Burst and Cosmic Background Neutrinos from Core-Collapse Supernovae

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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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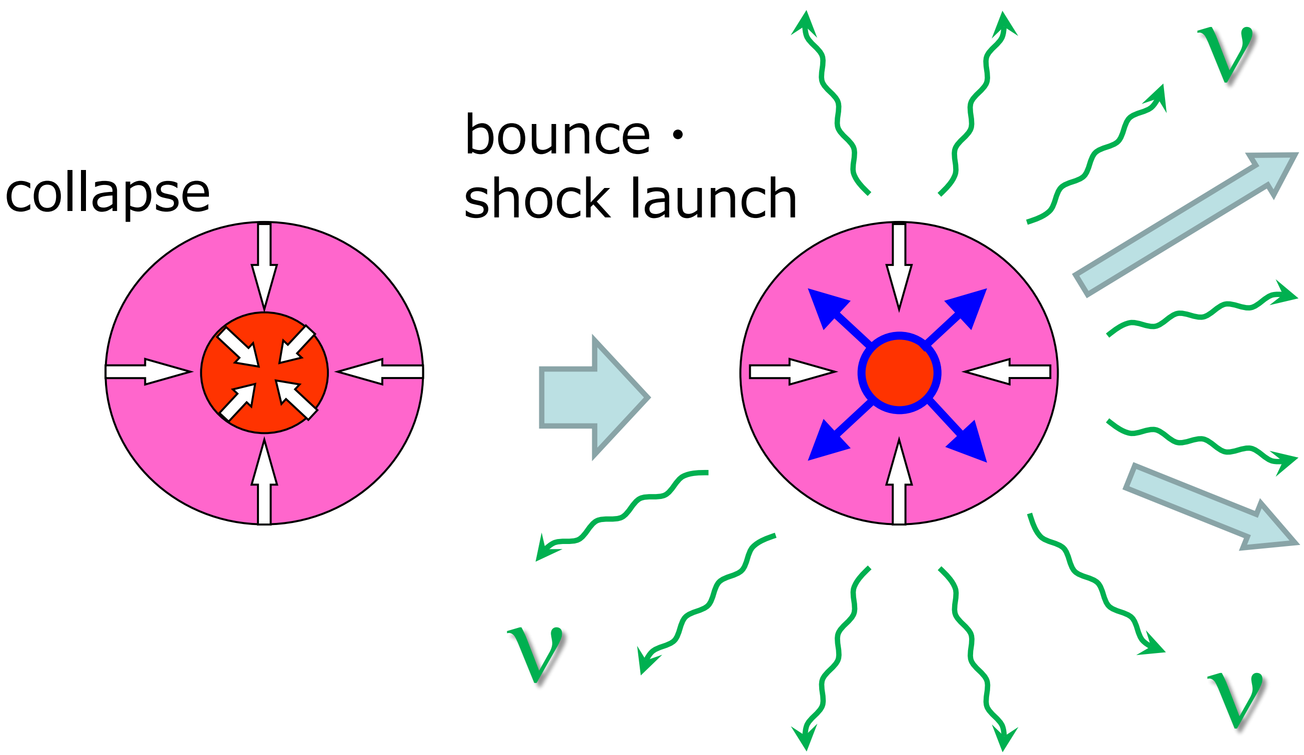
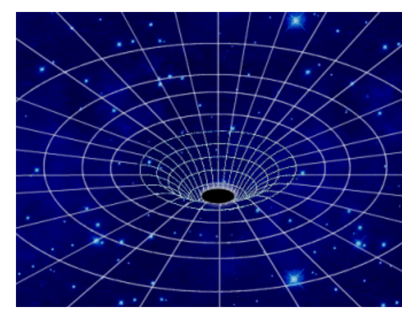
Core-collapse supernova

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

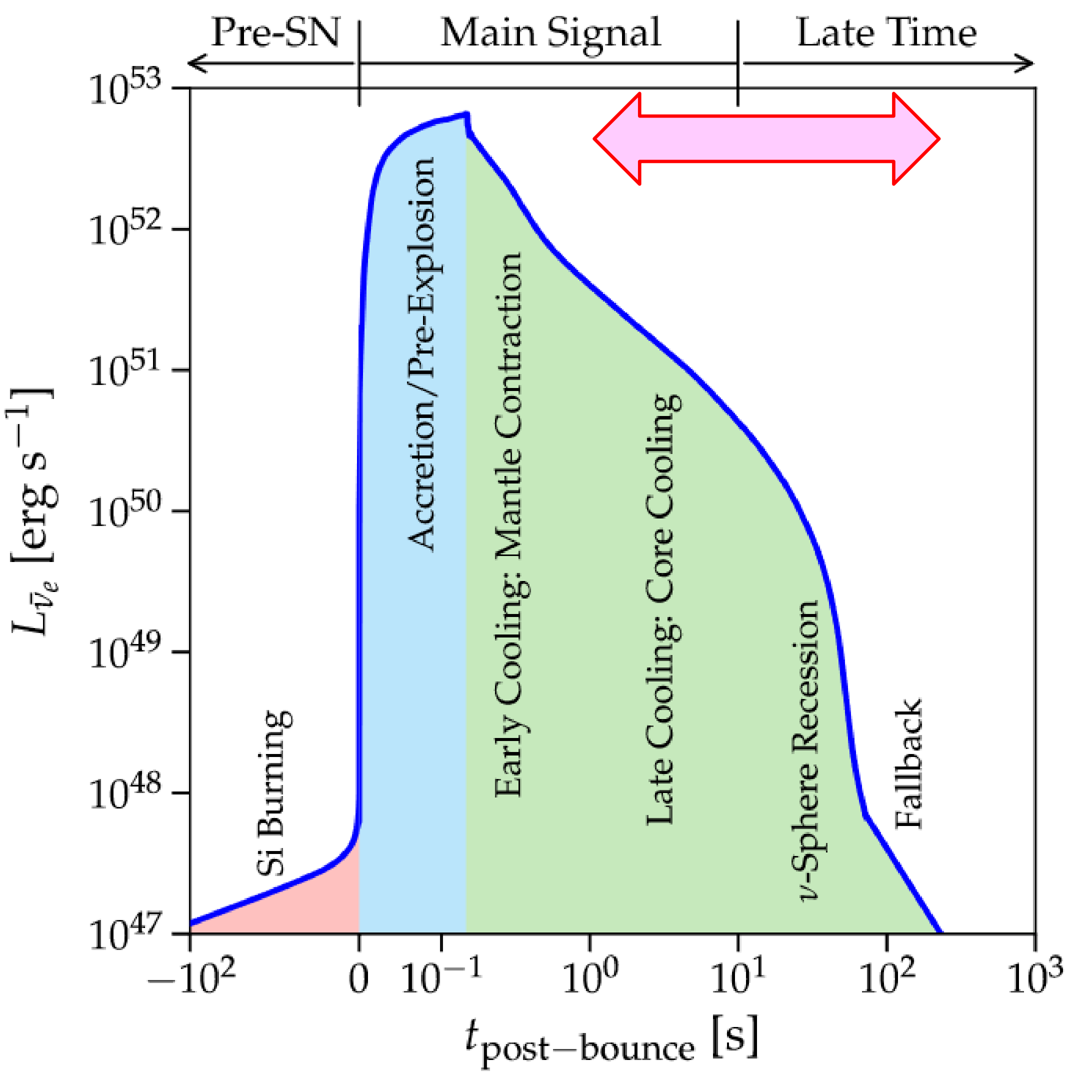


SN explosion → neutron star (NS)



black hole (BH)

