Ultra-high-energy neutrino searches and gravitational wave Follow-up with the Pierre Auger Observatory

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for the Pierre Auger Collaboration

XIX International Workshop on Neutrino Telescopes

February 23, 2021
The Pierre Auger Observatory Surface Detector (SD)

1.5 km spacing → Sensitive to EeV air showers

3000 km² → Large acceptance
Neutrino detection with the Auger SD

Multiple cascades, i.e. many particles → **broad** traces (signal vs. time)

Single particles → **narrow** traces
Neutrino detection with the Auger SD

Primary shower age: young → old

EM: Energetic electromagnetic radiation

μ: Muon

X_{vert, Auger}: Vertical depth in the Auger detector

CR: Cosmic rays

Earth-skimming ν: Neutrinos that barely interact on Earth's surface

Down-going ν: Neutrinos from deep underground sources

TOP OF ATMOSPHERE

EARTH

Signal vs. time [ns] plot for different particles and shower ages.
Neutrino detection with the Auger SD

Down-going Low (DGL)
Down-going High (DGH)
Earth-skimming (ES)

CR

Down-going $\nu$

TOP OF ATMOSPHERE

Earth-skimming $\nu_	au$

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Neutrino detection with the Auger SD

\[ \mathcal{A}(\theta, t) = \int_{0}^{\infty} E_{\nu}^{-2} A_{\text{eff}}(E_{\nu}, \theta, t) \, dE_{\nu} \]

“Effective area per energy”

Down-going Low (DGL)
Down-going High (DGH)
Earth-skimming (ES)
GW170817 visibility

- Excellent visibility of the merger
- Fast LIGO/Virgo + Fermi GCN circular
- Our follow-up routines were not automatized, manual unblinding was necessary
  - Now: immediate search initiation

**2017-08-17**

- DGL (60° < θ < 75°)
- DGH (75° < θ < 90°)
- ES (90° < θ < 95°)
- sum

**equatorial**

- GW (90% CL)
- NGC 4993 neutrino candidate (IceCube)
- neutrino candidate (ANTARES)
- IceCube horizon
- ANTARES horizon
- Auger FoV (Earth-skimming)
- Auger FoV (down-going)
GW170817 neutrino limits

- **No related neutrinos** detected by ANTARES, IceCube, and Auger

- Sensitivity high for ±500 s but reduced for 14 days
  - Good vs. periodic visibility
  - Lesson: lucky strikes happen, improved preparation (faster follow-up) might pay off in the future

Off-axis viewing angle, constrained to < 36° (at time of publication)
Follow-up searches of binary black hole mergers

- LIGO/Virgo binary black hole (BBH) mergers published until 2019-06-02
- GWTC-1 + open public alerts
  - 21 BBH mergers as hypothetical sources
  - Followed up immediately & automatically
  - Regular ultra-high energy (UHE) neutrino searches
  - Until 24 hours after the merger
  - Most probable source localization (90% CL)

- Sources combined by stacking

![Graph of S190412m with 90% CL contour and Auger fovs]
Source property assumptions:

- $E^{-2}$ spectrum
- Universal (all the same) isotropic UHE neutrino emission with luminosity $L(t-t_0)$

Peak luminosity in GWs

Source localization given as pixel-wise probability $P$

GW150914

Peak luminosity $[10^{56} \text{ erg/s}]$
Source property assumptions:
• $E^{-2}$ spectrum
• Universal (all the same) isotropic UHE neutrino emission with luminosity $L(t - t_0)$

Peak luminosity **in GWs**

![Graph showing peak luminosity in GWs with time after merger](image)

Source localization given as pixel-wise probability $P$

![Map showing source localization](image)

GW150914
Combining BBH mergers—Time-dependent stacking

Consider time after the merger in **bins $i$ of $\Delta t = 1 \text{ s}$**

- Obtain UHE neutrino sensitivity to each **source $s$ for each time bin $i$**
- Number of detected and identified neutrinos in time bin $i$, **from all sources $s$ combined**:

$$N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2}$$

Summation over **pixels $p$**

$\leftrightarrow$ “solid angle integration”
Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \]

\[ t - t_0 = 0.0 \text{ h} \]
Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \sum_p \frac{P_{p,s} A_{p,s,i}}{d_s^2} \]

\[ t - t_0 = 2.0 \text{ h} \]
Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \sum_p P_{p,s} A_{p,s,i} d_s^2 \]

\[ t - t_0 = 4.0 \text{ h} \]

Graph showing the visibility of sources with different colors representing different models (DGL, DGH, ES).
\[ N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \]

\[ t - t_0 = 6.0 \, \text{h} \]

Combining BBH mergers—Visibility of sources
Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \sum_{p} \frac{P_{p,s} A_{p,s,i}}{d_s^2} \]

\[ t - t_0 = 8.0 \text{ h} \]

