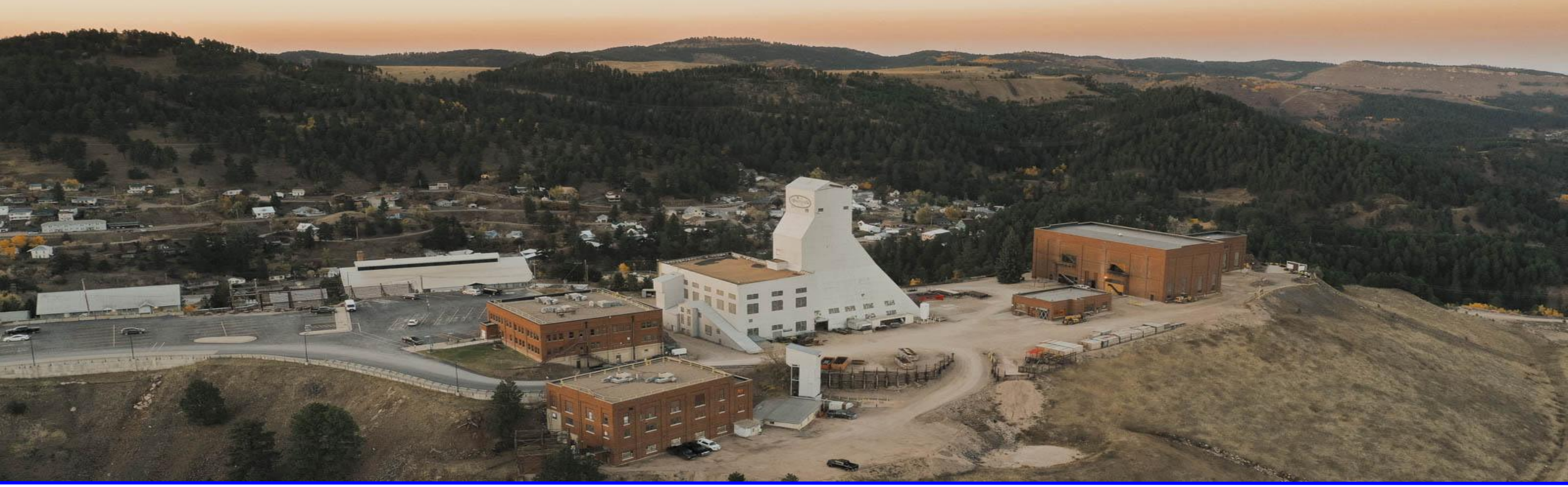

CEνNS-based Supernova Neutrino Detection with LZ

M. Elise McCarthy, on behalf of the LUX-ZEPLIN Collaboration

Magnificent CEνNS
13 June 2024, Valencia, Spain

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Overview

- Design and operation of the LUX-ZEPLIN (LZ) experiment
- LZ's sensitivity to astrophysical neutrinos
    - Observing ^{8}B neutrinos with CEνNS
    - Characteristics of the neutrino flux from core-collapse supernovae (CCSN)
    - Neutrino interactions in LZ during a galactic CCSN
    - Advantages of CEνNS-sensitive experiments
- Simulating LZ's response to galactic CCSN with ν`ESPER`
    - Architecture of ν`ESPER`
    - Relative rate in each neutrino interaction channel
- Detector response modelling with ν`ESPER` and `NEST`
    - Sensitivity as a function of progenitor distance
- Role of CEνNS-sensitive detectors in multi-messenger astronomy

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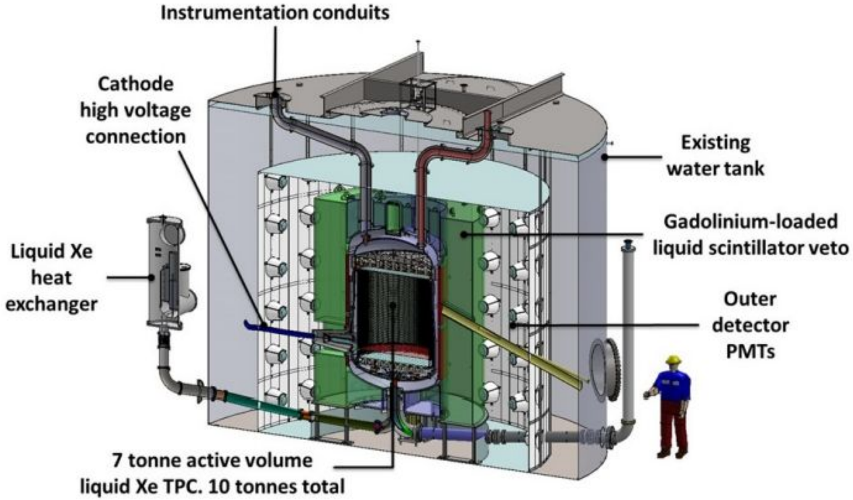
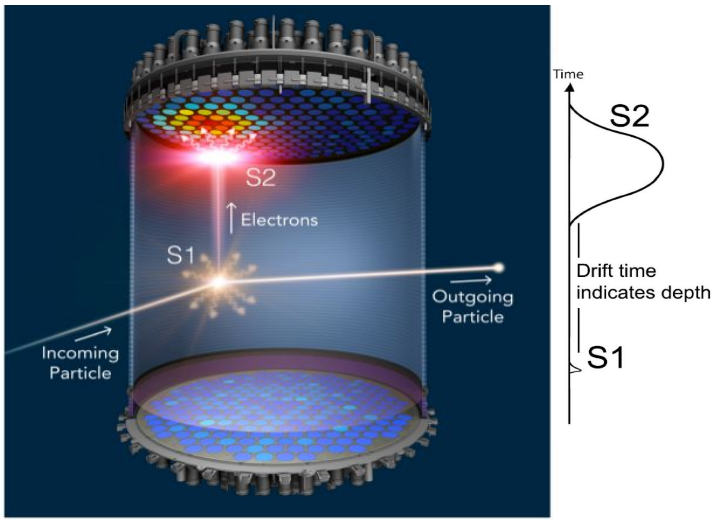
The LUX-ZEPLIN Experiment





The LUX-ZEPLIN (LZ) experiment is a low-threshold low-background dark matter direct detection experiment. LZ is deployed 4850 feet underground at the Sanford Underground Research Facility in Lead, South Dakota, USA.

First results from LZ's dark matter search were published in July 2023. We are in discovery mode.

- LZ's central volume is a time projection chamber (TPC).
  - 7 tonnes of liquid xenon (LXe).
- The Skin detector surrounds the TPC, serving as a gamma ray background veto.
  - 2 tonnes of LXe.
- The Outer Detector (OD), a neutron and gamma ray background veto, surrounds the TPC and Skin.
  - 238 tonnes of deionized water and 17 tonnes of gadolinium-loaded liquid scintillator.

Particle interactions in the TPC produce a prompt scintillation (S1) signal and a delayed electroluminescence (S2) signal.

