スーパーカミオカンデにおける Failed supernova候補からのニュートリノ探索

(F. Nakanishi et al., ApJL 997(2026)L9)

物2教室談話会

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15th May, 2026

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- Search for Neutrinos from Failed SN candidate in M31
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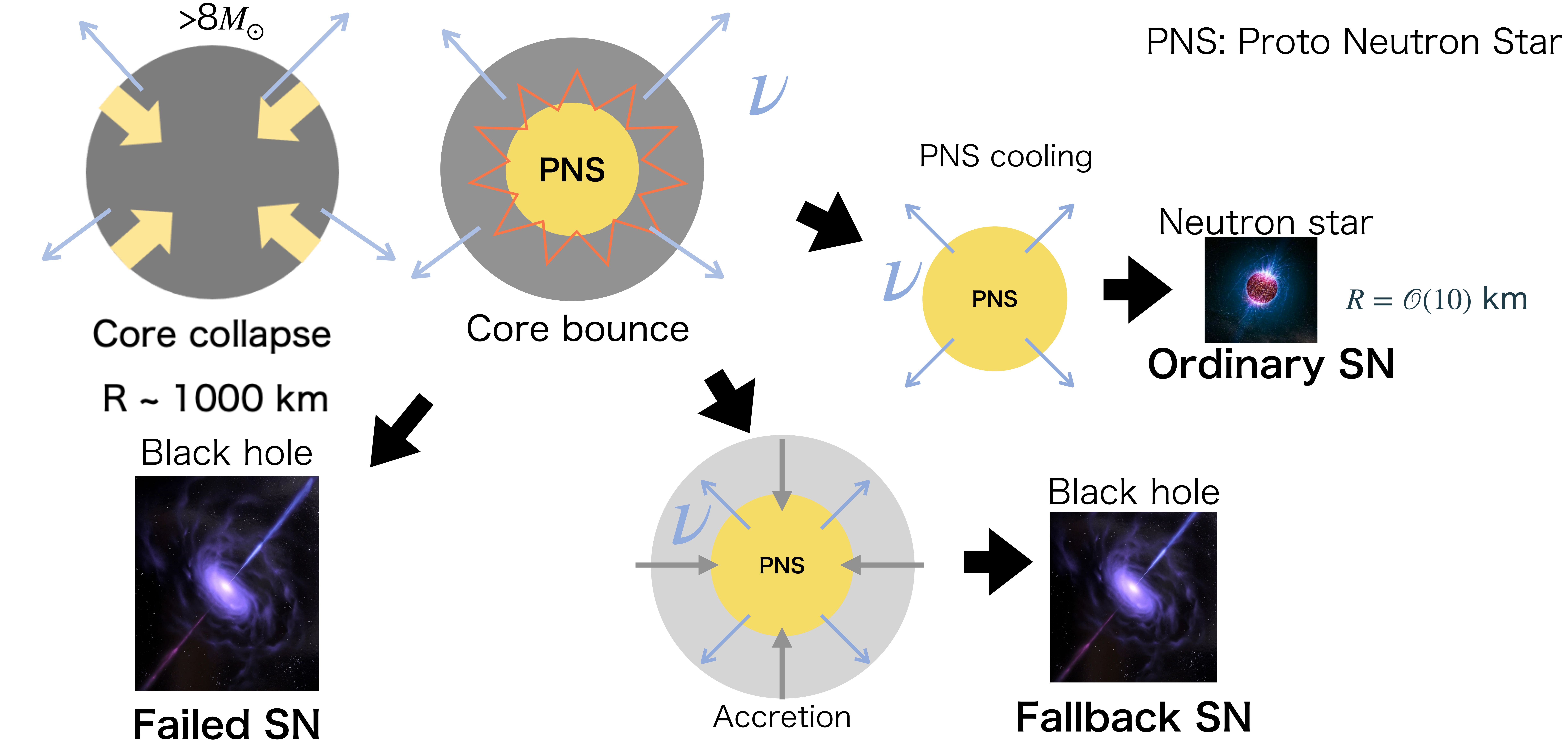
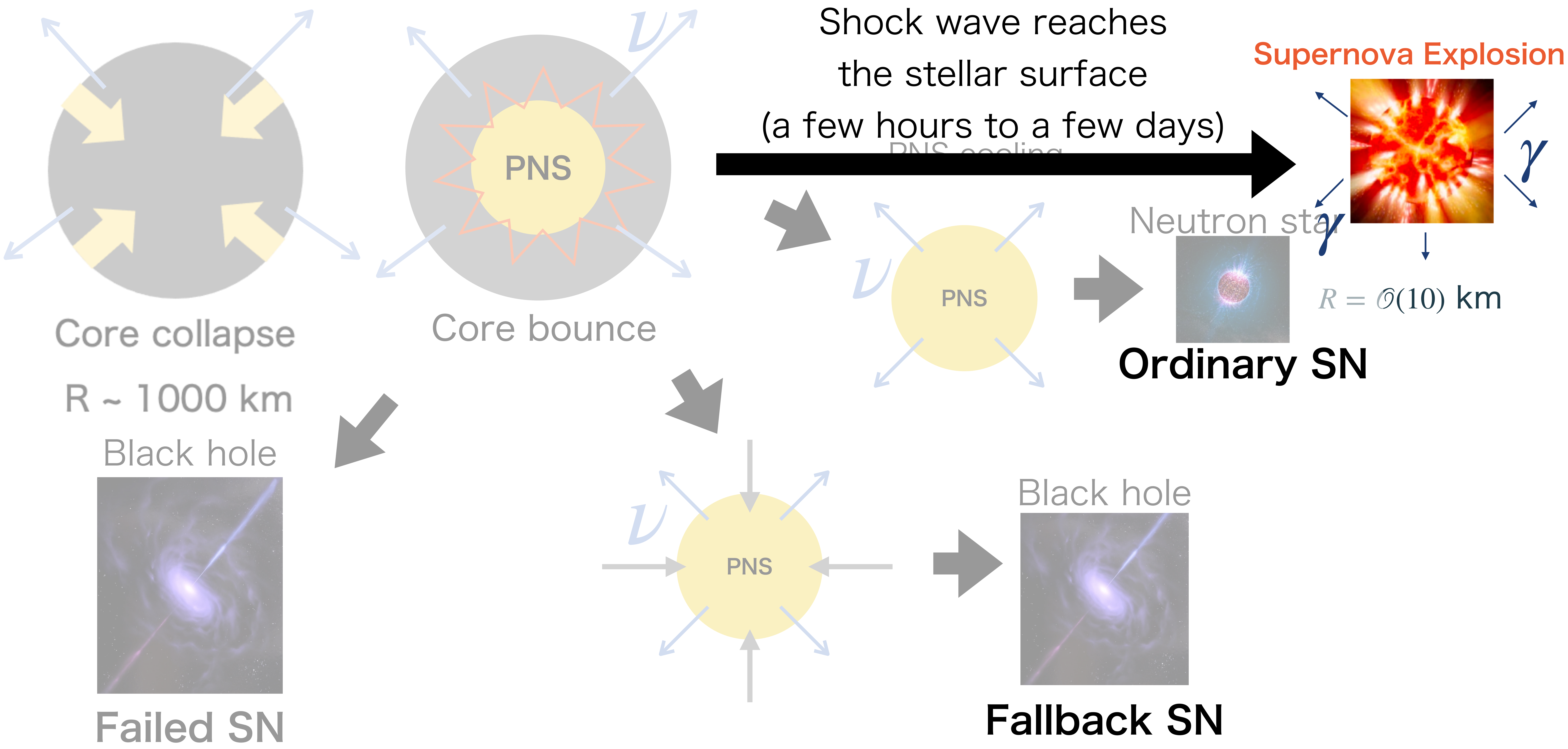
Introduction

Types of Supernovae



Types of Supernovae



Supernova Neutrinos

Neutronization burst (~30 ms)

Electron capture

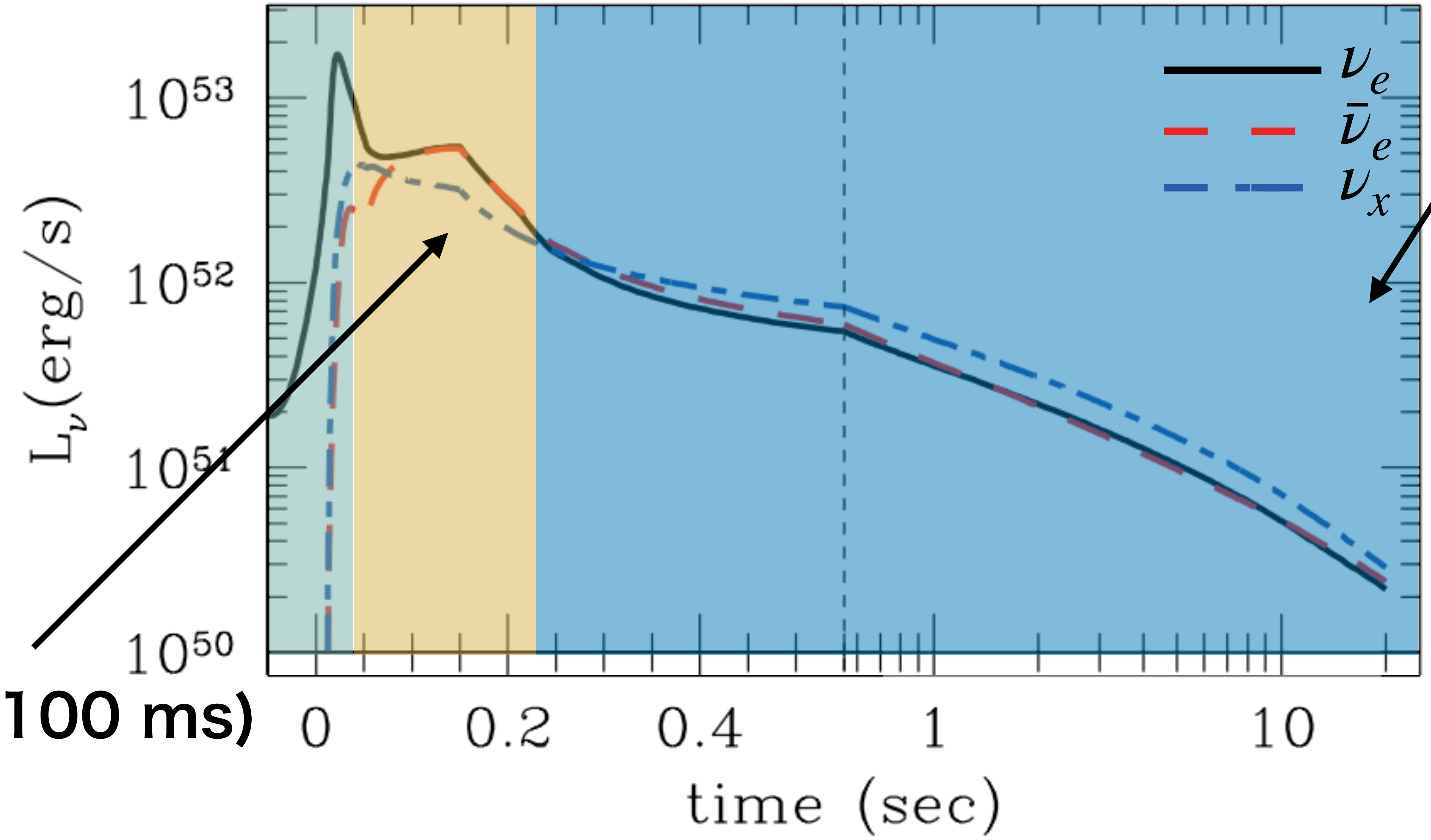
$p + e^- \rightarrow n + \nu_e$

Pair annihiration

$e^- + e^+ \rightarrow \nu + \bar{\nu}$ ..

Accretion phase (≥100 ms)

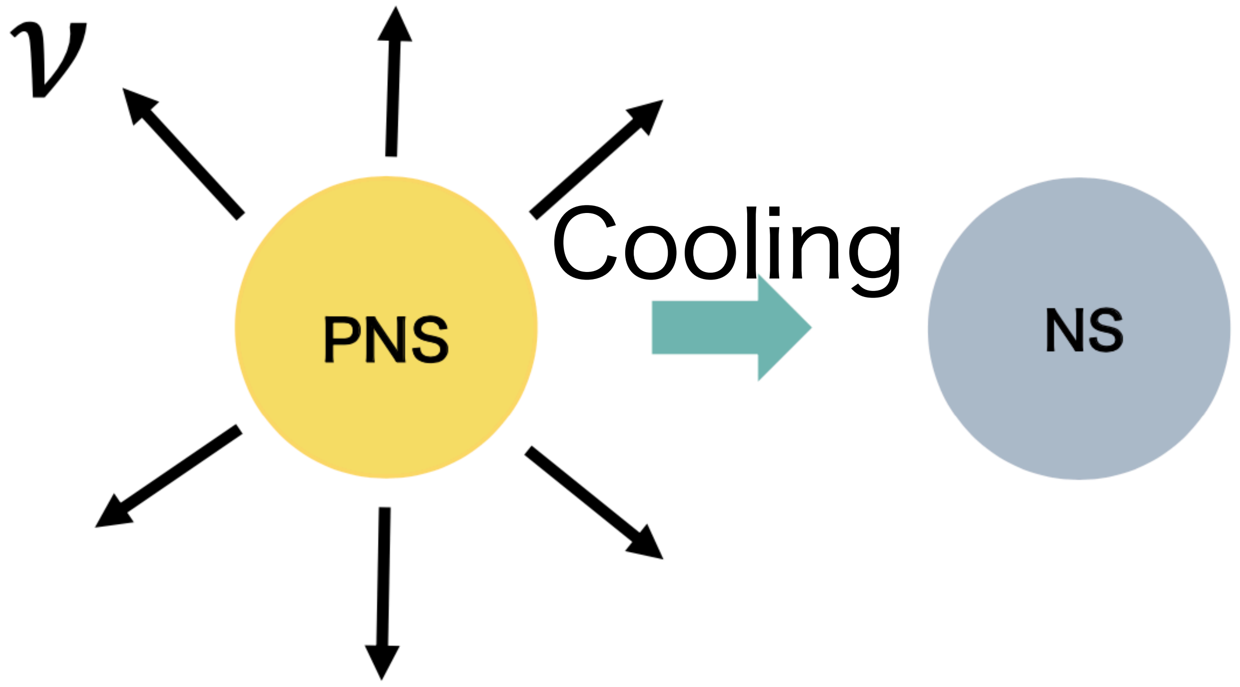
K. Nakazato et al., 2013



Cooling phase (up to ~20 s)

