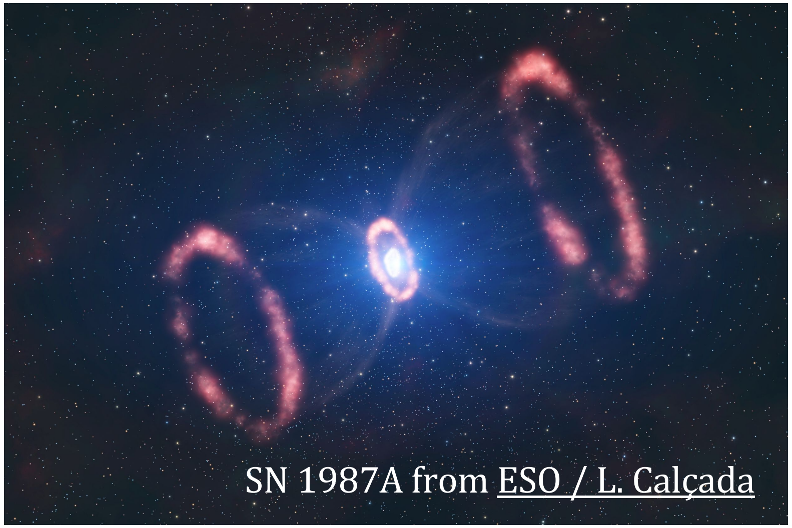
Supernova Neutrinos Detection in LZ



LIDINE 2017
2017/09/23

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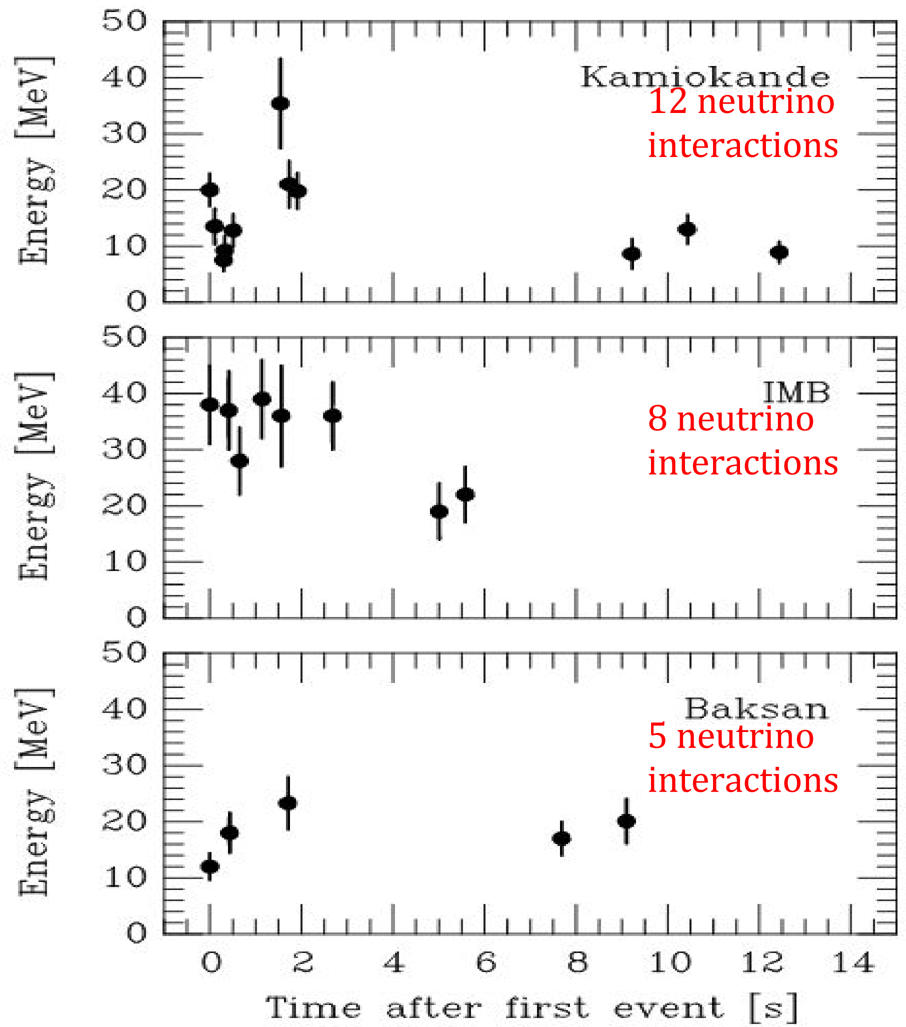
University of Rochester

