The Dawn of Multimessenger Astronomy

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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
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In this talk we focus on high energies

Motivations

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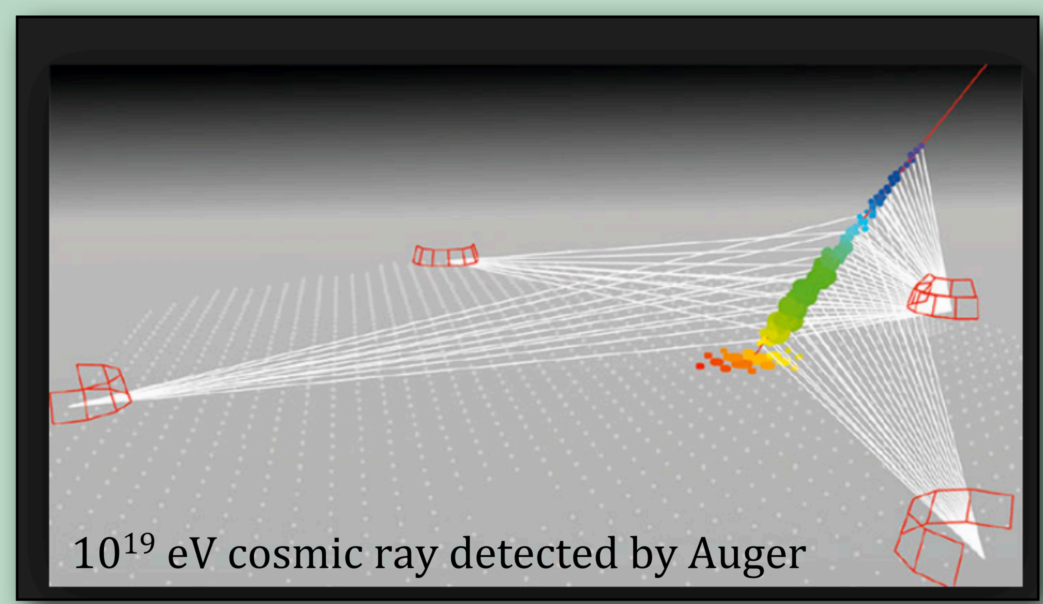
What makes these?



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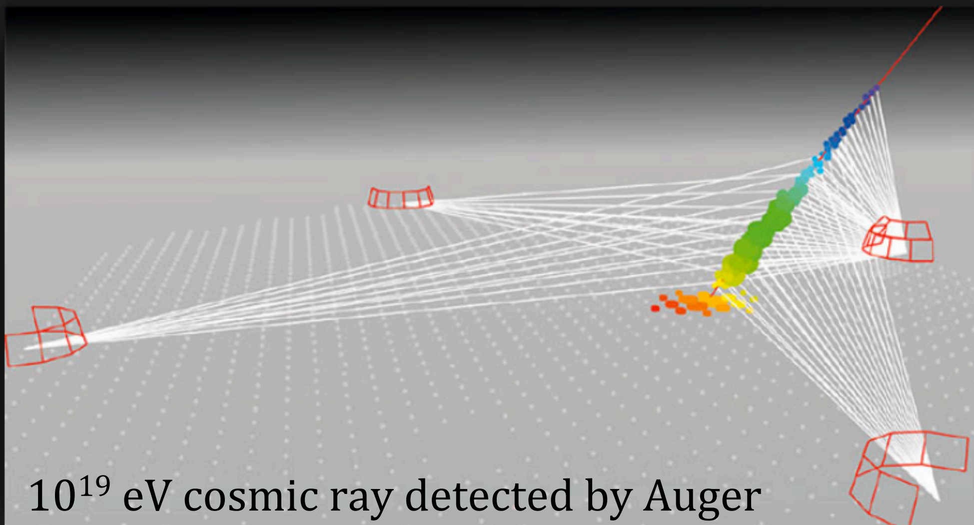
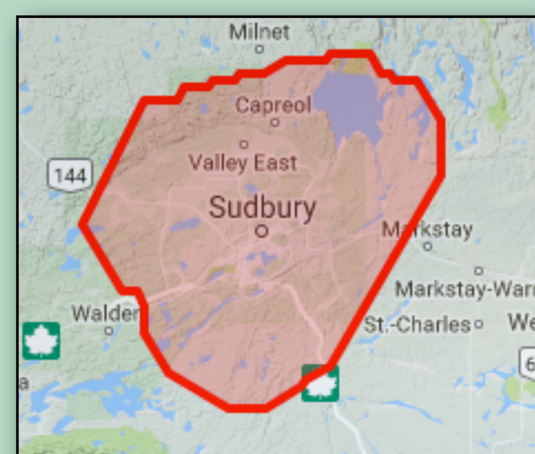


10^{19} eV cosmic ray detected by Auger

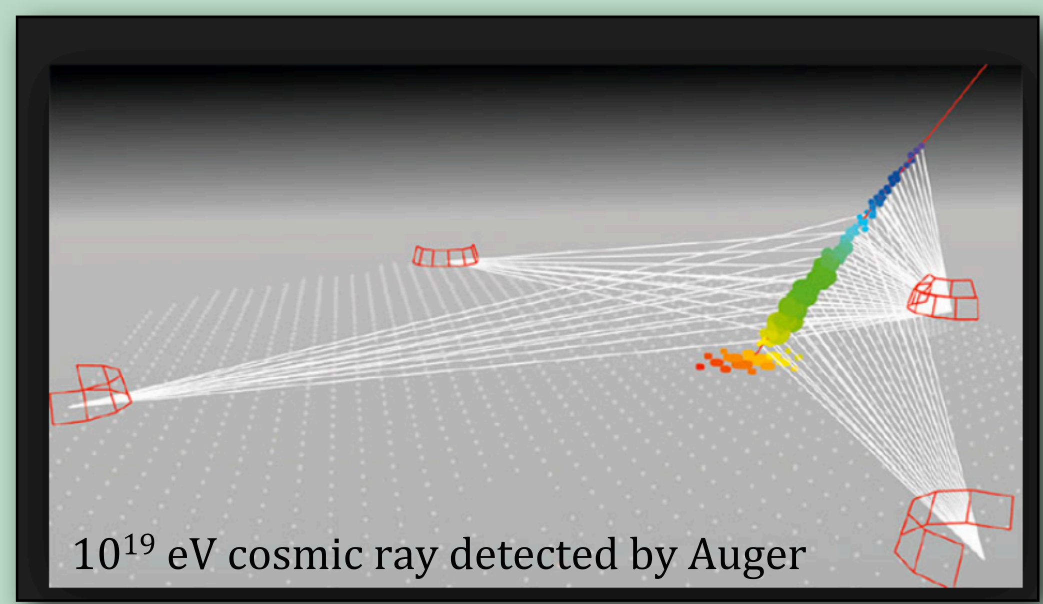


Auger superimposed on Sudbury

Motivations

What makes these?

