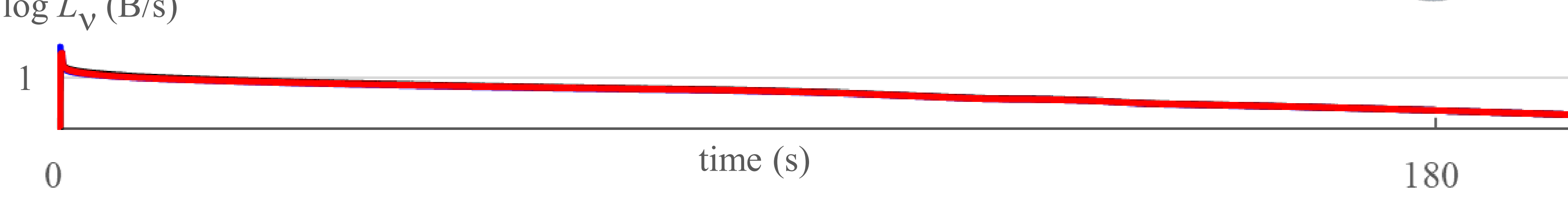
Long term behavior of supernova neutrino light curves



Ken'ichiro Nakazato

（Faculty of Arts & Science, Kyushu University）

Core-collapse supernova

- Explosion caused by the death of massive star with $\gtrsim 10M_\odot$.
  - a large amount of ν emission
  - formation of NS or BH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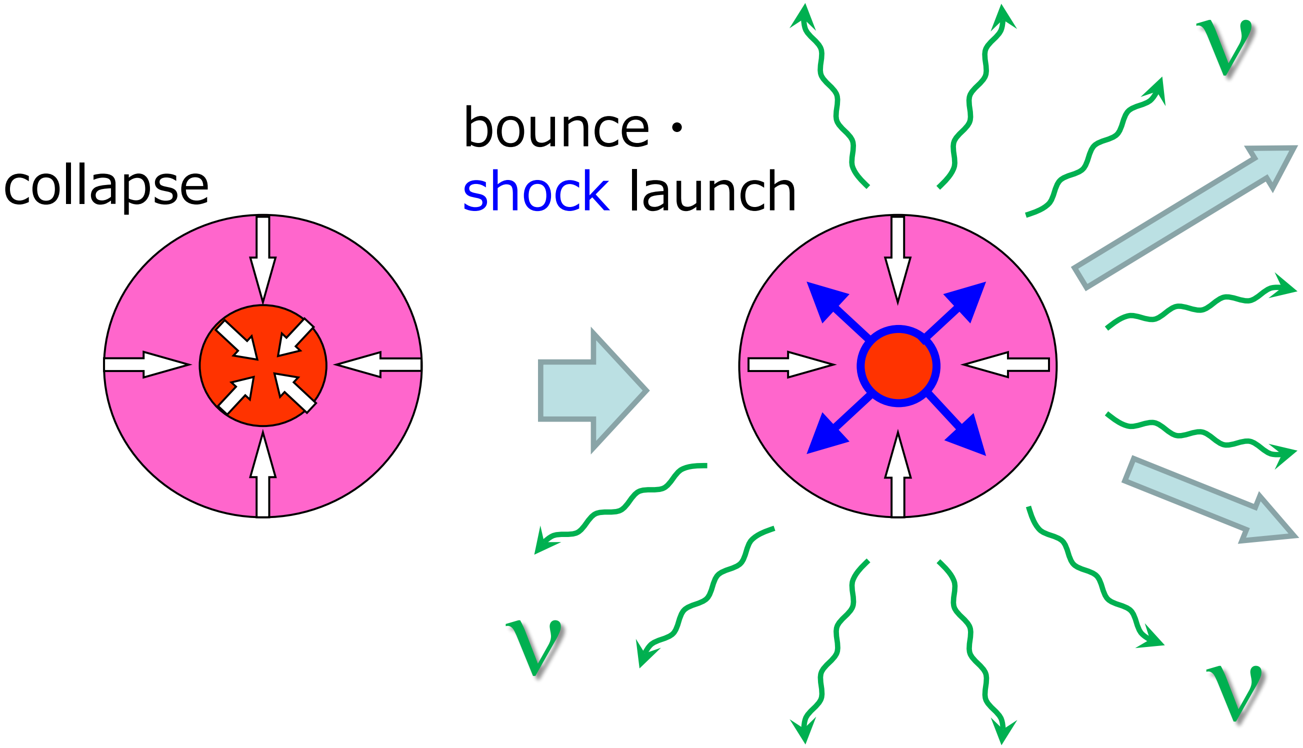
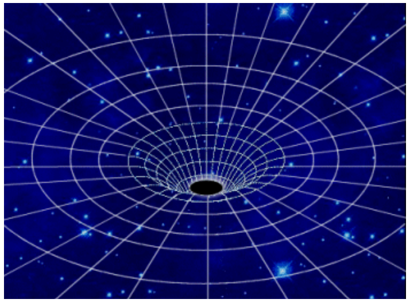
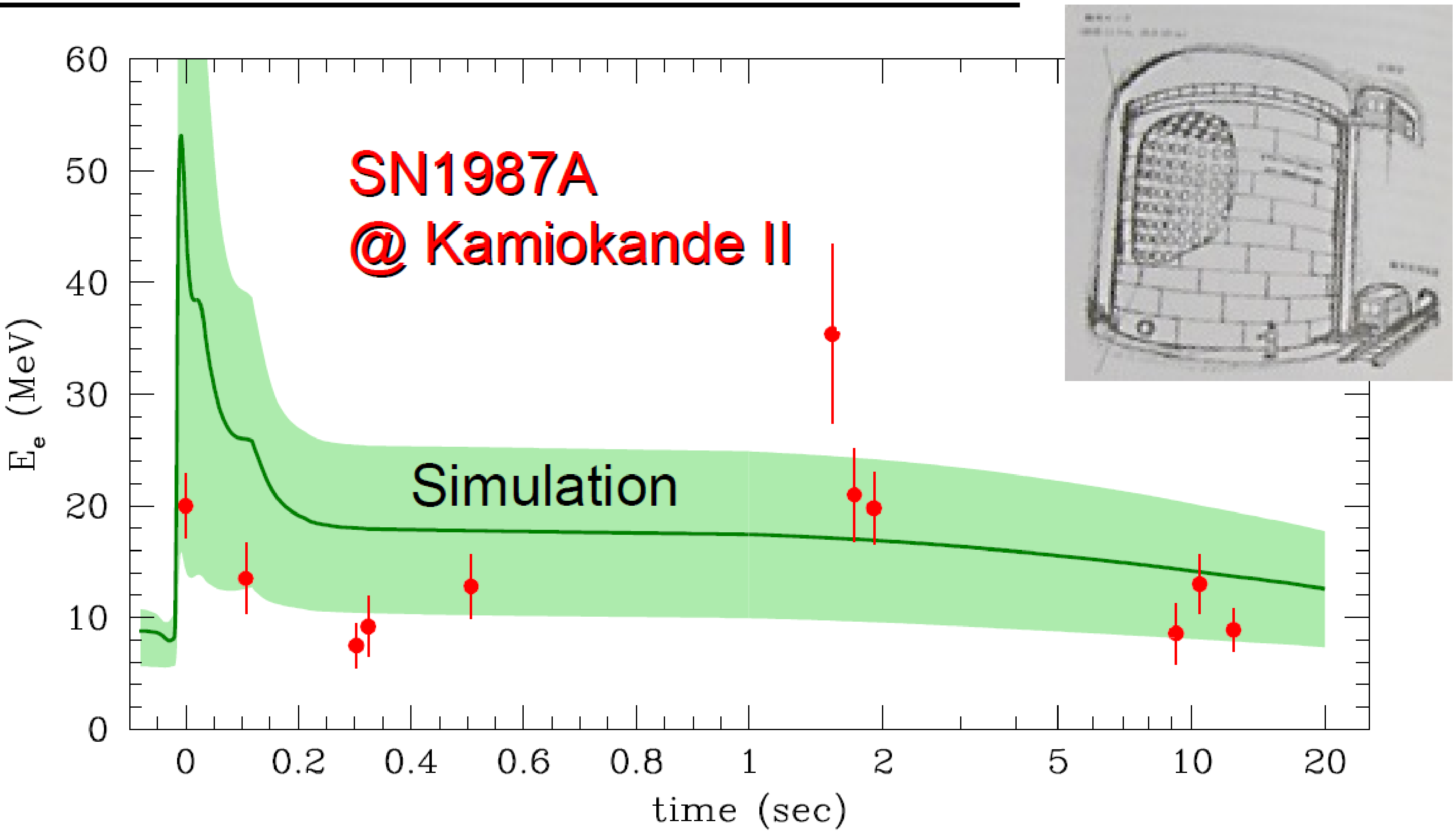

collapse

bounce ·
shock launch


SN explosion → neutron star (NS)


black hole (BH)

