NEUTRINO SIGNAL OF COLLAPSE-INDUCED THERMONUCLEAR SUPERNOVAE: THE CASE FOR PROMPT BLACK HOLE FORMATION IN SN 1987A

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ABSTRACT

Collapse-induced thermonuclear explosion (CITE) may explain core-collapse supernovae (CCSNe). We analyze the neutrino signal in CITE and compare it to the neutrino burst of SN 1987A. For strong ($\gtrsim 10^{51}$ erg) CCSNe, such as SN 1987A, CITE predicts a proto-neutron star (PNS) accretion phase lasting up to a few seconds that is cut off by black hole (BH) formation. The neutrino luminosity can later be revived by accretion disk emission after a delay time of a few to a few tens of seconds. In contrast, the neutrino mechanism for CCSNe predicts a short ($\lesssim 5$ s) PNS accretion phase, followed by slowly declining PNS cooling luminosity. We repeat statistical analyses used in the literature to interpret the neutrino mechanism, and apply them to CITE. The first 1–2 s of the neutrino burst are equally compatible with CITE and with the neutrino mechanism. However, the data points toward a luminosity drop at $t = 2–3$ s, which is in some tension with the neutrino mechanism but can be naturally attributed to BH formation in CITE. The occurrence of neutrino signal events at 5 s suggests that, within CITE, the accretion disk formed by that time. We perform two-dimensional numerical simulations showing that CITE may be able to accommodate this disk formation time while reproducing the ejected $^{56}$Ni mass and ejecta kinetic energy within factors of 2–3 of observations. We estimate the accretion disk neutrino luminosity, finding it to be on the low side but compatible with the data to a factor of 10. Given comparable uncertainties in the disk luminosity simulation, we conclude that direct BH formation may have occurred in SN 1987A.

Key words: accretion, accretion disks – stars: black holes – supernovae: general

1. INTRODUCTION

There is strong evidence that SNe II are explosions of massive stars initiated by the gravitational collapse of the stars’ iron core (Burbridge et al. 1957; Hirata et al. 1987; Smartt 2009). It is widely thought that the explosion occurs due to the deposition in the envelope of a small fraction ($\sim 1\%$) of the gravitational energy ($\sim 10^{51}$ erg) released in neutrons from the core, leading to the $\sim 10^{51}$ erg observed kinetic energy ($E_{\text{kin}}$) of the ejected material (see Bethe 1990; Janka 2012, for reviews). However, one-dimensional (1D) simulations indicate that the neutrons do not deposit sufficient energy in the envelope to produce the typical $E_{\text{kin}} \sim 10^{51}$ erg. While two-dimensional (2D) studies indicate successful explosions (Bruenn et al. 2013, 2016; Nakamura et al. 2015; Suwa et al. 2016), others indicate failures or weak explosions (Takiwaki et al. 2014; Dolence et al. 2015), and these studies are affected by the assumption of rotational symmetry and by an inverse turbulent energy cascade which, unlike many physical systems, appears to amplify energy on large scales. Therefore, three-dimensional (3D) studies are necessary to satisfactorily demonstrate the neutrino mechanism, but 3D studies have so far resulted in either failures or weak explosions (Takiwaki et al. 2014; Lentz et al. 2015; Melson et al. 2015a, 2015b).

Burbridge et al. (1957) suggested a different mechanism for the explosion that does not involve the emitted neutrons. They suggested that the adiabatic heating of the outer stellar shells as they collapse triggers a thermonuclear explosion (see also Hoyle & Fowler 1960; Fowler & Hoyle 1964). This collapse-induced thermonuclear explosion (CITE) has the advantage of naturally producing $E_{\text{kin}} \sim 10^{51}$ erg from the thermonuclear burning of $\sim M_{\odot}$ of light elements with a gain of $\sim$ MeV per nucleon. A few 1D studies have suggested that this mechanism does not lead to an explosion because the detonation wave is ignited in a supersonic in-falling flow (Colgate & White 1966; Woosley & Weaver 1982; Bodenheimer & Woosley 1983), and the idea was subsequently abandoned. While the results of these studies are discouraging, they only demonstrate that some specific initial stellar profiles do not lead to CITE and they do not prove that CITE is impossible for all profiles.

Recently, Kushnir & Katz (2015) have shown that CITE is possible in some (tuned) 1D initial profiles that include shells of mixed helium and oxygen, but these profiles result in weak explosions, $E_{\text{kin}} \lesssim 10^{50}$ erg, and negligible amounts of ejected $^{56}$Ni. Subsequently, Kushnir (2015a) used 2D simulations of rotating massive stars to explore the conditions required for CITE to operate successfully. It was found that for stellar cores that include slowly (a few percent of breakup) rotating shells of mixed He–O with densities of $\sim 10^{3}$ g cm$^{-3}$, a thermonuclear detonation that unbinds the stars’ outer layers is obtained. With a series of simulations that cover a wide range of progenitor masses and profiles, it was shown that CITE is a robust process that leads to supernova explosions for rotating massive stars. The resulting explosions have $E_{\text{kin}}$ in the range of $10^{49}$–$10^{52}$ erg and ejected $^{56}$Ni masses ($M_{\text{Ni}}$) of up to $\sim 1 M_{\odot}$, both of which cover the observed ranges of core-collapse supernovae (CCSNe, including types II and Ibc).

It is difficult to test observationally if the initial conditions required for CITE exist in nature. Nevertheless, CITE makes a few predictions that are different from the predictions of the neutrino mechanism and that can be compared to observations. For example, CITE predicts that stronger explosions (i.e., larger $E_{\text{kin}}$ and higher $M_{\text{Ni}}$) are obtained from progenitors with higher pre-collapse masses. Kushnir (2015b) showed that the observed correlation between $M_{\text{Ni}}$ and the luminosities of the
progenitors for SNe II is in agreement with the prediction of CITE and possibly contradicts the neutrino mechanism. Another prediction of CITE is that neutron stars (NSs) are produced in weak ($E_{\text{kin}} \lesssim 10^{51} \text{erg}$) explosions, while strong ($E_{\text{kin}} \gtrsim 10^{51} \text{erg}$) explosions leave a black hole (BH) remnant. This prediction suggests that a BH was formed in SN 1987A ($E_{\text{kin}} \approx 1.5 \times 10^{51} \text{erg}$; Utrobin & Chugai 2011) during the first few seconds after core collapse (direct BH formation, to be distinguished from BH formation from fallback, which lasts hours to days). In contrast, simulations based on artificially triggered explosions within the neutrino mechanism predict that the compact object in SN 1987A is an NS (see, e.g., Perego et al. 2015). At the time this paper was written, no NS had been detected at the cite of SN 1987A (Graves et al. 2005; Larsson et al. 2011), but see Zanardo et al. (2014) for a possible recent hint.

In this paper, we continue to explore the observational consequences of CITE. We focus on the neutrino signal and derive constraints from the neutrino burst that accompanied SN 1987A (Bionta et al. 1987; Hirata et al. 1987). Specifically, we ask, and begin to answer, the following two questions.

