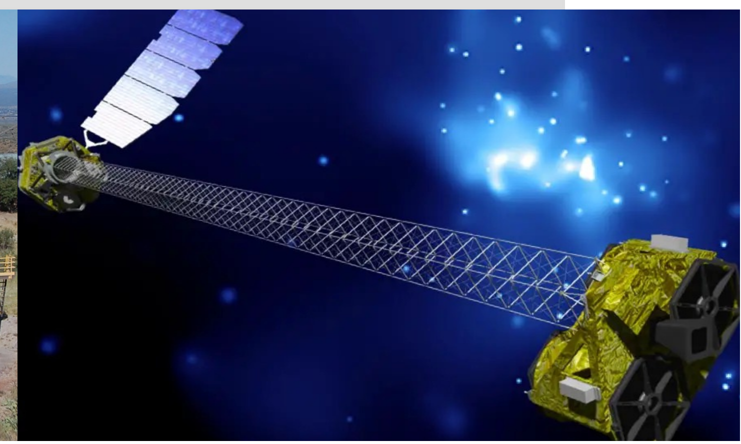
Gamma-ray and X-ray follow-ups of astrophysical neutrinos

Reshmi Mukherjee
on behalf of the VERITAS Collaboration
Barnard College, Columbia University



TeVPA, Naples, September 2023

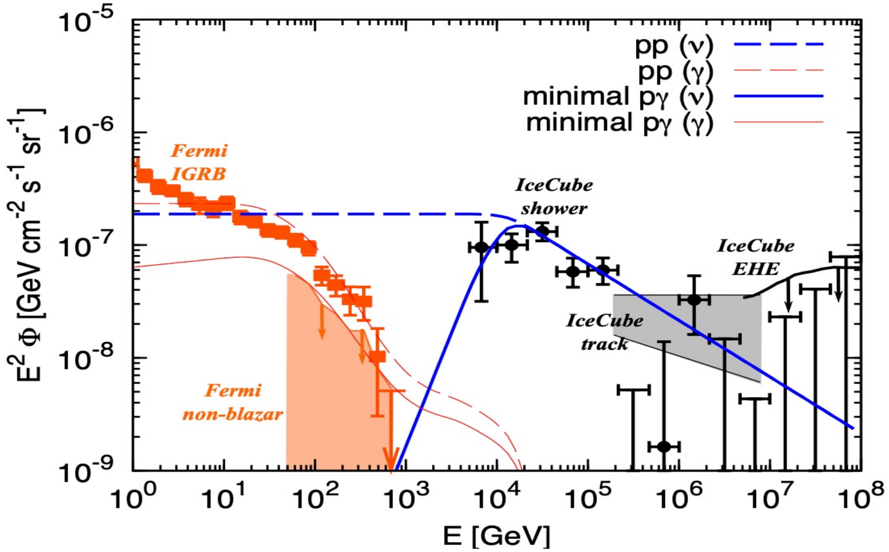
Outline

- Background and current status
- VERITAS-Neutrino multi-messenger program
    - Active follow-up Target of Opportunity (ToO) program
    - Several complementary neutrino alert streams
    - ~ 30 hours/year of deep observations of few (~3/yr) candidates
    - MWL observations with NuSTAR, Swift-UVOT and Swift-XRT
- Future plans

Background

Potential Astrophysical Associations of IceCube Neutrinos

- Arrival directions of astrophysical neutrinos detected by IceCube suggests extragalactic origin for HE neutrinos [IceCube Science 2013]
- Association of a 200-TeV neutrino event from direction of flaring blazar TXS 0506+056 in 2017 [IceCube Science 2018, 187.8816]
- Association of a 170-TeV neutrino event from flaring blazar PKS 0735+178 in 2021 [VERITAS+H.E.S.S. et al. ApJ 2023]
- Strong evidence for TeV neutrino emission from nearby starburst galaxy NGC 1068 [IceCube Science 2023]
- Observation of diffuse Galactic plane in neutrinos [IceCube Science 2023]

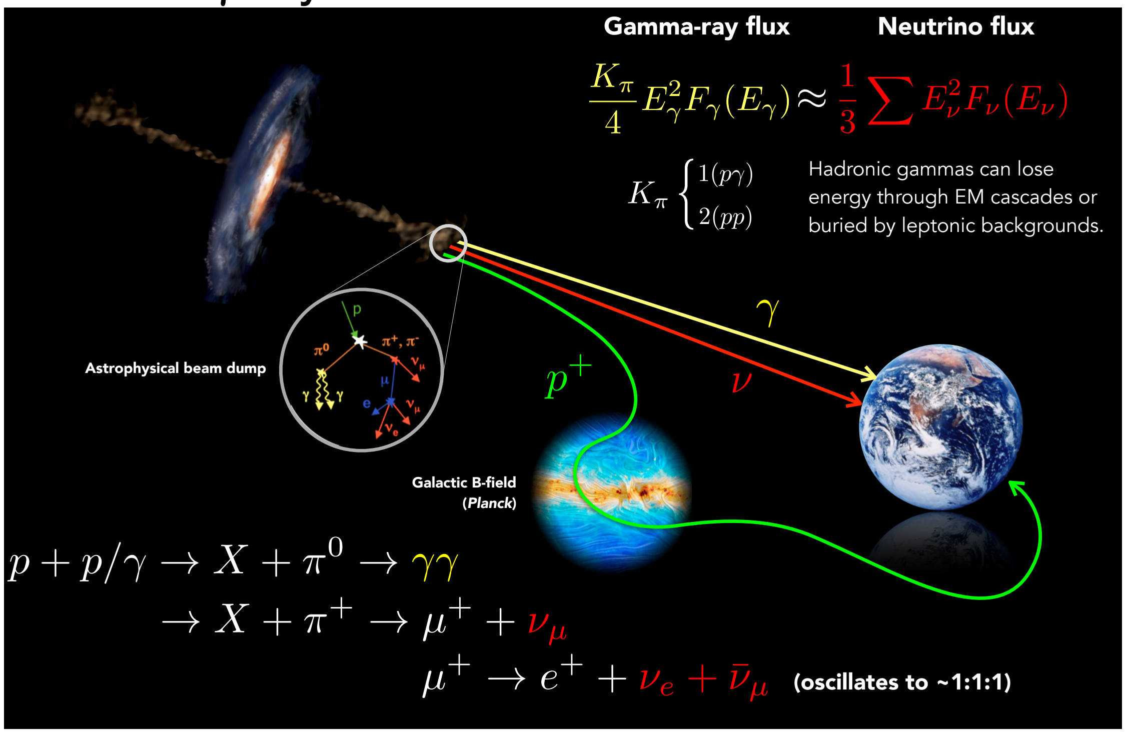


However, there is still no firm identification of any neutrino point sources

Kurahashi, Murase, Santander, arXiv:2203.11936

Hadronic Cosmic Ray Interactions and Neutrinos

- Neutrinos are produced in hadronic CR interactions: Accompanied by hadronic γ rays



Spatial and temporal correlations of neutrino events and EM radiation could provide “smoking gun” for joint emission processes

Santander ICHEP 2016

- Hadronic cosmic-ray interactions produce not only neutrinos but also γ-rays (neutral pion decays) and X-rays (synchrotron radiation)

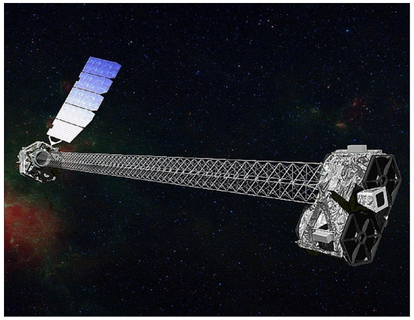
Multiple Strategies for Following IceCube Neutrinos

VERITAS follow up program (similar to H.E.S.S. and MAGIC) consists of multiple approaches:

- Single neutrino event (Bronze/Gold alert streams (30%/50% astrophysical probability)
- "GFU" events (Gamma-ray follow-up) – Pre-defined targets, neutrino multiplets in IC online data stream. Alerts shared via MoU with IACTs

