

Development of analysis method for late-phase neutrino emission from the supernova in Super-Kamiokande

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Outline

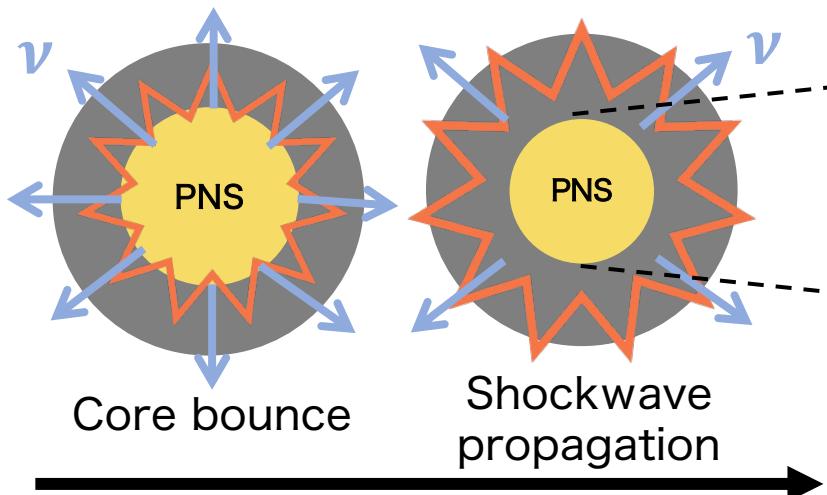
- Introduction
 - Supernova neutrinos
- Analysis method
 - Determination of time duration
 - Model identification
- Result

Identification performance was validated
- Summary

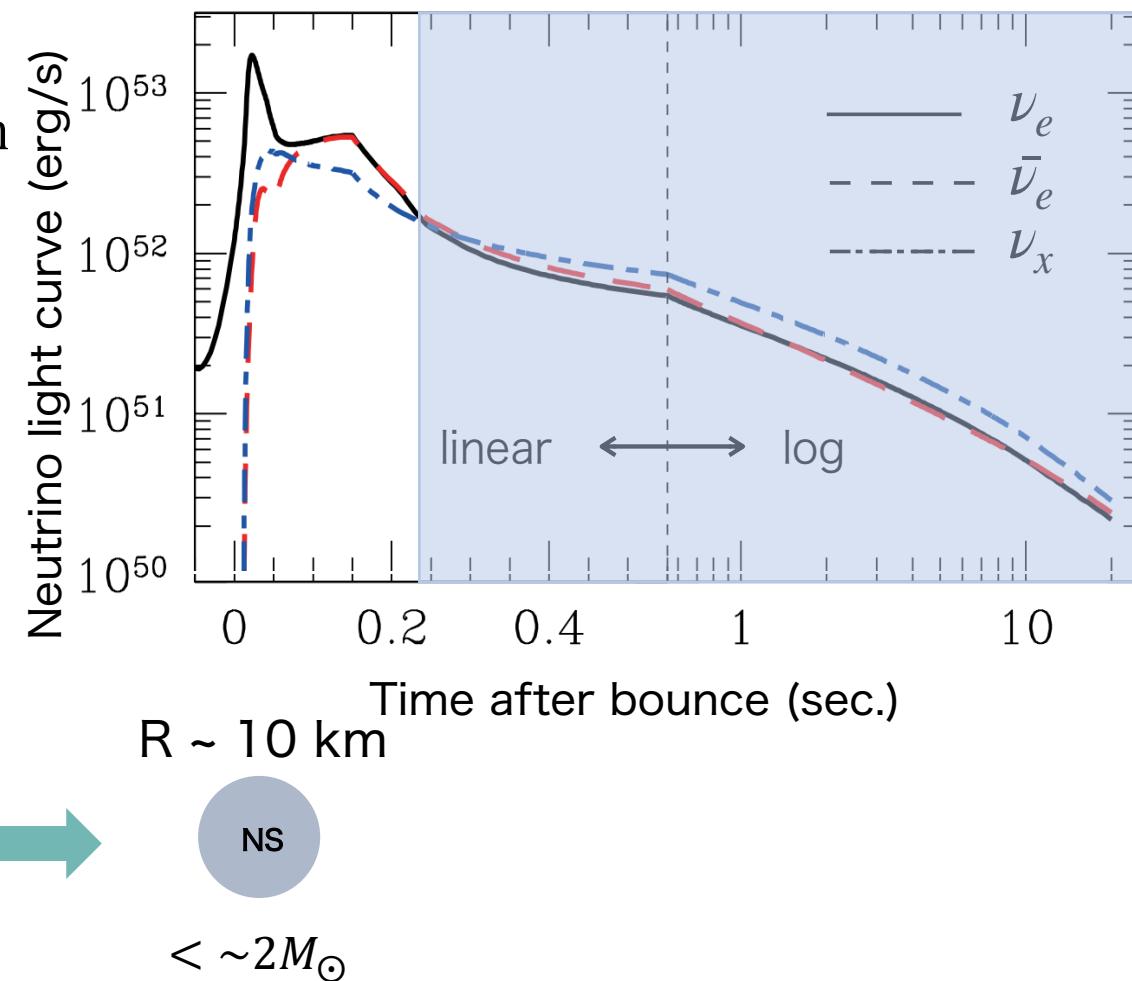
I developed an analysis method for supernova model identification by neutrino observation.
Determining neutron star mass and nuclear equation of state may be possible when a supernova neutrino is observed.

Supernova (SN) neutrino from PNS cooling

- SN neutrinos provide information for
 - neutron star formation and explosion mechanism
- PNS cools down due to neutrino emission and becomes a neutron star (NS)
- Neutrinos emitted during the cooling phase (late phase neutrinos) depend only on the mass and radius of the PNS.
→ less uncertainty.



$R = \mathcal{O}(10)$ km and $1.4M_{\odot} < M < \sim 2.0M_{\odot}$
→ Extremely high-density

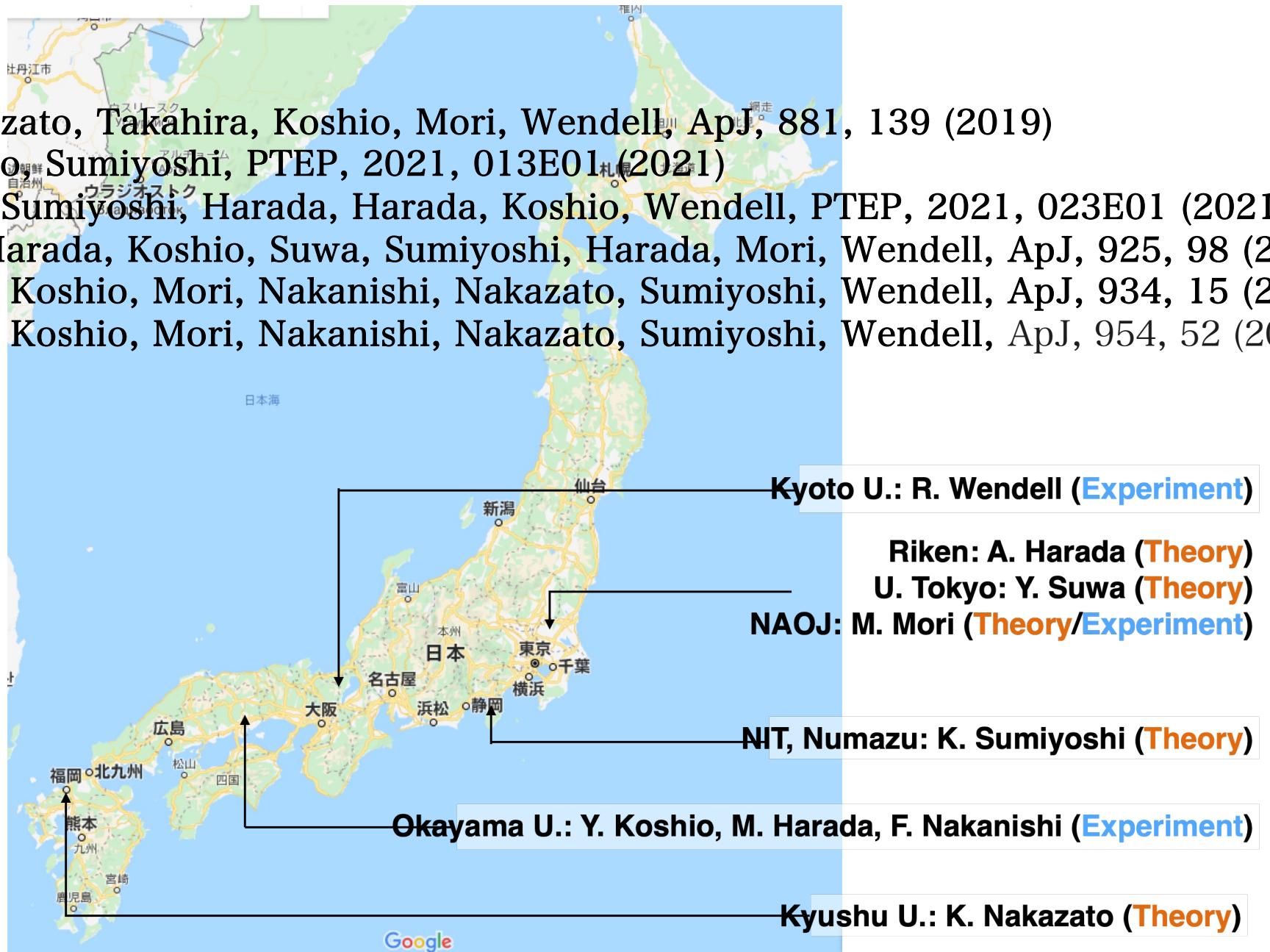


Observation of the late phase neutrinos is important

nuLC collaboration

Papers:

- Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019)
- Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 013E01 (2021)
- Mori, Suwa, Nakazato, Sumiyoshi, Harada, Harada, Koshio, Wendell, PTEP, 2021, 023E01 (2021)
- Nakazato, Nakanishi, Harada, Koshio, Suwa, Sumiyoshi, Harada, Mori, Wendell, ApJ, 925, 98 (2022)
- Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022)
- Harada, Suwa, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 954, 52 (2023)



Equation of state (EOS)

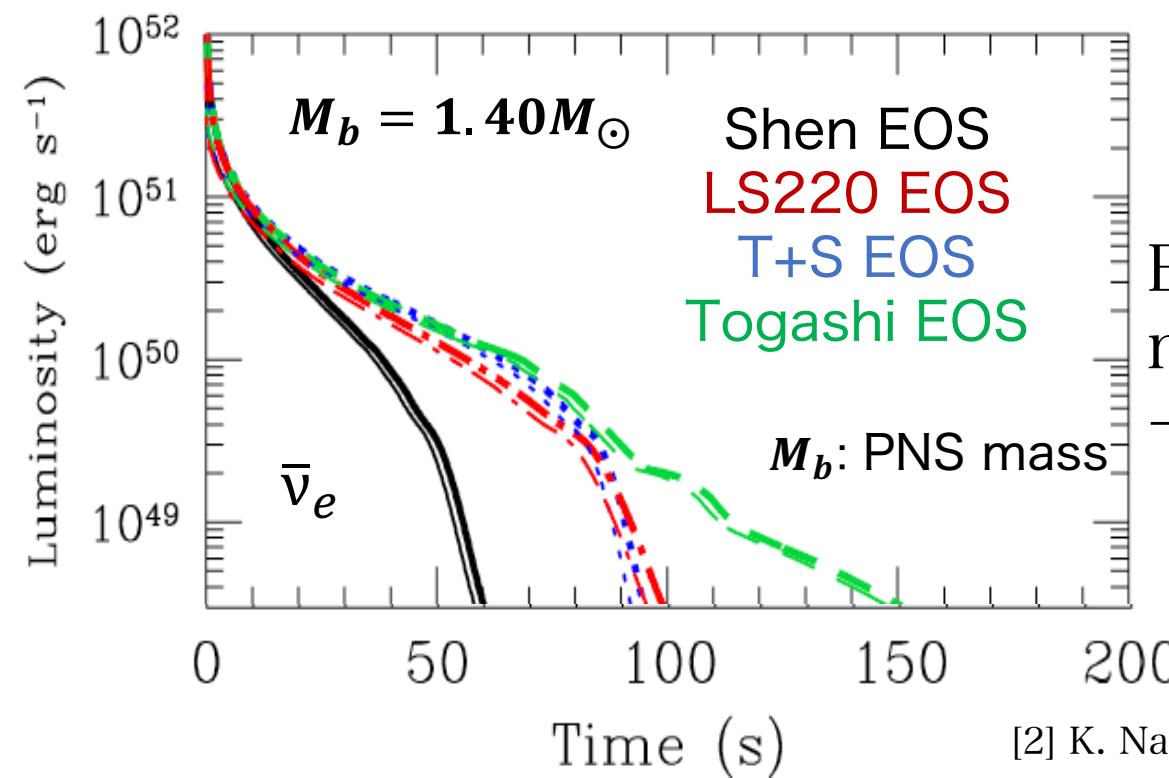
Structure of NS is given by $\frac{dM(r)}{dr} = 4\pi r^2 \rho(r), \quad \frac{1}{\rho(r)} \frac{dp(r)}{dr} = -\frac{GM(r)}{r^2}$

to solve this..

