The Diffuse Supernova Neutrino Background in the Standard and Double Collapse Models

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The diffuse supernova neutrino background (DSNB) is a powerful future tool to constrain core-collapse explosion mechanisms without observation of a nearby event, and the corresponding signal has been calculated for a variety of collapse models. For Supernova (SN) 1987A, a peculiar double neutrino burst was detected, but models for the double collapse have never been studied in the DSNB context. Here, we fill this gap and compare the DSNB signal expected in the Standard Collapse (SC) and the Double Collapse (DC) models in various future detectors, including Hyper-Kamiokande, JUNO, DUNE and the Large Baksan Neutrino Telescope (LBNT). We calculate the spectra of diffuse neutrinos and antineutrinos in the DC model and determine the rate of registered events as a function of energy of the detected particle, taking into account detector parameters. For each detector, we estimate the corresponding uncertainties and the background and compare the signals expected for the SC and DC models. We conclude that the combination of DUNE and LBNT data will have the highest sensitivity to discriminate between the SC and DC models.

I. INTRODUCTION

Core-Collapse Supernovae (CCSN) is an event which is the final stage of a stellar evolution ($M > 8 M_{\odot}$, where $M_{\odot}$ is the mass of the Sun, $M$ is the stellar mass of the progenitor star). At the beginning of the 20th century it was predicted that during extreme processes in the interior of massive stars before their explosion, radiation of neutrinos and antineutrinos should occur. In the last seconds of its life, the star emits a large number of neutrinos and antineutrinos $\sim 10^{58}$, releasing almost all of the star’s energy $\sim 10^{53}$ erg [1] (see also [2–4]). The spectrum of neutrinos from CCSNe makes it possible to get closer to understanding the final stage of stellar evolution [5–7]. However, the rarity of nearby events ($\sim 3$ events per century [8–10]) makes the prospect of direct registration of neutrinos and antineutrinos from a single event uncertain. Direct registration of the diffuse neutrino flux would allow one not to wait for such a rare event, but to get knowledge about the stellar evolution, collecting the neutrino background from the entire Universe. To this day, Diffuse Supernovae Neutrino Background (DSNB) remains undetected experimentally while theoretical predictions suffer from large uncertainties in the CCSNe rate and explosion models, caused by the relative rarity of nearby supernovae and the presence of only one event, SN 1987A, detected in the neutrino channel.

The only registered SN neutrino detection occurred in 1987, and the observed neutrino light curve from SN 1987A had two peaks separated in time by about 4.7 hours [11–14]. The double neutrino signal the supernova SN 1987A can not be explained within the standard collapse scenario. Based on the available data, models have been developed to explain the cause of the unusual time distribution of neutrinos [15]. Recent studies suggest that the number of SNe subjected to non-standard scenario is about $(0.1 - 1)\%$ of the total core collapses [16], which forces us to turn to alternative models, for instance, the magneto-rotational mechanism model [17] or the rotational mechanism [18–20], which will be considered in this study.

Measurement of the DSNB signal will help to discriminate between various scenarios of core collapses [21], [22]. However, the double collapse model has not been considered in the context of the DSNB yet, and the present work fills this gap. We estimate below the capabilities of relevant future instruments such as Hyper-Kamiokande (HK), JUNO, DUNE and the Large Baksan Neutrino Telescope (LBNT) [23–27]. Based on the analysis of the expected parameters of the detectors, it will be concluded that it is possible to distinguish the models in the course of future experiments, as well as to choose the most suitable detector for this purpose.

II. THE RATE OF CORE-COLLAPSE SUPERNOVAE

The CCSNe rate is known up to large uncertainties, related in particular to the overall normalization. Various approximations [28–30] are commonly used. We focus on the approximation proposed in [31] with the normalization obtained as a result of observations of the nearest...
where $E_{\nu}^{\text{tot}} \approx 3 \times 10^{53} \text{erg}$ is the total energy carried by neutrinos and antineutrinos of all flavors. This energy is equal to the difference in gravitational energy during the collapse of a star [2–4], $E_{\nu_i}$ is the neutrino and antineutrino energy near the stellar surface, $T_{\nu_i}$ is the temperature of the neutrinosphere [39] (further, typical neutrinosphere temperatures are $T_{\nu_e} = 5 \text{ MeV}$, $T_{\nu_x} = 6 \text{ MeV}$, $T_{\bar{\nu_e}} = T_{\nu_x} = T_{\bar{\nu}_x} = 7 \text{ MeV}$ [40]), $i$ denotes the flavor. It is assumed that neutrinos and antineutrinos carry away approximately the same fraction of gravitational energy in this case [1].

