スーパーカミオカンデでの超新星ニュートリノ観測における酸素原子核反応の研究

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2023年3月3日

第9回超新星ニュートリノ研究会@九州大学伊都キャンパス

Outline

- Introduction
  - Neutrino observation in Super-Kamiokande (SK)
  - Oxygen interaction with supernova neutrinos
  - Neutral current reaction
- Previous study
- Analysis
  - Simulation method
  - Comparison of the energy spectrum between supernova models
- Summary and Future prospect

Neutrino observation in Super-Kamiokande(SK)

- Several interactions are introduced into supernova neutrino simulator in SK

$\bar{\nu}_e + p \rightarrow n + e^+$ (88%/89%) (Inverse beta decay) [1]

$\nu_e + e^- \rightarrow \nu_e + e^-$ (1.5%/1.5%) (Elastic scattering) [2]

$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ (<1%/<1%) (Elastic scattering) [3]

$\nu_x + e^- \rightarrow \nu_x + e^-$ (1%/1%) (Elastic scattering) [4]

$\boldsymbol{\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F}$ (2.5%/<1%) (^{16}O interactions: charged current) [5]

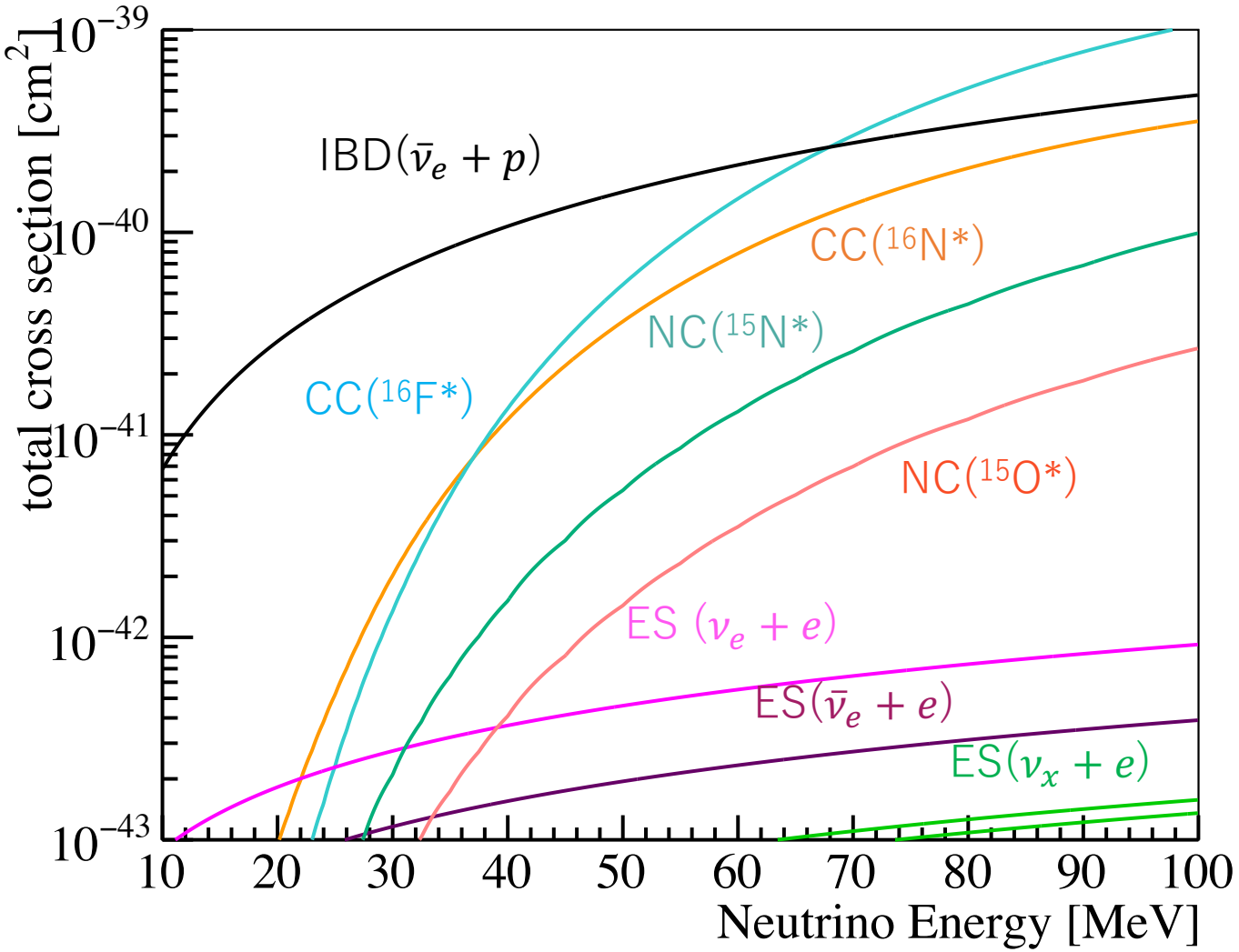
$\boldsymbol{\bar{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N}$ (1.5%/1%) (^{16}O interaction: charged current) [6]

$\boldsymbol{\nu_x + {}^{16}O \rightarrow \nu_x + O^*/N^* + \gamma}$ (5%/6%) (^{16}O interaction: neutral current) [7]

(Number) : % of the number of events for each interaction observed in SK(with NH(MSW)/without oscillation)

Ikeda *et al*, The Astrophysical Journal, 669:519Y524, 2007

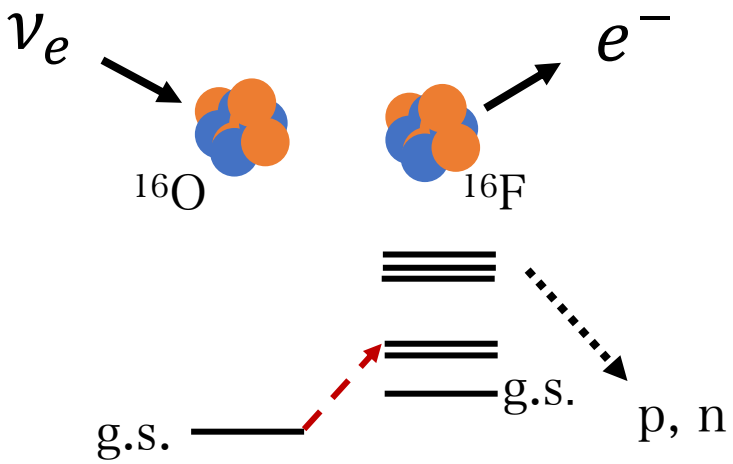
Cross section



Oxygen interactions become non-negligible in higher energy region

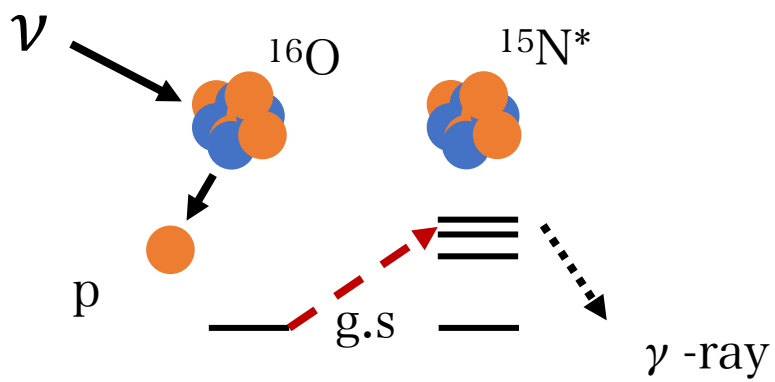
Oxygen interaction in supernova neutrinos

Charged current(CC)
React with $\nu_e/\bar{\nu}_e$ and emits e^-/e^+



→reported in previous this workshop

Neutral current(NC)
Reacts with all neutrinos



→simulate NC reactions realistically

✓Independent on neutrino oscillation
→Possible to access the total flux of supernova neutrinos