Strategy

- Follow up with VERITAS/IACTs
- NuSTAR ToO program (~1/yr)
- ToO for flaring blazar close to the neutrino in space/time



X-ray and TeV γ-ray are the most constraining. Observations at γ-ray and X-ray bands are critical for studies of neutrinos and cosmic rays

Individual Flaring Blazars as Sources of HE Neutrinos

- Blazars exhibit strong and highly variable γ-ray and X-ray emission
- γ-rays from blazars can be produced by leptonic or hadronic interactions
- Flares from individual high-powered γ-ray blazars provide promising opportunities for the identification of neutrino emitters [e.g., Murase et al. 2018]
- Neutrino emission from blazars requires high energy density in energetic protons, high maximum energy of ~100 TeV, and sustained activity

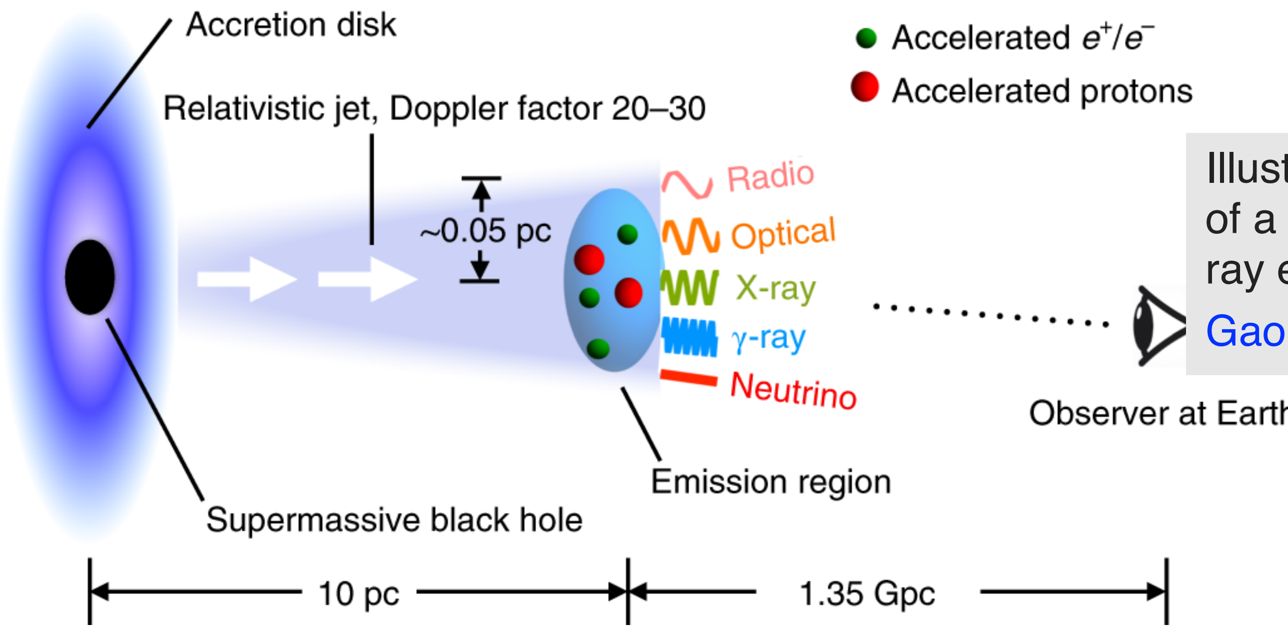


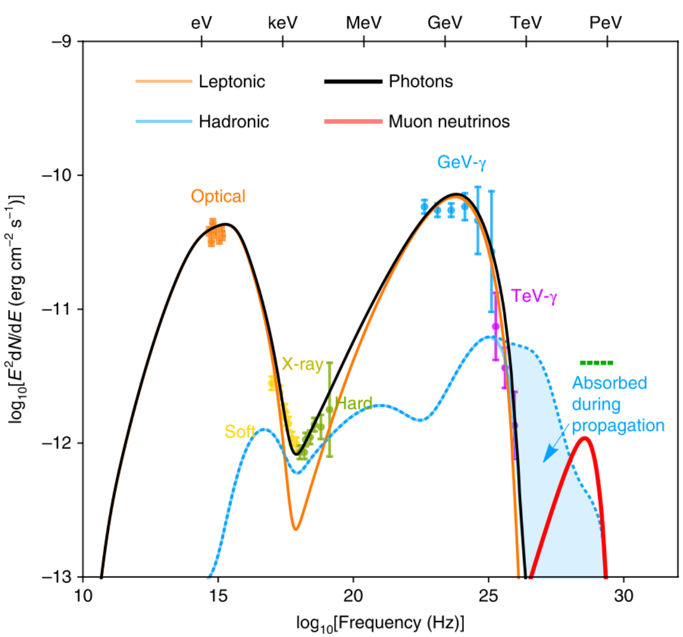
Illustration of the emission region of a blazar as a potential ν and γ-ray emitter

Gao et al. Nature Astro. 2019

Searching for Neutrino-emitting Blazars in the Hard X-ray Band

NuStar ToO Program **[NASA GI Proposal - Feng et al. 2020-2023]**

- Target-of-opportunity observations of a candidate neutrino-emitting blazar
- Triggered by combination of IceCube neutrino alert and detections of spatially coincident blazar by *Fermi*-LAT and *Swift*-XRT
- 40 ks of initial NuSTAR obs within 24 hrs, on best-effort basis, after trigger
- If hard-X-ray flux from initial observation is > 1.5×10^{-12} erg $cm^{-2} s^{-1}$ additional 40 ks of follow-up observations to characterize low-flux



SED of IC 170922A requires a hadronic emission component from TXS 0506+056

Hadronic emissions from blazars manifest themselves as highly correlated neutrinos of TeV – PeV energies, γ rays at TeV energies, and X-rays detectable by *Swift* and NuSTAR

Gao et al. Nature Astro. 2019

The Observations

- PKS 0735+178 associated with IceCube-211208A Dec 2021
  - Work done in collaboration with H.E.S.S. (see 2023ApJ...954...70A)

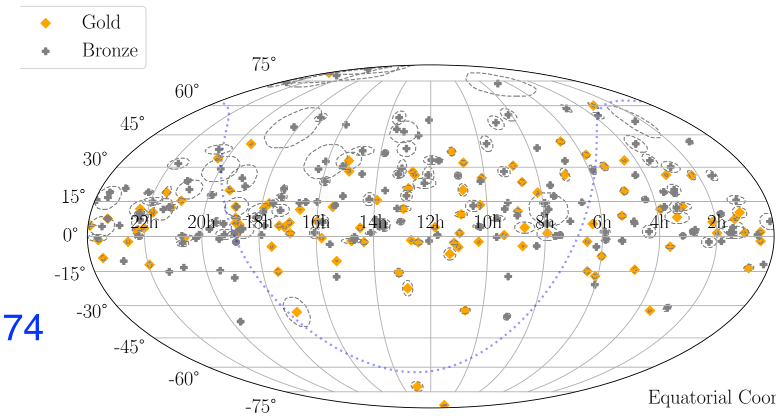
- B3 2247+381 associated with IceCube GFU alert in Sep 2022

An IceCube track-like event with an energy Eν ≈ 171 TeV

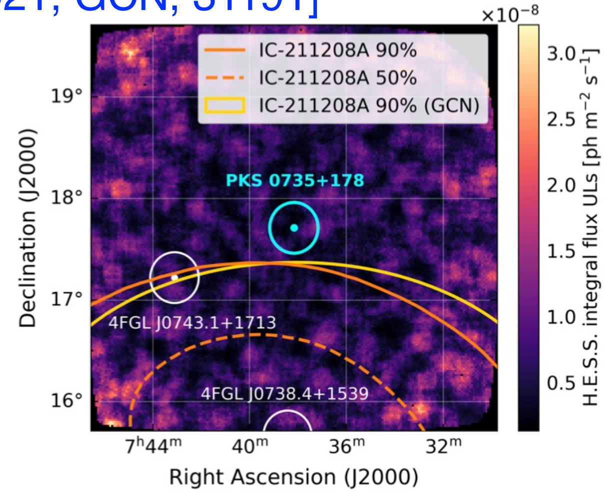
IceCube: track-like event **IC-211208A** on 8 Dec 2021 [2021, GCN, 31191]

