First Constraints on the Diffuse Supernova Neutrino Background from the LZ experiment

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On behalf of the LZ Collaboration

35th Rencontres de Blois
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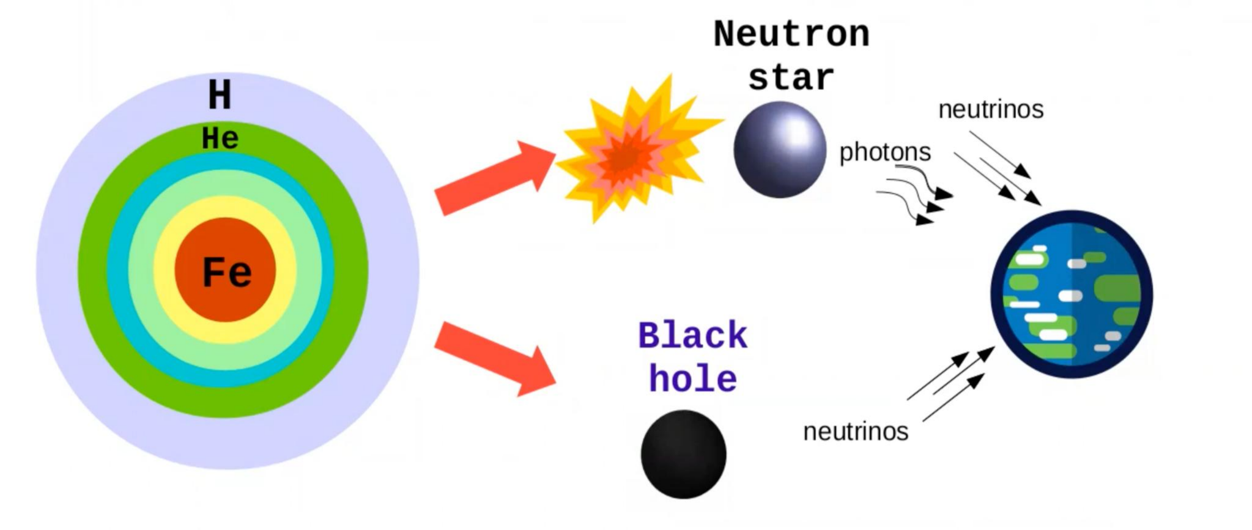
Understanding core collapse supernovae through DSNB

- **Diffuse Supernova Neutrino Background (DSNB):** a nearly isotropic flux of neutrinos cumulatively originating from **all past core-collapse supernovae**
- Prediction: Core collapse supernova releases ~2 x 10^{59} MeV in neutrinos of all flavors in similar amounts
- Detecting DSNB is the only feasible way of probing average neutrino emission per core collapse



Understanding core collapse supernovae through DSNB

- DSNB flux for a single neutrino flavor:

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

Phys. Rev. D **105**, 043008 (2022)

Understanding core collapse supernovae through DSNB

- DSNB flux for a single neutrino flavor:

supernova rate density

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

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- What we can learn from DSNB:
  - f_{NS} , f_{BH}: Fraction of neutron star (NS) and black hole (BH)- forming progenitors
  - Nuclear equation of state
  - Neutrino flavor evolution in the supernova
  - Non-standard physics: Neutrino decay; DSNB interacting with cosmic relic neutrinos and dark matter
  - …

Existing limits on DSNB

- Understanding of core collapse depends on probing DSNB in all flavors
- Stringent limits have been set on $\overline{\upsilon}_e$ (2.7 cm^{-2}s^{-1} by Super-K) and υ_e (19 cm^{-2}s^{-1} by SNO). Super-K is close to a first detection of DSNB $\overline{\upsilon}_e$*
  - Primary channel in Super-K:

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

  - Primary channel in SNO:

$$\nu_e + d \rightarrow e^- + p + p$$

*DOI: 10.1038/d41586-024-02221-y

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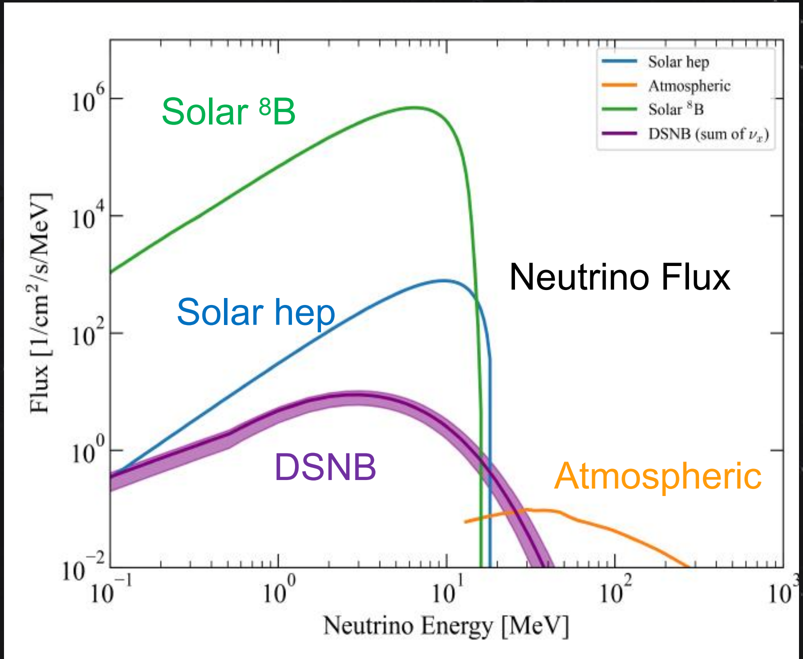
- Limits on υ_x (each of $\upsilon_\mu, \overline{\upsilon}_\mu, \upsilon_\tau, \overline{\upsilon}_\tau$) are weak ~10^3 cm^{-2}s^{-1}

$$\nu_x + e^- \rightarrow \nu_x + e^-$$
$$\bar{\nu}_x + e^- \rightarrow \bar{\nu}_x + e^-$$

Probing DSNB with Xenon Detectors

- DSNB flux dominates other neutrino fluxes in a narrow energy range



Probing DSNB with Xenon Detectors

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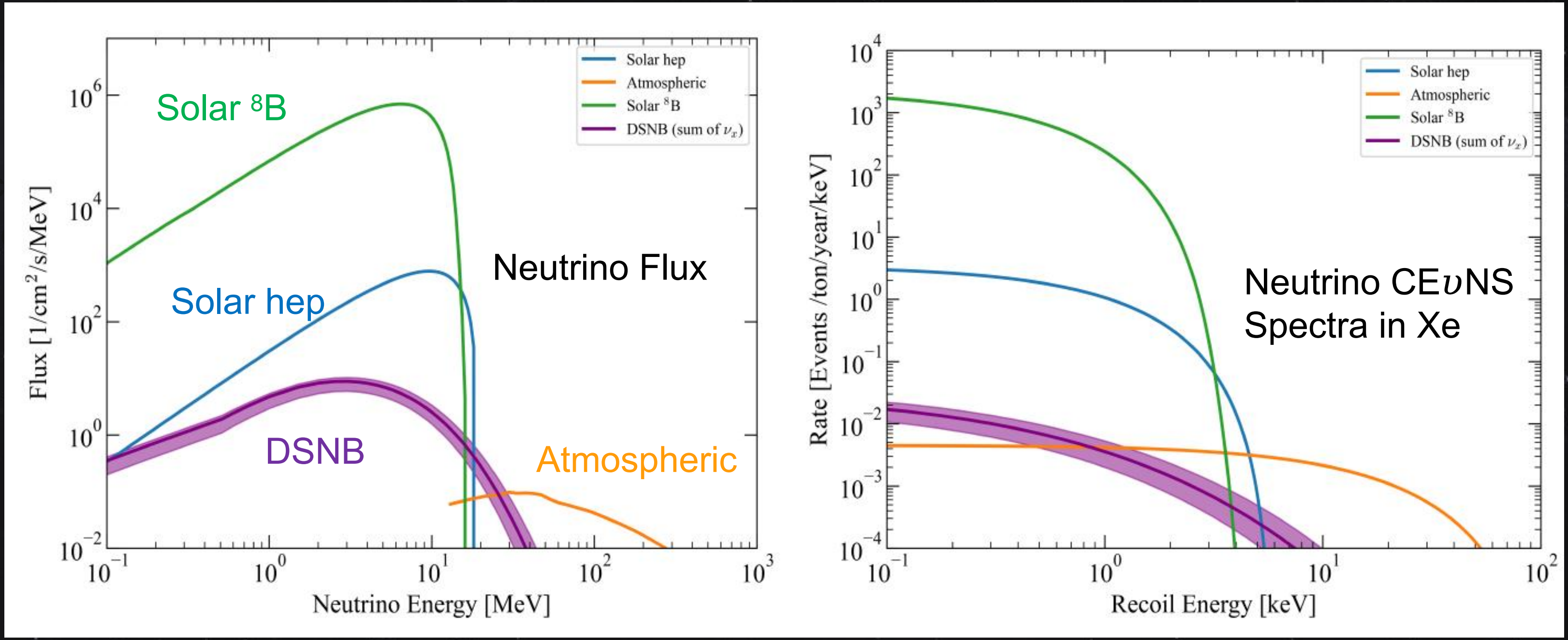
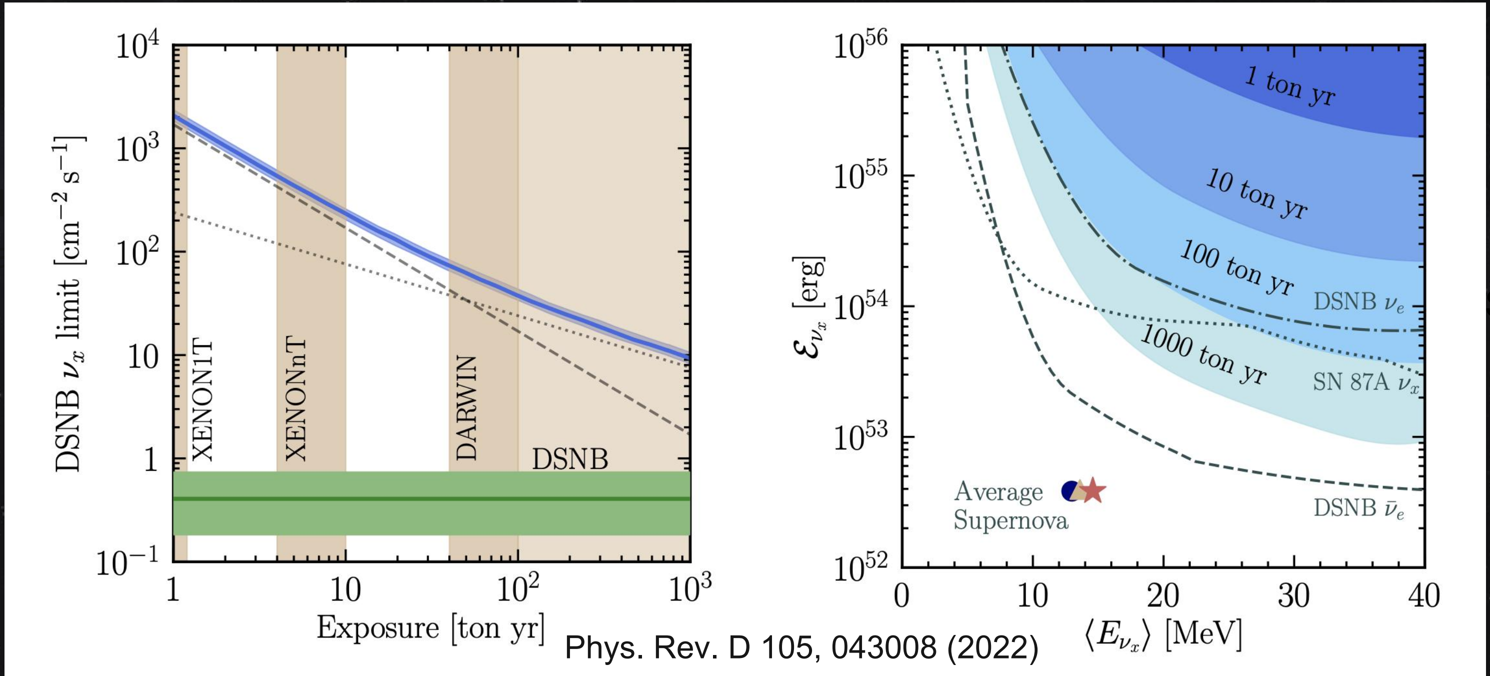


