超新星ニュートリノから引き出す原始中性子星の物理量

諏訪雄大

（東大総合文化 & 京大基研）

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*

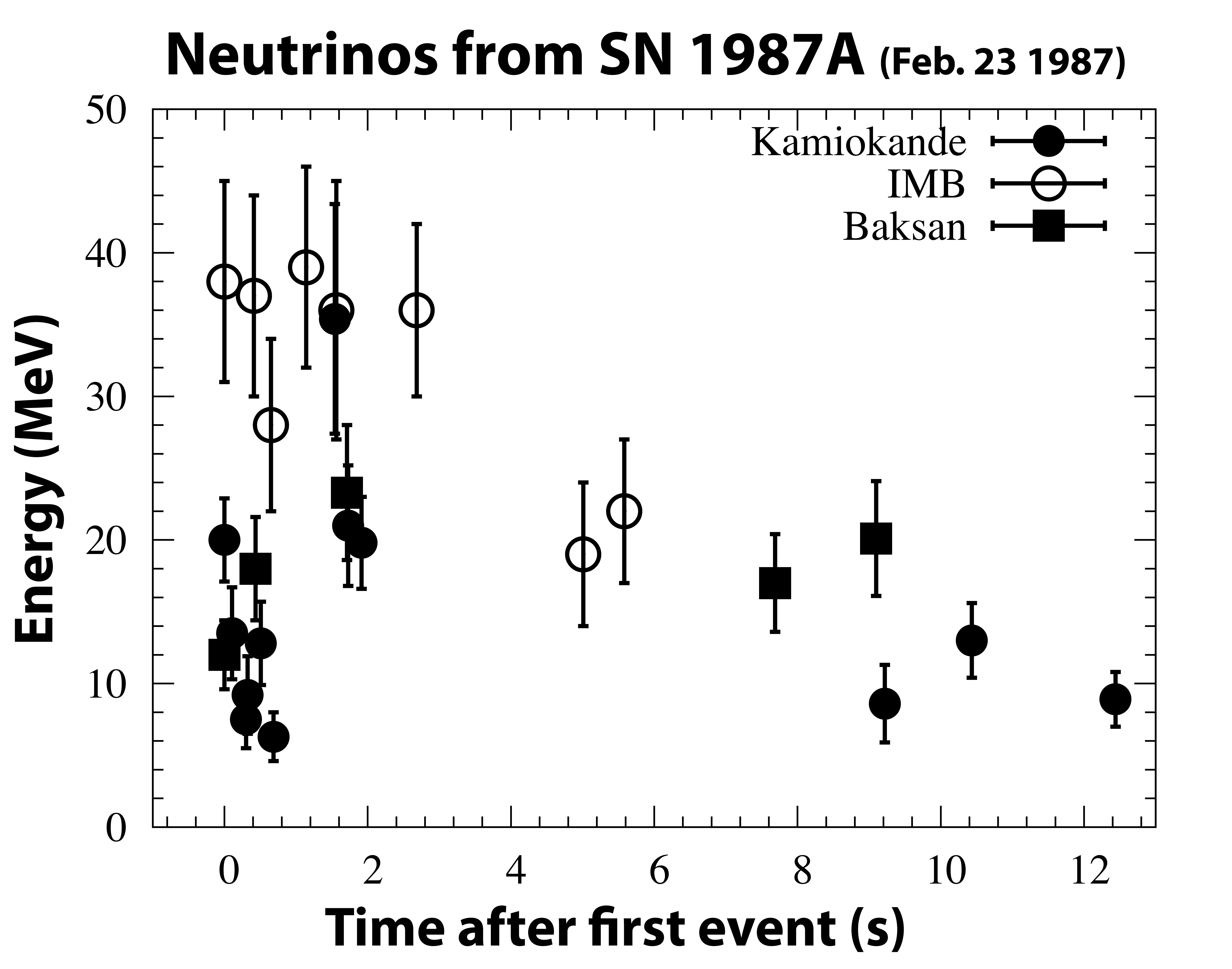
We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This 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