Energy $E_{\nu} \approx 171$ TeV

Probability of being astrophysical origin ≈ 50%



IceCat-1 arXiv:2304.01174



Bradascio et al. ICRC 2023

Fermi-LAT: Gamma-ray blazar PKS 0735+178 (redshift z = 0.45) 2.2° away from the best-fit position of the neutrino event IceCube-211208A [Petkov et al. 2021]

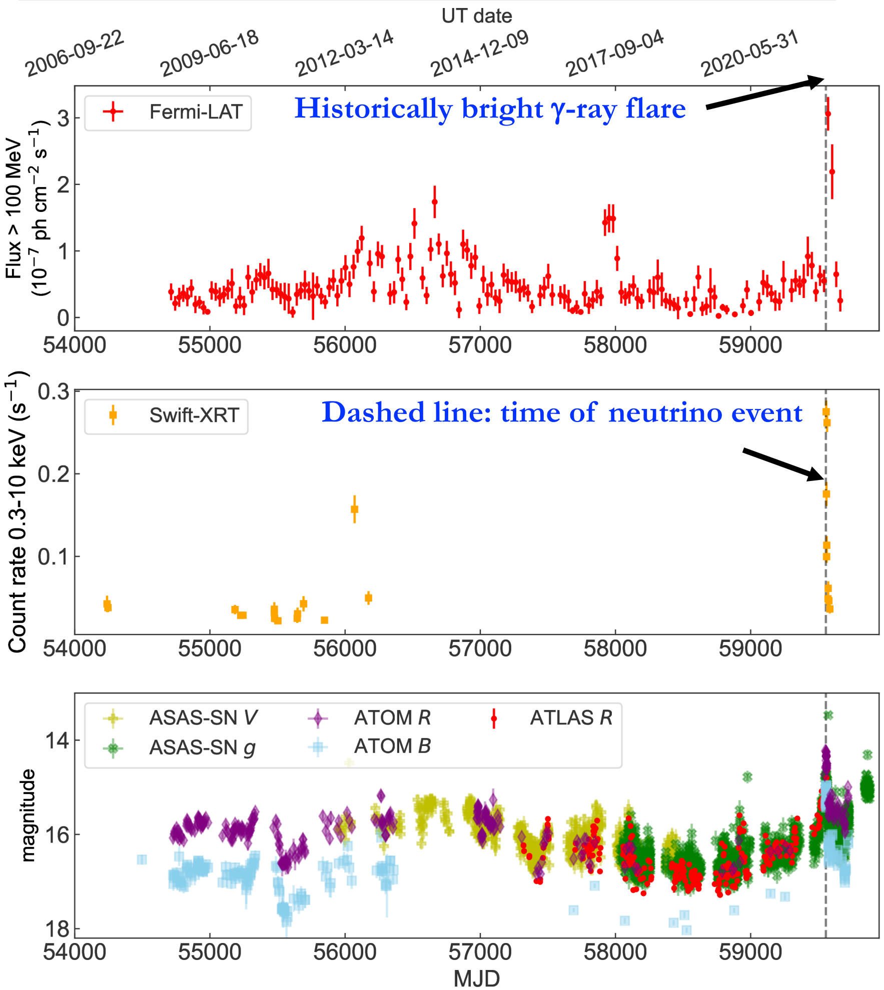
Baikal-GVD: high-energy neutrino candidate event with energy $E_{\nu} \approx 43$ TeV ~ 4hrs after IceCube event, ~ 4.7° from position of PKS 0735+170 [Dzhilkibaev et al. 2021]

KM3NeT: reported one up-going muon neutrino candidate (~18 TeV) on 15 Dec 2021 in spatial coincidence with PKS 0735+178 [Filippini et al. 2022]

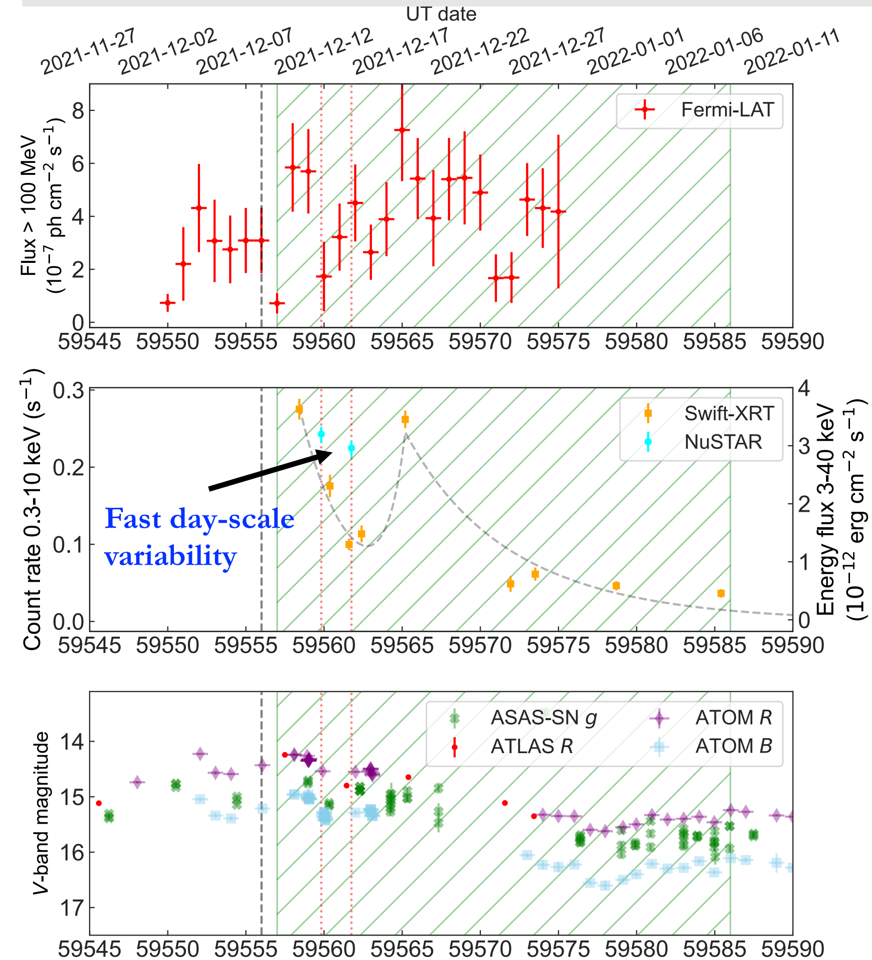
Baksan Underground Scintillation Telescope: reported observation of a GeV neutrino candidate event four days before IceCube-211208A [Petkov et al. 2021]