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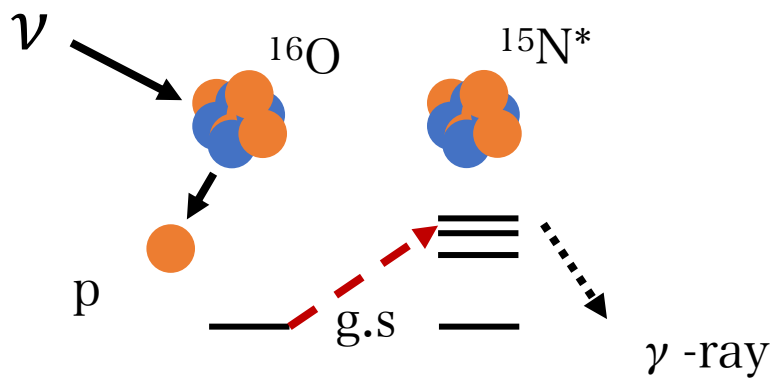
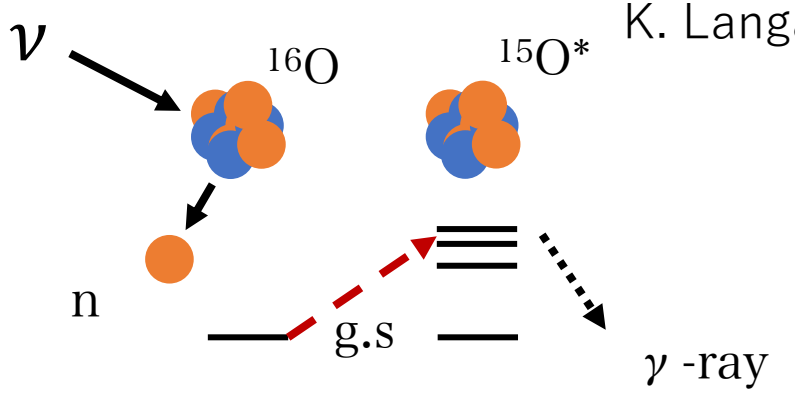
Neutral current reaction

- Emits proton or neutron when ^{16}O is excited above the particle threshold

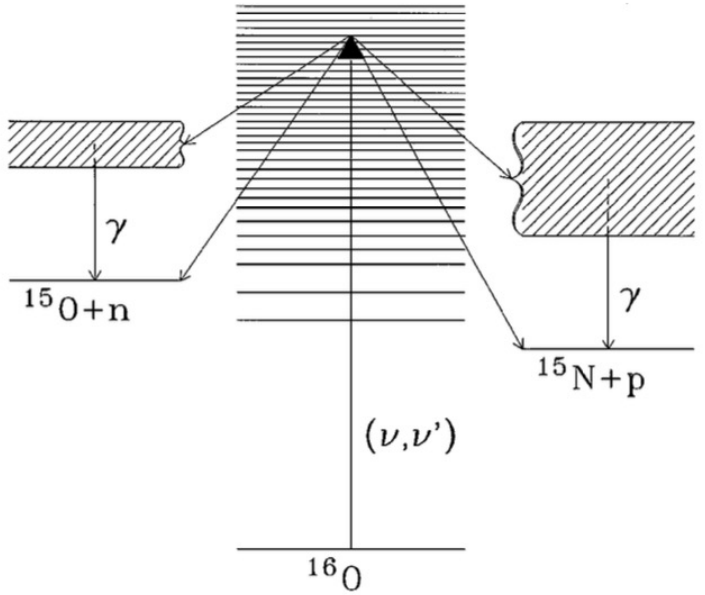




K. Langanke, P. Vogel, and E. Kolbe et al(1996)

✓$^{15}N^*$ and $^{15}O^*$ emit only gamma-ray

Illustration of a giant resonance

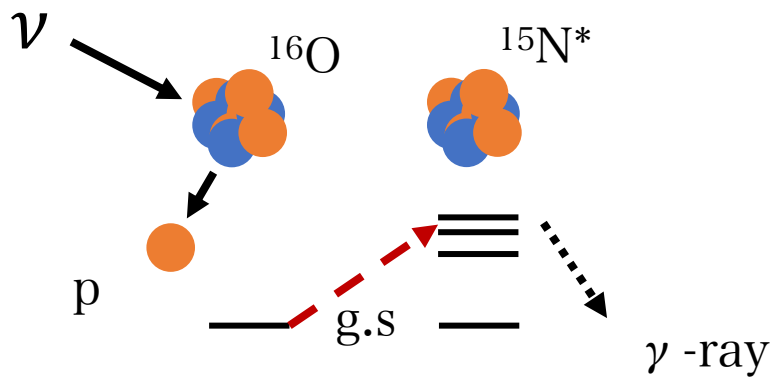


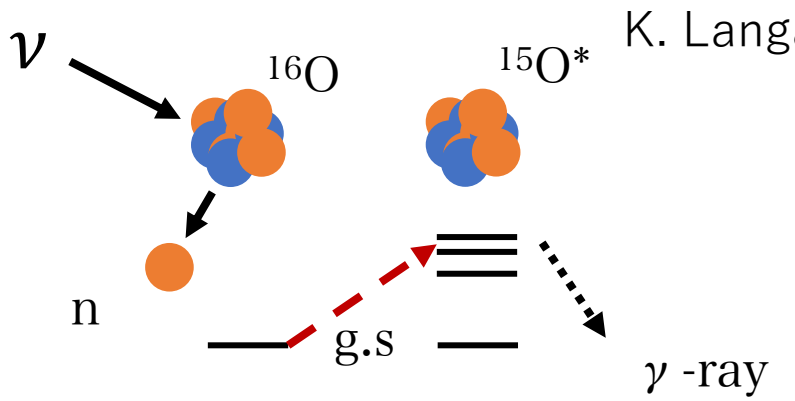
$^{15}N^*$ excited states [MeV]
5.18
6.18
6.69
7.28

$^{15}O^*$ excited states [MeV]	
5.27	8.32
6.33	8.57
7.16	9.05
7.56	9.76

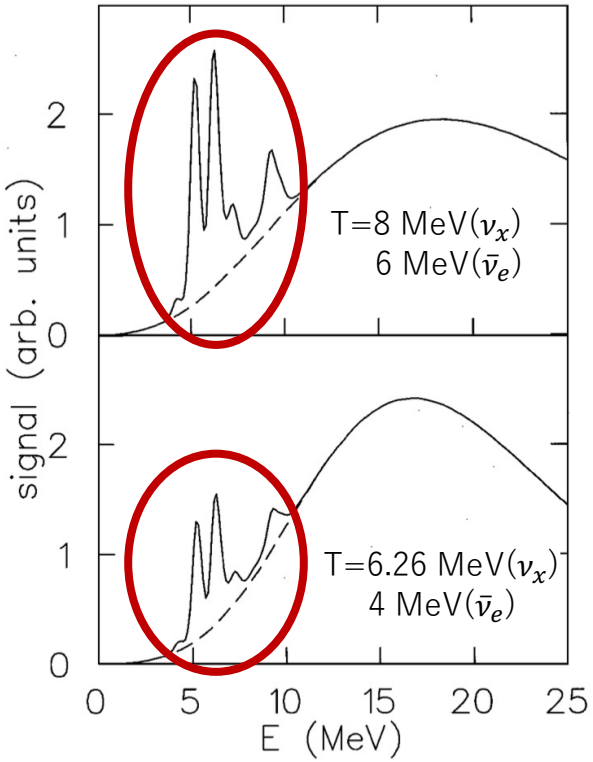
Neutral current reaction

- Emits proton or neutron when ^{16}O is excited above the particle threshold





K. Langanke, P. Vogel, and E. Kolbe et al(1996)



✓1[illegible] only

$^{15}N^*$ excited states [MeV]
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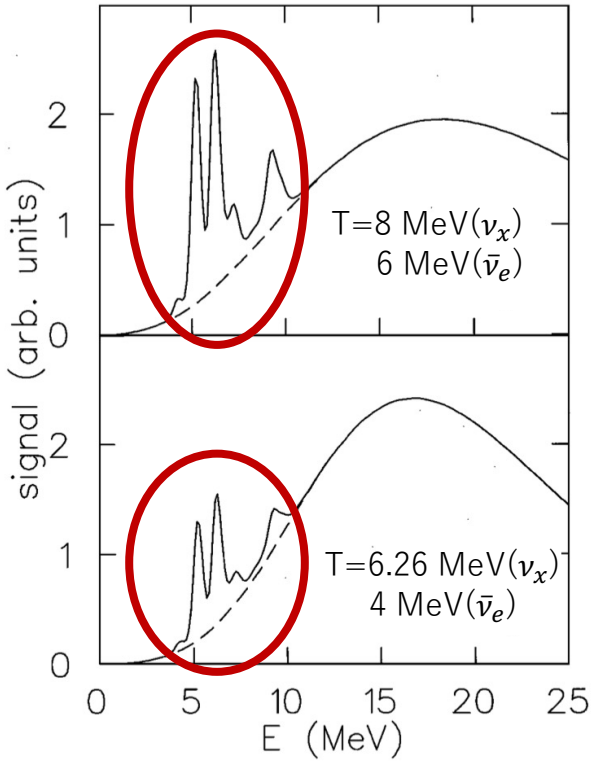
Studies of the NC reactions observed in SK more precisely

K. Langanke, P. Vogel, and E. Kolbe et al(1996)

- Issues in the previous study
  - Had not assumed a realistic supernova model
    →Introduce Fermi-Dirac distribution
  - Realistic energy resolution was not introduced
    →apply $14\%/\sqrt{(E/10\mathrm{MeV})}$



