 seconds)
- Distribute timestamps, RA/Dec, angular error, charge deposited and probability of an event being signal-like and track-like
- 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

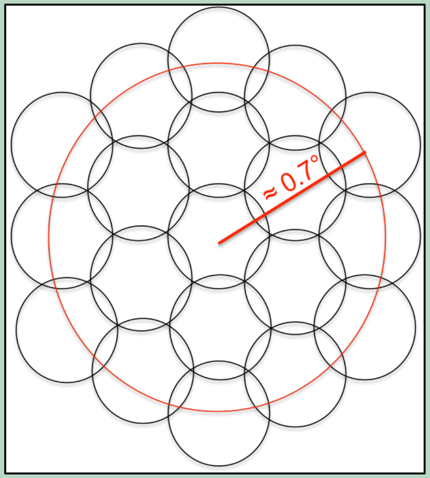
Alert name/type	161103/HESE	160814A/HESE	160806A/EHE	160731A/HESE	160731A/EHE	160427A/HESE
RA/DEC (rev1) RA/DEC (rev2)	[40.87°, 12.62°] [40.83°, 12.56°]	[199.31°, -32.02°] [200.25°, -32.35°]	[122.80°, -0.73°] [122.81°, -0.81°]	[215.11°, -0.46°] [214.54°, -0.33°]	[215.09°, -0.42°] [214.54°, -0.33°]	[239.66°,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

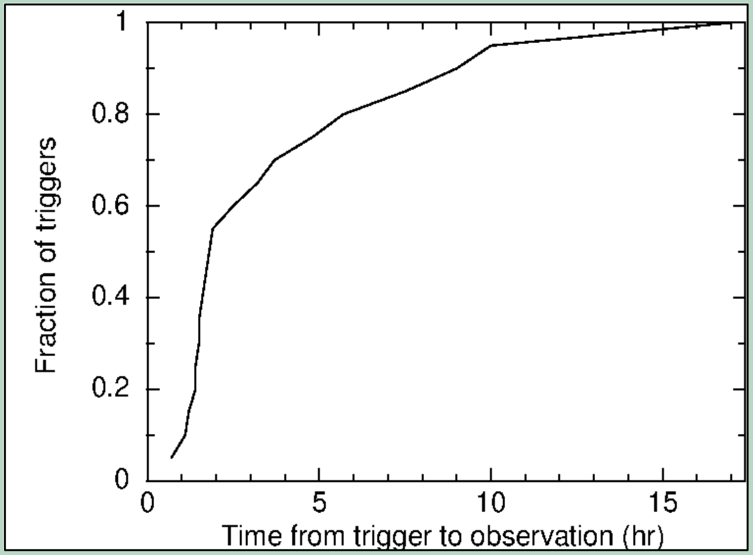


Analysis II: Swift an Ideal Follow-up Facility

Our proposal:

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



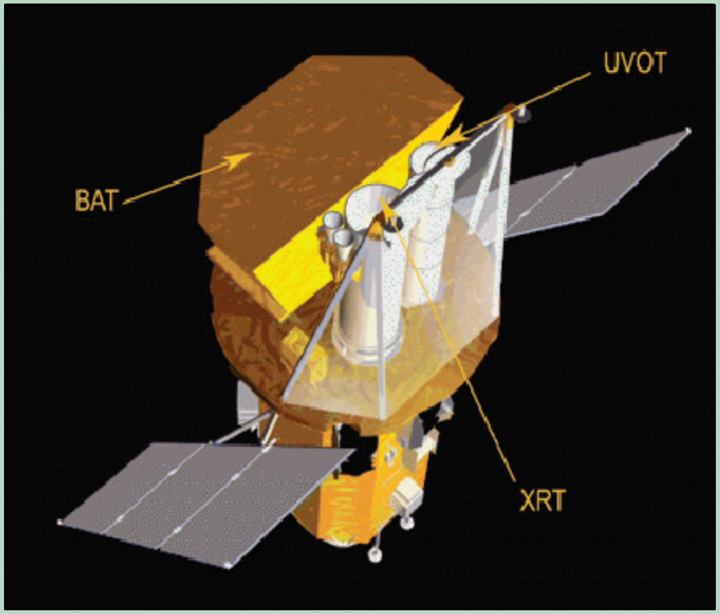


Evans, P. A. et al, 2015 MNRAS, 448, 3.