And these?



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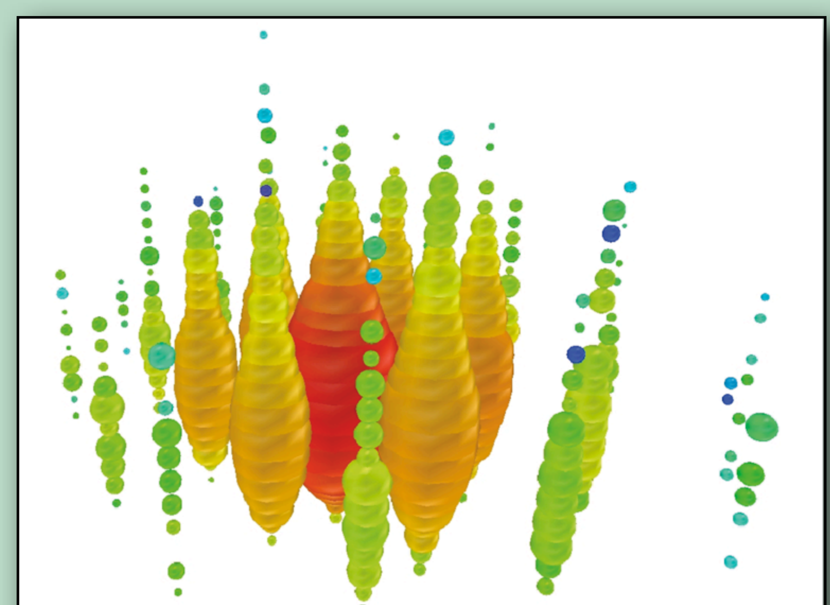

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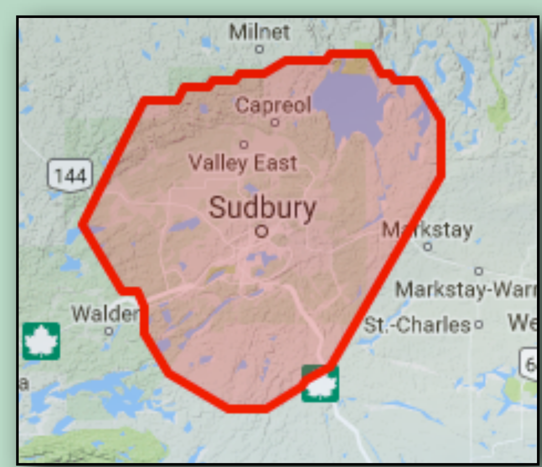

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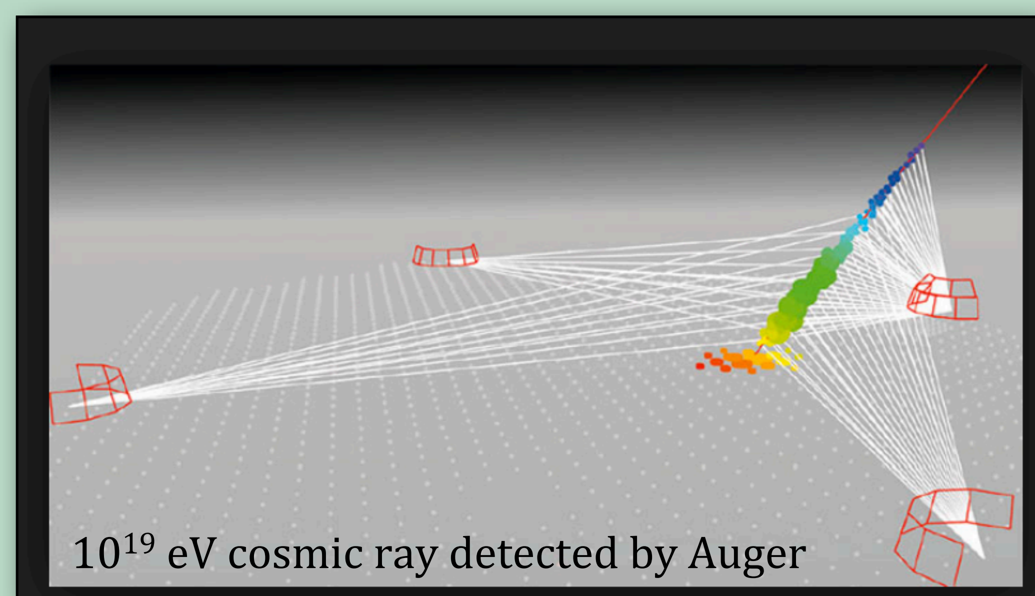

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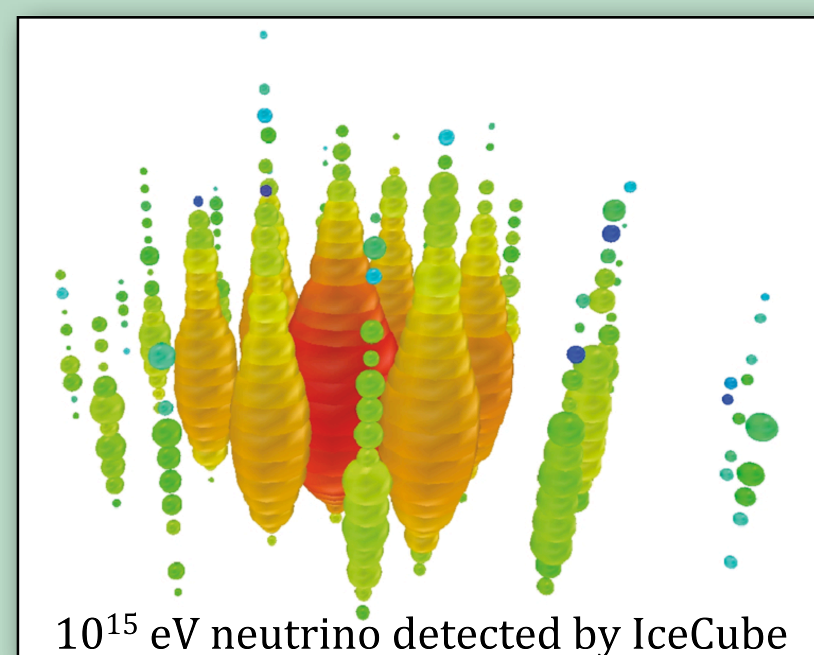

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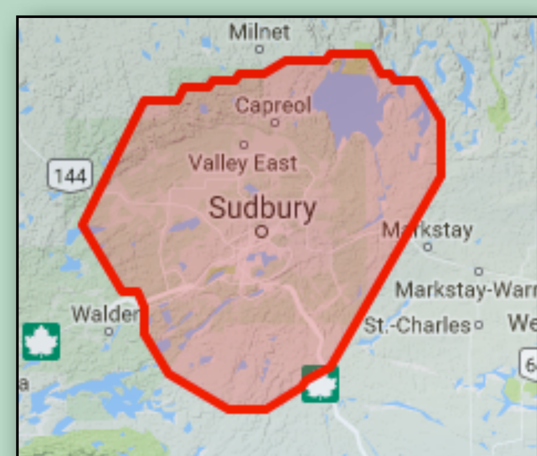

