超新星爆発の長時間計算と近傍超新星爆発の解析手法開発

Long-term supernova simulation and an analysis method of nearby supernovae

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Contents

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2. Neutrino signals on earth
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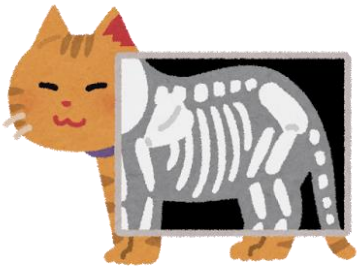
Keywords

Supernova neutrino, Super-Kamiokande, Neutrino observation

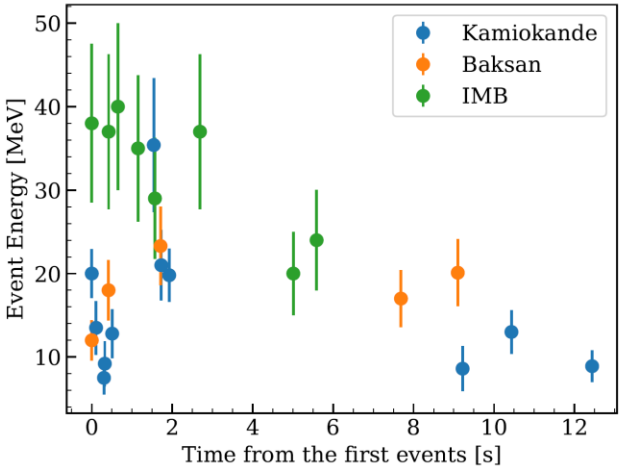
Supernova and Neutrino

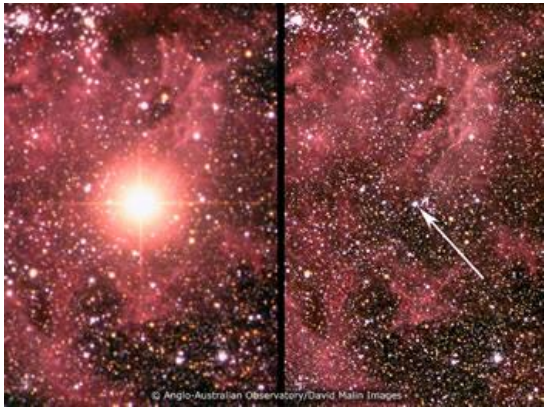
- Huge explosion of heavy stars at their death
- “Brightest” neutrino source
- 99% of Its energy released as neutrinos
  - Neutrinos can penetrate the center
  - ➢Only one observed example: SN1987A



SN1987A events

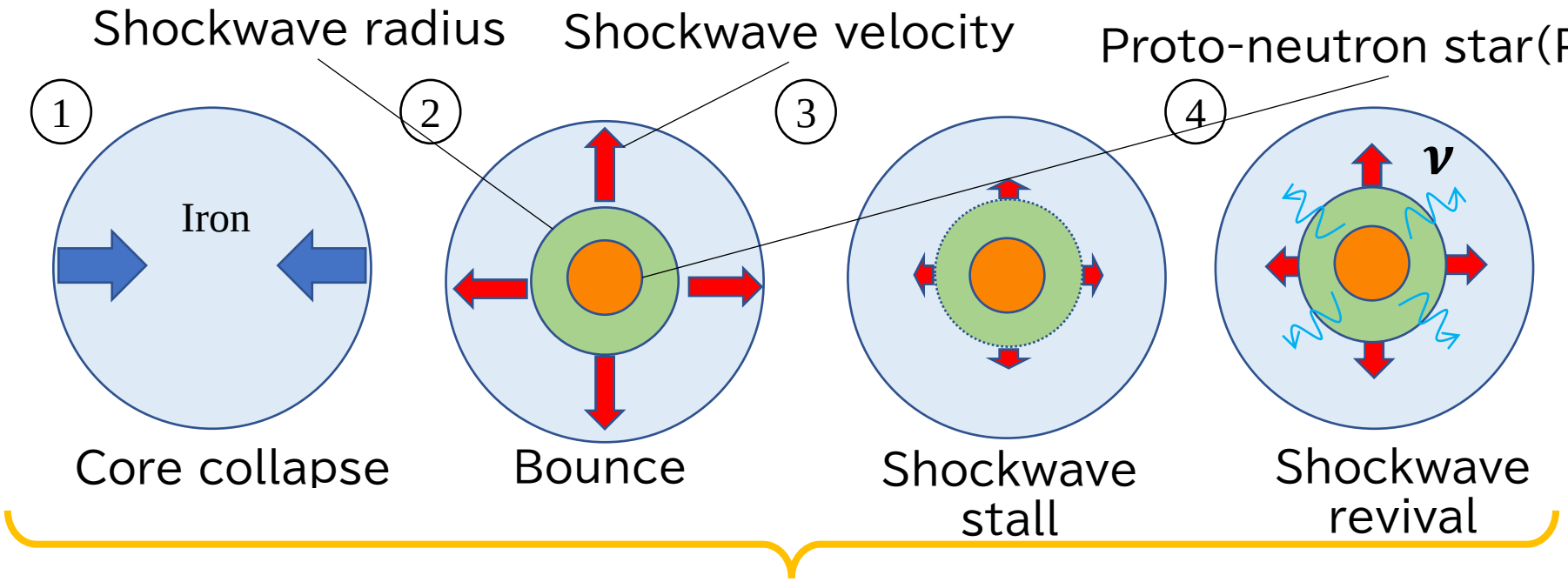
- 11: Kamiokande[1]
- 8: IMB [2]
- 5: Baksan [3]





