

*Burst and Cosmic
Background Neutrinos
from Core-Collapse
Supernovae*

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Contents

1. Neutrino Burst from Core-Collapse Supernova

- Proto-Neutron Star (PNS) cooling
(Nakazato & Suzuki 2019, 2020)

2. Cosmic Background

Neutrino (a.k.a. DSNB)

- Diffuse Supernova Neutrino Background
(Ashida, Nakazato & Tsujimoto 2023)

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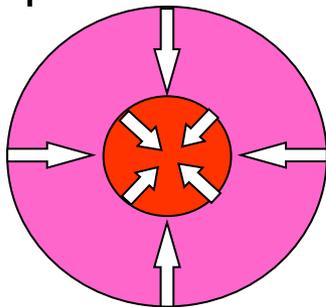
Core-collapse supernova

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

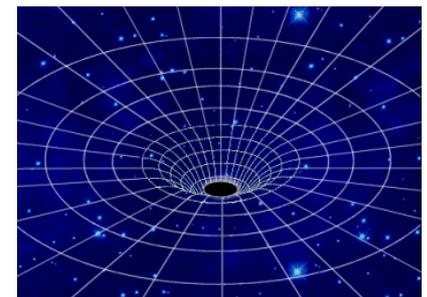
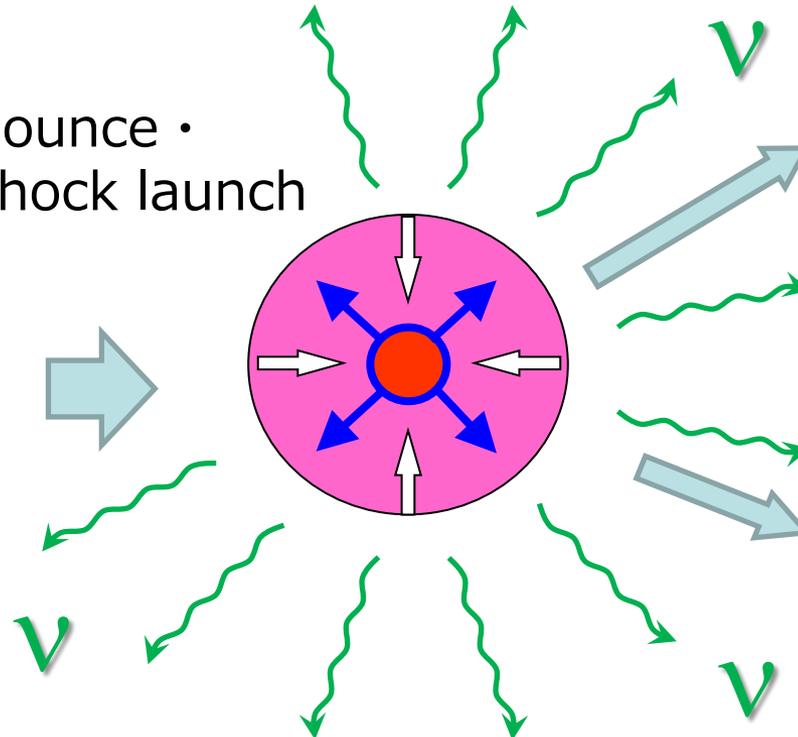


SN explosion \rightarrow
neutron star (**NS**)

collapse

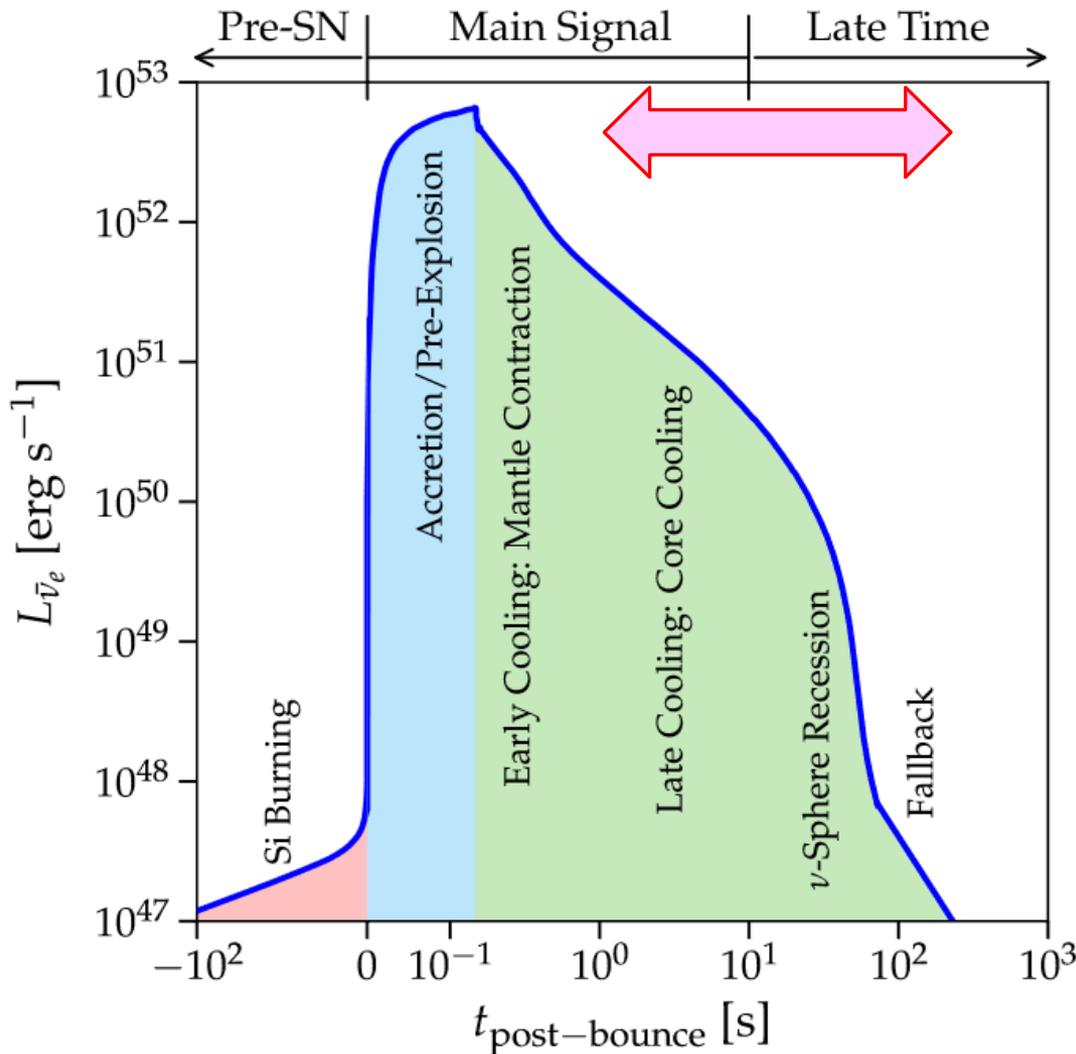


bounce •
shock launch



black hole (**BH**)

