The Pierre Auger Observatory

FD

SD

Michael Schimp
February 18, 2019
Multimessenger astrophysics with the Pierre Auger Observatory
VHEPA 2019, Kashiwa
Energy estimation with the Pierre Auger Observatory

V. de Souza, Vulcano 2018
Energy estimation with the Pierre Auger Observatory

V. de Souza, Vulcano 2018

M. Unger, ICRC2017

\[ E_{\text{surface}} = f(S_{1000}, \theta) \]
Multimessenger activities

- GW follow-up searches with neutrinos (and photons)
  BBH mergers, BNS merger GW170817

- UHECR-neutrino correlation searches
  (Auger, IceCube, TA)

- Neutrons from the Galaxy

- Deeper Wider Faster
Neutrino detection with the Pierre Auger SD

- Down-going (DG) $\nu_{\tau}$ (most sensitive)
- Earth-skimming (ES) $\nu_{\tau}$
- TOP OF ATMOSPHERE
- CR
- Down-going (DG) $\nu$
- Earth-skimming (ES) $\nu_{\tau}$
- $\sim 850$ g cm$^{-2}$
- $\sim 800$ g cm$^{-2}$
- hadr, $e^{\pm}$, $\gamma$
- (shower front)
- shower age
- primary
- young
- old
- $\mu$

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VHEPA 2019, Kashiwa
Reasonable separation: \( \theta > 60° \)

- Down-going low
- Down-going high
- Earth-skimming

\[ \tau \] (most sensitive)

\[ \theta \]

\[ 60° \]

\[ 75° \]

\[ 90° \]

\[ 95° \]

\[ 120° \]

\[ 135° \]

\[ 150° \]

\[ 165° \]

\[ 180° \]

\[ \text{TOP OF ATMOSPHERE} \]

\[ \text{EARTH} \]

\[ \sim 850 \text{ g cm}^{-2} \]
Neutrino search and identification

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

![Graph showing signal over time with Peak and Area labeled]
Neutrino search and identification

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

![Graphs showing candidate regions and efficiencies](image)

- \(\theta > 90^\circ\): Candidate region with 95% efficiency
- \(\theta = 66^\circ \pm 1.5^\circ\): Candidate region with 72% efficiency

No candidates so far
Neutrino exposure

By direction

By flavor

Enrique Zas, ICRC 2017
Limits on diffuse neutrino flux

- Single flavor: $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$
- Proton, strong & weak evolution, $E_{p,\text{max}} = 10^{20}$ eV (Kampert 2012)
- Pulsars SFR evol. (Fang 2014)
- AGN (Murase 2014)
- Iron, 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)

90% CL limit
- Auger (2017)
- IceCube (2017)
- ANITA I+II+III (2018)
### Implications on diffuse neutrino models

<table>
<thead>
<tr>
<th>Diffuse flux neutrino model</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmogenic - proton - strong source evolution  (Kampert 2012)</td>
<td>~ 5.2</td>
</tr>
<tr>
<td>Cosmogenic - proton, FRII evol. (Kotera 2010)</td>
<td>~ 9.2</td>
</tr>
<tr>
<td>Cosmogenic - proton - moderate source evolution  (Aloisio 2015)</td>
<td>~ 2.0</td>
</tr>
<tr>
<td>Cosmogenic - proton, SFR evol, $E_{\text{max}} = 10^{21}$ eV (Kotera 2010)</td>
<td>~ 1.8</td>
</tr>
<tr>
<td>Cosmogenic - proton, SFR evol. (Kampert 2012)</td>
<td>~ 1.2</td>
</tr>
<tr>
<td>Cosmogenic - proton, GRB evol. (Kotera 2010)</td>
<td>~ 1.5</td>
</tr>
<tr>
<td>Cosmogenic - proton - normalized to Fermi-LAT GeV $\gamma$-rays</td>
<td></td>
</tr>
<tr>
<td>Cosmogenic - proton, Fermi-LAT, $E_{\text{min}} = 10^{19}$ eV (Ahlers 2010)</td>
<td>~ 4.0</td>
</tr>
<tr>
<td>Cosmogenic - proton, Fermi-LAT, $E_{\text{min}} = 10^{17.5}$ eV (Ahlers 2010)</td>
<td>~ 2.1</td>
</tr>
<tr>
<td>Cosmogenic - mixed (Galactic) UHECR composition (Kotera 2010)</td>
<td>~ 0.7</td>
</tr>
<tr>
<td>Cosmogenic - iron, FRII (Kampert 2012)</td>
<td>~ 0.35</td>
</tr>
<tr>
<td>Astrophysical sources</td>
<td></td>
</tr>
<tr>
<td>Astrophysical - radio-loud AGN (Murase 2014)</td>
<td>~ 2.6</td>
</tr>
<tr>
<td>Astrophysical - Pulsars - SFR evol. (Fang 2014)</td>
<td>~ 1.3</td>
</tr>
</tbody>
</table>

