Observing Supernova Neutrino Light Curves with Super-Kamiokande

Yudai Suwa

(UT, Komaba & YITP)

with *nuLC* collaboration

YS, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019)
YS, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 013E01 (2021)
Mori, YS, Nakazato, Sumiyoshi, Harada, Harada, Koshio, Wendell, PTEP, 2021, 023E01 (2021)
Nakazato, Nakanishi, Harada, Koshio, YS, Sumiyoshi, Harada, Mori, Wendell, ApJ in press., arXiv:2108.03009

Supernovae are made by neutron star formation

Remarks on Super-Novae and Cosmic Rays

5. *The super-nova process*

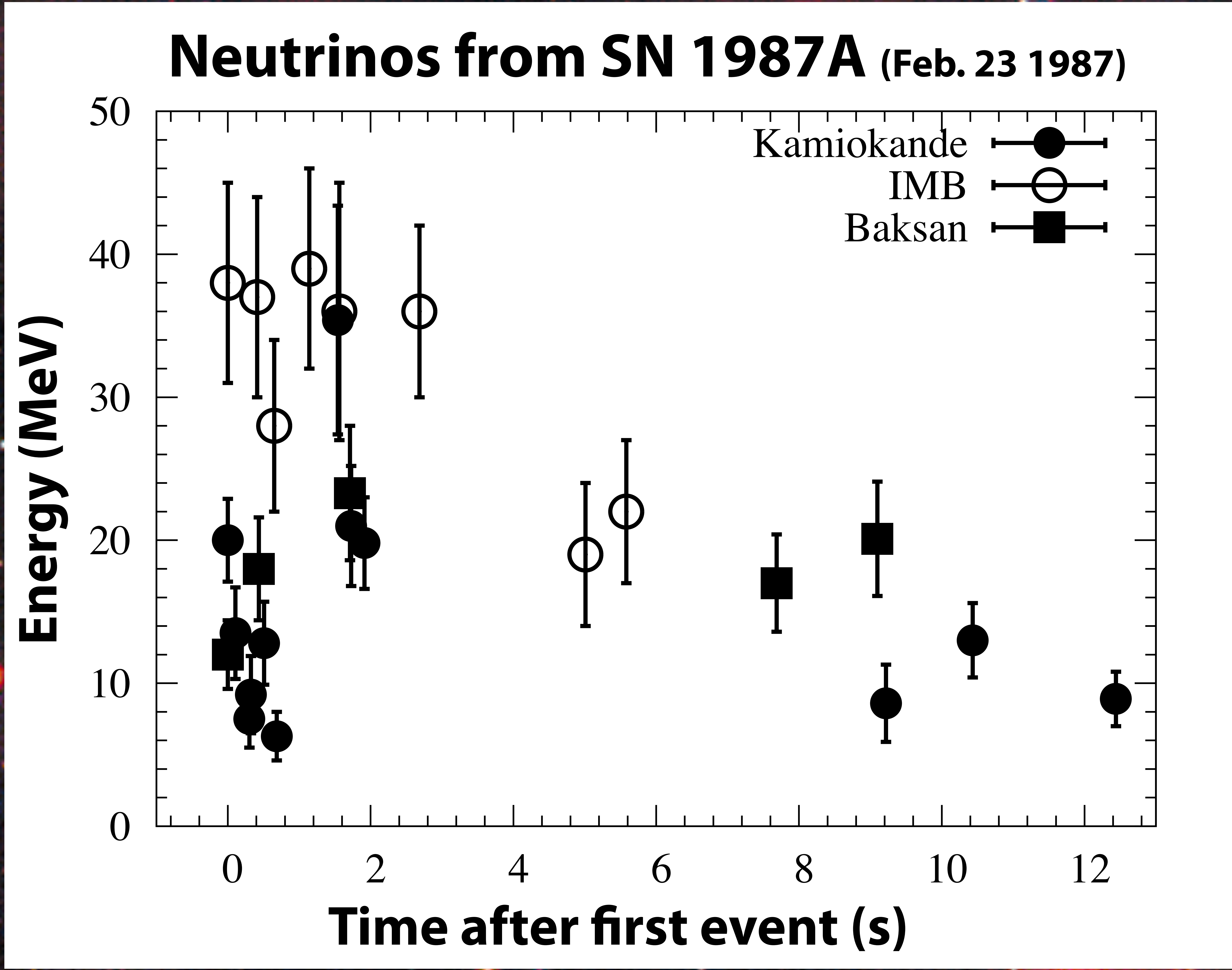
We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. BAADE
F. ZWICKY

Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

Baade & Zwicky (1934)

SN1987A



NASA/ESA

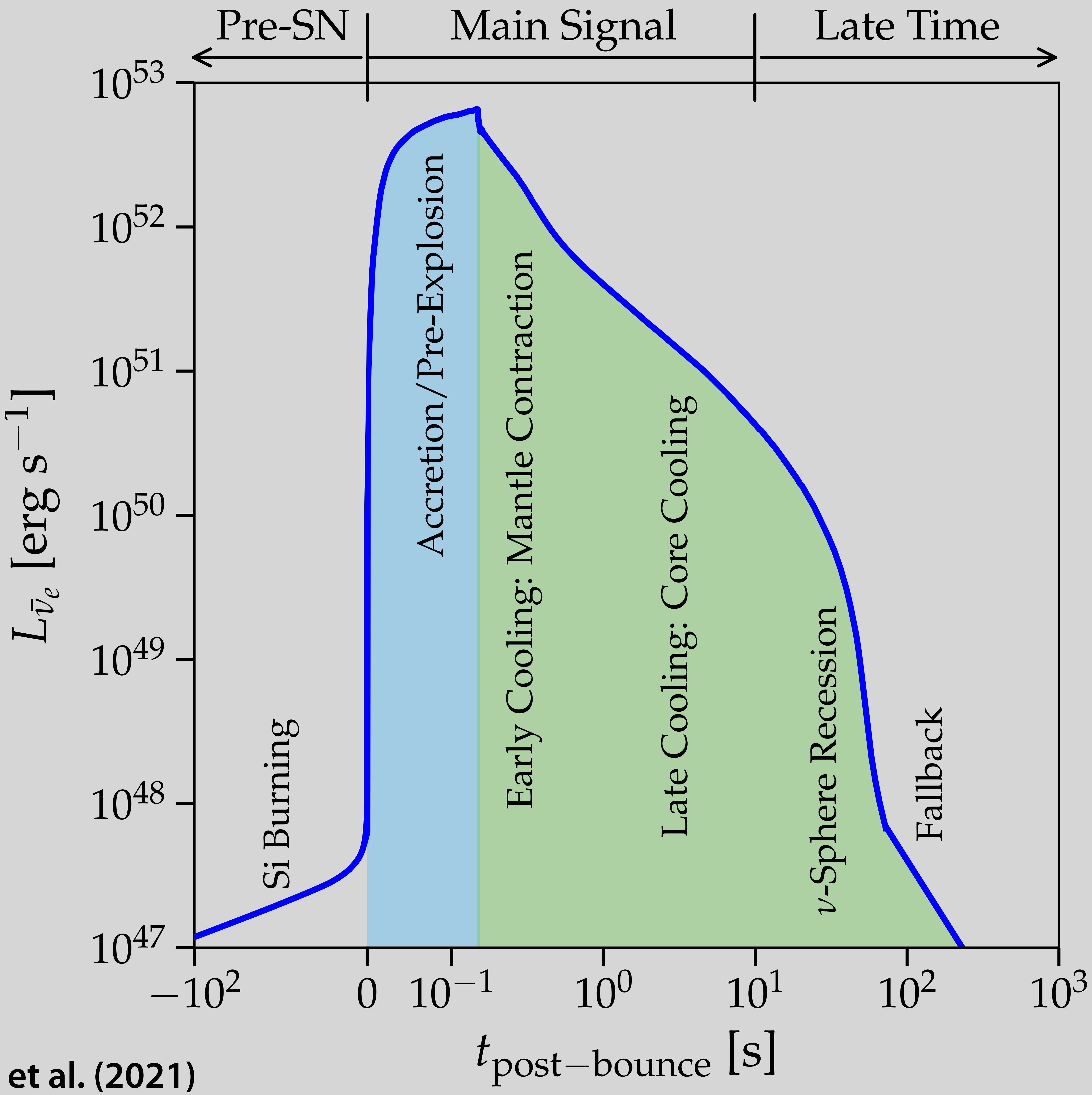
What can we extract from neutrino observations?

- **Properties of neutron stars**
  - **Binding energy**
    - *important for energetics, done with SN1987A*

$$E_b \approx \frac{GM_{\rm NS}^2}{R_{\rm NS}} = \mathcal{O}(10^{53})\mathrm{erg}\left(\frac{M_{\rm NS}}{1.4M_\odot}\right)^2\left(\frac{R_{\rm NS}}{10\mathrm{km}}\right)^{-1}$$

  - **Mass**
    - *important for discriminating final object (NS or BH)*
  - **Radius**
    - *important for discriminating nuclear equation of state*