1. As mentioned above, CITE predicts that a BH was formed directly during the event of SN 1987A. The reason for this expectation is that a strong explosion ($E_{\text{kin}} \gtrsim 10^{51} \text{erg}$) requires a high mass for the He–O shell ($\gtrsim 1 M_\odot$), which in turn requires a massive core ($\gtrsim 4 M_\odot$) below the shell. By the time CITE operates (on the order of the free-fall time of the He–O layer ~30 s), the mass below the He–O shell accretes onto the central proto-neutron star (PNS), topping the critical mass and turning it into a BH (within ~1–3 s; O’Connor & Ott 2011).

Direct BH formation in SN 1987A has previously been considered to be unlikely, as it was argued to abruptly terminate the PNS neutrino emission. This would be incompatible with the detection of neutrinos at later times (Burrows 1988; Loredo & Lamb 2002); as we review below, neutrino signal events were detected 5–10 s after core collapse. Our first question is as follows.

Does this argument rule out CITE?

Here, we show that the answer is negative. CITE, and more generally direct BH formation, can be reconciled with the SN 1987A neutrino signal. Even though BH formation should indeed temporarily quench the neutrino burst, the subsequent formation of an accretion disk around the BH can produce a neutrino luminosity consistent with observations.

The fact that the accretion disk during stellar collapse can produce the required late-time neutrino luminosity should come as no surprise. Similar scenarios have been investigated in the literature in the context of the collapsar model for gamma-ray bursts (GRBs; MacFadyen & Woosley 1999), and the resulting disks have been shown to exhibit copious neutrino emission (MacFadyen & Woosley 1999; Popham et al. 1999; Chen & Beloborodov 2007; Liu et al. 2015). It is interesting to note that Loredo & Lamb (2002), in their analysis of SN 1987A, found that direct BH formation is favored by the neutrino data, but they set a prior against this possibility. Here, we repeat a similar likelihood analysis of SN 1987A and show that CITE can indeed provide a somewhat better fit to the data.

2. A key to CITE is the formation of a rotationally induced accretion shock (RIAS) during the collapse of the stellar envelope below the He–O layer (Kushnir 2015a). The RIAS provides the match for thermonuclear explosion. Importantly for us here, the RIAS formation time is precisely the formation time of the accretion disk that is needed to restart the neutrino luminosity after BH formation. As mentioned above, the SN 1987A data implies that the accretion disk neutrino luminosity should be operative by $t \sim 5$ s. Our second question is as follows.

Can CITE operate successfully with an RIAS formation time as early as a few seconds?

Kushnir (2015a) conducted preliminary studies of the dependence of CITE on the pre-collapse stellar profile, but for profiles which resulted in strong explosions ($E_{\text{kin}} > 10^{51} \text{erg}$) the RIAS formation times considered there were significantly larger than 5 s. Here, we extend the analysis of Kushnir (2015a) using further numerical simulations. Guided by the neutrino data of SN 1987A, we tailor the initial profile to initiate neutrino emission from a disk at $t_{\text{disk}} \approx 5$ s. With this $t_{\text{disk}}$ constraint, we are able to find a profile in which CITE operates and yields values of $M_{\text{NS}} \sim 0.035 M_\odot$ and $E_{\text{kin}} \sim 0.6 \times 10^{51} \text{erg}$, in the ballpark of, though a factor of 2–3 below, observations for SN 1987A (Hamuy 2003; Utrobin & Chugai 2011).

We further estimate the neutrino emission from the accretion disk at the base of the RIAS, finding a $\nu_\nu$ luminosity of about $L_{\nu_\nu} \sim 0.5 \times 10^{51} \text{erg s}^{-1}$ and a mean neutrino energy of ~10 MeV. These results are on the low side, but are not inconsistent with the range allowed by the data. While more simulations are needed for conclusive results, our preliminary findings indicate that CITE can operate in rough agreement with the neutrino data of SN 1987A.

In Section 2, we review the neutrino light curve from SN 1987A, recalling the signal events at 5–10 s that place an important constraint on CITE. We further note a hint for a drop in $\nu_\nu$ luminosity around $t \sim 2$ s, and examine it in Section 2.1. While the luminosity drop is not very statistically significant, we find it interesting to repeat a likelihood analysis as in Loredo & Lamb (2002) and Pagliaroli et al. (2009) for the neutrino mechanism, but focusing on interpretation within CITE. In Section 2.2, we show that the neutrino mechanism is in some tension with the luminosity drop, i.e., of the order of two standard deviations. In Section 2.3, we provide a toy model parameterization of the neutrino burst expected in CITE with the same number of free parameters as used in Loredo & Lamb (2002) and in Pagliaroli et al. (2009) to describe the neutrino mechanism. The CITE model is fit to data with reasonable parameters and naturally addresses the luminosity drop at $t \sim 2$ s.

In Section 3, we use 2D numerical simulations to demonstrate that CITE can operate successfully with early RIAS formation time $t_{\text{disk}} \sim 5$ s, yielding $E_{\text{kin}}$ and $M_{\text{NS}}$ in rough agreement with SN 1987A. We show that the BH accretion disk at the base of the RIAS can revive the neutrino emission with luminosity in the ballpark seen in the data. We conclude in Section 4. In the Appendix, we recap some of the details of the

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4 Another frequent argument in the literature (see, e.g., Mirizzi et al. 2016) is that BH formation would not be compatible with the neutrino mechanism for the explosion. This argument is of course irrelevant to our analysis here.
2. SN 1987A NEUTRINO DATA

Figure 1 depicts the time series of the SN 1987A neutrino burst. Blue (diamond), red (circle), and black (cross) markers denote the reconstructed event energies for the Kamiokande, IMB, and Baksan detectors, respectively, with 1σ error bars. Horizontal blue line denotes the traditional 7.5 MeV threshold imposed in analyses of the Kamiokande data. Note that the three time series are offset by unknown relative delays, likely of the order of 100 ms; here, we set these delays to zero.

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phenomenological modeling of the neutrino mechanism and add some more statistical analyses.

2.1. A Luminosity Drop at t ∼ 2 s?

To obtain a basic assessment of the neutrino source luminosity, we make two simplifying assumptions. (i) We assume that the neutrino distribution function at the source is a modified Fermi–Dirac spectrum with instantaneous temperature $T(t)$ and $\bar{\nu}_e$ luminosity $L_{\bar{\nu}_e}(t)$:

$$\frac{dN_{\bar{\nu}_e}(t)}{dEdt} = \frac{L_{\bar{\nu}_e}(t)}{c_T(\alpha)P_2(t)} \frac{(E/T(t))^{2+\alpha}}{\exp (E/T(t)) + 1},$$

where $\alpha$ is a normalization constant. The mean $\bar{\nu}_e$ energy for this spectrum is

$$x_{\bar{\nu}_e}(t) = \frac{\langle E_{\bar{\nu}_e}(t) \rangle}{c_T(\alpha)T(t)}$$

with $c_T(\alpha) = c_T(\alpha)/c_T(\alpha - 1)$. We set $\alpha = 2$. The superscript on $dN_{\bar{\nu}_e}/dEdt$ denotes the spectrum at the source, before neutrino flavor mixing.