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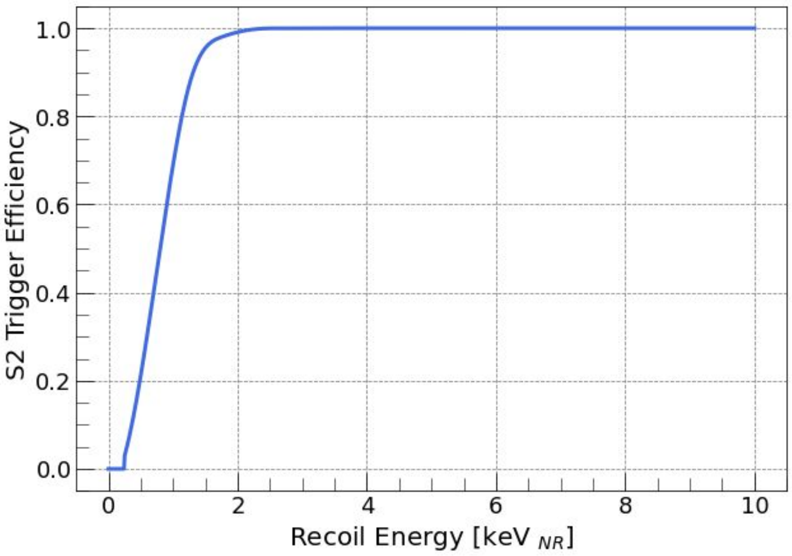
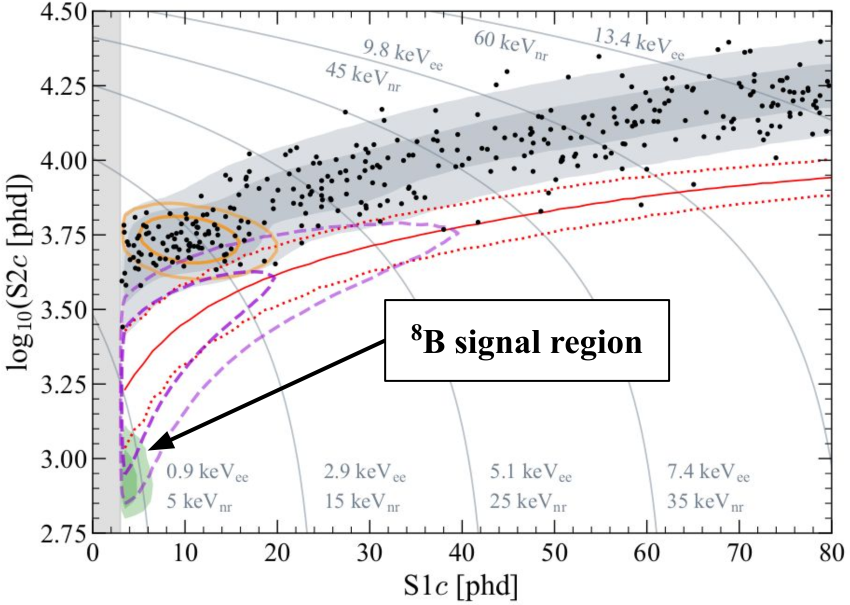
CEνNS in LZ: ^{8}B solar neutrino search

Figures reported in LZ SR1 Results





^{8}B signal region

CEνNS interactions in liquid xenon are O(1) keV nuclear recoil events, a region of the parameter space to which LZ is highly sensitive. LZ utilizes a triggered data acquisition system. The S2 trigger is ~50% efficient for 1 keV nuclear recoil (NR) interactions, and 100% at 2 keV NR.

LZ is sensitive to neutrinos from astrophysical sources, including ^{8}B solar neutrinos interacting via CEνNS in the TPC. The ^{8}B signal is modelled as part of the WIMP search background.

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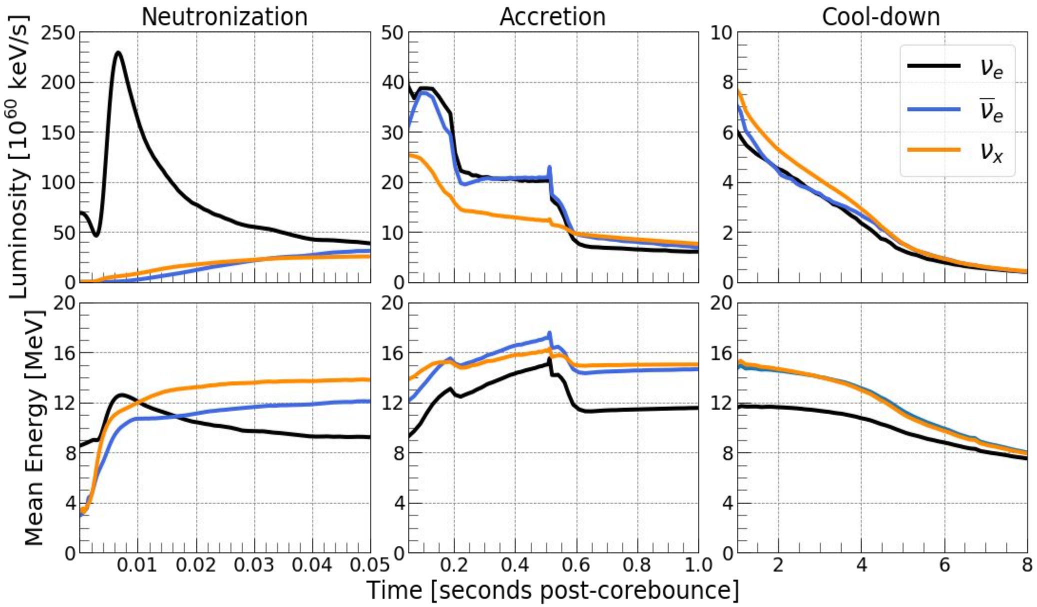
Neutrino emission from core-collapse supernovae

In the first 10 seconds of a CCSN, O(10^{57}) neutrinos are emitted.

- Mean energy of emitted neutrinos is ~10 MeV.
- Neutrinos carry away ~99% of the progenitor star's gravitational potential energy.

During a CCSN, neutrino emission is divided into three phases:

- Neutronization
    - First ~50 ms of event.
    - Primarily electron neutrinos.
- Accretion
    - Follows neutronization, up to ~0.5 s after the onset of collapse.
    - Electron and heavy-lepton neutrino luminosities increase.
- Cool-down
    - Follows explosion and lasts up to 10 s after the onset of collapse.
    - Roughly equal contribution from all neutrino flavors.



27 M$_\odot$ 1D CCSN model by MPA Garching

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Neutrino interactions in LZ during a CCSN

Detector	Mass	Target	ν_e CC	anti-ν_e CC	non-CEνNS NC	CEνNS	ν-e$^-$ elastic
TPC and Skin	7 t (TPC) and 2 t (Skin)	Xenon	x	x		x	x
OD Water and Scintillator	27 t (water) and 2.1 t (scintillator)	Hydrogen		x			x
OD Water	211 t	Oxygen	x	x	x		x
OD Scintillator	15 t	Carbon	x	x	x		x
OD Scintillator	17.1 kg	Gadolinium	x	x		x	x

During a galactic CCSN, LZ will experience charged-current, CEνNS, and other neutral-current interactions in all detector volumes.

Astrophysical CEνNS observations with LZ

Low-threshold low-background liquid noble element detectors like LZ are promising observatories for the next galactic CCSN.