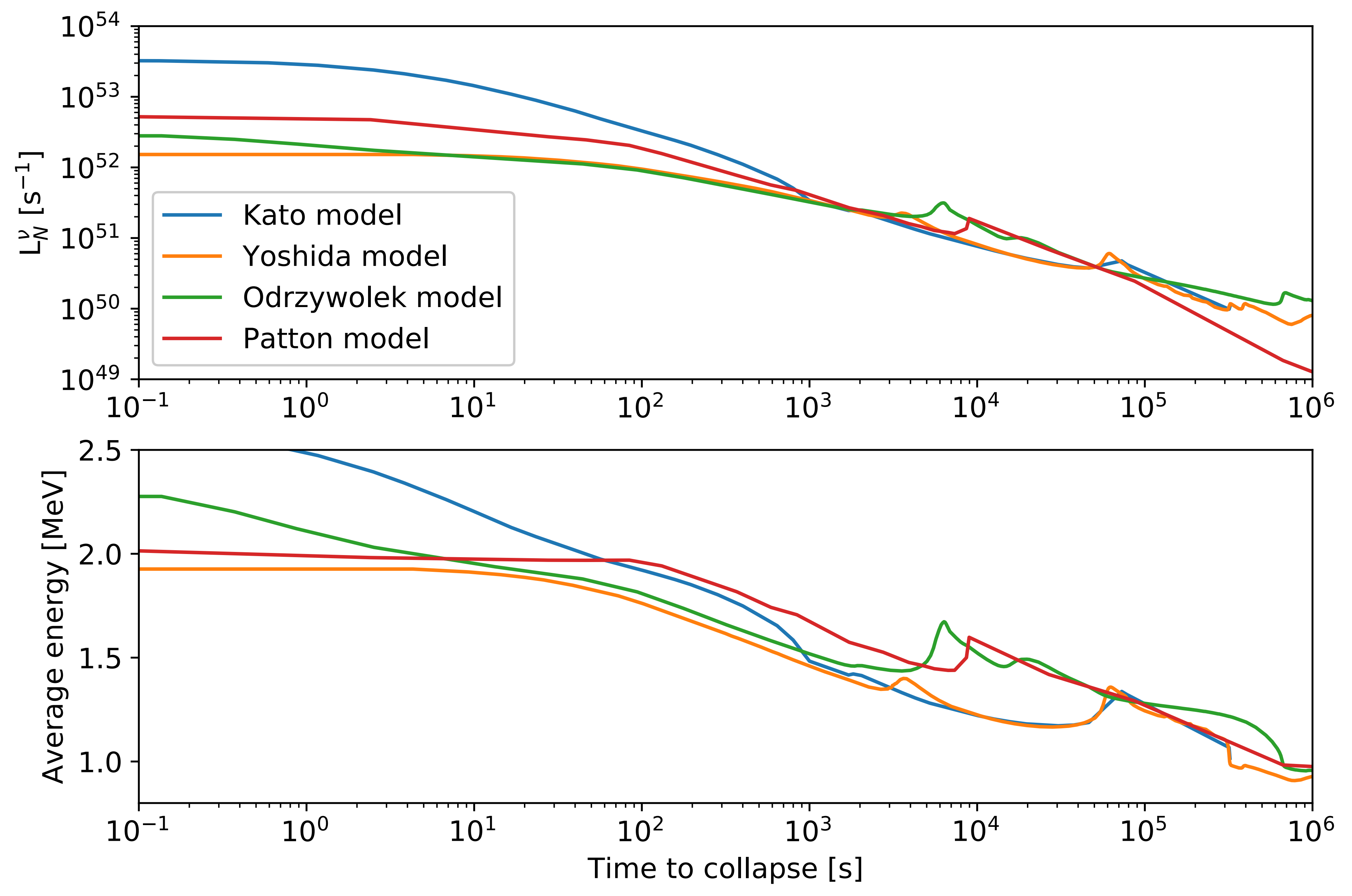
Supernova neutrinos: basics



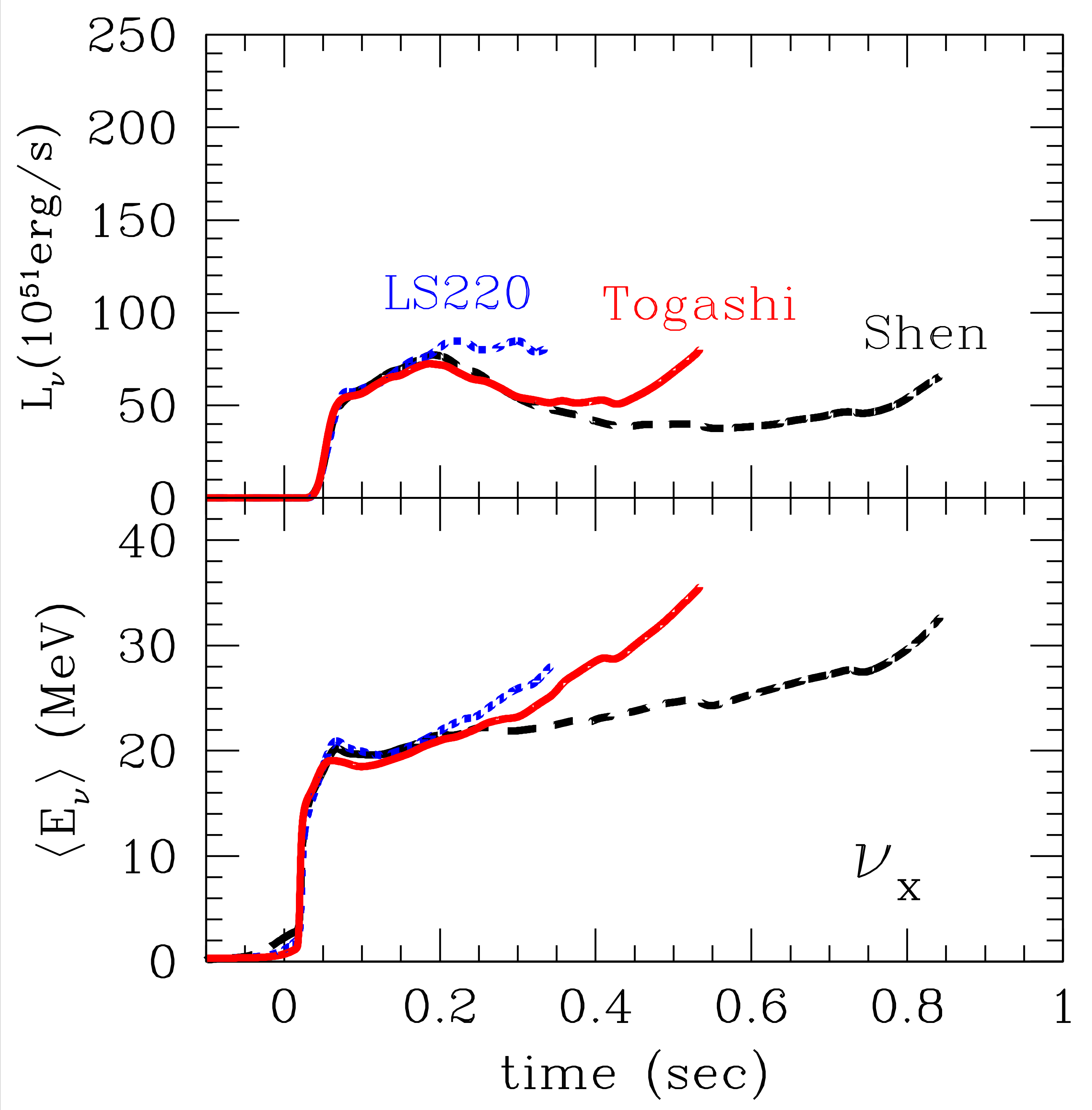
Li et al. (2021)

- **Si burning**
  - final phase of stellar evolution
- **Accretion/Pre-explosion**
  - neutrino trapping
  - neutronization burst
- **Cooling**
  - early phase
    - hydrodynamical instabilities, explosion mechanism, shock revival, PNS contraction…
  - late phase
    - neutrino diffusion
  - volume cooling phase
    - transparent for neutrinos

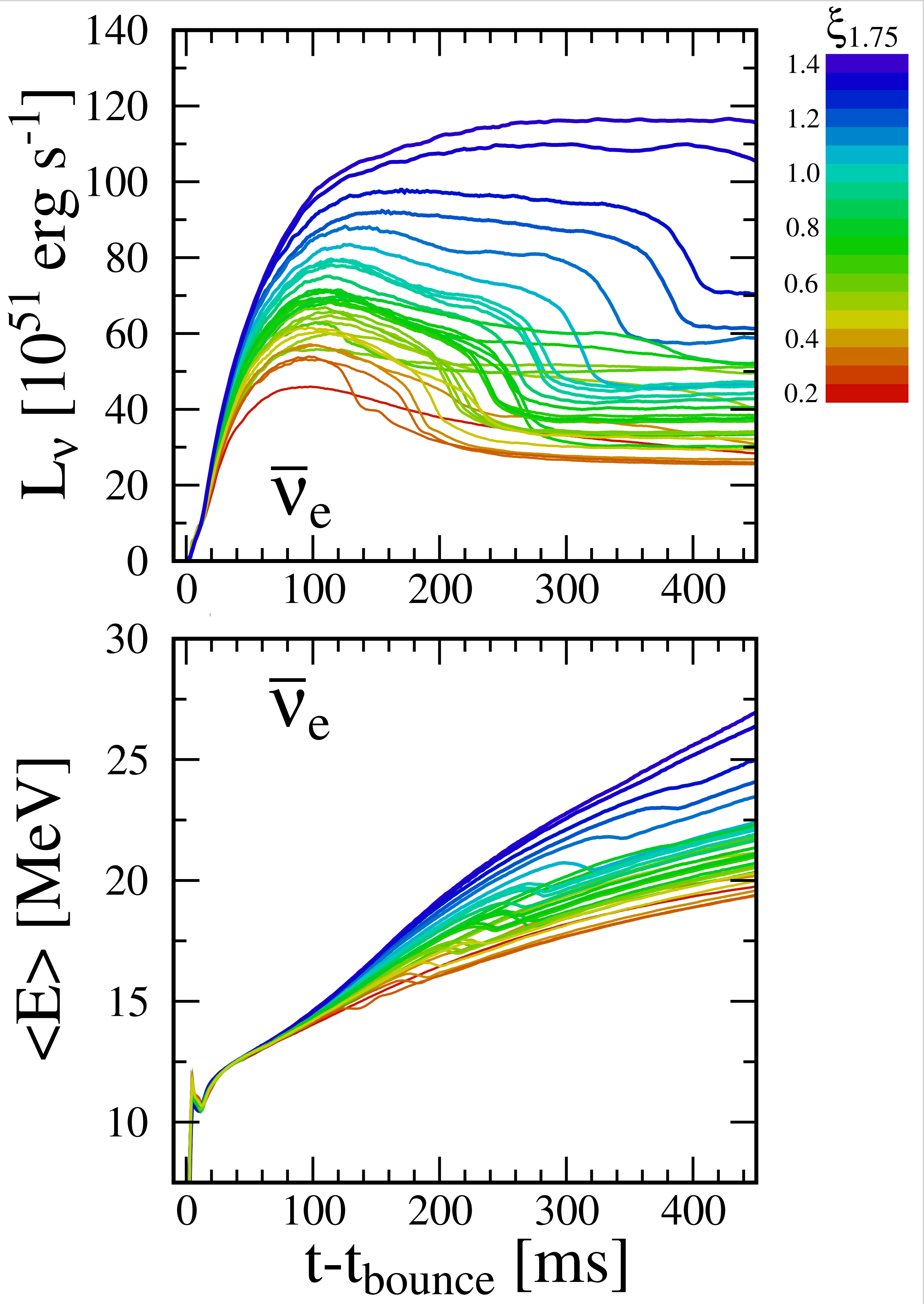
Simulations: Si burning/accretion/pre-explosion



Kato et al. (2020)
stellar evol., presupernova



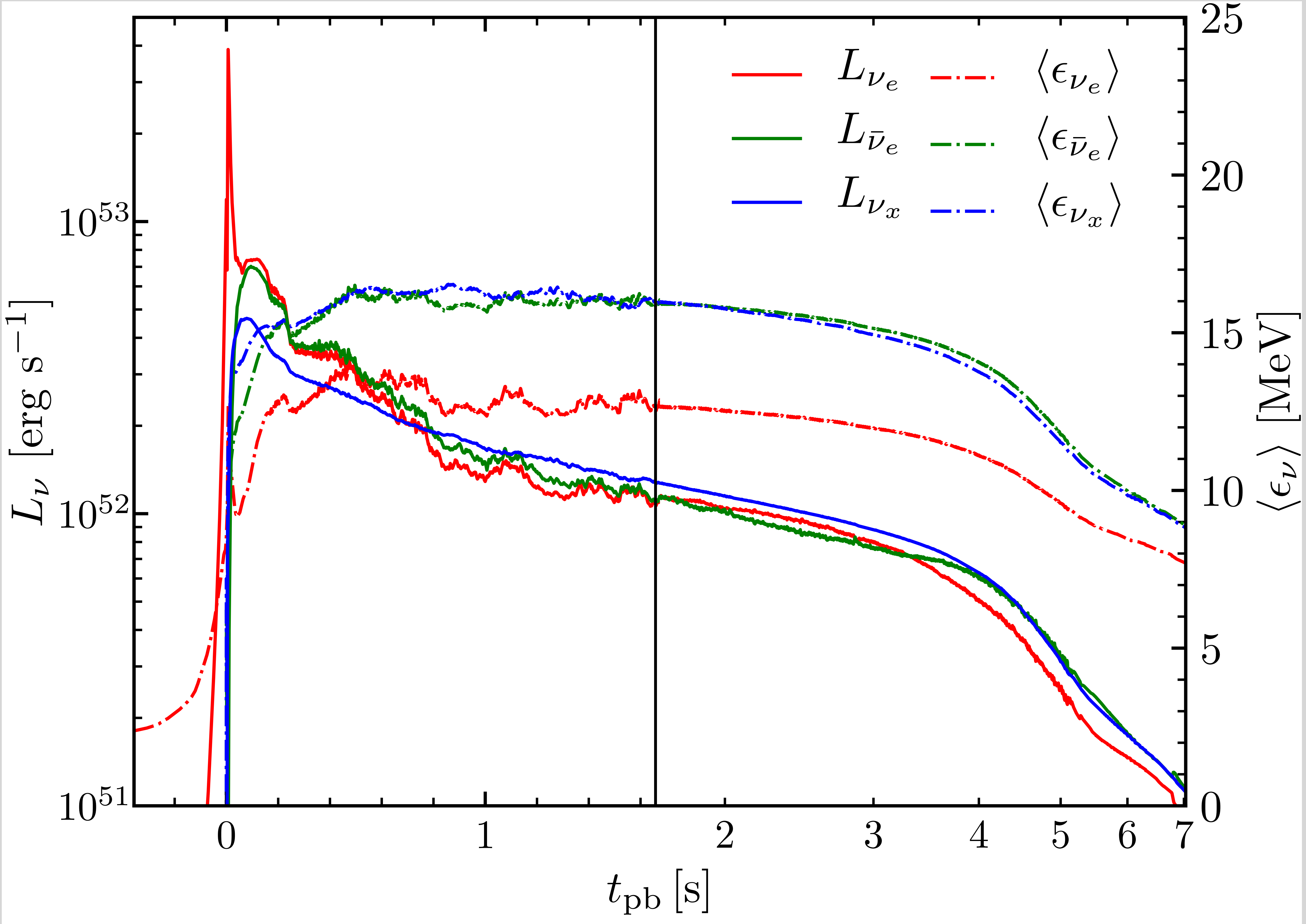
Nakazato et al. (2021)
EOS dependence, BH formation