\section{III. COLLAPSE MODELS}

Here, we concentrate on the general features of the neutrino and antineutrino emission and not on details which vary depending on particular details of the supernova models. We will compare the Standard Collapse and the Double collapse models. Their distinctive features with respect to the neutrino and antineutrino spectra are discussed in this section.

\subsection{A. The Standard Collapse}

For the purpose of this work, we do not distinguish any variations of models of stellar collapse and subsequent supernova explosion which predict a single neutrino signal per event; we call them "Standard Collapse" (SC) models. Detailed descriptions of these models are available e.g. in Refs. [1], [35]. Implications of variations and uncertainties of these models to DSNB have been widely discussed in [36]. The integrated spectrum of neutrinos and antineutrinos in the Standard Collapse is in good agreement with the thermal spectrum and is given by the following formula [1], [37], [38],

$$f_{\nu_i}^{\text{SC}}(E_{\nu_i}, T_{\nu_i}) = \frac{E_{\nu_i}^{\text{tot}}}{6} \frac{120}{\pi^2} \frac{E_{\nu_i}^2}{T_{\nu_i}^4} (e^{E_{\nu_i}/T_{\nu_i}} + 1)^{-1},$$

For $E_{\nu_i}, T_{\nu_i}$ close to the neutrinosphere temperatures, $T_{\nu_i} \approx T_{\nu_x}$, and $E_{\nu_i} \approx E_{\nu_x}$, the SC formula can be approximated by

$$f_{\nu_i}^{\text{SC}}(E_{\nu_i}, T_{\nu_i}) \approx \frac{E_{\nu_i}^{\text{tot}}}{6} \frac{120}{\pi^2} \frac{E_{\nu_i}^2}{T_{\nu_i}^4} \approx \frac{E_{\nu_i}^{\text{tot}}}{6} \frac{120}{\pi^2} \frac{E_{\nu_i}^2}{T_{\nu_i}^4} \approx \frac{E_{\nu_i}^{\text{tot}}}{6} \frac{120}{\pi^2} \frac{E_{\nu_i}^2}{T_{\nu_i}^4} \approx \frac{E_{\nu_i}^{\text{tot}}}{6} \frac{120}{\pi^2} \frac{E_{\nu_i}^2}{T_{\nu_i}^4},$$

where $E_{\nu_i}^{\text{tot}} \approx 3 \times 10^{53} \text{erg}$ is the total energy carried by neutrinos and antineutrinos of all flavors. This energy is equal to the difference in gravitational energy during the collapse of a star [2–4], $E_{\nu_i}$ is the neutrino and antineutrino energy near the stellar surface, $T_{\nu_i}$ is the temperature of the neutrinosphere [39] (further, typical neutrinosphere temperatures are $T_{\nu_e} = 5 \text{ MeV}$, $T_{\nu_x} = 6 \text{ MeV}$, $T_{\bar{\nu}_e} = T_{\nu_x} = T_{\bar{\nu}_x} = 7 \text{ MeV}$ [40]), $i$ denotes the flavor. It is assumed that neutrinos and antineutrinos carry away approximately the same fraction of gravitational energy in this case [1].

\subsection{B. The Double Collapse}

We use the most elaborated DC model described in detail in Refs. [18], [19], [20]. In this model, fast rotation of neutron-star progenitor results in core deformation into disk which splits into two small neutron stars.

The first neutrino burst is associated with the explosion of the smaller neutron star which becomes unstable after accretion of matter on the bigger one and occurs within rotational mechanism [18–20]. The second neutrino burst is associated with the collapse of the formed massive neutron star.

Hence, the total contribution of a supernova to the DSNB in this model is the sum of these two signals.

\subsubsection{1. Neutrinos from The First Burst}

When a matter is neutronized during the stellar collapse,

$$e^- + p \rightarrow n + \nu_e,$$

only electron neutrinos are born.

Neutrino and antineutrino of other flavors are born during the rescattering of electron neutrinos in the opaque area. Hence, the spectra of electron neutrinos from the transparent area and neutrinos and antineutrinos of other flavors from the opaque area are different.