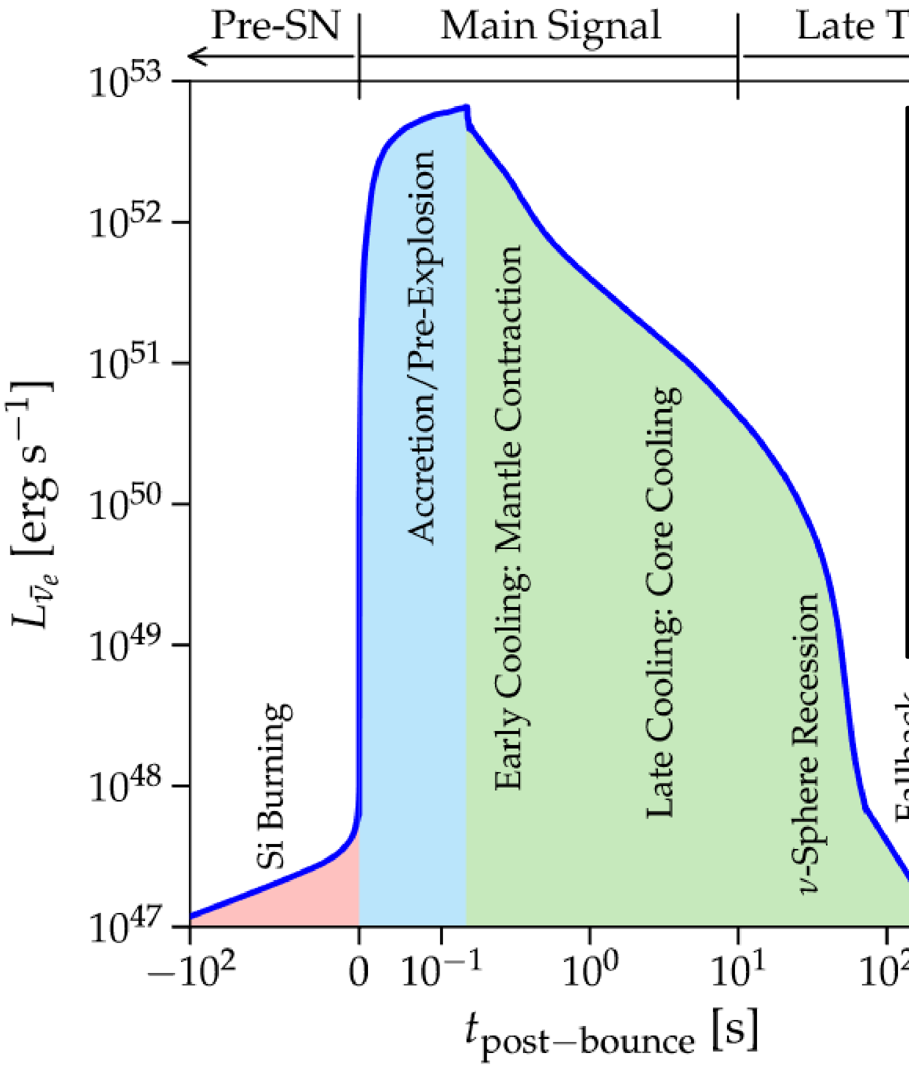
Neutrinos from SN1987A



- The standard scenario is confirmed from event number, energy and duration.

What to learn next

Li et al., PRD **103** (2021), arXiv:2008.04340



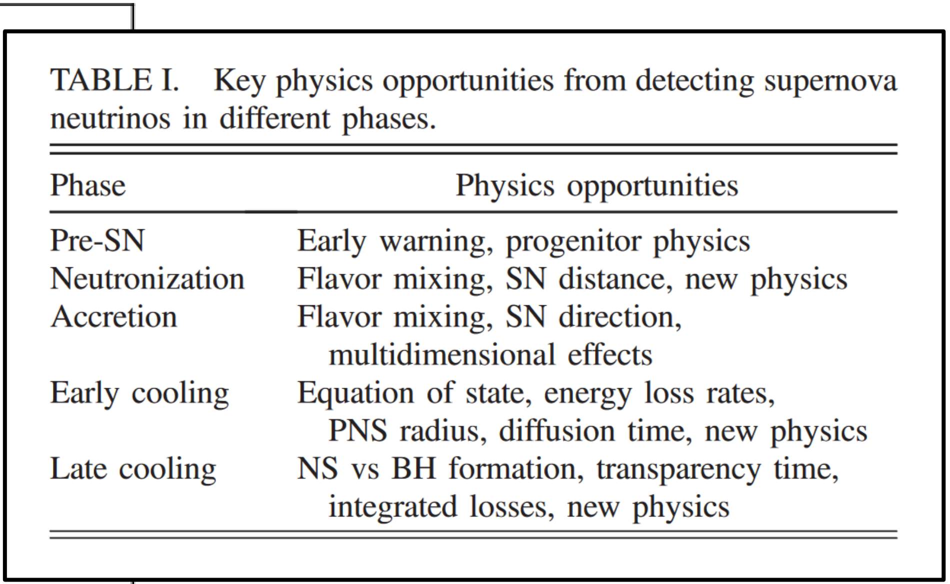


TABLE I. Key physics opportunities from detecting supernova neutrinos in different phases.

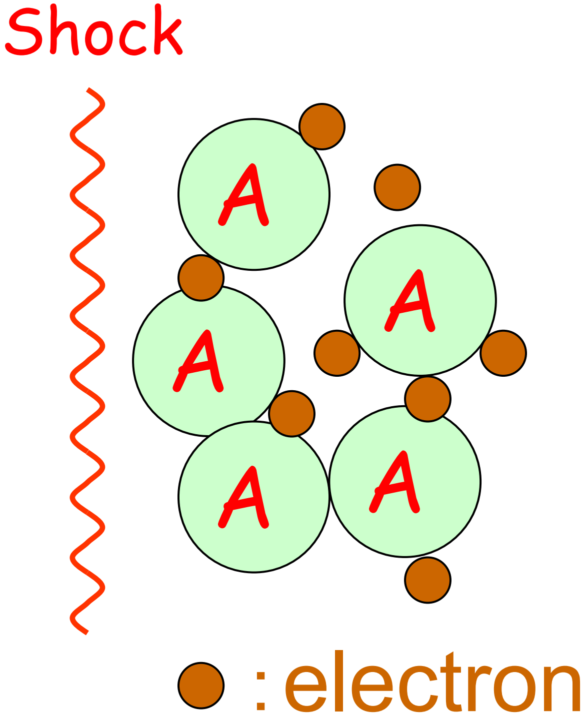
Phase	Physics opportunities
Pre-SN	Early warning, progenitor physics
Neutronization	Flavor mixing, SN distance, new physics
Accretion	Flavor mixing, SN direction, multidimensional effects
Early cooling	Equation of state, energy loss rates, PNS radius, diffusion time, new physics
Late cooling	NS vs BH formation, transparency time, integrated losses, new physics

- Key physics opportunity depends on the phase.

① *Neutronization burst*

- Shock dissociates nuclei.
- Protons capture electrons emitting ν_e.

  → deleptonization



① *Neutronization burst*

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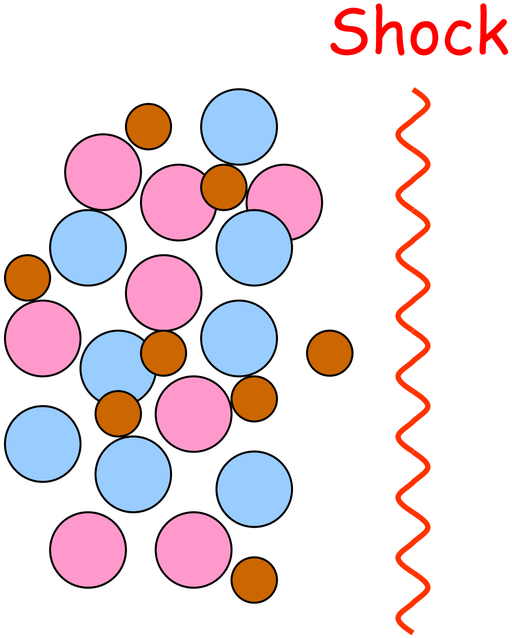
- Protons capture electrons emitting ν_e.
  → deleptonization

