Long time supernova simulation and supernova burst search at Super-Kamiokande

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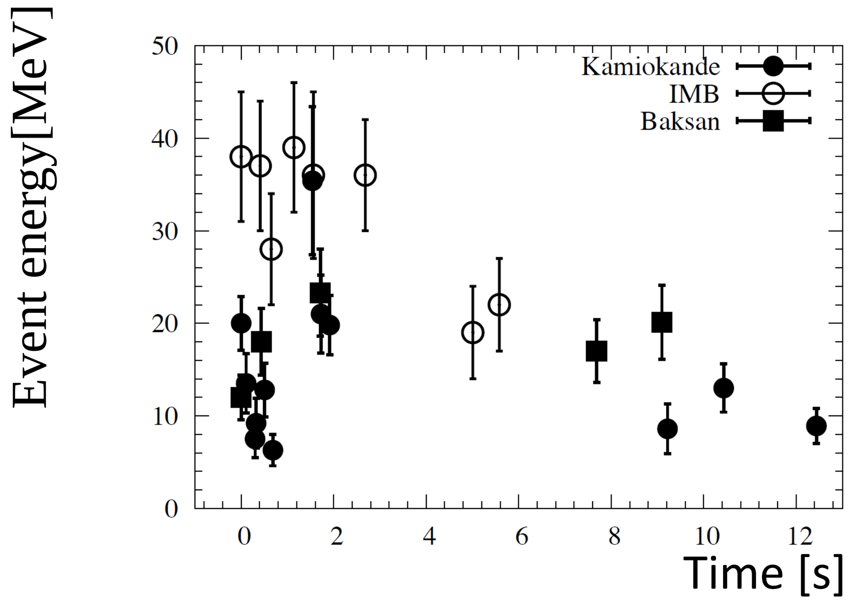
Overview

- This study consists of both numerical simulation and search.
- A new long time simulation was developed and called **Mori model**.
- In addition, searched for a distance supernova using the simulation.

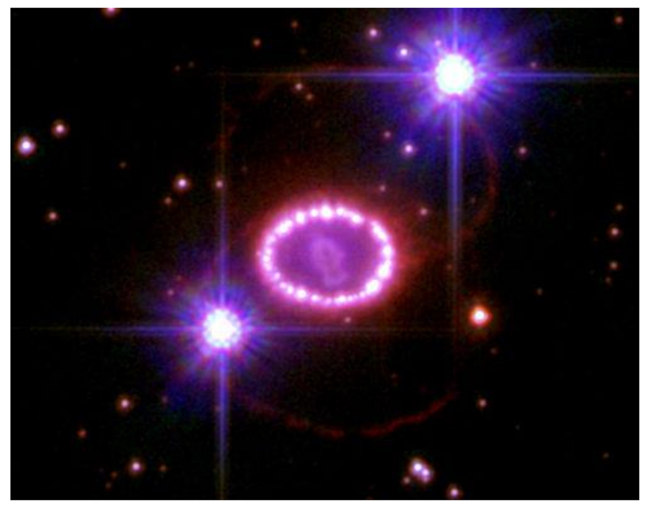
Supernova

- 8 times heavier stars than the sun can hugely explode at their ends.
- Releases a huge amount of neutrino.
- Only one detection of supernova neutrino is SN1987A

Neutrino Events from the SN1987A



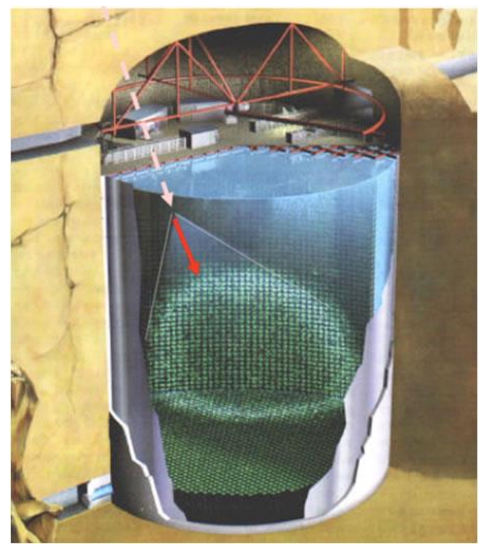
The three detectors in the world observed neutrino from SN1987A for 10 sec. Hirata at el. (1988)