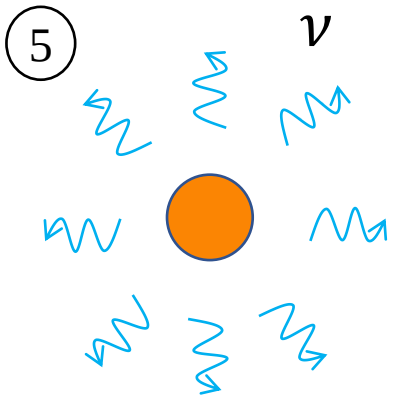
[1]Hirata et al. 1987
[2]Bionta et al. 1987
[3]Alekseev et al. 1987

Supernova evolution



About 1 sec.

More than 1 min.

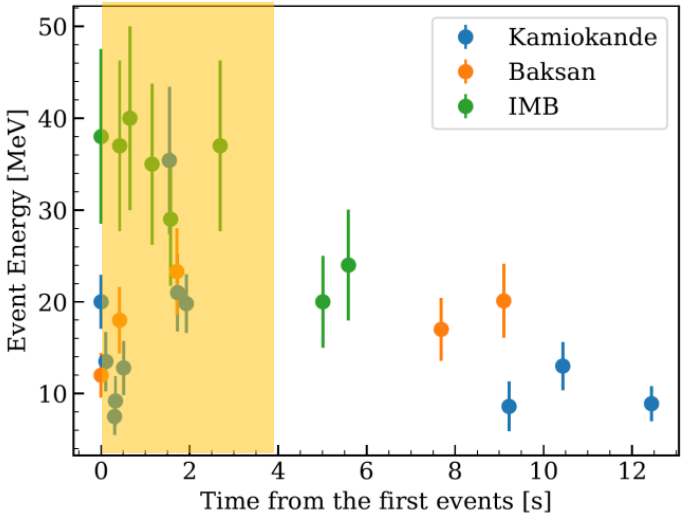


Neutron star cooling

Why long-term simulation needed?

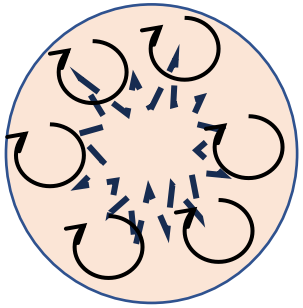
1. Observe neutrinos over 10 s from galactic supernovae
2. Fewer uncertainties at late phase

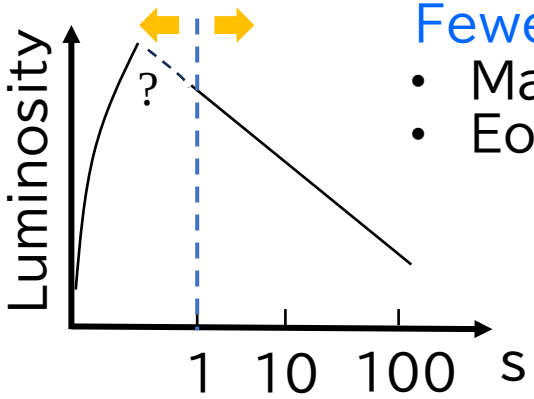
Many Multi-D simulation



More uncertainties (< 1s)

- Mass
- EoS
- Turbulence
- Neutrino oscillation
- etc..



