Long time supernova simulation and search for supernovae at Super-Kamiokande

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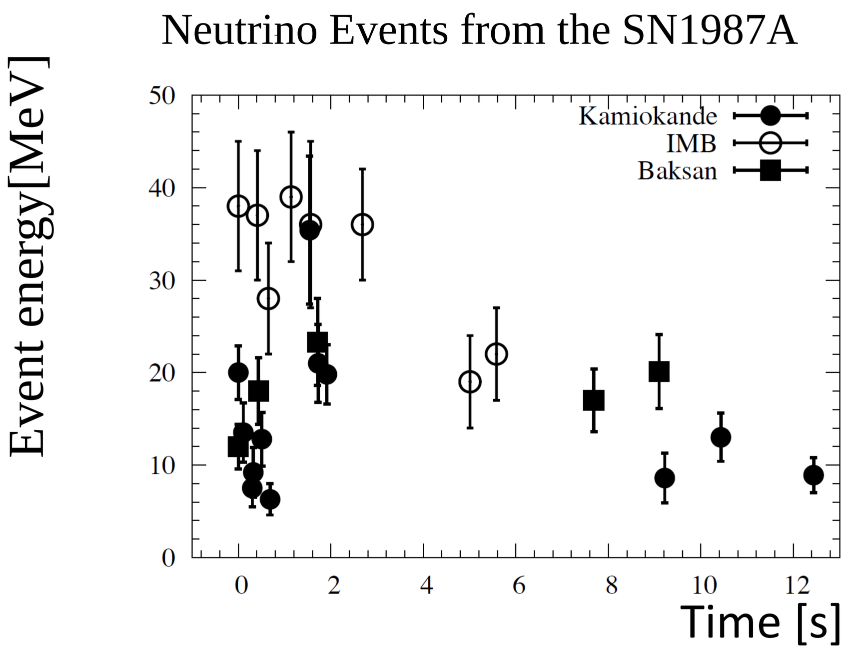
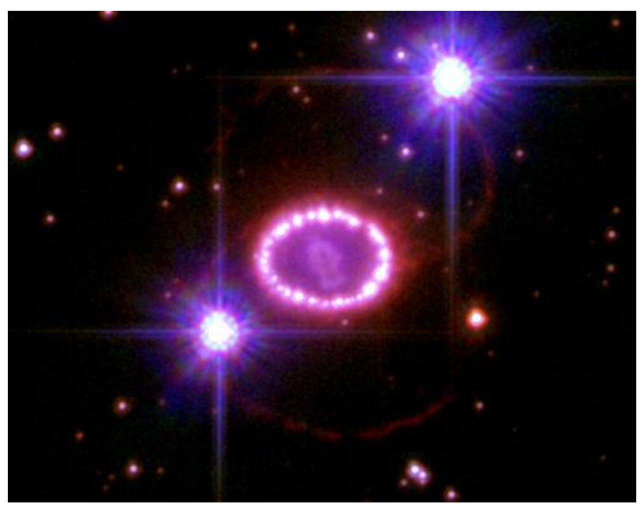
Supernova

- 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

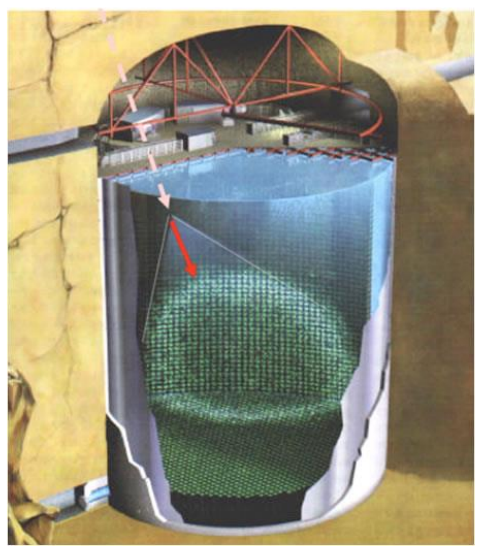


The three detectors in the world observed neutrino from SN1987A for 10 sec. Hirata at el. (1988)



Remnant of SN1987A
http://astro-dic.jp/sn1987a/

Super-Kamiokande(SK)



