IL NUOVO CIMENTO **40 C** (2017) 111
DOI 10.1393/ncc/i2017-17111-9

Colloquia: SciNeGHE 2016

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

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received 31 July 2017

Summary. — In early 2016 the LIGO and Virgo Collaborations reported the breakthrough observation of the first gravitational-wave transient with the twin detectors of Advanced LIGO in September 2015 (event GW150914), followed three months later by the detection of GW151226. Both events were produced by the coalescence of black holes. Although no electromagnetic emission is generally expected from such events, in the presence of magnetic fields and debris from the formation of black holes, radiation of ultra-high energy (UHE) neutrinos might be possible and, if detected, could help constrain the direction of the source of the events. The Pierre Auger Observatory is capable of identifying air-shower events initiated by ultra-high energy neutrinos, using the data from its surface detector. The emission of neutrinos with energy $> 10^{17}$ eV can be detected from point-like sources contained in the equatorial declination band between -65 and $+60$ degrees, including a portion of the 90% CL inferred position for GW150914 and GW151226. A search for neutrinos in temporal and directional proximity with the GW events (and for the GW candidate event LVT151012) was performed. Constraints to the energy radiated in UHE neutrinos are derived from the non-detection of neutrinos in the search windows.

1. – Introduction

Gravitational Waves (GW) were detected on September 14, 2015 and on December 26, 2015 by the two Advanced LIGO detectors [1] for the first time. For both observed events the inferred source is the coalescence of a stellar mass binary black hole system at luminosity distances $D_s = 410^{+160}_{-180}$ Mpc and $D_s = 440^{+180}_{-190}$ Mpc, respectively. These sources might provide a potential environment where cosmic rays can be accelerated to

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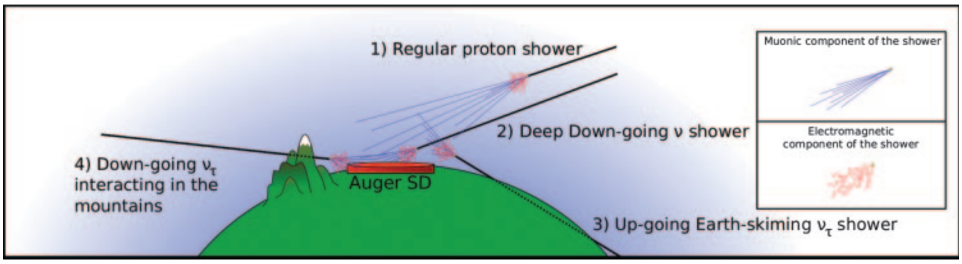

Fig. 1. – Principle of detection of neutrinos with the surface detector of the Pierre Auger Observatory (from [2]). Showers originated by neutrinos are searched in two channels defined by the local zenith angle range: the Earth-Skimming (ES) —case (3)— sensitive to tau neutrinos only and Downward-Going at High angle (DGH) —case (2) and (4)— sensitive to all flavours. Neutrino-induced air showers, being initiated closer to the observation level, are characterised by a larger electromagnetic component (see text) with respect to the overwhelming background of showers induced by nucleons —case (1).

ultra-high energies provided there are magnetic fields and disk debris remaining from the formation of the black holes [3, 4]. Such a system may also emit ultra-high energy gamma-rays and neutrinos. If GW events occur at distances farther than a few tens of Mpc, neutrinos are the only messengers at EeV energies capable of probing their sources.

We use the data collected from the surface detector (SD) of the Pierre Auger Observatory to search for neutrinos above 100 PeV in two time windows of ± 500 s around ("coincidence") and 1 day after ("afterglow") the gravitational-wave events.

2. – Searching for UHE neutrinos with the Pierre Auger Observatory

The SD of the Pierre Auger Observatory, located in Southern Argentina (latitude $\lambda = -35.2°$), consists of 1,600 water-Cherenkov stations, deployed over $3000\,\text{km}^2$ in a triangular grid with a 1500 m spacing, capable of sampling at ground level the secondary particles of air showers initiated by primary cosmic rays in the terrestrial atmosphere [5]. Neutrinos with energies above $\simeq 100$ PeV can also initiate air showers in the atmosphere. Due to their small cross section, neutrinos induce showers that are deeply penetrating. At large zenith angles —corresponding to a large atmospheric depth of observation with the SD— they have a significant "electromagnetic"(em) component (*i.e.*, secondary $e^{\pm}$ and γ), while background showers initiated by nucleons consist of mostly muons, since the em component is absorbed in the atmosphere before it reaches ground.

