Recent updates on the VERITAS multimessenger program: searching for electromagnetic counterparts of high-energy neutrino and gravitational-wave events

Weidong Jin on behalf of the VERITAS Collaboration

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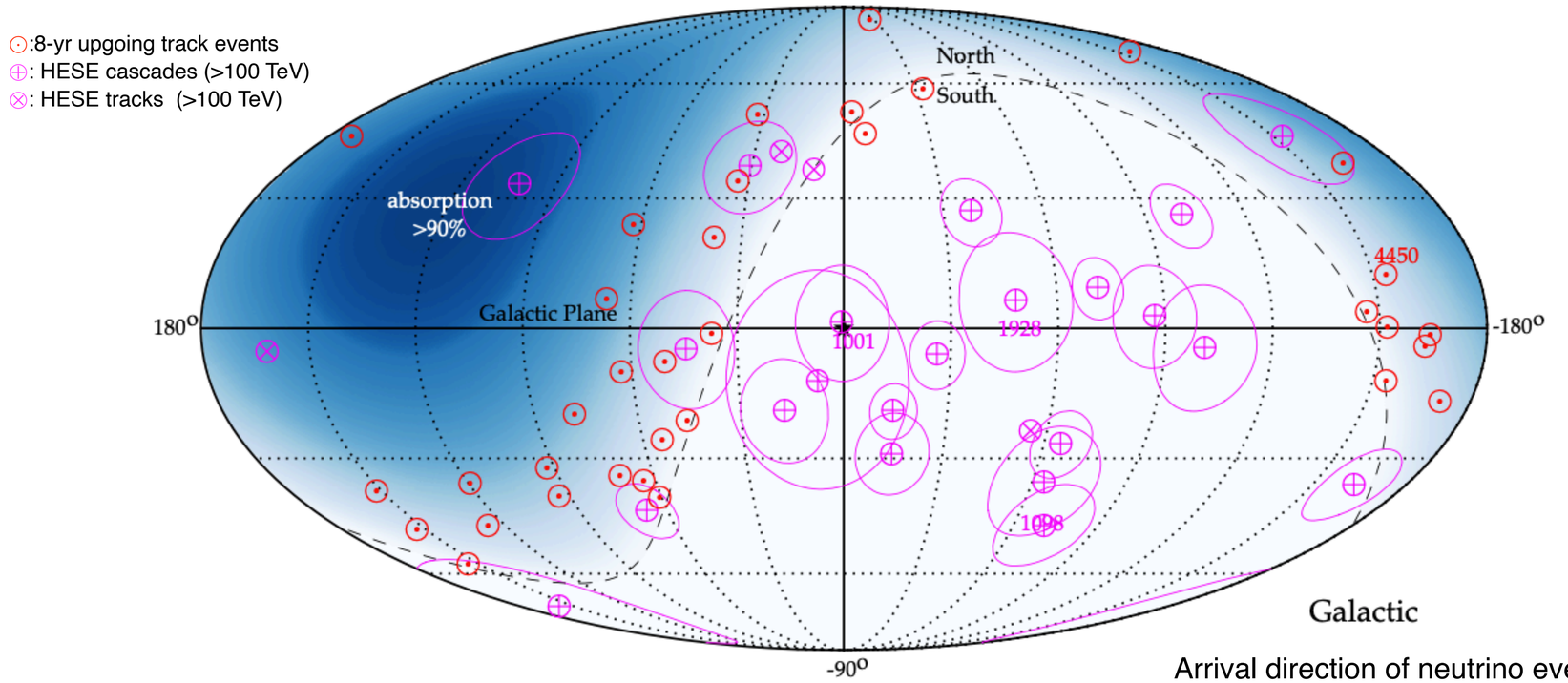
TeV Particle Astrophysics 2022

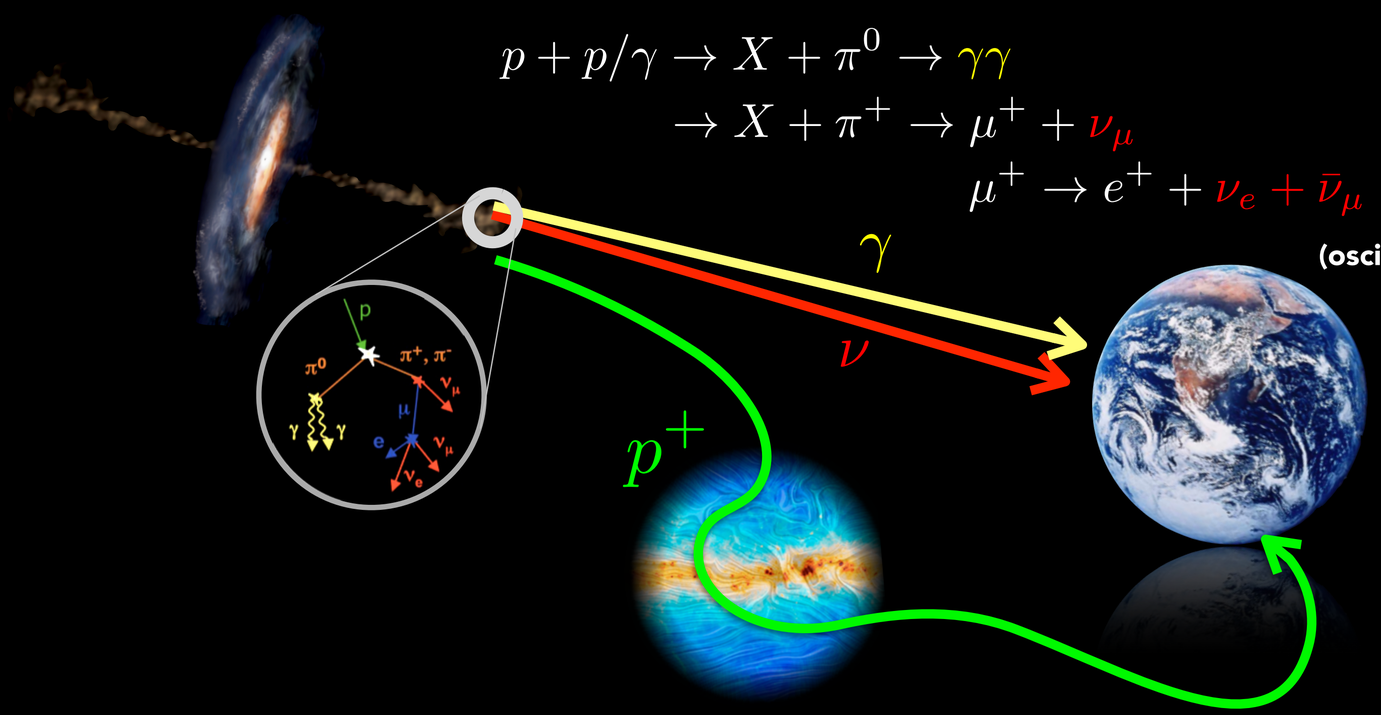
IceCube and the first evidence of high-energy cosmic neutrinos



Arrival direction of neutrino events. Ahlers, M., & Halzen, F. (2018).

