Search for neutrinos from Failed SN in Super-kamiokande

スーパーカミオカンデにおけるFailed SN由来のニュートリノ探索

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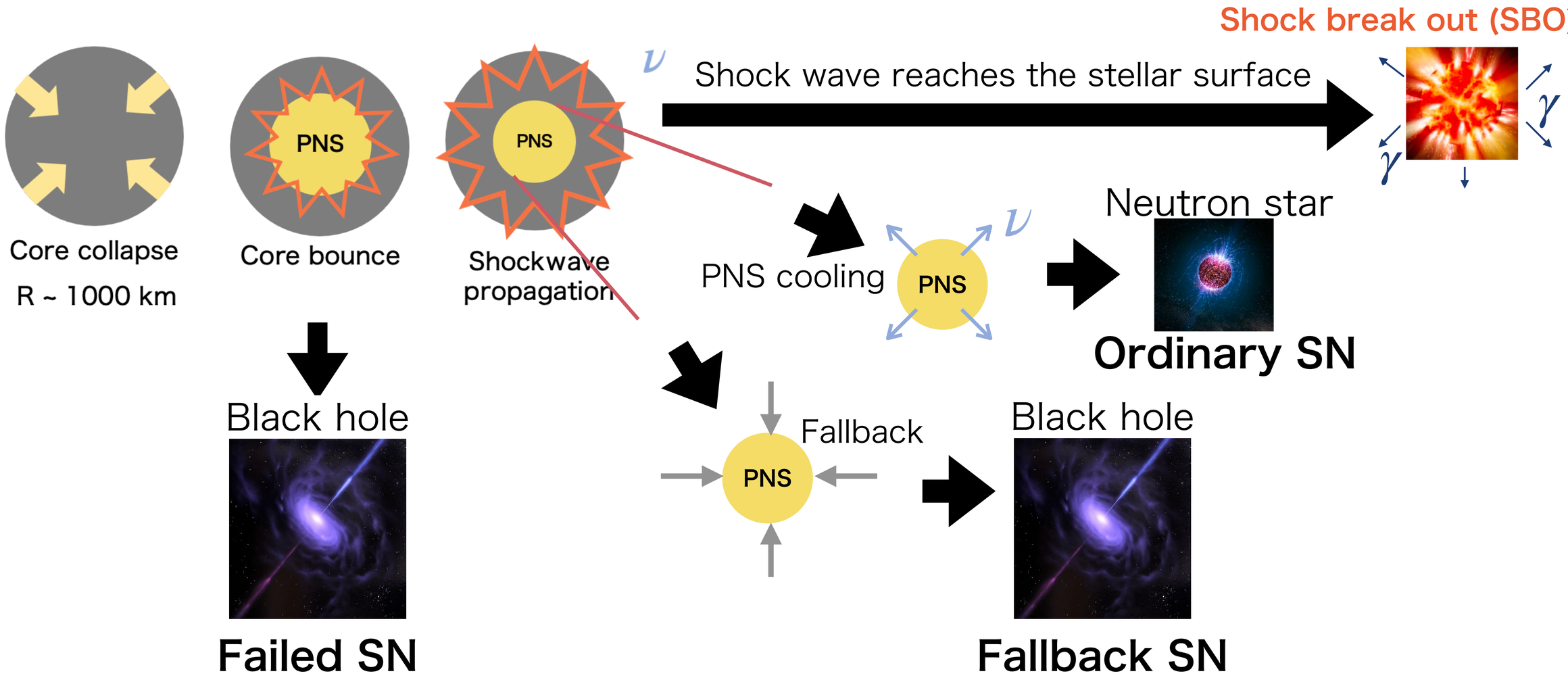
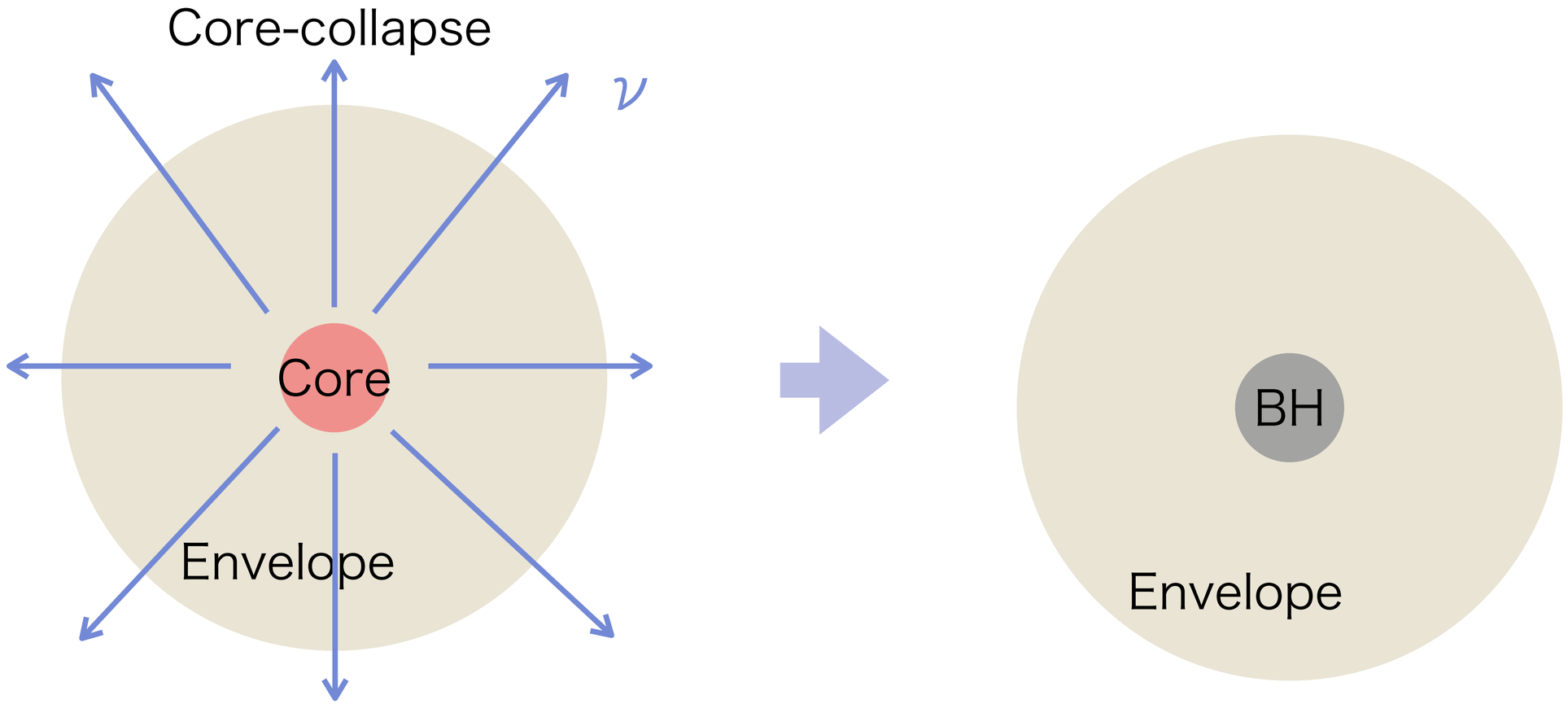
Contents

