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Candidate Tidal Disruption Event AT2019fdr Coincident with a High-Energy Neutrino

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The origins of the high-energy cosmic neutrino flux remain largely unknown. Recently, one high-energy neutrino was associated with a tidal disruption event (TDE). Here we present AT2019fdr, an exceptionally luminous TDE candidate, coincident with another high-energy neutrino. Our observations, including a bright dust echo and soft late-time x-ray emission, further support a TDE origin of this flare. The probability of finding two such bright events by chance is just 0.034%. We evaluate several models for neutrino production and show that AT2019fdr is capable of producing the observed high-energy neutrino, reinforcing the case for TDEs as neutrino sources.

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Se encuentra en una encrucijada

Neutrino astronomy is at a crossroads: While a flux of high-energy cosmic neutrinos has been firmly established through observations with the IceCube Neutrino Observatory [1–4], identifying their sources has been a challenge. The emission of cosmic neutrinos is a smoking-gun signature for hadronic acceleration (see Ref. [5] for a recent review), and discovering their sources will allow us to resolve long-standing questions about the production sites of high-energy cosmic rays.

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donde aceleran

Three sources have thus far been associated with neutrinos at post-trial significance of $\approx 3\sigma$, which can be considered evidence for a true association [6]. In 2017, the flaring blazar TXS $0506+056$ was identified as the likely source of neutrino alert IC170922A [7]. This same source was also associated with a neutrino flare in 2014–2015 [8], occurring during a period without significant electromagnetic flaring activity [9]. In 2019, the tidal disruption event (TDE) AT2019dsg was identified as the likely source of IC191001A [10]. More recently, the IceCube Collaboration reported a clustering of neutrinos from the direction of the active galactic nucleus (AGN) in the nearby galaxy NGC 1068 [11]. AGN are galaxies with high levels of supermassive black hole (SMBH) accretion, and have been long proposed as high-energy neutrino sources [12–17]. These associations and other conceptual arguments suggest that the neutrino flux may arise from a mixture of different astrophysical populations [18–20], although AGN or another source class can still be dominant [21].

TDEs are rare transients that occur when stars pass close enough to SMBHs and get destroyed by tidal forces. The result of this destruction is a luminous electromagnetic flare with a timescale of ~months. Theoretical studies have suggested that TDEs might be sources of high-energy neutrinos and ultrahigh-energy cosmic rays [22–39]. Some models consider emission from a relativistic jet, while others propose additional neutrino production scenarios, e.g., in a disk, disk corona, or wind (see Refs. [36,40]). In the case of AT2019dsg, radio observations confirmed long-lived nonthermal emission from the source [10,41–44], but generally disfavor those models relying on the presence of an on-axis relativistic jet [35] in the standard leptonic radio emission scenario.

TDEs and AGN flares are ultimately both modes of SMBH accretion. Some models highlight this potential similarity, and have developed common frameworks for neutrino emission from both cases (see, e.g., Ref. [36]). However, AGN flares are vastly more numerous than TDEs, injecting significantly more energy into the Universe. If TDEs sin embargo nonetheless contribute significantly to the neutrino flux, they must be very efficient neutrino emitters. Whether there are particular characteristics of TDEs that enable efficient neutrino production, and whether these conditions are also present in particular classes of AGN accretion flares, remain open questions for neutrino astronomy.

Bridging these two astrophysical populations, we here report new observations of AT2019fdr, a candidate TDE in a Narrow-Line Seyfert 1 (NLSy1) active galaxy [45]. Similar to AT2019dsg, AT2019fdr was identified as a likely neutrino source by the neutrino follow-up program of the Zwicky Transient Facility (ZTF) [46–48]. AT2019fdr lies within the reported 90% localization region of the IceCube high-energy neutrino IC200530A [49]. The observations were processed by `nuztf`, our multimessenger analysis pipeline [50,51], which searches for extragalactic transients in spatial and temporal coincidence with high-energy neutrinos [10,52], and AT2019fdr was reported as a candidate [53].

