Impact of late-time neutrino emission on the diffuse supernova neutrino background

Nick Ekanger\textsuperscript{1,*}, Shunsaku Horiuchi\textsuperscript{1,2}, Kei Kotake\textsuperscript{3,4}, and Kohsuke Sumiyoshi\textsuperscript{5}

\textsuperscript{1}Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA.
\textsuperscript{2}Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
\textsuperscript{3}Department of Applied Physics, Fukuoka University, Nanakuma Jonan 8-19-1, Fukuoka 814-0180, Japan
\textsuperscript{4}Research Institute of Stellar Explosive Phenomena, Fukuoka University, Nanakuma Jonan 8-19-1, Fukuoka 814-0180, Japan and
\textsuperscript{5}National Institute of Technology, Numazu College of Technology, Ooka 3600, Numazu 410-8501, Japan

(Dated: February 15, 2023)

In the absence of high-statistics supernova neutrino measurements, estimates of the diffuse supernova neutrino background (DSNB) hinge on the precision of simulations of core-collapse supernovae. Understanding the cooling phase of protoneutron star (PNS) evolution (≥ 1 s after core bounce) is crucial, since approximately 50% of the energy liberated by neutrinos is emitted during the cooling phase. We model the cooling phase with a hybrid method by combining the neutrino emission predicted by 3D hydrodynamic simulations with several cooling-phase estimates, including a novel two-parameter correlation depending on the final baryonic PNS mass and the time of shock revival. We find that the predicted DSNB event rate at Super-Kamiokande can vary by a factor of ~ 2–3 depending on the cooling-phase treatment. We also find that except for one cooling estimate, the range in predicted DSNB events is largely driven by the uncertainty in the neutrino mean energy. With a good understanding of the late-time neutrino emission, more precise DSNB estimates can be made for the next generation of DSNB searches.

I. INTRODUCTION

When the cores of massive (≈ 8 M\textsubscript{\odot}) stars collapse, ≥ \texttimes10\textsuperscript{53} erg of gravitational binding energy is released via neutrinos [1–4]. In 1987, one such nearby collapse allowed the observation of tens of neutrino events [5–7]. Since the historic 1987 supernova, the astrophysical community awaits the next nearby core collapse which will provide a high-statistics neutrino event sample and a wealth of information about, e.g., the dynamical stellar properties and the core-collapse explosion mechanism (see e.g., Refs. [2, 8, 9] and motivated by simulations, e.g., Refs. [10–12]).

The core-collapse supernovae (CCSNe) that have occurred over cosmological history give rise to a diffuse background of neutrinos (i.e., the diffuse supernova neutrino background or “DSNB”), see [13–16] for reviews and see [17–48] for recent progress in DSNB predictions. The DSNB has not been detected yet, but recent upper flux limits at Super-Kamiokande (“Super-K” or “SK”) strongly disfavor optimistic models [49, 50] and its confirmed detection is on the horizon [51, 52]. Additional upcoming experiments like Hyper-Kamiokande [53], JUNO [54], and DUNE [55] will also probe the DSNB in the near future.

With only a single sample of supernova neutrino detections from 1987, DSNB predictions are informed primarily by the neutrino emission predicted by simulations (e.g., Refs. [43, 45] and with extensive simulation sets, see Refs. [44, 47]). Because of this, DSNB predictions are subject to inherent uncertainties of the simulations.

In the last few years, there have been a great number of successful examples of fully three-dimensional (3D), robust CCSN simulations (see e.g., Refs. [56–62]). These capture the dynamic details that spherically symmetric 1D simulations inherently cannot. One example is turbulent processes like convection that affect the neutrino-driven explosion mechanism (see Ref. [4] and references therein). Another is the simultaneous mass accretion and explosion that can increase the neutrino luminosities, neutrino mean energies, and explosion energies compared to 1D simulations [58, 63, 64]. As a result, this “accretion phase” which occurs ≤ 1 s is increasingly better understood by simulations in recent years.

Calculations post ~ 1 s, however, are less common and often limited by high computational costs. After ~ 1 s, the cooling of the protoneutron star (PNS) becomes the dominant source of neutrinos. While progenitor dependent, typically > 50% of the total liberated neutrino energy is emitted in this phase. Moreover, these neutrinos are also important, e.g., for the determination of neutron star properties [10–12]. While studies of the cooling phase in the context of a nearby CCSNe exist (e.g., [10–12]), the extent to which they play a role in the DSNB has been explored much less. References [44, 47] are two examples where extensive simulation sets inform the predicted DSNB neutrino emission, but rely on other methods for estimating the long-term cooling-phase neutrino emission. Reference [44] for example took simple analytic estimates for the PNS to estimate the energy liberated in neutrinos, while Ref. [47] used 1D simulations with calibrated engines.

The primary focus of this study is to implement and compare different methods for estimating the cooling-phase neutrino emission, in order to quantify how the cooling phase impacts the DSNB signal. We find that,
within reasonable variations of cooling-phase estimates, the predicted DSNB rate can vary by a factor of ∼2–3. Recently, SK has been enhanced with gadolinium salt ("SK-Gd") which will allow for neutron tagging of true DSNB events and reject backgrounds [50, 73]. This dramatically improves the detection prospects of the DSNB in the next decade. Our study suggests that improving the understanding of the late-phase neutrino emission will be important for the uncertainties in the DSNB as we enter the SK-Gd era.

This paper is organized as follows. In Sec. II A we describe the simulation data we use in our study. In Sec. II B we describe the different methods for estimating the cooling phase of neutrino emission. In Sec. II C we check the validity of these strategies against the results of a 3D simulation. In Sec. III we give quantitative DSNB event rates at SK-Gd. Finally, in Sec. IV we discuss our framework and summarize how our late-phase strategies lead to a large difference in DSNB rates.

II. CHARACTERIZING THE COOLING PHASE

A. Simulation survey

We first summarize the core-collapse simulation sets used in our study, including studies of the cooling phase, but also the accretion phase and collapse to black holes.

In Table I we highlight a selection of recent studies of core collapse into the PNS cooling phase using a variety of techniques spanning spatial dimensionality, nuclear equation of state (EOS), and implementation for shock revival. Here, the EOS includes Shen [74], LS220 [75], SFHo [76], TM1/TM1e [77]/[78] (where TM1 is an updated version of the Shen EOS), and Schneider [79]. These simulations do not make up an exhaustive list but begin to reveal how spatial dimension, EOS, implementation details, and perhaps artificial biases lead to systematic differences.