Electron neutrinos from the transparent area spectrum and electron antineutrinos (and other flavors and types except electron neutrinos) from the opaque area spectrum can be found from the approximation of the plots presented in [18], [19]. The expression for the $\nu_e$ spectrum in units MeV$^{-1}$ from the transparent region is

$$f_{\text{rot},1}(E_{\nu_e}) \approx \chi_1 \left( \frac{E_{\nu_e}}{\text{MeV}} \right)^5 \left( 1 + \exp \frac{E_{\nu_e}}{\omega_1} \right)^{-1},$$

and the $\nu_i, \bar{\nu}_i$ spectra from the opaque region are

$$f_{\text{rot},2}(E_{\nu_i}, \bar{\nu}_i) \approx \chi_2 \left( \frac{E_{\nu_i}, \bar{\nu}_i}{\text{MeV}} \right)^5 \left( 1 + \exp \frac{E_{\nu_i}, \bar{\nu}_i}{\omega_2} \right)^{-1},$$
where \( E_{\nu_e}, E_{\nu_{\mu}, \bar{\nu}_e} \) are in MeV; \( \omega_1 = 6.32 \text{ MeV}, \omega_2 = 6.28 \text{ MeV}; \chi_1 = 2.33 \times 10^{51}, \chi_2 = 1.29 \times 10^{50} \) are dimensionless.

2. Neutrinos from The Second Burst

The second neutrino burst presumably occurs [20] within the SC described in section III A. Note that during the neutralization of the matter only electron neutrinos are born and neutrino and antineutrino of other flavors are born during the electron neutrinos rescattering on the opaque area.

3. The Double Collapse Spectrum

The total energy of the two bursts is

\[
\alpha (E_{\text{rot,}1} + 6E_{\text{rot,}2}) + \beta (6E_{\nu_e} - (E_{\text{rot,}1} + 6E_{\text{rot,}2})),
\]

where \( E_{\text{rot,}1} = 3.14 \times 10^{52} \text{erg} \) is the \( \nu_e \) energy from transparent region, \( E_{\text{rot,}2} = 1.7 \times 10^{52} \text{erg} \) is that carried away by the only one neutrino and antineutrino flavor after the rescattering [19], and \( \alpha \) and \( \beta \) are the undefined coefficients.

The ratio of these coefficients is equal to the ratio of the total energies in the first and second signals,

\[
\frac{\alpha}{\beta} = \frac{E_{\text{rot,}1} + 6E_{\text{rot,}2}}{6E_{\nu_e} - (E_{\text{rot,}1} + 6E_{\text{rot,}2})}.
\]

The total energy does not depend on the choice of the model, so we equate (5) to 6\( E_{\nu_e, \bar{\nu}} \). Solving the system (5) and (6) with respect to \( \alpha \) and \( \beta \), we find:

\[
\begin{aligned}
\alpha &\approx 0.17 \\
\beta &\approx 1.05.
\end{aligned}
\]

The electron neutrino spectrum in the case of the DC becomes

\[
f_{\nu_e}^{\text{DC}}(E_{\nu_e}) = \alpha (f_{\text{rot,}1}(E_{\nu_e}) + f_{\text{rot,}2}(E_{\nu_e})) + \beta f^{\text{SC}}(E_{\nu_e}, T_{\nu_e}).
\]

And the spectrum of neutrinos and antineutrinos of other flavors (including electron antineutrinos) in the case of the DC are given by following formulas.

\[
f_{\nu_i, \bar{\nu}_i}^{\text{DC}}(E_{\nu_i, \bar{\nu}_i}) = \alpha f_{\text{rot,}2}(E_{\nu_i, \bar{\nu}_i}) + \beta f^{\text{SC}}(E_{\nu_i, \bar{\nu}_i}, T_{\nu_i, \bar{\nu}_i}),
\]

where \( i \) denotes the flavor.

IV. THE MIKHEYEV-SMIRNOV-WOLFENSTEIN EFFECT

The Mikheyev-Smirnov-Wolfenstein (MSW) effect is the effect of transformation of one neutrino species (flavor) into another one in a medium with varying density [41]. During this process, neutrinos (hereinafter, the normal hierarchy of neutrino masses is assumed) pass from one type to another according to the following formulas for the SC [21, 42–44]:

\[
f_{\nu_e}^{\text{SC,MSW}} = f_{\nu_e}^{\text{SC}}, \quad f_{\nu_e}^{\text{SC,MSW}} = c_2^2 f_{\nu_e}^{\text{SC}} + s_2^2 f_{\bar{\nu}_e}^{\text{SC}}, \quad f_{\bar{\nu}_e}^{\text{SC,MSW}} = 1 + s_2^2 f_{\nu_e}^{\text{SC}} + (2 + c_2^2) f_{\bar{\nu}_e}^{\text{SC}},
\]

where \( c_2^2 = 1 - s_2^2 \) and \( s_2^2 = 0.310 \) are the mixing angles, \( f_\nu \) is the neutrino flux without the MSW-effect, \( \nu_x \) is muon or tau neutrino. The neutrino and antineutrino spectra for the DC with the MSW effect are given by the following formulas.

\[
f_{\nu_e}^{\text{DC,MSW}} = \alpha (f_{\text{rot,}1}(E_{\nu_e}) + f_{\text{rot,}2}(E_{\nu_e})) + \beta f^{\text{SC,MSW}}, \quad f_{\nu_e}^{\text{DC,MSW}} = \alpha f_{\text{rot,}2}(E_{\nu_e}) + \beta f^{\text{SC,MSW}},
\]

\[
f_{\nu_e}^{\text{DC,MSW}} = \alpha f_{\text{rot,}2}(E_{\nu_e}) + \beta f^{\text{SC,MSW}}.
\]

It should be noted that the MSW-effect is already taken into account in the first terms of the formulas (13) – (15), since this is the neutrino spectrum after interaction with the stellar matter [19].