- Sensitive to all flavors of emitted neutrino via CEνNS
    - Sensitivity to the heavy-lepton component of the CCSN neutrino flux is critical for reconstruction of the total neutrino luminosity
- 7 tonne Xe target mass
- Detector livetime of ~97% during first science campaign

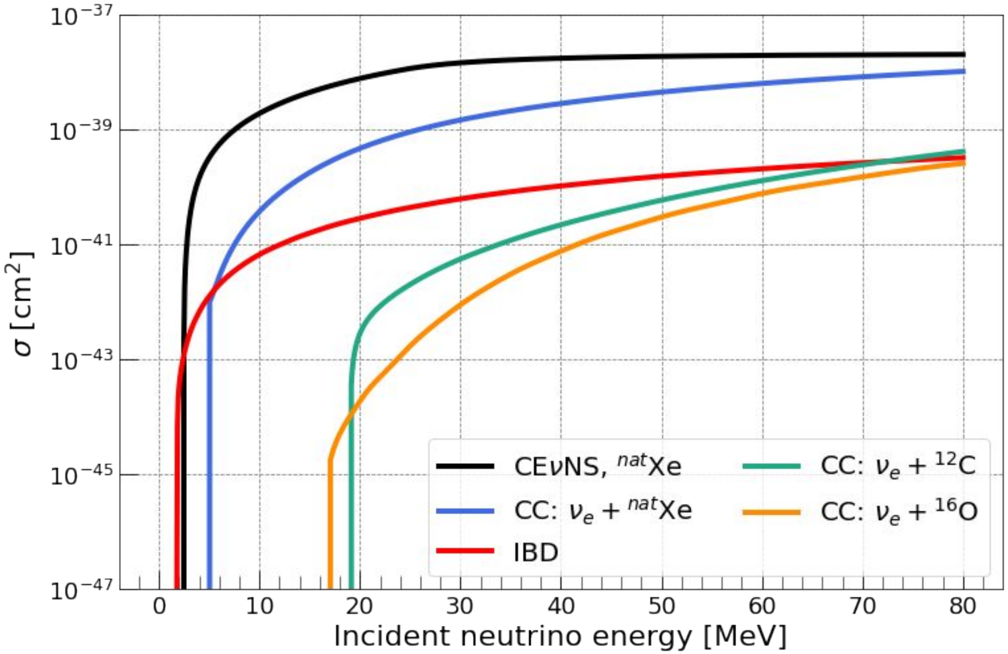
CEνNS-sensitive experiments have many potential contributions to multi-messenger astronomy. Work to prepare these experiments for the next galactic CCSN is active and ongoing.

Modelling LZ's CCSN response with νESPER

To simulate LZ's response to a flux of CCSN neutrinos, we have developed νESPER: the Neutrino Engine Simulating the Process of Energetic Recoils. νESPER is a Python 3 simulation package.

νESPER utilizes CCSN neutrino emission models produced by the simulations group at MPA Garching.

Interactions via charged- and neutral-current channels are simulated in the TPC and OD.



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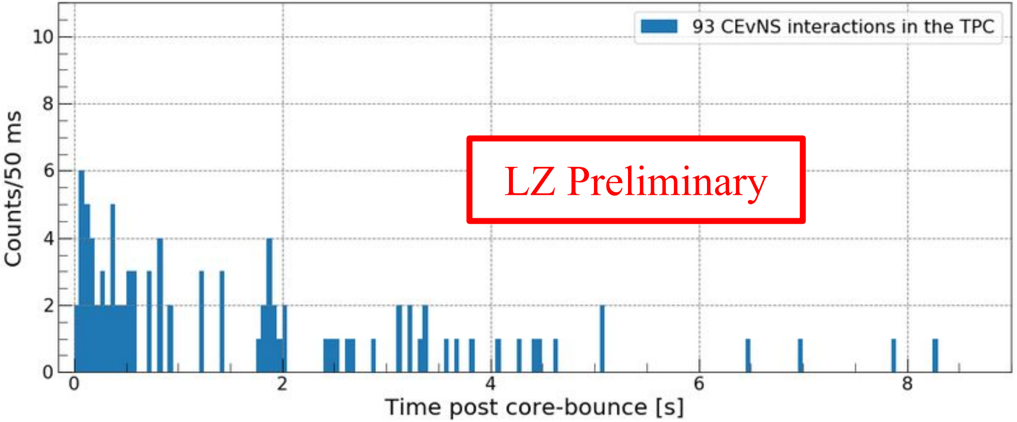
Modelling LZ’s CCSN response with νESPER

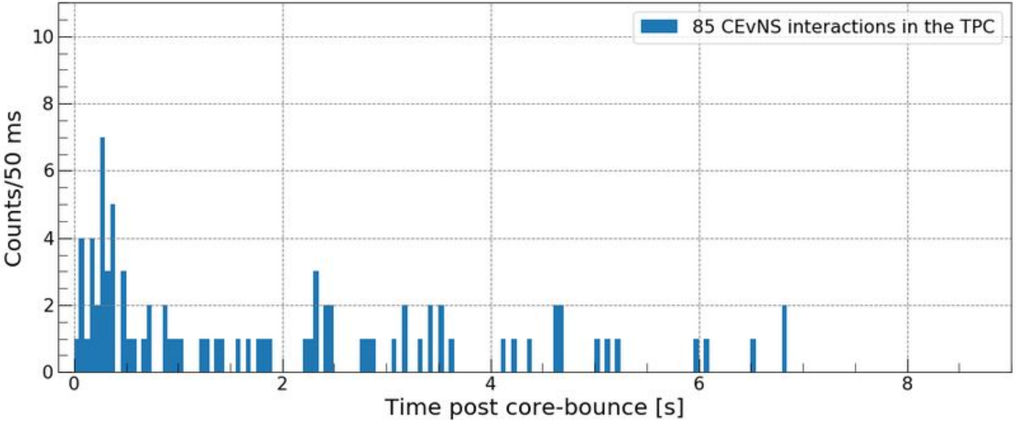
Each neutrino emission model is handled by a dedicated processing harness.

Simulations are configurable via the top-level driving file. The user may select:

- The CCSN progenitor model.
- Distance from earth to the CCSN progenitor.
- Which neutrino flavors to simulate.
- The detector volume to simulate
- The nuclear form factor for CEνNS interactions.
- Detection threshold - the smallest recoil energy which will be observable in the detector.

Each run of νESPER is one explosion of the user-selected CCSN progenitor, returning a time series of neutrino interactions in the user-specified volume.





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νESPER: CCSN ν interaction rates in the TPC

In the TPC, charged-current interactions may be a significant background to a CEνNS-based CCSN neutrino detection.

The high-energy CC interaction and cascade of charged particles may cause detector deadtime, reducing our sensitivity to CEνNS interactions occurring simultaneously.

To assess the relative rate in each interaction channel, a 27 $M_\odot$ 1D CCSN progenitor located 10 kpc from Earth is simulated with νESPER. The average interaction rate in each channel is reported in the below table.

As expected, CEνNS interactions are the dominant interaction mechanism. We predict one charged current interaction, $\nu_e + \text{Xe} \rightarrow \text{Gd}^* + e^-$, in the TPC.