AT2019fdr, a long-duration flare (see Fig. 1) of apparent nuclear origin, was first discovered by ZTF one year prior to the neutrino detection [45,54]. AT2019fdr reached a peak flux of 1.3×10^{-12} erg s^{-1} cm^{-2} in the optical ZTF g band on August 10, 2019, before slowly fading. With a peak g-band luminosity of $L_{\mathrm{peak}}=2.9\times10^{44}$ erg s^{-1}, AT2019fdr was an extraordinarily luminous event. At the time of neutrino detection, it had decayed to ~30% of its peak flux, and was still detected by ZTF as of August 2021. Forced photometry using data from ZTF (up to 400 days prior to the flare) as well as from the Palomar Transient Factory (2010–2016) [55] shows no historical variability.

AT2019fdr was classified as a probable TDE, though an extreme AGN flare origin could not be ruled out [45]. High-resolution spectra yielded a redshift of $z=0.267$. Using a spectrum from the Alhambra Faint Object Spectrograph and Camera (ALFOSC), on the Nordic Optical Telescope (NOT; PI: Sollerman), a virial black hole mass estimate of $M_{\mathrm{BH}}=10^{7.55\pm0.13}\,M_{\odot}$ was inferred; for further details refer to the Supplemental Material [57].

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Though the classification of AT2019fdr based on early observations included the possibility of it being a Type II superluminous supernova (SLSN-II, see Ref. [176]) [177], leading to further studies [178], its subsequent spectroscopic and photometric evolution was not consistent with expectations for SLSNe. Frederick *et al.* [45] already disfavored the SLSN hypothesis based on the long-lived U-band and the UV emission, the flare's longevity, emission at the blue end of the Balmer line profiles as well as its proximity to the nucleus of the galaxy. Here we add a late-time x-ray detection and the detection of a strong infrared echo, rendering a SLSN interpretation less likely (see below).

After discovery, AT2019fdr was also observed by the Ultraviolet and Optical Telescope (UVOT) [179] aboard the *Neil Gehrels Swift Observatory* (*Swift*) [45,180]. Additional observations continued up to June 7, 2020, including one epoch shortly after the neutrino detection. By that point, the transient had faded by 84% in the UVW1-band from its peak luminosity of 2.1×10^{44} erg s^{-1}. AT2019fdr was not detected in any of the simultaneous x-ray observations by the