Probing DSNB with Xenon Detectors

- DSNB flux dominates other neutrino fluxes in a narrow energy range
- Detection in xenon-based detectors is challenging
- However, useful limits can be set on υ_x through the CEυNS channel in Xe

Sensitivity predictions by theorists (A. M. Suliga, J. Beacom & I. Tamborra):



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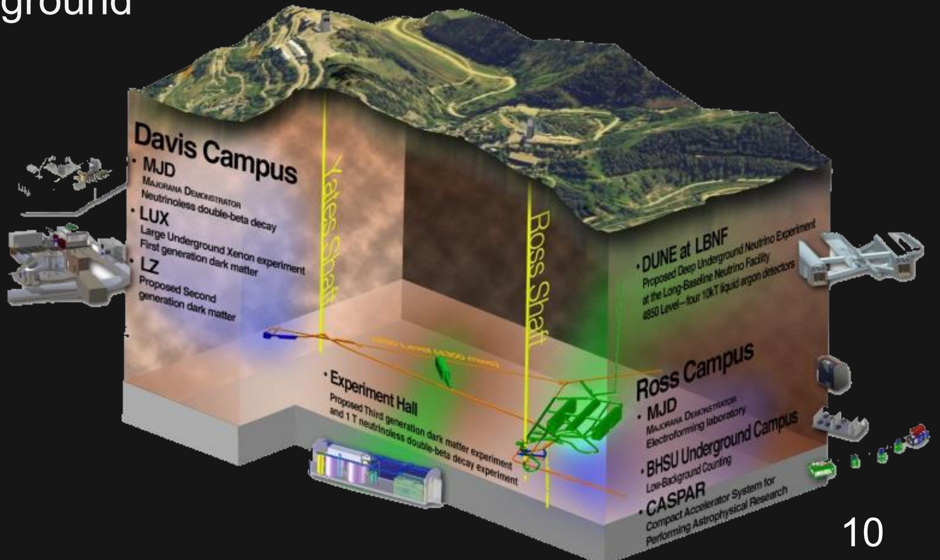
LZ @ Sanford Underground Research Facility