Final phase of massive star



Neutrino emission of failed SN

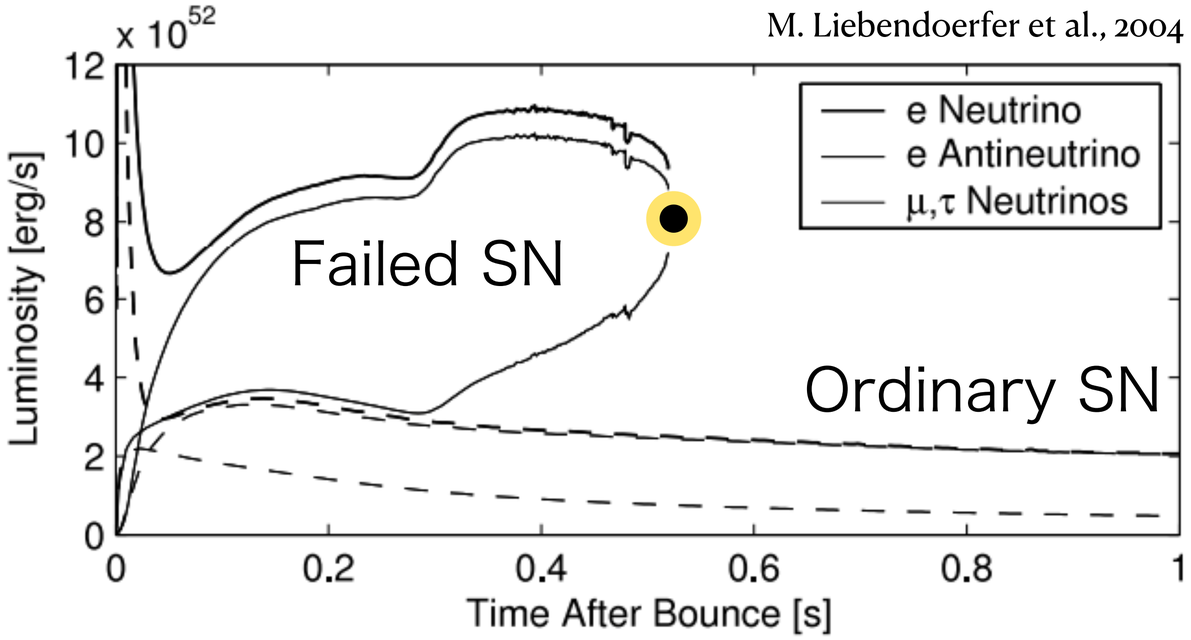
- Neutrinos are emitted during core-collapse
- Neutrino emission is stopped when a black hole is formed



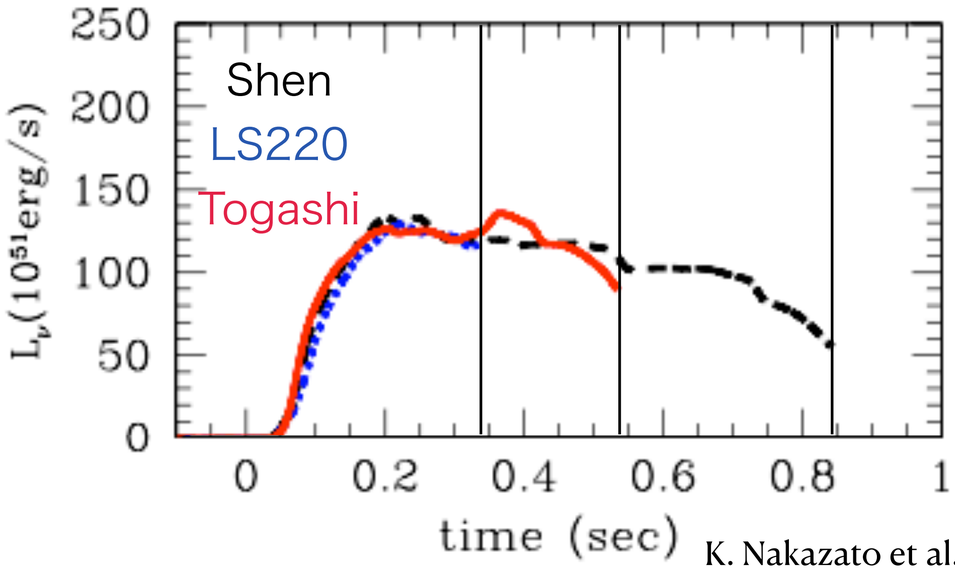
Neutrino emission of failed SN

- Neutrino emission is more luminous and hotter
- The neutrino emission depends on the time from bounce to black hole formation