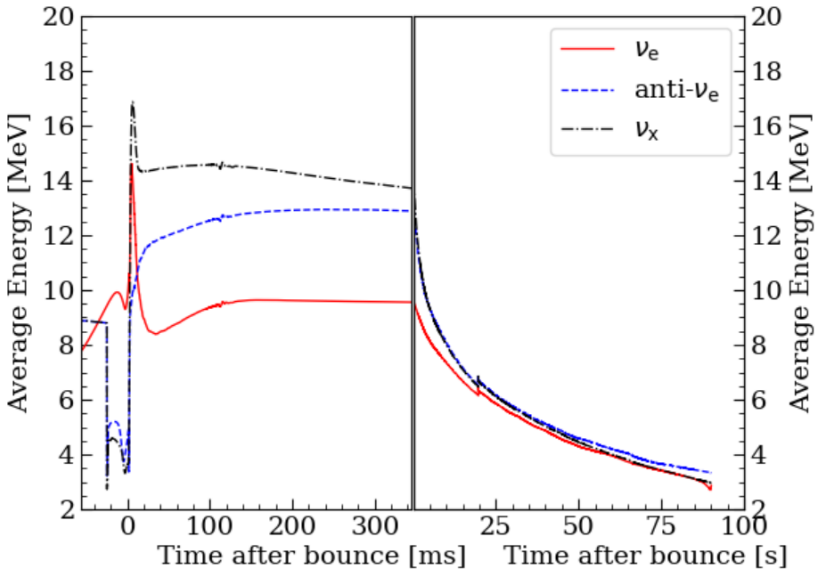


Fewer uncertainties (>1s)

- Mass
- EoS

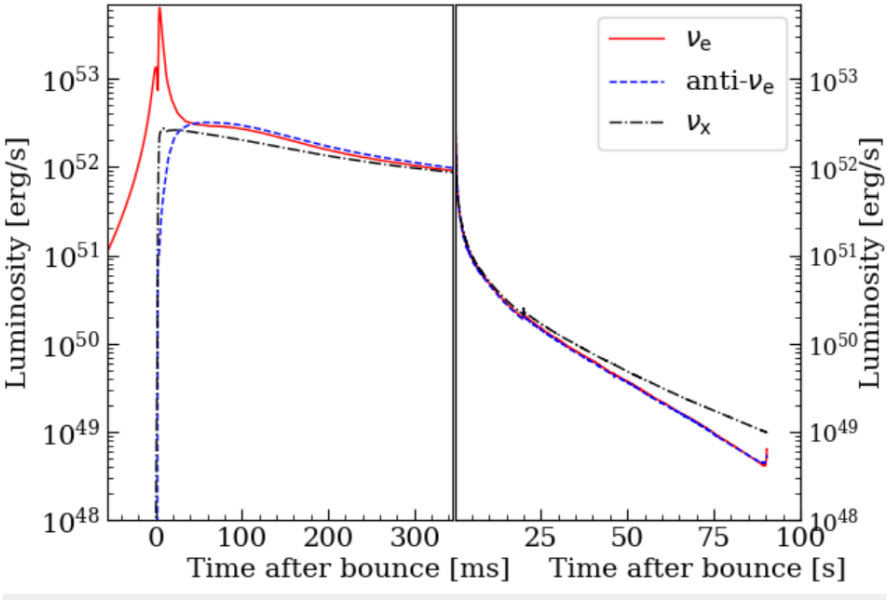
Long-term supernova neutrino simulaiton

Neutrino average energy



ν_x : μ and τ (anti) neutrinos

Neutrino luminosity



Mori et al. 2021

Features

- Simulator: GR1D, EOS: DD2, Progenitor 9.6 Msun

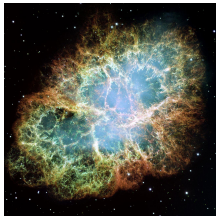
1. General relativistic neutrino radiation hydro simulation in 1D
2. Longest general relativistic neutrino radiation hydro simulation

Neutrino signals on earth

Developing new software

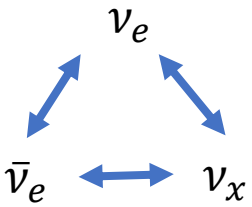
- FORcasting Events from Supernovae Theoretical modeling (FOREST)

- Simulates how signals of supernovae look like on earth
- Mock Samples are used for analysis practice and detector evaluation.