- $P(r)$: pressure
- $\rho(r)$: density
- $M(r)$: included mass inside a radius r



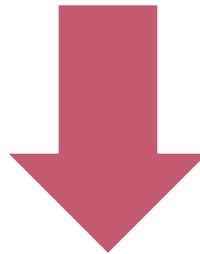
Different EOSs result in different NS structure



Each EOS has different time evolution of neutrino emission.
→ EOS can be identified using duration time

Purpose of this study

Developing an analysis method for supernova model identification from observation of late phase neutrinos



Enable the determination of nuclear EOS and neutron star mass

Outline

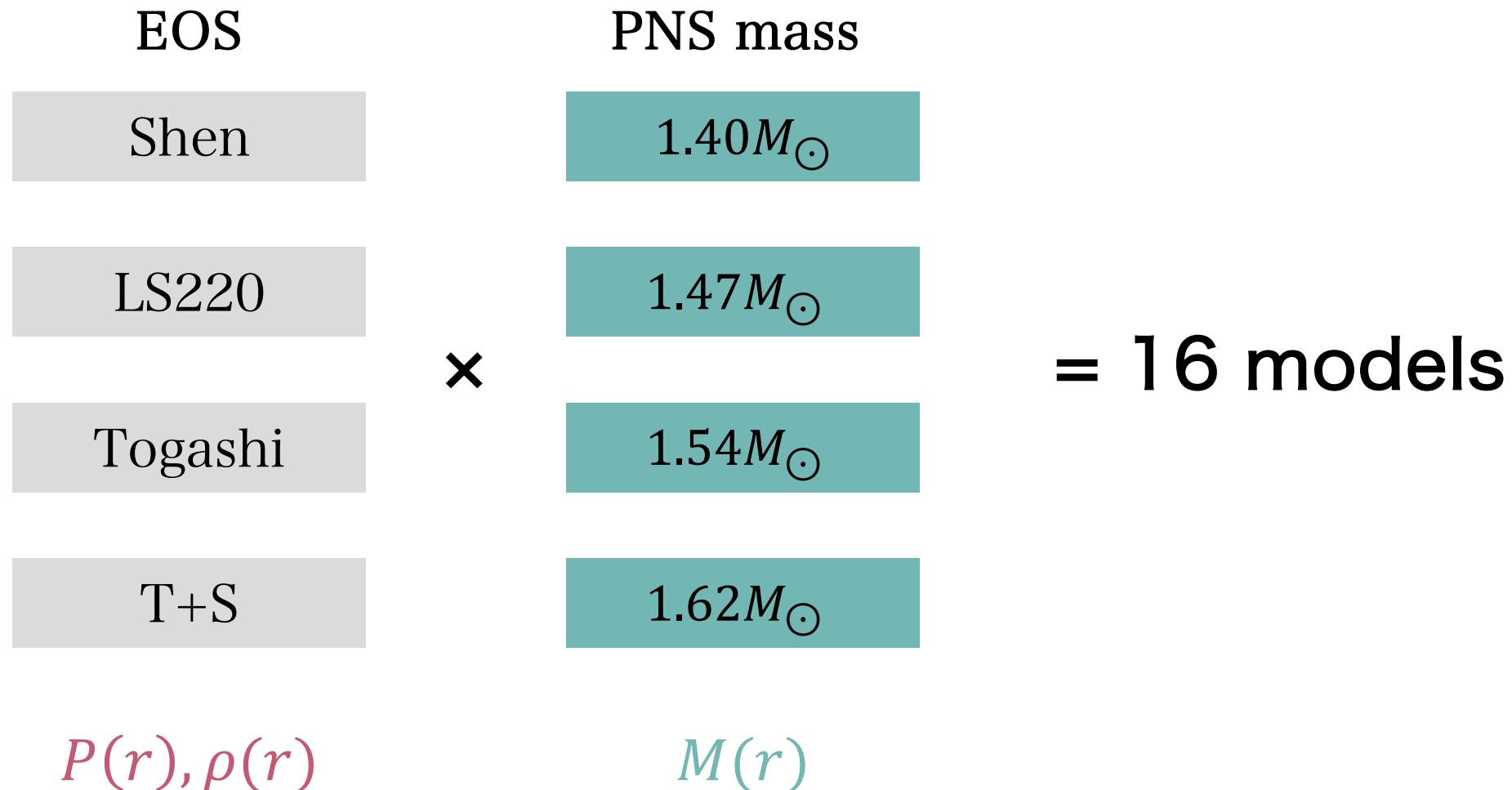
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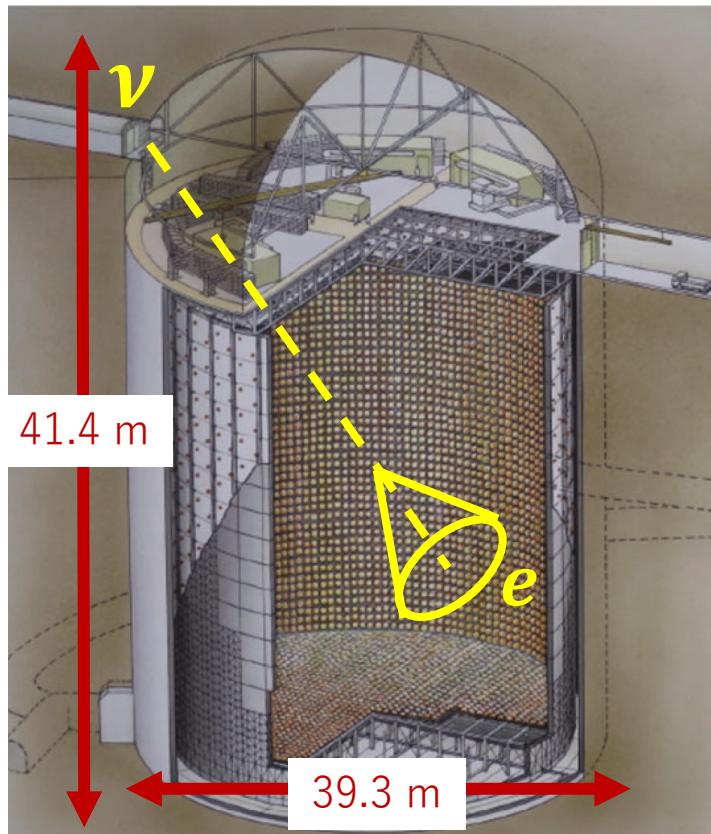
Theoretical models in this study

- A total of 16 models with different PNS mass and EOS

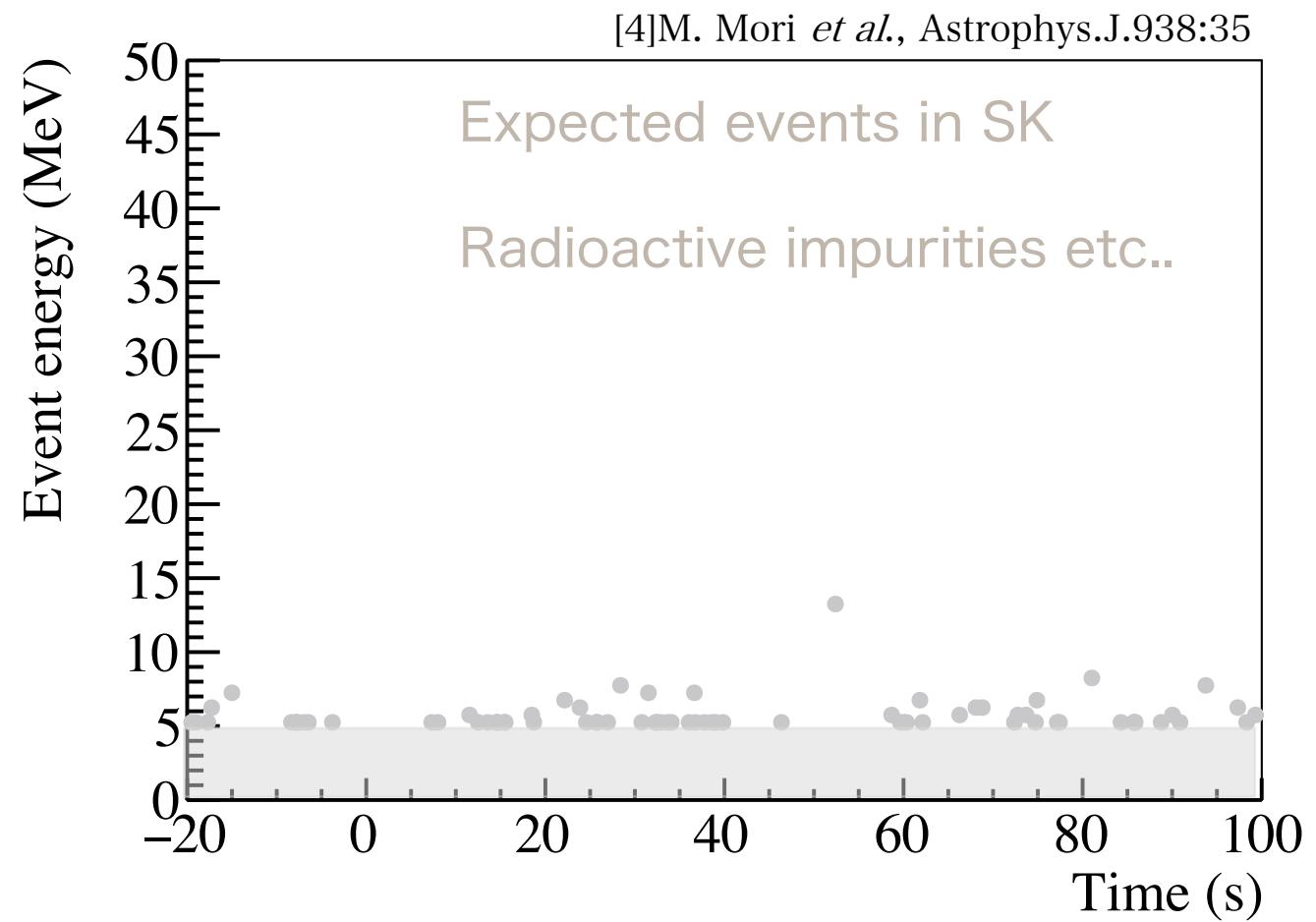


Super-Kamiokande (SK)

- Large water Cherenkov detector
- Observe Cherenkov light from charged particles
- Accurately determine energy(E) and time(T) for each event

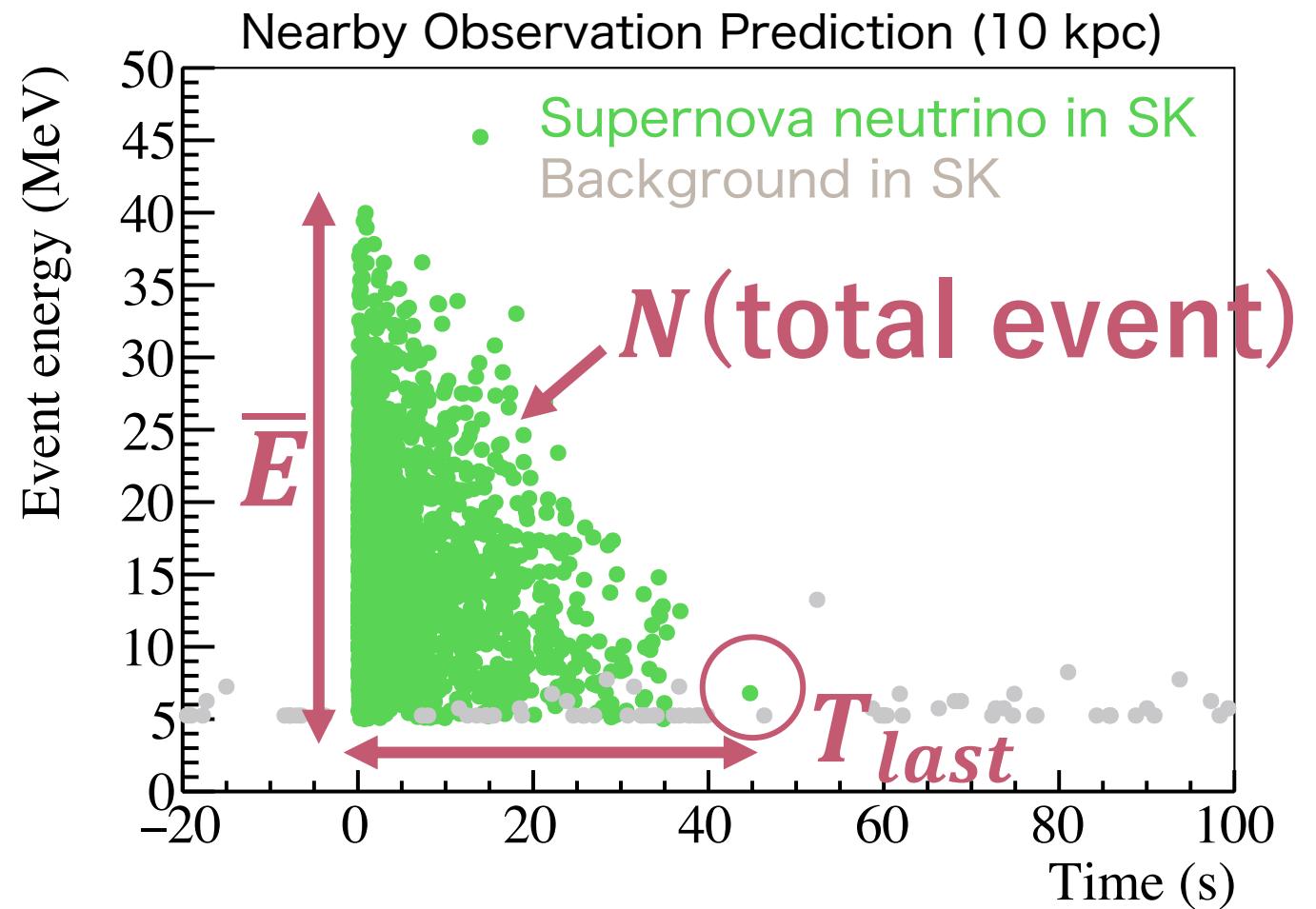
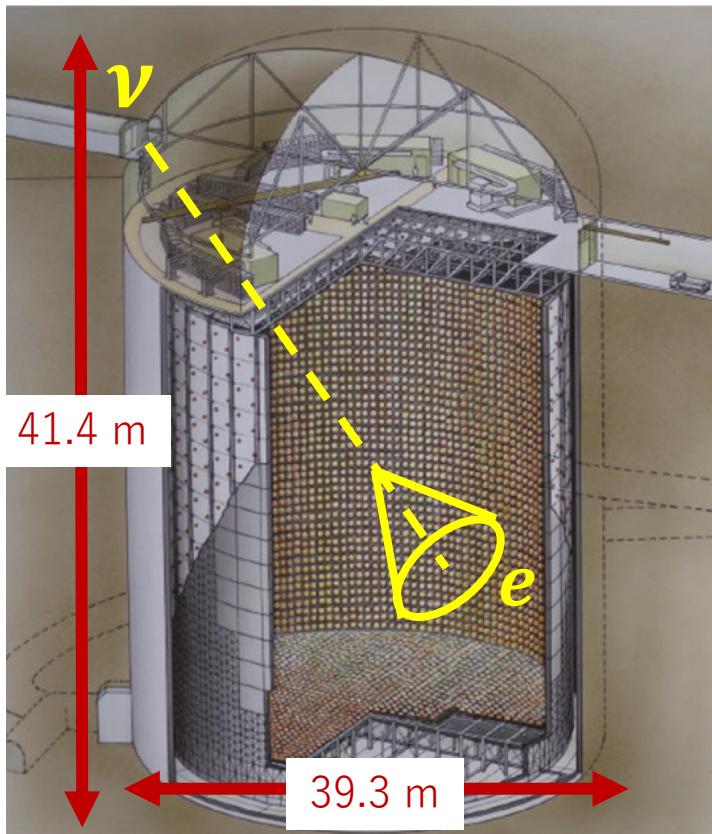


