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Is the High-energy Neutrino Event IceCube-200530A Associated with a Hydrogen-rich Superluminous Supernova?

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Abstract

The Zwicky Transient Facility follow-up campaign of alerts released by the IceCube Neutrino Observatory has led to the likely identification of the transient AT2019fdr as the source of the neutrino event IC200530A. AT2019fdr was initially suggested to be a tidal disruption event in a Narrow-Line Seyfert 1 galaxy. However, the combination of its spectral properties, color evolution, and feature-rich light curve suggests that AT2019fdr may be a Type IIn superluminous supernova. In the latter scenario, IC200530A may have been produced via inelastic proton-proton collisions between the relativistic protons accelerated at the forward shock and the cold protons of the circumstellar medium. Here, we investigate this possibility and find that at most $4.6 \times 10^{-2}$ muon neutrino and antineutrino events are expected to be detected by the IceCube Neutrino Observatory within 394 days of discovery in the case of excellent discrimination of the atmospheric background. After correcting for the Eddington bias, which occurs when a single cosmic neutrino event is adopted to infer the neutrino emission at the source, we conclude that IC200530A may originate from the hydrogen-rich superluminous supernova AT2019fdr.

Unified Astronomy Thesaurus concepts: Type II supernovae (1731); Neutrino astronomy (1100); Particle astrophysics (96)

1. Introduction

In 2013, the IceCube Collaboration reported the detection of a flux of high-energy neutrinos of astrophysical origin, marking the beginning of the high-energy neutrino astronomy era. Despite the growing number of high-energy neutrino events detected by the IceCube Neutrino Observatory, the sources of the cosmic neutrino flux remain to be unveiled (Aartsen et al. 2018a, 2020; Abbasi et al. 2021a, 2021b).

High-energy neutrino events have been reported to be in likely coincidence with blazars (Kadler et al. 2016; Aartsen et al. 2018b; Krauß et al. 2018; Garrappa et al. 2019; Franckowiak et al. 2020; Giommi et al. 2020). However, association studies of blazars hint toward no excess from the broader population (Aartsen et al. 2017). Various other source classes have been proposed as factories of the observed cosmic neutrino flux (Mészáros et al. 2017a; Ahlers & Halzen 2018; Vitagliano et al. 2020), such as gamma-ray bursts, cluster of galaxies, star-forming galaxies, and tidal disruption events (TDEs; Tamborra et al. 2014; Zandanel et al. 2015; Wang & Liu 2016; Mészáros et al. 2017; Dai & Fang 2017; Lunardini & Winter 2017; Murase 2017; Senno et al. 2017; Waxman 2017; Pitik et al. 2021). Nevertheless, the neutrino emission from each of these source classes cannot fully account for the observed neutrino flux.

The growing number of cosmic neutrino alerts has triggered follow-up searches for coincident detection of electromagnetic radiation, see, e.g., Abbasi et al. (2021c), Garrappa et al. (2019), Acciari et al. (2021). On 2019 October 1, the IceCube Collaboration reported the detection of a muon track neutrino of likely astrophysical origin, IC191001A. This event has been suggested to be the neutrino counterpart of the TDE candidate AT2019dsg, which was discovered by the Zwicky Transient Facility (ZTF)—see, e.g., Bellm et al. 2019; Stein et al. 2021. Various theoretical models have been discussed to interpret this likely association (Liu et al. 2020; Murase et al. 2020; Winter & Lunardini 2021); however the jetted version of these models is being challenged by the most recent work on the radio properties of AT2019dsg (Cendes et al. 2021; Mohan et al. 2022; Matsumoto et al. 2022; Matsumoto & Piran 2021).

More recently, the follow-up campaign of IceCube neutrino alerts carried out by the ZTF Collaboration has led to another transient association. On 2020 May 31, IceCube Collaboration (2020), Reusch et al. (2020a) detected another muon track candidate (IC200530A), which was suggested to be associated with the optical transient AT2019fdr/ZTF19aatubsp located at redshift $z = 0.2666$. The IC200530A event was detected $\sim$394 days after the discovery of the transient (hereafter identified with the onset of the shock breakout) and about 300 days after the peak of the electromagnetic emission. This neutrino event has a reconstructed neutrino energy of $E_\nu \sim 80$ TeV and a signalness larger than 50% (Reusch et al. 2020a; IceCube Collaboration 2020; Stein 2021).

The intriguing coincidence of two IceCube neutrino events with two ZTF transient sources has triggered searches by the ANTARES Collaboration (Albert et al. 2021) and led to stringent upper limits on the neutrino emission from both sources. In addition, the Baikal-GVD Collaboration is currently investigating clusters of neutrino events detected along the
same angular directions of both ZTF sources (Suvorova et al. 2021).

AT2019fdr is located close to the nucleus of its host galaxy and shows strong narrow hydrogen emission lines within its spectra. This led to the initial classification of AT2019fdr as either a flaring active galactic nucleus (AGN) in a Narrow-Line Seyfert 1 galaxy (Frederick et al. 2021) or a tidal disruption event (Chornock et al. 2019). This has resulted in interpretations of IC200530A being associated with an accreting black hole transient event (Stein 2021). However, Yan et al. (2019) proposed that AT2019fdr is a hydrogen-rich superluminous supernova (otherwise named superluminous supernova of Type IIn, SLSN IIn). Hydrogen-rich SLSNe exhibit strong narrow Balmer emission lines within their spectra, but are more luminous than standard type IIn supernovae (SNe IIn), achieving luminosities typically with \( M < -20 \) at peak brightness (Gal-Yam 2012; Smith 2014; Gal-Yam 2019). The narrow emission lines within SNe IIn are indicative of interaction between the SN ejecta with a dense shell of surrounding circumstellar material (CSM) in which kinetic energy is efficiently converted into thermal energy. The high luminosity of SLSNe IIn is thought to be the result of one of the following: a highly energetic explosion [with typical energies \( E_{\text{ej}} \approx O(10^{51} - 10^{52}) \) ergs], an interaction with an unusually massive CSM (Moriya et al. 2018), or some combination of the two scenarios.

Proton acceleration, even beyond PeV energies, could take place in the proximity of the SLSN shock expanding in the dense CSM. The interaction of these protons with those of the shocked CSM may lead to copious neutrino emission (Katz et al. 2011; Murase et al. 2011, 2014; Cardillo et al. 2015; Petropoulou et al. 2016; Zirakashvili & Ptuskin 2016; Petropoulou et al. 2017; Murase 2018). In this work, we investigate the possibility that IC200530A originates from AT2019fdr, under the framework that this transient is a SLSN IIn.

This paper is organized as follows. After introducing the main features characterizing AT2019fdr in Section 2, we outline the setup adopted to predict the neutrino signal in Section 3. Our findings are presented in Section 4 together with a discussion on the dependence of the neutrino signal on the uncertain parameters characteristic of AT2019fdr. A discussion on our findings and caveats is reported in Section 5, followed by our conclusions in Section 6. In addition, Appendix A discusses how the AT2019fdr parameter space is constrained by the observational constraints on AT2019fdr that we apply from neutrino and electromagnetic data. We investigate the temporal evolution of the maximum proton energy as a function of the model parameters considered for AT2019fdr in Appendix B.

2. AT2019fdr: A Type IIn Superluminous Supernova

AT2019fdr exhibits many properties compatible with those of other documented SLSNe IIn from the literature. Spectroscopically, the event shows intermediate-width (~1000 km s\(^{-1}\)) Balmer emission lines combined with narrow galaxy emission lines from the host, superimposed upon a blue continuum.\(^8\) The intermediate-width Balmer emission features are characteristic of interacting core-collapse SNe (SNe IIn and

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\(^8\) The classification spectra are publicly available on https://www.wiserep.org/object/12537.
For extremely large (radius) density decreases (gradient describes the density gradient larger than this sketch radius of the ejecta radially outwards. The black, dotted line marks the location of the deceleration (see Figure 1) as in this sketch) for a relatively large CSM mass compared to the ejecta mass or larger than $R_{\text{CSM}}$ for very massive ejecta and rafied CSM; see Equation (4). For extremely large $M_{\text{CSM}}/M_{\text{ej}}$, it is possible that $R_{\text{dec}} < R_{\text{w}}$.