(ii) We neglect the contribution of $\nu_\mu$ and $\nu_\tau$ at the source. Using Equation (1), we compute the $\bar{\nu}_e$ differential flux at the detector,

$$\Phi_{\bar{\nu}_e}(t) = \frac{P_{\bar{\nu}_e}}{4\pi D_{SN}^2} \frac{dN_{\bar{\nu}_e}(t)}{dEdt},$$

with the electron antineutrino survival probability $P_{\bar{\nu}_e} = 0.67$ and with $D_{SN} = 50$ kpc the distance to SN 1987A.

We perform a Poisson likelihood analysis for the Kamiokande, IMB, and Baksan neutrino data of SN 1987A, including background and detector efficiency effects. We implement the analysis suggested in Pagliaroli et al. (2009) and Ianni et al. (2009) that modifies the method of Loredo & Lamb (2002) in the treatment of detector efficiency. We include only the dominant inverse-beta decay (IBD) reaction (Strumia & Vissani 2003). For detector efficiency and backgrounds, we use the updates given by Vissani (2015).

5 We also note that Kamiokande observed four additional events at times 17.6, 20.3, 21.4, and 23.8 s, with energies of 6.5, 5.4, 4.6, and 6.5 MeV, respectively. These late-time events were below the threshold for the original Kamiokande analysis. Nevertheless, they were included (together with proper background treatment) in the likelihood analysis of Loredo & Lamb (2002). Pagliaroli et al. (2009), and Ianni et al. (2009), and though we do not show them in Figure 1, we include these events in our analysis too.

6 For reference, $c_T(0) \approx 5.68$, $c_T(2) \approx 118.26$, $c_T(0) \approx 3.15$, and $c_T(2) \approx 5.07$. subsequent reduced luminosity on times $t > 5$ s. In fact, there is a time gap between the Kamiokande event at $t = 1.9$ s and the next Kamiokande events at $t > 9$ s. A comparably significant gap (the statement of significance requires modeling that we provide later) exists between the IMB event at $t = 2.7$ s and the next pair of events at $t = 5$ and 5.6 s.

The time gaps in the neutrino data were noted in, e.g., Spergel et al. (1987), Lattimer & Yahil (1989), and Suzuki & Sato (1988). Spergel et al. (1987) commented on the possible hint for a discontinuity, but fit a continuous exponential PNS cooling model to the neutrino light curve, finding a reasonable global fit. We have redone the analysis of Spergel et al. (1987) and agree with their numbers. Indeed, the SN 1987A neutrino data is too sparse for conclusive detailed modeling. However, it is important to note that Spergel et al. (1987) and other analyses (such as, e.g., Loredo & Lamb 2002; Ianni et al. 2009; Pagliaroli et al. 2009) did not have a theoretical model contender to the PNS accretion and cooling luminosity predicted within the neutrino mechanism. The situation for us is different. A time gap in the neutrino data, with intense PNS luminosity for $t \lesssim T_{BH} \sim 1$–3 s, silence for a few seconds, and renewed accretion disk luminosity, is precisely what we expect from CITET. In the next subsections, we explore this point further with some statistical analyses.
Our first analysis of the data is as follows. We split the full neutrino event time series (16 events in Kamiokande, 8 events in IMB, and 5 events in Baksan) into 8 time bins of equal log-space duration delimited by [0, 0.25, 0.5, 1, 2, 4, 8, 16, 32] s. In each time bin, centered around the time \( t \), we fix the source parameters \( L_\nu(t) \) and \( T(t) \) to constant values \( L_i \), \( T_i \), which are independent from bin to bin. We then perform a bin by bin likelihood analysis in the two source parameters \( L_i \) and \( T_i \).

Figure 2 shows the result for the fitted source luminosity \( L_\nu \). In each bin, the blue error bar marker denotes the best-fit luminosity, with the thick (thin) vertical error bars obtained by fixing \( T_i \) to its best-fit point and letting \( L_i \) vary within \( \Delta \chi^2 < 1 \) (\( \Delta \chi^2 < 4 \)). The black circles are explained in the Appendix, and are not important for the discussion in this section.) The horizontal bars denote the time bin duration. The time gap in Figure 1 is reproduced in Figure 2 as an order of magnitude drop in the \( \nu_e \) luminosity around \( t \sim 2 \) s.

Regarding our parameterization in Equations (1)–(2), other assumptions about neutrino flavor mixing or source flavor composition can be made by reinterpreting the product \( P_\nu L_\nu \). Our results are not affected significantly by the choice of \( \alpha \). A plain thermal spectrum would have \( \alpha = 0 \). Our choice of \( \alpha = 2 \) applies if the dominant \( \nu_e \) source is \( e^+ e^- \to p\bar{p} \) from a plasma containing free nucleons and \( e^- \) pairs, a reasonable scenario if the luminosity is dominated by accreting matter (see, e.g., Perego et al. 2015). Contributions due to \( \nu_\mu \) and \( \nu_\tau \) are straightforward to include and do not affect our conclusions. Finally, our parametrization of neutrino mixing ignores possibly important matter and neutrino self-induced oscillation effects (see, e.g., Kartavtsev et al. 2015; Mirizzi et al. 2016). Our choice of \( P_ee = 0.67 \approx \cos^2 \theta_{12} \) applies for normal mass hierarchy, with a strong matter effect causing adiabatic alignment of the \( \nu_e \) flavor state with the mass eigenstate \( \nu_1 \) (Fogli et al. 2002). We chose this treatment of flavor conversion mainly to facilitate comparison with previous work that used the same prescription (Loredo & Lamb 2002; Ianni et al. 2009; Pagliaroli et al. 2009).

We now wish to compare different theoretical models for the supernova. In Section 2.2, we follow Loredo & Lamb (2002) and Pagliaroli et al. (2009) and perform a likelihood analysis of the neutrino mechanism using phenomenological models. In Section 2.3, we devise analogous models with the same number of free parameters for the neutrino luminosity expected in CITE. We compare the performance of CITE models to that of the neutrino mechanism.

### 2.2. Neutrino Mechanism

Calculations within the neutrino mechanism suggest that the supernova explosion, if it is to occur at all, should occur within a few hundred milliseconds after core collapse (see, e.g., O’Connor & Ott 2011; Pejcha & Thompson 2015). Before the explosion, the accretion of the stellar envelope onto the PNS produces an accretion luminosity with nontrivial time dependence that (for \( \nu_e \) and \( \nu_x \)) can dominate over the cooling luminosity of the PNS. However, after the explosion has cleared away the accreting matter, for post-bounce times \( t > 1 \) s, the neutrino mechanism has a robust prediction of continuous PNS cooling luminosity that is slowly decreasing with a characteristic timescale of a few seconds.