[3]Y. Suzuki, *Eur. Phys. J. C*, Vol. 79, No. 4, (2019)



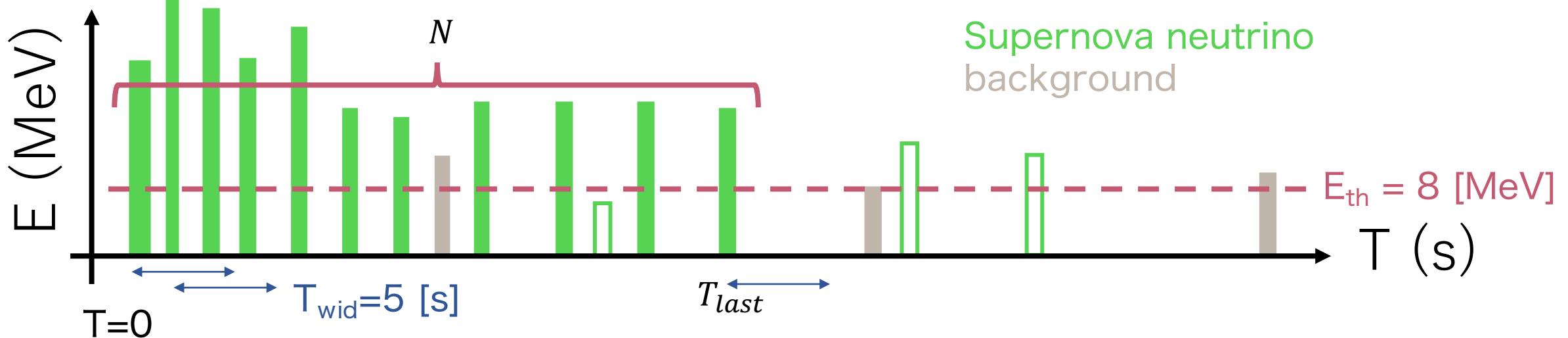
Supernova neutrinos observation

- $\bar{E} = \mathcal{O}(10) \text{ MeV}$, $N = \mathcal{O}(1000)$, $T_{last} = \mathcal{O}(10) \text{ s}$
- Use number of events (N), averaged energy (\bar{E}), and duration time (T_{last})



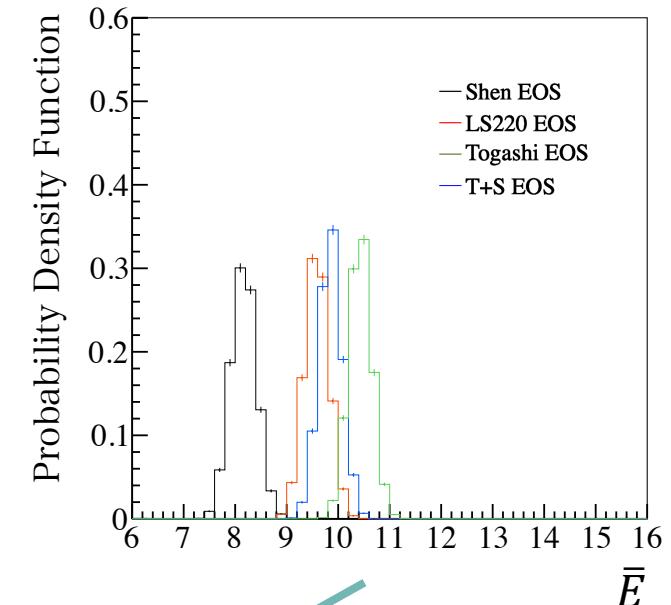
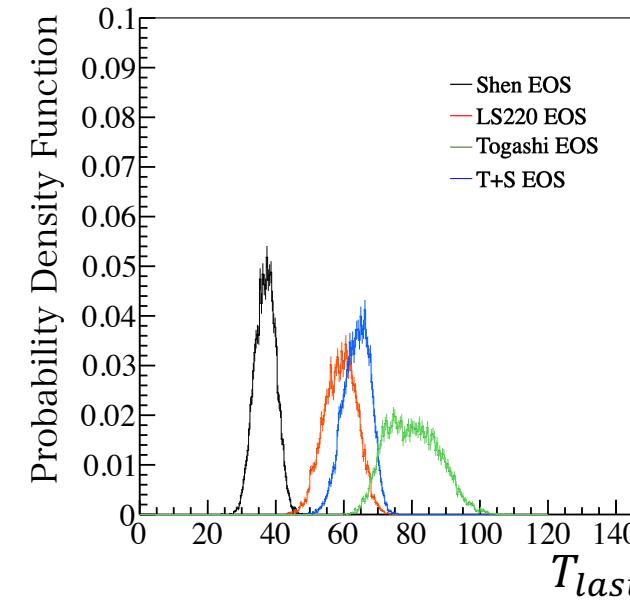
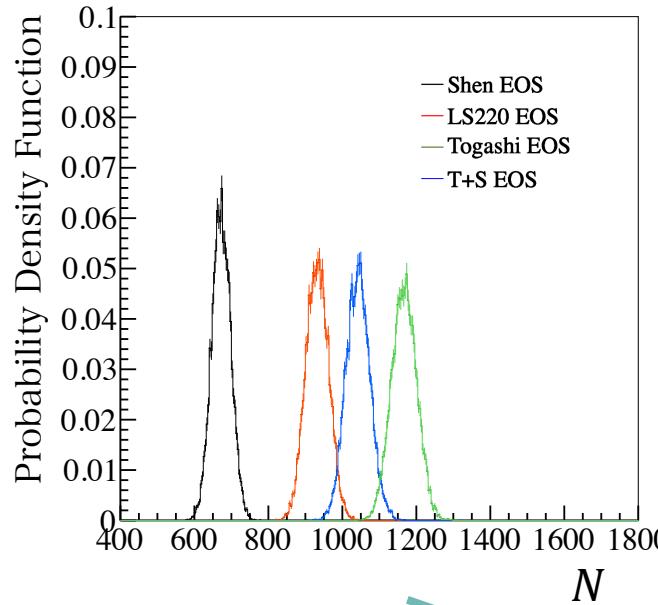
T_{last} determination

- difficult to determine the last observed event due to background
- $\rightarrow T_{last}$ can be determined with appropriate energy threshold E_{th} and timing window T_{wid}
- Optimize T_{wid} and E_{th} to determine T_{last} accurately.
 $\rightarrow T_{wid} = 5 \text{ s}$ and $E_{th} = 8 \text{ MeV}$
- N and \bar{E} is determined using events before T_{last} .



Log-likelihood calculation

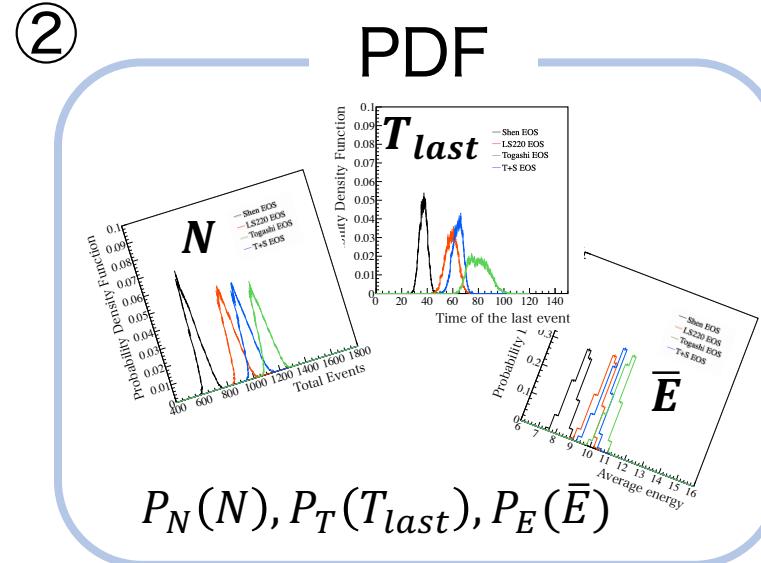
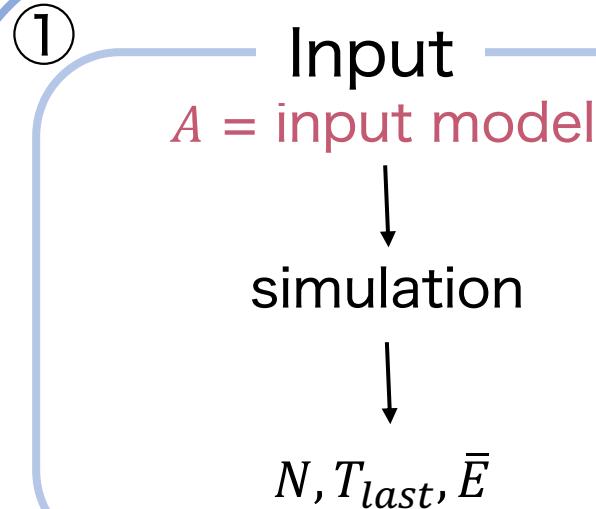
- Probability density function (PDF) from 10,000 simulations
→ We can get PDF $P_N(N)$, $P_T(T_{last})$, $P_{\bar{E}}(\bar{E})$



$$\mathcal{L} = \log(P_N \times P_T \times P_{\bar{E}})$$

Evaluation method

1000 SN \times 16 models



③ likelihood

$$\begin{aligned} \mathcal{L}^1 &= \log(P_N^1 \times P_T^1 \times P_{\bar{E}}^1) \\ &\vdots \\ \mathcal{L}^{16} &= \log(P_N^{16} \times P_T^{16} \times P_{\bar{E}}^{16}) \end{aligned}$$

④ Selection

$$\mathcal{L}^x = \max\{\mathcal{L}^1, \dots, \mathcal{L}^{16}\}$$

$x = \text{selected model}$

⑤ Result

If $A = x \rightarrow \text{success!!}$
 If $A \neq x \rightarrow \text{fail...}$

Return to ①



Evaluate identification performance for 16 models

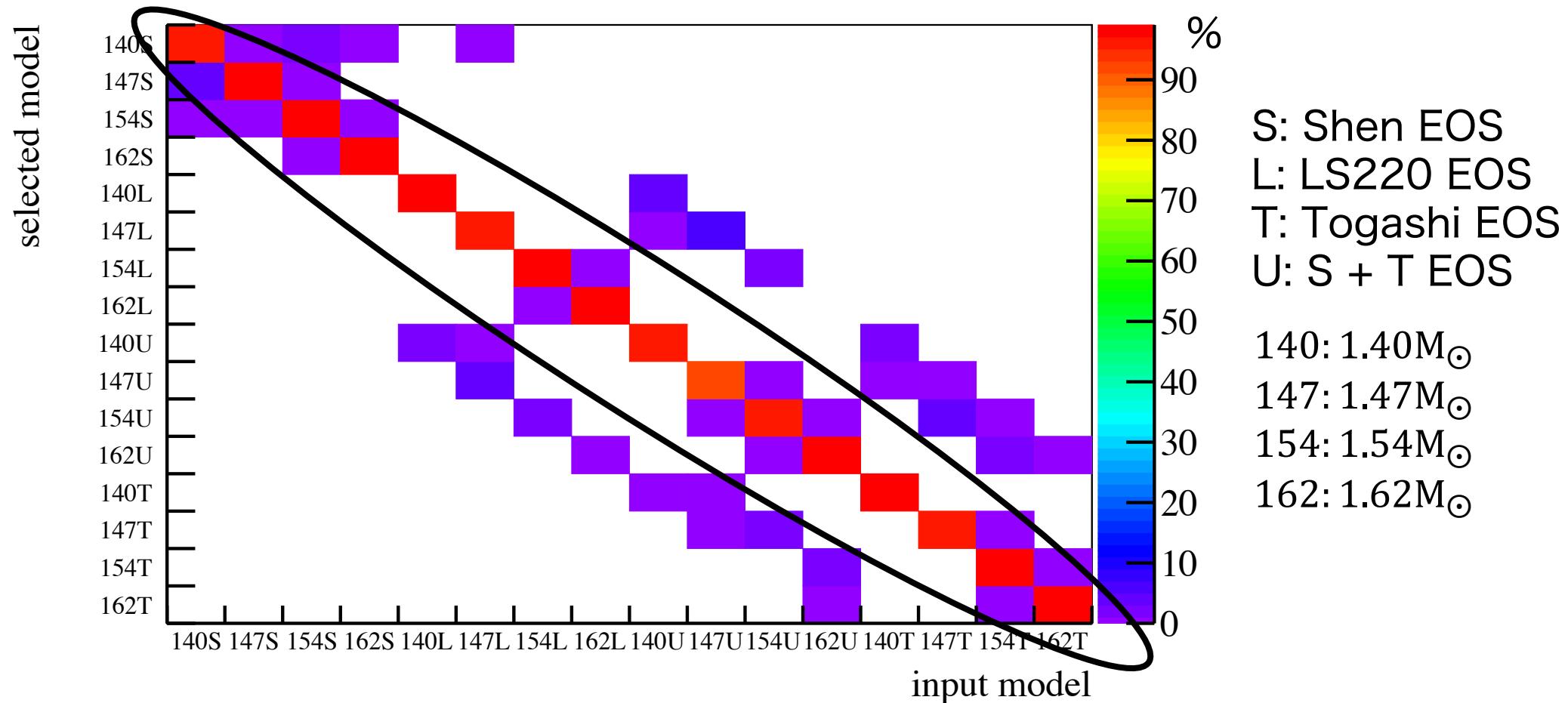
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Identification performance

