Exploring the Multi-Messenger Universe with VERITAS

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Abstract The promise of multi-messenger astrophysics was clearly shown through coordinated observation campaigns in 2017 and 2018. These led to the detection of a flaring gamma-ray blazar that was potentially associated with a high-energy neutrino event, and the first detection of gravitational waves from a neutron star merger by LIGO/Virgo. The multi-messenger group in VERITAS has been using real-time and archival data to search and study potential very-high-energy gamma-ray counterparts of various transients, including GRBs, AGN flares, high-energy neutrinos and gravitational wave events. In this poster, we will present target-of-opportunity observations of the blazars PKS 0735+178, PKS 0446+11, and B3 2247+381 with VERITAS and NuSTAR. We will discuss implications for leptonic and hadronic models of emission in blazars based on the constraints from hard X-ray and TeV gamma-ray observations. We will show VERITAS as a critical component in the global network for a joint study of IceCube neutrino events by combining all four major imaging atmospheric Cherenkov telescopes. We will discuss the prompt search for very-high-energy gamma-ray signals from the LIGO-Virgo-KAGRA O4 run, as well as the investigation of low-significance gravitational wave events using VERITAS archival data.

The VERITAS Observatory

- Location: Whipple Observatory (FLWO), AZ (32°N, 111°W).
- Energy range: 100 GeV to > 30 TeV, 15-25% energy resolution.
- Sensitivity: 1% Crab in ~25h.
- Angular resolution: < 0.1° at 1 TeV (68% containment radius). 3.5° FoV cameras.
- Observation time: ~1300 h per year.

VERITAS IceCube Neutrino follow-up program:

- **Active IceCube neutrino target of opportunity (ToO) follow-up program.**
- **IceCube alert streams: gamma-ray follow-up (GFU) program.**
- **~ 30 hours/year of deep observations for a few (~3/yr) candidates.**
- **Multi-wavelength (MWL) observations with NuSTAR, *Swift*-UVOT and *Swift*-XRT.**
- **Joint analysis with other imaging atmospheric Cherenkov telescopes (IACTs).**

VERITAS gravitational wave (GW) follow-up program:

- **VERITAS carried out observations of 12 significant GW events during the LIGO-Virgo observing run (O3) from April 1, 2019 to March 27, 2020.**
- **Another 12 GW events observed so far during the LIGO-Virgo-KAGRA O4 which started on May 24, 2023.**
- **Investigation of low-significance gravitational wave events using VERITAS archival data.**

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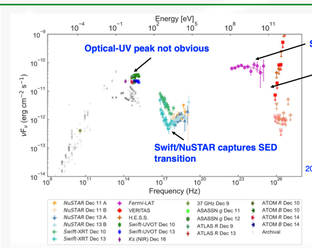

NuSTAR observation of the blazar PKS 0446+11 as a follow-up on IceCube-240105A

ATel #16417; *Jooyun Woo (Columbia University), Atreya Acharyya (University of Southern Denmark, Odense, Denmark), Qi Feng (University of Utah), Kaya Mori (Columbia University), Reshmi Mukherjee (Barnard College/Columbia University), Martin Pohl (University of Potsdam, Potsdam-Golm, Germany and DESY, Zeuthen, Germany), Raj Prince (Polish Academy of Sciences, Warsaw, Poland), Marcos Santander (University of Alabama), Ruo-Yu Shang (Barnard College/Columbia University)*

on 25 Jan 2024; 04:00 UT

Credential Certification: Jooyun Woo (jw3855@columbia.edu)

IceCube Neutrino follow up: blazar PKS 0735+178, PKS 0446+11 and B3 2247+381

PKS 0735+178: located 2.2° away from the best-fit position of the IceCube neutrino event IceCube-211208A (GCN 31191). Broadband spectral energy distribution (SED) includes *Swift*-XRT, NuSTAR, *Fermi*-LAT, VERITAS, and H.E.S.S., SED cutoff near 100 GeV. Model fit: lepto-hadronic model with external target photons.

PKS 0446+11: 0.4 deg away from the best-fit position of IceCube-240105A (GCN 35485). NuSTAR (ATel: 16417) and NICER observations triggered.

B3 2247+381: triggered from IceCube GFU program. 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.

Ref: Acharyya, A., et al. The Astrophysical Journal 954.1 (2023): 70.

