Neutrinos produced in the Sun by electron capture reactions on $^{13}$N, $^{15}$O and $^{17}$F, to which we refer as ecCNO neutrinos, are not usually considered in solar neutrino analysis since the expected fluxes are extremely low. The experimental determination of this sub-dominant component of the solar neutrino flux is very difficult but could be rewarding since it provides a determination of the metallic content of the solar core and, moreover, probes the solar neutrino survival probability in the transition region at $E_\nu \sim 2.5$ MeV. In this letter, we suggest that this difficult measure could be at reach for future gigantic ultra-pure liquid scintillator detectors, such as LENA.
1 Introduction

One of the main goals of the present and next generation ultra-pure liquid scintillator detectors, such as Borexino [1], SNO+ [2] and LENA [3], is the determination of the neutrino fluxes produced by the CNO cycle in the Sun. The evaluation of CNO cycle efficiency is, in fact, connected with various important problems, like e.g. the determination of globular clusters age [4] from which we extract a lower limit to the age of the Universe. Moreover, it can provide clues to solve the so-called “solar composition problem”, i.e. the fact that Standard Solar Models (SSM) implementing the latest photospheric heavy element abundances [5] are not able to reproduce the helioseismic results, see e.g. [6, 7, 8].

The present experimental efforts in this direction are devoted to the observation of neutrinos originating from the $\beta^+$ decay of $^{13}$N, $^{15}$O and $^{17}$F, the so-called CNO neutrinos, that represent about 1% of the total solar neutrino budget. Their detection is, however, a difficult task. The CNO neutrinos have continuous energy spectra with endpoints at about 1.5 MeV and do not produce specific spectral features that permit to extract the signal unambiguously from the background in high purity liquid scintillators (see e.g. [9] for a discussion).

In this work, we consider a different source of neutrinos in the CNO cycle that is generally neglected. It was pointed out by [10] and [11] that neutrinos can be also produced in the Sun by electron capture reactions on $^{13}$N, $^{15}$O and $^{17}$F. The resulting fluxes, to which we refer as ecCNO neutrino fluxes, are extremely small, at the level of 0.1% with respect to the “conventional” CNO neutrino fluxes. However, ecCNO neutrinos are monochromatic and have larger energies equal to $E_\nu \sim 2.5$ MeV.

We suggest that these characteristics, together with the development of gigantic (i.e. with masses $\sim 10$ kton or more) ultra-pure liquid scintillator detectors, such as LENA [3], could make their detection possible. Clearly, the determination of this sub-dominant component of the solar neutrino flux is extremely difficult but could be rewarding in terms of physical implications. In fact, besides testing the efficiency of the CNO cycle, ecCNO neutrinos could permit to determine the metallic content of the solar core and also probe the electron neutrino survival probability in an energy region that is otherwise inaccessible, with important implications for the final confirmation of the LMA-MSW flavour oscillation paradigm.

Is thus useful to investigate the potential of future gigantic liquid scintillator experiments for ecCNO neutrino detection. With this spirit, in sect. 2 we review and update the predictions of ecCNO neutrinos fluxes by [10] in light of the recent SSM calculations and we calculate the event spectrum expected in liquid scintillator experiments. In sect. 3 we compare our results with the expected background rates. In sect. 4 we give our conclusions.

2 ecCNO neutrinos

The dominant hydrogen burning mechanism in the Sun is the pp-chain which accounts for $\sim 99\%$ of the total energy (and neutrino) production. A sub-dominant contribution is given by the CNO cycle that produces significant neutrino fluxes originating from the $\beta^+$ decay of $^{13}$N, $^{15}$O and $^{17}$F. The SSM predictions for the CNO neutrino fluxes are given in the first three lines of Tab.1. These values were obtained in [12] by assuming, as input for SSM calculations, the “old” high surface metallicity of GS98 [13] and the “new” low surface metallicity of AGSS09 [5].

