All-sky search for correlations in the arrival directions of astrophysical neutrino candidates and ultrahigh-energy cosmic rays

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[2] http://www.auger.org/archive/authors_icrc_2017.html

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High-energy neutrinos, being neutral and weakly interacting particles, are powerful probes of the sites of production and acceleration of cosmic rays. The challenging discovery of cosmic neutrinos by the IceCube Collaboration has moved the field closer to realizing the potential of neutrino astronomy. Meanwhile, ground-based cosmic ray detectors like the Pierre Auger Observatory and the Telescope Array have reached an unprecedented accuracy in the determination of the features of the cosmic rays at the highest energies. We report on a collaborative effort between IceCube, the Pierre Auger Observatory and Telescope Array to identify directional correlations between the arrival directions of the highest-energy cosmic rays from both hemispheres and of the most probable cosmic neutrino events detected by IceCube. We describe the updated results of two independent searches using seven years of IceCube neutrino data and the most energetic cosmic-ray events detected by the Pierre Auger Observatory and the Telescope Array. The directional correlation found between UHECRs and neutrinos is reported with a significance of $\sim 2\sigma$.

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Introduction

The determination of the origin of cosmic rays (CRs) is a difficult task since CRs are deflected during propagation. The extent of this angular deflection is still poorly constrained. Neutrinos produced during hadronic interactions of CR primaries propagate unaffected from their sources to us. They can therefore deliver potentially valuable information on the most energetic CR sources of the Universe. Neither of the observatories of neutrinos or ultrahigh-energy cosmic rays (UHE-CRs) dedicated to unravel the quest of the CR origin have delivered evidence for specific cosmic sources. This search for a common origin of UHECRs and neutrinos results from a joint collaboration between the IceCube Neutrino Observatory, the Pierre Auger Observatory and the Telescope Array (TA). Previous results of this work [1] provided a potentially interesting connection between neutrino and UHECR directions at the 3σ level. We update that work here including two additional years of neutrino data from IceCube and one more year of TA data.

1. The observatories and the data sets

The IceCube South Pole Neutrino Observatory

IceCube [2] is a cubic-kilometer high-energy neutrino detector (energy threshold $>\sim 100\,\text{GeV}$) located at the geographic South Pole at about 1.5 to 2.5 km beneath the ice sheet surface. It is composed of 86 strings instrumented by 5160 photomultiplier tubes housed in pressure resistant spheres. Since 2005, data have been taken with partially completed configurations (9, 22, 40, 59 and 79 strings) until its final completion in December 2010. In 2013, a neutrino flux compatible with astrophysical neutrino expectations was reported [3, 4, 5]. Cumulating four years of data, the hypothesis of a pure atmospheric origin has been rejected at $\sim 6.5\sigma$ level. These detected neutrinos are of all flavors interacting inside the detection volume (starting events) with deposited energies ranging from 60 TeV up to 2 PeV. They compose the HESE dataset ('High-Energy Starting Events'). They are mostly composed of shower-like events (cascades) characterized by an angular resolution of $\sim 15°$ above 100 TeV. The track-like events are induced by muons and have a better angular resolution of $\lesssim 1°$. The resolution of the deposited energy for tracks and cascades is around 15% [6] but cascades have a better resolution for the reconstructed neutrino energy since most of the energy is deposited in the detector, which is not the case for tracks.

In this analysis, we present results on the published updated sample of 39 HESE cascades and 7 HESE tracks [1] with two additional years of data composed of 19 cascades and 8 tracks, giving a total of 58 cascades and 15 tracks constituting the 6-year HESE dataset [7].

A complementary dataset of through-going muons induced by charged current interactions of candidate ν_μ from the Northern sky [8] is also added to the track dataset. It has been reported that events giving this set of tracks do have a spectrum that is inconsistent with the hypothesis of atmospheric neutrino origin at the level of 5.6σ. The events considered here are 35 tracks corresponding to seven years of data from the 8-year data sample presented in [9]. Only events with 'signalness' > 50% are considered, where the signalness is defined as the ratio of the astrophysical expectation over the sum of the atmospheric and astrophysical expectations for a given energy proxy and best-fit neutrino spectral index of 2.16. This requirement of 'signalness' > 50% translates to a selection of events with a lower energy threshold of $\sim 200\,\text{TeV}$ of the muon energy proxy [8].

