# Search for Neutrinos from Supernovae out to 10 Mpc in Super-Kamiokande

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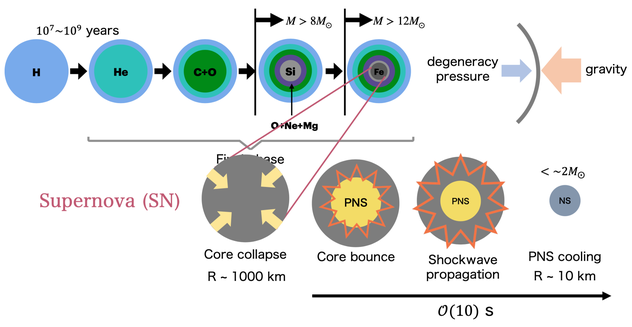
## 1. Introduction: What we looked for?

### supernova (SN) explosion

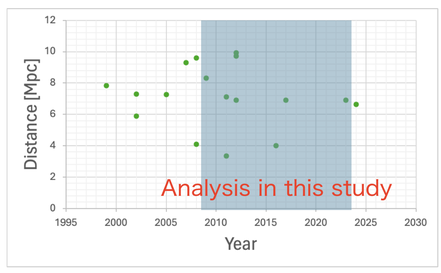
- >99% of gravitational energy in SN explosion is released as $\nu$
- SN neutrino provides information about the explosion mechanism




### Supernova out to 10 Mpc

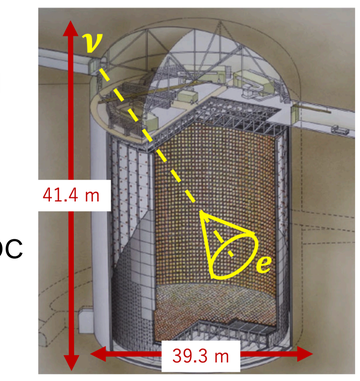
- Super-Kamiokande can search for neutrinos
- Search for neutrinos from SNe since 2009 in this time

| | Distance [Mpc] | Detection date | Estimated SBO date | Signal region | Live time [day] |
|---|---|---|---|---|---|
| SN2023ixf | ~ 7 | May 19, 2023 | May 18, 2023 | May 9 - 19, 2023 | 9.8 |
| SN2017eaw | ~ 7 | May 14, 2017 | May 06, 2017 | Apr. 26 - May 07, 2017 | 11.1 |
| SN2012aw | ~ 10 | Mar. 16, 2012 | Mar. 15, 2012 | May 03 - 16, 2012 | 9.8 |
| SN2012A | ~ 10 | Jan. 07, 2012 | Jan. 04 or 8, 2012 | Dec. 26 - Jan. 08, 2012 | 9.7 |
| SN2011dh | ~ 7 | May 31, 2011 | May 31, 2011 | May 20 - Jun. 1, 2011 | 11.8 |
| SN2011ja | ~ 3 | Dec. 18, 2011 | Dec. 12, 2012 | Dec. 02- 13, 2011 | 9.6 |
| SN2009hd | ~ 8 | Jul. 02, 2009 | Jun. 19, 2009 | Jun. 07 - 20, 2009 | 8.8 |



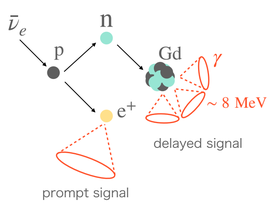

### Super-Kamiokande

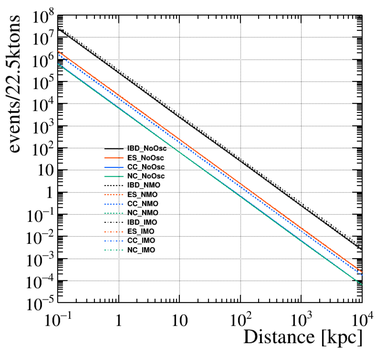
- Observe Cherenkov light from charged particles[1]
- Determine the energy ($E$) and time ($T$) for each neutrino event accurately
- Expected event in SK: O(1) events in about 10 Mpc
- Neutrons can be detected using the delayed coincidence method as below




### SK-Gd experiment

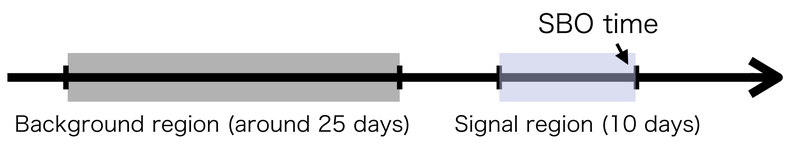
- Started from 2020 to improve neutron detection efficiency by thermal n-capture on Gd[2, 3]
- Gd mass concentration: 0.03%
- Capture fraction on Gd: ~75%
  → >60% of neutron can be identified