$p + e^- \rightarrow n + \nu_e$

$e^- + e^+ \rightarrow \nu + \bar{\nu}$



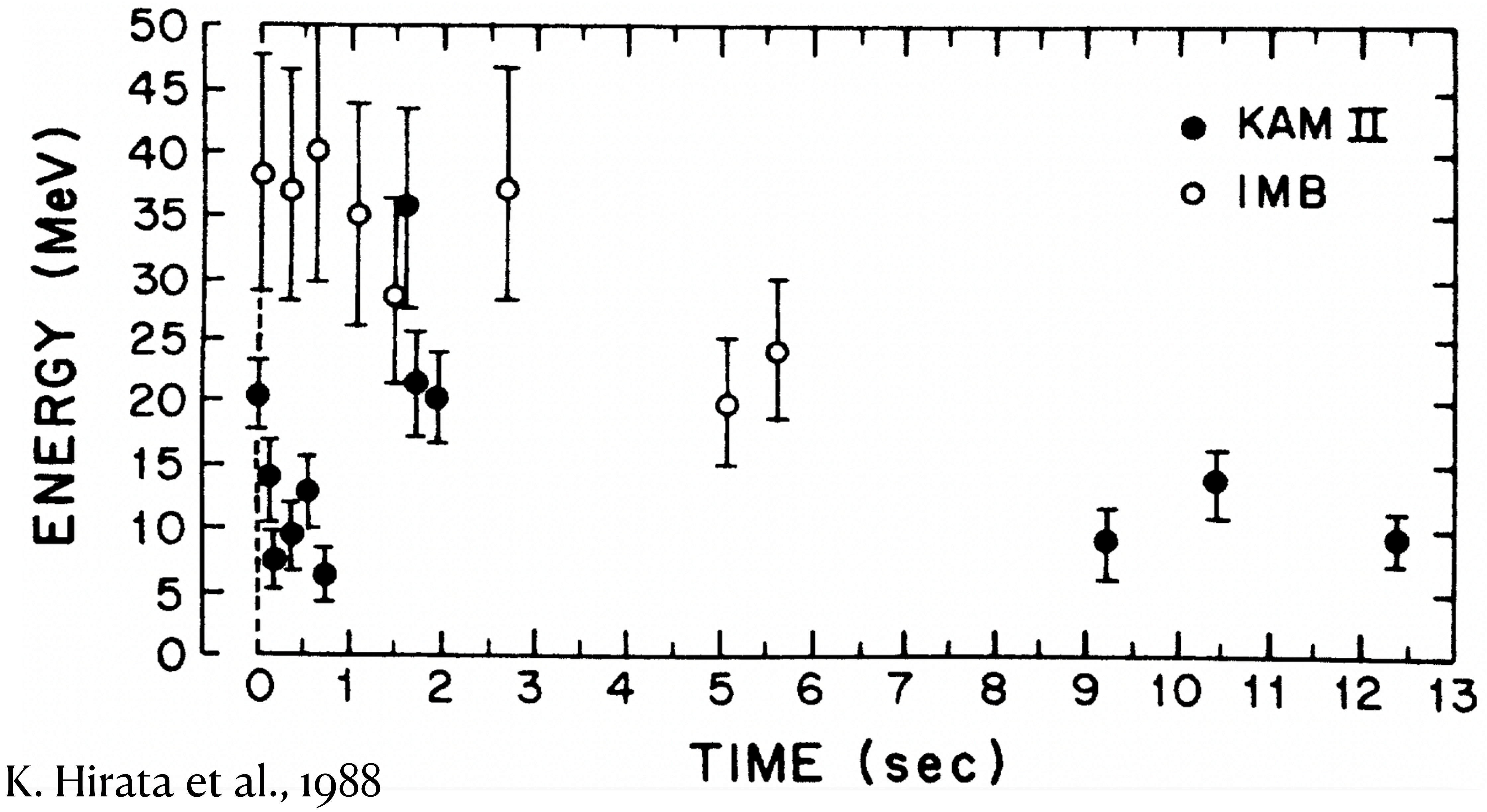
99% of energy is emitted as neutrinos

→**Neutrino observation is essential** to understand SN explosion mechanisms

Neutrinos from Supernovae

Only one SN neutrino observation so far: SN1987A in the Large Magellanic Cloud

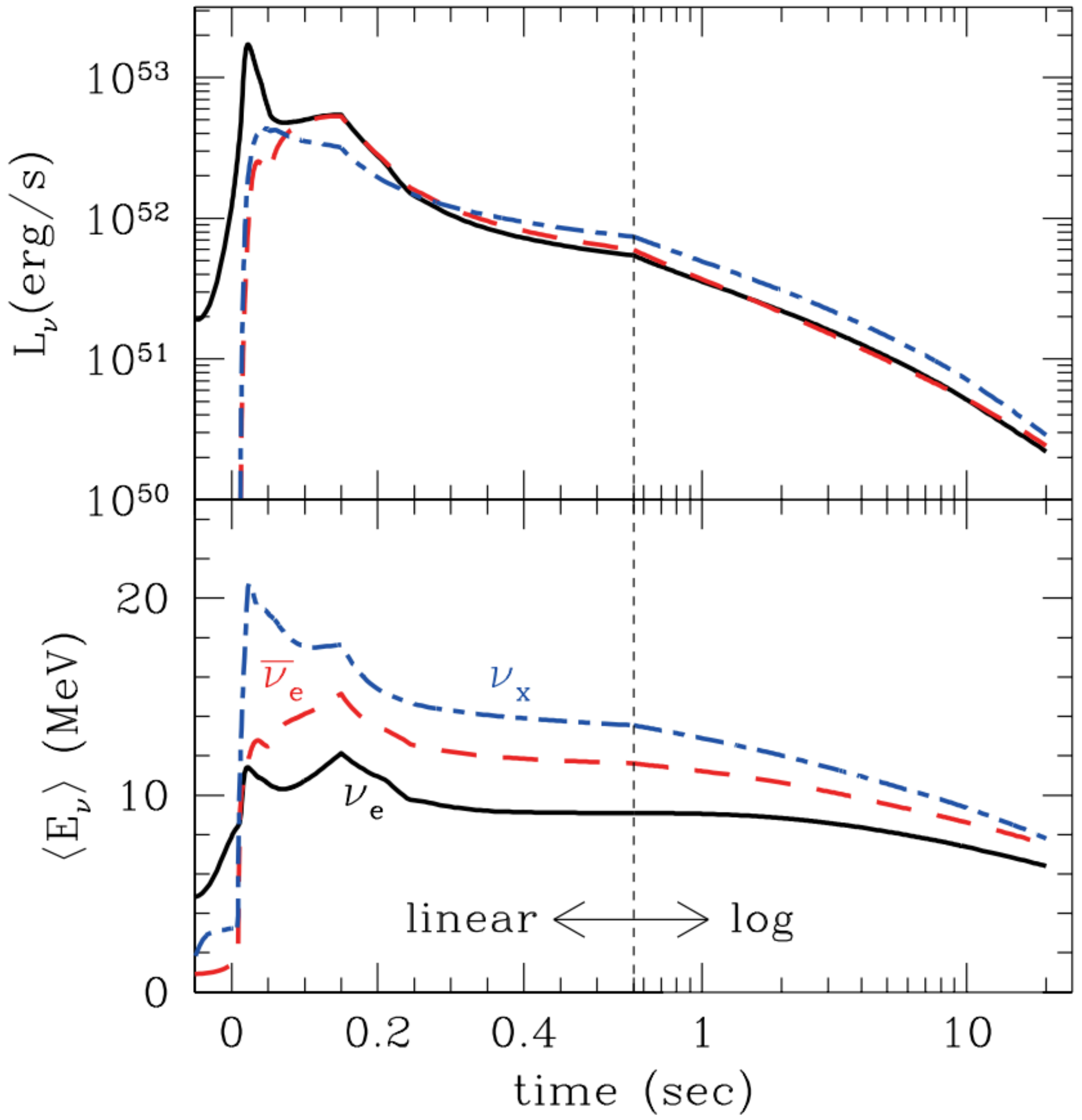
Neutrinos from SN1987A



K. Hirata et al., 1988

A lot of theoretical expectations based on numerical calculation

Neutrino light curve and average energy

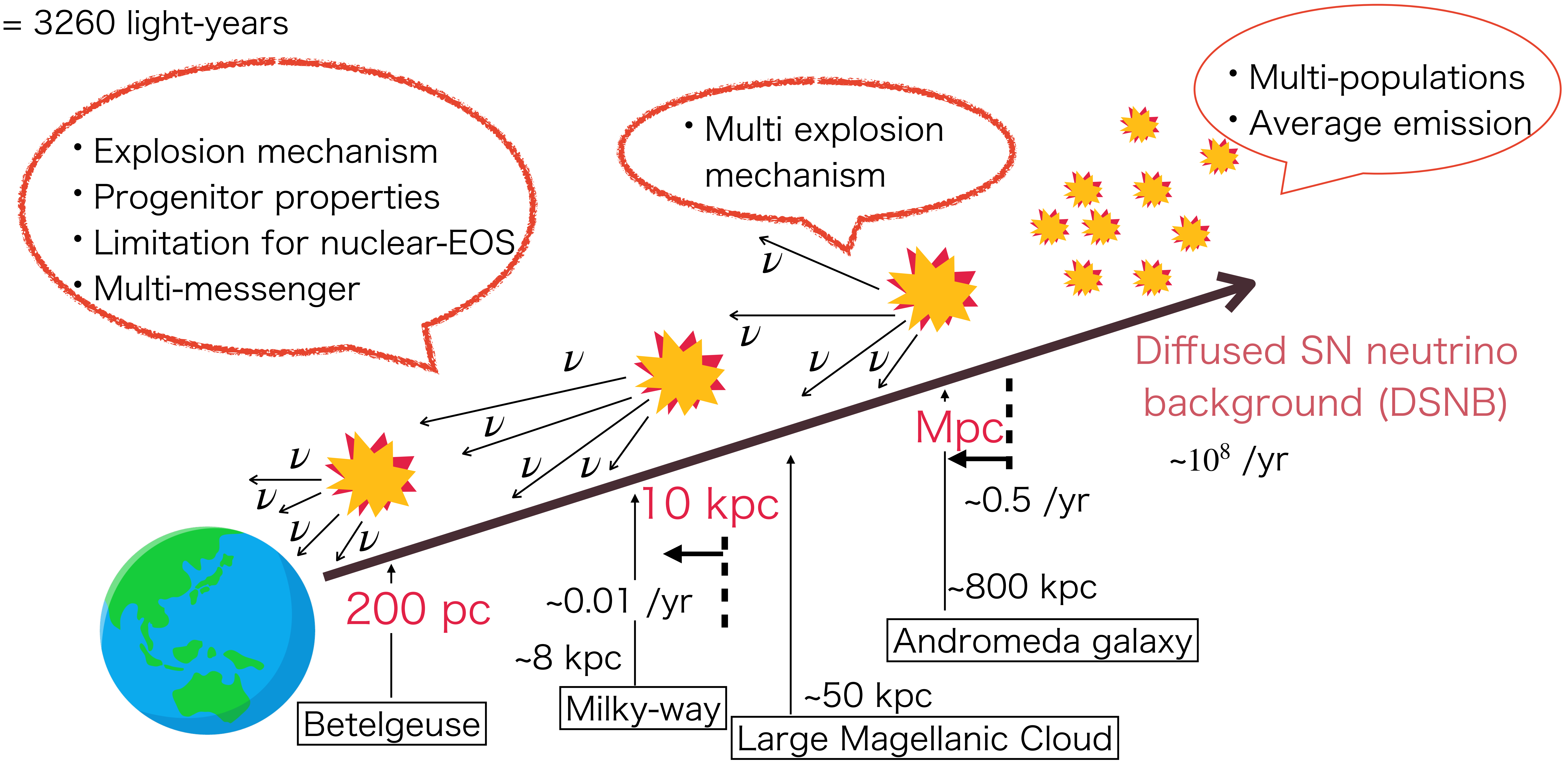


K. Nakazato et al., 2013

Observation of ν originating from SN is awaited

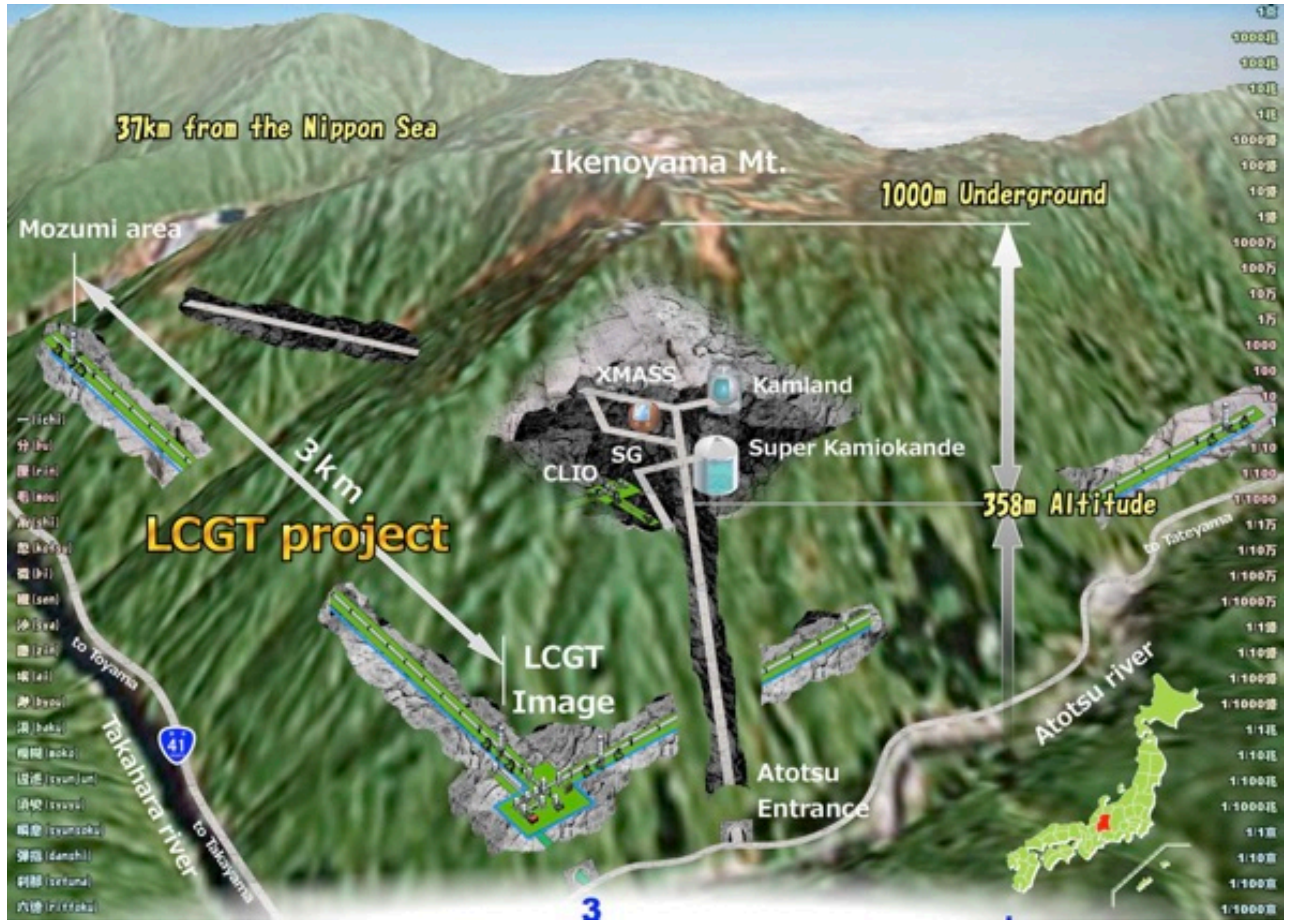
Distance Scales and Physics Outcomes

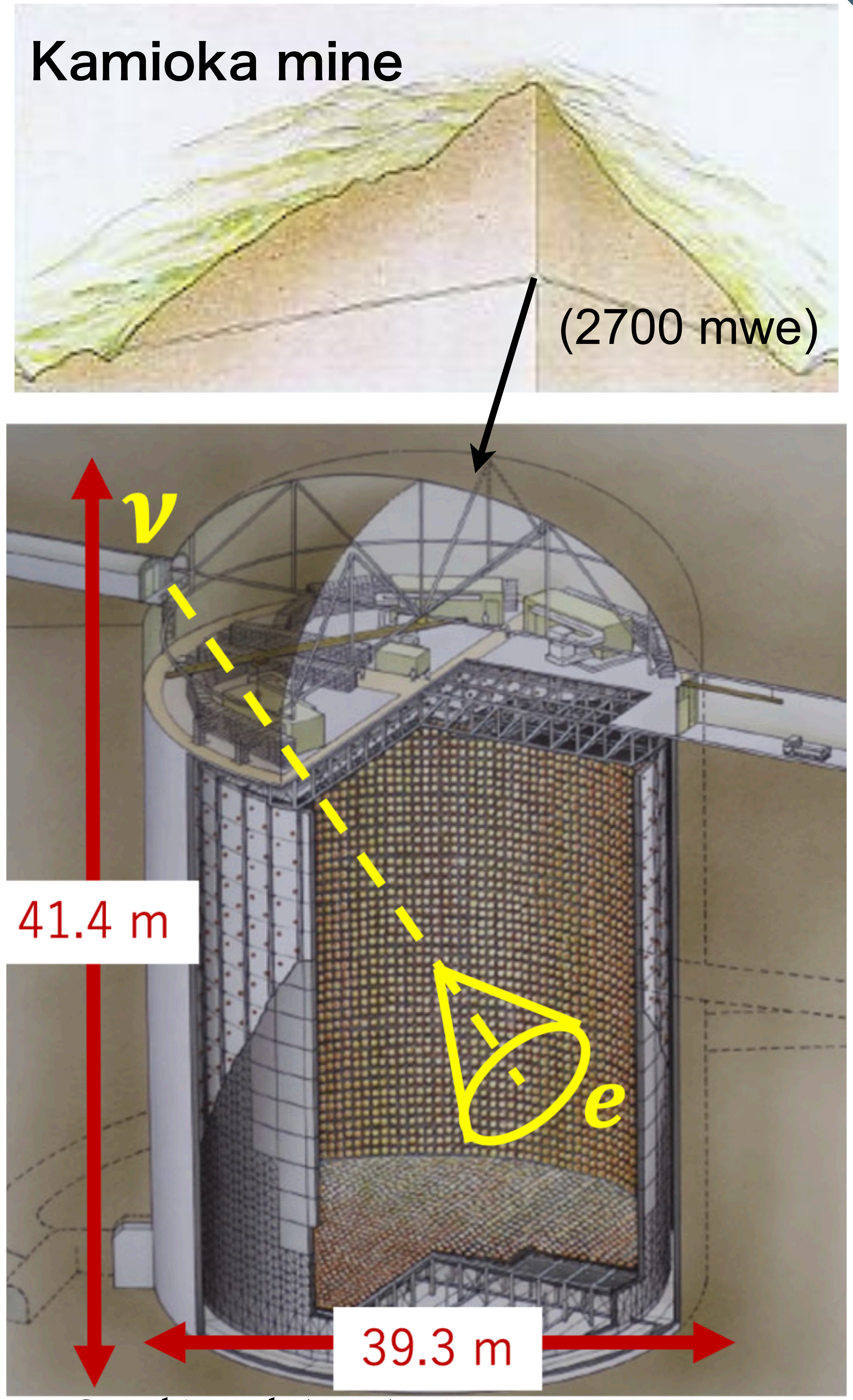
*1 kpc = 3260 light-years



Super-Kamiokande

- Super-Kamiokande (SK):
  50 ktons Water Cherenkov Detector
  - Observe Cherenkov light from charged particles



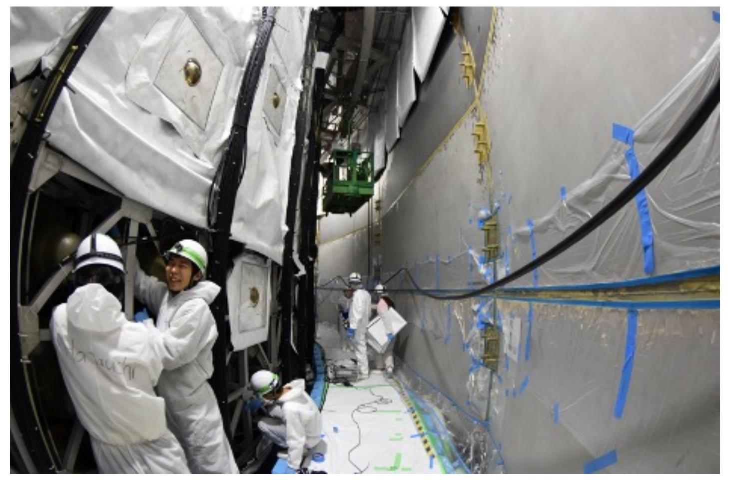


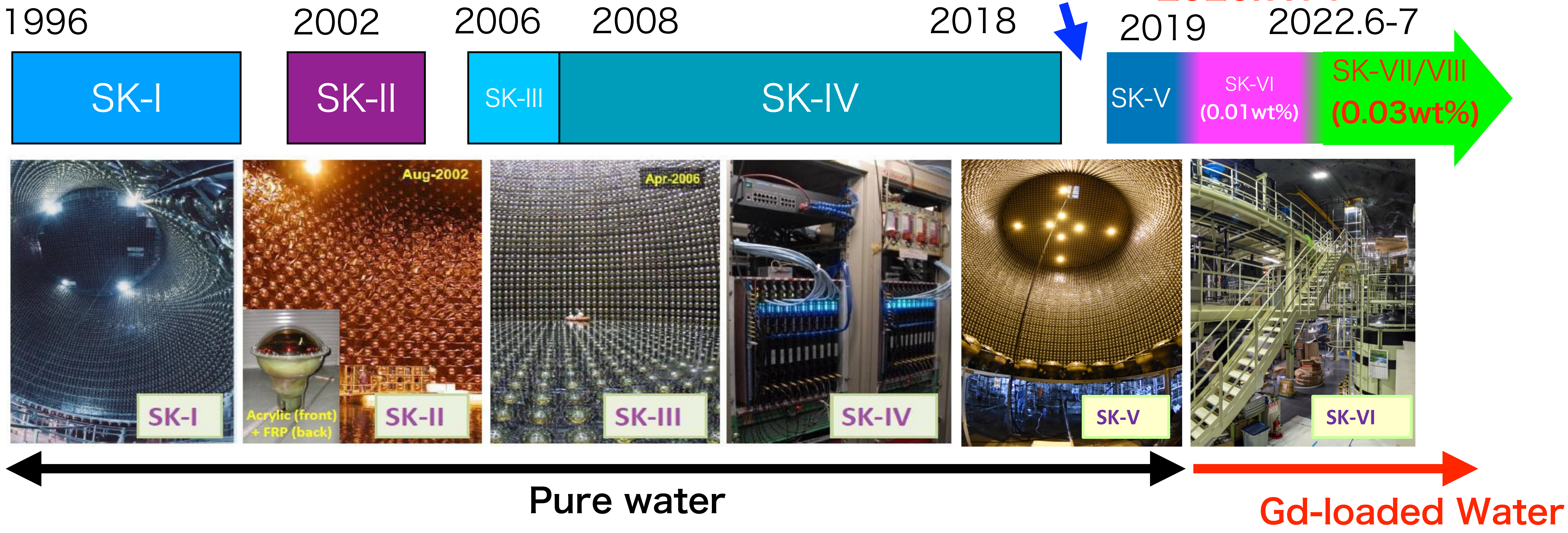
Y. Suzuki et al. (2019)

History of Super-Kamiokande

- Neutron detection became possible after the electronic upgrade in SK-IV

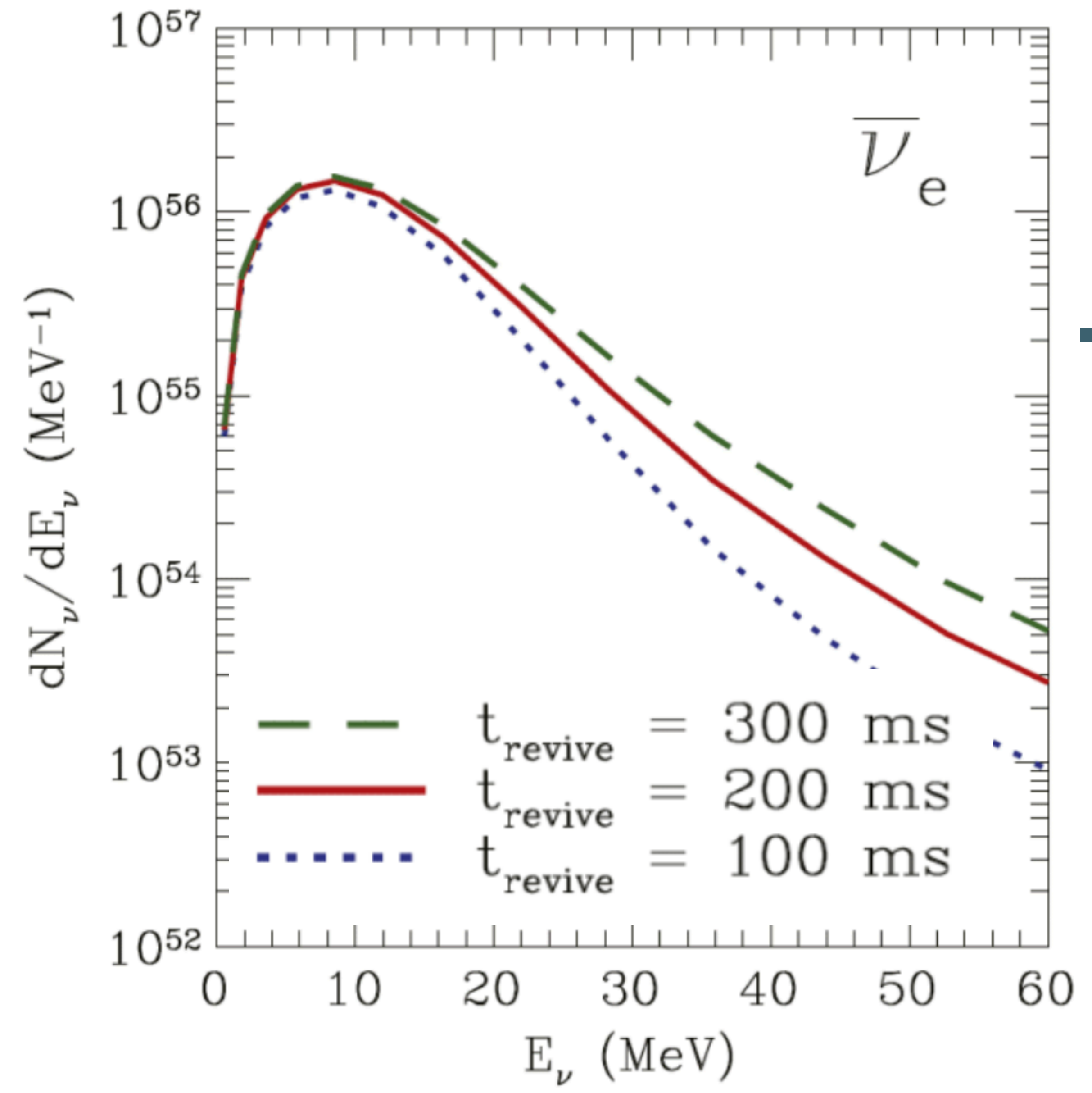
Tank refurbishment



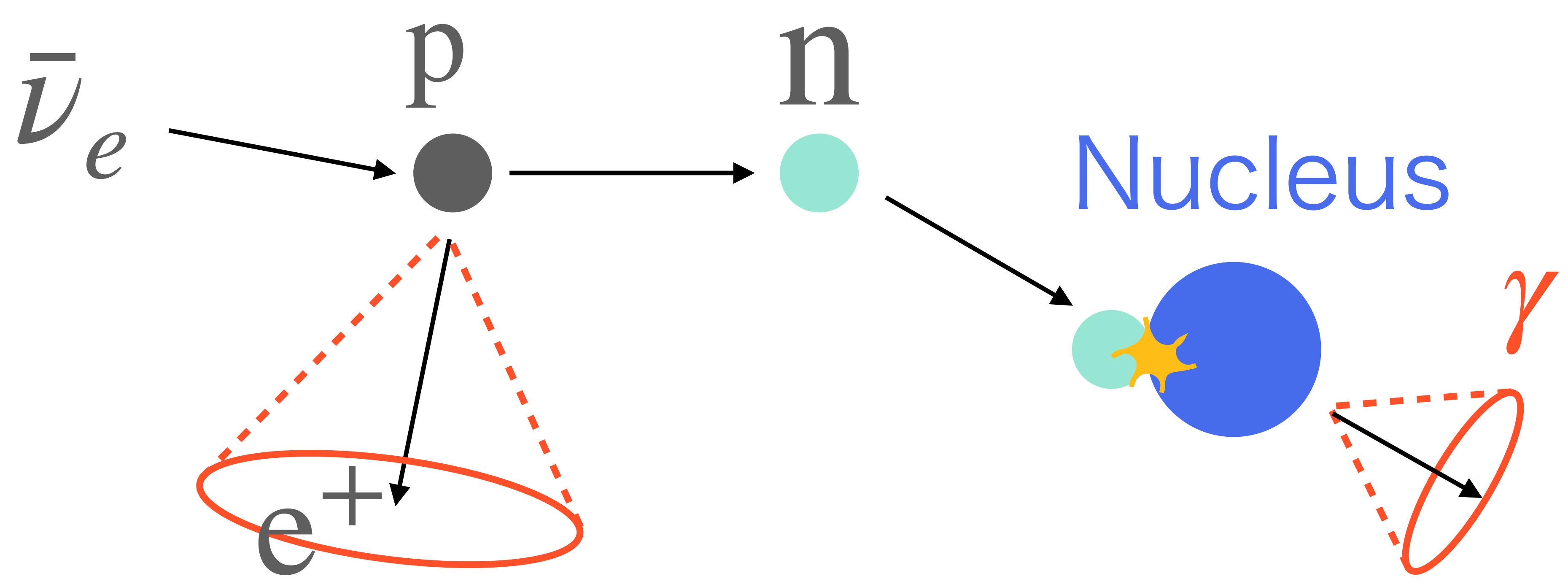


SN Neutrino Search in SK

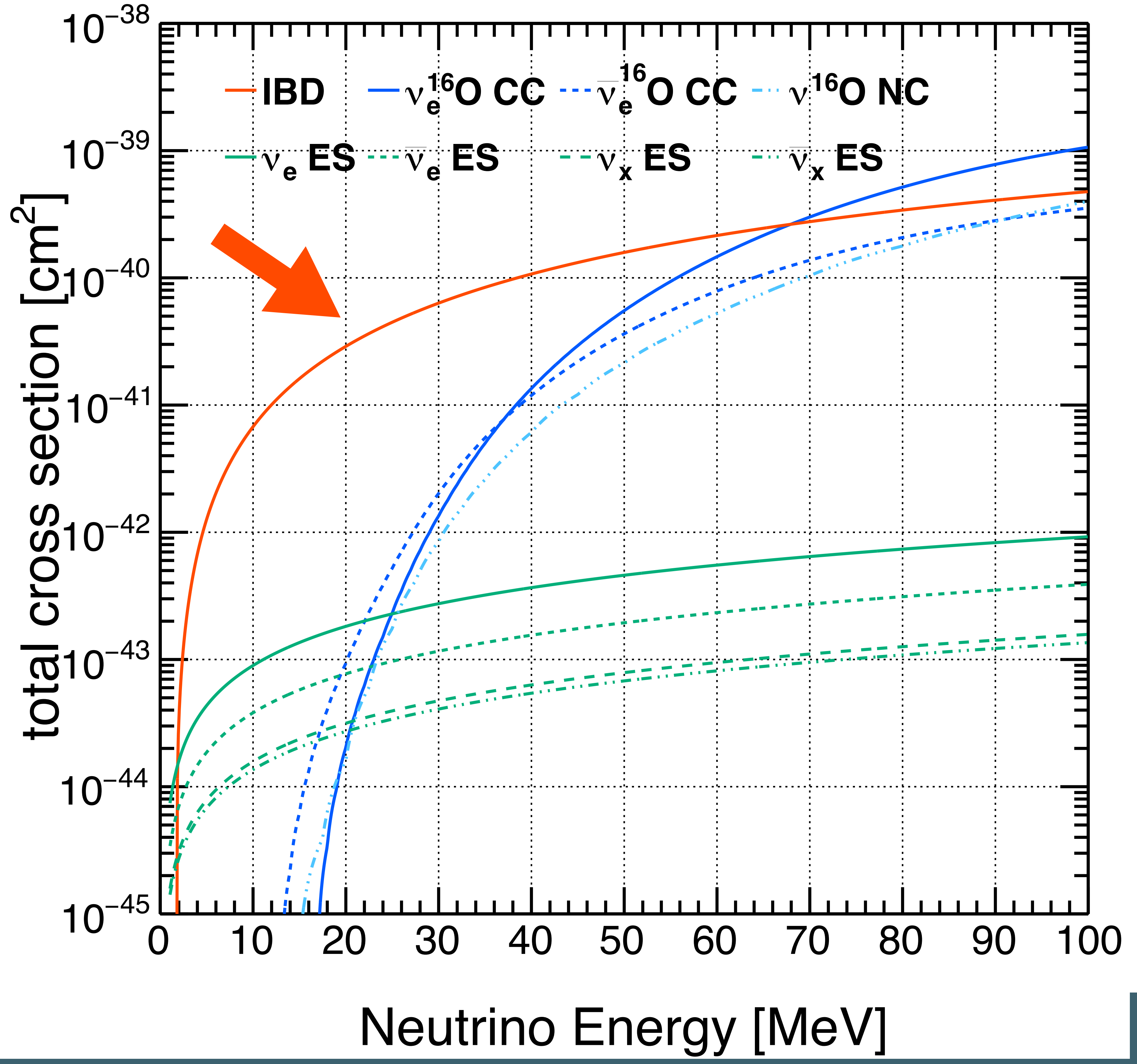
- Main channel: Inverse beta decay (IBD)
  - Largest cross-section among other interactions below 60 MeV