The same formulas work for antineutrinos if we take into account that there is no mixing between neutrinos and antineutrinos.

V. THE NEUTRINO OSCILLATIONS

After the neutrinos and antineutrinos escape from the collapsed star, they propagate in vacuum. It is at this stage that the effect of vacuum oscillations of neutrinos and antineutrinos becomes essential. Oscillations of electron antineutrinos are accounted following [45] (see also [21])

\[
f_{\nu_e, \bar{\nu}_e} = 0.548 f_{\nu_e, \bar{\nu}_e}^{\text{SC,MSW}} + 0.185 f_{\nu_e, \bar{\nu}_e}^{\text{SC,MSW}} + 0.267 f_{\nu_e, \bar{\nu}_e}^{\text{SC,MSW}},
\]

where \( f_{\nu_e, \bar{\nu}_e}^{\text{SC,MSW}} \) are fluxes of neutrino and antineutrino with the MSW-effect for the SC and

\[
f_{\nu_i, \bar{\nu}_i} = 0.548 f_{\nu_i, \bar{\nu}_i}^{\text{DC,MSW}} + 0.185 f_{\nu_i, \bar{\nu}_i}^{\text{DC,MSW}} + 0.267 f_{\nu_i, \bar{\nu}_i}^{\text{DC,MSW}}
\]

for the DC, where \( f_{\nu_i, \bar{\nu}_i}^{\text{DC,MSW}} \) are fluxes of neutrino and antineutrino with the MSW-effect for the DC.

VI. TOTAL NEUTRINO AND ANTINEUTRINO FLUXES ON THE EARTH

The electron neutrino and antineutrino fluxes are the most interesting in context of this study and, hence, ob-
observed on Earth fluxes are given by the following the formula [46],

$$\Phi_{\nu_m, \bar{\nu}_m}(E_0, T) = \frac{c}{H_0} \int_0^{z_{\max}} \frac{R_{CC} f_{osc,m}(E_0(1+z), T)}{\sqrt{\Omega_M(1+z)^3 + \Omega_{\Lambda}}} dz,$$

where \( c = 3 \cdot 10^{10} \, \text{cm s}^{-1} \) is the speed of light in a vacuum, \( H_0 = 2.19 \cdot 10^{-18} \, \text{s}^{-1} \) is the present Hubble constant, \( \Omega_M = 0.315 \) is the energy density of non-relativistic matter, \( \Omega_{\Lambda} = 0.685 \) is the dark energy density [47], index \( m \) refers to the collapse model (SC or DC), \( E_0 \) is energy of neutrino and antineutrino at the Earth. The limit of integration \( z_{\max} = 5 \) was chosen from the fact that SNe rate is estimated with a reasonable accuracy up to these redshifts, although the result almost does not depend on the high redshifts cut-off. Spectra of electron neutrinos and antineutrinos for various models are shown in Fig. 2.

VII. THE DSNB DETECTORS

To register DSNB, it is planned to use two main types of detectors: liquid scintillators and Cherenkov detectors. The energies of neutrinos and antineutrinos have characteristic values of the order of 10 MeV. Due to the large errors associated with the CCSNe rate and the specifics of the detectors (we remind that all the detectors we discuss are at their project stage currently), we take an approximate estimate of the error in determining the number of events \( \pm 50\% \). This conservative estimate is in good agreement with those presented in Refs. [42] and [22]. Detectors are characterized by several general parameters: the registration channel, filling, fiducial volume, the number of targets, the registration energy range and finally the efficiency.

Let us dwell in more detail on the cross-section of the registration channel. The main filling in detectors is either water (or water with gadolinium), linear alkylbenzene for liquid-scintillator detectors, or liquid argon. The main registration channel is Inverse Beta-Decay (IBD) in the case of water (or linear alkylbenzene),

$$\bar{\nu}_e + p \to n + e^+.$$

(19)

Some detectors such as DUNE and ICARUS use argon as a filling. The reaction with argon, which detects electron neutrinos, is given below

$$\nu_e + ^{40}Ar \to e^- + ^{40}K^*.$$

(20)

Cross-sections of these reactions as functions of electron (anti)neutrino energies are shown in Fig. 3 [49], [42], [50].

