Upward-Pointing Cosmic-Ray-like Events Observed with ANITA

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Extensive Air Showers with ANITA

ANITA detection channels are clearly distinguished by pointing, pulse spectrum, polarity, and polarization.

<table>
<thead>
<tr>
<th>Origin</th>
<th>RF production</th>
<th>Polarization</th>
<th>RF Direction</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Neutrinos</td>
<td>Askaryan</td>
<td>V-pol</td>
<td>Below Horizon</td>
<td>Normal</td>
</tr>
<tr>
<td>2) CR-reflected</td>
<td>Geo-synchrotron</td>
<td>H-pol</td>
<td>Below Horizon</td>
<td>Inverted</td>
</tr>
<tr>
<td>3) CR-direct</td>
<td>Geo-synchrotron</td>
<td>H-pol</td>
<td>Above Horizon</td>
<td>Normal</td>
</tr>
<tr>
<td>4) Tau Neutrino?</td>
<td>Geo-synchrotron</td>
<td>H-pol</td>
<td>Below Horizon</td>
<td>Normal</td>
</tr>
</tbody>
</table>
Extensive Air Shower Identification

ANITA identifies EAS events using pulse shape and polarization correlation to geomagnetic field.

ANITA-1 EAS Results

Credit: S. Hoover et al., PRL, 2010
One event that survived the blind analysis was up-going and below the horizon (possible $\tau$ lepton).

- One **up-going** ANITA event that passed blind analysis cuts (red square) pointed to the ice sheet but has the polarity of a direct event.
- This is consistent with an extensive air shower pointing up from the ground.
- Such signals could arise from decay of up-going $\tau$-lepton of neutrino origin.
EAS events can have a significant fraction of circular polarization providing additional discrimination against backgrounds.

- EAS events can have a significant fraction of circular polarization (Stokes V) with LOFAR (Scholten et al., PRL, 2016)
- Down-going direct events have up to 25% circular polarization fraction.
- Up-going event has 10% circular polarization fraction.
The geomagnetic polarization vector is different at Xmax for a reflected down-going EAS compared to a direct up-going EAS.

- The event is consistent with Xmax for an up-going geometry.
- Down-going reflected hypothesis is discrepant by 2.5σ.

Polarization vector provides additional discrimination between reflected and up-going hypotheses.
## Competing Hypotheses for Up-Going EAS Event

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Discrimination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthropogenic Background</td>
<td>• Anthropogenic backgrounds tested against 80,000 clustered events.</td>
</tr>
<tr>
<td></td>
<td>• Estimated probabilities of impulse shape, geomagnetic polarization, and Stokes V contents</td>
</tr>
<tr>
<td></td>
<td>• Estimated number of isolated background events is 1.6</td>
</tr>
<tr>
<td></td>
<td>• Including trials factor, we expect N=4x10^{-4} background events.</td>
</tr>
<tr>
<td></td>
<td>• EAS hypothesis is favored but not enough to exclude this possibility.</td>
</tr>
<tr>
<td>Reflected Down-going EAS Event</td>
<td>• Geomagnetic polarization is inconsistent at the 2.5σ level.</td>
</tr>
<tr>
<td></td>
<td>• Polarity mis-identification is negligible given high SNR.</td>
</tr>
</tbody>
</table>

Competing background hypotheses rejected at $\gtrsim 3.3 \sigma$ level.
τ-lepton hypothesis

State-of-the-art simulations built for constraining the acceptance and characterizing the observables.

- Detailed $\nu_\tau$ and $\tau$ lepton propagation simulations through Earth including regeneration, $\tau$ energy loss, and the effects of differentiated layers of Earth, including ice (arXiv:1707.00334).

- Radio emission of up-going airshowers with ZHAireS.

- Monte Carlo sampling based estimate of the acceptance to produce an upper bounds of the ANITA exposure for this process.
ZHAireS simulations were used to obtain a radio emission signal model to place an upper bound relevant to ANITA.

- For the **upper bound** estimate, we took the radio emission profile that radiates the most power.

- This corresponds to emergence angle of 25 degrees with the decay occurring on the ground.
Simulations are consistent with $\tau$ shower energy and emergence angle.

- ANITA $\tau$-candidate event has
  - Shower energy $0.6 \pm 0.4$ EeV
  - Emergence angle $24.4^\circ \pm 1^\circ$
- For tau neutrinos with energy $\sim 0.3$ EeV, simulations are consistent with the observations.
Upper Bounds on ANITA Exposure

ANITA exposure to $\tau$-lepton EAS of $\nu_\tau$ origin is significantly smaller than Auger and IceCube

- Assumed standard values of the neutrino cross-section and tau energy loss.
- Studied the effect of ice-shell thickness.
- Find that Auger and IceCube exposures are $\gtrsim 60$ times larger.
- Given neutrinos at UHE have not been detected, this makes diffuse $\nu$-flux origin the ANITA event unlikely.
Upper Bounds on ANITA Acceptance

ANITA acceptance to $\tau$-lepton EAS of $\nu_\tau$ origin is significantly smaller than Auger and IceCube.

• However, at the energy range consistent with the observables, the acceptance is 3 orders of magnitude lower than Auger and IceCube.

• This makes *transient* $\nu$-flux origin the ANITA event unlikely.

• Dedicated blind search for this class of events is now part of the ANITA-3 and ANITA-4 analysis.
Conclusions

• The origin of the up-going cosmic-ray-like ANITA event remains a mystery.

• Observables are consistent with a t-lepton air shower with backgrounds rejected at the $\gtrsim 3.3 \sigma$ level.

• The acceptance is 3 orders of magnitude smaller than IceCube and Auger

• Results from on-going blind analysis of ANITA-3 and ANITA-4 have the potential to confirm or falsify the astrophysical origin of this event.

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Backup
LOFAR has observed circular polarization in EAS from the ground Scholten et al., 2016

Stokes Parameters of three ANITA stratospheric extensive air showers.
Upper Bounds on ANITA Exposure

- We also studied the effect of varying the interaction models within SM uncertainties.
- Upper bounds on the exposure do not vary significantly enough to compensate.
- However, we do not have the dependence on SM uncertainties for Auger and IceCube so the comparison is inconclusive.
- Possibly a transient event?