44   The events from the HESE sample and that from the complementary dataset from the Northern
45   sky only confirm the picture of an isotropic neutrino emission, but measured differences in the
46   energy spectrum may suggest a mixed origin of the events detected in IceCube. Nonetheless, no
47   astrophysical counterpart has so far been supported by the current observational data.

48   **The Pierre Auger Observatory**

49   The Pierre Auger Observatory [10] is a hybrid high-energy cosmic-ray detector, covering an
50   area of about 3000 km^2, located in Argentina. It combines a large surface detector array (SD) com-
51   posed of 1660 water-Cherenkov detectors with an atmospheric fluorescence detector (FD) made of
52   27 fluorescence telescopes. The dataset used for this analysis is composed of 231 cosmic rays with
53   energies $E_{CR} \geq 52$ EeV recorded with the SD array from January 2004 to March 2014. The cut on
54   the zenith angle $\theta \leq 80°$ allows for a field-of-view ranging from $-90°$ to $+45°$ in declination. The
55   angular resolution, defined as the 68th percentile of the distribution of the opening angles between
56   the true and reconstructed directions of simulated events, is better than $0.9°$ [11].

57   **Telescope Array**

58   Telescope Array (TA) is a 700 km^2 cosmic-ray surface array detector located in the United
59   States [12]. It is composed of 507 plastic scintillators distributed on a square grid with 1.2 km
60   spacing overlooked by three fluorescence detector stations housing 38 telescopes. The selected
61   events have an energy $E_{\text{CR}} \geq 57$ EeV and zenith angles smaller than $55°$. The angular resolution of
62   these events is about $1.5°$. In addition to the 87 events detected from May 2008 to May 2014 and
63   used in [1], 22 additional events collected in an additional year of data were used, reaching a total
64   of 109 UHECRs from TA.

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66   In both UHECR observatories, the absolute energy scale is given by fluorescence calibrations,
67   using 'hybrid' events which are detected simultaneously by the SD array and the FD. For these
68   events, it is possible to take advantage of the quasi-calorimetric energy determination from the FD
69   technique. For the Pierre Auger Observatory, the systematic uncertainty on the energy scale is 14%
70   and the statistical energy uncertainty is smaller than 12% [13]. For TA, the energy resolution is
71    $\sim20\%$, while the systematic uncertainty on the energy scale is 22% [14]. In accordance with the
72   TA and Auger Energy Spectrum Working Group, and as presented in [1], the energy measured by
73   TA is downshifted by 13%, so that the measured Auger and TA energy spectra coincide at 10 EeV.

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75   The directions of the neutrinos detected by IceCube and the UHECRs detected by the Pierre
76   Auger Observatory and Telescope Array used in this work are shown in Figure 1 in Galactic coordi-
77   nates. The complementary field-of-views of the UHECR observatories allow for an all-sky search
78   for correlations with neutrinos of all-flavors detected by IceCube.

2. The methods

80   The search for correlations in the arrival directions of UHECRs and neutrinos relies on two in-
81   dependent methods adapted for this analysis [1]: the unbinned-likelihood and the cross-correlation
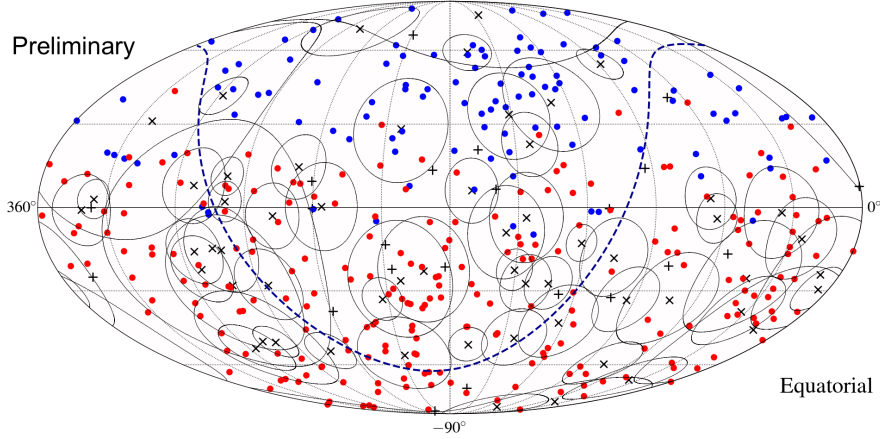82   method.

