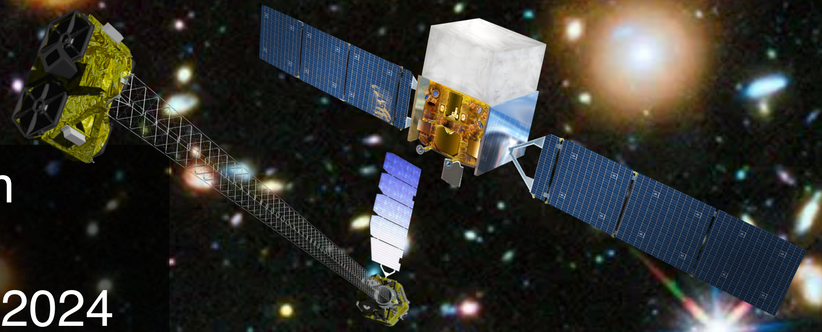
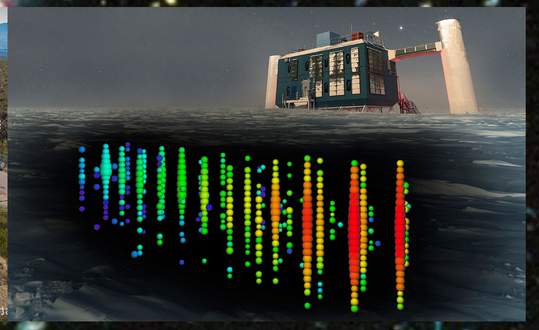
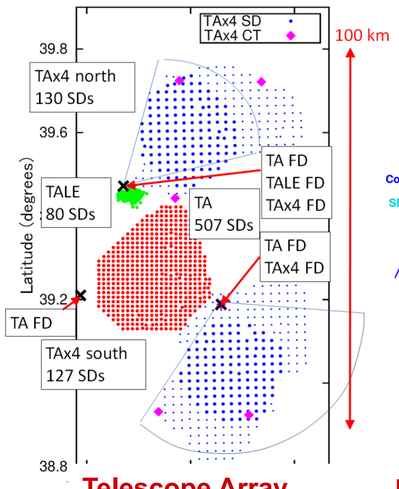
X-ray and Gamma-ray Follow-up Observations of IceCube Neutrino Alerts

Qi Feng for the VERITAS Collaboration
University of Utah
11th Fermi Symposium, September 9, 2024

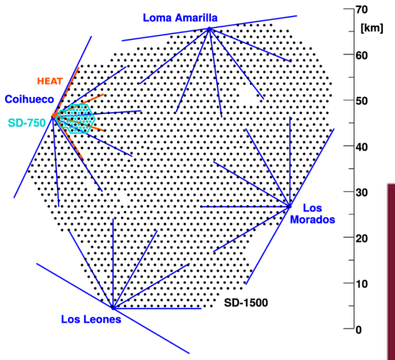




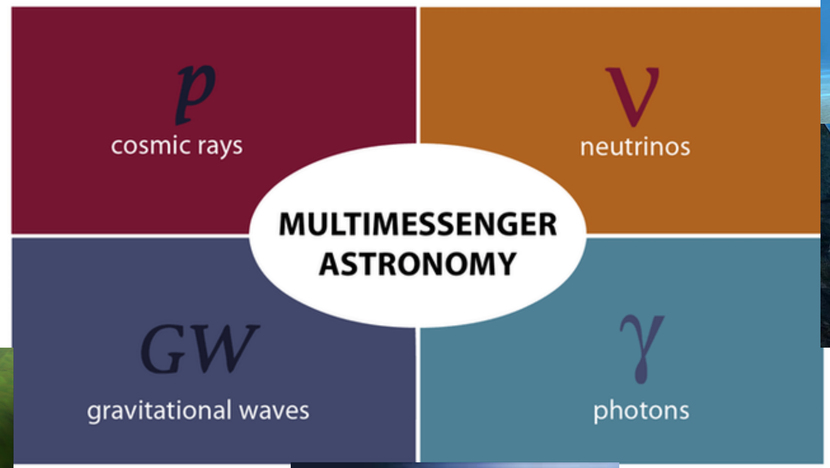
The landscape of multi-messenger astronomy