ν

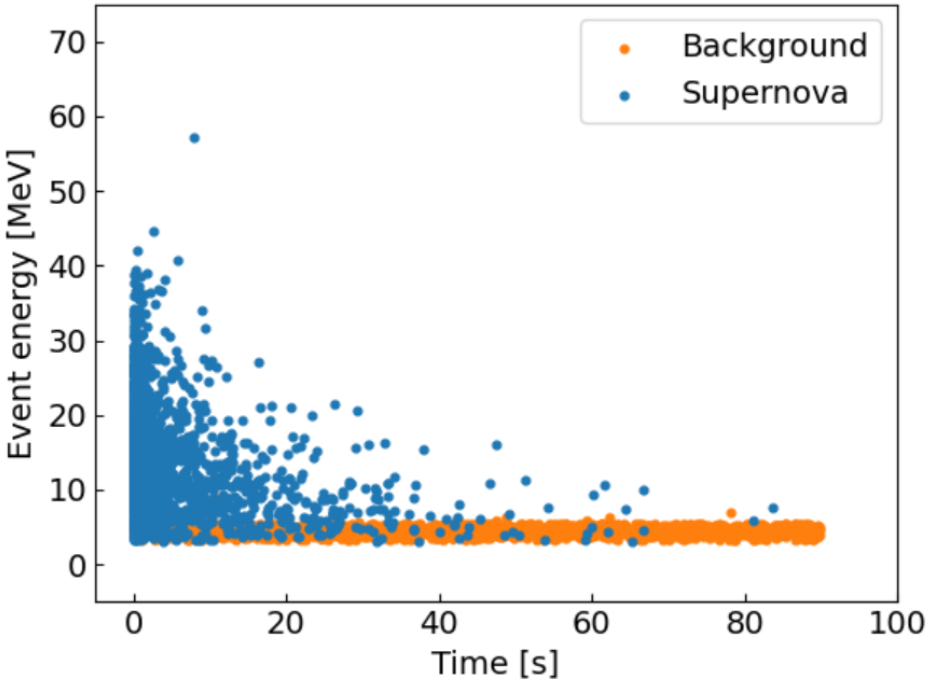
Neutrino oscillation



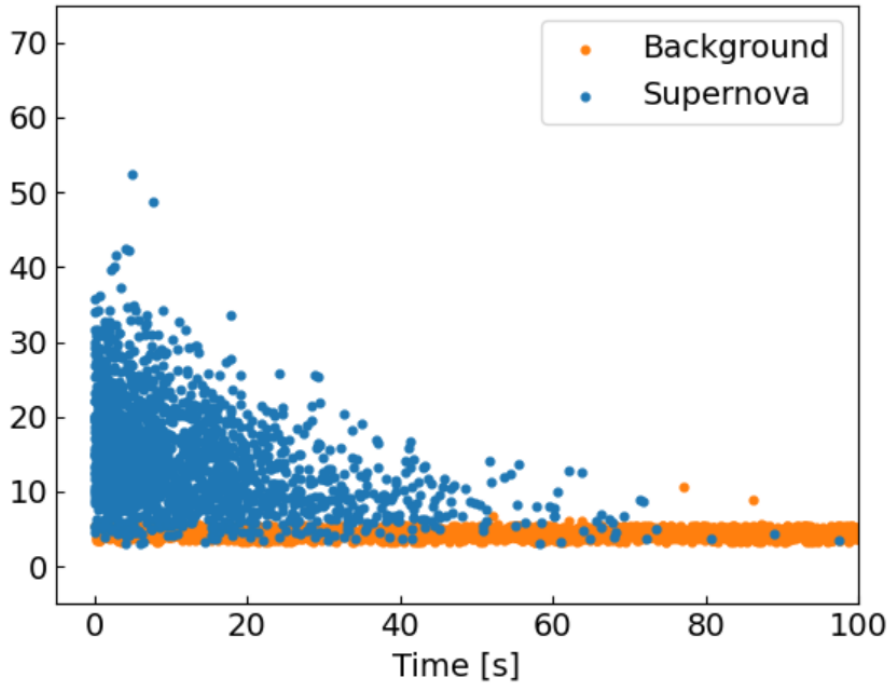
Super-Kamiokande

Mock samples

Simulation



Analytic formula



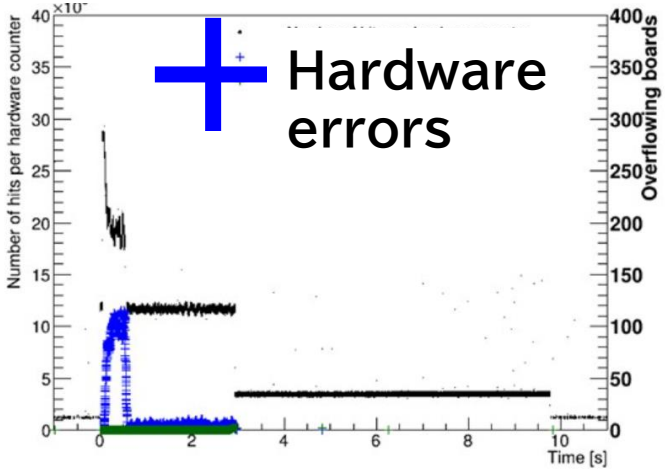
- Assumed a supernova occurs at 10 kpc away
  - Several events after 1 min.
- Analytic formula on the right
  - Suwa et al. (2021)
  - $R(t) = 720\mathrm{s}^{-1}\left(\frac{M_{\mathrm{det}}}{32.5\ \mathrm{kton}}\right)\left(\frac{D}{10\ \mathrm{kpc}}\right)^{-2}\left(\frac{M_{\mathrm{PNS}}}{1.4M_{\odot}}\right)^{15/2}\left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-8}\left(\frac{g\beta}{3}\right)^{5}\left(\frac{t+t_0}{100\ \mathrm{s}}\right)^{-15/2}$