K. Nakazato et al., 2015



F. Nakanishi et al., 2024



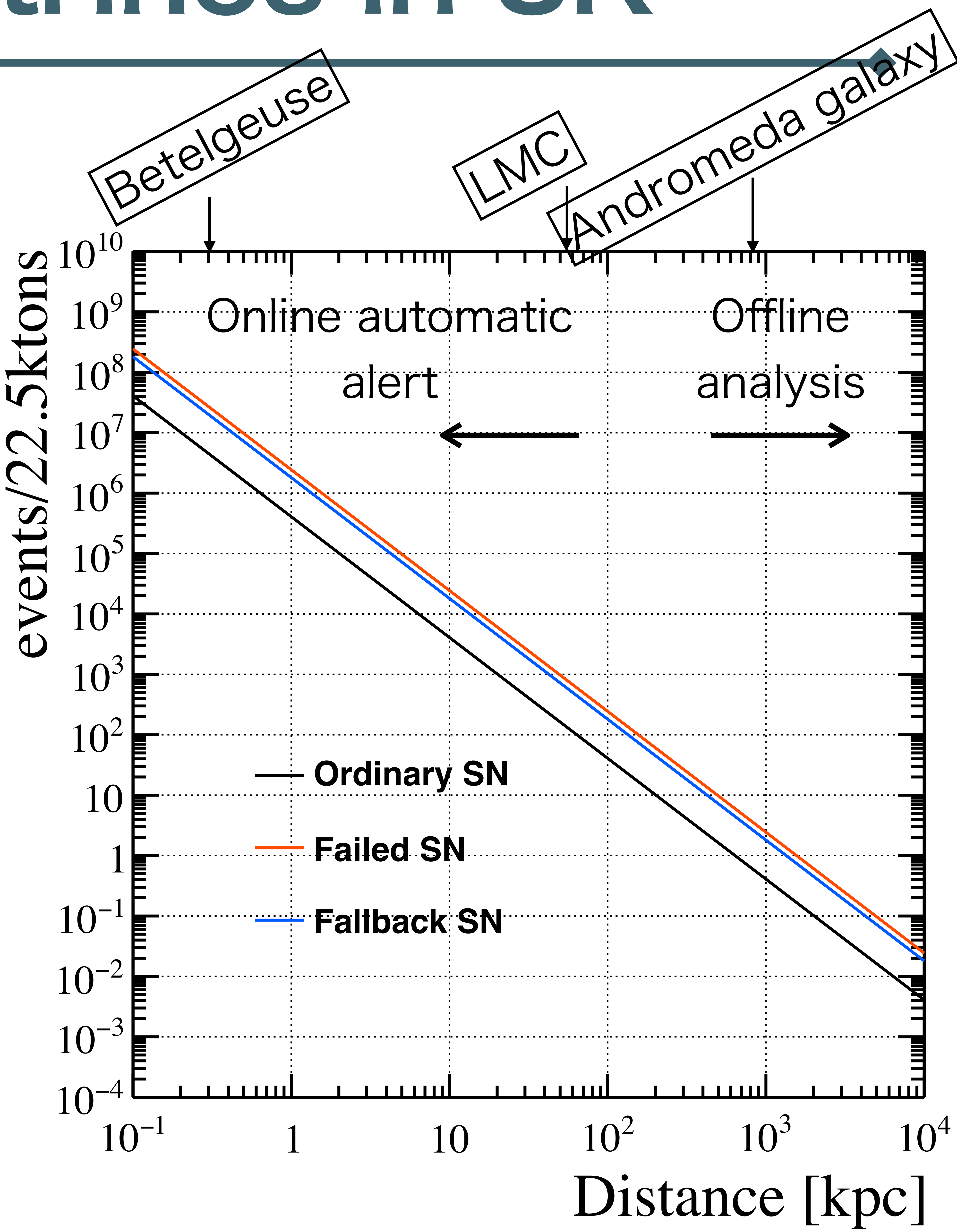
Sensitivity of SN Neutrinos in SK

- SN makes enough neutrino events to trigger an online automatic alert (≲100 kpc)

- Offline analysis enables an expanded neutrino search up to 10 Mpc
  - Increase expected SN rate

	10 kpc	1 Mpc	10Mpc
SN rate (/yr)	~0.01	~0.1	~0.8

→**SN neutrinos can be identified with proper background evaluation**



Search for Neutrinos from Failed SN Candidate in M31

Overview of Research History

Search for Neutrinos from failed SN candidate

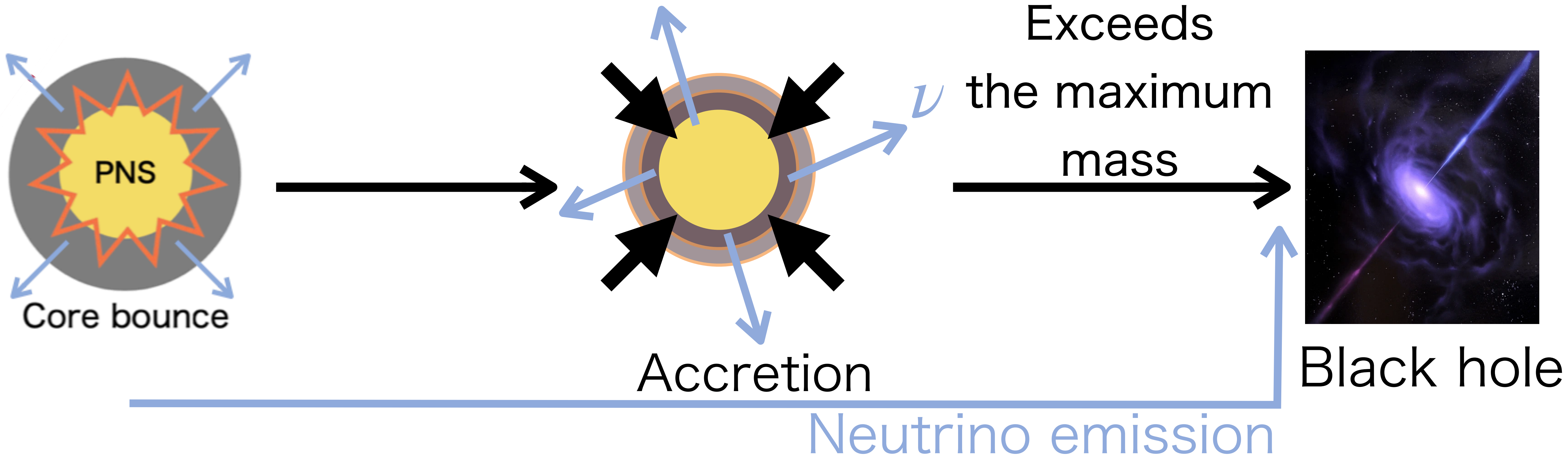
- A failed SN candidate in the Andromeda Galaxy was reported in 2024

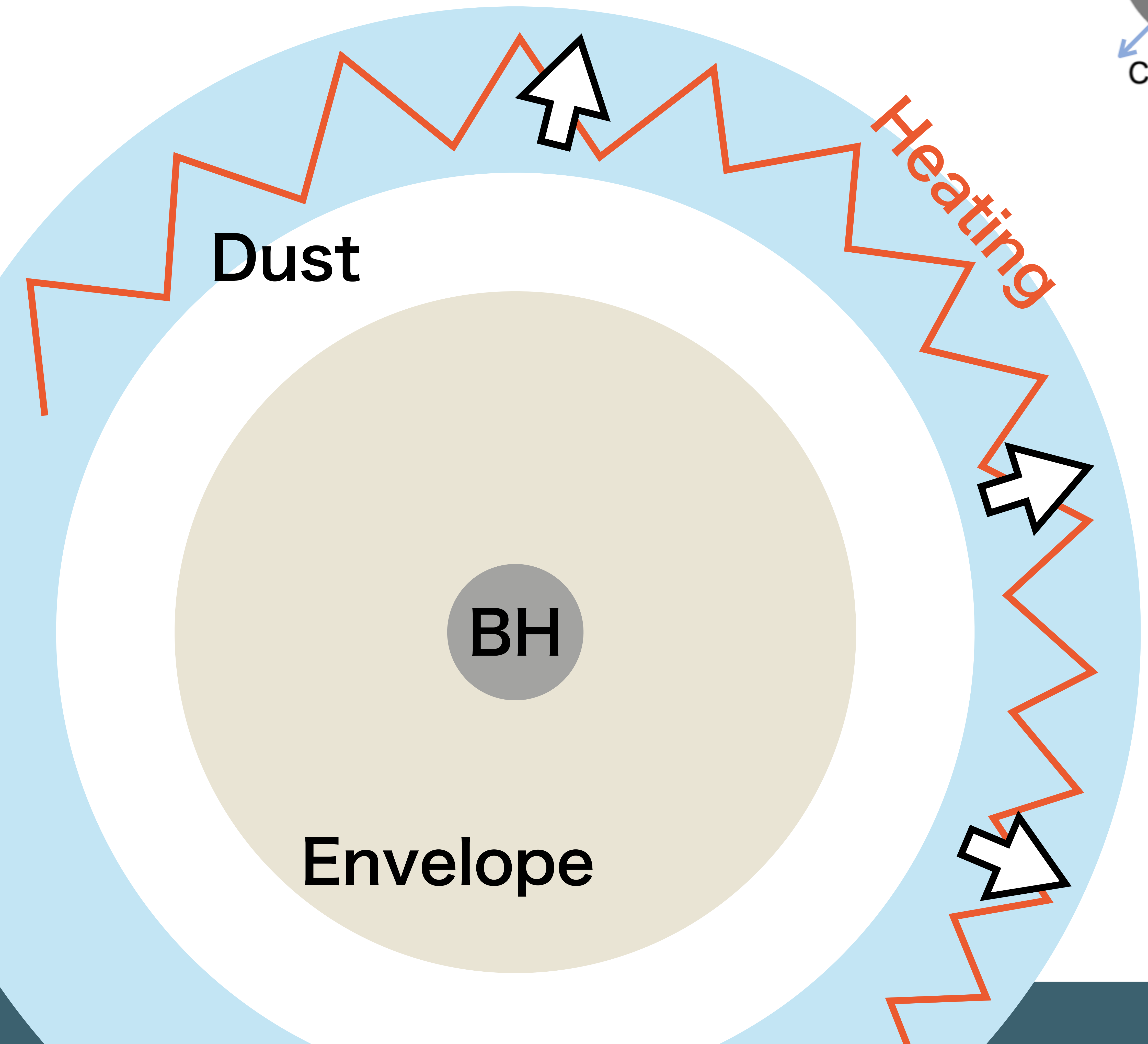
The disappearance of a massive star marking the birth of a black hole in M31

Kishalay De[1*], Morgan MacLeod[2], Jacob E. Jencson[3], Elizabeth Lovegrove[4], Andrea Antoni[5], Erin Kara[1], Mansi M. Kasliwal[6], Ryan M. Lau[7], Abraham Loeb[2,8], Megan Masterson[1], Aaron M. Meisner[7], Christos Panagiotou[1], Eliot Quataert[9] and Robert Simcoe[1]

K. De et al. 2024

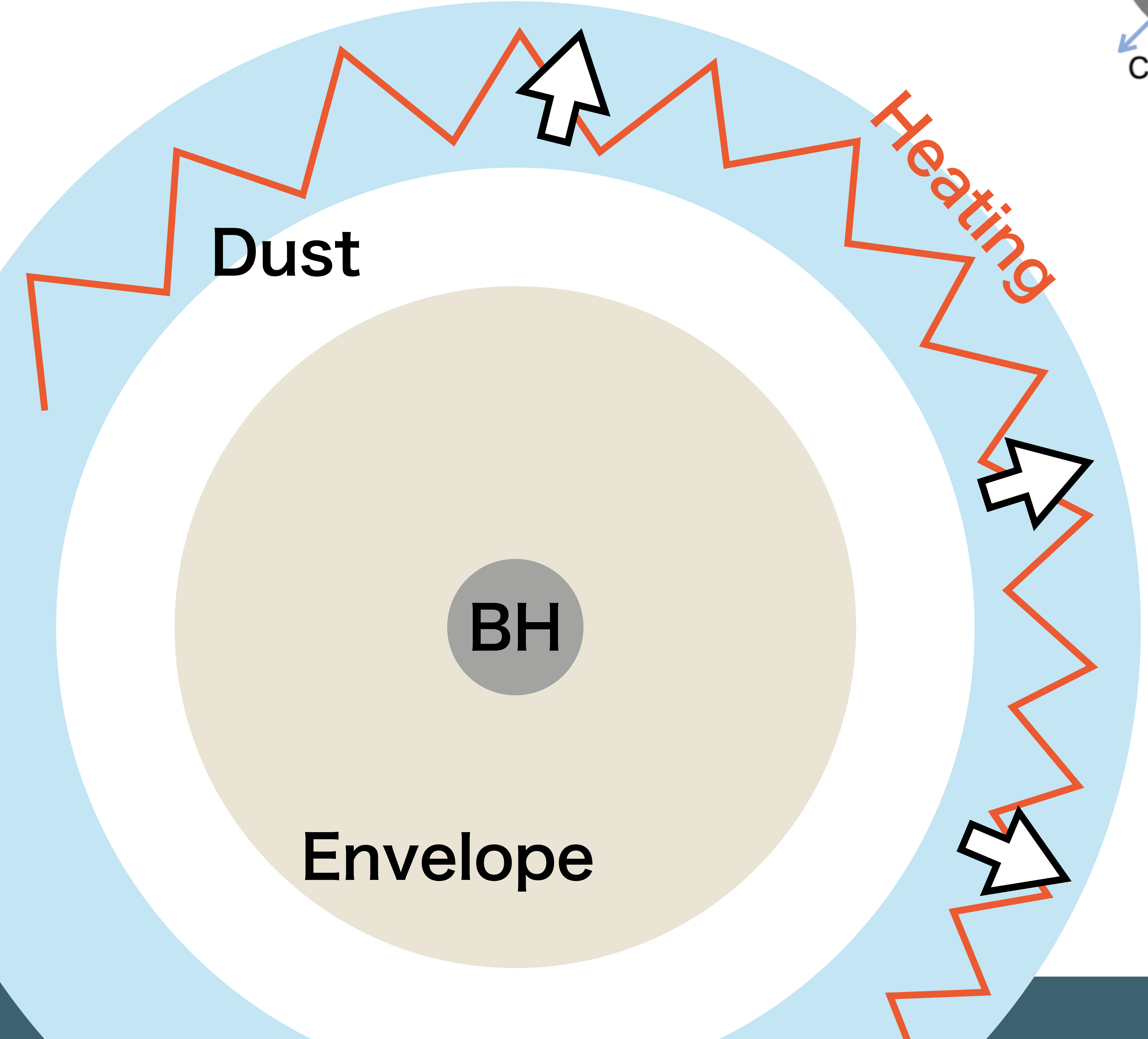
Failed Supernova

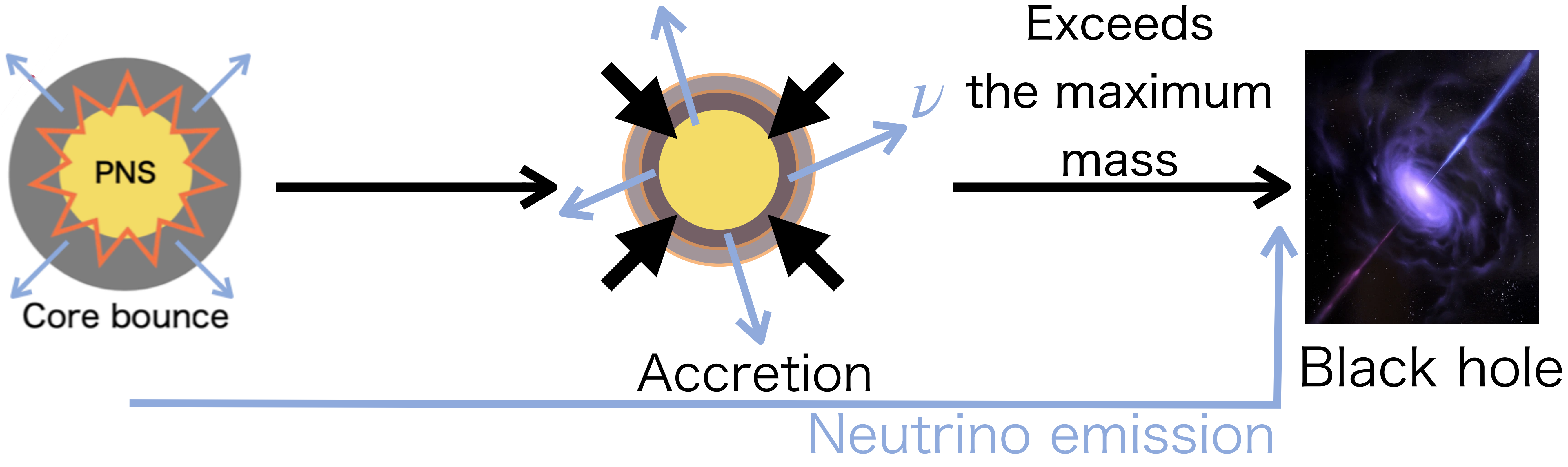




- After black hole formation, dust is heated by shock
  →emitting infrared radiation

M31-2014-DS1



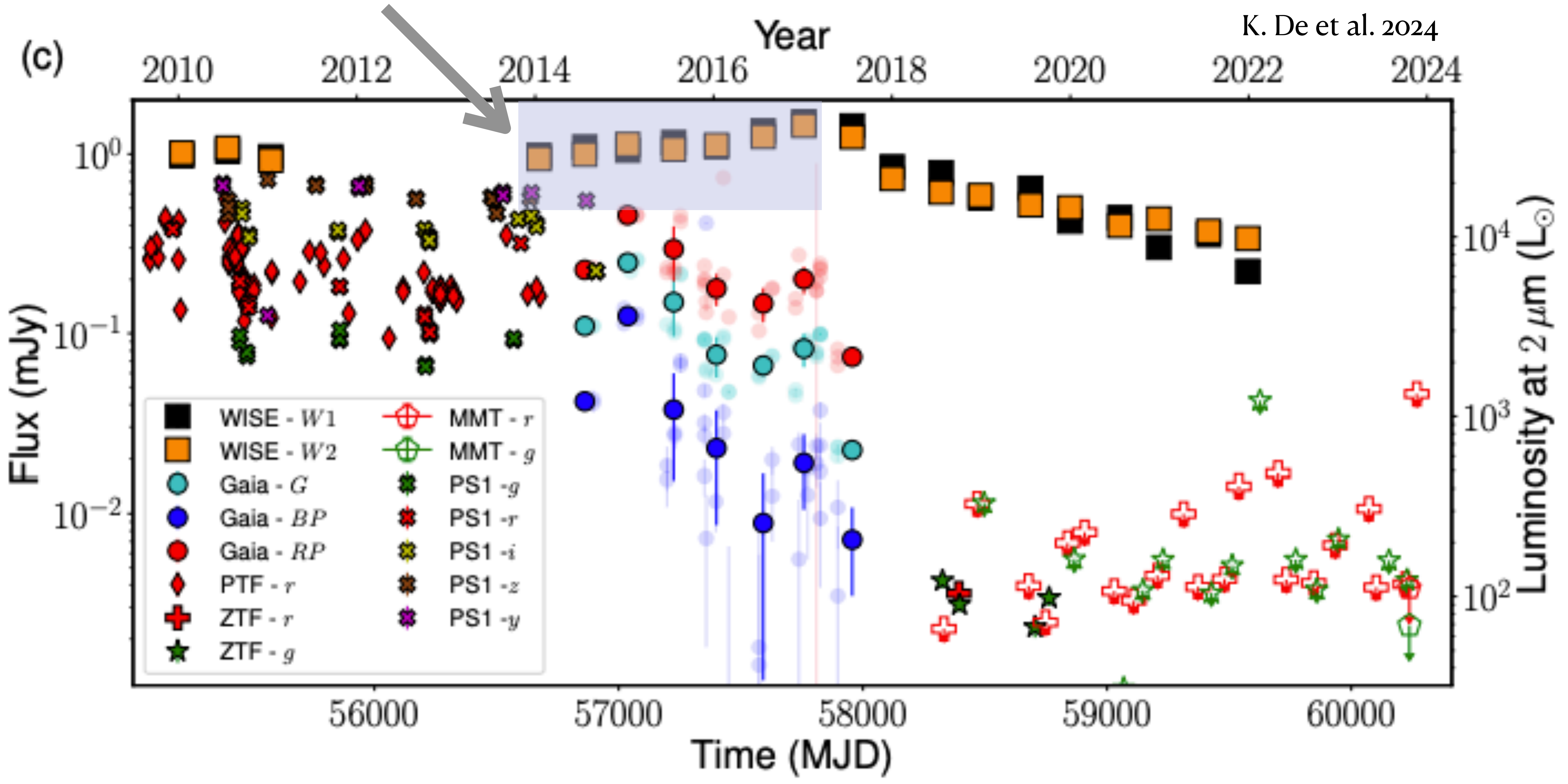


- M31-2014-DS1
  - Hydrogen-depleted supergiant
  - Distance: ~770 kpc
    (at Andromeda galaxy)
  - Stellar mass: $\approx 13 M_\odot$