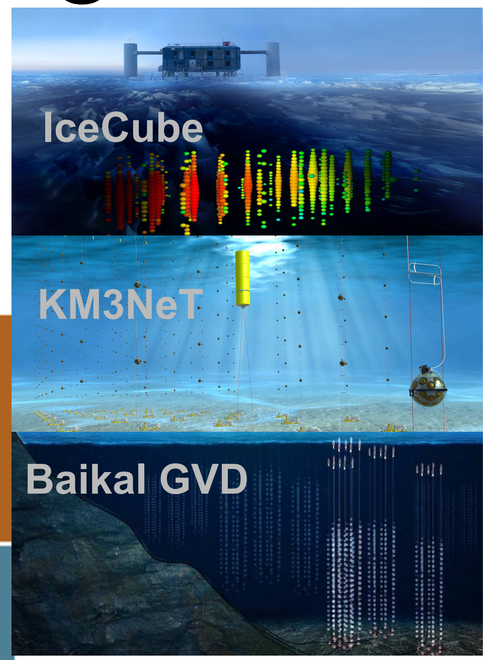


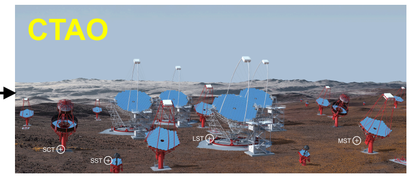
Telescope Array



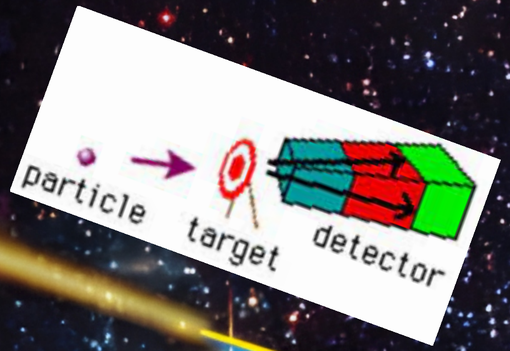
Pierre Auger Observatory







Neutrinos and Photons from Hadronic Cosmic Ray Interactions



Proton

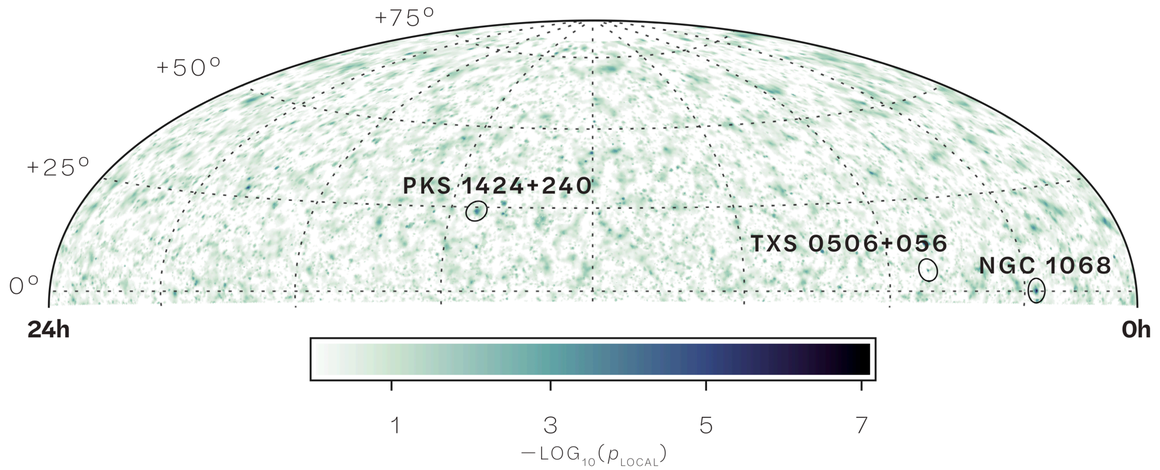
Photon

Neutrino

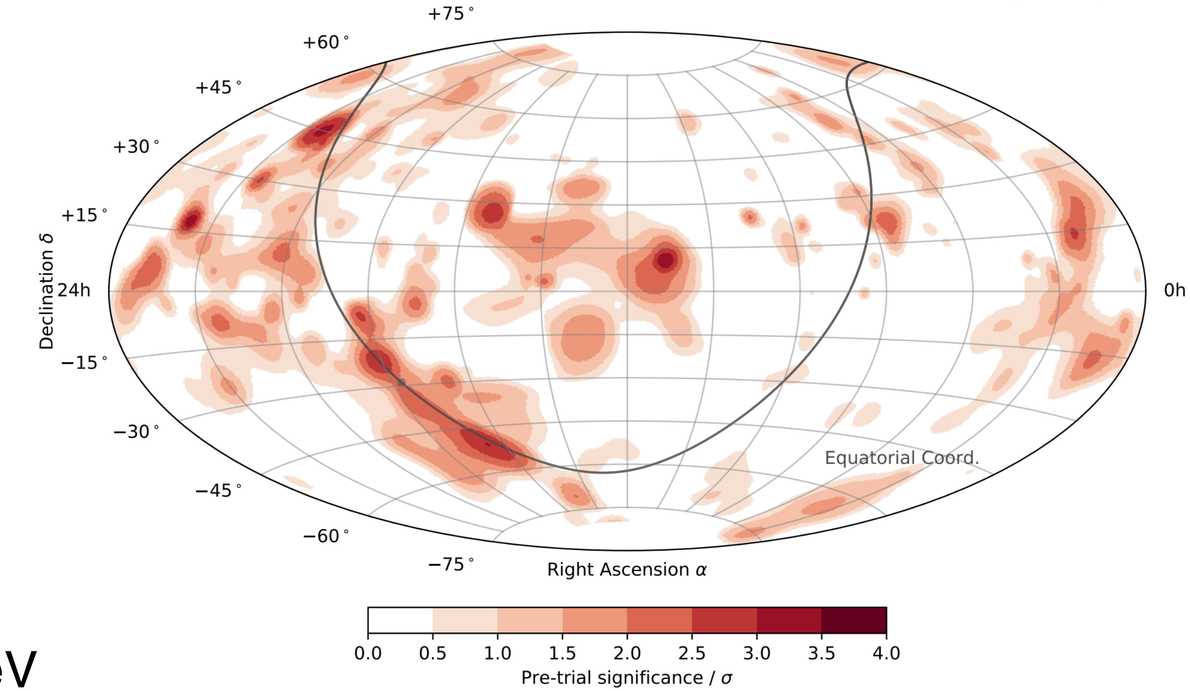
$$p + p/\gamma \rightarrow p/n + \pi^0$$
$$\rightarrow p/n + \pi^+$$
$$\pi^0 \rightarrow \gamma + \gamma$$
γ may cascade
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$n \rightarrow p + e^- + \nu_e$$

Current Status of the Neutrino Sky

The IceCube Collaboration, Science, 378, 6619, 538-543 (2022)



The IceCube Collaboration, Science, 380, 6652, 1338-1343 (2023)

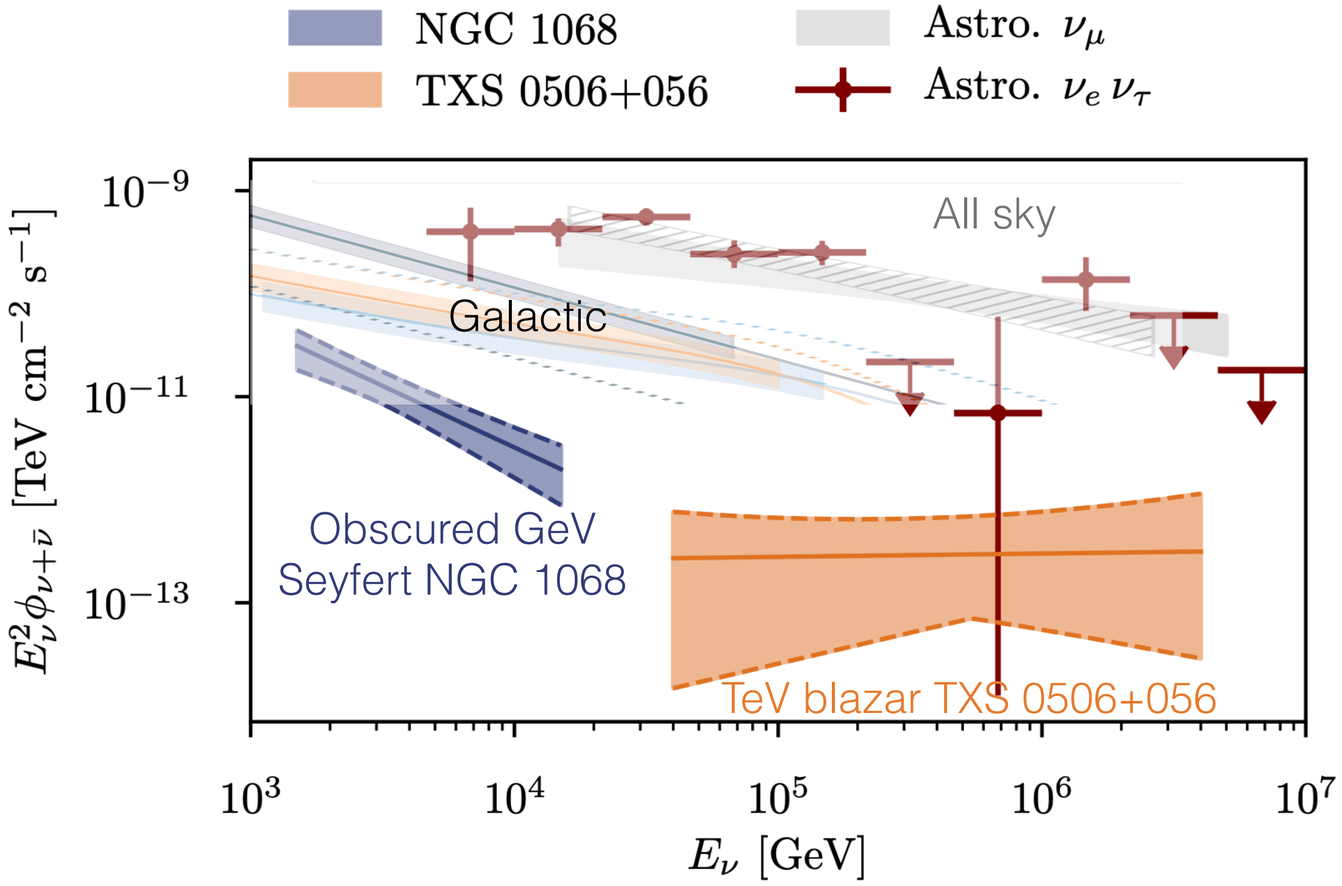


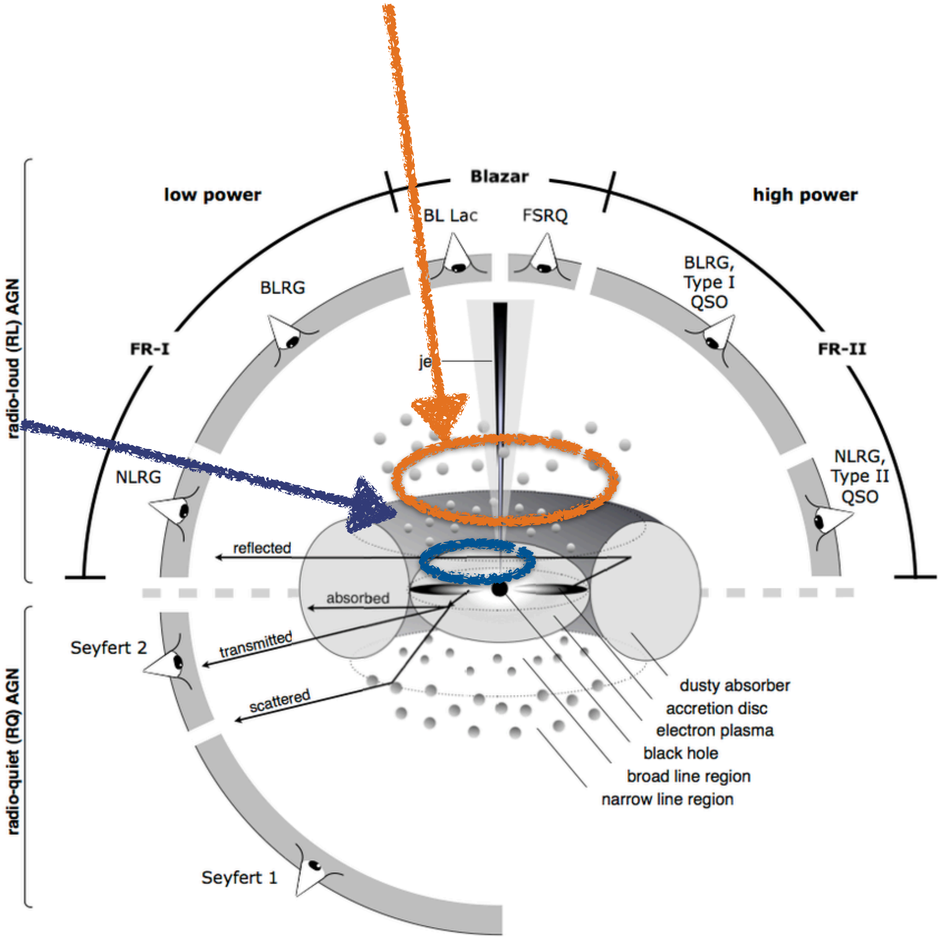
- Diffuse astrophysical neutrinos detected up to PeV
- It is difficult to find astrophysical neutrino sources in IceCube data —> why we need multi messenger
  - A few AGNs are promising:
    - Seyferts NGC 1068 @ 4.2σ, NGC 4151 @ 2.9σ (The IceCube Collaboration 2024 arXiv:2406.06684)
    - Blazars TXS 0506+056 @ 3.5σ, PKS 1424+240 @ 3.7σ
  - The Galactic plane detected @ 4.5σ

