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Search for neutrinos from the tidal disruption events AT2019dsg and AT2019fdr with the ANTARES telescope

A. Albert^{1,2}, S. Alves³, M. André⁴, M. Anghinolfi⁵, G. Anton⁶, M. Ardid⁷,
 J.-J. Aubert⁸, J. Aublin⁹, B. Baret⁹, S. Basa¹⁰, B. Belhorma¹¹,
 M. Bendahman^{9,12}, F. Benfenati^{21,27}, V. Bertin⁸, S. Biagi¹³, M. Bissinger⁶,
 J. Boumaaza¹², M. Bouta¹⁴, M.C. Bouwhuis¹⁵, H. Brânzaş¹⁶, R. Bruijn^{15,17},
 J. Brunner⁸, J. Busto⁸, B. Caiffi⁵, A. Capone^{18,19}, L. Caramete¹⁶, J. Carr⁸,
 V. Carretero³, S. Celli^{18,19}, M. Chabab²⁰, T. N. Chau⁹, R. Cherkaoui El
 Moursli¹², T. Chiarusi²¹, M. Circella²², A. Coleiro⁹, M. Colomer-Molla^{9,3},
 R. Coniglione¹³, P. Coyle⁸, A. Creusot⁹, A. F. Díaz²³, G. de Wasseige⁹,
 A. Deschamps²⁴, C. Distefano¹³, I. Di Palma^{18,19}, A. Domi^{5,25}, C. Donzaud^{9,26},
 D. Dornic⁸, D. Drouhin^{1,2}, T. Eberl⁶, T. van Eeden¹⁵, N. El Khayati¹²,
 A. Enzenhöfer⁸, P. Fermani^{18,19}, G. Ferrara¹³, F. Filippini^{21,27}, L. Fusco⁸,
 R. García¹⁵, Y. Gatelet⁹, P. Gay^{28,9}, H. Glotin²⁹, R. Gozzini⁶, K. Graf⁶,
 C. Guidi^{5,25}, S. Hallmann⁶, H. van Haren³⁰, A.J. Heijboer¹⁵, Y. Hello²⁴, J.J.
 Hernández-Rey³, J. Höfl⁶, J. Hofestädt⁶, F. Huang¹, G. Illuminati^{*21,27,9},
 C. W. James³¹, B. Jisse-Jung¹⁵, M. de Jong^{15,32}, P. de Jong¹⁵, M. Jongen¹⁵,
 M. Kadler³³, O. Kalekin⁶, U. Katz⁶, N.R. Khan-Chowdhury³, A. Kouchner⁹,
 I. Kreykenbohm³⁴, V. Kulikovskiy⁵, R. Lahmann⁶, R. Le Breton⁹, D. Lefèvre³⁵,
 E. Leonora³⁶, G. Levi^{21,27}, M. Lincetto⁸, D. Lopez-Coto³⁷, S. Loucatos^{38,9},
 L. Maderer⁹, J. Manczak³, M. Marcelin¹⁰, A. Margiotta^{21,27}, A. Marinelli³⁹,
 J.A. Martínez-Mora⁷, K. Melis^{15,17}, P. Migliozzi³⁹, M. Moser⁶, A. Moussa¹⁴,
 R. Muller¹⁵, L. Nauta¹⁵, S. Navas³⁷, E. Nezri¹⁰, B. Ó Fearraigh¹⁵, M. Organokov¹,
 G.E. Pávlaş¹⁶, C. Pellegrino^{21,40,41}, M. Perrin-Terrin⁸, P. Piattelli¹³, C. Pieterse³,
 C. Poiré⁷, V. Popa¹⁶, T. Pradier¹, N. Randazzo³⁶, S. Reck⁶, G. Riccobene¹³,
 A. Romanov⁵, F. Salesa Greus³, D. F. E. Samtleben^{15,32}, A. Sánchez-Losa²²,
 M. Sanguineti^{5,25}, P. Sapienza¹³, J. Schnabel⁶, J. Schumann⁶, F. Schüssler³⁸,
 M. Spurio^{21,27}, Th. Stolarczyk³⁸, M. Taiuti^{5,25}, Y. Tayalati¹², S.J. Tingay³¹,
 B. Vallage^{38,9}, V. Van Elewyck^{9,42}, F. Versari^{21,27,9}, S. Viola¹³, D. Vivolo^{39,43},
 J. Wilms³⁴, S. Zavatarelli⁵, A. Zegarelli^{18,19}, J.D. Zornoza³, and J. Zúñiga³