Pagliaroli et al. (2009) used phenomenological models of the neutrino flux to represent the predictions of the neutrino mechanism. The main models discussed there were the following: (i) simple exponential cooling of the PNS (EC model, details in Appendix), and (ii) exponential cooling + truncated accretion model (ECTA model, details in Appendix), with more free parameters added to describe the early accretion phase, which is truncated by hand at \( t_{\text{accretion}} = 0.55 \) s. We have reproduced the best-fit points for the ECTA and EC models, in agreement with Pagliaroli et al. (2009). We also reproduce the Poisson likelihood difference \( \Delta \chi^2 \approx -10 \) in favor of the ECTA model best-fit point as compared to that of the EC model. This statistical preference for the ECTA model led Loredo & Lamb (2002) and Pagliaroli et al. (2009) to argue that the data provides evidence for an early accretion phase on time \( t \lesssim 0.5 \) s.

Loredo & Lamb (2002) and Pagliaroli et al. (2009) did not have a model that could address a sharp luminosity drop at time \( t > 1 \) s. It is interesting to re-inspect their results, keeping in mind CITE as an alternative theory. The neutrino time series as shown in Figure 1 has no events in either Kamiokande or IMB\(^8\) during the time \( t = 2.7–5 \) s. We can use the best-fit EC and ECTA models of Pagliaroli et al. (2009) to calculate the Poisson probability for observing no events during this time. The results are given in Table 1. For the EC (ECTA) model, this probability is 0.4% (2.2%).

We learn that the time gap is somewhat unlikely from the point of view of the neutrino mechanism. In fact, we suspect that the improved global likelihood of the ECTA model, interpreted in Loredo & Lamb (2002) and in Pagliaroli et al. (2009) as evidence for an early accretion phase, may actually be driven to some extent by the need to not overshoot the late-time luminosity gap at \( t > 2 \) s. To clarify this point, in the Appendix, we construct a binned Monte Carlo (MC) analysis

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\(^{7}\) We find it more informative for our current purpose to plot the instantaneous mean luminosity \( L_\nu \) in each bin, rather than the energy per bin \( tL_\nu \), despite the logarithmic bin assignment. We thank John Beacom for discussion on this point.

\(^{8}\) There were no events in Baksan, either, for this time period.
Table 1: Poisson Probability for the Neutrino Data During $t = 2.7–5$ s

| Model       | Kamiokande | IMB | Poisson Probability |
|-------------|------------|-----|---------------------|
| EC ($\nu$ mechanism) | 3.65       | 1.56 | 0.4%                |
| ECTA ($\nu$ mechanism) | 2.23       | 1.17 | 2.2%                |
| CITE        | 0.03       | 0.01 | 62%                 |

Note. For each theoretical model, we calculate the number of signal events expected in each detector during this time. The Poisson probability for observing no events is given in the last column. IMB is assumed to have zero background. We take the threshold energy $E_{\text{th}} = 4.5$ MeV for Kamiokande, with which we expect 0.43 background events during $t = 2.7–5$ s.

that provides time-dependent information on the performance of the fit.

2.3. CITE: Accretion for $\sim 2–3 \text{ s}$, then BH Formation

The neutrino luminosity in CITE, for a progenitor star relevant to SN 1987A and skipping the abrupt initial $\nu_e$ deleptonization burst that is unimportant for our purpose, follows three main phases.

1. PNS forms on core collapse, followed by accretion through a quasi-static accretion shock. This is the usual stalled shock of the core bounce. Electron-flavor neutrino luminosity is dominated by nucleon conversion reactions with $L_{\nu_e} \approx L_{\nu_x}$, where

$$L_{\nu_e} \approx \frac{GM_{\text{ms}} M_{\text{ms}}}{2 R_{\text{ms}}} \sim 10^{52} \left(\frac{M_{\text{ms}}}{2 M_\odot}\right) \left(\frac{M_{\text{ms}}}{0.1 M_\odot}\right) \left(\frac{25 \text{ km}}{R_{\text{ms}}}\right) \text{ erg s}^{-1}.$$

PNS cooling produces additional luminosity $L_x \sim (0.3 - 0.6) L_{\nu_x}$, with $L_{\nu_x} \approx L_{\nu_x} \approx L_{\nu_x} \approx L_{\nu_x} \approx L_{\nu_x}$. State-of-the-art examples are presented in Perego et al. (2015) and Mirizzi et al. (2016). The accretion phase lasts for $1–3$ s after bounce, until the PNS accumulates baryonic mass $\sim 2–3 M_\odot$ (depending on details of the equation of state; O’Connor & Ott 2011) leading to BH formation.

2. BH forms, absorbing the matter downstream to the accretion shock on a timescale of milliseconds. Spherical accretion directly onto the BH produces small neutrino luminosity, $L_{\nu_e} \lesssim 10^{47} \text{ erg s}^{-1}$, because the accreting matter in the absence of a shock does not have time to radiate its gravitational binding energy before it goes through the horizon (or, from the perspective of an observer at infinity, gets redshifted to nothing). Thus, BH formation leads to an abrupt cut-off in the neutrino luminosity.

3. A quiescent phase, corresponding to quasi-spherical accretion on the BH, should begin at $t_{\text{BH}}$ and last for $\sim 1–10$ s. However, for CITE to work (Kushnir 2015a), angular momentum in the envelope must produce a centrifugal barrier, leading to an accretion disk and to the launch of the RIAS that propagates outward and eventually triggers the explosion. Matter in the disk at the base of the RIAS heats up and re-initiates neutrino emission, dominated again by nucleon conversion reactions and potentially reaching $\sim 10^{51} \text{ erg s}^{-1}$.

We construct a toy phenomenological parametrization for the neutrino luminosity of SN 1987A in CITE, in the spirit of the neutrino mechanism analysis of Loredo & Lamb (2002) and Pagliaroli et al. (2009). We use six free parameters, the same number of parameters as used in Loredo & Lamb (2002) and in Pagliaroli et al. (2009), to define the ECTA model of the neutrino mechanism.

Two of our parameters define the basic CITE timescales: $t_{\text{BH}}$ denoting BH formation, and $t_{\text{disk}}$ denoting accretion disk formation (and launch of the RIAS). To model the PNS accretion phase (phase 1 above), we build on the simulations of Perego et al. (2015) for their HC19.2 pre-supernova progenitor model, when their artificial trigger (denoted “PUSH” in Perego et al. 2015) is not used to start an explosion. We define two parameters, $f_{\text{L}}$ and $f_E$. During the interval $0 < t < 0.8$ s, where Perego et al. (2015) provided numerical results, our model luminosity is $L_{\nu_e}(t) = f_{\text{L}} L_{\text{E}19.2}^{\text{HC}}(t)$, $L_x(t) = f_{\nu_e} L_{\nu_e}^{\text{HC}}(t)$, with mean neutrino energy $\langle E_{\nu_e}(t) \rangle = f_{\text{L}} \times \langle E_{\nu_e}^{\text{HC}}\rangle(t)$, $\langle E_x(t) \rangle = f_{\nu_e} \times \langle E_x^{\text{HC}}\rangle(t)$. Here, $L_{\nu_e}^{\text{HC}}$ is the $\nu_e$ luminosity reported by Perego et al. (2015), etc. For $0.8 < t < t_{\text{BH}}$ (where Perego et al. 2015, did not provide numerical results), we let the luminosity decrease as $L_{\nu_e}(t) = L_{\nu_e}(t_{\text{BH}}) \times 1/t$, while the energies are set to rise linearly $\langle E_{\nu_e}(t) \rangle, \langle E_x(t) \rangle \propto t$. For $t > t_{\text{BH}}$, we set $L_{\nu_e}(t) = 0$, and $L_{\nu_e}(t) = \frac{2\nu_{\text{disk}}}{k - \nu_{\text{disk}}} (1 - e^{-D_{\text{disk}}/t})$ with $k = 100$. This form gives a fast rise for the accretion disk $\nu_e$, which is consistent with what we find in our numerical simulations in the next section. The mean energy during the disk phase is $\langle E_{\nu_e}(t) \rangle = \frac{2\nu_{\text{disk}}}{k - \nu_{\text{disk}}}.$