● : neutron

● : proton

● : electron



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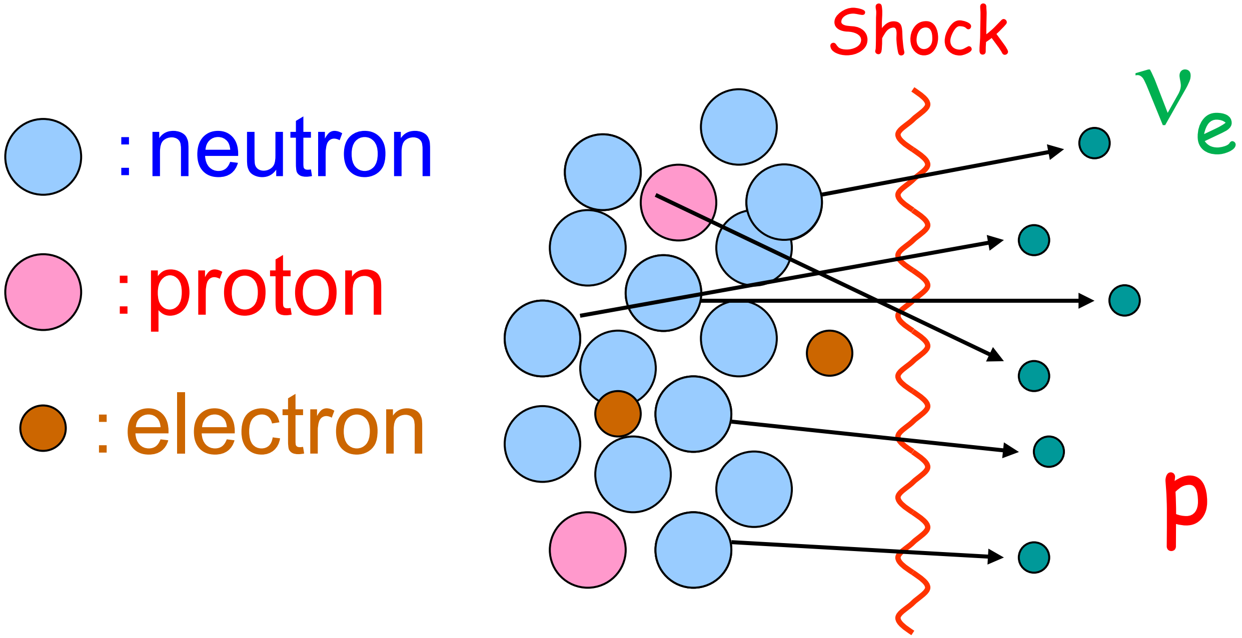
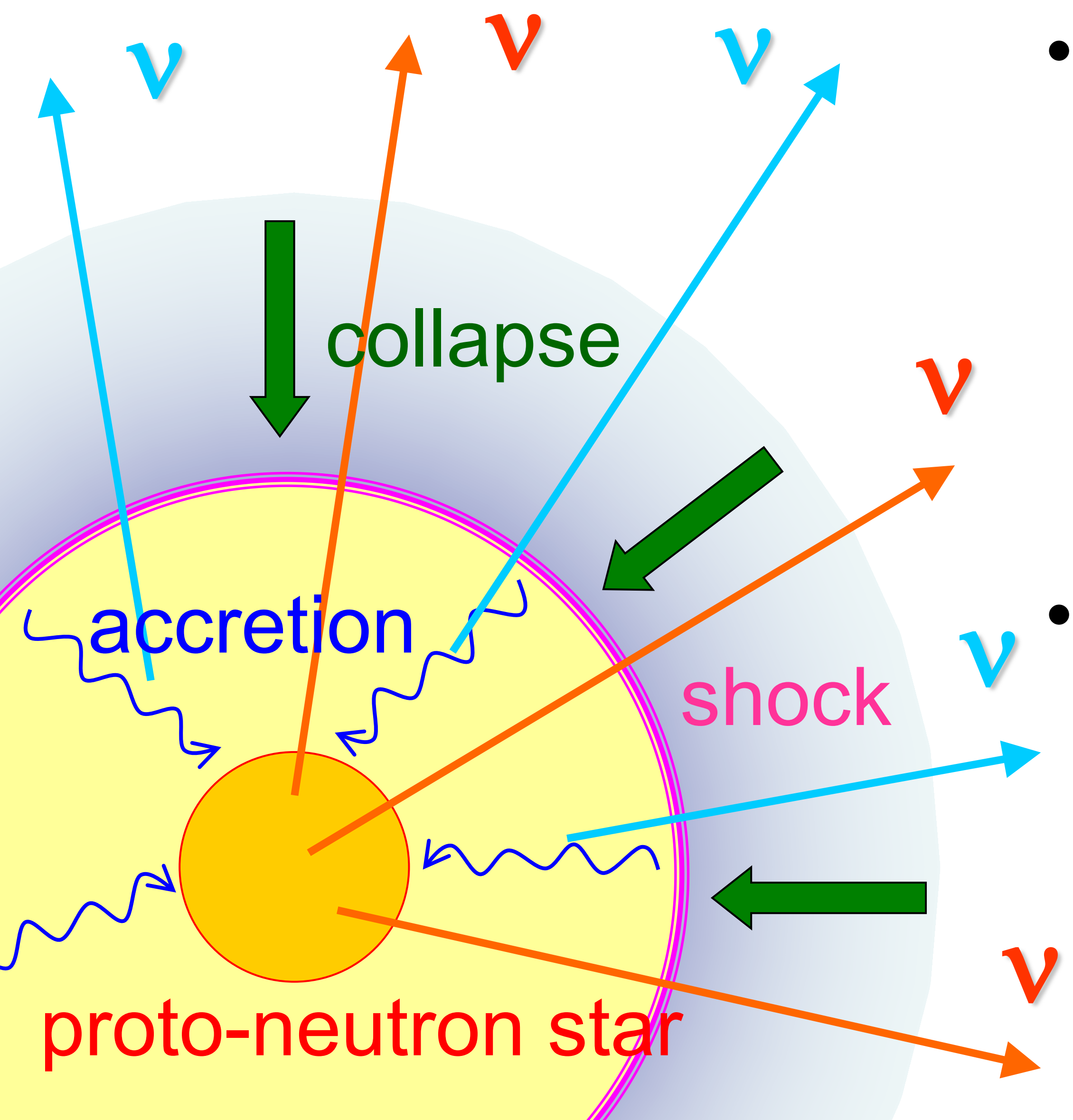


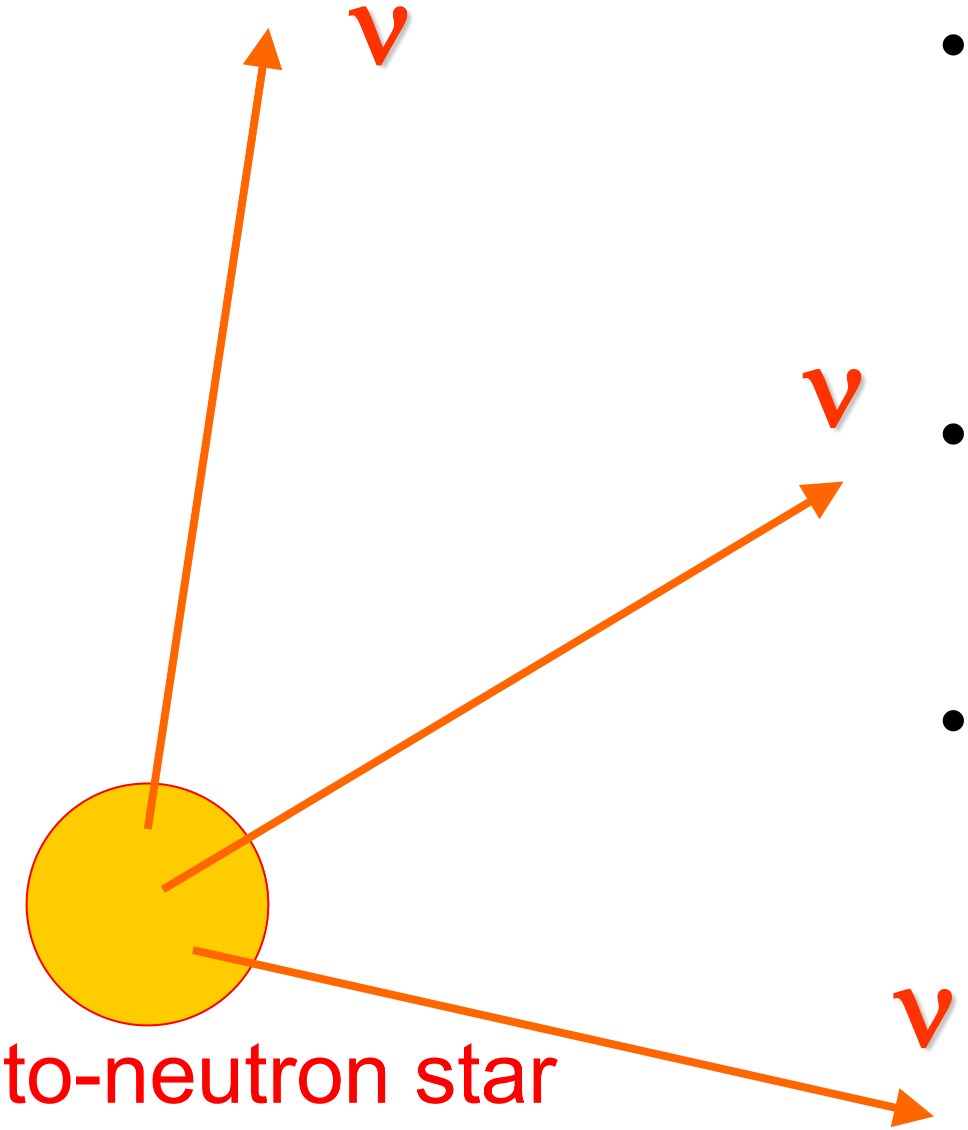
$$p + e \longrightarrow n + \nu$$

② *Accretion phase*



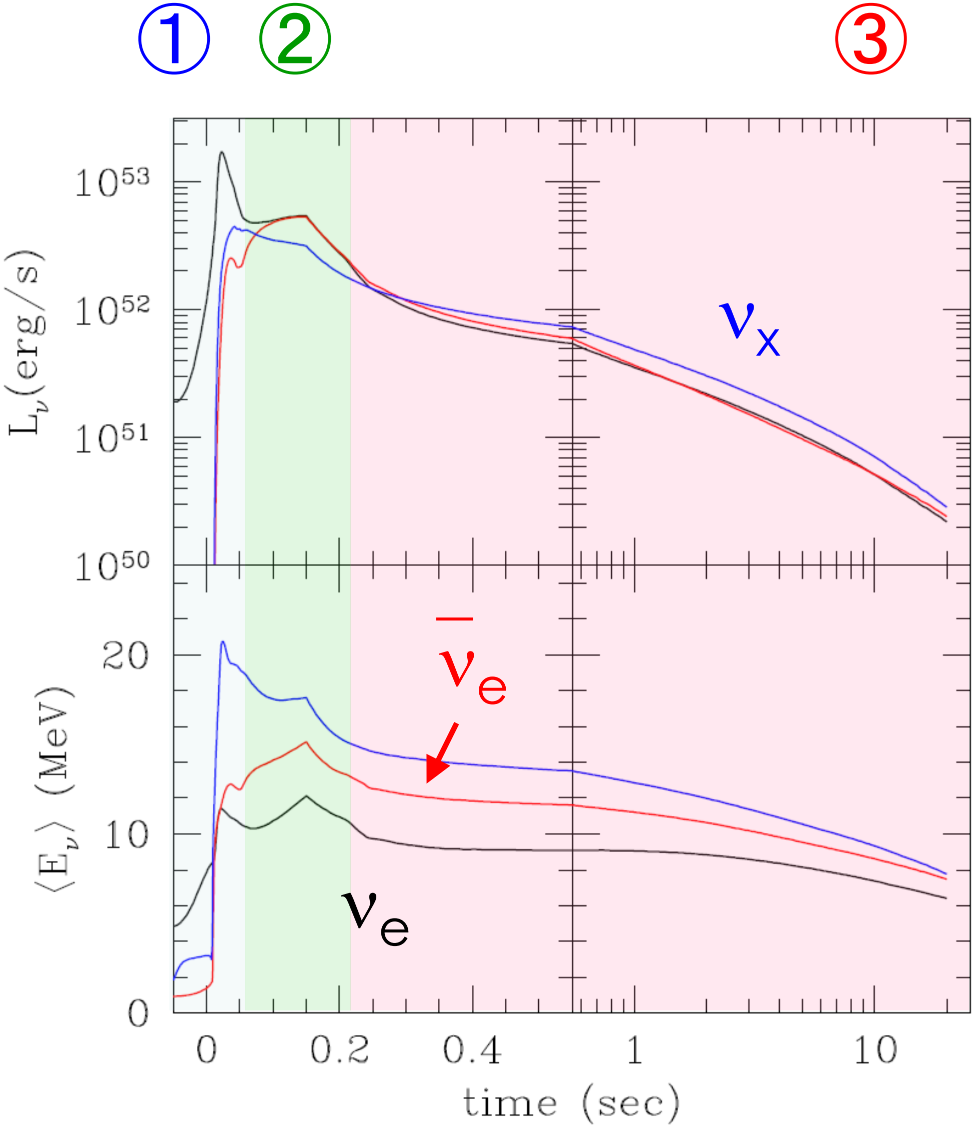
- Gravitational potential of accreted matter converts to thermal energy.
- Neutrinos of all flavors are emitted by thermal process.