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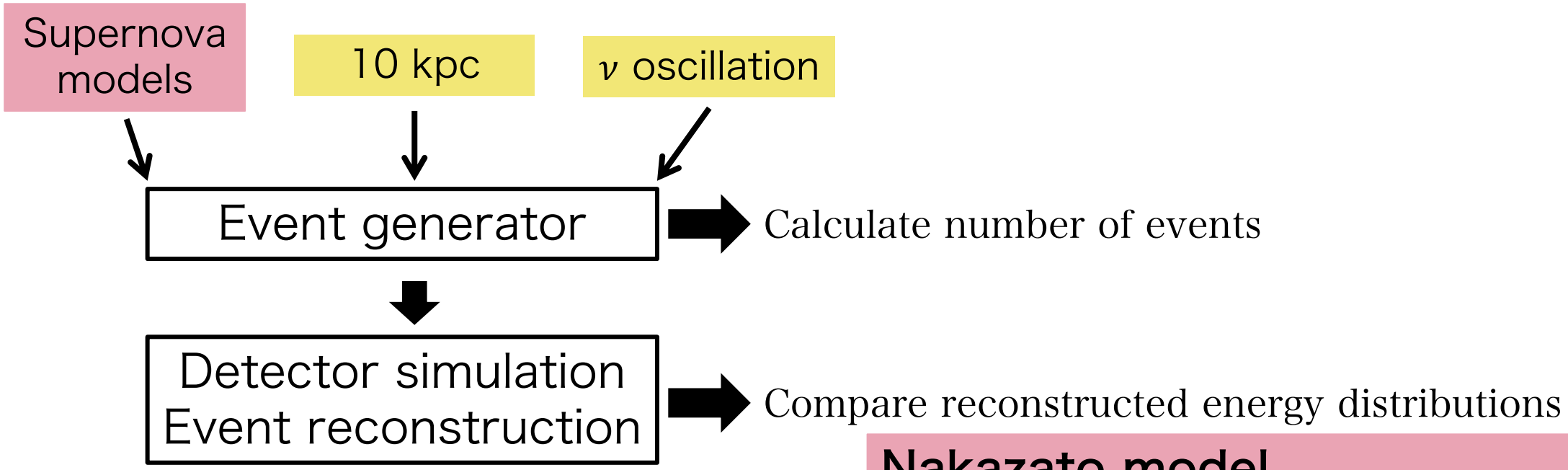
Simulation methods

- Flow of the simulation



Nakazato model

A model calculated from core-bounce

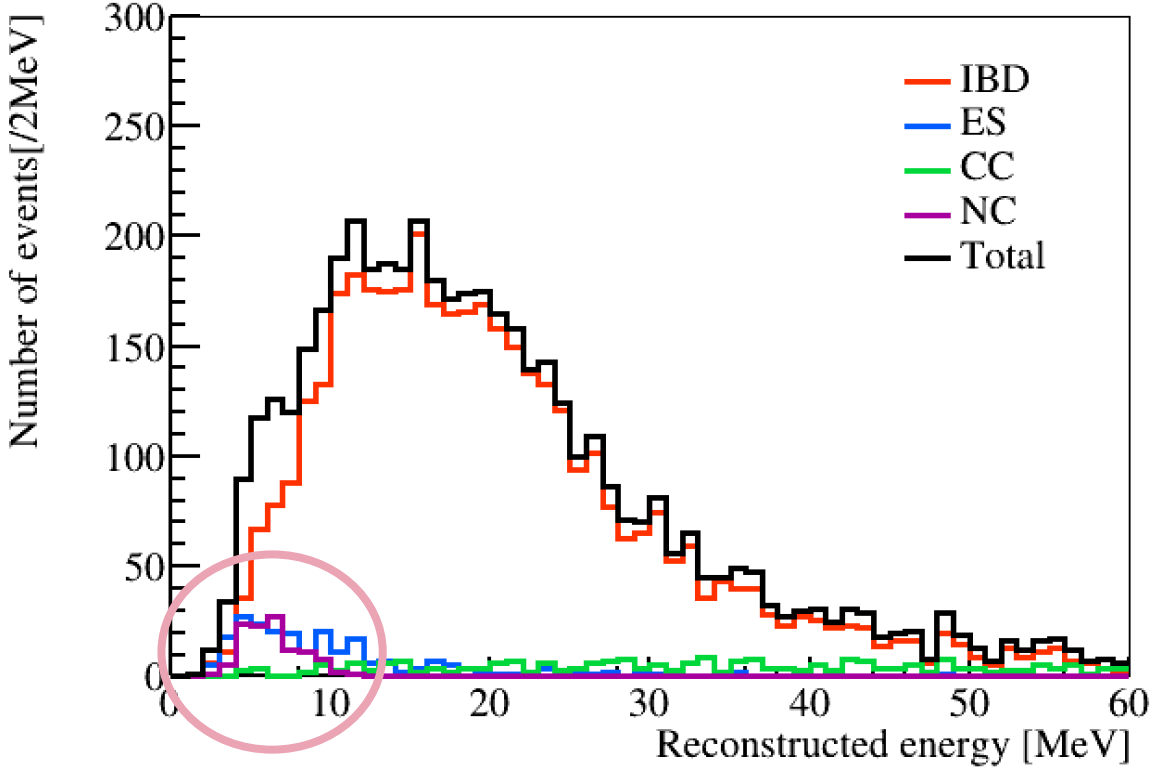
- ✓ Equation of state: Shen EOS
- ✓ Progenitor mass
  - $13M_{\odot}, 30M_{\odot}$
  - $30M_{\odot}$(Blackhole formation case)
- ✓ Shock revival time
  - 300 ms

K. Nakazato *et al.*, *Astrophys. J.* Supp. 205:2, 2013

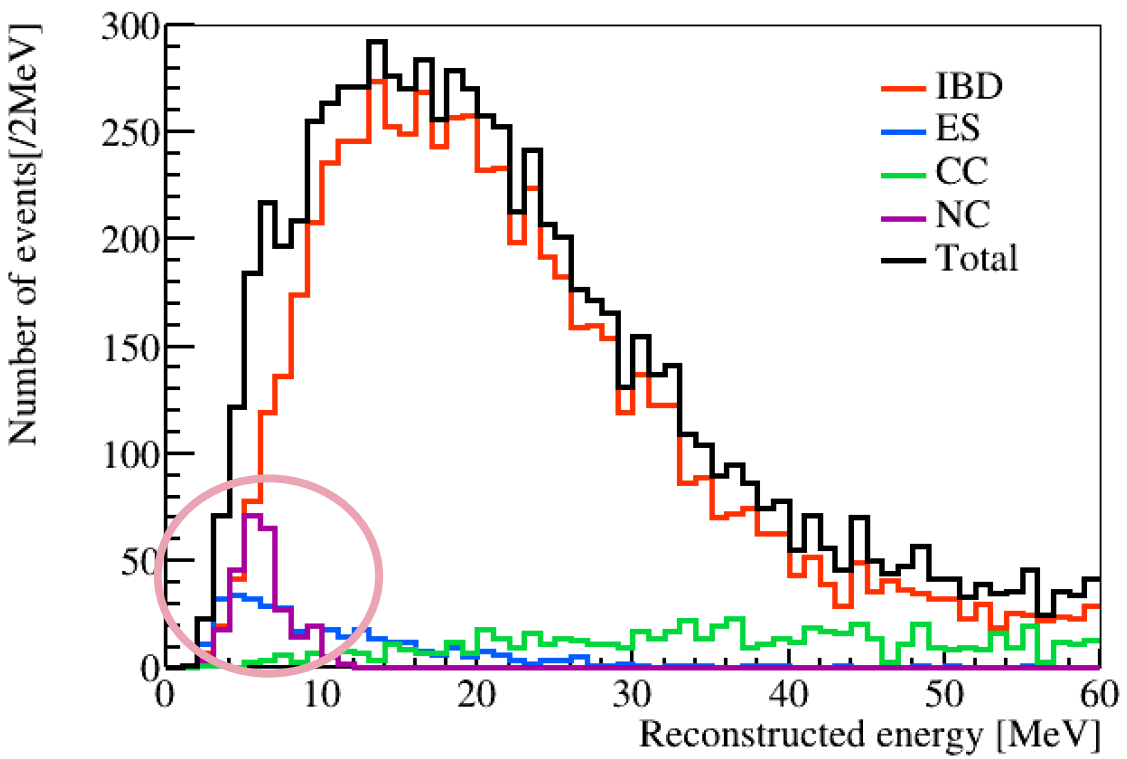
Energy spectrum

- SN model($13, 30M_{\odot}$) with Normal ordering
  - Energy of NC signal in SK: < 10 MeV
  - $30M_{\odot}$ case has higher average neutrino energy
    → Larger number of events expected