Three phases of neutrino emission



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

① pre-SN phase
~ O (−1 day)

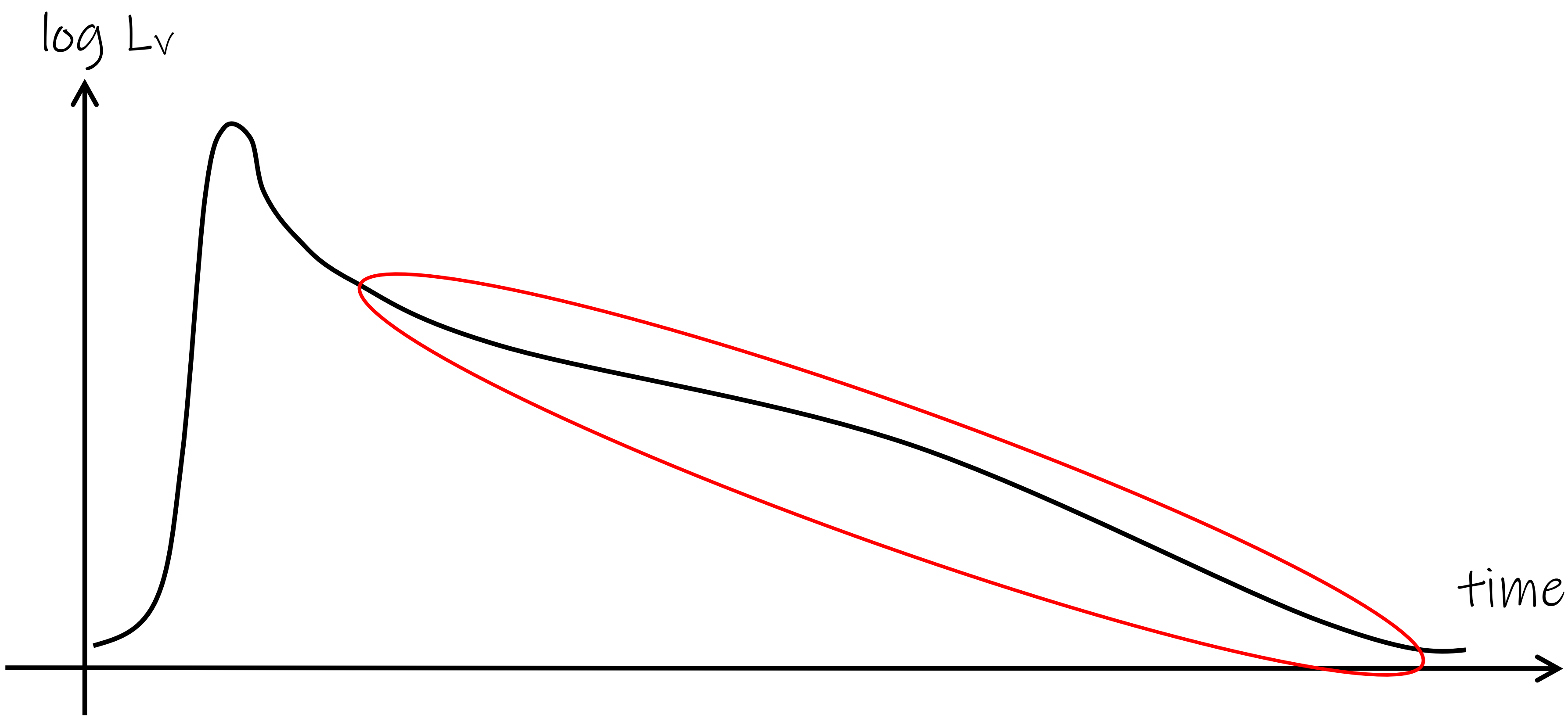
② hydrodynamical phase
~ O (1 sec)

③ proto-NS (PNS) cooling phase
~ O (1 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.