1987A

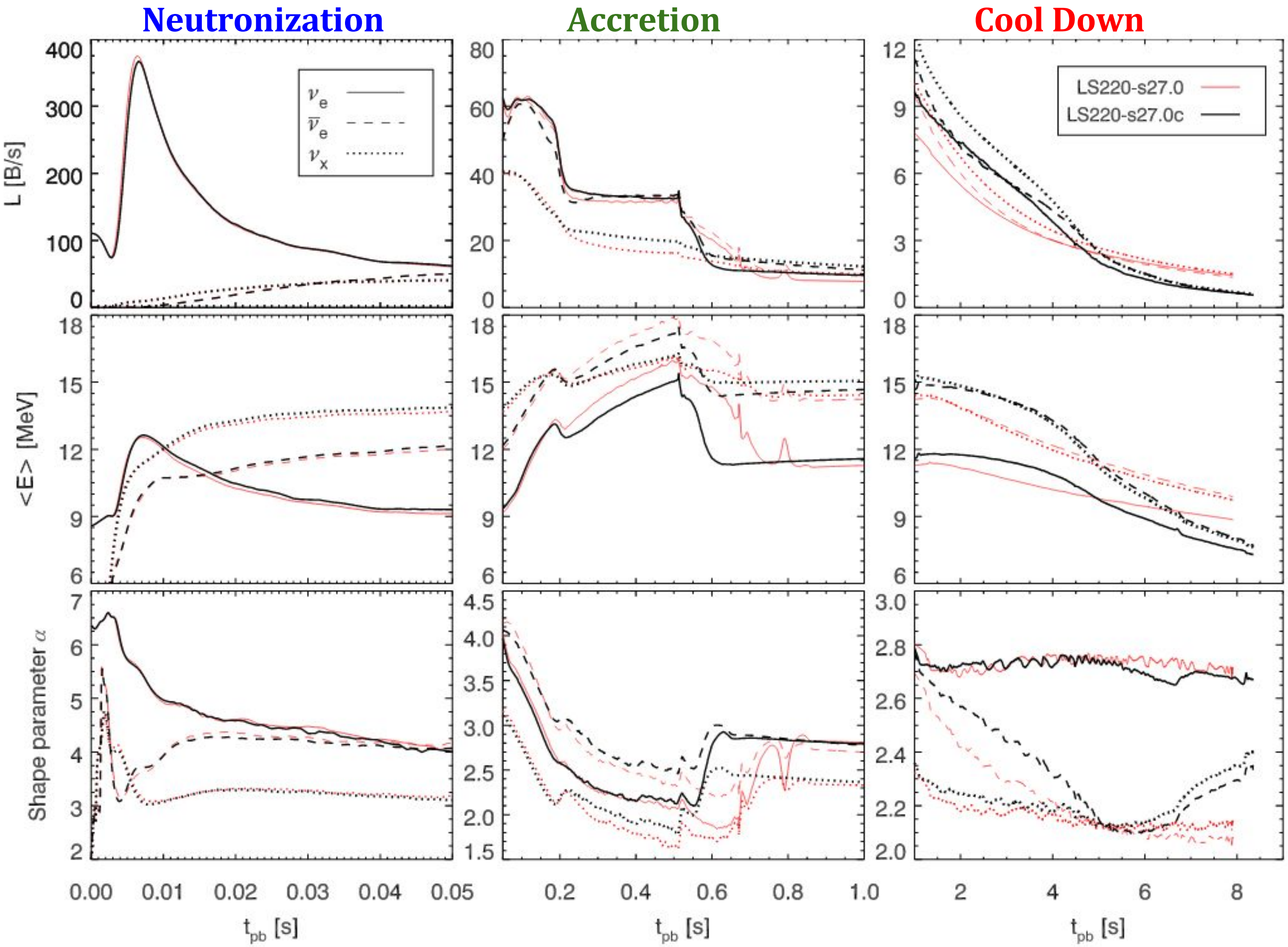
- First instance of neutrino detection from a core collapse supernova.
- Provided agreement with theoretical models that ~99% of the gravitational potential energy is carried away as neutrinos.
- The neutrino flash lasted ~12 seconds.
- Only electron antineutrinos inverse beta-decay was detected.
- Detected energy of secondary particles created from IBD.

- Supernovae are rare events.
- We expect to detect one every decade.



H. Th. Janka, Neutrino Emission from Supernovae, arxiv-link.

The Supernova Neutrino Signal



Alessandro Mirizzi et al., Supernova Neutrinos: Production, Oscillations and Detection, [10.1393/ncr/i2016-10120-8](https://doi.org/10.1393/ncr/i2016-10120-8), arxiv-link.

$\sim 10^{58}$ neutrinos emitted in ~ 10 seconds!