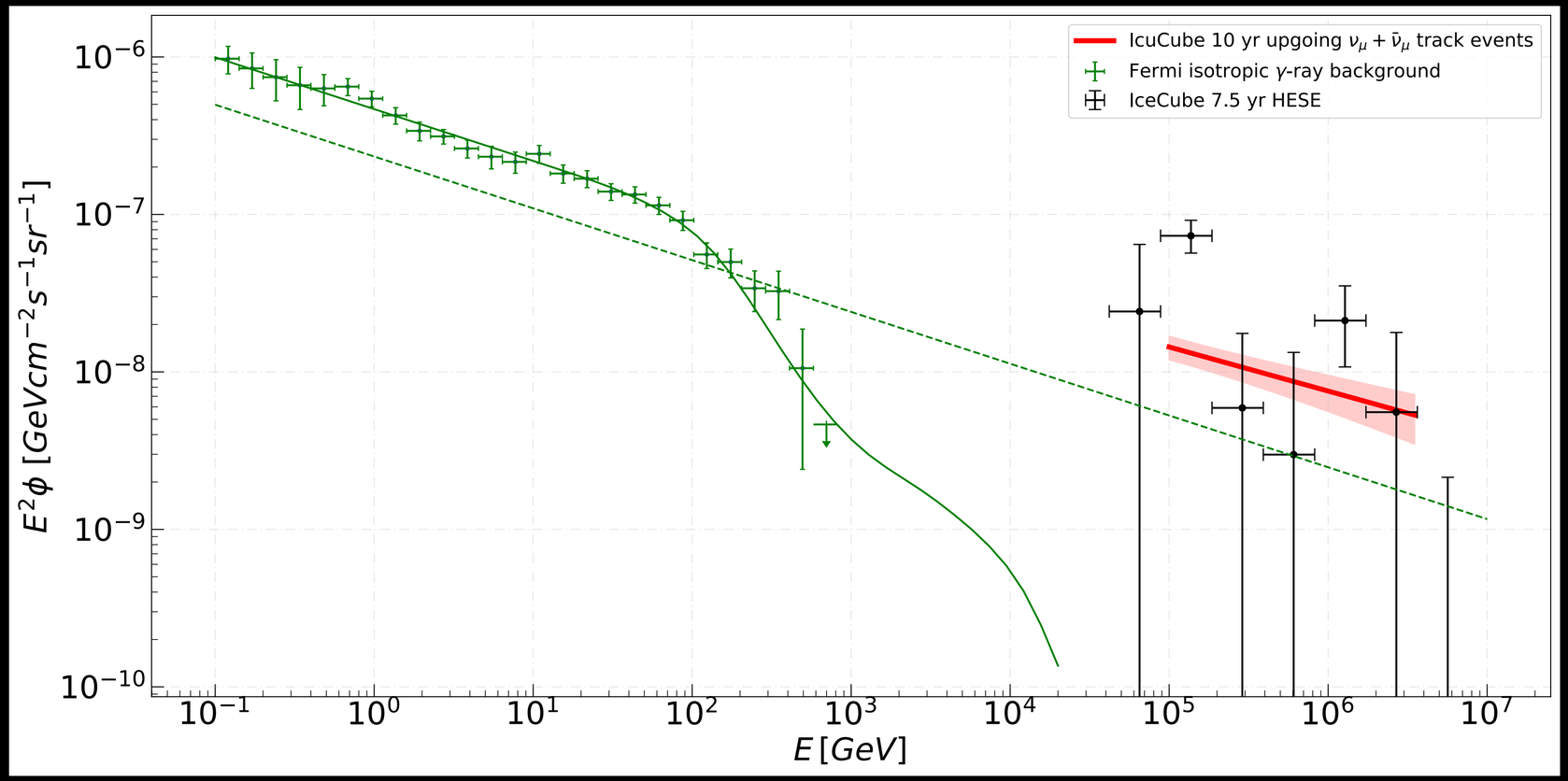
- IceCube has observed an excess of neutrino events at energies beyond 100 TeV which cannot be accounted for by the atmospheric neutrino flux;
- After correcting for absorption in the Earth, the arrival directions of cosmic neutrinos are:
  - **Isotropic** and show no **significant** correlation with the Galactic Plane;
- No strong point source has been identified (TXS 0506+056: 3σ).

The multi-messenger connection



- Locate the high-energy astrophysical neutrino source by searching for the VHE gamma-ray counterparts.
- Both neutrinos and pionic photons are produced with roughly equal rates through hadronic processes.
- VHE gamma-rays attenuated at the source (photon fields) or during propagation (EBL) and cascading to lower energies.

The multi-messenger connection

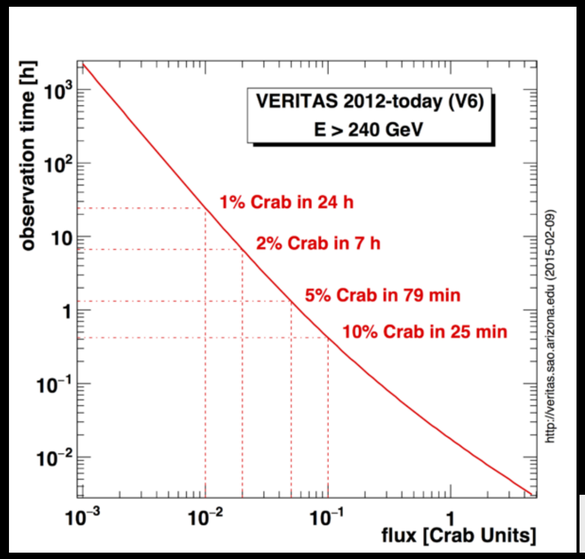


For detailed information, please refer to: K Murase, et al, 2013; M Ahlers & F Halzen, 2018.

- The *Fermi* isotropic γ-ray background (IGRB) is well fitted by assuming the same type of point source following $E^{-\gamma}$, then integrated over z from 0 to 4 weighting with source density (star-formation rate).
- The matching flux of *Fermi* IGRB and IceCube high-energy neutrinos suggests that they originate from the same hadronic processes.
- Multi-messenger studies of gamma-rays and neutrinos help us understand the main processes in the non-thermal universe and constrain the gamma-ray and neutrino point source models.

About VERITAS

- Located near Tucson, Arizona, currently operating with:
  - Array of 4 Davies-Cotton Imaging Air Cherenkov Telescopes.
  - Energy range: ~ 100 GeV - 30 TeV.
  - 3.5° FOV and 0.1° angular resolution > 1 TeV.
  - Detects the Crab Nebula in < 2 minutes.

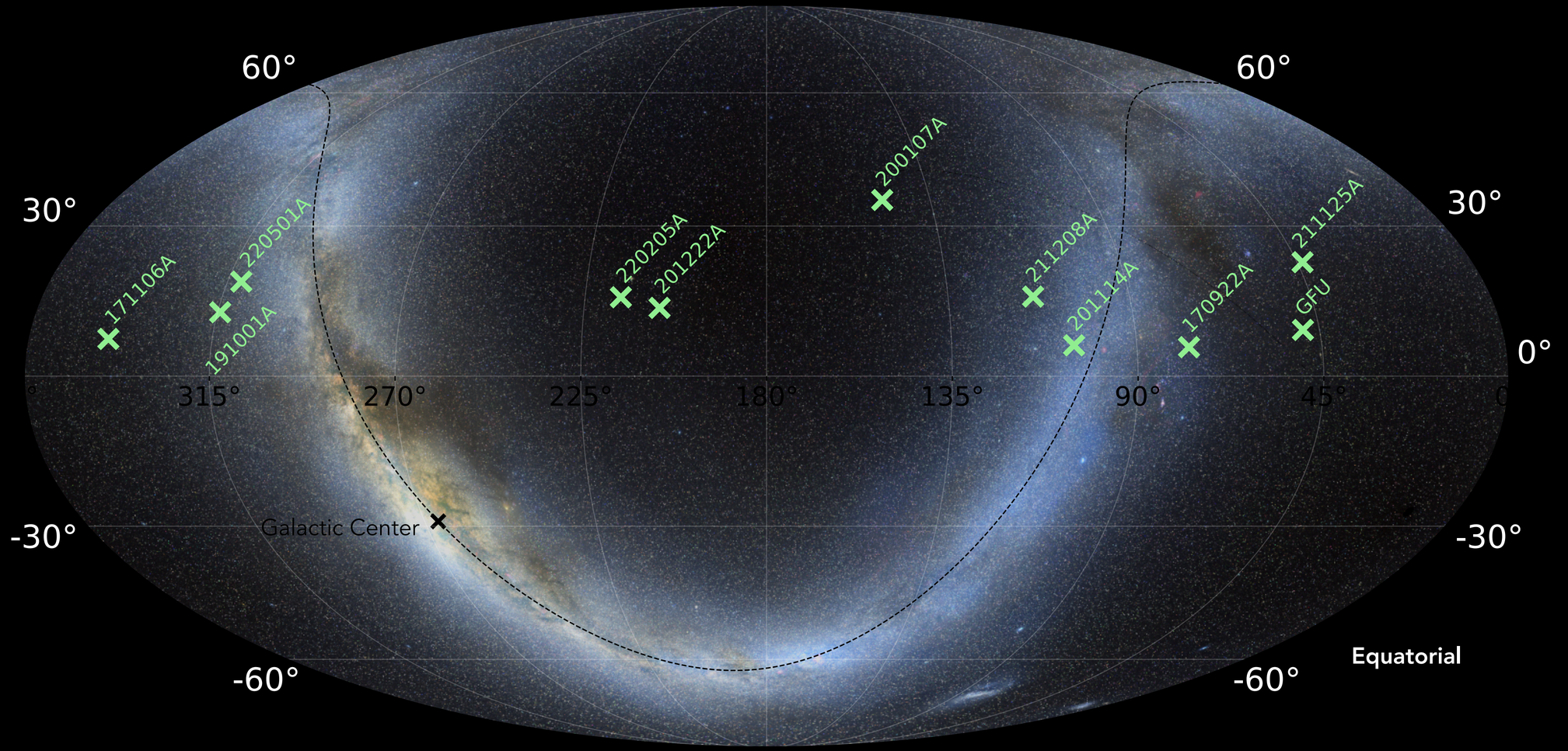


Observation time vs source strength for a 5 sigma signal or at least 10 events (elevation: 70 deg)

History of the program and current follow-up strategies

- First attempt: neutrino search associated with flares of three known VHE Blazars (Bayer et al. 2007).
- History of the program:
  - 2009 - observing hotspots in the IceCube point-source map;
  - 2011 - neutrino clusters around known VHE sources;
  - 2014 - observations of IceCube archival neutrino events;
  - 2016 - realtime alert follow-ups (few-min latency from IceCube detection to VERITAS observations);
  - 2018 - VERITAS detection of TXS 0506+056.
- Pre-approved follow-up observations of potential neutrino counterparts (45 hrs/yr). Part of the VERITAS Long Term Science Plan.
- Automatic repointing for alerts from IceCube through GCN (GOLD and BRONZE) or private email. Exposures between 3-25 h depending on neutrino astrophysical probability, proximity of potential EM counterparts, online analysis results.
- Counterpart: the searches typically cover the whole region of interest.