Thus, we can select the most promising detectors and evaluate their future performance over 20 years. In this paper, four detectors will be considered: HK, JUNO, DUNE and the LBNT. Another promising experiment to measure DSNB is planned to be installed in the Jing Ping Laboratory but we could not find sufficient information about this future detector to calculate the number of events in it. To calculate the number of events, we need expressions for the neutrino and antineutrino fluxes observed at the Earth (18), calculated with the account of the MSW-effect (10) - (15) and oscillations (16), (17) and the parameters of the detectors presented in the Table I.

It should be noted that electron antineutrinos (like any other flavor of neutrinos and antineutrinos) are observed indirectly due to difficulty of their direct registration (for example, according to the positrons they generate and according to Cherenkov radiation).

$$N = \varepsilon N_t \int \Phi(E, T) \sigma_i(E) dE,$$

(21)
TABLE I. Main parameters of the detectors considered [42], [48].

| Experiment | Registration Channel | Filling                  | Fiducial Mass (kt) | Targets   | Energy Range (MeV) | Efficiency(%) |
|------------|-----------------------|--------------------------|--------------------|-----------|--------------------|---------------|
| HK(Gd)     | IBD                   | Water + Gd               | 374                | $2.5 \times 10^{33}$ | 12-24             | 67            |
| JUNO       | IBD                   | $C_6H_5C_2H_25$          | 17                 | $1.21 \times 10^{33}$ | 10-22             | 50            |
| DUNE       | $\nu_e + Ar$          | Ar                       | 40                 | $6.02 \times 10^{12}$ | 19-32             | 86            |
| LBNT       | IBD                   | $C_6H_5C_2H_25$          | 10                 | $7.3 \times 10^{32}$ | 0-100             | 95-100        |

where $\varepsilon$ is the efficiency (%), $N_t$ is the number of targets, $\Phi(E)$ is the flux electron (positron) neutrino at the Earth ($eV^{-1} cm^{-2} s^{-1}$), $\sigma_i(E)$ is the cross-section (cm$^2$), the index $i$ refers to a registration channel, $t = 20$ yrs is the total registration time [22], [42].

VIII. THE TOTAL EVENT RATE

A. Hyper-Kamiokande

HK is a water detector with the addition of water-soluble gadolinium (Gd) sulfate which is under construction in Japan as a successor to the Super-Kamiokande. At present, it is planned that the detector will contain two cylindrical tanks with the fiducial mass of 187 kt each. The main reaction for registering electron antineutrinos is IBD. It has been calculated that adding GdCl$_3$ to water will reduce the muon background by 5 times [22], [51]. There are several backgrounds that significantly affect DSNB detection. These backgrounds arise as a result of the interaction of cosmic rays with the atmosphere and, as a consequence, the produced muon neutrinos and antineutrinos (charged current, CC), the emission of $\gamma$-rays that are born after the removal of excitations (which appear as a result of quasi-elastic interactions of cosmic rays with the atmosphere) of charged currents (NC), as well as the spallation of $^9$Li atoms. These backgrounds are expected to be non-removable [52], [42].

Using the formula (21) and taking into account the backgrounds, we can obtain a graph of the dependence of the number of events on the energies of positrons that are actually registered in this detector. This dependence with backgrounds is shown in Fig. 4.

B. JUNO

Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kt liquid-scintillator detector planned to be built in China [53]. The detector contains the central tank filled with linear alkybenzene. The central detector is immersed in the water Cherenkov detector surrounded by a muon tracker to reduce the muon background [22]. The efficiency of this detector also strongly depends on the background of fast neutrons, but, nevertheless, it can be greatly reduced by reducing the volume to 17 kt [53], since fast neutrons generated by cosmic muons should decay directly near the detector. Similar to HK, this detector is susceptible to background from CC and NC.

The event rate calculated with (21) and the background, are shown in Fig. 5.

FIG. 4. Estimated number of events in 20 years for HK as a function of positron energy. Red and blue lines are SC and DC event rates, respectively. Magenta, black, purple and gray dashed lines are Li spallation, invisible muons, atmospheric CC and atmospheric NC backgrounds, respectively.

FIG. 5. Estimated number of events in 20 years for JUNO as a function of positron energy. Red and blue lines are SC and DC event rates, respectively. Purple and magenta dashed lines are atmospheric NC and CC backgrounds, respectively.
C. DUNE

The Deep Underground Neutrino Experiment (DUNE) is a detector based on 40 kt of liquid argon to be built in South Dakota [50], [54]. Nowadays it is supposed to separate these 40 kilotons for 4 chambers of 10 kilotons. The main registration channel is,

\[ \nu_e + ^{40}Ar \rightarrow e^- + ^{40}K^* \]

It is planned that DUNE will have a trigger efficiency of about 90%, and a reconstruction efficiency 96% hence \( \varepsilon \) is 86% [22].