M. Liebendoerfer et al., 2004



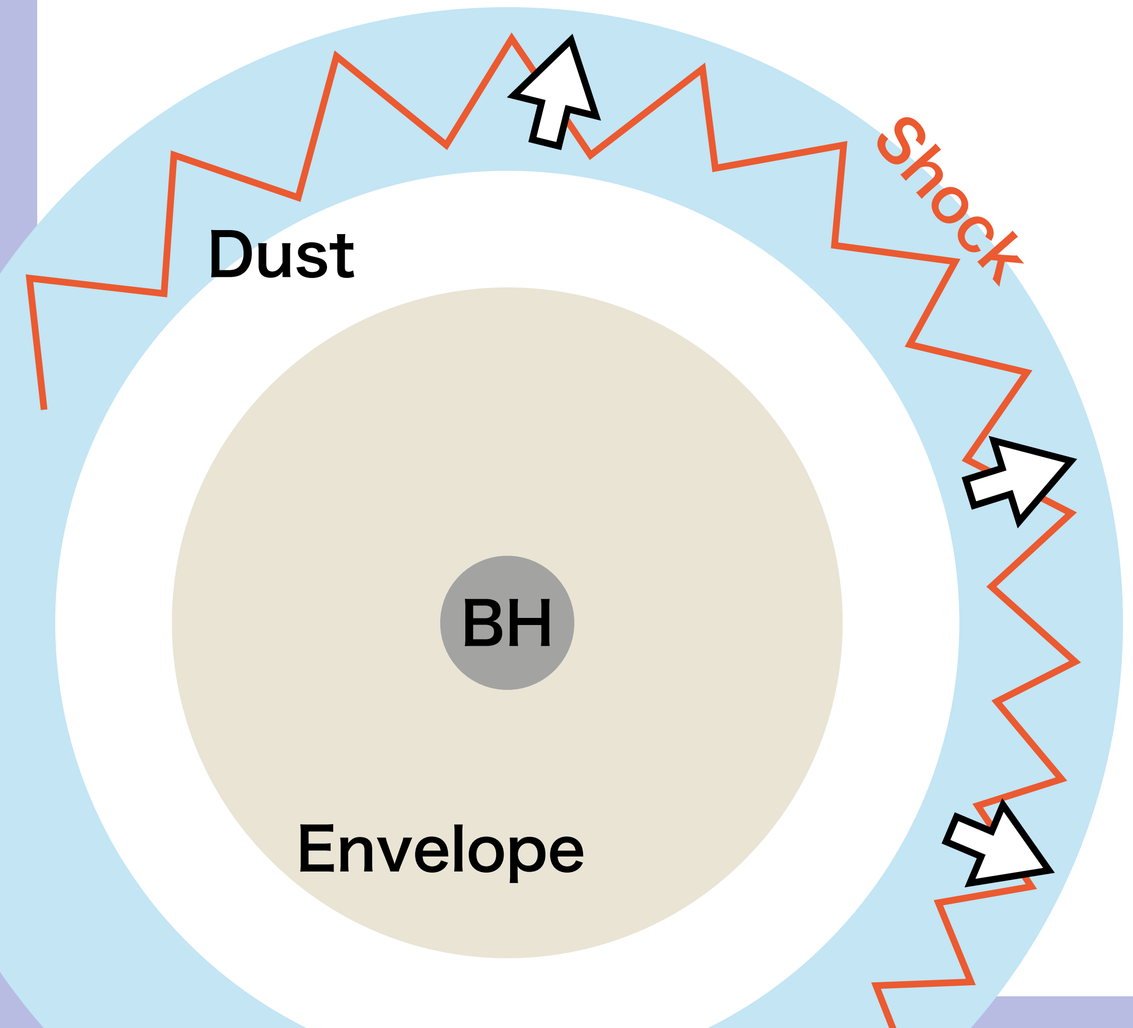
Time of black hole formation



K. Nakazato et al., 2021

Neutrino observation is essential to understand black hole formation mechanisms

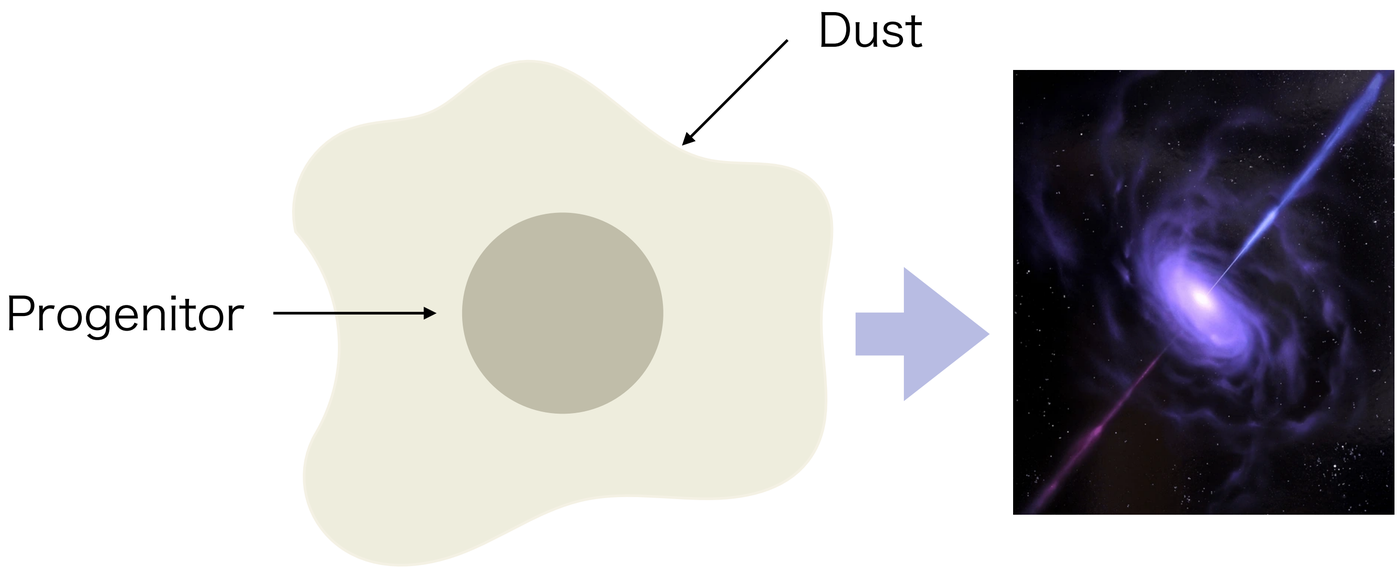
Black hole formation

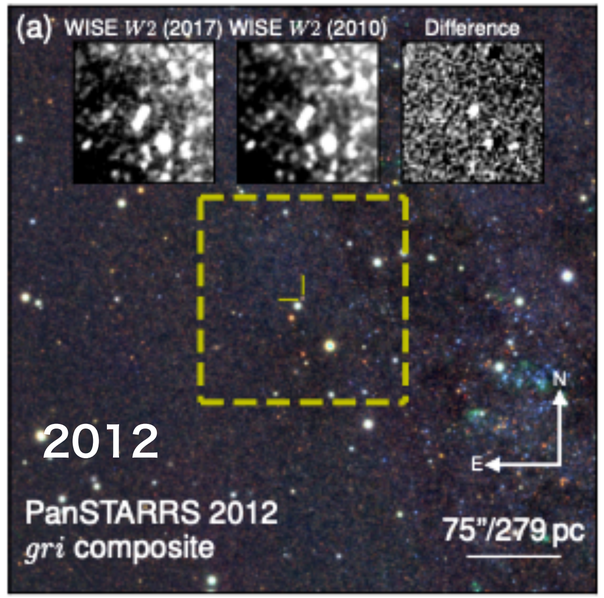


- After black hole formation, dust is heated by shock
  →emitting infrared radiation
- The timing of black hole formation can be determined by neutrino observation