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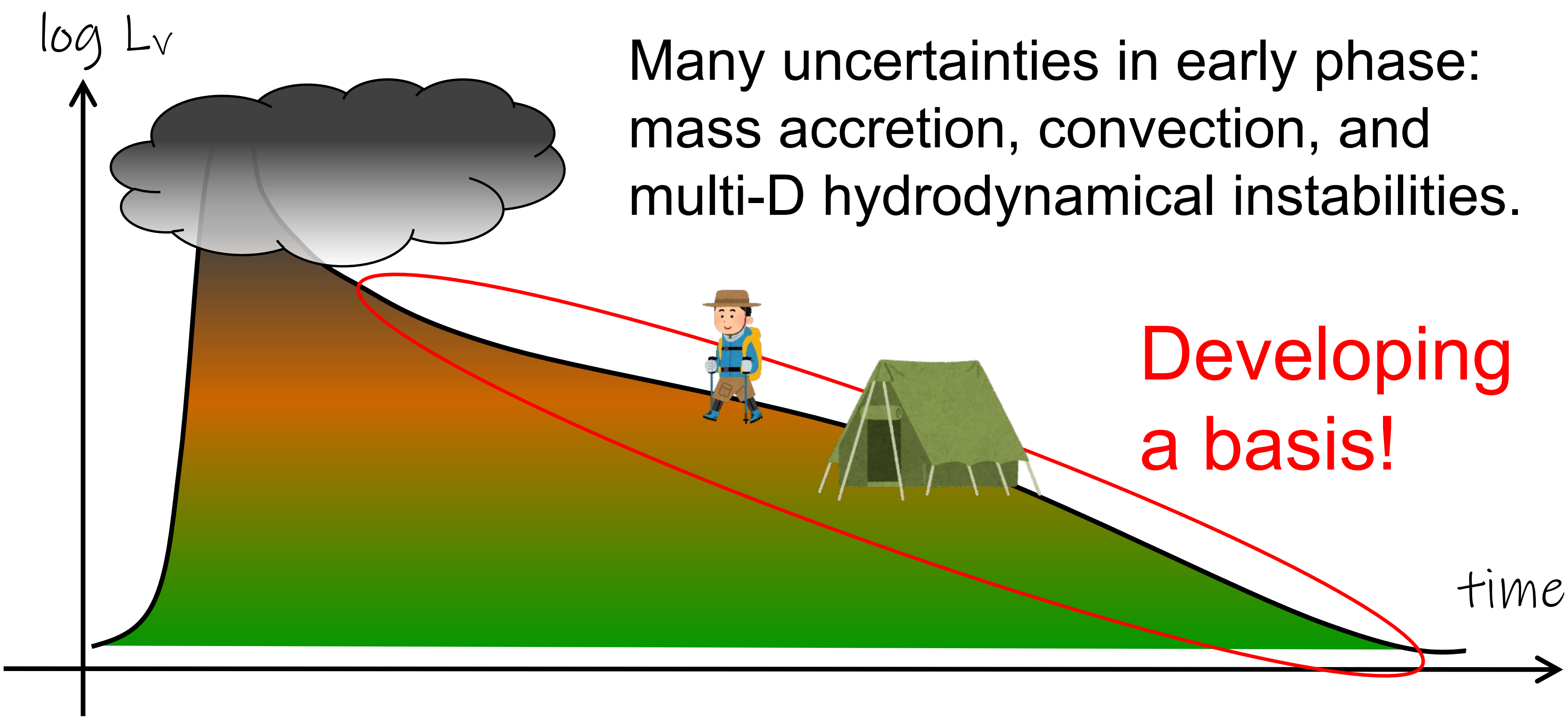
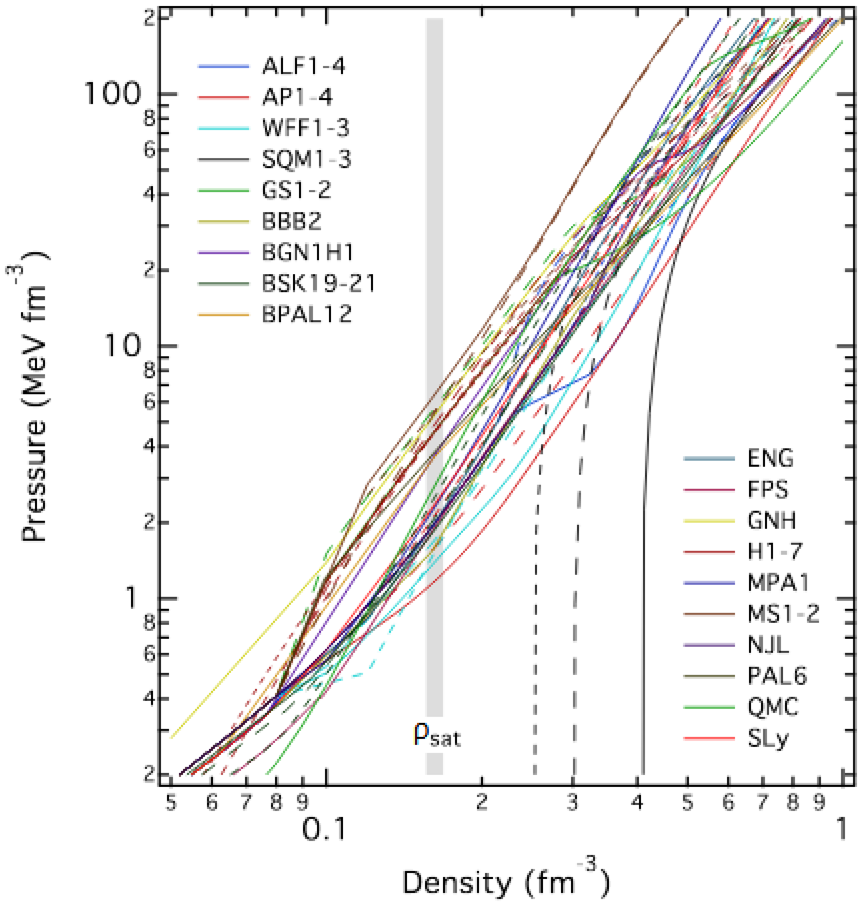
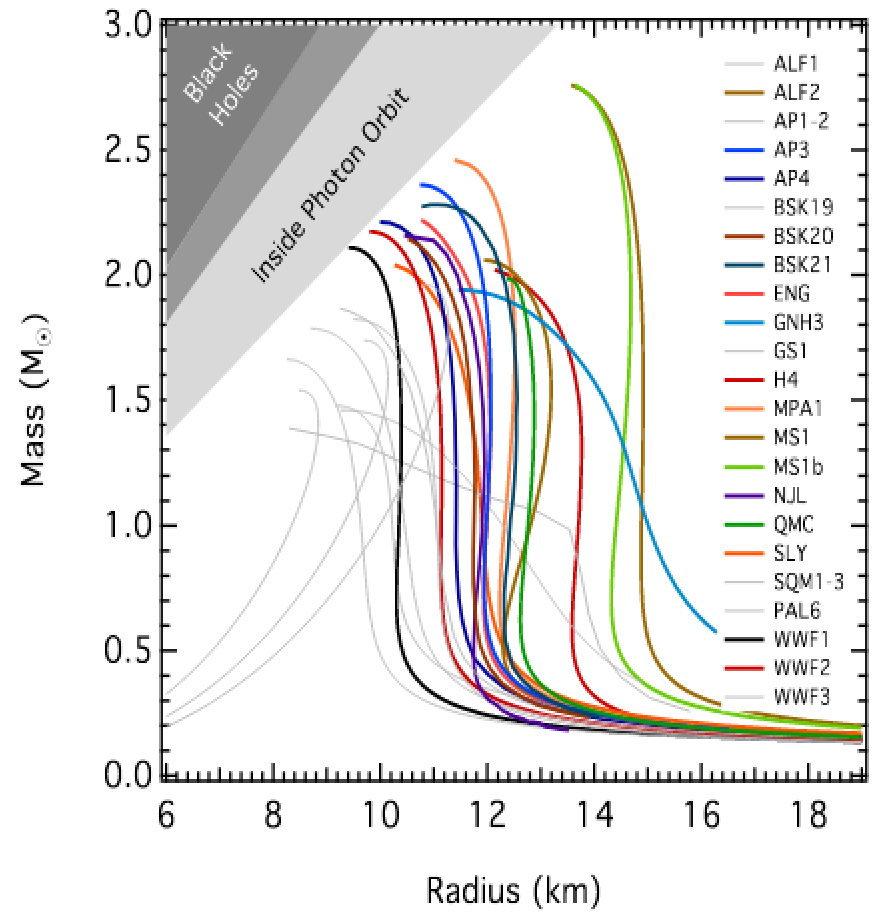


Mass-radius relation of NSs

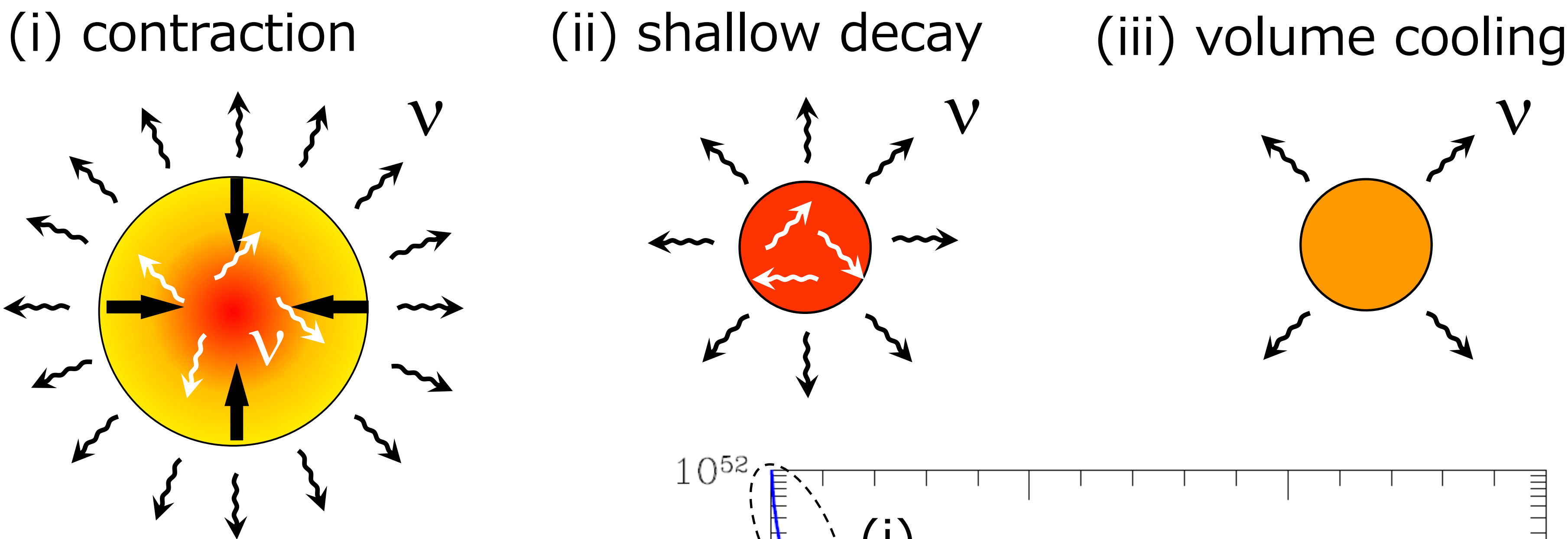
Özel & Freire, ARAA **54** (2016)