Remnant of SN1987A

http://astro-dic.jp/sn1987a/

Super-Kamiokande(SK)



Schematic of SK

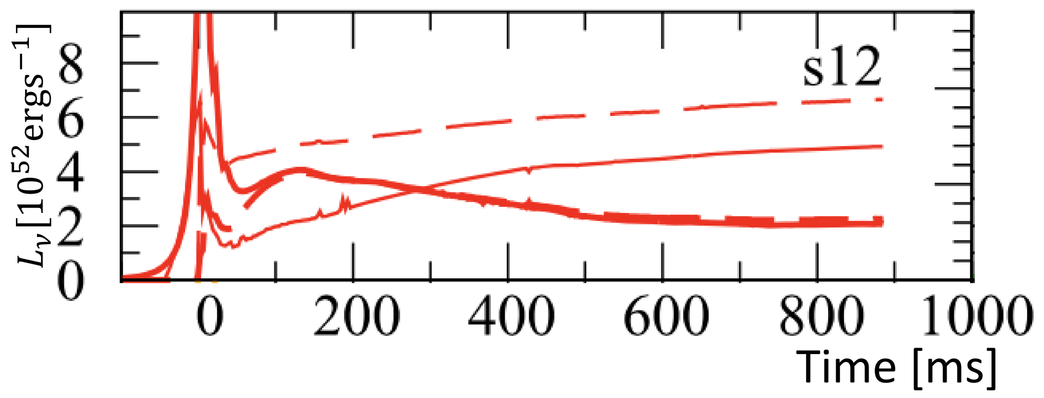
http://www-sk.icrr.u-tokyo.ac.jp/sk/index.html

The inner detector of SK

- The biggest water Cherenkov detector in Japan, which has about 11,000 PMTs and 50kton of water.
- Searching for proton decay and studying neutrino oscillations.
- Monitoring supernovae 24 hours a day.

Supernova neutrino modeling problem

- Most of the simulations concentrate on the first 1 sec.
- However, the neutrino emission continues for more than 10 sec.
- Thus, long time simulations are necessary.



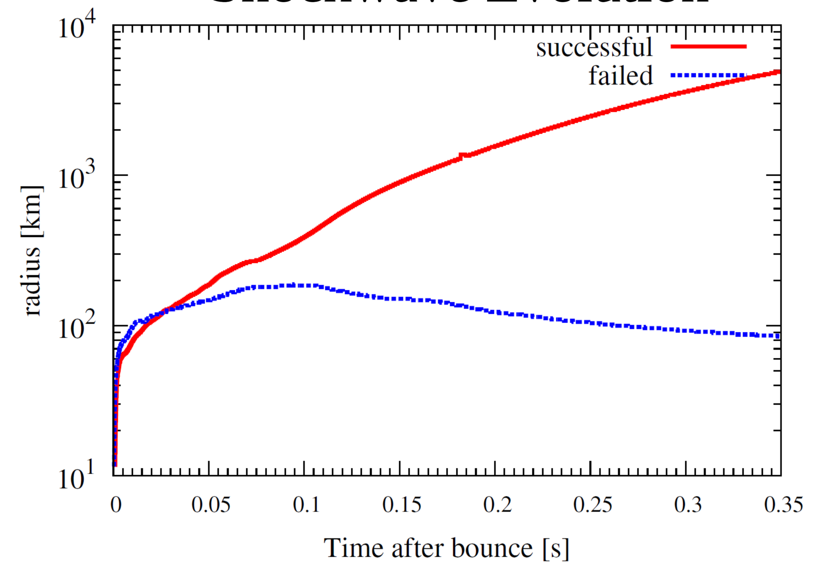
Example of supernova simulation. Suwa et al. (2016)

Note that there are a few simulations which deal with the cooling phase only after 1 sec.
Consistent simulations including protoneutron star cooling are necessary.