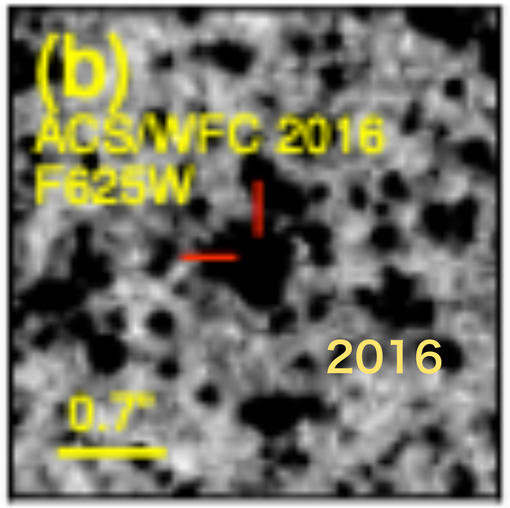
M31-2014-DS1

- Failed SN was discovered at M31
  - Hydrogen-depleted supergiant
  - Distance: 784 kpc
  - Stellar mass : $\approx 20 M_{\odot}$



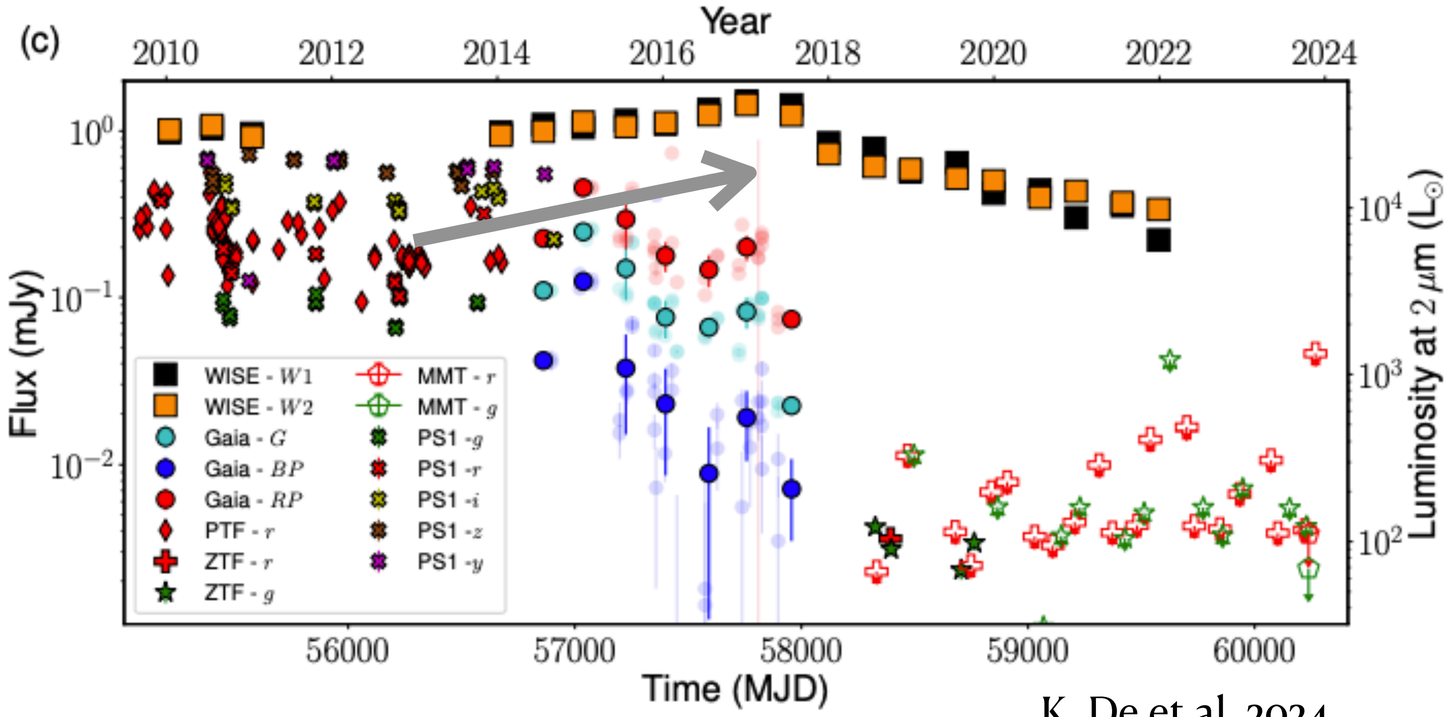


K. De et al. 2024



Evolution of the luminosity in Failed SN

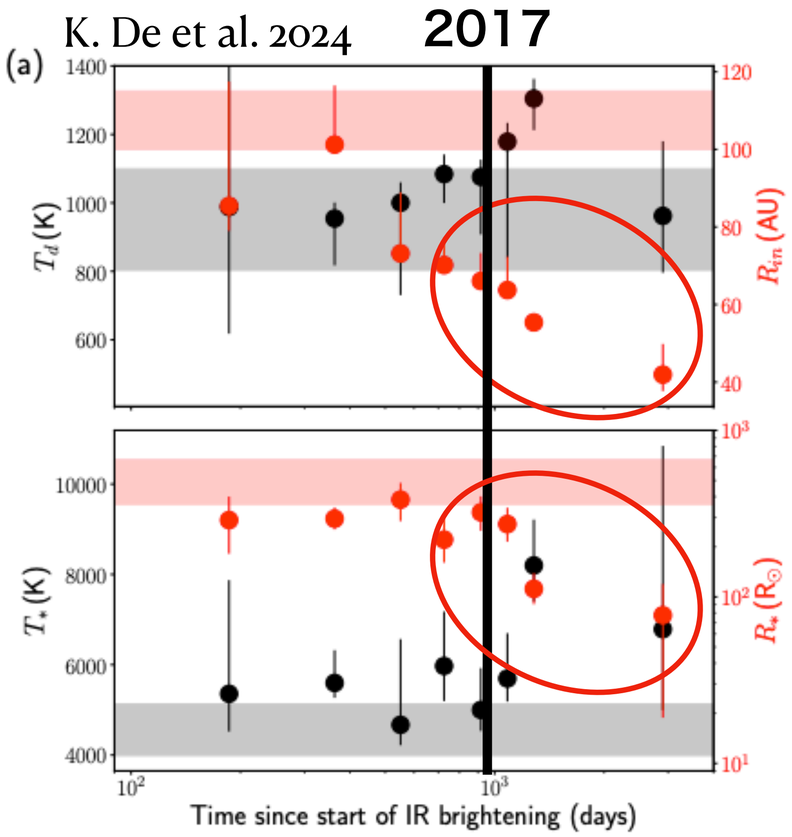
- Mid-infrared observation (NEOWISE)
  - Increased in MIR flux by ~50% over 2 years starting in 2014
- Optical & near-IR observation (MMT)
  - Undetected in optical & near-IR (NIR) imaging observations in 2023

