

## Failed Supernova (SN)

1. Core Bounce

2. Accretion

3. Black Hole Formation

The iron core collapse and shock wave propagates outward

Continuous accretion and neutrino emission

If the mass exceeds the limit, a black hole is formed

↳ carry information from the core, emitted through the collapse and accretion

- The sudden termination of neutrino emission is a signature of black hole (BH) formation
- Neutrino observations can therefore provide evidence for BH formation

Failed SN

Ordinary SN

BH formation

Dust

Envelope

BH

Central core hidden

Heating

- Neutrinos have higher energies (~18 MeV) compared to those from ordinary SN (~13 MeV)
- The sudden termination of neutrino emission is a signature of BH formation
- Optical/infrared emission continues after BH formation

## Detector and Search Period

**Super-Kamiokande (SK)**

- 50 ktons Water Cherenkov Detector
- Observe Cherenkov light from charged particles

**Inverse beta decay (IBD)**

- Largest cross-section among other interactions below 60 MeV

Search period: Jun. 1, 2013 - Dec. 31, 2017

- Livetime: about 3.88 years
- Pure water phase

## Search Result: No neutrino signal detected

**Higher mean  $\bar{\nu}_e$  energy**

→ Moderately strong constraints for the failed SN model

**Lower mean  $\bar{\nu}_e$  energy**

→ Moderately weak constraints for the failed SN model

90% C.L. upper limit obtained

Luminosity and energy space constrained

- Hyper-Kamiokande (HK) will significantly improve sensitivity

## Failed SN Candidate in the Andromeda Galaxy

**M31-2014-DS1**

- Hydrogen-depleted supergiant
- Stellar mass:  $\approx 13M_{\odot}$
- Distance:  $\sim 770$  kpc (M31)

Neutrino detection is expected

Flux increase observed over 2 years since 2014

**Optical observation**

- The stellar radius decreased around 2017
- The temperature increased around 2017

## Analysis Method: Cluster Search

**Search for multiple events occurring within a short time window**

- The expected probability of accidental clusters arising from background events
- Clusters are identified as signal candidates when the significance exceeds  $3\sigma$

**Toy MC (100,000 times realization)**

- Apply an energy threshold ( $E_{th}$ )
- Simulate random background events according to the measured background rate
- For each event, define a time window and identify clusters satisfying the condition of  $\geq 2$  events within 10 s.

**Mode-independent approach**

- The search window is sufficiently broad to cover all failed SN models considered in this study
- A conservative time window is adopted for cluster identification

**Cluster condition**

- $E_{th} = 18$  MeV
- $2 \geq$  within 10 s

Expected number of  $\nu$  event vs. energy threshold

Expected  $\nu$  event: 0.6 - 2.2

Expected number of events vs. energy threshold

Detection Probability @ 770 kpc → 4% to 72%

SK has sensitive to detect neutrinos from M31-2014-DS1

## Conclusion

- Neutrinos are emitted in the supernova explosion
- It is important to observe neutrinos to understand the explosion mechanism
- Search for neutrinos from M31-2014-DS1
  - No significant neutrino signal found
  - 90% C.L. upper limit on the total emitted  $\bar{\nu}_e$  energy was derived.
- Future Prospects**
  - If a similar event occurs and is observed by HK
  - Neutrino signal detection would be expected

**Reference**

[1] M. Liebendorfer et al., The Astrophysical Journal Supplement Series, 150(1):263–316 (2004)

[2] K De et al., Science, Volume 391, Issue 6786, pp. 689–693

[3] Model parameters are taken from Table 1 of Suwa et al., Open Journal of Astrophysics, vol 8 (2025)