We also note that AT2019fdr was not the only source suggested to be associated with the neutrino event IC200530A. AT2020lam and AT2020lls were also suggested to be possibly associated, as they were found within a 90.0% localization of the neutrino event (Reusch et al. 2020a). AT2020lam was classified using the Nordic Optical Telescope as a Type II SN located at $z = 0.033$ (Reusch et al. 2020c). However, the spectrum and light curve showed no evidence of CSM interaction, necessary for neutrino producing, leading Reusch et al. (2020c) to suggest that it was not associated with the neutrino event IC200530A.

AT2020lls was also classified using the Nordic Optical Telescope, but as a Type Ic SN located at $z = 0.04106$ that occurred ~8 days prior to the detection of IC200530A (Reusch et al. 2020b). As this source did not show broad absorption features consistent with a subclass of Type Ic SN called Type Ic-BL, which are commonly associated with off-axis gamma-ray bursts or choked jets, Reusch et al. (2020b) suggested this was not associated with the neutrino event IC200530A.

3. Model Setup

In this section, we introduce the method adopted to compute the neutrino spectral energy distribution from AT2019fdr and its temporal evolution, as well as the properties of AT2019fdr useful to this purpose. Details on the estimation of the neutrino flux and event rate expected at Earth follow.

3.1. Spectral Energy Distributions of Protons and Neutrinos

We assume a spherical, steady, and wind-like CSM with solar composition ejected from the massive progenitor in the final stages of its evolution, as sketched in Figure 2. We define its number density profile as

$$n_{\text{CSM}}(R) = \frac{\rho_{\text{CSM}}(R)}{m} = \frac{\dot{M}}{4\pi v_w m R^2},$$

where $\dot{M}$ is the stellar mass-loss rate, $v_w$ the wind velocity, $m = \mu m_H$ with $\mu = 1.3$ being the mean molecular weight for a neutral gas of solar abundance, and $R$ the distance to the stellar core.

The interaction of the stellar ejecta with the CSM leads to the formation of a forward shock (propagating in the CSM) and a reverse shock (propagating back into the stellar ejecta). Both the forward and reverse shocks could, in principle, contribute to the neutrino emission. Working under the assumption that the ejecta density profile decreases steeply (Chevalier & Fransson 2003), we neglect the contribution of the reverse shock since the forward shock is expected to predominantly contribute to the total energy dissipation rate and dominate the particle acceleration observed in SN remnants (e.g., Ellison et al. 2007; Patnaude & Fesen 2009; Schure et al. 2010; Slane et al. 2015; Sato et al. 2018; Suzuki et al. 2020). Hence, we focus on the neutrino emission from the forward shock for the sake of simplicity.

Following Chevalier (1982), Moriya et al. (2013), we assume that spherically symmetric SN ejecta of mass $M_{ej}$ and kinetic energy $E_k$ expand in the surrounding CSM homologously. The CSM extends up to an external radius $R_{\text{CSM}}$ (see Figure 5). The outer ejecta density profile, which is relevant for the interactions leading to neutrino production, scales as $n_{ej} \propto R^{-s}$, where we assume $s = 10$. The shocked SN ejecta and CSM form a thin dense shell because of efficient radiative cooling. Being that the thickness of the thin, shocked shell is much smaller than its radius, one can describe its evolution through the radius $R(t)$ in the ejecta-dominated phase, namely in the phase in which most part of the ejecta is still freely expanding (i.e., when the mass of the ejecta is larger than the swept-up CSM mass), the shock radius is given by the following (Moriya et al. 2013; Chevalier & Fransson 2017):

$$R_{sh}(t) = \frac{2}{s(s-4)(s-3)} \left[ \frac{[10(s-5)E_k]^{(s-3)/2} v_w}{[3(s-3)M_{ej}]^{(s-5)/2}} \right]^{1/(s-2)} \times t^{(s-3)/(s-2)},$$

with the corresponding shock velocity $v_{sh} = dR_{sh}/dt$.

Because of the high CSM density, the forward shock is initially expanding in a radiation-dominated region, and

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Figure 2. Schematic representation of AT2019fdr after the explosion, assuming spherical symmetry. The central compact object (in black) is surrounded by the SN ejecta (orange region, with the bordeaux arrows indicating the propagation of the ejected material) and a dense CSM envelope (yellow region) that extends up to its outer edge marked by $R_{\text{CSM}}$. The color gradient describes the density gradient (from darker to lighter hues as the density decreases). The dashed black line marks the position of the breakout radius ($R_b$). The indigo line represents the forward shock that propagates radially outwards. The black, dotted line marks the location of the deceleration radius of the ejecta ($R_{\text{dec}}$). The latter is located at radii smaller than $R_{\text{CSM}}$ (as in this sketch) for a relatively large CSM mass compared to the ejecta mass or larger than $R_{\text{CSM}}$ for very massive ejecta and rafied CSM; see Equation (4). For extremely large $M_{\text{CSM}}/M_{\text{ej}}$, it is possible that $R_{\text{dec}} < R_{\text{w}}$.

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\[8https://wis-tns.weizmann.ac.il/object/2020lam\]
\[9https://wis-tns.weizmann.ac.il/object/2020lls\]
particle acceleration is not efficient (Weaver 1976; Levinson & Bromberg 2008; Katz et al. 2011; Murase et al. 2011). Efficient particle acceleration takes place at radii larger than that of the shock breakout ($R_{bo}$), where the initially trapped photons are free to diffuse out to the photosphere; the shock breakout radius is computed by solving the following equation:

$$\gamma(R_{bo}) = \int_{R_{bo}}^{R_{CSM}} \rho_{CSM}(R) \kappa_{es} dR = \frac{c}{v_{sh}},$$

where $\kappa_{es} \sim 0.34 \text{ cm}^2 \text{ g}^{-1}$ (Pan et al. 2013) is the electron scattering opacity at solar abundances, and $c$ is the speed of light. When the SN ejecta mass $M_{ej}$ becomes comparable to the swept-up mass from the CSM, the ejecta enters the CSM-dominated phase. This transition happens at the deceleration radius

$$R_{dec} = M_{ej} v_{sh}.$$  

Note that $R_{dec}$ may be located at radii smaller than $R_{CSM}$ as shown in Figure 2, or larger than $R_{CSM}$ according to the relative ratio between $M_{ej}$ and $M_{CSM}$ (i.e., if $M_{CSM} > M_{ej}$, then $R_{dec} < R_{CSM}$ and vice versa). Furthermore, for $M_{CSM}$ extremely large with respect to $M_{ej}$, $R_{dec}$ can even be smaller than $R_{bo}$. For $R > R_{dec}$, the forward shock radius evolves as (Suzuki et al. 2020)

$$R_{sh}(t) = R_{dec} \left( \frac{t}{t_{dec}} \right)^{2/3},$$

where we have assumed adiabatic dynamical evolution for the sake of simplicity. At radii larger than $R_{bo}$, diffusive shock acceleration of the incoming CSM protons takes place. Following Finke & Dermer 2012, Petropoulou et al. 2016, the proton injection rate for a wind density profile is

$$Q_p(\gamma_p, R) = \frac{d^2 N_p}{d \gamma_p dR} = \frac{9 \pi R_{bo}^2 n_{bo}}{8 \ln(\gamma_p, \max / \gamma_p, \min)} \left( \frac{v_{sh}(R_{bo})}{c} \right)^2 \times \left( \frac{R}{R_{bo}} \right)^{2\alpha} H(\gamma_p - \gamma_p, \min) H(\gamma_p, \max - \gamma_p),$$