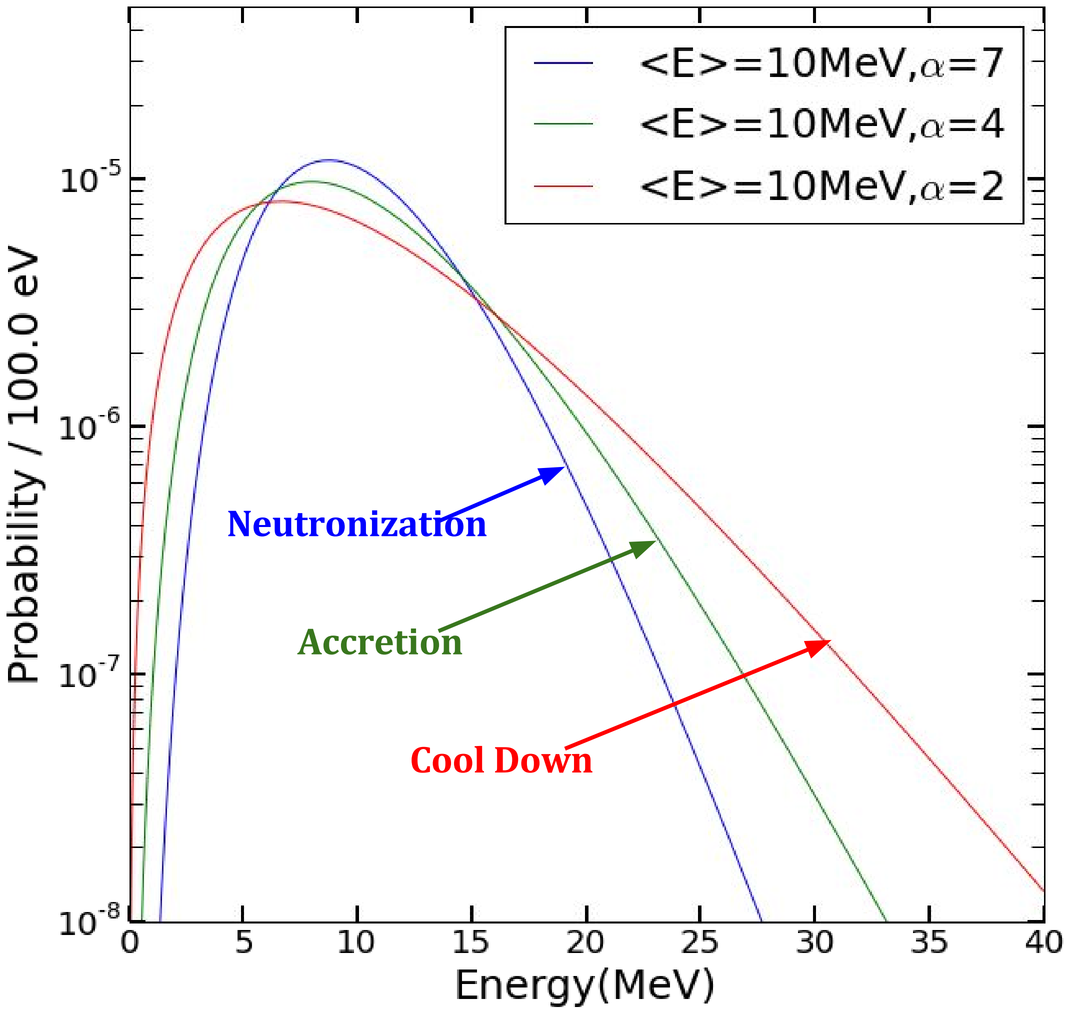
With mean energy 8-12 MeV

The Supernova Neutrino Signal

- Mean Energies in the range of 8-12 MeV.
- Very few high energy (>40 MeV) neutrinos.
- There is a time evolution to the signal.
- The empirical energy spectrum model:

$$f_\nu(E) \propto E^\alpha e^{\frac{-(\alpha+1])E}{E_{av}}}$$

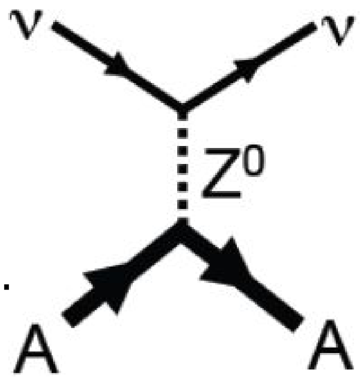
Where,
E is the energy in MeV
E_{av} is the average energy
α is a numerical parameter describing the spectral pinching



Irene Tamborra et al., High-resolution supernova neutrino spectra represented by a simple fit, Phys. Rev. D 86 125031, arxiv-link.

Neutrino Detection Methods

- Inverse Beta Decay Thresholds:
  - $\overline{\nu_e} + p = n + e^+$ 1.8 MeV
  - $\overline{\nu_\mu} + p = n + \mu^+$ 110 MeV
  - $\overline{\nu_\tau} + p = n + \tau^+$ 3.5 GeV
  - Muon and tau neutrino thresholds are too high for neutrinos from SN.
  - Miss ~2/3 of the of the neutrinos.

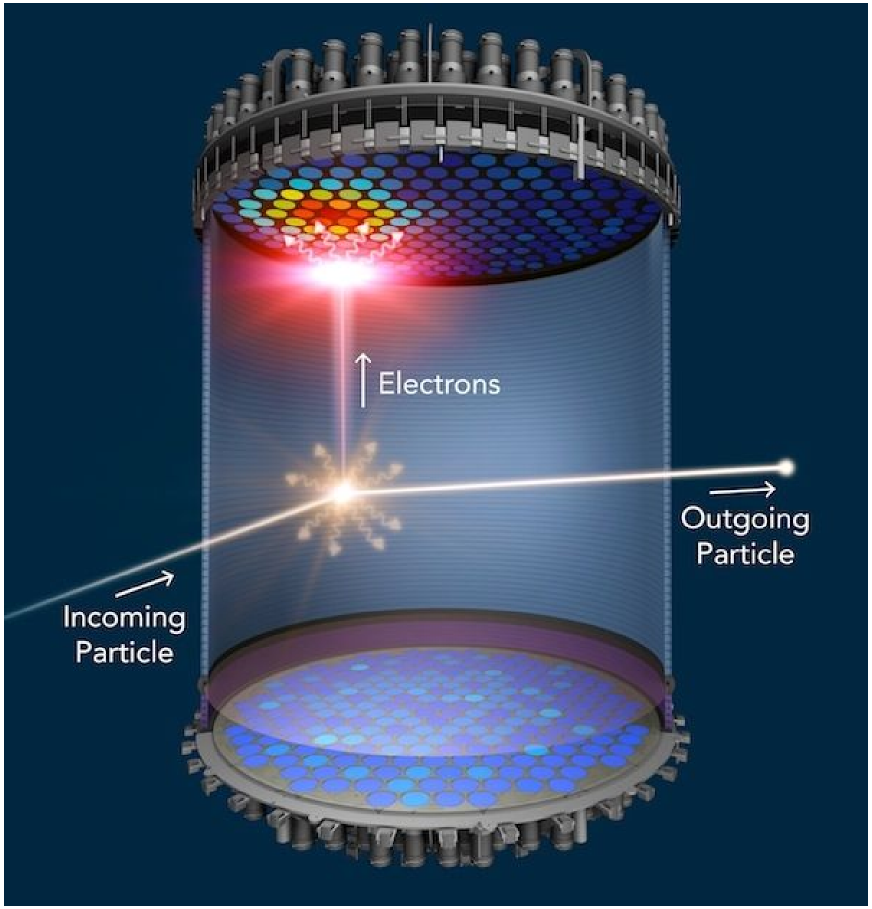


- Coherent elastic neutrino-nucleus scattering (CE**ν**NS):
  - $\nu + A \longrightarrow \nu + A^*$
  - Neutrino interacts with the nucleus producing a nuclear recoil.
  - Well predicted cross sections from the standard model.
  - N^2 enhancement to cross section in this energy range.
  - Trade off between number of neutrons per nucleus and energy deposition.
  - Recently detected by COHERENT collaboration.

