Neutrino results from the Pierre Auger Observatory

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Workshop on Perspectives on the Extragalactic Frontier: from Astrophysics to Fundamental in ICTP, Italy
Outline

• Searching for UHE neutrinos in Auger

• Limits to point-like sources and Gamma-Ray-Bursts (GRB) of UHEν

• Search for UHE neutrinos in coincidence with GW150914

• Summary
Identification of neutrinos

Protons & nuclei initiate inclined showers high in the atmosphere.
✓ Shower front at ground: electromagnetic component absorbed in atmosphere.
✓ mainly muons remaining

Neutrinos can initiate deep showers close to ground.
✓ Shower front at ground: electromagnetic + muonic components
Sensitivity to all flavours and channels

Down-going low angle (2 and 4)  
Down-going high angle (2, 4 and 5)  
Earth-skimming (3)  

Identification criteria applied “blindly” to the search data set  
=> No candidates found in Earth Skimming or Downward-going
Limits to flux of UHE$\nu$ from point sources

Find times in 1 sidereal day a source at given declination is seen at Auger with zenith angle $q$.


A point source moves across the sky in 1 sidereal day.

Source zenith angle $q$ with respect to the SD array changes.

A fraction of time per day the source is seen with:

$90^\circ < \theta < 95^\circ$ (ES)

$75^\circ < \theta < 90^\circ$ (DGH)

$60^\circ < \theta < 75^\circ$ (DGL)

$\cos \theta = \sin l \sin \delta + \cos l \cos \delta \sin(2\pi t + \varphi)$

$l \sim -35.2$ latitude of Auger Obs.
Fraction of time source visible vs declination

Integrate in time only when the source is visible.

Fraction of 1 sidereal day a source is seen in ES, DGH, DGL as a function of declination.

Source declinations visible:
- ES: $-52^\circ < \delta < 60^\circ$
- DGH: $-70^\circ < \delta < 55^\circ$
- DGL: $-90^\circ < \delta < 40^\circ$

Example:
Visibility of Centaurus A ($\delta \sim 42.97^\circ$)
- $\sim 7\%$ with $\theta \in (90^\circ, 95^\circ)$
- $\sim 16\%$ with $\theta \in (75^\circ, 90^\circ)$
- $\sim 13\%$ with $\theta \in (60^\circ, 75^\circ)$
Calculated Exposure

Weight with effective detection area \( \cos q A_{\text{eff}}(t,q) \) and probabilities of tau production & decay (ES only)
Assuming neutrino flux:
\[ \frac{dN}{dE} = k E^{-2} \] (GeV\(^{-1}\)cm\(^{-2}\)s\(^{-1}\))

90% C.L. limit on “k” vs source declination (old vs new limits)

Broad declination range with good sensitivity to UHE\(\nu\)
Directional limits

Assuming neutrino flux: $dN/dE = k E^{-2} \rightarrow$ 90% C.L. limit on $k$ vs declination

Note different energy ranges of experiments
Limits to flux of UHEν from GRB

\[ p \gamma_{\text{GRB}} \rightarrow n \pi^+ \rightarrow \nu \text{'s} \]

Projectile proton spectrum: \( E_p^{-2} \) (assumed)

Target photon spectrum: double power-law (measured)

Neutrino spectrum

Shape determined by target photon spectrum

Steepens due to synchrotron losses of parent pions

Projectile proton spectrum: \( E_p^{-2} \) (assumed)

Break energies

~ 1 keV  ~ 200 keV  ~ 10 MeV

\[ E_{\gamma}^{-1} \]

\[ E_{\gamma}^{-2} \]

\[ \gamma_{\text{GRB}} \]

\[ E_{\gamma} \]

\[ E_{\gamma}^{2} \cdot \frac{dN_{\gamma}}{dE_{\gamma}} \]

\[ E_{\nu}^{-1} \]

\[ E_{\nu}^{-2} \]

\[ E_{\nu}^{4} \]

~ \( 10^{14} \) eV

~ \( 10^{16} \) eV

\[ E_{\nu} \]

The GRB sample

- Based on Fermi, Swift and GBM catalogs
  - Equatorial coordinates measured => $\theta_{GRB}$ known
  - Time duration T90 & GRB fluence, … provided.
  - Redshift $z$ only measured for a few GRBs
  - Lorentz boost factor $\Gamma$ not measured

- Selected GRB:
  - visible from Auger in inclined directions when array is active:
    - Exclude GRBs during the dead-time
    - ES with $\theta \in [90^\circ, 95^\circ]$ DGH with $\theta \in [75^\circ, 90^\circ]$ DGL with $\theta \in [60^\circ, 75^\circ]$

- Model neutrino production in GRB sample:
  - Typical redshift $z=2$, Lorentz factor $\Gamma = 300$ (not measured)
  - This implies “break energy” > $10^{17}$ eV => $dN/dE \sim E^{-4}$ in Auger
  - Zenith angle of GRB does not change during $T_{90}$
GRB visible in Auger in ES, DGH or DGL