The structure and physics of the backgrounds for the DUNE are still under discussion, and thus we will use the assumption that the future DUNE and the current ICARUS [22], [55] are similar, since both detectors use the same method. This detector is strongly influenced by backgrounds from solar neutrinos. Another irreducible background is the atmospheric neutrinos background [50].

FIG. 6. Estimated number of events in 20 years for DUNE as a function of neutrino energy. Red and blue lines are SC and DC event rates, respectively. The dashed purple line is the atmospheric CC background.

The number of events as a function of electron neutrino energies is obtained in the similar way to HK and JUNO, taking into account backgrounds. The estimated event rates and the backgrounds are shown in Fig. 6, 7.

D. The Large Baksan Neutrino Telescope

The LBNT is the project of the scintillation telescope at the the Baksan Neutrino Observatory in Russia. With this telescope, it is planned to achieve the record efficiency indicators of the order of 95−100% for a registration energy range of 0−100 MeV [48]. Since the detector is at the design stage, the structure and physics of the backgrounds are still being discussed, and the effective volume of the detector is yet to be fixed. The detection technique of LBNT is similar to JUNO. The LBNT is expected to be protected from most backgrounds, except for NC and CC. It is estimated that the background of atmospheric neutrinos through NC and CC will be at the level of no more than \( \sim 1 \) and \( \sim 2 \) events per kiloton per year in the range up to 100 MeV, respectively. NC backgrounds dominate in energy range of 10-30 MeV (no more than 0.2 events per kiloton per year) [48]. These estimates included the possibility of using the signature of events associated with these backgrounds and analyzing the pulse shape to suppress the background. Accordingly, 10 kt for the fiducial volume and 95% for the efficiency were used for the calculations. Estimated event rate is shown in Fig. 8.

IX. SUMMARY AND DISCUSSIONS

The details for calculating the DSNB are not fully understood yet. In particular, the CCSNe rate, its normalization and the IMF should be clarified in the future. It should be noted that only generic double and standard collapse models have been considered in this paper.
There are alternative models, for instance, the magnetorotational collapse mechanism [17], models that take into account the formation of black holes during the collapse of massive stars [42], [57], [58] which can be analyzed in a similar way. By analyzing the spectrum for future detectors, it is possible to determine the best strategy to determine the true collapse mechanism or to obtain constraints on scenarios.

HK is a huge water Cherenkov neutrino detector under construction [51]. It is supposed to work at full capacity within the upcoming decade, earlier than all other detectors considered here. Nevertheless, this detector unfortunately is unable to distinguish the DC model from the SC anywhere in its working energy range (Fig. 4).

JUNO is a neutrino experiment still at the project stage. The backgrounds in the energy ranges from $\sim 30$ MeV up to $\sim 100$ MeV are not published yet, but, nevertheless, JUNO is a suitable detector for our purposes in terms of background reduction against backgrounds which gives accuracy and allows us to distinguish the DC from the background. According to the available data (Fig. 5), we can conclude that the main differences between the models are in energy range higher than $\sim 30$ MeV.

DUNE is very different from other detectors discussed in this work. Since it uses the argon reaction (20) as a detection channel, so DUNE is sensitive to electron neutrinos especially. Fig. 2 shows that the main differences between the DC and the SC should be in the sector of electron neutrinos (it is easy to see that in the scenario of the DC the number of electron neutrinos is much larger). In this work, we used a naive approximation of the cross-section for the reaction with argon which leads to additional inaccuracies. The DUNE is also at the design stage and there is not so much information on it today. Nevertheless, the differences in the number of events by an order of magnitude in the case of the DC allows us to conclude that DUNE will be very important for distinguishing between models.

The main advantage of the LBNT is the background suppression. This telescope is located far from nuclear power plants which makes it possible to register low-energy neutrinos. Also, this telescope is supposed to be built deep under the protection of a mountain shield. These factors and the experimental possibilities, which were described above, make it possible to almost get rid of backgrounds. Moreover, this detector is expected to achieve high accuracy. It should be noted that linear alkylbenzene is a relatively cheap filler which leads to an optimistic conclusion on the implementation of this project. However, this detector is at early design stage which introduces a lot of inaccuracies with its parameters. At least, it is not yet clear what the detector volume and efficiency will be. However, due to the very large registered energy range and small backgrounds (Fig. 8), one can confidently distinguish between the DC and the SC in the range of $30-60$ MeV, even with the help of electron antineutrino detection.