where the parameter $\alpha$ dictates the radial dependence of the shock velocity ($v_{sh} \propto R^{\alpha}$); it is $\alpha = -1/7$ in the free expansion phase ($R < R_{dec}$) and $\alpha = -1/2$ in the decelerating phase ($R > R_{dec}$). The fraction of the shocked thermal energy stored in relativistic protons is $\varepsilon_p$, while $H(x) = 1$ for $x > 0$ and zero otherwise. We set the proton spectral index $k = 2$ and the minimum Lorentz factor of the accelerated protons $\gamma_p, \min = 1$. The maximum Lorentz factor of protons ($\gamma_p, \max$) is obtained by requiring that the acceleration timescale in the Bohm limit, $t_{acc} \sim 20\gamma_p m_p c^3/3 e B v_{sh}^2$ (Protheroe & Clay 2004), is shorter than the total cooling timescale for protons: $t_{acc} \leq t_{p, cool}$. $B = \sqrt{32 \pi B m_p v_{sh}^2 n_{CSM}}$ is the magnetic field in the postshock region, whose energy density is a fraction $\varepsilon_B$ of the postshock thermal energy density $U_0 = (9/8) m_p v_{sh}^2 n_{CSM}$. The latter is obtained by considering the Rankine–Hugoniot jump conditions across a strong nonrelativistic shock with the compression ratio approximately equal to 4.

The most relevant energy loss mechanisms for protons are inelastic $pp$ collisions and the cooling due to adiabatic expansion of the shocked shell; hence $t_{p, cool} = \frac{1}{\gamma_p} + t_{ad}$, with $t_{pp} = (4 k_{pp} \sigma_{pp, n_{CSM}})^{-1}$, where we assume constant inelasticity $\sigma_{pp} = 0.5$ and energy-dependent cross-section $\sigma_{pp}(E_p)$ (Zyla et al. 2020). Following Fang et al. (2020), the adiabatic cooling is $t_{ad} = \min(t_{dyn}, t_{cool})$, where $t_{cool}$ is the typical cooling time of the thermal gas behind the shock, and $t_{dyn}$ is the dynamical time of the shock. When the shock is radiative, the particle acceleration region shrinks to a characteristic length $\sim \gamma_p v_{sh}$, limiting the maximum achievable particle energy. The cooling time is $t_{cool} = 3k_B T/2n_{sh} \Lambda(T)$ (Franco et al. 1992) where $k_B$ is the Boltzmann constant, $n_{sh} = 4n_{CSM}$ is the density of the shocked region, and $\Lambda(T)$ is the cooling function capturing the physics of radiative cooling. Here $T$ is the gas temperature immediately behind the forward shock front obtained by the Rankine–Hugoniot conditions, given by the following:

$$T = 2 \left( \frac{\gamma - 1}{\gamma + 1} \right)^2 \frac{\mu m_p v_{sh}^2}{k_B},$$

where $\gamma = 5/3$ is the adiabatic index of the gas. Finally, the cooling function [in units of erg cm$^3$ s$^{-1}$] is given by the following approximation (Chevalier & Fransson 1994):

$$\Lambda(T) = \begin{cases} 6.2 \times 10^{-19} T^{-0.6} & 10^5 < T < 4.7 \times 10^7 K \\ 2.5 \times 10^{-27} T^{0.2} & T > 4.7 \times 10^7 K \end{cases},$$

where line emission dominates at low $T$ and free-free emission at high $T$.

Relativistic protons in the shocked region may also interact with the ambient photons via $p\gamma$ interactions. However, in this work, we ignore this energy loss channel, consistent with the work of Murase et al. (2011), Fang et al. (2020), which show that $p\gamma$ interactions can be safely neglected for a wide range of parameters.

Since we aim to compute the neutrino emission, we track the temporal evolution of the proton distribution in the shocked region between the shock breakout radius $R_{bo}$ and the outer radius $R_{CSM}$.

The evolution of the proton distribution is given by the following (Sturmer et al. 1997; Finke & Dermer 2012, Petropoulou et al. 2016):

$$\frac{\partial N_p(\gamma_p, R)}{\partial R} = \frac{\partial}{\partial \gamma_p} \left( \frac{\gamma_p}{R} N_p(\gamma_p, R) \right) + \frac{N_p(\gamma_p, R)}{v_{sh}(R) t_{pp}} = Q_p(\gamma_p, R),$$

where $N_p(\gamma_p, R)$ represents the total number of protons in the shell at a given radius $R$ with Lorentz factor between $\gamma_p$ and $\gamma_p + d\gamma_p$. The radius $R$ is related to the time $t$ measured by an observer at Earth: $t = \tilde{t}(R) (1 + z)$, where we denote with a tilde all parameters in the reference frame of the central compact object hereafter. The second term on the left-hand side of Equation (9) takes into account energy losses due to the adiabatic expansion of the SN shell, while $pp$ collisions are treated as an escape term (Sturmer et al. 1997). Other energy loss channels for protons are negligible (Murase et al. 2011). Furthermore, in Equation (9), the diffusion term has been neglected since the shell is assumed to be homogeneous.

The neutrino production rates, $Q_{\nu, p}$ [GeV$^{-1}$ cm$^{-1}$], for muon and electron flavor (anti)neutrinos are given by the
following (Kelner et al. 2006):

\[ Q_{\nu, i}(E_{\nu}, R) = \frac{4n_{\rm CSM}(R) m_{\nu} c^{3}}{v_{\text{sh}}} \int_{0}^{1} \frac{\sigma_{\text{pp}}(E_{\nu}/x)}{x} \times N_p \left( E_{\nu} \frac{x}{m_{\nu} c^2}, R \right) (F_{\nu}^{(1)}(E_{\nu}, x) + F_{\nu}^{(2)}(E_{\nu}, x)), \]

(10)

\[ Q_{\nu, i}(E_{\nu}, R) = \frac{4n_{\rm CSM}(R) m_{\nu} c^{3}}{v_{\text{sh}}} \int_{0}^{1} \frac{\sigma_{\text{pp}}(E_{\nu}/x)}{x} \times N_p \left( E_{\nu} \frac{x}{m_{\nu} c^2}, R \right) F_{\nu}(E_{\nu}, x), \]

(11)

where \( x = E_{\nu}/E_{\nu} \). The functions \( F_{\nu}^{(1)}, F_{\nu}^{(2)}, \) and \( F_{\nu} \) follow the definitions in Kelner et al. (2006). Equations (10) and (11) are valid for \( E_{\nu} > 0.1 \) TeV, corresponding to the energy range under investigation.

### 3.2. Parameters Characteristic of AT2019fdr

Numerical simulations aiming to model SLSNe IIn light curves are undergoing, see, e.g., Dessart et al. (2015), Chatzopoulos & Tuminello (2019), Suzuki et al. (2019, 2021); however, the exact underlying physics that powers these sources is still uncertain. In the following, we outline the properties of AT2019fdr that are useful for modeling its neutrino emission.

By relying on existing data on AT2019fdr from ZTF (Patterson et al. 2019), ATLAS (Tonry et al. 2018; Smith et al. 2020), and Swift (Gehrels et al. 2004), we integrate the observed pseudo-bolometric light curve and estimate that the total radiated energy from AT2019fdr is \( E_{\text{rad}} = 1.66 \pm 0.01 \times 10^{52} \) erg. To take into account the uncertainties on the radiative efficiency, namely the fraction of the total energy that is radiated, we consider two characteristic values of the kinetic energy \( E_{\text{k}} \) of the ejecta: \( 5 \times 10^{52} \) erg and \( 10^{53} \) erg, which correspond to a radiative efficiency of \( \sim 35\% \) and \( 18\% \), respectively (see Chevalier & Irwin 2011, where the total radiated energy is estimated to be \( E_{\text{rad}} = 0.32 E_{\text{k}} \)).