As it was pointed out in [10, 11], along with these fluxes, neutrinos are produced by the electron capture reactions:

$$^{13}\text{N} + e^- \rightarrow ^{13}\text{C} + \nu_e$$
We briefly review the calculation of the ecCNO neutrino fluxes performed by [10] in order to obtain updated predictions that take into account the recent revisions in SSMs calculations. The ratios $r$ between $\beta^+$ decay and electron capture rates for $^{13}$N, $^{15}$O and $^{17}$F nuclei are measured in laboratory and are given by $r = 1.96 \times 10^{-3}$, $9.94 \times 10^{-4}$ and $1.45 \times 10^{-3}$ [10], respectively. However, the electron capture rates in the sun have to be rescaled proportionally to the electron number density at the nuclear site which has to be calculated by taking into account: the distortion of the electron wave functions in the Coulomb field of nuclei; electron capture from bound states; screening effects, as it is e.g. discussed in [14] where a comprehensive analysis of the $^7$Be electron capture was given. The ratios $\tilde{r}$ between electron capture rates in the Sun and laboratory are calculated in [10] by using the temperature and electron density profile of the Sun predicted by [15]. The values obtained by averaging over the entire solar volume are $\tilde{r} = 0.403$, $0.398$, and $0.405$, respectively. One calculates then the ecCNO neutrino fluxes by using $\Phi_{eX} = r \times \tilde{r} \times \Phi_X$, where $\Phi_{eX}$ ($\Phi_X$) is the flux produced by the electron capture ($\beta$ decay) of the X nucleus in the Sun and X = N, O and F; the results are shown in Tab. 1. The differences between the quoted values and those obtained in [10] are due to the fact that recent SSM calculations predict smaller “conventional” CNO fluxes, mainly as a consequence of revised solar surface composition and updated $S_{1,14}$ astrophysical factor [16]. Note that we made the reasonable assumption that the small differences in the temperature profile of the Sun which are implied by a different choice of the surface composition do not affect the $\tilde{r}$ parameter in a significant way. In this assumption, the ecCNO neutrinos carry exactly the same information as CNO neutrinos on the efficiency of the CNO cycle and on the metallic content of the solar core. They probe, however, the solar neutrino survival probability at a different energy, $E_\nu \sim 2.5$ MeV, which well corresponds to the transition between vacuum averaged and matter enhanced neutrino oscillations.

The spectrum of solar neutrinos, including the ecCNO neutrinos contribution, is shown in the left panel of Fig. 1 which updates the original figure produced by [10]. The continuous fluxes are given in cm$^{-2} \cdot$ s$^{-1} \cdot$ (100 keV)$^{-1}$ while the monochromatic fluxes are given in cm$^{-2} \cdot$ s$^{-1}$. The eF and eO component have been summed since their energies are almost equal; the eF contribution is, however,
Figure 1: Left Panel: The solar neutrino spectrum; Right Panel: The event rate produced by solar neutrinos in liquid scintillator detectors.

largely sub-dominant and will be neglected in the following. At the ecCNO neutrinos energies, the low energy tail of the $^8$B neutrino spectrum is also produced. The figure shows that ecCNO neutrinos emerge over the $^8$B contribution if they are observed in an hypothetical detector with a spectral response as narrow as $\sim$ few $\times$ 100 keV or better. In this respect, the optimal detector has an energy resolution at the 10% level or better and is based on a detection reaction that does not wash-out the information on the incoming neutrino energy (like e.g. charged current reaction on nuclei). Liquid scintillators meet the energy resolution requirement but, unfortunately, are based on a detection process ($\nu - e$ elastic scattering) that provides a response proportional to the integrated flux above the observation energy.

The integrated $^8$B neutrino flux is a factor $\sim 20$ larger than the expected ecCNO neutrino fluxes and it represents an irreducible background from which the ecCNO neutrino signal have to be extracted statistically. In the last line of tab. [1] we also report the SSMs predictions for the $^8$B neutrino flux.