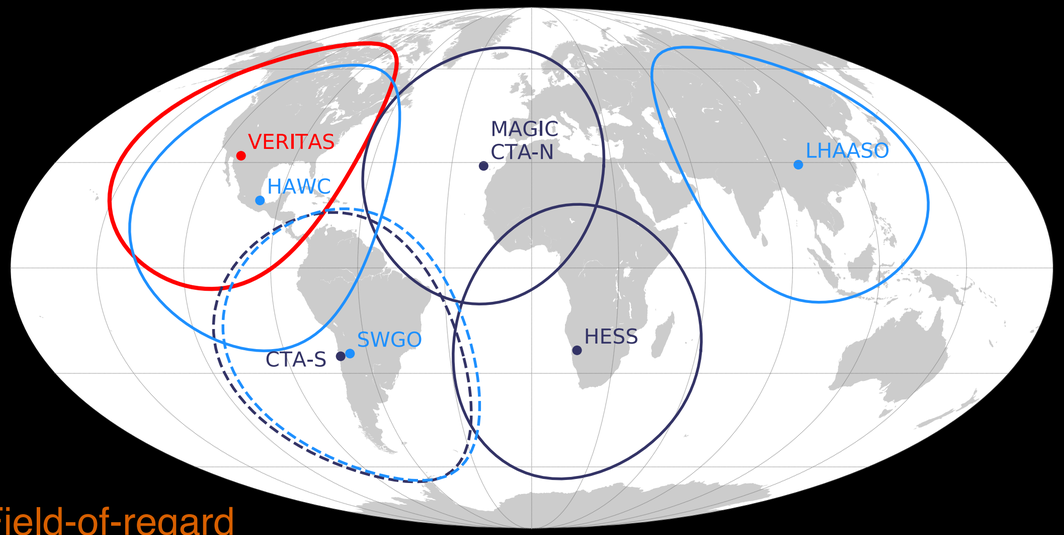
VERITAS NuToO program



- 9 follow-up observations of public real-time neutrino alerts since TXS 0506+056, 1 private alert from IceCube when the neutrino passes a pre-defined significance threshold for known gamma-ray sources: Gamma-ray Follow-Up (GFU) program.

- No significant associations have been found since TXS 0506+056 either in the best fit location of IceCube neutrino events or anywhere in the VERITAS field of view.

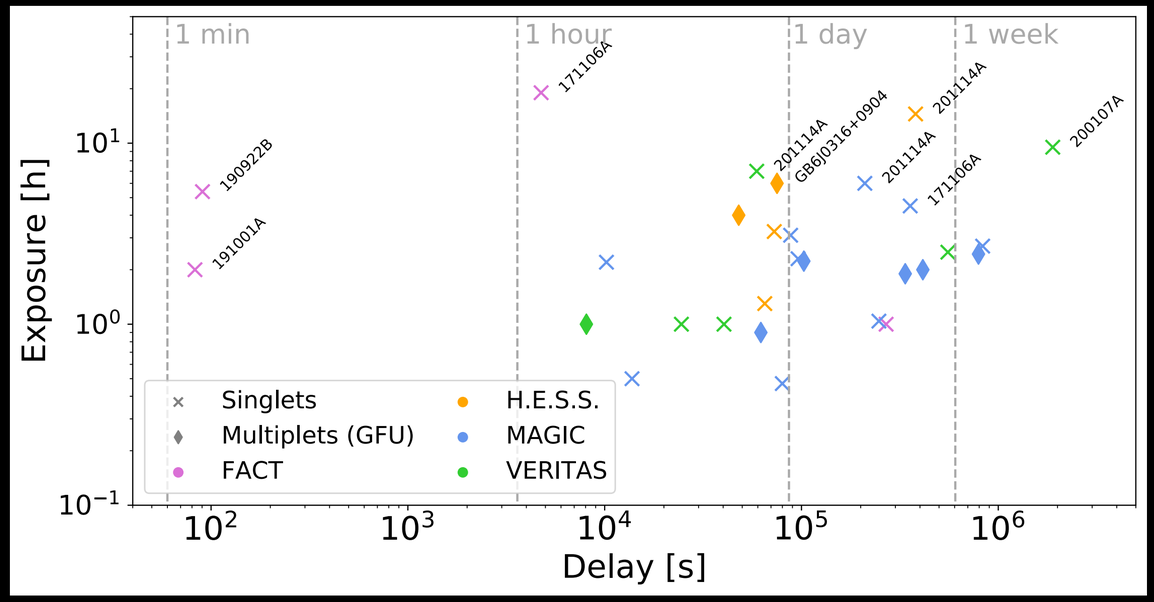
IACTs NuToO campaign



Field-of-regard

Air-shower arrays

IACTs

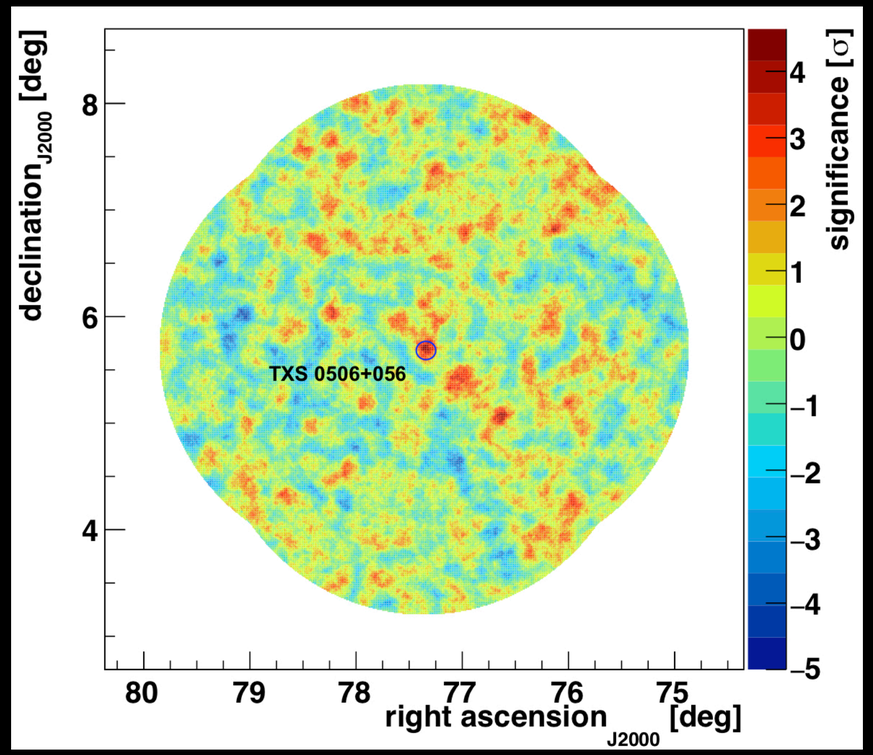


MAGIC, IceCube, FACT, H.E.S.S. and VERITAS collaborations
PoS ICRC2021 960

- From October 2017 to December 2020, IceCube sent 62 single event public alerts, 11 were observed by at least one IACT.
- In total, each collaboration spent ~20 h of observation time on public IceCube alert follow-up.
- Preliminary results presented in ICRC2021.