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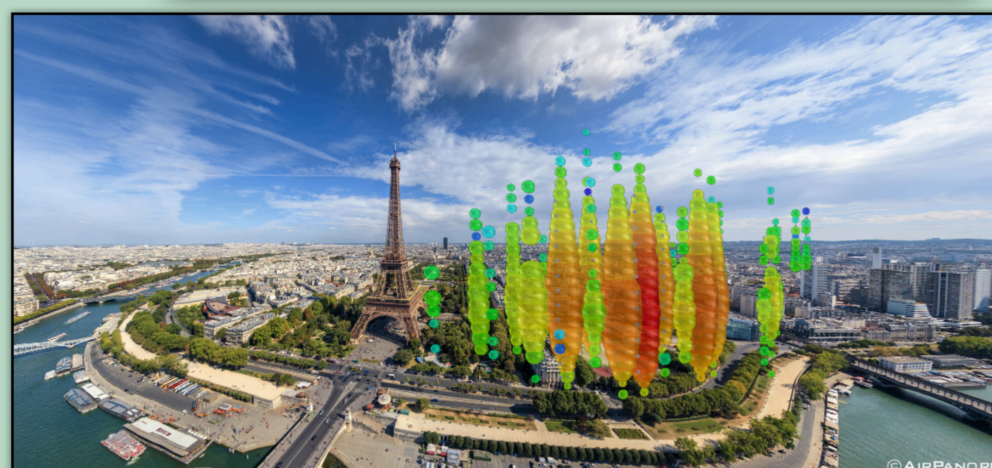

IceCube event visiting Paris

Motivations

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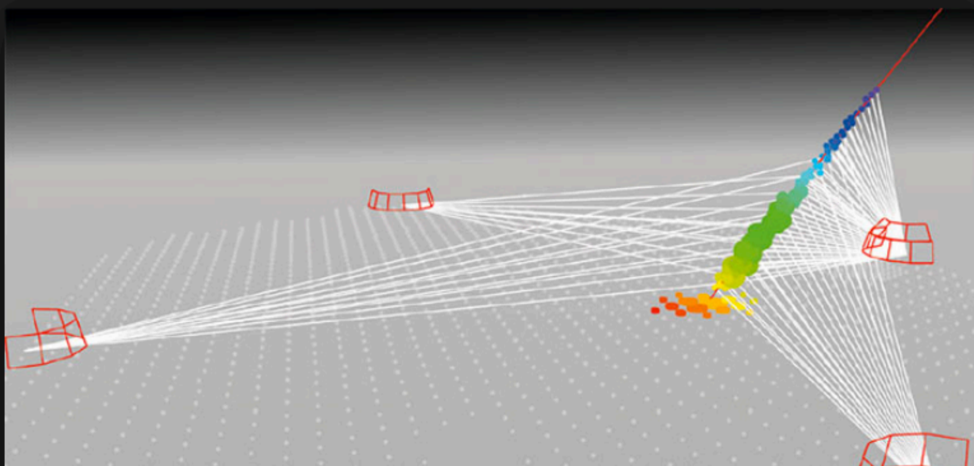
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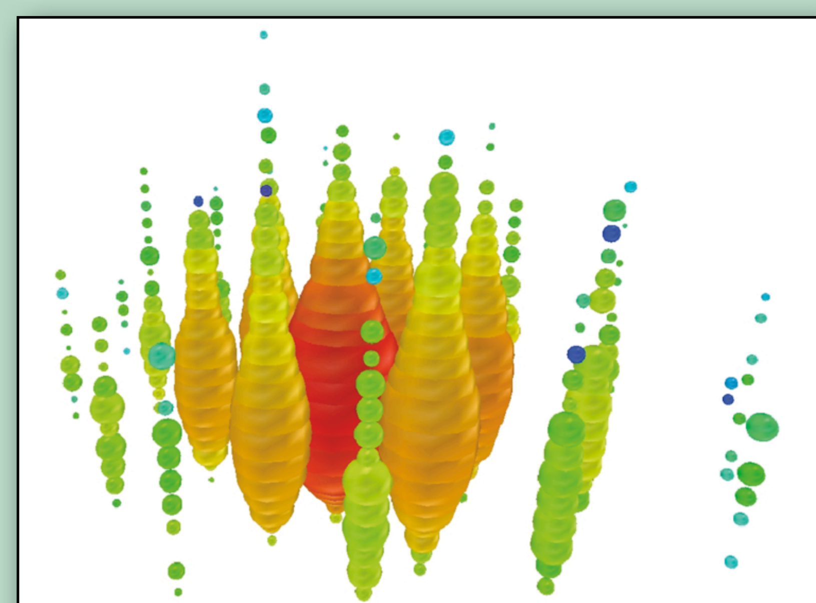
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Very difficult to answer when we get only one particle from any given source.

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?

