Supernova neutrino fluxes in HALO-1kT, Super-Kamiokande, and JUNO

A. Gallo Rosso

Department of Physics, Laurentian University, Sudbury ON P3E 2C6, Canada

Abstract

When the next galactic core-collapse supernova occurs, we must be ready to obtain as much information as possible. Although many present and future detectors are well equipped to detect $\nu_e$ and $\nu_x$ neutrinos, the detection of the $\nu_e$ species presents the biggest challenges. We assess the impact that a 1 ktonne lead-based detector, such as HALO-1kT, can have in constraining electron neutrino time-integrated fluxes. The study involves the detector taken alone as well as when combined with massive $\nu_e$-sensitive detectors such as Super-Kamiokande and JUNO. We find that HALO-1kT alone is not able to strongly constrain the emission parameters. When combined with other detectors, however, the orthogonal information might be helpful in improving the $\nu_e$ total emitted energy and mean energy accuracy, up to about 50%, if no other $\nu_e$-sensitive channel is implemented. A discussion on the reconstruction of $\nu_e$ and $\nu_x$ species, as well as the total emitted energy, is also presented.

1 Introduction

The direct detection of neutrinos coming from a galactic core-collapse supernova will have invaluable physical importance. Under an astronomical point of view, supernova neutrinos can provide astronomers with an early warning for optical detection [1, 2]. Their sensitivity to the properties of the compact object, such as the binding energy or the equation of state (see e.g. [3, 4] for a review) could help constraining such quantities [5, 6]. A neutrino signal is also a useful trigger for gravitational-wave detectors [7–11] opening the door to the possibility of combined, multi-messenger analyses [12–16].

The handful of electron antineutrinos detected back in 1987 [17–21] have already proved to be a unique source of information on the explosion mechanism of massive stars [22–24]. This helped affirm the current paradigm of neutrino-driven explosions and delayed-accretion shock mechanism [25–28] in which neutrinos play a crucial role in carrying out the energy and triggering the explosion.

Since the last detected event, numerical simulations have undeniably pushed forward our understanding of the theoretical framework underlying the explosion [29–32] and one-dimensional models have come to a general agreement [33]. However, despite this outstanding improvement, the global picture is far from being understood completely. The huge computational resources

---

$^*$Email: agallorosso@laurentian.ca.

$^1$In the following, supernova for short.
required by state-of-the-art three-dimensional simulations require some degree of approximation in the treatment of neutrino transport which could lead to misrepresenting results [34–37]. Moreover, a first look to the outcomes of three-dimensional simulations suggest that a supernova explosion is a multi-dimensional phenomenon, with peculiar features that could emerge in the detected fluxes, as e.g. discussed in Refs. [4, 38, 39].

A direct detection will also be an invaluable opportunity to cast a light onto the neutrino behavior in dense environments. The idea that neutrino self-interaction could lead to flavor conversion phenomena other than the MSW effect [40, 41] dates back to the early 90s [42–44] and is still developing (for a review, see e.g. [4, 45–47]). Recently, the fast pair-wise flavor conversion of neutrinos on very small scales has been shown to be possible [48, 49] remaining a matter of discussion [50–60]. Finally, the possibility of inferring new neutrino physics from a supernova explosion, such as the existence of sterile neutrinos [61–73] or non-standard interactions [67, 72, 74–79], have also been investigated.

When the next supernova happens, we will have to be ready to get the most of the signal. That is, a good time resolution and a good reconstruction of the flux for each neutrino flavor. Although the detectors built with the primary purpose of detecting supernovae are quite rare, at present there are many able to detect a signal employing different technologies, such as water/ice (e.g. Super-Kamiokande [80], IceCube [81]), liquid scintillator (e.g. KamLAND [82], SNO+ [83]), lead (e.g. HALO [84]) or noble gases (e.g. XENON [85]). Moreover, the next decade will see the commissioning of new, massive experiments able to see a supernova event with impressive statistics. The Jiangmen Underground Neutrino Observatory (JUNO) [86, 87], the Deep Underground Neutrino Experiment (DUNE) [88, 89], Hyper-Kamiokande (HK) [90, 91], and IceCube-Gen2 [92] will possibly open a golden era for supernova neutrino detection.

Dealing with supernova neutrinos, this kind of differentiation and overlapping is crucial. On one hand, the time-scale of a supernova is greater than that of a standard experiment. For instance, assuming a reasonable rate of \(1.63 \pm 0.46\) galactic supernovae per century [93] the probability for a detector to see one event is about 7.8\%, 15.0\%, 27.8\%, and 55.7\%, assuming it stays constantly operational for 5, 10, 20, and 50 years respectively. It is not unlikely that, once very massive (and expensive) experiments finish their life cycle, detection of supernova neutrinos will be left to stable, small-scale ones.

On the other hand, it seems now well-established that the reconstruction of the next supernova signal — and thus the breaking of the degeneracies introduced by the uncertainties on the spectral shape [94] — will require the combination of many sources of information, coming from different detection channels [5, 95–103]. However, the vast majority of the supernova detectors are mostly sensitive to electron antineutrinos through the capture on protons or Inverse Beta Decay (IBD), while the nuclear reactions used for detecting the \(\nu_e\) species usually come with low statistics and difficult tagging (see e.g. [104]).

For instance, recent calculations on the sensitivity of massive liquid scintillator detector such as JUNO [100, 101] have shown that a complete reconstruction of the three neutrino fluxes is indeed possible thanks to its major three channels (IBD and elastic scattering on protons and electrons). However, an accurate reconstruction of the \(\nu_e\) species is difficult to reach if the supernova is not extremely close. As a consequence, a future detection by DUNE seems our only chance to constrain the \(\nu_e\) flux (see e.g. [103]).

Among the possible alternatives, lead is particularly promising. It is mostly sensitive to \(\nu_e\) Charged-Current (CC) interactions, while the ones involving \(\bar{\nu}_e\) are suppressed thanks to the high number of neutrons (Pauli-blocking). Ref. [105] was the first one to suggest lead as an active
material for supernova neutrinos. In principle, lead can be use to retrieve useful information on neutrino temperatures [106] as well as to assess the deviation of the fluxes from a pure thermal behavior [107]. Neutrino interactions on lead have been studied in many theoretical calculations [107–111] and a direct measurement is planned at the Oak Ridge National Laboratory (ORNL) facility [112].

This technology has been concretely implemented by the Helium and Lead Observatory (HALO). A 79 ton version\(^2\) is currently running at SNOLAB [84], while an upgraded 1 kton version (HALO-1kT) will possibly be built at Laboratori Nazionali del Gran Sasso (LNGS). Under an experimental point of view, the whole configuration has been proven to be stable, reliable and characterized by a high livetime. On the theoretical side, the impact of HALO detectors has been investigated in Ref. [113]. In the paper, it is shown how the ratio between 1- and 2- neutron events detected in the actual configuration is sensitive to different neutrino temperatures and patterns of flavor transformation.

The aim of this paper is to deepen and broaden the discussion on the impact that a detector like HALO-1kT could have in the reconstruction of the detected time-integrated fluxes (fluence), with a special emphasis on the reconstruction of the \(\nu_e\) species as detected on Earth.\(^3\) HALO-1kT is considered both alone and in combination with Water-Cherenkov Super-Kamiokande (SK) and liquid scintillator-based JUNO. This is in order to assess the significance of the orthogonal information brought by HALO-1kT to massive supernova \(\nu_e\) detectors. In order to compare the concept of the different detectors, we consider a perfect version of them:\(^4\) namely, 100% efficiency, perfect response and no uncertainties on the nuclear cross sections.

In this work, the supernova explosion is assumed to be described by the models provided by Ref. [4] and the neutrino time-integrated fluxes are parameterized by standard quasi-thermal Garching distributions [114, 115]. This results in a problem with 9 degrees of freedom, tackled by a Monte Carlo based likelihood analysis. This is the first analysis of this kind for a HALO-like detector.

The present paper is structured as follows: in Section 2 we discuss in detail the hypotheses underlying our analyses, such as the assumptions on supernova models and detection channels. A description of the numerical approach implemented is presented in Section 2.4. The outcomes of the analyses are presented in Section 3. Section 3.4 is a parenthesis on \(\nu_e\) fluences and Section 3.5 on the total emitted energy \(E_{\text{tot}}\). Finally, section 4 is a conclusion.

\section{Hypotheses and method}

In our analyses, we assume a supernova explosion happening at a distance \(D\) of exactly 10 kpc. We take into account two different progenitor masses, as described by the one-dimensional models reported in Ref. [4]: 27 \(M_\odot\) in the first case (LS220-s27.0co) and 9.6 \(M_\odot\) in the second one (LS220-z9.6co). In both models, the equation of state (EoS) implemented comes from Ref. [116], convection has a mixing-length treatment, and beta reactions include self-energy shifts of nucleons. Since our goal is to assess the reconstruction of detected fluxes on Earth, as a first approximation no flavor transformation is implemented.