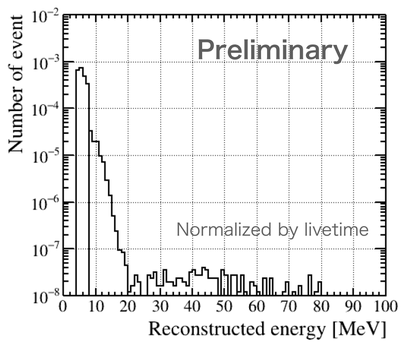




## 2. Analysis strategy: SN neutrino search method

**Determine signal & background region**




**Search for excess from background events**

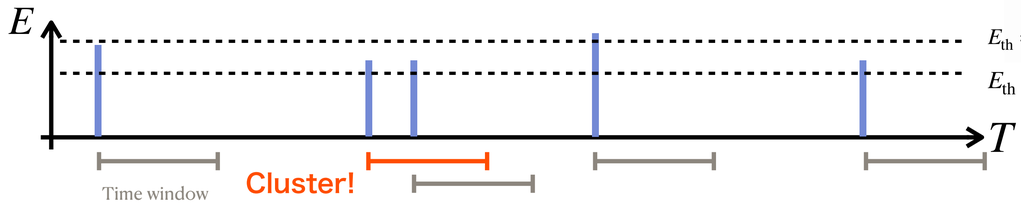


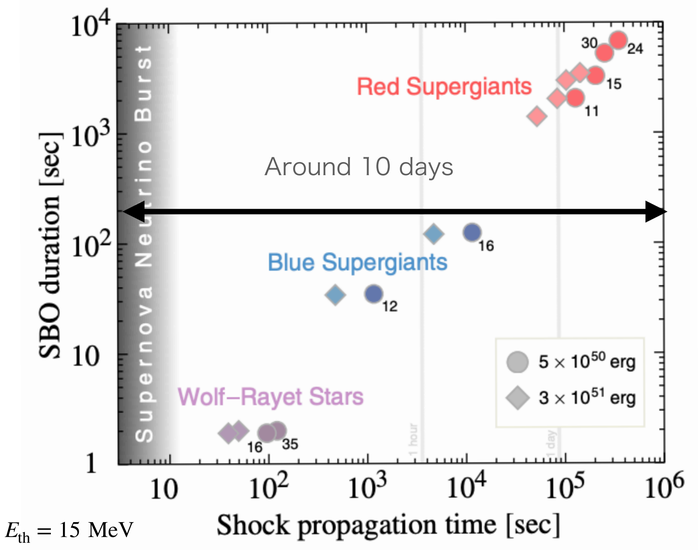

**Analysis condition**

1. Eth = 8 MeV, 15 MeV
2. Applying neutron tagging (Eth = 8 MeV)

**Cluster search in the signal region**

- Sliding window search in signal region
- Cluster condition: 2events / 10 sec




## 3. Results: upper limits and sensitivity

### Cluster search

→There was no cluster in the signal region

### Search for excess from background events

Minimum p-value: 0.62
→There was no excess from the background

| | BG exp | #of event | P-value | BG exp | # of event | P-value | BG exp (with ntag) | # of event (with ntag) |
|---|---|---|---|---|---|---|---|---|
| Energy thr | 8 MeV | 8 MeV | 8 MeV | 15 MeV | 15 MeV | 15 MeV | 8 MeV | 8 MeV |
| SN2023ixf | 99.4±6.2 | 108 | 0.82 | 0.8±0.3 | 0 | 0.51 | 0.1±0.07 | 0 |
| SN2017eaw | 104.6±6.3 | 97 | 0.77 | 1.5±0.8 | 1 | 0.61 | 0.3±0.04 | 0 |
| SN2012aw | 108.6±6.5 | 105 | 0.63 | 1.9±0.9 | 1 | 0.71 | 0.2±0.04 | 0 |
| SN2012A | 105.2±6.3 | 102 | 0.62 | 1.9±0.8 | 1 | 0.72 | 0.2±0.04 | 0 |
| SN2011dh | — | — | — | 1.6±0.8 | 3 | 0.13 | 0.3±0.04 | 0 |
| SN2011ja | 102.7±6.8 | 94 | 0.80 | 1.7±0.9 | 2 | 0.39 | 0.2±0.0.04 | 0 |
| SN2009hd | — | — | — | 1.2±0.7 | 2 | 0.22 | 0.2±0.0.03 | 0 |

### Fluence upper limit

$$\Phi_{lowe} = \frac{N_{90}}{N_T \int dE_\nu \lambda(E_\nu)\sigma(E_\nu)R(E_e, E_{vis})\varepsilon(E_{vis})}$$

$N_{90}$: 90% C.L. limit on neutrino events
$N_T$: #of targets number density
$\sigma(E_\nu)$: cross section
$\varepsilon(E_{vis})$: efficiency

- We assume the Nakazato model[4]: ($20M_\odot$, shock revival time = 200 ms, NMO)
- Fluence upper limit [/cm$^2$]

| | SN2023ixf | SN2017eaw | SN2012aw | SN2012A | SN2011dh | SN2011ja | SN2009hd |
|---|---|---|---|---|---|---|---|
| Eth = 8 MeV | $5.36 \times 10^8$ | $3.01 \times 10^8$ | $3.48 \times 10^8$ | $3.46 \times 10^8$ | – | $2.89 \times 10^8$ | – |
| Eth = 15 MeV | $5.04 \times 10^7$ | $6.58 \times 10^7$ | $6.39 \times 10^7$ | $6.39 \times 10^7$ | $1.11 \times 10^8$ | $8.45 \times 10^7$ | $9.12 \times 10^7$ |
| Eth = 8 MeV (with ntag) | $7.42 \times 10^7$ | $1.72 \times 10^8$ | $1.72 \times 10^8$ | $1.72 \times 10^8$ | – | $1.72 \times 10^8$ | – |

## 5. Summary:

- Search for neutrinos from supernovae within 10 Mpc
- Compared background events and the number of events in the signal region
  →could not find excess from background
- Searched cluster in the signal region
  →There was no cluster
- Calculated fluence upper limit [/cm$^2$] : $\mathcal{O}(10^7)$

[reference]
[1]Y. Suzuki, Eur. Phys. J. C, Vol. 79, No. 4,(2019)
[2]K. Abe et al., Phys. Rev. D 104, 122002 (2021)
[3] J. F. Beacom and M. R.Vagins, Phys. Rev. Lett. 93, 171101 (2004)
[4]K. Nakazato et al., Astrophys.J.205:2