(ANTARES Collaboration)

¹Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

²Université de Haute Alsace, F-68200 Mulhouse, France

³IFIC - Instituto de Física Corpuscular (CSIC - Universitat de València) c/ Catedrático José Beltrán, 2 E-46980 Paterna, Valencia, Spain

⁴Technical University of Catalonia, Laboratory of Applied Bioacoustics, Rambla Exposició, 08800 Vilanova i la Geltrú, Barcelona, Spain

⁵INFN - Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy

⁶Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany

- ⁷Institut d'Investigació per a la Gestió Integrada de les Zones Costaneres (IGIC) - Universitat Politècnica de València, C/ Paranimf 1, 46730 Gandia, Spain
- ⁸Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
- ⁹Université de Paris, CNRS, Astroparticule et Cosmologie, F-75006 Paris, France
- ¹⁰Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France
- ¹¹National Center for Energy Sciences and Nuclear Techniques, B.P.1382, R. P.10001 Rabat, Morocco
- ¹²University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000
- ¹³INFN - Laboratori Nazionali del Sud (LNS), Via S. Sofia 62, 95123 Catania, Italy
- ¹⁴University Mohammed I, Laboratory of Physics of Matter and Radiations, B.P.717, Oujda 6000, Morocco
- ¹⁵Nikhef, Science Park, Amsterdam, The Netherlands
- ¹⁶Institute of Space Science, RO-077125 Bucharest, Măgurele, Romania
- ¹⁷Universiteit van Amsterdam, Instituut voor Hoge-Energie Fysica, Science Park 105, 1098 XG Amsterdam, The Netherlands
- ¹⁸INFN - Sezione di Roma, P.le Aldo Moro 2, 00185 Roma, Italy
- ¹⁹Dipartimento di Fisica dell'Università La Sapienza, P.le Aldo Moro 2, 00185 Roma, Italy
- ²⁰LPHEA, Faculty of Science - Semlali, Cadi Ayyad University, P.O.B. 2390, Marrakech, Morocco.
- ²¹INFN - Sezione di Bologna, Viale Berti-Pichat 6/2, 40127 Bologna, Italy
- ²²INFN - Sezione di Bari, Via E. Orabona 4, 70126 Bari, Italy
- ²³Department of Computer Architecture and Technology/CITIC, University of Granada, 18071 Granada, Spain
- ²⁴Géozur, UCA, CNRS, IRD, Observatoire de la Côte d'Azur, Sophia Antipolis, France
- ²⁵Dipartimento di Fisica dell'Università, Via Dodecaneso 33, 16146 Genova, Italy
- ²⁶Université Paris-Sud, 91405 Orsay Cedex, France
- ²⁷Dipartimento di Fisica e Astronomia dell'Università, Viale Berti Pichat 6/2, 40127 Bologna, Italy
- ²⁸Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, BP 10448, F-63000 Clermont-Ferrand, France
- ²⁹LIS, UMR Université de Toulon, Aix Marseille Université, CNRS, 83041 Toulon, France
- ³⁰Royal Netherlands Institute for Sea Research (NIOZ), Landsdiep 4, 1797 SZ 't Horntje (Texel), the Netherlands
- ³¹International Centre for Radio Astronomy Research - Curtin University, Bentley, WA 6102, Australia
- ³²Huygens-Kamerlingh Onnes Laboratorium, Universiteit Leiden, The Netherlands
- ³³Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Emil-Fischer Str. 31, 97074 Würzburg, Germany
- ³⁴Dr. Reimis-Sternwarte and ECAP, Friedrich-Alexander-Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany
- ³⁵Mediterranean Institute of Oceanography (MIO), Aix-Marseille University, 13288, Marseille, Cedex 9, France; Université du Sud Toulon-Var, CNRS-INSU/IRD UM 110, 83957, La Garde Cedex, France
- ³⁶INFN - Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy
- ³⁷Dpto. de Física Teórica y del Cosmos & C.A.F.P.E., University of Granada, 18071 Granada, Spain
- ³⁸IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
- ³⁹INFN - Sezione di Napoli, Via Cintia 80126 Napoli, Italy
- ⁴⁰Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Piazza del Viminale 1, 00184, Roma
- ⁴¹INFN - CNAF, Viale C. Berti Pichat 6/2, 40127, Bologna
- ⁴²Institut Universitaire de France, 75005 Paris, France
- ⁴³Dipartimento di Fisica dell'Università Federico II di Napoli, Via Cintia 80126, Napoli, Italy