In the right panel of Fig. 1 we show the event rate produced by solar neutrinos through $\nu - e$ elastic scattering in liquid scintillator detectors in the visible energy region between $E_{\text{vis}} = 1.4 - 3.0$ MeV. We assume that the scintillator is based on linear-alkyl-benzene (LAB) which corresponds to that used in the future SNO+ and LENA detectors. We include the effect of LMA-MSW flavour oscillations by using the electron neutrino survival probability $P_{ee}$ of [17]. This corresponds to $P_{ee} \simeq 0.48$ and $\simeq 0.46$ for eN and eO neutrinos respectively, and to $(P_{ee}) \simeq 0.37$ when averaged over the entire $^8$B neutrino spectrum. We consider the neutrino fluxes predicted by SSMs that implements the GS98 admixture since these models produce a much better description of helioseismic observables [8]. Finally, we describe the detector energy resolution by a Gaussian with an energy dependent width that scale as $5\% \cdot \sqrt{E_{\text{ev}}/\text{MeV}}$, where $E_{\text{ev}}$ is the average energy of the event.

Being mono-energetic, eN and eO neutrinos produce Compton-shoulders, smeared by resolution effects, at the energies $E_{\text{vis}} = 1.99$ MeV and 2.52 MeV indicated by the two vertical dashed lines in Fig. 1. These shoulders can be identified if the detector counting rate is sufficiently high. The energy integrated rates produced by ecCNO neutrinos are given by:

$$R_{\text{tot}}^{\text{eCNO}} = 26 \text{ counts}/\text{1kton}/\text{year}$$

1 An interesting option for ecCNO neutrino detection could arise, in the future, from Li-doped water-based liquid scintillators (see e.g. [18] where they are proposed as a target for solar neutrinos) since these detectors could combine the requirement of good energy resolution with a detection reaction with good spectral response (i.e. charged current reaction on $^7$Li). An investigation of this possibility is outside the goals of this work and will be considered elsewhere.
Table 2: The event rates (counts/1kton/year) produced by ecCNO and $^8$B neutrinos in the energy window $[E_{\text{low}}, 2.5\text{MeV}]$. The last column give the values of the parameter $\eta$ defined in eq. (3).

| $E_{\text{low}}$(MeV) | $R_{\text{eN}}$ | $R_{\text{eO}}$ | $R_B$ | $\eta$ |
|------------------------|----------------|----------------|--------|--------|
| 1.5                    | 5.9            | 4.4            | 255    | 2.1    |
| 1.6                    | 4.7            | 4.0            | 229    | 1.8    |
| 1.7                    | 3.5            | 3.5            | 202    | 1.6    |
| 1.8                    | 2.3            | 3.0            | 176    | 1.3    |
| 1.9                    | 1.1            | 2.6            | 150    | 1.0    |
| 2.0                    | 0.3            | 2.1            | 125    | 0.7    |

We expect, however, that ecCNO neutrino signal is unobservable below $E_{\text{vis}} \sim 1.5\text{MeV}$ due to the much larger contribution provided by the conventional CNO neutrinos shown by the green line in the right panel of Fig.1. In order to explore the possibility to extract the ecCNO neutrino signal, we define the observation window $[E_{\text{low}}, 2.5\text{MeV}]$ and we calculate the rates for ecCNO and $^8$B neutrinos as a function of $E_{\text{low}}$ in Tab. 2. We estimate the significativity $\Sigma$ of a possible measure by comparing the expected signal $S$ due to ecCNO neutrinos to the statistical fluctuations of the background $B$ produced by $^8$B neutrinos. We obtain:

$$R_{\text{eO}}^{\text{tot}} = 12\text{ counts/1kton/year}$$

(2)

