The Pierre Auger Observatory
ultra-high energy neutrino follow-up
of the LIGO GW events

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The 2015 LIGO gravitational waves events

→ Breakthrough observation of GW events with the LIGO Advanced interferometer

→ GW150914 and GW151226 (and LVT151012 candidate)

→ Inferred source: coalescence of a BH binary @ 410 and 440 Mpc

→ Position: few 100 deg² uncertainty

→ Energy released in form of GW: ~ 3 and 1 solar masses

No electromagnetic counterpart generally expected from BH mergers
UHE vs from BH merger events?

→ Fermi GBM 3σ report of a 1s transient signal 0.4 s after GW150914 and consistent position

Models predicting emission of UHE neutrinos:
- UHECR accelerated by Fermi mechanism if relic magnetic field and debris from BH formation
  => emission of UHE neutrinos and photons
- if accretion disk present, proton acceleration up to \( \sim 10 \) EeV energy by electric fields in disk dynamo,
  UHE neutrinos from interaction with bkg photons and gas around BH Ancordoqui, PRD 94, 023010 (2016)

Search for UHE ν in coincidence with GW events with the Auger SD (E>100 PeV)
The surface detector (SD) of the Pierre Auger Observatory

Detection of Extensive Air Showers through secondary particles at ground level

~1660 Water Cherenkov stations triangular grid with 1500 m spacing 3,000 km² total area

→ sensitive to electromagnetic and muonic component
→ measure of the time structure of the signal induced by electrons and μs
Inclined showers and UHE 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

Search for neutrinos ⇒ look for inclined showers with electromagnetic component
Sensitivity to all flavours and channels

Selection criteria

1) regular shower initiated by proton
2) deep shower initiated by $\nu$ (muonic component of the shower)
3) up-going shower initiated by $\nu_\tau$
4) double-bang shower initiated by $\nu_\tau$
5) down-going shower initiated by $\nu_\tau$

Down-going high angle (2, 4 and 5) DGH $75^\circ-90^\circ$
 Earth-skimming (3) ES $90^\circ-95^\circ$

$\nu_\tau$ all flavours
Selection of inclined events

1. Elongated footprint

2. Apparent velocity $V$ of propagation of the shower front along major axis $L$

3. Reconstructed zenith angle (DGH channel only)

- **Earth-Skimming (90°, 95°)**
  - $L/W > 5$
  - $\langle V \rangle \in (0.29, 0.31) \text{ m ns}^{-1}$
  - $\text{RMS}(V) < 0.08 \text{ m ns}^{-1}$

- **Down-going High (75°, 90°)**
  - $L/W > 3$
  - $\langle V \rangle < 0.313 \text{ m ns}^{-1}$
  - $\text{RMS}(V)/\langle V \rangle < 0.08$
  - $\theta_{\text{rec}} > 75°$
Identifying electromagnetic shower fronts

To find neutrinos => search for signals extended in time in inclined events.

Select stations with:
- Time-over-Threshold (ToT) trigger
- Large Area-over-Peak (AoP)

Definition of Area over Peak

\[
\frac{\text{AREA}}{\text{PEAK}} = \text{AoP}
\]
Searching for UHE $\nu$ in coincidence with GW events

→ Neutrino search method already defined and applied to the data collected up to June 2013 (upper limits to the diffuse flux and steady point-like sources of UHE neutrinos)


→ **Energy range: E > 100 PeV** - complementary to IceCube-Antares GW follow up

\textit{LIGO&VIRGO, IceCube, ANTARES Coll., PRD 93, 122010 (2016)}

→ Earth-Skimming and Downward-Going neutrino selection applied to data in spacial and temporal proximity to GW150914, GW151226 (and LVT151012).

\[ t \]

\[ \pm 500 \text{ s window around GW event time} \]

\[ \text{“coincidence” search} \]

1 day window after GW event time – GRB “afterglow” search

for each GW, data unblinded over an observations window $T_{\text{search}}$ of $1d + 500s$
Time coincidence with GW events: coverage

No neutrino candidate found in the time window $\pm 500$ s around the GW events
Sky map of visibility time fraction in 1 sidereal day

No neutrino candidate found in the 1 day window after any GW events in both search channels

Constraints to UHEν emission declination dependent
For a $kE_\nu^{-2}$ point source, U.L. to flux:

$$k^{GW}(\delta) = \frac{N^{GW}}{\int E_\nu^{-2} \varepsilon_{GW}(E_\nu, \delta) \, dE_\nu}$$

Upper limits to the UHE\(\nu\) spectral fluence ($E_\nu > 10^{17}$ eV)

Fluence U.L. derived combining the constraints from the two search channels and assuming constant flux and continuous emission over $T_{\text{search}}$. 