O'Connor & Ott (2013)
core compactness dependence

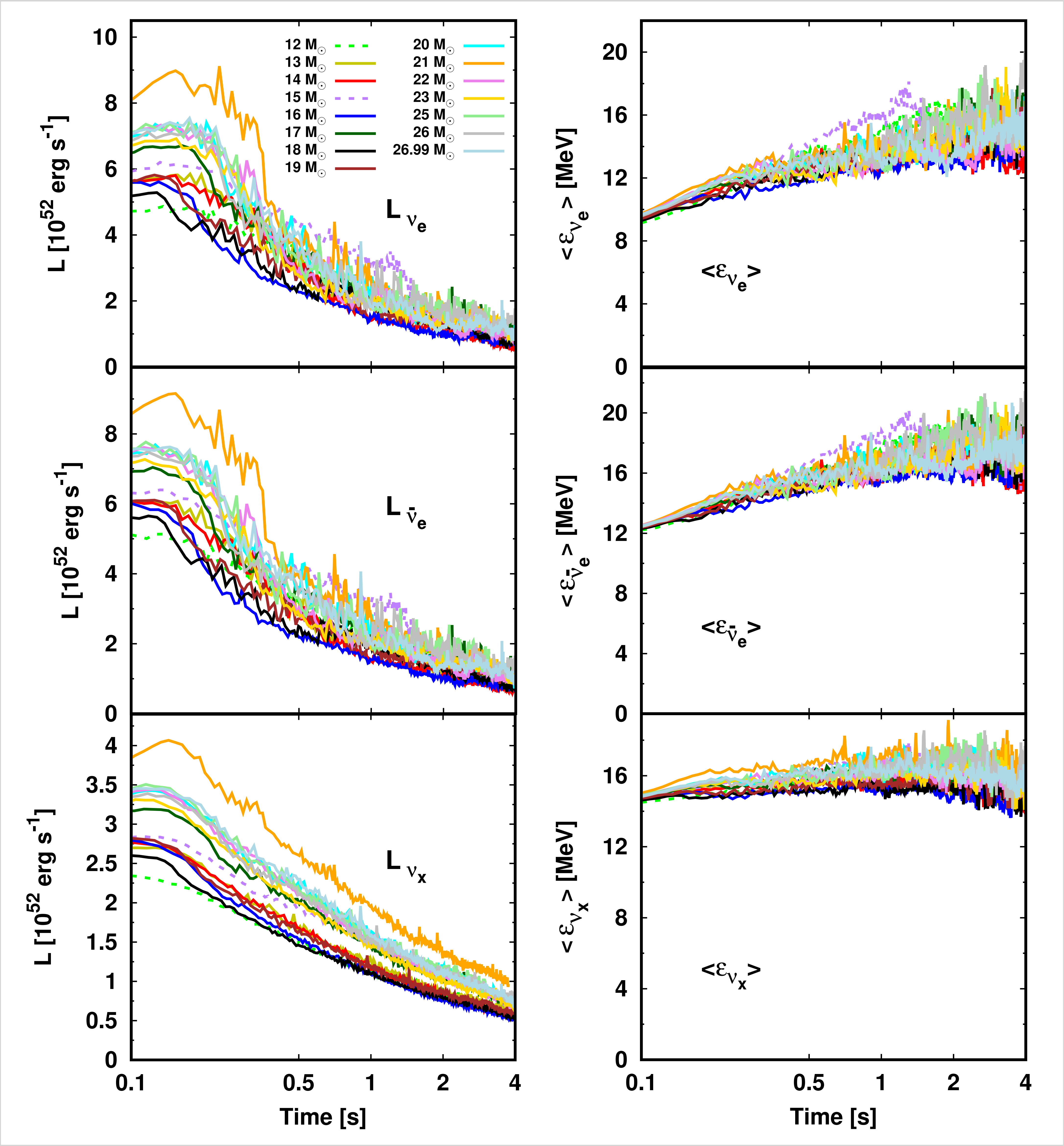
see talks by Nagakura-san, Shibagaki-san, Nakamura-san, Harada-san, Lucas

Simulations: early cooling phase



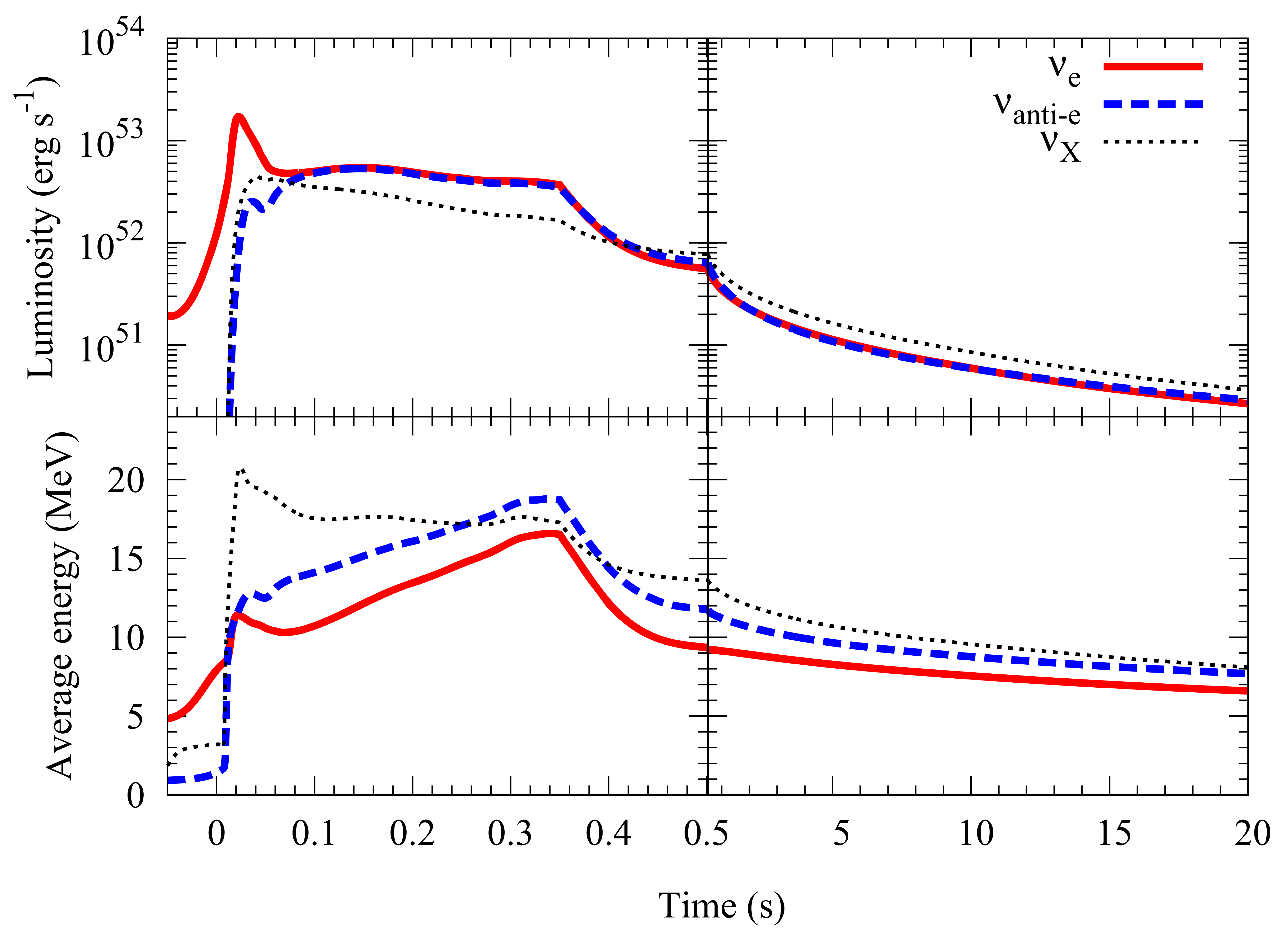
Bollig et al. (2021)
3D, longest model so far