$13M_{\odot}$



$30M_{\odot}$



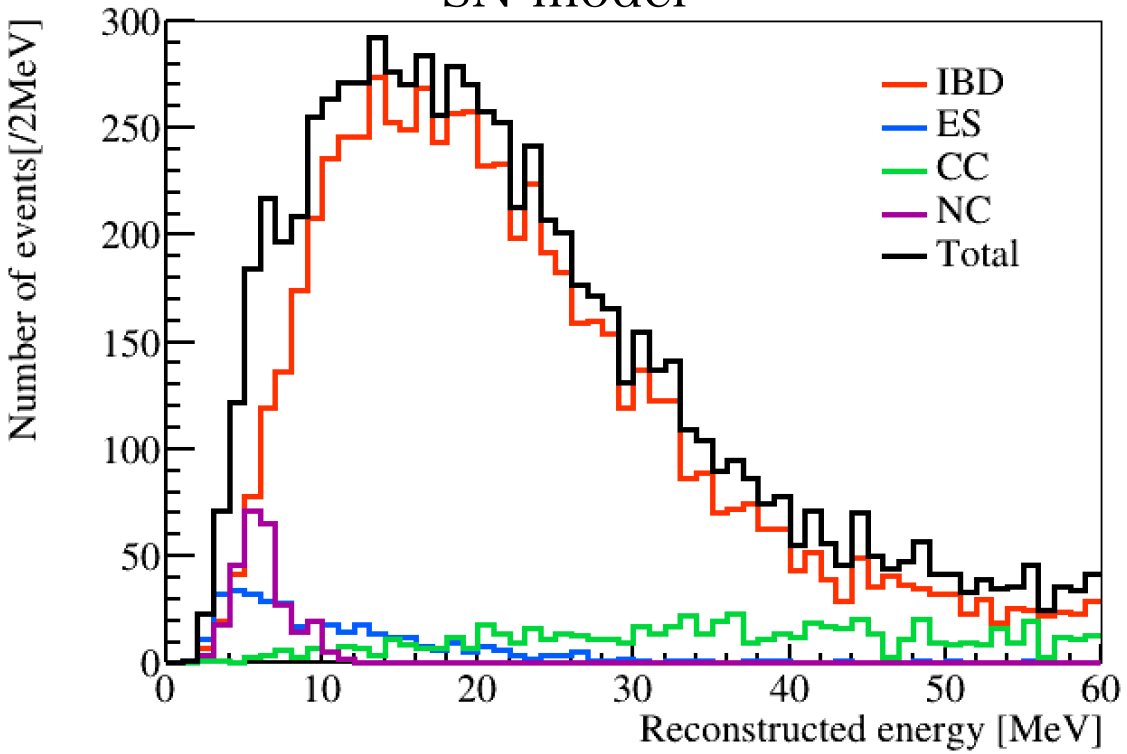
Energy spectrum

- Supernova (SN) and Black hole (BH) model ($30M_{\odot}$) with normal ordering

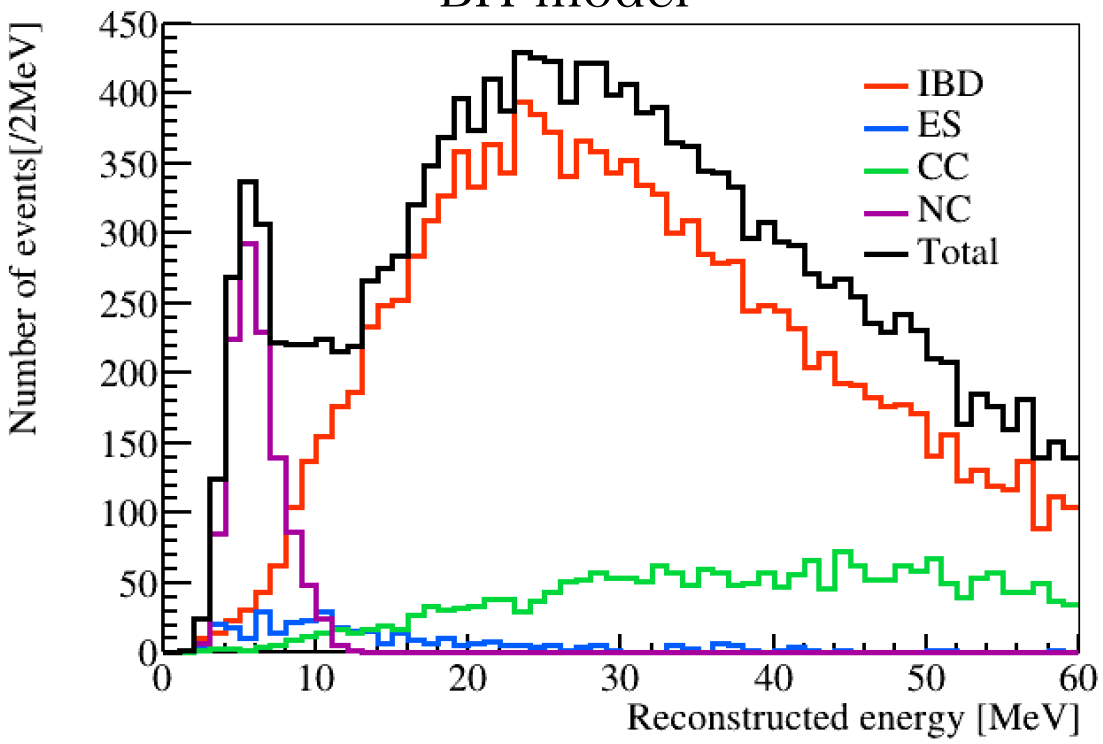
  BH model has higher average neutrino energy