Black Hole Formation Time

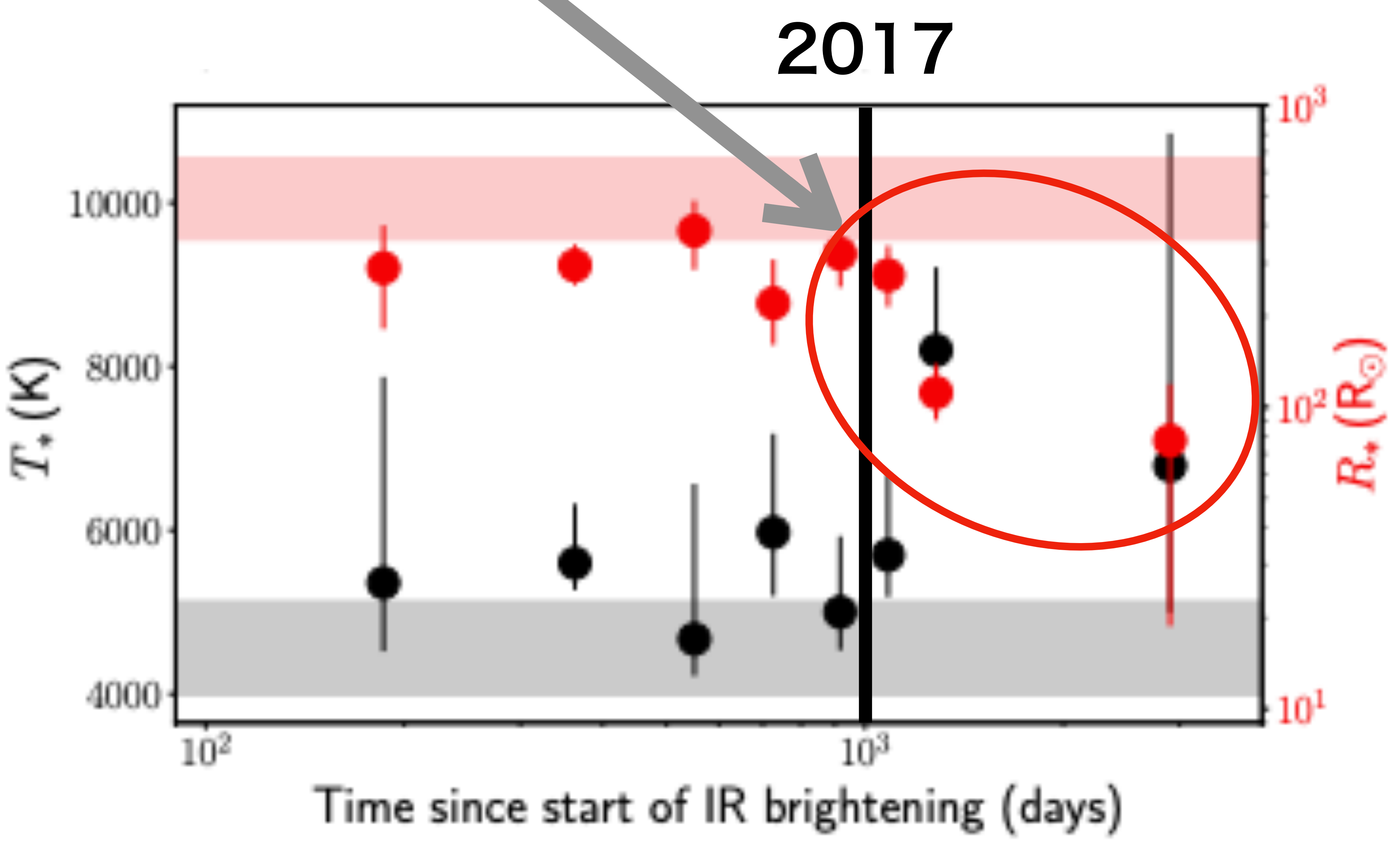
- Mid-Infrared Obs. (NEOWISE)
  - Flux increase observed over 2 years since 2014

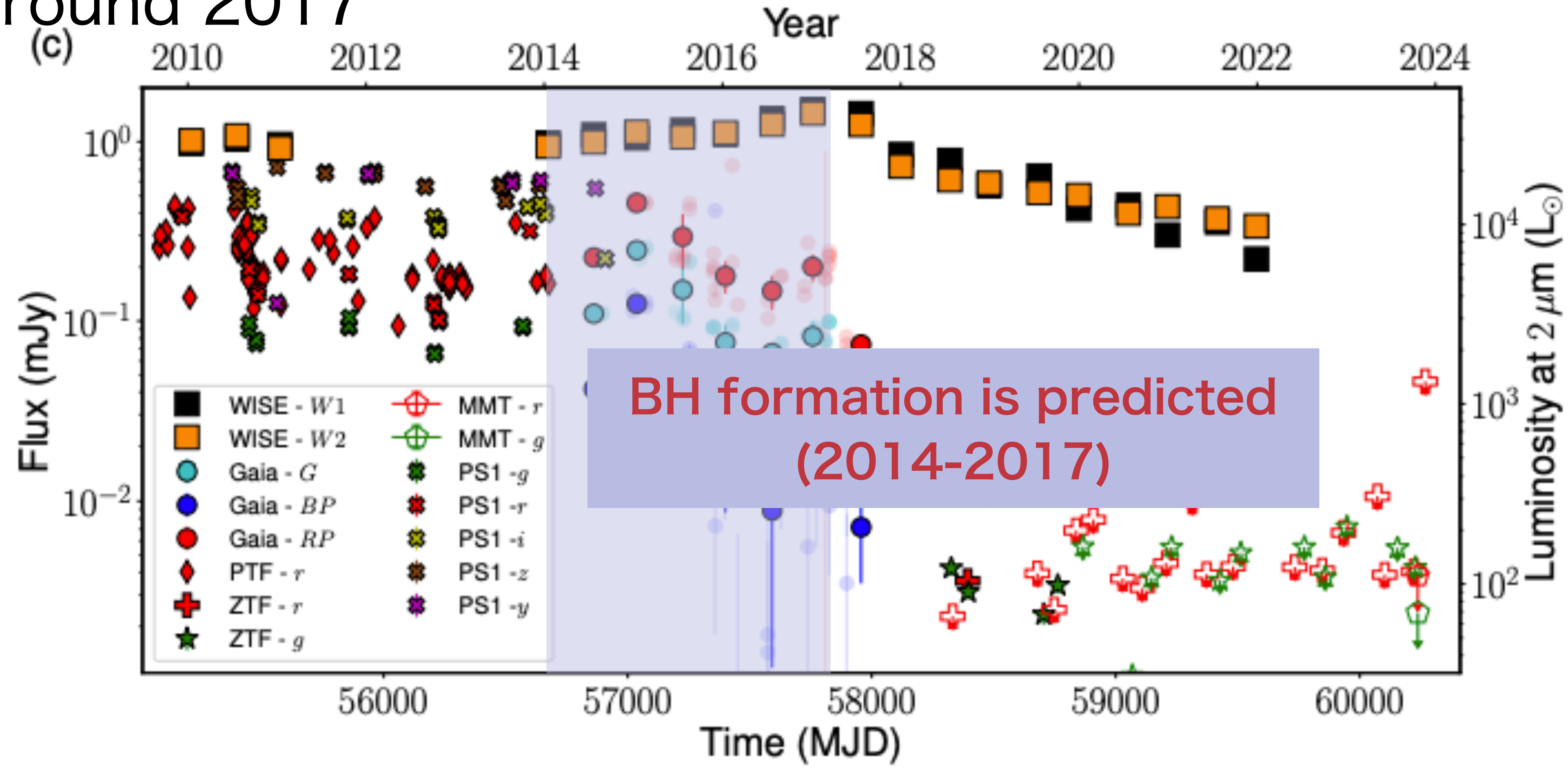
K. De et al. 2024



Black Hole Formation Time

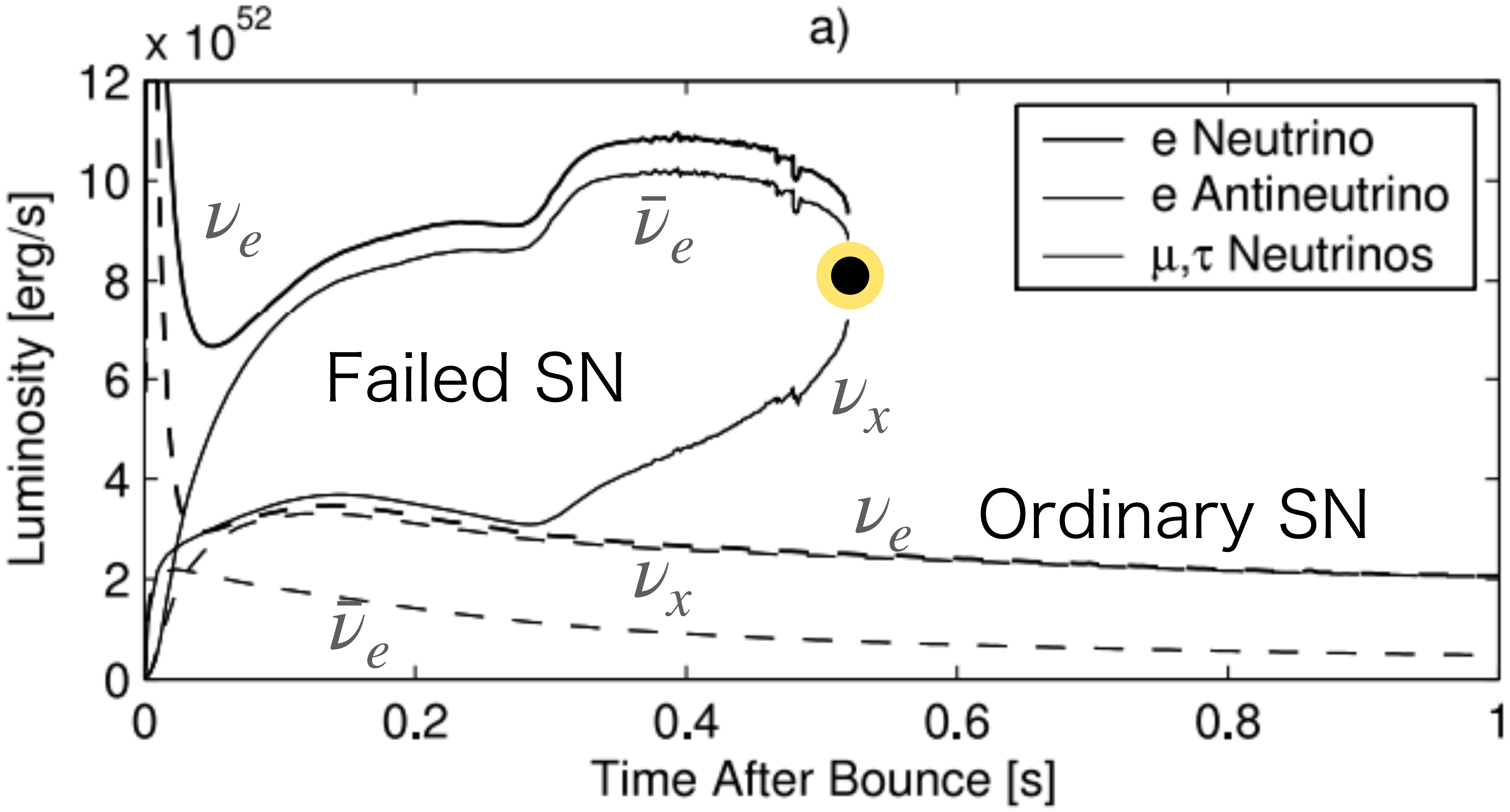
- Optical observation
  - The stellar radius decreased around 2017
  - The temperature increased around 2017





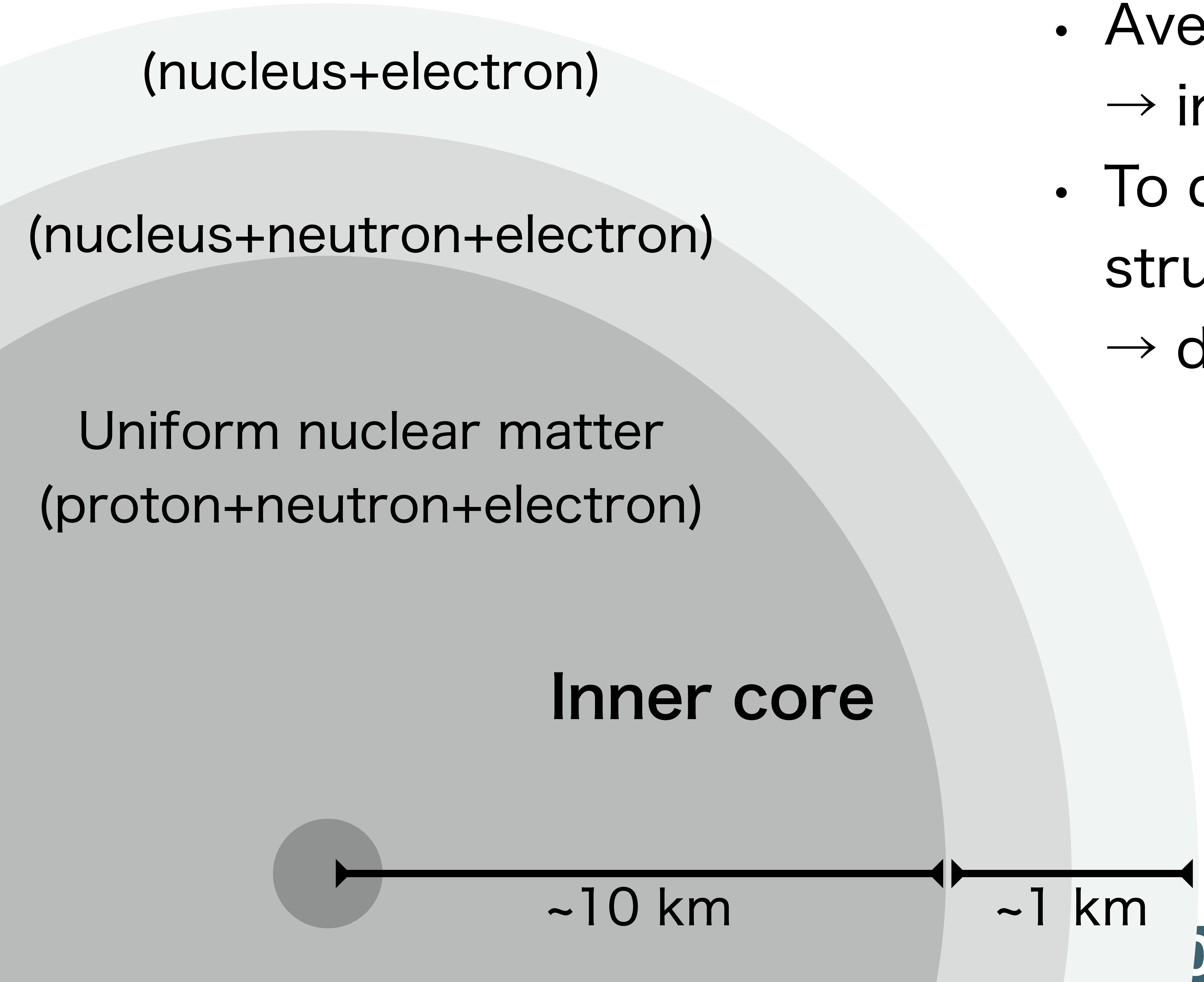
Characteristics of Neutrino Emission

- Neutrinos have higher energies compared to those from ordinary SN
- Emission duration is determined by the time to black hole formation



Nuclear Equation of State (EOS)

- Structure of PNS

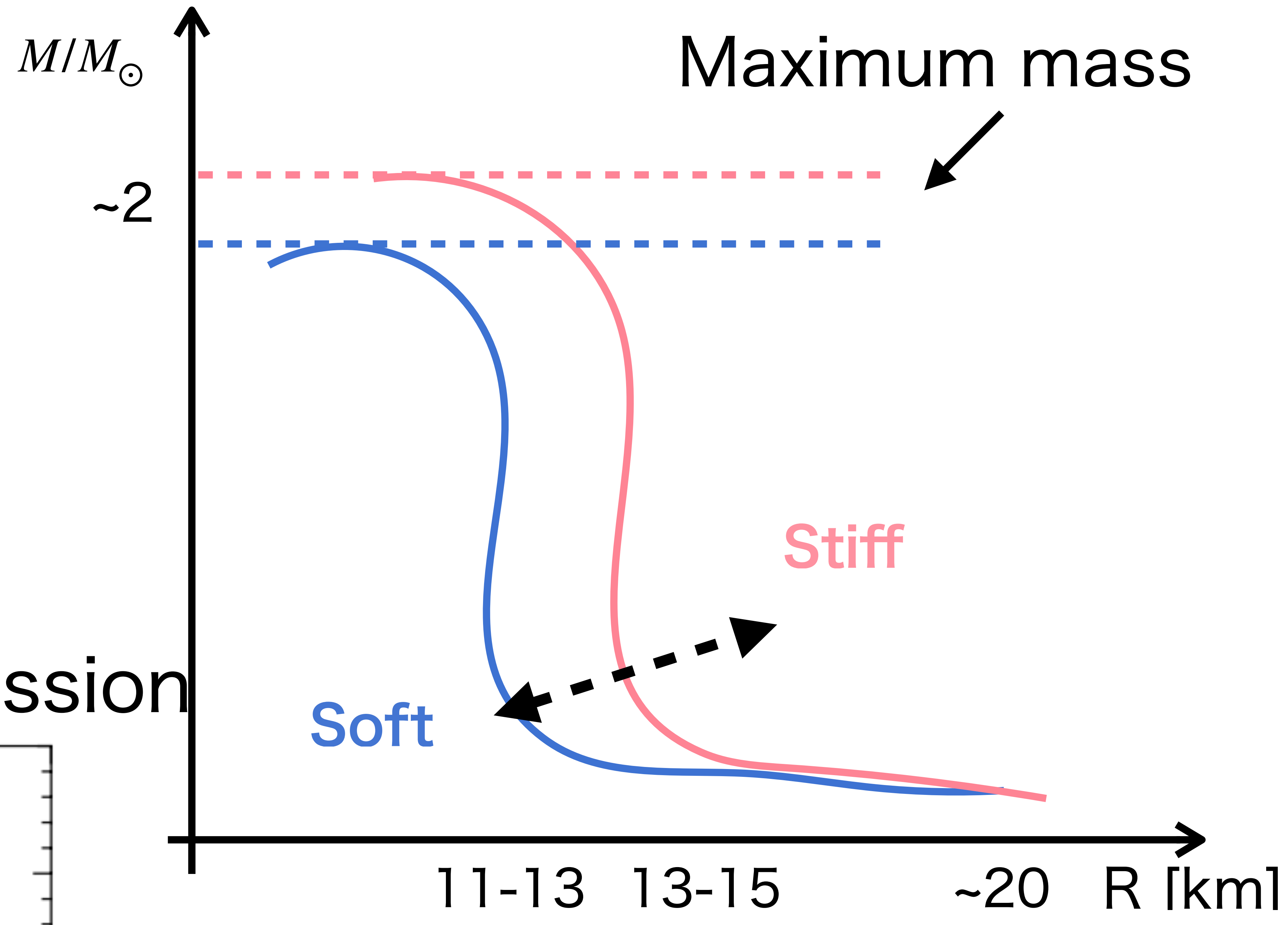


- Average central density: 10^{15} g/cm^{-3}
  → inner core is composed of nuclear matter
- To determine the composition of the internal structure
  → determines the mass-density relation

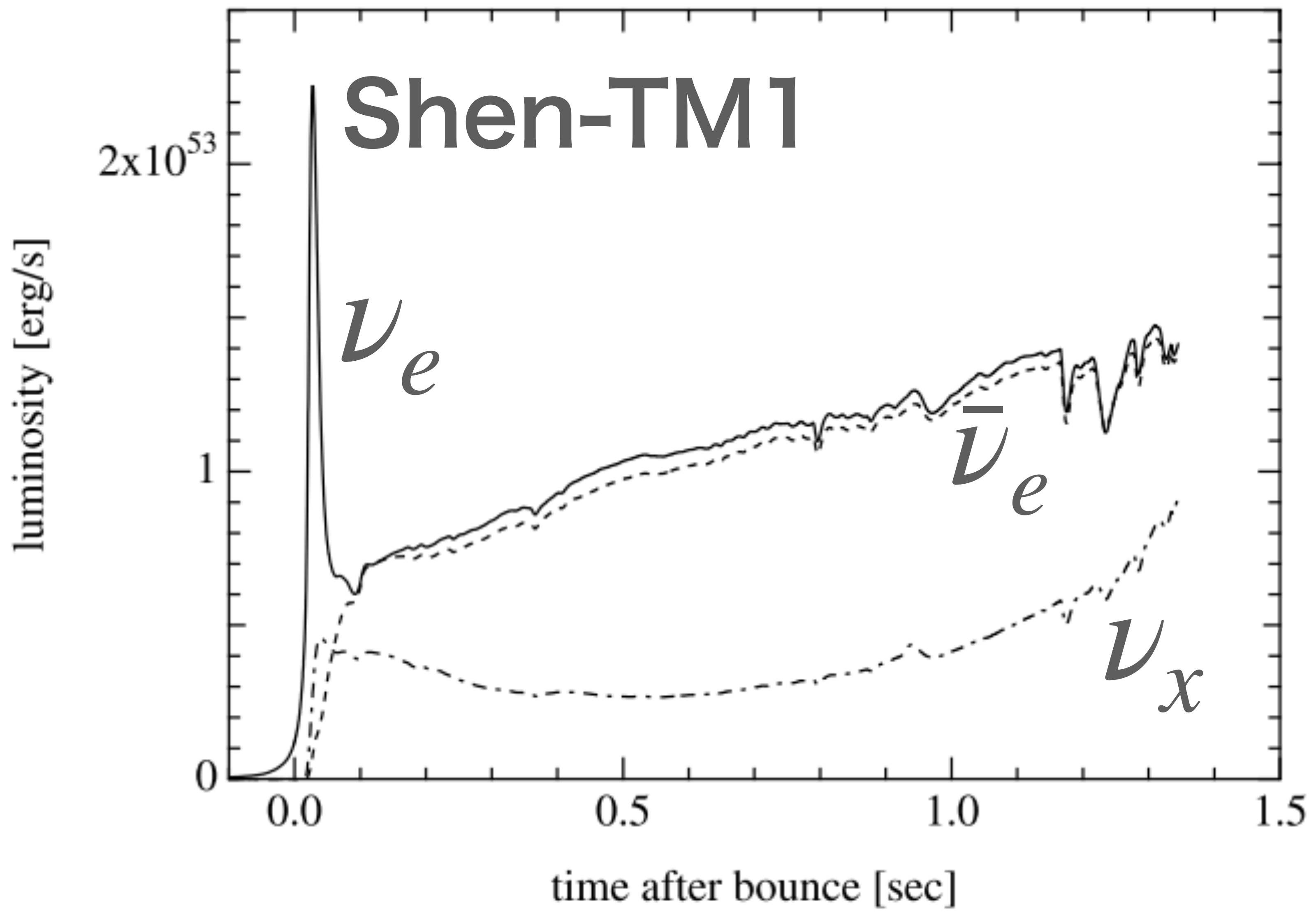
Nuclear equation of state (EOS)

Nuclear Equation of State (EOS)

