Cosmic Rays and High Energy Neutrinos

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Results from Current Ultra High Energy Cosmic Ray Experiments
Hybrid Fluorescence/Surface Detector Experiments

**Auger**
3000 km² in Argentina

**Telescope Array**
700 km² in Utah
Evidence for GZK-like Suppression

Auger Telescope Array

$E^2(E)$ [eV² km⁻² sr⁻¹ yr⁻¹]

$E [\text{eV}]$

$10^{18}$ $10^{19}$ $10^{20}$

Auger 2018 preliminary

$\Delta E/E = 14\%$

$E^2(E)$ vs $\log_{10}(E/\text{eV})$

- Proton, $\beta = 2.6, m = 0$
- Proton, $\beta = 2.25, m = 5$
- Iron, $\beta = 2.3, m = 0$
- Combined

$J^2(E)$ [eV² m⁻² s⁻¹]

$\log_{10}(E/\text{eV})$

- SD Spectrum
- Monocular Spectrum
- Hybrid Spectrum
Hints of correlation with local distribution of matter from both experiments, but more data needed.

Including composition information may strengthen correlations.

Prescription-based searches and joint global analyses are underway.
Composition and Interactions

Auger

HiRes

Different estimators and selections
Some observations

• “Composition” is a convenient way of describing changes in shower development, which is what is actually being measured.

• An alternative hypothesis is that interactions rather than beam particles are changing.

• Well-motivated theoretical models describe many features of the data.
  – arXiv 1307:2322 (Farrar and Allen)
    Restoration of chiral symmetry in QCD
Particle Physics from Astrophysics: p-Air Cross Section at $\sqrt{s}=57$ TeV

Low energy extensions (e.g. TALE) can cross-calibrate with LHC
Showers are not well-described by models tuned at LHC

Auger

Telescope Array

muon excess

Mismatch between calorimetric and MC energies

$E_{SD} = E'_{SD}/1.27$
What have we learned?

There is a flux suppression near the energy expected for the GZK suppression

But accelerators are also reaching their limits.

There are hints of anisotropy

But not enough statistics to identify sources.

There are changes in the characteristics of showers in this energy region

Could be a composition change...

...or evidence for a change in interactions (e.g. chiral symmetry restoration in QCD)
What next?

• Better handles on composition and interactions
  – Event-by-event composition diagnostics are the goal.
  – Muon identification is key

• Larger aperture for more statistics
  – Determine anisotropy and identify sources
  – Extend spectrum beyond GZK region
Surface Array Upgrades and Expansions

Enhanced muon identification and increased dynamic range helps in unfolding the details of shower development for composition and interaction studies.

Auger plans to propose an upgrade consisting of:
• Increased FADC speed and dynamic range (improves muon ID and reconstruction)
• Extended Dynamic Range with an additional small PMT
• Muon detection enhancements of the surface array (technology TBD)
• Increased fluorescence duty cycle

TA could be expanded to match the size of Auger In the northern hemisphere.
There are discussions of a new large ground array project by European groups, but no definite proposal.
### High Statistics from Space Based Observations

<table>
<thead>
<tr>
<th>Source</th>
<th>Area (km²)</th>
<th>Events/yr &gt;60EeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auger+TA</td>
<td>3700</td>
<td>25</td>
</tr>
<tr>
<td>Earth</td>
<td>5x10⁸</td>
<td>3.4x10⁶</td>
</tr>
<tr>
<td>JEM-EUSO</td>
<td>4x10⁴</td>
<td>250</td>
</tr>
</tbody>
</table>

(20% duty cycle, nadir mode)

*Other concepts: SWORD (radio),...*
Current High Energy Neutrino Experiments
Kilometer$^3$-scale detectors

IceCube

Antares, Baikal, KM3NET (future)
Neutrinos Above 1 TeV

π/K Atmospheric ν Charm Astrophysical (E^{-2}) GZK
Have the first High Energy Astrophysical Neutrinos been observed by IceCube?