Abstract

On October 1, 2019, the IceCube Collaboration detected a muon track neutrino with high probability of being of astrophysical origin, IC191001A. After a few hours, the tidal disruption event (TDE) AT2019dsg, observed by the Zwicky Transient Facility (ZTF), was indicated as the most likely counterpart of the IceCube track. More recently, the follow-up campaign of the IceCube alerts by ZTF suggested a second TDE, AT2019fdr, as a promising counterpart of another IceCube muon track candidate, IC200530A, detected on May 30, 2020. These are the second and third associations between astrophysical sources and high-energy neutrinos after the compelling identification of the blazar TXS 0506+056. Here, the search for ANTARES neutrinos from the directions of AT2019dsg and AT2019fdr using a time-integrated approach is presented. As no significant evidence for space clustering is found in the ANTARES data, upper limits on the one-flavour neutrino flux and fluence are set.

Introduction - High-energy cosmic neutrinos are a unique probe of the high-energy universe: their detection is critical to identify the acceleration sites of cosmic rays and to discover distant

*Corresponding author

sources otherwise inaccessible with γ -rays. Several milestones have been achieved in the field of neutrino astronomy in the past decade, which also opened new unresolved questions.

The IceCube Collaboration has detected an isotropic high-energy cosmic neutrino flux with a high level of significance in several diffuse flux searches [1, 2]. A mild excess, consistent with the IceCube findings, has been seen also in the ANTARES data [3]. However, the sources responsible for the diffuse cosmic signal have not been yet identified.

In 2017, a ~ 200 TeV IceCube muon neutrino was found positionally coincident with the direction of a known blazar in a flaring state, TXS 0506+056 [4, 5]. Soon after, the IceCube Collaboration reported a compelling evidence for an earlier neutrino flare from the same direction found in the archival data [6]. This led to the first association of high-energy neutrinos with an astrophysical source. However, the expected neutrino emission from the blazar TXS 0506+056 can only contribute to the IceCube cosmic neutrino flux for less than 1% [6]. The region around TXS 0506+056 was studied also by the ANTARES Collaboration, yielding no significant correlation in time and/or space with the IceCube neutrinos [7].

In 2020, a new likely association between an IceCube neutrino, IC191001A, and an astrophysical source, the tidal disruption event (TDE) AT2019dsg, was announced [8]. Soon after, a second TDE, ZTF19aatubsj/AT2019fdr, hereafter referred to as AT2019fdr, was found positionally coincident with another IceCube neutrino, IC200530A [9]. TDEs are rare transient phenomena that occur when a star passes close enough to a supermassive black hole and is disrupted by the strong tidal forces (for recent reviews see [10, 11]). The accretion process onto the black hole involves about half of the stellar mass and, in some cases, results in a relativistic jet. Consequently, both jetted and non-jetted TDEs are observed. Since TDEs show non-thermal radio emission, they have been suggested as promising sources of ultra-high energy cosmic rays and high-energy neutrinos (see [12] and references therein). Nonetheless, the contribution to the IceCube diffuse flux from the TDEs detected before AT2019dsg and AT2019fdr has been constrained to be at most $\sim 1.3\%$ ($\sim 26\%$) in the jetted (non-jetted) TDE case [13].