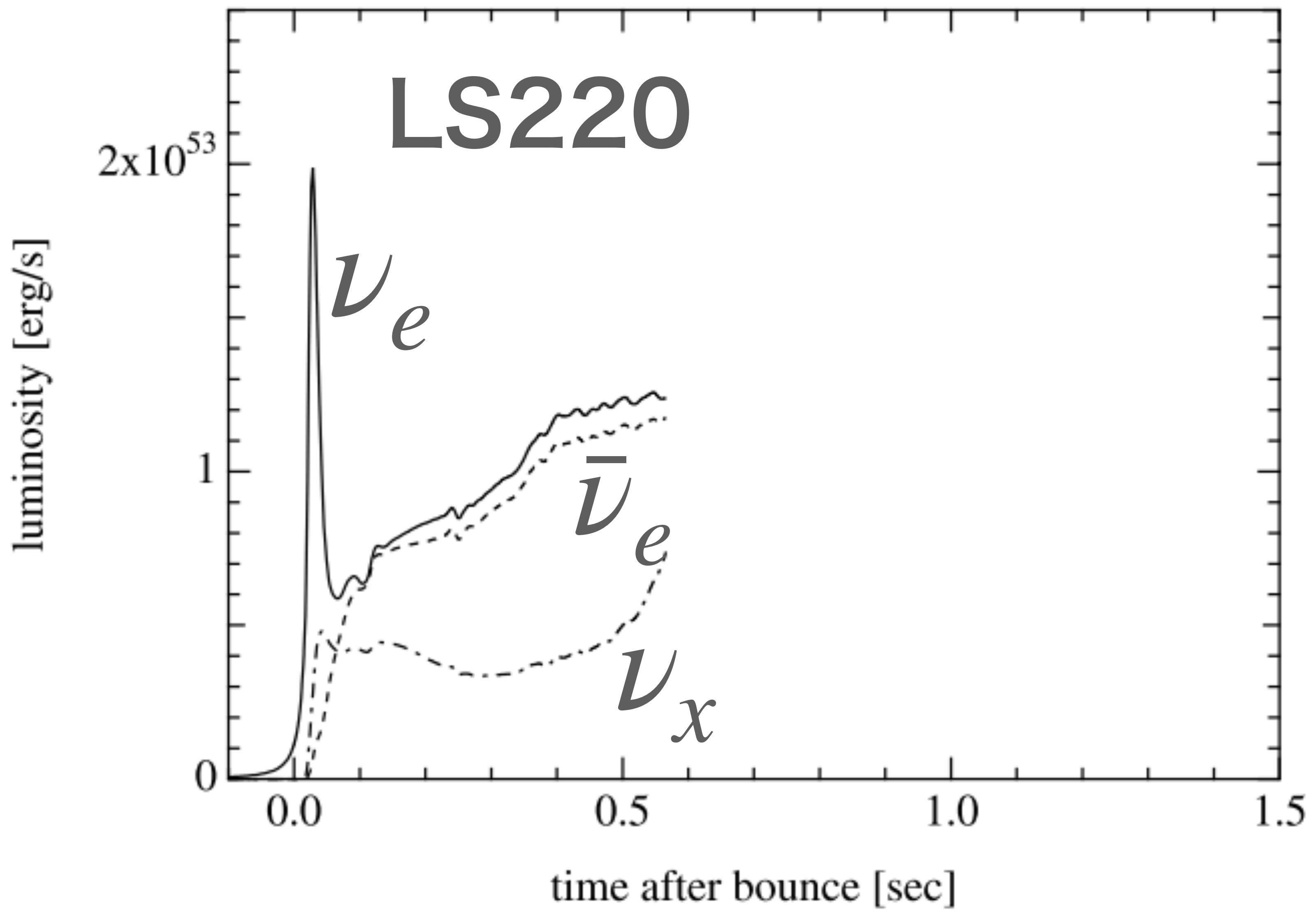
- Difference between stiff and soft EOS
  - Stiff EOS: large maximum mass
  - Soft EOS: small maximum mass



Stiff EOS ⟺ Long emission



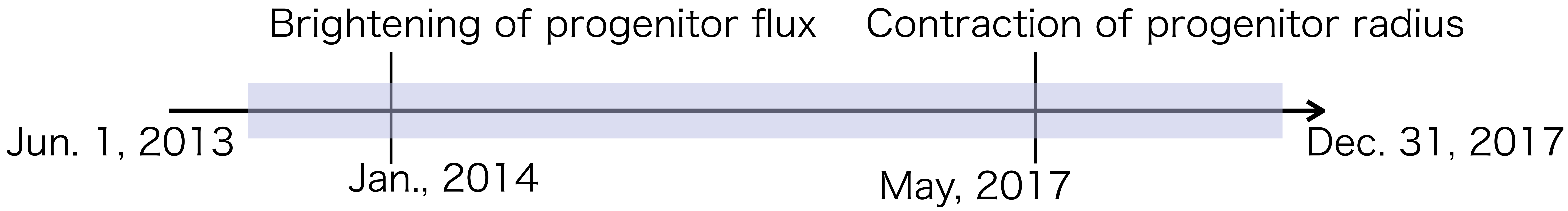
Soft EOS ⟺ Short emission



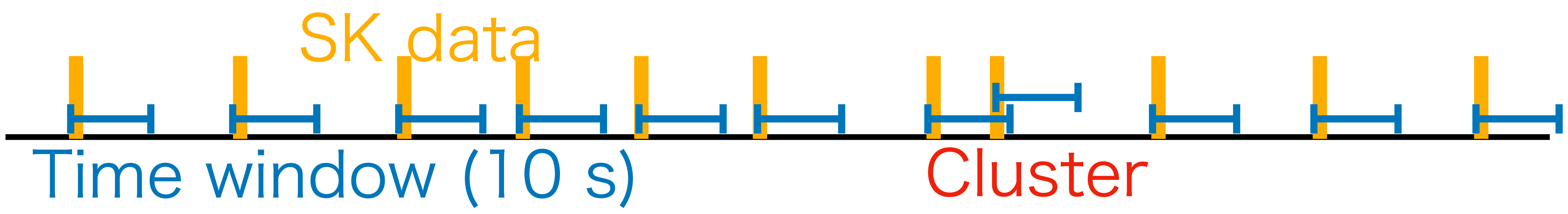
Analysis Method

Strategy for Cluster Search

- **Enough to include the black hole formation time**
  →Wide signal time range

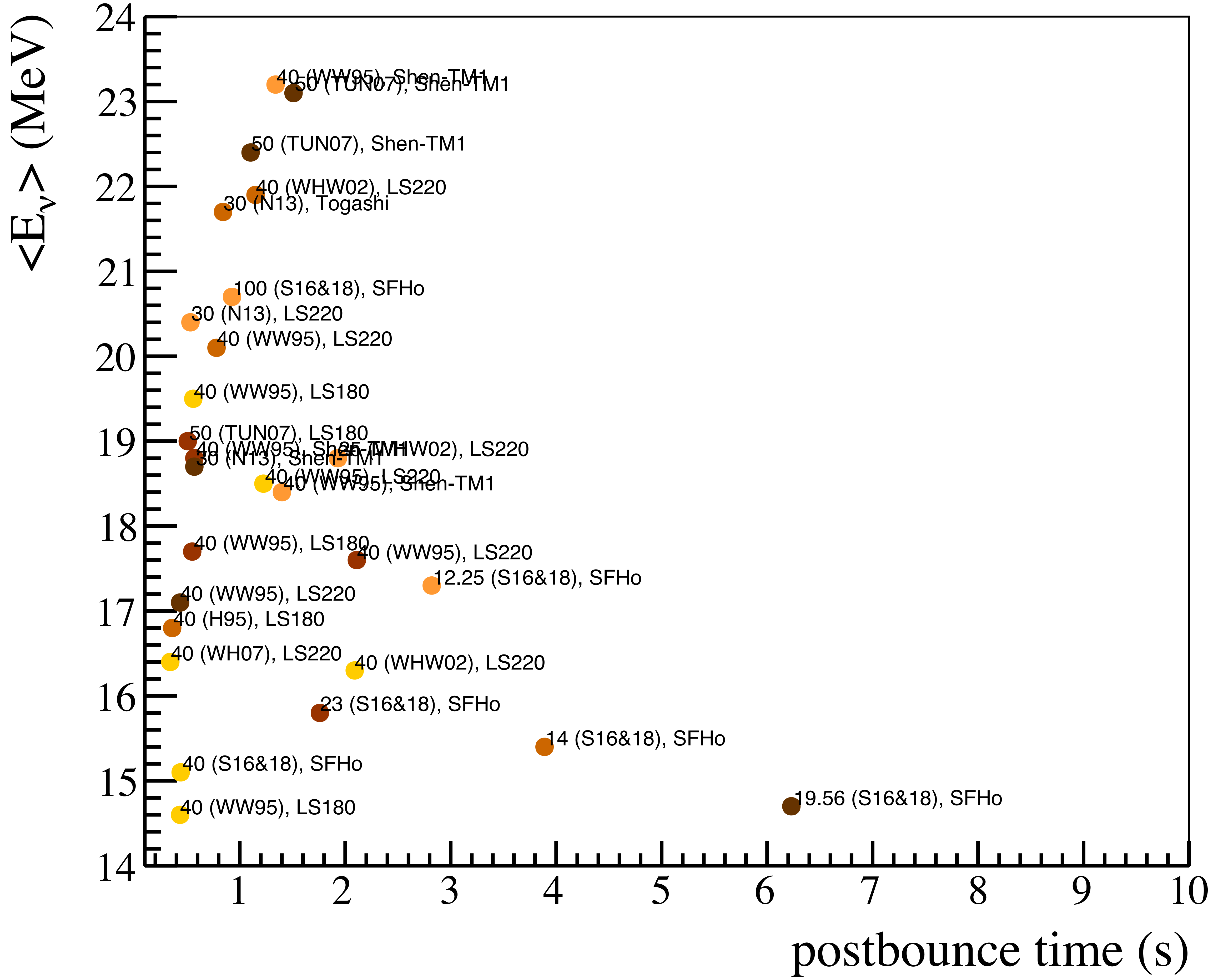


- Search period: Jun. 1, 2013 - Dec. 31, 2017
  - Livetime: about 3.88 years
  - Pure water phase
- Search for multiple events occurring within a short time window



Strategy for Cluster Search

- **Model-Independent approach**
  - Enough to cover all failed SN models considered in this study
  - Conservative time window for cluster



Cluster condition
2 ≥ / 10 s

Background Event Reduction

1. **First reduction**
   - Non-physics data cut, trash event cut

2. **Second reduction**
   - Muon spallation cut (based on a data-driven method)
   - Signal efficiency is 50-80%, while spallation efficiency is ~10%

3. **Third reduction**
   - Atmospheric neutrino event cut (based on MC simulations)
   - Signal efficiency ~90% with atmospheric neutrino events reduced to ~15%

Background Event Reduction

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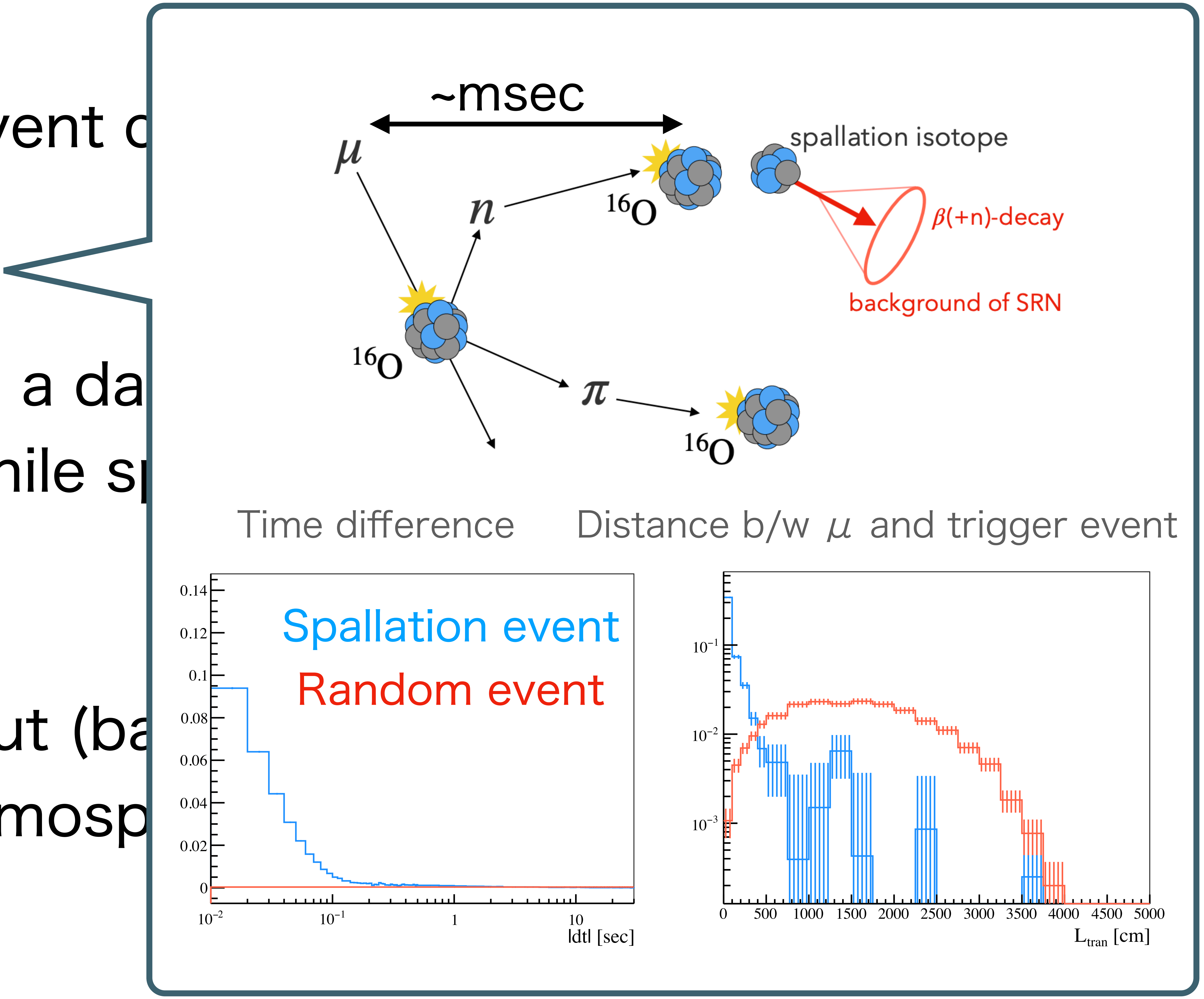
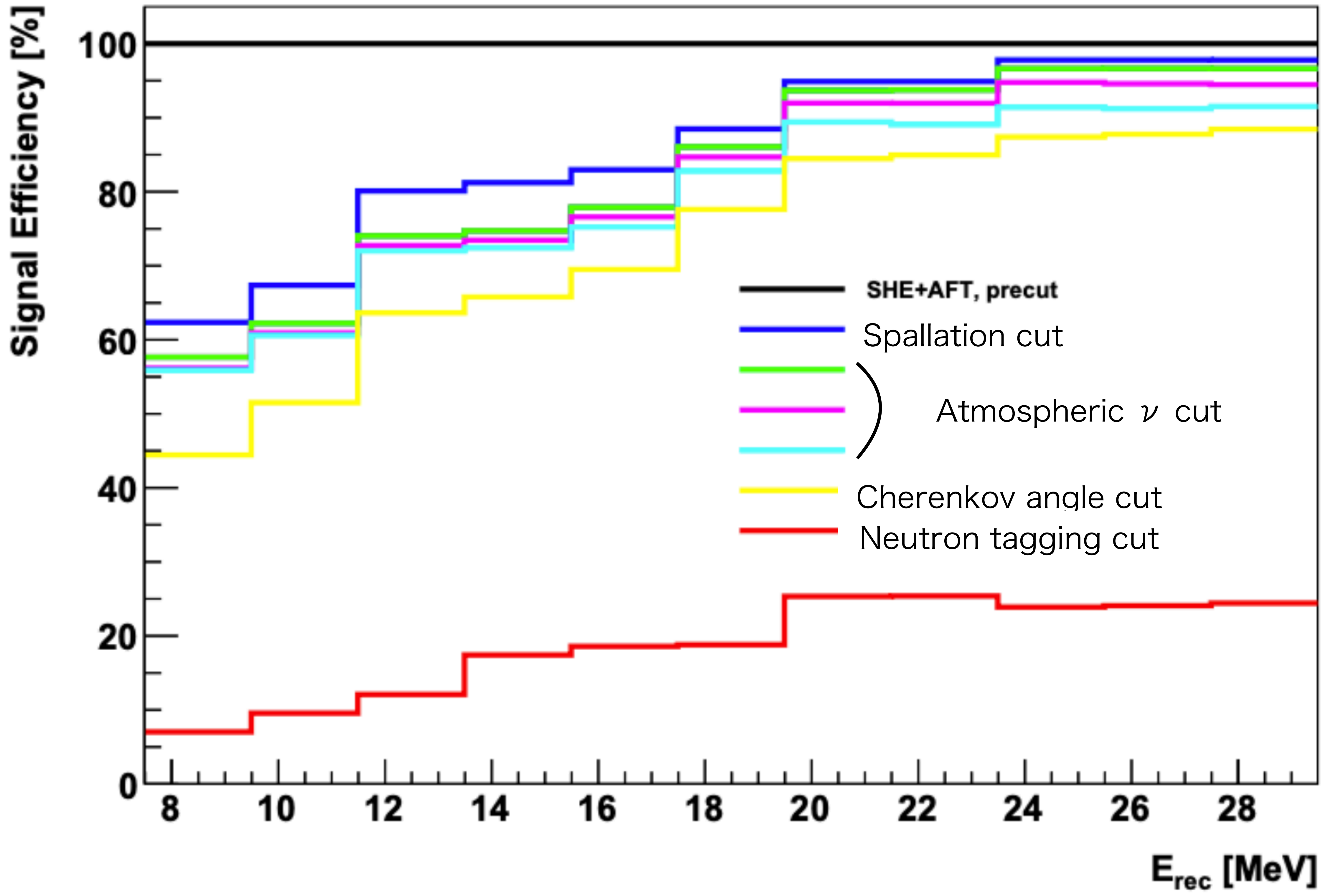


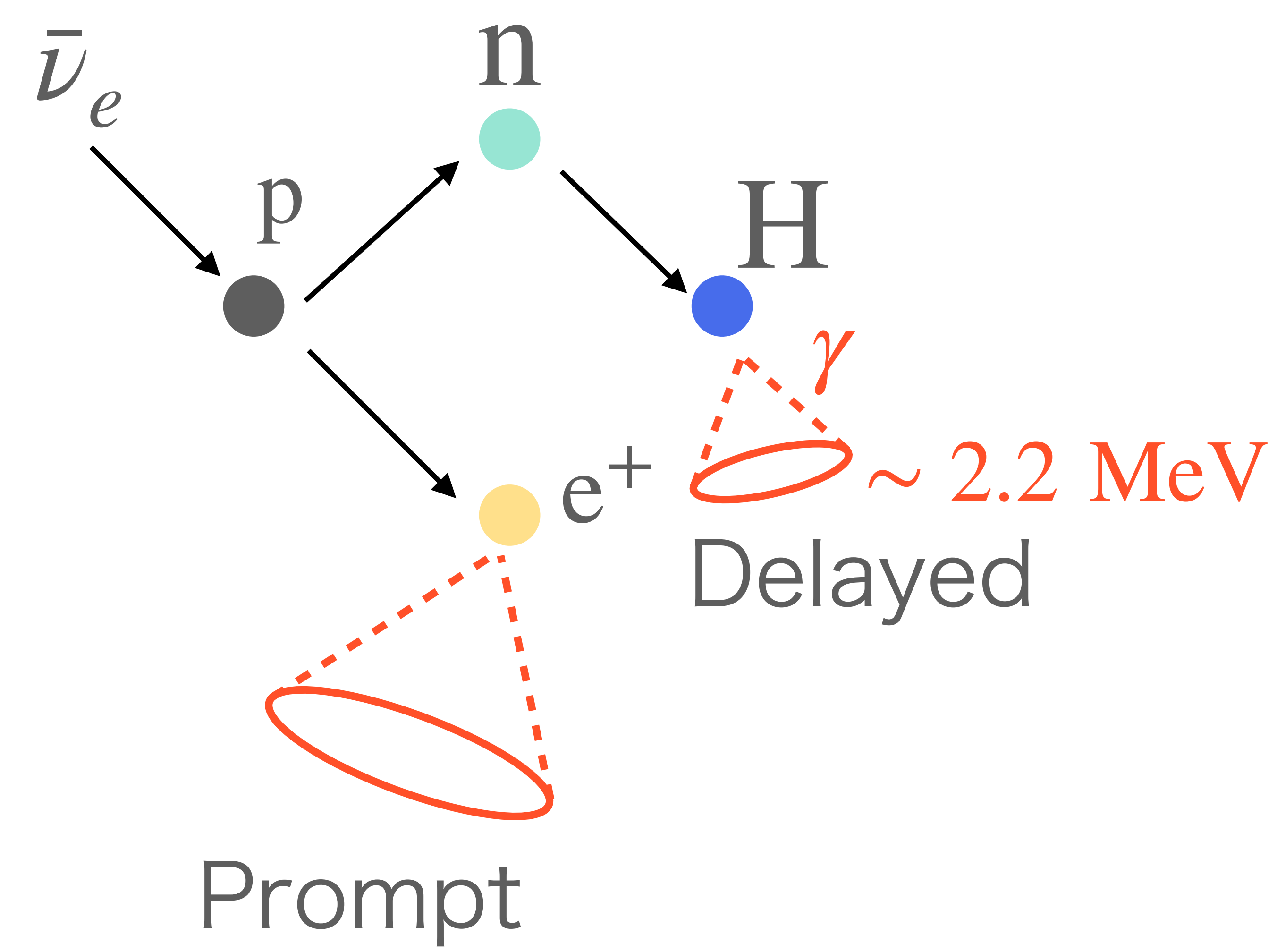
Event Selection using Neutron

- Delayed neutron signal: 2.2 MeV γ from capture on hydrogen
  →Below the Cherenkov threshold

