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First Constraint on the Diffuse Supernova Neutrino Background through the CEνNS process from the LZ experiment

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We report the limits on the diffuse supernova neutrino background (DSNB) flux and the fundamental DSNB parameters measured from the first science run of the LUX-ZEPLIN (LZ) experiment, a dual-phase xenon detector located at the Sanford Underground Research Facility in Lead, South Dakota, USA. This is the first time the DSNB limit is measured through the process of the coherent elastic neutrino-nucleus scattering (CEνNS). Using an exposure of 60 live days and a fiducial mass of 5.5 t, the upper limit on the DSNB ν_x (each of ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$) flux is $686 - 826$ cm^{-2}s^{-1} at the 90% confidence level for neutrino energies E>19.3 MeV, assuming the flux for each ν_x flavor is the same. The interval accounts for the uncertainty in existing DSNB models. The present result is comparable to the existing best limit and further improvements are expected after collecting data from an estimated 1,000-day exposure in the future.

1 Introduction

The diffuse supernova neutrino background (DSNB) is theorized to be a nearly isotropic flux of neutrinos cumulatively originating from all past core-collapse supernovae. Each supernova core collapse is predicted to produce 10^{58} neutrinos on average[1]. The detection of the DSNB is the only feasible method to probe the average neutrino emission per core-collapse event, as there has not been a nearby core-collapse event since SN 1987A, which occurred 37 years ago. Furthermore, even if another such event were to occur in the near future, there is no guarantee it would represent a typical supernova[2]. The understanding of core collapse depends on probing the DSNB in all flavors. The current best upper limit on the $\bar{\nu}_e$ DSNB flux is 2.7 cm^{-2}s^{-1}, measured by Super-Kamiokande (SK), and it is close to a discovery[3,4]. The upper limit on the ν_e flux is 19 cm^{-2}s^{-1}, set by the Sudbury Neutrino Observatory (SNO)[5], and will be improved by the future Deep Underground Neutrino Experiment (DUNE)[6,7]. However, the best upper limit on the DSNB flux of ν_x, i.e., each of ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$, measured using neutral current neutrino-electron scattering from SK is very weak[8], at the level of approximately 10^3 cm^{-2}s^{-1}, due to this detection channel's small interaction cross section.

New ideas have been proposed to enhance the DSNB sensitivity to all flavors[2]. One of these ideas involves probing the DSNB using direct-detection dark-matter experiments through the CEνNS process, where a neutrino interacts with a nucleus via the exchange of a Z boson. The COHERENT experiment has made the first detection of the neutrino CEνNS process, which is sensitive to all flavors of neutrinos and antineutrinos[9]. The CEνNS process dominates in medium-A nuclei for neutrino energies less than about 50 MeV[10], including the DSNB which consists of $\mathcal{O}$(MeV) thermal neutrinos. Therefore, CEνNS is the most promising channel for xenon-based detectors to probe the DSNB. We report here the first upper limit on the DSNB flux measured