③ *Cooling phase*



- Shock revives and propagates to outer layer.
- Heating by matter accretion stops.
- Luminosity and mean energy of neutrinos drop.

Three phases of neutrino emission



Nakazato et al., ApJS **205** (2013)

① neutronization burst

~ *O* (10 ms)

② accretion phase

~ *O* (100 ms)

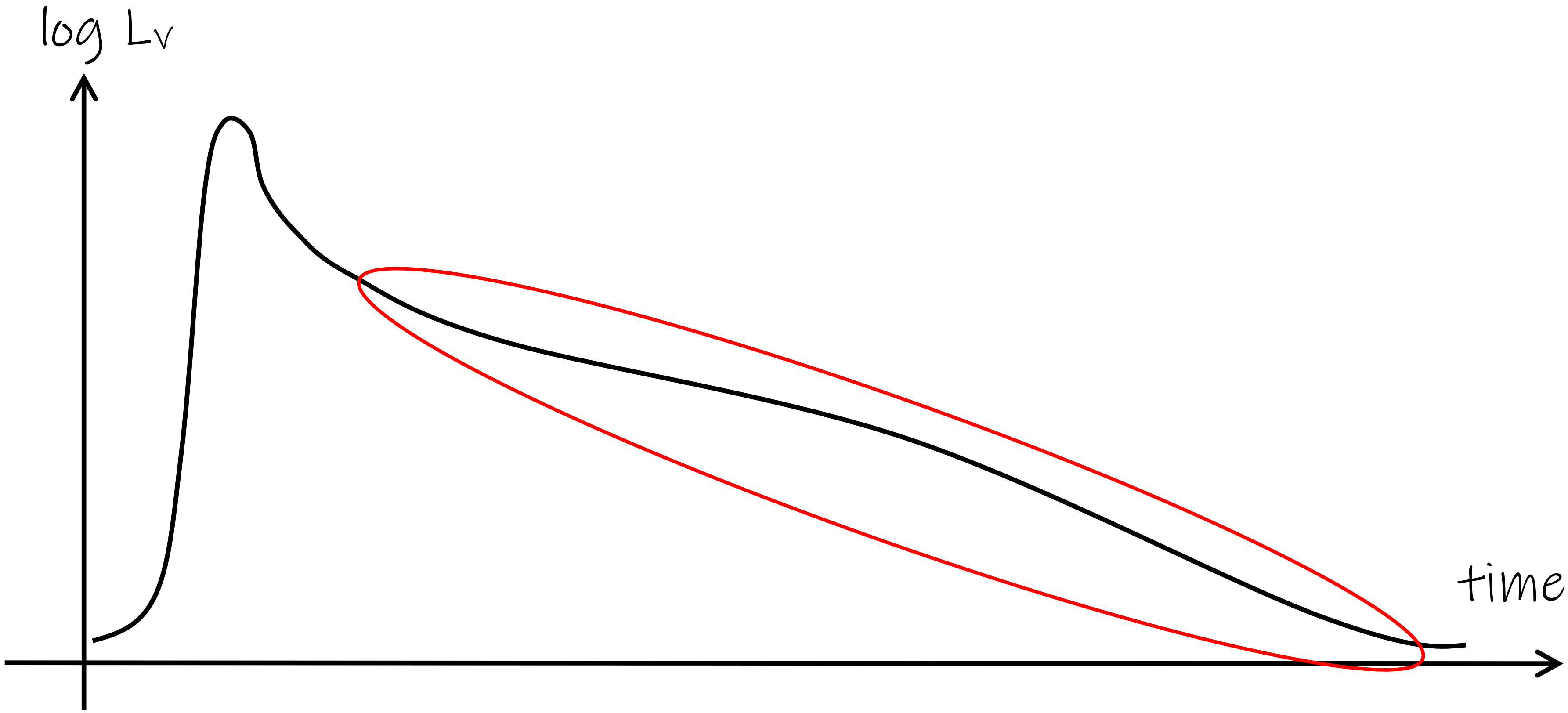
③ cooling phase

~ *O* (1 min)

target of this study

Why late phase?

- The neutrino signal is mainly determined by a relatively small number of parameters: mass, radius, and surface temperature.



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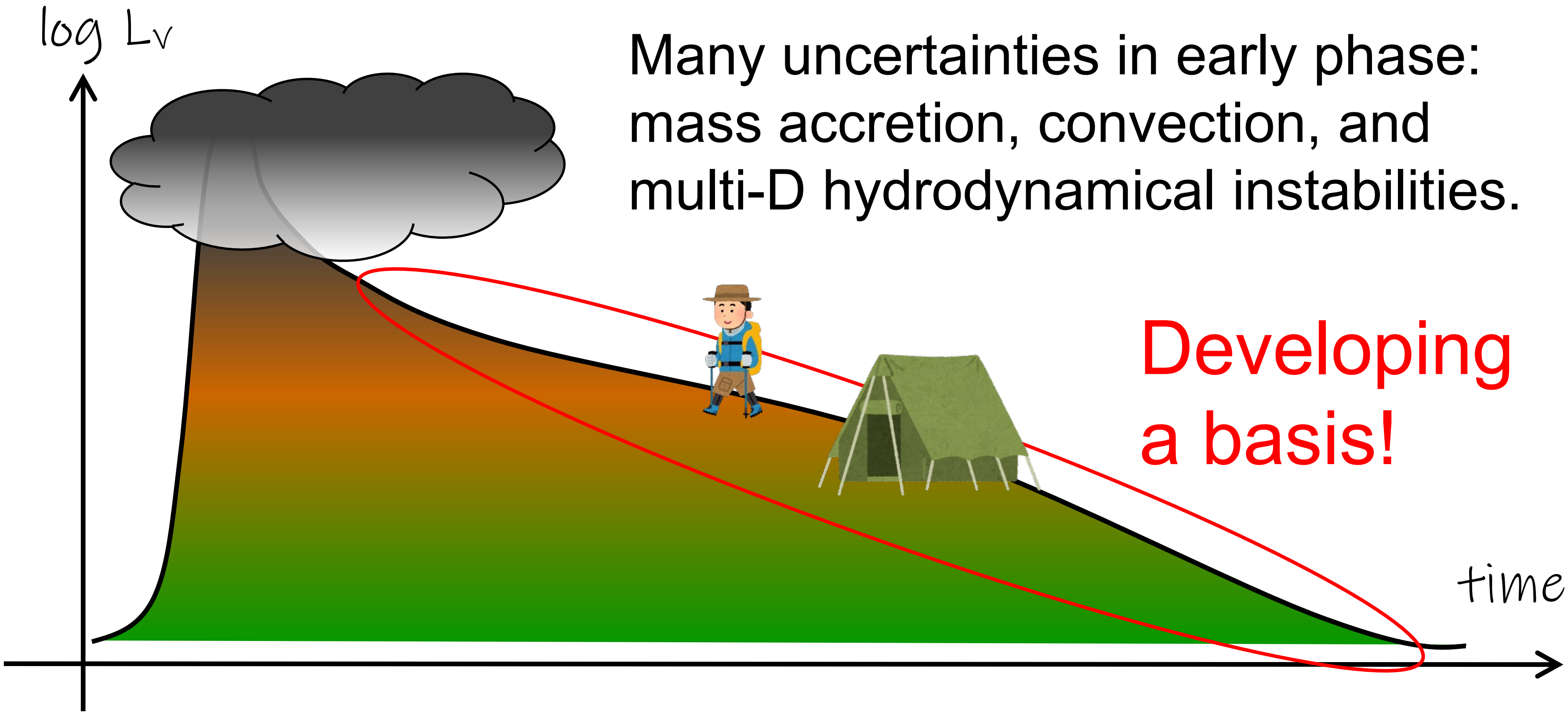


Many uncertainties in early phase: mass accretion, convection, and multi-D hydrodynamical instabilities.

Developing a basis!