Figure 1: Directions of the UHECR events detected by Telescope Array (blue points) and the Pierre Auger Observatory (red points). The directions of the shower-like neutrino events detected by IceCube are shown in black crosses surrounded by the angular uncertainties shown in black circles. The track-like events are shown with 'plus' signs. The Galactic plane is represented by the dashed blue line.

Cross-correlation method

The cross-correlation method consists in computing the relative excess in the number of neutrino-UHECR pairs as a function of their angular separation over the expectation of isotropically distributed CR arrival directions, keeping the arrival directions of the neutrinos fixed. The isotropic distribution of the arrival directions of UHECRs is simulated according to the corresponding geometric exposures of the observatories. We also compare the number of pairs to an isotropic distribution of neutrinos, keeping the arrival directions of the UHECRs fixed and thus preserving the degree of anisotropy in the arrival directions of CRs. The isotropic flux of neutrinos is simulated by producing random right ascensions and keeping their declination fixed to account for the declination dependence in the IceCube acceptance. The angular separation in this study ranges from $1°$ to $30°$ with steps of $1°$. This angular scan does not require one to make an assumption on the deflection of CRs while they propagate from their (supposedly) common source with neutrinos.

The unbinned-likelihood method

The second test is a stacking likelihood test assuming that the stacked sources are the neutrino directions. This test requires a hypothesis on the CR deflections. We have nonetheless made a scan on different values of the deflections also to account for the uncertainty on the composition of the CRs.

We considered a few models of cosmic ray deflections, which are based on backtracking simulations of UHECRs in the Galactic magnetic field models of Pshirkov et al. [15] and Jansson and Farrar [16]. Assuming a pure proton composition with an energy $E_{CR}=100$ EeV, we obtained a median angular deflection of $2.7°$ due to the Galactic magnetic field. In this work, the assumed angular deflections in the CR directions are thus taken as $3° \times 100$ EeV$/E_{CR}$. To account for a possible heavier composition or larger contribution of the intervening magnetic fields, additional test values of $6° \times 100$ EeV$/E_{CR}$ and $9° \times 100$ EeV$/E_{CR}$ were considered. It is to be noted that the

likelihood test is less optimal but not insensitive if the 'true' deflection of CRs is slightly different than foreseen by models. The expression of the log-likelihood is defined as:

$$\ln \mathscr{L}(n_s) = \sum_{i=1}^{N_{\text{Auger}}} \ln \left(\frac{n_s}{N_{\text{CR}}} S^i_{\text{Auger}} + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B^i_{\text{Auger}} \right) + \sum_{i=1}^{N_{\text{TA}}} \ln \left(\frac{n_s}{N_{\text{CR}}} S^i_{\text{TA}} + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B^i_{\text{TA}} \right),$$

where n_s, the number of signal events, is the only free parameter, $N_{\text{CR}} = N_{\text{Auger}} + N_{\text{TA}}$ is the total number of UHECR events (340), S^i_{Auger} and S^i_{TA} are the signal PDFs (Probability Distribution Functions) for Auger and for TA, respectively, and B^i_{Auger} and B^i_{TA} are the corresponding background PDFs. The signal PDFs, in which the different neutrino positions are stacked, take into account the exposure and angular resolution of the CR observatories, the assumed CR magnetic deflections and the likelihood maps for the reconstruction of the ν arrival directions (Figure 2). Thus, for each CR i at a given direction $\vec{r}_i$ and energy E_i, the signal PDF is expressed as:

$$S^i_{\text{CR observatory}}(\vec{r}_i, E_i) = R_{\text{CR observatory}}(\delta_i) \cdot \sum_{j=1}^{N_{src}} S_j(\vec{r}_i, \sigma(E_i)) \tag{2.1}$$

