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Low-energy neutrino astronomy in LENA

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Abstract

LENA (Low Energy Neutrino Astronomy) is a proposed next-generation neutrino detector based on 50 kilotons of liquid scintillator. The low detection threshold, good energy resolution and excellent background rejection inherent to the liquid-scintillator detectors make LENA a versatile observatory for low-energy neutrinos from astrophysical and terrestrial sources. In the framework of the European LAGUNA-LBNO design study, LENA is also considered as far detector for a very-long baseline neutrino beam from CERN to Pyhäsalmi (Finland).

The present contribution gives an overview LENA's broad research program, highlighting the unique capabilities of liquid scintillator for the detection of low-energy neutrinos from astrophysical sources. In particular, it will focus on the precision measurement of the solar neutrino spectrum: The search for time modulations in the ^{7}Be neutrino flux, the determination of the electron neutrino survival probability in the low-energy region of the ^{8}B spectrum and the favorable detection conditions for neutrinos from the CNO fusion cycle.

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Keywords:

1. Introduction

In recent years, large-volume neutrino detectors have achieved substantial progress in the detection of low energy neutrinos from the Sun. The steady flux of neutrinos generated by thermonuclear fusion in the solar center has been investigated by several experiments: The water Cherenkov detectors SNO and (Super-)Kamiokande have provided an energy (and flavor-)resolved measurement of the high-energy part of the solar neutrino spectrum [1, 2], while most of the low-energy components of the spectrum have been resolved by the liquid-scintillator experiment Borexino [3, 4].

Albeit their successes, a decisive leap in observational sensitivity can only be achieved by a new generation of very large volume detectors on a target mass scale from 50 to 500 kilotons. In Europe, the most promising detection

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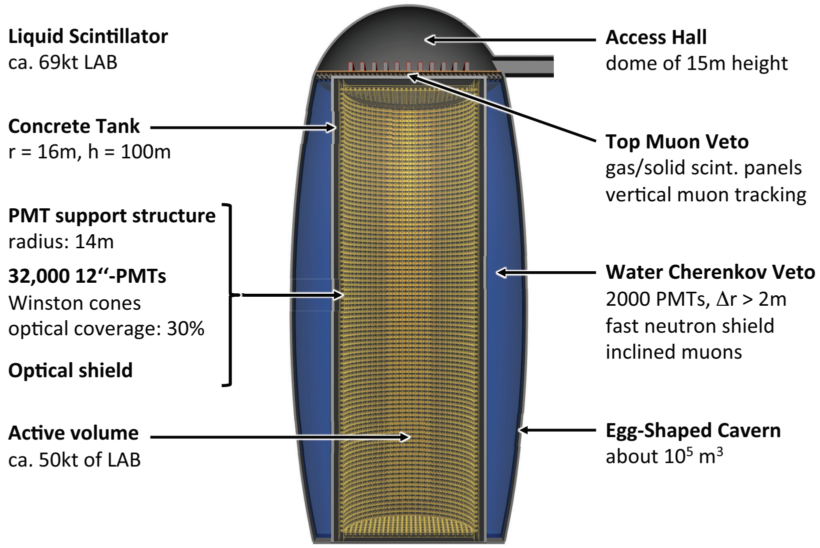

Figure 1. Conceptual design of the LENA detector and cavern.

technologies have been studied in the common LAGUNA(-LBNO) framework. LAGUNA tries to combine a low-energy neutrino observatory with a long-baseline neutrino oscillation (LBNO) experiment, aiming at the determination of the neutrino mass hierarchy as well as the CP-violating phase δ_{CP} in the PMNS neutrino mixing matrix.

Amongst the proposed projects, the liquid scintillator-based LENA (Low Energy Neutrino Astronomy) [5] concept (sec. 2) offers the best detector performance for the observation of the low-energy solar neutrino spectrum. The present contribution tries to highlight the range of opportunities present in this specific aspect of the broad scientific program of LENA (sec. 3): The search for low-intensity modulations in the solar neutrino flux (sec. 4), the investigation of the vacuum-matter transition in the oscillations of ^{8}B neutrinos (sec. 5) as well as the favorable conditions for the detection of neutrinos from the catalytic CNO fusion cycle (sec. 6).