Simulations of PNS colling

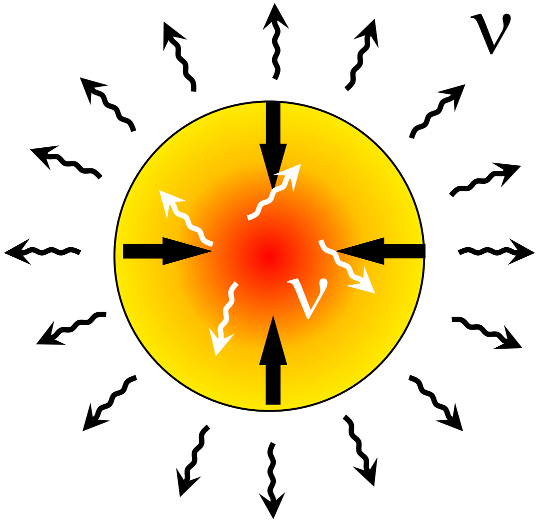
- Initial conditions are taken form the results of core-collapse simulations.
  - PNSs with baryon mass of 1.40－1.86$M_\odot$.

- Quasi-static evolutionary calculation of PNS
  - transfer of ν_e , $\bar{\nu}_e$, ν_μ (= ν_τ= $\bar{\nu}_\mu$= $\bar{\nu}_\tau$) is treated in Multigroup Flux Limited Diffusion scheme
  - $e^- + p \leftrightarrow n + \nu_e$, $e^+ + n \leftrightarrow p + \bar{\nu}_e$, $\nu + N \leftrightarrow \nu + N$, $\nu + e \leftrightarrow \nu + e$, $\nu_e + A \leftrightarrow A' + e^-$, $\nu + A \leftrightarrow \nu + A$, $e^- + e^+ \leftrightarrow \nu + \bar{\nu}$, $\gamma^* \leftrightarrow \nu + \bar{\nu}$, $N + N' \leftrightarrow N + N' + \nu + \bar{\nu}$

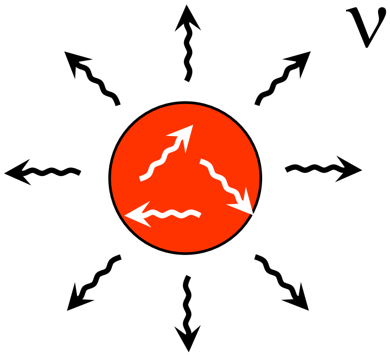
- Some realistic EOS models are used.

Schematic picture of PNS cooling

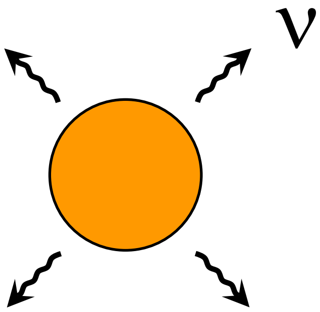
(i) contraction

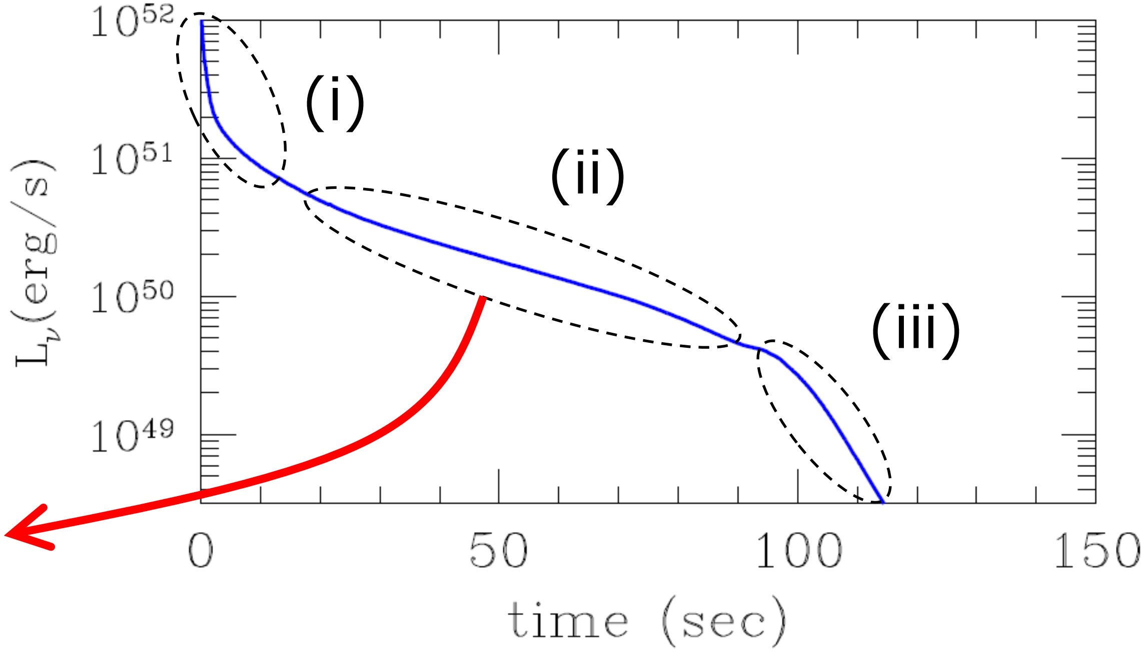


(ii) shallow decay



(iii) volume cooling





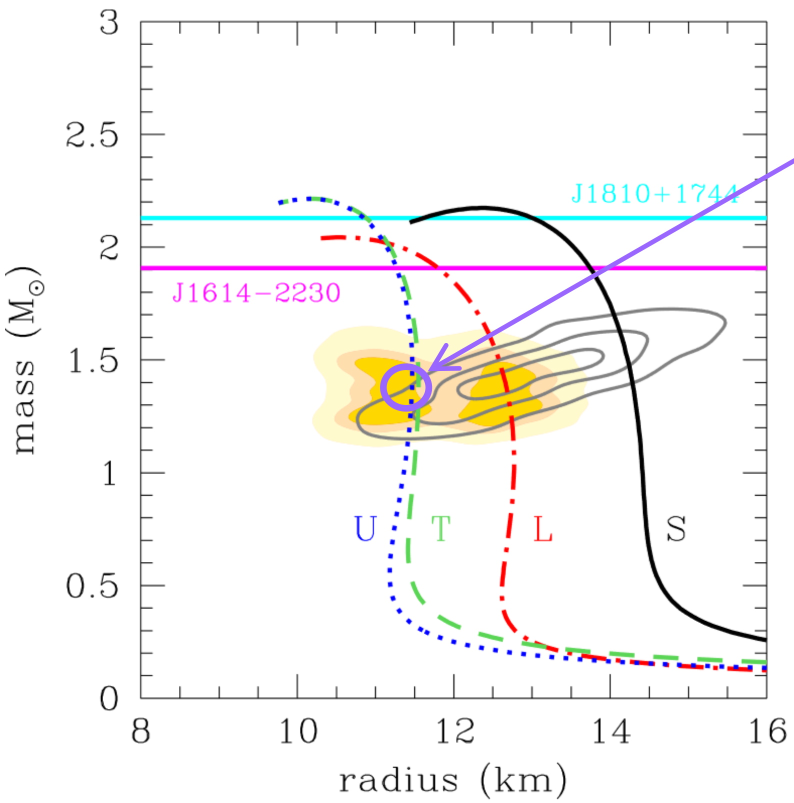
- Decay time of neutrino light curve has the maximum here.

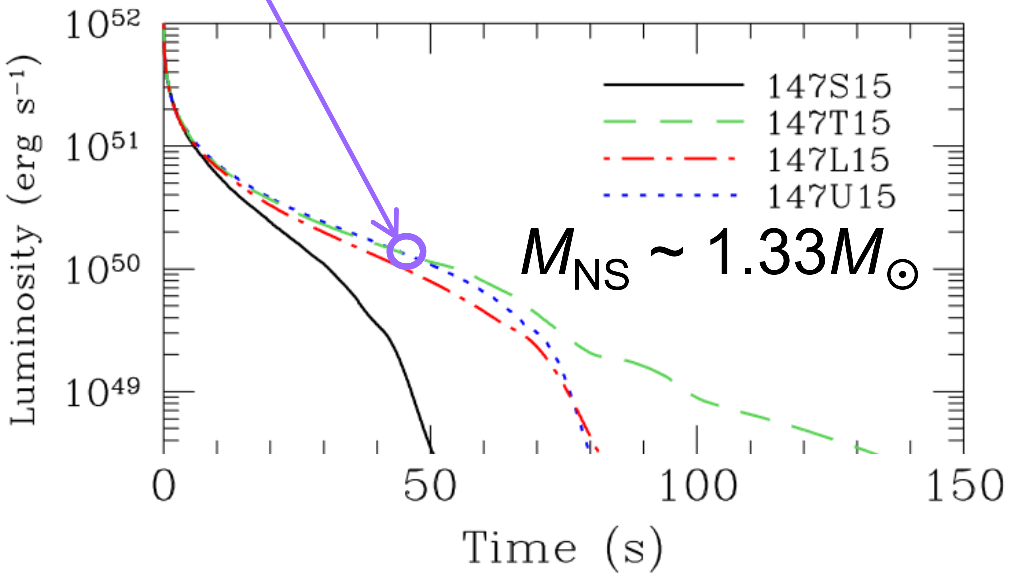
EOS dependence

Nakazato et al., arXiv:2108.03009, accepted by ApJ

– Shen EOS
– LS220 EOS
– Togashi EOS
– T+S EOS
high ρ: Togashi
low ρ: Shen

same high ρ model





$M_{\mathrm{NS}} \sim 1.33 M_\odot$

- Light curve for the shallow decay phase is characterized by the high-density EOS.