- SURF in Lead, South Dakota is the deepest underground lab in the U.S.
- LZ is located on the 4850 level ~1.5 km underground
- ~10^6 reduction in cosmic muon flux
- Primary goal is to detect WIMPs*

Refer to Albert's talk for the latest LZ WIMP results



LZ @ Sanford Underground Research Facility

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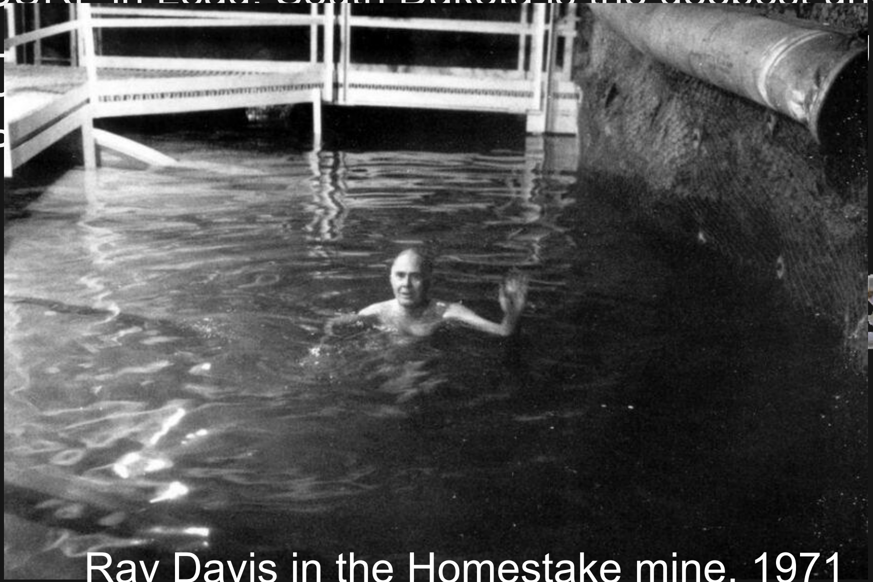
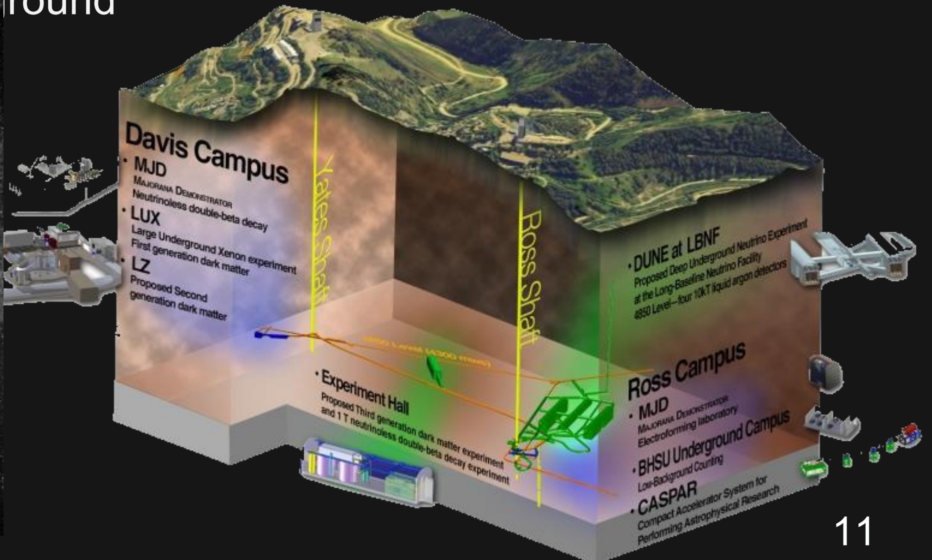
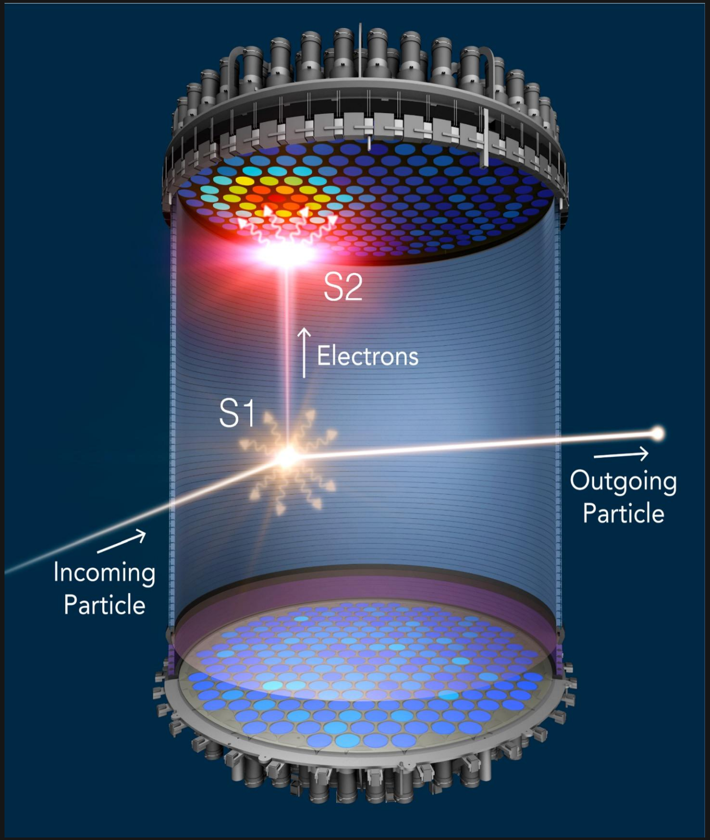
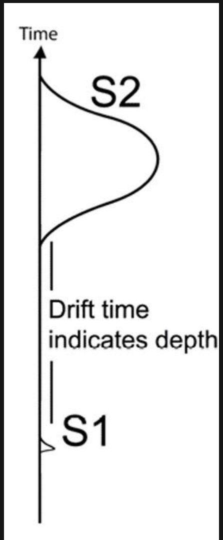