Graph showing visibility of sources over time with different colors representing different models (DGL, DGH, ES).
Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \]

\( t - t_0 = 10.0 \) h

\[
\begin{array}{c}
0.00000 & 0.00002 & 0.00004 & 0.00006 & 0.00008 & 0.00010 \\
\end{array}
\]

\[
\begin{array}{c}
P_{p,A_p} \quad \text{[cm}^2\text{GeV]} \\
\end{array}
\]
Combining BBH mergers—Visibility of sources

\[ N_{\nu, i} = L_i \Delta t \sum_s \frac{\sum_p P_{p, s} A_{p, s, i}}{d_s^2} \]

\[ t - t_0 = 12.0 \text{ h} \]
Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \sum_p \frac{P_{p,s} A_{p,s,i}}{d_s^2} \]

\[ t - t_0 = 14.0 \text{ h} \]

\[ P_{p-A_p} \text{ [cm}^2\text{ GeV]} \]

\[ \theta [^\circ] \]

\[ A_{\text{cm}^2/\text{GeV}} \]

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Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \]

\[ t - t_0 = 16.0 \, \text{h} \]
Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \]

\( t - t_0 = 18.0 \text{ h} \)

\[ P_{p-A_p} \text{ [cm}^2\text{ GeV]} \]

\[ A \text{ [cm}^2\text{ GeV]} \]

\[ \theta[\degree] \]

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$N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2}$

$t - t_0 = 20.0 \, \text{h}$

Combining BBH mergers—Visibility of sources
Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \]

\[ t - t_0 = 22.0 \text{ h} \]
Combining BBH mergers—Visibility of sources

\[ N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \]

“Number of neutrinos per time bin per luminosity”

Alternating domination by different sources
Combining BBH mergers—Luminosity limit

\[ N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \]

No neutrinos observed during 24 h after any merger: \textbf{90 \% CL upper limit on} \( L_i \)

\[ N_{\text{up},\nu,i} = \frac{N_{\text{up},\nu,\text{tot}}}{N_{\text{bins}}} = \frac{2.44 \cancel{24 \text{ h}}}{24 \Delta t} = \frac{2.44}{86400} \]

\[ \Rightarrow L_{\text{up},i} = \frac{2.44}{86400} \text{ s} \left( \sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \right)^{-1} \]
Combining BBH mergers—Luminosity limit

\[
E_{\text{up}} = 1.35 \cdot 10^{52} \text{ erg}
\]

\[
L_{\text{up},i} = \frac{2.44}{86400 \text{ s}} \left( \sum_s \sum_p P_{p,s} A_{p,s,i} \right)^{-1}
\]
Conclusions
Conclusions

- Moving field of view of the Pierre Auger Observatory → strong enhancement of UHE neutrino sensitivity in certain directions → Chance for transient follow up

- UHE neutrino follow-up searches performed for LIGO/Virgo BBH mergers
- Method for **combining all sources** making simple assumptions

- Sensitive to neutrino luminosities below $5 \cdot 10^{46}$ erg/s for certain periods during 1-day follow-up searches
- Overall limit on emitted UHE neutrino energy per source: $1.35 \cdot 10^{52}$ erg

- **Stay tuned for new results this year!** >60 sources, full “4D” GW information
The End
Follow-up of GW events O3

- LIGO/Virgo switched to **open public alerts (OPAs)**, communicated via GCN

- Previously: MoU to share data with LIGO/Virgo, now we **automatically** follow-up the OPAs

- O3 runs since April 2019 with increased sensitivity
  - Increased rates / horizon / source volume
  - + possibly NS-BH mergers
Source Distances

The diagram shows the source distances for different events labeled O1, O2, O3, and TXS 0506+056. The distances are measured in Mpc and range from 0 to 4000 Mpc. The data points are scattered across the range, indicating the distribution of source distances for these events.
Neutrino search and identification

- Pre-select **inlined** and **young** showers
- Neutrino **identification** by zenith-dependent event classification
- Crucial variable: **Area over Peak (AoP)**

![Graph showing the relationship between time and signal, with markers for Peak and Area, and the formula for AoP: \( \text{ AoP} = \frac{\text{Area}}{\text{Peak}} \cdot \text{cal.const.} \)]
Neutrino search and identification

- Pre-select **inclined** and **young** showers
- Neutrino **identification** by zenith-dependent event classification
  - Earth-skimming: <AoP> of all stations in event
  - Down-going: Optimized linear discriminant
  - **Combination of AoPs** of certain stations (esp. early and late ones)
    → “Fisher value”

\[ \theta > 90^\circ \]
\[ \theta = 66^\circ \pm 1.5^\circ \]