Table I. Overview of the simulation sets studied in this paper. Although this list is not exhaustive, it highlights several simulations done that include a cooling-phase component. Many are long enough so that the impact of this later phase on the DSNB can be studied. A check mark (✓) means that we used that set in our analysis. “D” refers to the spatial dimension of the simulation. “Duration(s)” refers to the length of each simulation. Finally, “Explosion model and cooling signal” describes the method by which the explosion is induced and/or method for calculating the late neutrino signal. “PNSC” refers to proto-neutron star cooling.

| Simulation set            | D | Duration(s) | EOS           | Explosion model and cooling signal                                                                 |
|---------------------------|---|-------------|---------------|-----------------------------------------------------------------------------------------------------|
| Fischer et al. (2009) [65]| 1D| ≈ 10        | Shen          | Enhance electronic charged current rates                                                              |
| ✓ Nakazato et al. (2013) [66]| 1D| 20         | Shen          | Assumed transition time to PNSC simulation                                                            |
| ✓ Hüdepohl (2014) [67]    | 1D| ≈ 10        | Shen/LS220    | Artificially decrease density                                                                          |
| Sukhbold et al. (2016) [68]| 1D| 1          | LS220         | Calibrated central engine [69]                                                                       |
| Summa et al. (2016) [70]  | 2D| ≈ 1         | LS220         | Self-consistent shock revival                                                                          |
| ✓ Horiiuchi et al. (2018) [44]| 2D| 100       | LS220         | Self-consistent shock revival, late-time analytic                                                      |
| ✓ Burrows et al. (2019) [58]| 3D| ≈ 1         | SFHo          | Self-consistent shock revival                                                                         |
| ✓ Sumiyoshi et al. (2019) [71]| 1D| 60         | TM1/TM1e     | Hydrodynamic simulations set initial conditions for PNSC                                              |
| ✓ Suwa et al. (2019) [10] | 1D| > 50        | TM1           | Consistent cooling, connect to Nakazato et al. (2013)                                                |
| Li et al. (2021) [11]     | 1D| ≈ 100       | Schneider     | Replace outer layers with pressure boundary                                                           |
| ✓ Bollig et al. (2021) [60]| 3D| ≈ 7         | LS220         | Self-consistent shock revival, connect to 1D sim at ∼ 1.7 s                                         |
| Nagakura et al. (2021) [72]| 2D| ≈ 4         | SFHo          | Self-consistent shock revival                                                                         |

We show the time-integrated $\tau_\nu$ liberated energy (top panel) and the $\tau_\nu$ mean energies (bottom panel) in Fig. 1, for a subset of core-collapse simulations in Table I. We compare the neutrino emission properties accounting for the final baryon mass of the PNS. In general, we confirm previously found trends of increased neutrino liberated energy and mean energy as the final PNS mass is increased (e.g., [66]). However, different strategies introduce systematic differences. For example, the EOS plays a big role in the mean energy. We can see this from comparing the Shen and LS220 simulations by the “Hüdepohl” study [67]. Also, the “Bollig” [60] simulation, which is spatially three dimensional until ∼ 1.7 s before connecting to a 1D simulation, point to higher neutrino energetics and mean energies than Hüdepohl [67], “Nakazato” [66], and “Sumiyoshi” [71] which are fully simulated in spherical symmetry. While this seems to be driven in part by aspherical mass infall and outflows, conclusive statements cannot be made with only one simulation comparison. Finally, we can see that the Sumiyoshi simulations using the TM1 and TM1e EOS result in very similar integrated neutrino emission to those of Nakazato, and both yield significantly lower liberated and mean energies when compared to other 1D simulations. This could arise from differences in how the cooling phase is initiated and/or in more subtle implementation details like numerical methods, resolution, and neutrino interactions.

For the DSNB we also need neutrino emission from the early hydrodynamic phase of core-collapse evolution which precedes the cooling phase. For this, we use the angle-averaged three-dimensional simulation data from Ref. [58] (referred to as “Burrows” hereafter, see also Ref. [80] for discussion of the neutrino emission). This simulation set includes more than a dozen progenitors...
each simulated until close to 1 s postbounce. We exclude, however, the 13, 14 and 15 $M_\odot$ progenitors since they do not explode by the end of simulation run-time. We augment the Burrows set with the neutrino signal from Ref. [81], an electron-capture supernova of an ONeMg core.

Finally, we also want to account for the neutrino emissions from core collapses directly to black holes, i.e., failed CCSNe. To do this, we take a similar method to that of Ref. [45] in their conservative scenario. More specifically, they assume all progenitors with initial masses > 40 $M_\odot$ become black holes (~8.4% of core collapse) and adopt the neutrino signal based on two simulations, the “s40” and “s40s7b2” models of Ref. [67], both using the LS220 EOS. There are also cases of fallback black hole formation where material falls back onto the PNS after shock revival [11], but we ignore their contribution since they are estimated to be rare [68, 82, 83].

B. Late-phase strategies

Here we estimate the neutrino emission from the late cooling phase of PNS evolution with several strategies. We discuss five estimates using four strategies. In the next section, we will explore how they impact the DSNB.

1. Constant mean energy method

The simplest of our strategies is a simple analytic treatment. First, as was done in Ref. [44], we assume that the mean energy is constant after the hydrodynamic simulation concludes. Next, to estimate the energy liberated, we again follow Ref. [44] and assume that all of the remaining gravitational binding energy released after simulation is released as neutrinos. This requires the evolution of the PNS mass, which is taken from Ref. [84] as $M(t) = M_0 + M_1(1 - e^{-t/t_M})$, where the parameters $M_0$, $M_1$, and $t_M$ are found by fitting to the PNS mass evolution in the simulation. However, we adopt a final PNS radius of 12 km, rather than 15 km in Ref. [44], which is more consistent with the SFHo EOS. With both of these final parameters, we can calculate the binding energy after the simulation.

In reality, the mean energy decreases in the cooling phase. Thus, the results we calculate from the constant mean energy method should be seen as upper limits.

2. Analytic solution method

In Ref. [85], analytic solutions of the neutrino luminosity and mean energy of PNS cooling are derived assuming spherical symmetry and a thermal energy spectrum. We take the one-component functional form from Ref. [85] to estimate the luminosity and mean energy after ~ 1 s. As input parameters, these functions require the final PNS baryonic mass, radius, and the total liberated energy. The analytic method is also dependent on two additional parameters: $g$ and $\beta$, the density correction and opacity boosting factors which are used in Ref. [85] as effective parameters to parametrize the PNS differences from the Lane-Emden structure and model the increased scattering due to heavy nuclei, respectively.

We aim to add the analytic cooling solutions to the ends of the Burrows simulations. We take the final mass as $M_{\text{end}}$, where $M_{\text{end}}$ is the PNS mass at the end of simulation and $M_{\text{max}}$ is the maximum NS mass from the SFHo EOS [76]. We then use the SFHo mass-radius relationship to estimate the final radius, giving us enough information to estimate the remaining gravitational binding energy. As was done in Ref. [85], to
The effective density correction $g$, and opacity boosting factor $\beta$, compared to the hydrodynamic neutrino data for the $9 M_\odot$ progenitor (black). These parameters are chosen to best agree with the mean energy data and then are used in the luminosity function. Around the end of the simulation time, the functional form underpredicts the neutrino luminosity and mean energy. Later comparisons show that integrating these functions still gives reasonable results, but ideally would be applied to longer-duration ($\gtrsim 10$ s) data.