Ray Davis in the Homestake mine, 1971

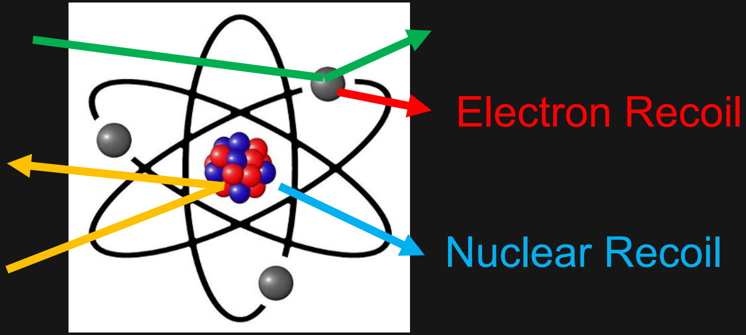


Dual Phase Xenon Time Projection Chamber (TPC)





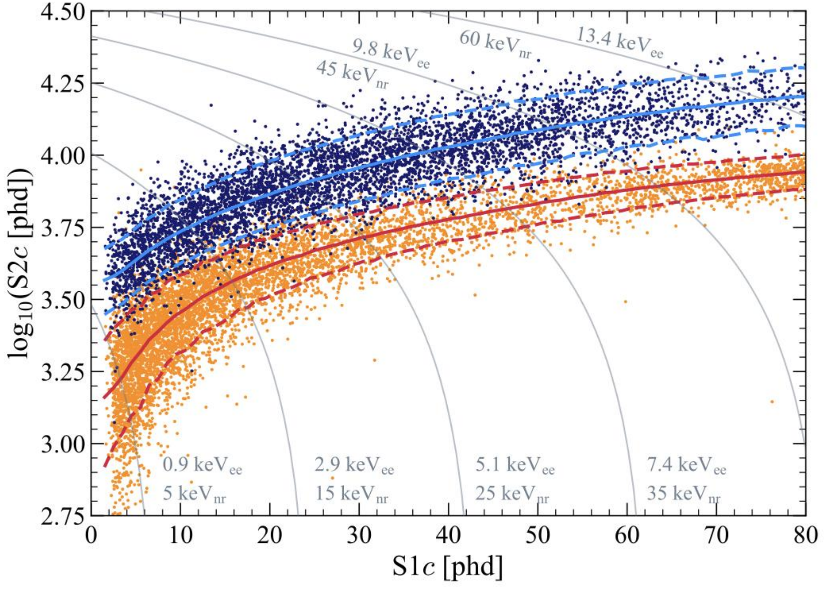
- Signal vs. background discrimination
  - Charge (S2)/ light (S1) ratio is different between electron recoil (ER) and nuclear recoil (NR)



- Electrons and gammas interact with atomic electrons, produce ER
- WIMPs, neutrinos (and neutrons) interact with Xe nuclei, produce NR

Calibration Data

- Dark blue points: Tritium beta data (ER)* (continuum betas up to 18.6 keV)
- Orange points: DD neutron data (NR)* (2.45 MeV neutrons produced through Deuterium-Deuterium fusion)
- **ER/NR discrimination: <0.5% ER leakage past the median of the NR population**