Neutrinos from heavily obscured and more transparent sources

The IceCube Collaboration, Science, 378, 6619, 538-543 (2022)

The IceCube Collaboration, Science, 380, 6652, 1338-1343 (2023)

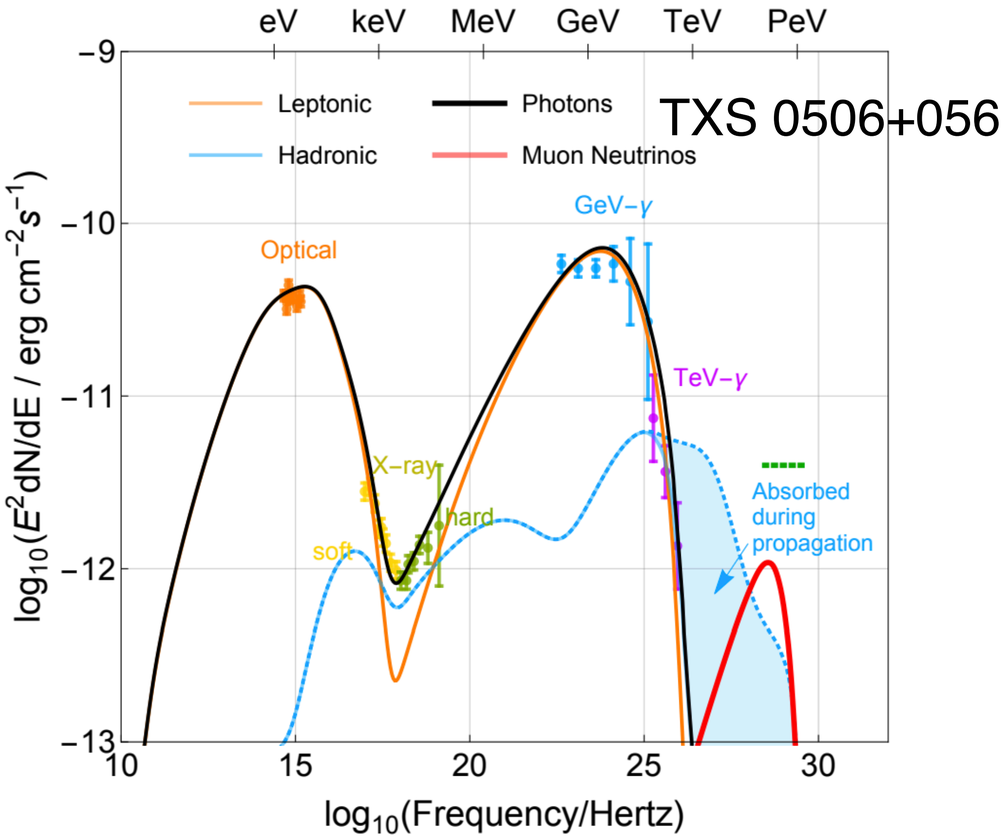




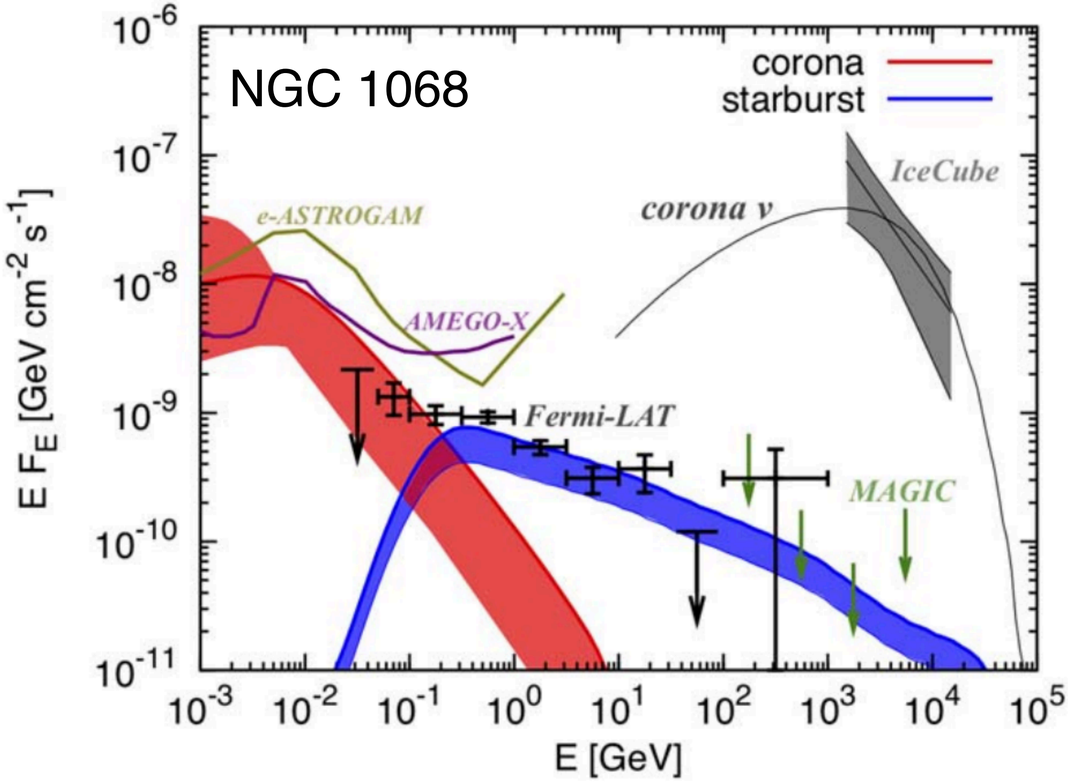
- Different source types and emission mechanisms must exist (extragalactic dominating)
- TeV blazars like TXS 0506+056 are interesting candidates above ~100 TeV

X-Rays and Gamma Rays

Gao et al., Nature Astronomy, 3, 88 (2019)