K. Abe et al. 2021



Pure-water



→ **Low signal efficiency (~20%)**

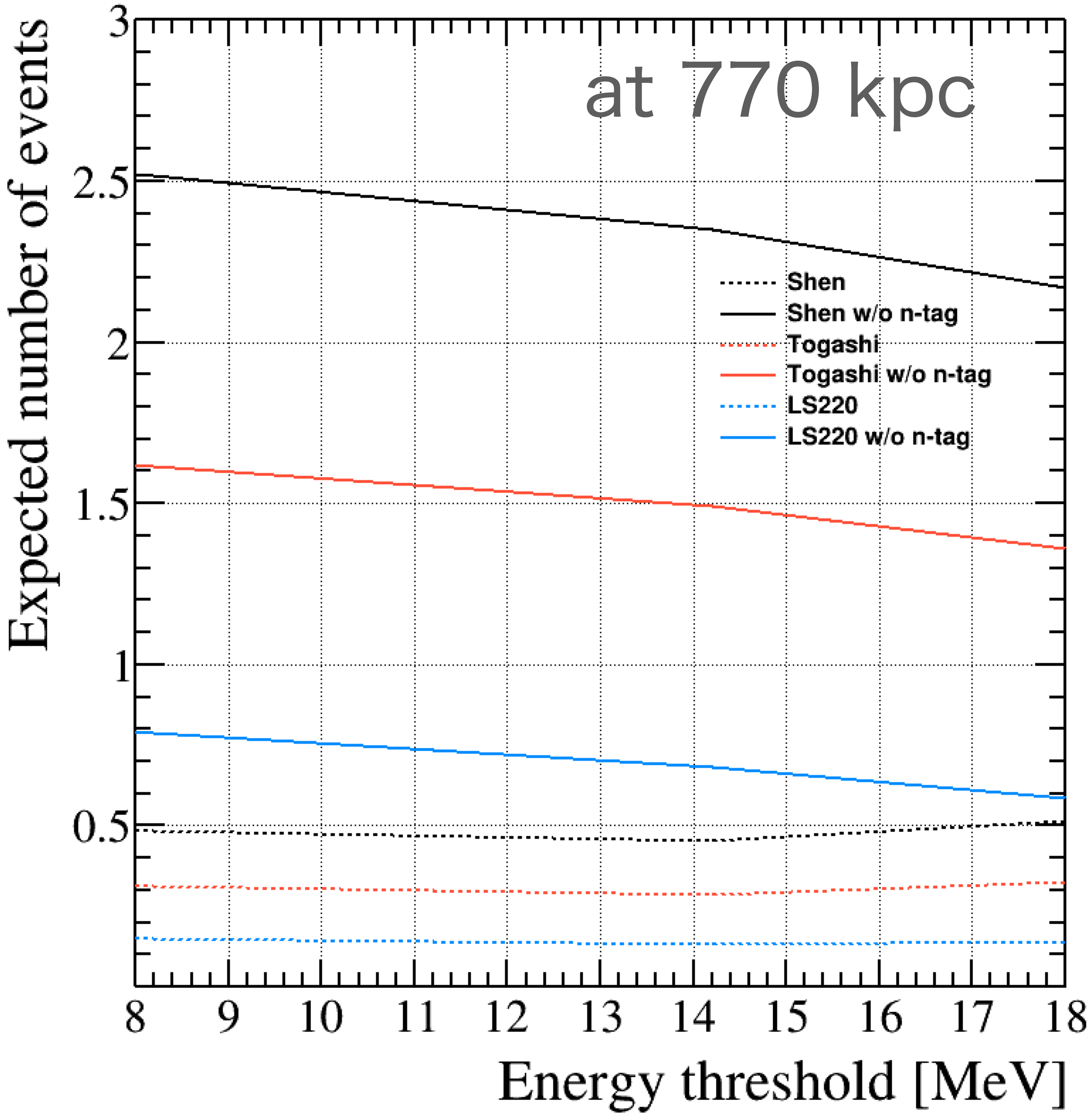
Sensitivity for M31-2014-DS1

- Neutron tagging reduces the expected number of neutrino events to < 1

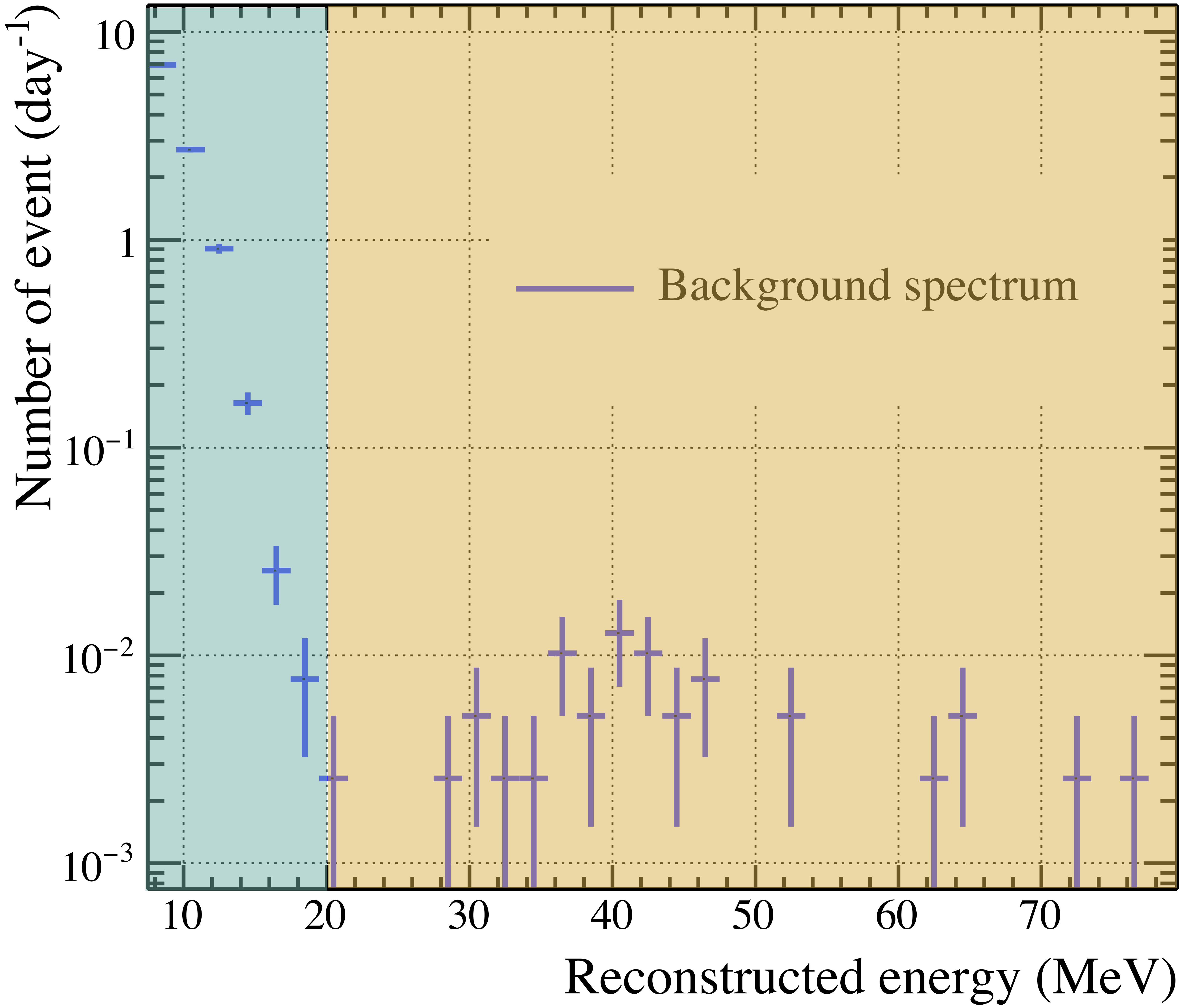
Neutron tagging is not applied in this analysis to maintain signal efficiency

- Expected ν event: 0.6 - 2.2

Expected ν event vs. energy threshold



Remaining Background After Event Selection



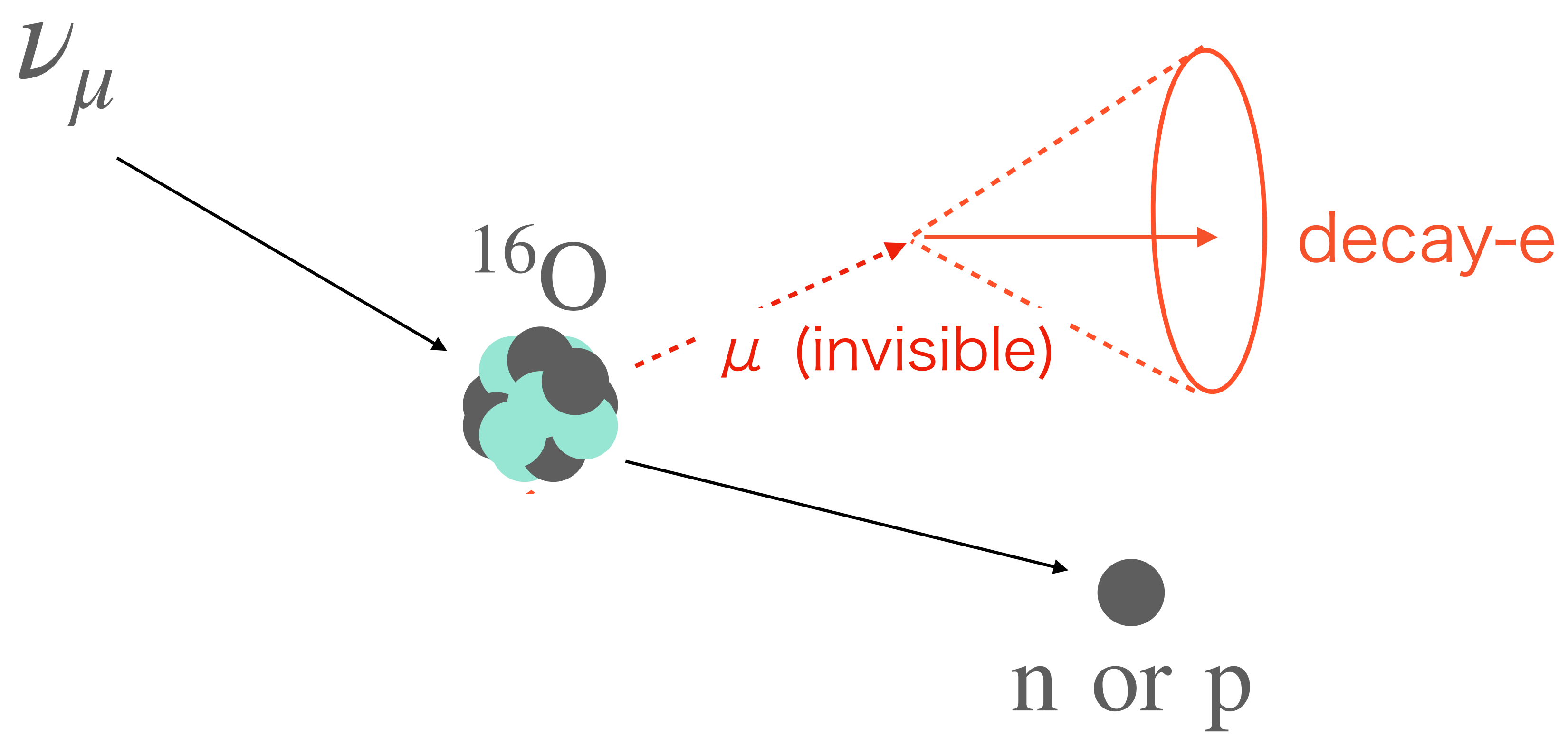
- Background estimated using data excepting search period

8-20 MeV region

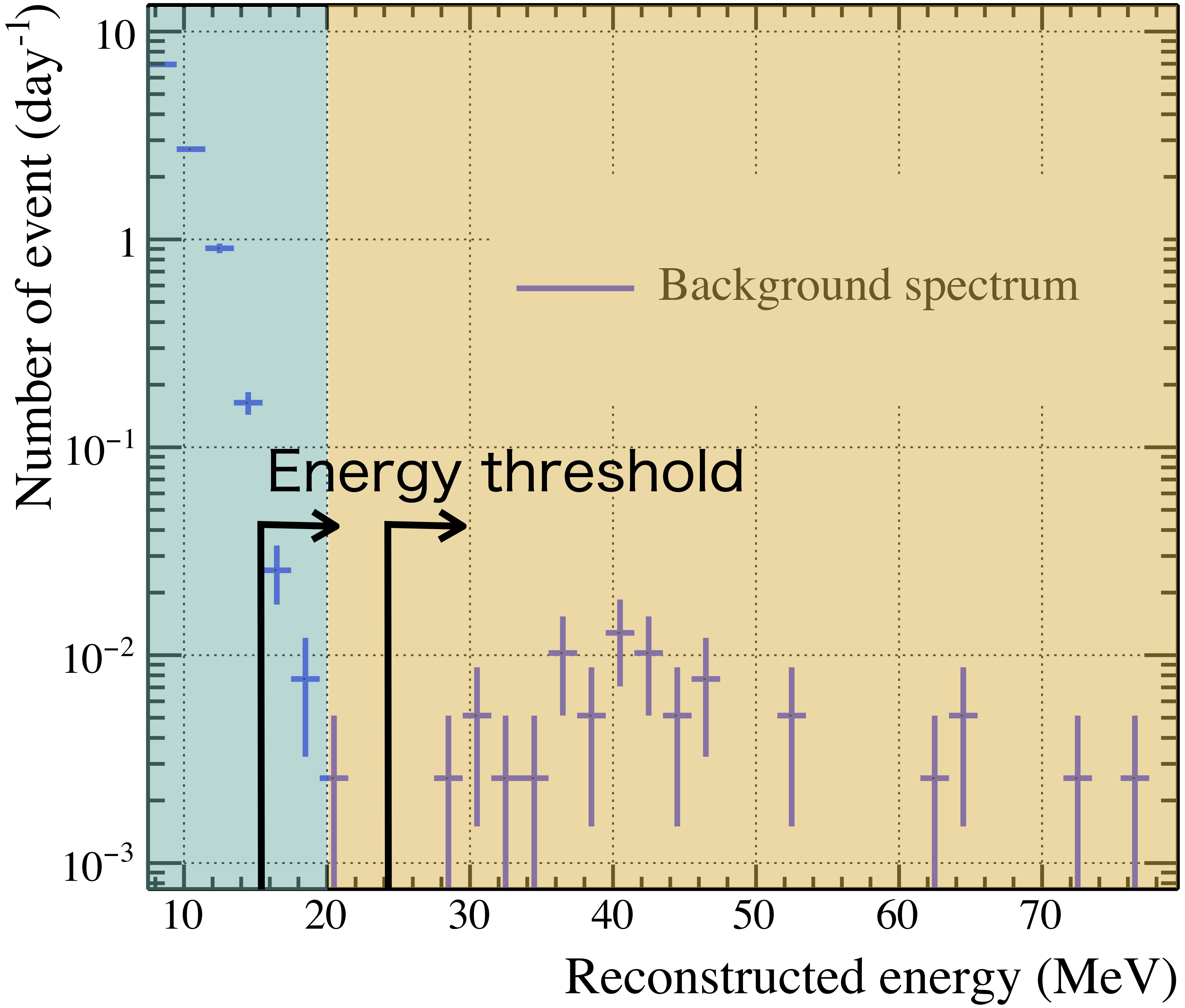
Muon Spallation Event

More than 20 MeV

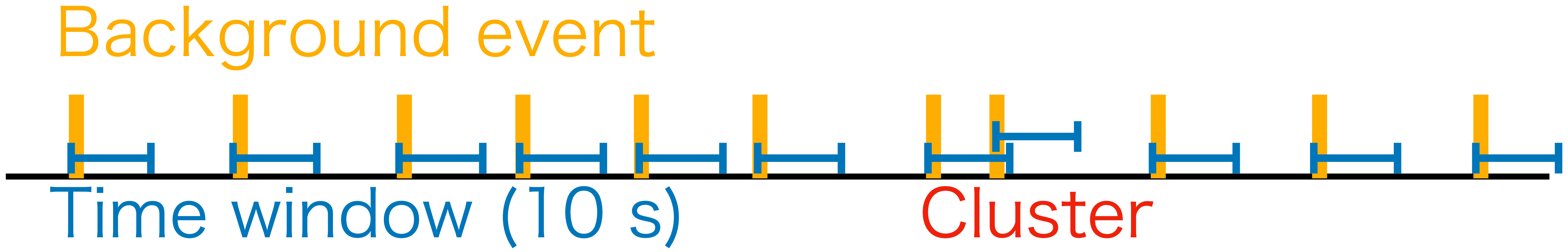
Decay electrons from atmospheric neutrinos



Determination of Energy Threshold



- Background events can occasionally form accidental clusters



- Suppressing background events reduces the probability of contamination the accidental cluster

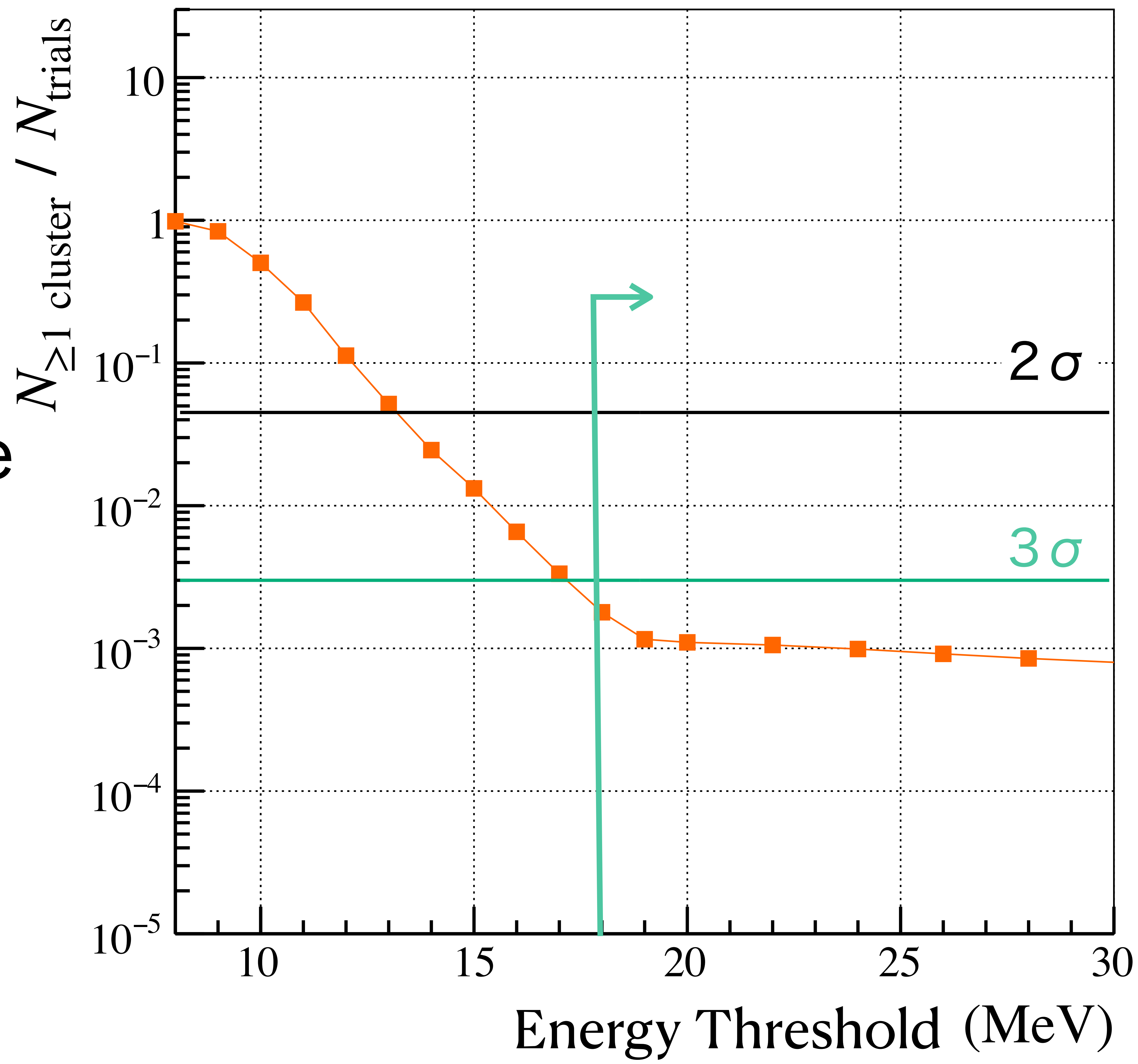
Condition: Accidental background clusters rejected at >3 σ

Determination of Energy Threshold

- The expected probability of accidental clusters due to the background

- Condition: Clusters are identified as signal with ≥3σ significance

→E_{th} = 18 MeV

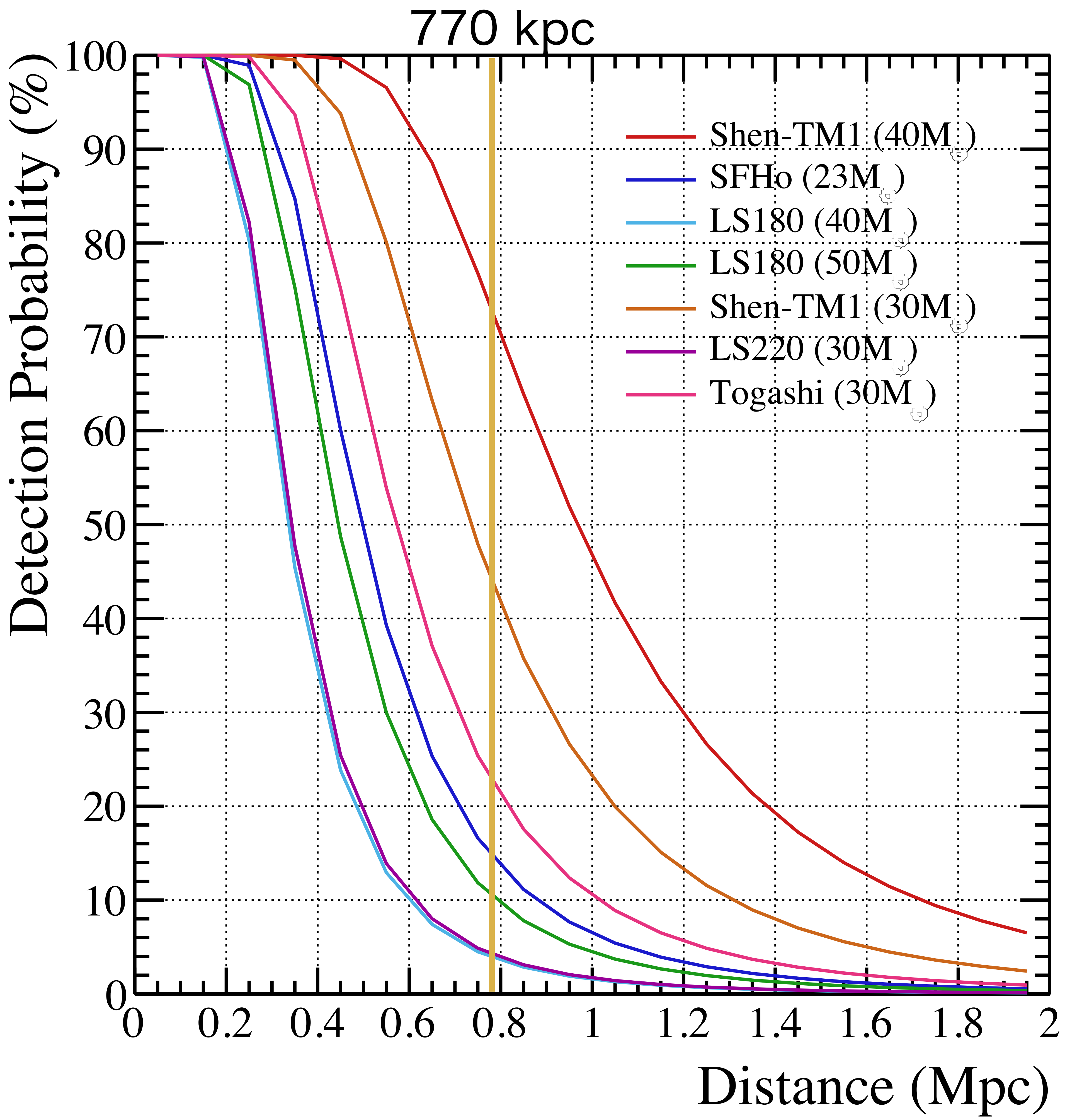


Detection Probability

Detection probability accounting for the search conditions

- $P(N_\nu \geqq 2)$: Probability of detecting two or more events
- Detection probability as a condition of E_{th} = 18 MeV
- At 770 kpc, the detection probability ranges from 4% to 72%