We assume the proton fraction equal to \( \varepsilon_{\text{p}} = 0.1 \) (Murase et al. 2011). This value is consistent with simulations of particle acceleration and magnetic field amplification at nonrelativistic quasi-parallel shocks (Caprioli & Spitkovsky 2014). A discussion on the impact of different values of \( \varepsilon_{\text{p}} \) on the expected neutrino event rate is reported in Section 5. The fraction of the postshock internal energy that goes into amplification of the magnetic field is instead assumed to be \( \varepsilon_{\text{B}} = 3 \times 10^{-4} \) (Petropoulou et al. 2017).

The wind velocity is considered to be \( v_{w} = 100 \) km s\(^{-1}\) (Moriya et al. 2014). The average mass-loss rate is given by the following (Suzuki et al. 2021):

\[ \dot{M} = 0.3 M_{\odot} \text{yr}^{-1} \left( \frac{M_{\text{CSM}}}{10 M_{\odot}} \right) \left( \frac{R_{\text{CSM}}}{10^{16} \text{cm}} \right)^{-1} \left( \frac{v_{w}}{100 \text{ km s}^{-1}} \right), \]

(12)

where \( M_{\text{CSM}} \) is the CSM mass contained within a shell of radius \( R_{\text{CSM}} \).

By fitting a basic polynomial to the bolometric light curve and available nondetections of AT2019fdr to extrapolate beyond the detection limits of ZTF, we estimate that its rise time (i.e., the time during which the luminosity reaches peak value, see Figure 1) is \( t_{\text{rise}} \sim 98 \) days. In addition, in order to link \( t_{\text{rise}} \) to the other model parameters characteristic of AT2019fdr, we rely on the following relation (Suzuki et al. 2020):

\[ t_{\text{rise}} \simeq t_{\text{diff}}(t) = \frac{(R_{\text{ph}} - R) \tau_{\gamma}(R)}{c}, \]

(13)

where the diffusion time is the time required for the radiation to travel from \( R_{\text{ph}} \) to \( R_{\text{CSM}} \), and \( \tau_{\gamma}(R) \) is the optical depth of the CSM at radius \( R \). The rise time is expected to increase as a function of \( M_{\text{CSM}} \), since a massive and dense CSM prolong the photon diffusion timescale. Yet, in order to predict the correct behavior of \( t_{\text{rise}} \), one should take into account the effect of the variation of all the parameters: \( E_{k}, M_{ej}, M_{\text{CSM}}, \) and \( R_{\text{CSM}} \).

The exact values of \( M_{ej}, M_{\text{CSM}}, \) and \( R_{\text{CSM}} \) are highly uncertain for AT2019fdr, and degeneracies may be at play when interpreting the AT2019fdr light curve. The reprocessing of information from the explosion by interaction with the CSM masks the properties of the SLSN explosion underneath it. Although the CSM density can be estimated in several ways, e.g., from the strength of the \( H-\alpha \) line (Taddia et al. 2013) or through X-ray and radio observations (Chandra 2018), AT2019fdr lacks the necessary time series mult*wavelength and spectroscopic data required to constrain it. Hence, we consider ranges of variability for the most uncertain parameters: \( M_{ej} \in [5, 150] M_{\odot}, \) \( M_{\text{CSM}} \in [5, 150] M_{\odot}, \) and \( R_{\text{CSM}} \in [2, 4] \times 10^{16} \) cm. Out of these, we only take into account those in agreement with the measured \( t_{\text{rise}} \) allowing for an uncertainty of 50% and requiring that the production of the neutrinos observed by the IceCube Observatory at \( \sim 394 \) days after the breakout takes place inside the CSM, namely \( t(R_{\text{CSM}}) - t(R_{\text{bo}}) \gtrsim 394 \) days. See Appendix A for more details. A summary of the default values for the parameters considered for AT2019fdr is reported in Table 1.

### 3.3. Neutrino Flux and Event Rate at Earth

The neutrino and antineutrino flux \( (\nu_{\alpha}, \bar{\nu}_{\alpha}) \) at Earth from a SN at redshift \( z \) and as a function of time in the

| Parameter | Symbol | Default Value |
|-----------|--------|---------------|
| Radiated energy | \( E_{\text{rad}} \) | \( 1.66 \times 10^{52} \) erg |
| Radiative efficiency | \( \eta \) | \( 18\% - 35\% \) |
| Rise time | \( t_{\text{rise}} \) | \( 98 \) days |
| Redshift | \( z \) | \( 0.2666 \) |
| Declination | \( \delta \) | \( 26^\circ 85' \) |
| Right ascension | \( \alpha \) | \( 257^\circ 28' \) |
| Accelerated proton energy fraction | \( \varepsilon_{\text{p}} \) | \( 0.1 \) |
| Magnetic energy density fraction | \( \varepsilon_{\text{B}} \) | \( 3 \times 10^{-4} \) |
| Proton spectral index | \( k \) | \( 2 \) |
| Wind velocity | \( v_{w} \) | \( 100 \) km s\(^{-1}\) |
| Ejecta density slope | \( s \) | \( 10 \) |
| Ejecta mass | \( M_{ej} \) | \( 5 - 150 M_{\odot} \) |
| CSM mass | \( M_{\text{CSM}} \) | \( 5 - 150 M_{\odot} \) |
| CSM radius | \( R_{\text{CSM}} \) | \( (2 - 4) \times 10^{16} \) cm |

Note. For the most uncertain ones, we consider a range of variability.
Neutrinos change their flavor while propagating; hence the flavor transition probabilities are given by the following (Anchordoqui et al. 2014):

\[ P_{\nu_x \rightarrow \nu_y} = P_{\nu_y \rightarrow \nu_z} = \frac{1}{4} \sin^2 2\theta_{12}, \]

\[ P_{\nu_y \rightarrow \nu_y} = P_{\nu_{\bar{y}} \rightarrow \nu_{\bar{y}}} = \frac{1}{8} (4 - \sin^2 2\theta_{12}), \]

\[ P_{\nu_{\bar{y}} \rightarrow \nu_{\bar{y}}} = 1 - \frac{1}{2} \sin^2 2\theta_{12}, \]

with \( \theta_{12} \approx 33.2^\circ \) (Esteban et al. 2020), and \( P_{\nu_0 \rightarrow \nu_0} = P_{\nu_{\bar{0}} \rightarrow \nu_{\bar{0}}} \). The luminosity distance \( d_L(z) \) is defined in a flat \( \Lambda \)CDM cosmology as

\[ d_L(z) = (1 + z) \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M + \Omega_\Lambda (1 + z')^3}}, \]

where \( \Omega_M = 0.315, \Omega_\Lambda = 0.685, \) and the Hubble constant is \( H_0 = 67.4 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \) (Aghanim et al. 2020).

The neutrino fluence [GeV\(^{-1}\)cm\(^{-2}\)] is calculated using

\[ \Phi_{\nu_0 + \nu_0}(t) = \int_{t_{\text{bo}}}^{t_{\text{bo}} + 394} F_{\nu_0 + \nu_0}(E_\nu, t) dt, \]

with \( t_{\text{bo}} = t(R_{\text{bo}}) \) and the time integral being restricted to 394 days.