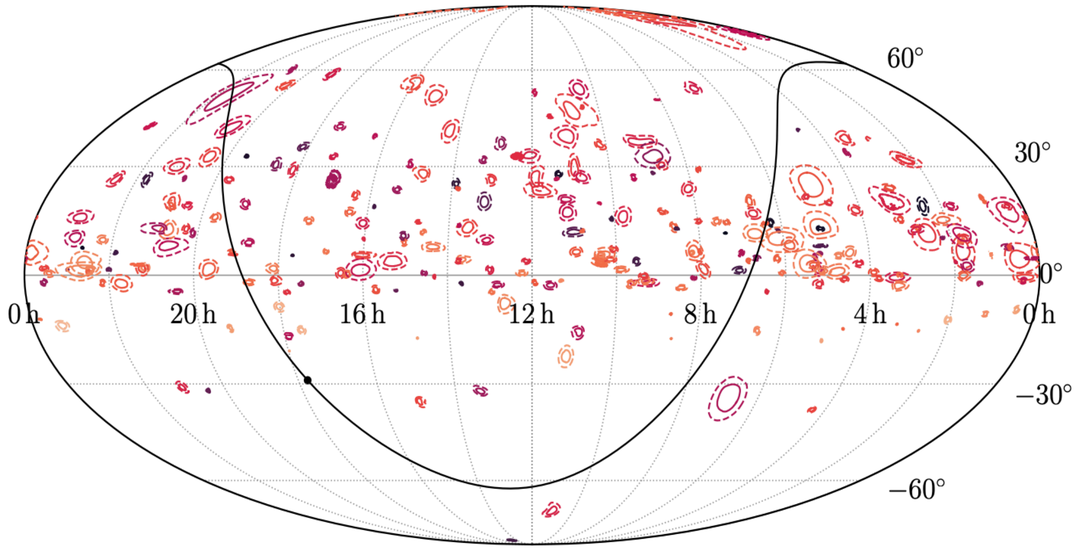
Ajello, Murase, & McDaniel, ApJL, 954, 49 (2023)



Hadronic cosmic-ray interactions produce neutrinos, gamma rays (neutral pion decays), and X-rays (synchrotron radiation from secondary electrons)

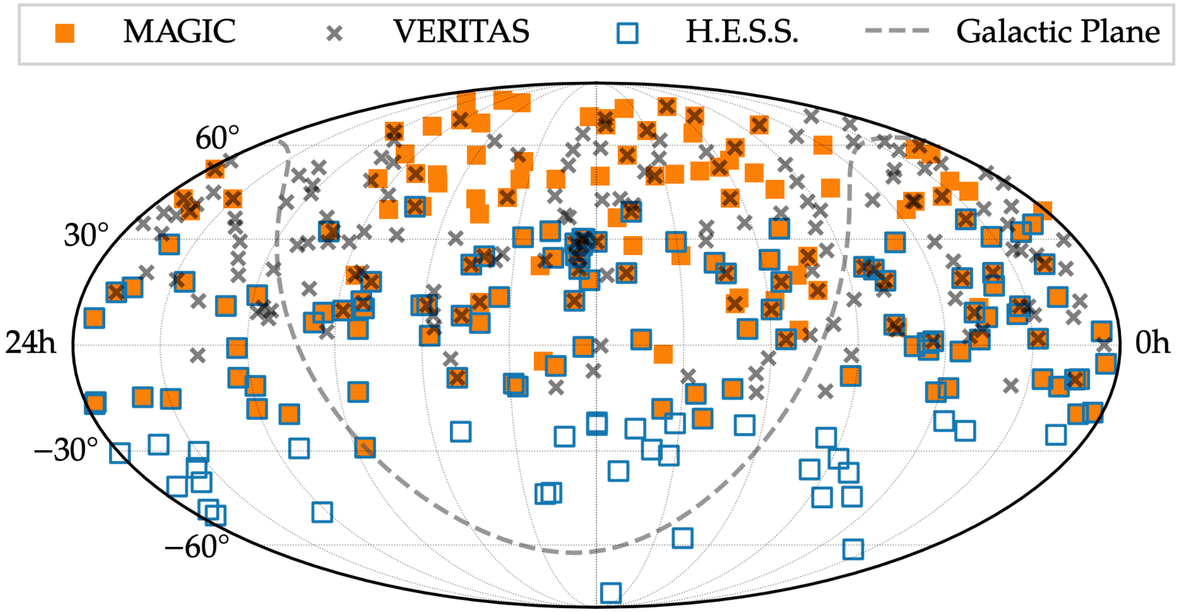
VERITAS Follow-Up of IceCube Candidate Neutrino Sources

- Singlet neutrino events - real-time alerts
- Gamma-ray Follow-Up (GFU) alerts (multiple neutrino events from known gamma-ray sources)
- Target-of-opportunity programs focusing on critical bands:
  - Gamma rays (Fermi-LAT & VERITAS) and X-rays (Swift-XRT & NuSTAR ~1 trigger per year)
- Deep observations of steady neutrino candidate sources (e.g., NGC 4151)



The IceCube Collaboration, ApJ, 951, 45A (2023)

IceCube singlet neutrino real-time alerts
~10 “gold” alerts per year ≳50% prob. astrophysical

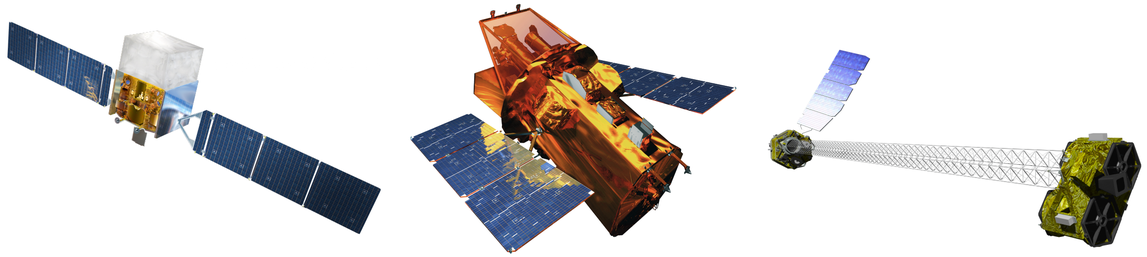


Kintscher, T., PhD Thesis, Humboldt University, Berlin (2020)

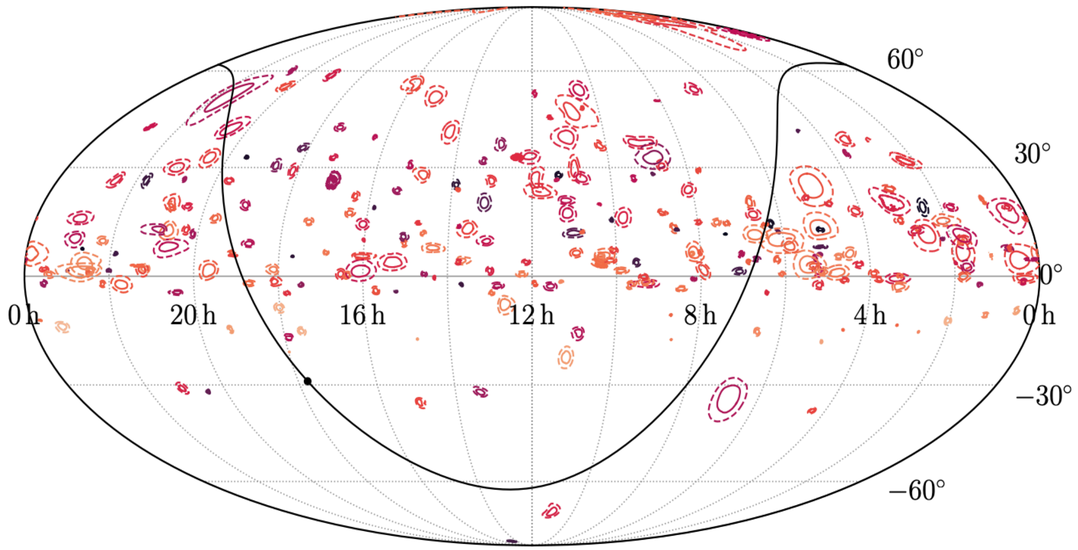
IceCube GFU alerts
339 selected known gamma-ray sources

The Observations

- Real-time alert follow-up:
  - PKS 0735+178 possibly associated with IceCube-211208A in Dec 2021
    - In collaboration with H.E.S.S. (see 2023ApJ...954...70A)
  - PKS 0446+11 possibly associated with IceCube-240110A in Jan 2024
- GFU alert follow-up:
  - B3 2247+381 triggered by IceCube GFU alert in Sep 2022