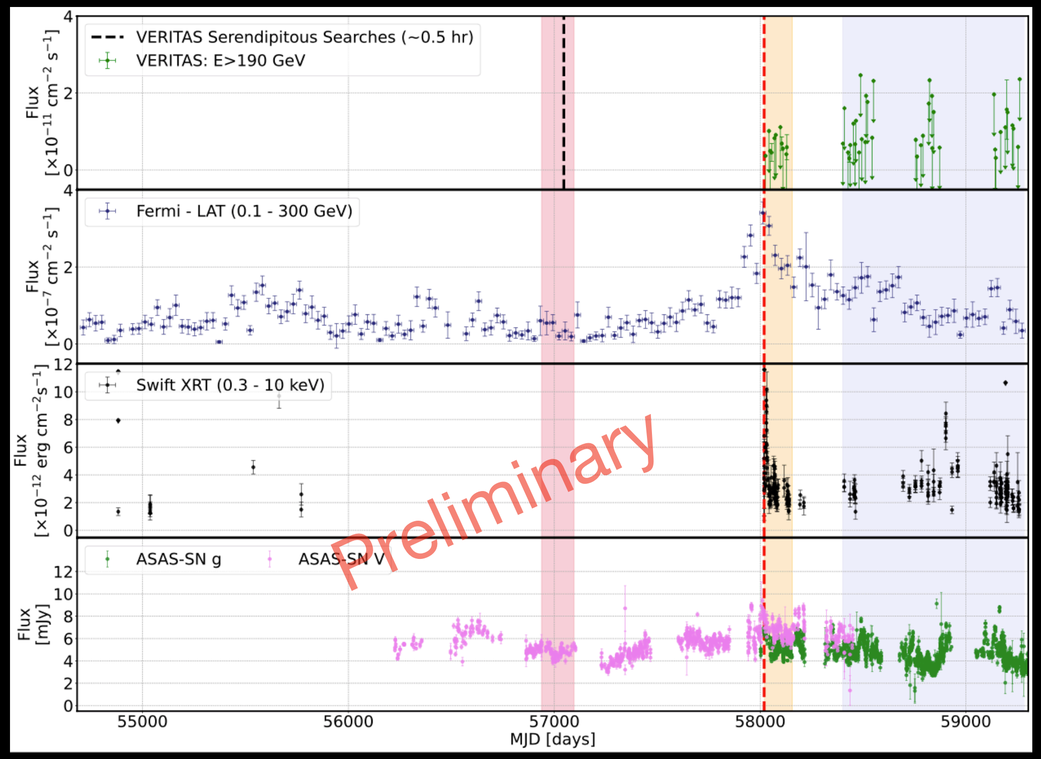
Name	Energy [TeV]	Signalness	FACT	H.E.S.S.	MAGIC	VERITAS
IceCube-171106A	230	0.75	19 h	—	4.5 h	2.5 h
IceCube-181023A	120	0.28	1 h	—	—	—
IceCube-190503A	100	0.36	—	—	0.5 h	—
IceCube-190730A	299	0.67	—	—	3.1 h	—
IceCube-190922B	187	0.50	5.4 h	—	2.2 h	—
IceCube-191001A	217	0.59	2.0	—	2.3 h	1.0 h
IceCube-200107A	—	—	—	—	2.7 h	9.5 h
IceCube-200926A	670	0.44	—	1.3 h	1.0 h	
IceCube-201007A	683	0.88	—	3.25 h	0.5 h	—
IceCube-201114A	214	0.56	—	14.5 h	6 h	7 h
IceCube-201222A	186	0.53	—	—	—	1.0 h

IceCube-170922A (TXS 0506+056)



Continued monitoring (2018-21)

Jin, W., & Sharpe, R. (2021) arXiv/2108.05463 - PoS ICRC2021 945

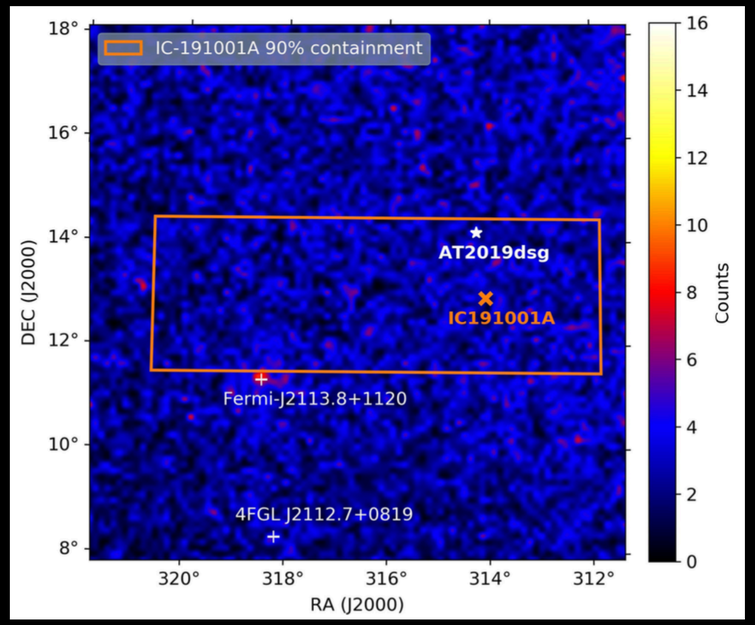


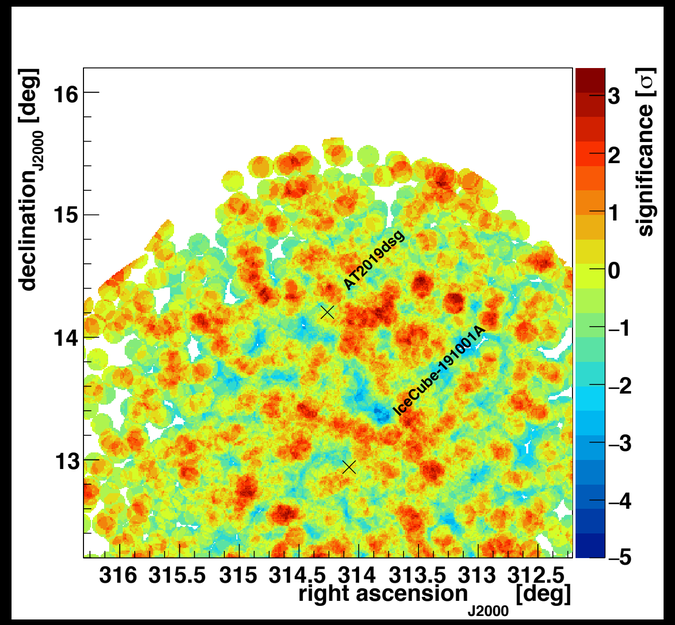
Multiwavelength lightcurves of TXS 0506+056.

Red: archival neutrino excess during 2014/2015.
Orange: VERITAS initial follow-up.
Lavender: long term follow-up studied in this investigation.

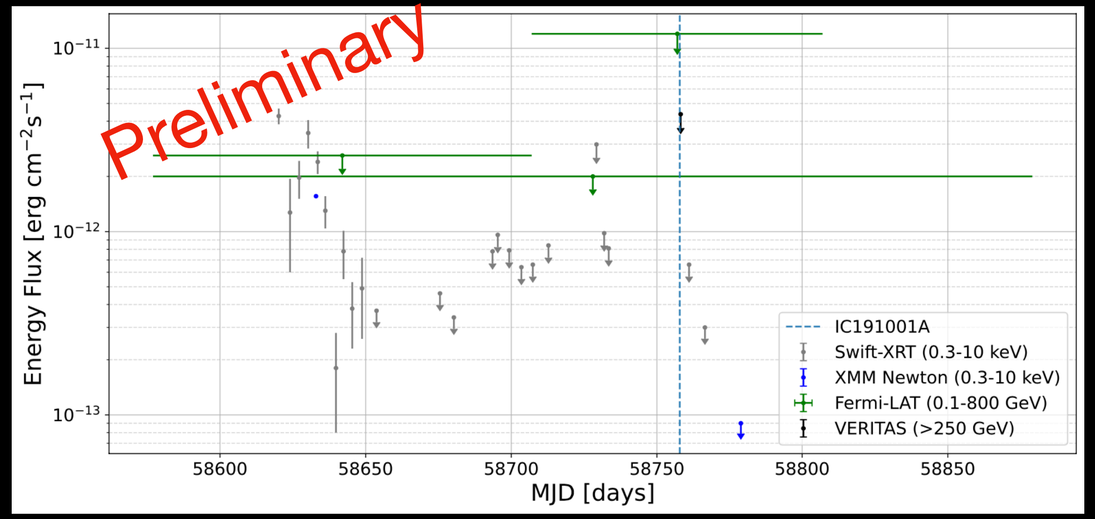
- Part of our Long Term Plan of observations. Collected >100 hrs so far.
- MWL campaigns including NuSTAR+*Swift* to characterize long-term behavior. Low-flux state since 2018 (0.5% Crab in 61 hrs).
- Archival search found ~0.3 hr data during 2014/2015 (no detection). Analysis is ongoing. Paper in preparation.

IceCube-191001A (AT2019dsg, GCN 25913)





Stein, Robert, et al. *Nature astronomy* 5.5 (2021): 510-518.