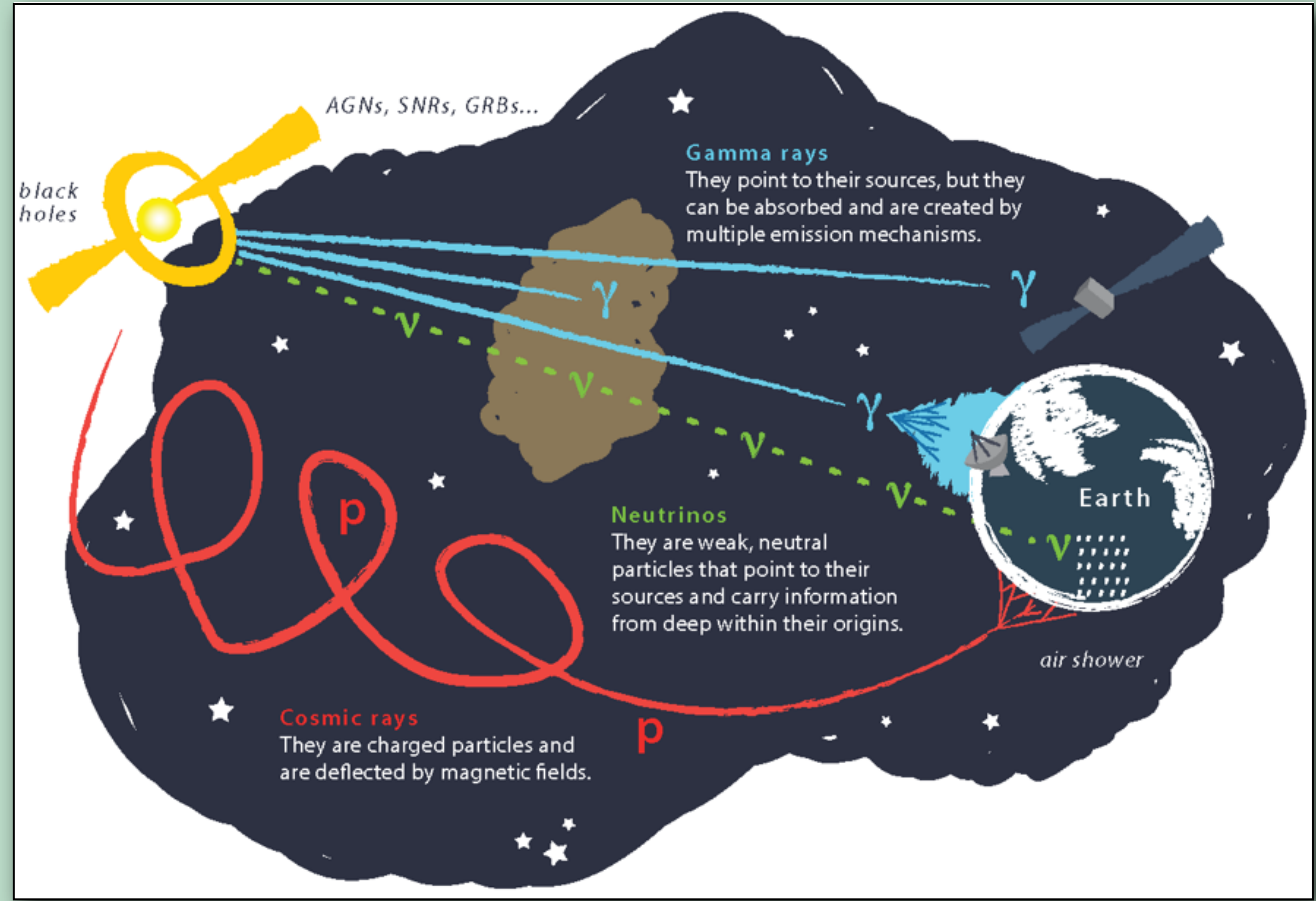
Candidate Astrophysical Sources

- 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	Penetrating
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
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  - IceCube
- Grav. Waves
  - a-LIGO

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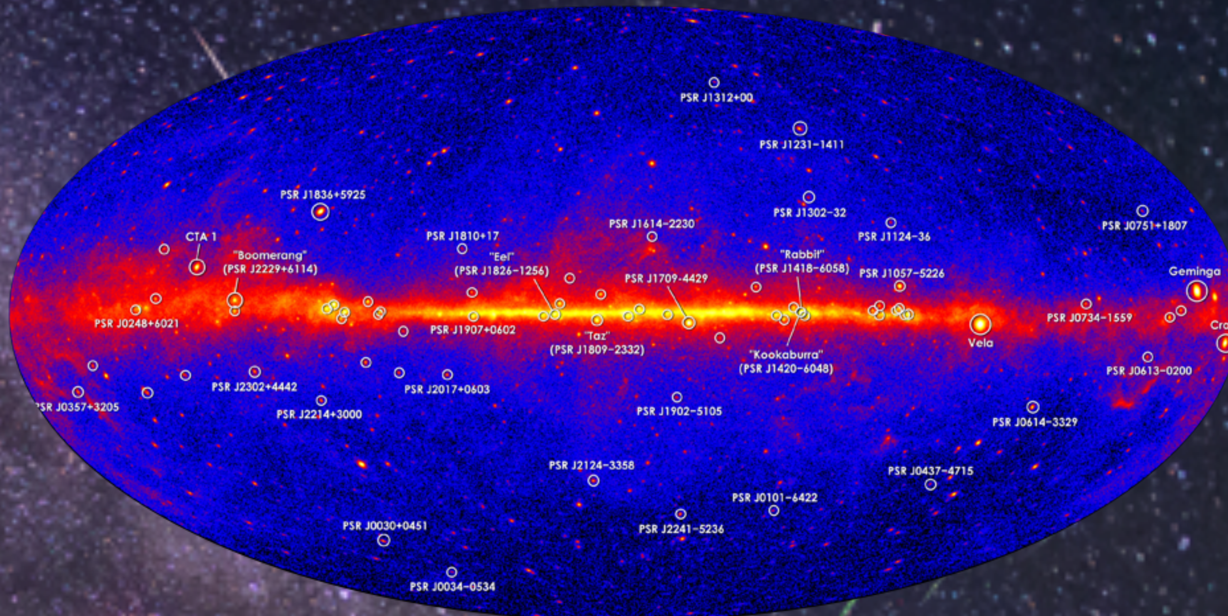

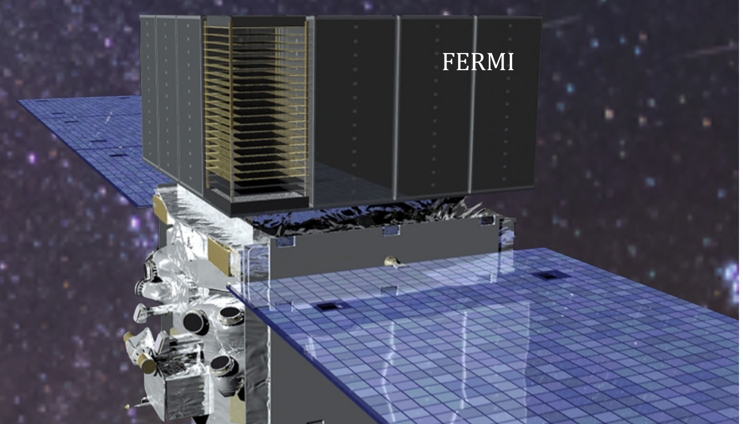

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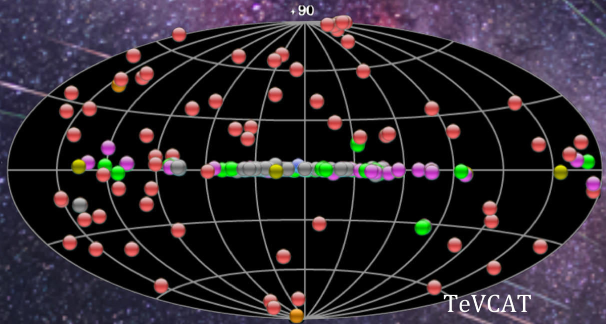
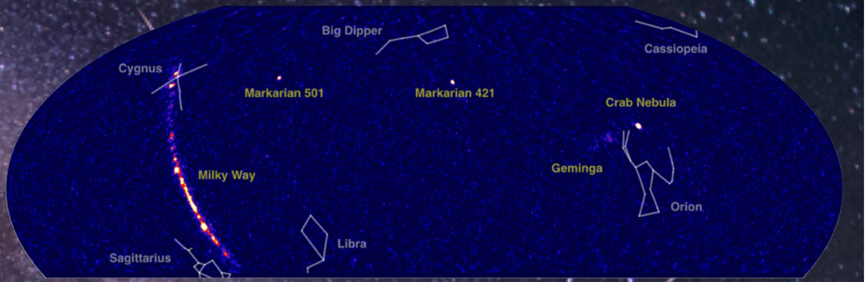


TeVCAT




HESS, MAGIC, VERITAS, FACT, et al.