Finally, the event rate of muon neutrinos and antineutrinos expected at the IceCube Neutrino Observatory is

\[ \dot{N}_{\nu_\mu + \bar{\nu}_\mu}(t) = \int_{E_{\nu, \text{min}}}^{E_{\nu, \text{max}}} dE_\nu A_{\text{eff}}(E_\nu, \delta) F_{\nu_\mu + \bar{\nu}_\mu}(E_\nu, t) \]

where \( A_{\text{eff}}(E_\nu, \delta) \) is the detector effective area (Abbasi et al. 2021a). The minimum neutrino energy is \( E_{\nu, \text{min}} = 100 \, \text{GeV} \) for the declination of interest (Abbasi et al. 2021a), and \( F_{\nu_\mu + \bar{\nu}_\mu}(E_\nu, t) \) has been introduced in Equation (14). In the following, we work under the assumption of perfect discrimination between astrophysical and atmospheric neutrinos; see Section 5 for a discussion on the expected event rate if the event sample should be contaminated by atmospheric neutrinos in the energy region below 100 TeV. The maximum neutrino energy \( E_{\nu, \text{max}} \) is related to the maximum proton energy: \( E_{\nu, \text{max}} = x E_{p, \text{max}} \).

The total number of muon neutrinos and antineutrinos is computed over the temporal interval of 394 days:

\[ \dot{N}_{\nu_\mu + \bar{\nu}_\mu} = \int_{t_{\text{bo}}}^{t_{\text{bo}} + 394} dt \, \dot{N}_{\nu_\mu + \bar{\nu}_\mu}(t). \]

### 4. Forecast of the Neutrino Signal

In this section, we present the results on the neutrino signal expected from AT2019fdr. First, we discuss the neutrino spectral energy distribution and the event rate expected in the IceCube Neutrino Observatory. We then investigate the dependence of the expected signal on the uncertainties of the SLSN Ibn model.

#### 4.1. Energy Fluence and Temporal Evolution of the Neutrino Event Rate

Before focusing on the energy fluence and event rate of the detectable neutrino signal, we explore the characteristic cooling times of protons and the acceleration timescale characteristic of AT2019fdr, introduced in Section 3.1. In order to give an idea of the variation of the cooling and acceleration timescales across the SLSN shell, Figure 3 shows the proton cooling times as a function of the proton energy in rest frame for the SLSN configuration with \( (E_\nu, R_{\text{CSM}}, M_{\text{CSM}}) = (10^{35} \, \text{erg}, 4 \times 10^{16} \, \text{cm}, 6 \, M_\odot, 49 \, M_\odot) \). The acceleration timescale, \( \gamma p \), and adiabatic cooling timescales are represented in red, green, and light blue, respectively. Protons are strongly cooled by \( pp \) energy losses for all the SLSN-parameter configurations considered in this work.
in magnitude. However, it is worth noting in magnitude. Within the

\[ E_{\nu} \text{[GeV]} \quad E_{\nu}^2 [\text{GeV}^2] \]

Figure 4. Muon neutrino and antineutrino fluence from AT2019fdr as a
function of the neutrino energy. The reconstructed neutrino energy \( (E_{\nu} \sim 80 \text{ TeV}) \) for IC200530 is marked by a black, dotted vertical line. The band encloses the uncertainties on the parameters characterizing AT2019fdr, see Table 1. In the proximity of the energy of interest for the interpretation of IC200530, the fluence can vary up to a factor \( O(10^3) \) in magnitude. Within the allowed parameter space, the lowest fluence is foreseen for configurations with large \( R_{\text{CSM}} \), low \( M_{\text{CSM}} \), and high \( M_{\nu} \). The largest neutrino fluence is instead obtained for intermediate values of \( M_{\text{CSM}} \) and low \( M_{\nu} \), which moreover allow a higher proton energy cutoff.

following:

\[
E_{p,\text{max}} = \frac{eB_{\nu\text{lab}}^2}{24e^2k_{pp} \sigma_{pp} n_{\text{CSM}}} \sim \begin{cases} M_{\nu}^{-15/14} M_{\text{CSM}}^{-13/14} R^{4/7} & R < R_{\text{dec}} \\ M_{\text{CSM}}^{-2} R^{-1/2} & R > R_{\text{dec}}. \end{cases} \tag{22}
\]

Appendix B provides more details on the scaling of \( E_{p,\text{max}} \) as a function of the SLSN-model parameters.

The muon neutrino and antineutrino fluence, defined as in Equation (19), is shown in Figure 4 as a function of the neutrino energy. The band takes into account the uncertainties on the parameters characterizing AT2019fdr (see Section 3.2) and is defined by the parameter configurations leading to the highest and lowest neutrino fluence. Note that, for the SLSN parameters adopted in this work, the synchrotron cooling of charged pions and muons produced via \( pp \) interactions is negligible. In fact, the typical energies for which this energy loss becomes relevant are at least three orders of magnitude larger than the maximum achievable proton energies. Therefore, the neutrino spectra are not affected by the cooling of mesons.

Given our selection criterion (i.e., the observation of IC200530 about 394 days after the shock breakout and the constraints on the rising time of the light curve of AT2019fdr), the scenarios with the lowest fluence are those corresponding to configurations with large \( R_{\text{CSM}} \), low \( M_{\text{CSM}} \), and high \( M_{\nu} \). On the other hand, given the reduced parameter space allowed for low \( R_{\text{CSM}} \) (see Appendix A), the most optimistic scenario corresponds to the highest \( R_{\text{CSM}} \), the lowest accessible \( M_{\nu} \), and the intermediate values of \( M_{\text{CSM}} \) \( (M_{\text{CSM}} \approx 30-50M_{\odot}) \). We refer the reader to Section 4.2 for a discussion on the dependence of the neutrino fluence from the SLSN-characteristic parameters.

The reconstructed neutrino energy for the IC200530 neutrino event is marked with a dotted vertical line, and it falls in the same energy range as the predicted fluence. One can see that, around the reconstructed energy of IC200530, the fluence can vary up to \( O(10^3) \) in magnitude. However, it is worth noting that the reconstructed energy carries an intrinsic uncertainty and may differ from the real energy of the detected neutrino; nevertheless we show it in order to guide the eye.

The muon neutrino and antineutrino event rate expected in IceCube (Equation (20)) is shown in Figure 5 as a function of time. The band in Figure 5 takes into account the uncertainties on the characteristic quantities of AT2019fdr summarized in Table 1. For all SLSN cases within the envelope in Figure 5, the event rate increases rapidly at early times. After the peak, the event rates for the SLSN scenarios representing the edges of the envelope decline because of the dominant decreasing trend of \( v_{\nu} \). The event rate has a steeper or shallower decay. These two different trends are related to the evolution of the shock velocity and the maximum proton energy \( E_{p,\text{max}} \). Indeed, \( E_{p,\text{max}} \) increases up to \( R_{\text{dec}} \) as \( t \) increases and declines later. Since the detector effective area \( A_{\text{eff}} \) increases as a function of \( E_{\nu} \), the rate increases faster. Viceversa, when both \( E_{p,\text{max}} \) and \( v_{\nu} \) decrease, the event rate drops faster. Around the day of detection of IC200530 (marked by a vertical dotted line), the neutrino event rate is expected to vary between \( [1.3 \times 10^{-5}, 3.3 \times 10^{-5}] \) days\(^{-1} \).

It is important to note that only a subsample of the SLSN-parameter set reported in Table 1 allows us to obtain a neutrino
signal compatible with our observational constraints. For example, none of the SLSN scenarios with \( \tilde{E}_k = 10^{53} \text{ erg} \) and \( R_{\text{CSM}} = 2 \times 10^{16} \text{ cm} \) passes our selection criteria, since the shock crosses the CSM envelope in a time shorter than 394 days.