Follow-Up of IceCube real-time alerts



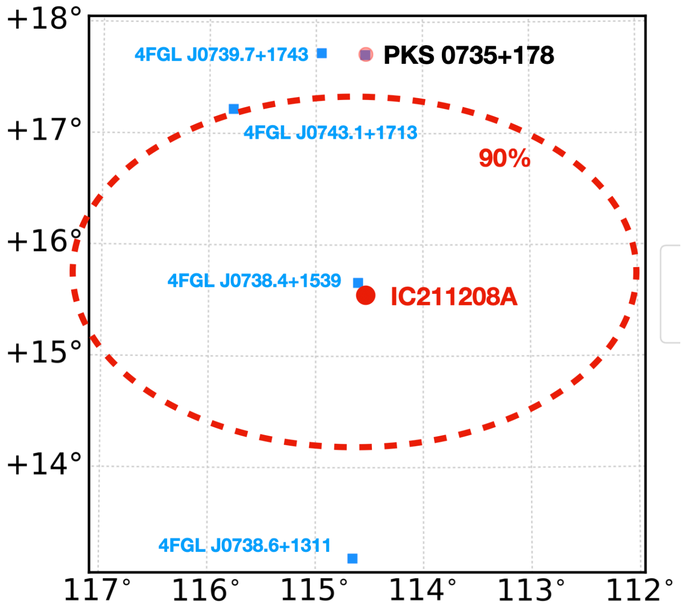
The IceCube Collaboration, ApJ, 951, 45A (2023)

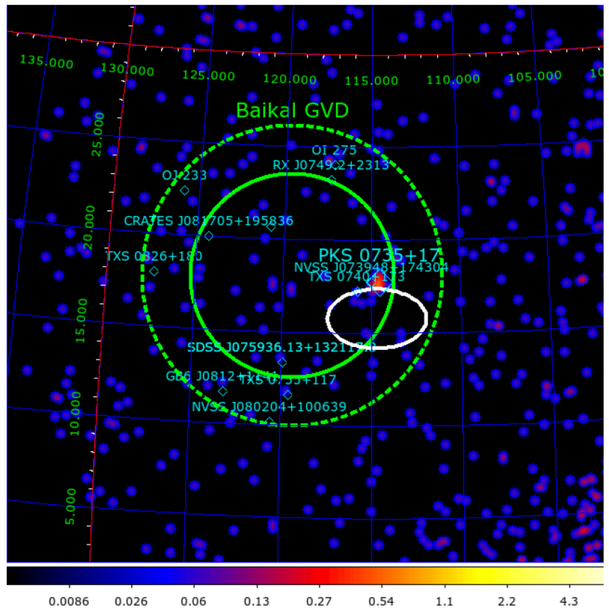
IceCube singlet neutrino real-time alerts
~10 “gold” alerts per year ≳50% prob. astrophysical

- Assume singlet neutrino alerts could be associated with flaring blazar
- Aim to characterize the spectrum and variability of the source:
  - Is there evidence for hadronic emission?
  - Can there be a hadronic component that explains both the neutrino and EM radiation?

Follow Up IceCube Singlet Neutrino Alerts - PKS 0735+178

- Neutrino event IceCube-211208A (170 TeV; 50% probability of being astrophysical)
- Baikal-GVD cascade event at 43 TeV 4 hours after IceCube-211208A
- A nearby flaring blazar PKS 0735+178 at the boundary of the neutrino 90% localization
  - Historic high flux & variable daily in GeV, X-ray, and optical
  - VERITAS/HESS upper limits above 300 GeV





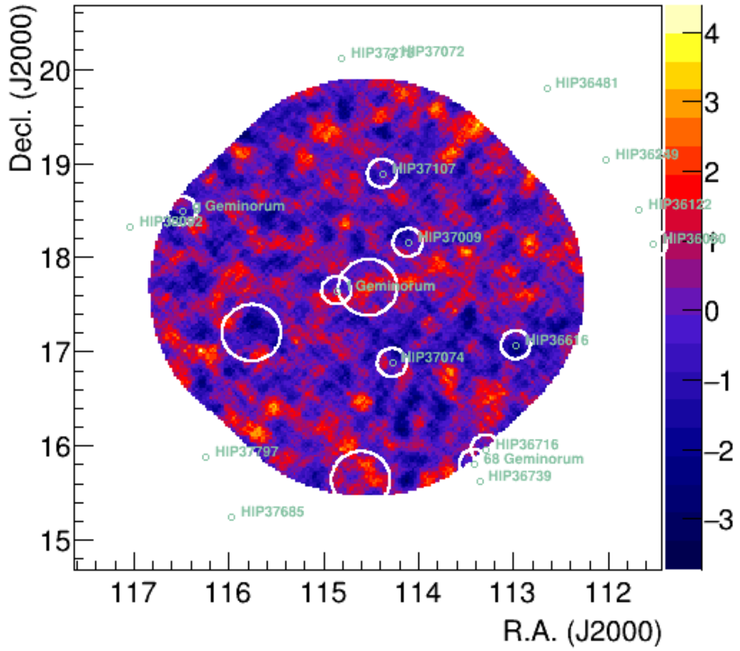
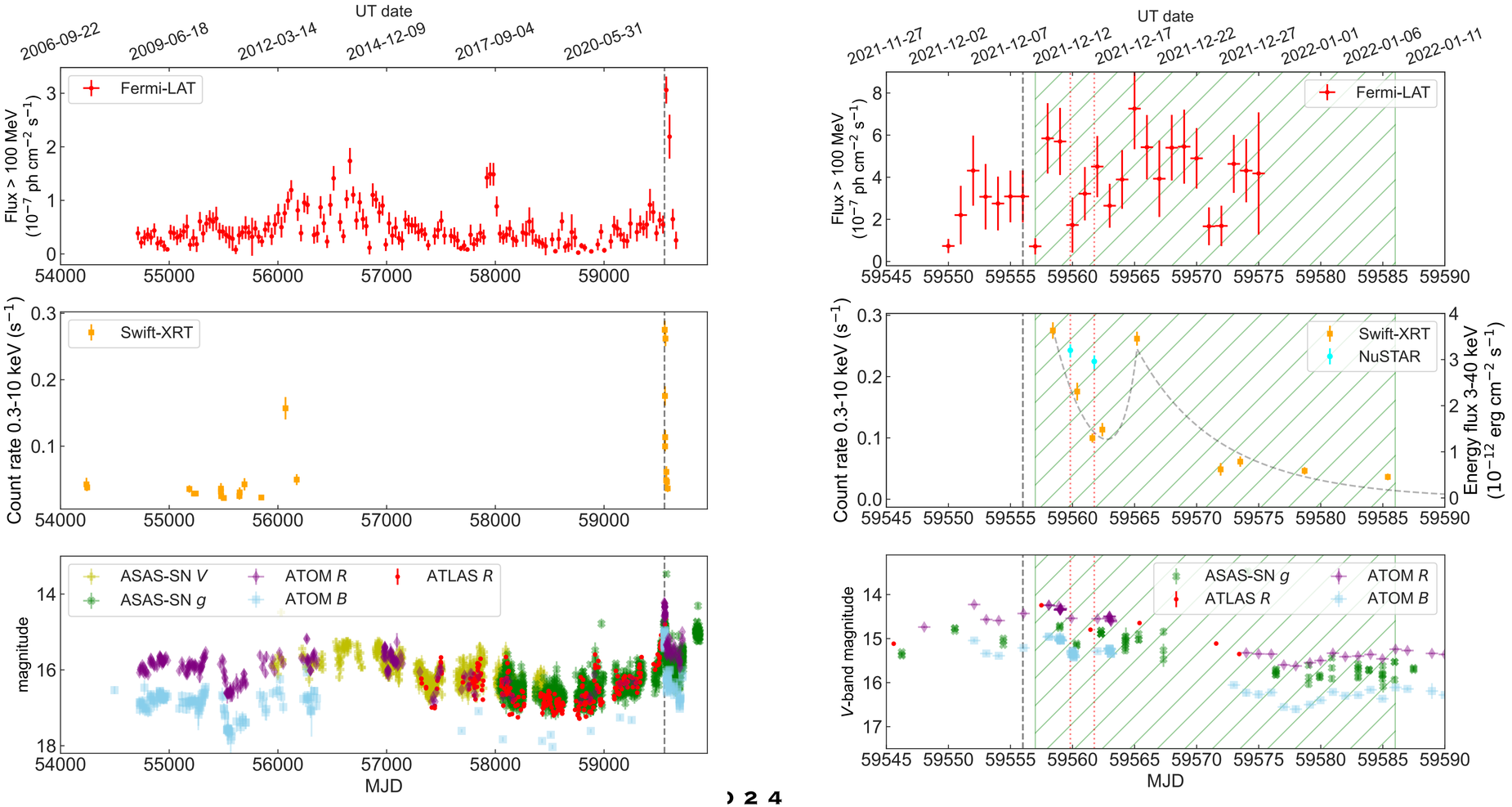