  →Can see **clear peak of NC reaction in the BH model**

SN model

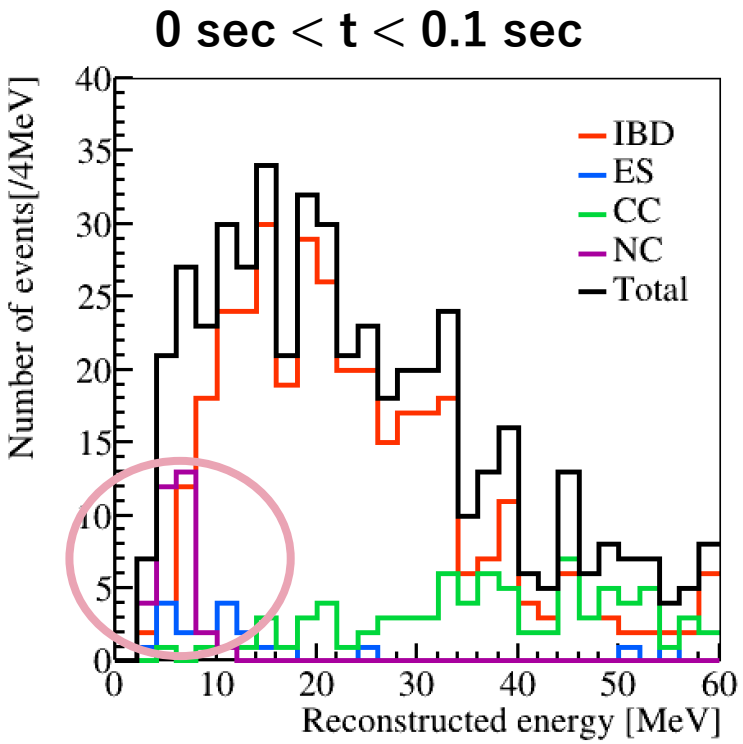


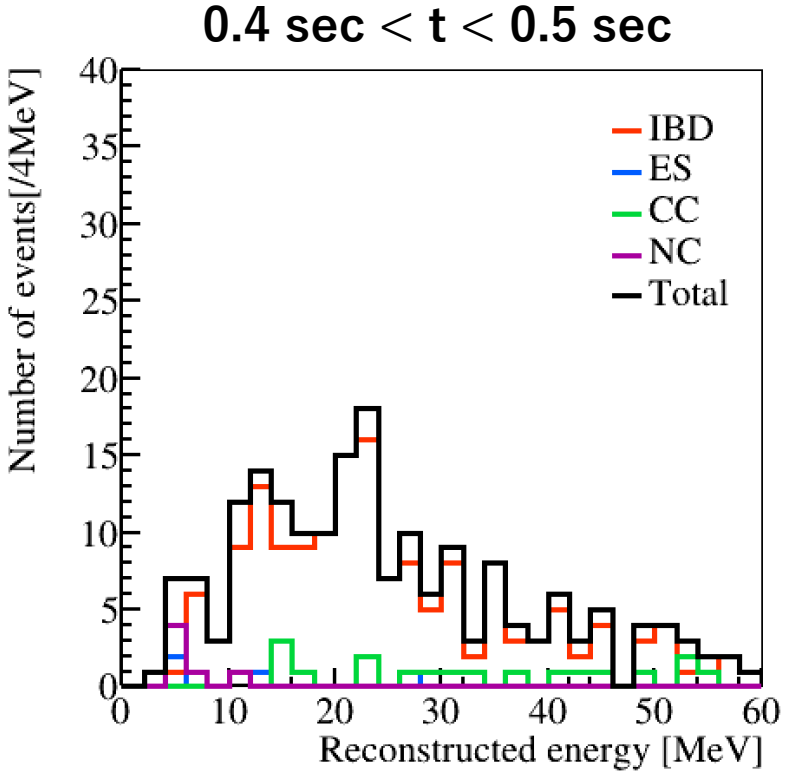
BH model

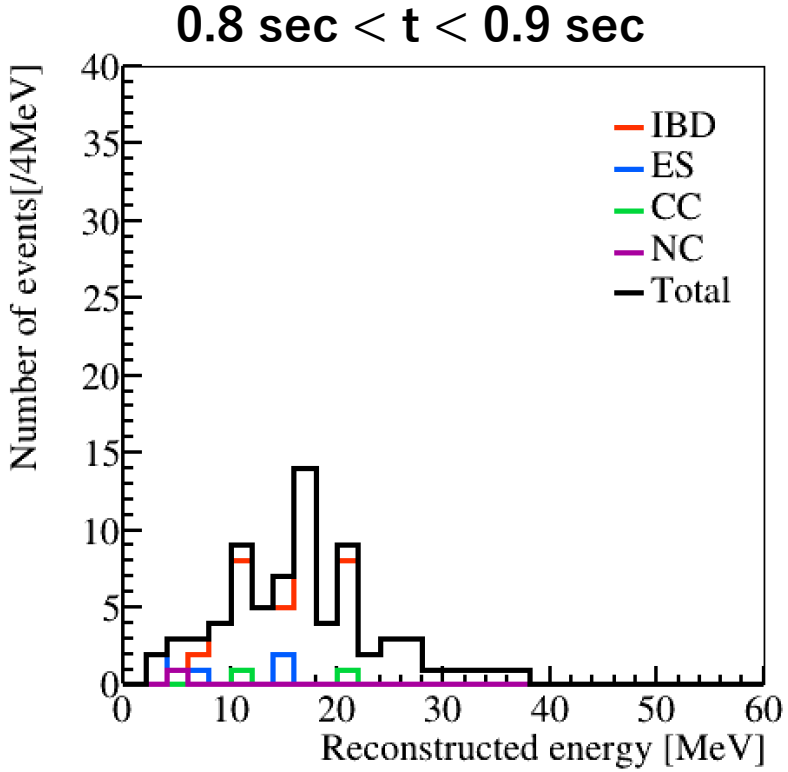


Energy spectrum by time

- SN model ($30M_{\odot}$) with normal ordering







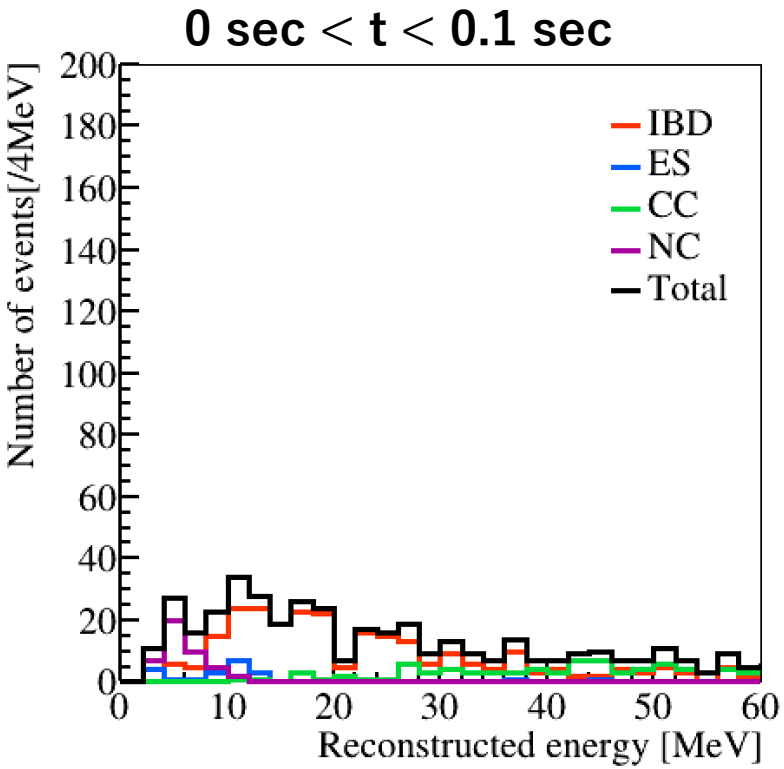
Average neutrino energy in the early phase is higher than one in the late phase

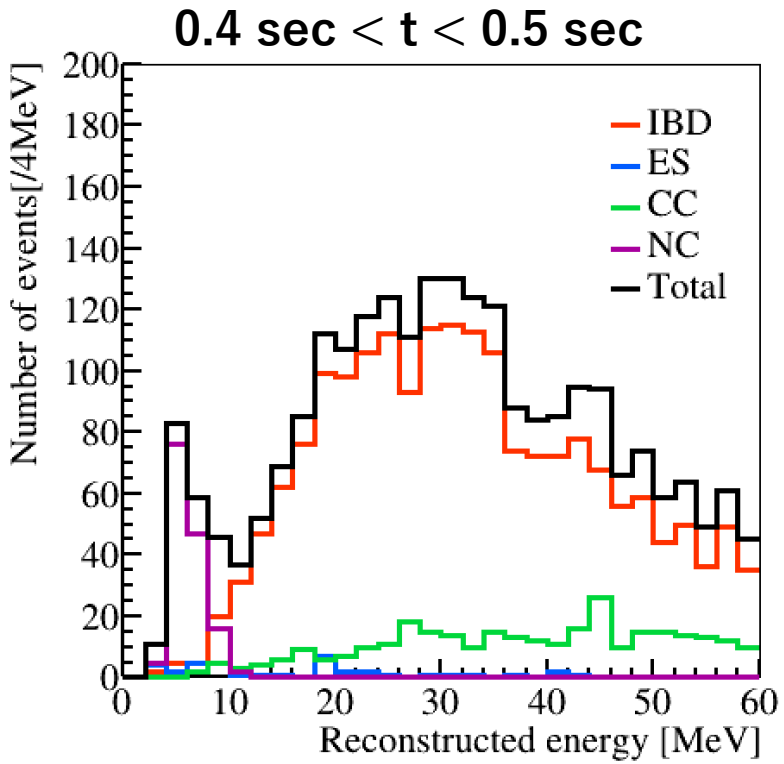
→NC reaction is dominant below 10 MeV

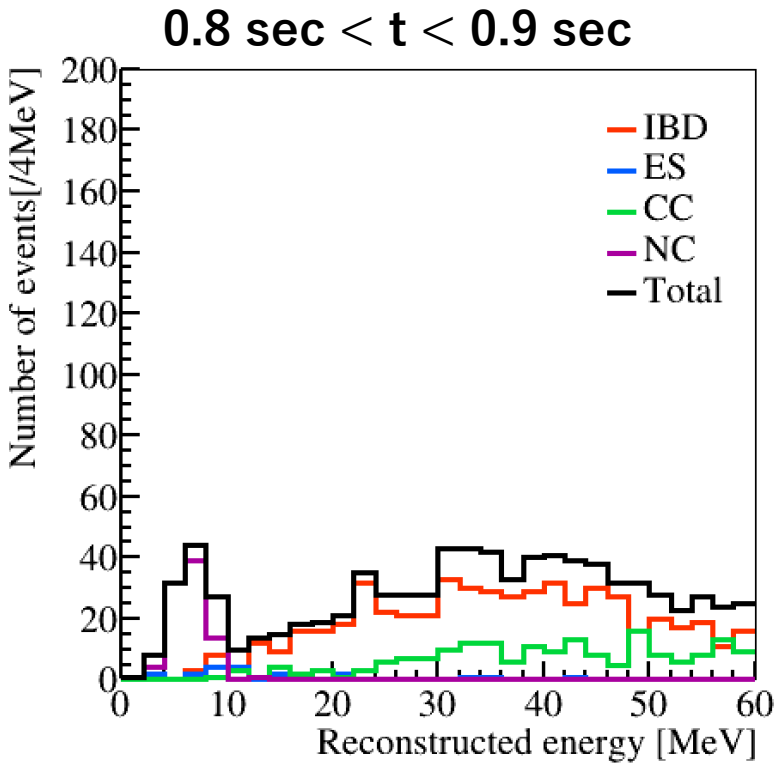
Energy spectrum by time

- BH model with normal ordering

A black hole is formed at t~0.84sec.