For our next strategy, we use the Supernova Neutrino Database of Ref. [66] and examine properties of the late-phase spectral parameters. This database is particularly valuable as a reference of long-term simulations that are carried out for 20 s post-core-collapse for 21 progenitors. In Refs. [38, 41], a correlation was found between neutrino emission, shock revival time, and PNS mass. Further, it was shown that this dependence can leave an imprint on the DSNB signal. We confirm this correlation, and also quantify a new linear relationship of the logarithm of energy liberated and mean energy with the shock revival time and final PNS baryon mass for the cooling phase. We show these relationships in Fig. 3 for $\nu_e$ neutrinos for all progenitors of the Supernova Neutrino Database.

It should be noted that the simulations of Ref. [66] are 1D and do not attempt to tune the models to explode. Rather, the revival time is ad hoc, set by an assumed transition time from accretion hydrodynamical simulation to the PNS cooling simulation. The simulations of Ref. [66] also use the Shen EOS [74]. This limits the range of final masses and, thus, the range of applicability of this method. It should, in principle, turn out that other EOSs lead to modifications to this method, including the range of final masses that it applies to. We discuss this and account for some of this in the next section, Sec.II B 4.

In Table II we show the linear fits to these data for all neutrino flavors for the logarithm of liberated energy first, then the mean energies. These fits are of the form

$$\log_{10}(E) = \alpha_{i}^{(E)} M_{\text{fin}} + \beta_{i}^{(E)} t_{\text{rev}} + \gamma_{i}^{(E)},$$

$$\epsilon_i = \alpha_{i}^{(\epsilon)} M_{\text{fin}} + \beta_{i}^{(\epsilon)} t_{\text{rev}} + \gamma_{i}^{(\epsilon)},$$

Correlation method

FIG. 2. The functional form from Ref. [85] (red) using the effective density correction $g$, and opacity boosting factor $\beta$, compared to the hydrodynamic neutrino data for the $9 M_\odot$ progenitor (black). These parameters are chosen to best agree with the mean energy data and then are used in the luminosity function. Around the end of the simulation time, the functional form underpredicts the neutrino luminosity and mean energy. Later comparisons show that integrating these functions still gives reasonable results, but ideally would be applied to longer-duration ($\gtrsim 10$ s) data.
where $M_{\text{fin}}$ is the final baryonic mass of the PNS, $t_{\text{rev}}$ is the shock revival time, and $\alpha$, $\beta$, and $\gamma$ are the fit coefficients for neutrino flavor $i$. Since the cooling data from the Supernova Neutrino Database are computed from shock revival time to 20 s, this method yields the time-integrated neutrino emission for the cooling phase until $\sim 20$ s. We only show results in this section for $\nu_e$, but other flavors show similar trends; see the Appendix, Figs. 7 and 8.

4. Renormalized correlation method

One-dimensional CCSN simulations, with some exceptions, require artificial induction of explosion, and the strategy for inducing explosions introduces model dependence. Furthermore, the EOS will impact the evolution of the PNS cooling phase. To cover these and other range of physics possibilities, we make use of additional cooling-phase simulations by Ref. [67]. In these H"udepohl simulations, a small suite of spherically symmetric simulations are carried out to $\sim 10$ s for both Shen and LS220 EOS. For our purposes, we use their standard simulations which do not use a mixing-length scheme to model multi-

![Image of a diagram showing time-integrated neutrino emission]
dimensional dynamics and corrections to neutrino opacities. However, Ref. [67] considered only four progenitors, less than the sample studied by Ref. [66] discussed in the previous section and not enough to robustly extract a trend. Therefore, we compare outcomes of Refs. [66, 67], and explore how the simulation dependence and progenitor dependence can be incorporated by a renormalization factor.

To this end, we first integrate the simulations of [66] out to 10 s, i.e., comparable to the duration of the simulations of Ref. [67], for a fair comparison. We then take the overall normalization as a free parameter and perform a sum-of-least-squares fitting procedure to the four simulations of Ref. [67], assuming a revival time of 500 ms (this is when the explosion is artificially induced in the H{"u}depohl simulations). In other words, we calculate \( E'_i = N'_i E_i \) and \( \epsilon'_i = N'_i \epsilon_i \) where \( E_i \) and \( \epsilon_i \) are defined in Eqs. (1) and (2), \( N'_i \) is the overall normalization parameter for neutrino flavor \( i \), and this is done for both the Shen and LS220 EOSs. Note that we found the final mass-revival time correlation with the logarithm of energy liberated, but we renormalize the energy liberated linearly.

The results of this procedure are shown in Fig. 4, where the blue curves are the original trends of [66] and the orange and purple curves are the renormalized curves to the LS220 and Shen EOS simulations of [67], respectively. Interestingly, the original trend of [66] shows a remarkably good description of the [67] simulations, as seen by how well the renormalized curves fit through the simulation points. The comparison also highlights the large impact the EOS plays on the neutrino average energy (and much less for the liberated energy). This large mean energy difference ends up playing an important role in the predicted DSNB events, as we see in later sections. We only show results in this section for \( \nu_e \), but other flavors show similar trends; see the Appendix, Figs. 9 and 10. Finally, in Table III, we show the renormalization constants, \( N'_i \), to the Corr strategy.

As with the previous correlations, we construct the renormalized form for the integrated neutrino spectral parameters from shock revival time to 20 s. This constitutes our final late-time strategy.

| Flavor \( i \) | Shen \( N' \) | LS220 \( N' \) |
|------------|-----------|-----------|
| \( E'_i \) | \( \nu_e \) | 2.57 | 2.33 |
| \( \nu_x \) | 2.71 | 2.46 |
| \( \nu_x \) | 1.72 | 1.63 |
| \( \epsilon'_i \) | \( \nu_e \) | 1.13 | 1.28 |
| \( \nu_x \) | 1.15 | 1.32 |
| \( \nu_x \) | 1.00 | 1.16 |

C. Comparison to 3D simulation

To make sure our late-phase strategies return reasonable results, we test them against the Bollig simulation [60], which extends a 3D hydrodynamic simulation with a 1D cooling simulation out to \( \sim 7 \) s postbounce. We first estimate the time-integrated luminosity and mean energy up to the end of the simulation. We then compare these with the values calculated from the five estimates. The results are shown in Table IV.