To summarize, our six free parameters are the following: (1) $t_{\text{BH}}$ and $t_{\text{disk}}$ denoting BH and subsequent disk formation times; (2) $f_{\text{L}}$ and $f_{\nu_e}$, which are constant factors by which we modulate the numerical results for the HC19.2 SN 1987A progenitor model of Perego et al. (2015) to obtain the luminosity before BH formation; and (5) $L_{\nu_{\text{disk}}}$ and (6) $E_{\nu_{\text{disk}}}$ characterizing the late neutrino emission of the accretion disk around the BH.

Calculating the likelihood for our CITE parametrization, we find several configurations with Poisson likelihood superior to the best-fit ECTA model of Pagliaroli et al. (2009). For instance, the following model,

\begin{align}
\text{CITE:} & & t_{\text{BH}} = 2.7 \text{ s}, & & t_{\text{disk}} = 5 \text{ s}, & & f_{\text{L}} = 0.67, & & f_{\nu_e} = 0.56, \\
L_{\nu_{\text{disk}}} = 4 \times 10^{51} \text{ erg s}^{-1}, & & E_{\nu_{\text{disk}}} = 15 \text{ MeV},
\end{align}

has $\Delta \chi^2$ smaller by 6.8 compared to the ECTA model of the neutrino mechanism. For comparison, within the neutrino mechanism, the ECTA model has $\Delta \chi^2$ smaller by 9.8 than that of the EC model, with the latter having three parameters less; this was considered in Loredo & Lamb (2002) and in Pagliaroli et al. (2009) as evidence for an accretion phase.

Our CITE model is obviously consistent with no events during the time $t = 2.7–5$ s. We give the Poisson probability in Table 1. Compared to the neutrino mechanism, the 2.7–5 s time gap is the source for the improved likelihood of CITE. In the Appendix, we repeat our binned MC analysis for the model in Equation (3). Incidentally, as we have based the first second of our CITE model light curve on the non-exploding numerical simulation of Perego et al. (2015), it is safe to say that the early time neutrino data does not require a transition between accretion luminosity to PNS cooling luminosity. Continued accretion is consistent with the data.

While we did not specify the CITE explosion time, the explosion should occur within about $\Delta t_{\text{CITE}} \sim 20$ s of core collapse, corresponding roughly to the free-fall time of the He-
O layer (in the numerical simulations of Section 3.2 below, for example, explosion is obtained at $t_{\text{CITE}} \approx 25$ s). The disk luminosity is expected to be cut-off at $t_{\text{CITE}}$ by the explosion, preventing further accretion. By this time, our accretion disk model above has radiated a total energy of $E_{\text{tot, disk}} \approx 2 L_{\text{disk}} t_{\text{disk}} \ln \left( \frac{1 + \frac{t_{\text{CITE}}}{2}}{2} \right) \approx 4 \times 10^{52}$ erg in $t_d$, and a similar amount in $\nu_e$. These numbers are comparable to the (per flavor) total energy inferred in Pagliaroli et al. (2009) for the PNS cooling phase in the neutrino mechanism. The total energy emitted in neutrinos is important for and constrained by the PNS cooling phase in the neutrino mechanism. The total energy $E_{\text{disk}}$ in the disk luminosity, our results are consistent with DSNB limits (see Figure 6 in Beacom 2010), but the potential sensitivity of the disk emission phase to the explosion cut-off merits further work to study if some initial stellar profiles can be ruled out by DSNB in CITE.

Finally, we comment on the fit results in (3).

1. The value of $t_{\text{BH}} = 2.7$ s is in good agreement with progenitor models as in Perego et al. (2015). We view $t_{\text{finit}} \sim 1 \pm 3$ s as a prediction of CITE for strong explosions, as can be seen form analytical estimates as well as numerical simulations (O’Connor & Ott 2011). We view the requirement $t_{\text{disk}} = 5$ s as an observational constraint on CITE, at least when attempting to interpret SN 1987A IMB data. We analyze the implications of this constraint further in the next section. We do not see anything particularly unnatural with $t_{\text{disk}}$ of a few seconds as long as CITE can operate successfully. However, we should stress that while the formation of the disk, by itself, is a built-in ingredient in CITE, the precise timing $t_{\text{disk}} = 5$ s we deduce here from the neutrino data is not a generic a priori prediction of the model: as seen in Kushnir (2015), CITE could operate just as well with $t_{\text{disk}} > 10$ s. This is to be contrasted with the more robust prediction of $t_{\text{BH}}$ in the previous item.

2. The values of $f_\nu$ and $f_\nu$ we find correspond to moderate modulation of the results of Perego et al. (2015). Much larger modulations could arise from varying the input pre-collapse profile within observational constraints.

3. Finally, the best-fit disk neutrino energy $E_{\text{disk}}$ is higher by about a factor of 2, and the best-fit disk neutrino luminosity $L_{\text{disk}}$ is higher by about an order of magnitude than our estimate of the disk emission in the next section. However, these parameters are not tightly constrained by the data. For example, keeping the other parameters at the same value as in (3) but reducing $L_{\text{disk}}$ to $10^{51}$ erg s$^{-1}$ gives Poisson likelihood for CITE that is worse by $\Delta \chi^2 \approx 6.2$ compared to the $L_{\text{disk}} = 4 \times 10^{51}$ erg s$^{-1}$ of (3), but still improved by $\Delta \chi^2 \approx 0.6$ compared to the analogous ECTA model of the neutrino mechanism. Varying both $L_{\text{disk}}$ and $E_{\text{disk}}$ within $\Delta \chi^2 = 4$ around the reference values in (3) we find values in the range $L_{\text{disk}} \sim (1-10) \times 10^{51}$ erg s$^{-1}$ and $E_{\text{disk}} \sim 10-20$ MeV, with higher $L_{\text{disk}}$ correlated with lower $E_{\text{disk}}$ and vice versa.

3. NUMERICAL SIMULATIONS

In this section, we perform 2D numerical simulations of CITE. We have the following two goals:

i. to verify that CITE can operate with RIAS launch time $t_{\text{disk}} \approx 5$ s, reproducing $E_{\text{kin}}$ and $M_{\text{BH}}$ in the ballpark of observations for SN 1987A;

ii. to study the accretion disk neutrino luminosity relevant for CITE on times $t > t_{\text{disk}}$.