![Graphs showing UHE neutrino spectral fluence as a function of declination with 90% CL declination GW150914 and GW151226.]
Constraints to the energy radiated in UHEν for GW150914 ($E_\nu > 10^{17}$ eV)

For isotropic emission, using luminosity distance.

less than $(0.5, 3)$ solar masses depending on the source declination

$< 14\%$ of $E_{GW}$
Constraints to the energy radiated in UHEν for GW151226 (E_ν >10^{17} eV)

For isotropic emission, using luminosity distance.

less than (0.5,3) solar masses depending on the source declination

< 44.1% of E_{GW}

Pierre Auger Coll., arXiv:1608.07378
Conclusions

- **Auger follow up of 2015 LIGO gravitational-wave events**
  - search for UHE neutrinos in temporal and spatial proximity with LIGO GW events
  - no neutrino candidate found
  - first constraints at $E_\nu > 10^{17}$eV (complementary to IceCube)

- **In future more GW events expected**
  - closer, brighter or produced by other sources more likely to produce UHE neutrinos
  - UHE neutrino (and photons) counterparts if observed by Auger can help pinpointing the location of the source
Backup
Identification of UHE neutrinos in Auger data

Example: Earth Skimming

\[ <\text{AoP}> = \text{mean value of Area-over-Peak in the event} \]

\[ \approx 90\% \text{ of } \nu \text{ events selected} \]

\[ <\text{AoP}> > 1.83 \]

\[ \nu_\tau \text{ candidate region} \]

~20% of the data are used to estimate the expected background

Identification criteria applied “blindly” to the search data set

=> No candidates found in Earth Skimming or Downward-going

Data taking:
01/01/04 – 20/06/13
Neutrino exposure calculation

Upper limit to the number of neutrinos: Feldman-Cousins + Conrad (includes uncertainties in the exposure calculation)

Upper limits for a $k E^{-2}$ spectrum:

$$k^{90\%} = \frac{N^{90\%}}{\int E_{\nu}^{-2} \varepsilon_{\text{tot}} (E_{\nu}) dE_{\nu}}$$

Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>±</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations</td>
<td>~ +4%, -3%</td>
</tr>
<tr>
<td>$\nu$ cross-section &amp; $\tau$ E-loss</td>
<td>~ +34%, -28%</td>
</tr>
<tr>
<td>Topography</td>
<td>~ +15%, 0%</td>
</tr>
<tr>
<td>Total</td>
<td>~ +37%, -28%</td>
</tr>
</tbody>
</table>
Upper limits to the diffuse flux of neutrinos

Phys. Rev. D 91 (2015) 092008

\[ \frac{dN}{dE} = k \ E^{-2} \]

\[ \rightarrow \ k \sim 6.4 \times 10^{-9} \ \text{GeV cm}^{-2} \ \text{s}^{-1} \ \text{sr}^{-1} \]

90% C.L. in the energy range 0.1 – 25 EeV

Auger limit constrains models with proton primaries & strong evolution with redshift
Auger constraints on models

- Koteru & Silk (ApJLett 823, L29, 2016): events such as GW1501914 can account for UHECR above $10^{19}$ eV
  - sufficient power to accelerate CR up to $10^{20}$ eV (if $B_{\text{field}} > 10^{11}$ G)
  - with $< 3$% of energy released in GW: UHECR energy budget achieved
- UHEv if BHs surrounded by debris where $p\gamma$ interactions occur.

Upper limit to diffuse UHE neutrino flux from BH mergers:

$$E^2dN/dE \sim 1.5 - 6.9 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ (theory)}$$

above Auger limit

$$E^2dN/dE \sim 6.4 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ (Auger)}$$

- Implications:
  - optical depth to $p\gamma$ SMALLER than 1
  - ONLY a fraction of energy in protons goes into charged pions $\rightarrow$ neutrinos
  - ONLY a fraction of luminosity extracted from BH goes into UHECR acceleration