The detection of IC191001A, a ~ 200 TeV muon neutrino with 59% probability of being of astrophysical origin, registered by IceCube on October 1, 2019 [14, 15], triggered dedicated follow-ups by multiple telescopes, including the Zwicky Transient Facility (ZTF) [16, 17]. While several optical transients were found within the 90% localisation uncertainty of the neutrino direction (~ 26 deg²) by ZTF, the TDE AT2019dsg, being one of the few ever detected radio-emitting TDEs, was soon identified as the most promising candidate neutrino source [15, 8]. Analogously, IC200530A, a ~ 80 TeV muon neutrino with 59% probability of being of astrophysical origin, detected by IceCube on May 30, 2020 [14, 18], was followed by ZTF, which indicated AT2019fdr as the likely counterpart of the neutrino event [9].

AT2019dsg and AT2019fdr were first discovered by ZTF on April 9, 2019 [19] and on April 27, 2019 [20], respectively. The TDEs showed a luminosity peak in the optical/UV bands, and appeared to have reached a luminosity plateau by the time of the neutrino detections, which happened ~ 150 days and about one year after the peak, respectively [8, 20]. As detailed in [8], after the discovery, AT2019dsg was also detected in several follow-up observations in optical/UV, X-rays and radio, indicating particle acceleration to relativistic energies. The probability of finding by chance a radio-emitting TDE as bright as AT2019dsg in bolometric energy flux and in coincidence with the IceCube neutrino was estimated to be 0.2%. The expected neutrino flux from AT2019dsg has been calculated for different models of multi-messenger emission both in the jetted [21, 22] and non-jetted [23] TDE cases. The most optimistic scenarios predict a neutrino fluence of $\sim 10^{-2}$ GeV cm⁻².

In this letter, the ANTARES follow-up of these findings is presented. In particular, the ANTARES data collected since the discovery of AT2019dsg and AT2019fdr are investigated to look for a steady neutrino emission from the direction of the TDEs.

Detector and data sample - The ANTARES neutrino telescope [24] is a three-dimensional array of 885 photomultiplier tubes (PMTs) located 40 km off-shore from Toulon, France, below the surface of the Mediterranean Sea. The 10-inch PMTs are distributed along 12, 450 m long, vertical lines anchored to the sea-bed at a depth of about 2500 m and held taut by a buoy at the top, instrumenting a total volume of $\sim 0.01 \text{ km}^3$. The neutrino detection principle is based on the collection of the Cherenkov light induced by relativistic charged particles produced in neutrino interactions within and around the instrumented volume. The information provided by the position, time and collected charge of the signals in the PMTs is used to infer the direction and energy of the incident neutrino.

Different neutrino flavours and interactions leave distinct signatures in the detector. Two event topologies can be identified in the ANTARES telescope: tracks and showers. Tracks are originated by the passage in water of relativistic muons produced in charged current (CC) interactions of muon neutrinos. The long lever arm of the track topology allows to reconstruct the parent neutrino direction of high-quality selected events with a median angular resolution of 0.4° for energies above 100 TeV [25]. All-flavour neutral current (NC) as well as ν_e and ν_τ CC interactions induce showers, characterised by an almost spherical light emission around the shower maximum, with an elongation of a few metres. A median angular resolution of $\sim 3^\circ$ for high-quality selected events with energies between 1 TeV and 0.5 PeV is achieved for this topology [25].

The search for neutrinos from the direction of AT2019dsg (AT2019fdr) presented in this letter includes both track-like and shower-like events recorded in ANTARES from the day of the discovery of the TDE, 2019 April 9 (2019 April 27), until the day of the last available fully-calibrated ANTARES data, 2020 February 29, corresponding to a livetime of 315 (298) days. The track and shower events are selected using the criteria described in [25]. The selection is optimised to minimise the neutrino flux needed for a 5σ discovery of a point-like source emitting with an energy spectrum $\propto E_\nu^{-2.0}$. Cuts are applied on the zenith angle, the angular error estimate and parameters describing the quality of the reconstruction. In the shower channel, an additional cut is applied on the interaction vertex, required to be located within a fiducial volume slightly larger than the instrumented volume. A total of 413 (390) tracks and 8 (7) showers, resulting from the selection, are employed in the search for a cluster of events from the direction of AT2019dsg (AT2019fdr).