With respect to item (ii), we stress that our calculations are preliminary. Our code is Newtonian and our treatment of neutrino transport is simplistic. More sophisticated codes exist in the literature, e.g., O’Connor & Ott 2011; Mirizzi et al. 2016; Perego et al. 2015; our estimates here motivate the application of these tools to the scenario of CITE. Beyond the technical limitations of the simulation, the problem of the neutrino luminosity of BH accretion disks suffers from theoretical uncertainties due to the implementation of viscosity. Here, we set the viscosity to zero. Estimates for different assumptions of the viscosity can be found, e.g., Popham et al. (1999), MacFadyen & Woosley (1999), and Chen & Beloborodov (2007). Because of these limitations, we do not attempt to reproduce the neutrino light curve in any detail aside from the rough luminosity and timescales.

We aim to simulate the process of the accretion disk at times $t > 3$ s and the subsequent CITE, and we do not attempt to reproduce the early phase of PNS and BH formation (again see, e.g., O’Connor & Ott 2011; Mirizzi et al. 2016; Perego et al. 2015, for details of this early phase). We assume that once sufficient mass, $M > 2-3 M_\odot$, has accreted through the inner boundary of our simulation, $r_{\text{inner}}$ (to be specified below), the central object forms a BH. Before this time, the flow below $r \sim 10^7$ cm in our simulation does not correctly capture the standing shock above the PNS; however, for $t > t_{\text{finit}}$, the shocked material is quickly absorbed in the BH and by $t > 4$ s —still many dynamical times prior to disk formation in our simulation—we expect that our calculation provides a reasonable approximation of the flow down to the last stable orbit.

3.1. Pre-collapse Profile

We use the same methods from Kushnir (2015), and so here we only highlight a few aspects of the simulations. We do not simulate the collapse at $r < r_{\text{inner}}$ and details of the progenitor on $r < r_{\text{inner}}$ are unimportant for the results. On $r > r_{\text{inner}}$, the pre-collapse profile is composed of shells with constant entropy per unit mass, s, constant composition, and in hydrostatic equilibrium. We place $1.6 M_\odot$ within $r < 2 \times 10^8$ cm, representing a degenerate iron core. This choice roughly reproduces the PNS mass in Perego et al. (2015) for their HC19.2 progenitor model when PUSH is not used to trigger an explosion. The region between $r_{\text{outer}}$ and $r = 2 \times 10^8$ cm is filled with $s = 1.3 k_B$ iron (in hydrostatic equilibrium), which is prevented from burning. This prescription is chosen for simplicity and we defer more detailed analysis to future work. Note that the region inwards of $r = 2 \times 10^8$ cm falls through $r_{\text{inner}}$ in time $t \approx \pi \sqrt{r^3/2GM(r)} \approx 0.4$ s after core collapse, so that the composition in this region has a negligible effect on the results of the simulation.
The base of the He–O shell is placed at a mass coordinate of 6 $M_\odot$, a radius of 4.25 $\times$ 10$^9$ cm, and a density of 10$^4$ g cm$^{-3}$. The shell is composed of equal mass fraction of helium and oxygen. The local burning time at the base of the shell is $\approx$ 700 s, which is 100 times the free-fall time at this position. The total mass of the He–O shell is $\approx$ 2.7 $M_\odot$. Pure oxygen (helium) is placed below (above) the He–O shell. Oxygen is replaced with silicon where $T > 2 \times 10^9$ K to prevent fast initial burning. The angular momentum is initially distributed such that $f_{\text{rot}}$, the ratio of the centrifugal force to the component of the gravitational force perpendicular to the rotation axis, is constant $f_{\text{rot}} = 0.02$ throughout the profile, except for the following.

1. $f_{\text{rot}} = 0$ at $r < 1.2 \times 10^9$ cm.
2. $f_{\text{rot}} = 0$ at large radii, and increases linearly with decreasing radius between $r = 2 \times 10^9$ cm and $r = 10^{10}$ cm to $f_{\text{rot}} = 0.02$. This is done for numerical stability and has a small effect on the results.

For this choice of angular momentum, the normalized angular momentum $a = cJ/\mathcal{G}M^2$ is an increasing function of $M$ at least up to the He–O shell. We get $a \ll 1$ for $M = 2.5$ $M_\odot$ and $a = 1$ for $M \approx 3$ $M_\odot$, meaning that the angular momentum is not affecting the BH formation but is affecting further accretion onto the BH. The stellar profile used in the analysis is shown in Figure 3.

The stellar profile defined here is designed to achieve $t_{\text{disk}} \approx 5$ s and disk neutrino luminosity $L_{\nu_d} \approx 10^{51}$ erg s$^{-1}$. An estimate of the disk formation time is given by

$$t_{\text{disk}} \approx 2 \tau_{\text{ff}}(r_f) = \frac{r_f^3}{2 \mathcal{G} M(r_f)}.$$  

Here, $\tau_{\text{ff}}$ is the free-fall time at pre-collapse radial coordinate $r$, $M(r)$ is the enclosed mass, and $r_f$ is the radial coordinate on the $z = 0$ plane where the centrifugal force fraction $f$ first becomes greater than zero. The factor of 2 in Equation (4) sums (i) the (almost) free-fall trajectory of the mass element initially at $r_f$ down to the disk formation radius $r_{\text{disk}} \approx (f/2)r_f$, and (ii) the time it takes the rarefaction wave starting at core collapse to propagate out from $r = 0$ to $r_f$ (because the initial profile is in hydrostatic equilibrium, this sound travel time is again roughly equal to the free-fall time at $r_f$: Kushnir & Katz 2015). In Figure 3, $r_f = 1.2 \times 10^9$ cm and $M(r_f) = 2.34$ $M_\odot$, and so we estimate $t_{\text{disk}} \approx 5.2$ s.

The disk neutrino luminosity can be estimated by the gravitational binding energy accreting through the disk,

$$L_{\nu_d} \approx \frac{GM_{\text{disk}} M_{\text{disk}}}{2r_{\text{disk}}} \approx 10^{51} \left( \frac{(f/2) r_f}{10^9 \text{ cm}} \right) \left( \frac{M(r_f)}{2 M_\odot} \right) \left( \frac{M_{\text{disk}}}{0.05 M_\odot} \right) \text{ erg s}^{-1}. \quad (5)$$

This estimate assumes that half of the disk emission is in $\tilde{\nu}_e$. We scaled the mass accretion rate through the disk by a typical value.

Note that we do not use Equations (4)–(5) in the numerical calculations described next, but only to tune the initial stellar profile before running the numerical simulations. We emphasize that we have tailored the initial condition of $f_{\text{rot}}$ to reproduce the required $t_{\text{disk}}$ and $L_{\nu_d}$. The goal at this point is an existence proof for CITE, not a systematic exploration of the dependence on the initial conditions; the latter is an important task that we defer to subsequent work.