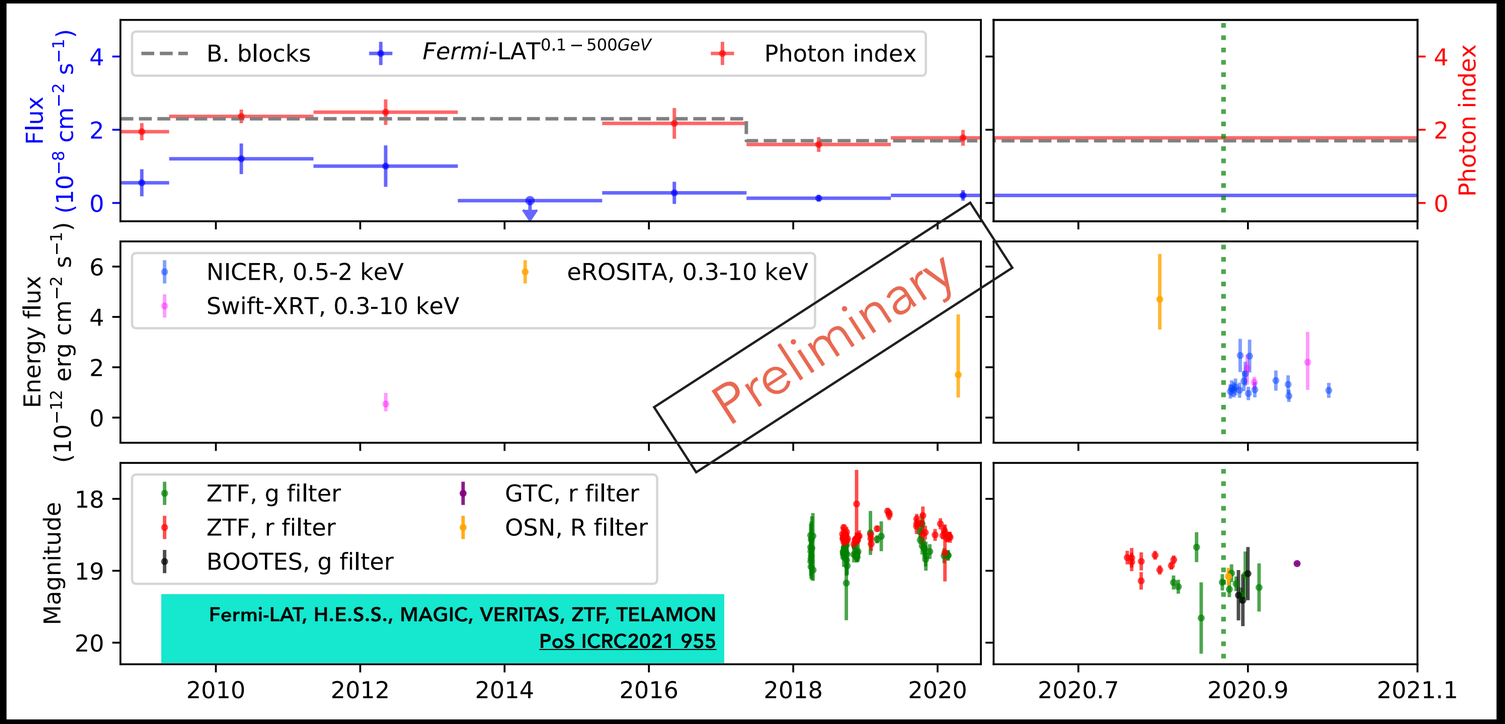
Data from Stein, Robert, et al. *Nature astronomy* 5.5 (2021): 510-518.

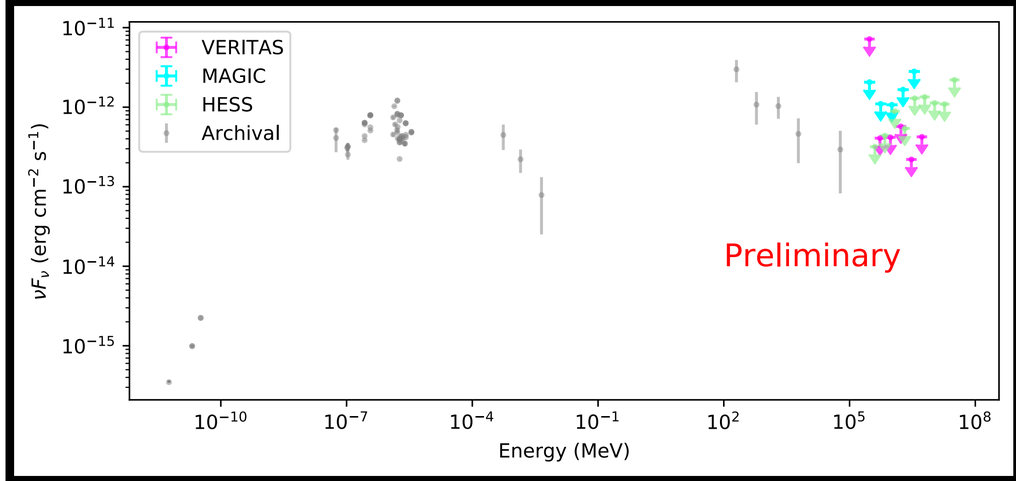
- A tidal disruption event (TDE) AT2019dsg (z=0.05) was found within 90% localization region of IC191001A. Chance of coincidence (~0.2%).

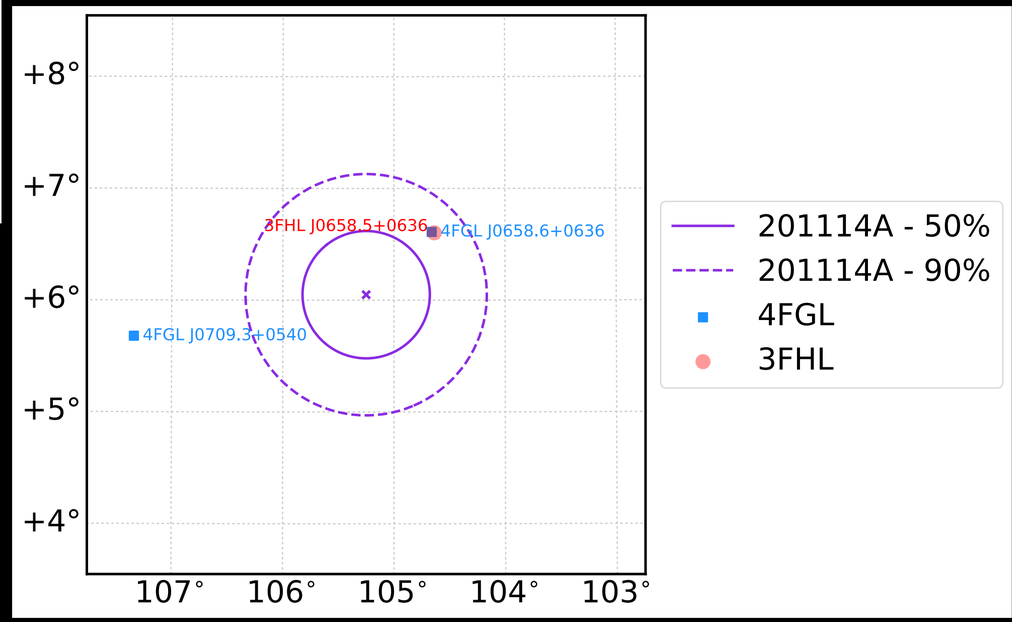
- VERITAS had 1 hr observation (~7 hrs after the alert), no detection. In agreement with the optically thick p-γ scenario.

- Integral upper limit: F(E > 250 GeV, 95% C.L.) = 4.37×10^{-12} [cm^-2 s^-1] (Rolke et al. 2005).