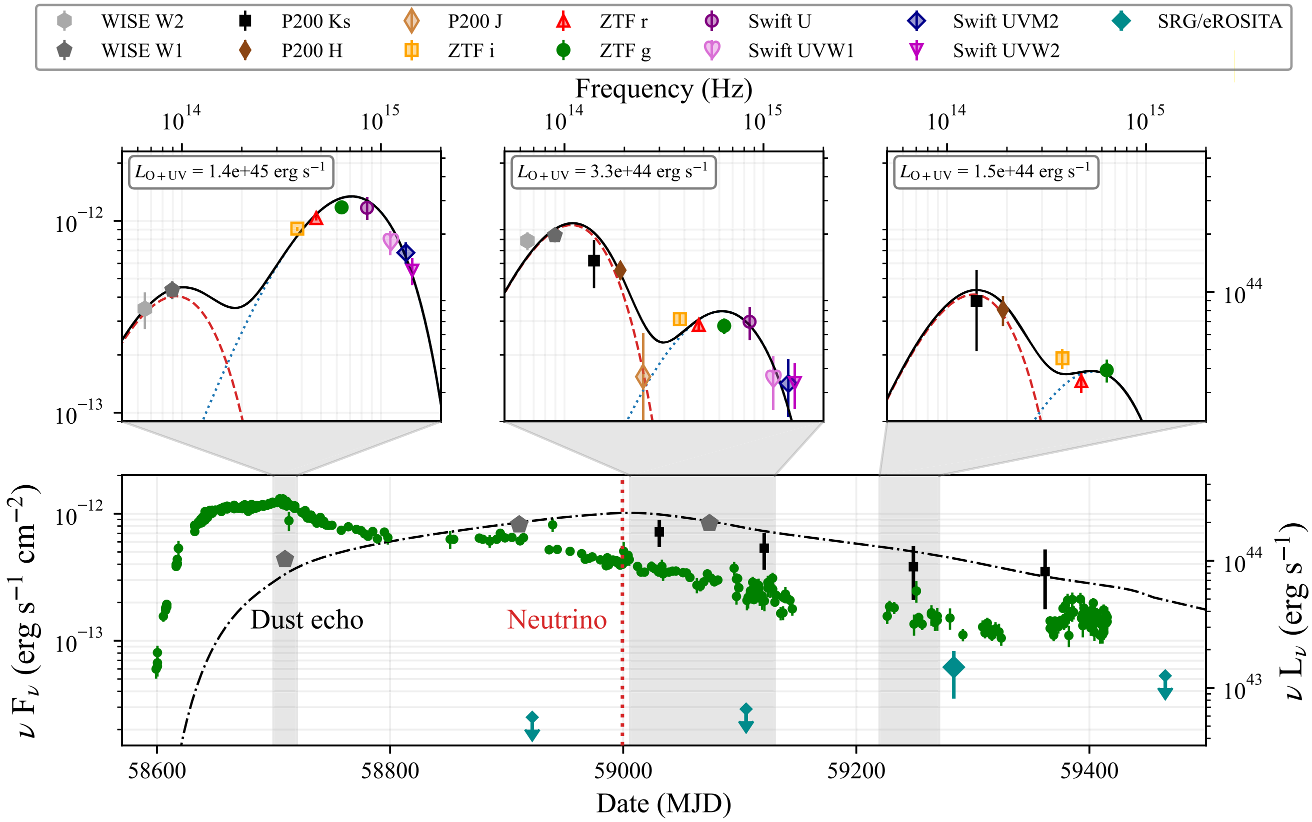

FIG. 1. The bottom plot shows the light curve in the optical ZTF g band, the infrared P200 Ks and *WISE* W1 band as well as the modeled dust echo (black line, dashdot), with the neutrino arrival time marked with a red dotted vertical line. The *SRG*/eROSITA x-ray measurements are also included. The shaded gray areas are averaged and their respective SEDs are shown in the top panels, including a fitted blue and a red blackbody (blue dashed and red dotted curve; lab frame), as well as the combined spectrum (black solid curve). The left axes all show νF_ν, where F_ν is the spectral flux density at frequency ν, while the right axes show νL_ν, where L_ν is the luminosity at frequency ν. Note: *SRG*/eROSITA data are given in units of integrated flux. The second epoch (middle plot on top) encompasses several months to include both *WISE* and P200 infrared data points. The global values for line-of-sight dust extinction are $A_V = 0.45^{+0.14}_{-0.14}$ mag, assuming $R_V = 3.1$ and the Calzetti attenuation law [56]. Note that the x-ray measurements were not included in the blackbody fits. The luminosities are given in the source rest frame.

Swift X-ray Telescope (XRT) [181], yielding a combined 3σ flux upper limit of 1.4×10^{-13} erg s^{-1} cm^{-2} for all observations before neutrino arrival (corrected for absorption).

The position of AT2019fdr was also visited by the eROSITA telescope [182] aboard the *Spectrum-Roentgen-Gamma* (*SRG*) mission [183] four times. The first two visits did not detect an excess, with a mean flux upper limit of 2.7×10^{-14} erg s^{-1} cm^{-2} at the 95% confidence level. However, at the third visit on March 10–11, 2021, it detected late time x-ray emission from the transient with an energy flux of $6.2^{+2.7}_{-2.1} \times 10^{-14}$ erg s^{-1} cm^{-2} in the 0.3–2.0 keV band, thus showing temporal evolution in the x-ray flux (see Fig. 1). The detection displayed a very soft thermal spectrum with a best fit blackbody temperature of 56^{+32}_{-26} eV.