2. LENA detector layout and site

The Center of Underground Physics in the Pyhäsalmi (CUPP) is located in central Finland. The operational copper and nickel mine is the deepest ore mine in Europe. The lowest level reaches a depth of 1,400 m, corresponding to an overburden of 4,000 mwe. Compared to the LNGS lab, the cosmic muon flux at this depth is reduced by more than a factor 3 and has been measured to $(1.1 \pm 0.1) \times 10^{-4}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$ [6]. The hard and dry bedrock allows for the construction of large caverns without the need for massive rock reinforcements.

The LENA detector design (figure 1) is driven by the requirement to optimize the light collection from the scintillator while accommodating a target mass of nearly 50 kt [5]. Unlike today's large liquid-scintillator (LS) detectors, the detector tank is shaped as a cylinder. Dimensions are 100 m height and 32 m diameter. The later is adjusted to the expected attenuation length of the scintillation light in the target liquid. Based on linear alkyl benzene (LAB), the scintillator is doped with the wavelength-shifters PPO (3 g/l) and bis-MSB (20 mg/l).

The scintillation light is collected by 32,000 encapsulated 12" PMTs mounted on a stainless-steel scaffolding. These optical modules (OMs) are equipped with a light concentrating mirrors and their front faces are at 14 m from the detector axis. The effective optical coverage achieved is 30 %. The OMs are directly emerged in the LS. To avoid a high trigger rate due to γ rays from radioactive elements in the PMT glass, each module houses a small volume of buffering oil (thickness of 30 cm) enclosed in its light concentrator. Moreover, the interspaces between the front faces of the OMs are closed by optically opaque (and possibly liquid-tight) sheets that separate the volume behind the modules from the active target volume.

The tank itself is constructed of concrete with a wall thickness of 60 cm. Chemical inertness and double containment with respect to the LS is achieved by a thin liner (1.5 mm) of stainless steel plates mounted to the inner tank wall. The LS-filled interspace between tank wall and OM scaffolding serve as a buffer volume to absorb γ-rays emitted by the concrete. On the outside, the tank is covered with a spray-on plastic layer to ascertain liquid tightness. The outside volume between tank and cavern walls is filled with pure water and equipped with 2,000 PMTs to form a muon Cherenkov veto.

The tank lid is formed by a top deck of carbon steel that holds the upper OMs as well as permitting for light- and air-tightness. The deck supports the top muon veto that consists of a large array of gas-filled drift chambers. In addition, it houses a clean room for detector operations as well as access to a number of service valves for calibration distributed over the whole area. It also allows for the feed-through of cabling to the dry electronics and a small computer farm that are located in a nearby auxiliary cavern.

The design of the detector, cavern and surrounding underground laboratory have been studied in the framework of the European LAGUNA and LAGUNA-LBNO design studies (FP7). Details on the construction may be found in the final reports[1].

3. Scientific program

LENA will be an excellent experiment for the detection of low-energy neutrinos from variety of sources [5]. Beyond the solar neutrino program detailed below, a primary objective is the observation of Supernova (SN) neutrinos. In case of a galactic core-collapse SN, a wealth of information can be extracted from the consequential neutrino burst. Compared to the handful of events detected at the last occurrence of a close-by Supernova in 1987, thousands of events will be registered. This energy-, time- and flavor-resolved measurement will complement the high-statistics signal on the overall neutrino flux provided by the large ice and sea water neutrino telescopes. Moreover, the large target mass combined with excellent background discrimination capabilities will give LENA the opportunity to detect the faint signal of the Diffuse Supernova Neutrino Background (DSNB), created by all SN explosions on cosmic scales [7]. In addition, LENA will be a formidable experiment for the detection of geoneutrinos stemming from the decay chains of radioactive isotopes naturally occurring in the Earth's crust and mantle.

