Studying neutrino events observed during cooling of a proto-neutron star in a supernova explosion

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OKAYAMA UNIVERSITY

NEUTRINO SEOUL 2022

The XXX International Conference on Neutrino Physics and Astrophysics May 30 (Mon), 2022 – June 4 (Sat), 2022 Virtual Seoul

1. Introduction

Supernova

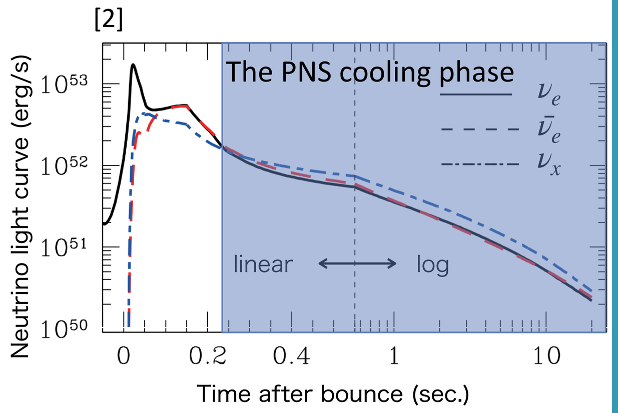
SN 1987A[1] is a supernova that has been observed only once before.
11 events were observed at Kamiokande, and the observation time was 12.4 sec.

The next observation is expected to have 1,000 to 10,000 events observation.
→**Long numerical simulations are required.**

After the core collapse, a proto-neutron star(PNS) is formed in the center of a star.

- In the PNS cooling phase
  - Compared to the initial state, the cooling phase has fewer PNS parameters. (only PNS mass, radius)
  - Fewer uncertainty

[2]

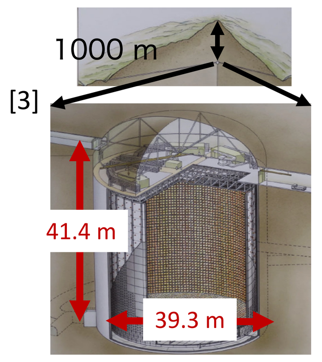


Understanding the late phase is essential to extracting physics from observations.

Super-Kamiokande(SK)

- 50 kton(Fiducial volume is 22.5 kton) water Cherenkov detector
- Located 1,000 m underground.
- 11,129 PMTs in the Inner Detector.

[3]

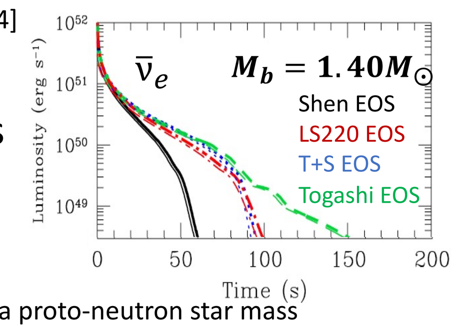


2. Neutrino light curves

Time evolution of neutrino luminosity

Neutrino emission times depend on the neutrino light curve models
Shen Model: Signal duration tends to be short
Togashi Model: Signal duration tends to be long

[4]

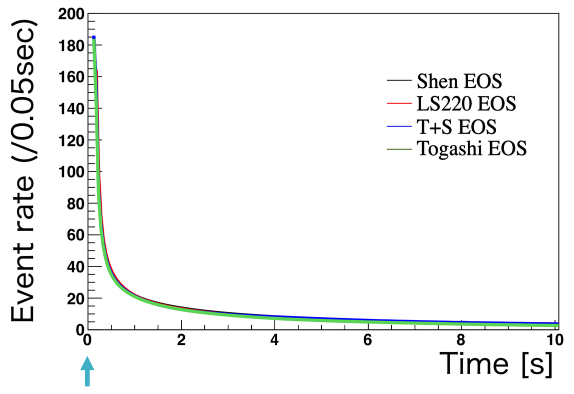


M_b: a proto-neutron star mass

3. Development of analysis solutions for Neutrino light curves

The Backward time analysis

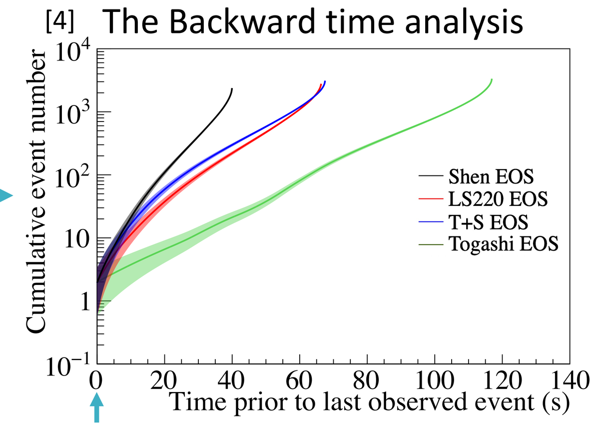
→Analysis to identify models from event rates



The time of the core bounce

Make the last event a time origin.
Integrate event rates back in time.

[4] The Backward time analysis



The time of the last event

It is easy to distinguish between neutrino light curve models without resorting to detailed numerical simulations.