- Performance result

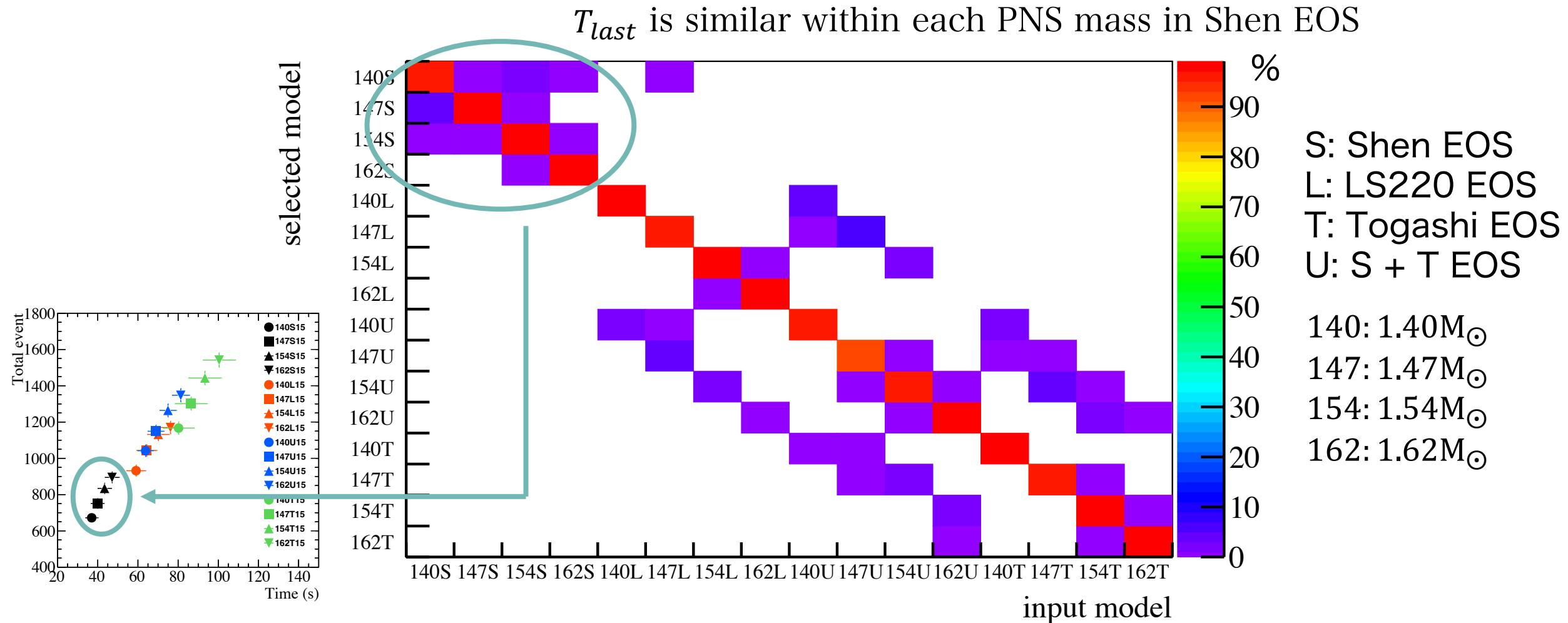


Identification performance of $\geq 90\%$ \rightarrow can determine $P(r), \rho(r), M(r)$

Identification performance

16

- Performance result



Identification performance of $\geq 90\%$ \rightarrow can determine $P(r), \rho(r), M(r)$

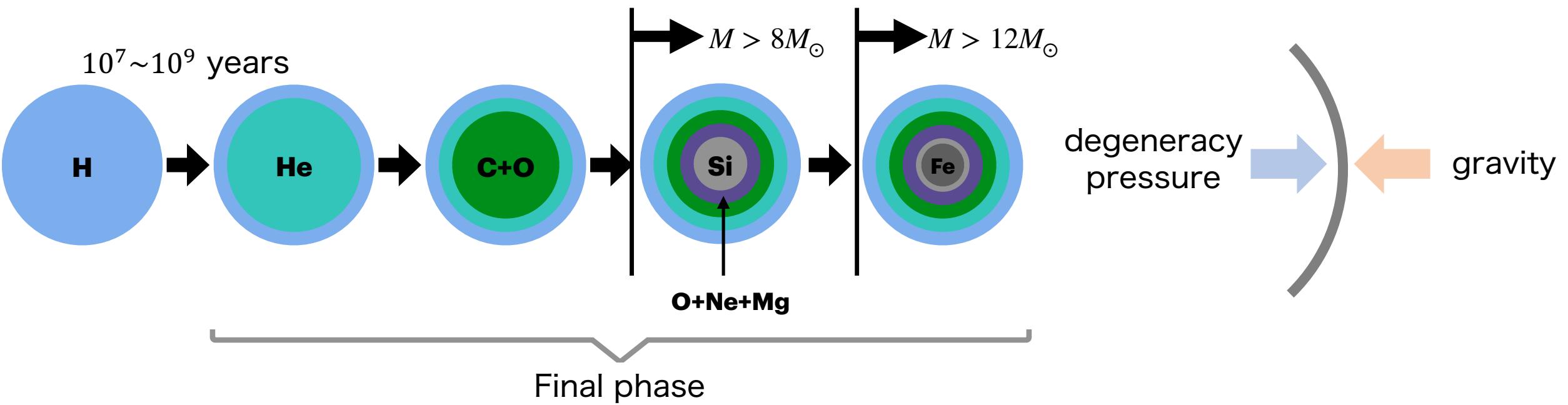
Summary

- Supernova neutrinos provide information on the physical conditions responsible for neutron star formation and on the supernova explosion mechanism.
- I developed a novel analysis method for supernova model identification by neutrino observation. Here, I focused on the cooling phase of PNS because the phenomena in this phase are simple.
- It uses time, energy, and the number of events when SK observes supernova neutrinos. The realistic backgrounds in SK, for example, radioactive impurities, were taken into account.
- It is concluded that 90% or more of the identification performance was achieved.

Backup

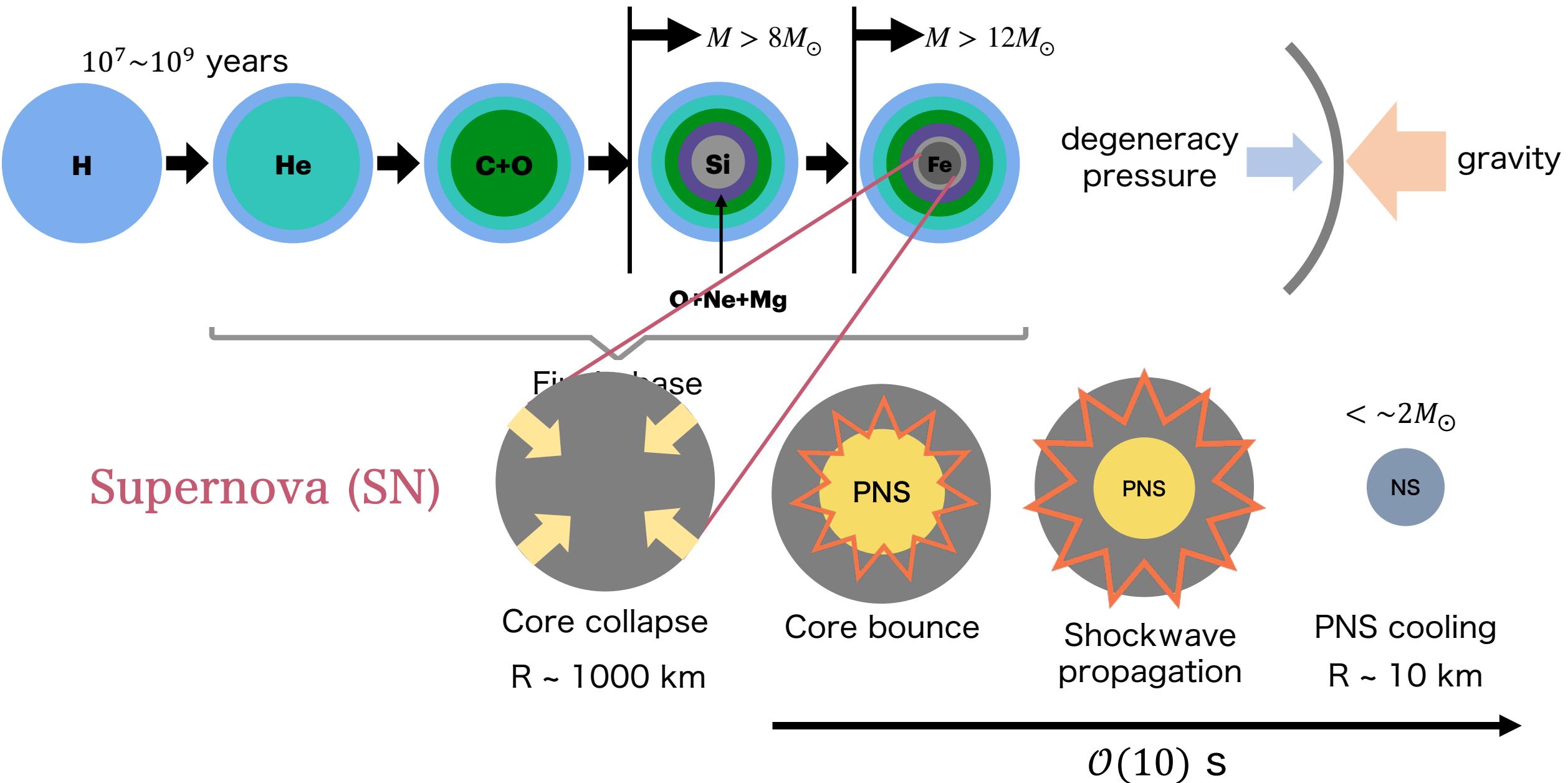
Final phase of star evolution

19

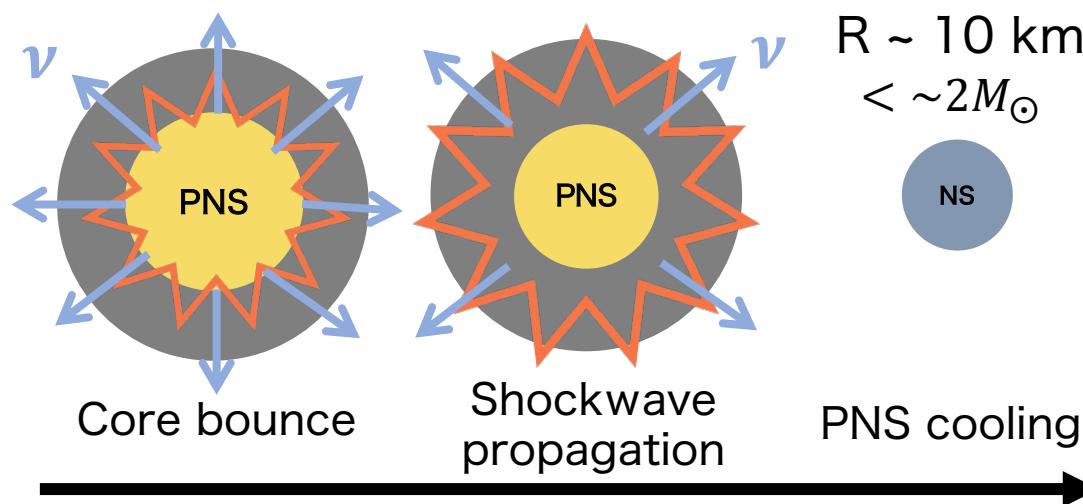
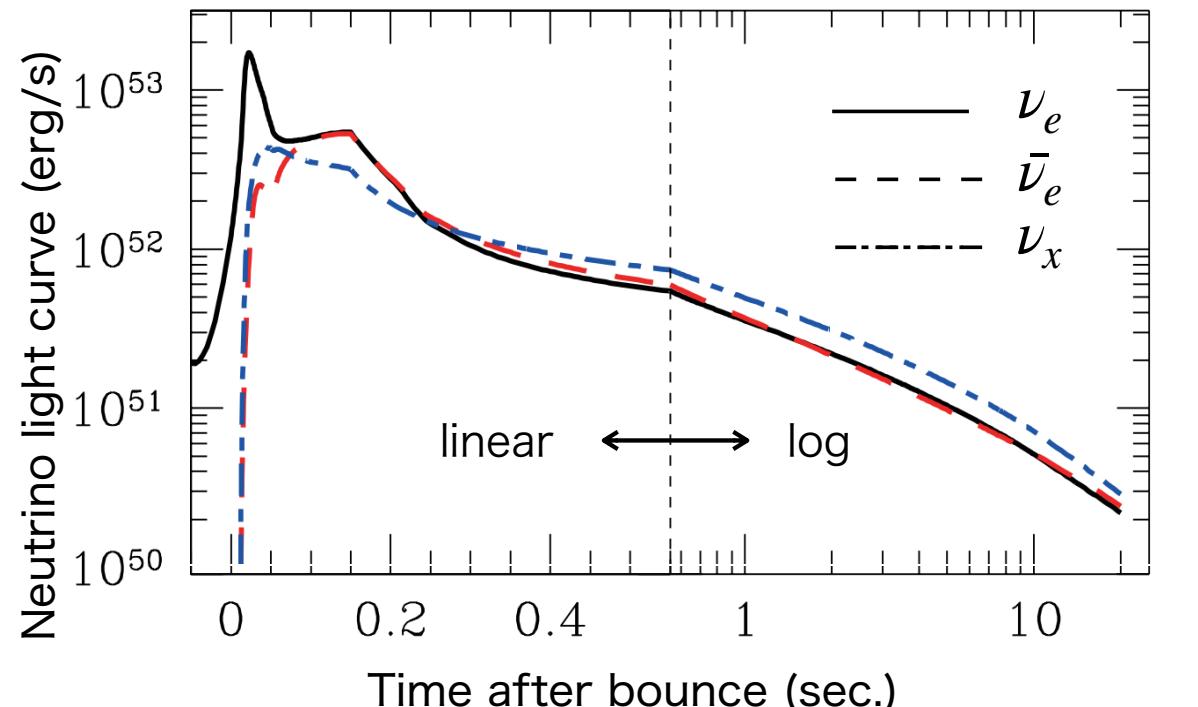