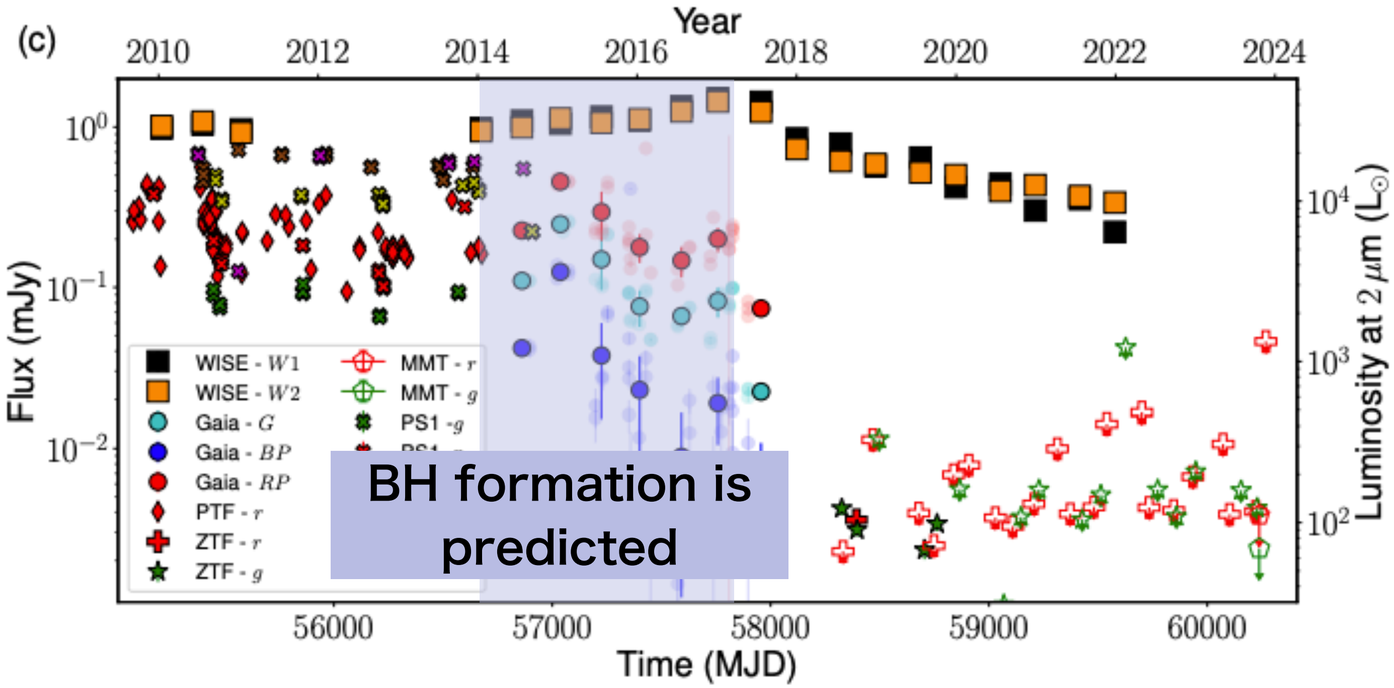


K. De et al. 2024

Estimation of black hole formation

- The inner shell radius decreased around 2017
- Considering the brightening of INR, it is estimated that the black hole formed between 2014 - 2017