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

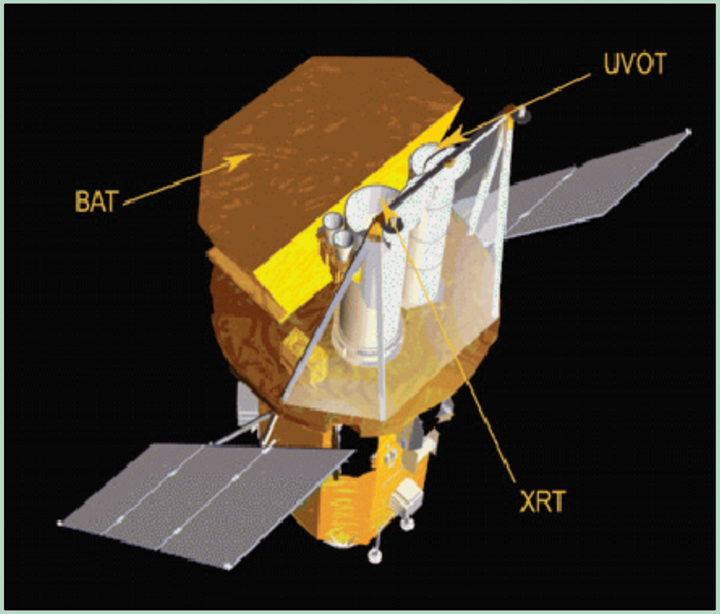
Analysis II:
Follow-up Plan I

- 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

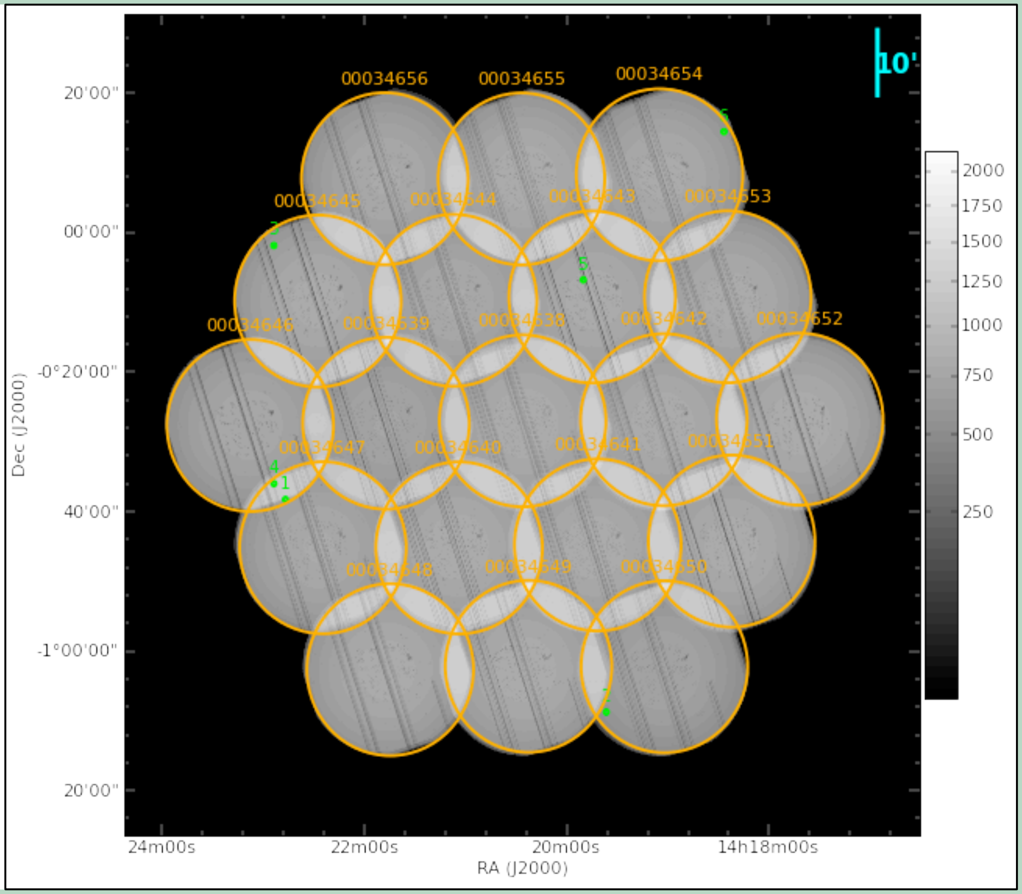
- Automated analysis of the XRT data: University of Leicester (Phil Evans)
- Sources selected for subsequent monitoring:
  - Bright and previously uncatalogued X-ray source
  - Variability over the course of the tiling observations
- Search UVOT data for new and interesting/variable sources to submit 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