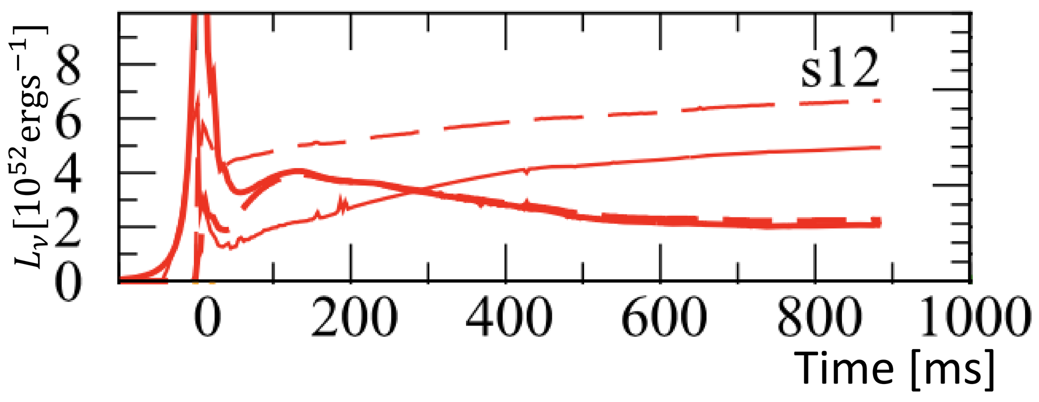
Schematic of SK
http://www-sk.icrr.u-tokyo.ac.jp/sk/index.html

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.

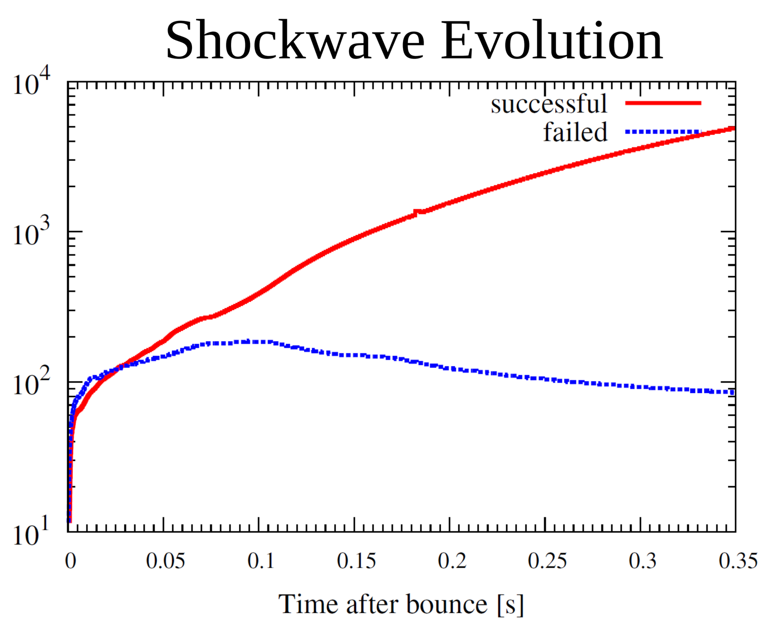


Example of supernova simulation. Suwa et al. (2016)

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.