Theory of PNS cooling timescale

- Kelvin-Hermholtz timescale

cooling timescale → $\tau_{\mathrm{KH}} = \dfrac{|E_g|}{L}$ ← gravitational energy ← luminosity

- For NS mass m and radius r, we assume:
  1. luminosity scales with surface area : $L \propto r^2$
  2. time dilation in general relativity
  3. $|E_g| \rightarrow E_b$ (binding energy of NSs)

$$\tau_{\mathrm{cool}} \propto \frac{E_b}{r^2\sqrt{1 - {2Gm}/{rc^2}}}$$

Binding energy of NS as a function of mass & radius

Lattimer & Prakash, ApJ **550** (2001)

- For a large class of EOSs, the following is approximately satisfied:

$$\frac{E_b}{mc^2} = \frac{0.6 \times {}^{Gm}/_{rc^2}}{1 - 0.5 \times {}^{Gm}/_{rc^2}}$$

m : NS mass

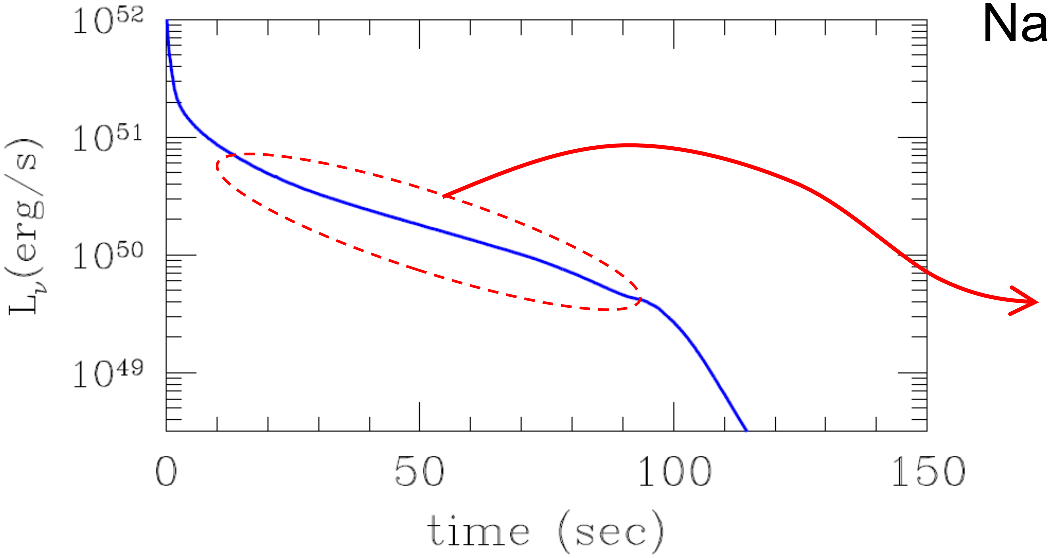
r : NS radius

E_b : Binding energy of NS

$$\Rightarrow \tau_{\text{cool}} \propto \left(\frac{m}{1.4M_\odot}\right)^2 \left(\frac{r}{10\text{ km}}\right)^{-3} \frac{1}{(1-0.5\beta)\sqrt{1-2\beta}}, \quad \beta = \frac{Gm}{rc^2}$$

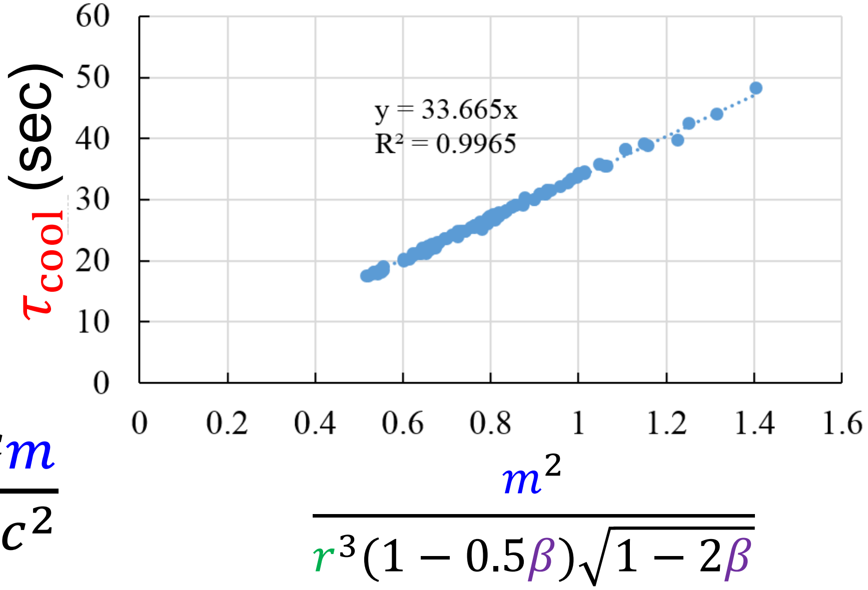
Decay timescale of ν light curve

Nakazato & Suzuki, ApJ **891** (2020),
arXiv:2002.03300



$$L_{\overline{\nu}_e}(t) \sim L_0 \exp\left(-\frac{t}{\tau_{\mathrm{cool}}}\right)$$

plots are from simulation results with different m and r



- PNS cooling timescale accounts for the decay timescale of neutrino light curve.

$$\tau_{\mathrm{cool}} \propto \frac{m^2}{r^3(1-0.5\beta)\sqrt{1-2\beta}}, \quad \beta = \frac{Gm}{rc^2}$$

Estimation of NS mass & radius

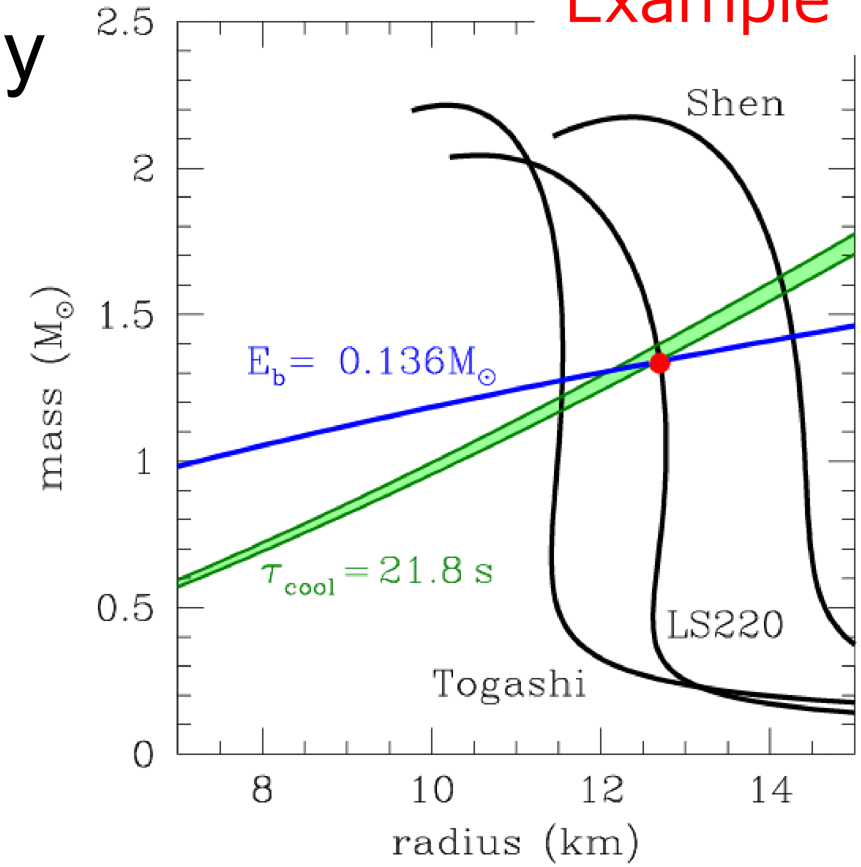
- Crossing point of neutrino cooling timescale

$$\tau_{\rm cool} = \tau^* \left(\frac{m}{1.4M_\odot}\right)^2 \left(\frac{r}{10\ {\rm km}}\right)^{-3} \frac{1}{(1-0.5\beta)\sqrt{1-2\beta}}$$

and total emission energy

$$\frac{E_b}{mc^2} = \frac{0.6\beta}{1-0.5\beta} \qquad \left(\beta = \frac{Gm}{rc^2}\right)$$

Example



- Numerical results with realistic EOSs also follow these trends.