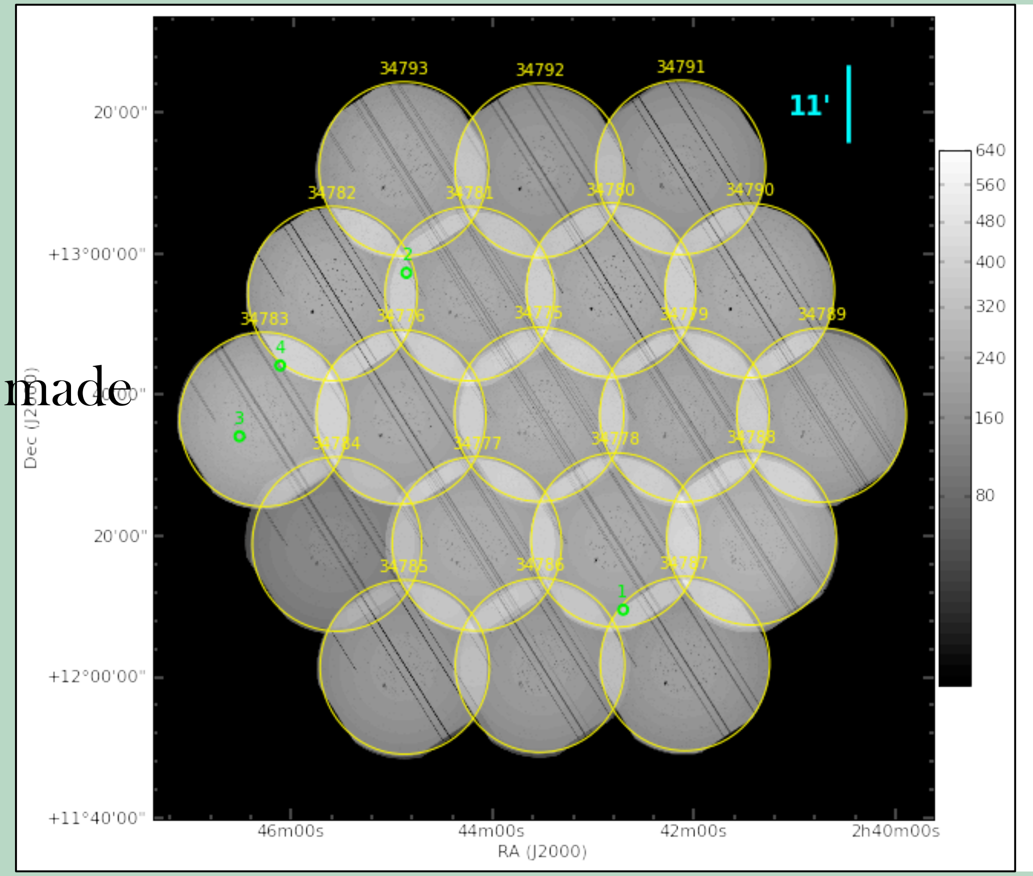
- IceCube-160731A:
  - 2016 July 31
  - (RA, Dec) = (215.109°, -0.458°)
  - Error 1.2°
- Swift followed up this event within about an hour
- Radius of 0.8°
- Observations:

  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

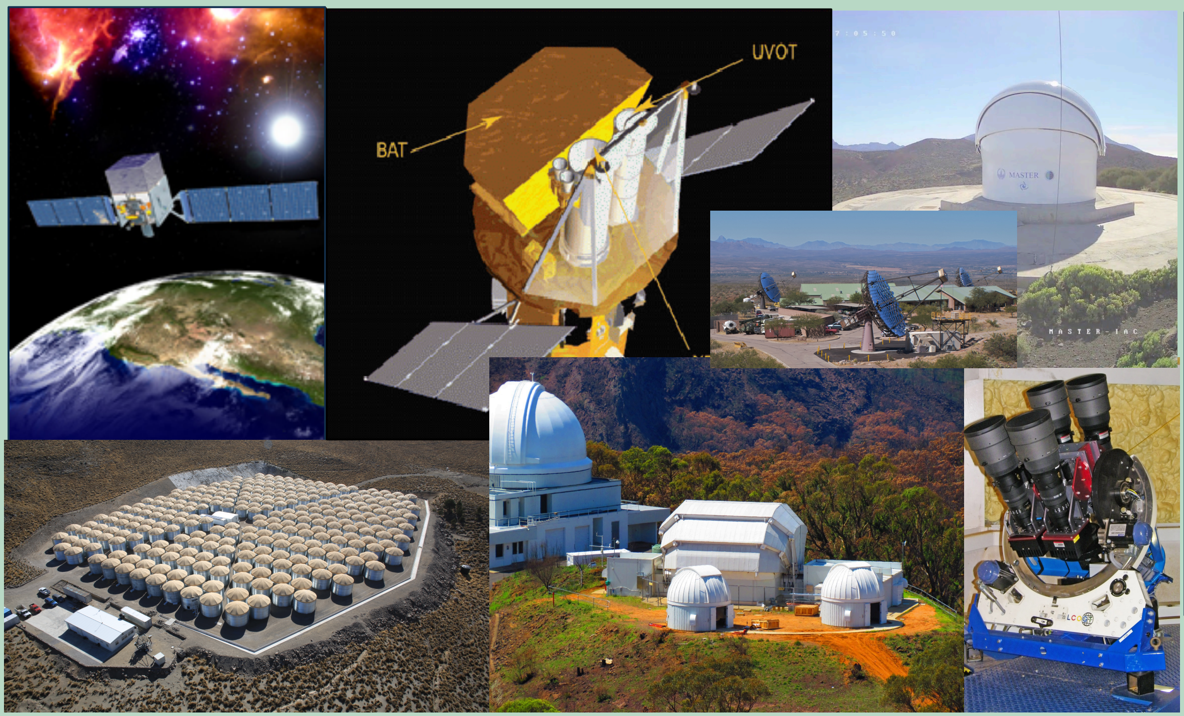
- IceCube-170321A: https://gcn.gsfc.nasa.gov/gcn3/20964.gcn3
- IceCube-170312A: https://gcn.gsfc.nasa.gov/gcn3/20890.gcn3
- IceCube-161103A: https://gcn.gsfc.nasa.gov/gcn3/20125.gcn3
- IceCube-160731A: https://gcn.gsfc.nasa.gov/gcn3/19747.gcn3

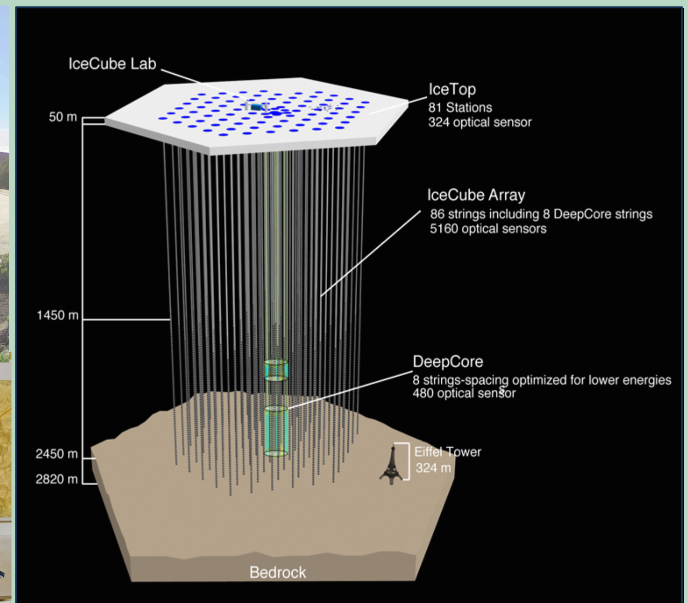
No significant counterpart has been discovered

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)