Image by D.Semikoz & A.Neronov

PKS 0735+178 Flux Variability

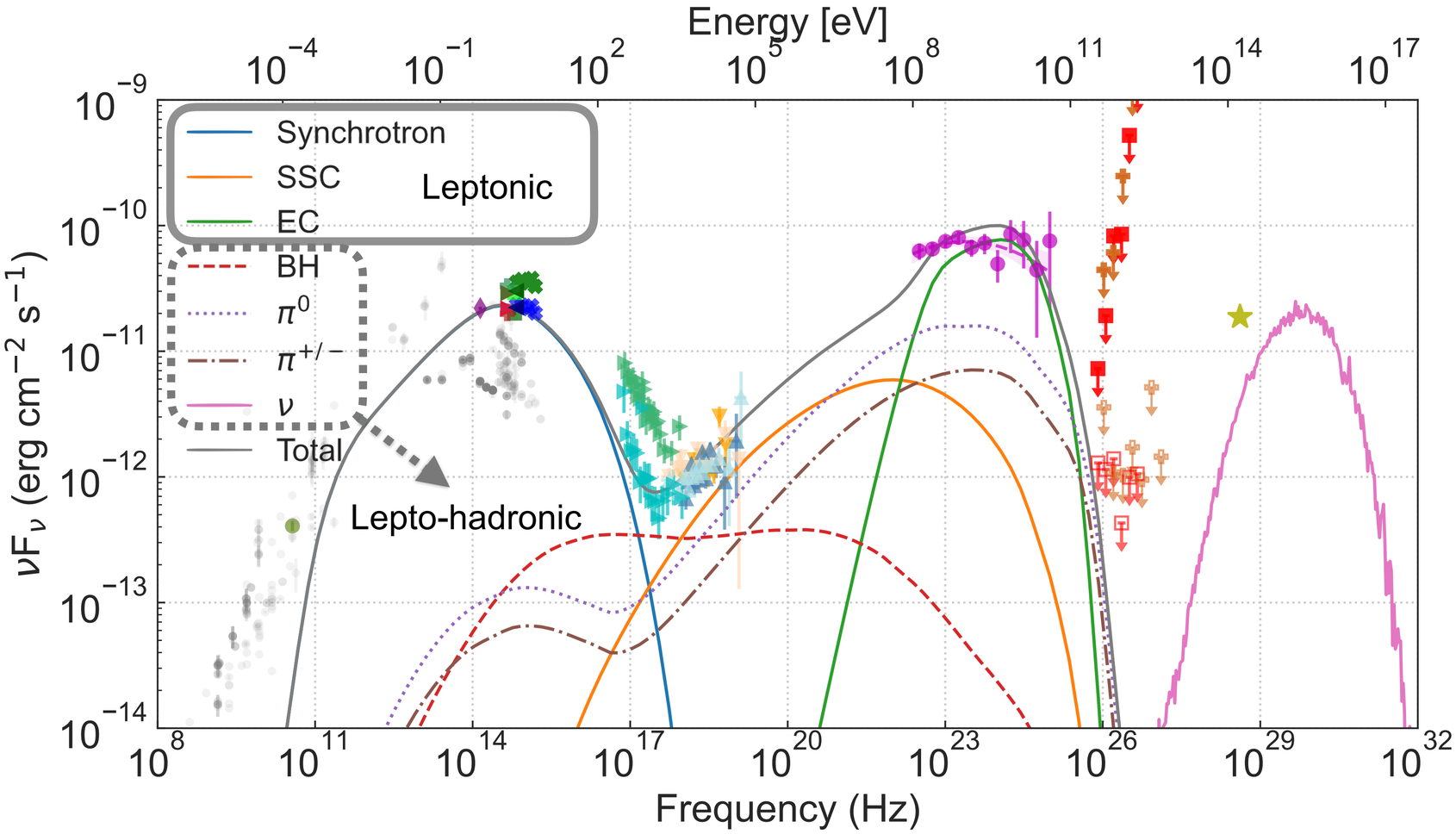
- On longer timescales (years): Historic high fluxes coincident with the neutrino
- On shorter timescales (days): fast, 1-day soft X-ray variability → R < ~5e16 cm

VERITAS/HESS Collaborations+, 2023, ApJ, 954, 70



PKS 0735+17 broadband spectrum

- Remarkable similarity to TXS 0506+056
- γ-ray spectral cutoff: need external photon field. (One-zone SSC doesn't work)
- Subdominant hadronic component constrained by X-ray and gamma-ray data
- Jet power / proton luminosity comparable to Eddington limit



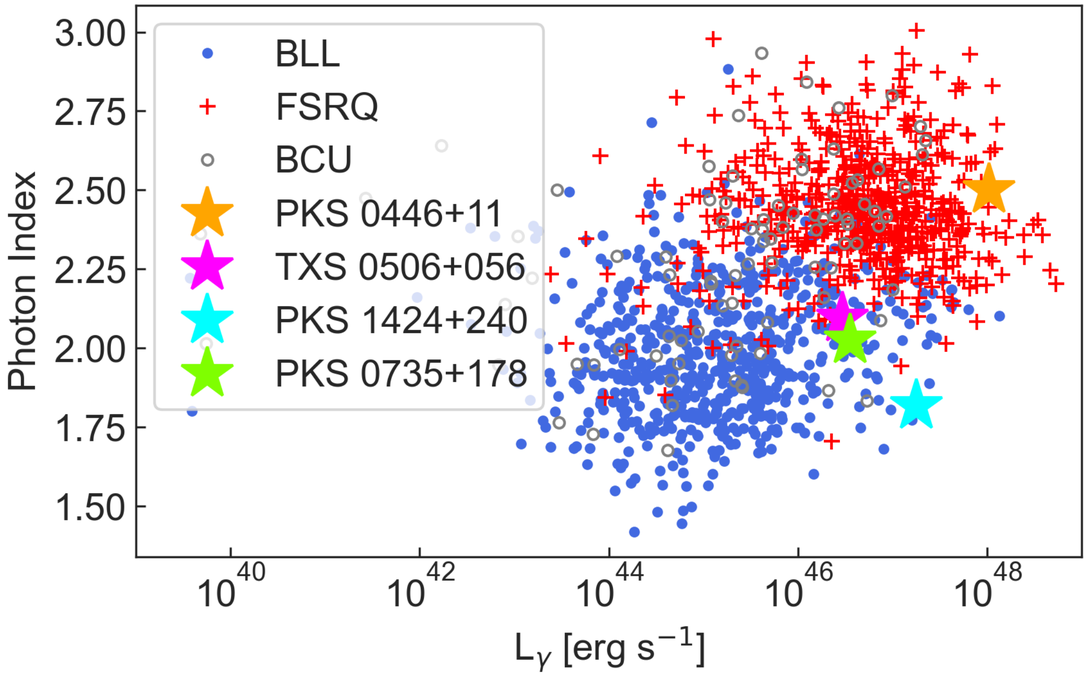
VERITAS/HESS Collaborations+, 2023, ApJ, 954, 70

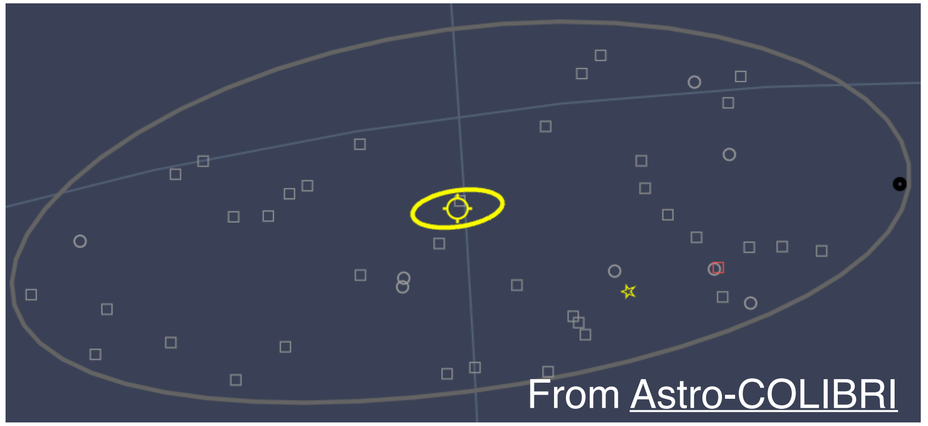
Follow Up IceCube Singlet Neutrino Alerts - PKS 0446+11