It is also reasonable to assume that the collapse model may depend on a particular star. As noted in the work [16], the number of supernovae collapsing in a double collapse maybe small. Simplified, if only the SC and the DC are found in nature, then the event rate is the sum of the event rates from the SC and the DC

$$N_{DSNB} = \lambda \cdot N_{DC} + (1 - \lambda) \cdot N_{SC}, \quad (22)$$

where $N_{DC}$ and $N_{SC}$ are the event rates of the DC and the SC, respectively, $\lambda \in [0, 1].$

Although the event rates in DUNE (Fig. 6, 7) and the LBNT (Fig. 8), if $\lambda = 1$ (or 0), give us a comprehension of the nature of the collapse according to the DC (SC) scenario, but if $\lambda$ is not equal to 1 (or 0), then the event rates will form a linear combination.

The combined model (22) can be distinguished from the SC within the detectors capabilities only if $\lambda \gtrsim 0.1.$ The only detectors that are able to distinguish between
these two models are DUNE and the LBNT. Namely, DUNE is able to conclusively distinguish between the models at the energies of $E \gtrsim 30$ MeV and the DC contribution of $\lambda \gtrsim 0.1$ (Fig. 9), and the LBNT distinguishes the models effectively at $E \gtrsim 50$ MeV and $\lambda \gtrsim 0.15$ (Fig. 10).

Despite all the discussed limitations, the present study demonstrates that the SC+DC model can be tested by observations of DSNB within upcoming decades. The choice of the strategy to test it should use the fact that DC models predict higher neutrino energies and a substantial $\nu_e$ flux, so the combination of DUNE ($\nu_e$) and LBNT (high energies) data is the most promising approach.

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

[2] C. J. Horowitz and J. Piekarewicz, *Neutron star structure and the neutron radius of P208b*, Physical Review Letters 86 (2001) 5647–5650.

[3] D. Page and S. Reddy, *Dense matter in compact stars: Theoretical developments and observational constraints*, Annual Review of Nuclear and Particle Science 56 (2006) 327–374.

[4] J. Lattimer and M. Prakash, *Neutron star observations: Propos for equation of state constraints*, Physics Reports 442 (2007) 109–165.

[5] H. Janka, K. Langanke, A. Maker, G. Martinezpinedo and B. Muller, *Theory of core-collapse supernovae*, Physics Reports 442 (2007) 38–74.

[6] S. Woosley and T. Janka, *The physics of core-collapse supernovae*, Nature Physics 1 (2005) 147–154.

[7] C. Lunardini, *Diffuse neutrino flux from failed supernovae*, Physical Review Letters 102 (2009).

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

[9] N. Y. Agafonova, M. Aglietta, P. Antonioli, V. V. Ashikhmin, G. Badino, G. Bari et al., *Implication for the core-collapse supernova rate from 21 Years of data of the Large Volume Detector*, Astrophysical Journal 802 (2015) 47 [1411.1799].

[10] K. Rozwadowska, F. Vissani and E. Cappellaro, *On the rate of core collapse supernovae in the Milky Way*, New Astronomy 83 (2021) 101498 [2009.03438].

[11] M. Aglietta et al., *On the event observed in the Mont Blanc Underground Neutrino observatory during the occurrence of Supernova 1987A*, Europhys. Lett. 3 (1987) 1315.

[12] E. N. Alekseev, L. N. Alekseeva, V. I. Volchenko and I. V. Krivosheina, *Possible detection of a neutrino signal on 23 February 1987 at the Baksan Underground Scintillation Telescope of the Institute of Nuclear Research*, JETP Lett. 45 (1987) 589.

[13] K. Hirata, T. Kajita, M. Koshiba, M. Nakahata, Y. Oyama, N. Sato et al., *Observation of a neutrino burst from the supernova SN1987A*, Physical Review Letters 58 (1987) 1490.

[14] 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*, Physical Review Letters 58 (1987) 1494.

[15] V. S. Berezinsky, C. Castagnoli, V. I. Dokuchaev and P. Galeotti, *On the possibility of a two-bang supernova collapse*, Nuovo Cim. C 11 (1988) 287.

[16] K. A. Postnov, A. G. Kuranov, D. A. Kolesnikov, S. B. Popov and N. K. Porayko, *Rapidly rotating neutron star progenitors*, Monthly Notices of the Royal Astronomical Society 463 (2016) 1642–1650.

[17] G. S. Bisnovatyi-Kogan, S. G. Moiseenko and N. V. Ardeleny, *Magnetorotational mechanism of the explosion of core-collapse supernovae*, Physics of Atomic Nuclei 81 (2018) 266–278.