The softness of the spectrum provides further evidence for AT2019fdr being a TDE rather than regular AGN variability, where soft spectra are rare [184]. Though NLSy1 galaxies generally exhibit softer x-ray spectra, the temperature of AT2019fdr is atypically low even in this context (lower than all NLSy1s in Refs. [185] and [186]). Furthermore, x-ray emission is rarely seen for SLSNe [187], with only the first SLSN ever observed, SCP 06F6 [188], possibly showing an x-ray flux exceeding the luminosity of AT2019fdr [189]. This provides more evidence against the SLSN classification.

AT2019fdr was further detected at midinfrared (MIR) wavelengths as part of routine NEOWISE survey observations [190] by the Wide-field Infrared Survey Explorer (*WISE*) [191]. Using pre-flare archival NEOWISE data as baseline, a substantial flux increase was detected in both W1 and W2 band. MIR emission reached a peak luminosity of 1.9×10^{44} erg s^{-1} on August 13, 2020, over one year after the optical and UV peak. Complementary near-infrared (NIR) measurements were taken with the P200 wide field infrared camera (WIRC) [192] in the J, H, and Ks band. After subtracting a synthetic host model (see Supplemental Material [57]), a fading transient infrared signal was detected in all three bands; see Fig. 1.

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We modeled this light curve as a composite of two unmodified blackbodies (a "blue" and a "red" blackbody). We interpret the time-delayed infrared emission as a dust echo: The blue blackbody heats surrounding dust, which then starts to glow. The light curve of this dust echo was inferred using the method described in Ref. [193] and the corresponding fit is shown in Fig. 1. An optical or UV bolometric luminosity of $L = 1.4^{+0.1}_{-0.1} \times 10^{45}$ erg s^{-1} at peak was derived. By integrating this component over time, we derived a total bolometric energy of $E_{\rm bol} = 3.4 \times 10^{52}$ erg (the red blackbody was not added, as dust absorption is already accounted for through the extinction correction). This is almost twice the inferred bolometric energy of ASASSN-15lh, which was one of the brightest transients ever reported [194] and was suggested to be a TDE [195]. Furthermore, the energy budget, bolometric evolution, and luminous dust echo suggest that AT2019fdr belongs to a class of TDE candidates observed in AGN (similar to PS1-10adi [196], AT2017gbl [197] or Arp 299-B AT1 [198]). For details on the modeling methods, see Supplemental Material [57].

Following the neutrino detection, we performed radio observations of AT2019fdr with a dedicated Very Large Array (VLA) [199] director's discretionary time (DDT) program three times over a period of four months, and obtained multifrequency detections. AT2019fdr shows a featureless power law spectrum consistent with optically thin synchrotron emission above ∼1 GHz with no significant intrinsic evolution between the epochs (see Supplemental Material [57]). The peak flux density was 0.39 ± 0.03 mJy in the 1–2 GHz band. The lack of apparent evolution suggests that the radio emission is not related to the transient, but rather originated from the AGN host. An additional subdominant transient component could be present.

No γ rays were detected by the *Fermi* large area telescope (*Fermi*-LAT) [200] between the first detection of AT2019fdr and one year after neutrino detection, yielding an upper limit of 1.3×10^{-12} erg s^{-1} cm^{-2} (see Ref. [201]).