$R_{\text{CR observatory}}(\delta_i)$ is the relative exposure for a given event declination and N_{src} is the number of stacked sources, 58 for the cascades and 49 for the tracks. The last term, $S_j(\vec{r}_i, \sigma(E_i))$, is the value of the normalized directional likelihood map for the jth source (i.e neutrino) taken at $\vec{r}_i$ and smeared with a Gaussian with standard deviation $\sigma(E_i)$. The Gaussian smearing takes into account the energy-dependent magnetic deflections imprint on the CR directions $\sigma(E_i) = \sqrt{\sigma^2_{\text{CR observatory}} + \sigma^2_{MD}}$, where $\sigma_{\text{CR observatory}}$ is the angular resolution of the CR observatory ($0.9°$ for Auger and $1.5°$ for TA) and $\sigma_{MD} = D \times 100\,\text{EeV}/E_{\text{CR}}$. Figure 2 represents the directional likelihood maps of the stacked neutrinos for shower-like and track-like topologies before smearing and convolved with the exposure of each CR observatory. The background PDFs are obtained from the normalized (by the total number of detected events by each observatory) exposures of the CR observatories. The test statistic TS is defined as: $TS = -2\ln \frac{\mathscr{L}(n_s)}{\mathscr{L}(n_s=0)}$ and follows a distribution close to χ^2 with one degree of freedom.

3. Results

Cross-correlation results

Applying the cross-correlation method to the data, it is found that the maximum departure from the expectation for an isotropic CR flux, keeping the arrival directions of the neutrinos fixed, occurs at an angular distance of $1°$ for tracks and $22°$ for cascades, with post-trial p-values of 0.48 and 5.4×10^{-3}, respectively. In Figure 3, the relative excess of neutrino-UHECR pairs found in the data, $[n_p(\alpha)/\langle n_p^{\text{iso}}(\alpha)\rangle] - 1$, as a function of the scanned separation angles is shown with respect to the expectations of an isotropic flux of CRs. Evaluating the significance under the hypothesis of an isotropic flux of neutrinos, keeping the arrival directions of the CRs fixed, we find that for the high-energy cascades the maximum departure from isotropic expectations is at $16°$, with a post-trial p-value of 1.0×10^{-2}.
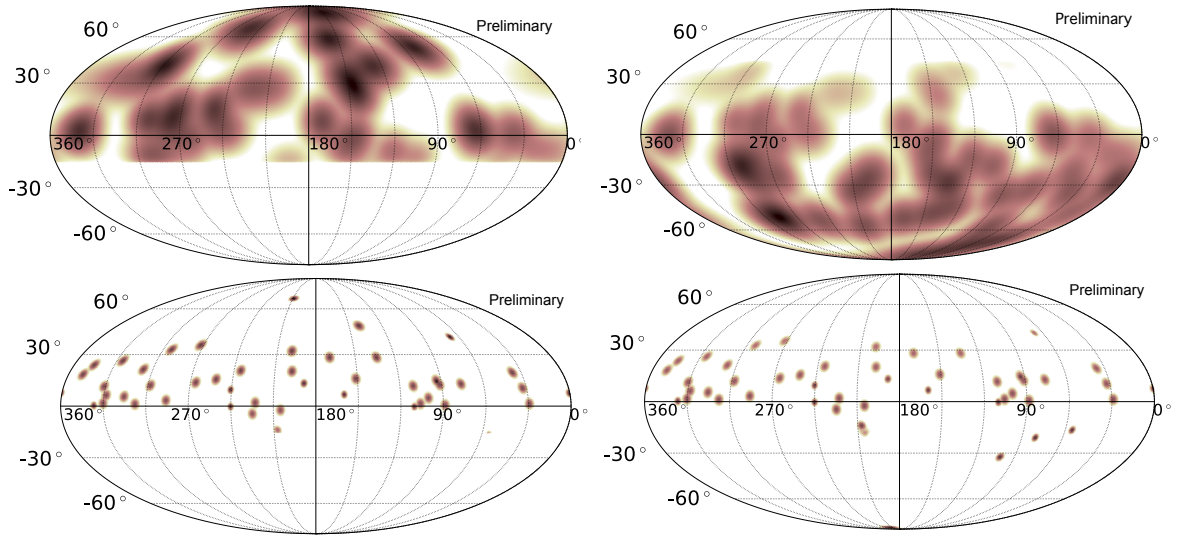
Figure 2: The signal PDFs before the Gaussian smearing in equatorial coordinates. The upper plots are for the high-energy cascades, while the lower ones are for the high-energy tracks. The declination-dependent exposure is applied for Auger in the right-hand plots and for TA in the left-hand plots.
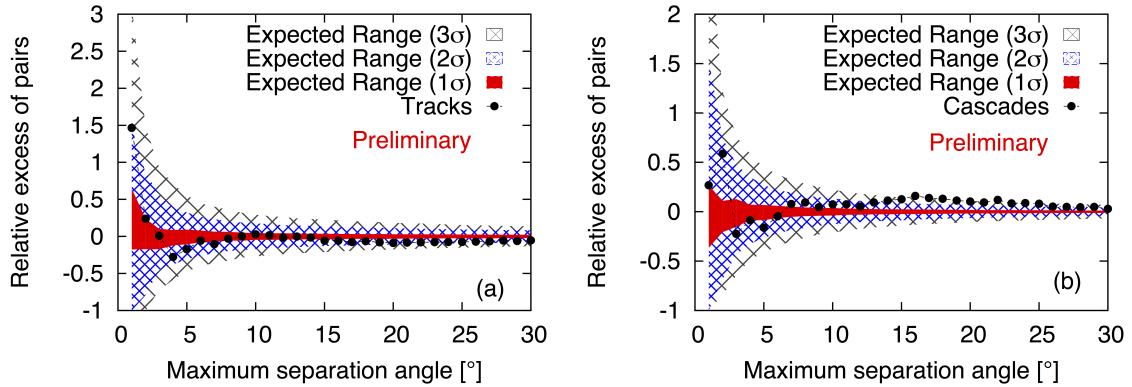