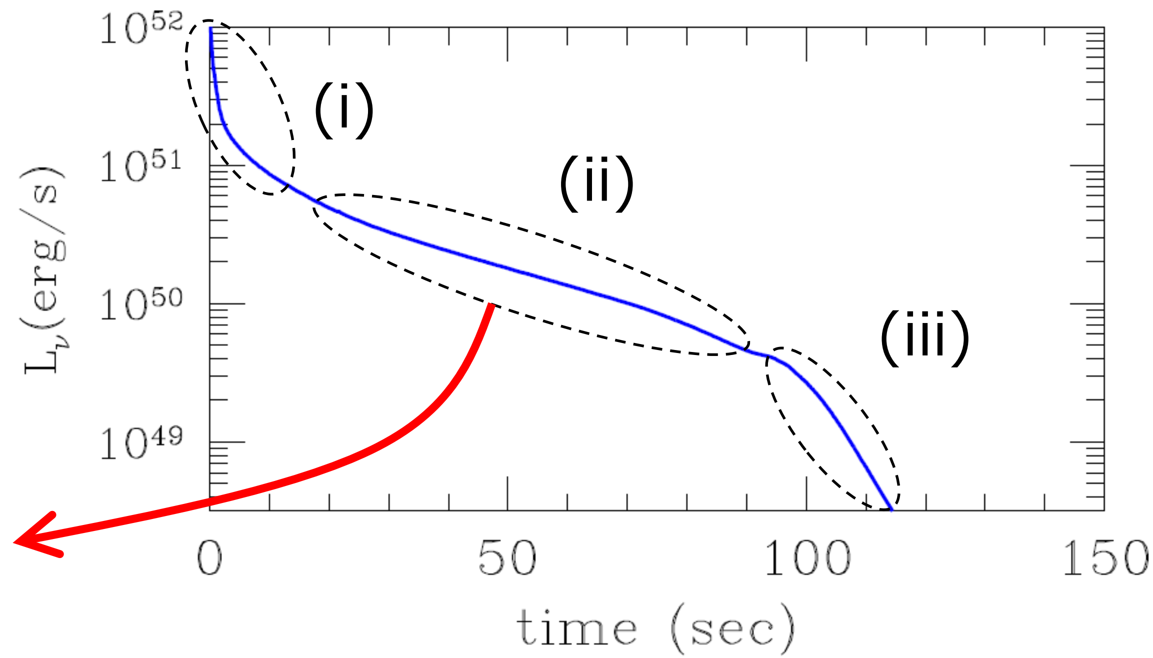


- Equation of state (EOS) of nuclear matter determines the mass and radius of NSs.

Schematic picture of PNS cooling



- Decay time of neutrino light curve is chara-cterized here.



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. $|E_g| \to E_b$ (binding energy of NSs)

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

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):

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

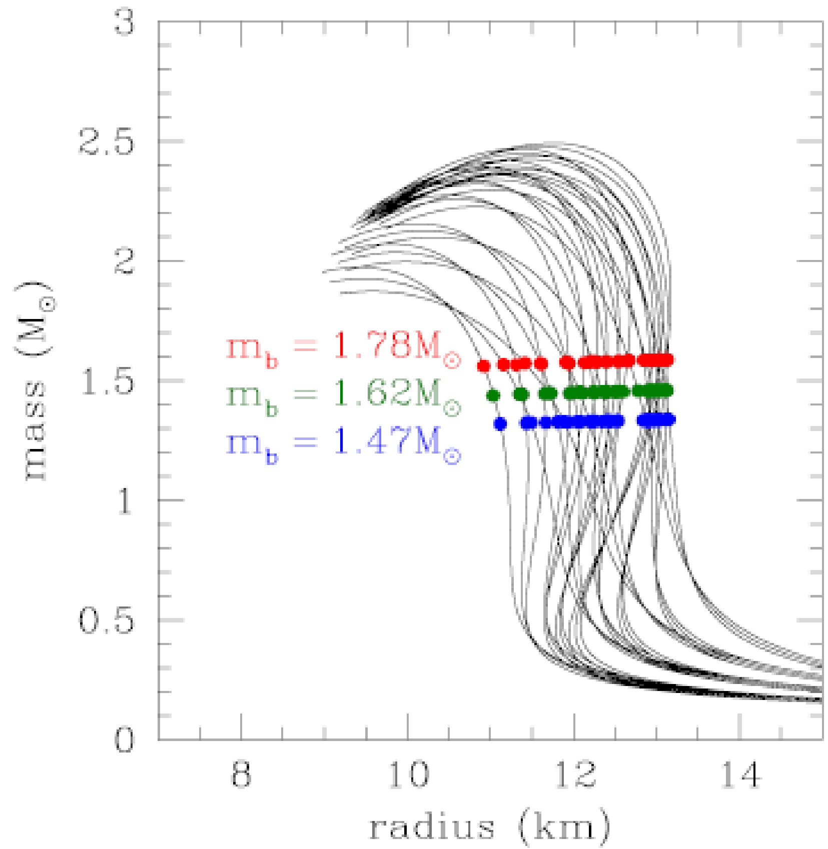
m: NS mass, r: NS radius

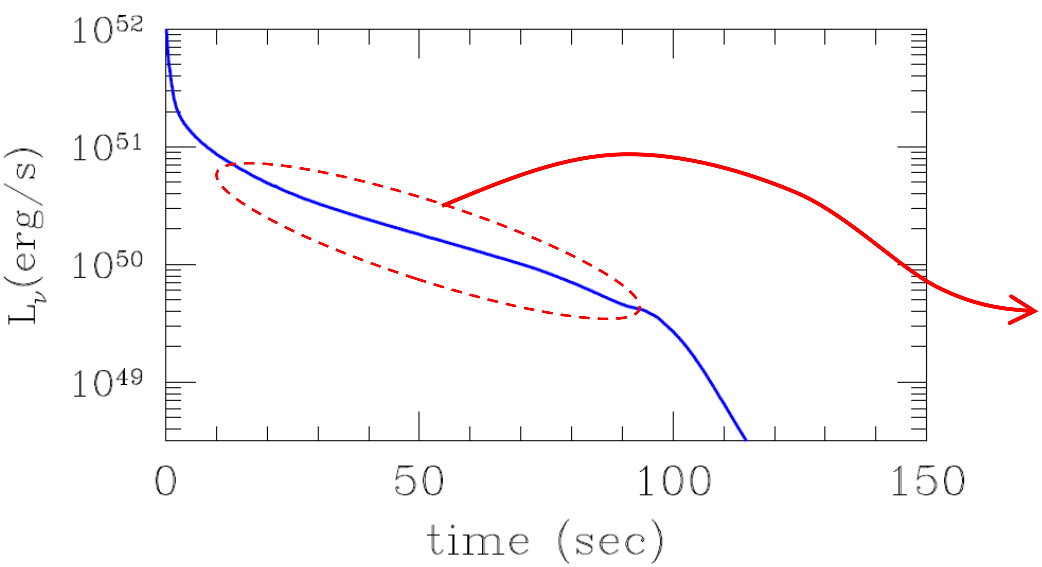
E_b: Binding energy of NS

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

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.