The neutrino detection criteria, used also in [6], are based on the selection of showers rich in em component, recognised through signals in SD stations more extended in time with respect to the average shower initiated by the bulk of cosmic rays (nucleons) and photons. The sensitivity of the detector to neutrinos is limited to large zenith angles and energies larger than $\simeq 10^{17}$ eV. Neutrino-induced showers are searched for in two channels (see fig. 1):

- Earth-Skimming (ES) showers (zenith angles 90°–95°), induced by ν_τ travelling upward with respect to the ground vertical, can skim the crust of the Earth and interact close to the surface producing a τ lepton which can decay in flight in the atmosphere close to the SD initiating an air shower that can be detected.

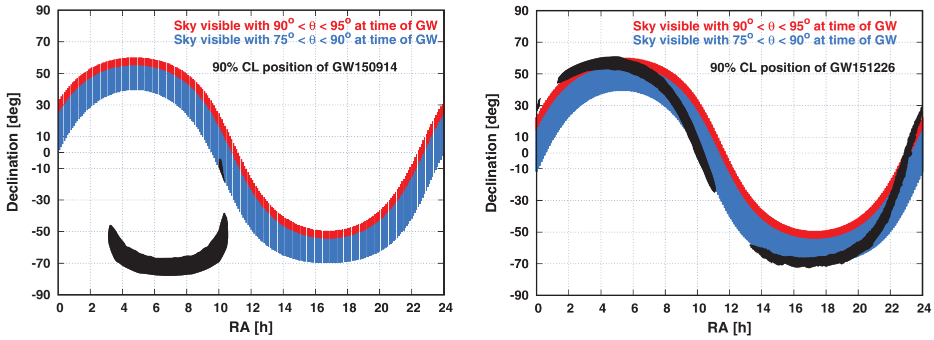

Fig. 2. – The instantaneous field of view of the Auger Observatory at the time of the two LIGO events GW150914 (left) and GW151226 (right) is shown in equatorial coordinates for the two neutrino search channels: ES in red and DGH in blue [7]. The black dots are distributed inside the boundary delimiting the directions of the events at 90% CL [1] (from [7]).

- Downward-Going at High angle (DGH) showers (75°–90°) produced by neutrinos of all flavours interacting in the atmosphere close to the SD through neutral or charged current interactions, as well as showers induced by ν_τ interacting in the mountains surrounding the observatory.

The search method, sensitive to neutrinos in the energy range [~ 100 PeV, ~ 25 EeV], was applied to the set of data collected until 2013, finding no candidate and setting an upper limit to the diffuse flux of neutrinos below the Waxman-Bahcall bound [6], and to the flux of potential point-like steady sources [8].

3. – Search for UHE neutrinos in coincidence and after the LIGO GW events

The criteria for the selection of neutrino-induced showers, described in the previous section, were used in the time period in close proximity (± 500 s) to the time of detection of the two LIGO events (and the GW candidate event LVT151012 [9]). Additionally UHE neutrinos were searched in a window of 1 day after the events as "afterglow" of the black hole merger. The directional coincidence requirement is for neutrinos to come from a direction enclosed in the large 90% CL contour set by the LIGO Collaboration for the direction. The two time windows are chosen on the basis of the association of mergers of compact objects with γ-ray bursts, and correspond, respectively, to upper limits to the duration of the prompt phase and of the afterglow phase of GRBs (see, *e.g.*, [10]).

- *Results of the coincidence search*: in the ± 500 s window there is only a small overlap between the position of event GW150914 and the SD field of view, in the DGH channel (fig. 2, left), while the direction of event GW151226 (and candidate event LVT151012) was visible in ES or DGH channel (fig. 2, right). No neutrino was detected in coincidence with the two GW events (and the candidate GW event).

- *Results of the "afterglow" search*: no events were identified as neutrino candidates in the search window of one day after the GW events, neither in, nor outside, the direction's 90% CL regions relative to the GW events (and candidate event).
  Since the fraction of the day in which a point-source in the sky is visible to the SD depends on the selection channel and on its equatorial declination δ (fig. 3), the

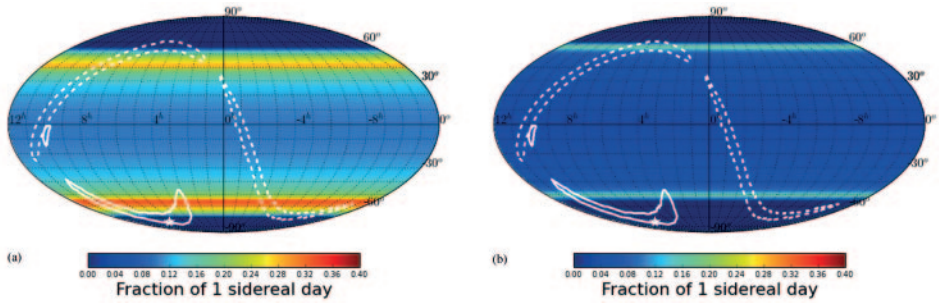

Fig. 3. – Fraction of the sidereal day in which a point-like source is visible from the Pierre Auger Observatory as a function of its position in the sky in equatorial coordinates. The visibility map is shown for the local zenith ranges corresponding to the DGH (left) and ES (right) search channel for UHE neutrinos (see text). The continuous and dashed lines delimit the 90% CL boundary to the position of GW150914 and GW151226 [1], the white star shows the best fit position of GW150914 obtained including data from *Fermi* GBM [11] (from [7]).