Target	CEνNS	ν_e CC	anti-ν_e CC	ν-e^- elastic
LZ TPC	84 ± 1	1.2 ± 0.1	0.02 ± 0.01	0.05 ± 0.02
1 tonne of LXe	12.0 ± 0.4	0.17 ± 0.04	0.003 ± 0.005	0.007 ± 0.008

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νESPER: CCSN ν interaction rates in the OD

Detector	Target	Mass	ν_e CC	anti-ν_e CC	non-CEνNS NC	CEνNS	ν-e^- elastic
Water and Scintillator	Hydrogen	Scintillator: 2.1 t		4.1 ± 0.2			3.9 ± 0.2
		Inner water: 13 t		26.8 ± 0.5			
		Outer water: 14 t		28.2 ± 0.5			
OD Water	Oxygen	211 t	0.20 ± 0.04	0.32 ± 0.06	0.85 ± 0.09		
OD Scintillator	Carbon	15 t	0.07 ± 0.03	0.08 ± 0.03	0.17 ± 0.04		
OD Scintillator	Gadolinium	17.1 kg	0	0		0.23 ± 0.05	

LZ Preliminary

In the OD, the interaction rate from this progenitor is negligible in most channels .

The dominant interaction mechanism in the OD is inverse beta decay (IBD), producing back-to-back 511 keV gamma rays from positron annihilation and possibly delayed MeV-scale gamma rays from neutron capture.

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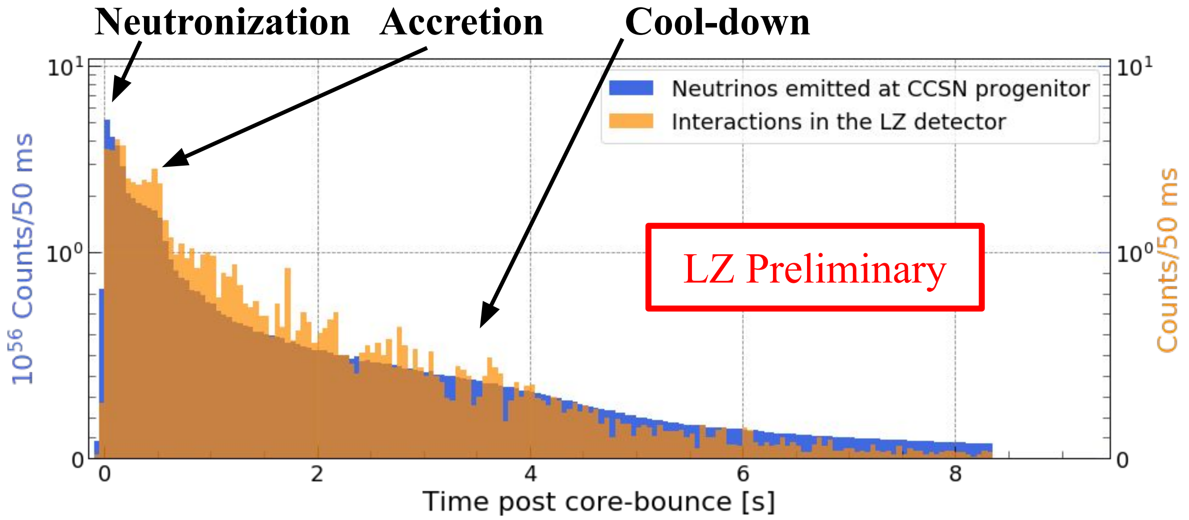
νESPER: CEνNS interactions in the TPC

The CEνNS signal has a maximum during the accretion phase of the CCSN.

During the ~0.5 s of the accretion phase, 23 ± 5 CEνNS interactions are predicted to occur in the TPC.

Studying detector background over CCSN neutrino flux timescales is ongoing.



Phase	Number of CEνNS interactions observed (>0.5 keV NR)	Duration of phase
Neutronization	3 ± 2	50 ms
Accretion	23 ± 5	~0.5 s
Cool-down	46 ± 7	~10 s

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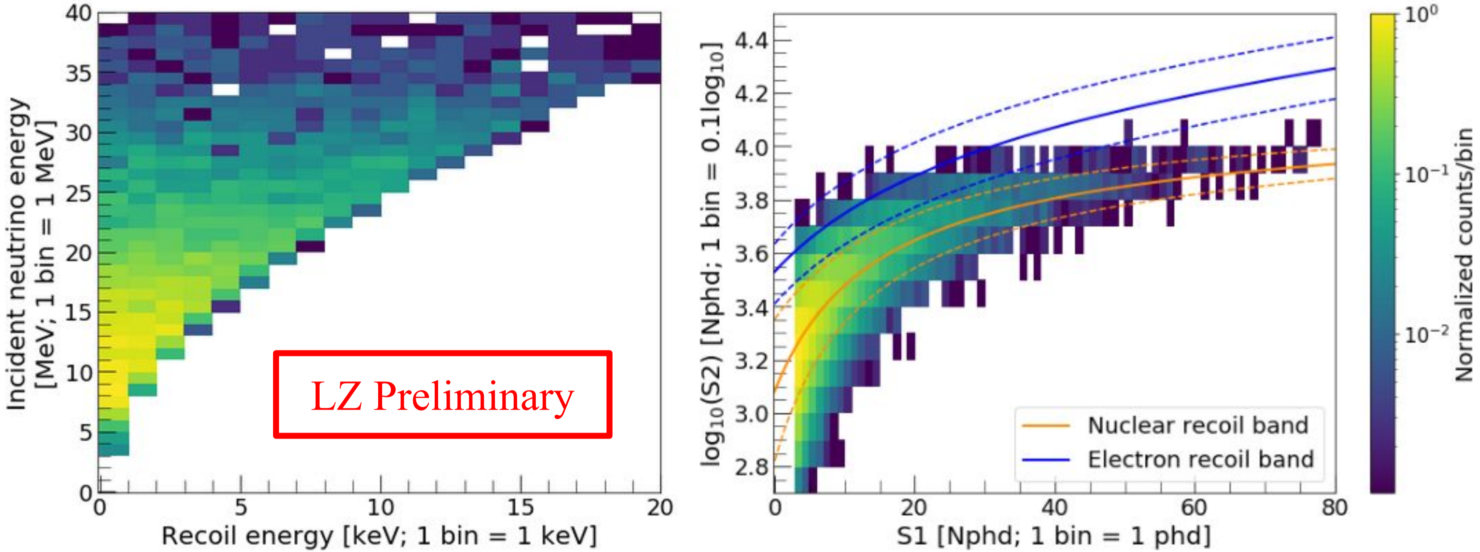
Modelling CEνNS response with νESPER and NEST



LZ Preliminary

The output of νESPER is passed to the Noble Element Simulation Technique (NEST) software to examine LZ’s response to the CEνNS signal in terms of detector observables (S1 and S2 signals). NEST has been tuned to match the LZ SR1 detector response.

Examining a 27 $M_\odot$ 1D CCSN progenitor, the smallest S2 from the CEνNS signal is ~600 photons detected (phd).