Very nearby supernovae (Mori et al. PTEP (2024))

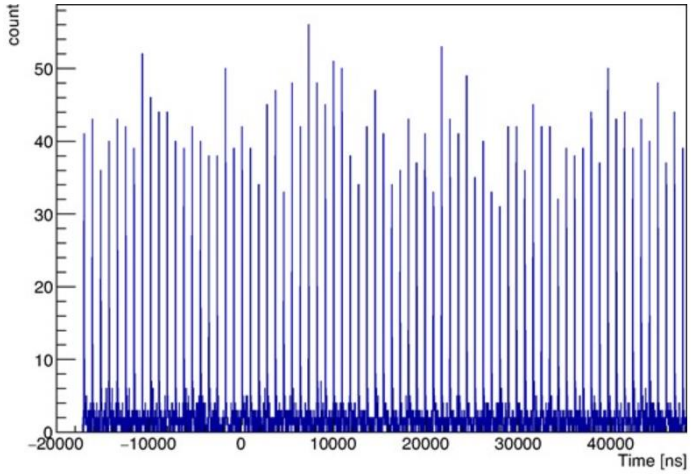
Closer supernovae make longer neutrino emission but…

- For example, Betelgeuse
  - 15 Million events for 10 seconds v.s. 1 event for 1 hour
- SK cannot reconstruct events for very nearby
  - Hardware constraints
  - See Guillaume-san's talk
    - Veto moduleがSKのトークでついに紹介されました!!
  - Neutrino pileups in one event

Hardware constraints



Neutrino pileups



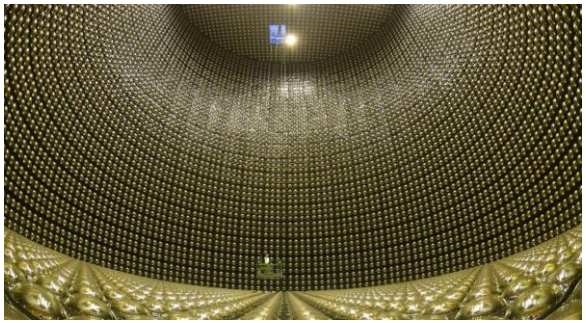
PMT hit analysis

Event

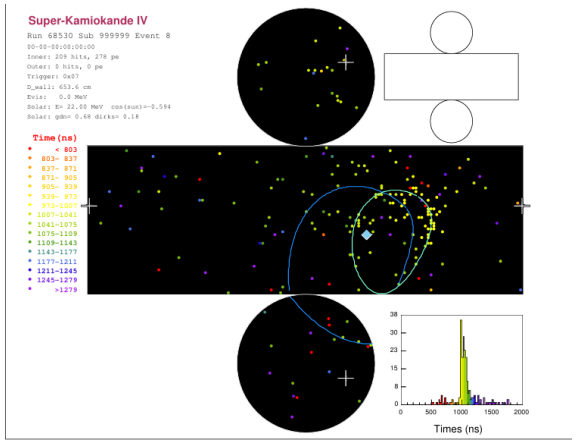
- Unit of physics analyses
- Various information (energy, direction, type of particle)
- Consists of multiple photon hits

PMT hit

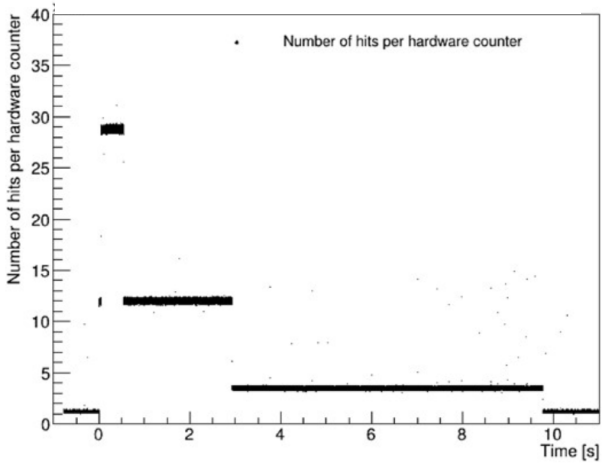
- Most primitive information
- Less information
- Recorded all time whatever happens