[a] https://lz.lbl.gov

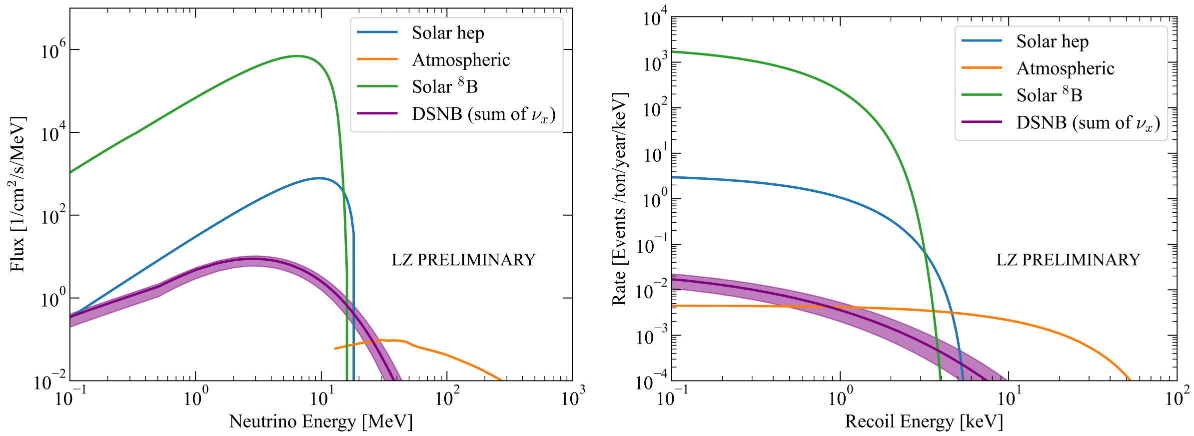


Figure 1 – Left: Predicted DSNB signal spectrum (sum of ν_x) and irreducible neutrino backgrounds. The solid purple line represents the fiducial DSNB model, and the purple band indicates the uncertainty set by the minimal and maximal DSNB models in Ref. [2]. Right: Predicted nuclear recoil spectrum in xenon for the DSNB (sum of ν_x) and irreducible backgrounds corresponding to the left plot.

through the CEνNS channel from the LUX-ZEPLIN (LZ) experiment.

2 The DSNB Signal Model

Depending on the progenitor mass, a core-collapse supernova will either lead to the formation of a neutron star (NS) or a black hole (BH). The neutrino flux from the BH formation is expected to be larger than that from NS formation, and the spectrum is expected to be harder because the collapsed cores of BH forming supernovae have higher mass and can generate more accretion onto them. The DSNB flux for a single neutrino flavor, in units of [cm^{-2}s^{-1}MeV^{-1}], can be written as [2]

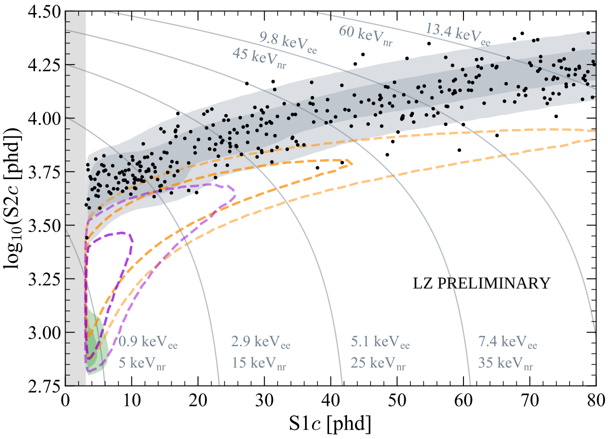
$$\Phi(E_\nu) = \frac{c}{H_0}\int_{8M_\odot}^{125M_\odot} dM \int_0^{z_{\max}} dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_{\rm M}(1+z)^3+\Omega_\Lambda}} \times [f_{\rm NS}F_{\rm NS}(E'_\nu,M)+f_{\rm BH}F_{\rm BH}(E'_\nu,M)], \quad (1)$$

where supernova progenitor masses (M) between $8-125$ solar masses that result in either NS or BH formation are considered. The neutrino emission spectrum $F(E'_\nu, M)$ per core collapse is predicted by 1D hydrodynamical simulations with Boltzmann neutrino transport from the Garching group [11]. E'_ν is the neutrino energy at emission, and is related to the neutrino energy at detection, E_ν, by $E'_\nu = E_\nu(1+z)$, where z is the red-shift. The supernova rate density for a given mass is $R_{SN}(z, M)$. Standard values are used for the speed of light c, Hubble constant H_0, dark matter fraction Ω_M, and dark energy fraction Ω_Λ [12].

Following Ref. [2], the fiducial DSNB model used in this work has $R_{SN}(z = 0) = 1.25 \times 10^{-4}$ Mpc^{-3}yr^{-1} and $f_{BH} \simeq 20\%$. For the minimal DSNB model, the pre-factor of R_{SN} is changed to 0.75 and f_{BH} is chosen to be $\simeq 10\%$ (fast-forming BH model). For the maximal DSNB model, the pre-factor for R_{SN} becomes 1.75 and $f_{BH} \simeq 40\%$ (slow-forming BH model). The adopted model uncertainty is based on a conservative evaluation of the observed $R_{SN}(z = 0)$ and f_{BH} from astronomical surveys. The total flux of DSNB ν_x (sum of ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$), as well as solar and atmospheric neutrinos and their nuclear recoil spectra in xenon are shown in Fig. 1.