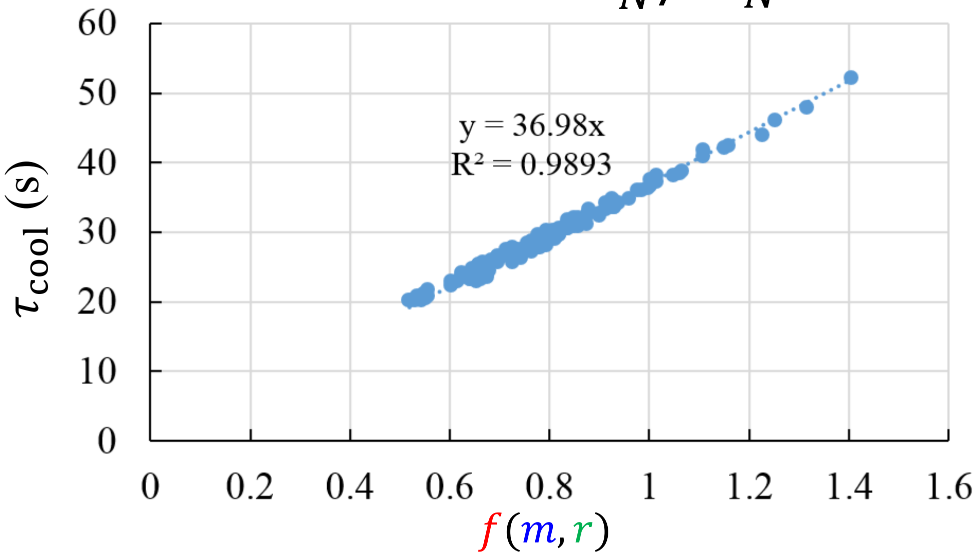
$$L_{\bar{\nu}_e}(t) \sim L_0 \exp\left(-\frac{t}{\tau_{\rm cool}}\right)$$

Theory vs. simulation results

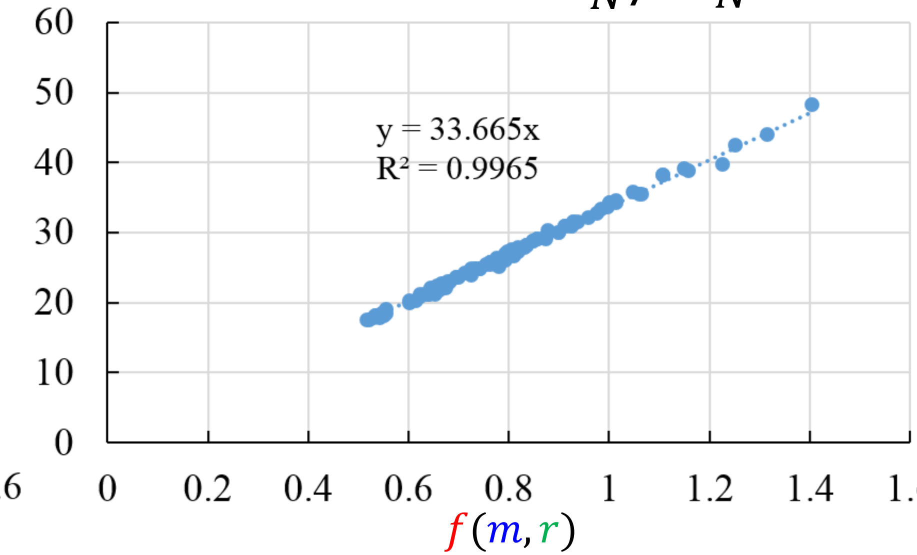
$$\tau_{\mathrm{cool}} = \tau^* \underbrace{\left(\frac{m}{1.4M_\odot}\right)^2 \left(\frac{r}{10\ \mathrm{km}}\right)^{-3} \frac{1}{(1-0.5\beta)\sqrt{1-2\beta}}}_{f(m,r)}, \quad \beta = \frac{Gm}{rc^2}$$

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

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



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



Estimation of NS mass & radius

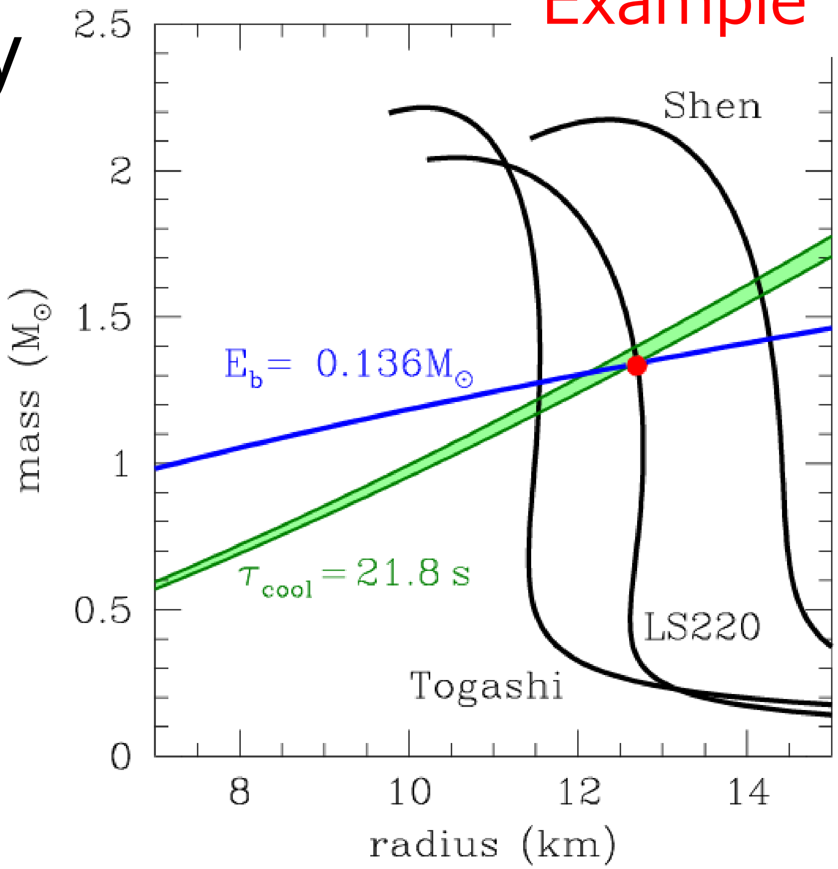
- Crossing point of neutrino cooling timescale