Milagro, HAWC

Daniel López

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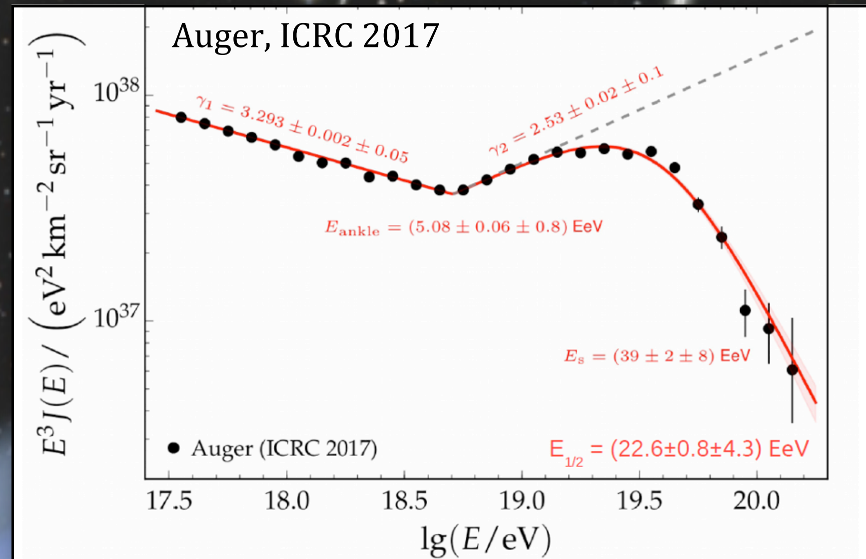

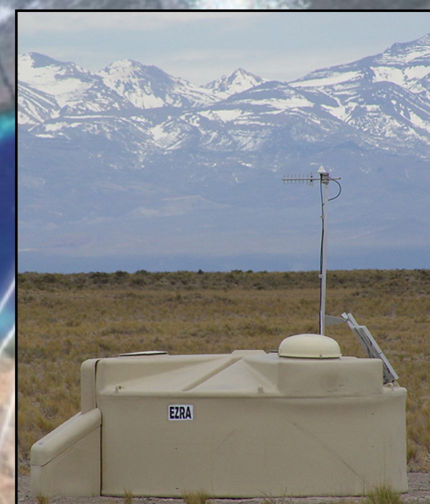

Pierre Auger, HiRes, AGASA, TA et al.

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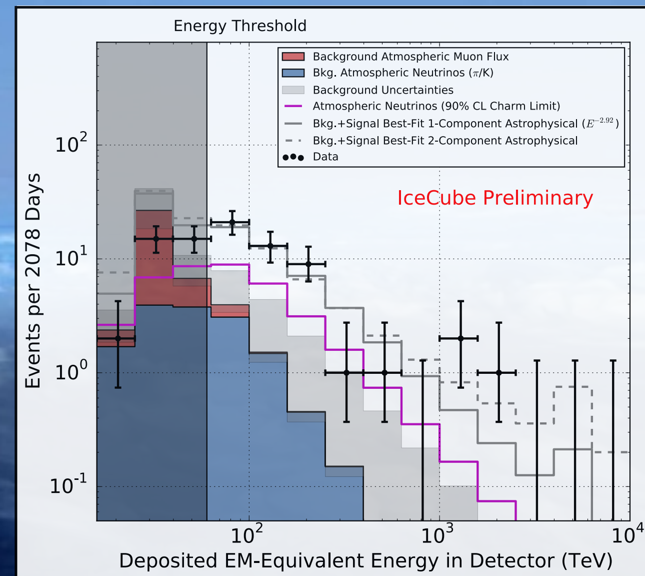

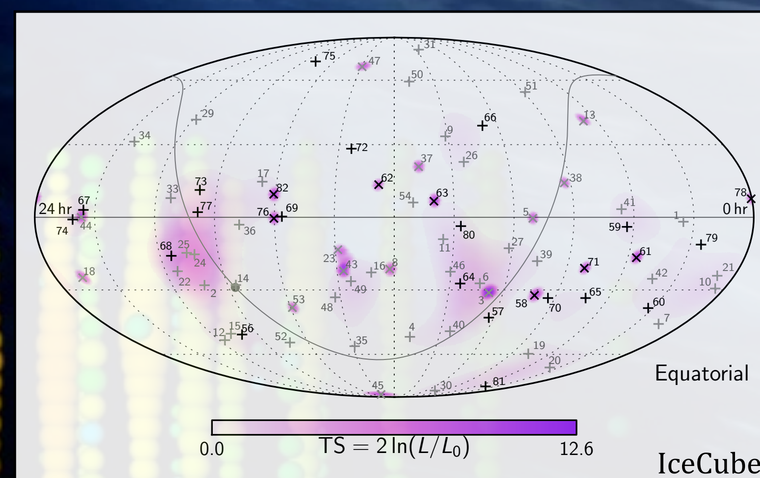

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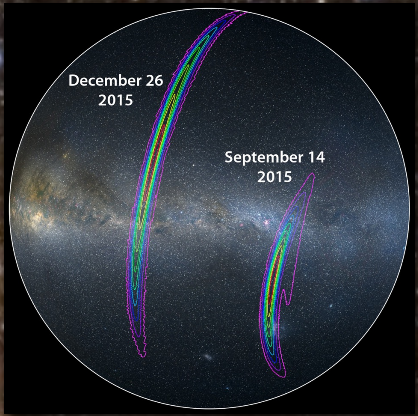

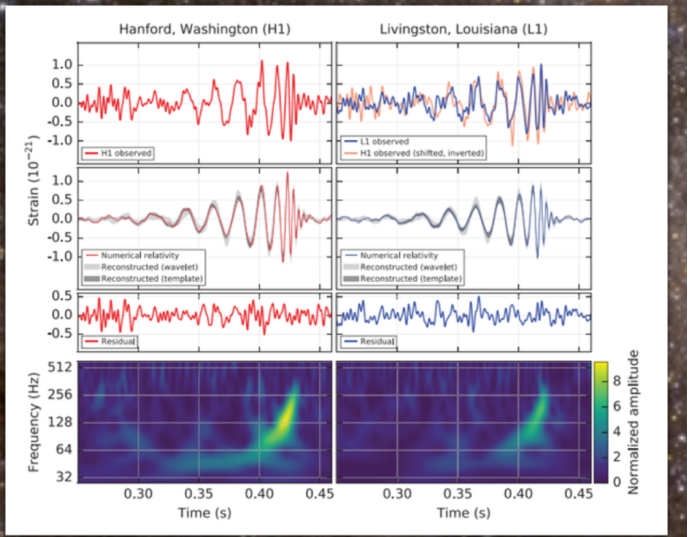

Exciting Times for Particle Astrophysics!