\(^2\)That is, metric tons, as it will always be understood in the following.
\(^3\)In fact, this is the first step of any further analysis.
\(^4\)This choice is especially well-suited for HALO-1kT and JUNO; since not yet operational, it is hard to predict the exact response and general characteristics.
Table 1: True parameters describing the time-integrated fluxes (fluences) from the two models LS220-s27.0co and LS220-z9.6co [4] fitted with distribution (1).

| Neutrino | LS220-s27.0co | LS220-z9.6co |
|----------|---------------|--------------|
| $\nu_e$  | $0.571 \times 10^{53}$ erg | $0.316 \times 10^{53}$ erg |
| $\bar{\nu}_e$ | $10.8$ MeV | $9.9$ MeV |
| $\nu_x$  | $2.42$ | $2.75$ |
| $\nu_e$  | $0.568 \times 10^{53}$ erg | $0.338 \times 10^{53}$ erg |
| $\bar{\nu}_e$ | $13.6$ MeV | $12.3$ MeV |
| $\nu_x$  | $2.26$ | $2.19$ |
| $\nu_e$  | $0.526 \times 10^{53}$ erg | $0.295 \times 10^{53}$ erg |
| $\bar{\nu}_e$ | $12.9$ MeV | $12.5$ MeV |
| $\nu_x$  | $1.85$ | $2.46$ |

In the following, we will consider the standard effective description that deals with just three neutrino species: $\nu_e$, $\bar{\nu}_e$, and $\nu_x$, where the latter indicates one of the species $\nu_\mu$, $\nu_\tau$, $\nu_\tau$. The fluences are described by standard quasi-thermal Garching distributions [114, 115], differential in the neutrino energy $E$:

$$
\frac{dF(\nu_i)}{dE} = \frac{E(\nu_i)}{4\pi D^2} \frac{[\alpha(\nu_i) + 1]^{\alpha(\nu_i)+1}}{\Gamma[\alpha(\nu_i) + 1]} \frac{\Gamma[\alpha(\nu_i) + 1]}{\langle E(\nu_i) \rangle^{\alpha(\nu_i)+2}} \exp \left[ -[\alpha(\nu_i) + 1] \frac{E}{\langle E(\nu_i) \rangle} \right].
$$

(1)

Here, $E(\nu_i)$ is the total emitted energy for a given neutrino species, $\langle E(\nu_i) \rangle$ is the mean energy and $\alpha(\nu_i)$ is the pinching parameter, describing the width of the distribution and thus its shape. Here, $\nu_i$ is the neutrino species. A fit of the fluxes integrated over time gives the sets of parameters assumed for the two models. They are reported in Table 1.

Since all three parameters for each neutrino species are left free to vary, this results in a problem with 9 degrees of freedom. The signal is considered to be given by three different detectors: HALO-1kT (HALO), Super-Kamiokande (SK) and JUNO. In the following, we discuss the hypotheses underlying the description of each detector.

2.1 HALO

In HALO detector, supernova neutrinos interacting in 1 kton of lead produce neutrons captured by $^3$He proportional counters. The signal is given by two classes of events: 1-neutron events (1n) and 2-neutron events (2n), given by a combination of both CC and NC interactions:

$$
\begin{align*}
\text{CC} \quad & \nu_e + ^{208}\text{Pb} \rightarrow e^- + (x-1)^{208}\text{Bi} + n; \\
& \nu_e + ^{208}\text{Pb} \rightarrow e^- + (x-2)^{208}\text{Bi} + 2n. \\
\text{NC} \quad & \nu + ^{208}\text{Pb} \rightarrow \nu + (x-1)^{208}\text{Bi} + n; \\
& \nu + ^{208}\text{Pb} \rightarrow \nu + (x-2)^{208}\text{Bi} + 2n.
\end{align*}
$$

(2)

The kinematical thresholds, weighted over the isotopic abundances, are $7.61\text{ MeV}$ ($10.47\text{ MeV}$) for NC (CC) 1n events and $14.64\text{ MeV}$ ($18.53\text{ MeV}$) for NC (CC) 2n events. The 1n and 2n neutrino-nucleus cross-sections assumed in this work are the ones provided by Engel et. al [107]. In principle, the theoretical calculation describes just the isotope $^{208}\text{Pb}$ but we apply it to lead in general. In fact, this is the only reference in the literature providing the 1n and 2n partial cross sections. Hopefully, the uncertainties affecting these quantities will be reduced to some 10%, thanks to direct measurements on mini-HALO detector at ORNL. The values are

\footnote{In the following, HALO-1kT will simply be denoted as HALO for short, since there cannot be room for confusion with the SNOLAB experiment.}
interpolated outside the tabulated ranges: $(10^{-95})$ MeV for 1n events and $(25^{-95})$ MeV for 2n events. The results show no significant dependency over the implemented interpolation method.

We assume 100% detection efficiency, a perfect reconstruction of the two classes of events, as well as an error-free cross-section. This is done as a proof of principle, to assess the impact HALO can theoretically have among other perfect detectors. In fact, it is worth mentioning that, dealing with supernova neutrinos, the limiting factor is rather the statistics than the detector response (see e.g. Ref. [102]). It is worth mentioning that the current 79 ton version of HALO has a measured single-neutron detection efficiency of about 28% on average. This value is expected to increase up to about 50% in the 1kton version. The number of expected 1n and 2n events for the two models are reported in Table 2.

### Table 2: Number of expected events for each detection channel: 1-neutron events on lead (1n), 2-neutron events on lead (2n), inverse beta decay (IBD), neutrino-electron elastic scattering (eES), neutrino-proton elastic scattering (pES), and CC scatterings on $^{12}$C. The fluences are described by the parameters reported in table 1, assuming the supernova models LS220-s27.0co and LS220-z9.6co [4].

|          | HALO-1kT | Super-K | JUNO |
|----------|----------|---------|------|
|          | 1n  | 2n  | eES | IBD | ν$_{e^{-12}}$C | ν$_{e^{-12}}$C |
| LS220-s27.0co | 152 | 17.3 | 5515 | 228 | 362 | 5376 | 40.2 | 111 |
| LS220-z9.6co | 58.7 | 4.8 | 2943 | 120 | 2883 | 203 | 491 | 2840 |

2.2 Super-Kamiokande

Super-Kamiokande is a water-based Cherenkov detector with a fiducial mass of 22.5 kton of water and a threshold of 5 MeV [117, 118]. The main detection channels are the CC inverse beta decay (IBD)

$$\nu_e + p \rightarrow n + e^+$$ (3)

and the neutrino-electron elastic scattering (eES)

$$\nu + e^- \rightarrow \nu + e^-.$$ (4)

Those channels are also the ones considered in the present work, and the way they are treated is the same as Refs. [5, 99]. As for HALO, the number of expected events for the two models is reported in Table 2.

In the following, we assume 100% detection and tagging efficiency. This is not far from the 90% expected from gadolinium doping [95, 119].

---

6C.J. Virtue, private communication.
2.3 JUNO

JUNO is a liquid scintillator-based detector, assumed to be composed by 20 kton [97, 100] of Linear Alkyl Benzene (LAB) with chemical formula $\text{H}_{28.360}\text{C}_{17.195}\text{N}_{0.002}\text{O}_{0.002}$. The considered channels are: IBD, eES, neutrino-proton elastic scattering (pES) and Charged-Current reactions on $^{12}$C ($^{12}$C-CC):\footnote{We neglect the subdominant contribution from the Neutral-Current reactions on $^{12}$C, since their statistics are outnumbered by other NC reactions.}

$$\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}^{(*)};$$

$$\overline{\nu}_e + ^{12}\text{C} \rightarrow e^+ + ^{12}\text{B}^{(*)}. \tag{5} \tag{6}$$

Charged-current reaction (5) has a threshold of 17.4 MeV and reaction (6) of 14.4 MeV. The emitted $e^\pm$ is observable, in principle, in coincidence with the $\beta^+ (\beta^-)$ decay of $^{12}\text{B} (^{12}\text{N})$, happening with a half-life of 20.2 ms (11.0 ms). On one hand, the signature is similar to the IBD one; on the other, it is much more difficult to tag, since the (anti)electrons from the $\beta^\pm$ decay distribute broadly in energy and time [104].

In the likelihood analysis, the $^{12}$C-CC events are analyzed separately. As for HALO, 100% efficiency and a perfect knowledge of the cross-section are assumed. In order to assess the impact of $^{12}$C-CC interactions in the analysis, three possible scenarios are considered:

1. The $^{12}$C-CC channel is not implemented. That is, $^{12}$C-CC $\nu_e$ and $\overline{\nu}_e$ events are assumed undetectable and thus not considered in the analysis.

2. The $\nu_e$ and $\overline{\nu}_e$ $^{12}$C-CC events can be extracted from other channels (IBD, eES) but cannot be distinguished. That means that, although detectable and separable from IBD and eES events, reactions (5) and (6) cannot be told apart between each other. This scenario is indicated by the letter “C” in the label.

3. The $\nu_e$ and $\overline{\nu}_e$ $^{12}$C-CC events can be extracted from other channels and can also be distinguished. It is indicated by the letters “Cd” in the label.

The pES events are treated in the same way as in Ref. [100]. The energy dependence of the light quenching has been described from the study of Von Krosigk [120] and it has subsequently been rescaled in order to match with the number of expected events given by Ref. [97]. Also in this case, and to assess the impact low-energy events have on the analysis, two possible scenarios are taken into account in the following:

1. Assuming the pES is detectable (“p” in the label), it is analyzed in the window that goes from 0.2 to 4 MeV. In this window, the contribution from other channels is neglected. The IBD and eES are then analyzed from 5 MeV, assuming no contamination from pES and 100% tagging efficiency for the IBD.