4.2. Dependence of the Neutrino Signal on the Parameters of AT2019fdr

In order to better explore the dependence of the neutrino signal expected in IceCube on \( M_{\text{ej}} \) and \( M_{\text{CSM}} \), for \( \tilde{E}_k = 10^{53} \text{ erg} \), first we investigate the neutrino fluence as a function of \( M_{\text{CSM}} \) for fixed \( R_{\text{CSM}} \) and \( M_{\text{ej}} \), and then we fix \( M_{\text{CSM}} \) and vary \( M_{\text{ej}} \). The choice of \( M_{\text{CSM}} \) and \( M_{\text{ej}} \) is guided by the SLSN configurations that better highlight the changes in the neutrino fluence for \( R_{\text{bo}} \leq R_{\text{dec}} \). From the panel on the left in Figure 6, we see that the fluence increases as \( M_{\text{CSM}} \) increases up to \( M_{\text{CSM}} = 85 M_{\odot} \). For larger \( M_{\text{CSM}} \), \( R_{\text{bo}} > R_{\text{dec}} \) and therefore a turnover with a slow drop can be observed. Furthermore, a slight shift of the neutrino cutoff energy toward lower energies is visible as \( M_{\text{CSM}} \) increases. The latter is due to the enhanced \( pp \) energy loss determined by the larger density as well as the smaller \( \nu_{\text{th}} \), which prevent particles from being accelerated to higher energies (see Equation (22)).

In the right panel of Figure 6, we observe an enhancement of the fluence as \( M_{\text{ej}} \) decreases. Nevertheless, this trend is inverted for \( M_{\text{ej}} \lesssim 13 M_{\odot} \), representative of the regime with \( R_{\text{bo}} > R_{\text{dec}} \), where the lower \( \nu_{\text{th}} \) is responsible for a slight decrease in the neutrino production, together with a shift of the neutrino energy cutoff to lower energies.

Figure 7 shows the temporal evolution of the muon neutrino and antineutrino flux for the scenarios with the highest (left panel) and the lowest (right panel) expected number of neutrinos. In all cases, the flux decreases as the time increases and shifts to lower or higher energies, for the most optimistic and pessimistic scenarios, respectively. Around the day of detection, the flux in the best scenario is a factor \( O(10^5) \) larger than the most pessimistic scenario.

In order to investigate the origin of IC200530, we integrate the event rate over 394 days of the neutrino signal for all selected SLSN configurations and obtain the total number of muon neutrino and antineutrino events, \( N_{\mu,\bar{\mu}} \) (Equation (21)). A contour plot of \( N_{\mu,\bar{\mu}} \) in the plane spanned by \( M_{\text{ej}} \) and \( M_{\text{CSM}} \) is shown in Figure 8 for \( R_{\text{CSM}} = 4 \times 10^{16} \text{ cm} \) and \( \tilde{E}_k = 10^{53} \text{ erg} \) as a representative example. The allowed region of the parameter space is delimited by the solid black line and plotted in orange (with the color gradient representing a low number of events in lighter hues), while the excluded parameter space is displayed in light yellow. The dotted contour lines show how the neutrino number is affected as the line \( R_{\text{bo}} = R_{\text{dec}} \) (along which the cusps of the dotted lines lie) is crossed.

In the region \( R_{\text{dec}} > R_{\text{bo}} \), for fixed \( M_{\text{ej}} \), the number of neutrino events increases as \( M_{\text{CSM}} \) increases; while for fixed \( M_{\text{CSM}} \) and increasing \( M_{\text{ej}} \), we find the opposite trend. The opposite behavior occurs for \( R_{\text{dec}} < R_{\text{bo}} \).

For the SLSN-parameter configurations under consideration, the most optimistic scenarios for the neutrino emission lead to \( N_{\mu,\bar{\mu}} \simeq 4.6 \times 10^2 \); the latter is achieved for relatively low values of \( M_{\text{ej}} = 6-9 M_{\odot} \) and intermediate \( M_{\text{CSM}} = 49-68 M_{\odot} \), with the best scenario corresponding to \( (\tilde{E}_k, R_{\text{CSM}}, M_{\text{ej}}, M_{\text{CSM}}) \simeq (10^{53} \text{ erg}, 4 \times 10^{16} \text{ cm}, 6 M_{\odot}, 49 M_{\odot}) \).

5. Discussion

Table 2 summarizes the total number of muon neutrino and antineutrino events expected within 394 days from the shock breakout from AT2019fdr for the most optimistic and pessimistic SLSN configurations in terms of neutrino emission. The largest [smallest] number of events is obtained for the SLSN configuration with \( (\tilde{E}_k, R_{\text{CSM}}, M_{\text{ej}}, M_{\text{CSM}}) = (10^{53} \text{ erg}, 4 \times 10^{16} \text{ cm}, 6 M_{\odot}, 49 M_{\odot}) \) \([5 \times 10^{52} \text{ erg}, 4 \times 10^{16} \text{ cm, 150 M}_{\odot}, 19 M_{\odot})\], and correspond to the edges of the band in Figure 5.

An important aspect to consider in the interpretation of the neutrino event IC200530 concerns the discrimination of the atmospheric neutrino background, which dominates over the
the optimistic (pessimistic) scenario.

![Figure 7](image1.png)

**Figure 7.** Temporal evolution of muon neutrino and antineutrino flux from AT2019fdr as a function of the neutrino energy for the most optimistic, ($E_{\nu}, R_{\text{CSM}}, M_{\odot}, M_{\text{CSM}}$) = (10^{53} \text{ erg}, 4 \times 10^{16} \text{ cm}, 6 M_{\odot}, 49 M_{\odot}) and pessimistic scenario (5 \times 10^{52} \text{ erg}, 4 \times 10^{16} \text{ cm}, 150 M_{\odot}, 19 M_{\odot}). The reconstructed energy for the IC200530 neutrino event is marked with a dotted vertical. In all cases, the flux decreases with time (growth) of the maximum neutrino energy in the optimistic (pessimistic) scenario.

![Figure 8](image2.png)

**Figure 8.** Contour plot of the total number of muon neutrino and antineutrino events expected in 394 days from the shock breakout from AT2019fdr in 394 days and in the plane spanned by $M_{\text{ej}}$ and $M_{\text{CSM}}$ for $E_{\nu} = 10^{53}$ erg and $R_{\text{CSM}} = 4 \times 10^{16}$ cm. The black solid lines mark the allowed region of the parameter space, defined by requiring that the location of the shock at the day of neutrino production is still in the CSM envelope and that the SLSN-model parameters are compatible with the the light-curve rise time. For fixed $M_{\text{CSM}}$, the total neutrino number decreases as $M_{\text{ej}}$ increases, given the decline of the shock velocity $v_{\text{sh}}$. Viceversa, for fixed $M_{\text{ej}}$, the number increases as $M_{\text{CSM}}$ increases, given the larger number of proton targets for $pp$ interactions. In the region $R_{\text{sh}} > R_{\text{dec}}$, one can see an inverted trend. The dotted lines correspond to the contour lines, which track the scenarios providing the number of neutrino events displayed, and show how the neutrino number is affected in the transition from $R_{\text{sh}} > R_{\text{dec}}$ to $R_{\text{sh}} < R_{\text{dec}}$ regions. See the main text for more details.

The astrophysical neutrino flux below $\approx 100$ TeV. As such, in Table 2 we distinguish between one case with the lower energy cutoff fixed at 100 GeV, mimicking excellent discrimination of the atmospheric neutrino background (see Section 3.3), and one more conservative case with the lower energy cutoff at 100 TeV. The latter case reproduces a situation where the atmospheric neutrino events could not be distinguished from the astrophysical ones in the lower energy range. Although a dedicated likelihood analysis is beyond the scope of this work, the last column of Table 2 reports $N_{\nu_{\mu} + \nu_{\tau}}(N_{\nu_{\mu} + \nu_{\tau}} + N_{\nu_{\mu} + \nu_{\tau}})$, which should give an idea of the expected signalness and gives an indication of the probability that a detected neutrino event could be of astrophysical origin. It is evident that only an optimal discrimination of the atmospheric neutrino background allows us to obtain a signalness of 40%, roughly comparable with that of the neutrino event IC200530. The evolution of the neutrino curve shown in Figure 5 should be considered carefully. In fact, some intermediate SLSN scenarios enclosed in the envelope in Figure 5, and compatible with the reconstructed energy of the neutrino event IC200530A, have an event rate still increasing at the day of detection, therefore increasing the neutrino detection chances at later times, as it is the case for the neutrino event IC200530.