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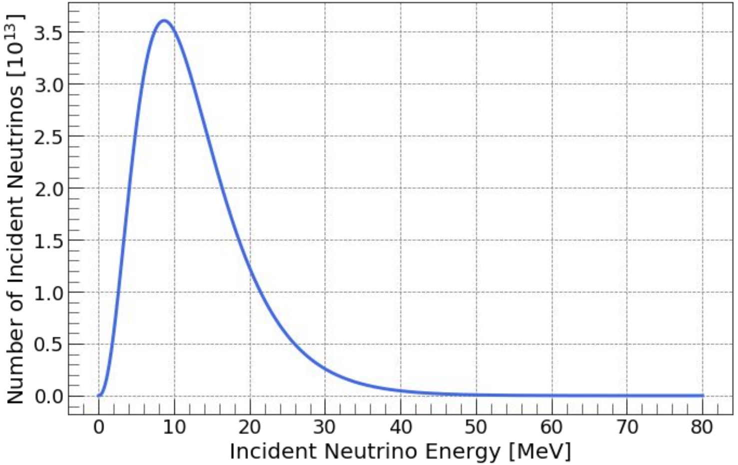
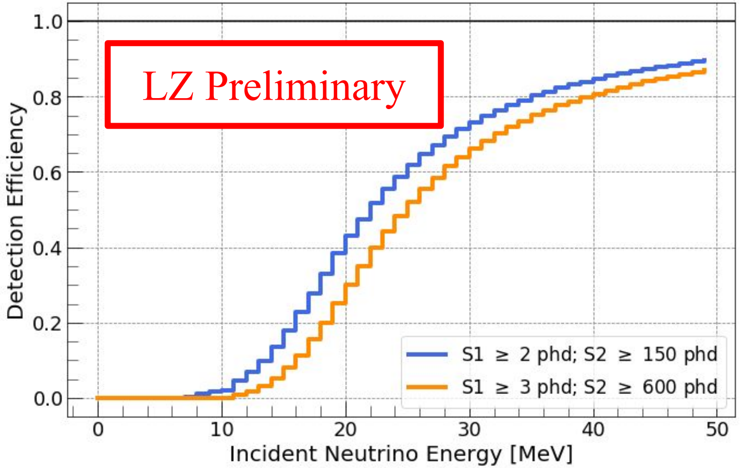
CCSN data analysis strategies and detection efficiency





Examining the detector response in (S1, S2) space, a range of analysis cuts are applied to the CCSN signal.

For each analysis strategy, LZ's CEνNS detection efficiency is calculated.

The SR1 WIMP search ROI specified a minimum S2 size of 600 phd. Because the CEνNS detection efficiency is independent of the minimum S2 size, the SR1 analysis threshold and detector response characterization can be applied to the CCSN CEνNS analysis.

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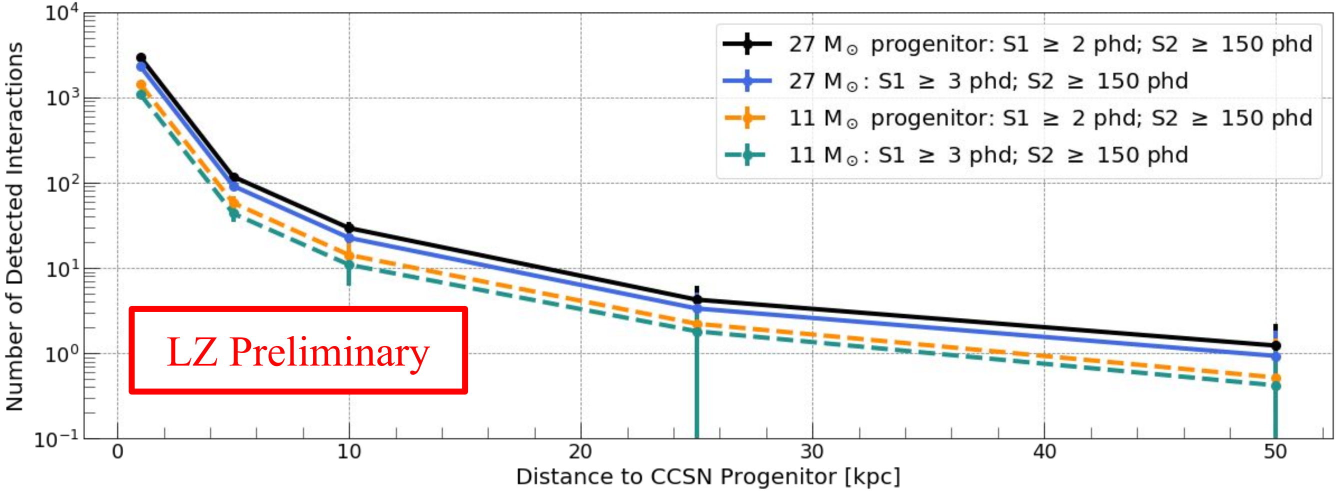
CCSN progenitor distance



To study the impact of progenitor distance on LZ’s detection capability, an 11 $M_\odot$ 1D progenitor and a 27 $M_\odot$ 1D progenitor are simulated at a variety of distances.

A 27 $M_\odot$ progenitor 50 kpc from Earth will produce 4 ± 2 CEνNS interactions in the LZ TPC. Requiring an S1 ≥ 3 phd, 1 ± 1 interaction from this progenitor will be detected.

This study places distance limits on LZ’s CCSN detection capabilities:

- Smaller CCSN progenitors (up to ~11 $M_\odot$) will be detectable within the Milky Way.
- Larger CCSN progenitors (27 $M_\odot$ and above) will be detectable within the local galactic cluster.

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Role of CEνNS-sensitive experiments in multi-messenger astronomy

CEνNS-sensitive liquid noble element detectors provide exciting new opportunities in multi-messenger astrophysics. A CCSN detection by LZ or our contemporary experiments will be the first observation of astrophysical neutrinos via CEνNS.

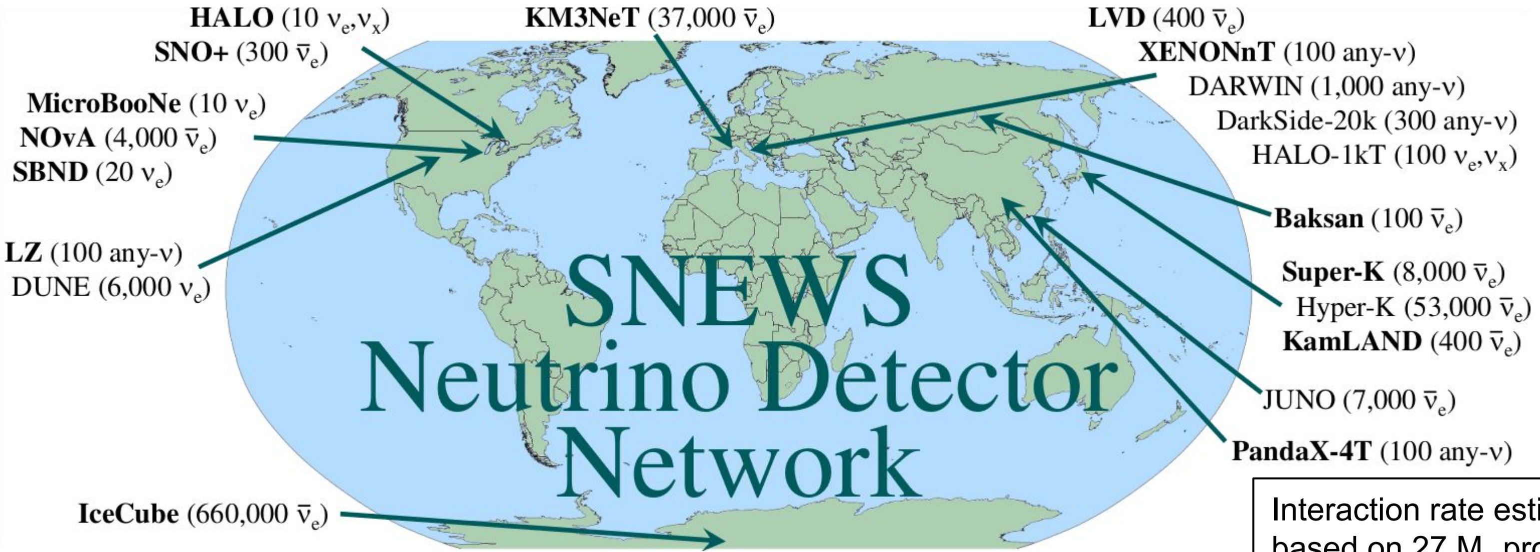
In a joint analysis with other experiments, CEνNS-sensitive detectors can extract critical information about the heavy-lepton component of the neutrino flux.