### 3.2. Simulations and Results

The problem considered is axisymmetric, allowing the use of 2D numerical simulations with high resolution. We employ the FLASH4.0 code with thermonuclear burning (Eulerian, adaptive mesh refinement Fryxell et al. 2000) using cylindrical coordinates $(R,z)$ to calculate one quadrant, with angular momentum implementation as in Kushnir (2015a). Layers below the inner boundary, $r_{\text{inner}}$, are assumed to have already collapsed, and the pressure within this radius is held at zero throughout the simulation. We include neutrino cooling and assume that neutrinos escape freely through the outer layers.

We perform two different simulation runs based on the same stellar profile.

1. First, the thermonuclear explosion was calculated with $r_{\text{inner}} = 60$ km, a resolution (i.e., minimal allowed cell size within the most resolved regions) of $\approx$14 km, and a 13-isotope $\alpha$-chain reaction network (similar to the APPROX13 network supplied with FLASH with slightly updated rates for specific reactions, especially fixing a typo for the reaction $^{28}\text{Si}(\alpha, \gamma)^{32}\text{S}$, which reduced the reaction rate by a factor $\approx$4). This setup is sufficient for calculating the disk formation, RIAS launch, and the resulting thermonuclear explosion. An ignition of a detonation wave was obtained at $t \approx 25$ s, which resulted in an explosion with $E_{\text{kin}} \approx 6 \times 10^{50}$ erg and $M_{\text{Ni}} \approx 0.035 M_\odot$. Both of these values are in the ballpark of, though smaller by a factor of $\approx$2–3 than, the observed values of SN 1987A (Uttrobin & Chugai 2011).

2. Second, to calculate the neutrino light curve, we used $r_{\text{inner}} = 30$ km, a resolution of $\approx$2 km, and the APPROX19 reaction network (to allow helium disintegration to nucleons). The required high resolution and

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**Figure 3.** Pre-collapse stellar profile (density, temperature, enclosed mass, and specific angular momentum on the equatorial plane, $f_{\text{rot}}$) used in CITE simulation (the profile below $r = 2 \times 10^8$ cm has negligible effect on the results, see the text for details). The density, temperature, and enclosed mass profiles are similar to pre-collapse profiles of a 20 $M_\odot$ star (dashed gray), calculated by Roni Waldman with MESA (Paxton et al. 2011).
A snapshot of the disk and RIAS at time 5.5 s is shown in Figure 5. The neutrino emission originates from radii of 30 to 100 km, but mostly dominated from 30 to 40 km where the typical densities are few $\times 10^6$ g cm$^{-3}$.

Increasing the resolution to $\approx$1 km changes the results by less than 10%, but increasing $r_{\text{inner}}$ to 40 km leads to a luminosity reduced by 30%–40% and energies reduced by 10%. We conservatively estimate that our results are accurate to only a factor of a few, as our simulations are Newtonian and velocities of $\approx 0.5c$ are achieved near the emission region. Furthermore, the Schwartzchild radius of the central BH at this time is $R_s \approx 10$ km, so that our disk, which ignores general relativistic effects, is located not far above the last stable circular orbit. Nevertheless, our results demonstrate that $L_{\nui} \approx 10^{51}$ erg s$^{-1}$ with $E_{\nui} \approx 10$ MeV is possible for $t > t_{\text{disk}}$.

Our results can be compared to those of Popham et al. (1999) and MacFadyen & Woosley (1999) in the context of the collapsar model, which shared a setup similar to ours (see also Chen & Beloborodov 2007). The latter included a free parameter to account for viscosity effects, finding accretion disk neutrino luminosity with a range encompassing our result here.

4. CONCLUSIONS

The neutrino burst of SN 1987A has traditionally been used to advocate for the neutrino mechanism operating in exploding CCSNe. Our goal in this paper was to provide a first analysis of the neutrino signal expected in CITE as a competing mechanism of CCSNe, and to compare it to the SN 1987A signal. The questions we addressed and our results were as follows.

There is a common claim in the literature that direct BH formation would be incompatible with SN 1987A. This claim is usually based on two arguments: (i) the neutrino mechanism predicts a NS remnant, and/or (ii) direct BH formation would cut off the neutrino emission, leaving the signal events at $t > 5$ s unexplained.

We find that this claim is, at least currently, unjustified. First, the neutrino mechanism has not yet been shown to operate successfully and reproduce the observations of SN 1987A. Therefore, its failure is not a good cause to exclude BH formation. CITE provides one potential counter example. Second, if the progenitor of SN 1987A possessed a rotating envelope, then an accretion disk would form around the BH. Such accretion disks are known to be copious neutrino emitters and could explain the late-time neutrino events of SN 1987A, 10.

In Section 2, we provided a statistical analysis of the neutrino emission in CITE, along the lines used by Loredo & Lamb (2002) to study the neutrino mechanism. While the statistical significance of such analysis is limited by the sparse data, we find the following: (i) there is a hint in the data for a luminosity drop around $t \approx 2$ s, which is right in the ballpark where CITE predicts BH formation; (ii) the neutrino mechanism is in some tension with this luminosity drop, while CITE could address it naturally.

The neutrino events at $t > 5$ s imply that CITE should be operative with RIAS formation as early as that. This is a nontrivial constraint that was not considered in Kushnir (2015a). It can be summarized by Equations (4)–(5) with $t_{\text{disk}} \approx 5$ s and $L_{\nui} \approx 10^{51}$ erg s$^{-1}$. In Section 3, we performed 2D numerical simulations guided by these constraints. Without yet attempting a systematic survey of possible profiles, we were

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9 Mean neutrino energy was approximated from the matter temperature, averaged by neutrino emissivity and assuming $\alpha = 2$ in Equation (1).

10 Hypothetical explosion mechanisms other than CITE, also associated with an accretion disk, include, e.g., the collapsar model (MacFadyen & Woosley 1999) and jet activity (Gilkis et al. 2015).
able to find such a profile that yields an explosion in the rough ballpark of the observations ($E_{\text{kin}}$ about a factor of 3 and $M_{\text{Ni}}$ about a factor of 2 below that of SN 1987A). Further study of different initial profiles is needed to derive more conclusive results. We also gave order of magnitude estimates of the luminosity and typical energy of the neutrino emission produced by the BH accretion disk at the base of the RIAS, finding results that are on the low side, but not inconsistent with the data.

We close with comments on further work.

1. We are eager to see independent simulations of CITE to compare with the work of Kushnir (2015a). In particular, it is important to investigate whether the pre-collapse initial conditions required for CITE can be obtained with stellar evolution models.

2. Many particle physics analyses used the neutrino burst of SN 1987A to constrain new physics beyond the Standard Model, such as axions or sterile neutrinos (see, e.g., Raffelt 1996). Most of these works assumed PNS cooling luminosity, as suggested within the neutrino mechanism. Our results here imply that these analyses may need to be revisited.

3. While the initial neutrino emission phase (PNS accretion luminosity) is similar in CITE and the neutrino mechanism, the second phase (disk emission in CITE versus PNS cooling in the neutrino mechanism) could be significantly different. This could have important consequences for the DSNB (Beacom 2010).

