(N12a)

超新星後期ニュートリノ放射の解析解

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with

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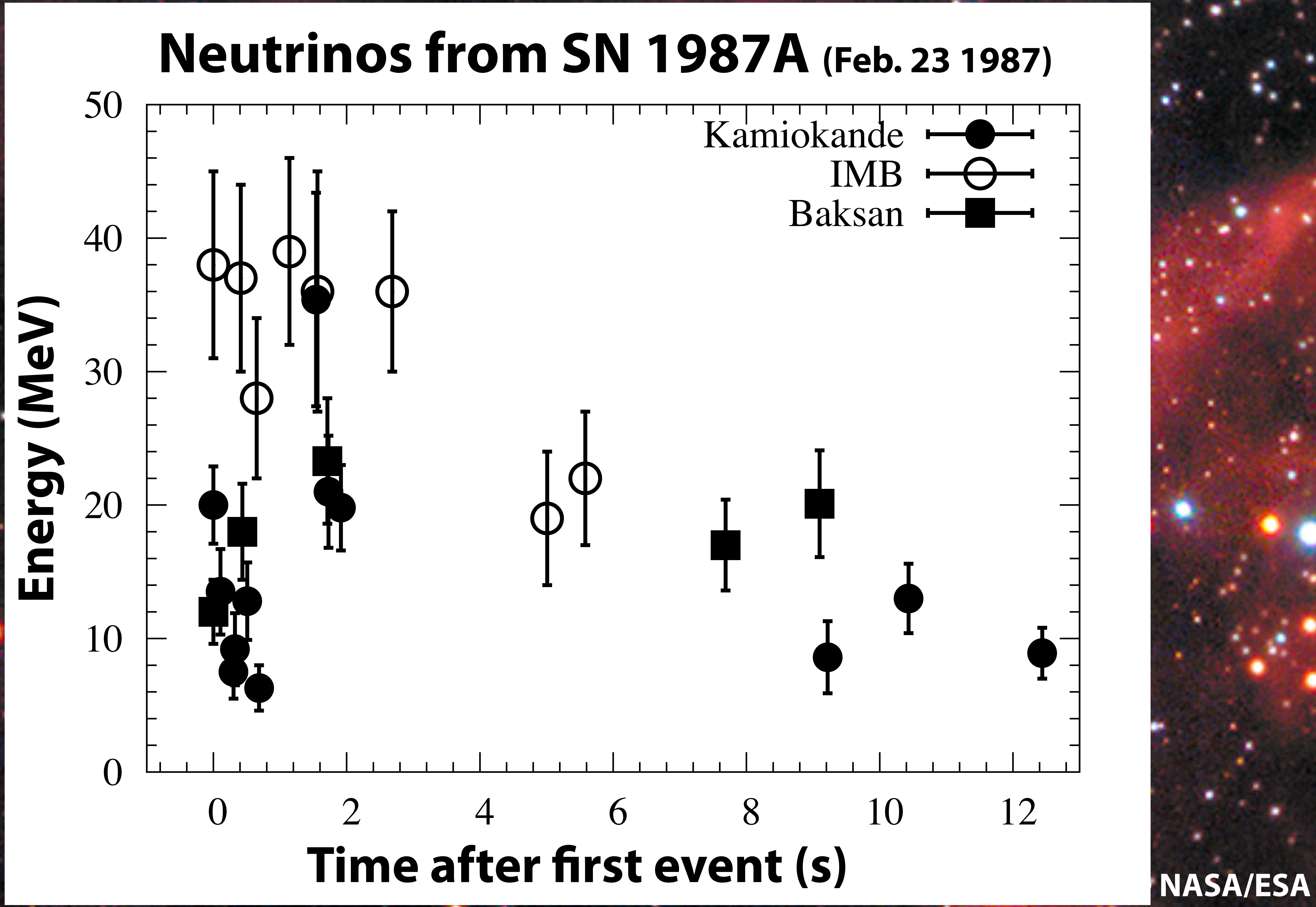
YS, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019)