2. Assuming the pES is not detectable (“n” in the label), the eES and IBD reactions are analyzed in the whole range $(0.2 - 100)$ MeV, assuming 100% tagging efficiency for the IBD.
Table 3: Different assumptions for JUNO detector and its channels, as well as the label for each configuration, as explained in Section 2.3. Namely: pES un/implemented (n/p), $\nu_e/\bar{\nu}_e$ $^{12}$C-CC reactions included (C), $\nu_e/\bar{\nu}_e$ $^{12}$C-CC reactions included and distinguishable (d).

| pES | eES | IBD | $^{12}$C-CC | Label |
|-----|-----|-----|-------------|-------|
| $\times$ | $> 0.2 \text{ MeV}$ | 100% tagging | $\times$ | n |
| $\nu_e/\bar{\nu}_e$ indistinguishable | $\nu_e/\bar{\nu}_e$ distinguishable |
| (0.2 − 4)MeV | $> 5 \text{ MeV}$ | $> 5 \text{ MeV}$ | $\times$ | p |
| no eES contamination | no pES contamination | 100% tagging | $\nu_e/\bar{\nu}_e$ indistinguishable | $\nu_e/\bar{\nu}_e$ distinguishable |
| $\nu_e/\bar{\nu}_e$ pC | $\nu_e/\bar{\nu}_e$ pCd |

Summarizing, each one of the analyses involving JUNO is performed six times, depending on the combination of the two assumptions about the pES channel (not implemented/included) and three assumptions about the $^{12}$C-CC channel (not implemented, $\nu_e-\bar{\nu}_e$ indistinguishable or $\nu_e-\bar{\nu}_e$ tagged). As for the aforementioned detectors, 100% efficiency is assumed for all channels. The six scenarios are summarized in Table 3, together with the label to designate them, while the number of expected events given the two supernova models are reported in Table 2.

2.4 Likelihoods

With the exception of the HALO events, all the detected channels are analyzed from their differential spectra by means of a binned likelihood:

$$L_j \propto \prod_{i=1}^{N_{\text{bin}}} \frac{n_i}{\nu_i} e^{-\nu_i} \quad \text{with} \quad j = \text{IBD, eES, pES, } \nu_e^{12}\text{C}, \nu_e^{-12}\text{C};$$

(7)

where $\nu_i$ is the number of expected events for the process $j$ (as a function of parameters) in the $i$-th bin and $n_i$ is the number observed in the simulation, in the same bin. Bin widths are not uniform but the coverage is denser at low energies; the partition depends on the detectors, the channels and the analyses. However, we found no significant dependency upon the different binnings that can be assumed.

Concerning the lead events in HALO, there is no spectrum to be detected. The only kind of available information is the two numbers of 1n and 2n events — see e.g. Ref. [113]. Therefore, the likelihood simply confronts the Poissonian deviation between the detected number $n_i$ and the expected number $N_i$ as a function of the parameters:

$$L_{\text{HALO}} \propto \frac{1}{\sqrt{N_1 N_2}} \exp \left[ -\frac{(n_1 - N_1)^2}{2 N_1} - \frac{(n_2 - N_2)^2}{2 N_2} \right].$$

(8)

The procedure of analysis follows a Monte Carlo approach. The 9 analyzed parameters define a 9-dimensional phase-space, explored by throwing in it random points $P$ extracted uniformly within some priors. Each point describes a particular set of neutrino fluences, which can be
accepted or rejected according to the value of its likelihood. A point is accepted within a certain confidence level (CL) if its likelihood satisfies the relation

$$\log \mathcal{L}(P) \geq \log \mathcal{L}_{\text{max}} - \frac{A}{2},$$

where $\mathcal{L}_{\text{max}}$ is the likelihood maximum inside the prior and $A$ is defined with an integral of a chi-square distribution with $N_{\text{dof}}$ degrees of freedom;

$$\int_{0}^{A} \chi^{2}(N_{\text{dof}}; z) \, dz = \text{CL}.$$  

In the following, we consider $\text{CL} = 3\sigma = 0.9973.$

The priors are broad enough to cover any plausible scenario. The total energies are constrained to vary in the interval

$$1 \times 10^{52} \text{erg} \leq E(\nu_{i}) \leq 2 \times 10^{53} \text{erg},$$

while the mean energies have the prior

$$2 \text{MeV} \leq \langle E(\nu_{i}) \rangle \leq 70 \text{MeV}.$$  

Concerning the pinching parameters, we recall that we are dealing with time-integrated fluxes. They are observed to be closer to a thermal distribution than the time-dependent ones, as discussed in Refs. [24, 121]. According to this latter reference, a reasonable conservative interval is $\alpha \in [1.5, 3.5].$ In the following, we consider as a prior

$$1.0 \leq \alpha(\nu_{i}) \leq 4.0.$$  

3 Results

Each analysis involves a different combination of detectors, namely: HALO alone, SK alone, JUNO alone, the combination HALO+SK, the combination HALO+JUNO, the combination SK+JUNO, and the combination HALO+SK+JUNO. We recall that each analysis involving JUNO has been performed six times, depending on the different assumptions on the detection channels (see Table 3).

Each analysis is performed collecting $7 \times 10^{4}$ accepted points at $3\sigma$ CL. The results are quantified by projecting the extracted points onto selected 2-dimensional scatter plots and 1-dimensional histograms. The parameters defining the neutrino spectra are extracted from the histograms. Their means and standard deviations are taken as reference values and associated errors. In the following, we focus our attention exclusively on $\nu_{e}$ and $\nu_{x}$; for a discussion on the $\nu_{e}$ species see Section 3.4.
3.1 HALO alone

The results of the analyses involving HALO alone are graphically shown in Figure 1, and quantitatively in Table 4. From those results, one can see that the only parameters somewhat constrained by HALO alone are $\nu_e$ and $\nu_x$ mean energies, although presenting huge low-energy tails. Indeed, the percentage precision for the reconstructed values is about $30\% - 40\%$ for the $\nu_e$ species and $\approx 50\%$ for the $\nu_x$ one. Even if the accuracies for the total energies $\mathcal{E}(\nu_e)$ and

Figure 1: Projections onto $\mathcal{E}(i) - \langle E(i) \rangle$ planes and probability distributions of the reconstructed parameters, from the HALO signal alone, given the supernova models LS220-s27.0co (left column) and LS220-z9.6co (right column). The top (bottom) row refers to the $\nu_e$ ($\nu_x$) species. The true values are marked by a star.
The low-energy events are very sensitive to the normalization of the fluences. The importance of the low-energy events that make up the pES channel. This is understandable, since the low-energy events are very sensitive to the normalization of the fluences.

As already mentioned, the pinching parameters $\alpha(\nu_e)$ and $\alpha(\nu_x)$ are omitted since their distributions are always nearly flat within the prior, no matter what combination of detectors and channels is considered. Although HALO, SK does not put a clear constraint on the $E(\nu_x)$ and $E(\nu_x)$ parameters either, even if it does a slightly better job than HALO for both models. Indeed, its distributions present a lower standard deviation than HALO (i.e., they are more peaked) even if there still are huge tails extending to the edge of the prior, and the reconstructed distributions somehow flatten at its low-energy edge. JUNO, on the other hand, gives the best results on the two emitted energies $E_{\nu_e}$, $E_{\nu_x}$. The precisions vary with the model and the different assumptions on the detector, in the raw range 50% – 60% for $\nu_e$ and 60% – 30% for $\nu_x$. Moreover, what emerges, in general, is the importance of the low-energy events that make up the pES channel. This is understandable, since the low-energy events are very sensitive to the normalization of the fluences.
Figure 2: Given the supernova model LS220-s27.0co \[4\] at \(D = 10\) kpc, these are the projections onto \(E(i) – \langle E(i) \rangle\) planes and probability distributions of the reconstructed parameters for the \(\nu_e\) (top) and \(\nu_x\) (bottom) species. The results given by Super-Kamiokande (SK) alone are shown in the first column in red. In the other two, the blue shades represent the results by JUNO when the pES channel is not implemented (n/nC/nCd) while the pink ones are when it is included (p/pC/pCd). For the meaning of the labels see Section 2.3 and Table 3. The true values are marked by a star.

Concerning the mean energies \(\langle E(\nu_e) \rangle\) and \(\langle E(\nu_x) \rangle\), the accuracy in the reconstruction for Super-Kamiokande is quite poor and comparable with the one of HALO. On the contrary, JUNO has always the best accuracy, especially when the CC interactions on \(^{12}\)C are implemented. Depending on the species and the model, it can reach up to \(\sim 20\%\), especially when more channels are included.

3.3 The inclusion of HALO

The reconstruction of the \(\nu_e\) species once HALO is added to SK or JUNO is visually shown in Figures 4 and 5, and in Tables 7 and 8, for models LS220-s27.0co and LS220-z9.6co respectively.

What clearly emerges from Figures 4a and 5a is that HALO improves the determination of the \(\langle E(\nu_e) \rangle\) parameter done by SK. In fact, the precision improves down to \(\approx 20\%\) (\(\approx 40\%\) for
Figure 3: Given the supernova model LS220-z9.6co [4] at $D = 10$ kpc, these are the projections onto $E(i) - \langle E(i) \rangle$ planes and probability distributions of the reconstructed parameters for the $\nu_e$ (top) and $\nu_x$ (bottom) species. The results given by Super-Kamiokande (SK) alone are shown in the first column in red. In the other two, the blue shades represent the results by JUNO when the pES channel is not implemented ($n/nC/nCd$) while the pink ones are when it is included ($p/pC/pCd$). For the meaning of the labels see Section 2.3 and Table 3. Note that in figure (c) the tail of the $E(n_e)$ distribution extends up to the edge of the prior, namely $2 \times 10^{53}$ erg. The true values are marked by a star.