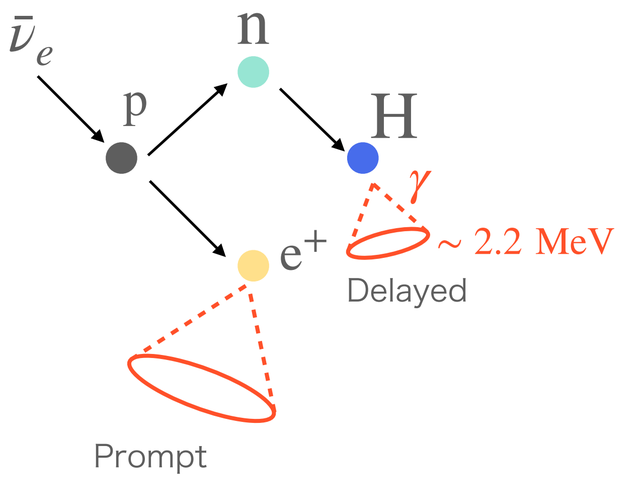


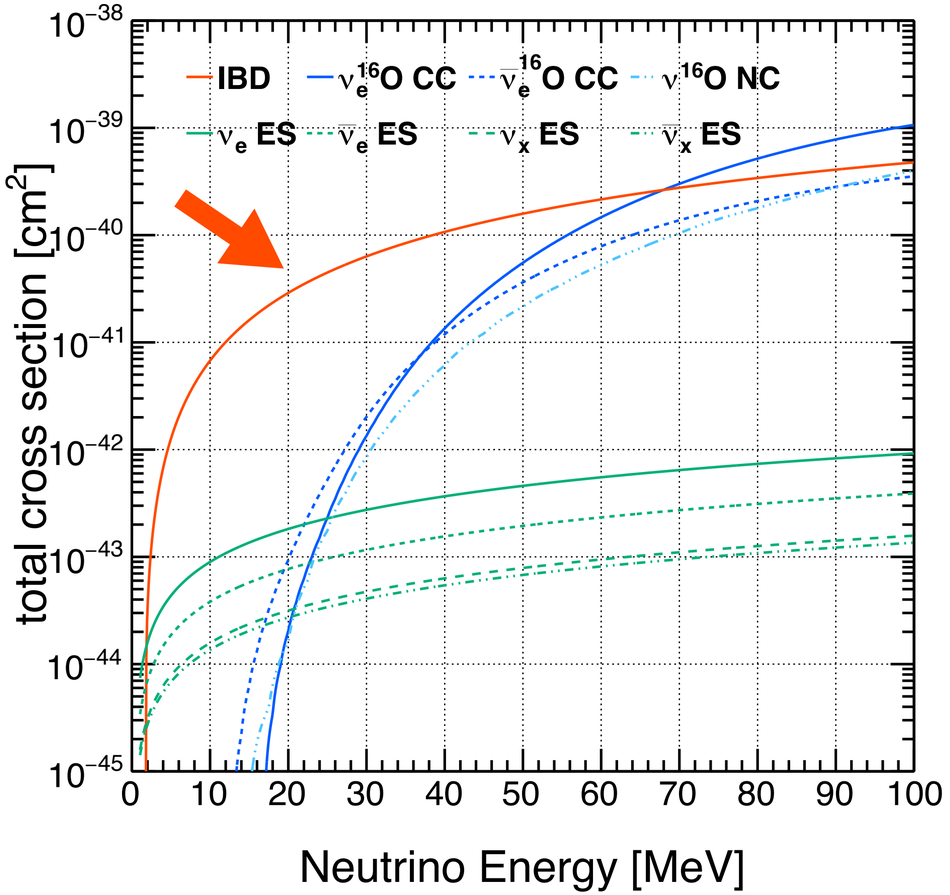
Neutrino search in SK

- Target: Inverse beta decay (IBD)

  $\bar{\nu}_e + p \rightarrow e^+ + n$

- Largest cross section until 30 MeV than the other interaction
- Pure water phase in SK
  - Neutron tagging efficiency: ~20%

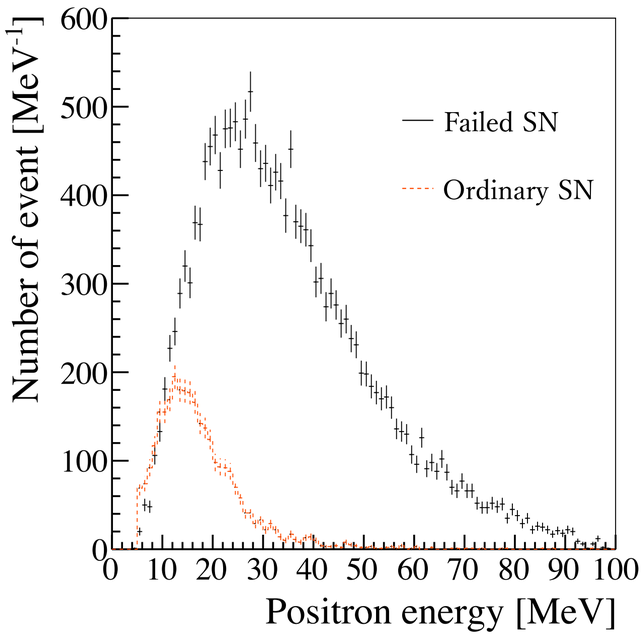




Expected Neutrino Events

- Both the neutrino expected and average energy are higher in Failed SN than in ordinary SN

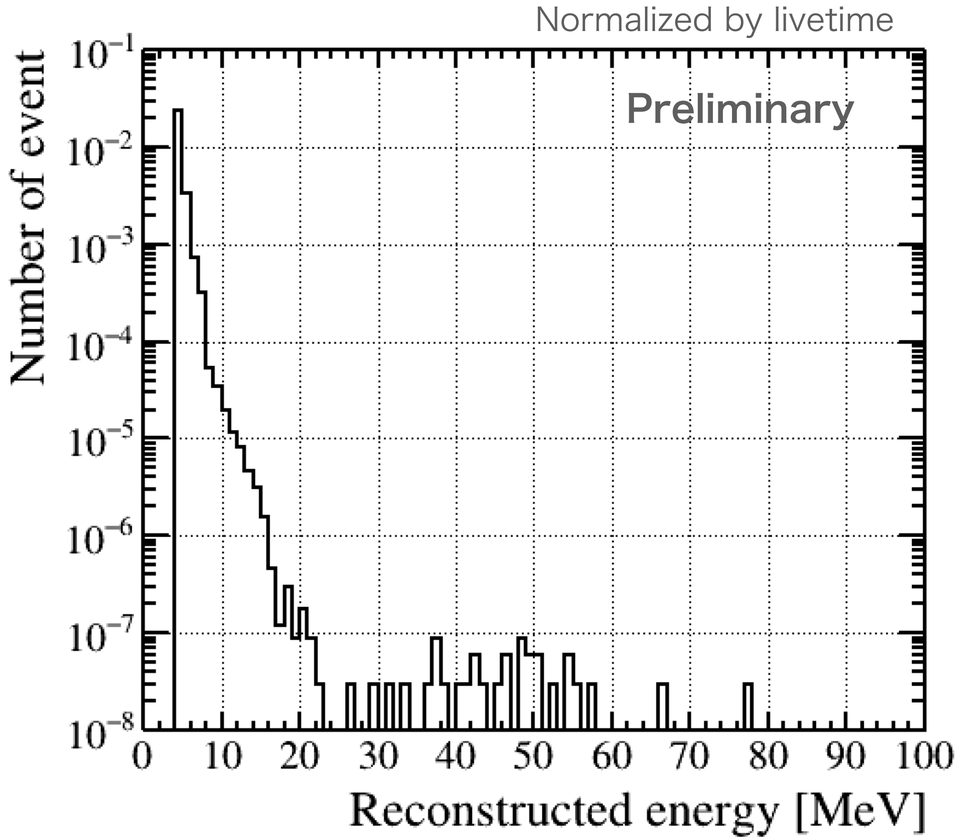
	10 kpc	1 Mpc	10Mpc	$< E_{\bar{\nu}_e} >$
SN rate (/year)	~0.01	~0.1	~0.8	—
Expected ν event in SK (event/ ordinary SN)	$\mathcal{O}(10^3)$	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-3})$	17.5
Expected ν event in SK (event/ Failed SN)	$\mathcal{O}(10^4)$	$\mathcal{O}(1)$	$\mathcal{O}(10^{-2})$	35.1