IceCube-201114A

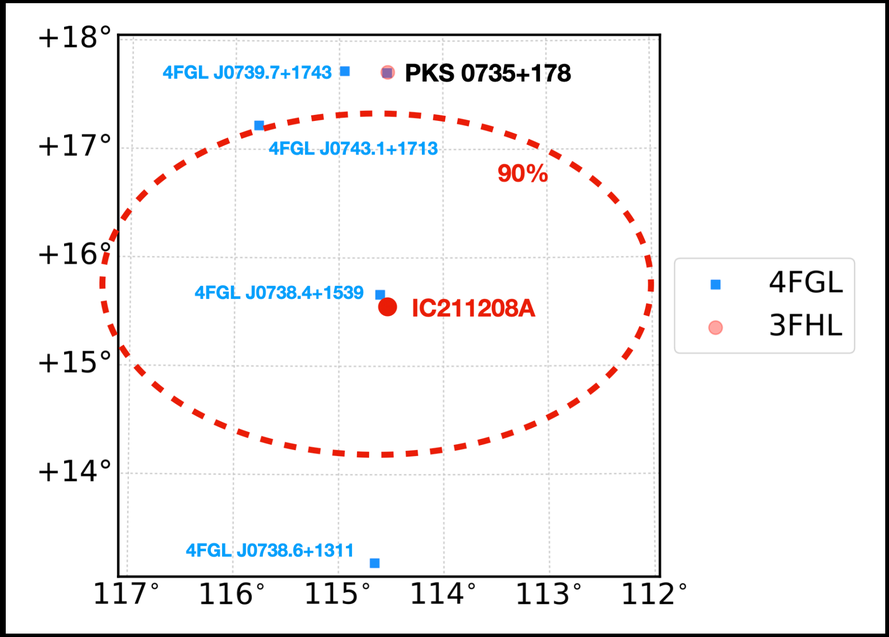






- On Nov 14, 2020, IceCube reported the detection of a high-energy neutrino (~214 TeV) event of likely astrophysical origin.
- 4FGL J0658.6+0636 (HSP blazar NVSS J065844+06371) 0.8° away from IceCube best fit location.
- Broadband MWL campaign.
- VERITAS exposure offers the most constraining ULs on VHE emission. Paper in preparation (led by *Fermi*-LAT).

IC211208A (PKS 0735+178, GCN 31191)



[Previous | Next | ADS]

NuSTAR observations of the blazar PKS 0735+178

ATel #15113; *Qi Feng (Barnard College/Columbia University), Weidong Jin (U. Alabama), Kaya Mori (Columbia University), Reshmi Mukherjee (Barnard College/Columbia University), Marcos Santander (U. Alabama), Jooyun Woo (Columbia University)*
on 14 Dec 2021; 22:08 UT
Credential Certification: Qi Feng (qifeng@nevis.columbia.edu)

Subjects: X-ray, Neutrinos, Request for Observations, AGN, Blazar

Referred to by ATel #: 15132

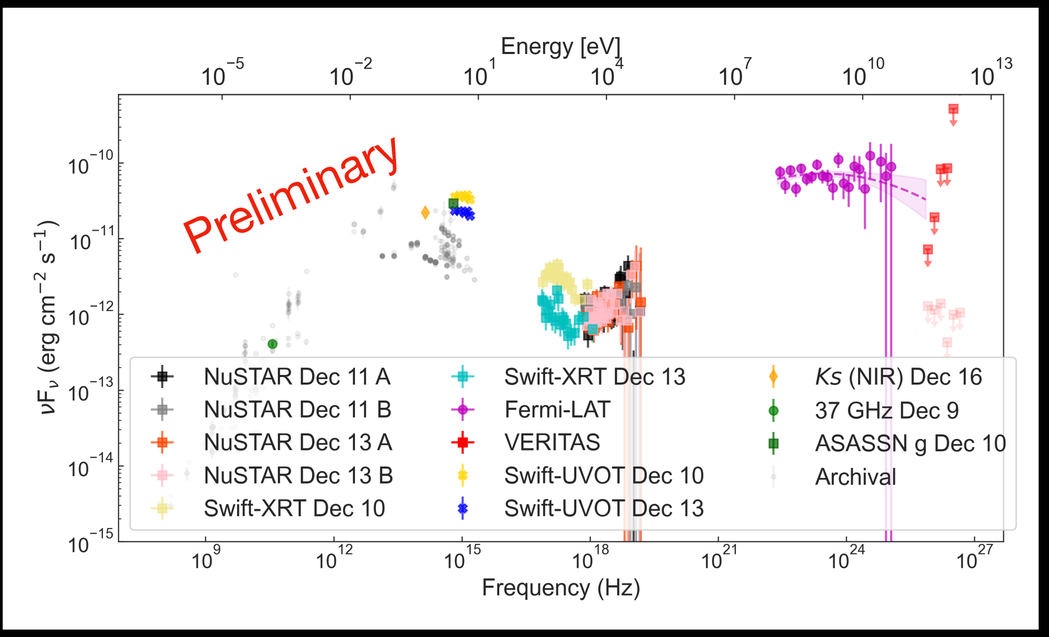
Tweet

We report on the recent target-of-opportunity NuSTAR observations of the blazar PKS 0735+178, located 2.2 deg away from the best-fit position of the IceCube neutrino event IC211208A (GCN #31191). Elevated fluxes from PKS 0735+178 were recently reported in the radio band (ATel #15105), in the optical band by MASTER (ATel #15098), in the X-ray band by Swift-XRT (ATel #15102, #15109), and in the GeV gamma-ray band by Fermi-LAT (ATel #15099) as part of the follow-up observations of the region around the IceCube event.

Two NuSTAR observations of PKS 0735+178 were performed:

1. from 2021 Dec 11 14:00 UT to Dec 12 01:30 UT, and
2. from 2012 Dec 13 12:35 UT to Dec 13 23:30 UT.

NuSTAR ToO triggered on 2021 Dec 11 and 13. ATel 15113



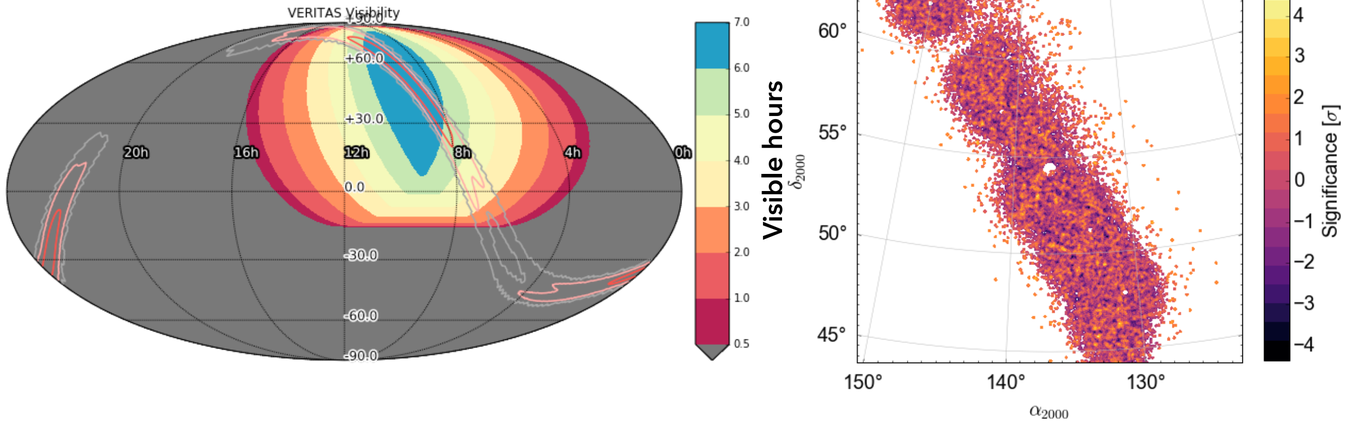
- Multiple high-energy neutrino events observed: IceCube track-like event (~172 TeV, 2021-12-08), Baikal-GVD (~43 TeV) and KM3NeT neutrino detectors (~18 TeV).
- A BL Lac object PKS 0735+178 (Z=0.45) is located 2.2 deg away from the IceCube neutrino best-fit position. Strong activity observed in radio (ATel 15105), optical (ATel 15098), X-rays (ATel 15102, 15109) and gamma-rays (ATel 15099).
- VERITAS collected ~20 hours data between Dec 09, 2021 and Jan 7, 2022. No detection made.
- Good SED dataset and working on modeling.

Gravitational-wave (GW) follow-up program

- VHE gamma-ray observations probe the electromagnetic energetics of GW emitters, potential nearby short gamma ray bursts (GRB).

- On Jan 5, 2017 VERITAS made follow-up observation of a GW event GW170104 (GCN #21153). First systematic follow-up of a GW event by VERITAS. Unfortunately, the majority of the exposures were affected by the presence of clouds.