AT2019fdr is the second probable neutrino-TDE association found by ZTF. To calculate the probability of finding two such coincident events by chance, while accounting for the fact that some TDEs will not be spectroscopically classified, we developed a broader sample of photometrically selected "candidate TDEs." We selected "nuclear" transients that are at least as bright as AT2019fdr from the sample of ZTF transients, and applied cuts to identify TDE-like rise times and decay times (see Supplemental Material [57] and Ref. [201] for details). Our sample begins in 2018 (the ZTF survey start), and we further required a flare peak date before July 2020. We excluded only transients for which a TDE origin was ruled out through spectroscopic classification (i.e., our sample contains all unclassified candidates and all classified TDEs). To compute the sky source density at any given time, we conservatively estimated their average lifetime at 1 yr after discovery, yielding an effective source density of 1.7×10^{-4} per deg^2 of sky in the ZTF footprint (most TDEs evolve on shorter timescales, which—if accounted for—would reduce the effective source density). When including all 24 neutrinos followed up by our program by September 2021 (covering a combined area of 154.33 deg^2, see Supplemental Material [57]), the probability of finding any photometrically selected TDE candidate by chance is 2.6×10^{-2}, while the probability of finding two by chance is 3.4×10^{-4} (3.4σ). We emphasize that these estimates rely solely on the optical flux and a nuclear location in the host galaxy, and thus do not account for the additional luminous dust echoes or postflare x-ray detections observed for AT2019dsg and AT2019fdr.

Neutrino emission from AT2019fdr.—With a single neutrino observed in association with AT2019fdr, the inference of the neutrino flux will be subject to a large Eddington bias [202] and hence very uncertain. However, we can make a more robust statement on the neutrino flux by considering the underlying population (see, e.g., Ref. [10]). The detection of two high-energy neutrinos implies a mean expectation for the full TDE catalog in the range $0.36 < N_{\nu,\rm tot} < 6.30$ at 90% confidence, where $N_{\nu,\rm tot}$ is the cumulative neutrino expectation for the nuclear transients that ZTF has observed. AT2019fdr emits ∼2% of the g-band peak energy flux for the population of nuclear transients, consisting of the 17 published ZTF TDEs (see Ref. [203]) and all TDE candidates as bright as AT2019fdr (see Supplemental Material [57] for the latter). If we take this as a proxy for the contribution of AT2019fdr to the neutrino emission, we would expect a total number of neutrinos $0.007 \lesssim N_\nu \lesssim 0.13$ for this source.

This estimate can be compared to model expectations. We present three different models invoking $p\gamma$ and/or pp interactions, where protons are efficiently accelerated in a disk corona, a subrelativistic wind or a relativistic jet (see Supplemental Material [57]). The resulting spectra are shown in Fig. 2. All models can explain the observed

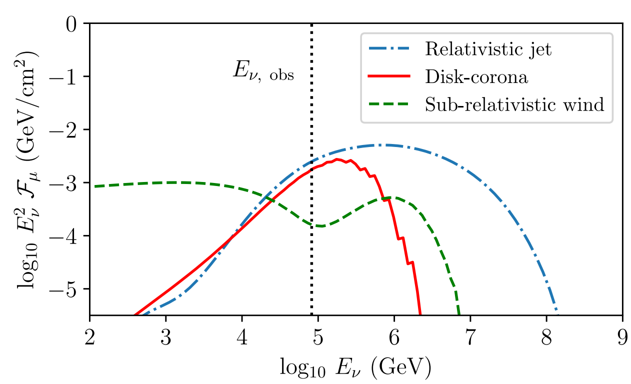

FIG. 2. Neutrino fluence for the three models described here. The reported energy of the neutrino event [49], represented by the dotted vertical line, should be viewed as a lower limit to the neutrino energy.

energy of the IC200530A neutrino event; they also make predictions for the underlying "neutrino light curve," though this can only be resolved once many neutrinos from TDEs have been detected. The obtained neutrino luminosities $L_\nu \lesssim 0.1 L_{\rm Edd} \simeq 5 \times 10^{44}$ erg s^{-1} are consistent with theoretical expectations for most models [39].