Multiwavelength Flare in PKS 0735+178 during IceCube Neutrino Event

The long-term variability of PKS 0735+178



MMW activity 2 months after neutrino event



2023ApJ...954...70A

Highest flux during IC neutrino event at all frequencies

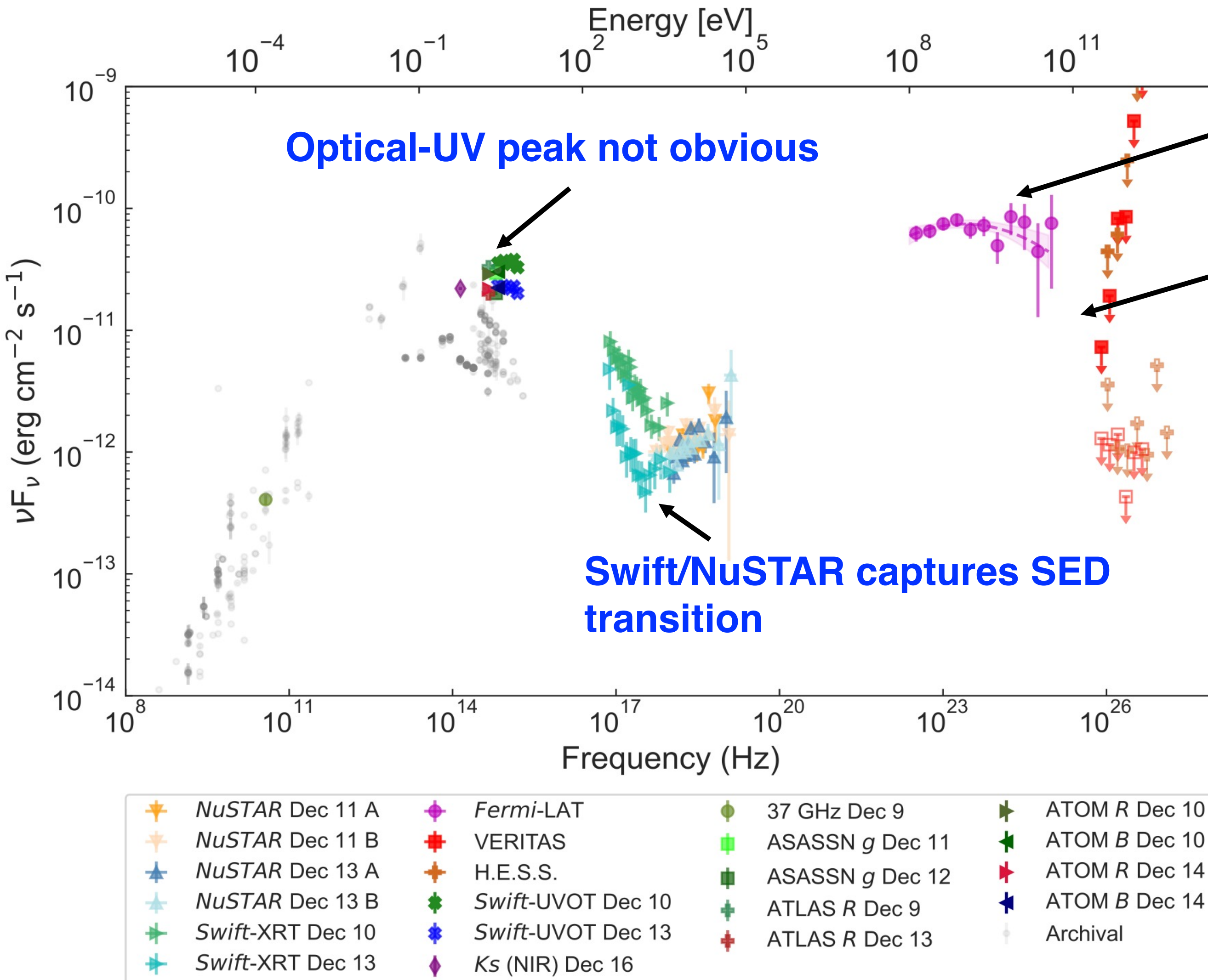
NuSTAR ToO Detects Hard X-ray Emission from PKS 0735+178

- Two NuSTAR ToOs of PKS 0735+178 triggered by IceCube211208A [ATel: 15113 (2021)]
- Flux increase from the PKS 0735+178 detected by Swift-XRT and Fermi-LAT.
- Two 22 ks observations on performed on Dec 11 and Dec 13, 2021

Best-fit photon index: $\Gamma = 1.85 \pm 0.06$ (1 σ statistical error) (Dec 11)

Best-fit photon index $\Gamma = 1.70 \pm 0.07$ (marginally harder) (Dec 13)

Observations of PKS 0735+178 Across 13 Decades in Energy



Optical-UV peak not obvious

Strong GeV detection

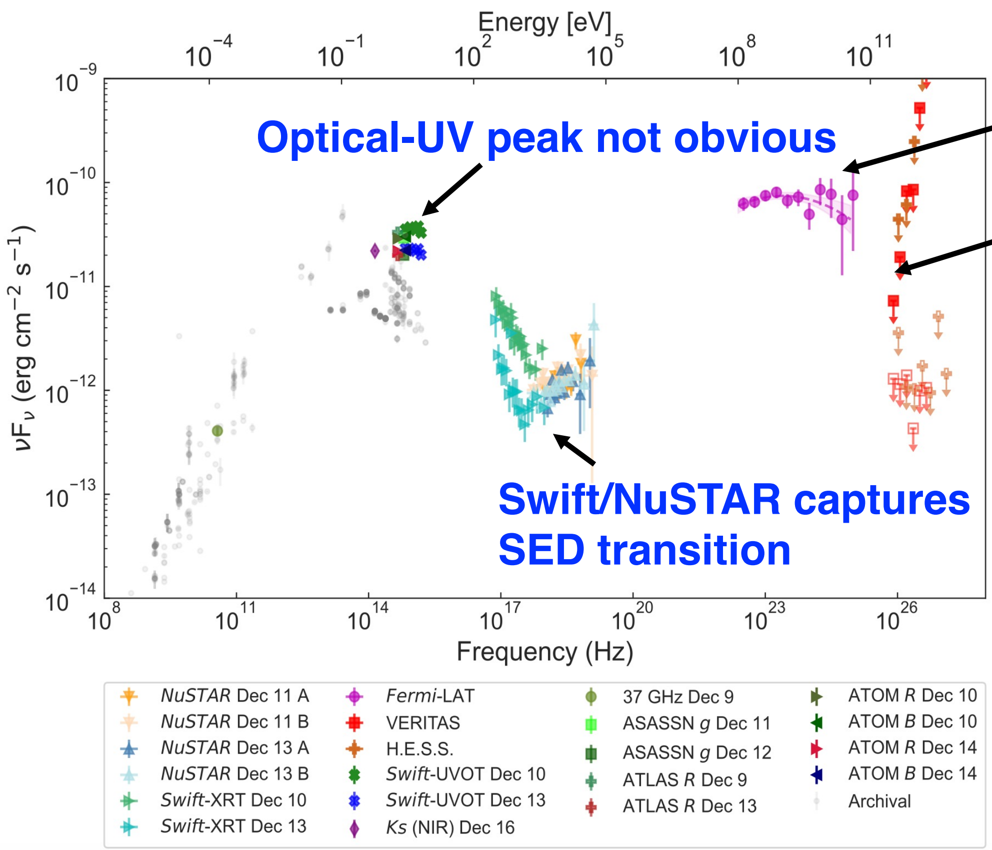
H.E.S.S./ VERITAS cutoff at ~100 GeV

UL by VERITAS at ~300 GeV

Swift/NuSTAR captures SED transition

2023ApJ...954...70A

One-Zone SSC Does Not Explain SED Well



Strong GeV detection

H.E.S.S./ VERITAS cutoff at 100 GeV

One zone leptonic SSC does not fit the data well

$$\gamma_{\rm peak} \approx \frac{3\times 10^5}{\sqrt{\epsilon_{\rm peak,eV}}}$$

$$\epsilon_{\rm peak,eV} \approx \frac{100}{\sqrt{D_{25}\,R_{16}}}$$

Synchrotron peak needs to extend up to ~100 eV to be consistent with cutoff at ~ 100 GeV

Neutrino Observation: Proton Injection Luminosity inconsistent with Eddington Limit

- Neutrino emission is likely from pγ processes in blazars [Gaisser et al. 1995]
- Observed IC neutrino energy $E_\nu \sim 170$ TeV
  - ➔ In the jet frame, assuming D = 25, $E'_\nu = 7$ TeV
  - ➔ Target photon energy ~ 25 keV (NuSTAR)

Estimated neutrino flux: $EF_\nu(E) \approx 1.5 \times 10^{-10}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