Three phases of neutrino emission



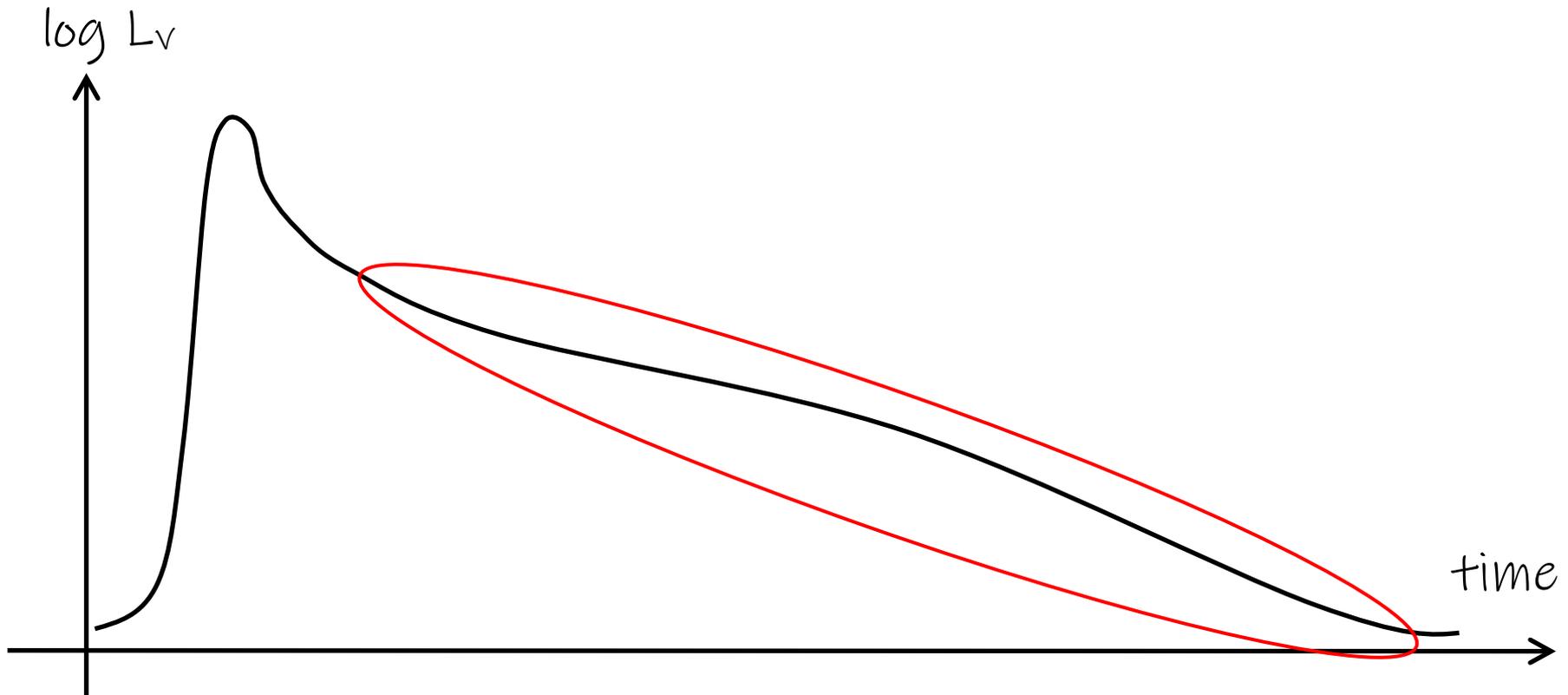
Li et al., PRD **103** (2021)

- ① pre-SN phase
 $\sim O(-1 \text{ day})$
- ② hydrodynamical phase
 $\sim O(1 \text{ sec})$
- ③ proto-NS (PNS) cooling phase
 $\sim O(1 \text{ min})$

target of this study

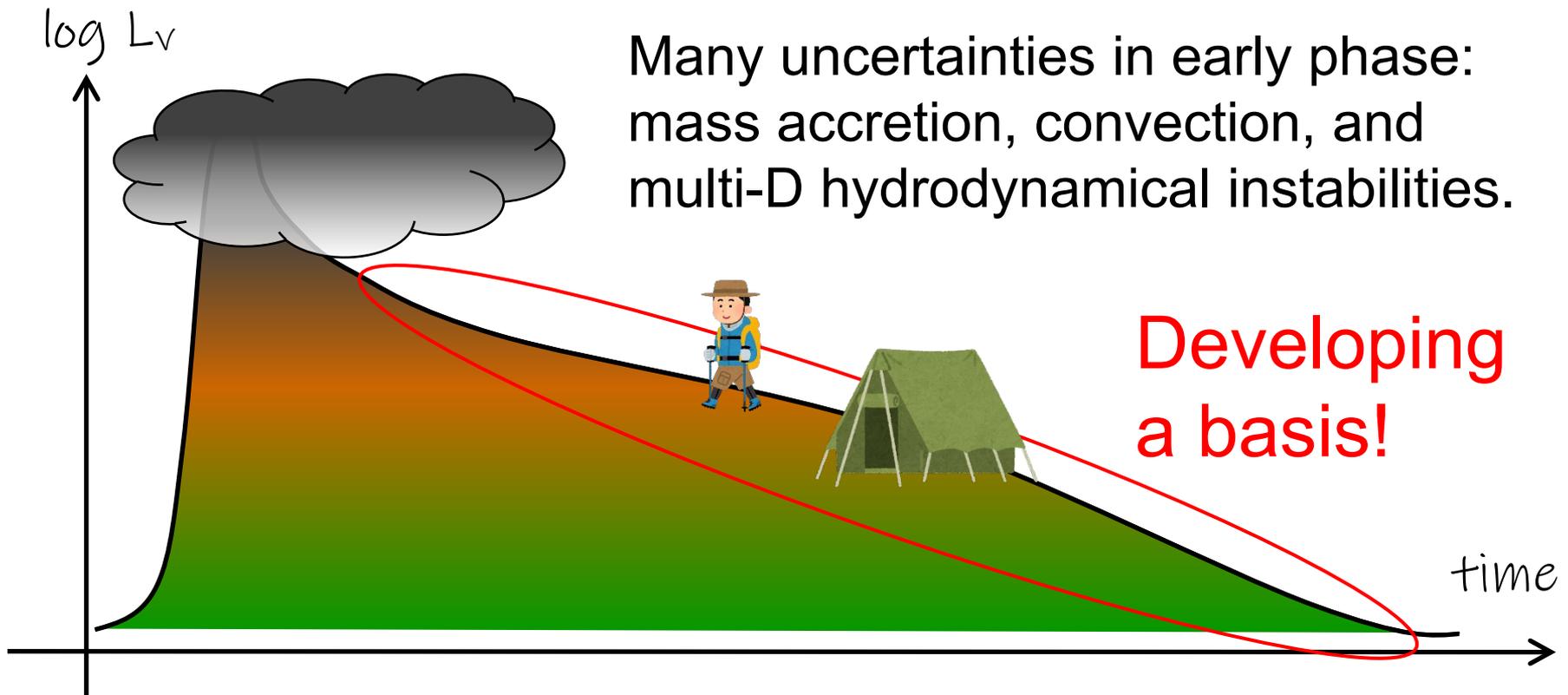
Why late phase?

- The neutrino signal is mainly determined by a few parameters: mass, radius, and surface temperature of a neutron star.