In terms of oscillation physics, the high-statistics information extracted from the signal of natural sources could be complemented by experiments with artificial sources. In case a long-baseline neutrino beam experiment will be established from CERN to Pyhäsalmi (as described in [8]), the event reconstruction capabilities of LENA will be sufficient to extract the neutrino mass hierarchy with a significance of 3σ (5σ) with a probability of >95 % (35-90 %, depending on true value of $\delta_{\rm CP}$) based on a 10-year measuring program. Oscillation experiments with radioactive neutrino generators or pion decay-at-rest sources would allow for a detailed study of the properties of the putative sterile neutrinos if evidence for their existence was found in the current generation of experiments. In addition, a DAEδALUS-like oscillation experiment will provide an alternative approach for the determination of the CP phase, largely complementary to the usually proposed long-baseline experiments. Last but not least, the large target mass of 50 kt will allow to search for proton decay processes, especially the channel $p \to K^+\bar{\nu}$ favored by SUSY models [9]. The rich physics program has been detailed in [5].

4. Solar neutrino flux modulations

The solar neutrino spectrum is composed of the contributions of several fusion reactions in the solar proton-proton chain as well as the catalytic CNO cycle. At energies below 1 MeV, the main spectral components are the neutrinos from the primary pp-I reaction as well as two monoenergetic lines from the electron capture on ^{7}Be. Like in Borexino, the detection of the 866 keV ^{7}Be line will be possible in LENA via neutrino-electron scattering. Crucial for this measurement is a very low level of radioactive contamination, especially what concerns the isotopes ^{85}Kr and ^{210}Bi/^{210}Po. Figure 2 shows the event spectra of both signal and background contributions expected for LENA, assuming that the excellent background conditions achieved in the initial phase of Borexino are reproduced. The

[1] to be published mid-2014

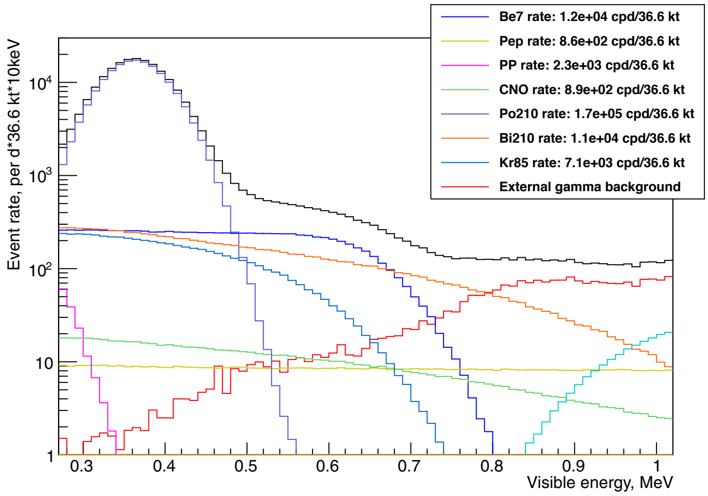

Figure 2. The electron-recoil spectrum expected for solar ^{7}Be neutrinos in LENA for a fiducial mass of 36.6 kt. The major background contributions are shown.

chosen fiducial volume corresponds to 35 kt. Forfeiting the outer 30 % of the target mass is rewarded by a substantial reduction in external γ-ray background.

The great target mass allows for the detection of $\sim 10^4$ ^{7}Be neutrino events per day. Due to the involved systematics, it will be difficult to surpass the projected accuracy of the final Borexino analysis (~3%). However, the high event rates will allow a very sensitive search for relative time variations in the ^{7}Be signal. Such a search seems attractive as there are several non-trivial processes that might potentially lead to periodic modulations in the detectable ν_e flux:

- During night time, neutrinos crossing the Earth on their way from the Sun to the detector will be subjected to the weak potential created by the terrestrial matter. This has a small but non-negligible effect on the ν_e survival probability. The MSW-LMA oscillation scenario predicts a day-night asymmetry for the detected ^{7}Be neutrino rate of the order of 0.1 %. First hints for a corresponding signature in the ^{8}B neutrino flux have been recently reported by Super-Kamiokande[2] [10].

- A periodic modulation of density or temperature in the solar center will change the conditions governing solar fusion rates and therefore the rate of neutrino production. It has been argued that helioseismic activity, especially the until now unobserved but predicted gravity-driven modes, could impose such periodic changes on the solar core region. A corresponding search has been performed on the SNO data set and returns the current best upper limit on the modulation amplitude of < 10 % (90 % C.L.) [11].