Since all of the strategies are intended to estimate the neutrino spectral parameters after \( \sim 20 \) s postbounce, we have to slightly modify the strategies to instead estimate these parameters until \( \sim 7 \) s postbounce. For “Const,” we do not modify the estimation for liberated energy since the PNS mass and radius do not change much between 7 and 20 s. However, to give a more reasonable comparison, we take the mean energy to be constant after \( \sim 1.7 \) s (the beginning of the 1D neutrino signal for the Bollig simulation) instead of the end of the simulation. For “Analyt,” we modify the method in the following way: We find the best-fit \( g \) and \( \beta \) parameters by finding the minimum sum of least squares in the time range between \( \sim 1.7 \) and \( \sim 7 \) s. To calculate the neutrino spectral parameters, we then integrate the Bollig and analytic solutions up to 7 s. Finally, for Corr and “RenormShen/LS” we find and apply correlations integrated to 7 s instead of 20 s, and adopt the time when the shock radius reaches 400 km as the shock revival time.

These Bollig simulation data are an interesting test case for the Analyt method because of how long this simulation is carried out. We found that low \( g \times \beta \) values fit the mean energy curve best by eye, but these low values may not be physically appropriate for the late-time solutions [85]. The sum-of-least-squares method of finding \( g \times \beta \) values return integrated neutrino spectral parameters that agree fairly well with Bollig spectral parameters, but do not resemble the mean energy and luminosity curves well. This likely is a result of the continued mass accretion postshock revival. Reference [85] also describes a two-component approach. This does a slightly better job than the one-component solution, but we use the results of the one-component solution in Table IV since this is the strategy we take when applying this method to the Burrows simulation data.

Overall, we find the strategies provide reasonable estimates for the Bollig liberated and mean energies, perhaps with the exception of the Corr where the liberated energy is notably lower. In liberated energy, the Const method is slightly higher than the simulation data since this is closer to estimates of the total gravitational binding energy released over the entire PNS evolution. The Analyt method and the renormalized correlations slightly underpredict the simulation data. In mean energy, the Const method understandably overpredicts the mean energy since the value does not reflect the PNS cooling that occurs at later times. The other strategies slightly underpredict the neutrino mean energy at the
end of simulation, but are especially close for the Analyt and RenormLS strategies.

D. Application to simulation suite

In this section we apply our strategies to the hydrodynamic simulation data of the Burrows set (see Sec. II A) and compare the outcomes. We show in the top panel of Fig. 5 the liberated energies. These are all quite similar and do not show any systematic preferences by strategy, with the exception of Corr which is systematically lower than the others by a factor $\sim 2$; this is consistent with the check against the Bollig simulation (see previous section). Interestingly, the comparison shows how different EOSs (Shen vs LS220) do not yield large differences in the total liberated energy.

Mean energies, however, show a clear spread in strategies. Unsurprisingly, Const returns the highest mean energies; in this method, the mean energy is kept fixed to the end of the hydrodynamical simulation and neglects the reduction during cooling. On the other end, Corr gives the lowest mean energies. Between these are the results renormalized by the simulation set of [67] (where RenormShen uses the same Shen EOS as Corr) and the results of the analytic solution method. As we will show in Sec. III B, the mean energy still leads to a large impact on the predicted DSNB, and highlights the importance of quantifying the neutrino mean energy of the late phase.

III. DSNB EVENT NUMBERS

A. Predicting the DSNB

In order to predict the DSNB rate, we need the mean neutrino emission spectrum and the occurrence rate of core collapses. Using the integrated neutrino spectral parameters (the liberated and mean energies from our cooling phase strategies), we estimate the neutrino energy distribution with a pinched Fermi-Dirac distribution

\[ f(E) = \frac{(1 + \alpha)^{1+\alpha} E_\nu^\alpha}{\Gamma(1+\alpha)} \frac{\epsilon_\nu^{2+\alpha}}{E_\nu^{2+\alpha}} \exp \left[ -\left(1 + \frac{\alpha}{\epsilon_\nu} \right) \frac{E}{\epsilon_\nu} \right], \]

where $\alpha$ is a shape parameter (sometimes called the pinching parameter), $E_\nu$ is the total liberated energy for neutrino $\nu$, and $\epsilon_\nu$ is the mean energy for neutrino $\nu$. We will consider separate neutrino emission spectra from successful and failed CCSNe since both are important for the DSNB.

To estimate the mean neutrino emission from a population of stars, we perform a weighted mean of stars based on the initial mass function (IMF). The IMF-weighted

| Strategy       | $E_{\nu} \text{ (10}^{52} \text{ erg)}$ | $\epsilon_{\nu} \text{ (MeV)}$ |
|----------------|----------------------------------------|-------------------------------|
| Bollig numerical | 7.65                                   | 14.82                         |
| Const          | 8.93                                   | 15.19                         |
| Analyt         | 5.54                                   | 14.74                         |
| Corr           | 3.14                                   | 12.38                         |
| RenormShen     | 6.90                                   | 12.61                         |
| RenormLS       | 6.44                                   | 13.96                         |

TABLE IV. A comparison of the integrated spectral parameters: liberated and mean energies for antielectron neutrinos. Bollig values represent values until the end of their simulation $\sim 7$ s [60] and the strategies have been modified to estimate these parameters up to the same time, instead of 20 s as intended.
average neutrino spectrum is given:

\[ \frac{dN}{dE} = \sum_i \int_{\Delta M_i}^{M_i} \psi(M) dM \int_{\Delta M_i}^{M_i} f_i(E) \]

where \( \Delta M_i \) is the mass range of mass bin \( i \) and \( \psi(M) = \eta M^\eta \) is the IMF. We use the IMF \( \psi(M) \propto M^\eta \) where \( \eta = -2.15 \) from Ref. [87]. Here we take \( M_8 = 8M_\odot \) and \( M_1 = 100M_\odot \). On the low mass end of the IMF, core collapses of ONeMg cores (or “electron-capture SNe”) make up a significant fraction of CCSNe, so we include a contribution from the 8.8 \( M_\odot \) progenitor of Ref. [81]. In the range of intermediate masses, we take the progenitors used by Burrows. Finally, following Ref. [45], we conservatively represent the black hole (BH) channel by assuming progenitors with initial masses above 40 \( M_\odot \) fail as CCSNe. For the ONeMg progenitor, we take \( \Delta M_i = [8M_\odot, 8.9M_\odot] \), for intermediate bins \( \Delta M_i = [(M_i-1 + M_i)/2, (M_i + M_{i+1})/2] \), for our 25 \( M_\odot \) progenitor, we take \( \Delta M_i = [22.5M_\odot, 40M_\odot] \), and for our BH channel we take mass bin \( \Delta M_i = [40M_\odot, 100M_\odot] \), where \( M_i \) is the initial mass. In total, we have 12 mass bins.