3 Data Analysis

Data presented in this paper are from the first science run of LZ, which were collected from 23 Dec 2021 to 11 May 2022 under stable detector conditions. The data selection is identical to that used in the WIMP search analysis [13], which results in a total livetime of 60±1 days and a fiducial volume LXe mass of 5.5±0.2 t. The background model used for the DSNB search is the



Source	Expected Events	Fit Result
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.1 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.1 ± 2.4
Atmospheric + ^{8}B + *hep* CEνNS	0.18 ± 0.02	0.18 ± 0.02
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.6^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
DSNB ν_x all flavors	–	$0.0^{+0.5}$
Total	–	333 ± 17

Figure 2 – Left: 60 live days of data from LZ's first science run (black dots) after all cuts in $\log_{10}$S2c-S1c space. Contours enclose the 1σ and 2σ regions of the following models: the best-fit background model (shaded gray regions), the atmospheric ν CEνNS component (dashed orange lines), the fiducial DSNB signal (dashed purple lines), and ^{8}B solar neutrinos (shaded green regions). Thin gray lines indicate contours of constant energies. Right: Number of background events from various components. The second column is the predicted number of events with uncertainties as described in Ref. [13]. The uncertainties are used as constraint terms in a combined fit of the background model plus the DSNB signal (fiducial model) to the selected data. The fit result is shown in the third column. ^{37}Ar and detector neutrons have non-Gaussian prior constraints and are summed up separately.

same as for the WIMP search, with the addition of two neutrino CEνNS background components from atmospheric and solar *hep* neutrinos. The expected number of events from these neutrino backgrounds, as well as all the other backgrounds in LZ's first science run are listed on the right of Fig. 2.

Statistical inference of the DSNB ν_x flux is performed with an unbinned profile likelihood statistic in the $\log_{10}$S2c−S1c 2D parameter space with a two-sided construction of the 90% confidence bounds [14], as shown in Fig. 2 (left). The black dots in the figure represent the 335 events passing all selections. The contours indicating the fiducial DSNB signal and the best-fit background model are also shown.

4 Results and Prospects

The results from the statistical analysis described in Section 3 show the data collected is consistent with the background-only hypothesis, as the best-fit number of DSNB signals is zero. The 90% confidence level (C.L.) upper limit on the DSNB ν_x flux per flavor for neutrino energies >19.3 MeV is shown in Fig. 3 (left). The energy window is chosen to match that from Ref. [2,8]. Because stringent constraints have already been placed on ν_e and $\bar{\nu}_e$ by SNO and SK, the limit on the DSNB ν_x flux is derived by neglecting the presence of the ν_e and $\bar{\nu}_e$ components of the DSNB and considering four ν_x flavors only, while assuming each of the four flavor fluxes is the same (following the conventions in Ref. [2]). This results in a 90% C.L. upper limit on the DSNB ν_x flux of 773 cm^{-2}s^{-1} per flavor, assuming the fiducial DSNB model, and 686 – 826 cm^{-2}s^{-1} per flavor after accounting for the model uncertainty between the minimal and maximal models [2]. Due to downward fluctuations in the number of background events, the limits above are power constrained to the -1σ range of the projected sensitivity following Ref. [15]. The projected sensitivity to the DSNB ν_x flux as a function of the detector live time for a fiducial mass of 5.5 tonnes assuming similar background levels as LZ's first science run is also shown in Fig. 3 (left).

Figure 3 (right) shows LZ's limits and future sensitivity on the fundamental ν_x emission parameters, characterized by the energy emitted per ν_x flavor and the average neutrino energy. The signal model used in the measurement is a simple DSNB model from Ref. [2], which assumes all supernovae emit the same thermal neutrino spectrum regardless of their NS or BH outcomes.