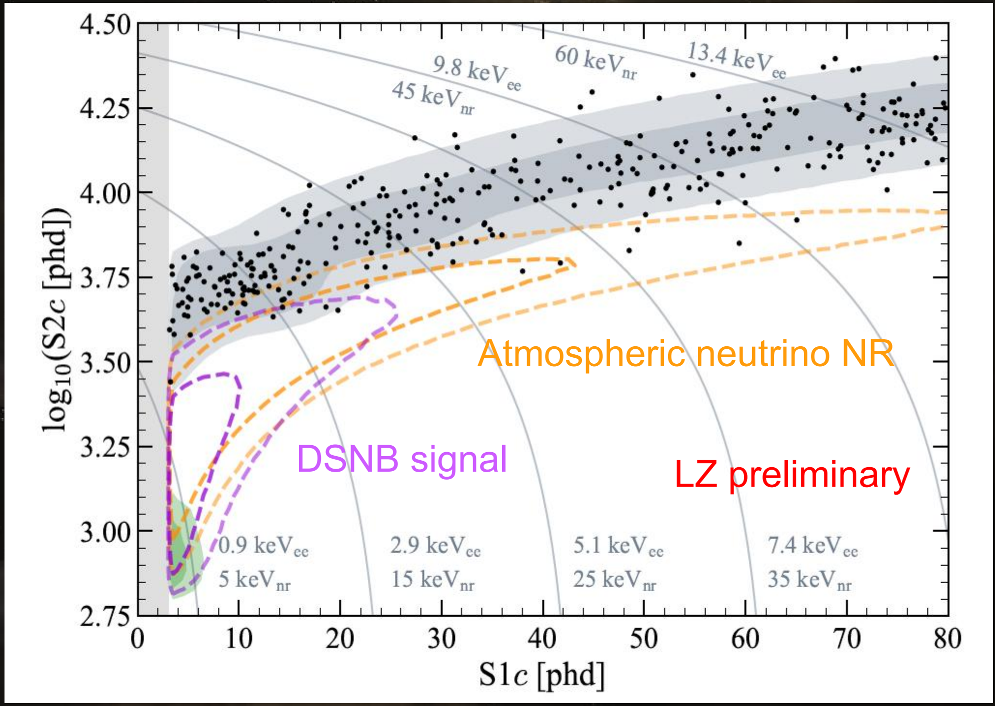


LZ Collaboration, Phys. Rev. Lett. **131**, 041002 (2023)

*Details about calibration source deployment: LZ Collaboration, *JINST* **19** P08027 (2024)

LZ Science Run I (SR1) Data (Dec. 2021 - May 2022)

- Exposure: 60 day x 5.5 t = 0.9 tonne-yr
- Black points: 335 events observed
- Shaded gray: best fit ER background model
- Purple curves: 1σ and 2σ contours of the DSNB signal
- Orange: Atmospheric neutrino NR
- Shaded green: ^{8}B neutrino



Limits on DSNB υ_x Flux

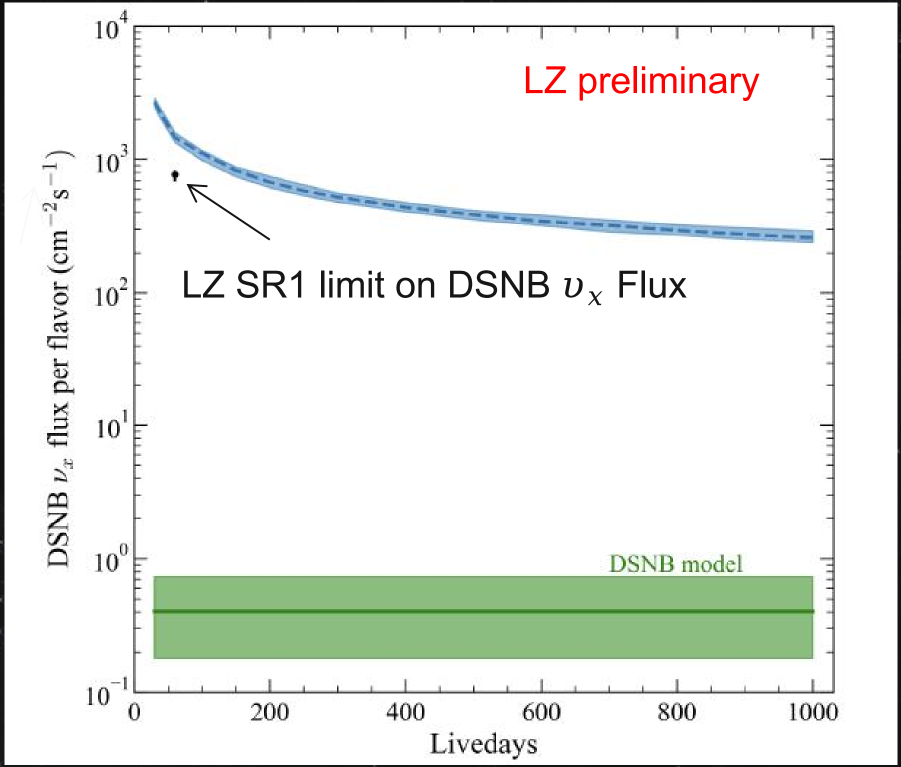
- LZ SR1 limit on DSNB υ_x flux: 686 - 826 $cm^{-2}s^{-1}$ at 90% C.L. for neutrino energy E > 19.3 MeV
- Blue: Projected sensitivity vs. livetime
- Green: DSNB model predicted flux