1D simulation over long times(Mori model)

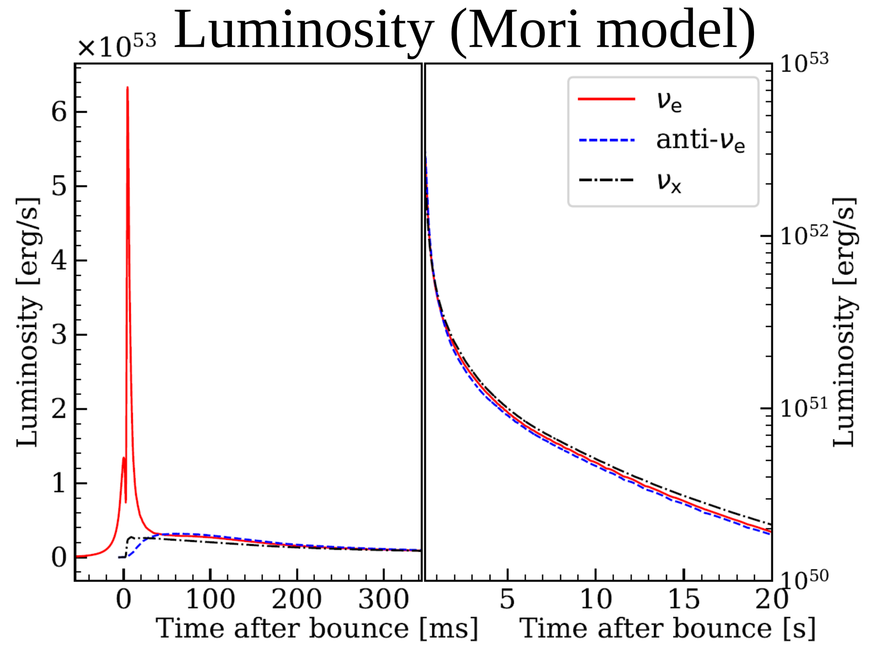
- Code: GR1Dv2 (http://stellarcollapse.org), O'Connor,ApJS 2015
- Parent Star:9.6 solar mass, Woosley and Heger,ApJS 2015
  - Many authors report that this model can explode in 1D.

Shockwave Evolution



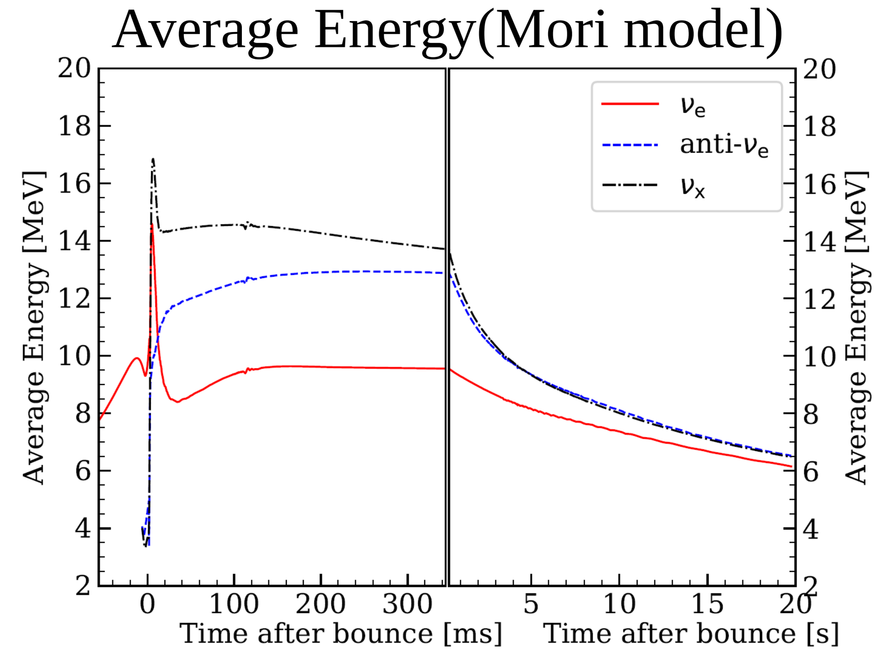
Red line shows the shock wave of the 9.6 solar mass model and blue line shows that of another model which fails to explode. In the successful model, the shock wave continues to expand.

Luminosity (Mori model)



ν_x: mu and tau (anti) neutrino

Average Energy(Mori model)



- **20 sec simulation is successful.**

Supernova burst search at SK

- SK always monitor supernova for 24 hours.
- However, this monitor can fail to detect distant supernovae.
- Therefore, searched for distance supernova burst .
- Assumed the long time simulation (**Mori model**).

Method

■ Searched for event clusters.