LS220-s27.0co (LS220-z9.6co), that is better than either HALO ($30\% - 40\%$) or SK ($40\% - 60\%$) taken alone. This is true for the emitted energy $E(n_e)$ too, although just for the LS220-s27.0co model, going from $\approx 60\%$ for SK and HALO to $\approx 40\%$ in the combined analyses. The same applies to $\nu_x$ species, although to a lesser extent. In general, the resulting distributions are more peaked and the uncertainty reduced, as e.g. for $\langle E(n_e) \rangle$ in LS220-s27.0co model, going from $\approx 50\%$ to $\approx 35\%$ accuracy.

The inclusion of HALO data to JUNO gives mixed results, depending on the number of channels considered. Concerning the $\nu_e$ mean energy, HALO improves once again the results, especially when the $^{12}$C-CC events are not implemented or not clearly distinguishable from $^{12}$C-CC $n_e$ ones. In this latter case, the mean energy is reconstructed with an accuracy around $10\% - 20\%$ for both models; that is, better than either HALO or JUNO alone. As for the emitted
energy $E(\nu_e)$, combining the two detectors makes its distribution more peaked in general, with the maximum of the distribution shifted towards the true value. The combination of these two factors leads to an improvement in the accuracy of some percent. Moreover, we should note the inclusion of HALO is able to limit the allowed region of the parameters; namely, reducing the low-energy events pushed towards the edge of the prior and/or the very high-energy ones — see e.g. Figures 4b, 5e, and 5f.

The inclusion of HALO data to JUNO does little to the $\nu_x$ species, although the $E(\nu_x)$ distributions are, also for this species, shifted. As one can see from Tables 7 and 8, the reconstructed values including HALO are lower and thus a little bit closer to the true values (within statistical fluctuations). Sometimes, however, neither the JUNO or the JUNO+HALO distributions are nicely peaked, with values piling up towards the low-energy edge of the prior. This may happen in the analyses that do not have the pES channel implemented and thus there is no clear information about the low-energy events. Concerning the mean energy $\langle E(\nu_x) \rangle$, the reconstructed distributions including HALO are almost identical to the ones from JUNO alone. When one of
Figure 5: Projections onto $E(\nu_e)$-$\langle E(\nu_e) \rangle$ planes and probability distributions, given the supernova model LS220-z9.6co [4]. In all the four panels, the orange region shows the results of HALO combined with SK (a), JUNO in the n configuration (b), nC configuration (c), nCd configuration (d), p configuration (e), pC configuration (f). For the meaning of the JUNO labels see section 2.3 and table 3. Note that in figure (e) and (f) the tail of the $E(\nu_e)$ distribution extends up to the edge of the prior, namely $2 \times 10^{53}$ erg. The true values are marked by a star.

the results improves, that is because the combination gets rid of the tails in the distribution.

HALO can have an impact not only on SK or JUNO taken alone, but also on their combination, depending on the number of channels implemented in JUNO. Figures 6 and 7 (for models LS220-s27.0co and LS220-z9.6co respectively) show the improvement in the $E(\nu_e)$ and $\langle E(\nu_e) \rangle$ reconstructed parameters, once HALO is added to some of the SK+JUNO configurations.

In general, the inclusion of HALO improves the distribution of the $E(\nu_e)$ parameter, especially when the pES channel and/or $^{12}$C-CC interactions are not implemented in JUNO. The improvement of the accuracy thanks to HALO is variable but on average it is about 10%, as one can see from Tables 7 and 8. Moreover, when the distributions have tails extending to the edge of the prior (e.g. Figures 7c and 7d) the inclusion of HALO helps in containing the region. Something similar happens for the $\nu_x$ emitted energy, although to an extent that is sometimes negligible.

Concerning the mean energies, the one of the $\nu_e$ species has a noticeable improvement if
Figure 6: Projections onto $E(\nu_e) - \langle E(\nu_e) \rangle$ planes and probability distributions, given the supernova model LS220-s27.0co [4]. In all the four panels, the orange regions show the results of HALO inclusion to the SK+JUNO results (purple), given the n configuration (a), nC configuration (b), nCd configuration (c), p configuration (d). For the meaning of the JUNO labels see Section 2.3 and Table 3. The true values are marked by a star.

JUNO is blind to clear $\nu_e$ information brought by carbon events — i.e., n, p, and even nC, pC configurations. In those cases, HALO helps to reduce the uncertainty up to about 50%. In the other cases, the inclusion of HALO makes no significant difference. As for the $\nu_x$ species, the lead information brings little to no improvement to the $\langle E(\nu_x) \rangle$ parameter reconstruction.

It is worth noting that, in general, when HALO improves JUNO results on $\nu_e$ species there is no guarantee that the addition of SK will enhance them further. On the other hand, when SK improves JUNO results, the inclusion of HALO always brings useful information.
Figure 7: Projections onto $E(\nu_e)-\langle E(\nu_e) \rangle$ planes and probability distributions, given the supernova model LS220-z9.6co [4]. In all the four panels, the orange regions show the results of HALO inclusion to the SK+JUNO results (purple), given the n configuration (a), nC configuration (b), p configuration (c), pC configuration (d). For the meaning of the JUNO labels see Section 2.3 and Table 3. Note that in figure (c) and (d) the tail of the $E(\nu_e)$ distribution extends up to the edge of the prior, namely $2 \times 10^{53}$ erg. The true values are marked by a star.

### 3.4 About the $\nu_e$ species

Although HALO is almost completely blind to the $\nu_e$ component of the time-integrated flux, it makes up the most of the signal in SK and JUNO. As a consequence, the reconstructed parameters of the $\nu_e$ species are the ones presenting the strongest constraints. As one can see in Table 5, SK and JUNO give comparable results. Since the signal is reconstructed through
Table 5: Reconstructed parameters of the $\bar{\nu}_e$ fluence, from the supernova models LS220-s27.0co and LS220-z9.6co [4], in Super-Kamiokande (SK), JUNO and a combination of the two. The analyses involving JUNO have been performed with (p) and without (n) the pES scattering — see Section 2.3 and Table 3. The first rows of each block, marked with $(\mu^* \pm \sigma^*)$, report the true value $\mu^*$ and the standard deviation $\sigma^*$ of a flat distribution in the assumed priors (12), (13), (14).

The IBD channel, there is almost no difference among the various configurations of JUNO — namely, including the handful of events from $^{12}$C-CC interactions makes no difference. Combining the two detectors gives the best results, with the precision depending on the considered model. Indeed, for the $\mathcal{E}(\bar{\nu}_e)$ parameter the overall uncertainties are almost the same, but the true value is different. Therefore, the $\mathcal{E}(\bar{\nu}_e)$ precision for the SK+JUNO analysis goes from $\approx 2\%$ (LS220-s27.0co) to $\approx 3\%$ (LS220-z9.6co), while the one for $\langle E(\bar{\nu}_e) \rangle$ goes from $\approx 2\%$ (LS220-s27.0co) to $\approx 3\%$ (LS220-z9.6co). Finally, the $\alpha(\bar{\nu}_e)$ parameter is the only pinching parameter that gets constrained, with an accuracy of around 10%.

3.5 About the total emitted energy

For a given analysis, once a point $P$ satisfies the likelihood condition and thus is accepted in the set, it can be used to reconstruct \textit{a posteriori} the total emitted energy $\mathcal{E}_{\text{tot}}$, as

$$\mathcal{E}_{\text{tot}}|_P = \mathcal{E}(\nu_e)|_P + \mathcal{E}(\bar{\nu}_e)|_P + 4\mathcal{E}(\nu_x)|_P.$$

The reconstructed results, for both models, are summarized in Table 6.

The first thing that clearly emerges is that HALO is not able to put any constraint on $\mathcal{E}_{\text{tot}}$. Indeed, the mean and standard deviation of the reconstructed distributions practically coincide with mean $(6.3 \times 10^{53} \text{erg})$ and standard deviation $(2.3 \times 10^{53} \text{erg})$ of the prior distribution; namely, the one given by eq. (15) when all the $\mathcal{E}(\nu_i)$ vary randomly inside their prior (12). We note that, in this latter case, the prior accuracy is 37%.
Super-Kamokande does a little better, although remaining unsatisfactory. The overall precision is no different from the prior one, but the reconstructed value does get shifted from the prior one towards the true one while the overall error decrease. Surprisingly, the inclusion of HALO seems to improve this trend, in general. This is especially evident when considering the combination with JUNO, the detector leading the $E_{\text{tot}}$ reconstruction. Alone, JUNO has an accuracy ranging from $\approx 30\%$ to $\approx 20\%$, depending on the model and the channels implemented. When combined with HALO, the value is always reconstructed closer to the true one and the uncertainty reduced by about 10\%. Remarkably, adding HALO to JUNO gives results that are comparably or slightly better than the ones from JUNO and SK. Similar to the discussion in Section 3.3, this means that HALO still has some (sometimes minor) impact when added to the combination of JUNO+SK, while the one of SK to the combination HALO+JUNO is sometimes null.

4 Conclusions

In this paper we have assessed the impact that a lead-based detector, such as HALO-1kT, can have if combined with high-statistics supernova detector such as Super-Kamiokande and JUNO. We performed a full-parameter likelihood analysis on the time-integrated fluxes (fluences), taking into account two supernova models without implementing any oscillation mechanism. This justifies the quantitative differences one might find with our previous works [5, 99].