Event display of SK

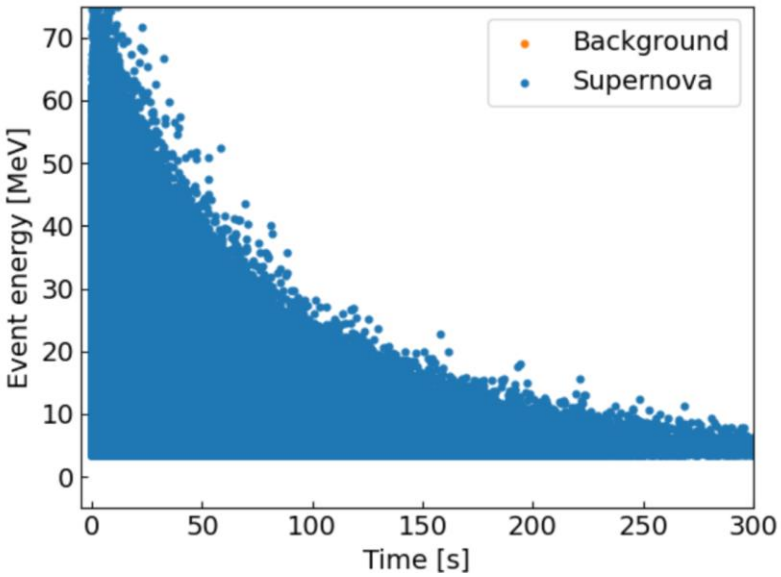


Hit evolution

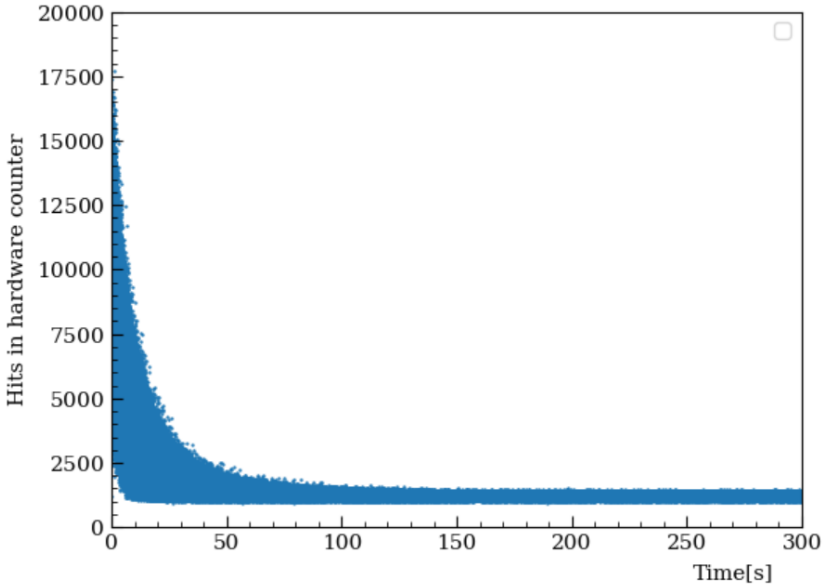


Event and hit simulation of Betelgeuse

Neutrino event



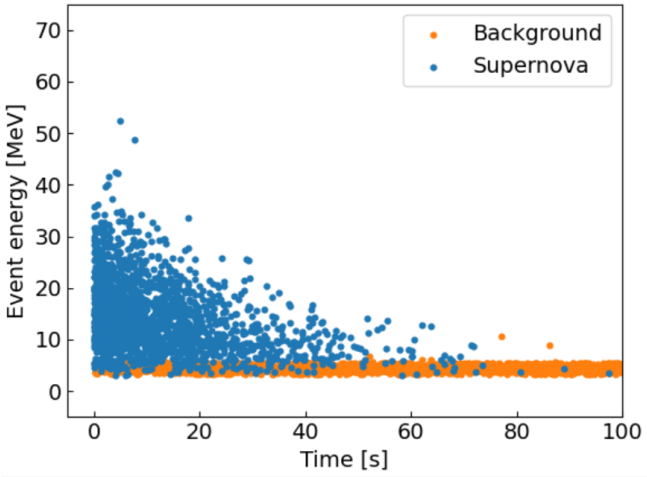
PMT hit rate



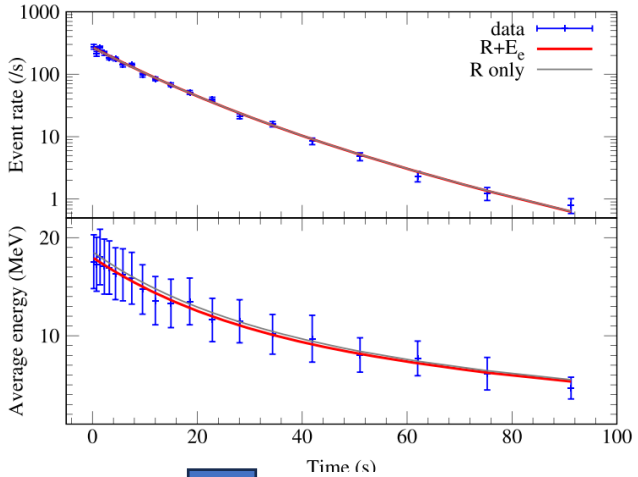
- Hit rate of Betelgeuse calculated by FOREST
- Parameters
  - $M_{PNS} = 1.5 M_{\odot}$
  - $R_{PNS} = 11.8\mathrm{km}$