where $\Sigma$ is the assumed detector exposure. In the above formula, since the signal has to be extracted from observed rate by subtraction, one implicitly assumes that the background in $[E_{\text{low}}, 2.5\text{MeV}]$ is known from independent observations with a fractional uncertainty lower than $1/\sqrt{B} \sim \text{few}\%$. This is plausible, from a statistical point of view. Indeed, $^8$B solar neutrinos and cosmogenic $^{11}$C nuclei, which are the dominant background sources (see below), mostly produce events outside the observation window $[E_{\text{low}}, 2.5\text{MeV}]$ and can thus be well constrained from observations in other spectral regions. This clearly requires that systematical errors on the spectral shapes (at few MeV) of $^8$B and $^{11}$C background are at the % level.

The parameter $\eta$ in eq. (3) represents the statistical significance of a measure with an exposure $\mathcal{E} = 10\text{kton} \times \text{year}$ and is given in the last column of tab. 2. We understand that detectors with fiducial masses equal to $\sim 10 \text{kton}$ or more are necessary, for statistical reasons, to extract the ecCNO neutrino signal.

3 Background

There are three additional types of background for the proposed measure: i) external gamma rays emitted by the materials that contain and surround the scintillator; ii) intrinsic radioactive background; iii) cosmogenic radio-isotopes produced in the liquid scintillator by traversing muons.

The external gamma background, which presently prevents a measurement of the solar $^8$B spectrum below 3 MeV in Borexino can be suppressed by self-shielding. It was shown in [19] that this background
source can be reduced at a negligible level in the proposed 50 kton LENA detector by applying a stringent volume cut that reduce the fiducial mass to 19 kton. This mass would be still sufficient for the proposed measure.

The intrinsic background depends on the radio-purity levels that will be achieved in the detector. We take as a reference the contamination levels that were obtained by Borexino during Phase-I \cite{11}. In the $^{238}$U chain, the radioisotope that produces events in the considered energy window is $^{214}$Bi that undergoes $\beta$-decay to $^{214}$Po with a total energy release $Q = 3.3$ MeV. The $^{238}$U contamination in Borexino is $(5.3 \pm 0.5) \times 10^{-18}$ g/g and corresponds to a total rate $R^{\text{tot}}(^{214}\text{Bi}) \simeq 2 \times 10^9\text{counts/year/kton}$. Fortunately, $^{214}$Bi events can be tagged with high efficiency by the subsequent $\alpha$-decay of $^{214}$Po. It was, e.g. noted in \cite{22} that 99.8% of the decay of $^{214}$Po occur outside trigger windows and thus can be efficiently identified in SNO+. In the remaining 0.2% cases, a discrimination can be obtained by looking at the time structure of the generated signal. All this shows that the $^{214}$Bi background can be potentially reduced at a level of $\sim$ few counts/year/kton or less (integrated over the entire energy spectrum) thus allowing for the proposed measure.

In the $^{232}$Th chain, the potentially dangerous radioisotope is $^{208}$Tl which undergoes $\beta$ decay to excited states of $^{208}$Pb followed by $\gamma$ particles emitted in the transitions to the $^{208}$Pb-ground state. The total energy of the emitted particles is equal to $Q = 5.0$ MeV with a minimum energy released in the detector equal to $\sim 2.6$ MeV that corresponds to the transition from first excited state to ground state of $^{208}$Pb. The $^{208}$Tl background, thus, fall outside the energy window proposed for the identification of ecCNO neutrinos. This is also shown in \cite{19} where the event rate expected in the LENA detector between [1.5, 3.0] MeV is calculated.\footnote{Borexino Phase-II reduced by an additional factor $\sim 10$ the $^{238}$U and $^{232}$Th contamination levels \cite{20}.}