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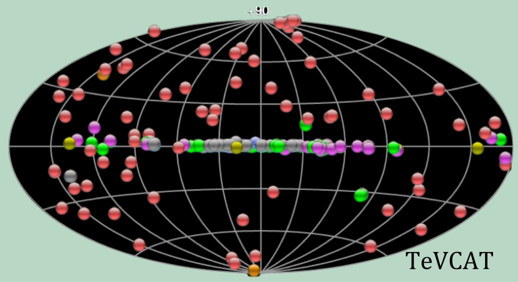
At high energies, why have we only been able to associate γ-rays with astrophysical sources?



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

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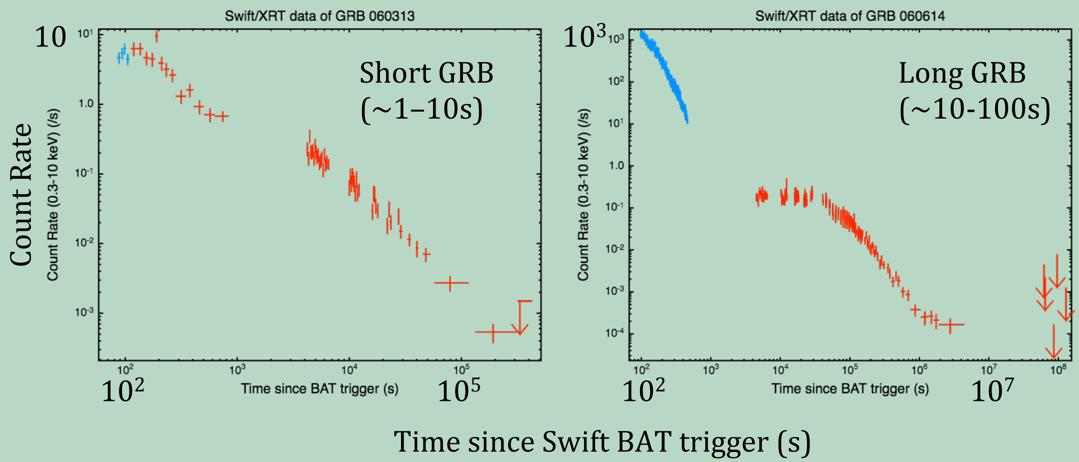
Waiting time: years

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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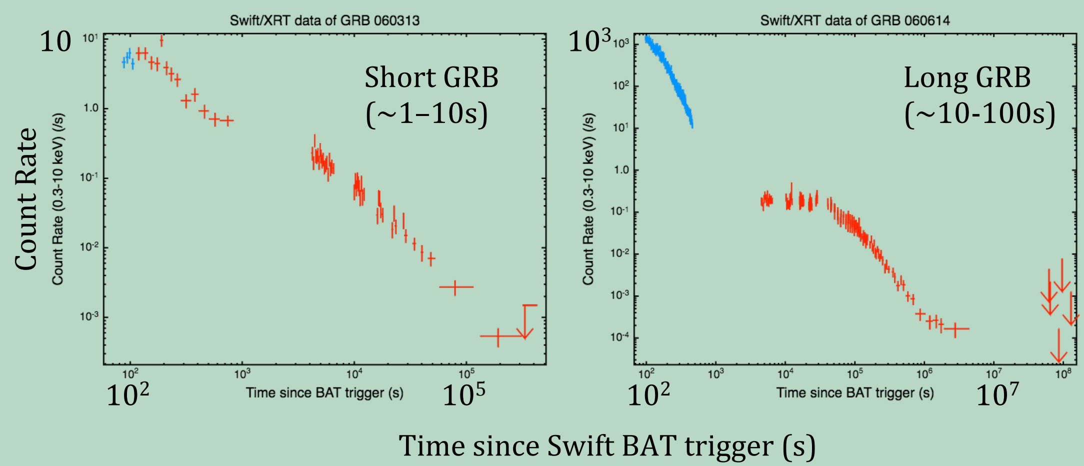
- Yes and yes.

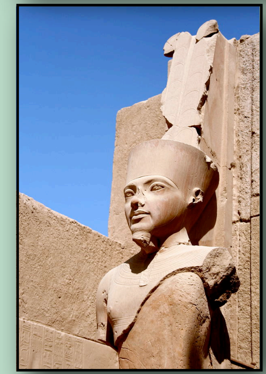


New Strategy: Short-Term

- 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

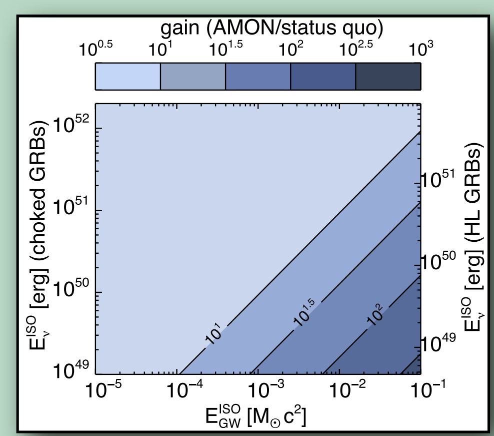


*European Strategy Forum on Research Infrastructures

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

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



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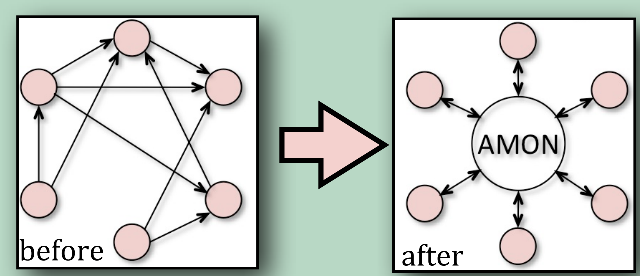
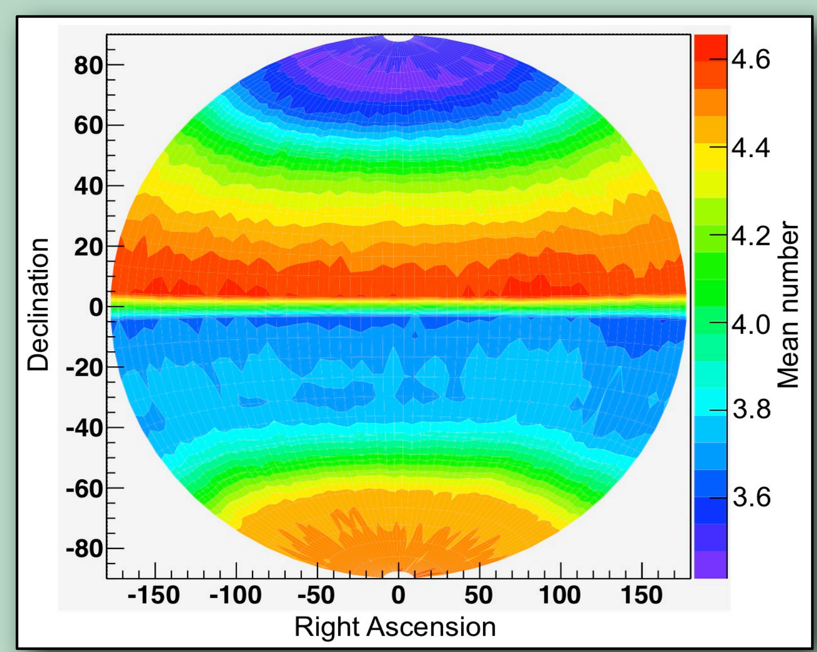