In order to assess whether the number of expected events in Table 2 is compatible with the detection of one neutrino event (IC200530) after 394 days from the shock breakout, we take into account the Eddington bias on neutrino observations. The

| Energy Cut | $N_{\nu_{\mu} + \nu_{\tau}, \text{pessimistic}}$ | $N_{\nu_{\mu} + \nu_{\tau}, \text{optimal}}$ | Signalness |
|------------|---------------------------------|---------------------------------|-----------|
| $E_{\nu_{\mu}} = 100$ GeV | $8 \times 10^{-6}$ | $4.6 \times 10^{-2}$ | $10^{-7}$ – 1% |
| $E_{\nu_{\mu}} = 100$ TeV | $9.5 \times 10^{-9}$ | $4.6 \times 10^{-3}$ | $10^{-7}$ – 40% |

**Note.** The most optimistic and pessimistic scenarios are shown, with the low-energy cutoff fixed at 100 GeV (i.e., excellent discrimination between the astrophysical and atmospheric signals) and 100 TeV (i.e., under the conservative assumption that the atmospheric background could not be eliminated). The most optimistic and pessimistic scenarios correspond to the following SLSN-model parameters: ($E_{\nu}, R_{\text{CSM}}, M_{\text{ej}}, M_{\text{CSM}}$) = (10^{53} \text{ erg}, 4 \times 10^{16} \text{ cm}, 6 M_{\odot}, 49 M_{\odot}) and (5 \times 10^{52} \text{ erg}, 4 \times 10^{16} \text{ cm}, 150 M_{\odot}, 19 M_{\odot}), respectively. In the last column, we estimate the signalness $[N_{\nu_{\mu} + \nu_{\tau}, \text{astro}}(N_{\nu_{\mu} + \nu_{\tau}, \text{astro}} + N_{\nu_{\mu} + \nu_{\tau}, \text{atm}})]$, by computing the number of atmospheric neutrino events over a period of 394 days, for 0.75 around the direction of the source.
Eddington bias must be taken into account when dealing with very small number of neutrino events, such as in this case; we refer the interest reader to Strotjohann et al. (2019) for a dedicated discussion. By relying on the local rate of SLSN IIn provided in Quimby et al. 2013 and integrating over the cosmic background may be challenging, our neutrino energy distribution of AT2019fdr falls in a region where the discrimination of the atmospheric neutrino background may be challenging, our findings hint toward a possible association of the neutrino event IC200530 to AT2019fdr. In addition, our results are compatible with the upper limits on the neutrino emission from the AT2019fdr source placed by the ANTARES Collaboration (Albert et al. 2021).

We should stress that the forecasted number of expected neutrino events includes some caveats related to our modeling. For example, one of the sources of uncertainty in the computation of the neutrino flux is the proton acceleration efficiency \( \varepsilon_p \). In this paper, we have adopted an optimistic \( \varepsilon_p = 0.1 \), assuming that the shocks accelerating protons are parallel or quasi-parallel, and therefore efficient diffusive shock acceleration occurs (Caprioli & Spitkovsky 2014). However, lower values of \( \varepsilon_p \) would be possible for oblique shocks, with poorer particle acceleration efficiency. Values as low as \( \varepsilon_p \approx 0.003-0.01 \) have been inferred in Aydi et al. 2020 for a nova, assuming shocks as the powering source of the simultaneously observed optical and \( \gamma \)-rays. However, observational constraints from other optical transients, including SLSNe, are still lacking; in addition, AT2019fdr is much more luminous than classical novae, possibly hinting to different conditions present in the acceleration region.

We stress that the neutrino flux scales linearly with \( \varepsilon_p \) allowing the reader to easily scale our results. All cases summarized in Table 2 would be compatible with the detection of one neutrino event, after taking into account the Eddington bias. Indeed, the detection of a single neutrino event may actually hint toward intermediate SLSN configurations, as well as values of \( \varepsilon_p \) lower than our benchmark one.

Similarly, in this work, we have assumed that protons are accelerated at the shock to a power law with slope \( k = 2 \), which is predicted by the test particle theory of diffusive shock acceleration. Nonetheless, nonlinear effects involving the amplified magnetic field can kick in, modifying the shock structure and making the cosmic ray spectra mildly steeper than \( k = 2 \) (Caprioli et al. 2021). Larger \( k \) would result in steeper neutrino spectra, since the latter inherit the shape of the parent proton spectrum; as a consequence, lower fluxes should be expected in the energy of interest.

Another caveat to take into account concerns the use of the AT2019fdr discovery date in the observer frame as the breakout time of the shock. In fact, based on the nondetections in the ZTF data, we have assumed an explosion epoch at the first detection at MJD = 58606 ± 6 days on the basis of a fit on the existing data. Nevertheless, even allowing for an onset of the shock breakout to be as much as \( \sim 20 \) days earlier than the first observed light, our predictions in Table 2 would not be affected by a factor larger than 10%.

Since initial submission of this manuscript, other publications have analyzed IC200530 under the paradigm of a TDE origin (Reusch et al. 2021). The additional data presented within these works suggest that an apparent increase in the late-time near-infrared (NIR) emission may be attributed to a dust from the TDE emission. However, increasing late-time NIR emission has been seen in other interacting SNe. For instance, the bright SN IIn SN2010jl exhibits such a NIR increase at late times; high-resolution spectroscopic observations show that this increasing emission was the result of rapid dust formation within the SN ejecta (Gall et al. 2014).

In addition, the vast majority of TDEs show bright X-ray emission over the full optical/UV evolution of an event (e.g., Auchettl et al. 2017; Brown et al. 2017; Wevers et al. 2021; Hinkle et al. 2021). Of those whose emission is dominated by optical/UV but has been detected in X-rays, the X-ray luminosities are an order of magnitude or more fainter than the eROSITA detection (e.g., Holoiien et al. 2019; Jonker et al. 2020; Hung et al. 2020, 2021). In addition, AT2019fdr is found close to the nucleus in a Narrow-Line Seyfert 1 active galaxy (Frederick et al. 2021). Seyfert AGN galaxies are known to exhibit bright X-rays, with a mean X-ray luminosity of \( \sim 10^{43} \) erg s\(^{-1} \) (e.g., Ricci et al. 2017) similar to that detected by eROSITA. Furthermore, Ricci et al. 2017 and references therewithin showed that a significant fraction of unobscured AGN, and particularly those selected in optical, tend to exhibit excess soft X-ray emission that can be best described by an absorbed blackbody. They found that this excess can be well fit with a rest-frame blackbody temperature ranging between \( \sim 0.5-0.25 \) keV, with a mean temperature of \( \sim 0.1 \) keV, which is consistent with the blackbody temperature derived by Reusch et al. (2021). Due to the angular resolution of eROSITA, further high-resolution X-ray observations would be necessary to confirm whether the detected X-ray emission arises from its host galaxy’s AGN or is consistent with the location of AT2019fdr.

If the latter was the case, a detection of X-rays from a SLSN at late times would not be surprising. The total luminosity of the shock and the preshock column density of the CSM medium determines the observation features of high-energy radiation. Unless we are in the presence of extremely high shock temperatures or a high ratio of the shock luminosity to the column density, which would guarantee the CSM ionization to a large extent, the photoelectric absorption is an important energy loss channel for high-energy photons. The latter could explain the nonobservation of X-rays at earlier times (Pan et al. 2013). Unfortunately, as already discussed, there could be degeneracies among the parameters, leading to similar properties of the SLSN light curve. Nevertheless, the slow rise of the optical light curve, the very high luminosity peak, and the nonobservation of X-rays for a considerable amount of time after the first detection would point toward scenarios with highly energetic and relatively low mass ejecta moving through extended high CSM mass stellar winds or shells.