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, arXiv:2108.03009

SN1987A



Neutrinos from SN 1987A (Feb. 23 1987)
Kamiokande
IMB
Baksan
Energy (MeV)
0
10
20
30
40
50
0
2
4
6
8
10
12
Time after first event (s)
NASA/ESA

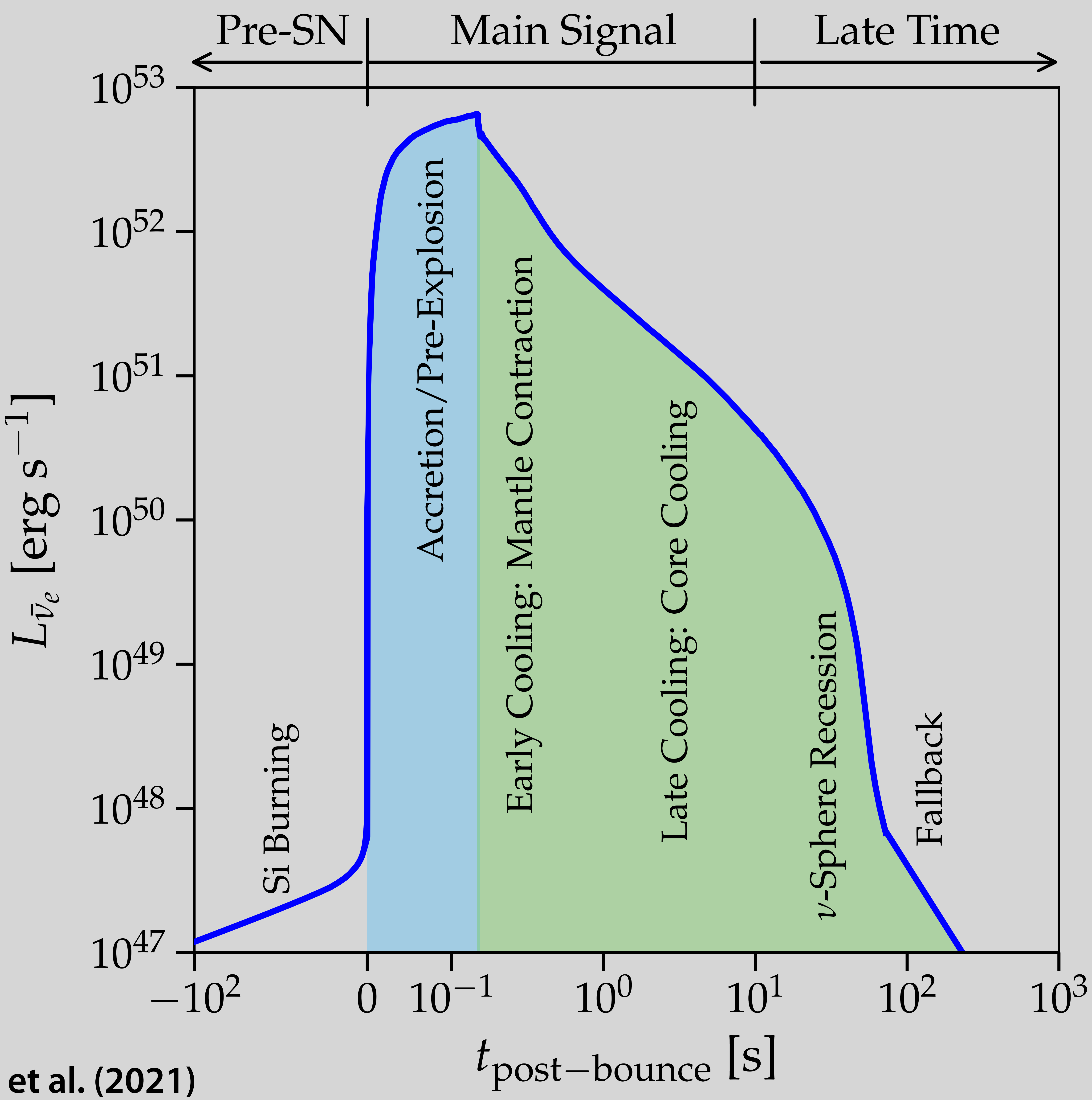
What can we extract from neutrino observations?