  *Error bar in black and band widths in blue and green come from DSNB model uncertainties
- Comparable to SK limits**:

$$\Phi_{\nu_\mu+\nu_\tau} < (1.0\text{–}1.4) \times 10^3 \text{ cm}^{-2} \text{ s}^{-1}$$

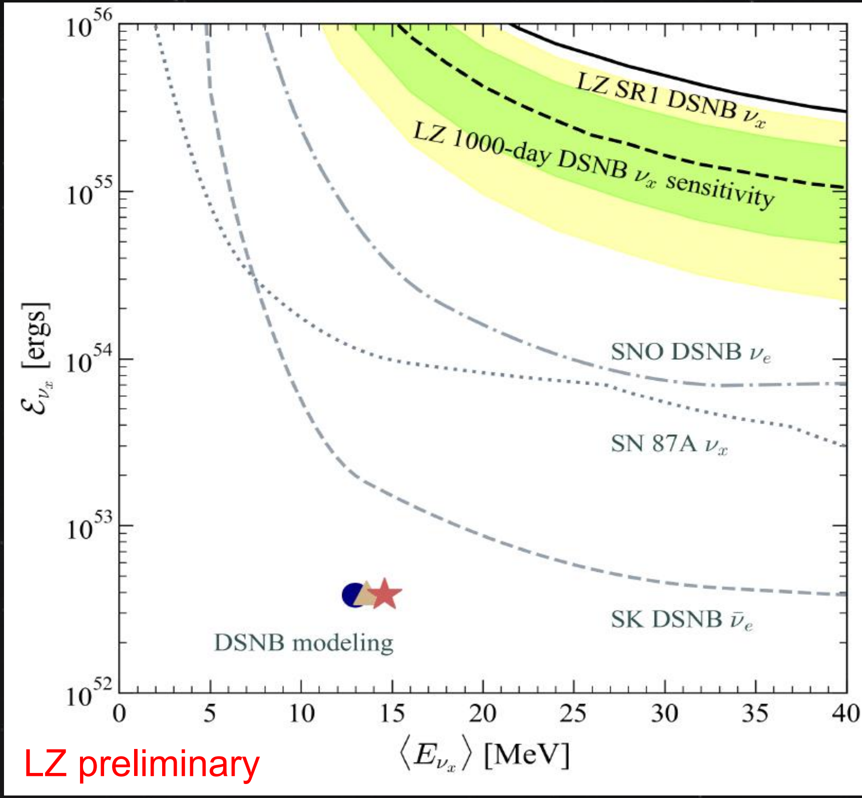
$$\Phi_{\bar{\nu}_\mu+\bar{\nu}_\tau} < (1.3\text{–}1.8) \times 10^3 \text{ cm}^{-2} \text{ s}^{-1},$$

**Lunardini and Peres, JCAP 08 033 (2008)



Limits on fundamental DSNB emission parameters

- Solid black: LZ SR1 limit on the total emitted energy per υ_x flavor ε_{υ_x} vs. average neutrino energy $\langle E_{\upsilon_x} \rangle$
- Green and yellow band: 1σ and 2σ sensitivity bands
- Three points indcate the average eimssion parameters in the fiducial, minimial and maximal DSNB models



Summary and outlook

- LZ can set competitive limit on DSNB υ_x through the CEυNS process
  - LZ's limit with an exposure of 0.9 tonne-yr is of the same order of magnitude as Super-K's limit with 1496 days x 22.5 kton of exposure
- Future LZ data will improve the limit by more than a factor of 3
- The current limit do not restrict any existing DSNB model but can be useful in the future, e.g.,
  - New astrophysical models where a larger neutron star or a black hole is formed ==> larger DSNB flux
  - New-physics models where neutrinos can escape more readily from the core of the proto-neutron star ==> larger mean neutrino energy