SK has sufficient sensitivity to detect neutrinos from M31-2014-DS1

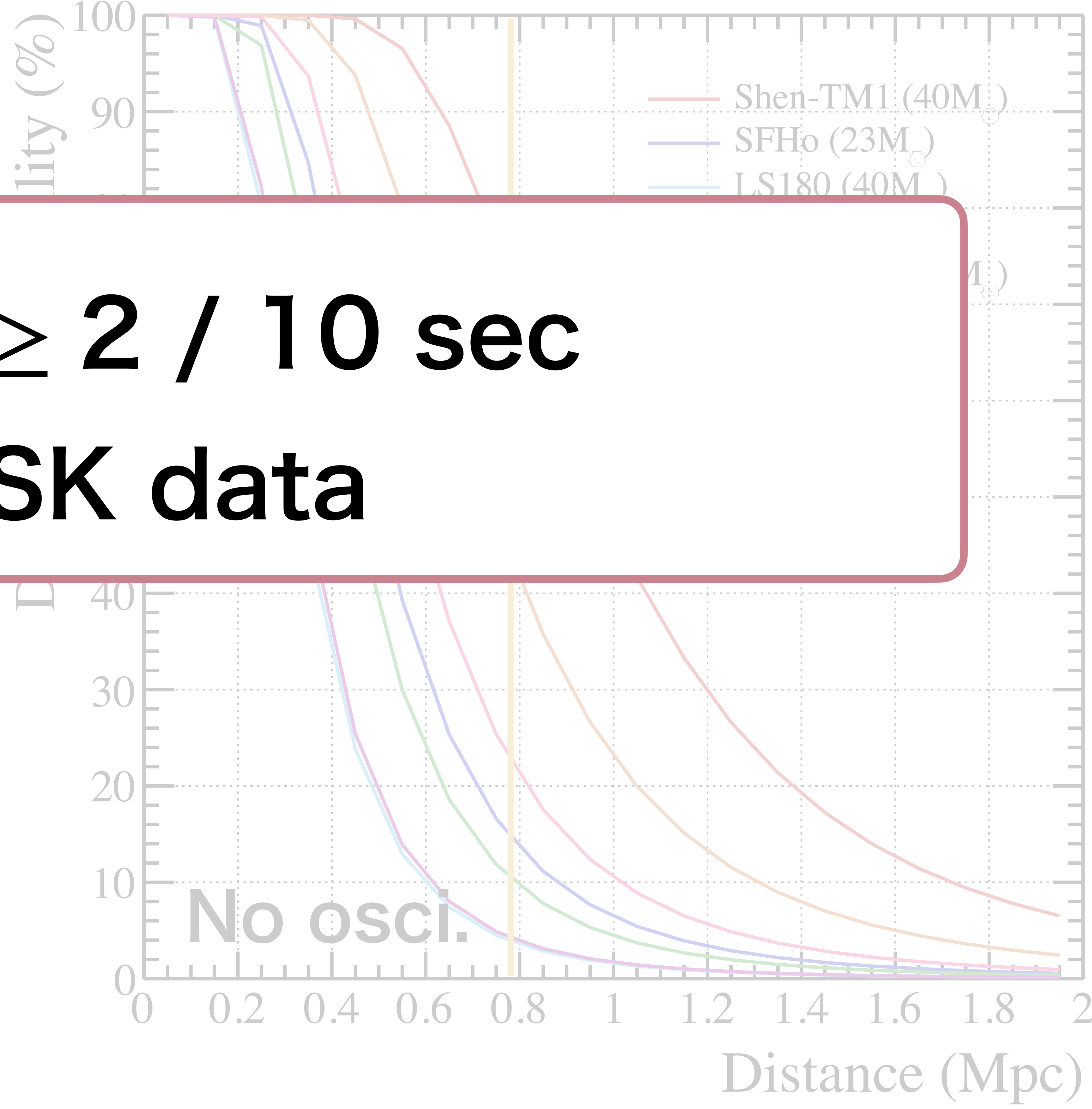


Search for Neutrinos from M31-2014-DS1

Detection probability accounting for the search conditions

- Detection probability as a condition of
  E_{th}
- At
  ra

Search clusters with ≥ 2 / 10 sec
in 1416 days of SK data



SK is sensitivity to M31-2014-DS1

Search Results

Search Result

Cluster Search Result

No clusters were found

An upper limit on how much time-integrated $\bar{\nu}_e$ luminosity ($L_{\bar{\nu}_\mathrm{e}}$)

can be placed

Upper Limit Calculation

Fluence upper limit: Time-integrated neutrino flux at Earth

$$\Phi\ [\mathrm{cm^{-2}}] = \frac{\boxed{\mathrm{N_{90}}}}{\boxed{\mathrm{N_T}}\int \mathrm{dE_{\bar{\nu}_e}}\boxed{\lambda(\mathrm{E_{\bar{\nu}_e}})}\boxed{\sigma(\mathrm{E_{\bar{\nu}_e}})}\boxed{\mathrm{R(E_{\bar{\nu}_e}, E_{vis})}}\boxed{\epsilon(\mathrm{E_{vis}})}}$$

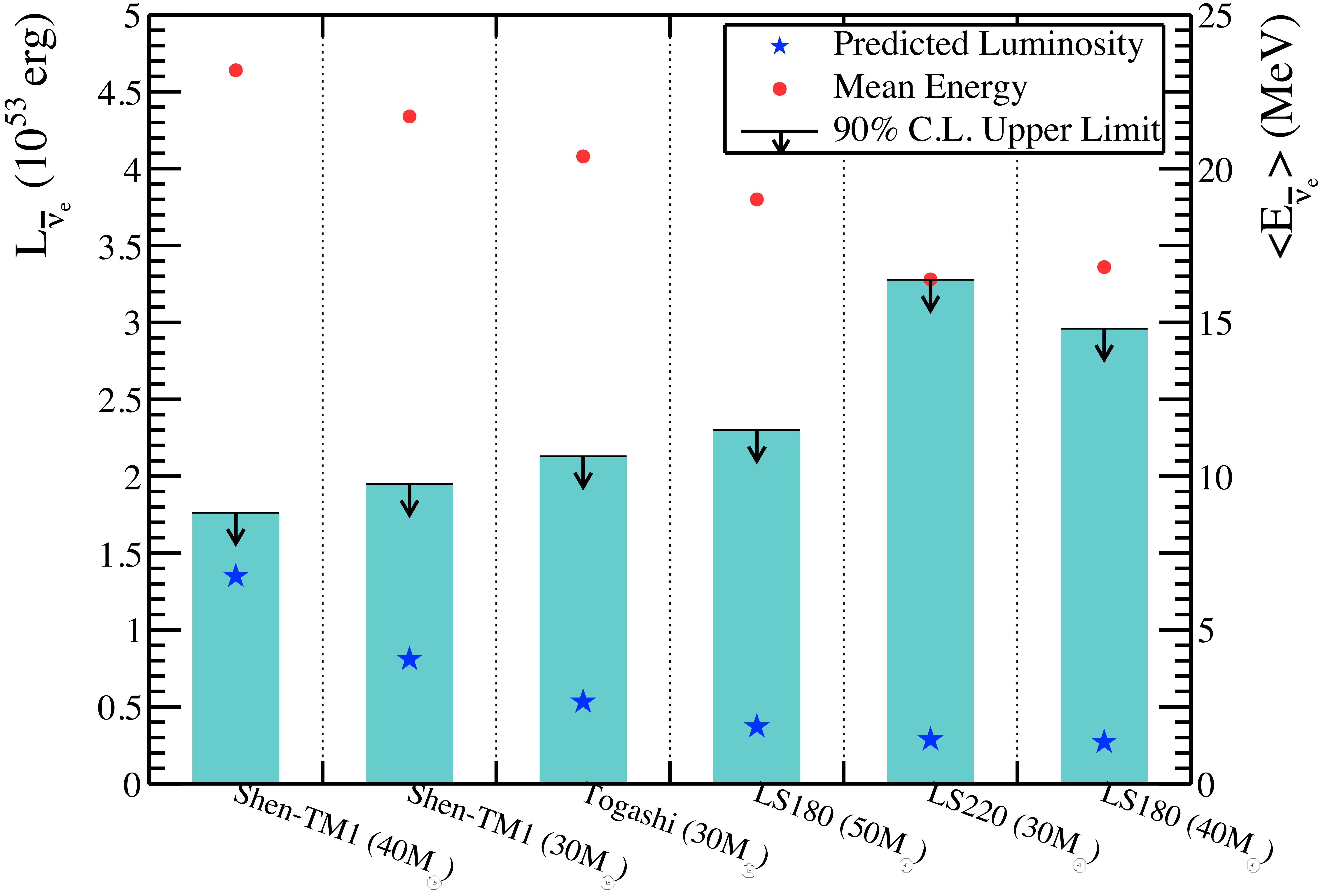
- N_{90}: 90% C.L. limit on ν events
- N_T: # of proton target
- $\lambda(E_{\bar{\nu}_e})$: Normalized ν energy spectrum
- $\sigma(E_{\bar{\nu}_e})$: IBD cross section
- $R(E_{\bar{\nu}_e}, E_{vis})$: Energy response function
- $\epsilon(E_{vis})$: Signal efficiency

- Since no neutrino event cluster (2 ≥ / 10 s) was observed, we set $N_{90} = 3.89$.
- From the fluence upper limit, the $L_{\bar{\nu}_e}$ [erg] upper limit is estimated

$$L_{\bar{\nu}_e} = 4\pi D^2 \langle E_{\bar{\nu}_e} \rangle \cdot \Phi$$

90% C.L. Luminosity Upper Limit

First experimental constraint on failed SN model



90% C.L. Luminosity Upper Limit

First experimental constraint on failed SN model

Shen-TM1EOS

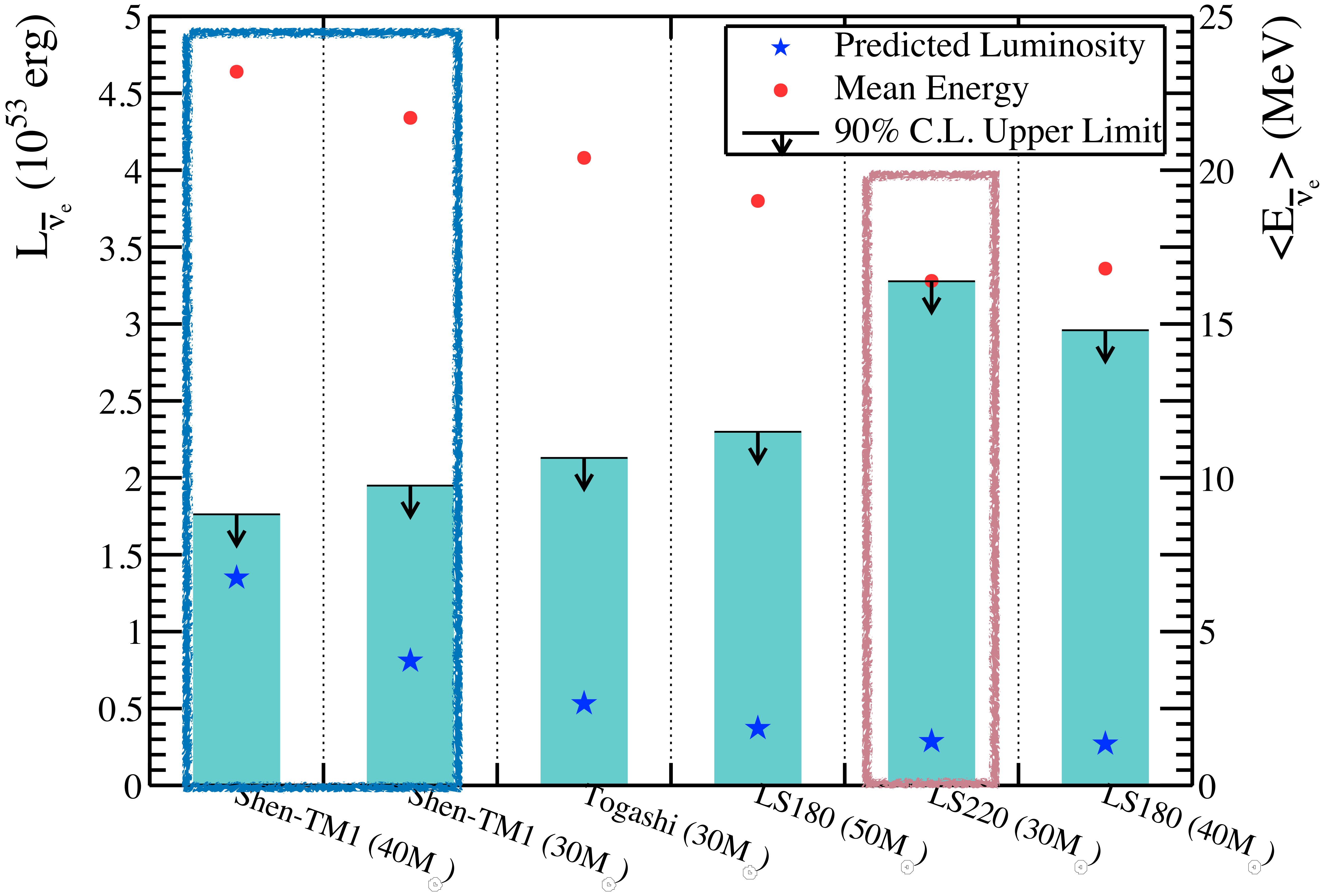
Higher mean $\bar{\nu}_e$ energy

→Moderately strong constraints for the failed SN model

LS220 EOS

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

→Moderately weak constraints for the failed SN model

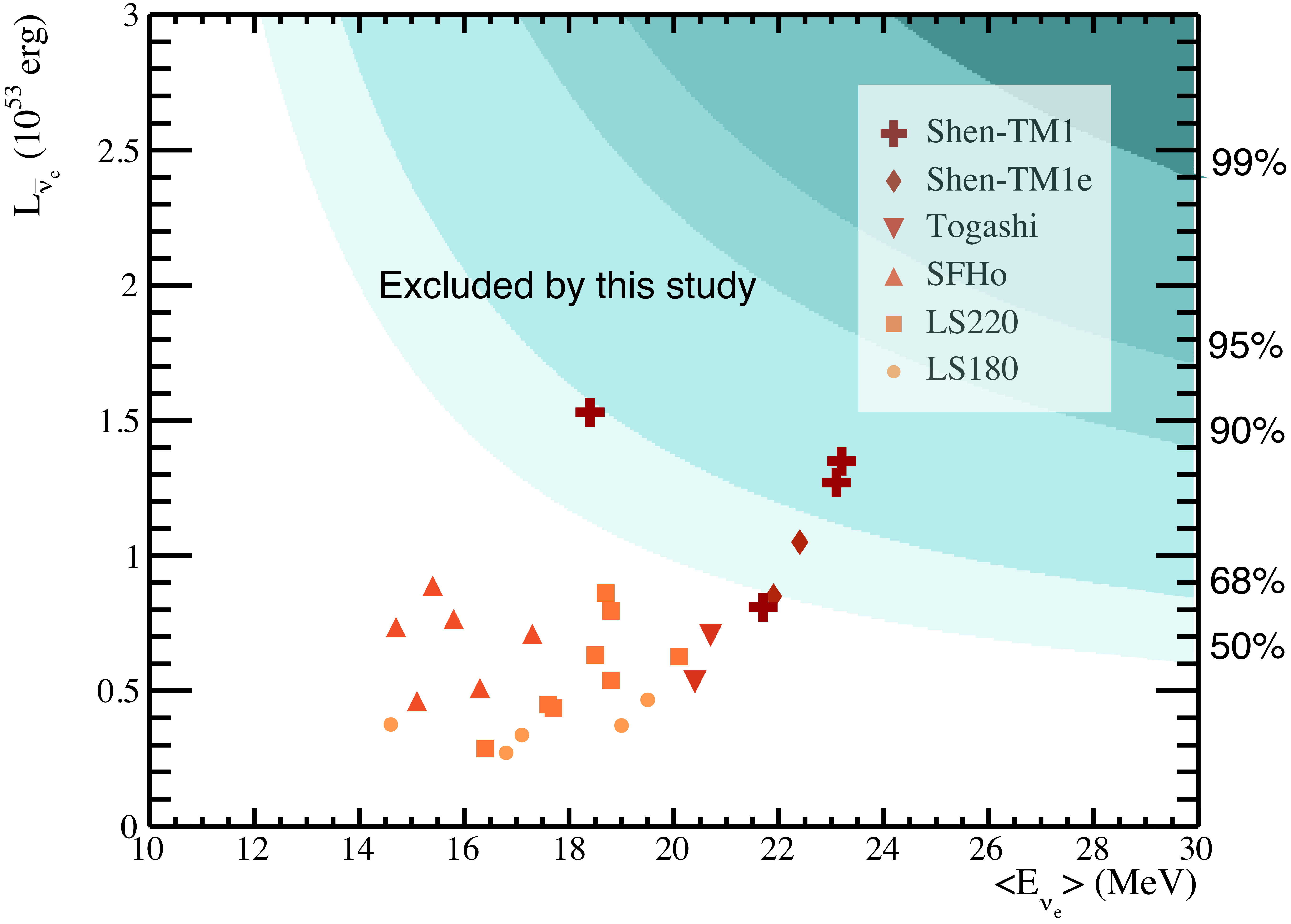


Upper Limit for Neutrino Luminosity

Unified constraints across supernova models

Probability of detection more than 2 events	Expected
50%	1.68
68%	2.35
90%	3.89
95%	4.74
99%	6.64

- Excluded the shaded region.
- Constraint for high average energy models: 68% (Shen-TM1)



Future Prospects

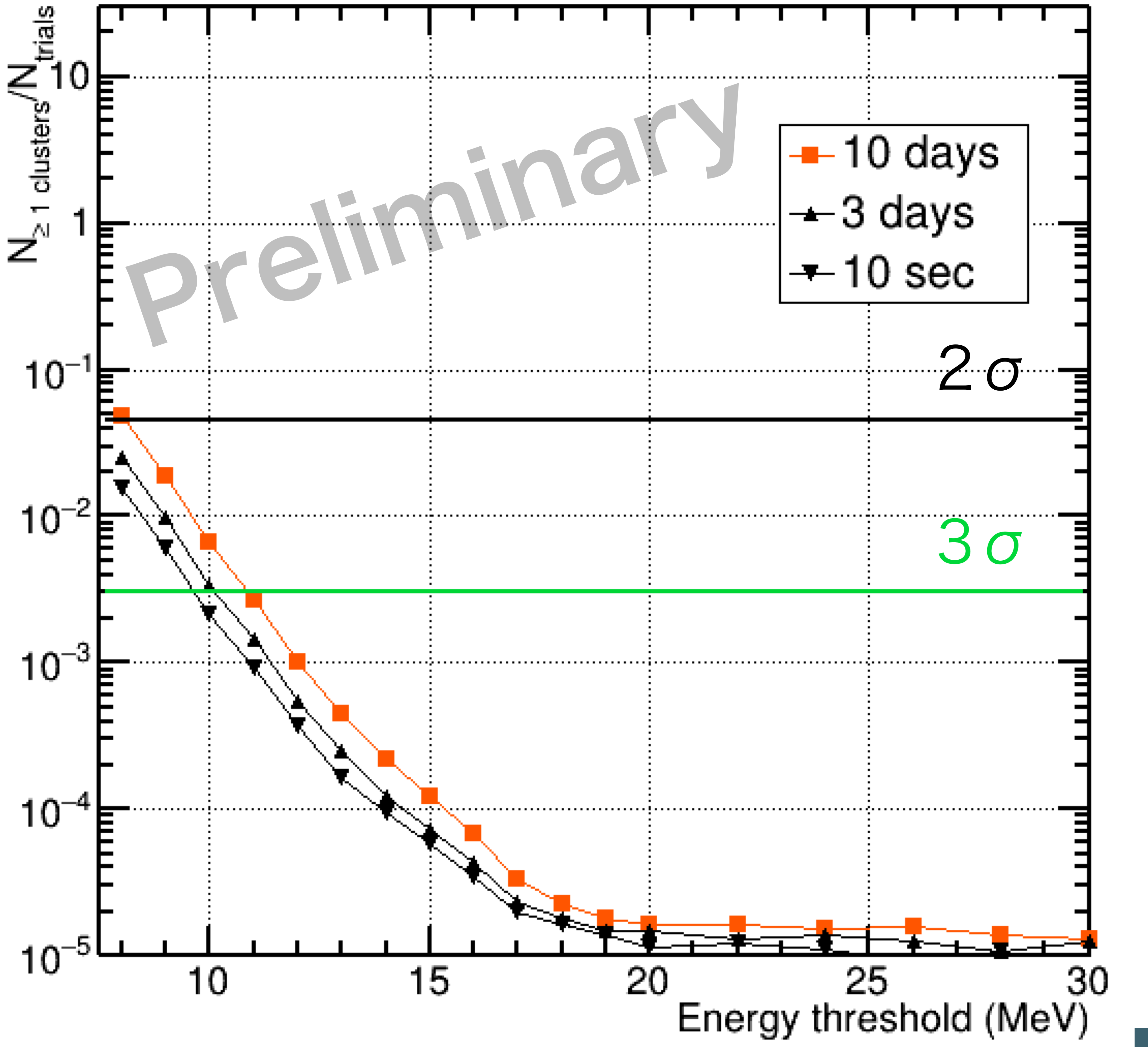
Reducing Signal Time Range

- Subaru Telescope optical data provide regular monitoring of the entire M31
  →may constrain the black hole formation time

	Positron energy threshold
10 days	11 MeV
3 days	10 MeV
10 sec	< 8 MeV

Constraints can also be placed on low-energy failed SN models

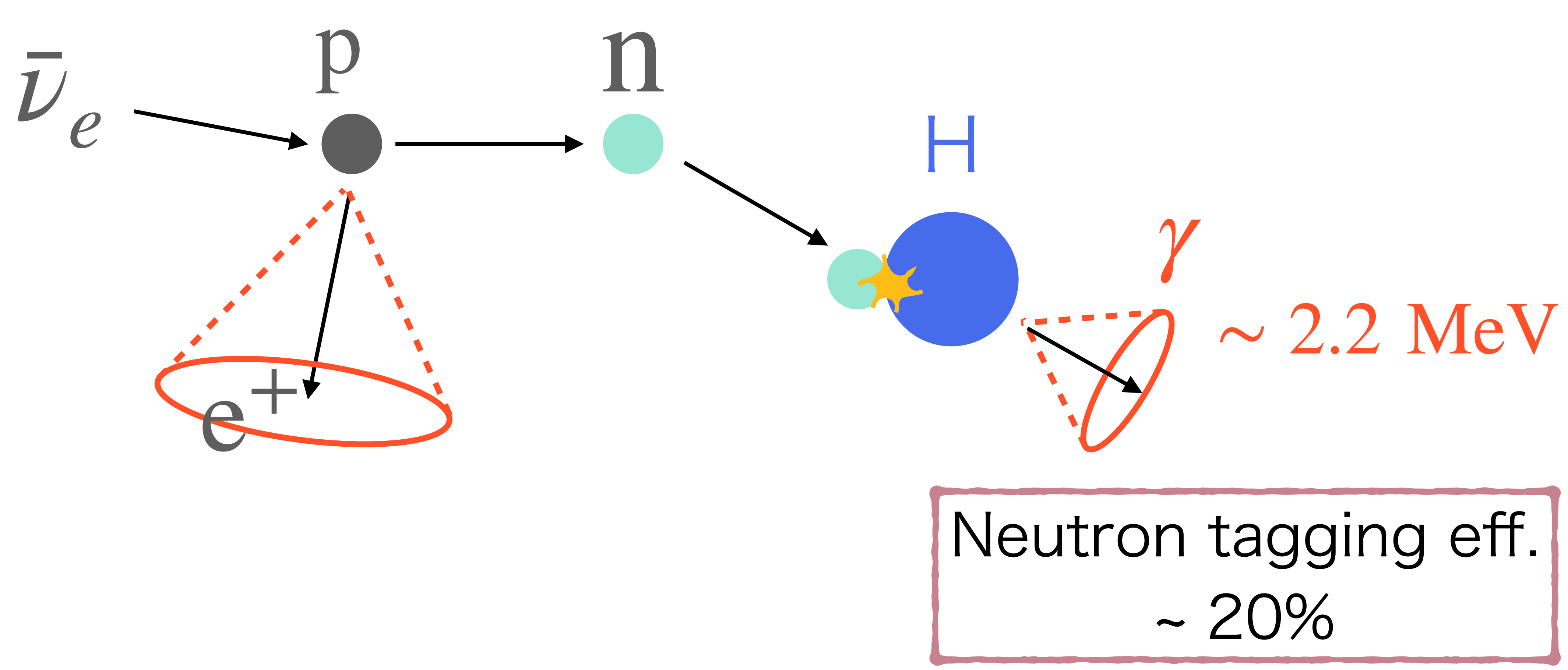
Expected # of clusters vs. energy threshold