- **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*

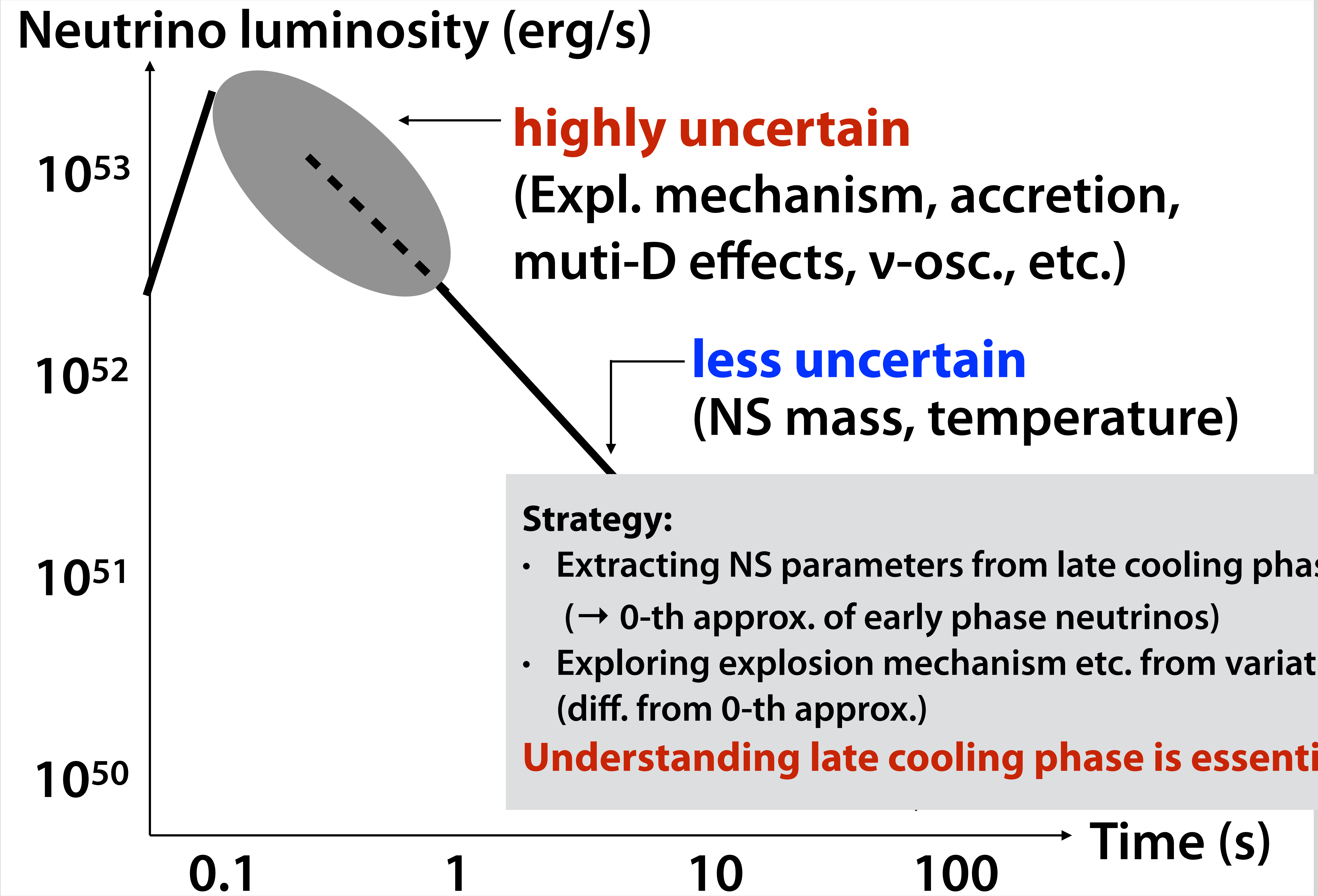
Supernova neutrinos: basics