LZ - Overview

- LUX-ZEPLIN (LZ) is a 7 tonne liquid xenon time projection chamber.
- To be begin operation 4850ft below the surface at the Sanford Underground Research Facility in 2019.
- Primary science goal is the search for dark matter.

- Sensitive to both ionization and scintillation.
- Uses an applied electric field to drift electrons to extract into the gas phase to produce an electroluminescence signal.

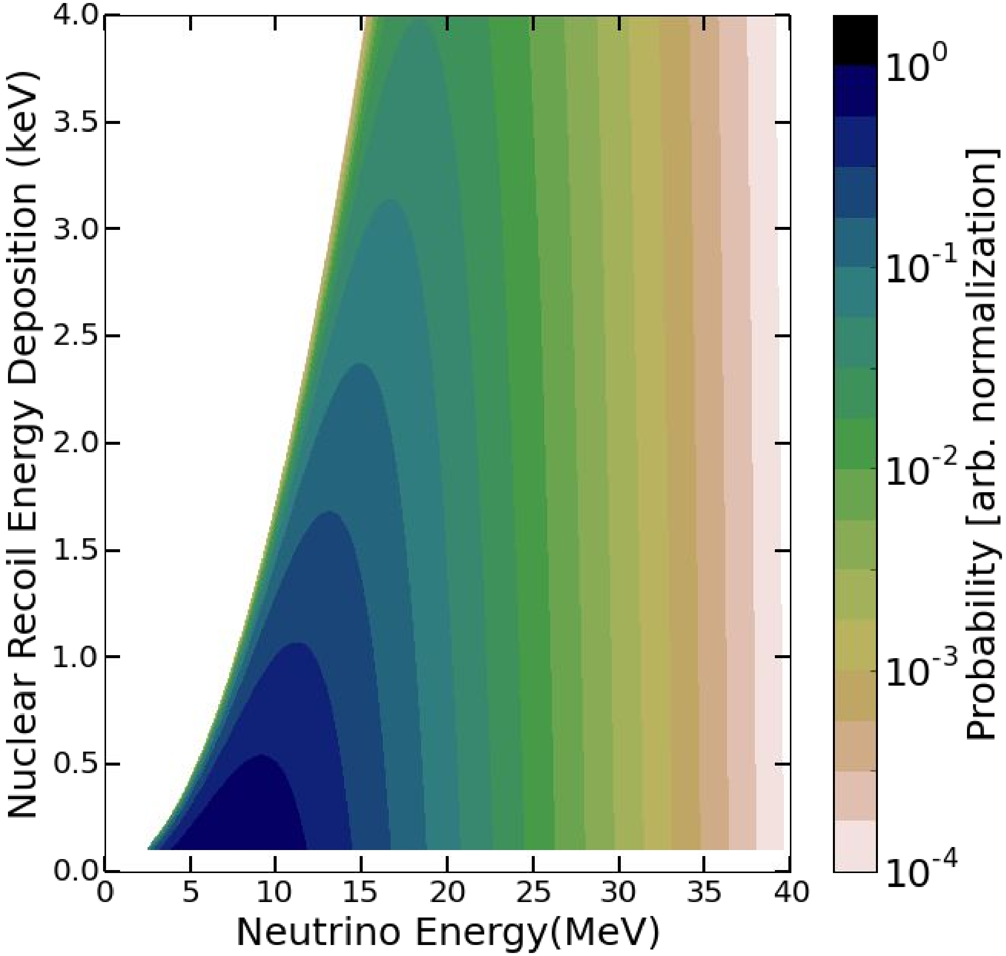


LZ Collaboration: Mount et al., The LUX-ZEPLIN (LZ) Technical design report, [arxiv-link].

CEνNS in Liquid Xenon

- CEνNS Cross section: $\frac{d\sigma}{dE_{Re}} = \frac{MG_f^2}{8\pi}[2 - \frac{2E_{Re}}{E_\nu} + (\frac{E_{Re}}{E_\nu})^2 - \frac{ME_{Re}}{E_\nu^2}]Q_W^2 F^2(Q^2)$
  - Summed over the Xe abundances.
  - A 5 MeV ν will deposit a maximum of ~0.5 keV during a recoil.
- Neutrino Flux:
  - Described by mean energy and spectral pinching α.
- Rate in the detector:

$$\frac{dR(t)}{dE_{Re}} = \frac{M_{det}N_A}{A(4\pi d^2)} \int_{E_{min}}^{\infty} \frac{d\sigma}{dE_{Re}}(E_\nu, E_{Re}) \times f_i(E_\nu, \langle E_\nu \rangle(t), \alpha(t)) dE_\nu$$