$90^\circ < \theta < 95^\circ$ (Earth-Skimming - ES) – 79 GRB

$75^\circ < \theta < 90^\circ$ (Downward-Going High-angle - DGH) – 149 GRB

$60^\circ < \theta < 75^\circ$ (Downward-Going Low-angle - DGL) – 183 GRB

GRB Skymap
Galactic coordinates
Limits to $\nu$ flux from GRB

Assuming neutrino flux: $\frac{dN}{dE} = k_{\text{GRB}} E^{-4}$ (GeV$^{-1}$ cm$^{-2}$ s$^{-1}$) we show:

90% C.L. limit on “$k_{\text{GRB}}$” vs GRB time duration $T_{90}$

- Better limits for ES than for DGH
- Better limits for longer GRB

NOTE: Limits to DGL not yet obtained – small contribution
Aggregate limits to $\nu$ fluence from GRB

PRELIMINARY

Waxman-Bahcall (215 GRB)

Auger (228 GRB)

ANITA (3 GRB)

IceCube (215 GRB)

Waxman-Bahcall (228 GRB)
Neutrino Search for GW150914

No neutrino candidates found in any of the data periods unblinded

• Data +/- 500 s around GW150914 (09:50:45 UTC):
  – No inclined events found in ES selection
  – No inclined events found in DGH (75° -- 90°) selection

• Data 1 day after GW150914:
  – 12 inclined events found in ES selection, none passed young shower selection => no candidates
  – 24 inclined events found in DGH (75° - 90°), none passed young shower selection => no candidates
Both 90% CL declination ranges overlap with the field of view of the ES and DGH channels for fractions of 1 sidereal day that can reach up to ~ 17% and ~ 35% respectively.
Limit to fluence

Values above the red line are excluded at 90% CL from the non-observation of neutrino events in Auger.

Declination bands of the 90% CL position of the GW150914 are shown as shaded rectangles.

\[ F_\nu(\delta) = \left[ \int_{E_\nu}^{E_\nu^{max}} E_\nu \frac{dN_{GW}}{dE_\nu} dE_\nu \right] \times \Delta t = \left[ \int_{E_\nu}^{E_\nu^{max}} E_\nu \frac{k^{GW}(\delta)}{E_\nu^2} dE_\nu \right] \times \Delta t \]
Summary

• Updated limits to point-like sources of UHE neutrinos:
  – Sensitivity to large fraction of sky
  – Best limits to n flux at EeV in particular to CenA

• Preliminary limits to GRB neutrino fluence:
  – Best limits to GRB fluence in the EeV range although still far from Waxman-Bahcall expectations.
  – Astrophysical implications on GRB to be explored

• No candidates observed within +/- 500 s and 1 day after GW150914 in Auger data. Observation of UHE neutrinos in coincidence with any future LIGO event would be a breakthrough!
Back Up
Some sources NOT seen in ES or DGH or DGL

Source too close to the North Pole
(NOT seen in ES, DGH or DGL)

Potential UHEν source at $\delta = 80$ deg.

Source too close to the South Pole
(only seen in DGL)

Potential UHEν source at $\delta = -75$ deg.

$$\cos \theta = \sin l \sin \delta + \cos l \cos \delta \sin(2\pi t + \varphi)$$
Selection of inclined events

(1) Elongated footprint

\[ V_{ij} = \frac{d_{ij}}{\Delta T_{ij}} \]

(2) Apparent velocity \( V \) of propagation of the shower front along major axis \( L \)

vertical shower
\[ V \gg c \]

horizontal Shower
\[ V \sim c \]

(3) Reconstructed zenith angle

<table>
<thead>
<tr>
<th>Earth-Skimming (90°, 95°)</th>
<th>Down-going High (75°, 90°)</th>
<th>Down-going Low (65°, 75°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L/W &gt; 5 )</td>
<td>( L/W &gt; 3 )</td>
<td>( \theta_{rec} &gt; 75° )</td>
</tr>
<tr>
<td>( \langle V \rangle \in (0.29, 0.31) \text{ m ns}^{-1} )</td>
<td>( \langle V \rangle &lt; 0.313 \text{ m ns}^{-1} )</td>
<td>( \theta_{rec} \in (58.5°, 76.5°) )</td>
</tr>
<tr>
<td>( \text{RMS}(V) &lt; 0.08 \text{ m ns}^{-1} )</td>
<td>( \text{RMS}(V)/\langle V \rangle &lt; 0.08 )</td>
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</tr>
</tbody>
</table>
Identifying electromagnetic shower fronts

Using the time structure of signals in WCDs, search for signals extended in time.