Nakazato model
(Shen EOS, ordinary SN: $20M_{\odot}$, Failed SN: $30M_{\odot}$)

Background event in SK

- Energy distribution of background event in fiducial volume
- There are many radioisotope backgrounds in the low energy region
- Above 8 MeV, background rate is low by strict background reduction cuts
- Main background above 20 MeV
  - Decay-e from Invisible muon
  - Charged current reaction from atmospheric neutrinos



Previous study

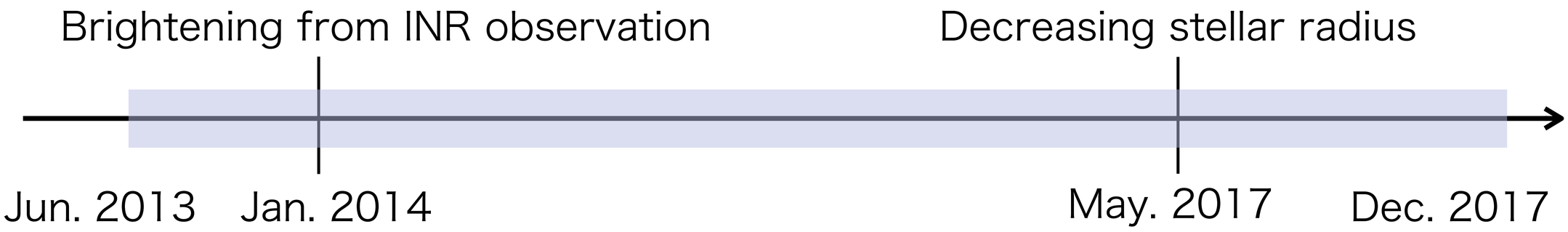
- SN burst search (M. Mori et al., 2022 ApJ **938** 35)
  - Cluster search was performed under the following condition
    - Energy threshold: 5.5 MeV

Condition 1	2 events / 0.5 sec
Condition 2	2 events / 2 sec
Condition 3	4 events / 10 sec

  - There was no cluster
    →cluster condition to be suitable for failed SN

Analysis plan

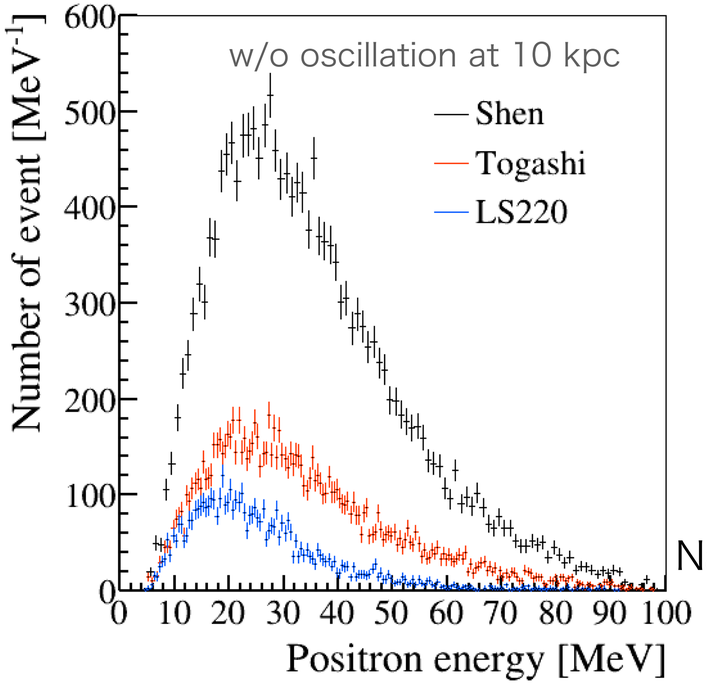
- Analysis region: Jun. 2013 - Dec. 2017 (about 4.58 years)



- Cluster search : 2 events / 10 sec
  - Considering the time of neutrino emission from black hole

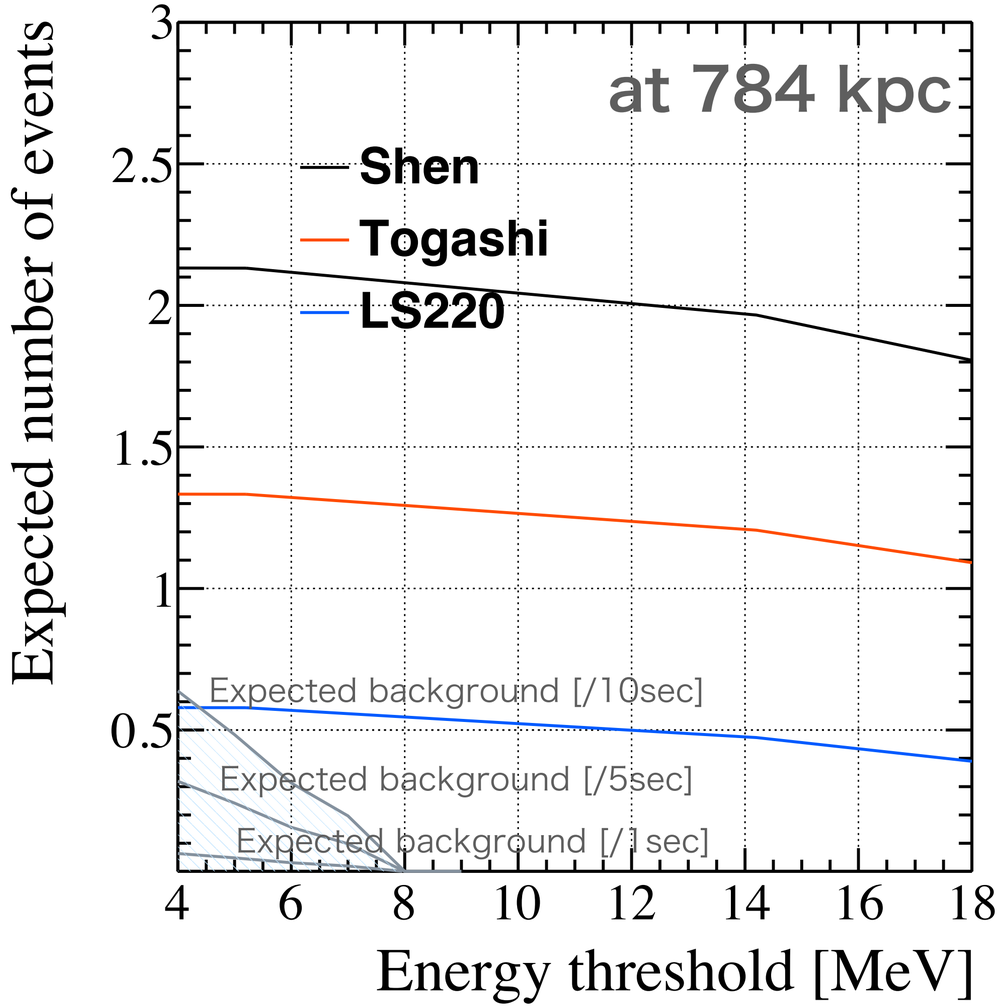
Expected Neutrino events for Failed SN

- Expected energy spectrum in SK



Nakazato model ($30M_{\odot}$)