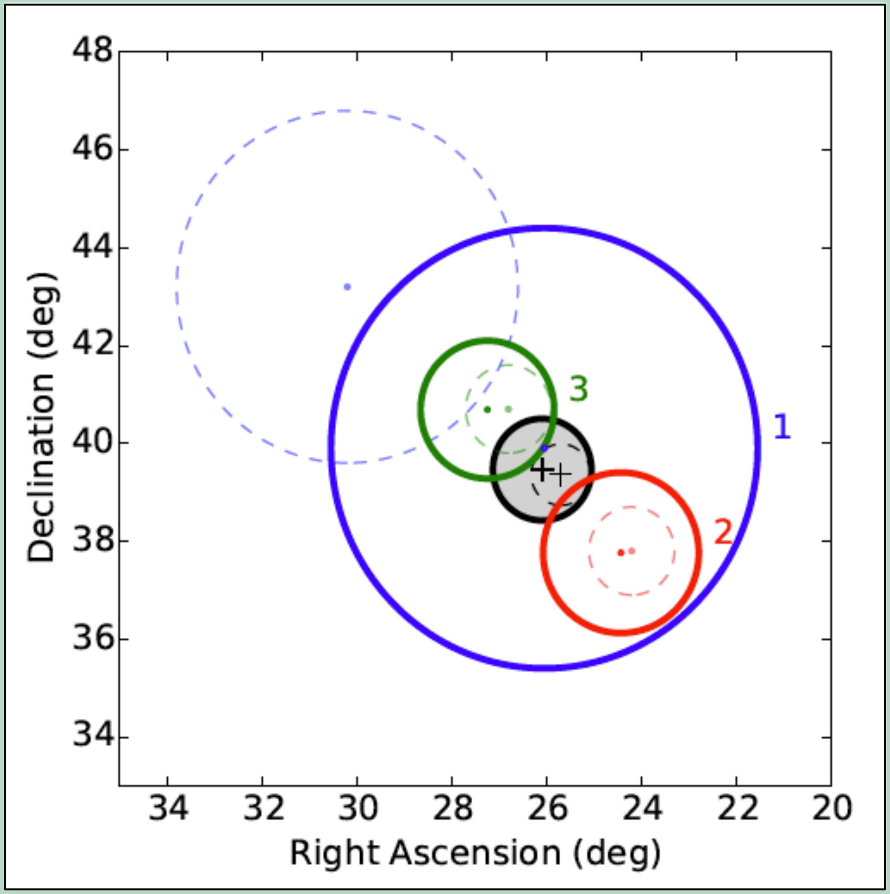
Multiwavelength follow-up of a rare IceCube neutrino multiplet





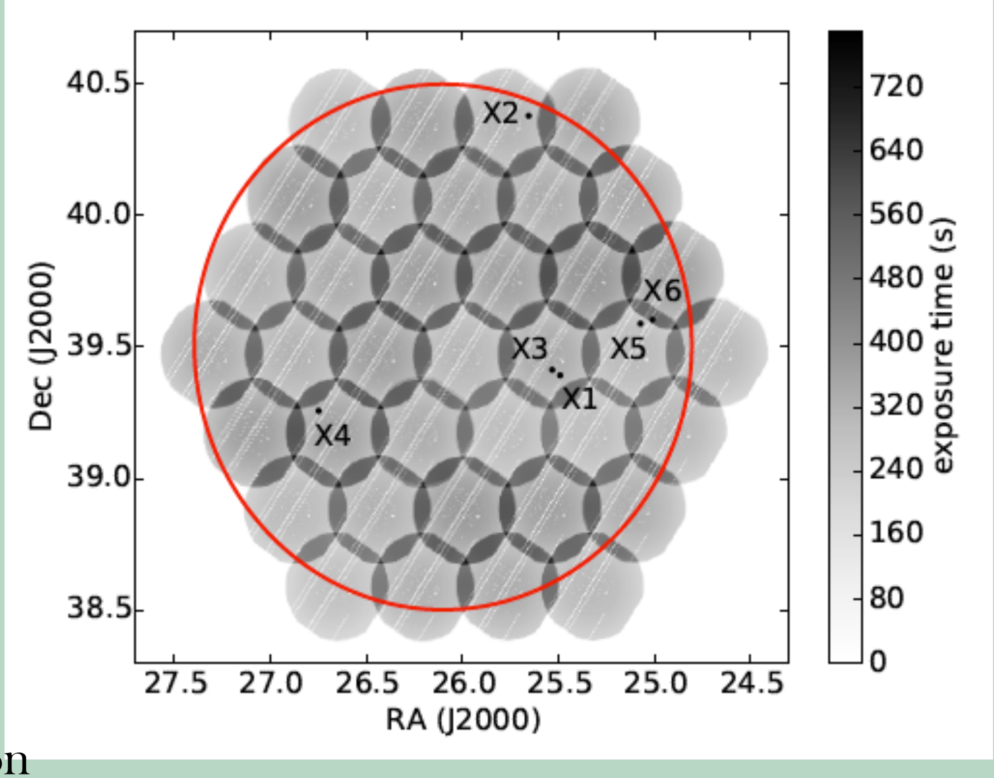
Analysis III:
IceCube Neutrino Multiplet