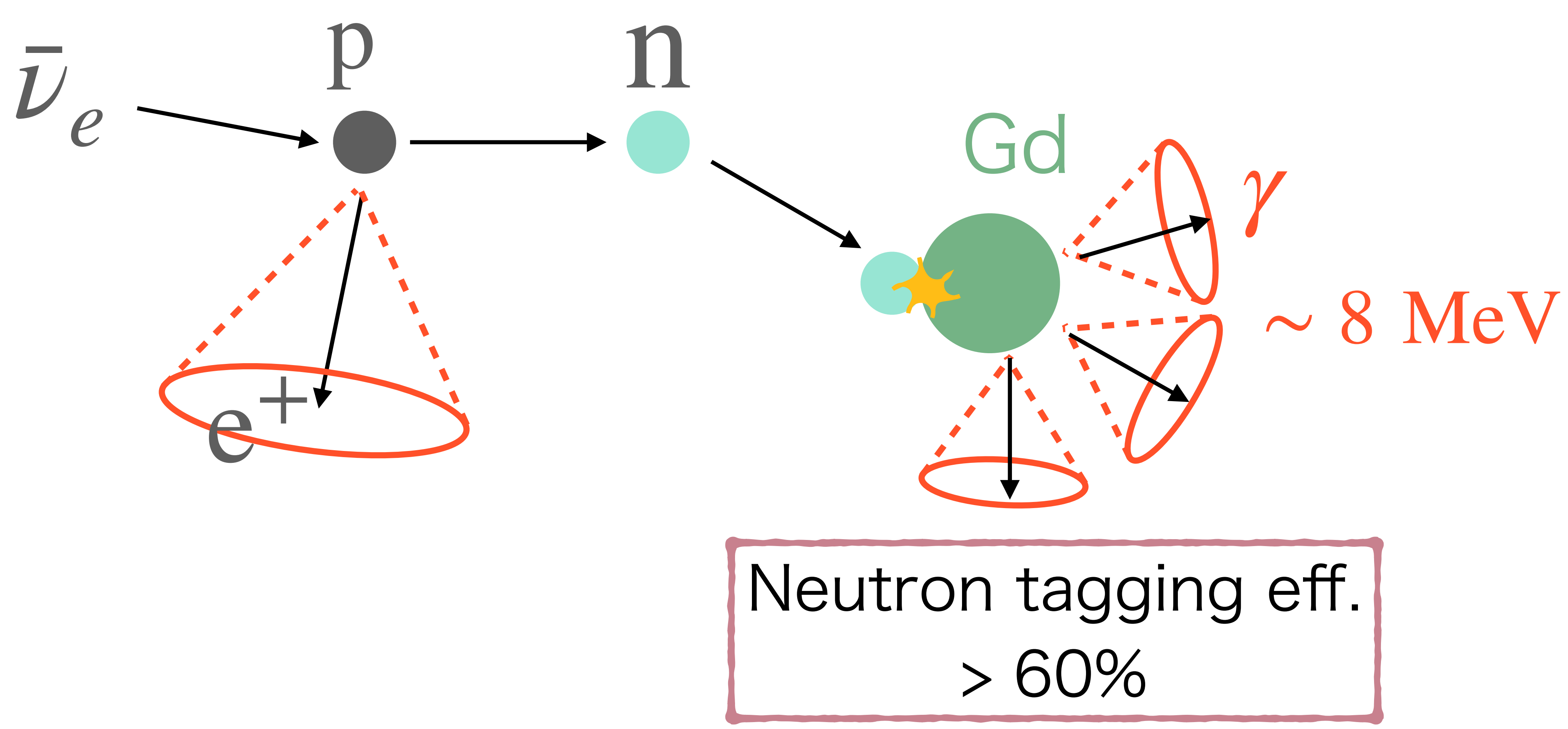
SK-Gd Experiment

- SK-Gd: improved neutron detection efficiency by loading Gd to the SK detector since 2020
  - Gadolinium (Gd): Largest cross-section of the thermal neutron capture
  - Total of ~8 MeV gamma-rays by neutron capture
    →**Improvement of neutron detection efficiency**

Pure-water

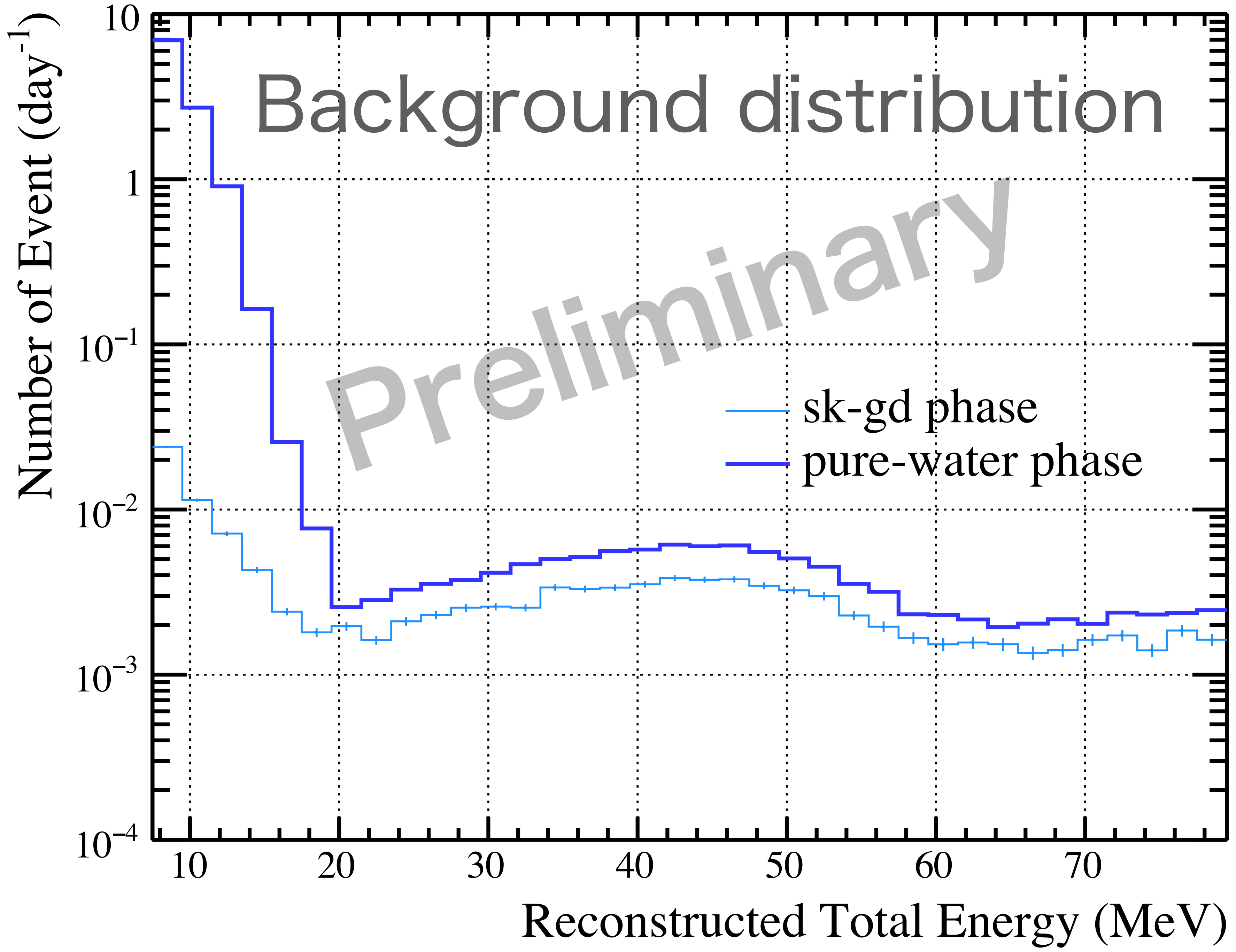


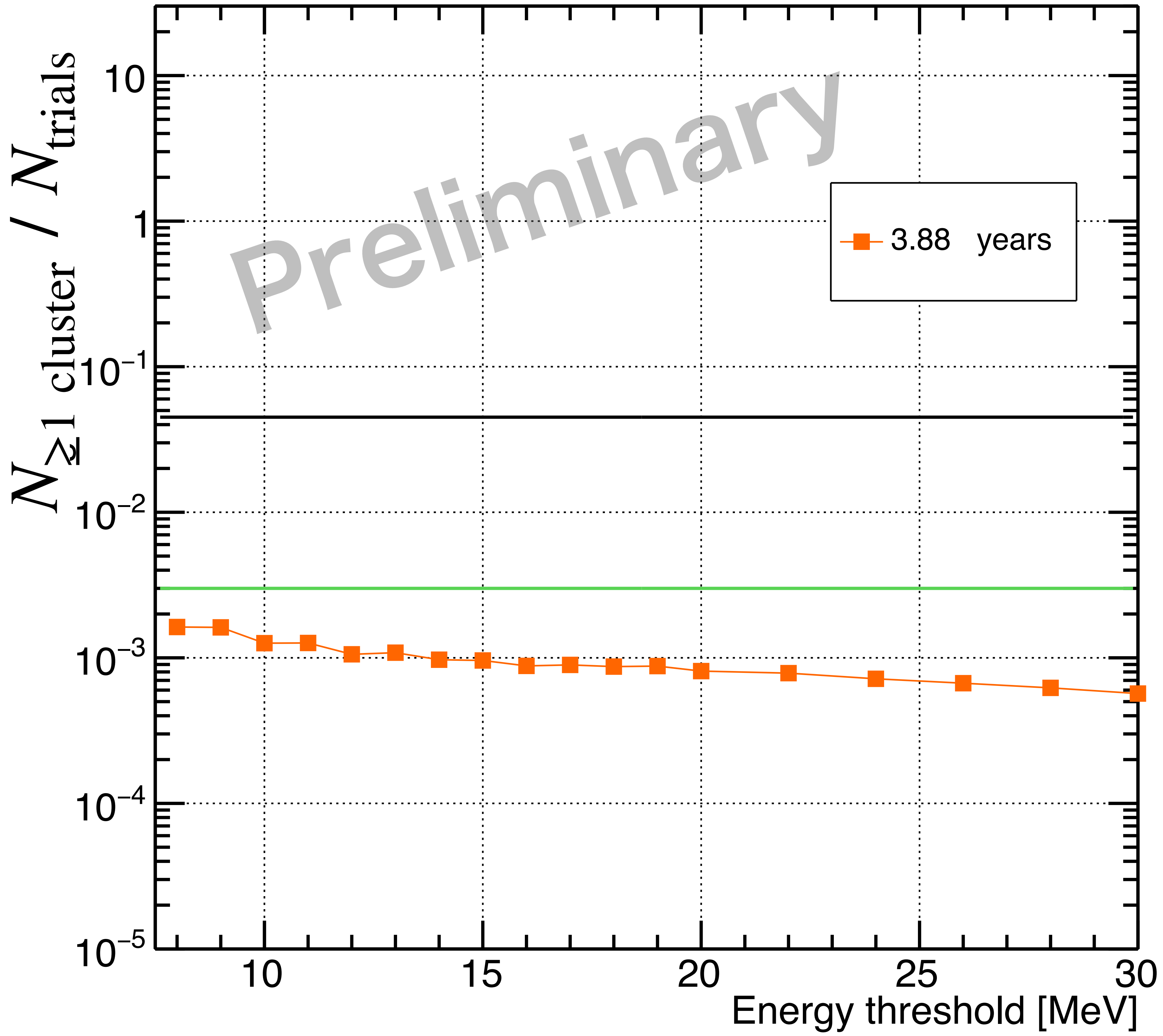
SK-Gd



Sensitivity for SK-Gd

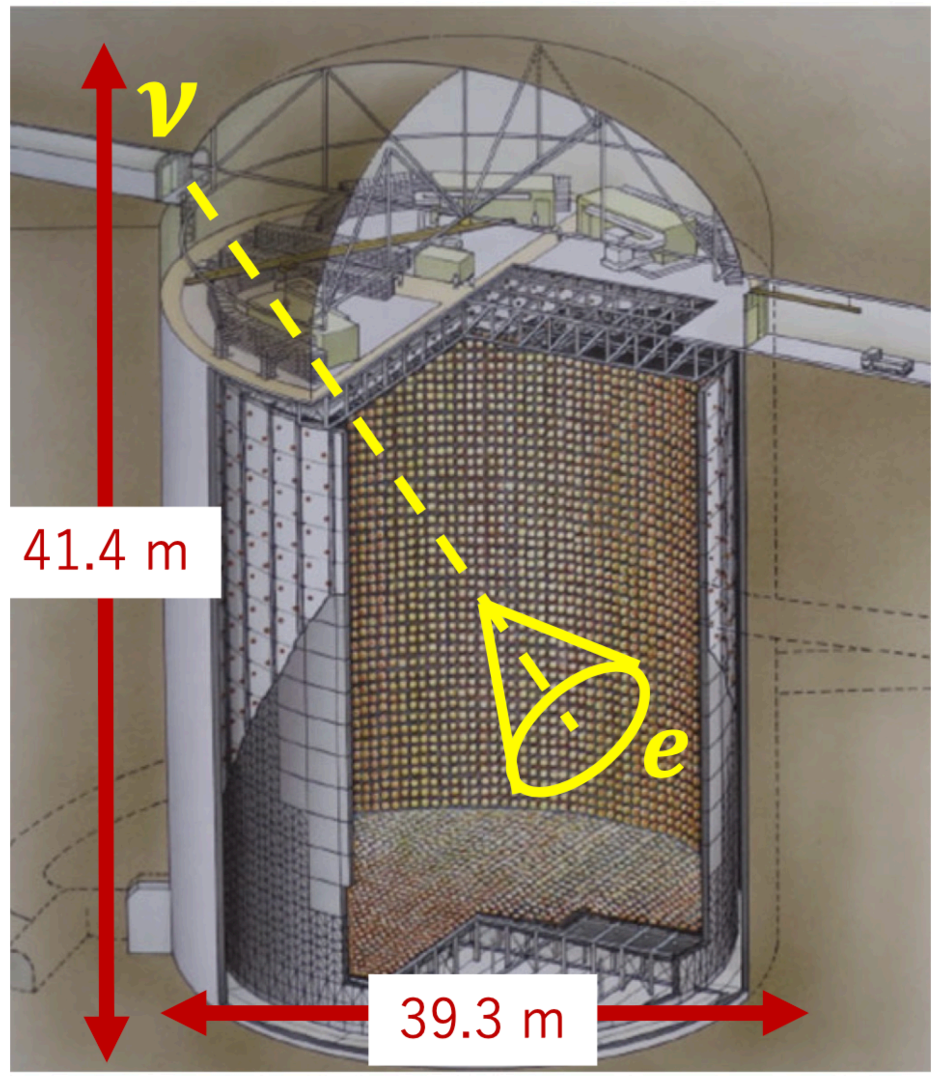
- Thanks to the improvement in neutron tagging performance in SK-Gd, the background rate is significantly reduced
- Cluster search down to 8 MeV with the same analysis conditions

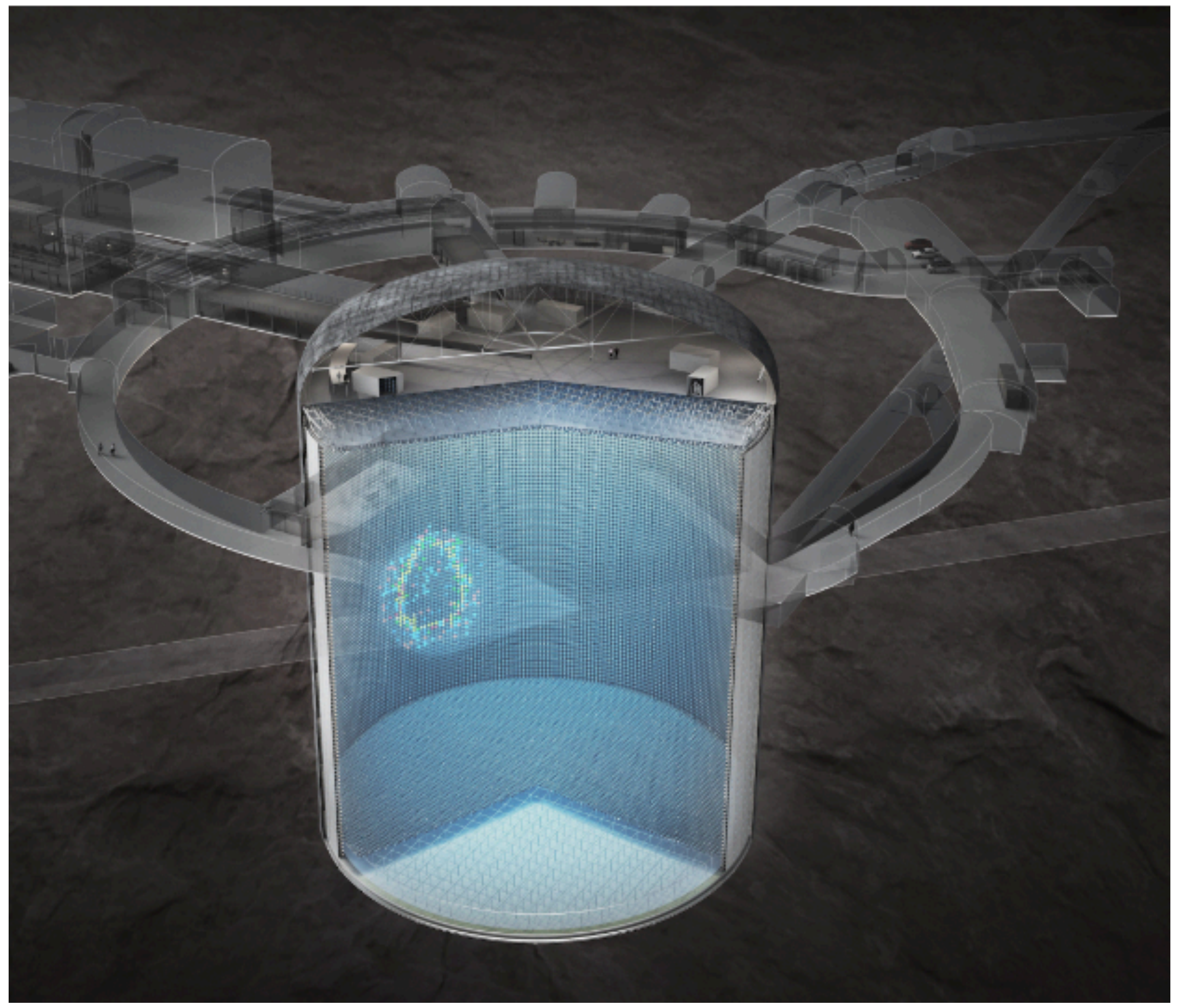




Hyper-Kamiokande

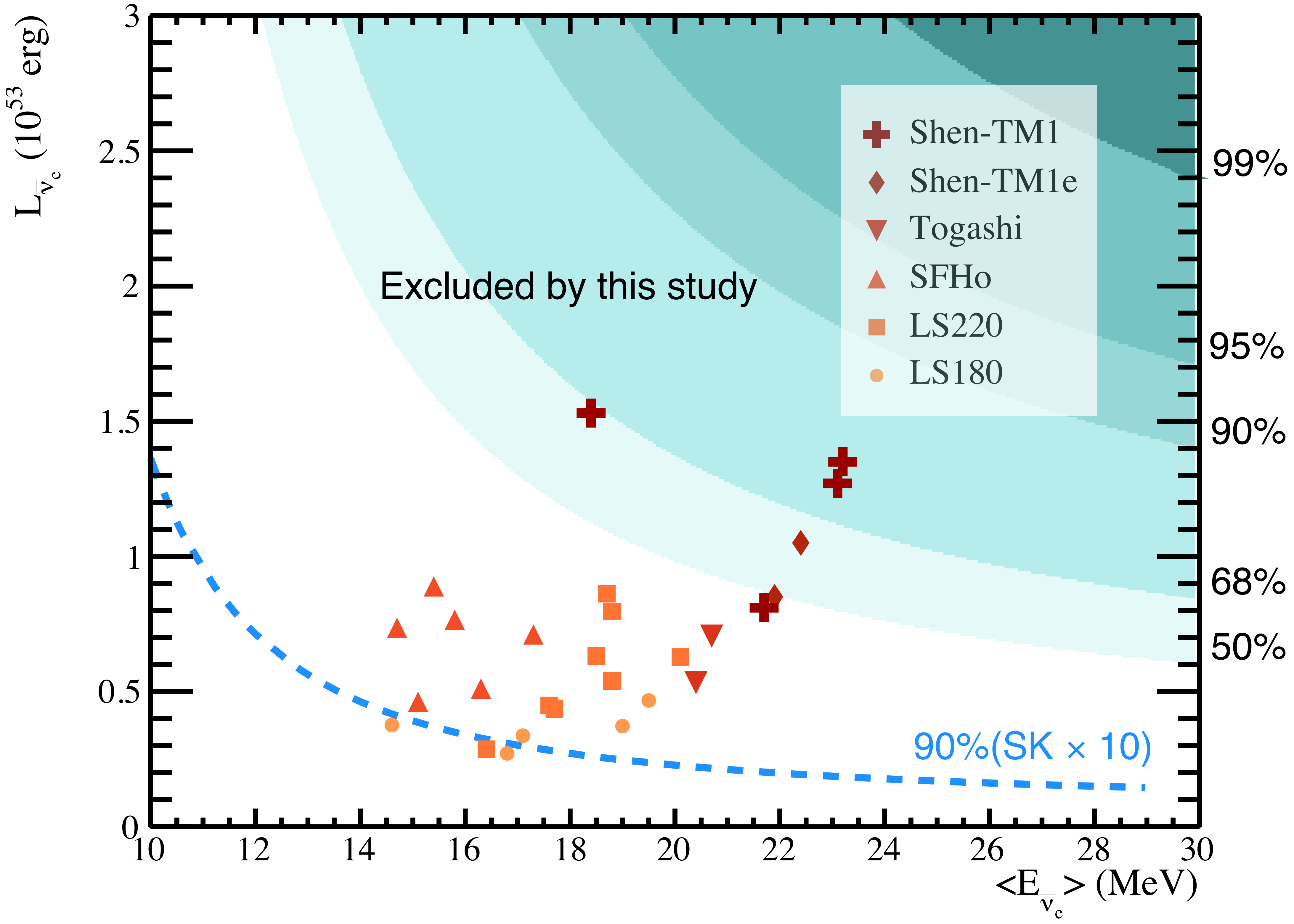
- **Super-Kamiokande (SK)**
  - Fiducial volume: 22.5 kton
  - Start of operation:1996-
  - Expected ν: 0.6-2.2 at M31
  - Detection probability: 4-72%
- **Hyper-Kamiokande (HK)**
  - Fiducial volume: ~187 kton
  - Start of operation: ~2028
  - Expected ν: 5-20 at M31
  - Detection probability: 50-100%





Sensitivity for failed SN candidate in HK

- Detector: with an effective volume about 10 times larger than that of SK
- 90% C.L. upper limit recalculated
  →HK is expected to detect neutrinos from a failed SN in M31



Summary

- Neutrinos are emitted in the supernova explosion
  →It is important to observe neutrinos to understand the explosion mechanism
- Focusing on the failed SN candidate (M31-2014-DS1)
  - A neutrino search was conducted using SK data
  - No significant cluster was found, and a 90% C.L. upper limit on the total emitted $\bar{\nu}_e$ energy was derived.
- Future prospects
  - Improved optical observations may further constrain the black hole formation time, allowing a narrower signal time range and a lower energy threshold for cluster search
  - If a similar event occurs and is observed by HK
    →Neutrino signal detection would be expected