Excluded at 90% CL: > 2.4 events
Implications on sources

- Pure proton
- Source evolution $\sim (1+z)^m$ up to $z_{\text{max}}$
- $E^{-2.5}$ flux

- Smaller proton fractions $\rightarrow$ less sensitivity
Effective area

![Graph showing effective area vs. energy for different neutrino channels and zenith angles for the Auger and IceCube experiments.](image)
Follow-ups of 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-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
Visibility of GW170817

Good visibility at time of merger
Neutrino limits for GW170817

- No related neutrinos detected by ANTARES, IceCube, and Auger
  - Sensitivity high for ±500 s but reduced for 14 days ➔ Good vs. periodic visibility

Viewing angle, constrained to < 36° (at time of publication)
Follow-up of GW events O3

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

- No MoU, we **automatically** follow-up the OPAs

- O3 starts in April 2019 with increased sensitivity
  - Increased rates / horizon / source volume
  - + possibly NS-BH mergers

- Photon follow-up search will join in

- KAGRA?
UHE photon separability from protons (=worst case)

\[ g_{LDF} \] accounts for **steeper** lateral particle density distribution (LDF) of photons

\[ g\Delta \] accounts for **slower rising signal** of photon induced air showers in the PMTs of the SD stations

**Caveat:** The GW events’ sources so far are further away than the UHE photon horizon

- We prepared the follow-up routines (no publications), ready for LIGO/Virgo O3, hope for close-by sources
Auger is complementary to other neutrino telescopes

- Flavor-dependency of sensitivity: Highest for $\nu_\tau$, smallest for $\nu_\mu$
- **Largest effective area in the EeV range** (but moving field of view)
  - Great sensitivity to **transients** (when they are in fov)
- Unique: Northern Hemisphere at EeV energies
Neutrino follow-up searches of published LIGO/Virgo GW events performed
BBH mergers: Sensitivity to emitted neutrinos of the order of emitted gravitational waves (in terms of total energy)
BNS merger GW170817: good visibility, fluence limits in the range of theoretical predictions
Photons (more background-prone) are ready to join in

Future: **increased event rates**, precision and maybe even other source classes
Exploring the correlation:

UHECR with $E > \sim 50$ EeV
(Auger + TA)

Neutrinos
(IceCube, soon ANTARES)

Two different methods:

- **Excess** of frequency of angular separation above isotropy assumption
- **Stacking likelihood** of angular correlations given MF models, assuming sources are at measured neutrino directions
Most significant excess with IceCube cascades at $\Delta \Psi \sim 22^\circ$

- Combination of cascade angular resolution ($\sim 15^\circ$) and UHECR deflection ($\sim 6^\circ/E_{100}$)

$p = 5 \times 10^{-3}$ (post trial)
Stacking likelihood analysis:
Most significant results with *cascades* and MF deflection of \( \sim 6^\circ/E_{100} \), backing up the angular separation analysis

\[ p = 2 \times 10^{-2} \text{ (post trial)} \]

Results used to be more significant (ICRC 2015)

- Vanishing of a fluctuation?
- Composition + MF deflection need to be better understood
Galactic neutrons

- **No** direct neutron identification possible in Auger
- Neutrons are not deflected in MFs and reach us from anywhere in the Galaxy at $E > 2$ EeV
- Assume hadronic photon and neutron production from
  - Galactic Center
  - Galactic Disc
  - Known gamma-ray sources (weighted combination)
- Look for increased particle flux from corresponding directions (i.e. missing diffusion by magnetic fields)
Galactic neutrons

- None of the searches provided evidence for a neutron flux from any “source class”

- Limit on neutron energy flux from Galactic gamma-ray sources w/ 6 years of data:
  \[0.10 - 0.15 \text{ eV cm}^{-2} \text{ s}^{-1} < \text{measured TeV photon flux}\]

- Fermi \(E^{-2}\) acceleration (protons) would imply more than that! ➔ Excluded!