Different combinations of detectors and channels were taken into account. What emerges from the results are, on one hand, that HALO-1kT alone is not able to give a strong constraint on the fluences. On the other hand, the orthogonal source of information it provides is precious when combined with other detectors. In that case, the combined results are in general better than the results of the detectors taken singularly, especially if they do not have a $\nu_e$ sensitive channel. HALO can also give a (minor) contribution in constraining the total emitted energy $E_{\text{tot}}$, although its impact strongly depends on the supernova model and the channels included in the analyses.

The analysis procedure followed in the present work can be extended in many ways. First of all, a realistic detector response can be implemented. Moreover, realistic uncertainties can be taken into account both on the neutrino-lead cross sections and on the neutrino-carbon ones. Finally, the number and kind of supernova models should be extended, together with the ones concerning the flavor transformation in dense environments.

The next supernova detection will surely be a once-in-a-lifetime event for many physical branches and it is eagerly awaited by the scientific community. While neutrino physics still justifies the construction of bigger and bigger detectors, HALO-1kT is a small, economical, and stable detector able to provide supplementary information and, hopefully, to act as an important piece of the supernova puzzle.

Acknowledgements

The author would like to thank C.J. Virtue, F. Vissani, and M.C. Volpe for their invaluable support, help, and comments. Without them, the realization of this work would have never been possible.
|                  | LS220-s27.0co | LS220-z9.6co |
|------------------|---------------|--------------|
|                  | $\mathcal{E}_{\text{tot}}$ | prec. | $\mathcal{E}_{\text{tot}}$ | prec. |
| $(\mu^* \pm \sigma^*)$ | $3.24 \pm 2.33$ | — | $1.83 \pm 2.33$ | — |
| HALO             | $5.98 \pm 2.34$ | 39 | $5.56 \pm 2.33$ | 41 |
| SK               | $4.71 \pm 1.79$ | 38 | $3.50 \pm 1.64$ | 46 |
| + HALO           | $4.02 \pm 1.41$ | 35 | $3.41 \pm 1.57$ | 46 |
| JUNO (n)         | $3.72 \pm 1.28$ | 34 | $2.17 \pm 0.70$ | 32 |
| + HALO           | $3.31 \pm 1.10$ | 33 | $2.17 \pm 0.70$ | 32 |
| JUNO (nC)        | $3.56 \pm 1.24$ | 34 | $2.15 \pm 0.69$ | 32 |
| + HALO           | $3.19 \pm 1.05$ | 32 | $1.82 \pm 0.68$ | 37 |
| JUNO (nCd)       | $3.52 \pm 1.16$ | 33 | $2.04 \pm 0.65$ | 31 |
| + HALO           | $3.33 \pm 1.07$ | 32 | $1.75 \pm 0.65$ | 37 |
| JUNO (p)         | $3.16 \pm 0.61$ | 19 | $2.72 \pm 0.87$ | 32 |
| + HALO           | $3.03 \pm 0.50$ | 16 | $2.41 \pm 0.62$ | 25 |
| JUNO (pC)        | $3.18 \pm 0.58$ | 18 | $2.71 \pm 0.85$ | 31 |
| + HALO           | $3.06 \pm 0.52$ | 16 | $2.40 \pm 0.61$ | 25 |
| JUNO (pCd)       | $3.12 \pm 0.55$ | 17 | $2.37 \pm 0.61$ | 25 |
| + HALO           | $3.05 \pm 0.51$ | 16 | $2.37 \pm 0.60$ | 25 |
| SK+JUNO (n)      | $3.82 \pm 1.27$ | 33 | $2.19 \pm 0.69$ | 31 |
| + HALO           | $3.56 \pm 1.09$ | 30 | $2.14 \pm 0.65$ | 30 |
| SK+JUNO (nC)     | $3.87 \pm 1.20$ | 31 | $2.15 \pm 0.68$ | 31 |
| + HALO           | $3.48 \pm 1.05$ | 30 | $2.13 \pm 0.65$ | 30 |
| SK+JUNO (nCd)    | $3.88 \pm 1.07$ | 27 | $1.99 \pm 0.62$ | 31 |
| + HALO           | $3.67 \pm 0.99$ | 26 | $2.04 \pm 0.62$ | 30 |
| SK+JUNO (p)      | $3.13 \pm 0.60$ | 19 | $2.87 \pm 0.90$ | 31 |
| + HALO           | $3.08 \pm 0.50$ | 16 | $2.80 \pm 0.82$ | 25 |
| SK+JUNO (pC)     | $3.15 \pm 0.55$ | 17 | $2.80 \pm 0.88$ | 31 |
| + HALO           | $3.08 \pm 0.51$ | 16 | $2.46 \pm 0.62$ | 25 |
| SK+JUNO (pCd)    | $3.18 \pm 0.55$ | 17 | $2.43 \pm 0.61$ | 25 |
| + HALO           | $3.11 \pm 0.51$ | 16 | $2.40 \pm 0.59$ | 24 |

Table 6: Reconstructed total energy $\mathcal{E}_{\text{tot}}$ (15) given different combination of detectors and supernova models: LS220-s27.0co and LS220-z9.6co [4]. Each row is doubled to show the impact of including HALO-1kT to the analysis. The first row, marked with $(\mu^* \pm \sigma^*)$, reports the true value $\mu^*$ and the standard deviation $\sigma^*$ of the prior distribution; i.e. the one given by the $\mathcal{E}(\nu_i)$ in eq. (15) varying randomly inside their prior (12). Each analysis involving JUNO is performed six times, corresponding to the six assumptions on its configuration summarized in table 3, namely: pES implemented (p), $\nu_e/\nu_e$ $^{12}$C-CC reactions included (C), $\nu_e/\nu_e$ $^{12}$C-CC reactions included and distinguished (d).
References

[1] Pietro Antonioli et al. “SNEWS: The Supernova Early Warning System”. In: *New J. Phys.* 6 (2004), p. 114. DOI: 10.1088/1367-2630/6/1/114. arXiv: astro-ph/0406214.

[2] S. Al Kharusi et al. “SNEWS 2.0: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy”. In: (Oct. 2020). arXiv: 2011.00035 [astro-ph.HE].

[3] James M. Lattimer and Maddapa Prakash. “Neutron Star Observations: Prognosis for Equation of State Constraints”. In: *Phys. Rept.* 442 (2007), pp. 109–165. DOI: 10.1016/j.physrep.2007.02.003. arXiv: astro-ph/0612440.

[4] Alessandro Mirizzi et al. “Supernova Neutrinos: Production, Oscillations and Detection”. In: *Riv. Nuovo Cim.* 39.1-2 (2016), pp. 1–112. DOI: 10.1393/ncr/i2016-10120-8. arXiv: 1508.00785 [astro-ph.HE].

[5] Andrea Gallo Rosso, Francesco Vissani, and Maria Cristina Volpe. “Measuring the neutron star compactness and binding energy with supernova neutrinos”. In: *JCAP* 11 (2017), p. 036. DOI: 10.1088/1475-7516/2017/11/036. arXiv: 1708.00760 [hep-ph].

[6] Andrea Gallo Rosso et al. “Late time supernova neutrino signal and proto-neutron star radius”. In: *JCAP* 12 (2018), p. 006. DOI: 10.1088/1475-7516/2018/12/006. arXiv: 1809.09074 [hep-ph].

[7] Nicolas Arnaud et al. “Detection of a close supernova gravitational wave burst in a network of interferometers, neutrino and optical detectors”. In: *Astropart. Phys.* 21 (2004), pp. 201–221. DOI: 10.1016/j.astropartphys.2003.12.005. arXiv: gr-qc/0307101.

[8] B. Abbott et al. “Astrophysically Triggered Searches for Gravitational Waves: Status and Prospects”. In: *Class. Quant. Grav.* 25 (2008). Ed. by Susan M. Scott and David E. McClelland, p. 114051. DOI: 10.1088/0264-9381/25/11/114051. arXiv: 0802.4320 [gr-qc].

[9] G. Pagliaroli et al. “Neutrinos from Supernovae as a Trigger for Gravitational Wave Search”. In: *Phys. Rev. Lett.* 103 (2009), p. 031102. DOI: 10.1103/PhysRevLett.103.031102. arXiv: 0903.1191 [hep-ph].

[10] Claudio Casentini. “Methodological studies on the search for Gravitational Waves and Neutrinos from Type II Supernovae”. In: *J. Phys. Conf. Ser.* 689.1 (2016), p. 012010. DOI: 10.1088/1742-6596/689/1/012010.

[11] Ko Nakamura et al. “Multimessenger signals of long-term core-collapse supernova simulations: synergetic observation strategies”. In: *Mon. Not. Roy. Astron. Soc.* 461.3 (2016), pp. 3296–3313. DOI: 10.1093/mnras/stw1453. arXiv: 1602.03028 [astro-ph.HE].

[12] Bernhard Mueller, Hans-Thomas Janka, and Andreas Marek. “A New Multi-Dimensional General Relativistic Neutrino Hydrodynamics Code of Core-Collapse Supernovae III. Gravitational Wave Signals from Supernova Explosion Models”. In: *Astrophys. J.* 766 (2013), p. 43. DOI: 10.1088/0004-637X/766/1/43. arXiv: 1210.6984 [astro-ph.SR].

[13] C.D. Ott et al. “Core-Collapse Supernovae, Neutrinos, and Gravitational Waves”. In: *Nucl. Phys. B Proc. Suppl.* 235-236 (2013), pp. 381–387. DOI: 10.1016/j.nuclphysbps.2013.04.036. arXiv: 1212.4250 [astro-ph.HE].
Atsushi Nishizawa and Takashi Nakamura. “Measuring Speed of Gravitational Waves by Observations of Photons and Neutrinos from Compact Binary Mergers and Supernovae”. In: *Phys. Rev. D* 90.4 (2014), p. 044048. DOI: 10.1103/PhysRevD.90.044048. arXiv: 1406.5544 [gr-qc].