  - Energy $= 1.5 \times 10^{53}\mathrm{erg}$
  - Distance = 168 pc

How to estimate supernova parameters

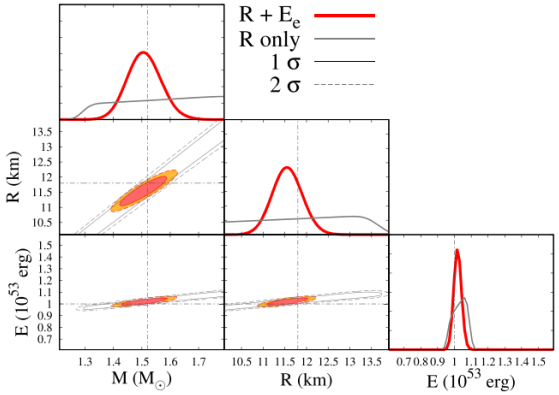
Supernova events



Distributed to time bins



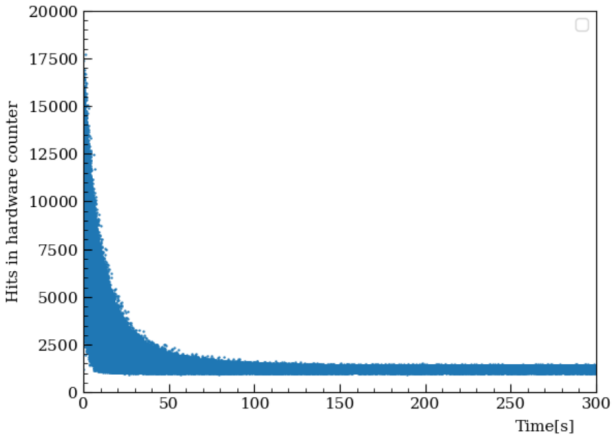
Event rate $R(t)$
and
Average energy $\langle E \rangle(t)$



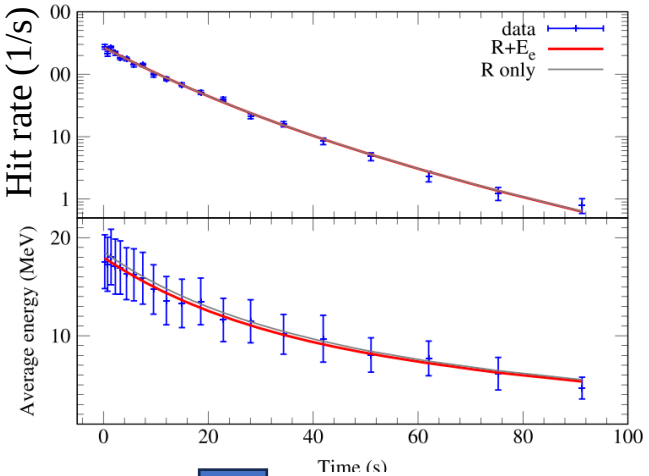
- Bayesian analysis (Suwa et al. (2022), Harada et al. (2023))