- Event clusters mean collections of events in a short time.
- Used data of SK from 2008 to 2018.
- Live time: 3318.41 days

■ Event selection

- Energy: > 5.5 MeV
- Distance from the wall: > 200 cm
- Time difference with a previous event: > 50 micro sec
- Fitting quality cut: Qvaq > 0.25 ($\langle \mathrm{Ovaq} \rangle_{SN}$ ~ 0.45)

■ Event cluster criteria

> 2 events in 0.5 sec or > 2 events in 2 sec or > 4 events in 10 sec

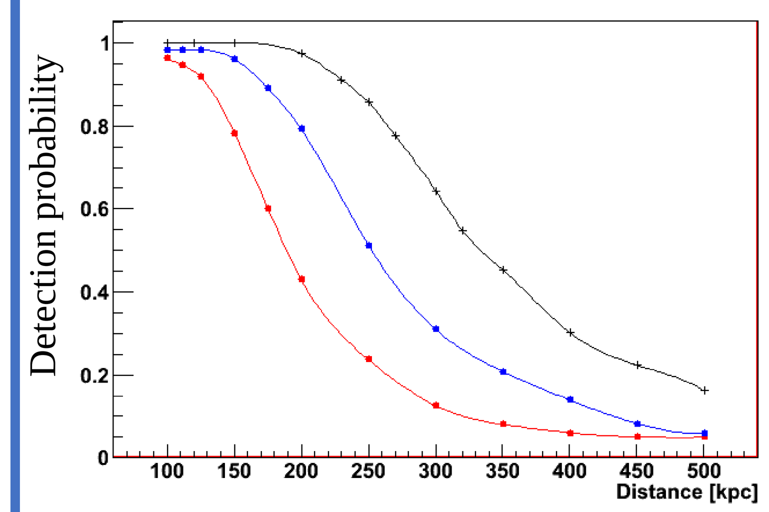
■ Check three cluster parameters

1. Cluster uniformity in space
   - Volume-like, plane-like, line-like and point-like
2. Mean Energy
   - $E_{\mathrm{mean}} = \frac{\sum_i E_i}{N}$
3. Mean distance between events
   - $R_{\mathrm{mean}} = \frac{\sum_{i=1}^{M-1}\sum_{j=i+1}^{M}|r_i - r_j|}{{}_M C_2}$

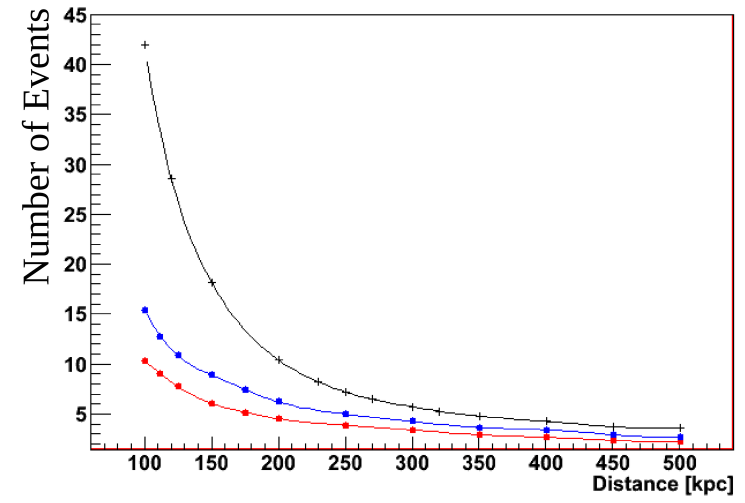
- These criteria were optimized using Mori model