In accretion flow models [34,36], the virial theorem implies a cosmic ray acceleration efficiency $\eta_{\rm CR} < (1/40)(R/10R_{\rm s})^{-1}$ [36] for a cosmic-ray luminosity $L_{\rm CR} = \eta_{\rm CR}\dot{M}c^2$, where R is the emission radius and $R_{\rm s} = 2GM/c^2$ is the Schwarzschild radius. Even for a mass accretion rate of $\dot{M} \sim 10L_{\rm Edd}/c^2$, the neutrino luminosity would not exceed $\sim 10^{44}$ erg s^{-1}. In the case of AT2019fdr, the Eddington ratio $\lambda_{\rm Edd} \equiv L/L_{\rm Edd} \lesssim 0.07$–$0.3$ in the first 2 epochs, implying accretion near the Eddington limit around the peak and sub-Eddington accretion around the time of the neutrino detection. For such high accretion the disk plasma is collisional, while the coronal region may allow particle acceleration and nonthermal neutrino production [36]. This model yields $N_\nu \sim 0.007$ when evaluating its spectrum under the effective area of the neutrino alert channel [204]. This is within the expected range, albeit at its lower end. The time delay is consistent with quasisteady coronal emission. Alternatively, because the accretion rate gradually decreases, the neutrino time delay can be attributed to the formation of a collisionless corona that allows ion acceleration [36].

We also considered a subrelativistic wind with a velocity of $\sim 0.1c$, consistent with what was observed for AT2019dsg. Such a wind is naturally launched from the TDE disk (e.g., Ref. [205]), and may interact with tidal disruption debris. A strong shock is also expected from interactions between tidal streams. Ions can be accelerated at the shock via diffusive shock acceleration and produce neutrinos through inelastic pp and $p\gamma$ collisions [36]. In this subrelativistic wind model, the maximum proton energy can be as high as ~ 10–100 PeV. If the cosmic ray luminosity is three times the optical luminosity, the expected number of muon neutrinos is $N_\nu \sim 0.002$, which falls outside the empirical range for this baryon loading factor. The neutrino light curve would trace the wind luminosity in the calorimetric limit, and the time delay is consistent with quasisteady radio emission.

In the relativistic jet model, external target photons from the disk are backscattered into the jet frame. Here we followed Ref. [35] for AT2019dsg, but adopted a unified model [206] to extrapolate to higher SMBH masses as given for AT2019fdr. We estimated a thermal far UV to x-ray spectrum with $T \simeq 34$ eV. This turned out to be consistent with the late-time x-ray detection within the uncertainties. The isotropization timescale of the photons is expected to be given by the system size, suggesting a possible correlation with the dust echo; as a consequence the isotropized x-ray and dust echo light curves look very similar. The jet model allows for efficient particle acceleration and results in a relatively large number of 0.027 neutrino events with a maximum $L_\nu \simeq 0.05 L_{\rm Edd}$ thanks to the beaming effect; however, direct signatures of the jet have not been observed.

Conclusions.—AT2019fdr was an exceptionally bright nuclear transient that was already identified in the literature as a probable TDE in an active galaxy [45]. In this Letter, we have presented new observational data, including the identification of a strong dust echo and soft late-time x-ray emission, which further support a TDE origin for this flare.

AT2019fdr was a very long-lived transient, one of the most luminous ever detected. For a TDE, the energy release would require a very massive star [207]. However, unlike for TDEs in quiescent galaxies, the AGN disk in AT2019fdr might provide the system with additional energy [208]. Furthermore, the post star-burst nature of the host increases the expected rate for TDEs [209–211].

AT2019fdr was the second candidate neutrino-TDE identified by our ZTF follow-up program. While AT2019fdr was far more luminous than AT2019dsg, the first TDE associated with a high-energy neutrino, it was also more distant. As a result, the two objects have comparable bolometric energy fluxes. The probability for finding two such bright neutrino-coincident TDEs by chance is just 3.4×10^{-4}, a 7veces sevenfold decrease relative to the previously reported single association [10]. The gain due to the second association is somewhat offset by the larger neutrino sample and the more inclusive candidate TDE selection. Within the framework of this Letter, the association of a second object results in a reduction of the chance probability by a factor of 75 versus a single association.