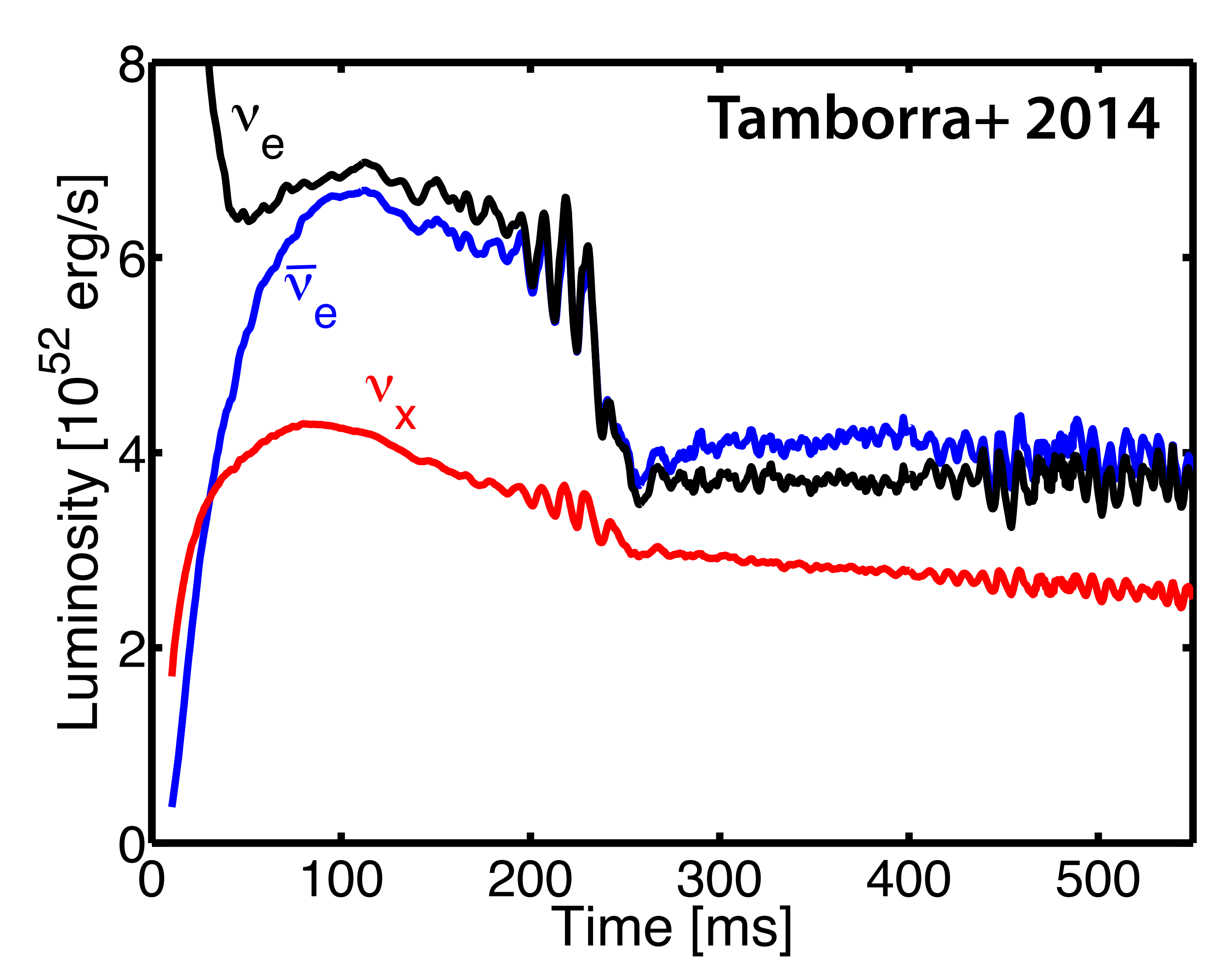


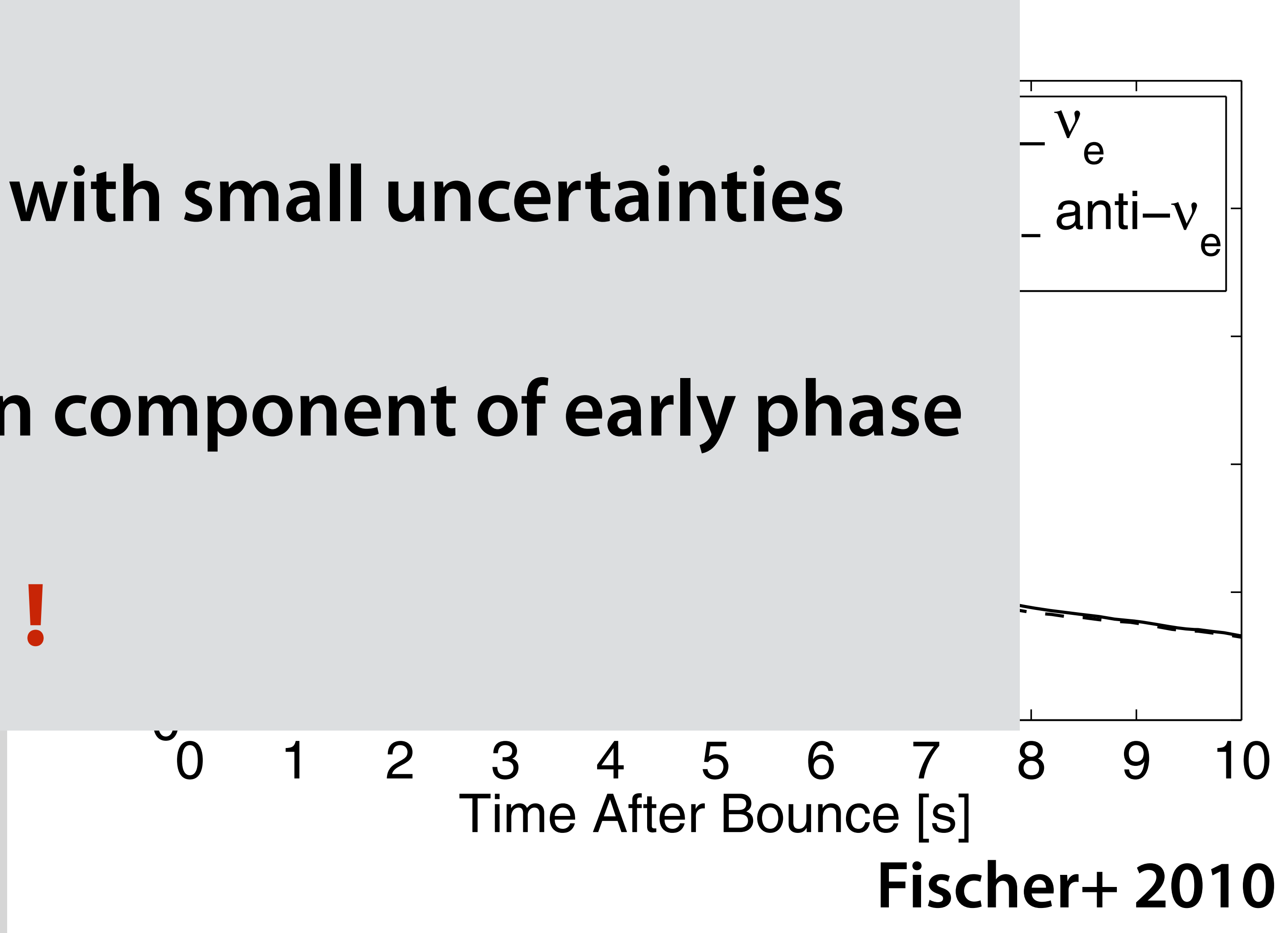
Li et al. (2021)

- **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

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.)

