Search for time and space correlations between ANTARES data and IceCube high energy neutrino events

G. Illuminati[1], A. Coleiro[1,2], on behalf of the ANTARES Collaboration

[1]Instituto de Física Corpuscular - Universitat de València / CSIC
[2]APC, Universite Paris Diderot, CNRS/IN2P3, CEA/IRFU

- A high-energy neutrino diffuse flux of cosmic origin has been observed with the IceCube telescope [1], the sources of which still have to be identified.
- Two of the neutrino events from the high-energy starting events sample (HESE) occurred within 1 day of each other with a p-value of 1.6% [2], which could be interpreted as the signature of a possible flaring emission.
- **The ANTARES data-set is scanned to look for time and space correlation with 54 IceCube neutrino candidates** selected from two high energy samples, treating each IceCube event as a potential transient neutrino source.

A maximum likelihood estimation is performed to identify clusters of cosmic neutrinos over the background of randomly distributed atmospheric neutrinos.

$$\log \mathcal{L}_{\mathrm{s+b}} = \sum_{\mathcal{J}\in\{tr,sh\}} \sum_{i\in\mathcal{J}} \log\left[\mu_{sig}^{\mathcal{J}}\mathcal{S}_i^{\mathcal{J}} + \mathcal{N}^{\mathcal{J}}\mathcal{B}_i^{\mathcal{J}}\right] - \mu_{sig},$$

- $\mathcal{S}_i^{\mathcal{J}}$ and $\mathcal{B}_i^{\mathcal{J}}$: signal and background PDFs for the event i in the sample $\mathcal{J}$ (tr for tracks, sh for showers).
- $\mu_{sig}^{\mathcal{J}}$ and $\mathcal{N}^{\mathcal{J}}$: number of unknown signal events and total number of data events in the $\mathcal{J}$ sample.
- The combined information of three parameters – **direction**, **energy** and **observation time** – is included in the definition of the PDFs.
- A generic **Gaussian shape** is **assumed for the signal time-dependent PDF**, with mean value being the observation time of the IceCube candidate, and sigma the unknown flare duration σ_t.
- The likelihood is maximised with respect to four parameters: the **number of signal events μ_{sig}**, the **flare duration σ_{t}**, the **signal spectral index γ** and the **position of the fitted source**.

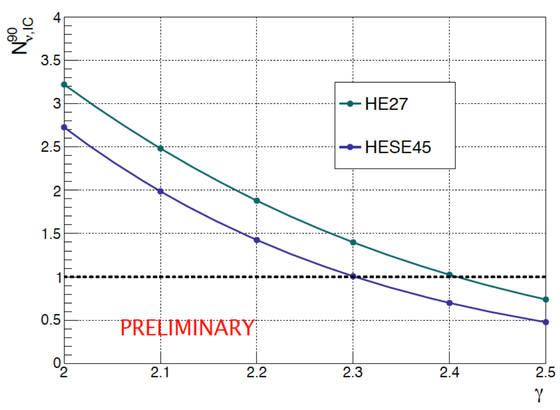
- No excess over the expected background is observed.
- Investigated candidate with the largest excess: HE15 (89% post-trial significance).
- Best-fit flare duration $\hat{\sigma}_t$ for the investigated IceCube events consistent with a positive fluctuation in fitted number of signal events:

HESE ID	$\hat{\sigma}_t[days]$	HESE ID	$\hat{\sigma}_t[days]$
3	≥ 120	44	≥ 120
5	≥ 120	45	66.3
8	≥ 120	53	≥ 120
13	≥ 120	58	18.5
23	≥ 120	63	66.6
28	≥ 120	71	≥ 120
43	25.9		

HE ID	$\hat{\sigma}_t[days]$	HE ID	$\hat{\sigma}_t[days]$
2	≥ 120	18	≥ 120
3	≥ 120	19	≥ 120
6	≥ 120	22	87.2
7	≥ 120	23	≥ 120
8	≥ 120	24	20.1
9	≥ 120	26	≥ 120
10	25.9	28	≥ 120
14	81.1	30	113.9
15	≥ 120	32	≥ 120
17	≥ 120	35	≥ 120

The non-observation of time correlation within a time window ≤ 0.1 days is translated into a limit on the number of ANTARES events in time correlation with an IceCube HESE/HE candidate equal to $n^{U.L.} = 2.3$ (assuming Poisson statistics), which can be converted into a limit on the neutrino fluence normalization for different spectral indices $\Phi_\gamma^{U.L.}$. From this, the 90% C.L. upper limit on the number of signal events expected to be observed by IceCube from a neutrino fluence $\Phi_\gamma^{U.L.}E^{-\gamma}$ is calculated as: $N_{\nu,IC}^{90} = \int \Phi_\gamma^{U.L.} \cdot A_{eff}^{IC} \cdot E^{-\gamma} dE$ with A_{eff}^{IC} being the IceCube effective area.