Search method - The location of AT2019dsg (RA = 314.26° , $\delta = 14.20^\circ$) and of AT2019fdr (RA = 257.28° , $\delta = 26.86^\circ$) has been investigated to search for spatial clustering of events above the known background expectation following an unbinned maximum likelihood ratio approach. The likelihood describes the ANTARES data in terms of signal and background probability density functions (PDFs) and is defined as:

$$\log \mathcal{L} = \sum_{\mathcal{J} \in \{tr, sh\}} \sum_{i \in \mathcal{J}} \log \left[\mu_{\text{sig}}^{\mathcal{J}} \mathcal{S}_i^{\mathcal{J}} + \mathcal{N}^{\mathcal{J}} \mathcal{B}_i^{\mathcal{J}} \right] - \mu_{\text{sig}}, \quad (1)$$

where $\mathcal{S}_i^{\mathcal{J}}$ and $\mathcal{B}_i^{\mathcal{J}}$ are the values of the signal and background PDFs for the event i in the sample \mathcal{J} (tr for tracks, sh for showers), $\mu_{\text{sig}}^{\mathcal{J}}$ and $\mathcal{N}^{\mathcal{J}}$ are respectively the number of unknown signal events and the total number of data events in the \mathcal{J} sample, and $\mu_{\text{sig}} = \mu_{\text{sig}}^{tr} + \mu_{\text{sig}}^{sh}$ is the total number of fitted signal events. The PDFs have been built using the 2007-2020 ANTARES data and Monte Carlo production in order to ensure sufficient statistics. The signal and background PDFs are given by the product of a directional and an energy-dependent term. While atmospheric neutrino events appear randomly distributed on the sky, neutrinos from point-like sources are

expected to accumulate around the source position. The energy information helps to distinguish signal from background, as a softer energy spectrum is predicted for atmospheric neutrinos with respect to the expected signal [26]. An unbroken power law neutrino spectrum, $\Phi_\nu(E_\nu) \propto E_\nu^{-\gamma}$, is assumed in this analysis for the signal emission, with γ being one of the three tested spectral indices, $\gamma = 2.0$, $\gamma = 2.5$, or $\gamma = 3.0$. The same definition of the PDFs used in the ANTARES 9-year point-source analysis [25] is employed in this search. The spatial signal PDF is a spline parametrisation of the point-spread function. It is defined as the PDF to reconstruct an event at a given angular distance from its original direction due to reconstruction uncertainties, and it is derived from Monte Carlo simulations of $\propto E_\nu^{-\gamma}$ cosmic neutrinos. The background is assumed to be uniform in right ascension, and the distribution of the sinus of the declination of the selected data is employed as spatial background PDF. Monte Carlo simulations of $\propto E_\nu^{-\gamma}$ energy spectrum cosmic neutrinos (signal) assuming neutrino flavour equipartition at Earth and of atmospheric neutrinos using the spectrum of [27] (background) are used to derive the energy PDFs. In the likelihood maximisation, the number of signal events, μ_{sig} , is the only free parameter. The test statistic, \mathcal{Q} , is defined from the likelihood as:

$$\mathcal{Q} = 2 \log \left[\frac{\mathcal{L}(\mu_{\text{sig}} = \hat{\mu}_{\text{sig}})}{\mathcal{L}(\mu_{\text{sig}} = 0)} \right], \quad (2)$$

where $\hat{\mu}_{\text{sig}}$ is the best-fit value that maximises the likelihood. The significance of the potential spatial cluster at the location of the TDE is estimated by means of pseudo-experiments (PEs) – pseudo-data sets of data randomised in time to eliminate any local clustering due to potential sources. The fraction of background-only PEs with a value of \mathcal{Q} larger than the one obtained with the data gives the significance (p-value) of the cluster.

The 5σ discovery potential of the search, $n^{5\sigma}$, is defined as the mean number of injected signal events needed for a 5σ discovery in 50% of the PEs. The obtained values are $n^{5\sigma} = 3.6$ and $n^{5\sigma} = 3.4$ for AT2019dsg and AT2019fdr, respectively, assuming an $E_\nu^{-2.0}$ neutrino spectrum, while $\sim 40\%$ more events are needed for the softer spectrum $E_\nu^{-3.0}$.