Final phase of star evolution

20



Supernova neutrinos



- Many neutrinos are emitted during supernova explosion

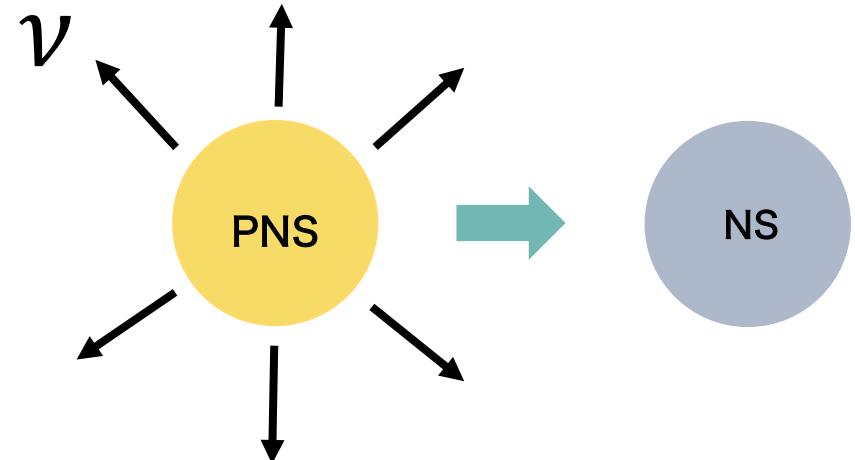
$$p + e^- \rightarrow n + \nu_e$$

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

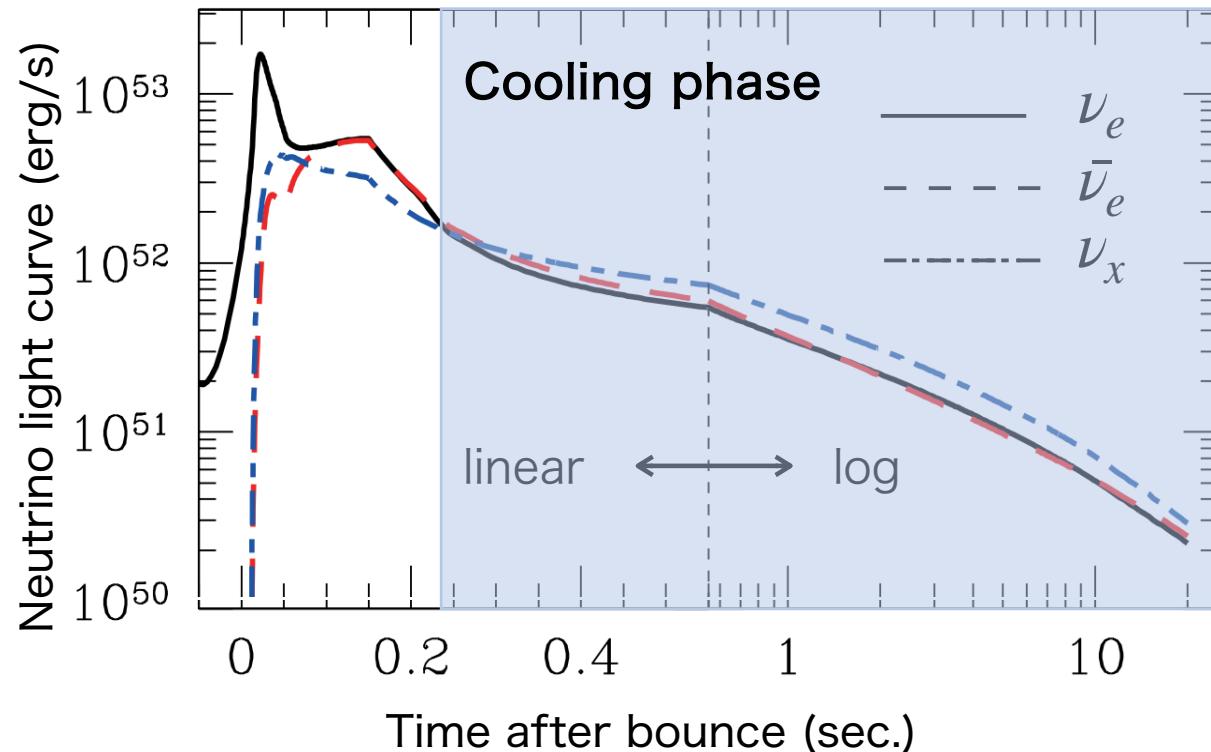
$$\vdots$$
- Neutrinos emit more than 99% of gravitational energy
- SN neutrinos provide information for
 - neutron star formation
 - explosion mechanism

Neutrinos from PNS cooling

- PNS cools down due to neutrino emission and becomes a neutron star (NS)



$R = \mathcal{O}(10)$ km and $1.4M_{\odot} < M < \sim 2.0M_{\odot}$
 →Extremely high-density



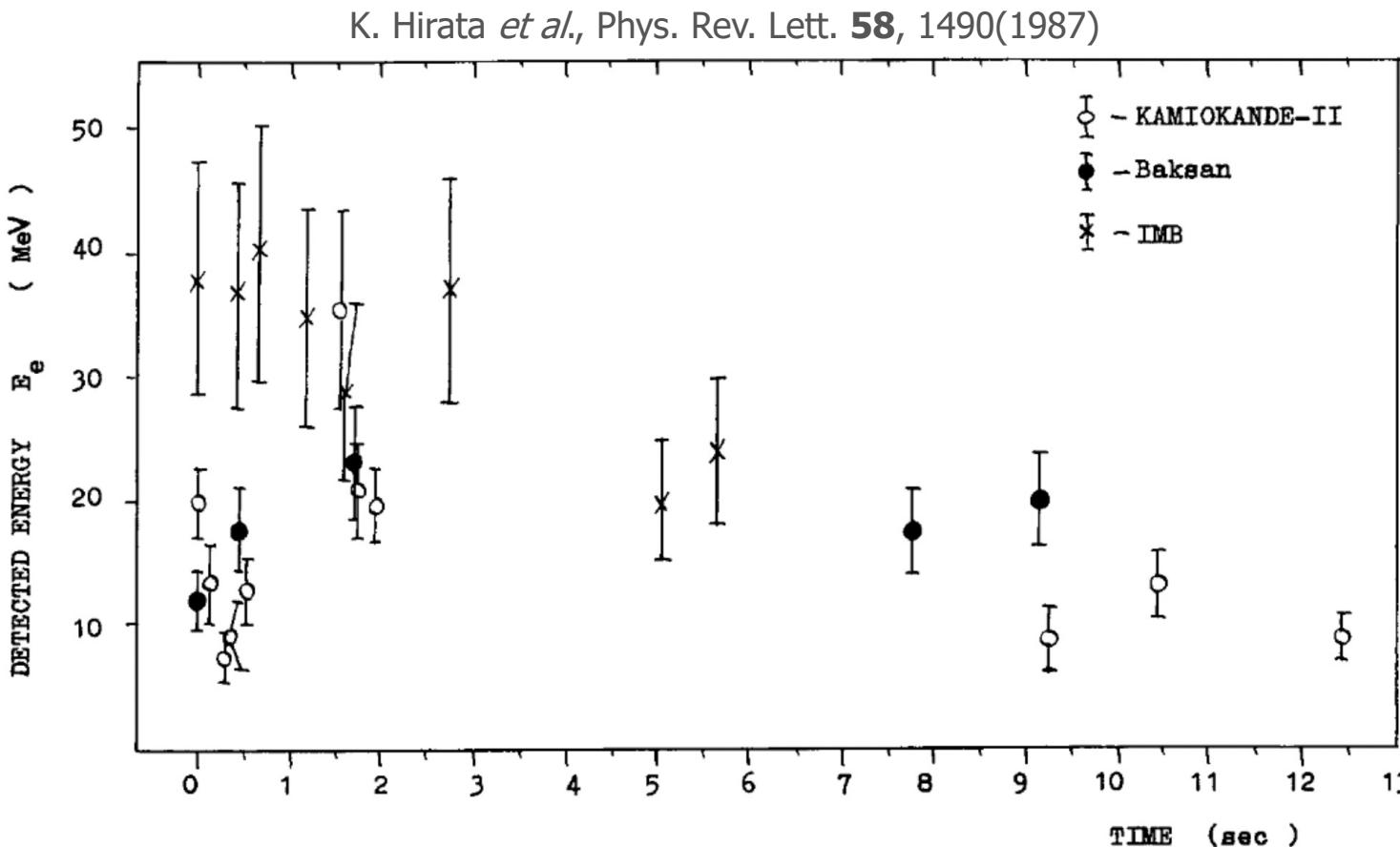
[1] K. Nakazato *et al*, *Astrophys.J.*205:2

- Neutrinos emitted during the cooling phase (late phase neutrinos) depend only on the mass and radius of the PNS. →less uncertainty.

Observation of the late phase neutrinos is important

Supernovae

- Observed supernova neutrinos only once in the past (SN1987A^[1])



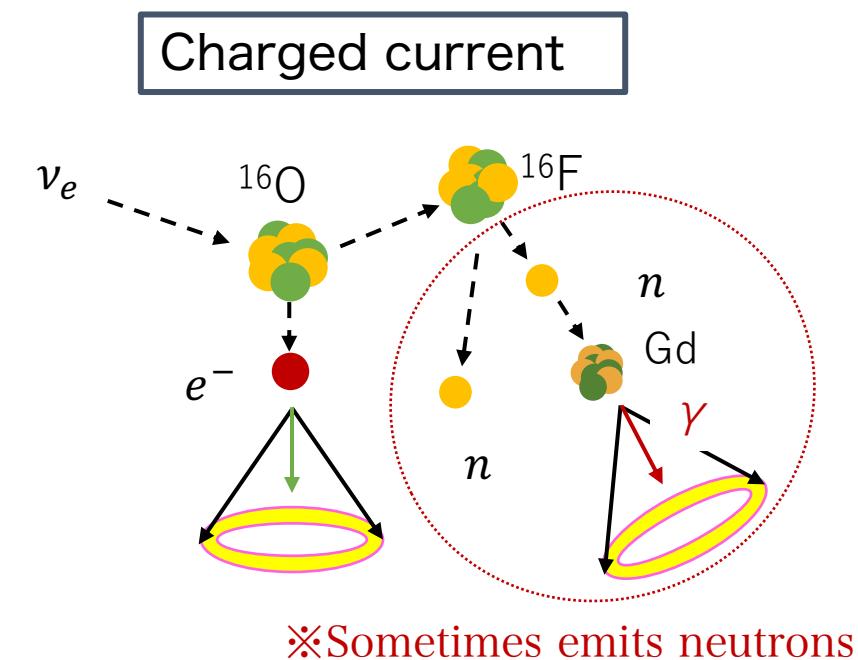
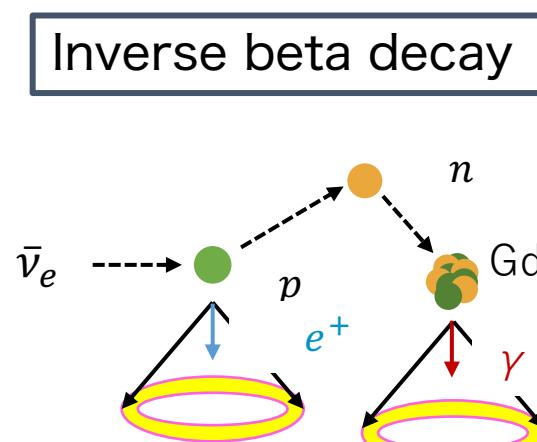
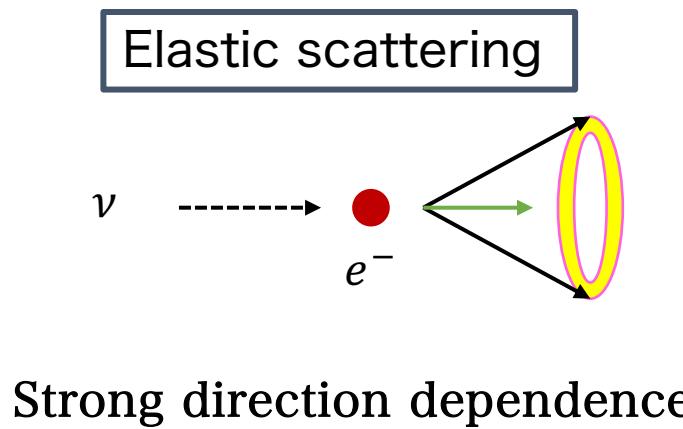
Observation at Kamiokande
Observation time: 12.4 [s]
Observation events: 11 events