The cosmogenic background is due to muon-induced production of radioactive nuclides. The majority of the produced radioisotopes have a short lifetime and, thus, the associated background can be efficiently rejected by vetoing the detector few seconds after the muon passage. The remaining cosmogenic isotopes with long lifetimes are $^{10}$C, $^{11}$Be and $^{11}$C. The production rate of these nuclei is roughly proportional to the muon flux at the experimental site which is equal to $\Phi_\mu = 28.8$ m$^{-2}$ d$^{-1}$ for LNGS (Borexino), $\Phi_\mu = 4.8$ m$^{-2}$ d$^{-1}$ for Pyhäsalmi (LENA) and $\Phi_\mu = 0.288$ m$^{-2}$ d$^{-1}$ for SNOLAB (SNO+). Following \cite{19}, we estimate the cosmogenic background in different detectors by rescaling the Borexino rates \cite{11} proportionally to $\Phi_\mu$, obtaining the results given in tab. \cite{3}. \footnote{We note, for completeness, that $^{232}$Th contamination in Borexino is $(3.8 \pm 0.8) \times 10^{-18}$ g/g. This corresponds to a total rate $R(^{208}\text{Tl}) \sim 5 \times 10^7\text{counts/year/kton}$. The amount of $^{208}$Tl can be determined from the observed number of $^{212}\text{Bi} - ^{212}\text{Po}$ coincidences (see e.g. \cite{11}).}

As it is discussed in \cite{19}, since $^{10}$C and $^{11}$Be have a much shorter lifetime than $^{11}$C, the background from these isotopes can be reduced by vetoing a cylinder with 2m radius around each traversing muon for a time $\Delta t = 4 \cdot \tau(^{10}\text{C}) = 111.2$ s. The suppression factor of the $^{10}$C and $^{11}$Be rates are approximately equal to $\exp(-\Delta t/\tau(^{10}\text{C})) \simeq 2 \times 10^{-2}$ and $\exp(-\Delta t/\tau(^{11}\text{Be}) \simeq 4 \times 10^{-3}$ with an introduced dead time equal to about 10% of the total exposure in Pyhäsalmi and less than 1% in SNOLAB. The resulting background rates are given in the last two columns of Tab. \cite{3} from which we see that cosmogenic production of $^{10}$C and $^{11}$Be nuclei do not prevent ecCNO neutrino detection if the detector is as deep as LENA or SNO+\footnote{In this work we do not discuss the potential of JUNO \cite{21}. Indeed, this experiment, being closer to the surface, is affected by a larger cosmogenic background that cannot be vetoed as discussed above.}.

The $^{11}$C cosmogenic background has a much larger rate and partially overlap with the energy window considered for the proposed measure. In fact, $^{11}$C nuclei undergo $\beta^+$ decay producing a positron with a continuous energy spectrum ($Q = 1.98$ MeV) which subsequently annihilates in the
| Isotope | $\tau$ (s) | $Q$ (MeV) | $R_{\text{tot}}^{\text{LNGS}}$ | $R_{\text{tot}}^{\text{Pyh}}$ | $R_{\text{tot}}^{\text{SNO}}$ |
|---------|------------|-----------|----------------|----------------|----------------|
| $^{10}$C | 27.8 | 3.7 | 1970 | $\rightarrow$ 330 | $\rightarrow$ 20 | $\rightarrow$ 0.36 |
| $^{10}$Be | 19.9 | 11.5 | 128 | $\rightarrow$ 21 | $\rightarrow$ 0.08 | 1.3 | $\rightarrow$ 0.005 |
| $^{11}$C | 29.4 min | 2.0 | $1.04 \times 10^5$ | $17 \times 10^3$ | $1.0 \times 10^3$ |

Table 3: The background rates produced by long-lived cosmogenic radio-isotopes for a detector located in LNGS, Pyhäsalmi and SNOLAB. The rates are expressed in counts/year/kton and are integrated over the entire energy spectrum. The two numbers that are shown for $^{10}$C and $^{11}$Be nuclei are the rates expected before (left) and after (right) introducing a veto for a cylinder with 2m radius around each traversing muon for a time $\Delta t = 4 \cdot \tau(10^C) = 111.2$ s.