Figure 3: Relative excess of pairs, $[n_p(\alpha)/\langle n_p^{iso}(\alpha)\rangle] - 1$, as a function of the maximum angular separation between the neutrino and UHECR pairs, for the analysis done with the high-energy tracks (left) and with the high-energy cascades (right). The 1σ, 2σ and 3σ fluctuations expected from an isotropic distribution of arrival directions of CRs, keeping the arrival directions of the neutrinos fixed, are shown in red, blue and grey, respectively.

Unbinned likelihood method results

The results for the stacking method are shown in Table 1. The most significant deviation from an isotropic flux of CRs occurs for the magnetic deflection parameter $D = 6°$ with the high-energy cascades. The observed pre-trial p-value of 1.0×10^{-2} corresponds to 2.2×10^{-2} post-trial, by considering 1000 realizations of randomly distributed CRs with $6° \times 100\,\mathrm{EeV}/E_{CR}$ deviation from the neutrino source positions. The test maintaining the CR directions fixed while simulating an

D	High-energy tracks		High-energy cascades	
	n_s	pre-trial p-value	n_s	pre-trial p-value
3°	0.9	0.44	45.5	2.7×10^{-2}
6°	-	underfluctuation	71.5	1.0×10^{-2}
9°	-	underfluctuation	84.7	1.5×10^{-2}

Table 1: Results for the stacking analyses with the sample of high-energy tracks and high-energy cascades assuming an isotropic flux of CRs.

isotropic flux of neutrinos results in a post-trial p-value of 1.7×10^{-2} for shower-like events.

4. Discussion

In [1], post-trial p-values of 2.7×10^{-4} and 5×10^{-4} with respect to an isotropic flux of UHECRs were found using the unbinned likelihood method and the cross-correlation method, respectively. With the addition of two years of HESE shower-like events, the updated p-values do not strengthen the hint of a possible anisotropic distribution of UHECRs and neutrinos previously found. Similarly, the computation of the p-values, assuming an isotropic flux of neutrinos while keeping the UHECR directions fixed, resulted in p-values which are less significant than those found in [1]. To illustrate the results found in this update, the UHECRs weights assuming $D = 6°$ and contributing to the signal PDF derived from equation 2.1 are shown in Figure 4 on top the neutrino directional maps in the exposures of the Auger Observatory and TA. Local clustering in the directions illustrate the $\sim 2.3\sigma$ level correlation found.