Supernova neutrino in Super-Kamiokande

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Supernova neutrino events in SK

- Elastic scattering ($\nu + e^- \rightarrow \nu + e^-$) (~5%)
- Inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) (~90%)
- Charged and neutral-current reactions with ^{16}O
($\nu_e + ^{16}\text{O} \rightarrow e^- + ^{16}\text{F}$, $\nu_x ^{16}\text{O} \rightarrow \nu_x + O^*/N^* + \gamma$) (~5%)



Equation of state (EOS)

Structure of NS is given by

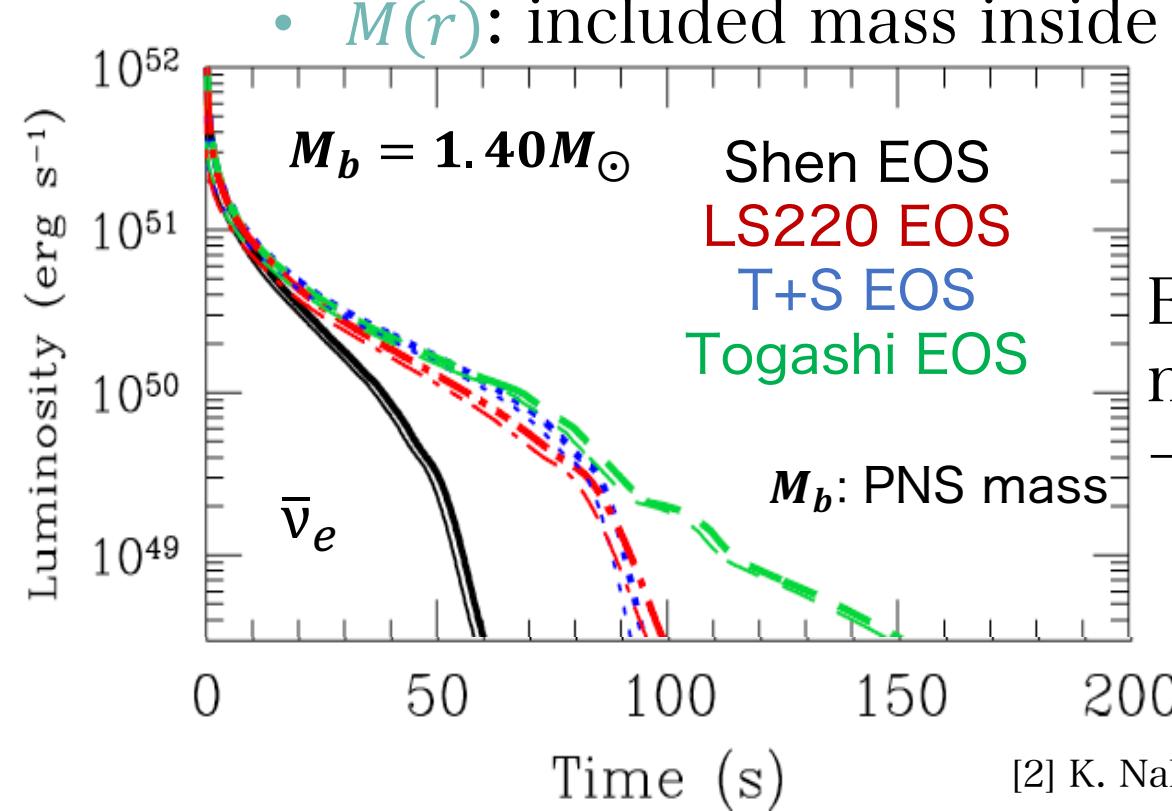
$$\frac{dP(r)}{dr} = -\frac{G\rho(r)M(r)}{r^2} \left\{ 1 + \frac{P(r)}{\rho(r)c^2} \right\} \left\{ 1 + \frac{4\pi P(r)r^3}{M(r)c^2} \right\} \left\{ 1 - \frac{2GM(r)}{rc^2} \right\}^{-1}$$

to solve this..

- $P(r)$: pressure
- $\rho(r)$: density
- $M(r)$: included mass inside a radius r



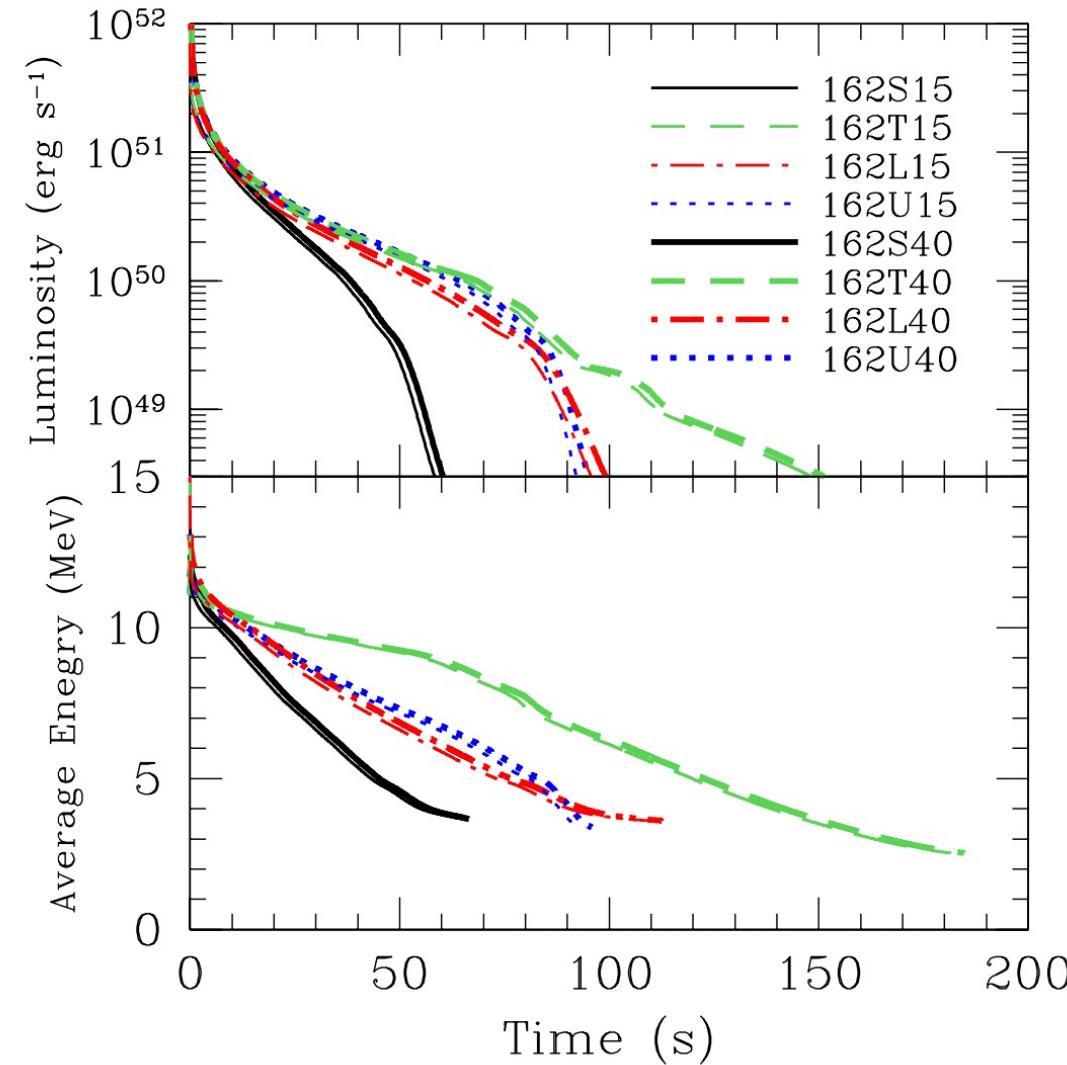
Various nuclear equation of state (EOS)
explaining high-density matter



Each EOS has different time evolution of neutrino emission.
→ EOS can be identified using duration time

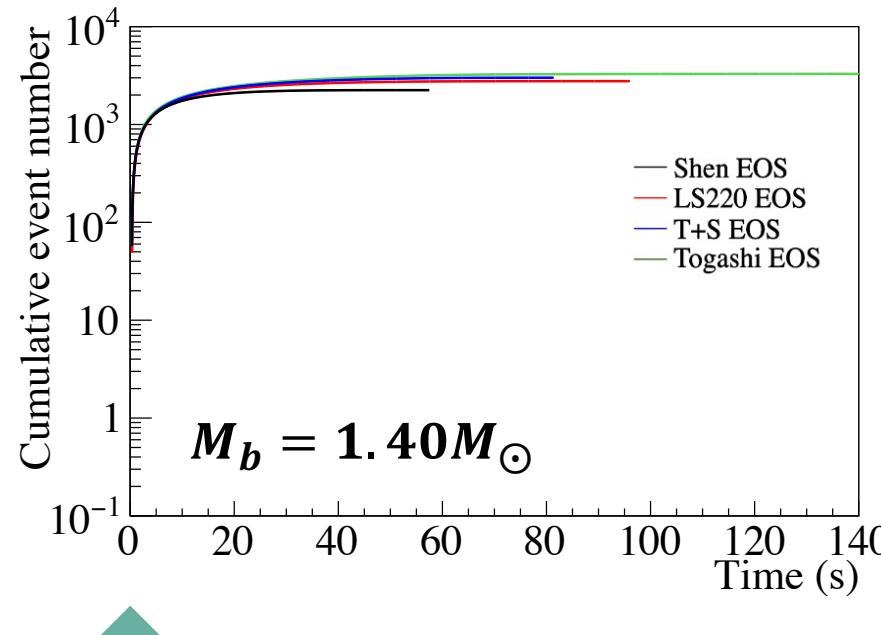
Average energy

- Energy distribution also changes between EOS



Neutrino light curve analysis

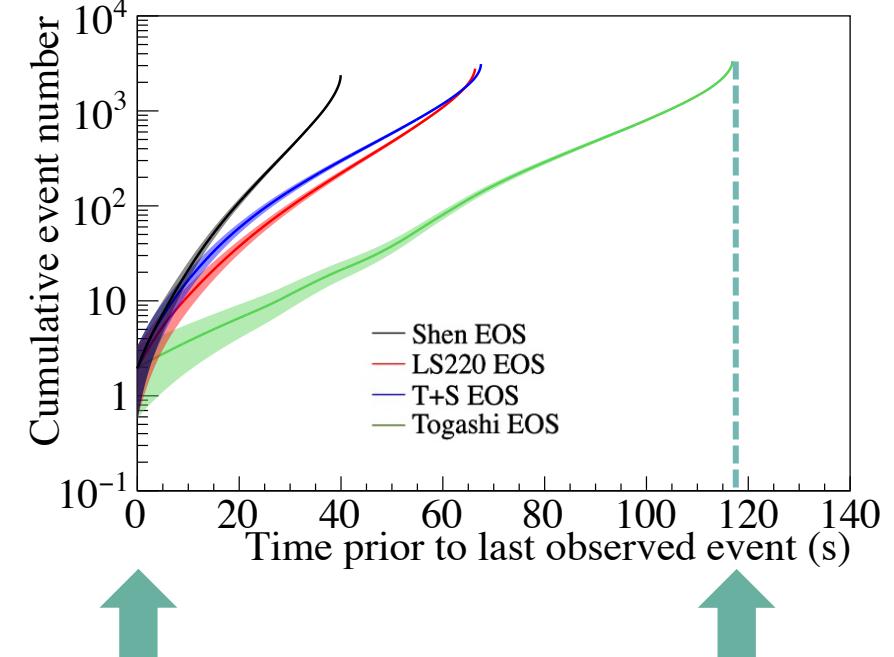
- Neutrino emission times are different depending on the nuclear equation of state(EOS).
- Device an analysis method for EOS identification