[18] V. S. Imshennik and O. G. Ryazhskaya, *A rotating collapsar and possible interpretation of the LSD neutrino signal from SN 1987A*, Astronomy Letters 30 (2004) 14–31.

[19] V. S. Imshennik, *Rotational explosion mechanism for collapsing supernovae and the two-stage neutrino signal from supernova 1987A in the Large Magellanic Cloud*, Physics-Uspekhi 53 (2010) 1081.

[20] O. G. Ryazhskaya, *Neutrinos from stellar core collapses: present status of experiments*, Physics-Uspekhi 49 (2006) 1017.

[21] C. Lunardini and I. Tamborra, *Diffuse supernova neutrinos: oscillation effects, stellar cooling and progenitor mass dependence*, Journal of Cosmology and Astroparticle Physics 2012 (2012) 012–012.

[22] K. Möller, A. M. Suliga, I. Tamborra and P. B. Denton, *Measuring the supernova unknowns at the next-generation neutrino telescopes through the diffuse neutrino background*, Journal of Cosmology and Astroparticle Physics 2018 (2018) 066–066.

[23] SUPER-KAMIOKANDE collaboration, *Diffuse Supernova Neutrino Background Search at Super-Kamiokande*, 2109.11174.

[24] Y. Novoseltsev, M. Boliev, I. Dzaparova, M. Kochkarov, A. Kurenya, R. Novoseltseva et al., *Supernova neutrino burst monitor at the Baksan Underground Scintillation Telescope*, Astroparticle Physics 117 (2020) 102404.

[25] J. Migenda, *Astroparticle physics in...*
A. Y. Smirnov, S. Horiuchi, J. F. Beacom and E. Dwek, *Diffuse supernova neutrino background*, *Research Notes of the AAS* **4** (2020) 4.

D. Hartmann and S. Woosley, *The cosmic supernova neutrino background*, *Astroparticle Physics* **79** (2017) 971–1143.

S. Ando, Cosmic star formation history and the future observability of supernova relic neutrinos, *The Astrophysical Journal* **651** (2006) 142–154.

A. G. Riess, C. McCully et al., *The rate of core collapse supernovae to redshift 2.5 from the CANDELS and UDF surveys*, *Astrophysical Journal* **790** (2020) 115.

Y. P. Porto-Silva and A. Y. Smirnov, *Coherence of oscillations in matter and supernova neutrinos*, *Journal of Cosmology and Astroparticle Physics* **2021** (2021) 029.

J.-S. Lu, Y.-F. Li and S. Zhou, *Getting the most from the detection of galactic supernova neutrinos in future liquid-scintillator detectors*, *Physical Review D* **94** (2016) 063013.

A. Palladino, M. Spurio and F. Vissani, *Neutrino Telescopes and High-Energy Cosmic Neutrinos*, *Universe* **6** (2020) 30 [2009.01919].

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

N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini et al., *Planck 2018 results. Astronomy and Astrophysics* **641** (2020) A6.

B. Lubandorzhiev, private communication, 2021.

J. A. Formaggio and G. P. Zeller, *From eV to MeV: Neutrino cross sections across energy scales*, *Reviews of Modern Physics* **84** (2012) 1307–1341.

DUNE collaboration, *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics*, 2002.03005.

HYPER-KAMIOKANDE collaboration, *HYPER-KAMIOKANDE Design Report*, 2015.04163.

K. Huang, *Measurement of the neutrino-oxygen neutral current quasi-elastic interaction cross-section by observing nuclear de-excitation γ-rays in the T2K experiment*, Ph.D. thesis, Kyoto U., 2015.

F. An, G. An, Q. An, V. Antonelli, E. Baussan, J. Beacom et al., *Neutrino physics with JUNO*, *Journal of Physics G: Nuclear and Particle Physics* **43** (2016) 033001.

DUNE collaboration, *Long-Baseline Neutrino Facility (LBNE) and Deep Underground Neutrino Experiment (DUNE): Conceptual Design Report, Volume 4 The DUNE Detectors at LBNF*, 1601.02984.

A. G. Cocco, A. Ereditato, G. Fiorillo, G. Mangano and V. Pettorino, *Supernova relic neutrinos in liquid argon detectors*, *Journal of Cosmology and Astroparticle Physics* **2004** (2004) 002–002.

G. Zhu, S. W. Li and J. F. Beacom, *Developing the MeV potential of DUNE: Detailed considerations of muon-induced spallation and other backgrounds*, *Physical Review C* **99** (2019) 014613.

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

I. Tamborra, B. Müller, L. Hüdepohl, H.-T. Janka and G. Raffelt, *High-resolution supernova neutrino spectra represented by a simple fit*, *Physical Review D* **86** (2012) 013016.