detector producing two gammas with $E_\gamma = m_e = 0.511$ MeV. The visible energy $E_{\text{vis}}$ produced in the detector is calculated by using $E_{\text{vis}} = E_e + k \cdot 2m_e$, where $E_e$ is the positron energy and the factor $k = 0.89$ takes into account that the scintillation light emitted when a $\gamma$ particle is fully absorbed is significantly lower than the light emitted by a $\beta$ particle with the same energy. The adopted value for the parameter $k$ has been estimated by comparing the quenching factors of electrons and gammas in Borexino as they are deduced from Fig. 8 and Fig. 46 of [1]. The obtained spectrum is then convolved with the assumed detector energy resolution obtaining the results which are presented in Fig. [2] for a detector in Pyhäsalmi (left panel) and SNOLAB (right panel). The cosmogenic $^{11}$C background rates in the energy windows $[E_{\text{low}}, 2.5 \text{ MeV}]$ are given in tab. [4] as a function of $E_{\text{low}}$. We see that they are comparable with (lower than) the irreducible background produced in the same energy range by $^{8}$B neutrinos for $E_{\text{low}} \geq 1.8$ MeV ($E_{\text{low}} \geq 1.5$ MeV) in Pyhäsalmi (in SNOLAB).

We use the above numbers to estimate of the significativity $\Sigma_i$ of a possible ecCNO neutrino measurement in Pyhäsalmi or SNOLAB. As done in the previous section, we compare the expected signal with the statistical fluctuations of the total background:

$$\Sigma_i = \frac{S}{B} = \frac{(R_{eN} + R_{eO})}{\sqrt{R_B + R_i(11^C)}} \sqrt{E}$$

(4)

where $i = \text{Pyh, SNO}$ and we included the $^{11}$C contribution (other background sources are not considered assuming that their rates are reduced at a level much lower than $R_B$). The quantity $E$ indicates the detector exposure and should be calculated by including the small dead-time ($\sim 10\%$ in Pyhäsalmi and $\leq 1\%$ in SNOLAB) introduced by cosmogenic cuts. We obtain:

$$\Sigma_i = \eta_i \sqrt{E/(10\text{kton} \times \text{year})}$$

(5)

with the parameters $\eta_{\text{Pyh}}$ and $\eta_{\text{SNO}}$ given in the two right columns of tab. [4]. We see that $\eta_{\text{Pyh}} \sim 1$ for $E_{\text{low}} \simeq 1.8$ MeV and $\eta_{\text{SNO}} \geq 1$ for $E_{\text{low}} \leq 1.9$ MeV indicating that the proposed measure, despite being extremely difficult, is not excluded from the statistical point of view. According to our estimate, a 20 kton detector located in Pyhäsalmi collects a sufficient number of events ($\sim 100$ counts/year above 1.8 MeV from ecCNO neutrinos) to extract the signal with a statistical significance of $\sim 3\sigma$ in 5 years of data taking. The significativity of the extraction could increase to $\sim 3.8\sigma$ for a detector with the same characteristics placed at SNOLAB.

\[\text{Note that Borexino active medium is a solution of PPO and pseudocumene, see [1] for details. We assume that the deduced value of } k \text{ is adequate also for LAB.}\]
Table 4: The background rate (counts/year/kton) produced by $^{11}$C in the visible energy window $[E_{\text{low}}, 2.5 \text{MeV}]$ for a detector located in Pyhäsalmi and SNOLAB. The last two columns give the predicted values of the sensitivity parameters $\eta_{\text{Phy}}$ and $\eta_{\text{SNO}}$ defined in eq. (4).