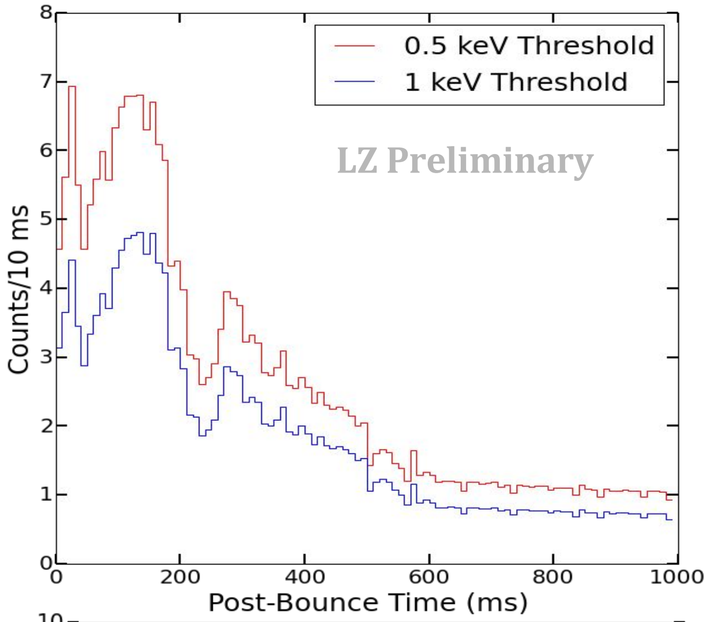


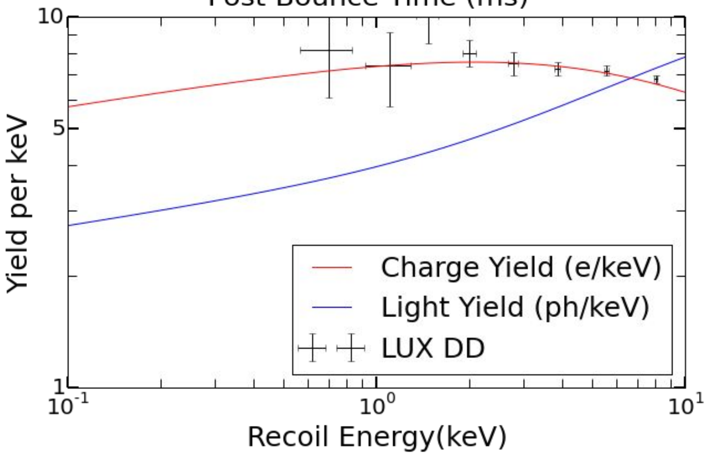
Phys. Rev. D 30 2295, Phys. Rev. D 68 023005, & 2015 J. Phys.: Conf. Ser. 606 012010.

CEνNS in Liquid Xenon

- Use the 27 M_{Sun} at 10 kpc SN ν flux model to calculate the expected number of interactions in LZ.
- We consider two possible detector thresholds:
  - ~320 ν interactions per SN at 1 keVnr threshold.
  - ~540 ν interactions per SN at 0.5 keVnr threshold.
- During the first 200 ms, the rate of ν interactions is ~500 Hz.

- From NEST:
  - 1 keVnr ~ 6 electrons
  - 0.5 keVnr ~ 3 electrons
- In LUX, a trigger threshold of 1 keVnr was achieved.
- We only consider the signal from electrons.





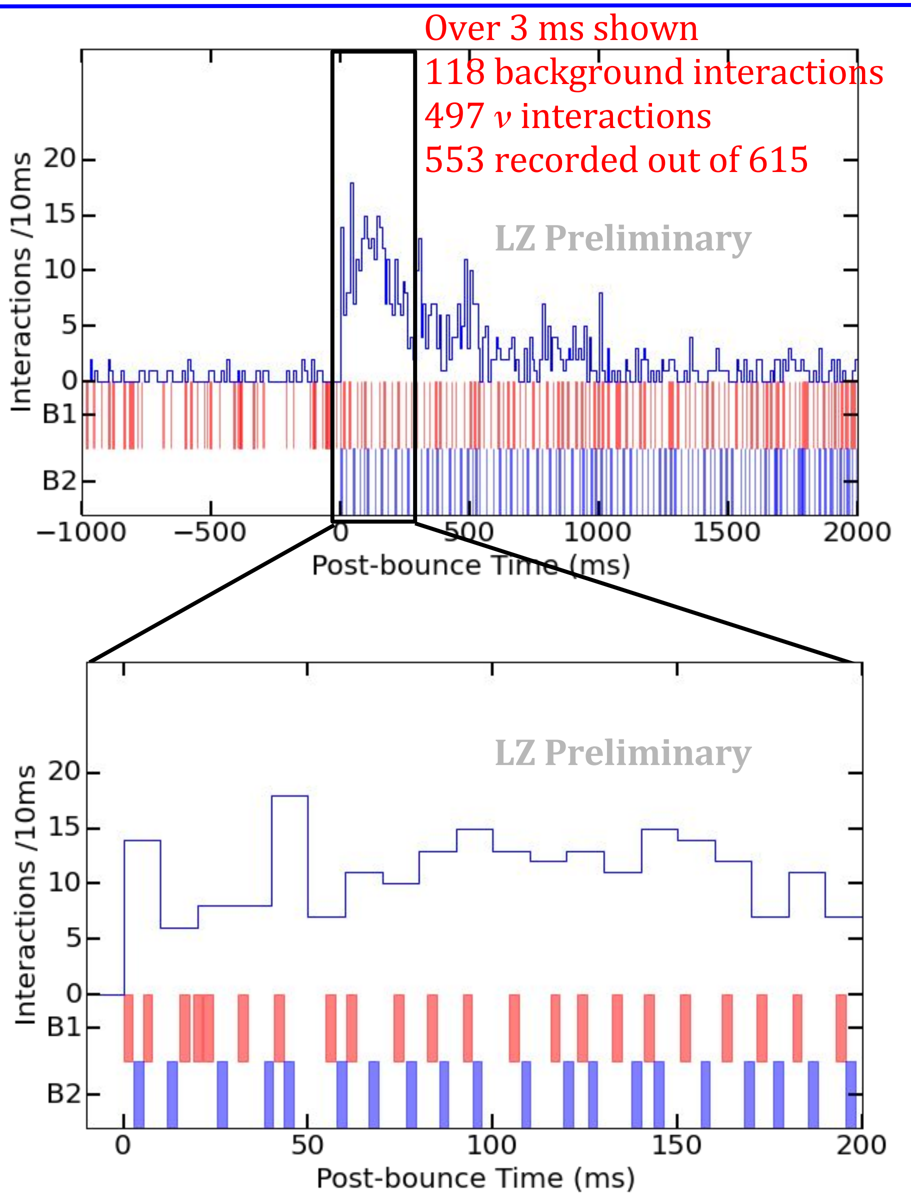
LUX Collaboration: D. S. Akerib et al., Low-energy (0.7-74 keV) nuclear recoil calibration of the LUX dark matter experiment using D-D neutron scattering kinematics, arxiv-link.