- Heavy-lepton flux component is critical for the reconstruction of the overall neutrino luminosity, and has never been previously observed.

With large-scale CEνNS-sensitive experiments only recently online, preparing these experiments to contribute to multi-messenger astrophysics is an active field.

- New simulation tools are under development.
- CEνNS and CEνNS-sensitive experiments are being added to existing simulation packages.
- Experiments are developing analysis pipelines, aiming to rapidly generate an alert to optical astronomers from a CEνNS-based observation.

Role of CEνNS-sensitive experiments in multi-messenger astronomy



HALO (10 ν_e,ν_x)
SNO+ (300 $\bar{\nu}_e$)
MicroBooNe (10 ν_e)
NOvA (4,000 $\bar{\nu}_e$)
SBND (20 ν_e)
LZ (100 any-ν)
DUNE (6,000 ν_e)
IceCube (660,000 $\bar{\nu}_e$)
KM3NeT (37,000 $\bar{\nu}_e$)
LVD (400 $\bar{\nu}_e$)
XENONnT (100 any-ν)
DARWIN (1,000 any-ν)
DarkSide-20k (300 any-ν)
HALO-1kT (100 ν_e,ν_x)
Baksan (100 $\bar{\nu}_e$)
Super-K (8,000 $\bar{\nu}_e$)
Hyper-K (53,000 $\bar{\nu}_e$)
KamLAND (400 $\bar{\nu}_e$)
JUNO (7,000 $\bar{\nu}_e$)
PandaX-4T (100 any-ν)

Interaction rate estimates based on 27 $M_\odot$ progenitor

CEνNS-sensitive experiments are already active multi-messenger astrophysics collaborators.

LZ is a member experiment of the Supernova Neutrino Early Warning System 2.0 (SNEWS2.0) collaboration. SNEWS2.0 is a consortium of neutrino-sensitive experiments, aiming to pool information from a CCSN detection and generate a fast alert to optical astronomers.

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Conclusions

- LZ is a low-threshold, low-background liquid noble element dark matter detector sensitive to CEνNS interactions.
    - Promising mechanism for the observation of neutrinos from galactic CCSN.
- We have developed ν`ESPER`, a Python 3 simulation package, to simulate the response of LZ to neutrinos from CCSN.
    - Utilizes neutrino emission models from the simulations group at MPI Garching.
    - Charged-current, neutral-current, and CEνNS interaction channels available.
    - Simulates the response in all sub-detectors of LZ.
- Using ν`ESPER` and `NEST`, LZ's response to a 27 $M_\odot$ 1D CCSN progenitor at 10 kpc from Earth is simulated.
    - Signal from a CCSN is dominated by CEνNS interactions, with a low rate of IBD interactions in the Outer Detector.
- Via CEνNS, LZ will be sensitive to smaller progenitors within the Milky Way and larger progenitors within the local galactic cluster.
- CEνNS-sensitive liquid noble element detectors are an exciting frontier in multi-messenger astrophysics, and work is ongoing to prepare these experiments for the next CCSN.

Any questions?

Thanks to our sponsors and 38 participating institutions!

UKRI Science and Technology Facilities Council

U.S. Department of Energy Office of Science

Sanford Underground Research Facility
South Dakota Science and Technology Authority

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Supplemental slides

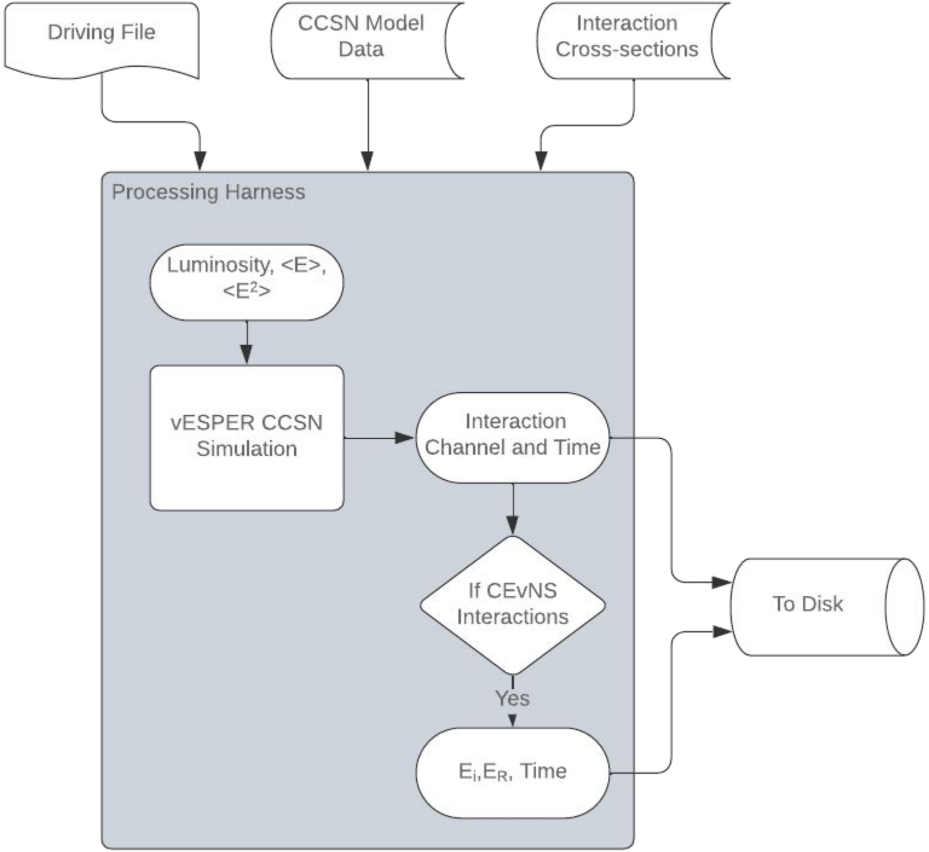
νESPER: Architecture

Each neutrino emission model is handled by a dedicated processing harness.