Definition of Area over Peak

\[
\frac{\text{AREA}}{\text{PEAK}} = \text{AoP}
\]

Select stations with:
- Time-over-Threshold (ToT) trigger
- Large Area-over-Peak (AoP)
Looking for broad signals: Area Over Peak (AOP)

FADC trace

AOP = Area/Peak

“Slow & broad signal”

“Fast & narrow signal”

Large AOP (> 3)

Small AOP (~ 1)
Identification of UHE neutrinos in Auger data

Example: Earth Skimming

\[ \langle \text{Aop} \rangle > 1.83 \]

\( \nu_\tau \) candidate region

\(~90\% \) of \( \nu \) events selected

\[ \langle \text{Aop} \rangle = \text{mean value of Area-over-Peak in the event} \]

Data taking: 01/01/04 – 20/06/13

Identification criteria applied “blindly” to the search data set

\( \rightarrow \) **No candidates** found in Earth Skimming or Downward-going
ν fluxes: data, limits & models

- **ν limits**
  - IceCube 2013 (x 1/3)
  - Auger (2013)
  - ANITA-II 2010 (x 1/3)

- **ν fluxes**
  - ANTARES '13 atmospheric
  - IceCube '14 atmospheric
  - IceCube '15 astrophysv

- **Cosmogenic models**
  - p, Fermi-LAT best-fit (Ahlers '10)
  - p, FRII & SFR (Kampert '12)
  - Fe, FRII & SFR (Kampert '12)
  - p or mixed, SFR & GRB (Kotera '10)

- **Astrophysical sources**
  - Waxman-Bahcall '01
  - GRBν (Waxman '01)
Take home message & outlook

• Updated limits to point-like sources of UHE neutrinos:
  – Sensitivity to large fraction of sky
  – Best limits to $\nu$ flux at EeV in particular to CenA
  – Limits complementary to those of IceCube

• Preliminary limits to GRB neutrino fluence:
  – Best limits to GRB fluence in the EeV range although still far from Waxman-Bahcall expectations.
  – Astrophysical implications on GRB to be explored

• Paper on point-like sources & GRB planned.
Times in 1 sidereal day a source is seen with large $\theta$

Source too close to the North Pole (NOT seen in ES, DGH or DGL)

Source too close to the South Pole (only seen in DGL)

Weight with effective detection area $\cos\theta A_{\text{eff}}(t,\theta)$ and probabilities of tau production & decay (ES only)

Integrate in time only when the source is visible.

Assuming a $\nu$ flux: $\frac{dN}{dE} = k E^{-2}$ (cm$^{-2}$ s$^{-1}$)

Obtain upper limit on normalization factor “$k$”

Repeat procedure as a function of declination $\delta$
Neutrino spectrum

$p\,\gamma_{\text{GRB}} \rightarrow n\,\pi^+ \rightarrow \nu$’s

Projectile proton spectrum: $E_p^{-2}$ (assumed)

Target photon spectrum: double power-law (measured)

Besson, Razzaque, Adams, Harris, Astropart. Phys. 26, 367 (2007);
Limit to fraction of energy in $\nu$ - GW150914, D=410 Mpc
Limits to UHEν flux from Centaurus A

- Auger → best limit in the EeV energy range / complementary to IceCube
- Approaching models of UHEν production in CenA
UHE neutrino follow-up of GW150914

\[ \langle AoP \rangle > 1.83 \]

\( \nu \) candidate region
Times in 1 sidereal day a source is seen with large $\theta$

A point source moves across the sky in 1 sidereal day.

Source zenith angle $\theta$ with respect to the SD array changes.

A fraction of time per day the source is seen with:

- $90^\circ < \theta < 95^\circ$ (ES)
- $75^\circ < \theta < 90^\circ$ (DGH)
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\[
\cos \theta = \sin l \sin \delta + \cos l \cos \delta \sin(2\pi t + \varphi) \quad l \sim -35.2 \text{ latitude of Auger Obs.}
\]
Limits to flux of UHE\(\nu\) from GRB

- Short \((T_{90} \sim 10^{-3} - 10^{3} \text{ seconds})\) flashes of gamma-rays with fluxes of \(\sim 0.1-100\) photons/cm\(^2\)/s/keV
  - Long GRBs \((T_{90} > 2\text{s})\): collapse of massive stars to Black Holes
  - Short GRBs \((T_{90} < 2\text{s})\): merging of binary compact objects

- Most powerful explosions in space:
  - visible across the universe
  - most luminous sources across the electromagnetic spectrum
  - afterglow lasts days.

- Rate \(\sim 10^{-7}/\text{yr/galaxy}\)

\[ E_{\nu,\text{tot}}(\delta) = \mathcal{F}_\nu(\delta) \times 4\pi D_s^2. \]

\[ E_{\text{GW}} \simeq 3.0^{+0.5}_{-0.5} M_\odot c^2 \simeq 5.4^{+0.9}_{-0.9} \times 10^{54} \text{ erg}, \]