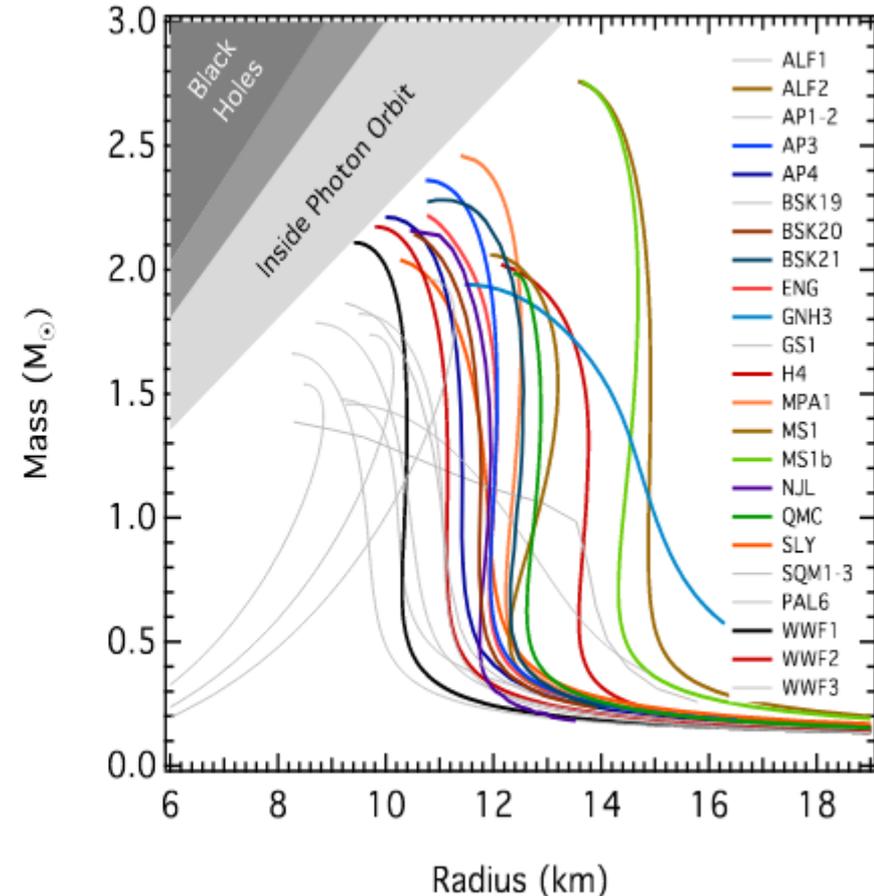
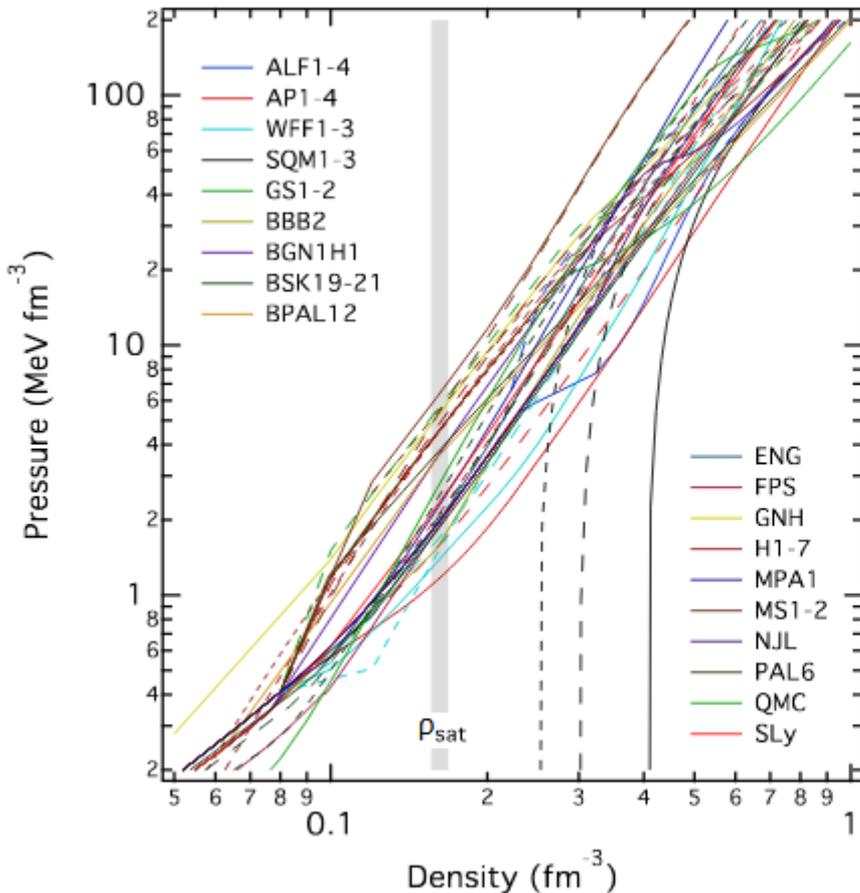
Why late phase?

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Mass-radius relation of NSs

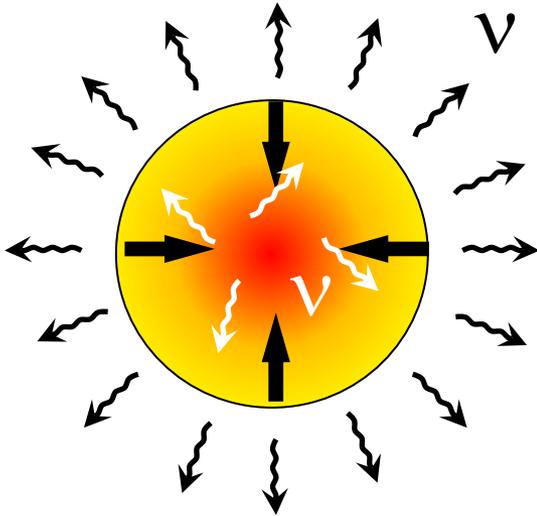
Özel & Freire, ARAA **54** (2016)



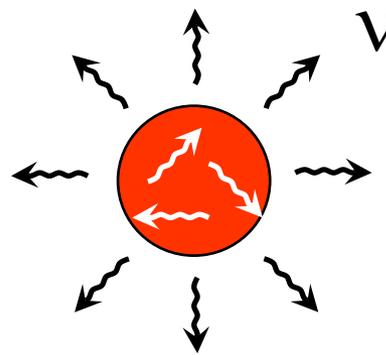
- Equation of state (EOS) of nuclear matter determines the mass and radius of NSs.

Schematic picture of PNS cooling

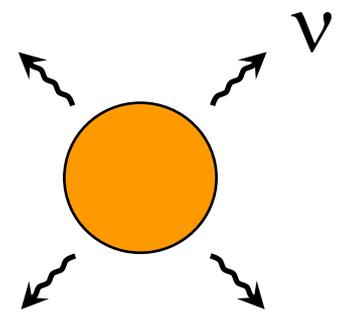
(i) contraction



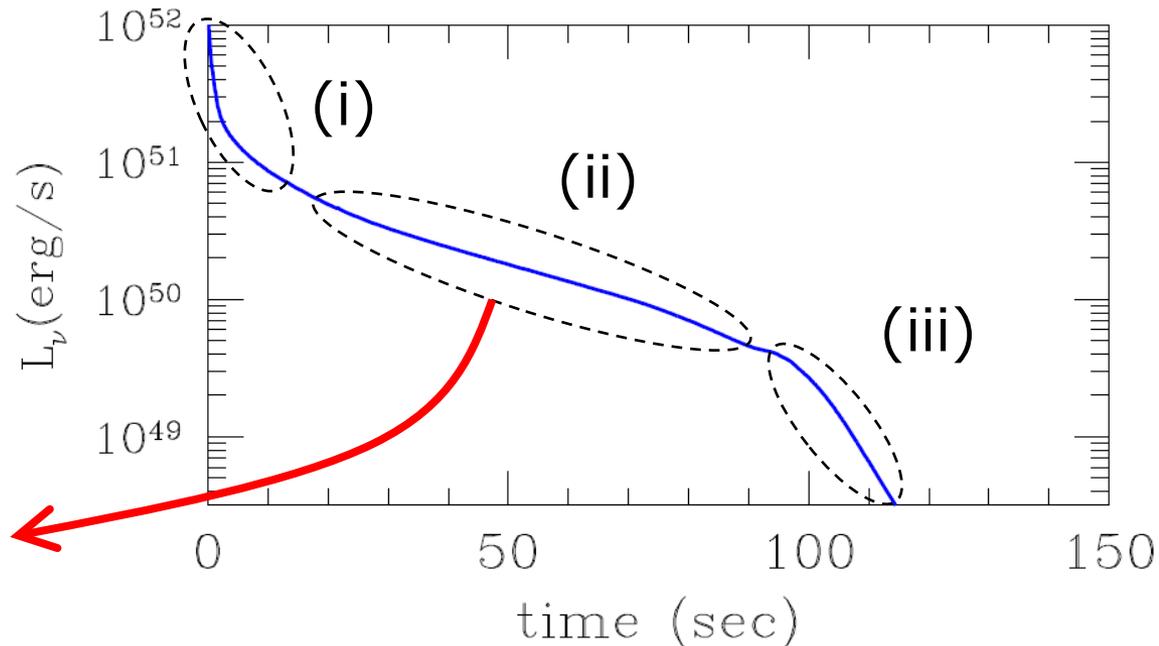
(ii) shallow decay



(iii) volume cooling



- Decay time of neutrino light curve is characterized here.