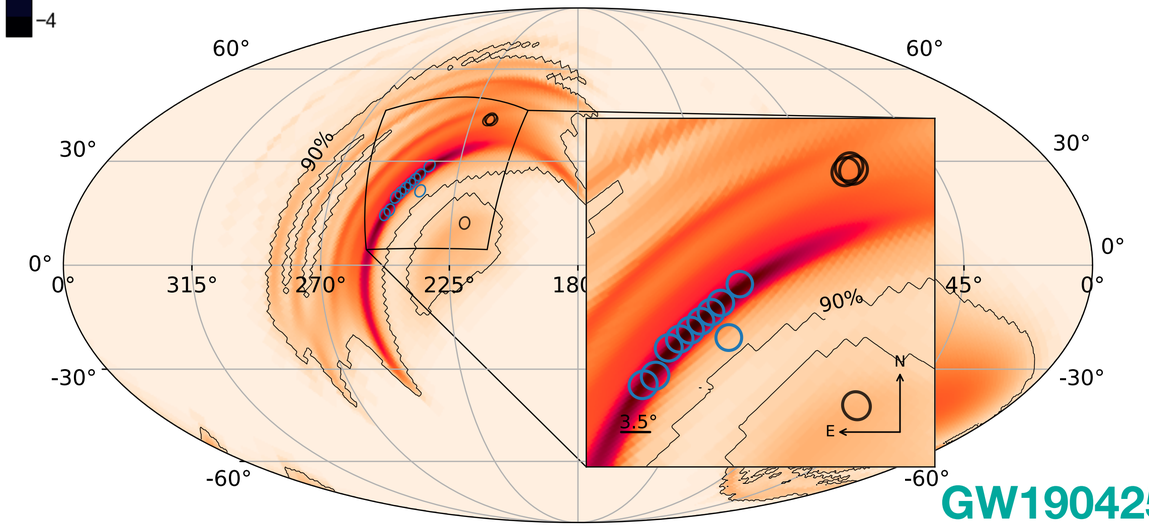
GW170104: 50-$M_\odot$ BBH merger @ z = 0.2.



GW ID	Delay [h]	Binary type	VERITAS obs
S190412m	24.1	BBH > 99%	3.1
S190425z	1.3	BNS > 99%	0.9
S190426c	17.6	NSBH 60%	2.5
S190707q	20.3	BBH > 99%	3.0
S190930s	12.4	MassGap 95%	3.0
S191215w	3.1	BBH > 99%	1.5
S191216ap	4.25	BBH > 99%	4.5
S200213t	20	BNS 63% Terr 37%	1.5
S200219ac	18.5	BBH 96%	1.0
S200224ca	7.5	BBH > 99%	0.5
S200225q	0.7	BBH 96%	2.5
S200316bj	5.0	MassGap > 99%	2.0

- LIGO/Virgo O3 run (2019-2020): Development of automated tiling algorithm for GW error regions.

- 12 GWs followed-up in O3. **Highlight: follow-up of the BNS merger GW190425. No VHE detection.**



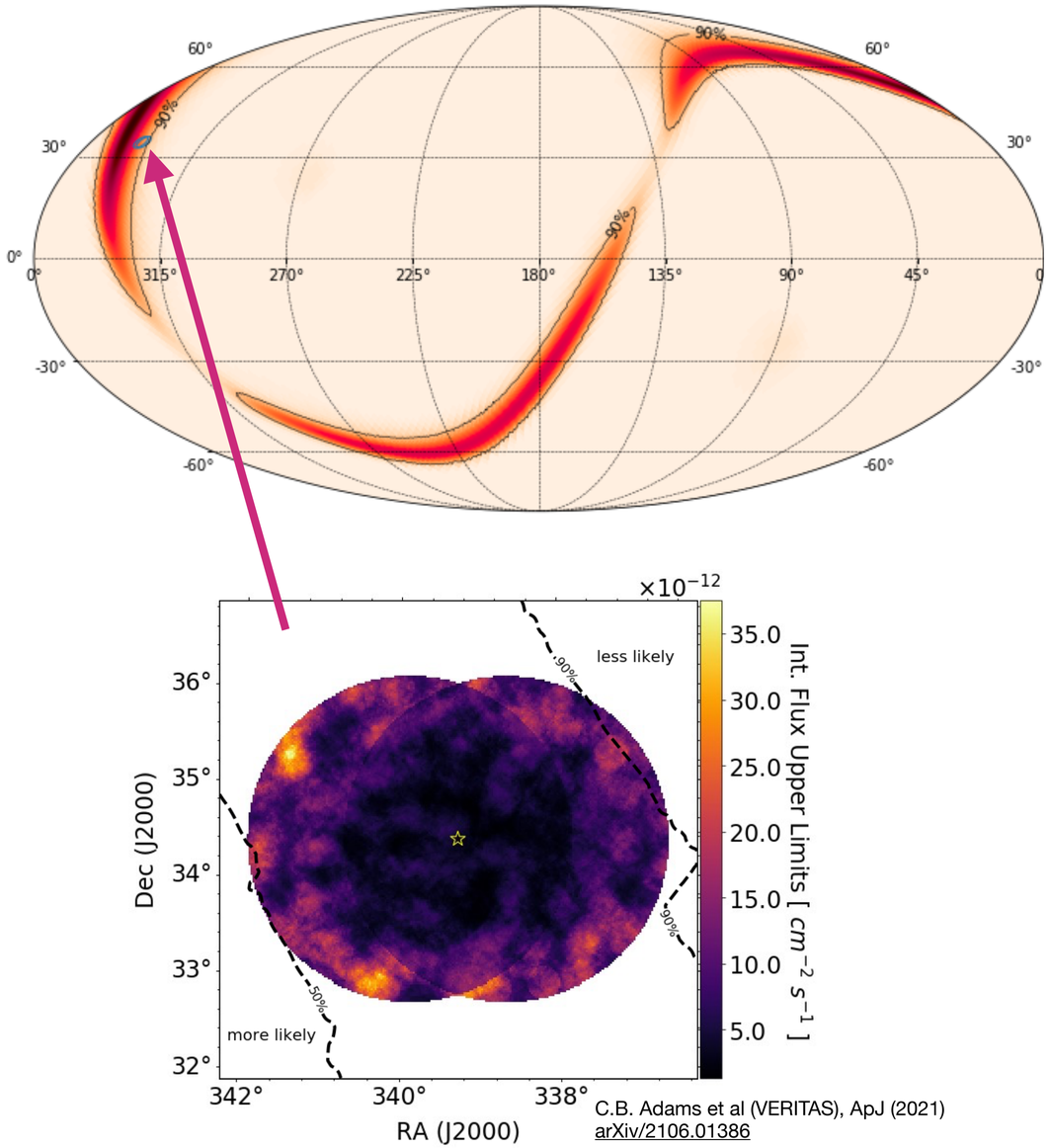
GW190425

Serendipitous searches involving GW events

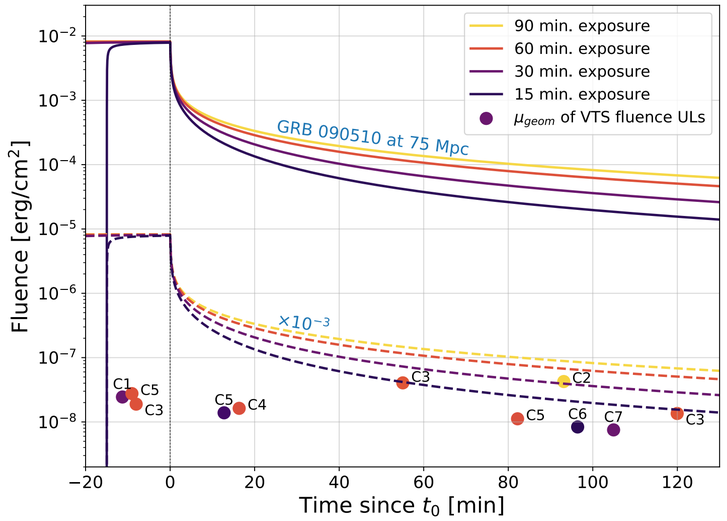
The Astrophysical Journal, 918:66 (11pp), 2021 September 10
https://doi.org/10.3847/1538-4357/ac0623

An Archival Search for Neutron-star Mergers in Gravitational Waves and Very-high-energy Gamma Rays

C. B. Adams[1], W. Benbow[2], A. Brill[1], J. H. Buckley[3], M. Capasso[4], J. L. Christiansen[5], A. J. Chromey[6], M. K. Daniel[2], M. Errando[3], A. Falcone[7], K. A. Farrell[8], Q. Feng[4], J. P. Finley[9], L. Fortson[10], A. Furniss[11], A. Gent[12], C. Giuri[13], D. Hanna[14], T. Hassan[13], O. Hervet[15], J. Holder[16], G. Hughes[2], T. B. Humensky[1], W. Jin[17], P. Kaaret[18], M. Kertzman[19], D. Kieda[20], S. Kumar[14], M. J. Lang[21], M. Lundy[14], G. Maier[13], C. E McGrath[8], P. Moriarty[21], R. Mukherjee[4], D. Nieto[22], M. Nievas-Rosillo[13], S. O'Brien[14], R. A. Ong[23], A. N. Otte[12], N. Park[24], S. Patel[18], K. Pfrang[13], M. Pohl[25], R. R. Prado[13], E. Pueschel[13], J. Quinn[8], K. Ragan[14], P. T. Reynolds[26], D. Ribeiro[1], E. Roache[2], J. L. Ryan[23], M. Santander[17], G. H. Sembroski[9], R. Shang[23], A. Weinstein[6], D. A. Williams[15], T. J. Williamson[16]
(VERITAS Collaboration),
and
I. Bartos[27],
and
K. R. Corley[1], S. Márka[1], Z. Márka[28], and D. Veske[1]
(Columbia Experimental Gravity Group (GECo))