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

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

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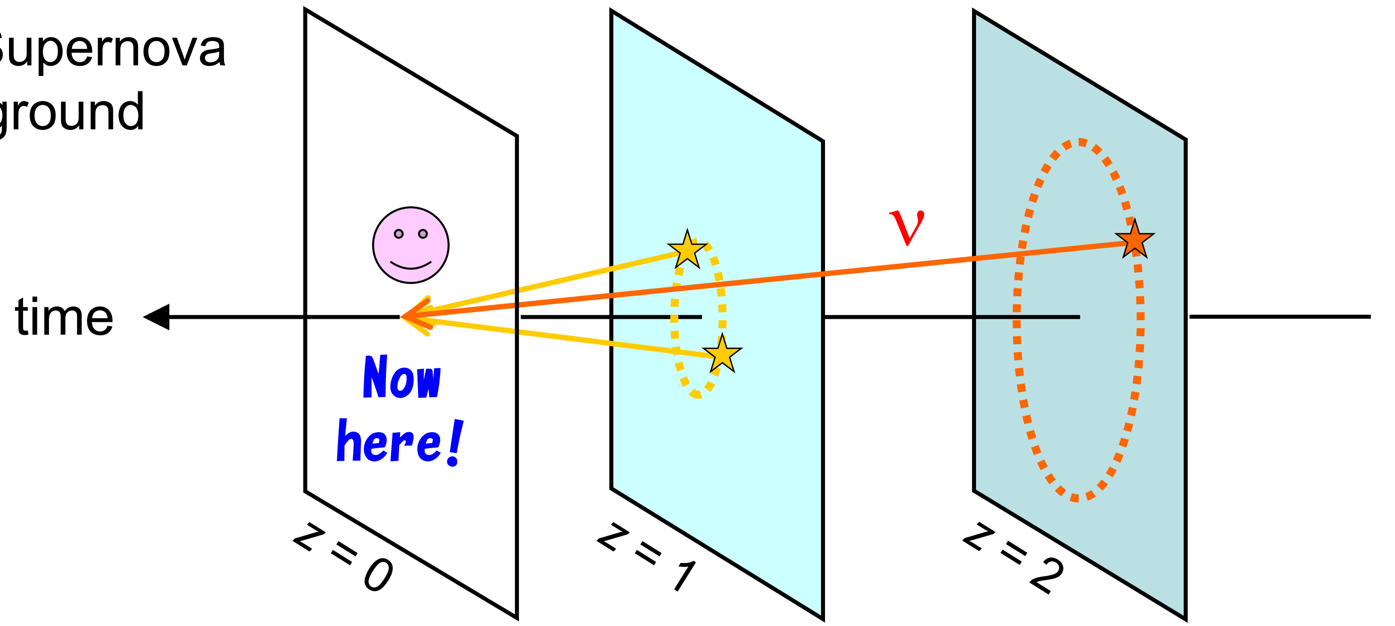
Cosmic background neutrinos

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

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

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

- Cosmological parameters:

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

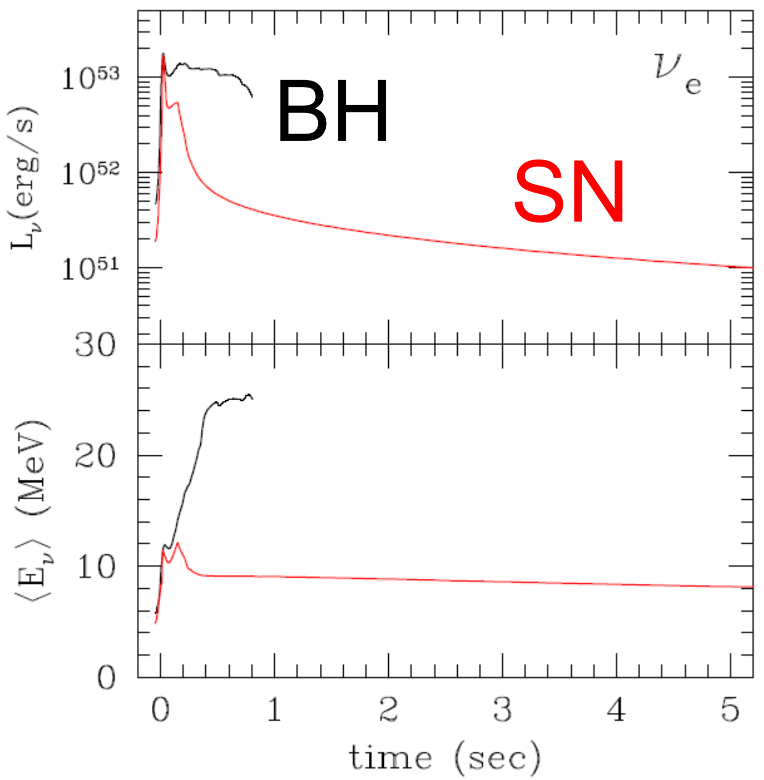
- Spectrum of supernova neutrinos: $\left\langle \frac{dN(E'_\nu)}{dE'_\nu} \right\rangle$

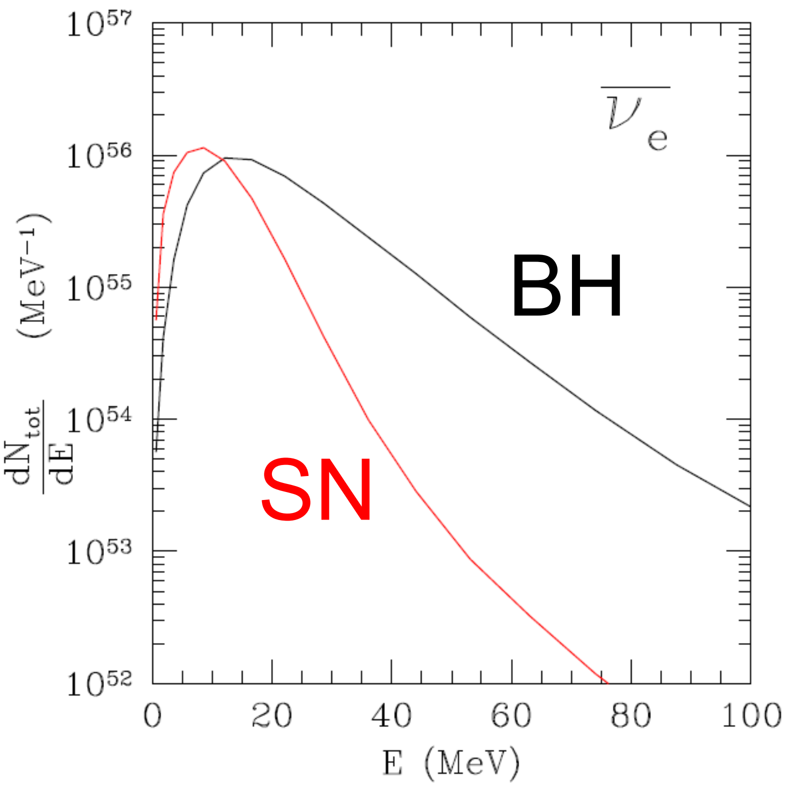
- Core-collapse rate: $R_{\rm CC}(z)$

（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.





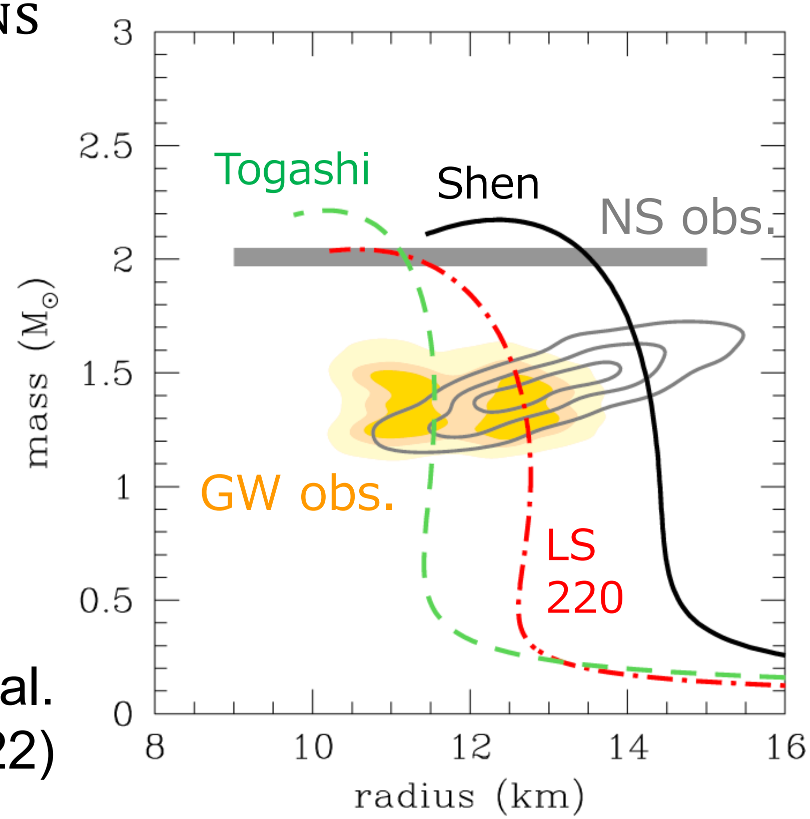
Neutrino emissions from SN with NS formation and BH formation