- Other, yet unknown mechanisms might induce changes in the neutrino flux. For instance, inconclusive hints have been found that the 22-year long solar activity cycle might translate to a corresponding modulation in neutrino production [12].

Based on the large statistics of the ^{7}Be signal and the intended 30-year detection program of LENA, the corresponding neutrino flux modulations could be probed on the level of 0.1 %. A modulation of this or greater amplitude would be detected at 3σ significance in 90 % of all cases for a large frequency range, reaching from modulation periods in the order of several minutes to and beyond the 11 year-period of solar activity. Compared to the current searches, this will mean a substantial improvement in sensitivity and the expected day-night effect seems well within reach. A corresponding analysis based on Lomb-Scargle periodograms has been presented in [13].

[2]Note that the expected day/night variation at ^{8}B energies is at least an order of magnitude larger.

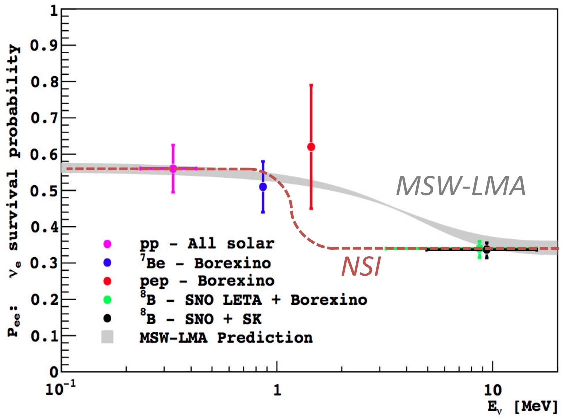

Figure 3. The solar electron neutrino survival probability P_{ee} as a function of neutrino energy. The grey band denotes the expectation of the MSW-LMA solution, the red dashed line an alternative oscillation scenario. Data points represent the results of experimental measurements [4].

5. Low-energy ^{8}B neutrinos and the MSW-LMA transition region

The understanding of the solar neutrino deficit by neutrino oscillations and the impact of solar matter on the electron neutrino survival probability P_{ee} have for a long time determined the focus of solar neutrino experiments. Figure 3 shows P_{ee} as a function of the neutrino energy E_ν. For high energies ($E_\nu \geq 5\,MeV$), the large water Cherenkov experiments (Super-)Kamiokande and SNO have been able to determine P_{ee} to ~ 0.3, corresponding to fully matter-dominated oscillation probabilities. For energies below 1 MeV, vacuum oscillations prevail. Here, Borexino has been able to determine $P_{ee} \approx 0.55$ for the ^{7}Be neutrino line[3].

However, experimental data on the course of $P_{ee}(E_\nu)$ in the transition region from about 1 to 5 MeV is still scarce. While figure 3 shows the expectation according to the standard MSW-LMA oscillation paradigm, alternative scenarios resulting in a different behavior for $P_{ee}(E_\nu)$ have been proposed, e.g. additional non-standard interactions (NSI) of neutrinos with the solar matter [14] or oscillations of active to very light sterile neutrinos ($m(\nu_1) < m(\nu_s) < m(\nu_2)$) [15]. Present-day experiments are trying to extend their spectral measurements into this region: Super-Kamiokande, SNO and Borexino have performed low-threshold analyses of the ^{8}B spectrum [2, 1, 16]. In addition to the lowest threshold of 3 MeV, Borexino has achieved a first measurement of the pep-neutrino line at 1.44 MeV that is located at the lower end of the transition region [4]. However, the accuracy of these measurements is not sufficient to identify possible deviations from the expected dependence of $P_{ee}(E_\nu)$, mostly due to the lack of statistics.