Nagakura et al. (2021)
2D, systematic

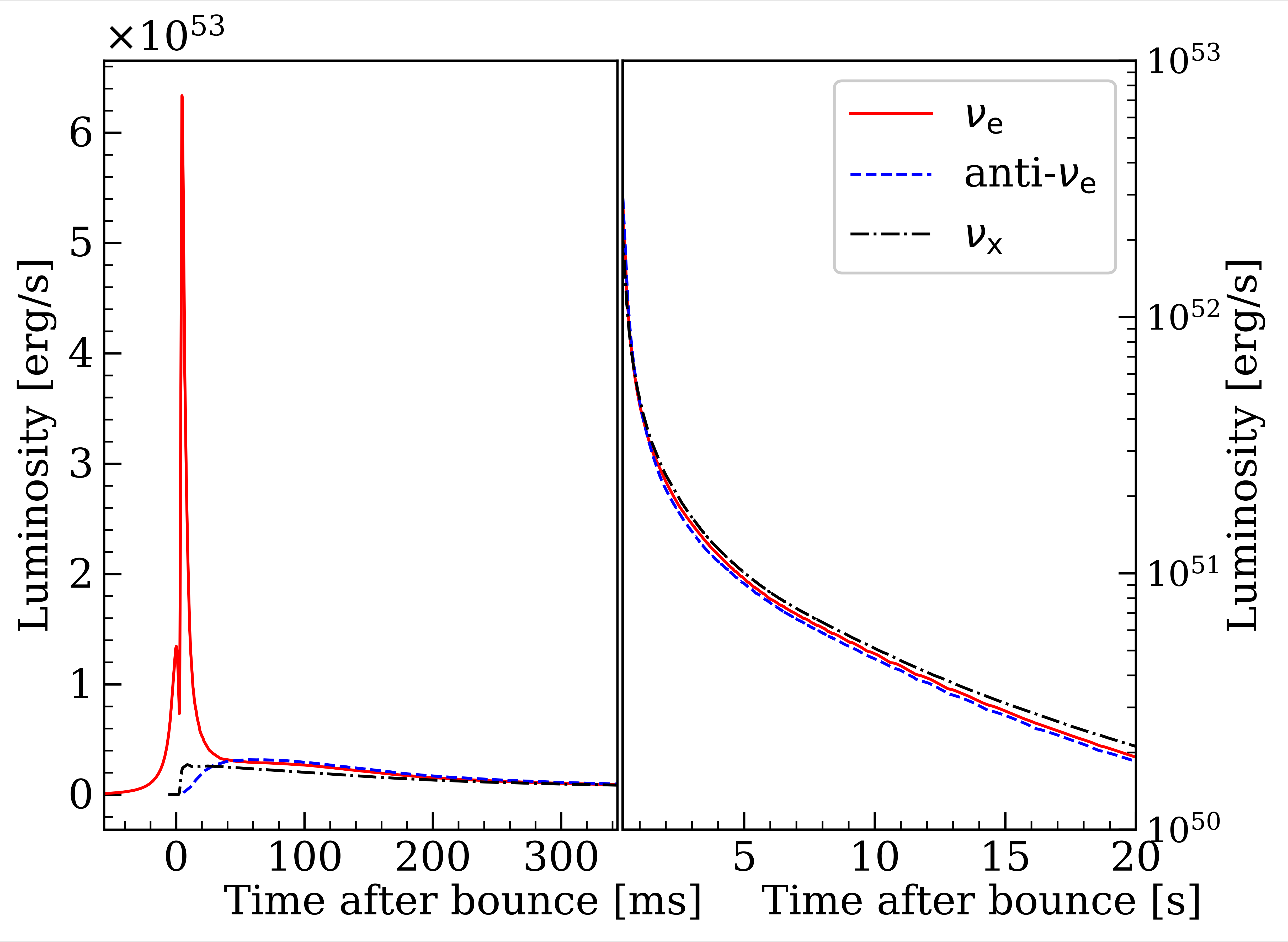


see talks by Nagakura-san, Kato-san, Zaizen-san

Simulations: late cooling phase



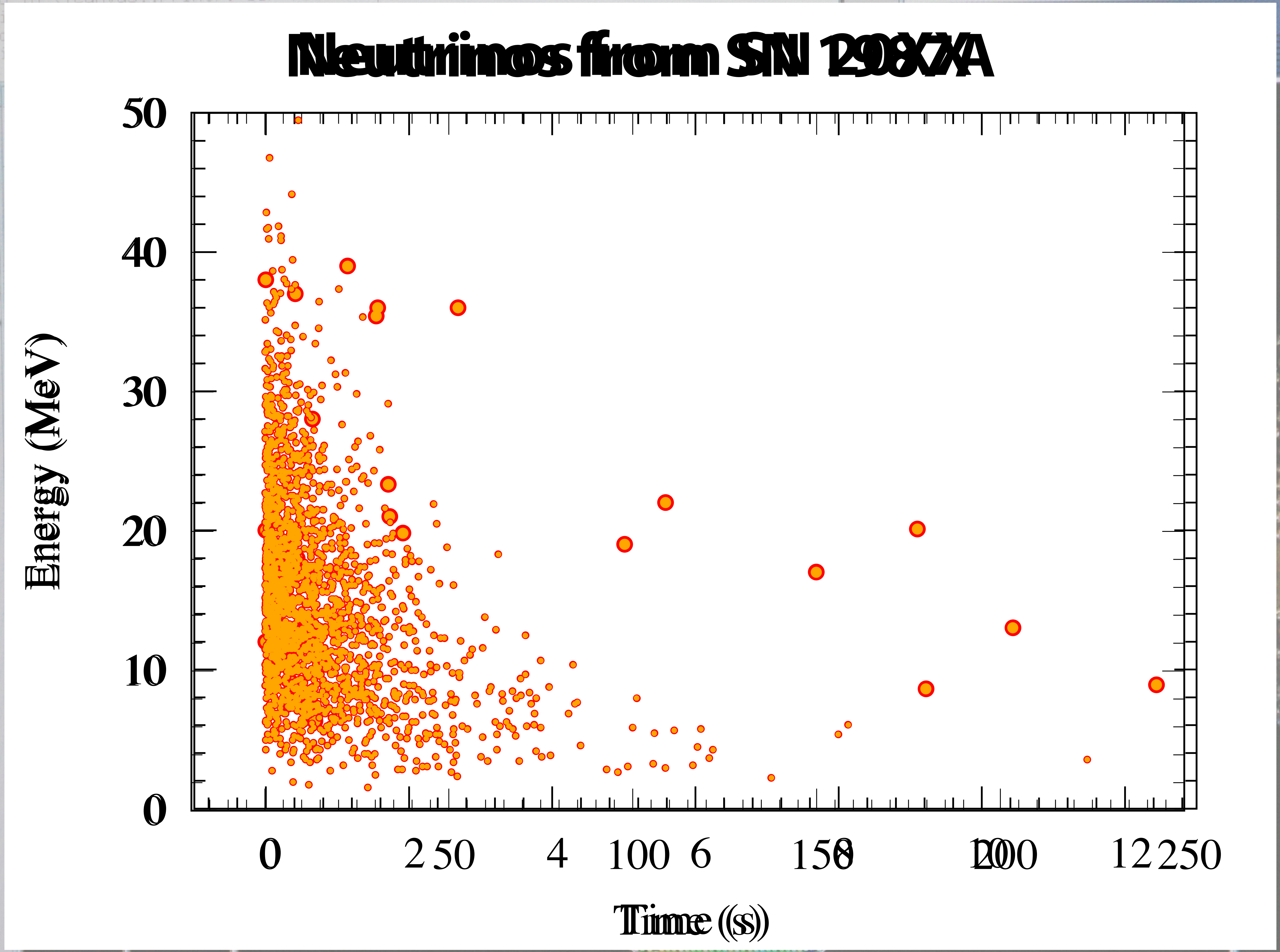
Suwa et al. (2019)
1D, artificial expl. treatment, systematic

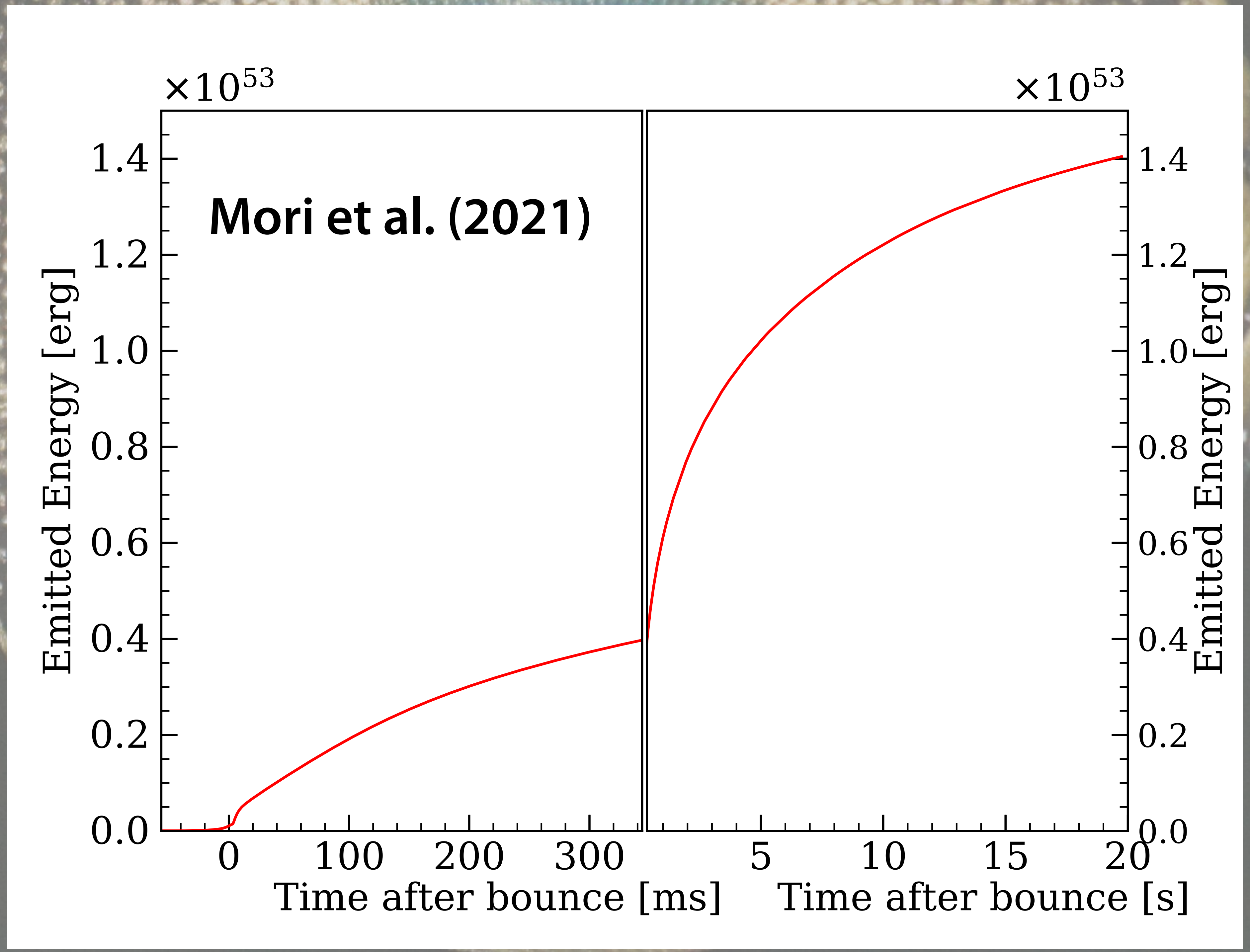


Mori et al. (2021)
1D, self-consistent, 1 model

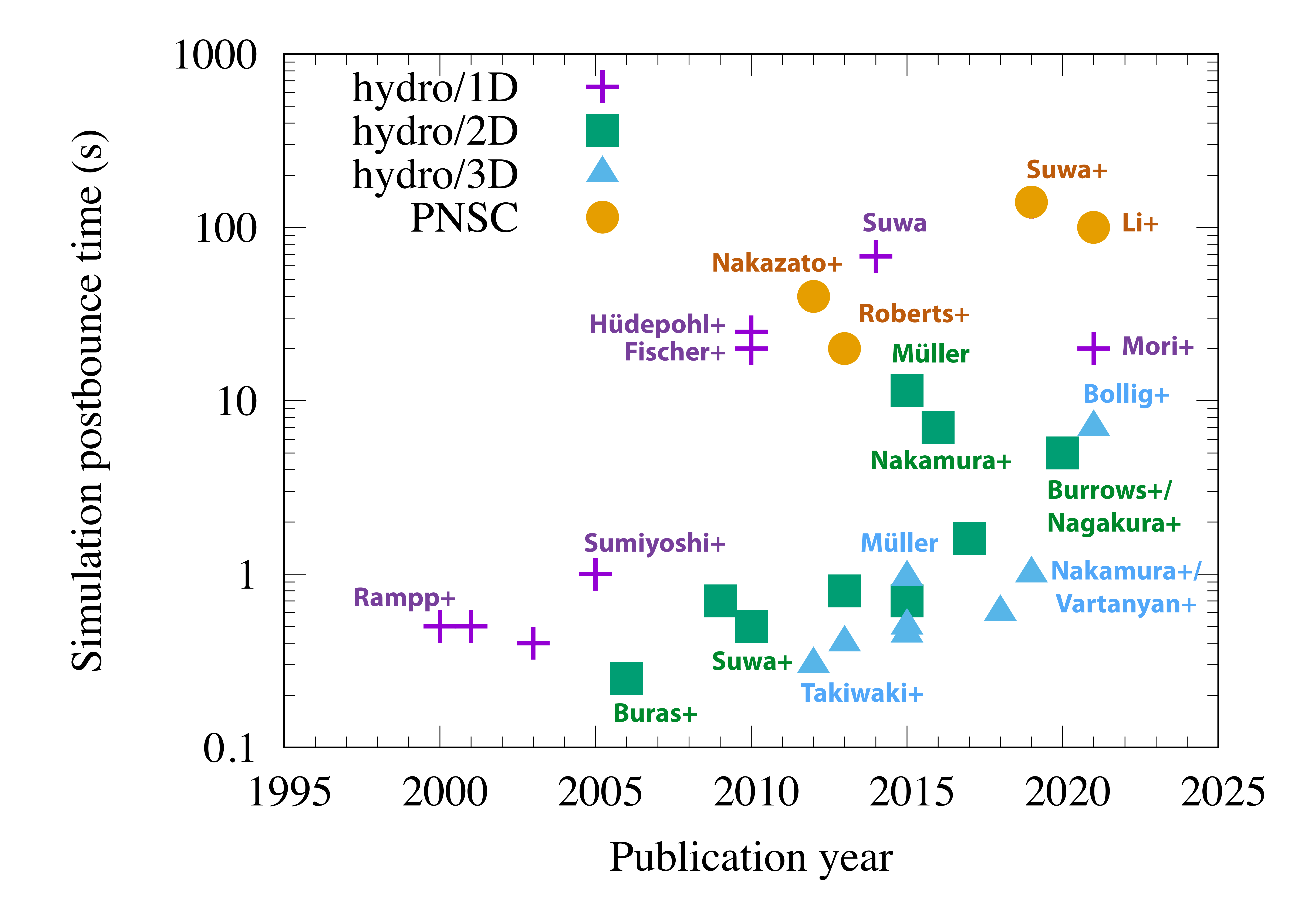
see talk by Nakazato-san

Long-term evolution is important





Current status of area



focusing on long-term simulations. definitely incomplete…

For the next Galactic supernova

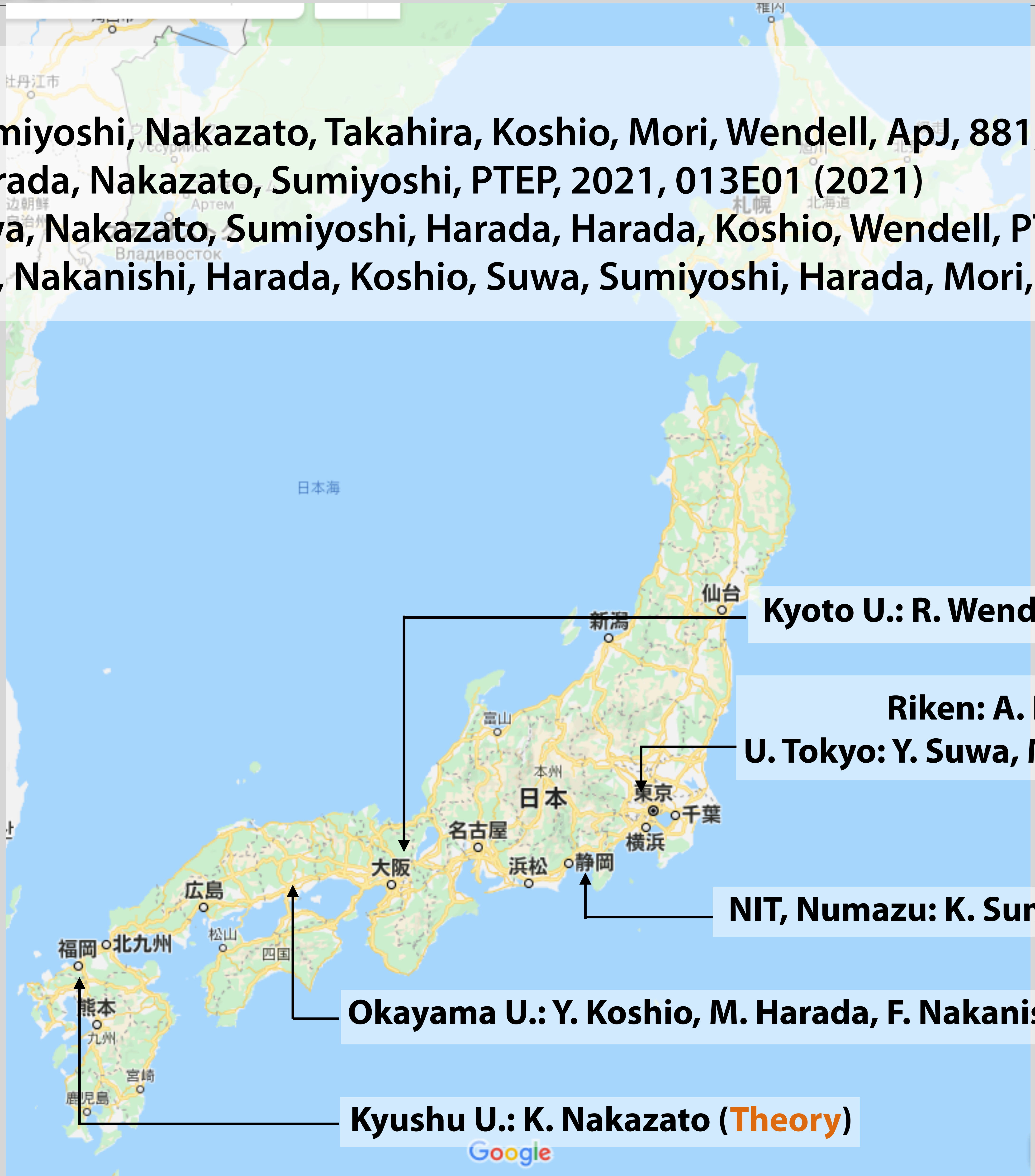
* **For optical observations of supernova explosions**
  1. building optical telescopes
  2. taking light curves with telescopes
  3. extracting physical values (ex, E_{exp}, M_{ej}, M_{Ni}) with simplified analytic model
  4. performing detailed numerical simulations for spectral analysis