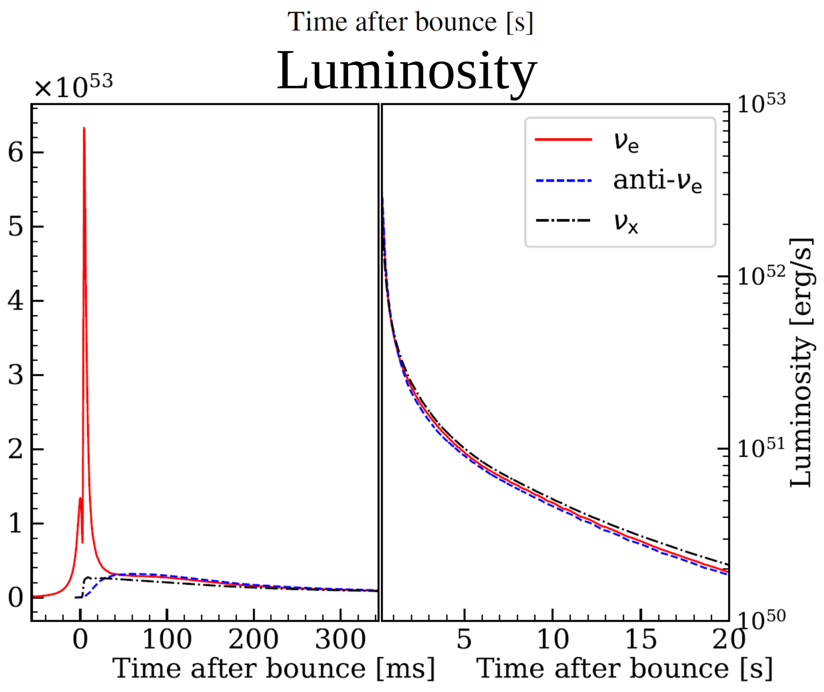
1D simulation over long times

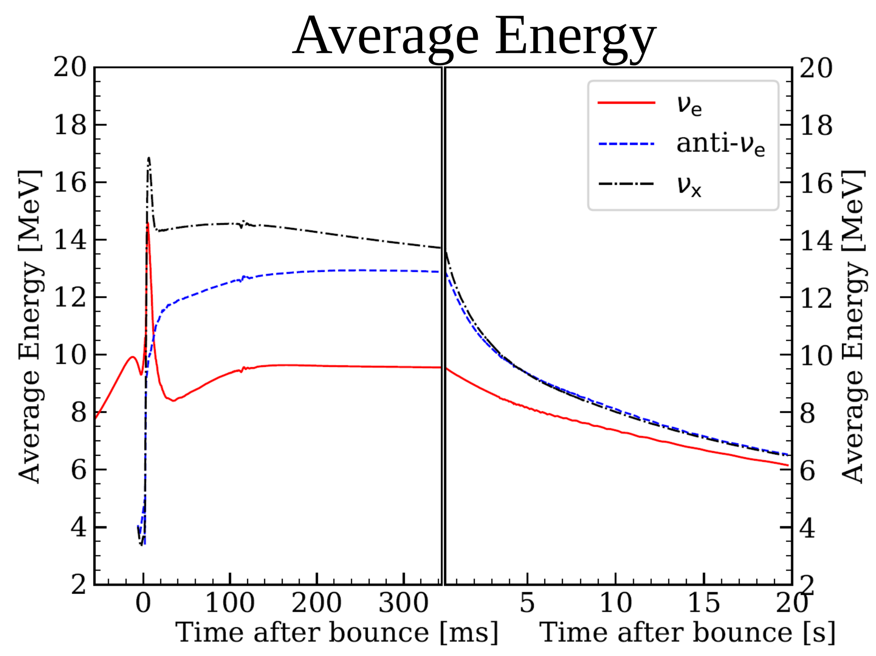
- Code: GR1Dv2 (http://stellarcollapse.org), O'Connor,ApJS 2015
- Parent Star:9.6 solar mass, Woosley and Heger,ApJS 2015
  - Many authors report that this model can explode in 1D.



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.

ν_x: mu and tau (anti) neutrino





- **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 previous long time simulation (called Mori model).

Method

■ Searched for event clusters.

- Event clusters mean a collection 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
- Ovaq > 0.25 (Related to fitting quality)