4. If CITE works in nature, then the neutrino burst of the next strong Galactic CCSN may give us front-row seats to the formation of an event horizon in real time with current neutrino detectors. This may have already happened, albeit with limited statistics, with SN 1987A. Access to phenomena near the event horizon motivates construction of a few Megaton neutrino detector that will observe extragalactic CCSNe on a yearly basis (Kistler et al. 2011).

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APPENDIX

MODELING OF THE NEUTRINO MECHANISM AND MONTE CARLO STUDY

We recap here some details on the EC and ECTA models of Loredo & Lamb (2002) and Pagliaroli et al. (2009). We also describe a Monte Carlo (MC) analysis designed to clarify the time dependence in the different models.

The EC model has three free parameters for the neutrino source: (i) NS initial temperature $T_r$, (ii) NS cooling time $\tau_c$, and (iii) NS neutrinosphere radius $R_c$. The $\nu$ luminosity is assumed to scale as $L_{\nu} \propto R_c^{-2} \alpha_2 \tau_{c}^{2}$ (with $\tau_{c} = T_r e^{-\pi}$). In addition to the source parameters, three unknown time shifts between the zero of time in the three detectors Kamiokande, IMB, and Baksan are also marginalized over, with the best-fit model of Pagliaroli et al. (2009) corresponding to these time shifts being zero. In addition to direct $\nu_e$ emission, equal luminosity is assumed to be emitted in $\mu$ and $\tau$ flavors, $L_{\nu_e} = L_{\nu_\mu} = L_{\nu_\tau} = L_{\nu}$. The $x$-flavor temperature is set by hand to 1.2 times the $\nu_e$ temperature. To account for $L_N$ in terms of the effective $L_{\bar{\nu}_e}$ of Equation (2), we convert $L_{\bar{\nu}_e}^{\text{effective}} = L_{\bar{\nu}_e}^{\text{model}} + (1 - \bar{P}_{\nu_e})^{-1} L_{\nu_e}^{\text{model}}$, with $L_{\bar{\nu}_e} = L_{\bar{\nu}_\mu} = L_{\bar{\nu}_\tau} = L_{\bar{\nu}}$.

The ECTA model adds, on top of the three parameters of EC, three more free parameters intended to describe an early accretion phase preceding the explosion: (iv) accretion temperature $T_{\nu_e}$ ($\nu_e$) accretion timescale $\tau_{\nu_e}$, and (v) a parameter $\mu$ proportional to the overall accretion luminosity. Pagliaroli et al. (2009) assumes that the accretion luminosity consists purely of $e$ flavor, setting $L_e = 0$ during the accretion phase and turning it back on once accretion is stopped and replaced by NS cooling as above. In addition to the free parameters (iv–vi), the time dependence for the accretion luminosity, $L_{\nu_e} \sim L_{\nu_e}/(1 + t/0.5 \text{ s})$, is introduced in Loredo & Lamb (2002) and in Pagliaroli et al. (2009) without counting the functional form or the timescale of 0.5 s as another free parameter (instead, the 0.5 s timescale is argued to arise in numerical simulations).

We move on to describe our binned MC procedure. In the limit that energy-dependent detector efficiency and background are not important, a good proxy for the source luminosity during some time interval $\Delta t$ is given by the sum of the event inverse-energy, $R_e/E_{\nu} \equiv \frac{1}{\Delta t} \sum \frac{1}{E_{\nu}}$, (6)

where the sum goes over the neutrino events detected during $\Delta t$.

To see this, note that the detection cross-section at the relevant energy is $\sigma(E_{\nu}) \approx \tilde{\sigma}(E_{\nu}/\text{MeV})^2$, with $\tilde{\sigma} = 6.8 \times 10^{-44} \text{ cm}^2$. Ignoring background and energy-dependent detector efficiency, we can compute the expected value of $R_e/E_{\nu}$ given the source luminosity $L_{\bar{\nu}_e}$ (constant in time during $\Delta t$),

$$\frac{R_e}{E_{\nu}} \approx \int dE_{\nu} \frac{\sigma(E_{\nu})}{E_{\nu}} \frac{dN_{\bar{\nu}_e}(0)}{dE_{\nu}} = \frac{N_p \rho_{\nu_e} \tilde{\sigma}}{4\pi D_{\text{SN}}^{2}} L_{\bar{\nu}_e}, \tag{7}$$

where $N_p$ is the effective number of target protons in the detector. For an ideal detector, we have $L_{\bar{\nu}_e} \approx \left(\frac{10^{52}}{N_p} \right) \frac{(R_e/E_{\nu})}{(\text{MeV}^{-1} \text{s}^{-1})} \times 10^{53} \text{ erg s}^{-1}$. In practice, energy-dependent efficiency introduces an effective low-energy threshold that lowers the proportionality coefficient on the right-hand side of Equation (7) in a detector-dependent way. In addition, a small correction is introduced due to the spread of energy between the incoming neutrino energy and the reconstructed positron energy in the IBD detection event. Combining all three detectors, we find that the replacement $N_p \rightarrow 0.29(N_{p, \text{Kam}} + N_{p, \text{IMB}} + N_{p, \text{Bak}}) = 1.8 \times 10^{52}$ in Equation (7) for the luminosity estimator $L_{\bar{\nu}_e}^{R_e/E_{\nu}} \approx \left(\frac{R_e/E_{\nu}}{\text{MeV}^{-1} \text{s}^{-1}}\right) \times 5.6 \times 10^{52} \text{ erg s}^{-1}$, (8)

reproduces the data well for the source parameter $\alpha = 2$ adopted in most of this section.\footnote{Changing to $\alpha = 0$, we find 0.29 $\rightarrow$ 0.25 for the scaling factor. None of our results is affected significantly.}
The result of applying Equation (8) to the data is shown by black circle markers in Figure 2. Note that the luminosity estimator in Equation (8) does not account for detector background, while the Poisson fit (blue error bar markers in Figure 2) automatically subtracts it. For this reason, the estimator does not decrease towards the last time bin, while the fit result does.

Armed with our quick-to-compute luminosity estimator \( L_{\nu_e}^{RE} \) from Equation (8), we generate mock data samples and compute the distribution of \( L_{\nu_e}^{RE} \) in different time bins. In Figure 6, we show the Monte Carlo (MC) results for \( L_{\nu_e}^{RE} \) (error bar markers), computed for the best-fit EC (left) and ECTA (right) models of Pagliaroli et al. (2009). The MC results we show are converged to a few percent with \( 5 \times 10^4 \) mock samples.

Figure 6 suggests that much of the statistical tension associated with the simple EC PNS cooling model is driven by the luminosity drop at \( t \approx 2 \) s. In order not to overshoot the event rate during this time, the EC model is forced to low luminosity at earlier times, leading to tension in the \( t \sim 0.25 \)–\( 0.5 \) s time bin. The ECTA model can fix some of this tension, raising the luminosity at \( t \lesssim 0.5 \) s while using extra free parameters to keep the late-time “cooling PNS” luminosity not too high.

In Figure 7, we repeat our MC procedure for the \( L_{\nu_e}^{RE} \) binned luminosity estimator in CITE using the model of Equation (3). Compared with the ECTA model, we find somewhat improved consistency with the data.

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