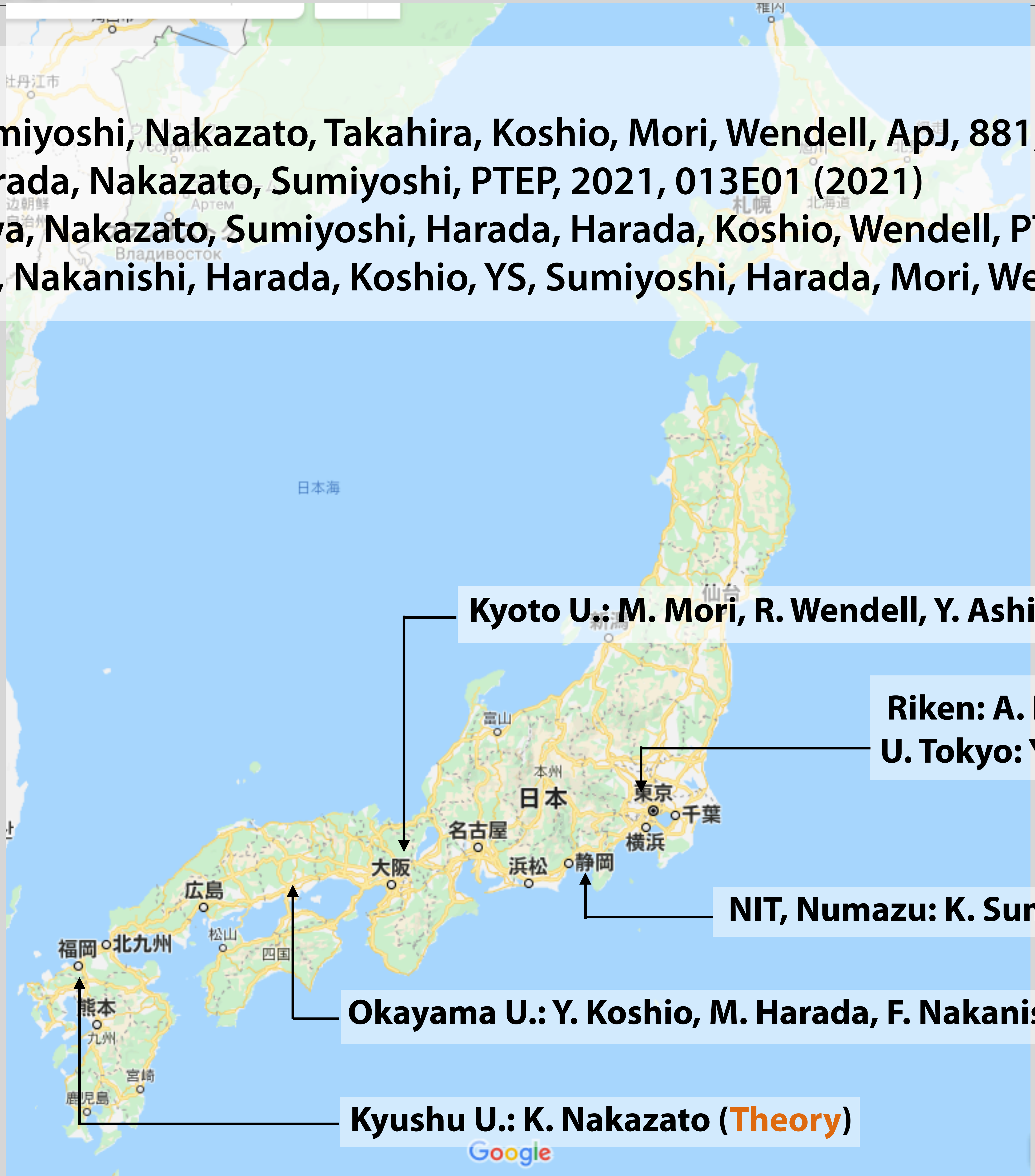
Understanding late cooling phase is essential !