Nuclear equation of state

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

    ∵ total energy is $E \sim \frac{GM_{\rm NS}^2}{R_{\rm NS}}$

  - for BH case, higher maximum mass → 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!!)

https://zenodo.org/record/4632495
https://zenodo.org/record/5778224

According to Tsujimoto (2023)

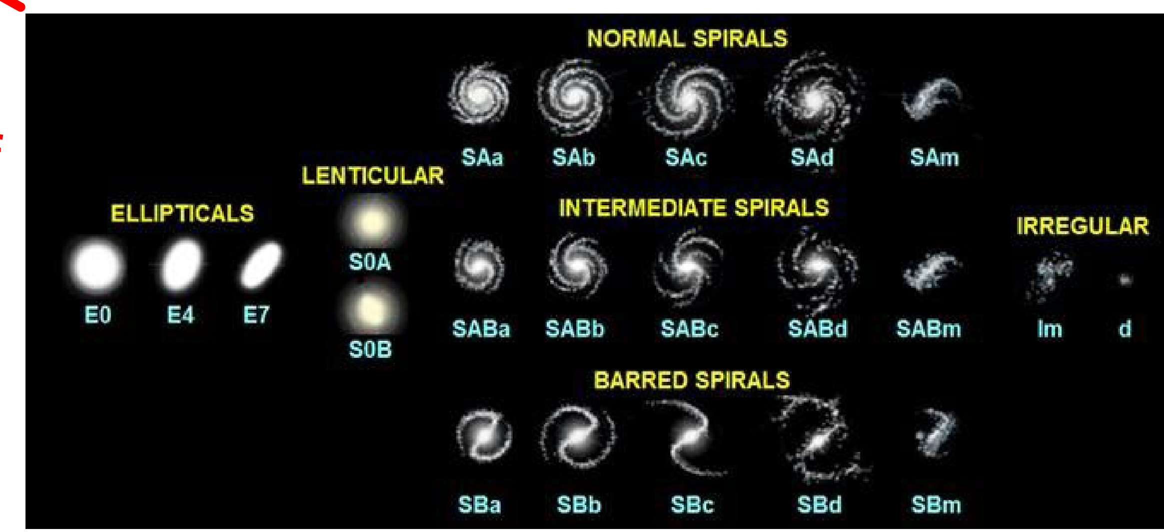
- Galactic chemical evolution implies that:
  1. E/S0, Sab galaxies have flatter IMF
  2. Progenitors with ≥ 18$M_\odot$ becomes BH

According to Tsujimoto (2023)

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

$x = -0.9$

fraction of massive stars is higher



$x = -1.35$
(Salpeter)

https://www.cloudynights.com/articles/cat/articles/basic-extragalactic-astronomy-part-6-galaxies-discovery-and-classification-r3248

According to Tsujimoto (2023)

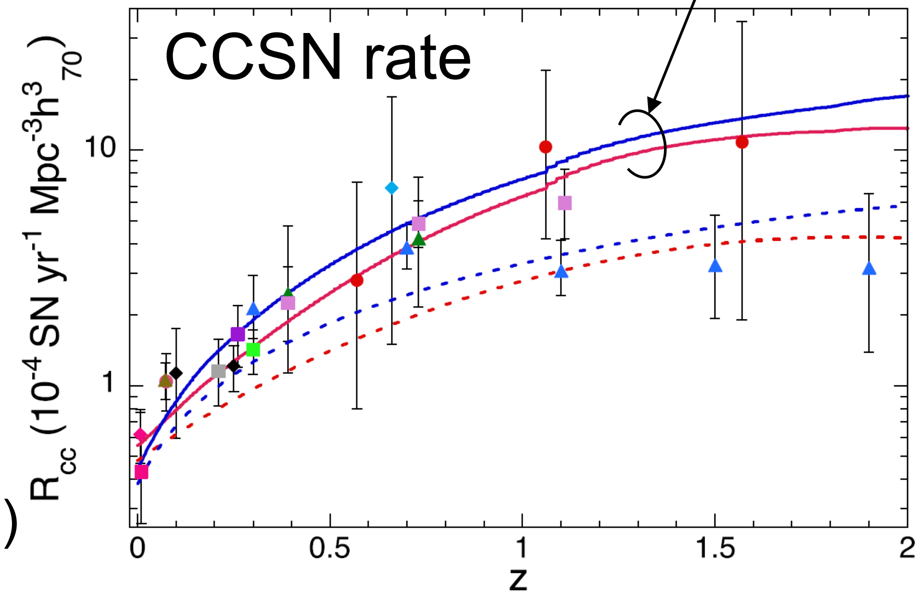
- Galactic chemical evolution implies that:
  1. E/S0, Sab galaxies have flatter IMF
  2. Progenitors with ≥ $18M_\odot$ becomes BH
- CCSN rate: $\dot{\rho}_*(z)\,\dfrac{\int_{8M_\odot}^{18M_\odot}\psi_{\rm IMF}(M)dM}{\int_{0.1M_\odot}^{100M_\odot}M\cdot\psi_{\rm IMF}(M)dM}$
  - cosmic star formation rate, $\dot{\rho}_*(z)$, is from

Hopkins & Beacom (2006)

Madau & Dickinson (2014)

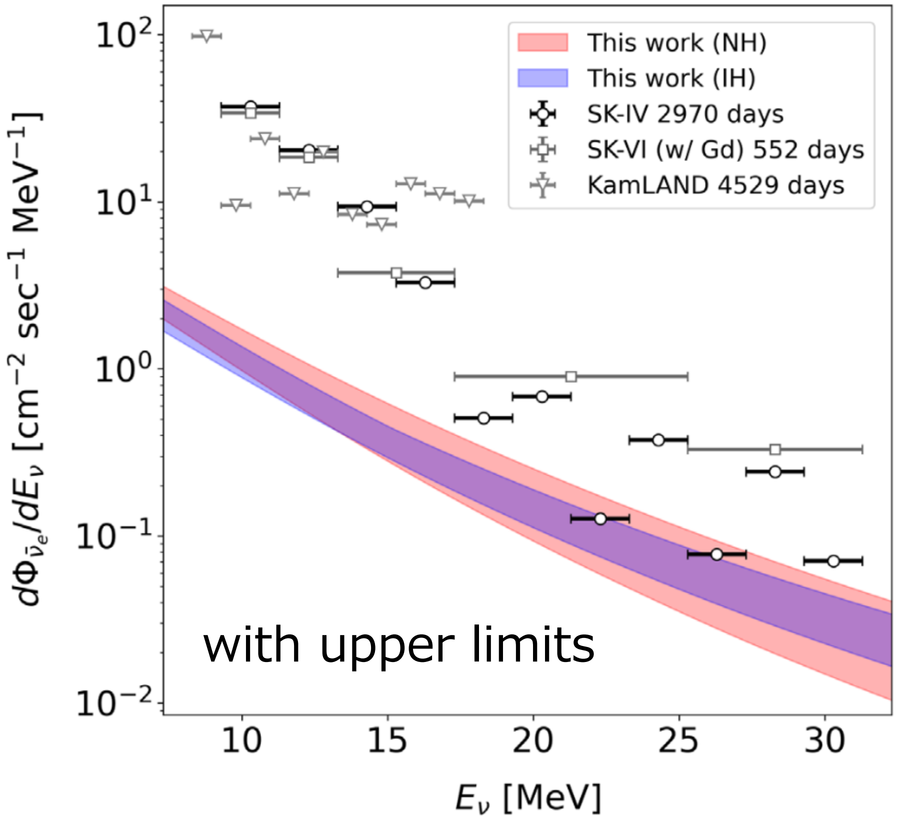
Tsujimoto, MNRAS **518** (2023)