No candidates so far
Neutrino exposure

By direction

![Graph showing neutrino exposure by direction](image1)

- Combined
- ES ($90^\circ < \theta < 95^\circ$)
- DGH ($75^\circ < \theta < 90^\circ$)
- DGL ($60^\circ < \theta < 75^\circ$)

By flavor

![Graph showing neutrino exposure by flavor](image2)

- Auger all flavors
- Auger $\nu_e$
- Auger $\nu_\mu$
- Auger $\nu_\tau$
- Auger $\nu_e$ Earth-Skimming only
- Auger all flavors downward-going only

Enrique Zas, ICRC 2017

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Limits on diffuse neutrino flux

- p, Fermi-LAT, $E_{\text{min}} = 3 \times 10^{17}$ eV (Ahlers 2010)
- AGN (Murase 2014)
- Pulsars SFR evol. (Fang 2014)
- proton, strong & weak evolution, $E_{p,\text{max}} = 10^{20}$ eV (Kampert 2012)
- $p$ or mixed, weak evolution, $E_{p,\text{max}} = 10^{20} - 3 \times 10^{21}$ eV (Kotera 2010)
- Iron, strong & weak evolution, $E_{p,\text{max}} = 10^{20}$ eV (Kampert 2012)

Graph showing the limits on diffuse neutrino flux with different evolutions and energy ranges.
Effective area

![Graph showing effective area vs. energy (E_\nu) for different neutrino types and detectors.](image)

- **Auger ES \( \nu_e \), \( \theta = 91^\circ \)**
- **Auger ES \( \nu_e \), \( \theta = 92^\circ \)**
- **Auger ES \( \nu_e \), \( \theta = 93^\circ \)**
- **Auger DGH \( \nu_e \) CC, \( \theta = 75^\circ \)**
- **Auger DGH \( \nu_e \) CC, \( \theta = 80^\circ \)**
- **Auger DGH \( \nu_e \) CC, \( \theta = 85^\circ \)**
- **Auger DGL \( \nu_e \) CC, \( \theta = 60^\circ \)**
- **Auger DGL \( \nu_e \) CC, \( \theta = 66^\circ \)**
- **Auger DGL \( \nu_e \) CC, \( \theta = 69^\circ \)**
- **IceCube \( \nu_\mu \) CC, \( \delta \in [30^\circ, 90^\circ] \)**
- **IceCube \( \nu_\mu \) CC, \( \delta \in [-5^\circ, 30^\circ] \)**
- **IceCube \( \nu_\mu \) CC, \( \delta \in [-30^\circ, -5^\circ] \)**
- **IceCube \( \nu_\mu \) CC, \( \delta \in [-90^\circ, -30^\circ] \)**
Follow-ups of O1+O2 GW events

LIGO/Virgo O1+O2: MoU between Auger and LVC:

Default neutrino search, considering only

- ±500 s around & +1 day after GW event
- Times at which location of the GW event is visible

BNS merger GW170817: ±500 s & 14 day period after the event
Follow-ups of O1+O2 GW events
Follow-Up of BBH merger GW150914

UHE neutrino sensitivity declination dependent

Newer events: More GW detectors → improved localization by triangulation

total neutrino energy = emitted GW energy
GW151226 Follow-Up—Results

No candidates → Flux limit → Limit on total emitted UHE ν energy

arXiv:1602.06961 (Kotera, Silk):
Binary BHs could produce the measured UHECR flux! → Needs ~ 3% “efficiency” ($E_{\text{UHECR}}/E_{\text{GW}}$)
<table>
<thead>
<tr>
<th>Source of systematic</th>
<th>Combined uncertainty band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations</td>
<td>~ +4%, −3%</td>
</tr>
<tr>
<td>$\nu$ cross section and $\tau$ E-loss</td>
<td>~ +34%, −28%</td>
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<tr>
<td>Topography</td>
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<tr>
<td>Total</td>
<td>~ +37%, −28%</td>
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</tbody>
</table>
O1 GW Follow-Up
Earth-Skimming $\nu_\tau$ Selection

Inclination: $90^\circ < \theta < 95^\circ$ → elongated footprint

“Ground signal speed” $\sim c$

Reject “muonic” events → > 60 % stations ToT triggered
Neutrinos vs. Photons

(a) $58.5^\circ < \theta_{\text{Rec}} \leq 61.5^\circ$

(b) $61.5^\circ < \theta_{\text{Rec}} \leq 64.5^\circ$

(c) $64.5^\circ < \theta_{\text{Rec}} \leq 67.5^\circ$

(d) $67.5^\circ < \theta_{\text{Rec}} \leq 70.5^\circ$

(e) $70.5^\circ < \theta_{\text{Rec}} \leq 76.5^\circ$