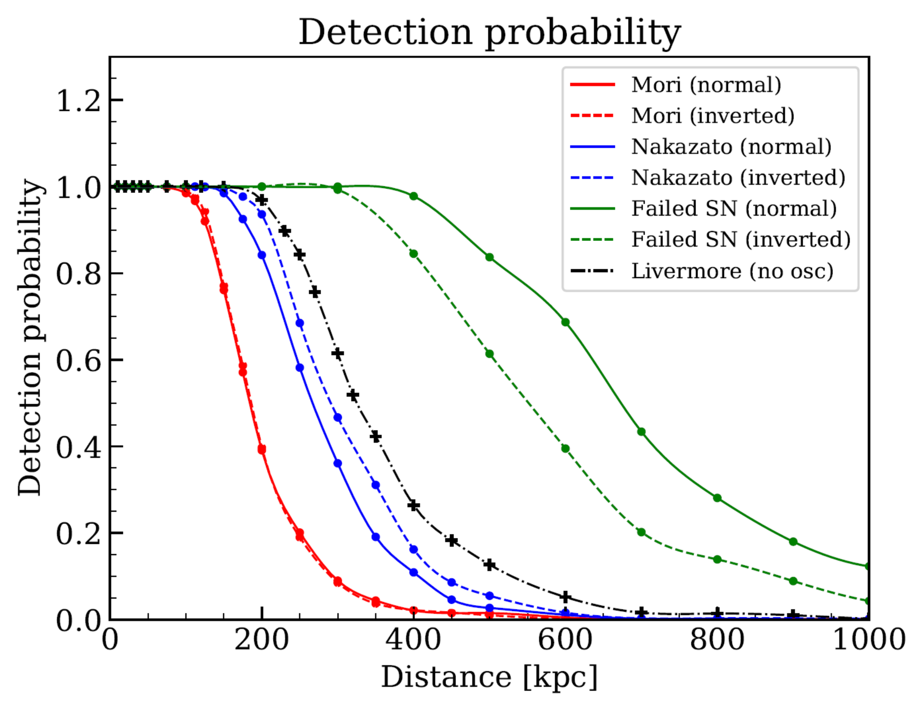
■ Event cluster criteria

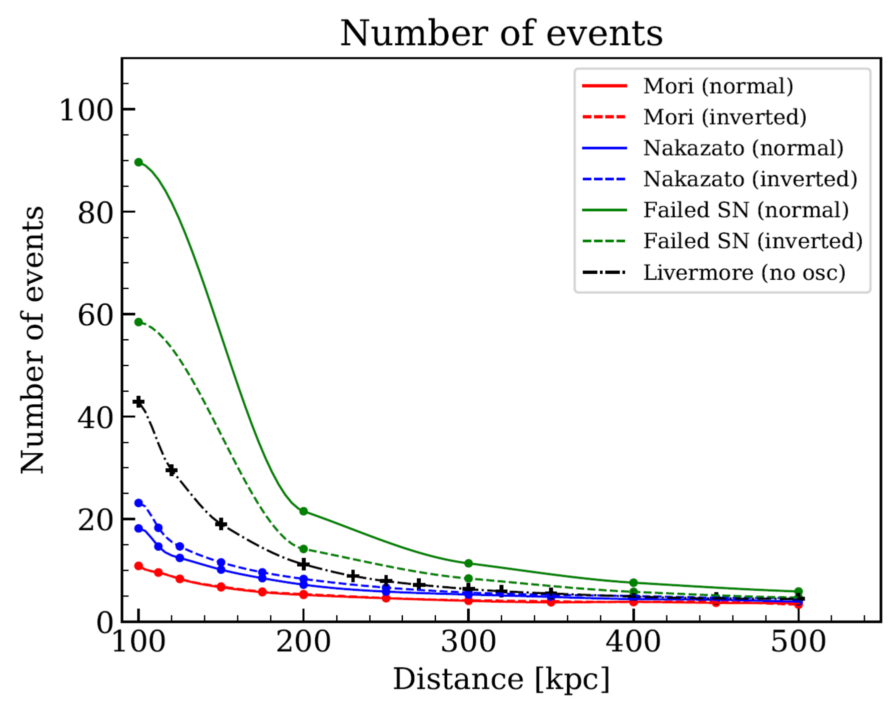
> 2 events in 0.5 sec or > 2 events in 2 sec or > 4 events in 10 sec