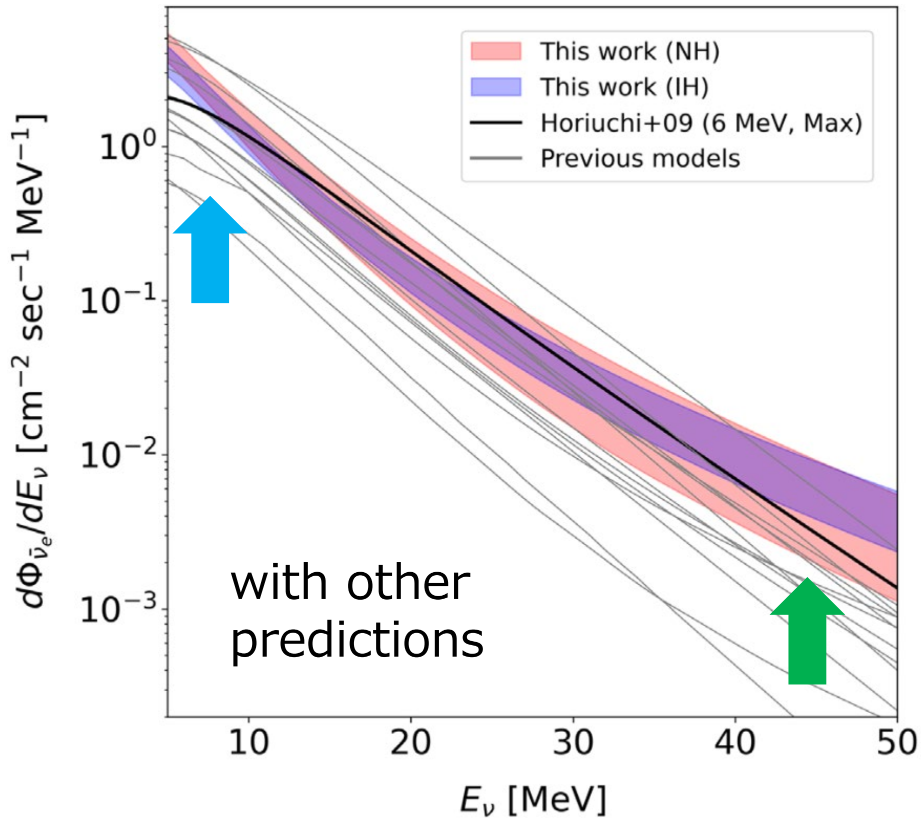
flatter IMF for early type galaxies



DSNB flux

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





- Comparing with other work, enhancement at low (≲10 MeV) and high (≳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（$13.3 < E_\nu < 17.3$ MeV） and high（$17.3 < E_\nu < 31.3$ MeV） energy event numbers： obs = $\{N_{\text{low}}, N_{\text{high}}\}$

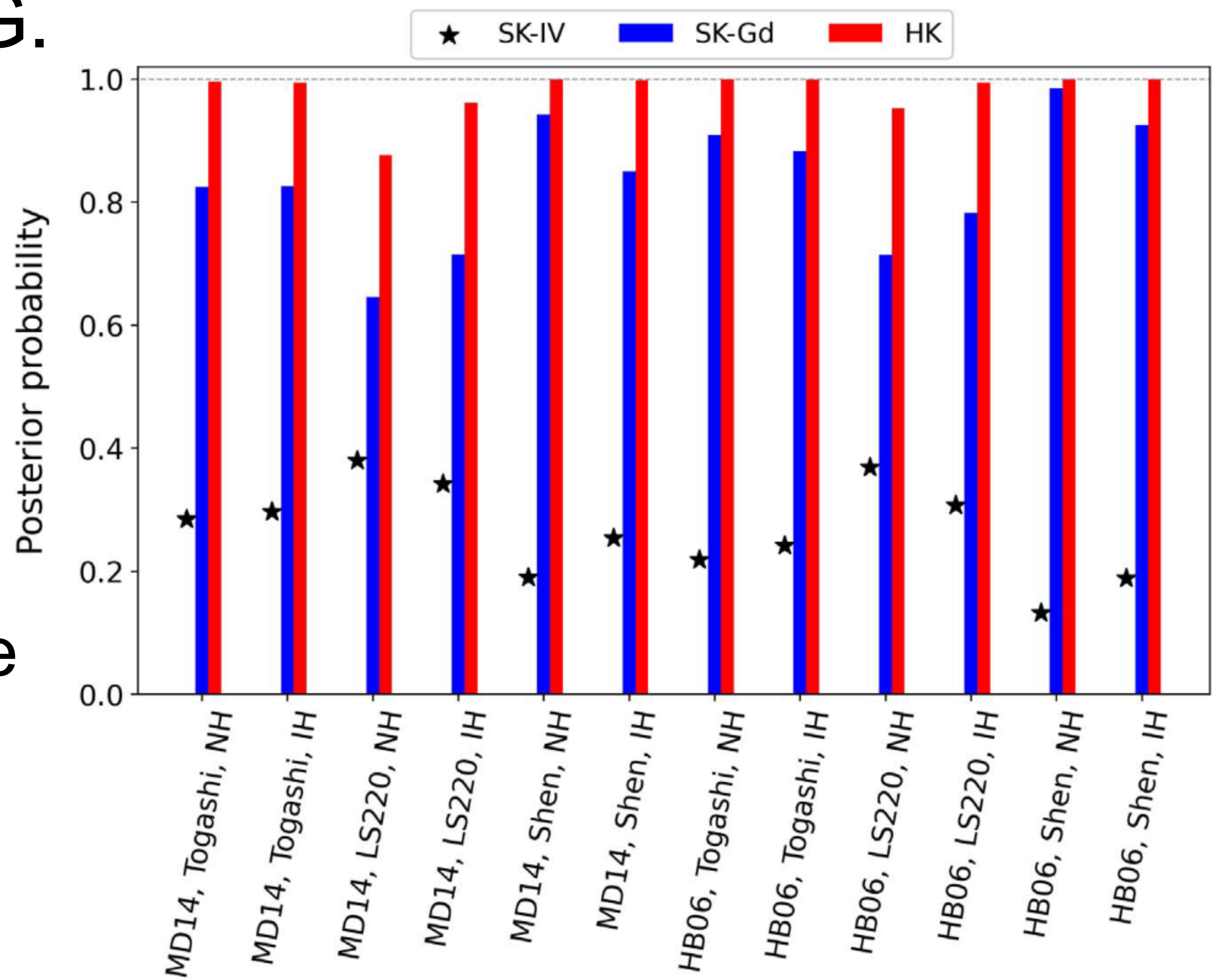
- Models with our DSNB + BG vs BG only
  - BG: non-NCQE, NCQE, accidental, Li9
  - Systematic and statistical errors are considered.

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.