The limits are shown for the two most energetic IceCube events of each sample. **Where $\mathbf{N_{\nu,IC}^{90}}$ is less than 1 (number of observed events), a transient origin with flare duration ≤ 0.1 days can be excluded at 90% C.L..**

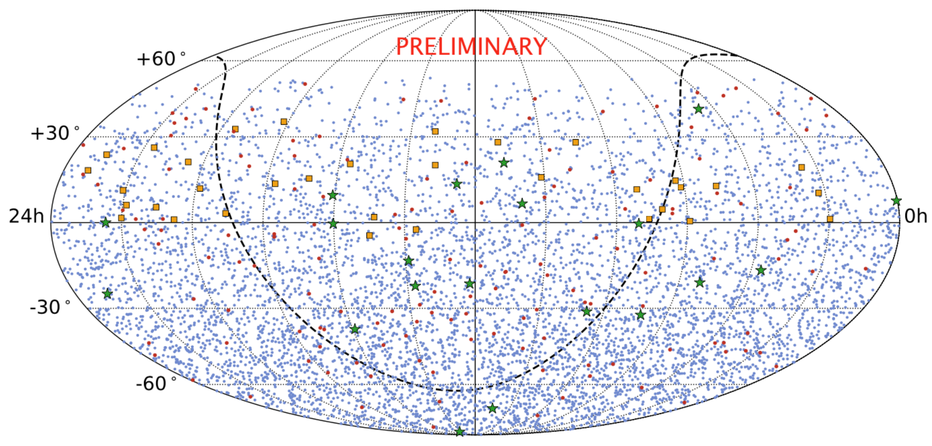


Only IceCube events classified as muon tracks, within the ANTARES field of view are included in the candidate list:

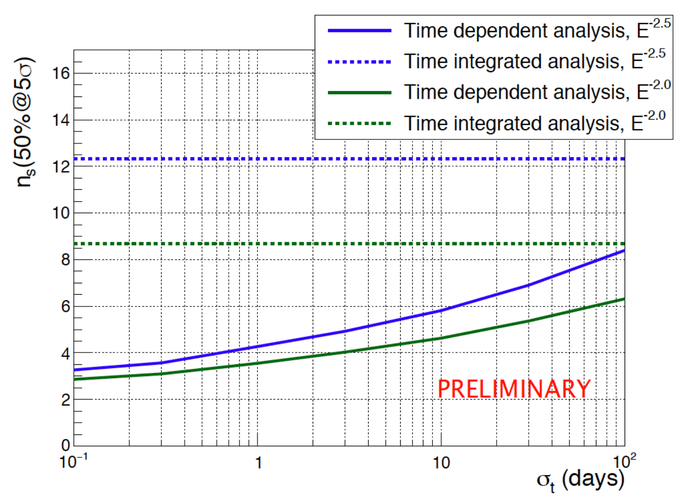
- **20** neutrino events from the HESE sample [1][3][4] (green stars).
- **34** neutrino events from charged current ν_μ from the Northern Hemisphere sample (HE) [5][6] (yellow squares).

ANTARES data sample:

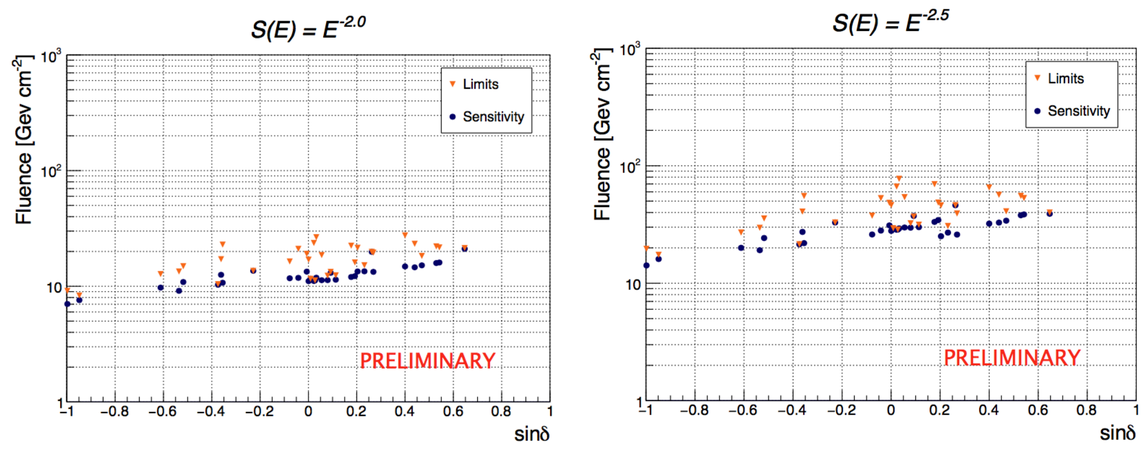
- events recorded between April 2009 and August 2016 (2157 days livetime) in order to overlap the IceCube events observation time and allow the search for flares lasting up to four months.
- **6310** track-like events (blue circles), **147** shower-like events (magenta circles).



When dealing with transient emissions, the background of atmospheric neutrinos can be significantly reduced by limiting the search to a small time window around source flares. When emission durations of a few hours are considered, **only about one third or less of the events needed in a time integrated analysis is necessary for a 5σ significant detection**, depending on the assumed signal energy spectrum: $S(E) = E^{-2.0}$ or $S(E) = E^{-2.5}$.



Upper limits at 90 % C.L. on the fluence (orange triangles) and sensitivity (blue dots) calculated for the time windows reported in the tables (hence only for sources consistent with a positive fluctuation in fitted number of signal events) for two assumptions of the signal energy spectrum: $S(E) = E^{-2.0}$ and $S(E) = E^{-2.5}$.



[1] Phys. Rev. Lett., 113 (2014) 101101
[2] Phys.Rev. D, 90 (2014) no.6, 063012
[3] PoS ICRC2015, 2016 (1081)
[4] PoS ICRC2017, 2017 (981)
[5] Astrophys. J., 833 (2016) no.1, 3
[6] PoS ICRC2017, 2017 (1005)

We gratefully acknowledge the financial support of Ministerio de Economía y Competitividad (MINECO): Plan Estatal de Investigación (ref. FPA2015-65150-C3-1-P), (MINECO/FEDER)), Severo Ochoa Centre of Excellence (MINECO), and Prometeo and Grisolía programs (Generalitat Valenciana), Spain.