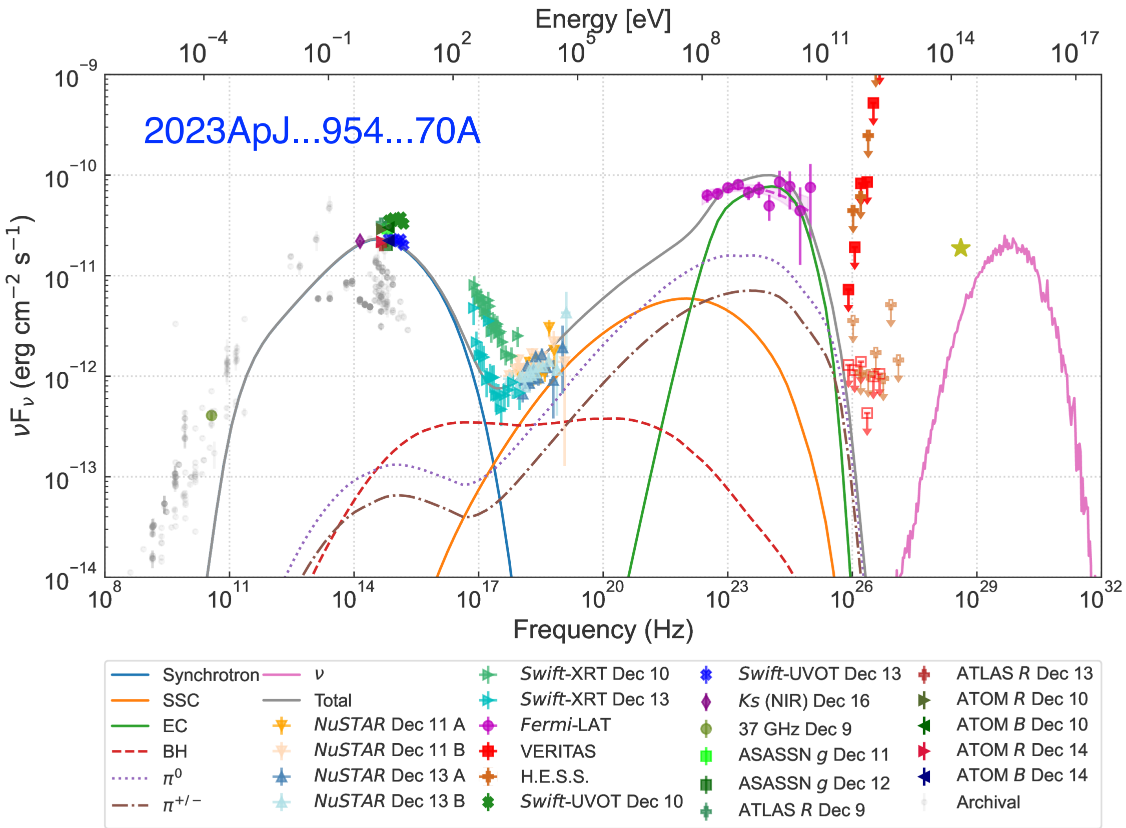
Assuming, E ~170 TeV for IC neutrino
Effective area of Bronze alerts ~ 30 m^2 (from IceCube)
One 170 TeV neutrino event observed within a month

Proton injection luminosity: $$L'_p \gtrsim \frac{R_{16}^2}{D_{25}}\left(\frac{30\ \mathrm{days}}{T_{\mathrm{act}}}\right)^2 (1.5 \times 10^{46}\ \mathrm{erg\ s^{-1}}).$$

In the AGN-frame the jet power is about D^2 higher and violates the Eddington limit
➔ Jet power needs to be lower to be consistent with observations
➔ (Similar to the case of TXS 0506+056)

2023ApJ...954...70A

Lepto-Hadronic Model Calculation for SED



The lepto-hadronic numerical model with an external photon field [M. Cerruti, MNRAS 2015]

- One zone leptonic SSC does not fit the data well
- An SSC/external Compton scenario also naturally provides the observed 100 GeV cutoff through the KN effect and γγ pair absorption
- With BLR photon field: purely leptonic EIC can explain the electromagnetic emission (dominate at multi-GeV and cutoff at > 100 GeV), Lepto-hadronic with pγ and EIC could also explain neutrino rate

Reference

VERITAS & H.E.S.S. Collaboration 2023, The Astrophysical Journal, 954:70
2023 September 1

arXiv > astro-ph > arXiv:2306.17819

Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 30 Jun 2023]

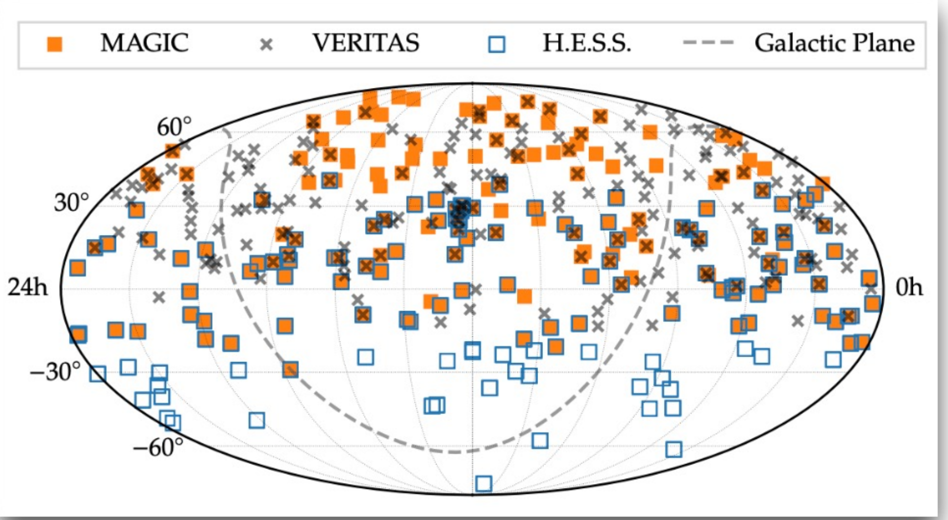
Multiwavelength Observations of the Blazar PKS 0735+178 in Spatial and Temporal Coincidence with an Astrophysical Neutrino Candidate IceCube-211208A

A. Acharyya, C. B. Adams, A. Archer, P. Bangale, J. T. Bartkoske, P. Batista, W. Benbow, A. Brill, J. H. Buckley, J. L. Christiansen, A. J. Chromey, M. Errando, A. Falcone, Q. Feng, G. M. Foote, L. Fortson, A. Furniss, G. Gallagher, W. Hanlon, D. Hanna, O. Hervet, C. E. Hinrichs, J. Hoang, J. Holder, T. B. Humensky, W. Jin, P. Kaaret, M. Kertzman, M. Kherlakian, D. Kieda, T. K. Kleiner, N. Korzoun, S. Kumar, M. J. Lang, M. Lundy, G. Maier, C. E McGrath, M. J. Millard, J. Millis, C. L. Mooney, P. Moriarty, R. Mukherjee, S. O'Brien, R. A. Ong, M. Pohl, E. Pueschel, J. Quinn, K. Ragan, P. T. Reynolds, D. Ribeiro, E. Roache, I. Sadeh, A. C. Sadun, L. Saha, M. Santander, G. H. Sembroski, R. Shang, M. Splettstoesser, A. Kaushik Talluri, J. V. Tucci, V. V. Vassiliev, A. Weinstein, D. A. Williams, S. L. Wong, J. Woo (The VERITAS Collaboration), F. Aharonian, J. Aschersleben, M. Backes, V. Barbosa Martins, R. Batzofin, Y. Becherini, D. Berge, K. Bernlohr, B. Bi, M. Bottcher, C. Boisson, J. Bolmont, M. de Bony de Lavergne, J. Borowska, M. Bouyahiaoui, F. Bradascio, M. Breuhaus, R. Brose, F. Brun, B. Bruno, T. Bulik, C. Burger-Scheidlin, S. Caroff, S. Casanova, R. Cecil, J. Celic, M. Cerruti, T. Chand, S. Chandra, A. Chen, J. Chibueze, O. Chibueze, G. Cotter, S. Dai, J. Damascene Mbarubucyeye et al. (110 additional authors not shown)

IceCube Alert Streams: Gamma-ray Follow-Up (GFU)

From Fabian Schussler's ICRC 2023

- Searches for neutrino multiplets ("flares") in the IC online data stream
  - Time periods ranging from seconds to 180days
- Predefined targets + all-sky search (in preparation)
- Alerts distributed privately under MoU
  - Northern Sky: MAGIC & VERITAS since 2012
    - CTA/LST-1 since 2023
  - Southern Sky: H.E.S.S. since 2019
- Source selection based on
  - GeV+TeV catalogs; variability; distance; visibility, …
- Aim: determine the state of the source
  - quiescence vs flaring state
  - spectral changes