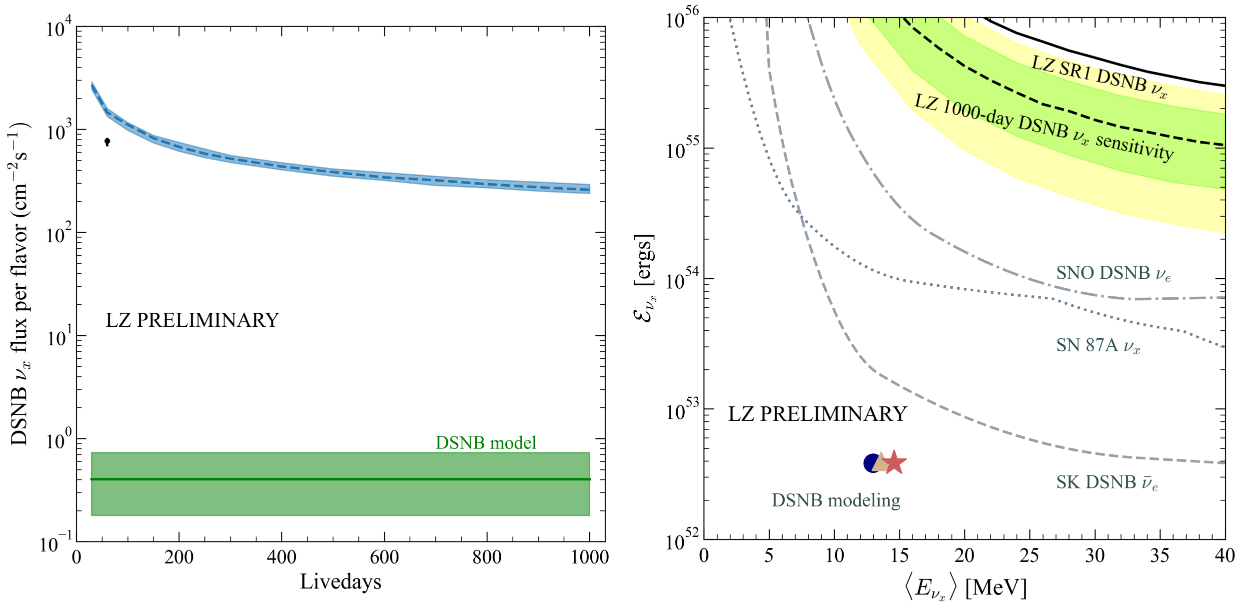


Figure 3 – Left: The 90% C.L. upper limit on the DSNB ν_x flux per flavor (black) for neutrino energy >19.3 MeV, using 60 live days of data from LZ. The dot is the upper limit on the fiducial DSNB model, with its uncertainty set by the minimal and maximal models from Ref. [2]. The dashed blue curve is the projected median sensitivity to the DSNB ν_x flux (fiducial model) with LZ as a function of the detector live time. The horizontal solid green line is the predicted ν_x flux from DSNB modelling (fiducial model). Both bandwidths in blue and green are also set by the minimal and maximal model. Right: Limits on the fundamental DSNB ν_x emission parameters: the total emitted energy per ν_x flavor and average neutrino energy. The solid black curve is the limit from LZ's 60 live days of data in the first science run. The dotted line is the median of the 1,000-liveday sensitivity projection. The green and yellow bands are the 1σ and 2σ sensitivity bands. Also shown are the present SK limit on DSNB $\bar{\nu}_e$ (dashed gray) [3], the SNO limit on DSNB ν_e (dashdotted gray) [5], and the SN 1987A limit on ν_x (dotted gray) [2], as well as three points that indicate the average emission per supernova collapse in the fiducial, minimal, and maximal DSNB models.

5 Conclusions

We have performed the first DSNB ν_x search through the CEνNS process using data from LZ's first science run. The LZ detector exposure and data selections used in this paper are the same as those from the experiment's first WIMP search results paper. With an exposure of 60 live days using a fiducial mass of 5.5 t, LZ sets an upper limit on the DSNB ν_x flux that is comparable to the current best limit (at the level of approximately 10^3 cm^{-2}s^{-1}, but using different DSNB models and conventions than those presented in this proceeding and Ref. [2] to set limits) from 1,496 days of SK data using 22.5 kton of fiducial mass [8], which demonstrates the power of probing DSNB ν_x through the CEνNS process in xenon detectors.

The LZ limits shown in Fig. 3 do not restrict any existing realistic DSNB model but could be useful in the future. In some astrophysical models, the flux could be larger, for example, if a more massive neutron star or a black hole is formed. In some new-physics models, the mean energy could also be larger, for example, if neutrinos can escape more readily from the core of the proto-neutron star, which would increase the average neutrino energy and hence the detectability. Either or both of these scenarios would improve the prospects for detection in future xenon experiments [16].

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