Takami Kuroda et al. “Correlated Signatures of Gravitational-Wave and Neutrino Emission in Three-Dimensional General-Relativistic Core-Collapse Supernova Simulations”. In: *Astrophys. J.* 851.1 (2017), p. 62. DOI: 10.3847/1538-4357/aa988d. arXiv: 1708.05252 [astro-ph.HE].

Shota Shibagaki et al. “Characteristic Time Variability of Gravitational-Wave and Neutrino Signals from Three-dimensional Simulations of Non-Rotating and Rapidly Rotating Stellar Core-Collapse”. In: (Oct. 2020). arXiv: 2010.03882 [astro-ph.HE].

K. Hirata et al. “Observation of a Neutrino Burst from the Supernova SN 1987a”. In: *Phys. Rev. Lett.* 58 (1987), pp. 1490–1493. DOI: 10.1103/PhysRevLett.58.1490.

K.S. Hirata et al. “Observation in the Kamiokande-II Detector of the Neutrino Burst from Supernova SN 1987a”. In: *Phys. Rev. D* 38 (1988), pp. 448–458. DOI: 10.1103/PhysRevD.38.448.

R.M. Bionta et al. “Observation of a Neutrino Burst in Coincidence with Supernova SN 1987a in the Large Magellanic Cloud”. In: *Phys. Rev. Lett.* 58 (1987), p. 1494. DOI: 10.1103/PhysRevLett.58.1494.

C.B. Bratton et al. “Angular Distribution of Events From Sn1987a”. In: *Phys. Rev. D* 37 (1988), p. 3361. DOI: 10.1103/PhysRevD.37.3361.

E.N. Alekseev et al. “Detection of the Neutrino Signal From SN1987A in the LMC Using the Inr Baksan Underground Scintillation Telescope”. In: *Phys. Lett. B* 205 (1988), pp. 209–214. DOI: 10.1016/0370-2693(88)91651-6.

Thomas J. Loredo and Don Q. Lamb. “Bayesian analysis of neutrinos observed from supernova SN-1987A”. In: *Phys. Rev. D* 65 (2002), p. 063002. DOI: 10.1103/PhysRevD.65.063002. arXiv: astro-ph/0107260.

G. Pagliaroli et al. “Improved analysis of SN1987A antineutrino events”. In: *Astropart. Phys.* 31 (2009), pp. 163–176. DOI: 10.1016/j.astropartphys.2008.12.010. arXiv: 0810.0466 [astro-ph].

F. Vissani. “Comparative analysis of SN1987A antineutrino fluence”. In: *J. Phys. G* 42 (2015), p. 013001. DOI: 10.1088/0954-3899/42/1/013001. arXiv: 1409.4710 [astro-ph.HE].

Stirling A. Colgate and Richard H. White. “The Hydrodynamic Behavior of Supernovae Explosions”. In: *Astrophys. J.* 143 (1966), p. 626. DOI: 10.1086/148549.

J. R. Wilson. “A Numerical Study of Gravitational Stellar Collapse”. In: *Astrophys. J.* 163 (1971), p. 209. DOI: 10.1086/150759.

D.K. Nadyozhin. “The neutrino radiation for the hot neutron star formation and the envelope outburst problem”. In: *Astrophys. Space Sci.* 53 (1978), pp. 131–153. DOI: 10.1007/BF00645909.

Hans A. Bethe and James R. Wilson. “Revival of a stalled supernova shock by neutrino heating”. In: *Astrophys. J.* 295 (1985), pp. 14–23. DOI: 10.1086/163343.
[44] G. Sigl and G. Raffelt. “General kinetic description of relativistic mixed neutrinos”. In: *Nucl. Phys. B* 406 (1993), pp. 423–451. DOI: 10.1016/0550-3213(93)90175-0.

[45] Huaiyu Duan and James P Kneller. “Neutrino flavour transformation in supernovae”. In: *J. Phys. G* 36 (2009), p. 113201. DOI: 10.1088/0954-3899/36/11/113201. arXiv: 0904.0974 [astro-ph.HE].

[46] Huaiyu Duan, George M. Fuller, and Yong-Zhong Qian. “Collective Neutrino Oscillations”. In: *Ann. Rev. Nucl. Part. Sci.* 60 (2010), pp. 569–594. DOI: 10.1146/annurev. nucl.012809.104524. arXiv: 1001.2799 [hep-ph].

[47] Irene Tamborra and Shashank Shalgar. “New Developments in Flavor Evolution of a Dense Neutrino Gas”. In: (Nov. 2020). DOI: 10.1146/annurev-nucl-102920-050505. arXiv: 2011.01948 [astro-ph.HE].

[48] R. F. Sawyer. “Neutrino cloud instabilities just above the neutrino sphere of a supernova”. In: *Phys. Rev. Lett.* 116.8 (2016), p. 081101. DOI: 10.1103/PhysRevLett.116.081101. arXiv: 1509.03323 [astro-ph.HE].

[49] Ignacio Izaguirre, Georg Raffelt, and Irene Tamborra. “Fast Pairwise Conversion of Supernova Neutrinos: A Dispersion-Relation Approach”. In: *Phys. Rev. Lett.* 118.2 (2017), p. 021101. DOI: 10.1103/PhysRevLett.118.021101. arXiv: 1610.01612 [hep-ph].

[50] Francesco Capozzi et al. “Fast flavor conversions of supernova neutrinos: Classifying instabilities via dispersion relations”. In: *Phys. Rev. D* 96.4 (2017), p. 043016. DOI: 10.1103/PhysRevD.96.043016. arXiv: 1706.03360 [hep-ph].

[51] Basudeb Dasgupta, Alessandro Mirizzi, and Manibrata Sen. “Simple method of diagnosing fast flavor conversions of supernova neutrinos”. In: *Phys. Rev. D* 98.10 (2018), p. 103001. DOI: 10.1103/PhysRevD.98.103001. arXiv: 1807.03322 [hep-ph].

[52] Francesco Capozzi et al. “Collisional triggering of fast flavor conversions of supernova neutrinos”. In: *Phys. Rev. Lett.* 122.9 (2019), p. 091101. DOI: 10.1103/PhysRevLett.122.091101. arXiv: 1808.06618 [hep-ph].

[53] Sajad Abbar and Maria Cristina Volpe. “On Fast Neutrino Flavor Conversion Modes in the Nonlinear Regime”. In: *Phys. Lett. B* 790 (2019), pp. 545–550. DOI: 10.1016/j.physletb.2019.02.002. arXiv: 1811.04215 [astro-ph.HE].

[54] Sajad Abbar et al. “On the occurrence of fast neutrino flavor conversions in multidimensional supernova models”. In: *Phys. Rev. D* 100.4 (2019), p. 043004. DOI: 10.1103/PhysRevD.100.043004. arXiv: 1812.06883 [astro-ph.HE].

[55] Hiroki Nagakura et al. “Fast-pairwise collective neutrino oscillations associated with asymmetric neutrino emissions in core-collapse supernovae”. In: (Oct. 2019). DOI: 10.3847/1538-4357/ab4cf2. arXiv: 1910.04288 [astro-ph.HE].

[56] Taiki Morinaga et al. “Fast neutrino-flavor conversion in the preshock region of core-collapse supernovae”. In: *Phys. Rev. Res.* 2.1 (2020), p. 012046. DOI: 10.1103/PhysRevResearch.2.012046. arXiv: 1909.13131 [astro-ph.HE].

[57] Milad Delfan Azari et al. “Fast collective neutrino oscillations inside the neutrino sphere in core-collapse supernovae”. In: *Phys. Rev. D* 101.2 (2020), p. 023018. DOI: 10.1103/PhysRevD.101.023018. arXiv: 1910.06176 [astro-ph.HE].
Robert Glas et al. “Fast Neutrino Flavor Instability in the Neutron-star Convection Layer of Three-dimensional Supernova Models”. In: Phys. Rev. D 101.6 (2020), p. 063001. DOI: 10.1103/PhysRevD.101.063001. arXiv: 1912.00274 [astro-ph.HE].

Sajad Abbar et al. “Fast Neutrino Flavor Conversion Modes in Multidimensional Core-collapse Supernova Models: the Role of the Asymmetric Neutrino Distributions”. In: Phys. Rev. D 101.4 (2020), p. 043016. DOI: 10.1103/PhysRevD.101.043016. arXiv: 1911.01983 [astro-ph.HE].

Shashank Shalgar, Ian Padilla-Gay, and Irene Tamborra. “Neutrino propagation hinders fast pairwise flavor conversions”. In: JCAP 06 (2020), p. 048. DOI: 10.1088/1475-7516/2020/06/048. arXiv: 1911.09110 [astro-ph.HE].

O.L.G. Peres and A.Yu. Smirnov. “(3+1) spectrum of neutrino masses: A Chance for LSND?” In: Nucl. Phys. B 599 (2001), p. 3. DOI: 10.1016/S0550-3213(01)00012-8. arXiv: hep-ph/0011054.

Michel Sorel and Janet M. Conrad. “Supernova neutrinos and the LSND evidence for neutrino oscillations”. In: Phys. Rev. D 66 (2002), p. 033009. DOI: 10.1103/PhysRevD.66.033009. arXiv: hep-ph/0112214.