6. Conclusions

The IceCube neutrino event IC200530 has been proposed to be in likely coincidence with the source AT2019fdr located at \( z = 0.2666 \), observed in the ultraviolet and optical bands, and interpreted as a TDE candidate in a Narrow-Line Seyfert 1
galaxy. In this paper, we show that the spectra, light curve, and color evolution of AT2019fdr may be compatible with those of a hydrogen-rich superluminous supernova instead.

Under this assumption, the neutrino event IC200530, detected ~300 days after the peak of the electromagnetic emission and with a reconstructed energy of 80 TeV, may have originated as a result of inelastic proton-proton collisions due to the interaction of the supernova ejecta with the circumstellar medium. We find that approximately $10^{-8} \times 5 \times 10^{-2}$ muon neutrino and antineutrino events could have been produced by AT2019fdr within the timeframe of interest (see Table 2), by taking into account the uncertainties on the total ejecta energetics, the ejecta mass, and the properties of the the circumstellar medium, as well as the uncertainties in the discrimination of the atmospheric and astrophysical neutrino fluxes. By considering the Eddington bias on neutrino observations, our findings may be compatible with the detection of one neutrino event from AT2019fdr.

In conclusion, the neutrino event IC200530 may be associated with the hydrogen-rich superluminous supernova AT2019fdr. As a deeper understanding of the electromagnetic data will become available, neutrinos could be powerful messengers to help to disentangle the nature of AT2019fdr and discover its physics.

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Appendix A

Parameter Space Adopted in the Modeling of AT2019fdr

In this appendix, we investigate how the space of the AT2019fdr parameters reported in Table 1 is constrained by our two selection criteria: (1) the time necessary for the forward shock to cross the CSM envelope between $R_{bo}$ and $R_{CSM}$ is at least 394 days, and (2) the rising time to the peak of the bolometric light curve (see Figure 1) is 98 days in the observer frame.

Because of the approximations involved in the definition of $t_{diff}$ in Equation (13), we take into account an uncertainty of 50% on the diffusion time. Figure 9 shows a contour plot of the

![Figure 9](image-url)
time that the shock takes to travel from $R_{\text{bo}}$ to $R_{\text{CSM}}$ for $\tilde{E}_k = 10^{53}$ erg. We can see that the smaller the CSM width, the shorter the time it takes for the shock to reach $R_{\text{CSM}}$. Indeed, in the left panel of Figure 9, as opposed to the right one, almost half of the SLSN configurations with $M_{ej} \lesssim 70 M_\odot$ and $M_{\text{CSM}} \lesssim 70 M_\odot$ are excluded. This is mainly due to the fact that $R_{\text{bo}} \ll R_{\text{dec}}$ for $M_{ej}/M_{\text{CSM}}$ that is not large, implying that most of the evolution of the shock in the CSM is in the free expansion phase (see Equation (2)), thus with larger velocities. Furthermore, this criterion completely excludes all the configurations with $R_{\text{CSM}} = 2 \times 10^{16}$ cm and $\tilde{E}_k = 10^{53}$ erg. As $R_{\text{CSM}}$ increases (see the right panel of Figure 9), the most stringent constraint comes from the compatibility of $t_{\text{diff}}$ with the observed light curve.

The same trend holds for the case with $\tilde{E}_k = 5 \times 10^{52}$ erg (not shown here), with the difference that there are compatible scenarios with our requirements already for $R_{\text{CSM}} = 2 \times 10^{16}$ cm. For this latter case, for fixed $M_{ej}$, $M_{\text{CSM}}$, and $R_{\text{CSM}}$, the shock velocity $v_{\text{sh}}$ is lower, allowing for longer times required to cross the CSM.

**Appendix B**

**Maximum Proton Energy**

In this appendix, we explore the temporal evolution of $E_{p,\text{max}}$ for the set of parameters $\tilde{E}_k$, $R_{\text{CSM}}$, $M_{ej}$ and $M_{\text{CSM}}$ considered in this work (see Table 1). We provide an idea of the behavior of $E_{p,\text{max}}$ by displaying in Figure 10 the ratio between its value at the CSM radius $R_{\text{CSM}}$ and the breakout radius $R_{\text{bo}}$, for $\tilde{E}_k = 10^{53}$ erg with $R_{\text{CSM}} = 3 \times 10^{16}$ cm (left panel) and $R_{\text{CSM}} = 4 \times 10^{16}$ cm (right panel). In both cases, the region where $E_{p,\text{max}}(R_{\text{CSM}})/E_{p,\text{max}}(R_{\text{bo}}) < 1$ is the one with relatively low values of $M_{ej}/M_{\text{CSM}}$. Here, either $R_{\text{bo}} > R_{\text{dec}}$ or $R_{\text{bo}} \ll R_{\text{dec}}$, meaning that most of the shock evolution occurs in the decelerating phase (see Equation (5)). When this is the case, the acceleration efficiency drops at a faster rate, leading to decreasing $E_{p,\text{max}}$ (see Equation (22)).

On the other hand, for large $M_{ej}/M_{\text{CSM}}$, $R_{\text{dec}} > R_{\text{CSM}}$ is satisfied, implying an increase of $E_{p,\text{max}}$. The intermediate regimes [$M_{ej}/M_{\text{CSM}} \sim O(1)$] are those in which both free expansion and deceleration occur between $R_{\text{bo}}$ and $R_{\text{CSM}}$, in which the latter is shorter compared to the former, and thus leaving the tendency of $E_{p,\text{max}}(R_{\text{CSM}})/E_{p,\text{max}}(R_{\text{bo}})$ to increase unaffected. By keeping $E_{\text{ej}}, M_{ej}$ and $M_{\text{CSM}}$ fixed, a larger $R_{\text{CSM}}$ leads to a lower CSM density, with longer $t_{\text{pp}}$; thus, a larger $E_{p,\text{max}}(R_{\text{CSM}})$ is achievable. This effect is more significant than the slight increase of $E_{p,\text{max}}(R_{\text{bo}})$ for larger $R_{\text{CSM}}$

Finally, lower values of $\tilde{E}_k$ do not compromise the overall trend outlined above. The only effect of decreasing the energy, while keeping all other parameters fixed, is to reduce $v_{\text{sh}}$ (see Equation (2)) and in turn the acceleration rate, which result in overall smaller values of $E_{p,\text{max}}$.

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**References**

Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2017, ApJ, 835, 45
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2018a, PhRvD, 98, 062003
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2018b, Sci, 361, eaat1378
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2020, PhRvL, 125, 121104
Abbas, R., Ackermann, M., Adams, J., et al. 2021a, arXiv:2101.09836
Abbas, R., Ackermann, M., Adams, J., et al. 2021b, PhRvD, 104, 022002
Abbas, R., Ackermann, M., Adams, J., et al. 2021c, ApJ, 910, 4
Aciari, V. A., Ansoldi, S., Antonelli, L. A., et al. 2021, in Proc. of 37th Int. Cosmic Ray Conf., PoS (ICRC2021), 395, 960
Aghanim, N., Akrami, Y., Ashdown, M., et al. 2020, A&A, 641, A6
Ahlers, M., & Halzen, F. 2018, PrPNP, 102, 73
Albert, A., Alves, S., André, M., et al. 2021, arXiv:2103.15526
Anchordoqui, L. A., Barger, V., Cholis, I., et al. 2014, JHEAp, 1, 1
Auchettl, K., Guillochon, J., & Ramirez-Ruiz, E. 2017, ApJ, 838, 149