It is noteworthy that this result can be explained by many facts. First, the not-yet-exhaustive knowledge of the CRs composition at such high energies and the poor knowledge of the Galactic magnetic field are the main limitations to the determination of the cosmic-ray sources using UHECRs. As already noted in [1], UHECRs can reach us from sources within the GZK horizon, meaning order of 10-100 Mpc. On the other hand, neutrinos can reach us from cosmological distances, so that if sources were stationary and uniformly distributed, only a few percent of neutrinos would be expected from the emitters of the detected UHECRs. Many speculations on the possible sources of the 4-year HESE sample still have not yet reached the significance of an evidence. The addition of two more years requires further correlation tests with various hypotheses of source candidates. It is also possible that there could be a contribution from galactic sources to the observed cosmic neutrino flux which would not be UHECR sources.

The future evolution of this search will concern the treatment of the magnetic deflection with updated models, the addition of updated data samples from the Pierre Auger Observatory and the cross-correlation with a sample of neutrinos of lower energy by IceCube and ANTARES.

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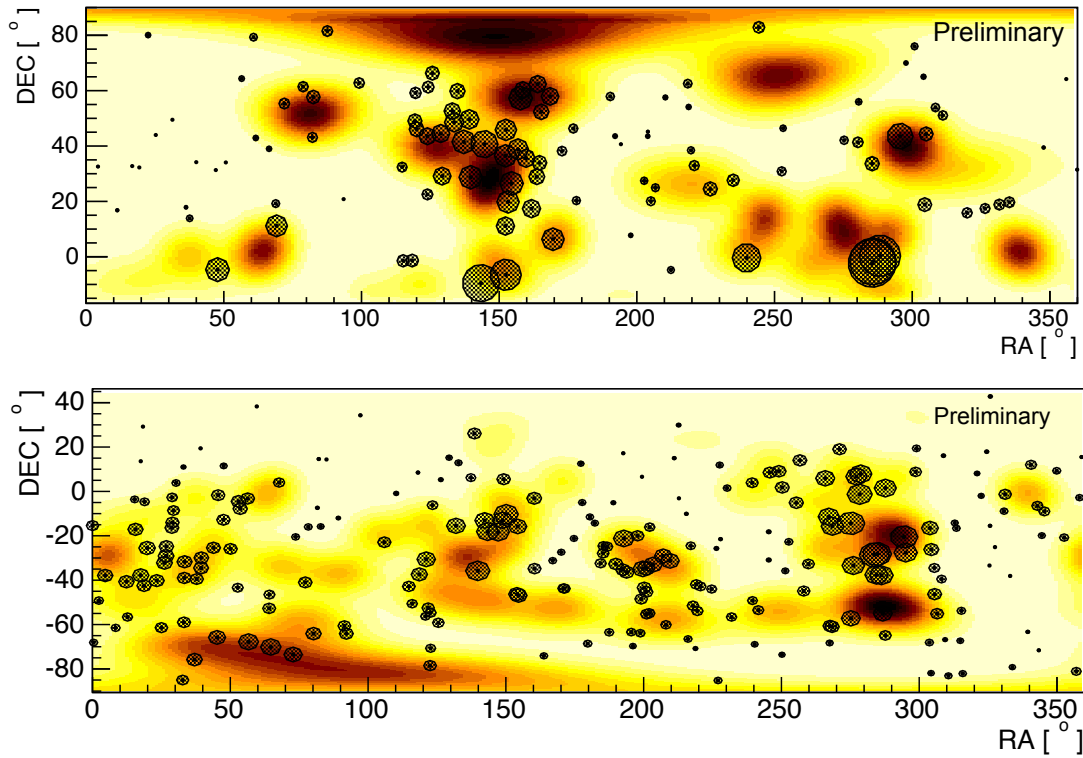
Figure 4: Neutrino signal PDF in the Telescope Array (top) and the Pierre Auger Observatory (bottom) exposures. The black dots represent the UHECRs directions. The black dashed circles radii are proportional to the weight assigned to each UHECR.

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