Explosion start

Reverse time

Backward time analysis^{[4][5]}

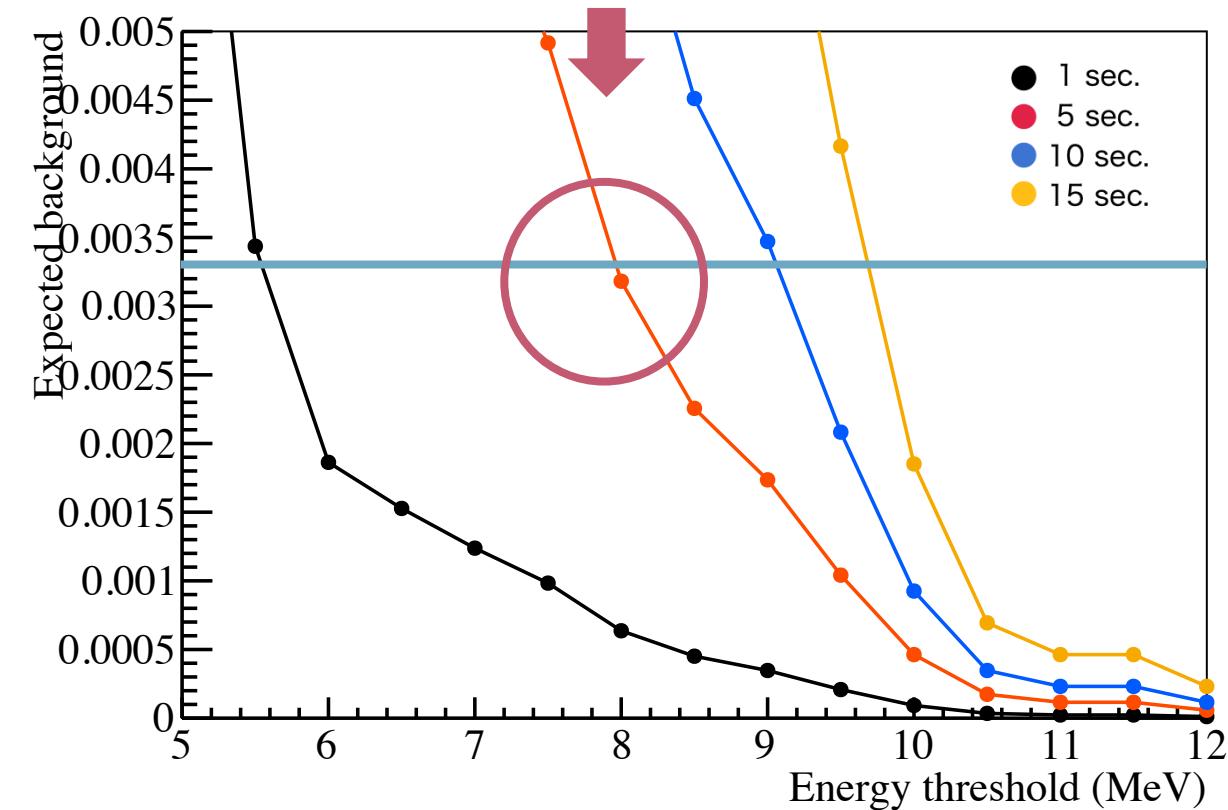
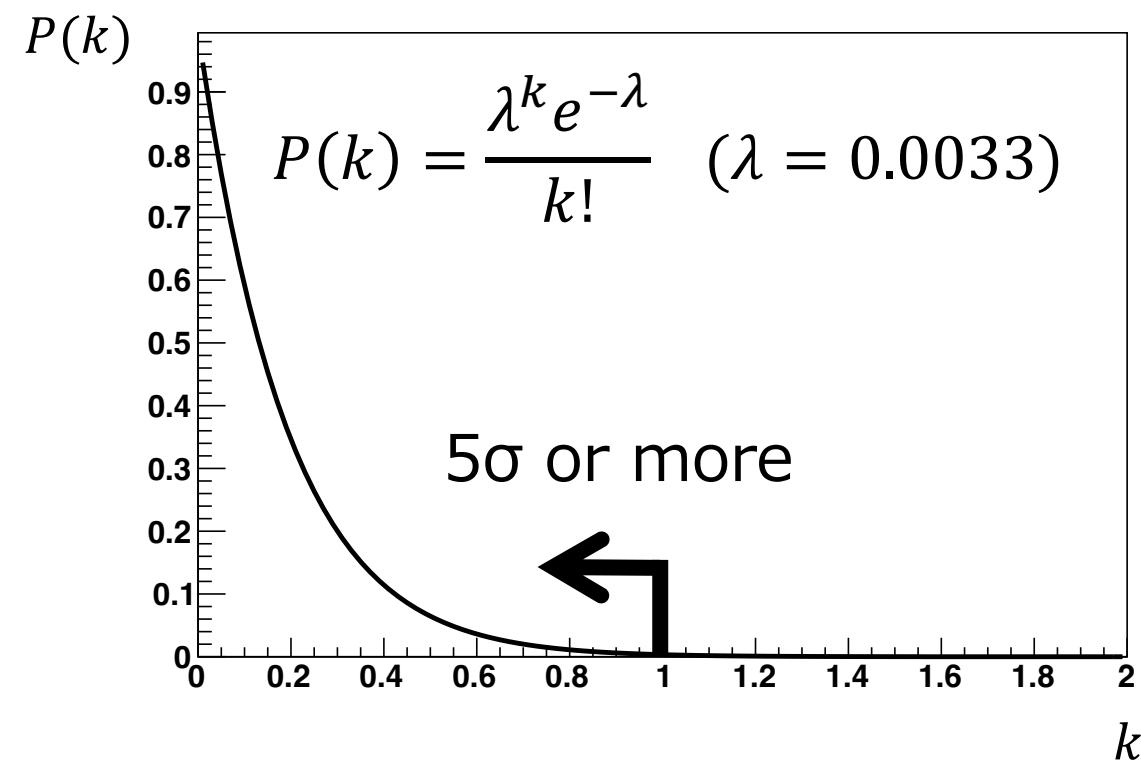


Last observed event

Explosion start

Evaluation of background events

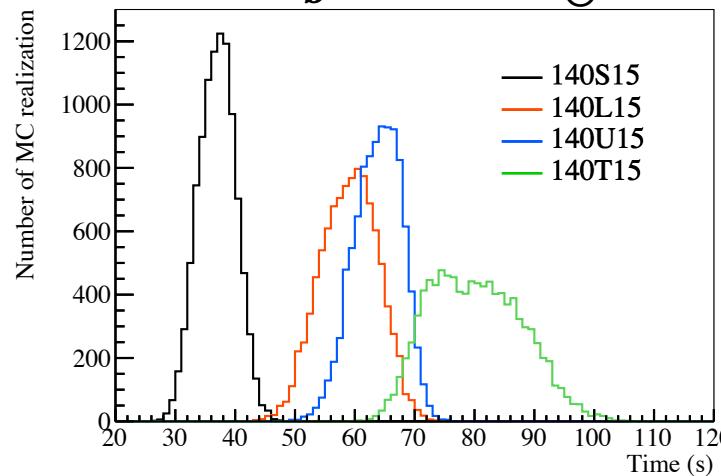
- Determine the time width T and energy threshold E_{th} for which the probability of Background not coming is more than 5σ .
- Used poisson distribution for evaluation of Background events.
- Determined $T = 5$ [s] and $E_{\text{th}} = 8$ [MeV]



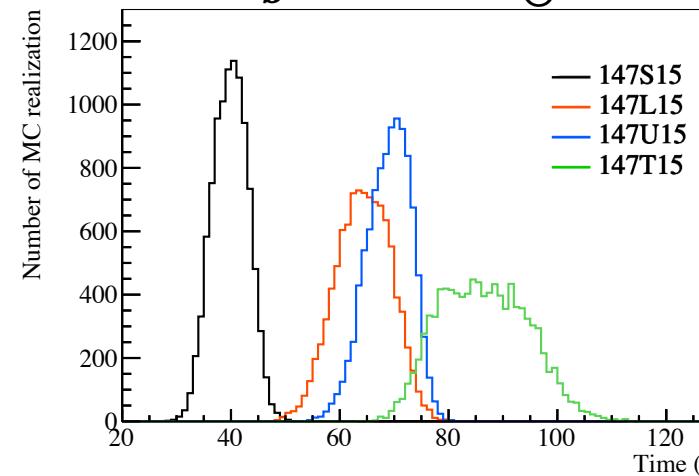
Time distribution of the last observed event

- Distribution for each model

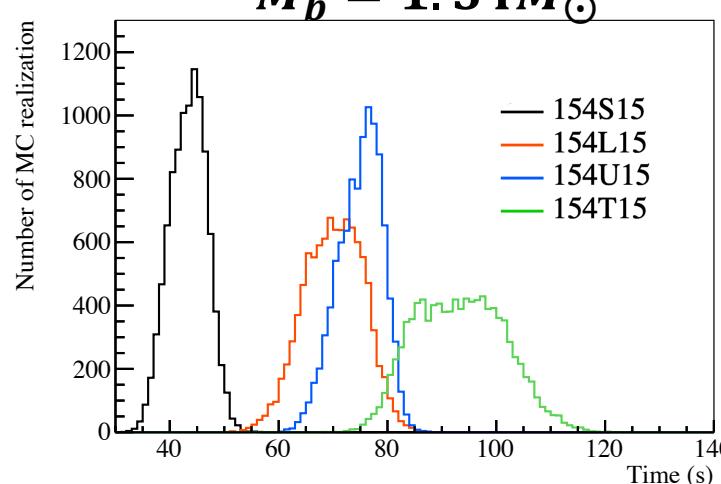
$$M_b = 1.40 M_{\odot}$$



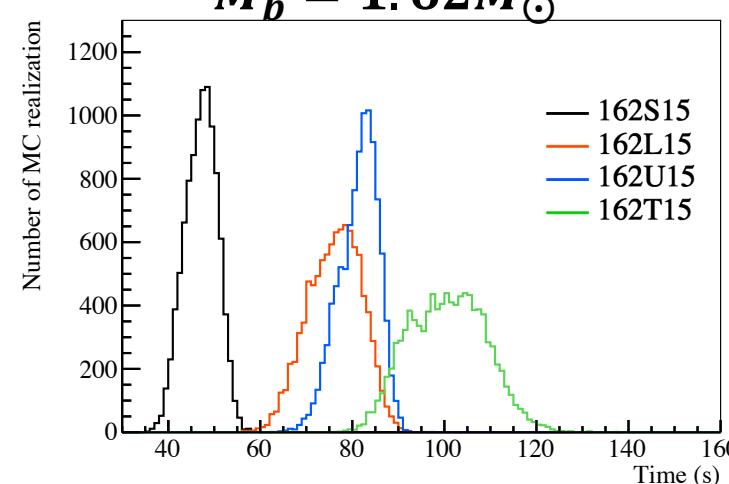
$$M_b = 1.47 M_{\odot}$$



$$M_b = 1.54 M_{\odot}$$

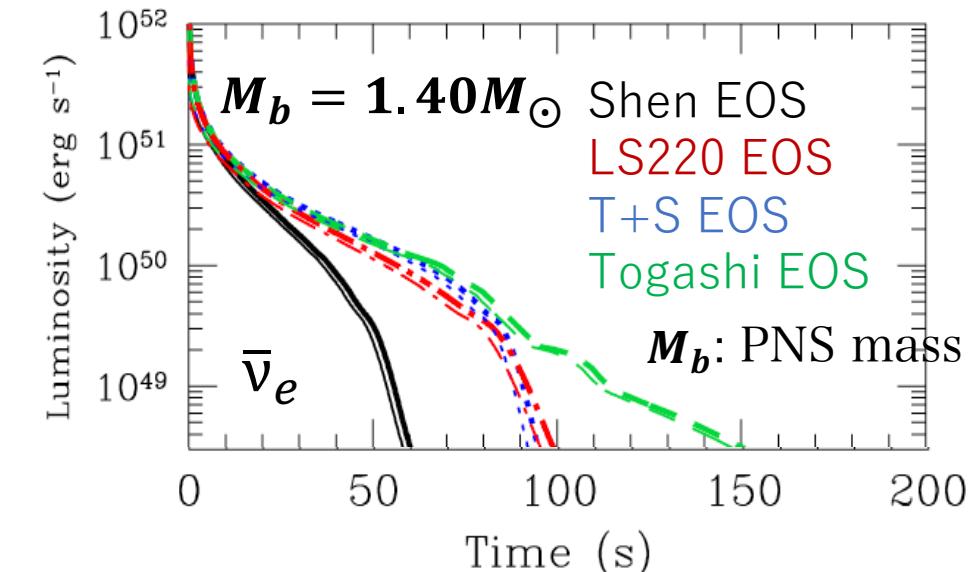


$$M_b = 1.62 M_{\odot}$$



The time of Shen EOS is fastest and Togashi EOS is slowest.

Togashi EOS has a spread in distribution.