Theory of PNS cooling timescale

- Kelvin-Helmholtz timescale

$$\text{cooling timescale} \rightarrow \tau_{\text{KH}} = \frac{|E_g|}{L} \quad \begin{array}{l} \leftarrow \text{gravitational energy} \\ \leftarrow \text{luminosity} \end{array}$$

- 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)

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

PNS cooling timescale formula

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

- Binding energy of NS as a function of (m , r)
 - For a large class of EOSs, the following is approximately satisfied (Lattimer & Prakash, ApJ **550**, 2001):

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

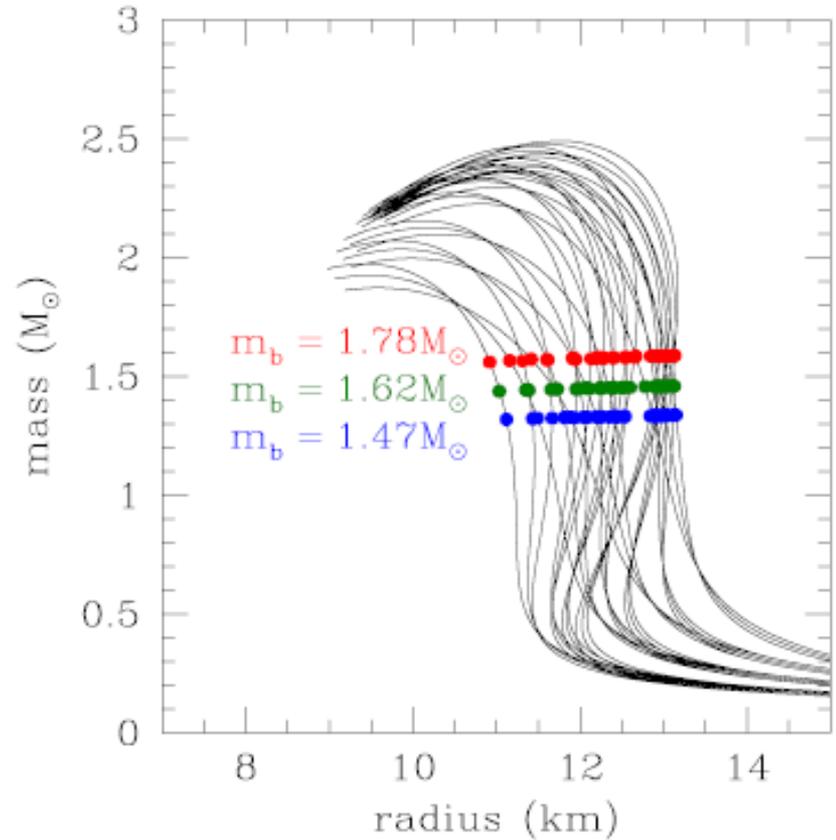
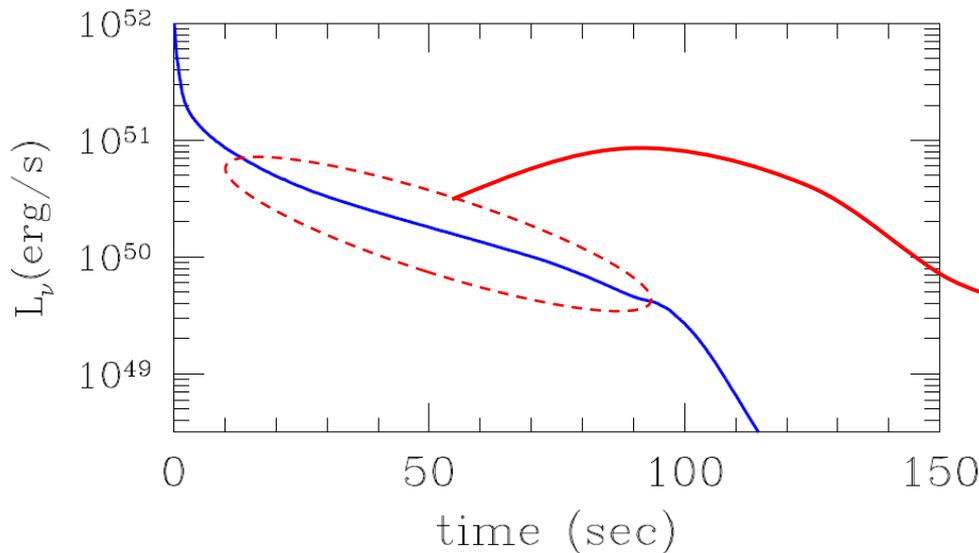
m : NS mass, r : NS radius

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

- Using parametric EOS, PNS cooling simulation is performed and decay timescale is evaluated for various models with different masses.



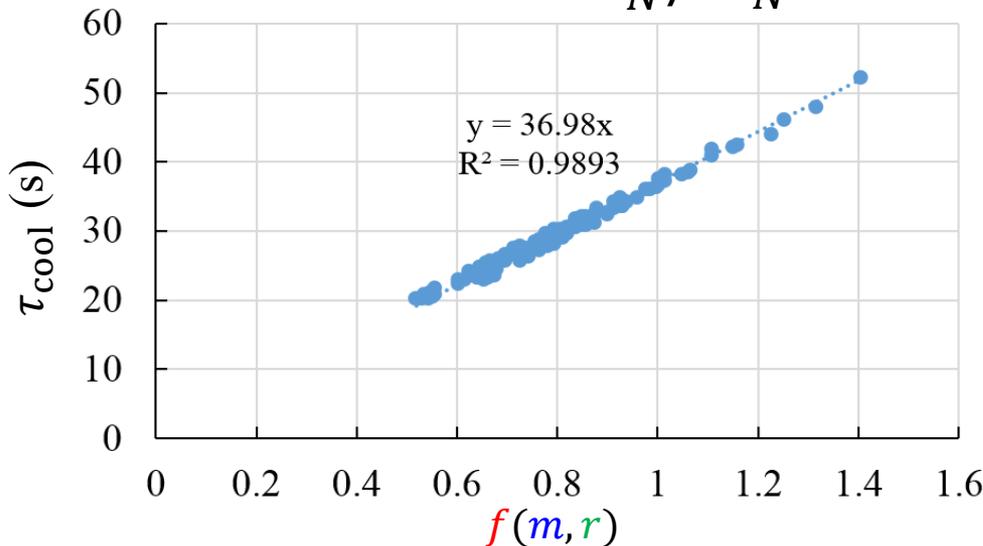
$$L_{\bar{\nu}_e}(t) \sim L_0 \exp\left(-\frac{t}{\tau_{\text{cool}}}\right)$$