Results - Figure 1 shows the distribution of the ANTARES events close to the location of the sources. In both cases, only one event has been detected within 5° from the TDE. The event close to AT2019dsg (AT2019fdr) is a track-like event, located at a distance of 1.7° (2.3°) from the source, and was registered on February 11, 2020 (September 25, 2019). The information on the two events is reported in Table 1.

Table 1: ANTARES event within an angular distance $\Delta\Psi < 5^\circ$ from AT2019dsg (first row) and AT2019fdr (second row). For each ANTARES event, the table reports the topology, equatorial coordinates (RA, δ), angular distance $\Delta\Psi$ from the TDE, Modified Julian Date (MJD), date (dd/mm/year), and fraction f of selected data events with energy estimator values larger than that of the event.

Source	topology	(RA, δ) deg	$\Delta\Psi$ deg	MJD	date dd/mm/year	f
AT2019dsg	track	(315.8, 13.4)	1.7	58890.99	11/02/2020	0.35
AT2019fdr	track	(259.6, 27.8)	2.3	58751.08	25/09/2019	0.15

The likelihood method fits less than one signal event at the direction of both TDEs for the three tested values of the spectral index $\gamma = 2.0$, $\gamma = 2.5$, and $\gamma = 3.0$. At the location of

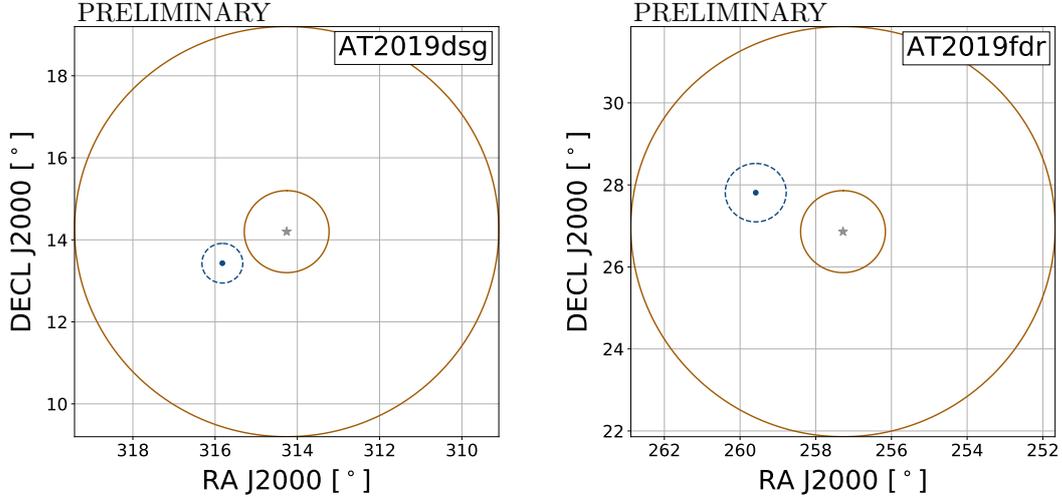


Figure 1: Distribution of ANTARES events in equatorial coordinates around the position of AT2019dsg (left) and AT2019fdr (right). The orange lines depict the one and five degree distance from the source position, indicated as a grey star. Only track-like events (blue points) have been detected within 5° from the location of the sources. The dashed circles around the events indicate the angular error estimate on the track reconstructed direction.

AT2019dsg, the largest deviation from the background expectation is obtained for an $E_\nu^{-3.0}$ spectrum, with a number of fitted signal events $\hat{\mu}_{\text{sig}} = 0.7$ and a p-value of 8.9% corresponding to 1.3σ significance (in the one-sided convention). The lowest p-value (6.7%) at the location of AT2019fdr is observed for an $E_\nu^{-2.0}$ spectrum, with a number of fitted signal events $\hat{\mu}_{\text{sig}} = 0.5$, yielding a significance of 1.5σ (in the one-sided convention).