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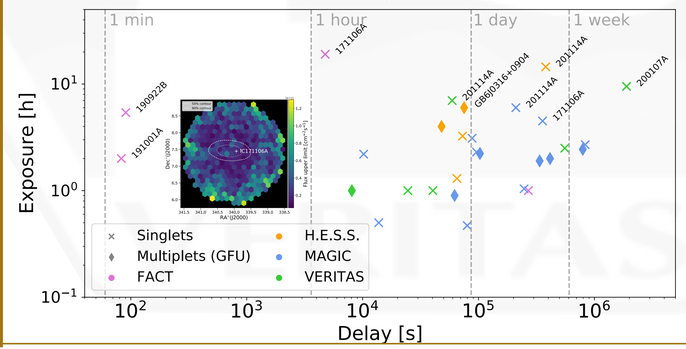
Prompt Searches for VHE signals on IceCube neutrino events by IACTs



We present joint searches for MWL emission associated with a set of IceCube alerts, both private and public, received between September 2017 and January 2021. We provide a detailed overview of each neutrino event and its potential counterparts. Furthermore, a joint analysis of all IACT data is included, yielding combined upper limits on the VHE gamma-ray flux.

Refs: Schüssler, Fabian, et al. PoS(ICRC2023)1501.

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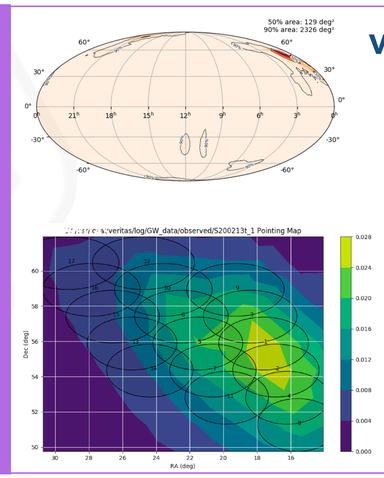

VERITAS GW follow-up summary for O3

- Event types for O3 with 2%-80% probability coverage:
  - 8 (96%-100%) BBH
  - 2 (95%- >99%) MassGap
  - 1 63% BNS, 37% Terrestrial
  - 1 58% Terrestrial, 24% BNS 12% MassGap, 6% NSBH
- **Example: GW event LV_S200213t**
- 63% BNS, 37% Terrestrial, ~27% probability coverage from O3.

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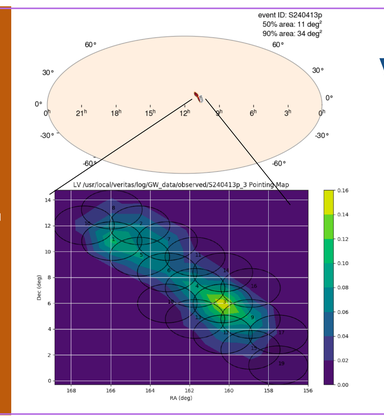

VERITAS GW follow-up summary for O4

Events types for O4 with 9-100% coverage:

- 12 (84% - 100%) BBH
- **Example: LV_S240413p**
- >99% BBH, 100% probability coverage from O4.

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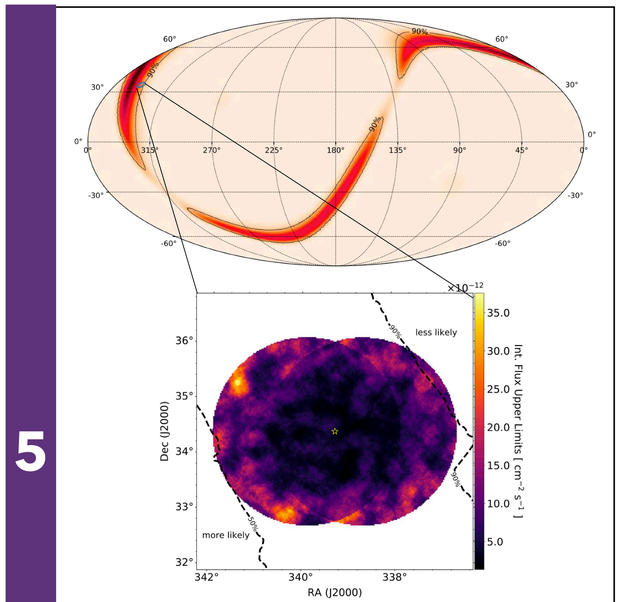

- We identified 11 VERITAS archival observations coincident spatially and temporally with LIGO/Virgo GW sub-threshold events.
- No significant excesses in 11 coinc. sets of VERITAS obs. We placed upper limits on the integral flux.
- Refs: Adams, C. B., et al. The Astrophysical Journal 918.2 (2021): 66.

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