4. Motivation

It is important to determine the last event in backward time analysis.

It is difficult to determine the last event with mixed background and a signal.

→The SK background was quantitatively evaluated, and the accuracy of the last 1 event decision was assessed using two methods.

1. Last event analysis
2. Signal to noise ratio analysis

Verify that the analysis method is applicable to any model.

5. A method of the last event analysis

How to determine the last signal event

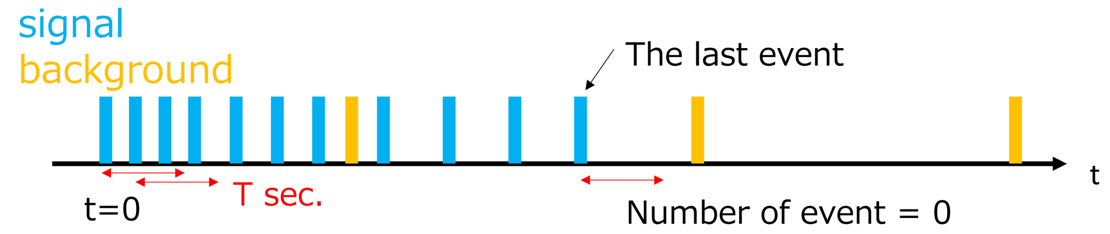
(1)Determine the time width T and energy threshold E_{th} for which the probability of Background not coming is more than Xσ.

→Events that come in T seconds are signals with a probability more than Xσ.

(2)Count the number of events within T seconds, starting from t=0.

(3)Defined as the end when the number f events coming in T seconds reaches 0.

→The last event that came in the time range before that one is considered the last event.



Determination of T and E_{th}

(1)Using only the background rate

(2)Using the Poisson distribution, find the expected value for which the probability that an event that will occur less than once is more than 5σ.

→0.0033 (event)

(3)Set a certain T and select an E_{th} below 0.0033 (event) from the background rate.

Expected value in SK(22.5 k tons)[5]

Energy threshold（MeV）	background rate（Hz）
5.0	0.0082
7.0	0.0012
9.0	0.0003
9.5	0.0002

Selected E_{th} → 9.5 / 0.0002 → T is 15 sec

The flow of a simulation

Simulate 1,000 times

Signal event

- MC simulation with each EOS
  Condition(1)：Explosion at the center of the Milky Way Galaxy
  Condition(2)：Observation in SK
  Condition(3)：Detection efficiency 100% above E_{th}=9.5 MeV

Background event

- Generate background event
  Condition(1)：background rate of E_{th} = 9.5 MeV
  →0.0002 Hz

Combine signal and background events to determine the last event

①compare the time distribution of the last event determined with the time obtained from the theoretically expected value

②Checking the validity of the analysis by calculating the "time lost by analysis"
"time means of the last event determined by this analysis - the last event time of theoretically expected value"

6. A method of signal to noise ratio analysis

①calculate the cumulative events for signal and background going back in time
Condition(1): E_{th} = 5 MeV

②calculate signal to noise ratio($S/\sqrt{B}$) using the value of ①

$$S/\sqrt{B} = \frac{\text{Cumulative signal expected value for each time bin}}{\sqrt{\text{Cumulative background expected value for each time bin}}}$$

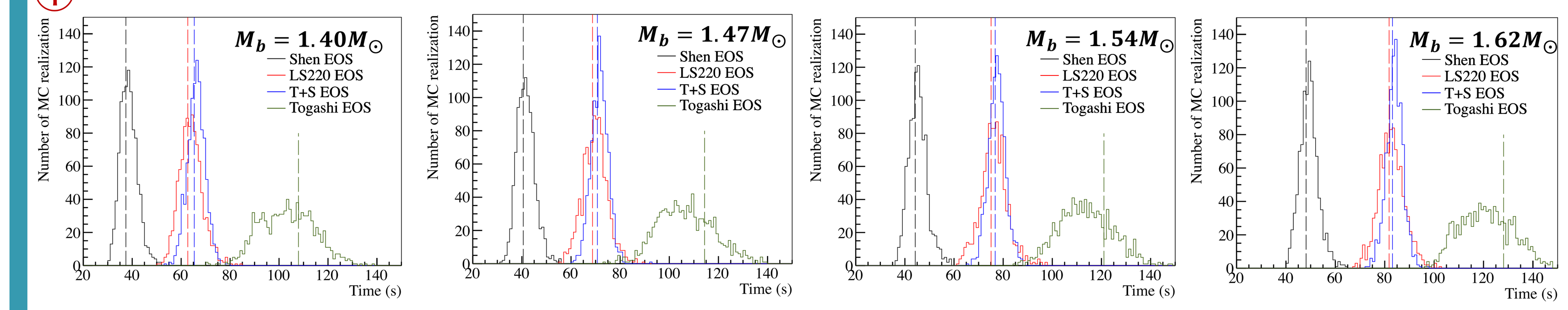
③Set conditions to define as a signal
→ the event $S/\sqrt{B}$ is more than 3σ is a signal.