* **The same strategy applies to neutrino observations**
  - [x] building neutrino detectors
  - [ ] taking data *(just waiting)*
  - [ ] simplified analytic model
  - [x] detailed numerical simulations *(but most are short period and limited numbers for long)*

nuLC collaboration

"nuLC"
=neutrino Light Curve

Papers:
1. Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019)
2. Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 013E01 (2021)
3. Mori, Suwa, Nakazato, Sumiyoshi, Harada, Harada, Koshio, Wendell, PTEP, 2021, 023E01 (2021)
4. Nakazato, Nakanishi, Harada, Koshio, Suwa, Sumiyoshi, Harada, Mori, Wendell, ApJ in press



Kyoto U.: R. Wendell (Experiment)

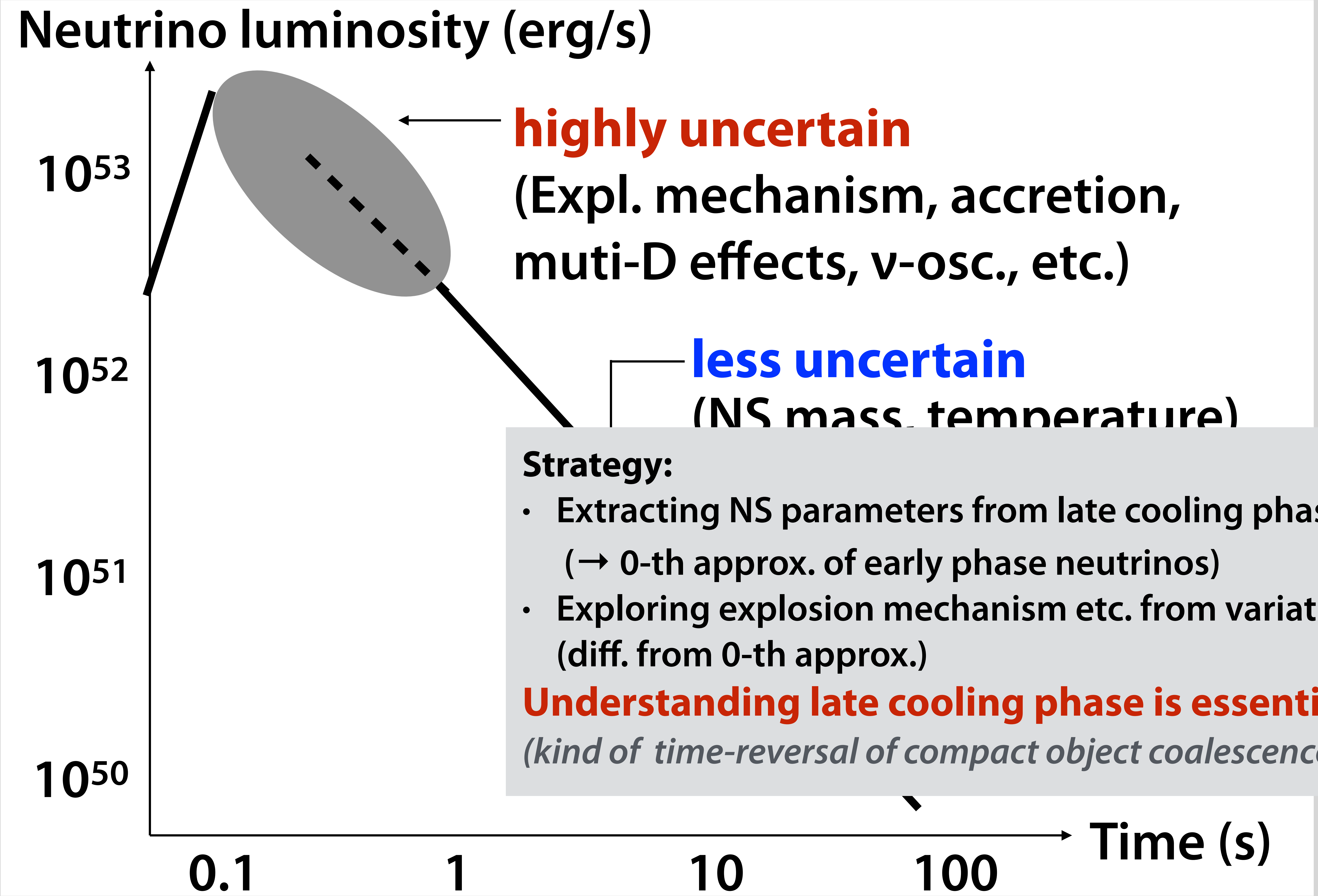
Riken: A. Harada (Theory)
U. Tokyo: Y. Suwa, M. Mori (Theory)

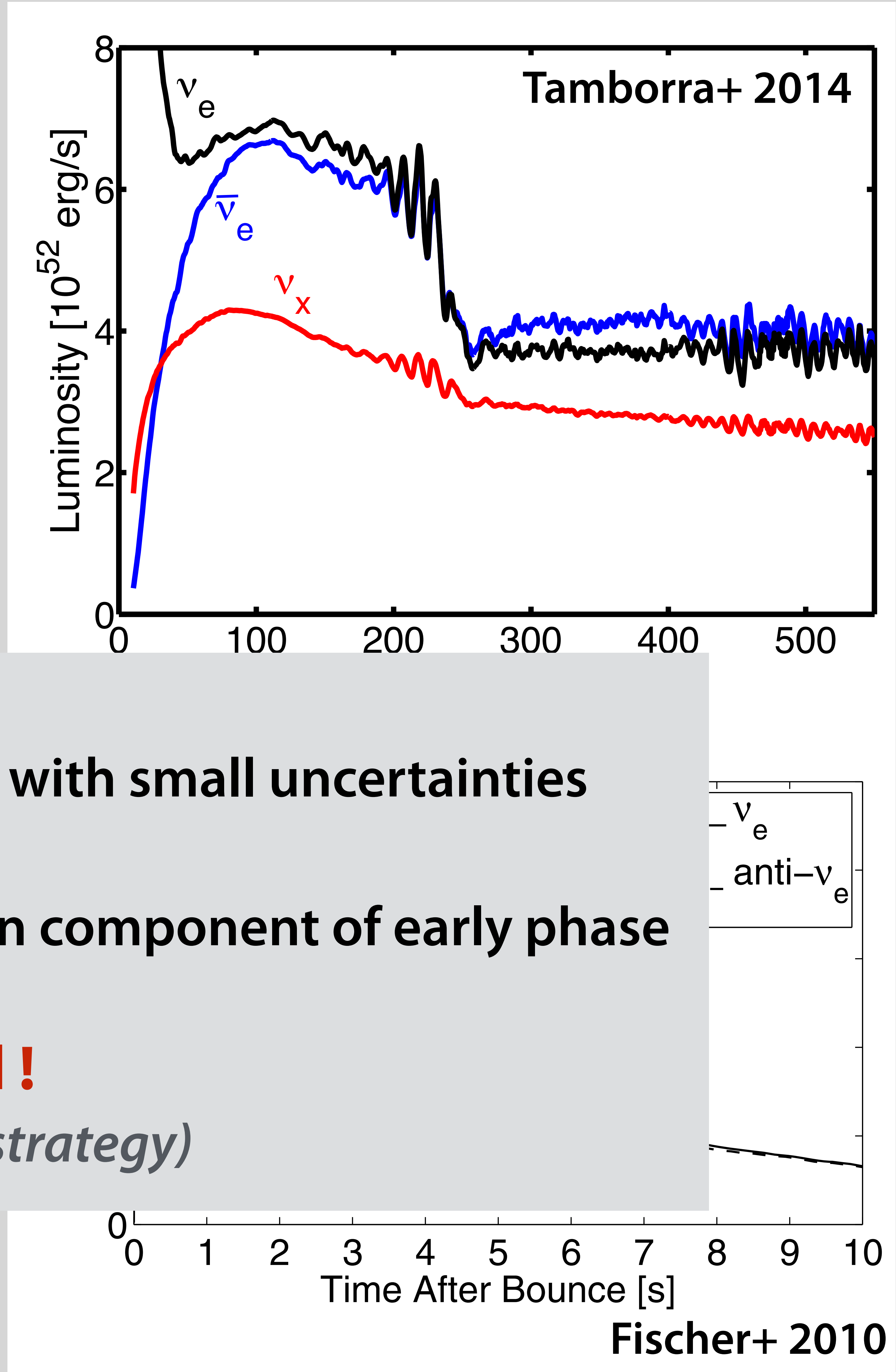
NIT, Numazu: K. Sumiyoshi (Theory)

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

Kyushu U.: K. Nakazato (Theory)

Late cooling phase is simpler and more understandable than early phase





Strategy:

- Extracting NS parameters from late cooling phase with small uncertainties
  (→ 0-th approx. of early phase neutrinos)
- Exploring explosion mechanism etc. from variation component of early phase
  (diff. from 0-th approx.)

Understanding late cooling phase is essential !

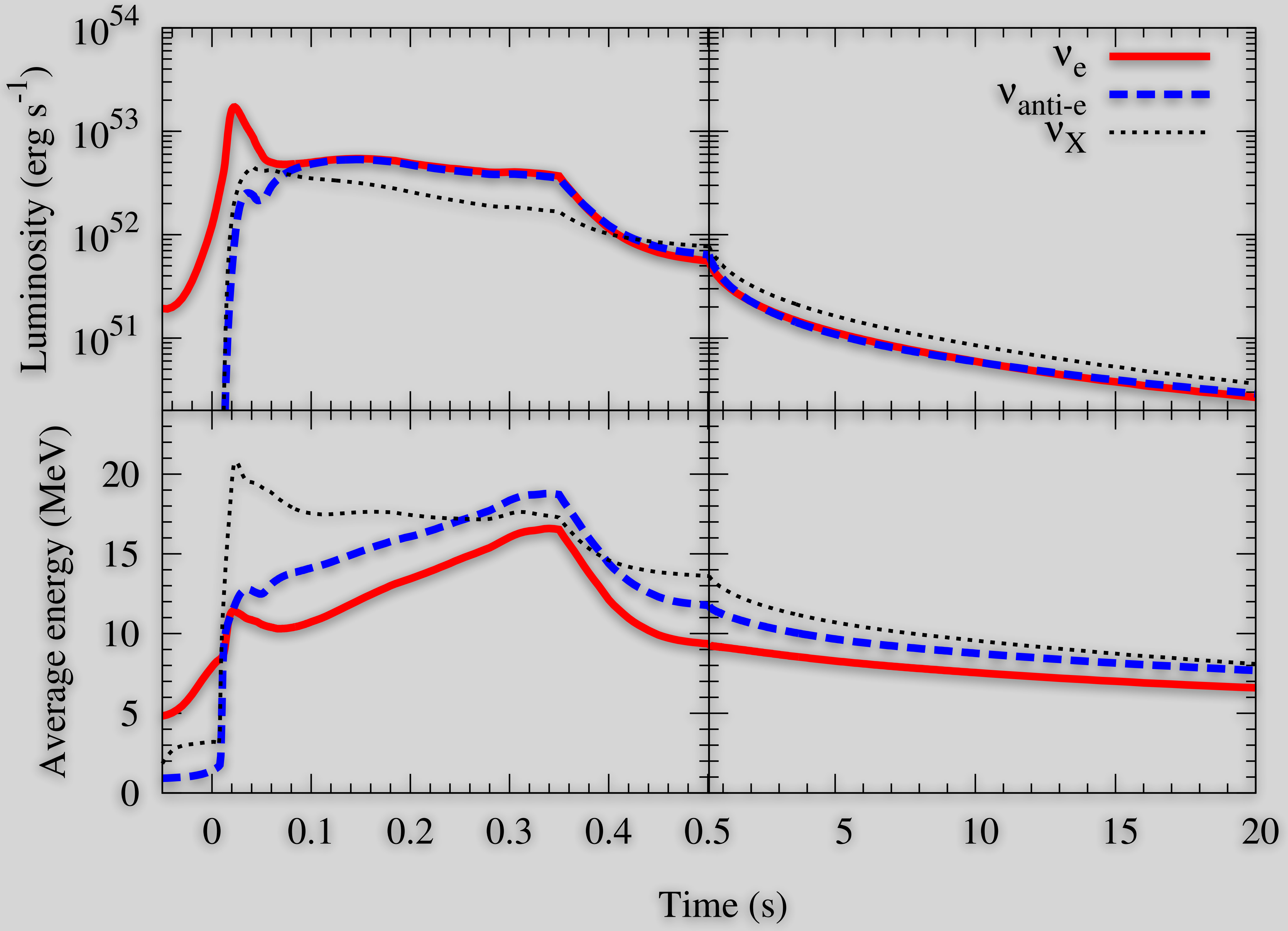
(kind of time-reversal of compact object coalescence strategy)