DAQ

- Two memory buffers to store data:
  - Each buffer records all interactions within 1 ms pre-trigger and 2.5 ms post-trigger.
  - Hold a maximum of ~45 interactions per buffer

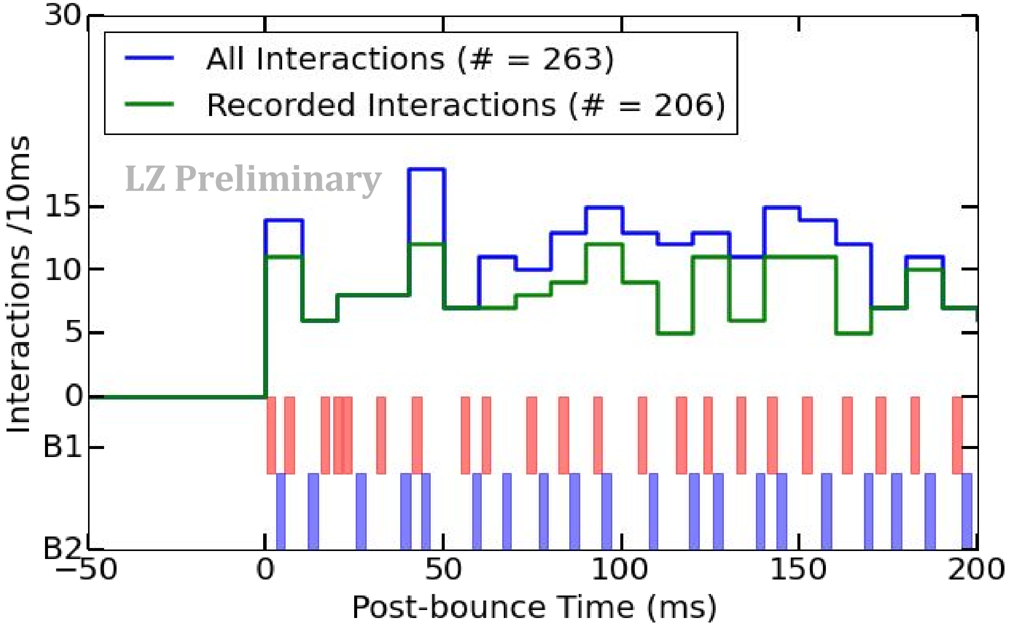
- While one memory buffer writes data to disk, the other buffer can record data.
- However, only one memory buffer can write data to disk at a time.
- If, both buffers are full and data is being offloaded then additional triggers will be missed.

- It takes ~1.3 milliseconds to write one neutrino interaction to disk.
  - It takes ~59 milliseconds to write 45 neutrino interactions to disk.



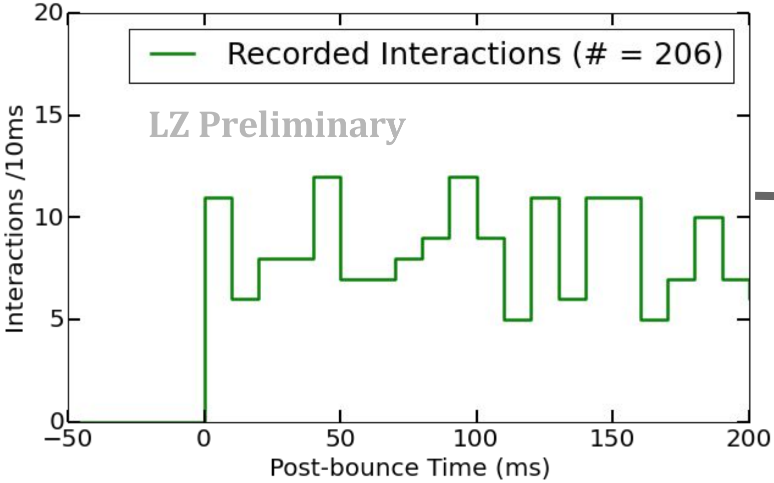
Neutrino Time Spectrum Analysis

- We simulate how the LZ DAQ performs in response to triggers that have a time profile that matches the SN neutrino flux.
  - Full simulation is 11 seconds (1 second pre-bounce, 10 seconds post-bounce).
  - +40 Hz background