28 events with a spectrum harder than that expected for any atmospheric backgrounds.

Cascade-dominated as expected.

Southern events more abundant as expected due to Earth attenuation.

Spectrum slightly softer than $E^{-2}$.

Insufficient statistics to identify sources; currently compatible with isotropy.

More to come as IceCube runs...
High Energy IceCube Extensions

Expanded surface array to reject atmospheric $\nu$ over wider geometry

Possible factor 3-5 increase in southern $\nu_\mu$ acceptance
High Energy IceCube Extensions

IceCube++: Options for ~10 km² extensions optimized for PeV neutrinos
PINGU: A Low Energy IceCube Extension

40 high density strings with IceCube as a veto, optimized for low threshold (few GeV).

Targeted at \( \nu \) mass hierarchy

See Gus Sinnis talk.
Neutrino Production: The GZK Process

GZK process: Cosmic ray protons (E > 10^{19.5} \text{ eV}) interact with CMB photons

\[ p + \gamma_{\text{cmb}} \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

Discover the origin of high energy cosmic rays through neutrinos?
GZK Neutrino Experiments using the Askaryan Effect

Electromagnetic cascades result in an evolving population of electrons, positrons, and photons as showers develop. Positrons are depleted by in-flight annihilation. Additional electrons are upscattered from the medium. The net effect is a negative charge excess (~20%) in the shower, moving relativistically.

Dominant RF mechanism in solids (ice, salt, regolith). Coherent Cherenkov Radiation at long wavelengths!

*Signal scales as $E^2$ => for typical detector parameters, higher sensitivity than optical detectors above ~10^{18}eV*

Ice is a particularly suitable medium (~km attenuation lengths)
IceCube Sensitivity to UHE Neutrinos

Best current limit $<10^{19}$ eV
ANITA-I & ANITA-II: Best Limit > $10^{19}$ eV

NASA Long Duration Balloon, launched from Antarctica
ANITA-I: 35 day flight 2006-07
ANITA-II: 30 day flight 2008-09

Instrument Overview:

- 40 horn antennas, 200-1200 MHz
- Direction calculated from timing delay between antennas
- In-flight calibration from ground
- Threshold limited by thermal noise

UHE Neutrino Search Results:

<table>
<thead>
<tr>
<th></th>
<th>ANITA-I</th>
<th>ANITA-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino Candidate Events</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Expected Background</td>
<td>1.1</td>
<td>0.97 +/- 0.42</td>
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</table>
Current Limits and Theoretical Expectations
Next Generation Askaryan Experiments
ARIANNA

Ground-based array of antennas on the surface of the Ross Ice Shelf

Ice-seawater interface reflects emission from downward-going events

ARIANNA Coll. See arXiv:1207.3846
ARA: Askaryan Radio Array

37-string array of antennas buried 200m below the surface at the South Pole

EVA: ExaVolt Antenna

NASA super pressure balloon incorporates an antenna
Similar sensitivity to 3-year ARA, and ARIANNA

→ Feed design: dual-polarization, broadband, sinuous antennas on inner membrane

Gorham et al. (2011)
Neutrino Sensitivity of Next-Generation Askaryan Experiments

What the sensitivity of a next-generation UHE neutrino detector looks like:

→ With tens of events per year, we’ll have a real high-energy neutrino observatory for particle physics and astrophysics.
Particle Physics from Astrophysics: UHE Neutrino Cross Sections

If UHE neutrinos are detected, their intensity as a function of zenith angle provides a measurement of the $\nu N$ cross section.

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**Graphs:**

- Upgoing and downgoing events as a function of $\cos \theta_z$
- Log-log plot of cross section vs. $E_\nu$ with different models.
Synergies

• Trans GZK cosmic rays sample the nearby universe (<~100 Mpc)
• GZK neutrinos travel over cosmological distances, and their flux depends both on composition and on the redshift evolution of the sources.

Combining cosmic ray and neutrino data can potentially yield a rich harvest.