It has been shown recently that a very large LS detector like LENA could perform a very precise measurement of the low-energy ^{8}B spectrum. The analysis strategy has been laid out in [17]. Figure 4 shows the expected electron recoil spectrum in LENA after a number of basic analysis steps: Short-lived cosmogenic isotopes have been rejected by a 1-second veto following each muon crossing the target volume, while the long-lived isotopes ^{10}C, ^{11}C, and ^{11}Be have been greatly reduced by a radial cut (2 m) around each muon track for 110 s ($\sim 5\tau_{^{10}C}$). Still, the analysis threshold is defined by the upper end of the ^{11}C spectrum at $\sim$ 2 MeV. The only intrinsic contamination expected above this threshold are the decays of ^{208}Tl in the LS volume. However, the ^{208}Tl rate can be accurately determined via the alternative decay of ^{212}Bi to ^{212}Po which provides an easy-to-tag coincidence signature. Finally, external γ rays pose a serious background in the low-energy region, but can be efficiently reduced by a very stringent fiducial volume cut to the innermost 19 kt of the LS volume ($E_{vis} < 3.5$ MeV).

Based on the remaining data set, an oscillation analysis of MC data has been performed, trying to identify the expected spectral upturn in $P_{ee}(E_\nu)$ below 5 MeV. As alternative to the standard MSW-LMA prediction, a model with flat $P_{ee}(E_\nu)$ has been used that would roughly correspond to the expectations of NSI or sterile neutrino oscillation (cf. figure 3). The two models can be distinguished at more than 3σ significance after 3 years of measurement, and 5σ

[3] P_{ee} for the pp neutrino spectrum can be determined by a combination of the results from real-time and radiochemical experiments[4].

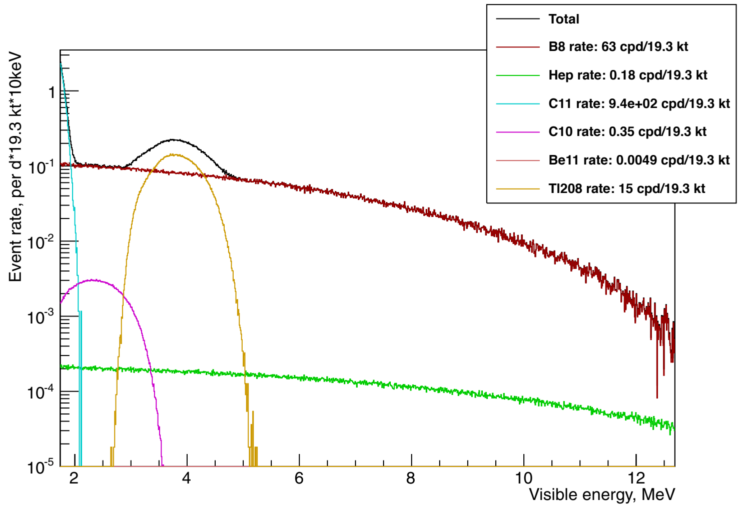

Figure 4. The electron-recoil spectrum expected for solar ^{8}B neutrinos in LENA for a fidcuial mass of 19.3 kt. The major background contributions are shown.

significance after 5 years [17]. This would be true even if the level of radioactive contaminations was two orders of magnitude higher than in Borexino. The decisive boost in sensitivity compared to present-day experiments is mostly due to the substantially increase in statistics and the possibility to access the ^{8}B spectrum between 2 and 3 MeV where the effect of the change in $P_{ee}(E_\nu)$ is the strongest. It is apparent that LENA will be able to perform a precision test of the course of $P_{ee}(E_\nu)$ in the transition region, closing this (supposedly) last remaining gap in the determination of solar neutrino oscillation probabilities.

6. CNO neutrinos

The detection of neutrinos from the catalytic CNO cycle is one of the primary goals of the present and next generation of solar neutrino experiments. This is mainly motivated by its great astrophysical importance: While the reaction cycle is predicted to contribute only 1-2 % to the total energy release by thermonuclear fusion in our Sun, this fraction greatly increases for heavier and older stars. Moreover, the CNO fusion rate features are strong dependence on the abundance of heavy elements (carbon, nitrogen and oxygen) at the solar center and is therefore an ideal probe for the solar metallicity. Therefore, an accurate CNO measurement might shed light on the on-going dispute on the metallicity of the solar center that has arisen from the discrepancy in the results from optical spectroscopy and helioseismology [18].