- “Bronze" alert IceCube-240105A (~110 TeV, ~30% astrophysical probability) GCN 35485, 35498

```
Date: 2024-01-05   Time: 12:27:42.57 UT
RA:    72.69 (+1.92, -1.85 deg 90% PSF containment) J2000
Dec: +11.42 (+0.50, -0.44 deg 90% PSF containment) J2000
```

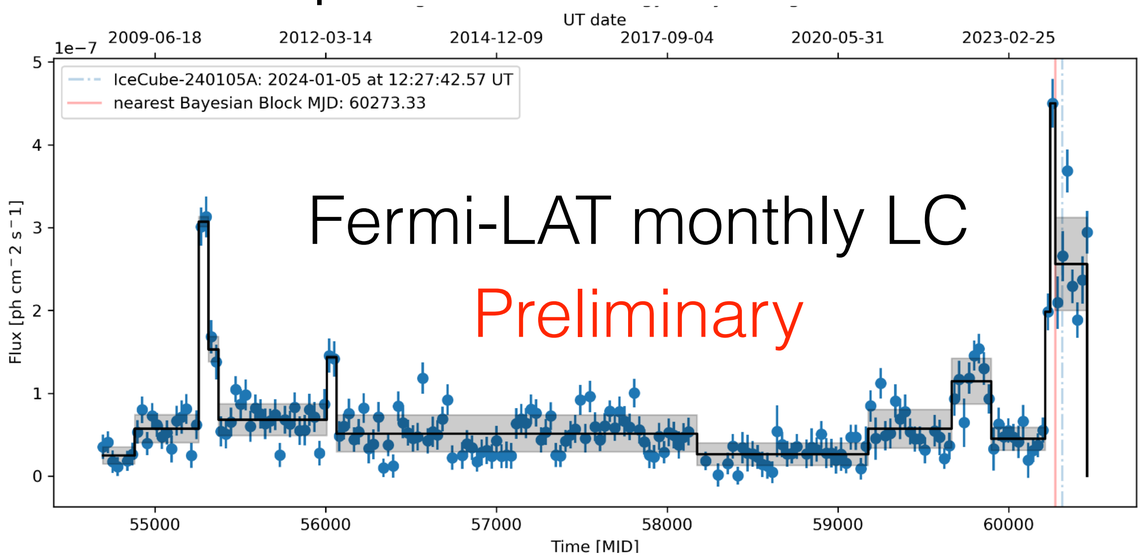
- ATels on PKS 0446+11 (FSRQ, 0.4 deg separation, z=2.15):
  - 16332: Fermi-LAT flare 18x 4FGL, harder spec (2.5 -> 2.1)
  - 16397: Swift-XRT ~16x brighter than 2015 (index 1.2-1.4)
  - 16399: TELAMON historic radio flare 6-44 GHz
  - 16414: IceCube 63-day UL 5.9 x 10^{-2} GeV cm^{-2} at 90% CL (~1.7 x 10^{-11} erg cm^{-2} s^{-1})
  - More ATels reporting X-ray detection from NuSTAR/NICER and optical measurements (minimal activity)
  - Optical emission line flux decreased by 5x while continuum flux increased by 10x (Paiano et al. 2024)

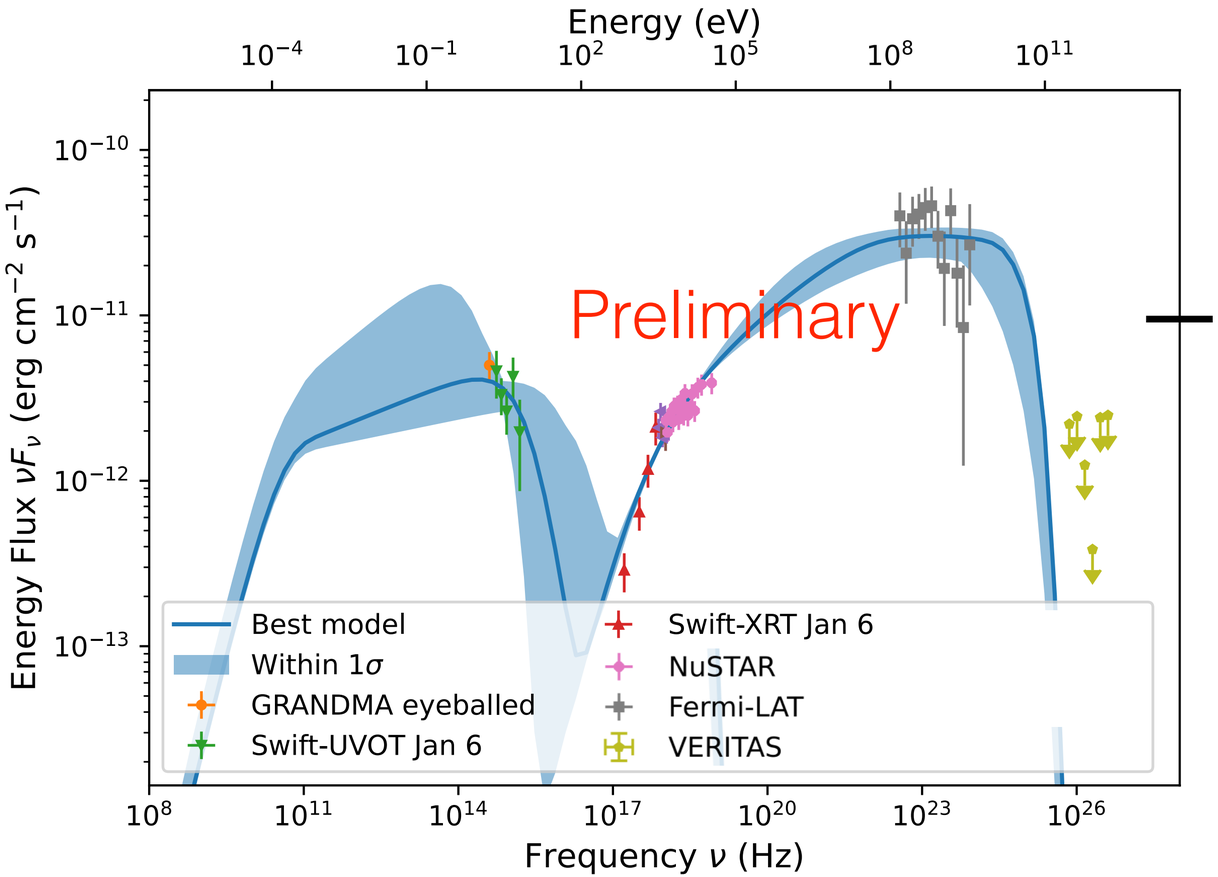




PKS 0446+11 broadband spectrum

- PKS 0446+11 was in a flaring state around the time of the neutrino event
- GeV flux peaked in Nov 2023 (~2 months before the neutrino event), remained high for more than 6 months
- X-ray spectral break due to uncertainty in neutral hydrogen absorption or break in electron distribution
- Not detected at TeV energies due to high z (2.153)
- A one-zone synchrotron self-Compton model fits the broadband spectrum well