Specifically, we take Ref. [81] for the neutrino emission in the ONeMg channel, Burrows and our late-phase strategies for the intermediate masses, and the “s40” and “s40s7b2” models from Ref. [67] as two different cases to represent the BH channel. For the successful CCSNe channel, we choose a constant \( \alpha = 2.3 \) to approximate thermal emission and for the failed channel, we use the spectral pinching parameters given by the simulations. In Fig. 6 we show the neutrino energy spectra for each of our five estimates, adopting the ONeMg signal and the s40 model for BH neutrino emission. The spectra using s40s7b2 are qualitatively similar.

Finally, the DSNB flux is given by the redshift integral over the core-collapse rate:

\[ \frac{d\phi}{dE} = c \int R_{CC}(z) \frac{dN}{dE} dE' \frac{dt}{dz} dz, \]

where \( E' = E(1+z) \) and \( |dt/dz| = H_0(1+z)[\Omega_m(1+z)^3 + \Omega_L]^{1/2} \). We integrate up to a maximum redshift of \( z = 5 \), which is sufficient for DSNB contributions (see e.g., Refs. [13, 44, 45]). We also assume “737” cosmology: \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3, \) and \( \Omega_L = 0.7 \) [88]. We model the core-collapse rate by:

\[ R_{CC} = \dot{N}_s(z) \int_{M_{\odot}}^{100M_{\odot}} \psi(M) dM \int_{0.1M_{\odot}}^{100M_{\odot}} M \psi(M) dM, \]

where \( \dot{N}_s(z) \) is the cosmic star formation rate in units of \( M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3} \) from Ref. [89] with parameters from Ref. [90]. Since the star formation rates are derived assuming a Salpeter IMF, we need a conversion factor to match our assumed IMF; this results in a rescaling factor of 0.55 [91].

## IV. DISCUSSION AND CONCLUSIONS

While recent multidimensional simulations have robust neutrino emission up to the first ~1 s, for the purposes of the DSNB it is necessary to have reasonable estimates for the ~10’s of seconds after this since ~50% of the...

---

**FIG. 6.** Energy spectra for the early + five late-phase neutrino emission estimates. These spectra include the contributions from an ONeMg progenitor and ~8% failed supernovae for progenitors with initial masses > 40 \( M_\odot \). The BH neutrino signal in this figure assumes the representative s40 model, but choosing s40s7b2 gives qualitatively similar results. Note that Analyt and RenormLS overlap.
neutrino energy is liberated at these later times. We characterize the PNS cooling phase by estimating the neutrino emission four different ways. These are (i) a constant mean neutrino energy method, (ii) an analytic model for the cooling PNS, (iii) correlations based on the shock revival time and PNS mass, and (iv) rescaled versions of the correlation method.

Based on these four methods, we estimate five DSNB rate predictions (we make two rescaled versions). We include three progenitor populations in our DSNB estimates: collapse of ONeMg cores, collapse of Fe cores to successful SNe, and collapse of Fe cores to black holes. For the ONeMg core channel we take the neutrino emission from Ref. [81]. For the successfully exploding Fe core channel, we take the neutrino emission computed for the hydrodynamic simulations of Burrows [58] and add on our five different cooling-phase estimates. For the BH channel we adopt the “conservative” estimate of [45]. We ultimately find a factor of $\sim 2$–$3$ difference in the predicted DSNB flux and event rate at SK-Gd, with the constant mean neutrino method (Const) the largest and the correlation method (Corr) the lowest.

It is unsurprising that the constant mean energy strategy overpredicts the DSNB rate: By assuming the mean energy value at the end of the simulations remains constant, it does not model the cooling of PNS evolution. On the low end, we find that compared to other simulations, the 1D simulations of the Supernova Neutrino Database, which drives the correlation method, have lesser liberated and mean energies which results in systematically lower DSNB predictions (although the simulation from Ref. [11] also has similar mean energies out to late times). The renormalized correlation methods (RenormShen and RenormLS) and the analytic solution strategy (Analyt) lie between these two limits. From Fig. 5, the five estimates primarily result in mean energy differences while, with the exception of the Corr result, the liberated energies are more similar. An important code comparison study of Ref. [93] showed that near the end of the accretion phase (Fig. 4, $\sim 0.5s$), there is an $\sim$ few MeV difference in mean energies between simulation codes, whereas the luminosities agree well throughout the simulations. These points suggest that, among the neutrino spectral parameters, the uncertainty on the mean energy must be treated carefully. Although it can be seen quantitatively through our cooling-phase estimations, this uncertainty primarily comes from simulation implementation. This is evidenced by the systematic differences between Corr and RenormShen/LS (between the Supernova Neutrino Database and Hüdepohl simulations) and by the comparative simulation study [93].

We keep all factors other than the cooling-phase neutrino emission fixed, but these also remain significantly uncertain. For example, there may be significant diversity in the neutrino emission from the BH channel (e.g., s40 vs. s40s7b2 [67] and different progenitors [94]). Further, simulations of failed SNe and their neutrino emission prove to be strongly EOS dependent, especially regarding the BH formation time [66, 67, 71, 95, 96]. In addition, the initial progenitor mass may not be a valid criterion for determining explodability (e.g., [44]); in fact, the $60M_\odot$ progenitor from the 3D simulations of Ref. [58] succeeds in exploding. Although the true failed SNe fraction could be much higher [45, 47, 97, 98], we keep a more conservative BH fraction so that it minimizes the impact the BH neutrino emission uncertainty has on the DSNB. Some uncertainties that come from implementation details like EOS and dimensionality, are shared between successful and failed cases, but including a smaller BH contribution gives us realistic DSNB results while also establishing the importance of the late-time neutrino emission.

Other factors include the spectral pinching parameter which we have kept fixed to $\alpha = 2.3$. Despite being variable at early times, $\alpha$ tends to evolve slowly at longer timescales [2, 99]. Its value of 2.3 is largely consistent with the “best-fit” procedure of Ref. [47]. We do, however, take the appropriate time-integrated $\alpha$ for the BH channels since we extract the data self-consistently from simulations.