While both Borexino and the up-coming SNO+ experiment stand a fair chance for a first glimpse at the spectral contribution from CNO neutrinos, an accurate determination of the CNO neutrino flux or even a mere positive detection seem very demanding. The main difficulties of the measurement can be appreciated from figure 5 that shows the expected signal and background spectra in the innermost 30 kt of the LENA target: The major part of the CNO recoil spectrum is covered by the irreducible background from ^{7}Be (and also pep) neutrinos. Above an energy threshold of ~ 0.8 MeV, the β^+ decay of cosmogenic ^{11}C, the β^- decay of ^{210}Bi as well as external γ events are the main remaining backgrounds.

It has been demonstrated by Borexino that the ^{11}C background can be greatly reduced by a threefold-coincidence veto including muons and neutrons as well as e^+/e^- pulse shape discrimination [4]. Moreover, a hard fiducial volume cut can remove the majority of the γ ray background. It has been argued that the ^{210}Bi rate can be determined by the succeeding and easy-to-tag α-decay of ^{210}Po once both isotopes are in secular equilibrium [19]. However, these vetoes will further reduce the initially low expected event rate of 0.5 counts per day and 100 t in the energy region

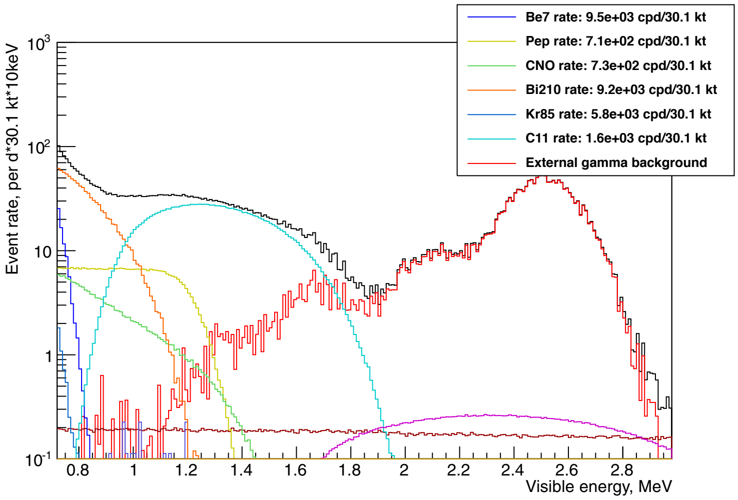

Figure 5. The electron-recoil spectrum expected for solar CNO neutrinos in LENA for a fidcuial mass of 30.1 kt. The major background contributions are shown.

above 0.8 MeV. So, even if backgrounds can be reduced to an acceptable level, the measurement accuracy in Borexino and (the current program of) SNO+ will ultimately be limited by statistics.

The main advantages of LENA in comparison to the current experiments is therefore in the substantially larger target mass and the possibility for a restrictive fiducial volume cut to suppress the external γ background (cf. figure 5). In 30 kt target mass, ~200 events per day are expected above 0.8 MeV. Compared to Borexino, ^{11}C production rate will be reduced by a factor 3, due to the greater rock shielding at CUPP. The final sensitivity will depend on the radiopurity of the scinitllator itself and more importantly on the realization of secular equilibrium between ^{210}Bi and ^{210}Po.

7. Conclusions

The next-generation LS detector LENA will be a multi-purpose observatory for the detection of low-energy neutrinos. One of the most interesting aspects of its broad scientific program will be the further exploration of the solar neutrino flux and spectrum. The high-statistics signal will allow to search for modulations in the flux of the ^{7}Be line at the 0.1 % level. The transition region from vacuum to matter-dominated oscillations will be tested by a precision measurement of the ^{8}B neutrino spectrum with a threshold of 2 MeV, allowing to validate or reject the MSW-LMA prediction at 5σ significance. Finally, LENA will offer the chance for a high-statistics measurement of the CNO neutrino flux, potentially providing information on the metallicity of the solar core.

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References

[1] B. Aharmim, et al., Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory, Phys.Rev. C88 (2) (2013) 025501. arXiv:1109.0763, doi:10.1103/PhysRevC.88.025501.

[2] Y. Koshio, Solar neutrino results from Super-Kamiokande, PoS ICHEP2012 (2013) 371.

[3] G. Bellini, J. Benziger, D. Bick, S. Bonetti, G. Bonfini, et al., Precision measurement of the 7Be solar neutrino. interaction rate in Borexino, Phys.Rev.Lett. 107 (2011) 141302. arXiv:1104.1816, doi:10.1103/PhysRevLett.107.141302.