④Checking the validity of the analysis by calculating "time lost by analysis"
"time of the last event determined by this analysis - time of the theoretically last event time"

7. Simulation results of the last event analysis

Time distribution of the last event (Simulation results including background)

①



Dotted line： Time of last obtained from the theoretically expected value

- **The difference in the time of the last event can be seen in the neutrino light curve models.**
- Shen, LS220 and T+S Model can determine the last event with high precision. (Time lost by analysis < 5 sec.)
- Togashi Model model has a large time span for late signal events
  →Togashi Model tends to be shorter than expected values.

②

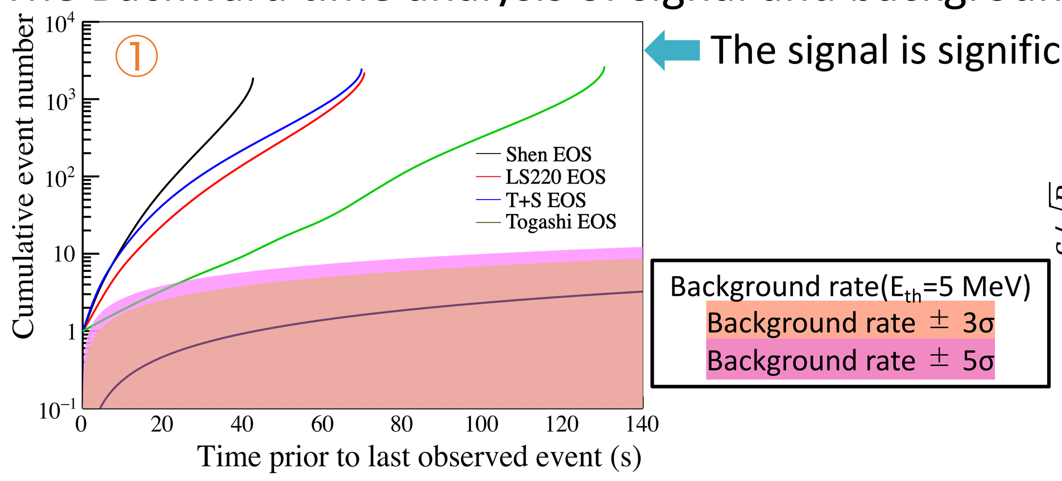
Togashi EOS	Time lost by analysis（sec.）
$1.40M_\odot$	4.28
$1.47M_\odot$	9.36
$1.54M_\odot$	7.90
$1.62M_\odot$	7.27

Losses of less than 10 seconds in models lasting more than 100 seconds.

No loss of signal duration differences between SN models
→The last event analysis can accurately determine the last event.

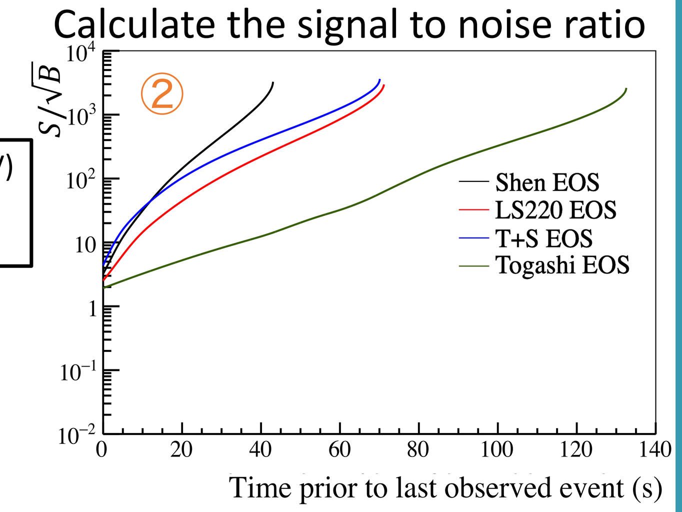
8. Simulation results of signal to noise ratio analysis

The Backward time analysis of signal and background



The signal is significant compared to the background

Calculate the signal to noise ratio



④

SN model	Time lost by analysis（sec.）
Shen EOS	0
LS220 EOS	1.0
T+S EOS	0
Togashi EOS	8.5

The last event can be properly retrieved in any model

9. Summary

- Focus on late neutrino events observed in SK during when supernova explosion
- Analysis of the last signal event observed in SK using two methods
  - 1. Last event analysis
  - 2. Signal to noise ratio analysis
- Checked the validity of the analysis
  - calculated "time lost by analysis" with two methods
    →Within 10 sec. for all models used in this study.
    Sufficient to confirm the difference in event durations by SN model.

Both analyses can be applied to any model.

[1] E. N. Alexeyev *et al.*, *Physics Letters B*, 564(1-2):42-54, July 2003. [2] K. Nakazato *et al*, 2013 *APJS* **205**2 [3]Y. Suzuki, *THE EUROPEAN PHYSICAL JOURNAL C*, Vol. 79, No. 4, (2019) [4]Nakazato *et al.*, Astrophys.J.925:98, arXiv:2108.03009 [5] M. Mori, PhD, Kyoto University