T. Kintscher, PhD thesis, Humboldt-University Berlin, 2020

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

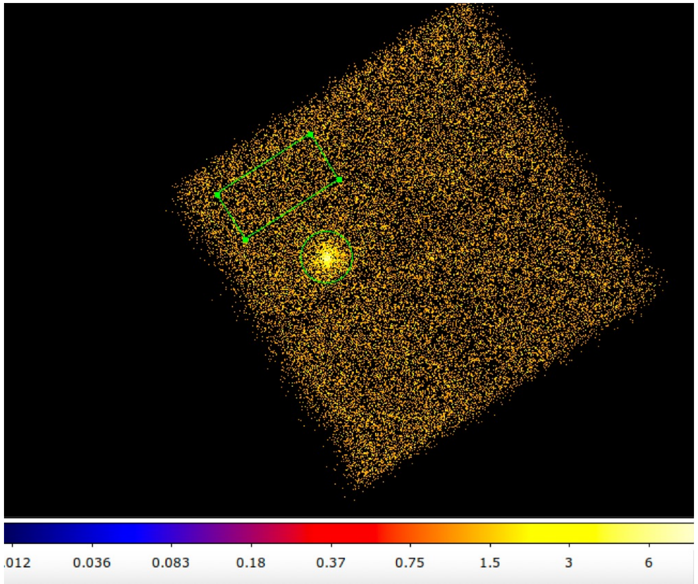
IceCube GFU alert near the location of TeV blazar B3 2247+381

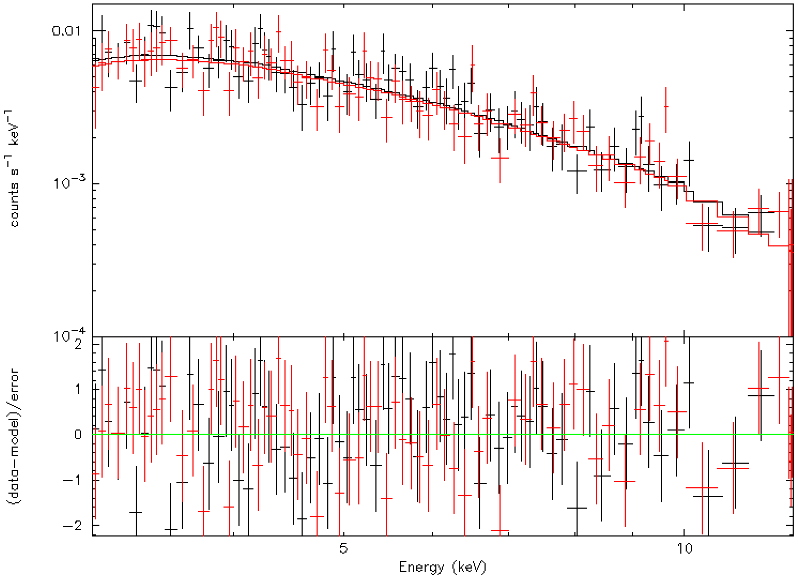
- Historical triggers at the location of TeV blazar B3 2247+381
- 7 events detected over a duration of 174 days between May and Nov 10, 2022
- Alerts generated at 3 σ threshold
- Shared via MOU with IceCube & IACTs [See Fabian Schussler ICRC PoS 2023]
- B3 2247+381 is a BL Lac, redshift $z = 0.119$
- Detected by MAGIC in a flaring state in 2010

- Similar to neutrino multiplet/1ES 1312-423 GFU [Schussler et al. ICRC 2023]
- GFU alert from IceCube ➔ ToO follow up from H.E.S.S. ➔ 1ES 1312-423 detected at ~4 σ

Follow ups of GFUs could help determine the state of the source (quiescence vs flaring state) or any spectral changes

NuSTAR ToO on B3 2247+381 as a follow up to ICeCube GFU





- NuSTAR ToO on B3 2247+381 for ~ 40.5 ks in Sep 2022
- B3 2247+381 strongly detected in the hard X-ray band (3-79 keV)
- VERITAS follow up observations carried out in Sep 2022
- Analysis underway. Joint work with IceCube Collaboration
- Stay tuned ….

Summary

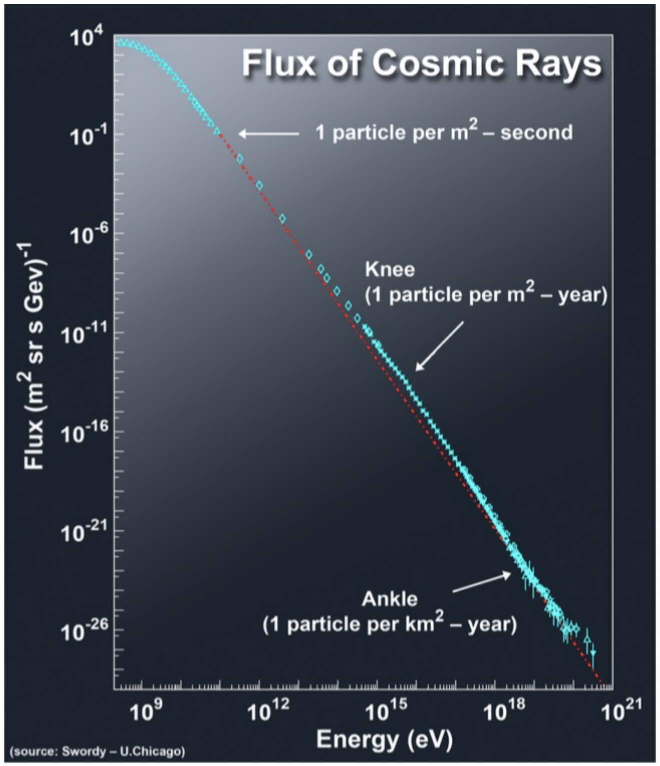
- Searching for temporally and spatially-correlated EM radiation with high-energy IceCube neutrino events is an important strategy for exploring the connection between neutrinos and high-energy blazars
- VHE γ-ray and hard X-ray follow up studies with NuSTAR have been carried out for several cases of IC astrophysical neutrinos
- NuSTAR ToO program yields ~ 1 follow up / year
- Observed multi-wavelength spectra of blazars can help determine if γ rays are consistent with the neutrino events.

Thank you

Extras

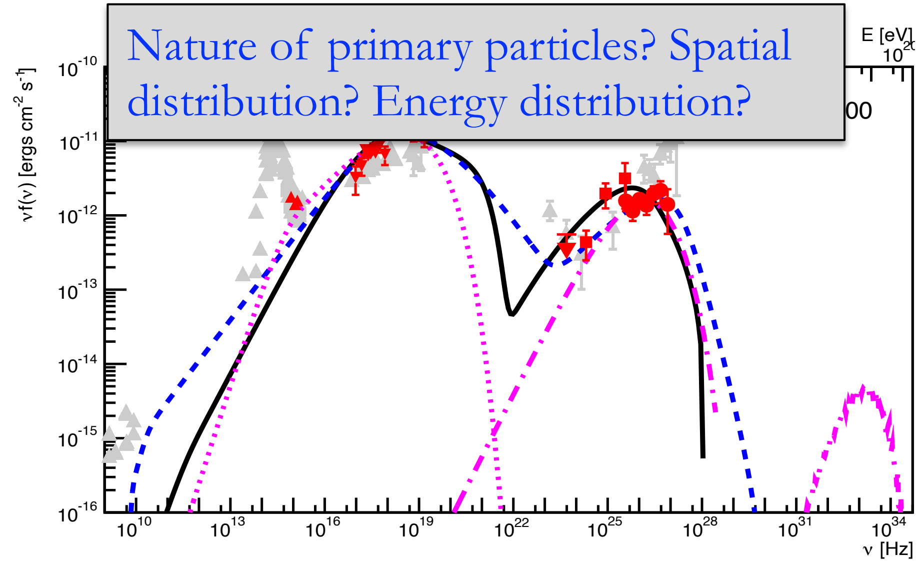
Astrophysical Drivers for High Energy γ rays