Important Questions for AMON et al.

- 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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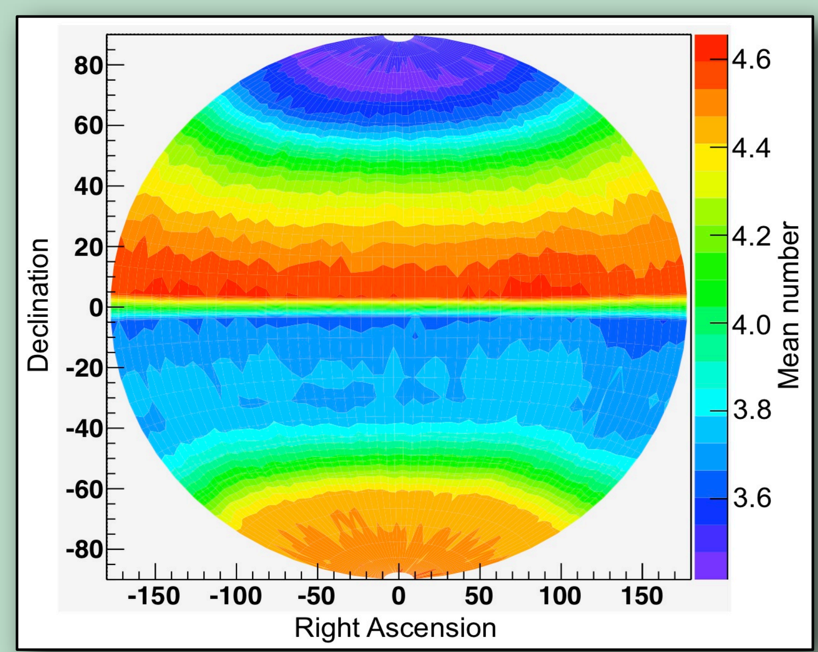
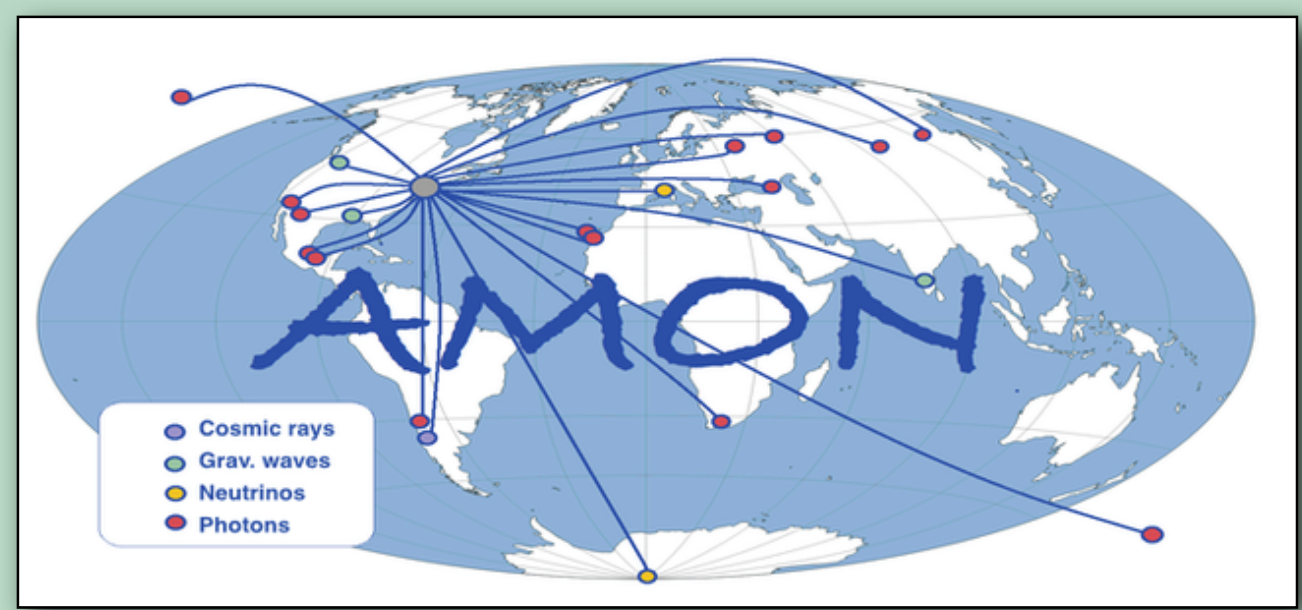


AMON

- 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

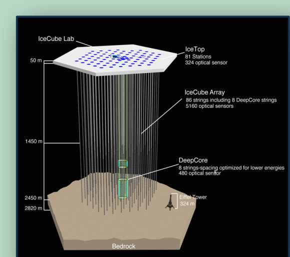
- Initially enabling archival analyses ("walk before we run"):
  - Fermi LAT + IC40 (A. Keivani et al., PoS(ICRC2015)786 (2015))
  - Fermi LAT + IC40/59 (C. F. Turley et al., in preparation)
  - Primordial black hole search (G. Tešić, PoS(ICRC2015)328 (2015))
  - VERITAS Blazars + IC40 (C. F. Turley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

