Ultra-High Energy Neutrinos at the Pierre Auger Observatory

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We now know in great detail about cosmic rays above $\sim 1 \text{ EeV} (10^{18} \text{ eV})$.

BUT we don't know exactly where they come from – they are charged and so get deflected in intergalactic magnetic fields.
The cosmic ray energy spectrum shows a cut-off as predicted: GZK cut-off. We assume that this is correct.

The GZK cut-off specifically refers to photo-pion production from cosmic ray protons and astrophysical (blue shifted to gammas) background photons.

\[\Pi^+ \text{ decays to } 3 \text{ neutrinos plus a positron}.\]

The resulting neutrinos are NEITHER absorbed nor deflected. They may point to the cosmic ray source.
Background Photon Spectrum

Fig. 6. The energy spectrum of the CMB [23] and the CIB in the IR/optical [48] and radio [54] range at $z = 0$. The thin dashed line shows our extrapolation to UV energies.
Predicted Neutrino Spectrum

**Figure 7.** Effects of various compositions on neutrino fluxes for all flavors. We present the cases of (i) a pure proton injection assuming a dip transition model (black solid), (ii) a proton dominated Galactic type mixed composition (pink dotted), (iii) pure iron composition (blue dashed) and (iv) the iron rich low $E_{\text{p, max}}$ model (red dash-dotted).
Interactions to search for:

**Charged Current**

\[ \nu_e \rightarrow \text{hadronic jet} \]

**Neutral Current**

\[ \nu_x \rightarrow \text{hadronic jet} \]

**FIG. 2.** Different types of atmospheric showers induced by neutrinos.
Possible event types: 'down going' and 'Earth-skimming'.

FIG. 1. Pictorial representation of the different types of showers induced by protons, heavy nuclei and “down-going” (DG) as well as “Earth-skimming” (ES) neutrinos. The search for down-going showers initiated deep in the atmosphere is the subject of this work.

See:
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We can use expected physical properties of the showers – content, timing, footprint shape etc. To build up a set of criteria to be satisfied by neutrino showers.
A 'normal' event.

See http://auger.colostate.edu/ED/
Detector station (10 m² water Cherenkov tank) signals

Close to the shower core

At a large core distance.
Developing Neutrino Search Criteria

Search Criteria:

Table 1: Criteria to select Earth-skimming $\nu_\tau$ and down-going $\nu$. See text for details.

<table>
<thead>
<tr>
<th></th>
<th>Earth-skimming</th>
<th>Down-going</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclined Showers</td>
<td>$N^\circ$ of Stations $\geq 3$</td>
<td>$N^\circ$ of Stations $\geq 4$</td>
</tr>
<tr>
<td></td>
<td>$L/W &gt; 5$</td>
<td>$L/W &gt; 3$</td>
</tr>
<tr>
<td></td>
<td>$0.29 \frac{m}{\text{ns}} &lt; V &lt; 0.31 \frac{m}{\text{ns}}$</td>
<td>$V &lt; 0.313 \frac{m}{\text{ns}}$</td>
</tr>
<tr>
<td></td>
<td>RMS$(V) &lt; 0.08 \frac{m}{\text{ns}}$</td>
<td>RMS$(V)$ $\frac{V}{\text{ns}} &lt; 0.08$</td>
</tr>
<tr>
<td></td>
<td>$\theta_{\text{rec}} &gt; 75^\circ$</td>
<td>Fisher discriminator based on AoP</td>
</tr>
<tr>
<td>Young Showers</td>
<td>ToT fraction $&gt; 0.6$</td>
<td></td>
</tr>
</tbody>
</table>
Rather strange directional exposure

The resulting upper limits

To Look for Specific Point Sources
Centaurus A (NGC 5128) is a 'nearby' likely source. The limits are tightening for its models also.

Table 2: Expected number of events for two diffuse neutrino flux models and two CenA neutrino flux models.

<table>
<thead>
<tr>
<th>Diffuse flux model</th>
<th>Earth-skimming</th>
<th>Down-going</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmogenic</td>
<td>0.71</td>
<td>0.14</td>
</tr>
<tr>
<td>Exotic</td>
<td>3.5</td>
<td>0.97</td>
</tr>
<tr>
<td>CenA flux model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuoco et al.</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>Kachelriess et al.</td>
<td>0.006</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Summary
The Pierre Auger Observatory:

Has measured fundamental astrophysical quantities (directions, composition, spectrum) at energies above $\sim 10^{18}$ eV (to $> 10^{20}$ eV).

We still have not identified specific sources and neutrino studies seem to offer a way of doing directional astrophysics for that.

The energy spectrum seems to show a GZK cut-off – neutrino studies should confirm or deny this.

Auger is competitive in UHE neutrino studies of the Southern skies.
Thanks