non-observation of candidates allows us to set constraints on the emission of UHE neutrinos that are declination dependent.

4. – Constraints on the emission of UHE neutrinos

Assuming a $k^{\rm GW}E_\nu^{-2}$ spectrum for a constant UHE neutrino flux per flavor, the expected number of events for a source at equatorial declination δ is

$$N_{\rm event}^{\rm GW} = \int_{E_\nu} k^{\rm GW} E_\nu^{-2}\ \mathcal{E}_{GW}(E_\nu,\delta)\ {\rm d}E_\nu, \tag{1}$$

where $\mathcal{E}_{GW}(E_\nu,\delta)$ is the effective exposure for a flux of energy E_ν originating at declination δ and is determined separately for the two ES and DGH neutrino search channels [6]. The exposure accounts for the geometric aperture (including the fraction of time of visibility for the SD), the neutrino cross-section for each channel, and is weighted with the efficiency of selection determined with Monte Carlo simulations. An upper limit at 90% CL to the normalization of the flux $k^{\rm GW}$ can be obtained from the non-observation neutrinos for the sources of GW150914 and GW151226,

$$k^{\rm GW}(\delta) = \frac{2.39}{\int_{E_\nu} E_\nu^{-2}\ \mathcal{E}_{\rm GW}(E_\nu,\delta)\ {\rm d}E_\nu}, \tag{2}$$

where systematic uncertainties are included in the limit using an extension of the Feldman-Cousins approach [12]. Assuming that GW sources emit UHE neutrinos isotropically and continuously in time in the total search window $T_{\rm search} = 1\,{\rm day} + 500\,{\rm s}$, a limit on the fluence can be derived from

$$E_\nu^2\,\frac{{\rm d}N_\nu}{{\rm d}E_\nu} \times T_{\rm search} = k^{\rm GW}(\delta)\ T_{\rm search}. \tag{3}$$

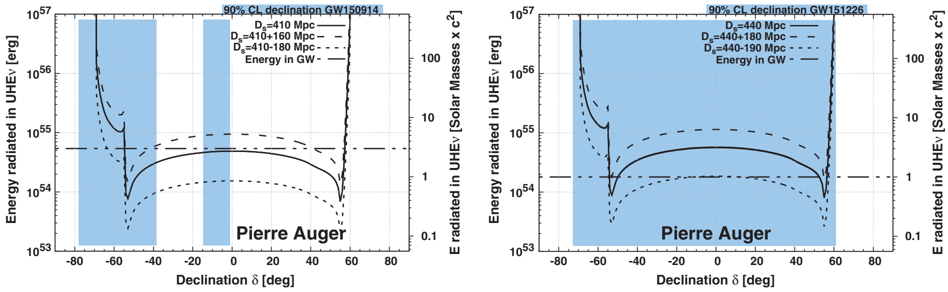

Fig. 4. – Upper limits at 90% CL (continuous line) to the energy radiated in UHE neutrinos above 100 PeV for the two LIGO events GW150914 (left) and GW151226 (right) as a function of equatorial declination for the estimated value of the luminosity distance D_S. Dashed and dotted lines show the same limits computed for the maximum and minimum distance allowed by the uncertainty given in [1]. Highlighted in blue: the declination bands in which the 90% CL estimated direction for GW sources has non-zero visibility for the SD of the Auger Observatory in the neutrino selection channels. The horizontal lines represent the energy emitted in the form of gravitational waves [1], for comparison (from [7]).

Using the luminosity distance D_s, the limit on the fluence can be converted into a limit to the total energy radiated from the GW source in UHE neutrinos. Results depend on the direction and distance of the source and are shown in fig. 4. Additional details on the analysis can be found in [7]. In case of future detection of GW events with sources more likely to emit UHE neutrinos than the coalescence of black holes, the SD of the Auger Observatory can provide an additional tool to identify the sources through the detection of UHE neutrinos in the energy range above 0.1 EeV, complementary to the TeV–PeV region covered by IceCube and ANTARES [13].

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