Searching for TeV gamma-ray emission associated with IceCube high-energy neutrinos using VERITAS

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Outline

- Multi-messenger search for cosmic-ray sources
- IceCube astrophysical neutrinos
- VERITAS observations of neutrino positions
- Future plans
Multi-messenger astronomy

$p + p/\gamma$

\[
\begin{align*}
\pi^0 & \rightarrow \gamma\gamma \\
\pi^\pm & \rightarrow \nu_\mu + \mu
\end{align*}
\]

(oscillates to \(\sim 1:1:1\))
IceCube astrophysical neutrinos

- Evidence for astrophysical neutrinos first observed by IceCube using high-energy neutrino events with contained (C) interaction vertices.
- New analysis using up-going muon tracks with uncontained vertices (UC) shows a similar flux with a 3.7σ significance.
- Neutrino energies between tens of TeV to few PeV. Compatible with flavor equipartition.
- Best-fit power law spectra with indices in the 2.2 - 2.6 range.

\[ E^2 \phi(E) = 0.95 \pm 0.3 \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]
IceCube neutrino point-source searches

- Contained (C) sample: 37 neutrino candidate events in 3 years.
  - 28 cascades, ~15° ang. resolution (CC $\nu_{e\tau}$ + NC $\nu_{e\mu\tau}$)
  - 7 tracks, ~1° ang. resolution (CC $\nu_\mu$)
- No evidence for neutrino point sources.

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- Previous point-source searches (using muon tracks) have set ULs at a flux level that is $x10-100$ lower than the all-sky astrophysical flux.
- Large number of weak sources? transients?
Gamma-ray searches for neutrino sources

- Gamma-ray telescopes can be used to search for the hadronic gamma-ray counterpart.
- Fermi (GeV) and IACTs like VERITAS (TeV) can set limits on fluxes that are \(x1000-10000\) lower than the all-sky IceCube flux.
- Sensitivity is a function of redshift for VHE searches.
- No significant correlation between contained tracks and Fermi sources (arxiv/1505.00935)

IceCube flux from arxiv/1405.5303 converted 1:1 to gammas
Franceschini et al. EBL model arxiv/0805.1041
IACT FoVs and IceCube events

Cascade events

- HESS-I (5°)
- VERITAS
- MAGIC (3.5°)
- HESS-II (3.2°)

Track events

- Moon (~1°)
Muon positions to observe with VERITAS

- Three HE contained-vertex muons in the northern sky observable from VERITAS.
- Positions are publicly available.
- Angular uncertainty < 1.2° for muons.

- Uncontained muon events.
- Event positions from a 2-year sample of HE northern-sky muon neutrino candidates.
- 20 highest energy events in the sample.
- Relatively high astrophysical purity (ignoring atmospheric & astrophysical flux uncertainties)
- Event positions not yet published. Shared through IceCube-VERITAS MoU.
- Typical angular uncertainty < 1°.
VERITAS Overview

• First light in 2004
• Array of 4 Davis-Cotton Imaging Air Cherenkov Telescopes.
• Energy range: ~ 80 GeV - 30 TeV
• Effective area: ~ $10^5$ m$^2$
• Observing time: ~ 750 hr (dark) + 200 hr (moonlight)
• 0.1° angular resolution > 1 TeV
VERITAS observations of contained muons

- No significant gamma-ray emission detected above 100 GeV.
- Most significant hotspot is in the C37 field. Significance: $4.3\sigma$ pre-trials, $2.0\sigma$ post-trials.
Observations of uncontained muons

| ID  | Obs. time | UL (99%) | UL (99%) |
|-----|-----------|----------|----------|
|     | [min]     | [×10^{-12} cm^{-2} s^{-1}] | [C.U.]   |
| C5  | 180       | 8.3      | 2.3%     |
| C13 | 574       | 4.0      | 1.1%     |
| C37 | 275       | 7.3      | 2.0%     |
| UC2 | 25        | 21.2     | 5.8%     |
| UC3 | 180       | 6.3      | 1.7%     |
| UC4 | 122       | 9.9      | 2.7%     |
| UC5 | 90        | 6.7      | 1.8%     |
| UC6 | 25        | 9.5      | 2.6%     |
| UC7 | 15        | 39.6     | 10.9%    |
| UC8 | 60        | 9.3      | 2.6%     |
| UC9 | 40        | 15.2     | 4.2%     |
| UC10| 90        | 9.4      | 2.6%     |
| UC11| 209       | 4.4      | 1.2%     |
| UC12| 25        | 9.5      | 2.6%     |
| UC15| 90        | 7.4      | 2.0%     |
| UC16| 40        | 8.6      | 2.4%     |
| UC17| 150       | 4.4      | 1.2%     |
| UC19| 210       | 3.9      | 1.1%     |

*ULs with no trials corrections.

- Most 99% CL upper limits for uncontained muons are at the 1-5% Crab nebula flux above 100 GeV.
- Given the current limits and an neutrino spectral index of 2.3 this would rule out steady sources with a gamma-ray flux that is 1/1000 of the all-sky neutrino flux if they are at z < 0.2.
Conclusions and future plans

Summary

• ~40 hours of VERITAS data on IceCube HE neutrino positions.
• No significant detection of VHE gamma-ray emission associated at the neutrino positions. 99% flux ULs above 100 GeV at a few percent of the Crab nebula flux.
• These values start to constrain the number of steady sources and their distances.

Next steps

• *Fermi*-LAT analysis of the uncontained muons to search for GeV emission.
• Continue observations of HE muon events which are likely astrophysical.
• Preparing to receive real-time alerts from IceCube to increase the sensitivity to transient sources.
• CTA coming up with order-of-magnitude increase in sensitivity.