■ Check cluster parameters below

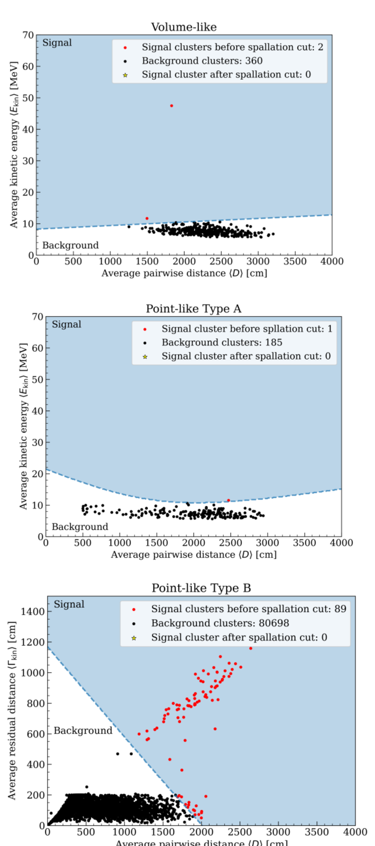
- Dimension
  - Volume-like, Plane-like, Line-like, Point-like
- Average kinetic Energy, where M is the number of events in clusters
  - $\langle E\rangle = \frac{\sum_i E_i}{M}$
- Average pairwise distance between events
  - $\langle D\rangle = \frac{\sum_{i=1}^{M-1}\sum_{j=i+1}^{M}|\boldsymbol{d}_i-\boldsymbol{d}_j|}{{}_M C_2}$
- Average residual distance, where $\boldsymbol{d}_0 = 1/M\sum_{i=1}^{M}\boldsymbol{d}_i$
  - $\langle\Gamma\rangle = \sqrt{\frac{1}{3(M-1)}\sum_{i=1}^{M}(\boldsymbol{d}_i-\boldsymbol{d}_0)^2}$
- These criteria were optimized using Mori model and machine learning

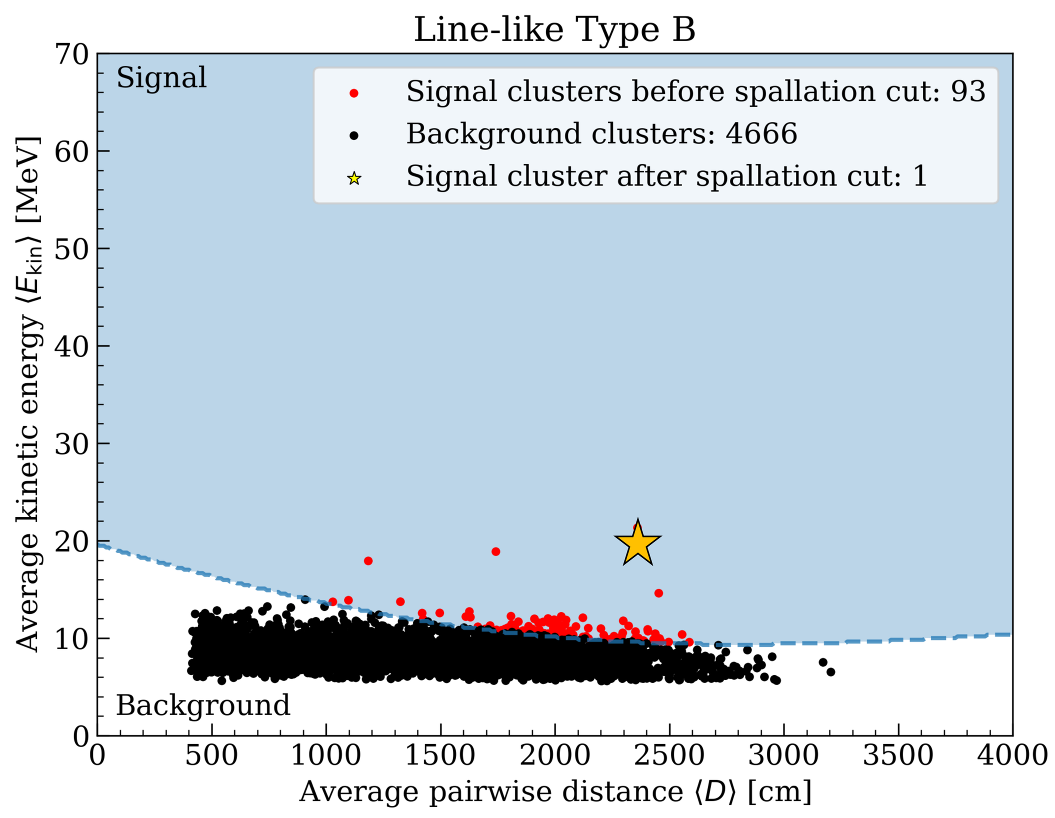
Detection probability and Predicted events





Search result





- One cluster labeled star remains after all cuts but this is not supernova-like.
- **No supernova candidate**

Summary and conclusion

- current supernova models simulate only 1 sec.
- Thus, a 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 distance in which probability is 100% is **0.36 [SN/year] (90%C.L.)**