Origin of Cosmic Rays?
Diffuse, all particle spectrum



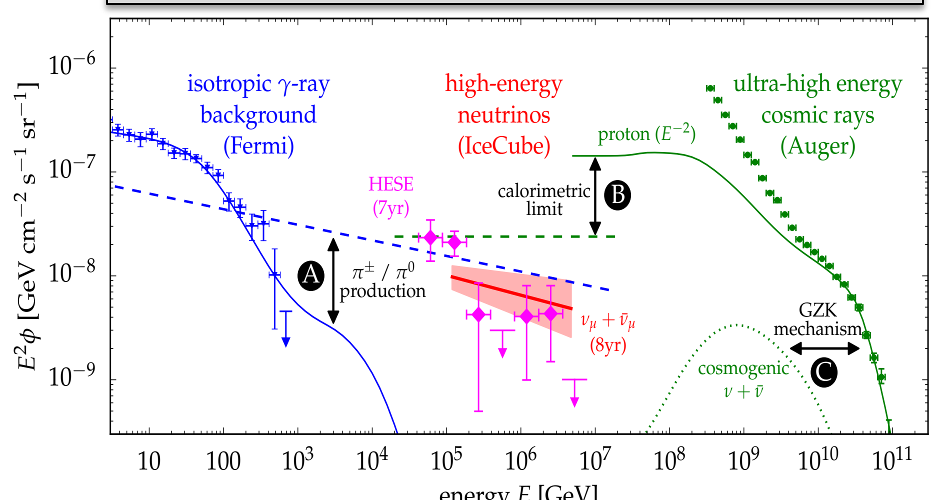
Neutral messengers: γ, ν are required to directly observe cosmic accelerators.

Nature of primary particles? Spatial distribution? Energy distribution?



Acciari et al. ApJ, 247 (2020)

Diffuse HE backgrounds



Ahlers et al. arXiv:1811.07633

Neutrino Production

$$p + \gamma \to \Delta^+ \to \begin{cases} \pi^+ + n & 1/3 \text{ of all cases} \\ \pi^0 + p & 2/3 \text{ of all cases} \end{cases} \tag{1}$$

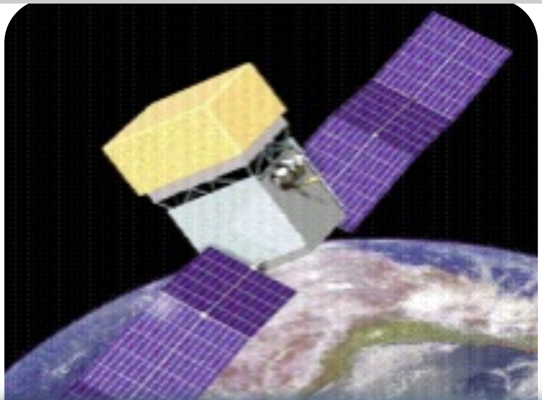
will lead, after pion decay

$$\begin{aligned} \pi^+ &\to \mu^+ + \nu_\mu \,, \\ & \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \,, \end{aligned} \tag{2}$$

For the pp collision mechanism, a nearly isotopically neutral mix of pions is expected from isospin invariance

$$\mathrm{p} + \mathrm{p} \to \begin{cases} \pi^+ + \text{anything} & 1/3 \text{ of all cases} \\ \pi^- + \text{anything} & 1/3 \text{ of all cases} \;. \\ \pi^0 + \text{anything} & 1/3 \text{ of all cases} \end{cases} \tag{3}$$

Gamma-Ray Instrument Synergies



Low-energy threshold - Satellites Fermi-LAT, AGILE: 100 MeV to > 30 GeV

Sky survey, transients

High sensitivity – Current IACTs H.E.S.S., MAGIC, VERITAS: 10s GeV to > 30 TeV

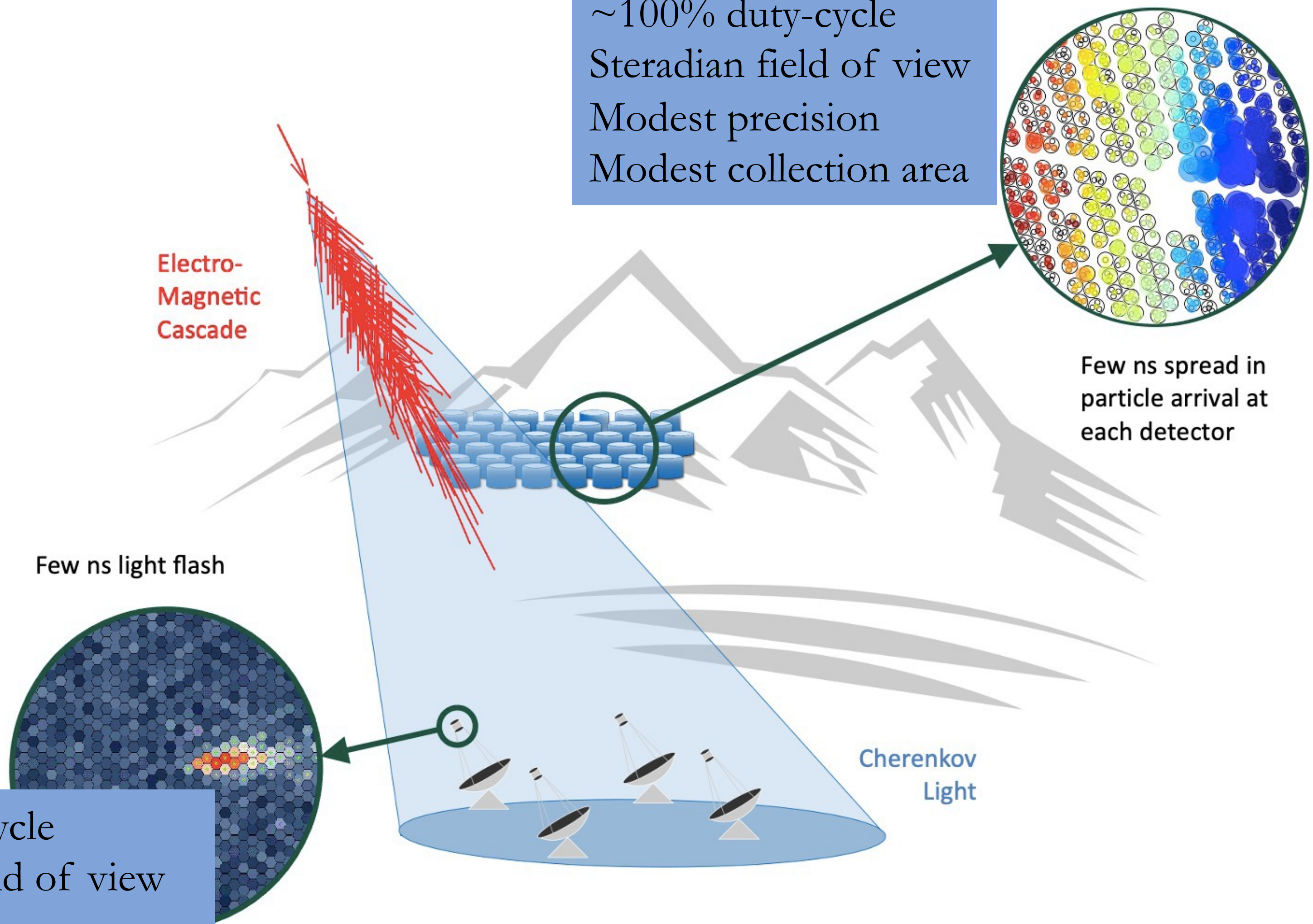
Exceptional sensitivity, but limited field of view, high resolution energy spectra, transients