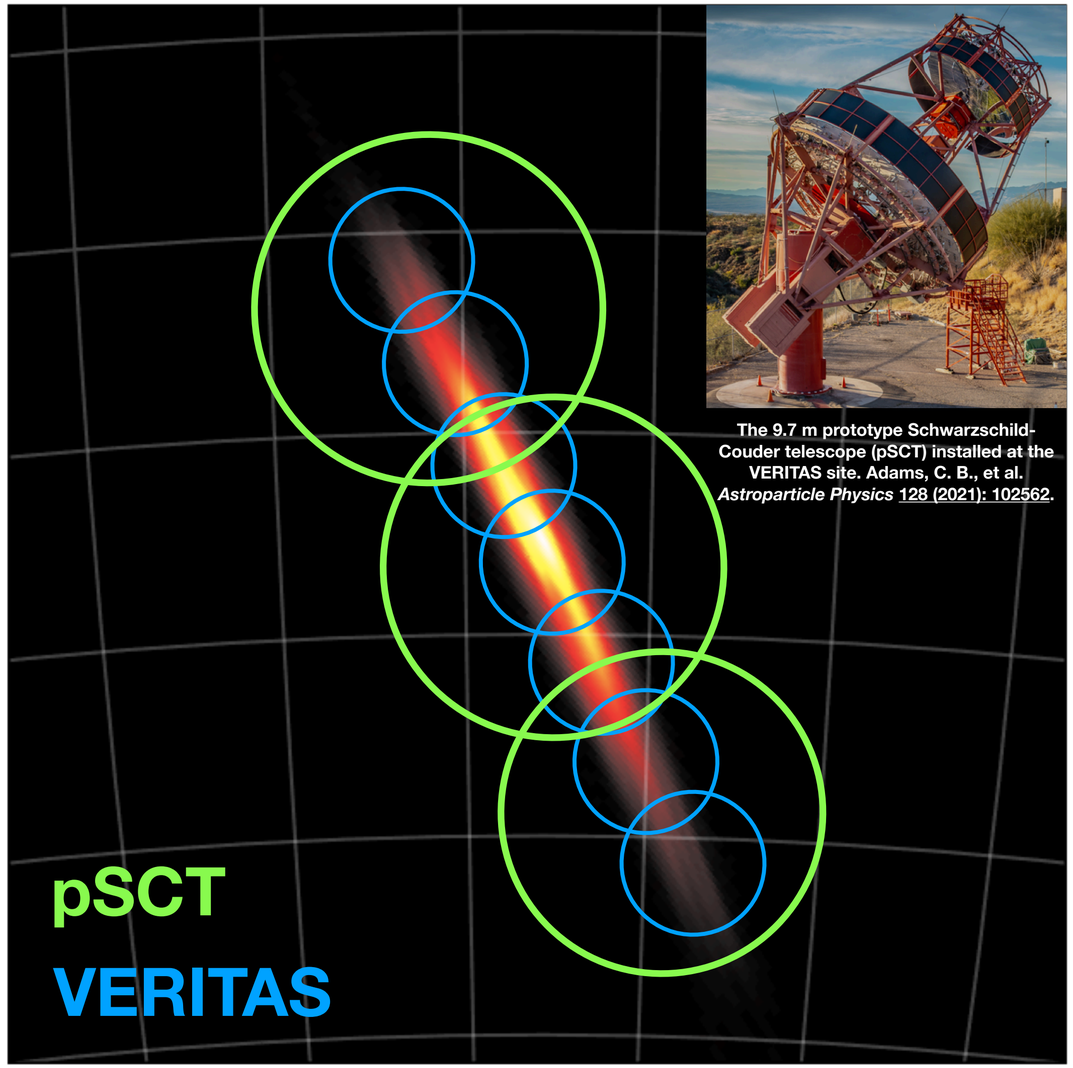


C.B. Adams et al (VERITAS), ApJ (2021)
arXiv/2106.01386



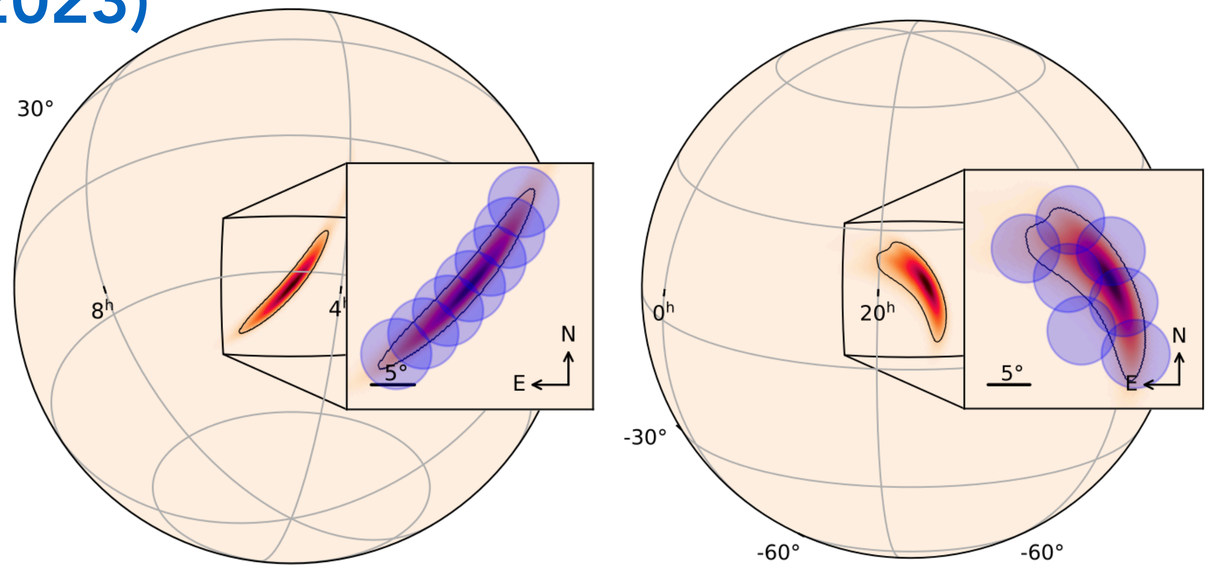
- Search archival VERITAS data for VHE emission coincident with low signal-to-noise ratio GW events.
- No VHE detection. ULs compared to GRB emission model.
- **Pathfinder study for CTA and future GW detectors.**
- Published in ApJ (2021)

Plans for LIGO/Virgo/Kagra O4 (March 2023)



The 9.7 m prototype Schwarzschild-Couder telescope (pSCT) installed at the VERITAS site. Adams, C. B., et al. *Astroparticle Physics* 128 (2021): 102562.

Tiling of the GW event GW170817 using VERITAS and the pSCT.



CTA tiling pattern suggested by the 'greedy' method (left) and 'honeycomb' method (right). I. Bartos, et al, MNRAS, (2019). ArXiv:1908.09832.

- VERITAS will keep optimizing our GW tiling algorithm and analysis pipeline.
- **Synergies with the pSCT:**
  - Large FoV (~8°) compared to VERITAS (~3.5°) provides improved coverage of poorly-localized transients/multimessenger events.

Conclusions

- The matching flux of *Fermi* IGRB and IceCube high-energy neutrinos suggest that a large fraction of energy in the nonthermal universe originates in hadronic processes.

- VERITAS will continue to follow-up IceCube alerts and to search for potential counterparts:

    - NuToO campaign: MAGIC, IceCube, FACT, H.E.S.S. and VERITAS.

    - TXS 0506+056: MWL campaigns including NuSTAR+Swift to characterize long-term behavior. Low-flux state since 2018.

    - IceCube-201114A: VERITAS exposure offers the most constraining ULs on VHE emission. Paper in preparation led by *Fermi*-LAT;

    - PKS 0735+178: Good SED dataset and working on modeling.

- VERITAS serendipitous searches of low signal-to-noise ratio GW events - pathfinder study for CTA and future GW detectors.

- Plans for LIGO/Virgo/Kagra O4: VERITAS will optimize our GW tiling algorithm and analysis pipeline. Also synergies with the pSCT.