Theory vs. simulation results

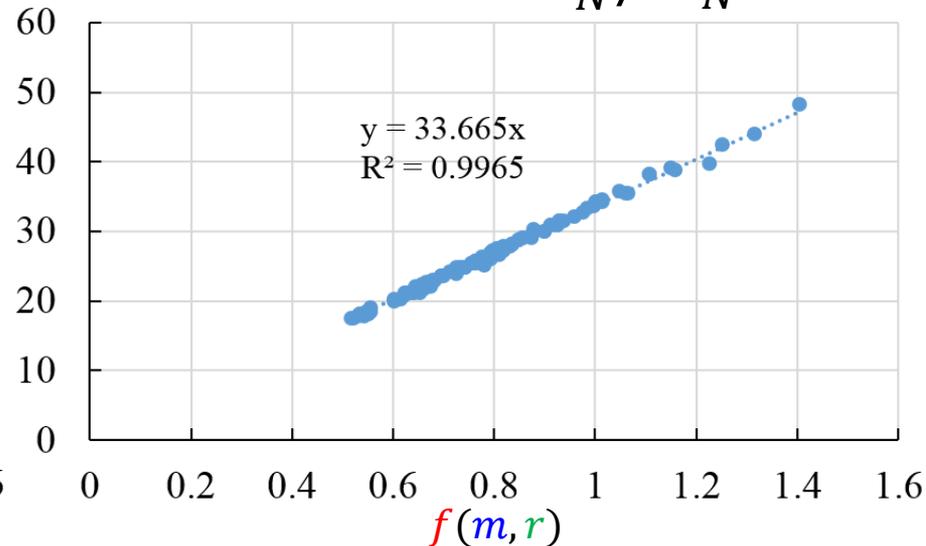
$$\tau_{\text{cool}} = \tau^* \underbrace{\left(\frac{m}{1.4M_{\odot}}\right)^2 \left(\frac{r}{10 \text{ km}}\right)^{-3}}_{f(m, r)} \frac{1}{(1-0.5\beta)\sqrt{1-2\beta}}, \quad \beta = \frac{Gm}{rc^2}$$

- ✓ Theory describes simulation results faithfully.
- ✓ $33.7 \text{ s} \leq \tau^* \leq 37.0 \text{ s}$ (depends on effective mass)

effective mass: $M_N^*/M_N = 1$



effective mass: $M_N^*/M_N = 0.5$



Estimation of NS mass & radius

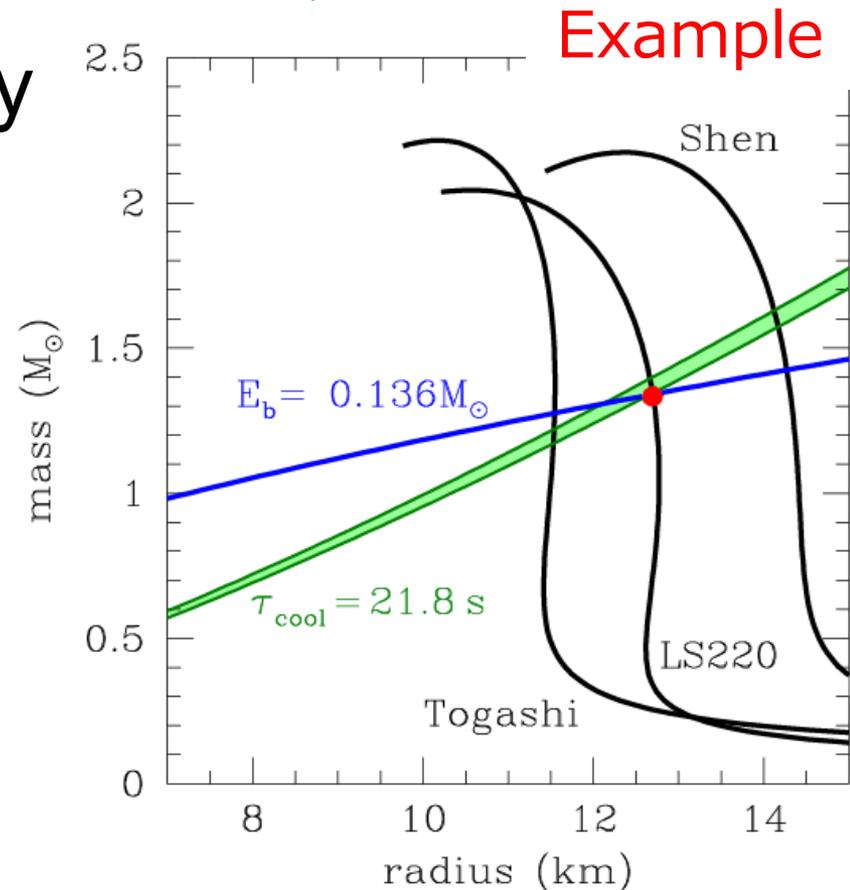
- Crossing point of neutrino cooling timescale

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

and total emission energy

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

- Numerical results with realistic EOSs also follow these trends.
→ future EOS constraints



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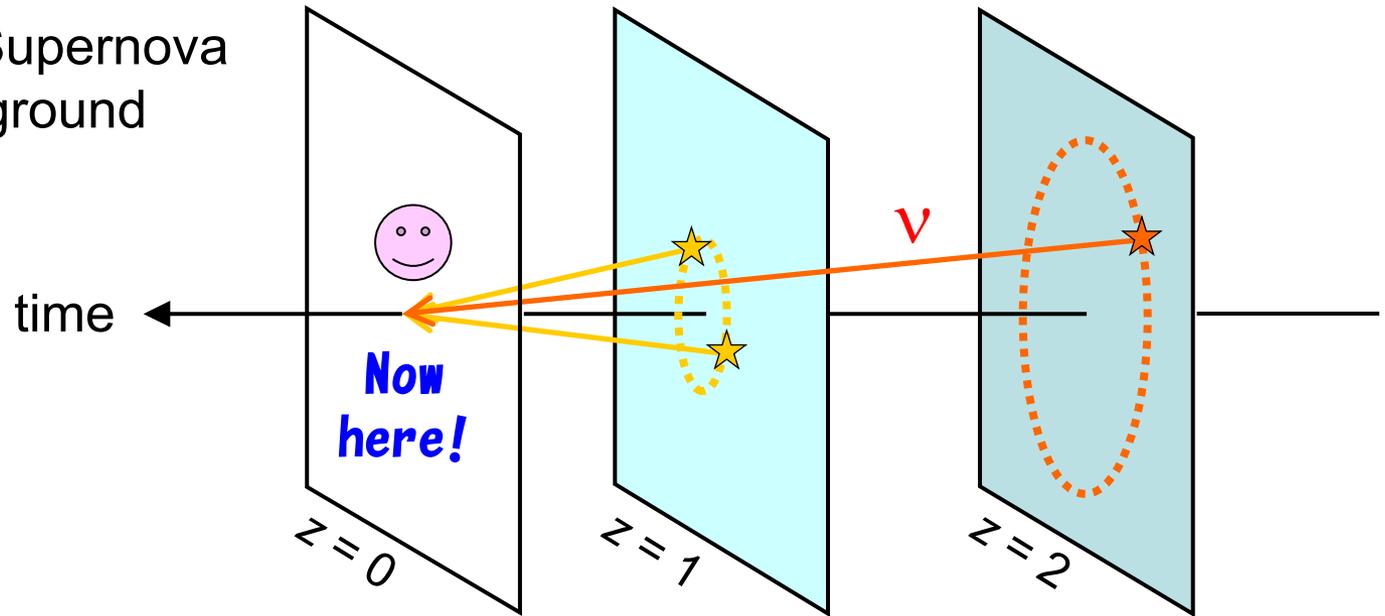
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(Ashida, Nakazato & Tsujimoto 2023)

Cosmic background neutrinos

a.k.a. Diffuse Supernova
Neutrino Background
(DSNB)



- Neutrinos emitted by all core-collapse SNe in the causally-reachable universe constitute diffuse background radiation.
- Can we detect DSNB neutrinos? What determines their flux and spectrum?