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, YS, Sumiyoshi, Harada, Mori, Wendell, arXiv:2108.03009



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

Riken: A. Harada (Theory)

U. Tokyo: Y. Suwa (Theory)

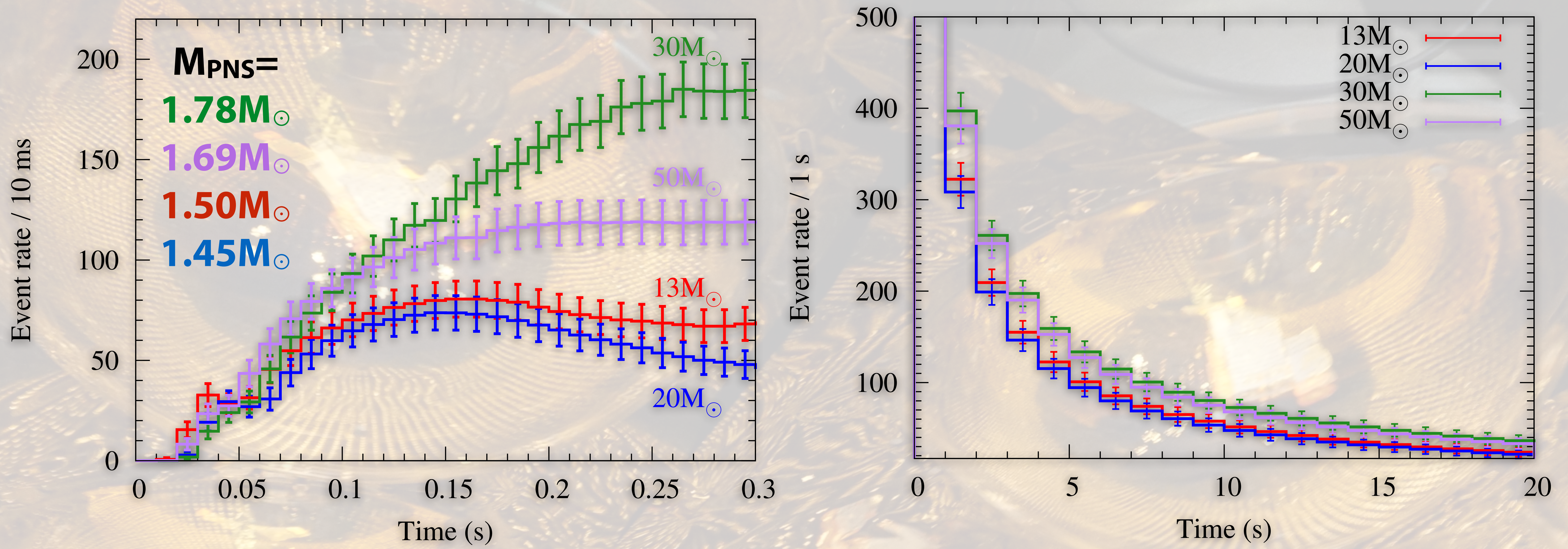
NIT, Numazu: K. Sumiyoshi (Theory)

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

Kyushu U.: K. Nakazato (Theory)

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**

Simplified analytic model

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

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

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

M_PNS: PNS mass
R_PNS: PNS radius
s: entropy
$\alpha = R_\mathrm{PNS}/\pi$

- **Neutrino transport with diffusion approximation**

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

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

- **Neutrino luminosity with given entropy**

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

- **Time evolution**

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

g: surface density correction (~0.1)
β: opacity boost by coherent scattering
E_th: total thermal energy of PNS