Another factor is the overall core-collapse (and/or star formation) rate. Measurements are subject to a number of uncertainties such as disagreement between measured and predicted core-collapse rate [90], “invisible” supernovae [100], and on the overall normalization [90, 91]. Additionally, including phenomena like mass transfers and mergers in binary systems can enhance the neutrino signal [101]. Neutrino oscillations like the Mikheyev-Smirnov-Wolfenstein (MSW) effect may also have implications for detection at SK-Gd and other experiments like Hyper-K, DUNE, and JUNO where flavor sensitivity varies [102] and be more impactful in the case of large failed SNe fractions [47]. We do not include flavor oscil-

---

**TABLE V. DSNB rate $R_\nu$ in events yr$^{-1}$ and integrated flux $\phi$ in cm$^{-2}$ s$^{-1}$ at SK-Gd ($10 < E_\nu < 26$ MeV) with each late-phase strategy. These include the early-phase contribution from the 3D simulations of Ref. [58], an ONeMg progenitor from Ref. [81], and a conservative contribution from the failed SNe channel using the neutrino signal from Ref. [67].**

| Strategy       | s40 BH $R_\nu$ (events yr$^{-1}$) | s40s7b2 BH $R_\nu$ (events yr$^{-1}$) | s40 BH $\phi$ (cm$^{-2}$ s$^{-1}$) | s40s7b2 BH $\phi$ (cm$^{-2}$ s$^{-1}$) |
|----------------|----------------------------------|--------------------------------------|----------------------------------|--------------------------------------|
| Const          | 2.69                             | 2.45                                 | 4.57                             | 4.25                                 |
| Analyt         | 2.12                             | 1.88                                 | 3.92                             | 3.60                                 |
| Corr           | 1.10                             | 0.86                                 | 2.14                             | 1.82                                 |
| RenormShen     | 1.86                             | 1.62                                 | 3.73                             | 3.41                                 |
| RenormLS       | 2.17                             | 1.93                                 | 4.04                             | 3.72                                 |

TABLE V. DSNB rate $R_\nu$ in events yr$^{-1}$ and integrated flux $\phi$ in cm$^{-2}$ s$^{-1}$ at SK-Gd ($10 < E_\nu < 26$ MeV) with each late-phase strategy. These include the early-phase contribution from the 3D simulations of Ref. [58], an ONeMg progenitor from Ref. [81], and a conservative contribution from the failed SNe channel using the neutrino signal from Ref. [67]. Columns 2 and 3 are the number of events and flux, assuming the neutrino signal from the s40 BH model while columns 4 and 5 assume the s40s7b2 model. These fluxes are well below the current SK upper limits for $E_\nu < 17.3$ MeV [50]. The Const strategy follows Ref. [44]. Analyt strategy is based on the work done in Ref. [10]. Corr uses the data available from Ref. [66], and RenormShen/LS uses the data available from Ref. [87].
TABLE VI. DSNB integrated flux $\phi$ in cm$^{-2}$ s$^{-1}$ (10 < $E_\nu$ < 26 MeV) with each late-phase strategy. These include the early-phase contribution from the 3D simulations of Ref. [58], an ONeMg progenitor from Ref. [81], and a conservative contribution from the failed SNe channel using the neutrino signal from Ref. [67] (∼40 model here). Columns 2 and 3 are the fluxes for $\nu_e$ and $\nu_x$, respectively.

| Strategy   | $\nu_e \phi$ (/cm$^2$/s) | $\nu_x \phi$ (/cm$^2$/s) |
|------------|---------------------------|---------------------------|
| Const      | 3.68                      | 4.13                      |
| Analyt     | 2.56                      | 3.60                      |
| Corr       | 1.30                      | 1.97                      |
| RenormShen | 2.44                      | 2.84                      |
| RenormLS   | 2.75                      | 3.30                      |

lation for simplicity and want to highlight the effects of the cooling-phase estimations. However, we include Table VI to show the integrated flux with each late phase strategy for $\nu_e$ and $\nu_x$. This highlights that the late-phase strategy chosen is still important for the other neutrino flavors and leads to the same factor of $\sim$ 2–3 difference and that this conclusion is independent of flavor. Many of these others uncertainties, though, serve to raise or lower the overall rate, not distinguish between different estimations of cooling-phase neutrino emission.

In the future, the most straightforward solution to cooling phase is a large number of long-term ($\sim$ 20 s), three-dimensional CCSN simulations (see Ref. [60] for a recent successful 3D simulation). However, this is almost computationally prohibitive at present. In the meantime, less expensive strategies can be useful. We find that our RenormLS method, where we renormalize the revival-time–final-mass correlations, gives intermediate libereted and mean energies. The correlations themselves (Corr method) and assuming final constant mean energies (Const method) produce systematically too low and high integrated neutrino spectral parameters, respectively. An alternative is to estimate the neutrino luminosity and mean energy with the analytic functional form of Ref. [85] and fit these to simulation data (Analyt). However, this method is only preferred if enough simulation data are available past the intense mass accretion phase; it may otherwise lead to unreasonable fits soon after revival time, as in Fig. 2. In this context, longer-term two-dimensional simulation sets can be very valuable even if done up to several seconds.

In conclusion, the factor of $\sim$ 3 difference in DSNB event rates highlights the relative importance of the late cooling phase and shows that a good understanding of this stage will give more precise DSNB signal estimates, relevant for the upcoming generation of searches.

ACKNOWLEDGMENTS

We thank Hiroki Nagakura and the Princeton supernova simulation group for providing and helping us understand the simulation data used in this work. We also thank Mukul Bhattacharya, Yudai Suwa, and Ken’ichiro Nakazato for helpful discussions. Numerical computations were in part carried out on Cray XC50 at Center for Computational Astrophysics, National Astronomical Observatory of Japan. N.E. is supported by NSF Grant No. PHY-1914409. The work of S.H. is supported by the U.S. Department of Energy Office of Science under Award No. DE-SC0020262, NSF Grants No. AST1908960 and No. PHY-1914409, and JSPS KAKENHI Grant No. JP22K03630. This study was supported in part by World Premier International Research Center Initiative by the Ministry of Education, Science and Culture of Japan (MEXT), by Grants-in-Aid for Scientific Research of the Japan Society for the Promotion of Science (Grant No. JP22H01223), the MEXT (Grants No. JP17H06364, No. JP17H06365, No. JP19H05811, No. JP19K03837, and No. JP20H01905), by the Central Research Institute of Explosive Stellar Phenomena (REISEP) at Fukuoka University, and an associated project (Project No. 207002), and JICFuS as “Program for Promoting Researches on the Supercomputer Fugaku” (Toward a unified view of the universe: from large scale structures to planets, Grant No. JPMXP1020200109). K.S. acknowledges the support by high performance computing resources at Computing Research Center, KEK, Research Center for Nuclear Physics, Osaka University, and Yukawa Institute of Theoretical Physics, Kyoto University.

Appendix A: Correlations of Other Flavors

In the correlation and renormalization methods (Corr and RenormShen/LS) we find approximately linear correlations between the neutrino spectral parameters, the final baryonic mass of the PNS, and the shock revival time. In Figs. 3 and 4 we show these for the antielectron neutrino flavor but we find very similar results for $\nu_e$ and $\nu_x$; we see linear trends and renormalized curves that fit through the Hüdepohl simulation results well. Here, we show the correlations from the Supernova Neutrino Database for $\nu_e$ and $\nu_x$ in Figs. 7 and 8. We also show the renormalized curves for $\nu_e$ and $\nu_x$ in Figs. 9 and 10.