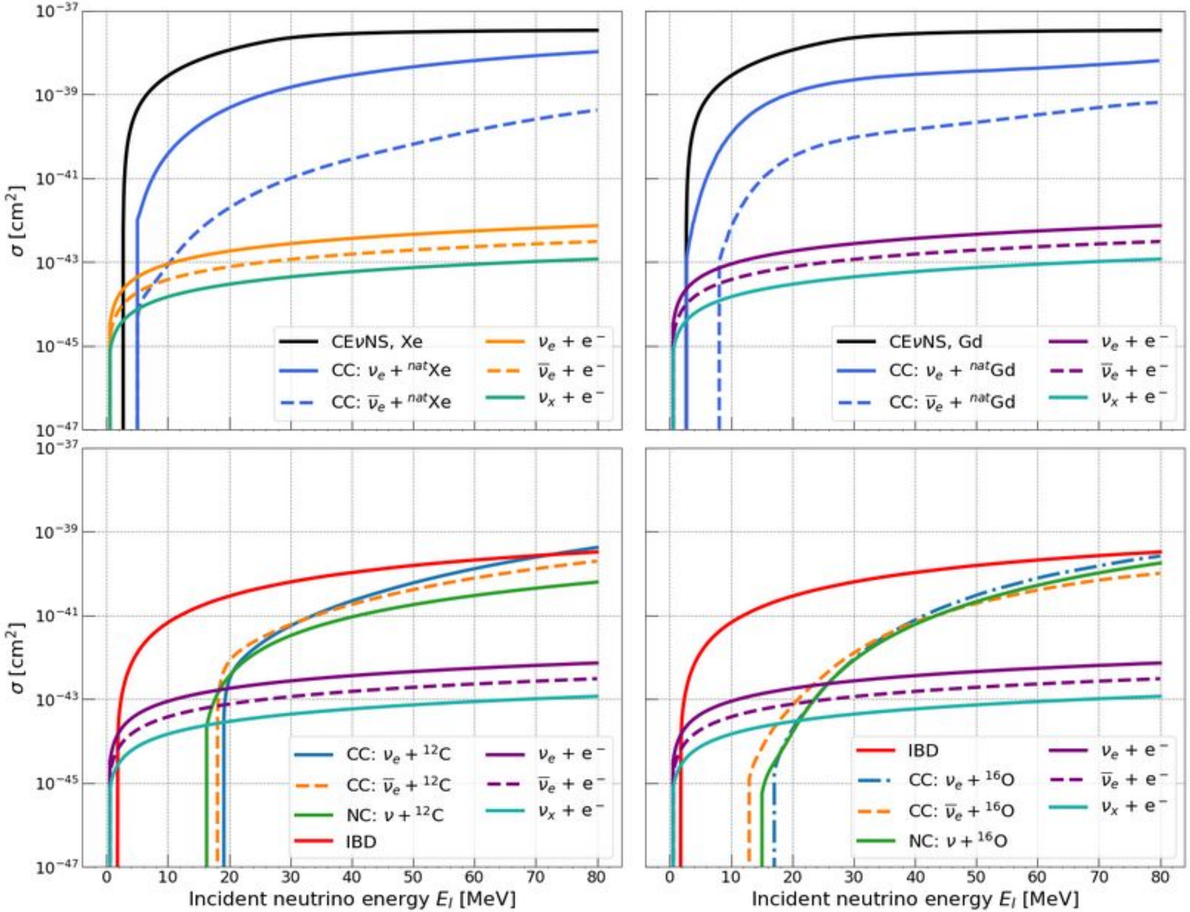
Simulations are configurable via the top-level driving file. The user may select:

- The CCSN progenitor model.
- Distance from earth to the CCSN progenitor.
- Which neutrino flavors to simulate.
- The detector volume to simulate
- The nuclear form factor for CEνNS interactions.
- Detection threshold - the smallest recoil energy which will be observable in the detector.

Each run of νESPER is one explosion of the user-selected CCSN progenitor, returning a time series of neutrino interactions in the user-specified volume.



vESPER: Interaction channels



Top left: TPC

Top right: Gadolinium component of OD Scintillator

Bottom left: Linear Alkylbenzene component of OD Scintillator

Bottom right: OD Water

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MPA Garching: CCSN data archive link

https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/

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Neutrino observations from SN1987A

Detector	Interaction mechanism/ flavor sensitivity	Target mass [tonnes]	# of neutrinos observed during SN1987A	# of neutrinos observed per tonne of detector material
IMB	IBD/electron antineutrinos	~9400	8	~9E-4
Kamiokande II	IBD/electron antineutrinos	3000	11	~4E-3
Baksan	IBD/electron antineutrinos	330	5	~0.02
LZ	CEvNS/all flavors	7	4*	~0.6*

*Projected using vESPER

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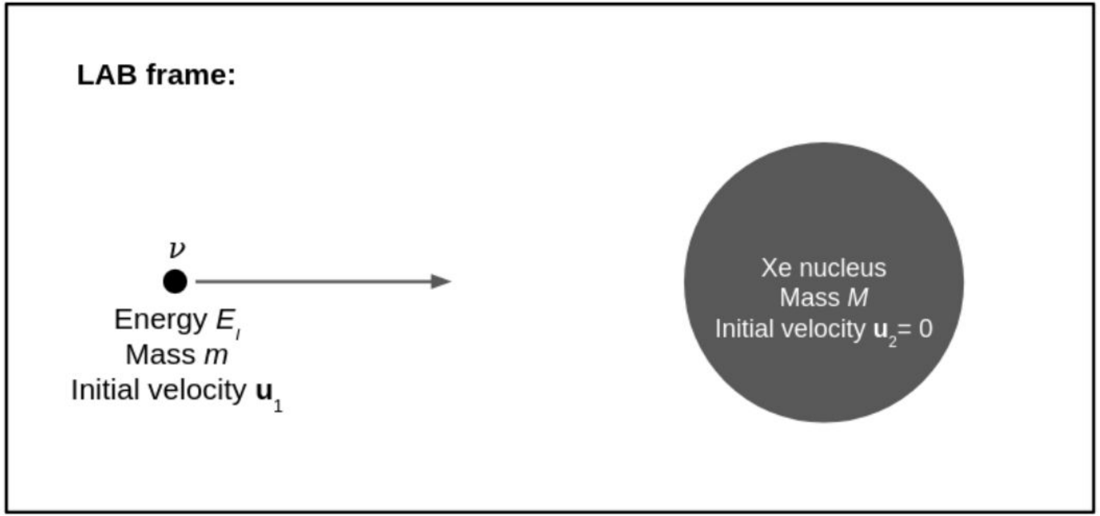
Hard-sphere scattering: Recoil energy probability distribution



A neutrino of energy E_I is incident on an Xe nucleus of mass M. The Xe nucleus is initially at rest in the LAB frame.

The neutrino and Xe nucleus scatter elastically (as in a CEvNS interaction), causing the Xe nucleus to recoil with some energy E_R.

The recoil energy may take any value in the range $0 < E_R \leq \frac{2\mu^2\mathbf{u}_1^2}{M}$ where $\mu = \frac{mM}{m+M}$ is the reduced mass of the neutrino-nucleus system.