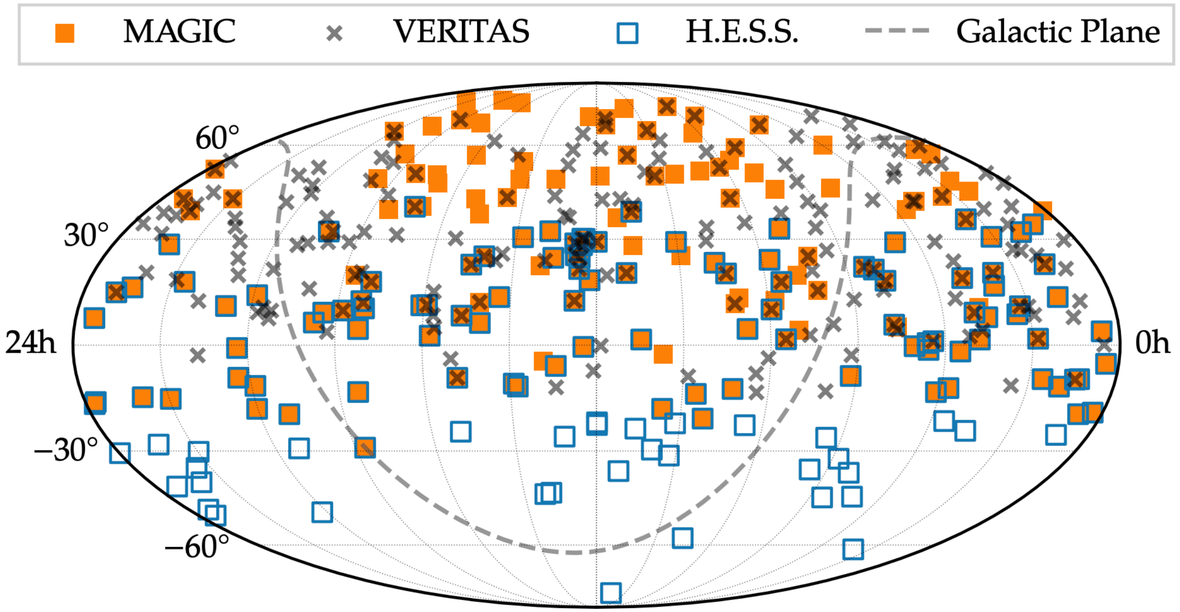




Follow-up of IceCube GFU alerts

- IceCube GFU alerts on neutrino multiplets (“flares” from seconds to 6 months) in online data stream
- Aim to determine the state of the source:
  - Quiescent vs flaring states
  - Spectral changes
- Pre-defined targets based on gamma-ray catalogs, variability, distance, and visibility
- Alerts currently shared privately under MoU

IceCube Collaborations ICRC 2023



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IceCube GFU alerts
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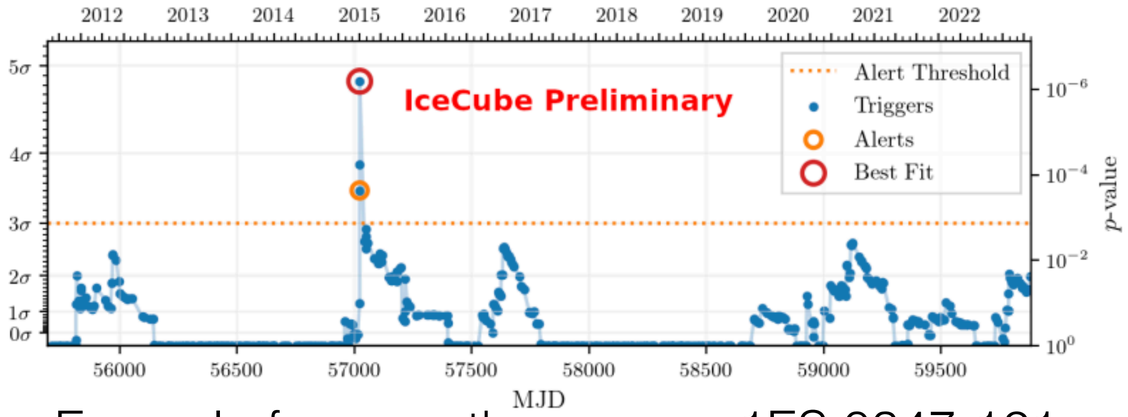
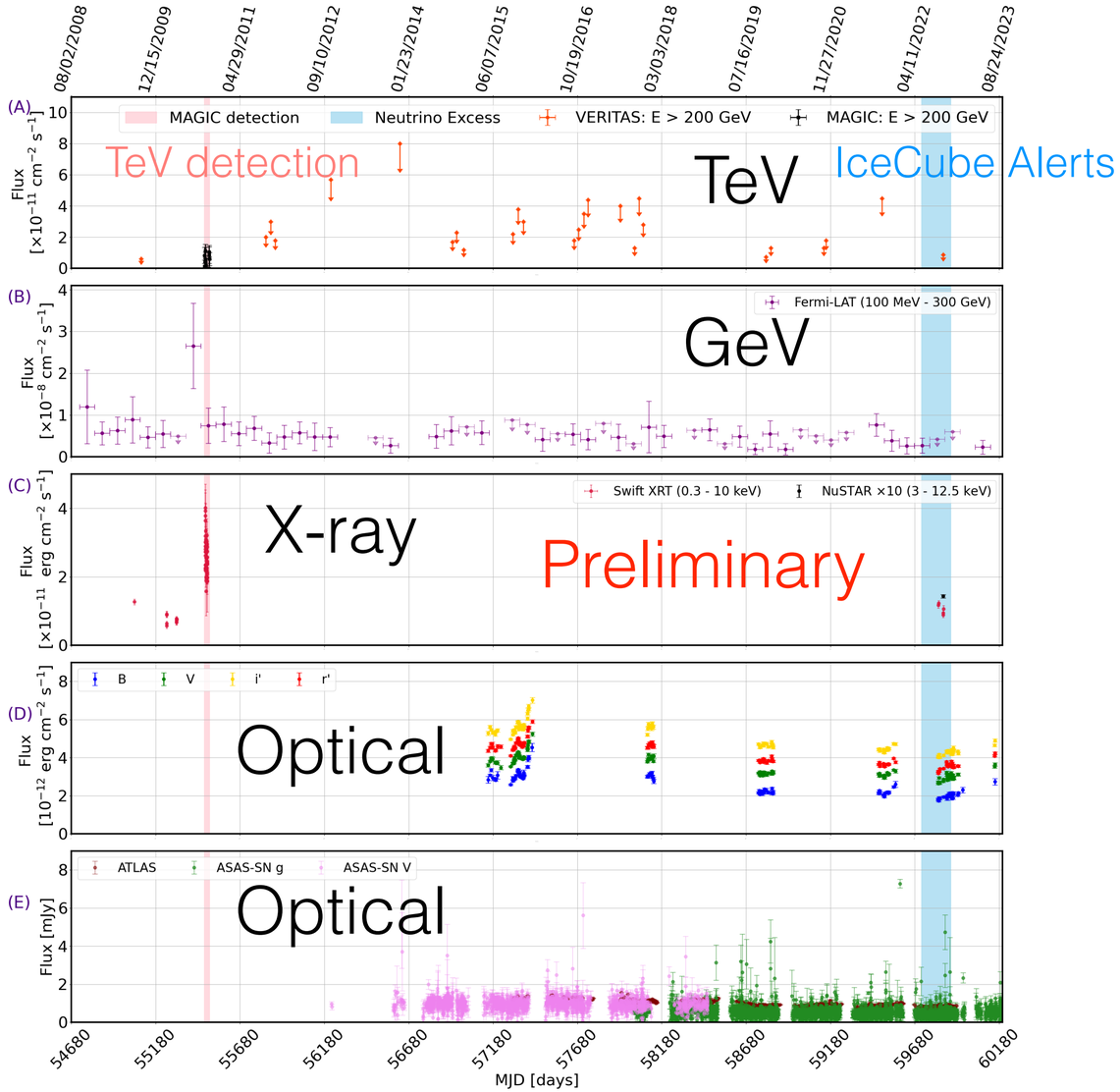
Follow-up of IceCube GFU alerts - B3 2247+381

- Alerts from IceCube at the location of TeV blazar B3 2247+381; 7 events detected over a duration of 174 days between May and Nov, 2022. Shared via MOU with IceCube & IACTs
- B3 2247+381 was in a low-flux state for the time interval corresponding to the neutrino alerts; strongly detected in hard X-ray
- A one-zone synchrotron self-Compton model fits the broadband spectrum well



Example from another source 1ES 0347-121

IceCube Collaborations ICRC 2023 arXiv:2307.15501



VERITAS + IceCube Collaborations in prep.

Summary

- Neutrinos are elusive and candidate sources are few. More questions are raised than answered, and we need more data on all possible scenarios
- Searching for EM radiation temporally and spatially correlated with high-energy IceCube neutrino events is an important strategy for exploring the connection between neutrinos and high-energy blazars. Density of the environment starts to emerge as a key
- VHE gamma-ray and hard X-ray follow-up studies with NuSTAR have been carried out for several cases of IceCube high-energy neutrinos
- NuSTAR ToO program yields ~ 1 follow up / year
- Observed multi-wavelength spectra of blazars can help determine if gamma-rays are consistent with the neutrino events.
- Observations so far suggest the EM radiation from blazars is primarily driven by leptonic processes, with possible subdominant lepto-hadronic contributions that align with the observed neutrinos.