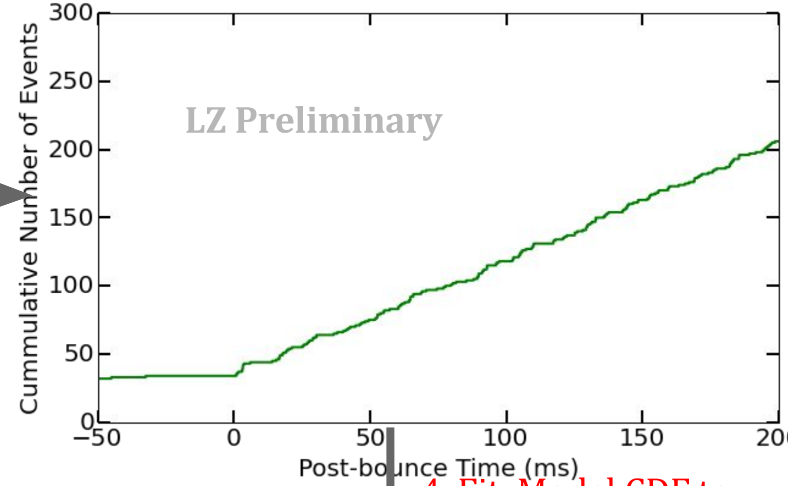


- Using the time distribution of recorded interactions and the known SN ν flux model we construct a cumulative counts vs time distribution.
- We account for DAQ deadtime in the SN ν flux model.
- Perform least squares fitting between the time of recorded interactions and the model.
  - Reconstruct the post-bounce time and number of neutrinos

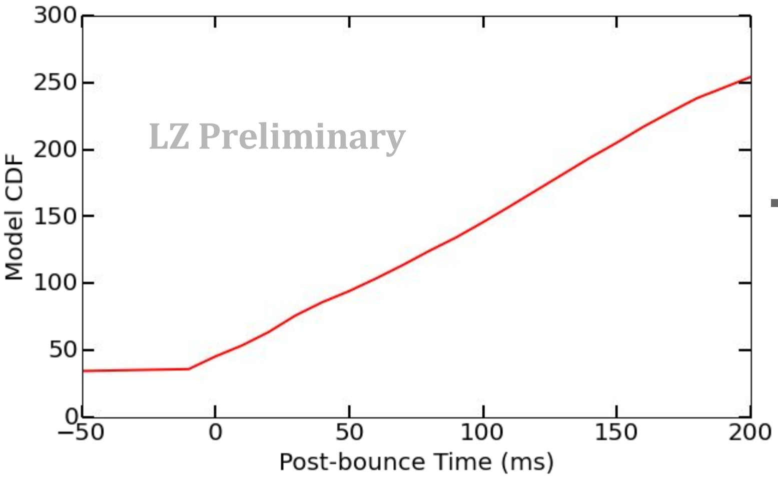
Neutrino Time Spectrum Analysis



1. Integrate counts to create time spectrum

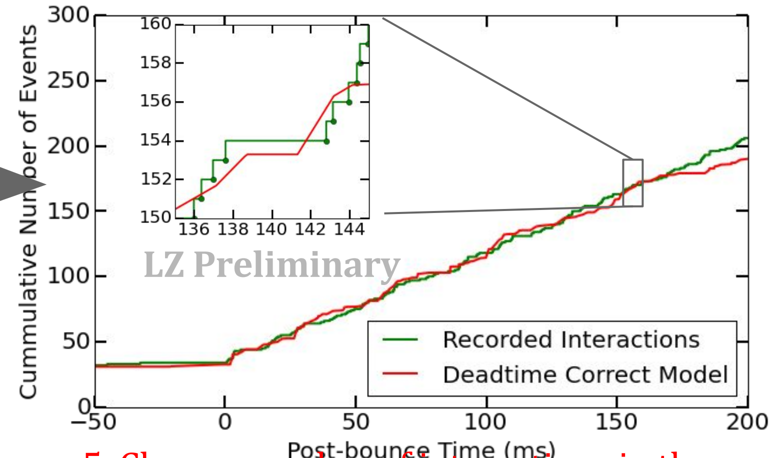


2. Generate Model Cumulative Density Function Composed of Background and SN ν Flux.



3. Correct Model for DAQ deadtime

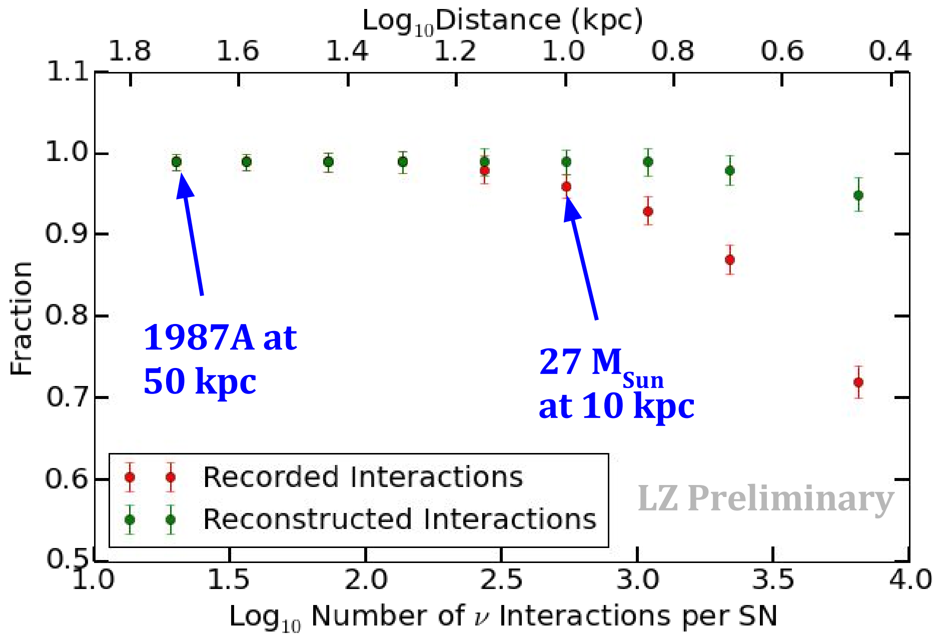
4. Fit Model CDF to the recorded interaction times.