→ future EOS constraints

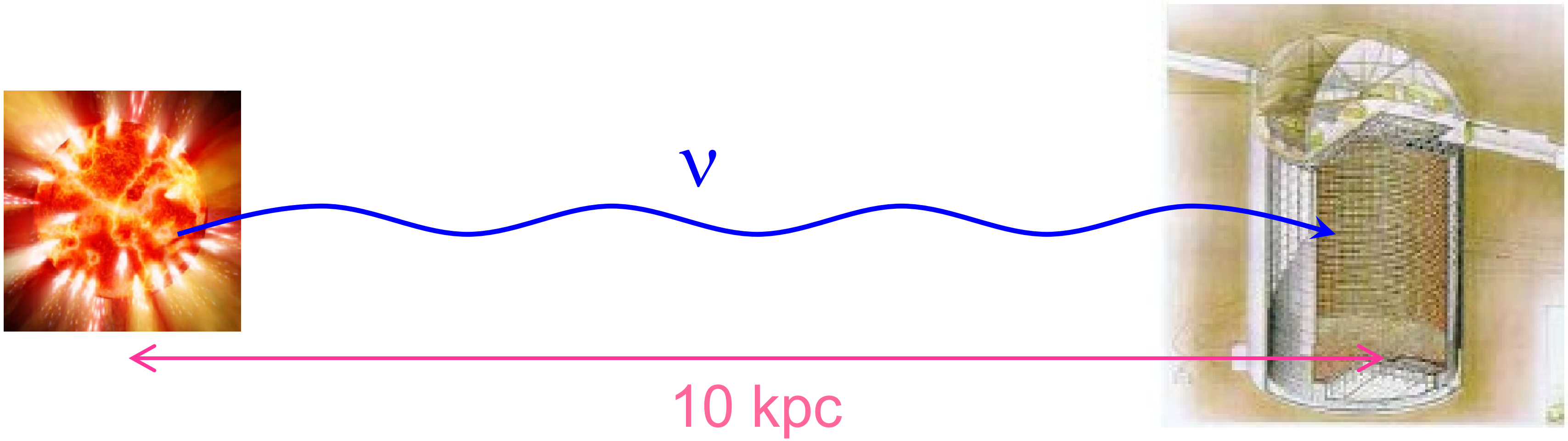
Evaluation of event rate

Nakazato et al., arXiv:2108.03009, accepted by ApJ

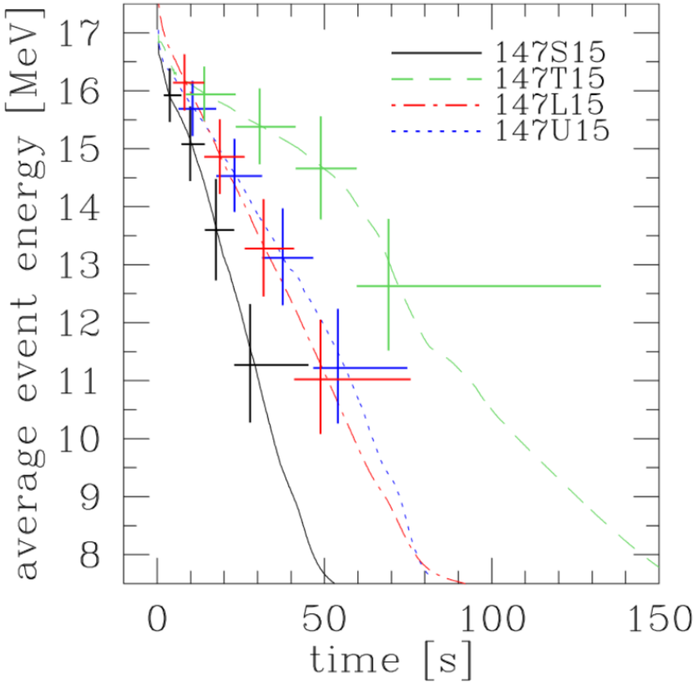
- Assuming the detection at SuperKamiokande (32.5 kton, E_{th} = 5 MeV, w/ energy resolution) from a supernova of D = 10 kpc distance.

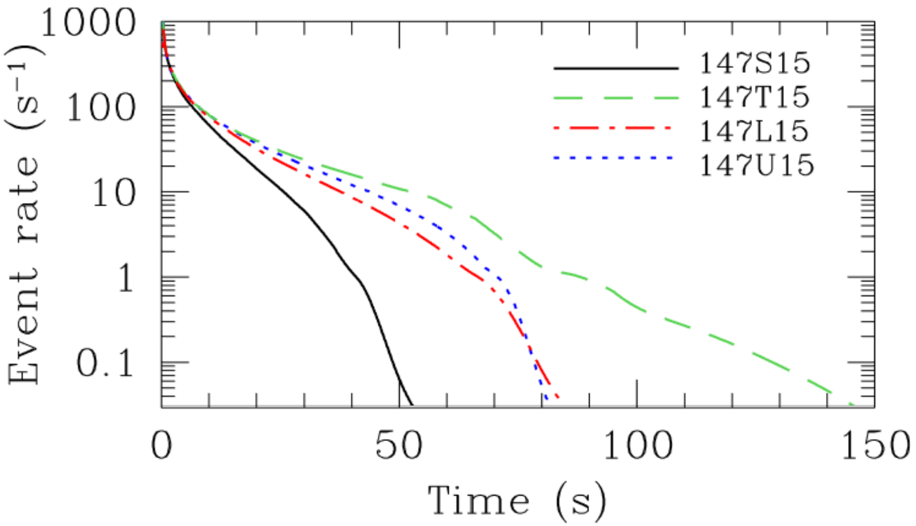
- Energy spectrum of inverse β decay.
  - Strumia & Vissani (2003)

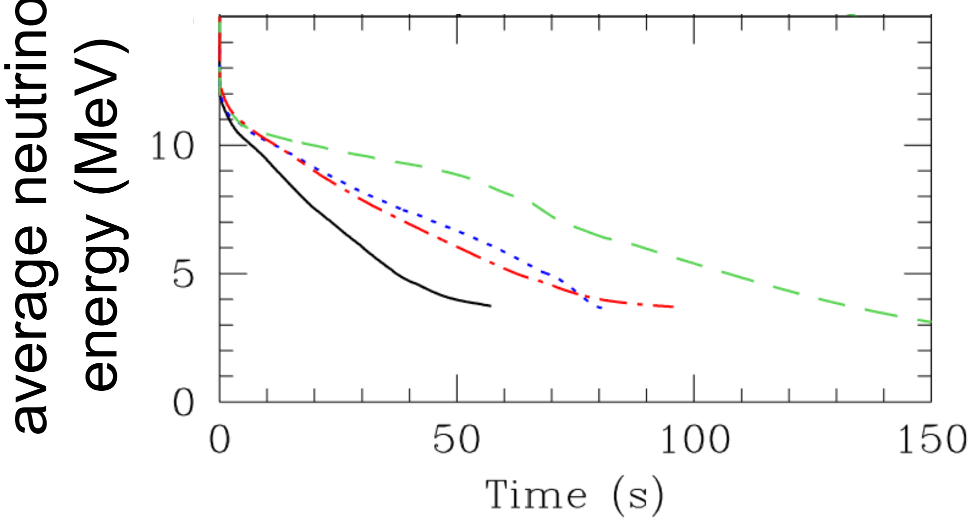
$$\bar{\nu}_e + p \to e^+ + n$$



Results







- The event rate depends not only on the luminosity but also on the average energy.

→ The degeneracy of T and U is lifted.

Nuclei near PNS surface

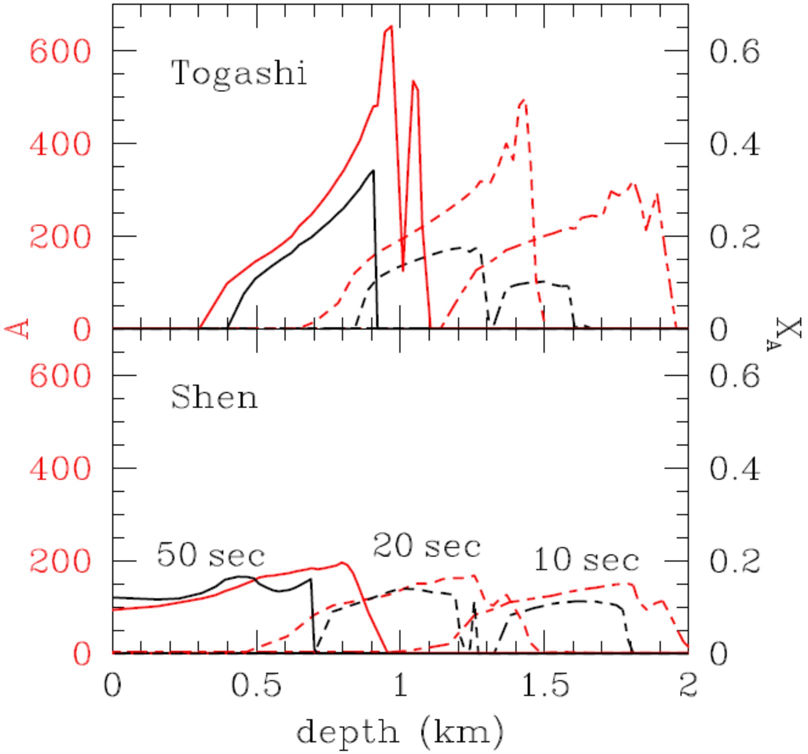
Nakazato et al.,
PRC **97** (2018),
arXiv:1710.10441

- Larger nuclear mass number is estimated for Togashi EOS than T+S (Shen) EOS.

  → Cross section of the coherent elastic scattering is enhanced making the average ν energy higher.