Formulation

$$\left(\frac{dE'_\nu}{dE_\nu} = 1 + z \right)$$

$$\frac{d\Phi(E_\nu)}{dE_\nu} = c \int_0^{z_{\max}} \underline{R_{\text{CC}}(z)} \left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle \frac{dz}{H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

- **Cosmological parameters:**

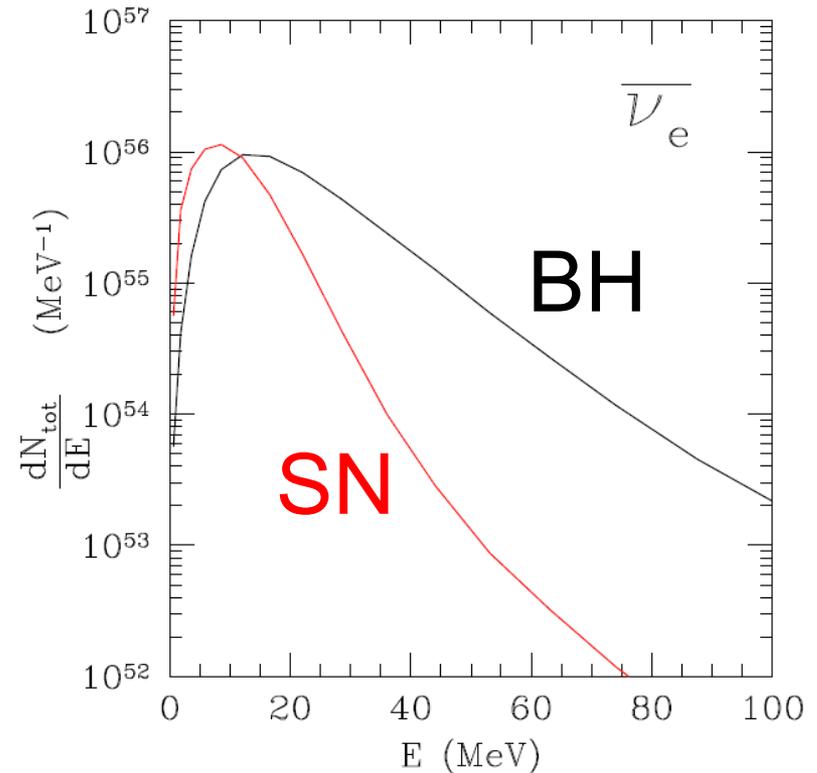
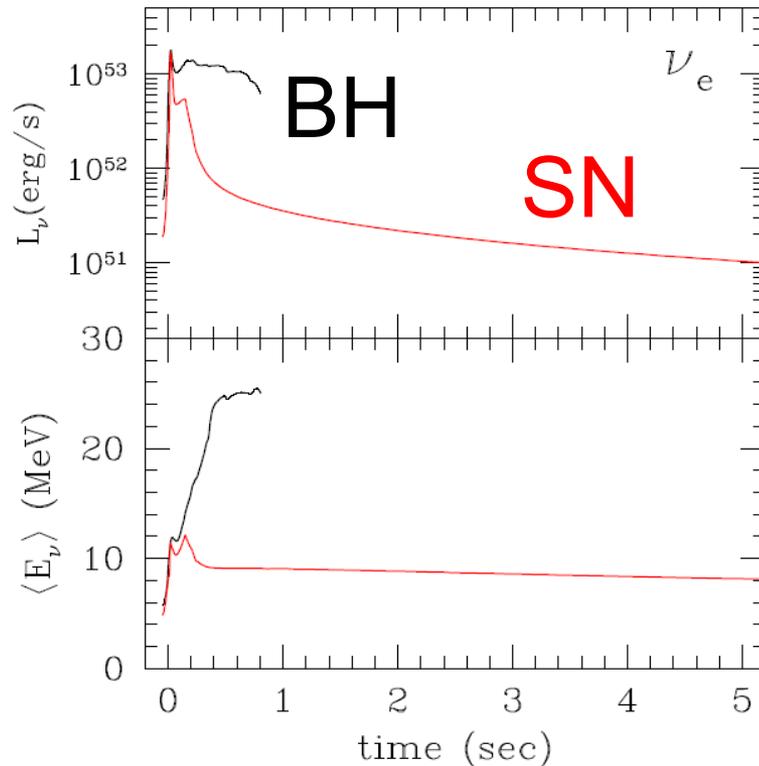
$$H_0 = 67.7 \text{ km/s/Mpc}, \Omega_m = 0.31, \Omega_\Lambda = 0.69$$

- **Spectrum of supernova neutrinos:** $\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle$

- **Core-collapse rate:** $R_{\text{CC}}(z)$
(from Tsujimoto, 2023)

Neutrinos from BH formation

- Mean neutrino energy is higher.
 - because the mass accretion continues until the BH formation and the core is heated.



Neutrino emissions from SN with NS formation and BH formation

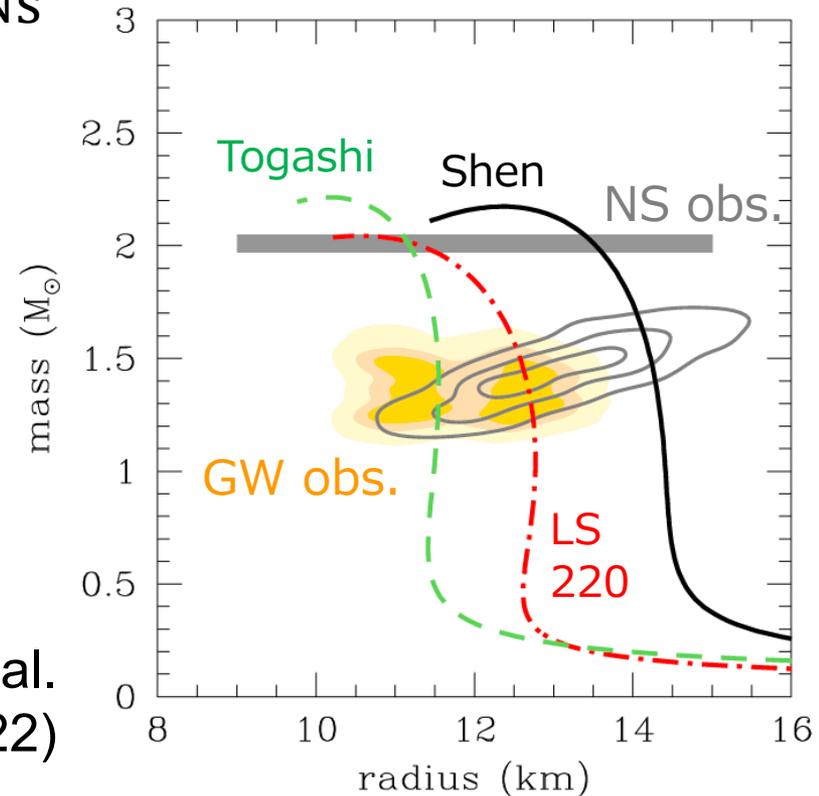
Nuclear equation of state

- Impacts on the neutrino emission:
 - for NS case, smaller radius \rightarrow larger emission

\therefore total energy is $E \sim \frac{GM_{\text{NS}}^2}{R_{\text{NS}}}$

- for BH case,
higher maximum mass
 \rightarrow larger emission
- We adopt 3 types of EOS in this study.