| $E_{\text{low}}$ (MeV) | $R_{\text{Phy}}(^{11}\text{C})$ | $R_{\text{SNO}}(^{11}\text{C})$ | $\eta_{\text{Phy}}$ | $\eta_{\text{SNO}}$ |
|-------------------------|-------------------------------|-------------------------------|-------------------|-------------------|
| 1.5                     | 3130                          | 187                           | 0.6               | 1.6               |
| 1.6                     | 1470                          | 88.4                          | 0.7               | 1.5               |
| 1.7                     | 500                           | 30.0                          | 0.8               | 1.5               |
| 1.8                     | 98.0                          | 5.9                           | 1.0               | 1.2               |
| 1.9                     | 7.8                           | 0.5                           | 0.9               | 1.0               |
| 2.0                     | 0.2                           | 0.0                           | 0.7               | 0.7               |

4 Conclusions

In this work, we analyzed the potential of gigantic ultra-pure liquid scintillator detectors for the detection of ecCNO neutrinos. The obtained results are encouraging as indicated by the fact that the sensitivity parameters $\eta_{\text{Phy}}$ and $\eta_{\text{SNO}}$ (defined in eq. (5)) that give the statistical significance of a measure with an exposure of 10kton $\times$ year in Pyhäsalmi and SNOLAB, are $\sim$ 1. Few comments are necessary to further elaborate on our results:

i) Below 2.5 MeV, ecCNO neutrinos provide a contribution to the total signal that is comparable to the statistical fluctuations for a detector with an exposure $\mathcal{E} = 10 \text{ kton} \times \text{ year}$ or larger. This means that they cannot be neglected in statistical analysis that aim at the reconstruction of the low energy upturn of the electron neutrino survival probability predicted by the LMA-MSW solution of the solar neutrino problem;

ii) According to our estimate, the detection of ecCNO neutrinos in the proposed 50 kton LENA detector cannot be excluded. In a recent study [19], it was shown that the external background in LENA can be reduced to a negligible level in a fiducial mass of 19 kton, thus allowing to measure the $^8\text{B}$ solar neutrinos event spectrum down to $E_{\text{vis}} \sim 1.9 \text{ MeV}$ and to explore the energy region where the contribution of ecCNO neutrinos is not negligible. Our background estimates are derived along the same lines of [19] and agree with this analysis. However, that it would advisable that the LENA experimental collaboration investigates the actual possibility of observing ecCNO neutrinos with a complete detector simulation and optimized cuts.

iii) In order to go beyond detection and to use ecCNO neutrinos as a probe for the solar composition and/or to observe the low energy upturn of $P_{\text{ee}}$, an accuracy at the level of $\sim$ 15% or better is required. Indeed, the predictions for the ecCNO neutrino fluxes disagree by $\sim$ 30% when different surface compositions are considered. Incidentally, the electron neutrino survival probability at ecCNO neutrino energies is also $\sim$ 30% larger than the high energy value. In an ideal detector, with the characteristic described in our analysis and placed so deep that the cosmogenic background is negligible, the 15% accuracy goal corresponds to an exposure $\mathcal{E} \geq 100 \text{ kton} \times \text{ year}$.

iv) Finally, our results are based on a simplified description of the detector properties. Being the signal extremely small, the results may critically depend on the assumed detector characteristics, e.g. the assumed purification levels; the parametrization of the energy resolution function; the description of the detector response (i.e. the $k$ parameter). As an example, the parameter $\eta_{\text{Phy}}$ (calculated for
Figure 2: The expected event rate as a function of the visible energy $E_{\text{vis}}$ for a liquid scintillator detector located at Pyhäsalmi (left) and SNOLAB (right).

$E_{\text{low}} = 1.8 \text{ MeV}$ is reduced from 1.0 to 0.9 if the detector energy resolution at 1 MeV is increased from 5% to 7% and from 1.0 to 0.8 if the parameter $k$ is increased from 0.89 to 0.95. We look forward for a complete analysis by the experimental collaborations working in the field.

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