→Calculate the expected events for each energy threshold

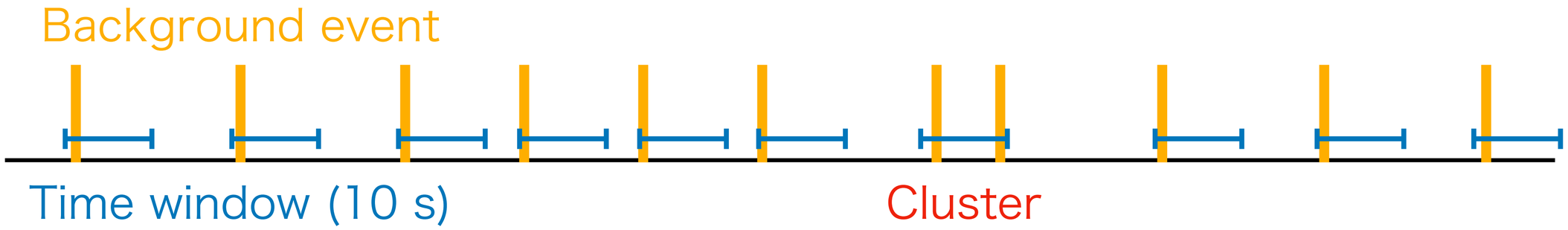


- Estimate the energy threshold considering the expected background

Evaluation of cluster occurrence probability

- Estimation of the number of clusters using background rate
  - Generate random events following the background rate
  - Count the number of clusters (2 events / 10 sec)
    →calculate the expected number of clusters by 100000 times event generation

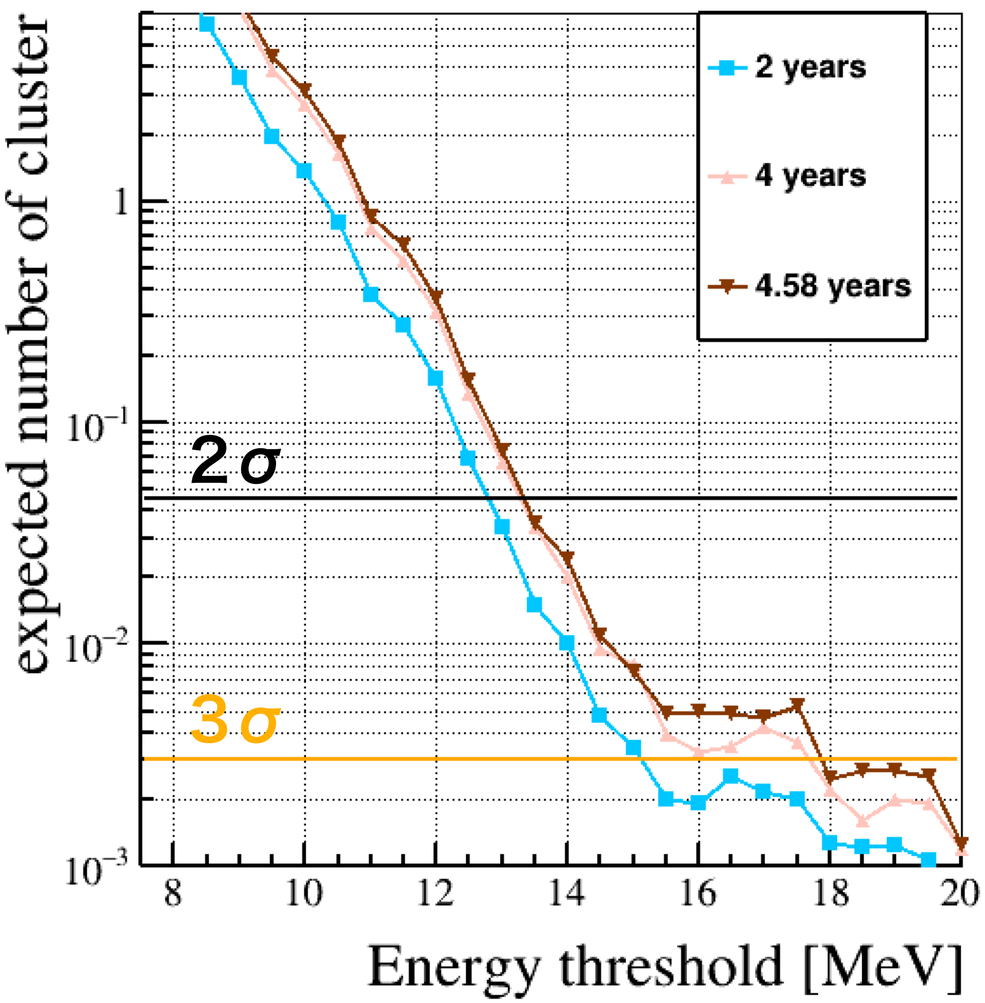
- Find the energy threshold where clusters do not exist more than 3σ



Analysis strategy

- Estimation of the number of clusters
- The energy threshold that clusters do not exist more than 3σ

	Energy threshold [MeV]
Seach region [2 years]	>15.0 MeV
Search region [4 years]	>18.0 MeV
Search region [4.58 years]	**>18.0 MeV**



Summary

- In the final phase of a massive star, a black hole is formed
- The formation time of a black hole can be identified from neutrino observations
- Hydrogen-depleted supergiant (M31-2014-DS1) identified via a mid-infrared brightening in 2014
  - Black hole formation is expected around 2014 - 2017
- 0.4 - 1.7 events are expected to be observed at 784 kpc
- We determine the analysis region and cluster search condition in SK
  - Analysis region: Jun. 2013 - Dec. 2017
  - Cluster condition: 2 events / 10 s