Nakazato et al.
ApJ. **925** (2022)



Neutrinos from PNS cooling

- Provided in Zenodo (**advertisement!!**)

The image shows a Zenodo record page for a dataset. The header is blue with the Zenodo logo, a search bar, and links for 'Upload' and 'Communities'. On the right, there are 'Log in' and 'Sign up' buttons. The main content area has a date 'January 31, 2022' and labels 'Dataset' and 'Open Access'. The title is 'Supernova Neutrino Light Curves from Proto-Neutron Star Cooling with Various Nuclear Equation of State'. Below the title is the author 'NAKAZATO, Ken'ichiro; the nuLC Collaboration'. A paragraph of text describes the model spectra of neutrinos emitted from proto-neutron star (PNS) cooling. To the right, there are statistics: 256 views and 198 downloads. Below that, it says 'Indexed in OpenAIRE'. A large pink box is overlaid on the page, containing two URLs: 'https://zenodo.org/record/4632495' and 'https://zenodo.org/record/5778224'. At the bottom, there is a 'supernova neutrinos' tag, 'Related identifiers:' section with a reference to '2022ApJ...925...98N (Journal article)', and a 'License (for files):' section with 'Creative Commons Attribution 4.0 International'.

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January 31, 2022 Dataset Open Access

Supernova Neutrino Light Curves from Proto-Neutron Star Cooling with Various Nuclear Equation of State

NAKAZATO, Ken'ichiro; the nuLC Collaboration

We present the model spectra of neutrinos emitted from proto-neutron star (PNS) cooling used in Nakazato et al., *Astrophys. J.* **925** (2022) 98, arXiv:2108.03009 [astro-ph.HE]. So as to obtain the time evolution of neutrino spectra, PNS cooling simulations are performed with use of four nuclear equation of state (EOS) models and eight PNS cooling models with different initial conditions are involved for each EOS. The format of the spectral data is the same with that of [Supernova Neutrino Database](#). For the details, see [readme.pdf](#)

256 views 198 downloads See more details...

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supernova neutrinos

Related identifiers:
References
[2022ApJ...925...98N](#) (Journal article)

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Supernova Neutrino Light Curves from Proto-Neutron Star Cooling with Various Nuclear Equation of State

According to Tsujimoto (2023)

- Galactic chemical evolution implies that:
 1. E/S0, Sab galaxies have flatter IMF
 2. Progenitors with $\geq 18M_{\odot}$ becomes BH

According to Tsujimoto (2023)

- Galactic chemical evolution implies that:
 - E/S0, Sab galaxies have flatter IMF
 - Progenitors with $\geq 18M_{\odot}$ becomes BH
- Initial mass function (IMF): $\psi_{\text{IMF}} = \frac{dN}{dM} \propto M^{x-1}$

$x = -0.9$
fraction of
massive
stars is
higher



$x = -1.35$
(Salpeter)

According to Tsujimoto (2023)

- Galactic chemical evolution implies that:

1. E/S0, Sab galaxies have flatter IMF

2. Progenitors with $\geq 18M_{\odot}$ becomes BH

- CCSN rate: $\dot{\rho}_*(z) \frac{\int_{8M_{\odot}}^{18M_{\odot}} \psi_{\text{IMF}}(M) dM}{\int_{0.1M_{\odot}}^{100M_{\odot}} M \cdot \psi_{\text{IMF}}(M) dM}$

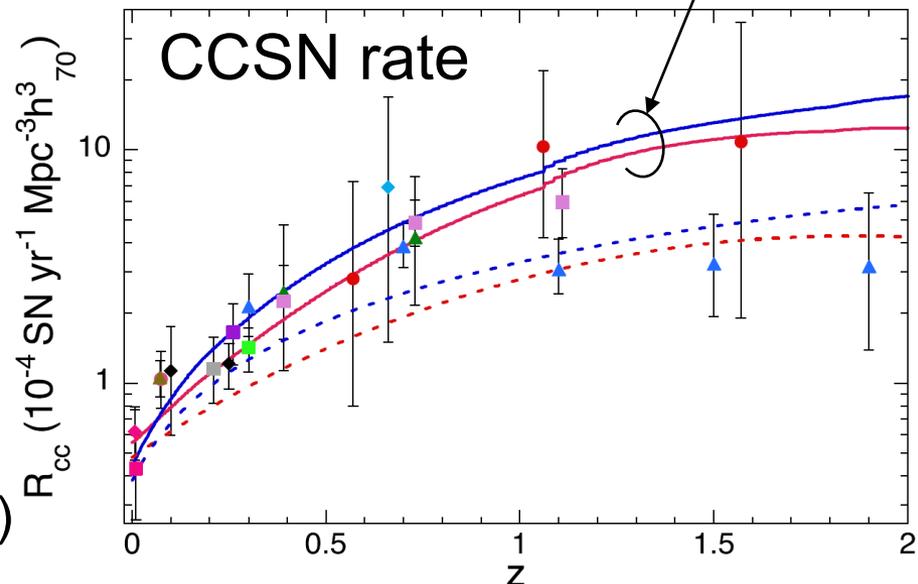
➤ cosmic star formation rate, $\dot{\rho}_*(z)$, is from

Hopkins & Beacom (2006)

Madau & Dickinson (2014)

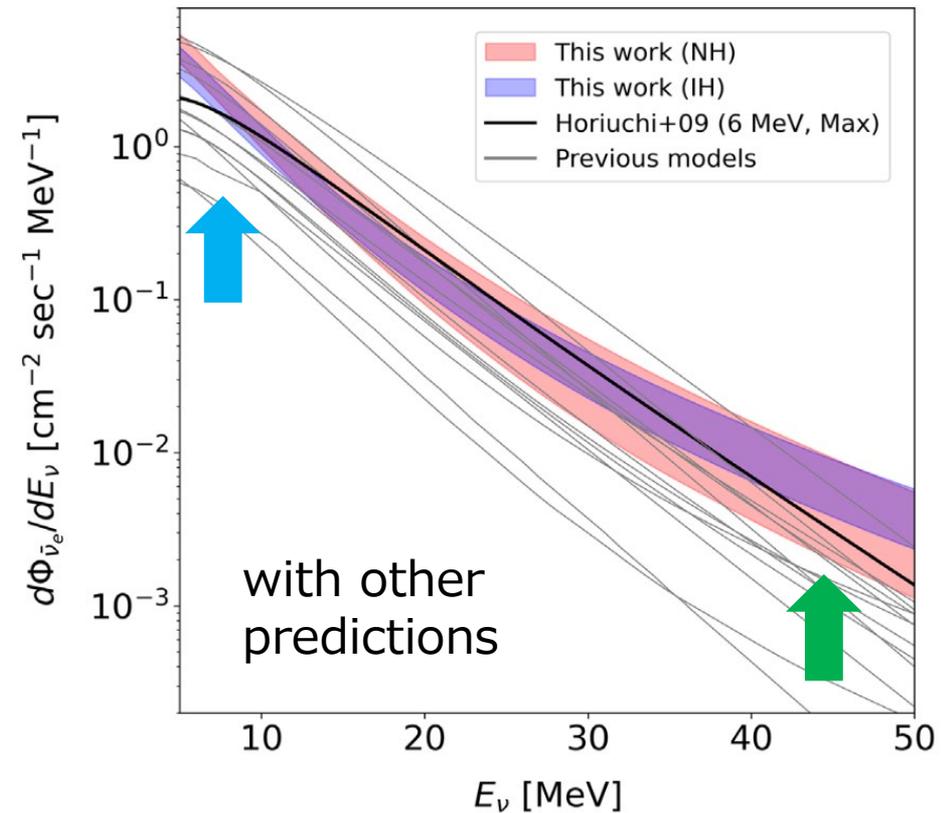
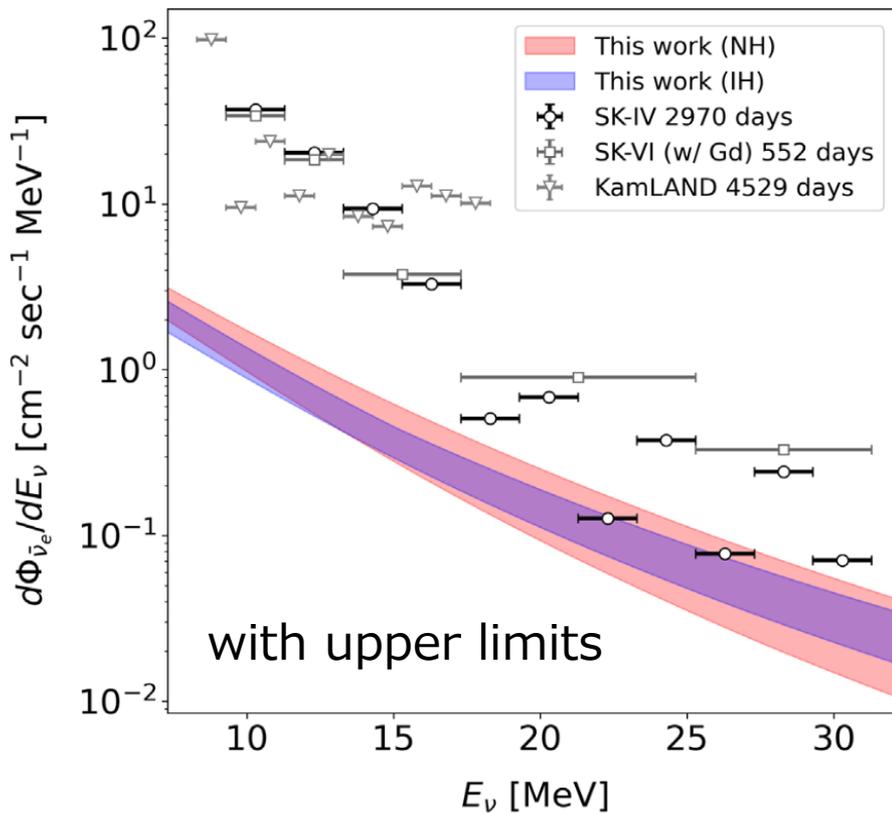
Tsujimoto, MNRAS **518** (2023)