- Thermal insulation by nuclei

$$\begin{cases} \sigma \propto A^2 \\ 1/\lambda \propto X_A \cdot A \end{cases}$$

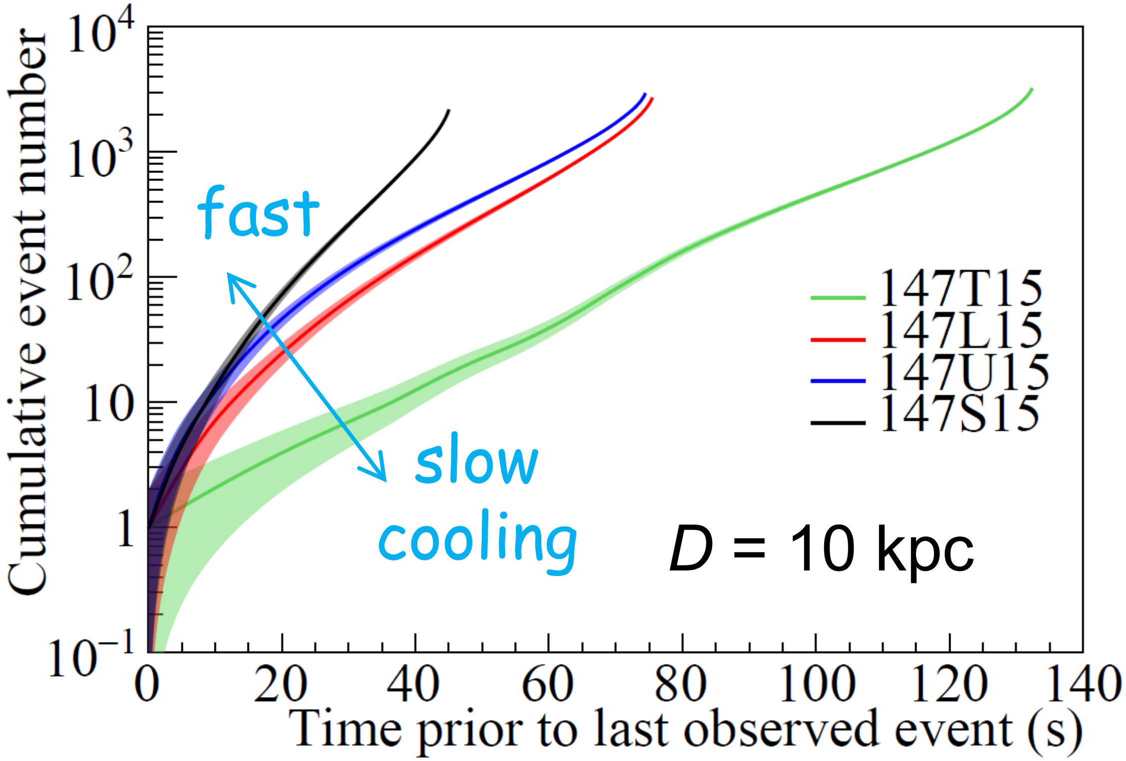


A; mass number

X_A; fraction of nuclei

How to observe the cooling

- Backward cumulative event number

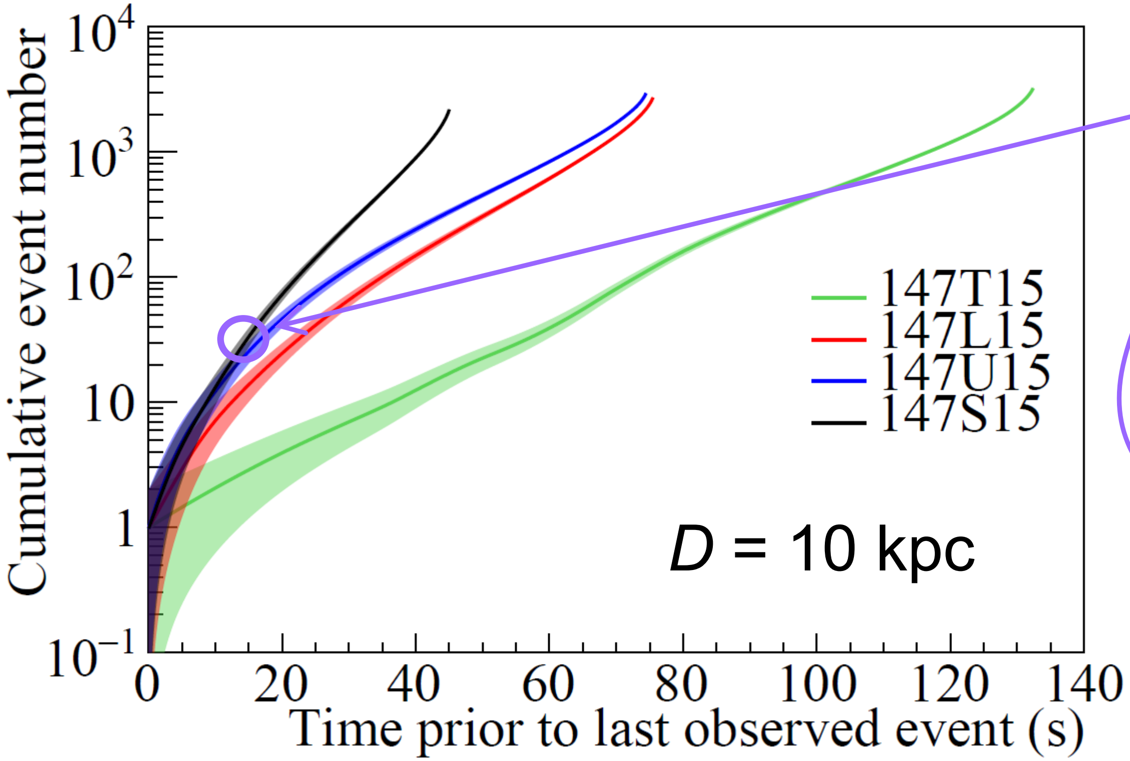


– Togashi EOS
– LS220 EOS
– Shen EOS
– T+S EOS
high ρ: Togashi
low ρ: Shen

- It is taken as function of backward time from the last observed event.

How to observe the cooling

- Backward cumulative event number



same low ρ model

– Togashi EOS

– LS220 EOS

– Shen EOS

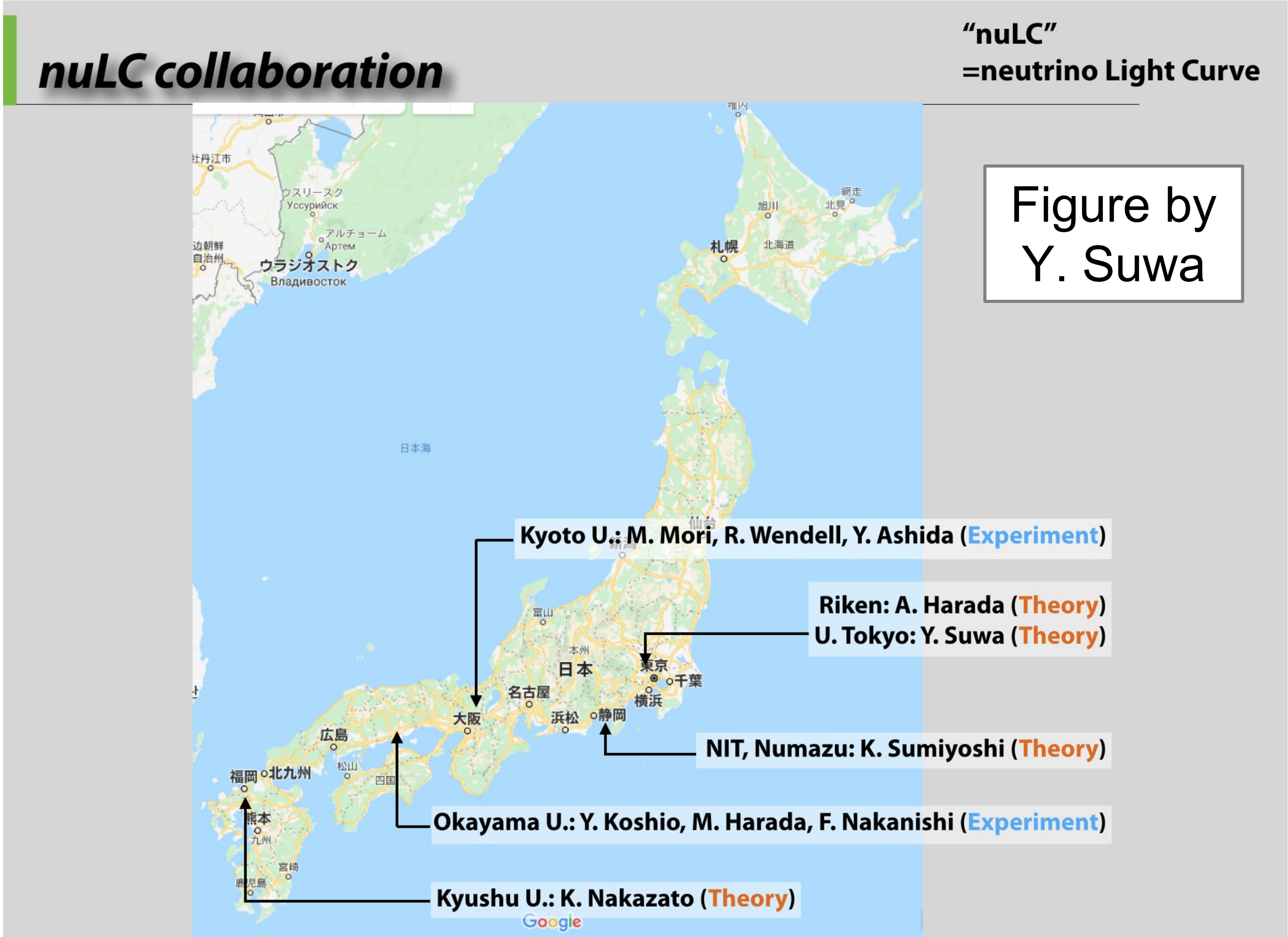
– T+S EOS

high ρ: Togashi

low ρ: Shen

- It is taken as function of backward time from the last observed event.

Advertisement



nuLC collaboration

"nuLC"
=neutrino Light Curve

Figure by
Y. Suwa

Kyoto U.: M. Mori, R. Wendell, Y. Ashida (Experiment)

Riken: A. Harada (Theory)
U. Tokyo: Y. Suwa (Theory)

NIT, Numazu: K. Sumiyoshi (Theory)

Okayama U.: Y. Koshio, M. Harada, F. Nakanishi (Experiment)

Kyushu U.: K. Nakazato (Theory)

Summary

- Neutrino detection from next supernova will provide various physics opportunities.
  - It depends on the phase.
- To develop a basis of neutrino light curve analysis, the late phase is important.
  - It is less uncertain than the early phase.
- Neutrino light curve on the late phase is determined by EOS as well as the NS mass.
  - The high- and low-density properties have different impacts on the neutrino signal through the NS radius and surface temperature.