- Luminosity ratio \(L_n / L_p < 0.006\) (galactic plane, proton emission estimations)
Deeper Wider Faster

- Multi-instrument (> 30) project, participants from radio through ultra-high energies and non-photons (Auger)
- University of Tokyo 1 m Telescope (for follow-up)
- ~ 10 groups observe simultaneously to get deep+wide-field fast-sampled multi-wavelength / multi-messenger measurements of the same field
- Radio: Fast radio bursts (< 1 s)
- Higher energies: second to hour transients, also GW
- Real-time (< ~ minutes) candidate identification
- Fast response (~ minutes) ToO follow-up observations
- Long-term follow-up with ~ 1 – 4 m-class telescopes
Deeper Wider Faster

- 4 to 6 consecutive nights per semester (next: June 2019)

- Auger: All SD events from DWF field of view selected, **no coincidences** so far

- Extensive software development (compression, transient identification, visualization, collaborative workspaces, machine learning)
Subsummary UHECR - neutrinos, neutrons, DWF

- Correlations between Auger + TA UHECRs and IceCube (soon + ANTARES) neutrinos are searched for
  - Most interesting correlation ($\rho \sim 10^{-3}$ (post trial)) for IceCube cascades, corresponding to angular distances of $\sim 20^\circ$

- Galactic neutron searches
  - No evidence for substantial EeV neutron flux
  - Hadronic pion-production in gamma-ray sources with $E^{-2}$ up to highest energies excluded

- Deeper Wider Faster
  - Extensive program of simultaneous multi-wavelength/messenger observations, targeting FRBs and other transients (also GW)
  - No coincident detection by Auger, project ongoing
The End
<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>
</tr>
<tr>
<td>Topography</td>
<td>~ +15%, 0%</td>
</tr>
<tr>
<td>Total</td>
<td>~ +37%, −28%</td>
</tr>
</tbody>
</table>
GW Follow-Up—Results (Münster slide)

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” \( \frac{E_{\text{UHECR}}}{E_{\text{GW}}} \)
Follow-Up of GW events

- Last published BH-BH merger so far
- Fluence limits to be calculated, expected to be good
Visible Solid Angle

```
Fraction of 1 sidereal day (%)

Source declination \(\delta\) [deg]

Auger ES \((90^\circ < \theta < 95^\circ)\)
Auger DGH \((75^\circ < \theta < 90^\circ)\)
Auger DGL \((60^\circ < \theta < 75^\circ)\)
```
**No candidate** in [–500 s, 1 day] around GW events
→ Calculate **exposure** taking into account
  • Time-dependent aperture (area x solid angle)
  • \(\nu\)-nucleon cross section + efficiencies \((E,\delta)\)
Cen A limits

Centaurus A, $\delta = -43^\circ$

- **Pierre Auger 2017**
- **IceCube 2017**
- **CenA core (Kachelriess et al. 2009)**
- **CenA core (Cuoco et al. 2008)**
- **ANTARES 2017**

$E^2 \frac{dN}{dE}$ (GeV cm$^{-2}$ s$^{-1}$)

$E_\nu$ (eV)

- $10^{-10}$
- $10^{-9}$
- $10^{-8}$
- $10^{-7}$
- $10^{-6}$

$10^{13}$ $10^{14}$ $10^{15}$ $10^{16}$ $10^{17}$ $10^{18}$ $10^{19}$ $10^{20}$
Cen A limits

![Graph of Cen A limits](image)

- **Pierre Auger 2017**: Red line
- **CenA core (Kachelriess et al. 2009)**: Gray line
- **IceCube 2017**: Blue line
- **CenA core (Cuoco et al. 2008)**: Black line
- **ANTARES 2017**: Green line

Centaurus A, $\theta = -43^\circ$
Inclination: $90^\circ < \theta < 95^\circ$
- Elongated footprint

"Ground signal speed" $\sim c$

Vertical shower
$V \gg c$

Horizontal shower
$V \sim c$

Reject “muonic” events $\rightarrow > 60\%$ stations ToT triggered
CC vs NC Fisher Values

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{Fisher Values for CC and NC Monte-Carlo simulations and background.}
\end{figure}
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) $70.5^\circ < \theta_{\text{rec}} \leq 76.5^\circ$