Sandhya Choubey, N.P. Harries, and G.G. Ross. “Probing neutrino oscillations from supernovae shock waves via the IceCube detector”. In: Phys. Rev. D 74 (2006), p. 053010. DOI: 10.1103/PhysRevD.74.053010. arXiv: hep-ph/0605255.

Sandhya Choubey, N.P. Harries, and G.G. Ross. “Turbulent supernova shock waves and the sterile neutrino signature in megaton water detectors”. In: Phys. Rev. D 76 (2007), p. 073013. DOI: 10.1103/PhysRevD.76.073013. arXiv: hep-ph/0703092.

Georg G. Raffelt and Shun Zhou. “Supernova bound on keV-mass sterile neutrinos reexamined”. In: Phys. Rev. D 83 (2011), p. 093014. DOI: 10.1103/PhysRevD.83.093014. arXiv: 1102.5124 [hep-ph].

Irene Tamborra et al. “Impact of eV-mass sterile neutrinos on neutrino-driven supernova outflows”. In: JCAP 01 (2012), p. 013. DOI: 10.1088/1475-7516/2012/01/013. arXiv: 1110.2104 [astro-ph.SR].

Meng-Ru Wu et al. “Impact of active-sterile neutrino mixing on supernova explosion and nucleosynthesis”. In: Phys. Rev. D 89.6 (2014), p. 061303. DOI: 10.1103/PhysRevD.89.061303. arXiv: 1305.2382 [astro-ph.HE].

Arman Esmaili, O.L.G. Peres, and Pasquale Dario Serpico. “Impact of sterile neutrinos on the early time flux from a galactic supernova”. In: Phys. Rev. D 90.3 (2014), p. 033013. DOI: 10.1103/PhysRevD.90.033013. arXiv: 1402.1453 [hep-ph].

MacKenzie L. Warren et al. “Sterile neutrino oscillations in core-collapse supernovae”. In: Phys. Rev. D 90.10 (2014), p. 103007. DOI: 10.1103/PhysRevD.90.103007. arXiv: 1405.6101 [astro-ph.HE].

Tarso Franarin, Jonathan H. Davis, and Malcolm Fairbairn. “Prospects for detecting eV-scale sterile neutrinos from a galactic supernova”. In: JCAP 09 (2018), p. 002. DOI: 10.1088/1475-7516/2018/09/002. arXiv: 1712.03836 [astro-ph.HE].

Leonardo Mastrototaro et al. “Heavy sterile neutrino emission in core-collapse supernovae: Constraints and signatures”. In: JCAP 01 (2020), p. 010. DOI: 10.1088/1475-7516/2020/01/010. arXiv: 1910.10249 [hep-ph].
[72] Anna M. Suliga, Irene Tamborra, and Meng-Ru Wu. “Tau lepton asymmetry by sterile neutrino emission – Moving beyond one-zone supernova models”. In: JCAP 12 (2019), p. 019. DOI: 10.1088/1475-7516/2019/12/019. arXiv: 1908.11382 [astro-ph.HE].

[73] Jian Tang, TseChun Wang, and Meng-Ru Wu. “Constraining sterile neutrinos by core-collapse supernovae with multiple detectors”. In: JCAP 10 (2020), p. 038. DOI: 10.1088/1475-7516/2020/10/038. arXiv: 2005.09168 [hep-ph].

[74] A. Esteban-Pretel, R. Tomas, and J.W.F. Valle. “Probing non-standard neutrino interactions with supernova neutrinos”. In: Phys. Rev. D 76 (2007), p. 053001. DOI: 10.1103/PhysRevD.76.053001. arXiv: 0704.0032 [hep-ph].

[75] Charles J. Stapleford et al. “Nonstandard Neutrino Interactions in Supernovae”. In: Phys. Rev. D 94.9 (2016), p. 093007. DOI: 10.1103/PhysRevD.94.093007. arXiv: 1605.04903 [hep-ph].

[76] Yue Yang and James P. Kneller. “Neutrino flavor transformation in supernovae as a probe for nonstandard neutrino-scalar interactions”. In: Phys. Rev. D 97.10 (2018), p. 103018. DOI: 10.1103/PhysRevD.97.103018. arXiv: 1803.04504 [astro-ph.HE].

[77] Allan Sung, Huitzu Tu, and Meng-Ru Wu. “New constraint from supernova explosions on light particles beyond the Standard Model”. In: Phys. Rev. D 99.12 (2019), p. 121305. DOI: 10.1103/PhysRevD.99.121305. arXiv: 1903.07923 [hep-ph].

[78] André de Gouvêa, Ivan Martinez-Soler, and Manibrata Sen. “Impact of neutrino decays on the supernova neutronization-burst flux”. In: Phys. Rev. D 101.4 (2020), p. 043013. DOI: 10.1103/PhysRevD.101.043013. arXiv: 1910.01127 [hep-ph].

[79] Shashank Shalgar, Irene Tamborra, and Mauricio Bustamante. “Core-collapse supernovae stymie secret neutrino interactions”. In: (Dec. 2019). arXiv: 1912.09115 [astro-ph.HE].

[80] M. Ikeda et al. “Search for Supernova Neutrino Bursts at Super-Kamiokande”. In: Astrophys. J. 669 (2007), pp. 519–524. DOI: 10.1086/521547. arXiv: 0706.2283 [astro-ph].

[81] R. Abbasi et al. “IceCube Sensitivity for Low-Energy Neutrinos from Nearby Supernovae”. In: Astron. Astrophys. 535 (2011). [Erratum: Astron.Astrophys. 563, C1 (2014)], A109. DOI: 10.1051/0004-6361/201117810e. arXiv: 1108.0171 [astro-ph.HE].

[82] Kazumi Tolich. “Supernova detection with KamLAND”. In: Nucl. Phys. B Proc. Suppl. 221 (2011). Ed. by Geoffrey Mills et al., p. 355. DOI: 10.1016/j.nuclphysbps.2011.10.005.

[83] J. Rumleskie and C. Virtue. “Supernovae and SNO+”. In: J. Phys. Conf. Ser. 1342.1 (2020). Ed. by Ken Clark et al., p. 012135. DOI: 10.1088/1742-6596/1342/1/012135.

[84] K. Zuber. “HALO, a supernova neutrino observatory”. In: Nucl. Part. Phys. Proc. 265-266 (2015), pp. 233–235. DOI: 10.1016/j.nuclphysbps.2015.06.059.

[85] Shayne Reichard et al. “Supernova Neutrino Physics with Xenon Dark Matter Detectors”. In: J. Phys. Conf. Ser. 888.1 (2017), p. 012260. DOI: 10.1088/1742-6596/888/1/012260.

[86] Fengpeng An et al. “Neutrino Physics with JUNO”. In: J. Phys. G 43.3 (2016), p. 030401. DOI: 10.1088/0954-3899/43/3/030401. arXiv: 1507.05613.

[87] Lino Miramonti. “Status and the perspectives of the Jiangmen Underground Neutrino Observatory (JUNO)”. In: Mod. Phys. Lett. A 35.09 (2020), p. 2030004. DOI: 10.1142/S0217732320300049.
[88] R. Acciarri et al. “Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE); Conceptual Design Report, Volume 2: The Physics Program for DUNE at LBNF”. In: (Dec. 2015). arXiv: 1512.06148 [physics.ins-det].

[89] Babak Abi et al. “Volume III. DUNE far detector technical coordination”. In: JINST 15.08 (2020), T08009. doi: 10.1088/1748-0221/15/08/T08009. arXiv: 2002.03008 [physics.ins-det].

[90] K. Abe et al. “Hyper-Kamiokande Design Report”. In: (May 2018). arXiv: 1805.04163 [physics.ins-det].

[91] Yoshitaka Itow. “Status and prospects of the Hyper-Kamiokande project”. In: PoS ICRC2019 (2020), p. 924. doi: 10.22323/1.358.0924.

[92] M.G. Aartsen et al. “IceCube-Gen2: The Window to the Extreme Universe”. In: (Aug. 2020). arXiv: 2008.04323 [astro-ph.HE].

[93] Karolina Rozwadowska, Francesco Vissani, and Enrico Cappellaro. “On the rate of core collapse supernovae in the milky way”. In: New Astron. 83 (2021), p. 101498. doi: 10.1016/j.newast.2020.101498. arXiv: 2009.03438 [astro-ph.HE].

[94] H. Minakata et al. “Parameter Degeneracy in Flavor-Dependent Reconstruction of Supernova Neutrino Fluxes”. In: J. Cosmol. Astropart. Phys. 0812 (2008), p. 006. doi: 10.1088/1475-7516/2008/12/006. arXiv: 0802.1489 [hep-ph].

[95] R. Laha and J. F. Beacom. “Gadolinium in water Cherenkov detectors improves detection of supernova $\nu_e$”. In: Phys. Rev. D89 (2014), p. 063007. doi: 10.1103/PhysRevD.89.063007. arXiv: 1311.6407 [astro-ph.HE].

[96] Ranjan Laha, John F. Beacom, and Sanjib Kumar Agarwalla. “New Power to Measure Supernova $\nu_e$ with Large Liquid Scintillator Detectors”. In: (Dec. 2014). arXiv: 1412.8425 [hep-ph].

[97] Jia-Shu Lu, Yu-Feng Li, and Shun Zhou. “Getting the most from the detection of Galactic supernova neutrinos in future large liquid-scintillator detectors”. In: Phys. Rev. D94.2 (2016), p. 023006. doi: 10.1103/PhysRevD.94.023006. arXiv: 1605.07803 [hep-ph].