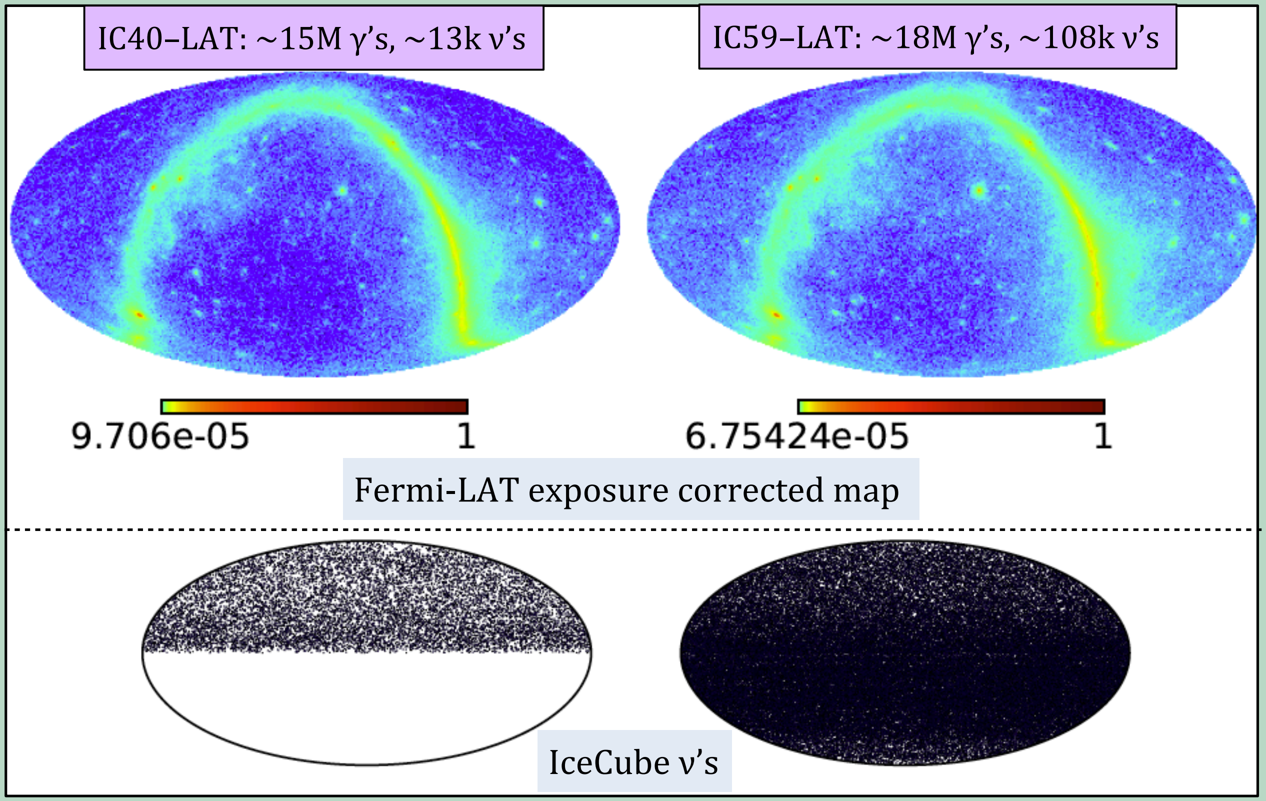
- For these efforts, AMON provides/provided (since April 2016)
  - a software framework for real-time coincidence analyses & alert emission
  - a database populated with private and public data from numerous observatories
  - a "pass-through" service for sending out alerts via GCN
    - E.g., IceCube's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



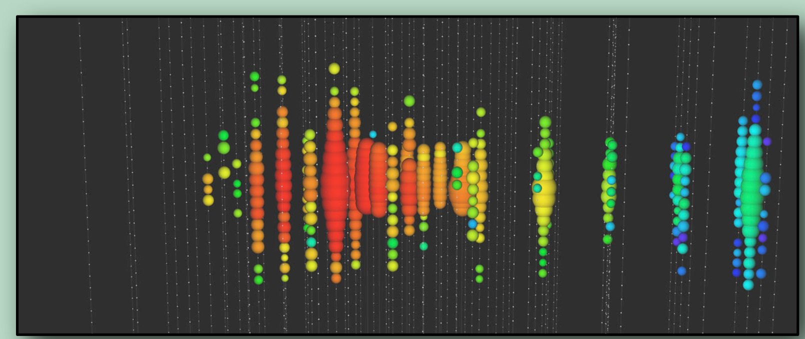
IC40–LAT:
Data: 2138 γ+ν pairs
BG: 2207±40 γ+ν pairs
p-value: 15%

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

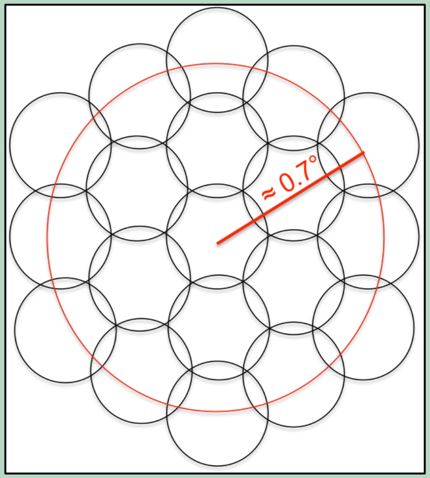
A. Keivani et al., PoS(ICRC2015)786 (2015) (w/pass 7)
C. F. Turley et al., in preparation (w/pass 8)

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



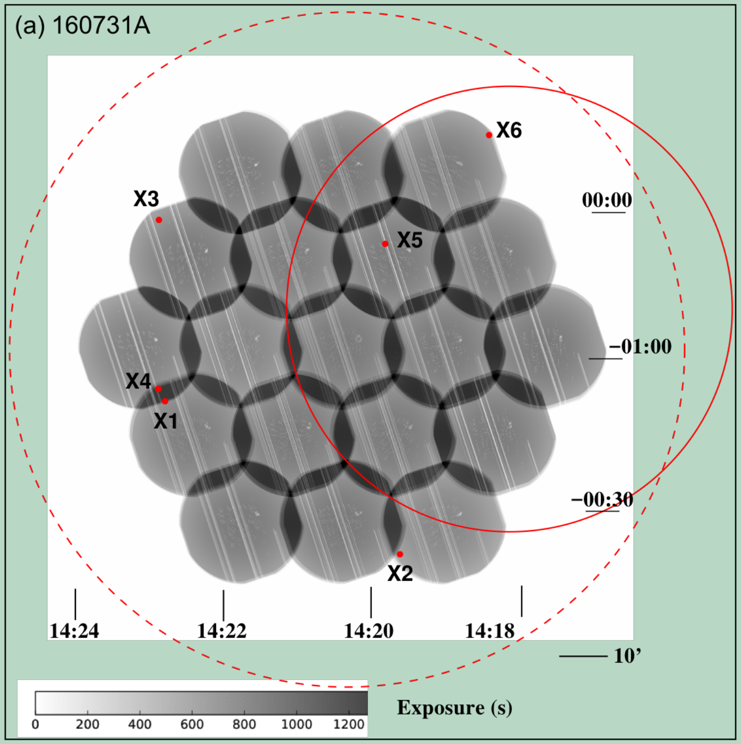
Example track-like HESE: ~1° pointing resolution.



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

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  - 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!*