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

250 scientists, engineers, and technical staff

https://lz.lbl.gov/

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
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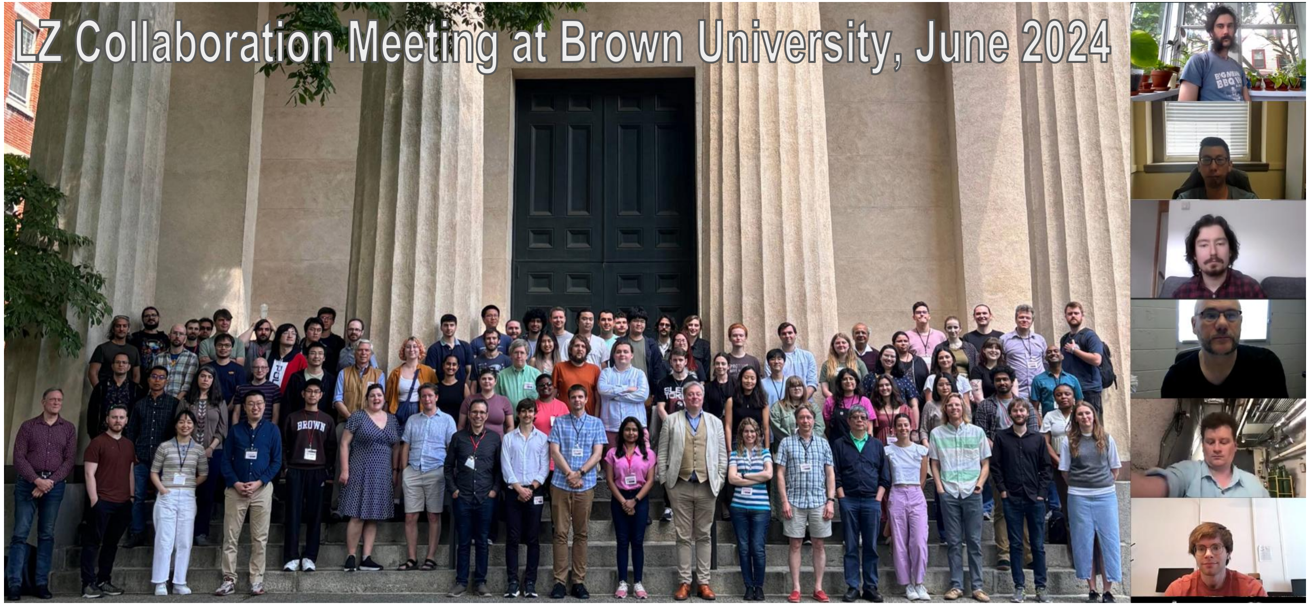
US Europe Asia Oceania



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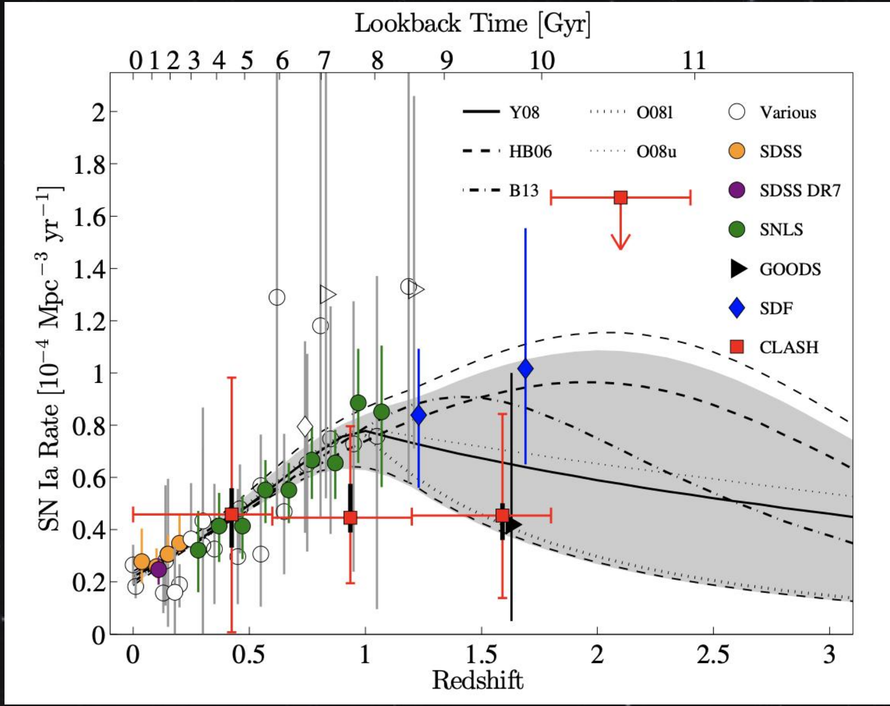
Thank you!

Why not setting limits on the supernova rate density?

- The total supernova rate density is much better understood (to ~10% uncertainty) than the flux from individual supernova collapse (we know nearly nothing about)



O. Graur et al 2014 ApJ **783** 28

LZ Science Run I Fit Results

LZ preliminary

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