Numerical simulations

Supernova Neutrino Database
http://asphwww.ph.noda.tus.ac.jp/snn/

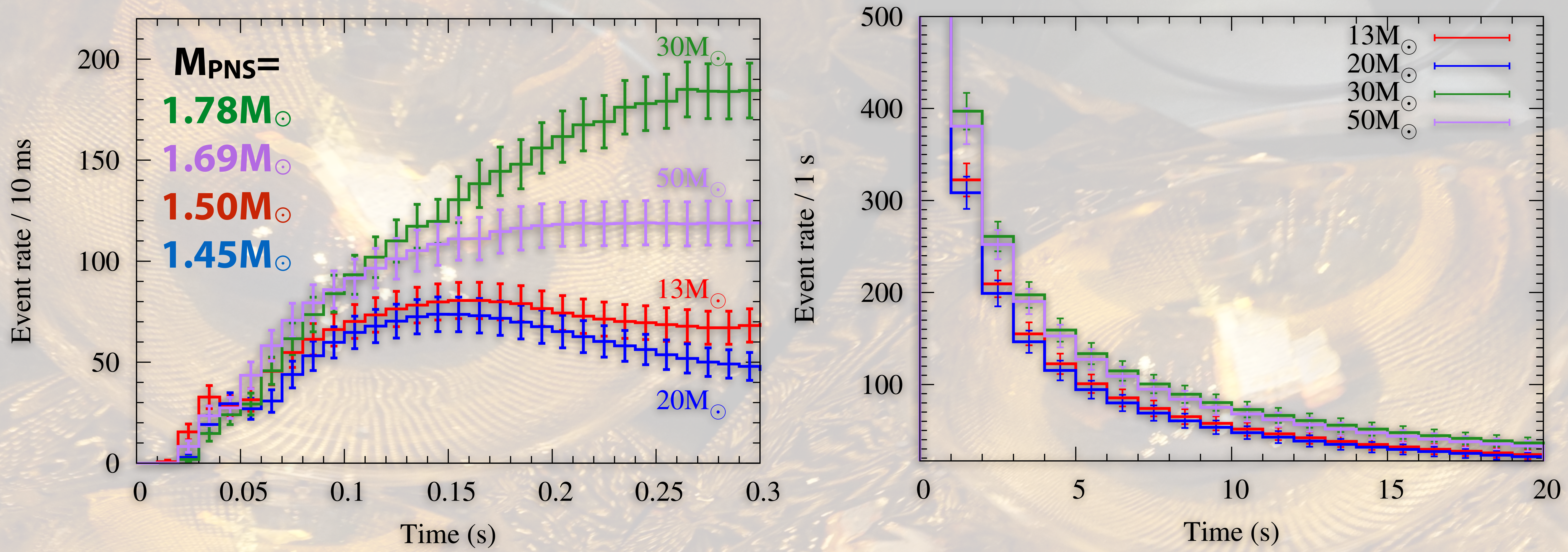
* **Hydro. simulation (t<0.3s)**
  - dynamical, GR, Boltzmann neutrino transport, nuclear EOS, 1D
    Yamada 1997, Sumiyoshi+ 2005
* **PNS cooling simulation (t>0.3s)**
  - static (TOV), FLD neutrino transport, nuclear EOS, 1D
    Suzuki 1993
* **Connection**
  - Interpolate two results with t_{revive}=100, 200, 300 ms (appox. explosion time)
    Nakazato+ 2013
* **Progenitor**
  - 13, 20, 30, 50 $M_\odot$
    Umeda+ 2012

13$M_\odot$, t_{revive}=300 ms



Event rate evolution

[Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019)]



* **Event rate evolution is calculated up to 20 s**
  - with neutrino luminosity and spectrum
  - with full volume of SK's inner tank (32.5 kton)
  - from an SN at 10 kpc
  - only with inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
* **Event rate is not related to progenitor mass, but PNS mass**

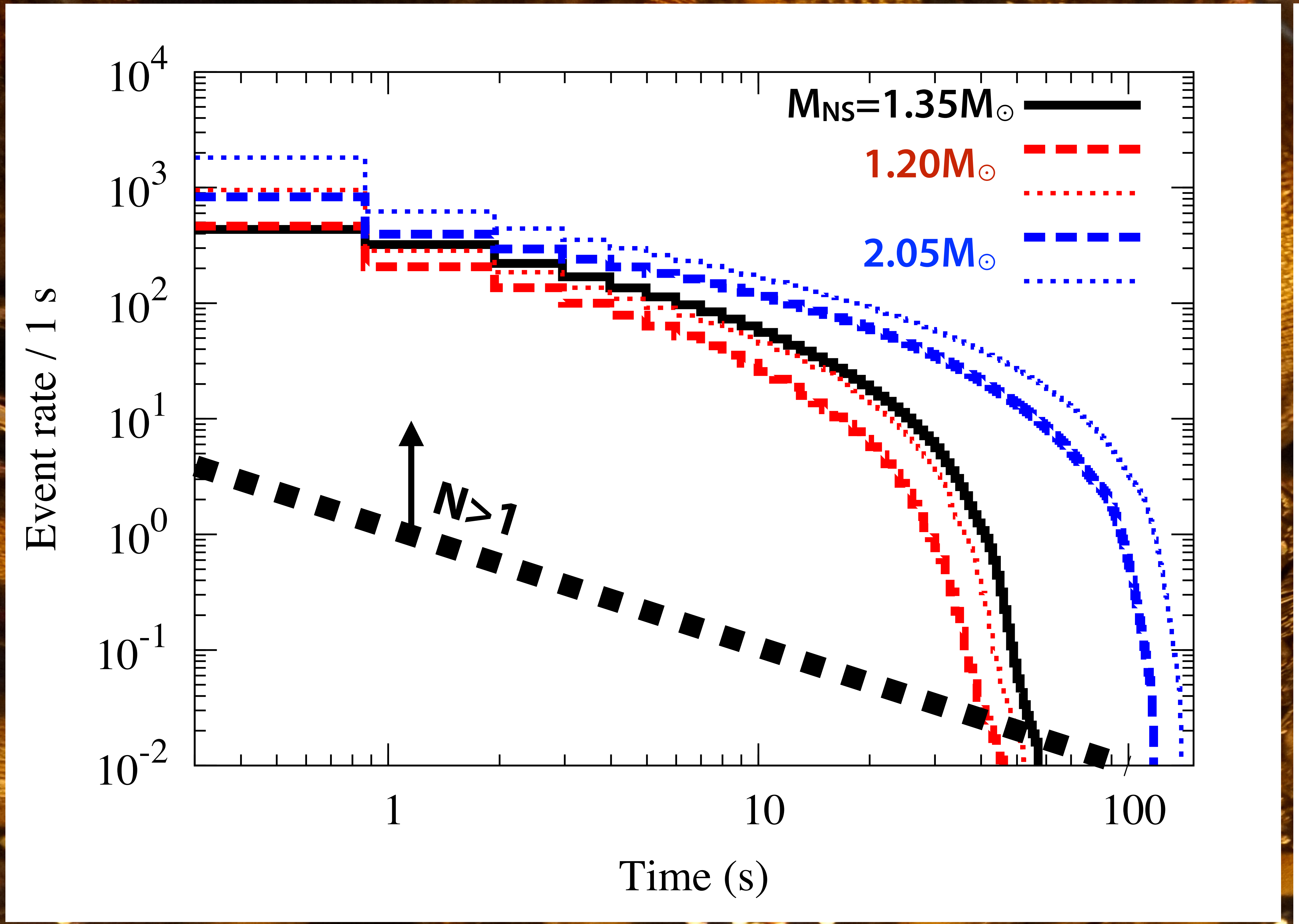
Longer simulations with broader NS mass range

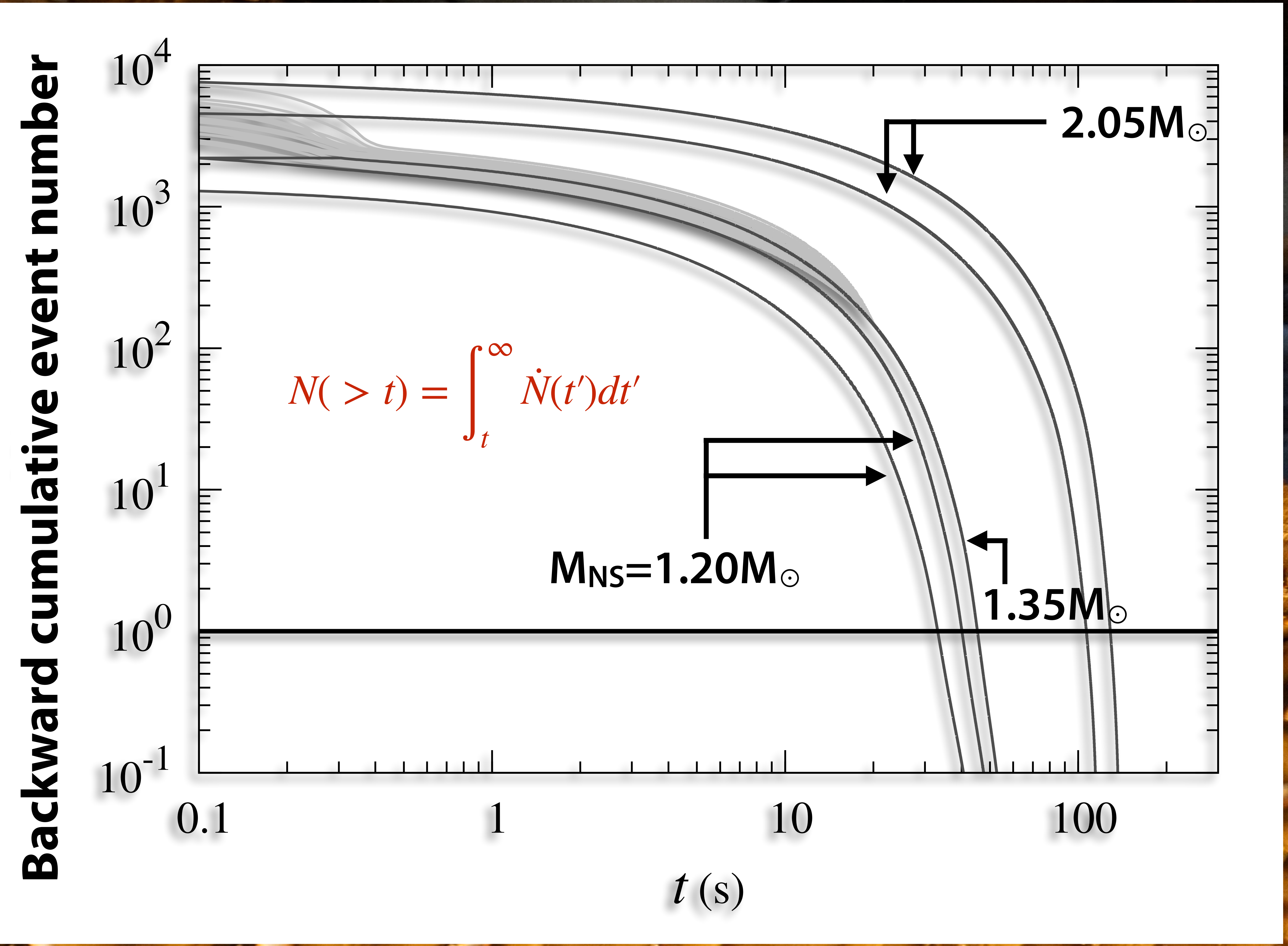
- Even 20 s after the explosion, the event rate is still high
- known mass range of NS is large: [1.17, 2.01]$M_\odot$
  Demorest+ 2010, Antoniadis+ 2013, Martinez+ 2015
  (see also Cromartie+ 2019, Romani+ 2021, for more recent update)

- **Additional long-term simulations for PNS cooling**
  - canonical model has M_{NS}=1.35$M_\odot$
  - parametric models
    - with M_{NS}=1.20$M_\odot$ and 2.05$M_\odot$
    - with two extreme entropy profiles (low and high)
  - up to the *last* detectable event

How long can we see SN with neutrinos?

[Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019)]





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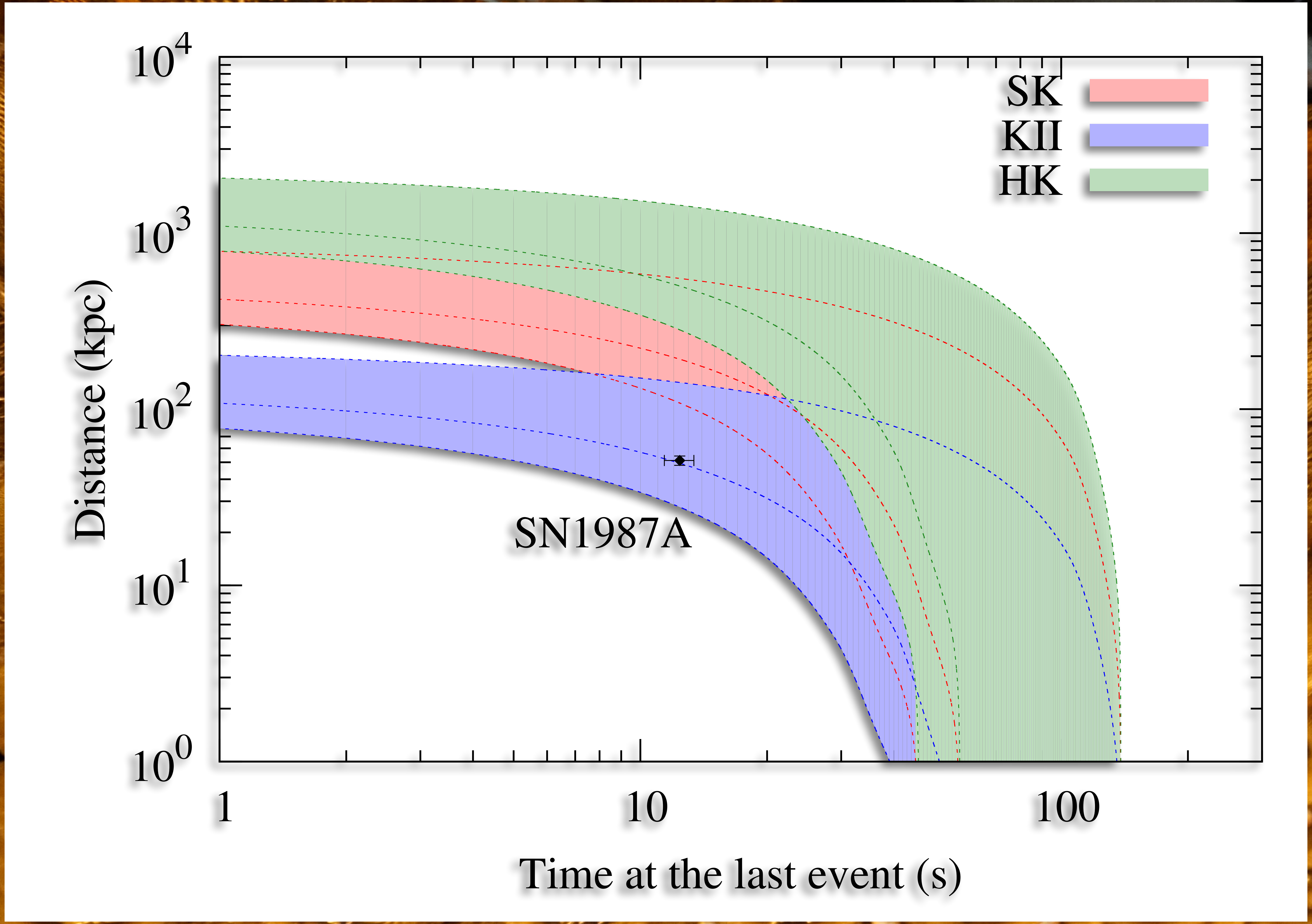
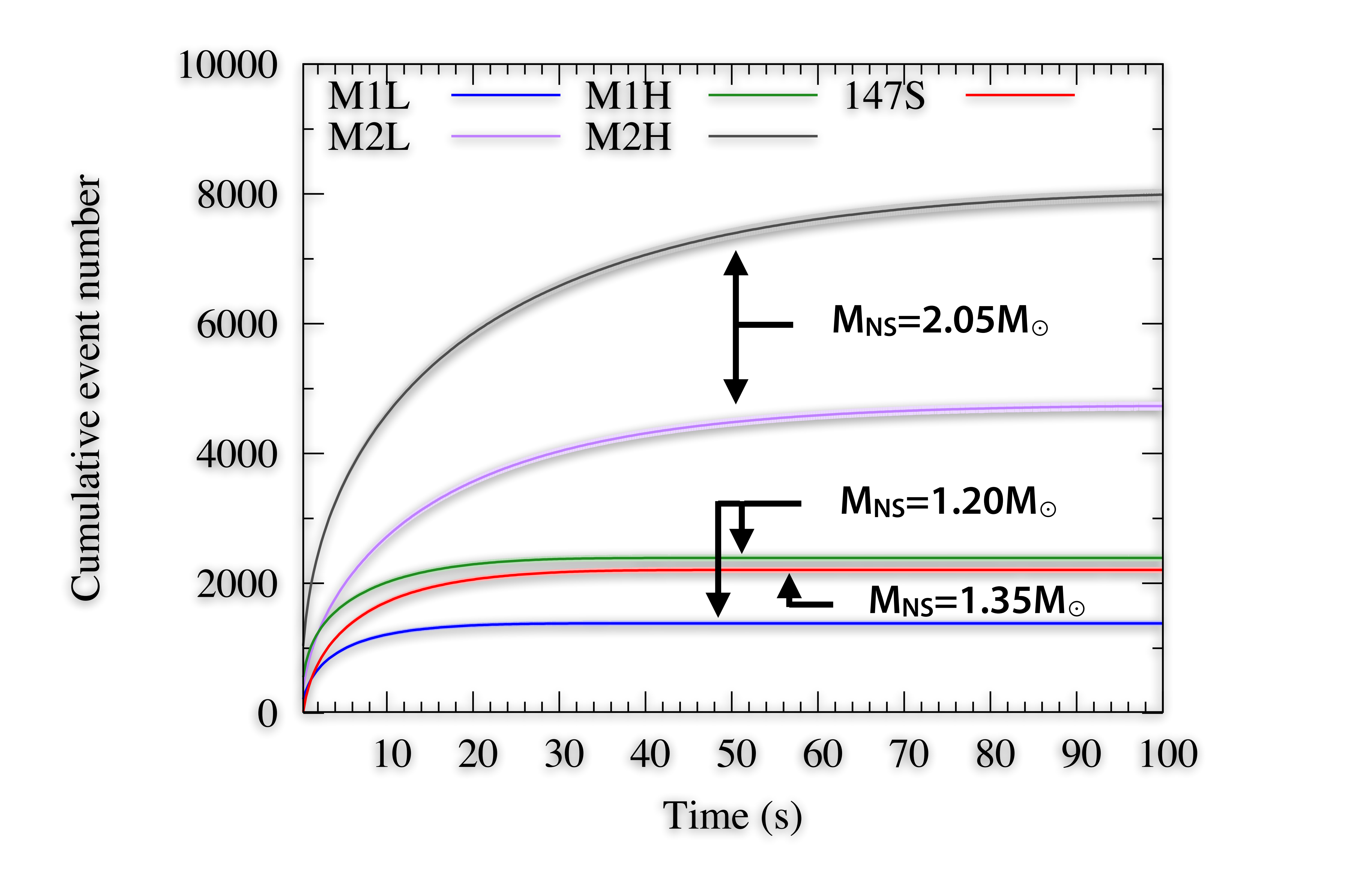
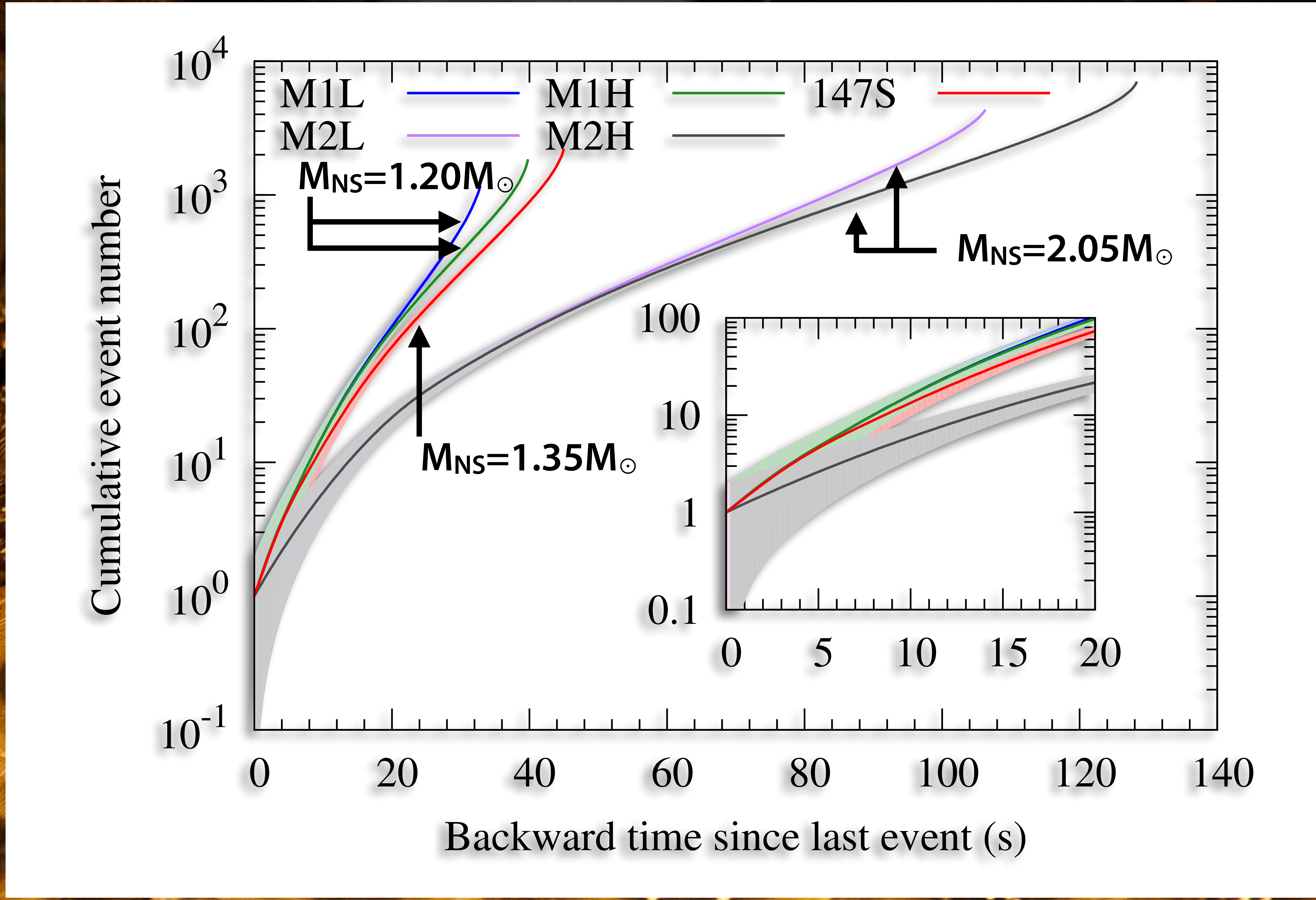