[4] G. Bellini, et al., First evidence of pep solar neutrinos by direct detection in Borexino, Phys.Rev.Lett. 108 (2012) 051302. arXiv:1110.3230, doi:10.1103/PhysRevLett.108.051302.

[5] M. Wurm, et al., The next-generation liquid-scintillator neutrino observatory LENA, Astropart.Phys. 35 (2012) 685–732. arXiv:1104.5620, doi:10.1016/j.astropartphys.2012.02.011.

[6] T. Enqvist, A. Mattila, V. Fohr, T. Jamsen, M. Lehtola, et al., Measurements of muon flux in the Pyhasalmi underground laboratory, Nucl.Instrum.Meth. A554 (2005) 286–290. arXiv:hep-ex/0506032, doi:10.1016/j.nima.2005.08.065.
[7] M. Wurm, F. von Feilitzsch, M. Goeger-Neff, K. Hochmuth, T. M. Undagoitia, et al., Detection potential for the diffuse supernova neutrino background in the large liquid-scintillator detector LENA, Phys.Rev. D75 (2007) 023007. arXiv:astro-ph/0701305, doi:10.1103/PhysRevD.75.023007.
[8] A. Stahl, et al., Expression of Interest for a very long baseline neutrino oscillation experiment (LBNO).
[9] T. M. Undagoitia, F. von Feilitzsch, M. Goger-Neff, C. Grieb, K. Hochmuth, et al., Search for the proton decay p -¿ K+ anti-nu in the large liquid scintillator low energy neutrino astronomy detector LENA, Phys.Rev. D72 (2005) 075014. arXiv:hep-ph/0511230, doi:10.1103/PhysRevD.72.075014.
[10] A. Renshaw, et al., First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation, Phys.Rev.Lett. 112 (2014) 091805. arXiv:1312.5176, doi:10.1103/PhysRevLett.112.091805.
[11] B. Aharmim, et al., A Search for periodicities in the B-8 solar neutrino flux measured by the Sudbury neutrino observatory, Phys.Rev. D72 (2005) 052010. arXiv:hep-ex/0507079, doi:10.1103/PhysRevD.72.052010.
[12] P. Sturrock, Time-Frequency Analysis of GALLEX and GNO Solar Neutrino Data: Evidence Suggestive of Asymmetric and Variable Nuclear BurningarXiv:0802.3370.
[13] M. Wurm, B. Caccianiga, D. D'Angelo, S. Davini, F. von Feilitzsch, et al., Search for modulations of the solar Be-7 flux in the next-generation neutrino observatory LENA, Phys.Rev. D83 (2011) 032010. arXiv:1012.3021, doi:10.1103/PhysRevD.83.032010.
[14] A. Friedland, C. Lunardini, C. Pena-Garay, Solar neutrinos as probes of neutrino matter interactions, Phys.Lett. B594 (2004) 347. arXiv:hep-ph/0402266, doi:10.1016/j.physletb.2004.05.047.
[15] P. de Holanda, A. Y. Smirnov, Solar neutrino spectrum, sterile neutrinos and additional radiation in the Universe, Phys.Rev. D83 (2011) 113011. arXiv:1012.5627, doi:10.1103/PhysRevD.83.113011.
[16] G. Bellini, et al., Measurement of the solar 8B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector, Phys.Rev. D82 (2010) 033006. arXiv:0808.2868, doi:10.1103/PhysRevD.82.033006.
[17] R. Möllenberg, PhD Thesis, Technische Universität München, Germany (2013).
[18] A. Serenelli, S. Basu, J. W. Ferguson, M. Asplund, New Solar Composition: The Problem With Solar Models Revisited, Astrophys.J. 705 (2009) L123–L127. arXiv:0909.2668, doi:10.1088/0004-637X/705/2/L123.
[19] F. Villante, A. Ianni, F. Lombardi, G. Pagliaroli, F. Vissani, A Step toward CNO solar neutrinos detection in liquid scintillators, Phys.Lett. B701 (2011) 336–341. arXiv:1104.1335, doi:10.1016/j.physletb.2011.05.068.