How to estimate supernova parameters

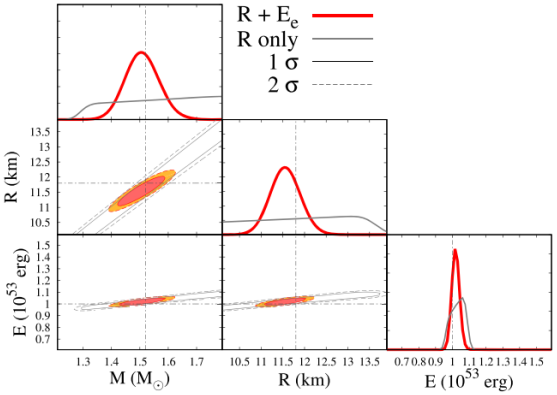
Supernova hit



Distributed to time bins



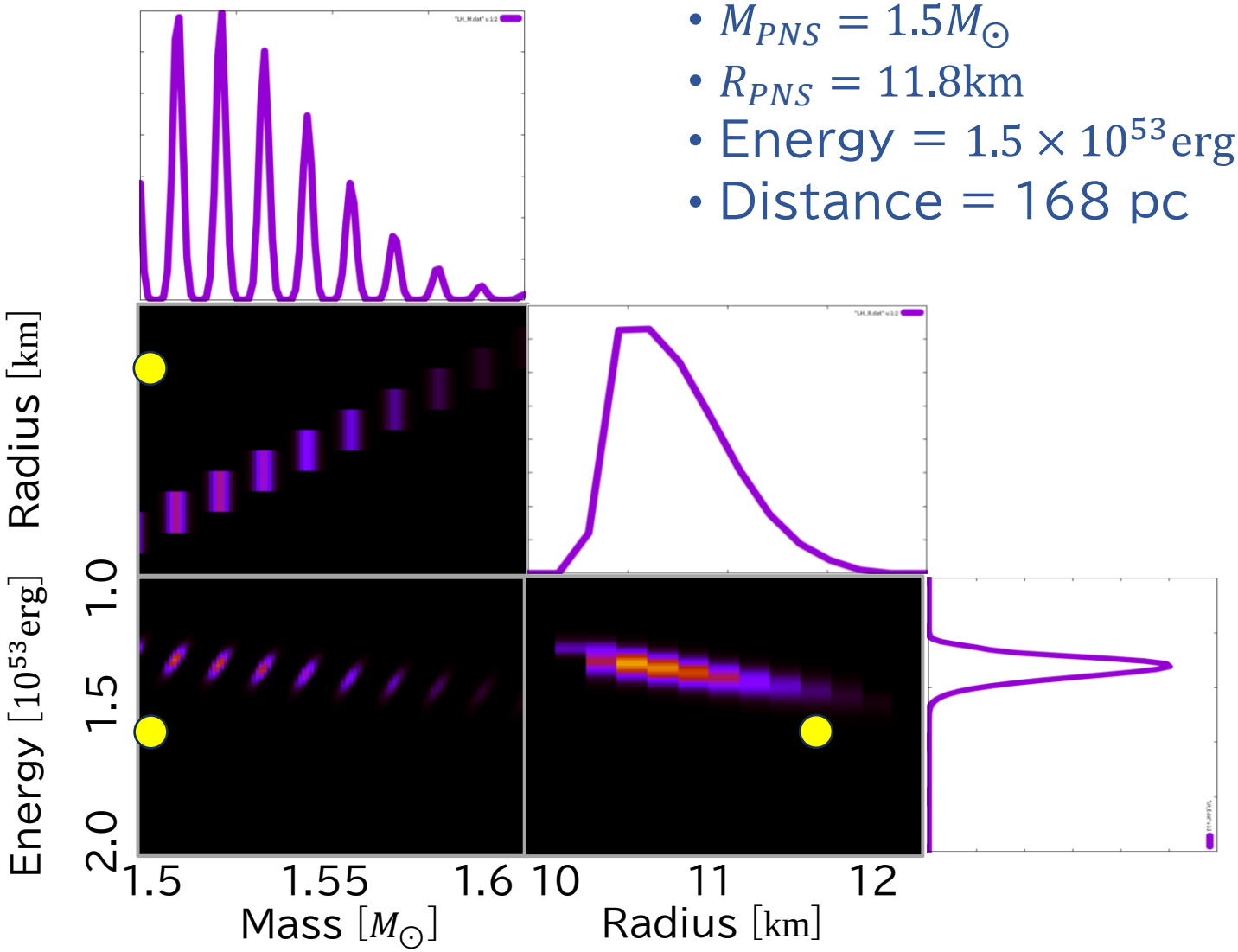
Hit rate $\mathrm{Hit}(t)$
and
Average energy $\langle E \rangle(t)$



- Developing a new analysis with photon hits
- Assumed that energy is partially reconstructed
  - Mori et al. (2024)

Demonstration of Betelgeuse analysis (preliminary)

- Supernova parameters
  - $M_{PNS} = 1.5 M_{\odot}$
  - $R_{PNS} = 11.8\mathrm{km}$
  - Energy $= 1.5 \times 10^{53}\mathrm{erg}$
  - Distance = 168 pc



Summary

- Need long-term simulation for future detection of nearby supernovae
- Established long-term supernova simulation and event simulation at Super-Kamiokande
- Need hit-based analysis for very nearby supernovae
  - Under development
  - The mass distribution oscillates