AT2019fdr and AT2019dsg share other similarities beyond their potential association with a high-energy neutrino. Intriguingly, AT2019dsg also displayed an unusually strong dust echo signal [201], indicating that the presence of large amounts of matter and an associated high star formation rate in the environment could be a common signature for high-energy neutrino production in such systems. A dedicated search for further associations based on this signature is presented in Ref. [201] and provides more supporting evidence for neutrino production in TDEs.

We studied neutrino emission from AT2019fdr using models previously applied to explain the observations of AT2019dsg. Similar to AT2019dsg, various plausible cosmic ray acceleration sites have been identified, such as the corona, a subrelativistic wind, or a relativistic jet. The number of expected muon neutrinos predicted by the corona and jet models is consistent with empirical constraints derived from the two TDE-neutrino associations. All models require efficient neutrino production at a neutrino luminosity comparable to a sizable fraction of the Eddington luminosity. The neutrino delay may be related to the size of the newly formed system (jet model) or the formation of a collisionless corona (corona model).

With two objects being associated with IceCube neutrino alerts, out of a number of 11.5 expected astrophysical neutrinos (summed alert signalness, see Supplemental Material [57]), we obtain a fraction of $18^{+38}_{-15}\%$ (90% confidence level) of astrophysical neutrinos that could be explained due to ZTF-detected TDE candidates. Accounting for the incompleteness of our sample with the procedure in Ref. [10], our results imply that at least 7.8% of astrophysical neutrinos would come from the broader TDE population.

The search for neutrinos resulting in public alerts has a high energy threshold to reduce the background. Even when considering the full energy range of IceCube [212], the expected number of neutrino events from AT2019fdr remains below one. Therefore, the detection of additional lower-energy neutrinos from AT2019fdr is not expected (see also the search by the ANTARES neutrino observatory [213]).

Fully understanding the role of TDEs as particle accelerators will only be possible with comprehensive multiwavelength and -messenger data. While the detailed production processes remain uncertain, the observations presented here provide further evidence that TDEs are highly efficient sources of high-energy neutrinos.

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S. R. first identified AT2019fdr as a candidate neutrino source, performed the SED and the dust echo analysis and was the primary author of the manuscript. A. F., M. K., R. St. and S. v. V. contributed to the manuscript, the data analysis, and the source modeling. A. F. and M. K. have initiated the ZTF neutrino follow-up program. C. L., K. M. and W. W. performed the neutrino production analysis. J. C. A. M.-J. contributed the VLA observations. M. Gi. performed the SRG/eROSITA observations and data analysis. S. B. and S. Ga. analyzed the Fermi data. S. R. analyzed the Swift-XRT data. S. A., K. D., and S. R. performed and analyzed the P200 IR observations. S. Ge. and S. S. requested and reduced the Swift-UVOT data. V. S. P. contributed the black hole mass estimate. E. Z. contributed to the neutrino event rate calculation. M. G. analyzed the archival radio data. S. S. K and B. T. Z. performed parts of the neutrino production analysis. V. K. and N. L. S. contributed PTF forced photometry. C. B., T. S., and J. S. ruled out other candidates in the follow-up. T. A., M. W. C., M. M. K., and L. P. S. enabled ZTF ToO observations. J. Ne., S. R., and R. St. developed the analysis pipeline. V. B., J. No. and J. v. S. developed AMPEL, and contributed to the ToO analysis infrastructure. E. C. B., S. B. C., R. D., M. J. G., R. R. L., B. R., M. R., and R. W. contributed to the implementation of ZTF. P. M. and R. Su. contributed to the implementation of SRG/eROSITA. S. F., S. Ge., A. G.-Y., A. K. H. K, E. K., and D. A. P. contributed comments and to discussions. All authors reviewed the contents of the manuscript.

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