[1] K. Kotake, K. Sato, and K. Takahashi, Explosion mechanism, neutrino burst, and gravitational wave in core-collapse supernovae, Rept. Prog. Phys. 69, 971 (2006).

arXiv:astro-ph/0509456.

[2] A. Mirizzi, I. Tamborra, H. T. Janka, N. Saviano, K. Scholberg, R. Bollig, L. Hüdepohl, and
| Final PNS Mass [M☉] | ν<sub>e</sub> Liberated Energy [Log 10(erg)] | 100ms | 200ms | 300ms |
|---------------------|------------------------------------------|-------|-------|-------|
| 1.5                 | 52.25                                    |       |       |       |
| 1.6                 | 52.30                                    |       |       |       |
| 1.7                 | 52.35                                    |       |       |       |
| 1.8                 | 52.40                                    |       |       |       |
| 1.9                 | 52.45                                    |       |       |       |

| Final PNS Mass [M☉] | ν<sub>e</sub> Mean Energy [MeV] | 100ms | 200ms | 300ms |
|---------------------|--------------------------------|-------|-------|-------|
| 1.5                 | 8.2                           |       |       |       |
| 1.6                 | 8.3                           |       |       |       |
| 1.7                 | 8.4                           |       |       |       |
| 1.8                 | 8.5                           |       |       |       |
| 1.9                 | 8.6                           |       |       |       |

| Final PNS Mass [M☉] | ν<sub>e</sub> Liberated Energy [Log 10(erg)] | 100ms | 200ms | 300ms |
|---------------------|------------------------------------------|-------|-------|-------|
| 1.5                 | 52.25                                    |       |       |       |
| 1.6                 | 52.30                                    |       |       |       |
| 1.7                 | 52.35                                    |       |       |       |
| 1.8                 | 52.40                                    |       |       |       |
| 1.9                 | 52.45                                    |       |       |       |

| Final PNS Mass [M☉] | ν<sub>e</sub> Mean Energy [MeV] | 100ms | 200ms | 300ms |
|---------------------|--------------------------------|-------|-------|-------|
| 1.5                 | 8.2                           |       |       |       |
| 1.6                 | 8.3                           |       |       |       |
| 1.7                 | 8.4                           |       |       |       |
| 1.8                 | 8.5                           |       |       |       |
| 1.9                 | 8.6                           |       |       |       |

FIG. 7. Same as Fig. 3 but for ν<sub>e</sub>.

FIG. 8. Same as Fig. 3 but for ν<sub>ν</sub>.

S. Chakraborty, Supernova neutrinos: production, oscillations and detection, *Nuovo Cimento Rivista Serie* **39**, 1 (2016), arXiv:1508.00785 [astro-ph.HE].

[3] H.-T. Janka, Neutrino emission from supernovae, *Handbook of Supernovae*, 1575–1604 (2017).

[4] A. Burrows and D. Vartanyan, Core-collapse supernova explosion theory, *Nature* **589**, 29–39 (2021).

[5] K. Hirata *et al*., Observation of a neutrino burst from the supernova SN1987a, *Nucl. Phys. A* **478**, 189 (1988).

[6] R. M. Bionta, G. Blewitt, C. B. Bratton, D. Casper, A. Ciocio, R. Claus, *et al*., Observation of a neutrino burst in coincidence with supernova 1987a in the large magellanic cloud, *Phys. Rev. Lett.* **58**, 1494 (1987).

[7] E. Alexeyev, L. Alexeyeva, I. Krivosheina, and V. Volchenko, Detection of the neutrino signal from sn 1987a in the lmc using the irr baksan underground scintillation telescope, *Physics Letters B* **205**, 209 (1988).

[8] K. Scholberg, Supernova neutrino detection, *Annual Review of Nuclear and Particle Science* **62**, 81–103 (2012).

[9] S. Horiuchi and J. P. Kneller, What can be learned from a future supernova neutrino detection?, *J. Phys. G* **45**, 043002 (2018), arXiv:1709.01515 [astro-ph.HE].

[10] Y. Suwa, K. Sumiyoshi, K. Nakazato, Y. Takahira, Y. Koshio, M. Mori, and R. A. Wendell, Observing supernova neutrino light curves with super-kamiokande: Expected event number over 10 s, *The Astrophysical Journal* **881**, 139 (2019).

[11] S. W. Li, L. F. Roberts, and J. F. Beacom, Exciting prospects for detecting late-time neutrinos from core-collapse supernovae, *Phys. Rev. D* **103**, 023016 (2021).

[12] K. Nakazato, F. Nakanishi, M. Harada, Y. Koshio, Y. Suwa, K. Sumiyoshi, A. Harada, M. Mori, and R. A. Wendell, Observing supernova neutrino light curves with super-kamiokande. ii. impact of the nuclear equation of state, *The Astrophysical Journal* **925**, 98 (2022).

[13] S. Ando and K. Sato, Relic neutrino background from cosmological supernovae, *New Journal of Physics* **6**, 170–170 (2004).

[14] J. F. Beacom, The diffuse supernova neutrino background, *Annual Review of Nuclear and Particle Science* **60**, 439–462 (2010).

[15] C. Lunardini, Diffuse supernova neutrinos at underground laboratories, *Astroparticle Physics* **79**, 1494 (2017).

[16] E. Vitagliano, I. Tamborra, and G. Raffelt, Grand unified neutrino spectrum at earth: Sources and spectral components, *Rev. Mod. Phys.* **92**, 045006 (2020).

[17] L. M. Krauss, S. L. Glashow, and D. N. Schramm, Anti-neutrinos Astronomy and Geophysics, *Nature* **310**, 191 (1984).

[18] A. Dar, Has a cosmological neutrino background from gravitational stellar collapse been detected?, *Phys. Rev. Lett.* **55**, 1422 (1985).

[19] T. Totani and K. Sato, Spectrum of the relic neutrino background from past supernovae and cosmological models, *Astropart. Phys.* **3**, 367 (1995), arXiv:astro-ph/9504015.
FIG. 9. Same as Fig. 4 but for $\nu_e$.

FIG. 10. Same as Fig. 4 but for $\nu_x$. In the bottom panel, the renormalization constant for mean energy is equal to 1 between Corr and RenormShen.

[20] T. Totani, K. Sato, and Y. Yoshii, Spectrum of the Supernova Relic Neutrino Background and Evolution of Galaxies, *Astrophys. J.* **460**, 303 (1996), arXiv:astro-ph/9509130 [astro-ph].

[21] R. A. Malaney, Evolution of the cosmic gas and the relic supernova neutrino background, *Astropart. Phys.* **7**, 125 (1997), arXiv:astro-ph/9612012.