Table 2 summarises the results of the searches in terms of best-fit number of signal events and p-value, and reports the upper limits on the one-flavour neutrino flux normalisation, Φ_0 , for three values of γ , where the neutrino flux has been parameterised as $\Phi_\nu = \Phi_0 \left(\frac{E_\nu}{1 \text{ GeV}}\right)^{-\gamma}$. Moreover, upper limits are set on the one-flavour neutrino fluence, \mathcal{F} , defined as the integral in time and energy of the neutrino energy flux:

$$\mathcal{F} = \int_{t_{\text{min}}}^{t_{\text{max}}} \int_{E_{\text{min}}}^{E_{\text{max}}} E_\nu \cdot \Phi_\nu dE_\nu dt = \Delta t \cdot \Phi_0 \cdot \int_{E_{\text{min}}}^{E_{\text{max}}} E_\nu \cdot \left(\frac{E_\nu}{1 \text{ GeV}}\right)^{-\gamma} dE_\nu, \quad (3)$$

where E_{min} and E_{max} are the boundaries of the energy range containing 90% of the expected signal events for the given γ , and Δt is the livetime of the search.

The absence of any significant detection of neutrinos from AT2019dsg is consistent with all proposed emission models for the TDE, being their predictions much below the ANTARES neutrino detection threshold [21, 22, 23]. The expected neutrino fluence resulting from those models is too low to be constrained by the upper limits set in this analysis.

Conclusions - The ANTARES follow-up of AT2019dsg and AT2019fdr, the TDEs recently indicated as the most likely counterparts of two high-energy IceCube neutrinos, IC191001A and

Table 2: Results of the search at the location of AT2019dsg and AT2019fdr in terms of best-fit number of signal events $\hat{\mu}_{\text{sig}}$, p-value, 90% C.L. sensitivity and upper limits on the one-flavour neutrino flux normalisation $\Phi_0^{90\% \text{C.L.}}$ (in units of $\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$), and on the one-flavour neutrino fluence $\mathcal{F}^{90\% \text{C.L.}}$ (in units of GeVcm^{-2}), for different values of the spectral index γ . The boundaries, E_{min} and E_{max} , of the energy range containing 90% of the expected signal events, employed in the calculation of the fluence, are listed in the last column.

Source		Results						
Name	γ	$\hat{\mu}_{\text{sig}}$	p-value	$\Phi_0^{90\% \text{C.L.}}$		$\mathcal{F}^{90\% \text{C.L.}}$		$\log(\frac{E_{\text{min}}}{\text{GeV}}) - \log(\frac{E_{\text{max}}}{\text{GeV}})$
				sensitivity	limit	sensitivity	limit	
AT2019dsg	2.0	< 0.1	12.4%	7.3×10^{-8}	1.0×10^{-7}	14	19	3.6 - 6.6
	2.5	0.2	10.2%	1.5×10^{-5}	2.2×10^{-5}	29	43	2.8 - 5.5
	3.0	0.7	8.9%	1.2×10^{-3}	2.0×10^{-3}	230	380	2.1 - 4.7
AT2019fdr	2.0	0.5	6.7%	8.5×10^{-8}	1.3×10^{-7}	15	23	3.6 - 6.6
	2.5	0.5	7.9%	2.1×10^{-5}	3.0×10^{-5}	39	55	2.8 - 5.5
	3.0	0.6	9.1%	2.0×10^{-3}	3.0×10^{-3}	360	540	2.1 - 4.7

IC200530A, has been presented. The ANTARES data collected since the discovery of AT2019dsg and AT2019fdr have been investigated to look for a steady neutrino emission from the direction of the TDEs, resulting in no evidence for signal in the data. Given the non-detection, 90% C.L. upper limits on the one-flavour neutrino flux and fluence have been set. Recent models proposed to explain the multi-messenger observations from AT2019dsg predict a neutrino emission well below the ANTARES sensitivity and can not thus be constrained by the upper limits set in this analysis. Nevertheless, alternative search methods such as stacking and time-dependent analyses will provide an effective way to enhance the discovery potential using the existing data. Moreover, a significant improvement in sensitivity is expected from the upcoming next generation neutrino telescope, KM3NeT [28], thanks to its larger effective area combined with an excellent angular resolution [29].

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