flatter IMF for early type galaxies



DSNB flux

Ashida, Nakazato & Tsujimoto,
ApJ **953** (2023), arXiv:2305.13543



- Comparing with other work, enhancement at low ($\lesssim 10$ MeV) and high ($\gtrsim 30$ MeV) energies → due to high z and BH sources, respectively

Evaluation of signal significance

- Analysis based on Bayes' theorem

$$P(\text{model}|\text{obs}) = \frac{P(\text{obs}|\text{model}) \times P(\text{model})}{\sum_{\text{model}} P(\text{obs}|\text{model}) \times P(\text{model})}$$

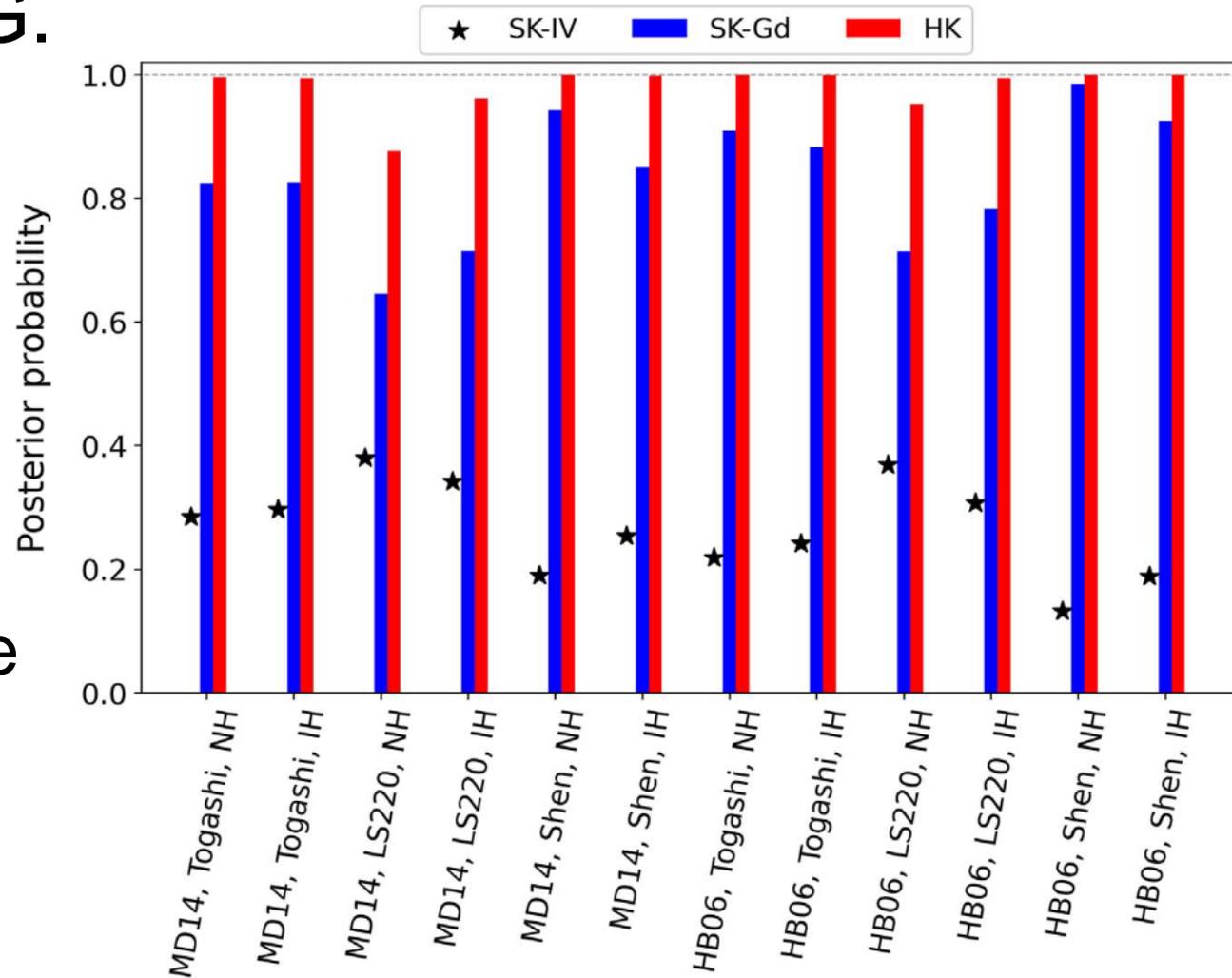
- Observables are low ($13.3 < E_\nu < 17.3 \text{ MeV}$) and high ($17.3 < E_\nu < 31.3 \text{ MeV}$) energy event numbers: $\text{obs} = \{N_{\text{low}}, N_{\text{high}}\}$
- Models with our DSNB + BG vs BG only
 - BG: non-NCQE, NCQE, accidental, Li9
 - Systematic and statistical errors are considered.

Results of signal significance

- Mostly, our signal models can be detected well over BG.

SK-Gd (10 yr):
70% neutron-tag efficiency

HK (10 yr):
neutron-tag efficiency same with SK-IV



Summary

- Neutrino detection from nearby and past supernovae will provide various physics opportunities.
- Neutrino light curve on the late phase is determined by EOS as well as the NS mass.
 - Cooling timescale depends on m and r .
- DSNB flux is evaluated based on the recent Galactic chemical evolution model.
 - Both the core-collapse rate and fraction of BH formations are higher than in previous models.
 - The detection will be achieved in near future.