[22] D. H. Hartmann and S. E. Woosley, The cosmic supernova neutrino background, *Astropart. Phys.* **7**, 137 (1997).

[23] M. Kaplinghat, G. Steigman, and T. P. Walker, Supernova relic neutrino background, *Phys. Rev. D* **62**, 043001 (2000).

[24] S. Ando and K. Sato, Supernova relic neutrinos and observational implications for neutrino oscillation, *Phys. Lett. B* **559**, 113 (2003), arXiv:astro-ph/0210502.

[25] M. Fukugita and M. Kawasaki, Constraints on the star formation rate from supernova relic neutrino observations, *Mon. Not. Roy. Astron. Soc.* **340**, L7 (2003), arXiv:astro-ph/0204376.

[26] L. E. Strigari, M. Kaplinghat, G. Steigman, and T. P. Walker, The Supernova relic neutrino background at KamLAND and Super-Kamiokande, *JCAP* **03**, 007, arXiv:astro-ph/0312346.

[27] F. Iocco, G. Mangano, G. Miele, G. G. Raffelt, and P. D. Serpico, Diffuse cosmic neutrino background from Population III stars, *Astropart. Phys.* **23**, 303 (2005), arXiv:astro-ph/0411545.

[28] L. E. Strigari, J. F. Beacom, T. P. Walker, and P. Zhang, The Concordance Cosmic Star Formation Rate: Implications from and for the supernova neutrino and gamma ray backgrounds, *JCAP* **04**, 017, arXiv:astro-ph/0502150.

[29] C. Lunardini, The diffuse supernova neutrino flux, supernova rate and sn1987a, *Astropart. Phys.* **26**, 190 (2006), arXiv:astro-ph/0509233.

[30] F. Daigne, K. A. Olive, P. Sandick, and E. Vangioni, Neutrino signatures from the first stars, *Phys. Rev. D* **72**, 013007 (2005).

[31] H. Yüksel, S. Ando, and J. F. Beacom, Direct measurement of supernova neutrino emission parameters with a gadolinium-enhanced super-kamiokande detector, *Phys. Rev. C* **74**, 015803 (2006).

[32] S. Horiuchi, J. F. Beacom, and E. Dwek, Diffuse supernova neutrino background is detectable in super-kamiokande, *Phys. Rev. D* **79**, 083013 (2009).

[33] C. Lunardini, Diffuse neutrino flux from failed supernovae, *Phys. Rev. Lett.* **102**, 231101 (2009).

[34] A. Lien, B. D. Fields, and J. F. Beacom, Synoptic sky surveys and the diffuse supernova neutrino background: Removing astrophysical uncertainties and revealing invisible supernovae, *Phys. Rev. D* **81**, 083001 (2010).
A. Summa, F. Hanke, H.-T. Janka, T. Melson, A. Marek, and B. Müller, Progenitor-dependent explosion dynamics in self-consistent, axisymmetric simulations of neutrino-driven core-collapse supernovae, The Astrophysical Journal 825, 6 (2016).

[87] I. K. Baldry and K. Glazebrook, Constraints on a universal stellar initial mass function from ultraviolet to near-infrared galaxy luminosity densities, The Astrophysical Journal 593, 258–271 (2003).

[88] M. T. Keil, G. G. Raffelt, and H. Janka, Monte Carlo study of supernova neutrino spectra formation, The Astrophysical Journal 590, 971–991 (2003).

[89] H. Yüksel, M. D. Kistler, J. F. Beacom, and A. M. Hopkins, Revealing the high-redshift star formation rate with gamma-ray bursts, The Astrophysical Journal 683, L5–L8 (2008).

[90] S. Horiuchi, J. F. Beacom, C. S. Kochanek, J. L. Prieto, K. Z. Stanek, and T. A. Thompson, The cosmic core-collapse supernova rate does not match the massive-star formation rate, The Astrophysical Journal 738, 154 (2011).

[91] A. M. Hopkins and J. F. Beacom, On the normalization of the cosmic star formation history, The Astrophysical Journal 651, 142–154 (2006).

[92] P. Vogel and J. F. Beacom, Angular distribution of neutrino inverse beta decay, $\bar{\nu}_e + p \rightarrow e^+ + n$, Phys. Rev. D 60, 053003 (1999), arXiv:hep-ph/9903554 [hep-ph].

[93] E. O’Connor, R. Bollig, A. Burrows, S. Couch, T. Fischer, H.-T. Janka, K. Kotake, E. J. Lentz, M. Liebendörfer, O. E. B. Messer, and et al., Global comparison of core-collapse supernova simulations in spherical symmetry, Journal of Physics G: Nuclear and Particle Physics 45, 104001 (2018).

[94] L. Walk, I. Tamborra, H.-T. Janka, A. Summa, and D. Kresse, Neutrino emission characteristics of black hole formation in three-dimensional simulations of stellar collapse, Phys. Rev. D 101, 123013 (2020).

[95] E. O’Connor and C. D. Ott, Black hole formation in failing core-collapse supernovae, The Astrophysical Journal 730, 70 (2011).

[96] K. Nakazato, K. Sumiyoshi, and H. Togashi, Numerical study of stellar core collapse and neutrino emission using the nuclear equation of state obtained by the variational method, Publications of the Astronomical Society of Japan 73, 639–651 (2021).
rate problems: implications for core-collapse supernova physics, Mon. Not. Roy. Astron. Soc. 445, L99 (2014), arXiv:1409.0006 [astro-ph.HE].

[98] J. M. M. Neustadt, C. S. Kochanek, K. Z. Stanek, C. M. Basinger, T. Jayasinghe, C. T. Garling, S. M. Adams, and J. Gerke, The search for failed supernovae with the Large Binocular Telescope: a new candidate and the failed SN fraction with 11 yr of data, Mon. Not. Roy. Astron. Soc. 508, 516 (2021), arXiv:2104.03318 [astro-ph.SR].

[99] I. Tamborra, B. Müller, L. Hüdepohl, H.-T. Janka, and G. Raffelt, High-resolution supernova neutrino spectra represented by a simple fit, Phys. Rev. D 86, 125031 (2012).

[100] A. Lien, B. D. Fields, and J. F. Beacom, Synoptic sky surveys and the diffuse supernova neutrino background: Removing astrophysical uncertainties and revealing invisible supernovae, Phys. Rev. D 81, 083001 (2010).

[101] S. Horiuchi, T. Kinugawa, T. Takiwaki, K. Takahashi, and K. Kotake, Impact of binary interactions on the diffuse supernova neutrino background, Phys. Rev. D 103, 043003 (2021).

[102] Z. Tabrizi and S. Horiuchi, Flavor triangle of the diffuse supernova neutrino background, Journal of Cosmology and Astroparticle Physics 2021 (05), 011.