NC signal can be seen clearly with passing time

Summary and Future prospect

- Currently, several neutrino interactions are introduced in SN event simulation in SK.
  - Focus on the neutrino interaction with ^{16}O
  - Introduced NC reaction into supernova neutrino event generator in SK

- Simulated Supernova neutrino events using several supernova models
  - SN model ($13, 30 M_{\odot}$) and BH model ($30 M_{\odot}$)

- Looked at a reconstructed energy spectrum
  - A peak of the NC reaction can be confirmed on BH model

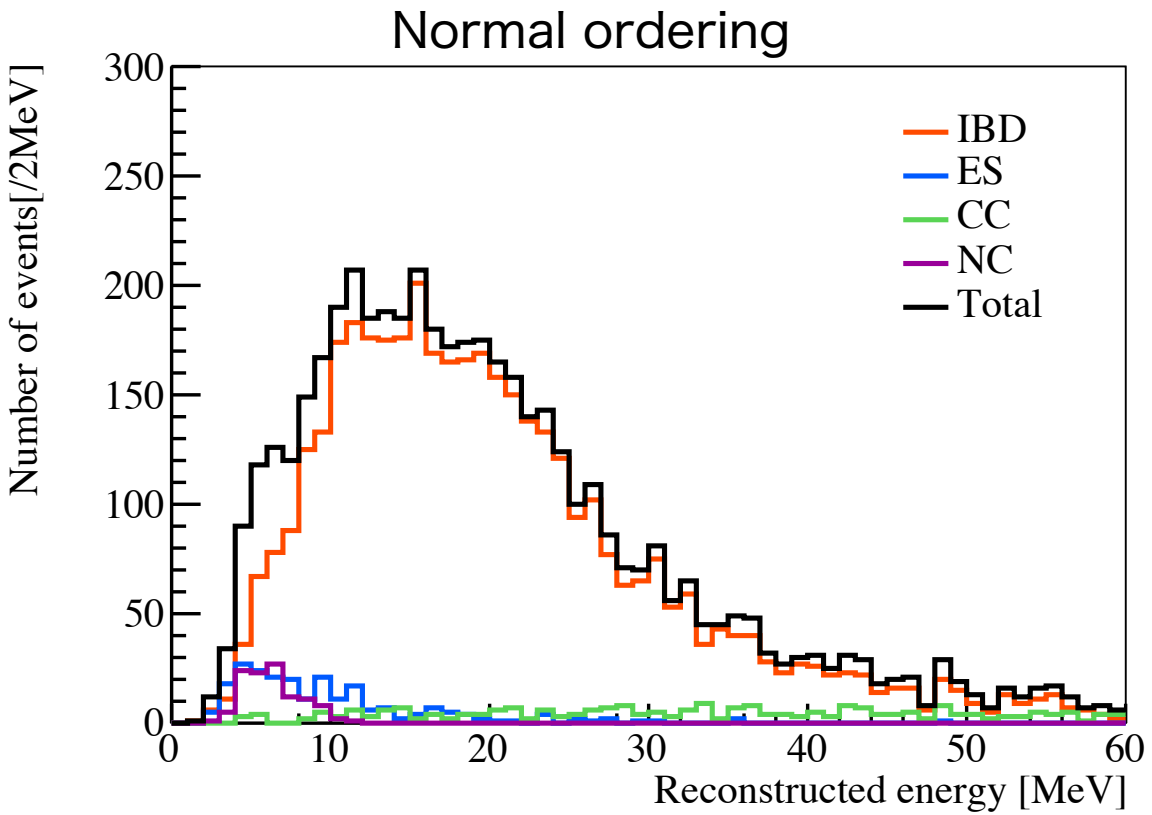
Future prospect

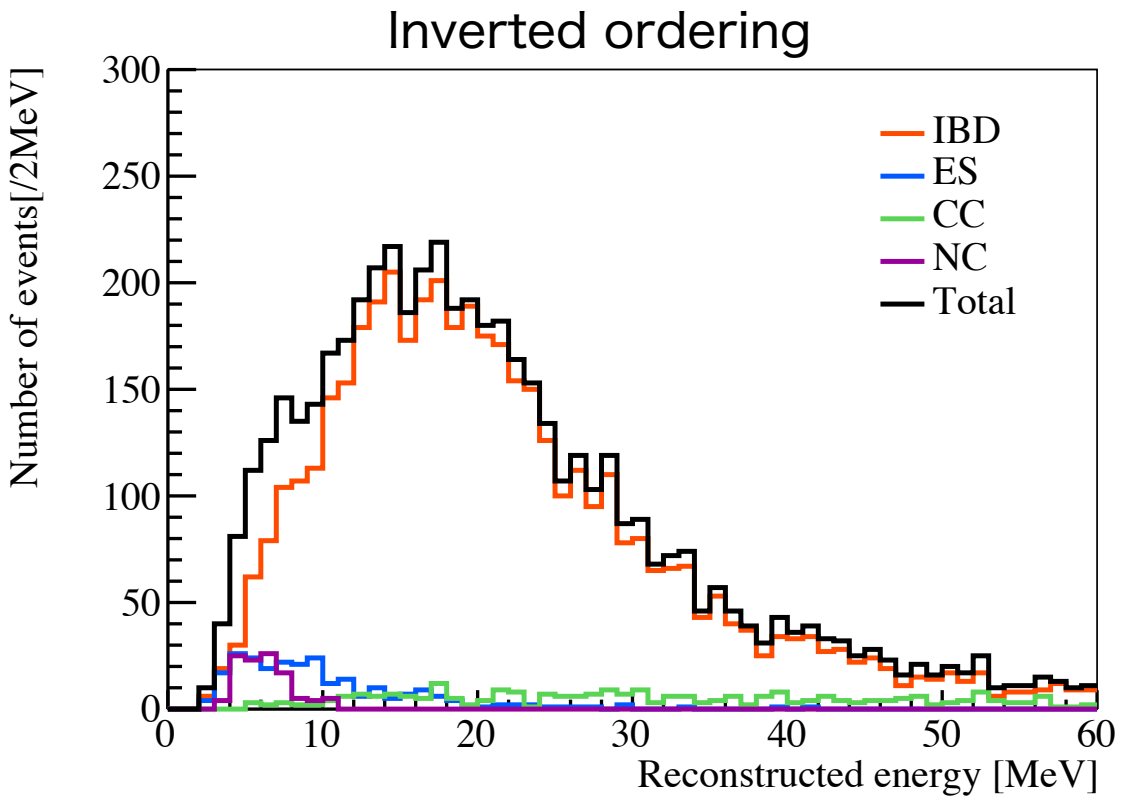
- Possible to access supernova models by looking at below 10 MeV

Back up

Energy spectrum

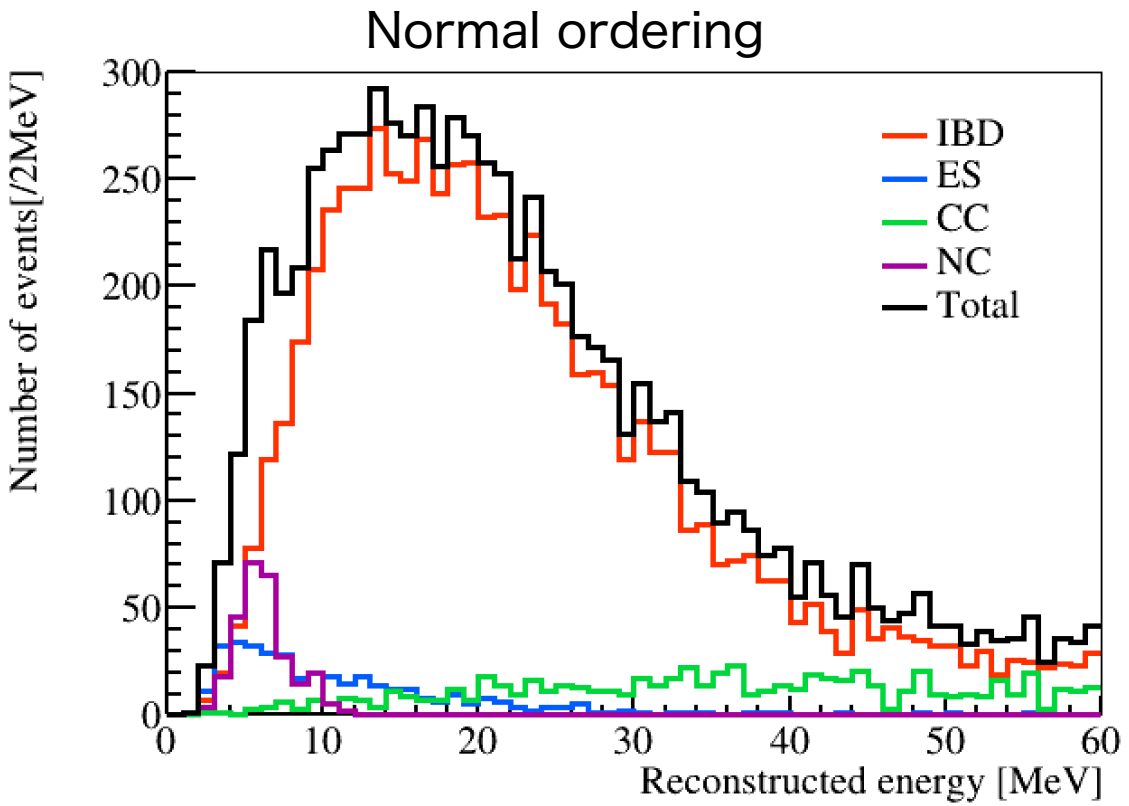
- SN model ($13M_{\odot}$) comparison of neutrino oscillation
  - NC reaction does not depend on neutrino oscillation