Analytic solutions

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

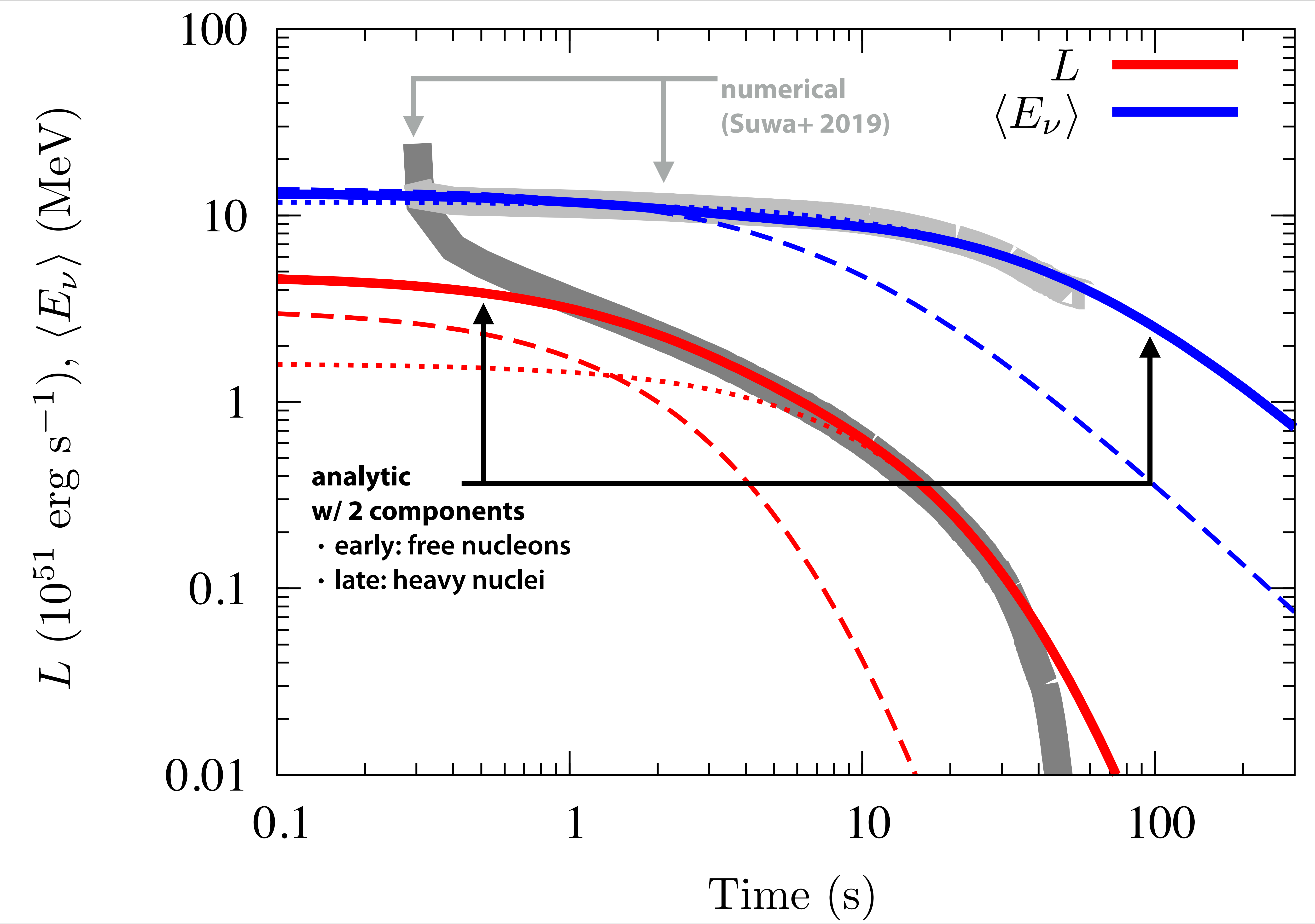
* **Solve neutrino transport eq. analytically**
  * **Neutrino luminosity**

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

  * **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**

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

- **Positron average energy**

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

- **PNS radius**

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

- **Consistency relation of analytic model**

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

Summary

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

- **Take home messages**
  - O(10^3) ν will be detected
  - Observable time scale is O(10)s, even > 100s
  - Simple analytic expressions of neutrino signals are available

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