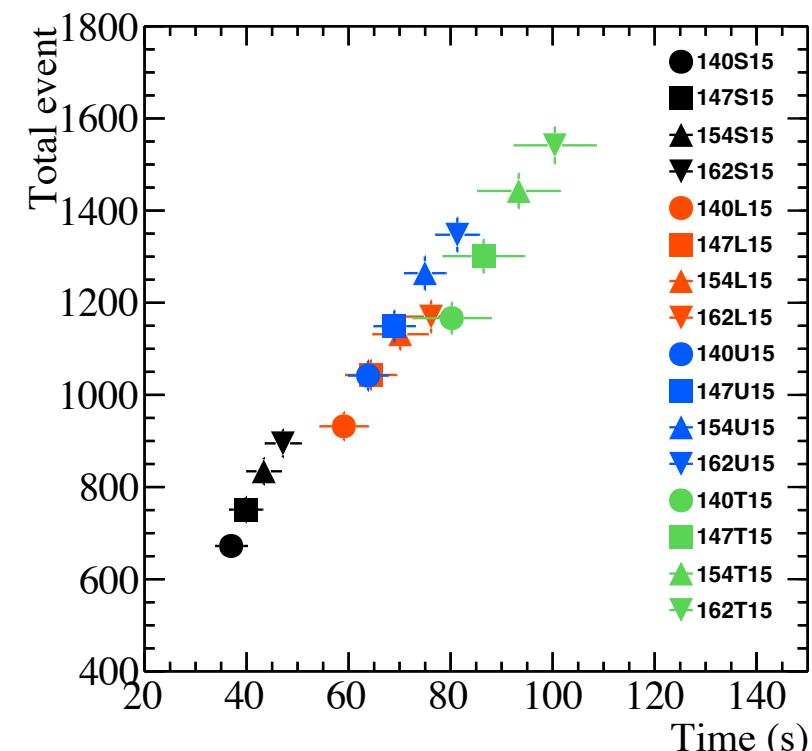
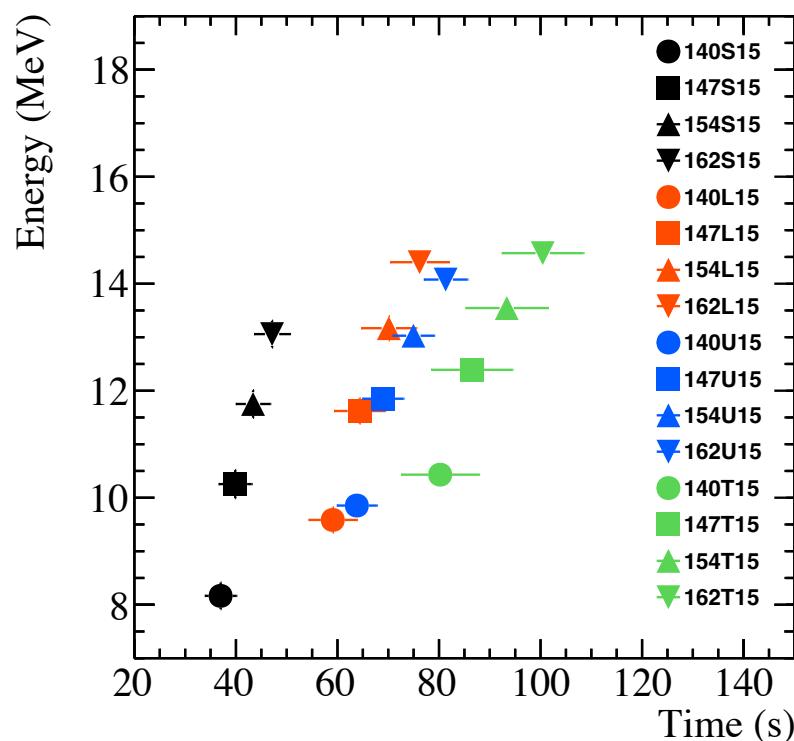
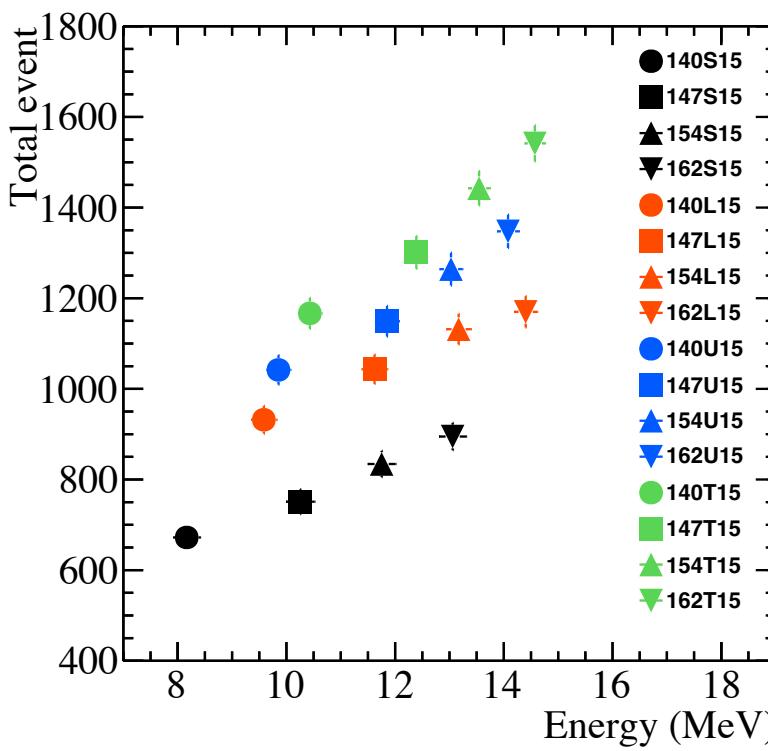
Developed a model identification method using time information

Background contamination rate

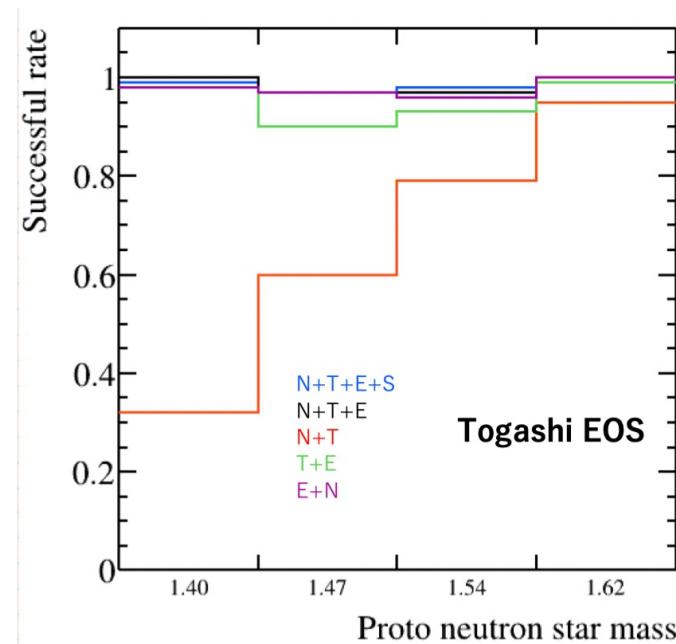
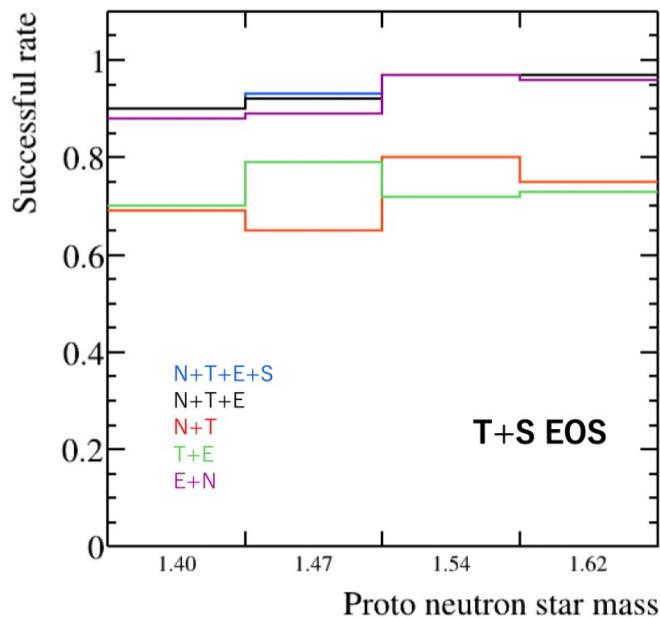
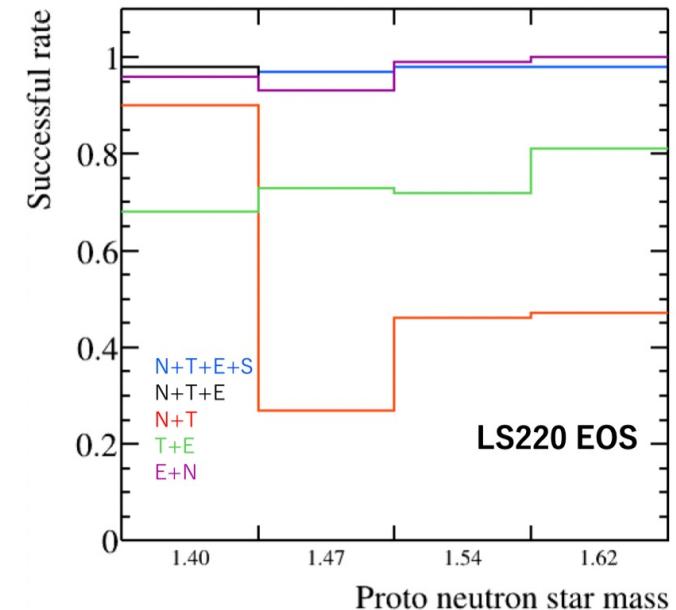
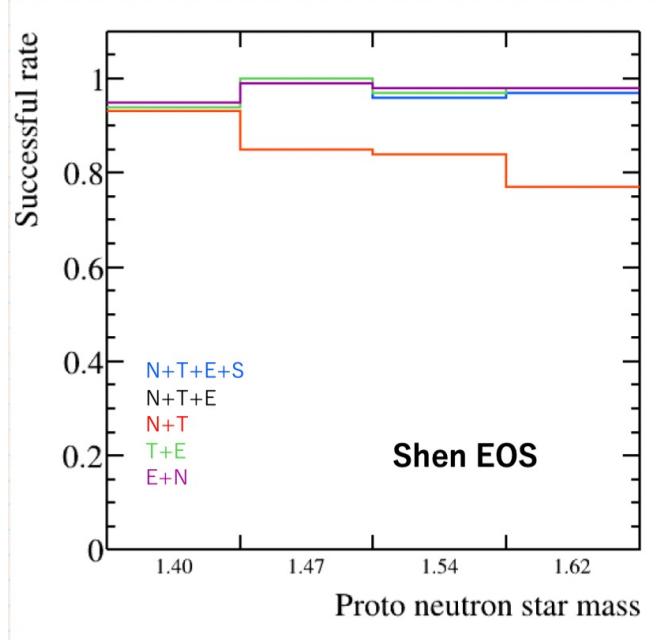
- Background contamination is enough small

	Shen EOS	LS220 EOS	T+S EOS	Togashi EOS
$1.40M_{\odot}$	2.0×10^{-4}	2.7×10^{-4}	2.7×10^{-4}	3.3×10^{-4}
$1.47M_{\odot}$	1.6×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	2.8×10^{-4}
$1.54M_{\odot}$	1.3×10^{-4}	1.9×10^{-4}	2.0×10^{-4}	3.2×10^{-4}
$1.62M_{\odot}$	1.2×10^{-4}	1.7×10^{-4}	1.8×10^{-4}	3.1×10^{-4}

Correlation diagram of each parameter



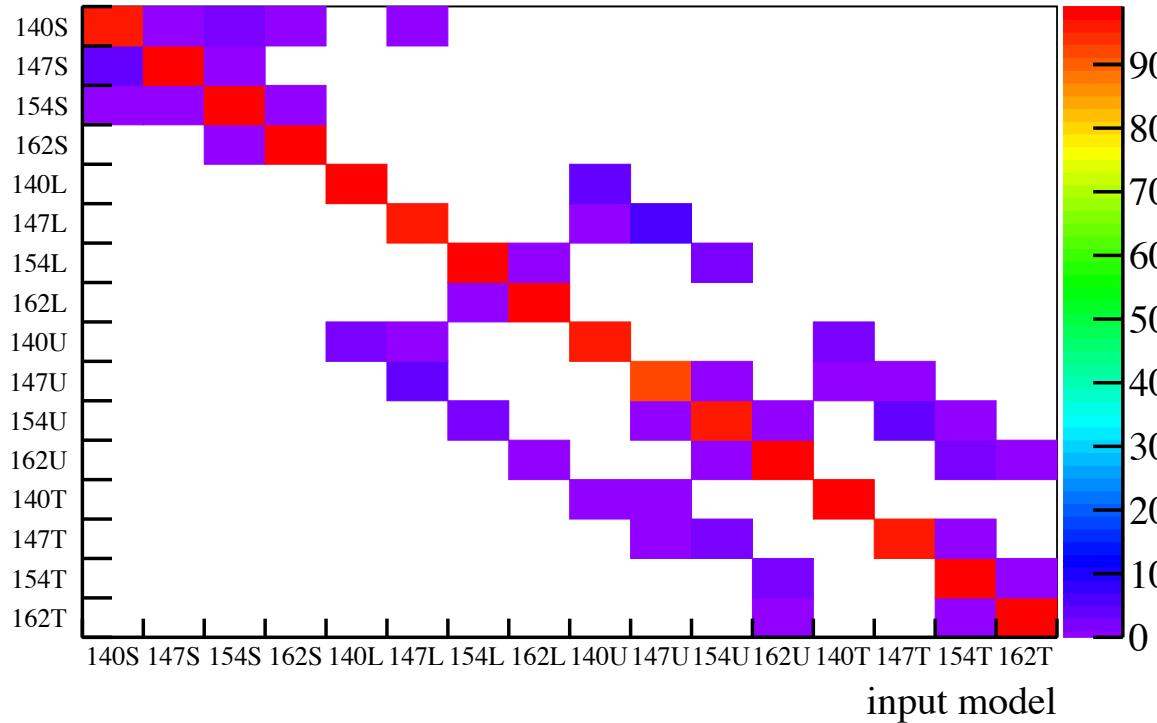
Identification performance



Identification performance

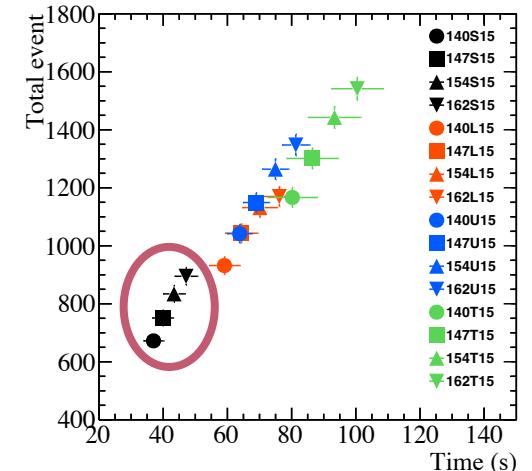
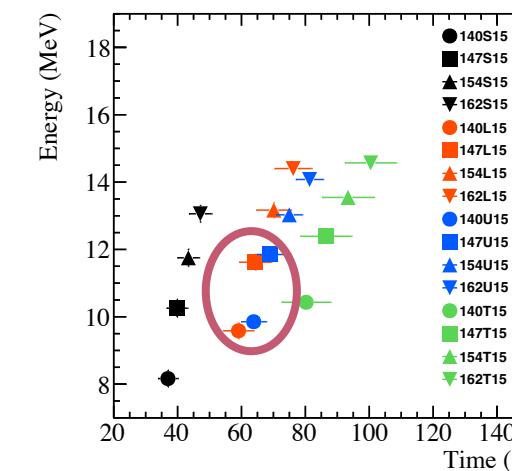
- Identification performance of 90% or more.

selected model



S: tendency to chose different masses

140U, 147U: tendency to chose different models



New parameters will be used to improve performance in the future.

Future plan

Master's Research

- Additional gadolinium loading to SK-Gd experiment
- Neutron tagging efficiency measurement
- Developing SN simulation with the accurate interaction model
- Evaluation of SN model identification method

Doctoral Research

- Set up an observation system for the next nearby supernova explosions in SK
 - Improve identification performance with more SN situations and models
 - Develop a fast-direction reconstruction algorithm for multi-messenger observation