Detection probablity and Predicted events

Detection probability



Predicted events

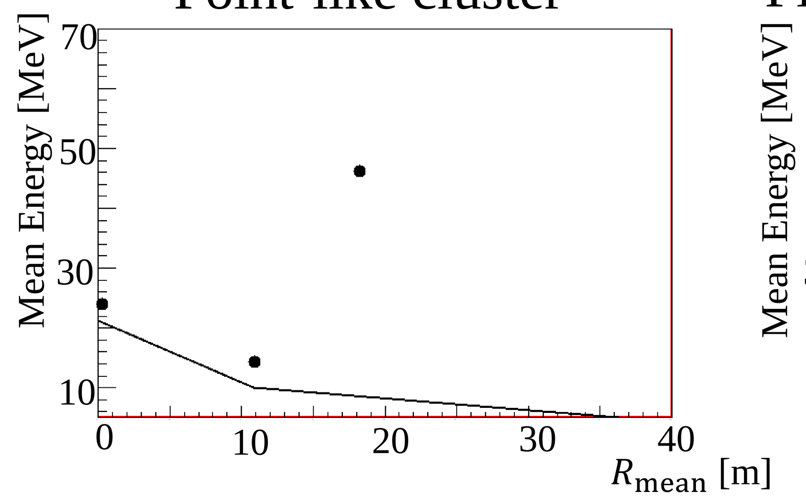


- Detection probability of this search is almost 100% up to 100 kpc.
  - Mori model: 96.3% at 100 kpc
  - Nakazato model: 98.4% at 100 kpc
- Predicted events at 100 kpc
  - Mori model: 10 events
  - Nakazato model: 20 events

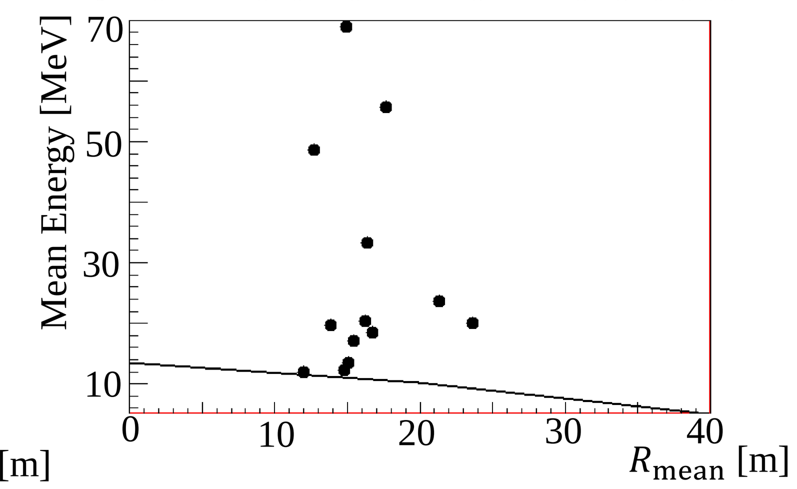
● Mori model
● Nakazato model
Nakazato et al. (2013)
+ Livermore model (for reference)
T. Totani et al. (1998)

Search result

Point-like cluster

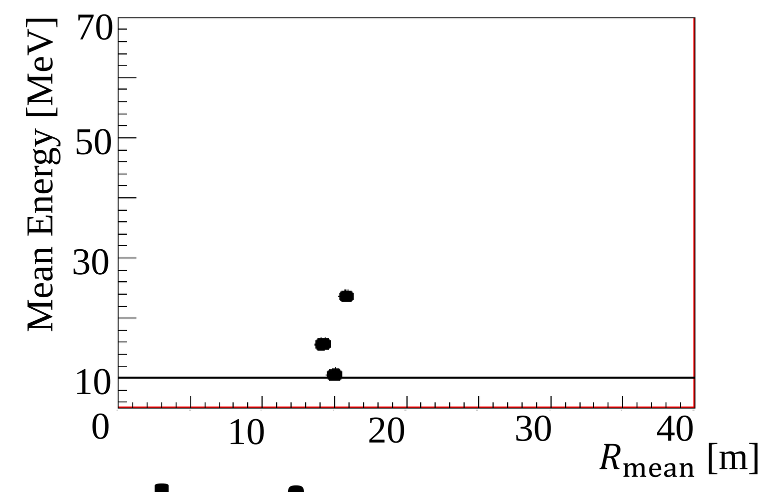


Plane-like and Line-like cluster



- Signal regions are above lines
  - Point-like: 4 clusters
  - Plane- and line-like: 13 clusters
  - Volume-like: 3 clusters
- However 1 cluster is spallation and the others are DAQ errors
- **No supernova candidate**

Volume-like cluster



Summary and conclusion

- Current supernova models simulate only 1 sec.
- Thus, the long time new model was developed.
- Next step, searched for a distant supernova with optimized with the new model at SK.
- No supernova candidate was found.
- The upper limit of supernova rate up to 100 kpc is

0.26 [SN/year] (90%C.L.)