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



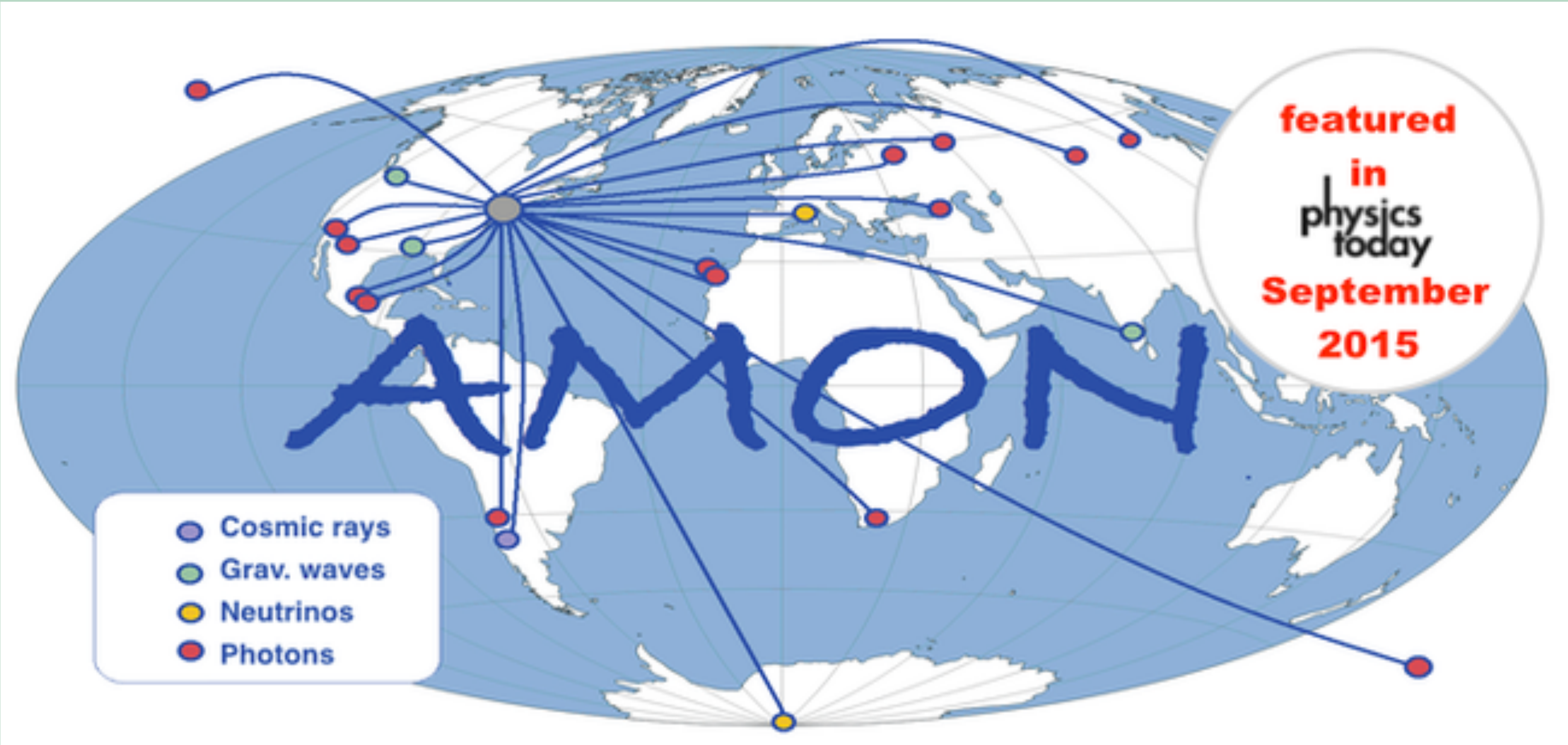
Analysis III: IceCube Neutrino Multiplet – Swift Searches

- 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}

Thanks



AMON
featured in physics today September 2015
Cosmic rays
Grav. waves
Neutrinos
Photons