How to analyze neutrinos? Backward cumulative plot is useful

[Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019)]





Next is analytic expression

- **Nakazato *et al.* (arXiv:2108.03009) has just published 32 more models with various NS mass and nuclear EOS**
- **A Grid of PNS cooling simulations is getting broader**

- **Next step is simplified analytic model**
- **How?**

Simplified analytic model

[Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 0130E01 (2021)]

- **PNS is assumed as Lane-Emden solution with n=1**

$$k_B T(r) = 30\,\mathrm{MeV}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{2/3}\left(\frac{R_{\rm PNS}}{10\mathrm{km}}\right)^{-2}\left(\frac{s}{1k_B\,\mathrm{baryon}^{-1}}\right)\left(\frac{\sin(r/\alpha)}{r/\alpha}\right)^{2/3}$$

$M_{\rm PNS}$: PNS mass
$R_{\rm PNS}$: PNS radius
s: entropy
$\alpha = R_{\rm PNS}/\pi$

- **Neutrino transport with diffusion approximation**

$$\frac{\partial \varepsilon}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 F\right) = 0,\ \ F = -\frac{c}{3}\frac{1}{\langle \kappa_t \rangle}\frac{\partial \varepsilon}{\partial r}$$

ε: energy density of neutrinos
F: flux of neutrinos
κ_t: opacity

- **Neutrino luminosity with given entropy**

$$L = 4\pi R_\nu^2 F = 1.2\times 10^{50}\,\mathrm{erg\,s^{-1}}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{4/5}\left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-6/5}\left(\frac{g\beta}{3}\right)^{-4/5}\left(\frac{s}{1k_B\,\mathrm{baryon}^{-1}}\right)^{12/5}$$

- **Time evolution**

$$\frac{dE_{\rm th}}{dt} = -6L$$

g: surface density correction (~0.1)
β: opacity boost by coherent scattering
$E_{\rm th}$: total thermal energy of PNS

Analytic solutions

[Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 0130E01 (2021)]

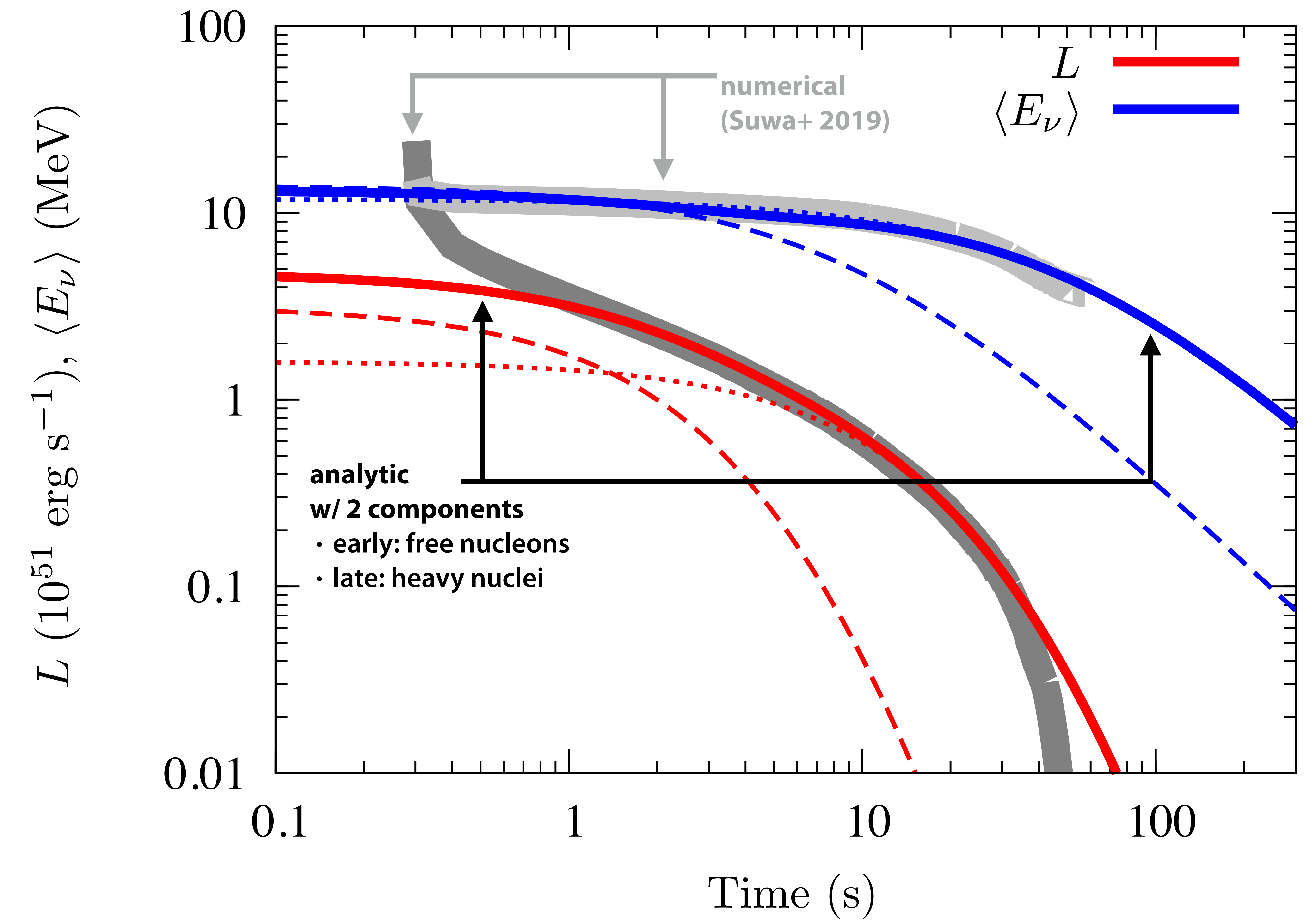
- **Solve neutrino transport eq. analytically**
  - **Neutrino luminosity**

$$L = 3.3\times 10^{51}\,\mathrm{erg\,s^{-1}}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{6}\left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-6}\left(\frac{g\beta}{3}\right)^{4}\left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-6}$$

  - **Neutrino average energy**

$$\langle E_\nu\rangle = 16\,\mathrm{MeV}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{3/2}\left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-2}\left(\frac{g\beta}{3}\right)\left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-3/2}$$

  - **two-component model**
    - early cooling phase (β=3)
    - late cooling phase (β=*O*(10))



Observables with analytic solutions

[Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 0130E01 (2021)]

- **Event rate w/ SK from SN @10kpc**

$$\mathcal{R} \approx 720\,\mathrm{s}^{-1}\left(\frac{M_{\rm det}}{32.5\,\mathrm{kton}}\right)\left(\frac{D}{10\,\mathrm{kpc}}\right)^{-2}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{15/2}\left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-8}\left(\frac{g\beta}{3}\right)^{5}\left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-15/2}$$

- **Positron average energy**

$$E_{e^+} \approx 25\,\mathrm{MeV}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{3/2}\left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-2}\left(\frac{g\beta}{3}\right)\left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-3/2}$$

- **PNS radius**

$$R_{\rm PNS} = 10\,\mathrm{km}\left(\frac{\mathcal{R}}{720\,\mathrm{s}^{-1}}\right)^{1/2}\left(\frac{E_{e^+}}{25\,\mathrm{MeV}}\right)^{-5/2}\left(\frac{M_{\rm det}}{32.5\,\mathrm{kton}}\right)^{-1/2}\left(\frac{D}{10\,\mathrm{kpc}}\right)$$

- **Consistency relation of analytic model**

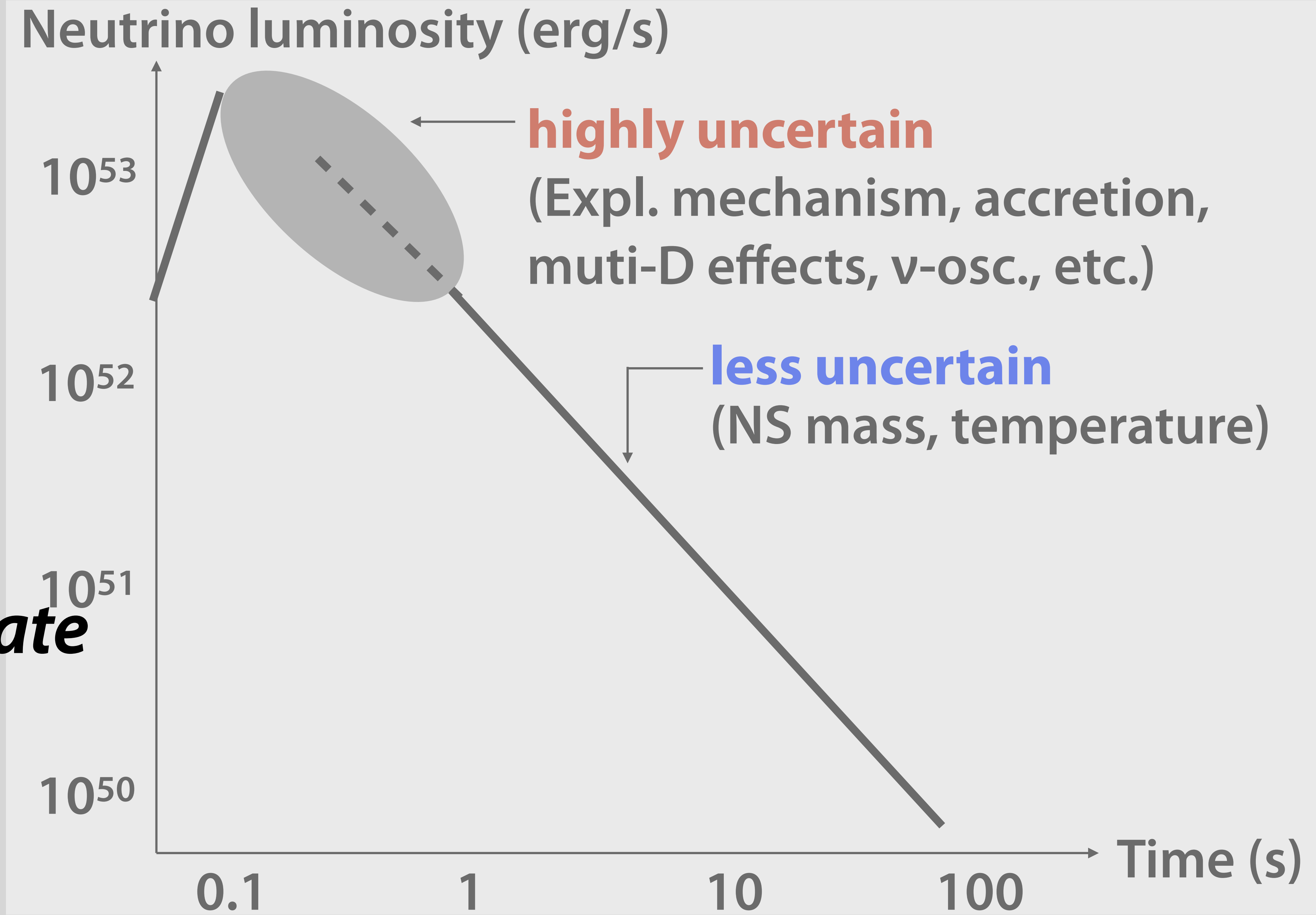
$$\frac{\mathcal{R}\ddot{\mathcal{R}}}{\dot{\mathcal{R}}^2} = \frac{17}{15}$$

Toward physics in the next Galactic supernova

* **Properties of neutron stars**
  * **Binding energy**
    * *important for energetics, done with SN1987A*

$$E_b \approx \frac{GM_{\rm NS}^2}{R_{\rm NS}} = \mathcal{O}(10^{53})\,{\rm erg}\left(\frac{M_{\rm NS}}{1.4M_\odot}\right)^2\left(\frac{R_{\rm NS}}{10{\rm km}}\right)^{-1}$$

  * **Mass**
    * *important for discriminating final object (NS or BH)*
    * *measurable with next SN*
  * **Radius**
    * *important for discriminating nuclear equation of state*
    * *measurable with next SN*



Summary

* **Neutrinos from the next Galactic SN are studied**

* **Take home messages**
  * O(10^3) ν will be detected, correlated to M_{NS}
  * Observable time scale is O(10)s, even > 100s
  * Simple analytic expressions are available
  * Data analysis framework is being constructed

* **Strategy of neutrino observations**
  * ☑ building neutrino detectors
  * ☑ taking data *(Monte-Carlo)*
  * ☑ simplified analytic model
  * ☑ detailed numerical simulations

* **Next step**
  * Spectral information in analytic solutions
  * Complete data analysis pipeline