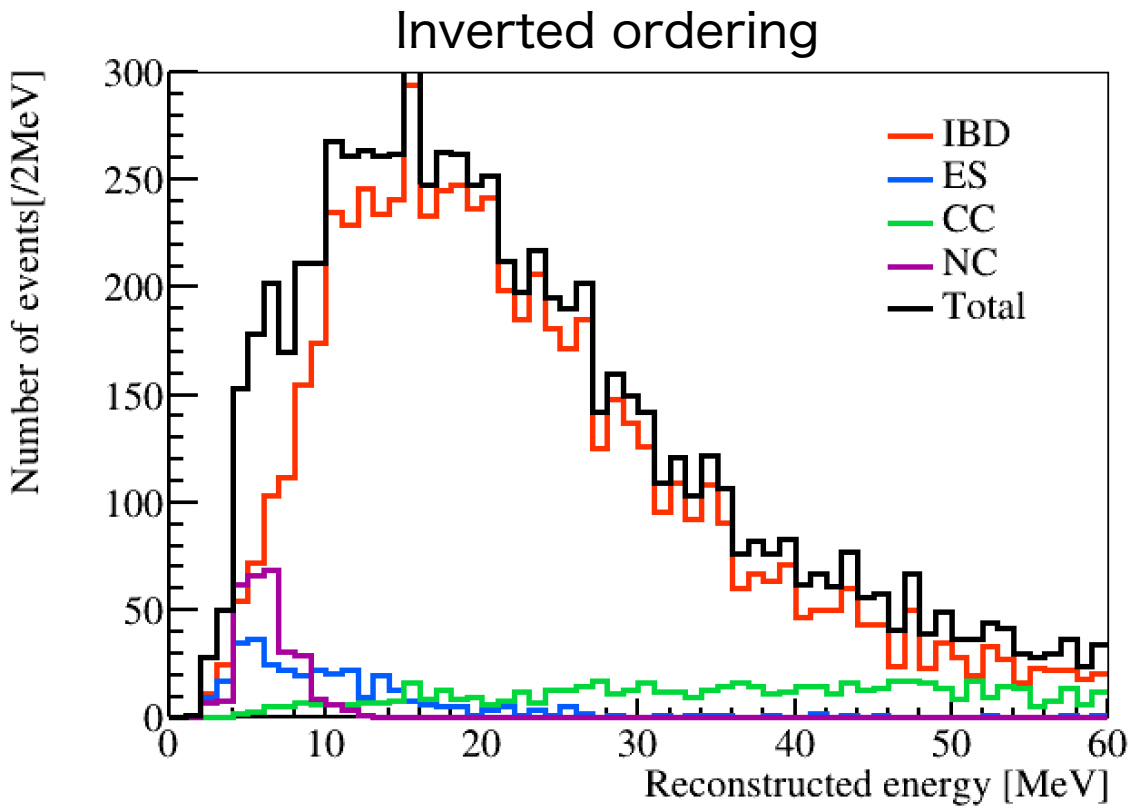




Energy spectrum

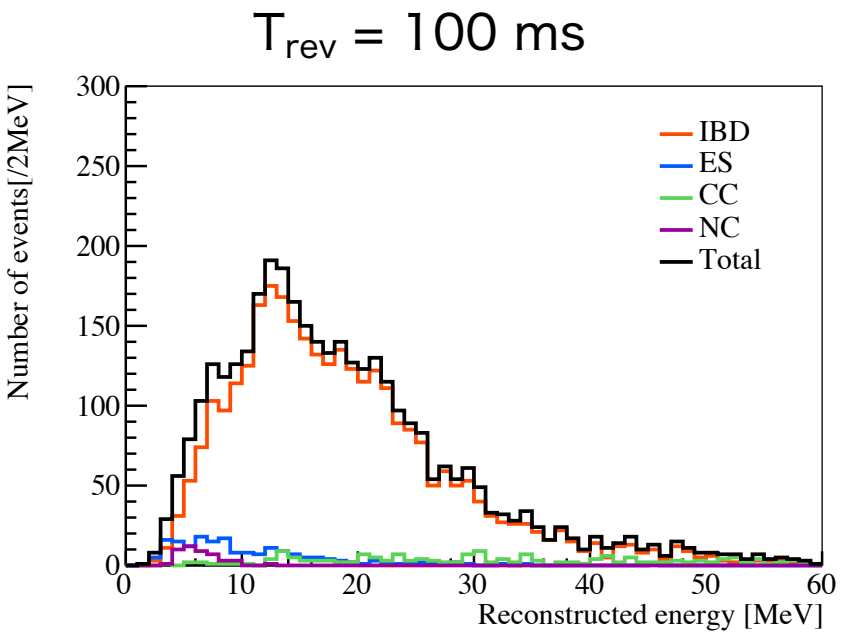
- SN model ($30M_{\odot}$) comparison of neutrino oscillation
  - NC reaction does not depend on neutrino oscillation