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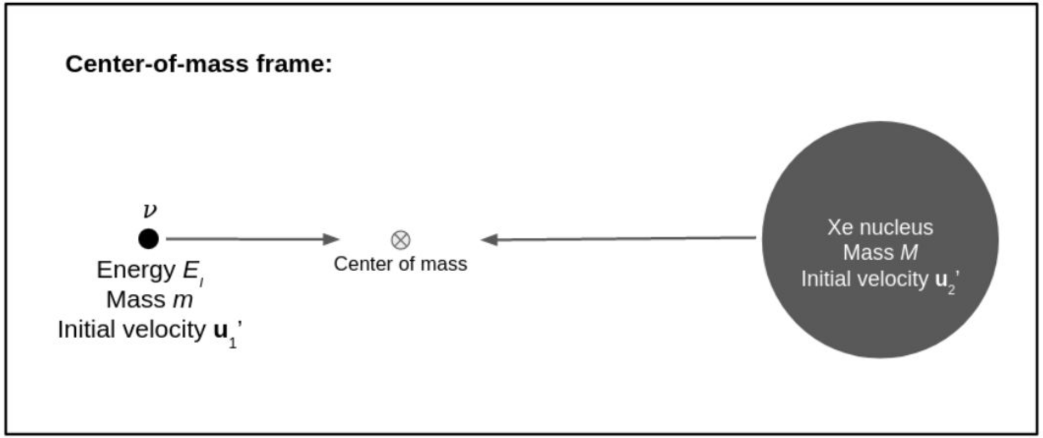
Hard-sphere scattering: Recoil energy probability distribution



Transforming to the center-of-mass frame, the Xe nucleus is moving towards the center of mass with initial velocity

$$\mathbf{u}_2' = \frac{m\mathbf{u}_1}{m+M}$$

and momentum

$$\begin{aligned}\mathbf{p}_i &= M\mathbf{u}_2' \\ &= \frac{Mm}{m+M}\mathbf{u}_1 \\ &= \mu\mathbf{u}_1.\end{aligned}$$

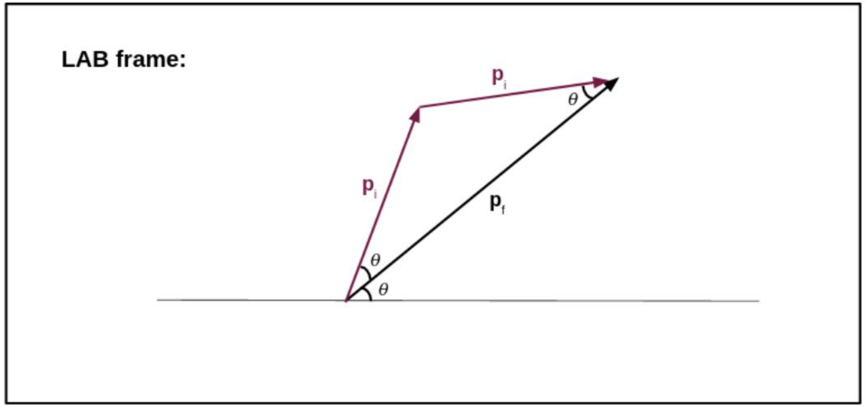
After the collision, the Xe nucleus recoils at some angle θ.

Because $m << M$, θ is approximately the same angle in the LAB and center-of-mass frames.

Hard-sphere scattering: Recoil energy probability distribution

Returning to the LAB frame, we decompose the final momentum vector of the Xe nucleus into two components, each with a magnitude p_i and oriented w.r.t. $\boldsymbol{p_f}$ at an angle θ. We use the law of cosines to obtain $\boldsymbol{p_f}$ in terms of p_i and θ:

$$\begin{aligned} p_f &= \sqrt{p_i^2 + p_i^2 + 2p_i p_i \cos(\pi - 2\theta)} \\ &= \sqrt{2p_i^2 + 2p_i^2 \cos(\pi - 2\theta)} \\ &= p_i\sqrt{2(1 + \cos(\pi - 2\theta)} \\ &= p_i\sqrt{2(1 - \cos(2\theta))} \\ &= p_i\sqrt{4\cos^2(\theta)} \\ \mathbf{p}_f &= 2p_i \cos\theta\ \hat{\theta}. \end{aligned}$$



The energy of the recoiling Xe nucleus is thus given by

$$\begin{aligned} E_R &= \frac{\mathbf{p}_f^2}{2M} \\ &= \frac{(2p_i\cos\theta)^2}{2M} \\ &= \frac{2\mu^2\mathbf{u}_1^2}{M}\cos^2\theta. \quad \bigstar \end{aligned}$$

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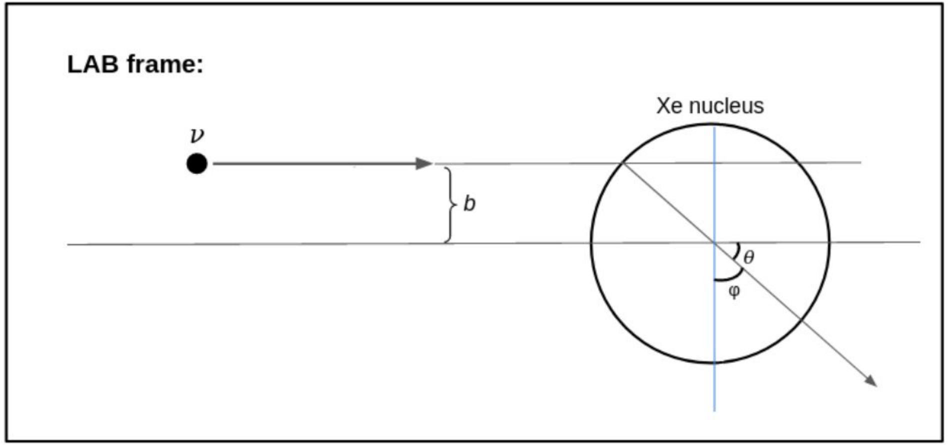
Hard-sphere scattering: Recoil energy probability distribution

The recoil angle θ is related to the impact parameter b between the neutrino and Xe nucleus. Assigning the neutrino a radius $R1$ and the Xe nucleus a radius $R2$,
$b = (R1 + R2) \sin\theta$.

To link θ and E_R, we differentiate E_R (★) and *b* w.r.t θ:

$$dE_R = \frac{-4\mu^2 \mathbf{u}_1^2}{M} \sin\theta \cos\theta d\theta$$
$$db = (R_1 + R_2) \cos\theta d\theta.$$



Dividing our range of allowed Xe recoil energies into bins of width dE_R, a recoil energy between E_R and E_R+dE_R corresponds to an impact parameter between b and $b+db$.

Hard-sphere scattering: Recoil energy probability distribution

We solve the equation for dE_R for $cos\theta d\theta$ and substitute the result into the equation for db:

$$dE_R = \frac{-4\mu^2\mathbf{u}_1^2}{M}\sin\theta\cos\theta d\theta$$

$$\to \cos\theta d\theta = \frac{-M}{4\mu^2\mathbf{u}_1^2}\frac{dE_R}{\sin\theta}$$

$$db = \frac{-M(R_1+R_2)}{4\mu^2\mathbf{u}_1^2}\frac{dE_R}{\sin\theta}.$$

The yield in a bin of width db is $2\pi bdb$, which is given in terms of E_R by:

$$\begin{aligned} yield &= 2\pi bdb \\ &= 2\pi(R_1+R_2)\sin(\theta)\times\frac{-M(R_1+R_2)}{4\mu^2\mathbf{u}_1^2}\frac{dE_R}{\sin\theta} \end{aligned}$$

$$\boxed{yield = \frac{\pi M(R_1+R_2)^2}{2\mu^2\mathbf{u}_1^2}dE_R}$$

This yield is INDEPENDENT of θ. Any interaction, regardless of b, could produce a recoil energy between E_R and dE_R.

The probability of observing a recoil energy E_R is uniform over the range $0 < E_R \leq \frac{2\mu^2\mathbf{u}_1^2}{M}$.

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