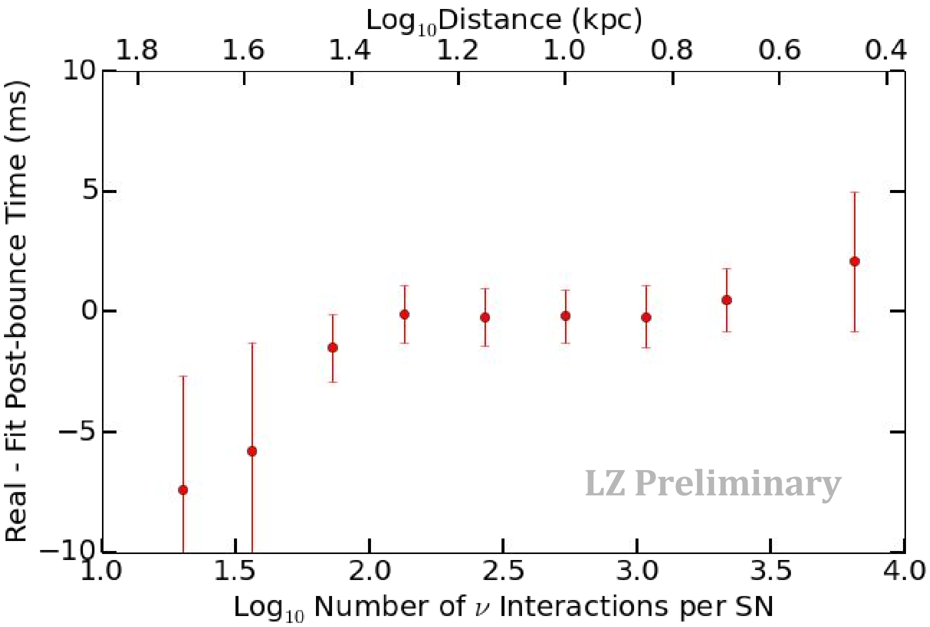
5. Change number of interactions in the model and re-attempt fit.

Neutrino Time Spectrum Analysis

Fitting Analysis to Reconstruct Number



Reconstruct Post-Bounce Time



- The results shown are for a 27 M_{Sun} star and a 0.5 keV detector threshold.
- For these cases shown it would be clear there was a SN event in the detector.
- We are able to reconstruct the number of neutrinos and the post-bounce time of the SN using the fitting analysis.

Conclusions

- During a core collapse supernova (SN) ~99% of its gravitational potential energy is emitted in the form of neutrinos within the first 10 s.

- These neutrinos are emitted with O(10 MeV) kinetic energy and will deposit O(1 keV) in liquid xenon.

- A 27 M_{Sun} SN at 10 kpc will produce 300-500 ν interactions within the 7 tonnes of liquid xenon in LZ.
  - A SN 1987A type supernova at 50 kpc would produce ~20 ν interactions in LZ.

- The double buffering system of the DAQ will allow a large fraction of SN ν interactions to be recorded.

- We have developed a fitting routine that allows us to reconstruct the number of missed interactions and the post-bounce time of the supernova.

Thank you

Any Other Questions/Thoughts?

References

- H. Th. Janka, Neutrino Emission from Supernovae, arxiv-link.
- Rafael F. Lang et al., Supernova neutrino physics with xenon dark matter detectors: A timely perspective, Phys. Rev. D 94 103009, arxiv-link.
- Alessandro Mirizzi et al., Supernova Neutrinos: Production, Oscillations and Detection, 10.1393/ncr/i2016-10120-8, arxiv-link.
- A. Drukier and L. Stodolsky. Principles and applications of a neutral-current detector for neutrino physics and astronomy, Phys. Rev. D 30 2295.
- C. J. Horowitz et al., Supernova Observation via neutrino-nucleus elastic scattering in the CLEAN Detector,Phys. Rev. D 68 023005, arxiv-link.
- Kate Scholberg, Coherent elastic neutrino-nucleus scattering, 2015 J. Phys.: Conf. Ser. 606 012010.
- LZ Collaboration: Mount et al., The LUX-ZEPLIN (LZ) Technical design report, arxiv-link.
- XMASS Collaboration: K. Abe et al., Detectability of galactic supernova neutrinos coherently scattered on xenon nuclei in XMASS, J. Astropart. Phys. 89 51., arxiv-link.
- Irene Tamborra et al., High-resolution supernova neutrino spectra represented by a simple fit, Phys. Rev. D 86 125031, arxiv-link.
- Kelly Patton et al., Neutrino-nucleus coherent scattering as a probe of neutron density distributions, Phys. Rev. C 86 024612, arxiv-link.
- J. Barranco et al., Probing new physics with coherent neutrino scattering off nuclei, J. High Energy Phys. 2 021, J. High Energy Phys. 12 021, arxiv-link.
- XENON Collaboration: E. Aprile et al., Physics Reach of the XENON1T dark matter experiment, J. Cosmo. & Astropart. Phys. 04 027, arxiv-link.
- Cecilia Lunardini, Diffuse supernova neutrinos at underground laboratories, J Astropart. Phys. 79 49, arxiv-link.
- LUX Collaboration: D. S. Akerib et al., Low-energy (0.7-74 keV) nuclear recoil calibration of the LUX dark matter experiment using D-D neutron scattering kinematics, arxiv-link.
- COHERENT Collaboration: D. Akimov et al., Observation
- of Coherent Elastic Neutrino-Nucleus Scattering, 10.1126/science.aao0990, arxiv-link.