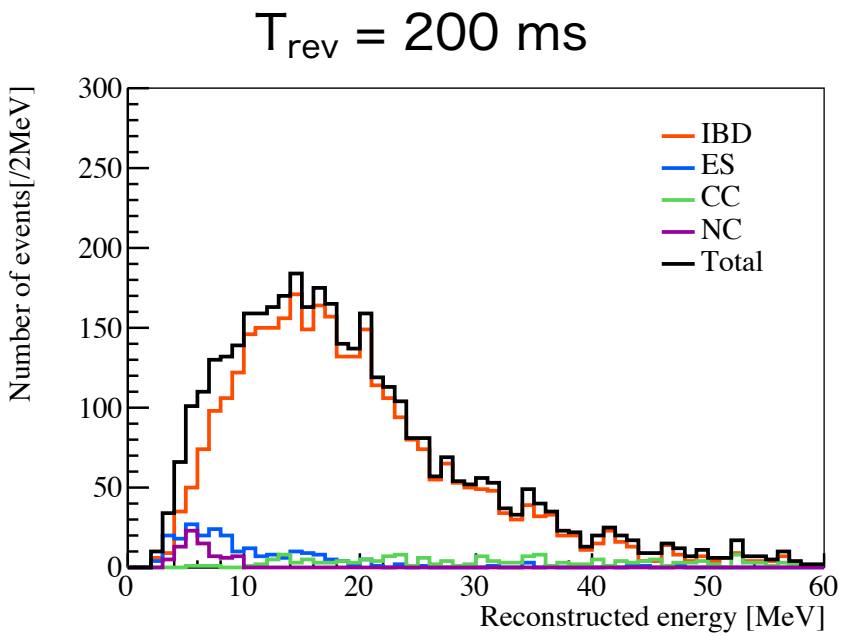


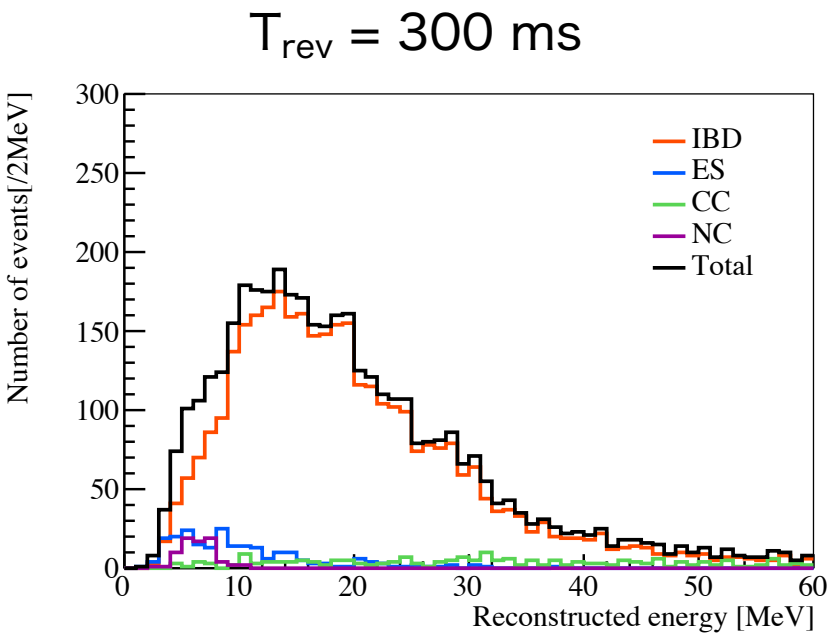


Energy spectrum

- SN model ($20M_{\odot}$) normal ordering

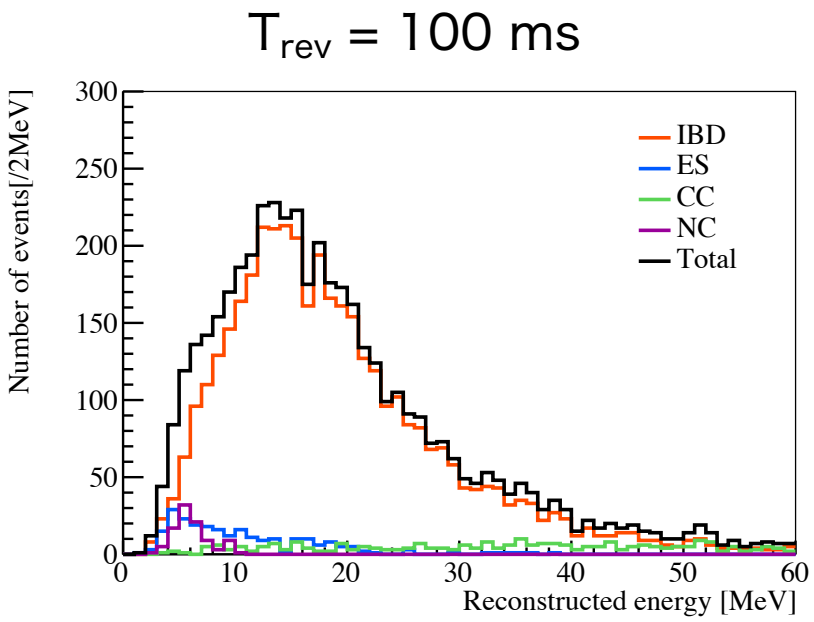


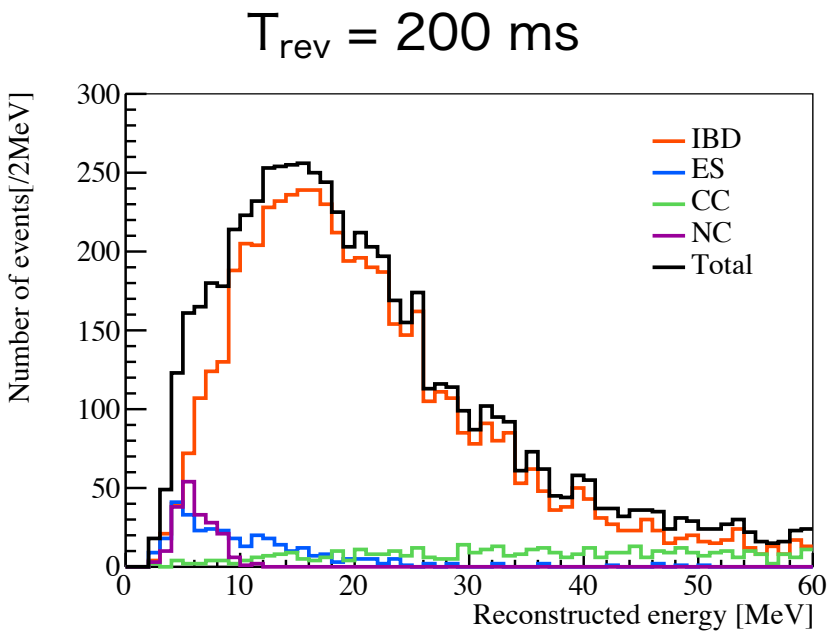


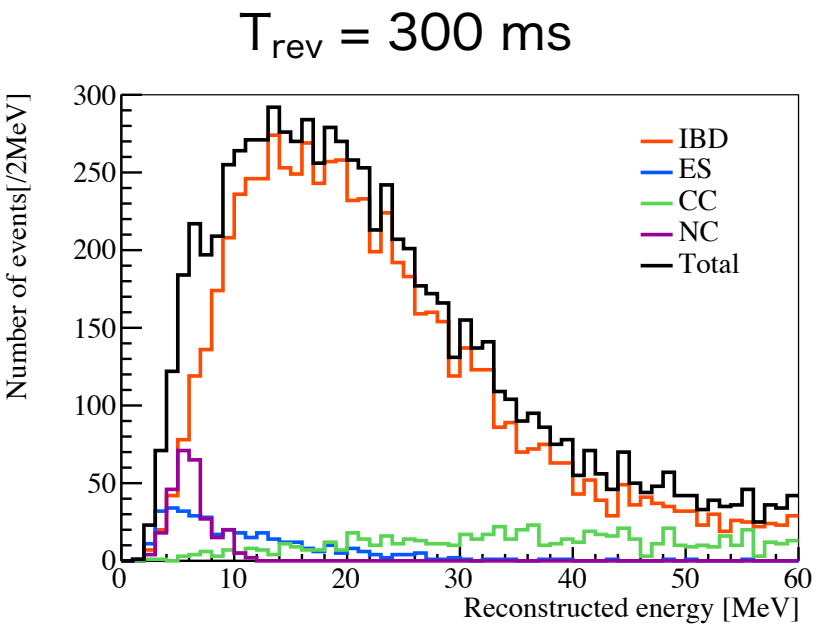


Energy spectrum

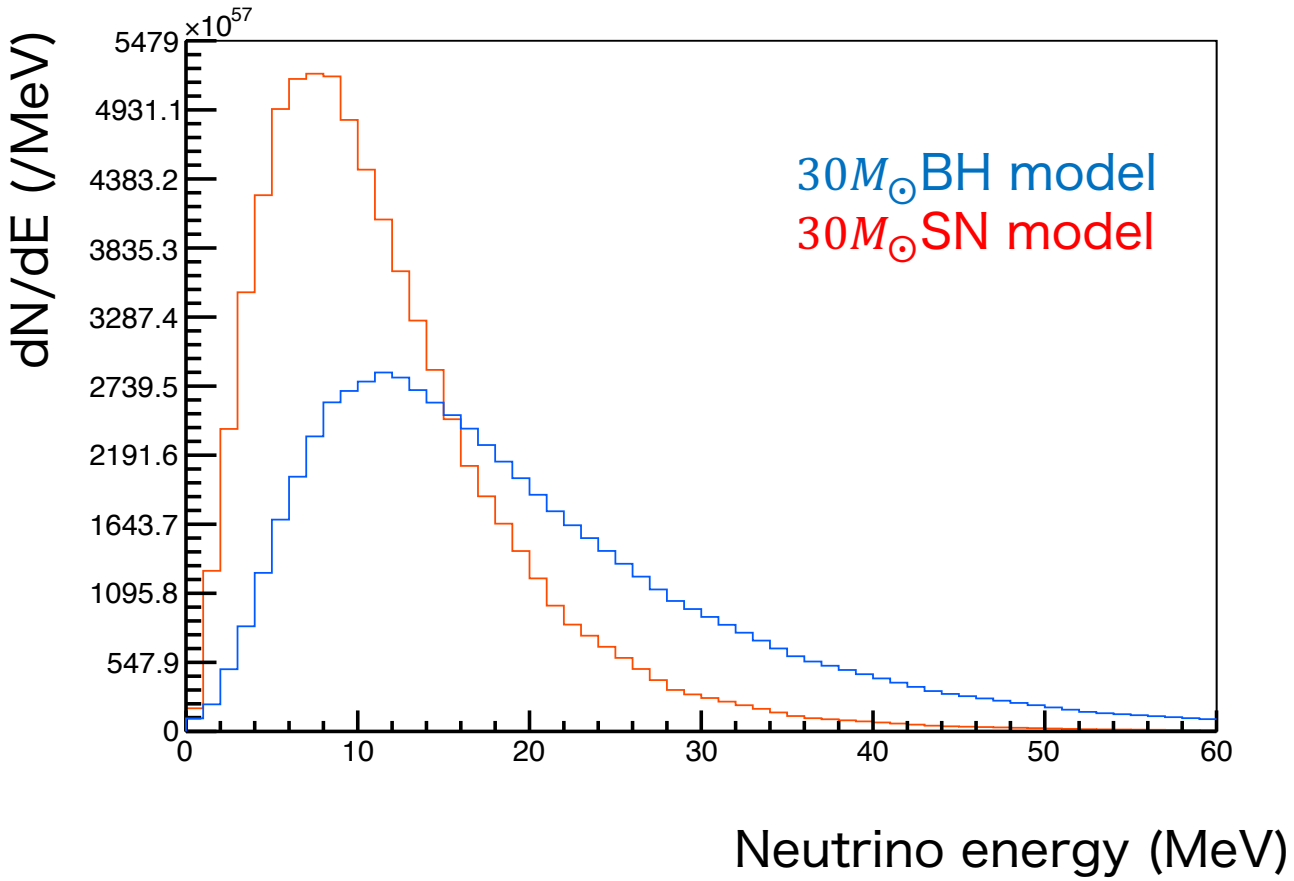
- SN model ($30M_{\odot}$) normal ordering







Neutrino spectrum



T_{rev}=300 ms

反応	$30M_{\odot}$BH model	$20M_{\odot}$SN model
$\bar{\nu}_e + p$	18332	2993
$\nu_e + {}^{16}O$	**2217**	**27.28**
$\bar{\nu}_e + {}^{16}O$	**1282**	**24.14**

Energy spectrum

- BH model