[98] Alex Nikrant, Ranjan Laha, and Shunsaku Horiuchi. “Robust measurement of supernova $\nu_e$ spectra with future neutrino detectors”. In: Phys. Rev. D 97.2 (2018), p. 023019. doi: 10.1103/PhysRevD.97.023019. arXiv: 1711.00008 [astro-ph.HE].

[99] Andrea Gallo Rosso, Francesco Vissani, and Maria Cristina Volpe. “What can we learn on supernova neutrino spectra with water Cherenkov detectors?” In: JCAP 04 (2018), p. 040. doi: 10.1088/1475-7516/2018/04/040. arXiv: 1712.05584 [hep-ph].

[100] Hui-Ling Li et al. “Towards a complete reconstruction of supernova neutrino spectra in future large liquid-scintillator detectors”. In: Phys. Rev. D97.6 (2018), p. 063014. doi: 10.1103/PhysRevD.97.063014. arXiv: 1712.06985 [hep-ph].

[101] Hui-Ling Li et al. “Model-independent approach to the reconstruction of multiflavor supernova neutrino energy spectra”. In: Phys. Rev. D 99.12 (2019), p. 123009. doi: 10.1103/PhysRevD.99.123009. arXiv: 1903.04781 [hep-ph].

[102] B. Abi et al. “Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment”. In: (Aug. 2020). arXiv: 2008.06647 [hep-ex].
[117] J. F. Beacom and P. Vogel. “Mass signature of supernova muon-neutrino and tau-neutrino neutrinos in Super-Kamiokande”. In: Phys. Rev. D58 (1998), p. 053010. DOI: 10.1103/PhysRevD.58.053010. arXiv: hep-ph/9802424 [hep-ph].

[118] M. B. Smy. “Low energy neutrino physics at Super-Kamiokande”. In: J. Phys. Conf. Ser. 203 (2010), p. 012082. DOI: 10.1088/1742-6596/203/1/012082.

[119] J. F. Beacom and M. R. Vagins. “GADZOOKS! Anti-neutrino spectroscopy with large water Cherenkov detectors”. In: Phys. Rev. Lett. 93 (2004), p. 171101. DOI: 10.1103/PhysRevLett.93.171101. arXiv: hep-ph/0309300 [hep-ph].

[120] Belina Von Krosigk. “Measurement of proton and α particle quenching in LAB based scintillators and determination of spectral sensitivities to supernova neutrinos in the SNO+ detector”. PhD thesis. Dresden, Tech. U., Dept. Math., 2015. URL: http://iktp.tu-dresden.de/IKTP/pub/15/Dissertation_BvKrosigk.pdf.

[121] Lorenz Hudepohl. “Neutrinos from the Formation, Cooling and Black Hole Collapse of Neutron Stars”. PhD thesis. Munich, Tech. U., Oct. 2013.
Table 7: Reconstructed parameters for the time-integrated fluxes from the supernova model LS220-s27.0co [4], given different combination of detectors. Each row is doubled to show the impact of including HALO-1kT to the analysis. The first row, marked with $(\mu^* \pm \sigma^*)$, reports the true value $\mu^*$ and the standard deviation $\sigma^*$ of a flat distribution in the assumed priors (12), (13), (14). Each analysis involving JUNO is performed six times, corresponding to the six assumptions on its configuration summarized in Table 3, namely: pES implemented (p), $\nu_e/\bar{\nu}_e$ $^{12}$C-CC reactions included (C), $\nu_e/\bar{\nu}_e$ $^{12}$C-CC reactions included and distinguished (d).
| Detector Configuration | $\mathcal{E}(\nu_e)$ [10^{53} \text{erg}] prec. | $\langle E(\nu_e) \rangle$ [MeV] prec. | $\mathcal{E}(\nu_x)$ [10^{53} \text{erg}] prec. | $\langle E(\nu_x) \rangle$ [MeV] prec. |
|------------------------|---------------------|---------------------|---------------------|---------------------|
| LS220-z9.6co           |                     |                     |                     |                     |
| $\mu^* \pm \sigma^*$   | $0.32 \pm 0.55$     | $9.9 \pm 19.6$     | $0.30 \pm 0.55$     | $12.5 \pm 19.6$     |
| HALO-1kT               | $0.91 \pm 0.56$     | $6.4 \pm 2.7$      | $0.93 \pm 0.55$     | $10.2 \pm 5.1$      |
| Super-K                | $0.53 \pm 0.41$     | $9.2 \pm 5.7$      | $0.66 \pm 0.42$     | $12.4 \pm 7.9$      |
| + HALO                 | $0.49 \pm 0.36$     | $8.0 \pm 3.3$      | $0.64 \pm 0.39$     | $11.3 \pm 5.3$      |
| JUNO (n)               | $0.32 \pm 0.13$     | $10.4 \pm 2.6$     | $0.38 \pm 0.20$     | $12.2 \pm 5.1$      |
| + HALO                 | $0.32 \pm 0.12$     | $10.0 \pm 1.6$     | $0.38 \pm 0.20$     | $11.4 \pm 3.4$      |
| JUNO (nC)              | $0.32 \pm 0.13$     | $9.6 \pm 1.8$      | $0.38 \pm 0.20$     | $12.8 \pm 5.3$      |
| + HALO                 | $0.37 \pm 0.12$     | $9.8 \pm 1.5$      | $0.28 \pm 0.19$     | $11.5 \pm 3.3$      |
| JUNO (nCd)             | $0.34 \pm 0.12$     | $10.0 \pm 1.4$     | $0.34 \pm 0.19$     | $12.8 \pm 5.7$      |
| + HALO                 | $0.38 \pm 0.12$     | $9.8 \pm 1.3$      | $0.26 \pm 0.18$     | $11.3 \pm 3.3$      |
| JUNO (p)               | $0.31 \pm 0.25$     | $9.2 \pm 4.0$      | $0.52 \pm 0.20$     | $11.2 \pm 1.7$      |
| + HALO                 | $0.26 \pm 0.11$     | $10.5 \pm 1.8$     | $0.46 \pm 0.17$     | $11.5 \pm 1.8$      |
| JUNO (pC)              | $0.30 \pm 0.23$     | $8.4 \pm 3.3$      | $0.52 \pm 0.20$     | $11.2 \pm 1.8$      |
| + HALO                 | $0.26 \pm 0.11$     | $10.3 \pm 1.7$     | $0.45 \pm 0.16$     | $11.6 \pm 1.8$      |
| JUNO (pCd)             | $0.26 \pm 0.11$     | $10.3 \pm 1.6$     | $0.44 \pm 0.16$     | $11.6 \pm 1.8$      |
| + HALO                 | $0.27 \pm 0.10$     | $10.3 \pm 1.6$     | $0.44 \pm 0.16$     | $11.6 \pm 1.8$      |
| SK+JUNO (n)            | $0.32 \pm 0.12$     | $10.2 \pm 2.7$     | $0.39 \pm 0.20$     | $12.5 \pm 4.8$      |
| + HALO                 | $0.32 \pm 0.12$     | $9.8 \pm 1.7$      | $0.37 \pm 0.19$     | $12.3 \pm 3.6$      |
| SK+JUNO (nC)           | $0.32 \pm 0.12$     | $9.4 \pm 1.9$      | $0.37 \pm 0.20$     | $13.5 \pm 5.0$      |
| + HALO                 | $0.32 \pm 0.12$     | $9.7 \pm 1.5$      | $0.37 \pm 0.19$     | $12.3 \pm 3.5$      |
| SK+JUNO (nCd)          | $0.35 \pm 0.12$     | $9.8 \pm 1.4$      | $0.33 \pm 0.18$     | $13.7 \pm 5.1$      |
| + HALO                 | $0.34 \pm 0.11$     | $9.8 \pm 1.4$      | $0.34 \pm 0.18$     | $12.1 \pm 3.5$      |
| SK+JUNO (p)            | $0.31 \pm 0.26$     | $9.1 \pm 4.0$      | $0.55 \pm 0.21$     | $10.9 \pm 1.8$      |
| + HALO                 | $0.26 \pm 0.11$     | $10.3 \pm 1.9$     | $0.47 \pm 0.17$     | $11.3 \pm 1.8$      |
| SK+JUNO (pC)           | $0.31 \pm 0.24$     | $8.4 \pm 3.2$      | $0.54 \pm 0.21$     | $11.0 \pm 1.7$      |
| + HALO                 | $0.26 \pm 0.10$     | $10.2 \pm 1.7$     | $0.46 \pm 0.17$     | $11.4 \pm 1.8$      |
| SK+JUNO (pCd)          | $0.26 \pm 0.10$     | $10.1 \pm 1.7$     | $0.46 \pm 0.17$     | $11.4 \pm 1.8$      |
| + HALO                 | $0.27 \pm 0.10$     | $10.1 \pm 1.6$     | $0.45 \pm 0.16$     | $11.5 \pm 1.8$      |

Table 8: Reconstructed parameters for the time-integrated fluxes from the supernova model LS220-z9.6co [4], given different combination of detectors. Each row is doubled to show the impact of including HALO-1kT to the analysis. The first row, marked with $(\mu^* \pm \sigma^*)$, reports the true value $\mu^*$ and the standard deviation $\sigma^*$ of a flat distribution in the assumed priors (12), (13), (14). Each analysis involving JUNO is performed six times, corresponding to the six assumptions on its configuration summarized in Table 3, namely: pES implemented (p), $\nu_e/\nu_e$ $^{12}$C-CC reactions included (C), $\nu_e/\nu_e$ $^{12}$C-CC reactions included and distinguished (d).