Large-FoV arrays - HAWC, Tibet ASγ, LHAASO: ~ 0.1 to 100 TeV

High duty cycle, extended sources

VHE Detection Techniques

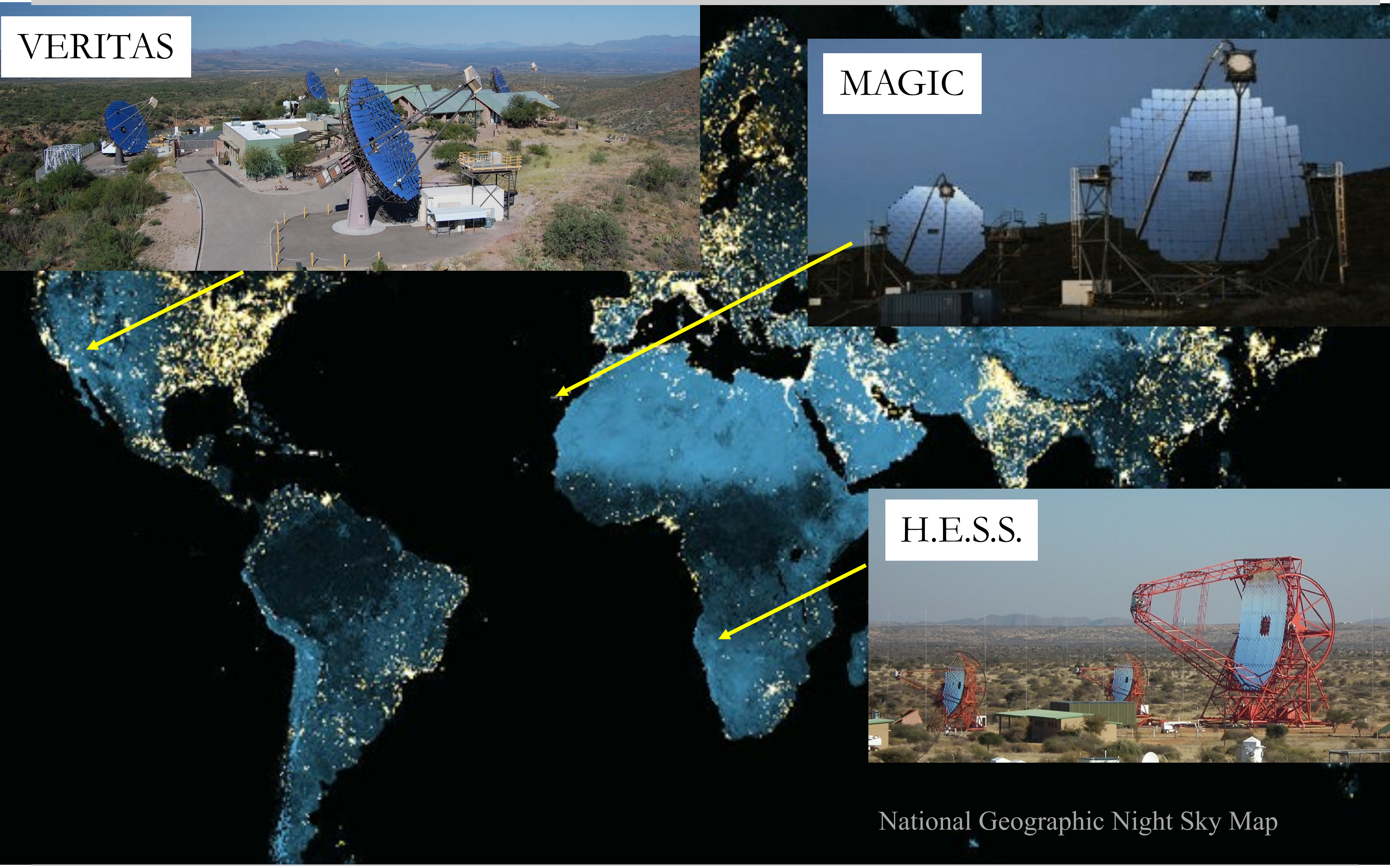
~100% duty-cycle
Steradian field of view
Modest precision
Modest collection area



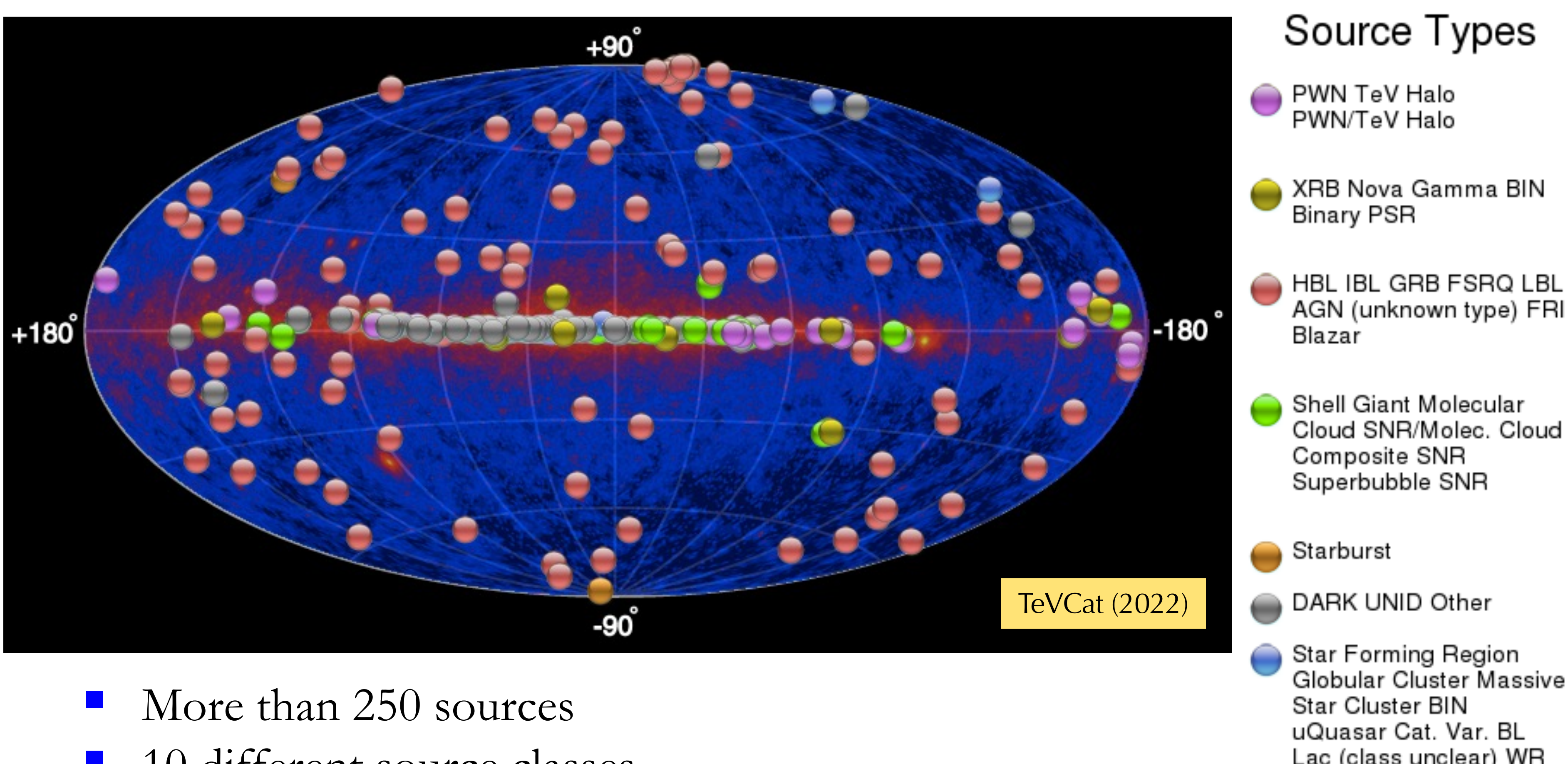
~15% duty-cycle
~4 degree field of view
High precision
Large collection area

Slide courtesy Jim Hinton, ICRC 2021

The Three Major IACTs



VHE Gamma-Ray Sky



- More than 250 sources
- 10 different source classes
- Detailed measurements of spectra and light curves