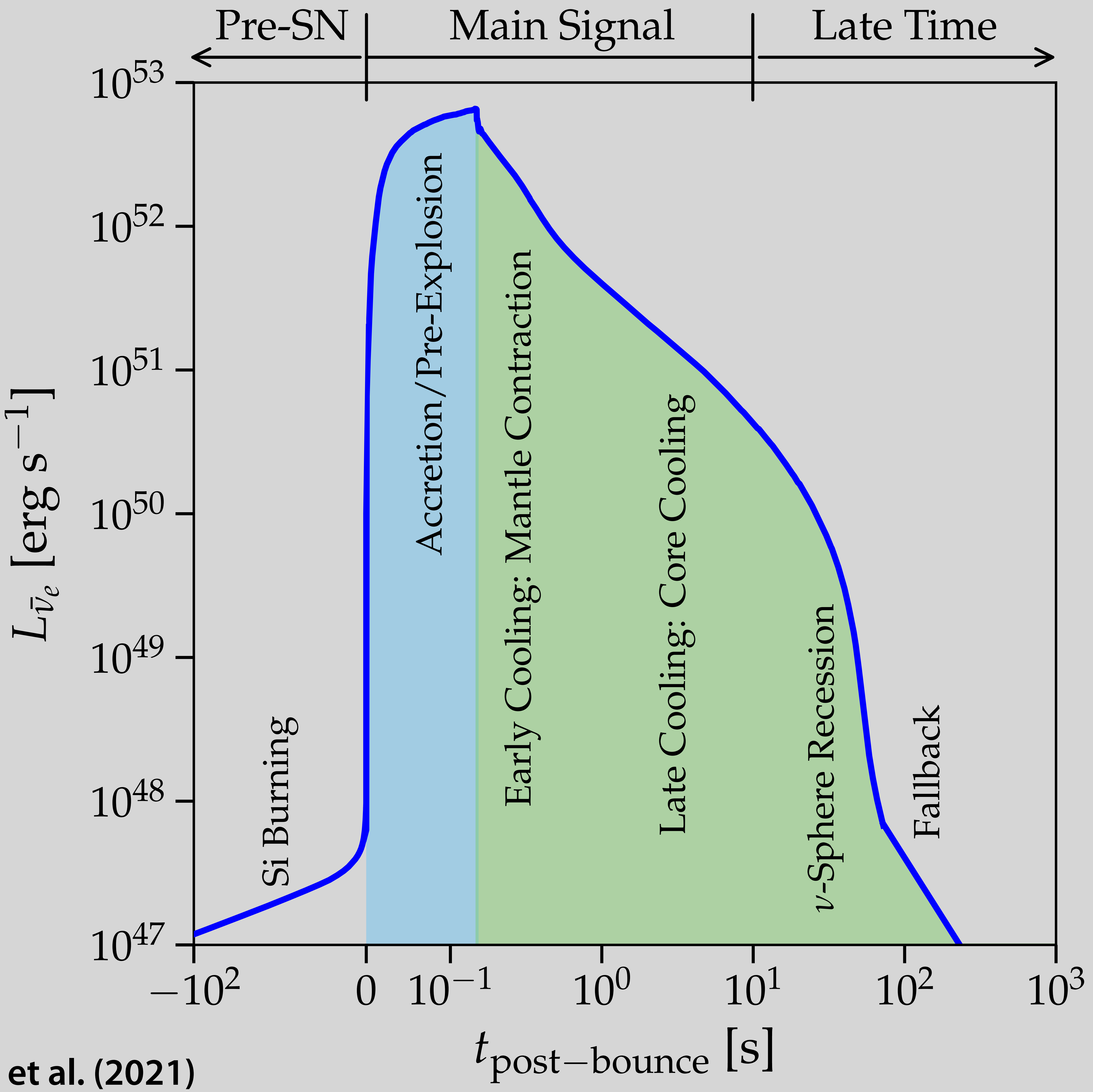
What can we extract from neutrino observations?

- **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*

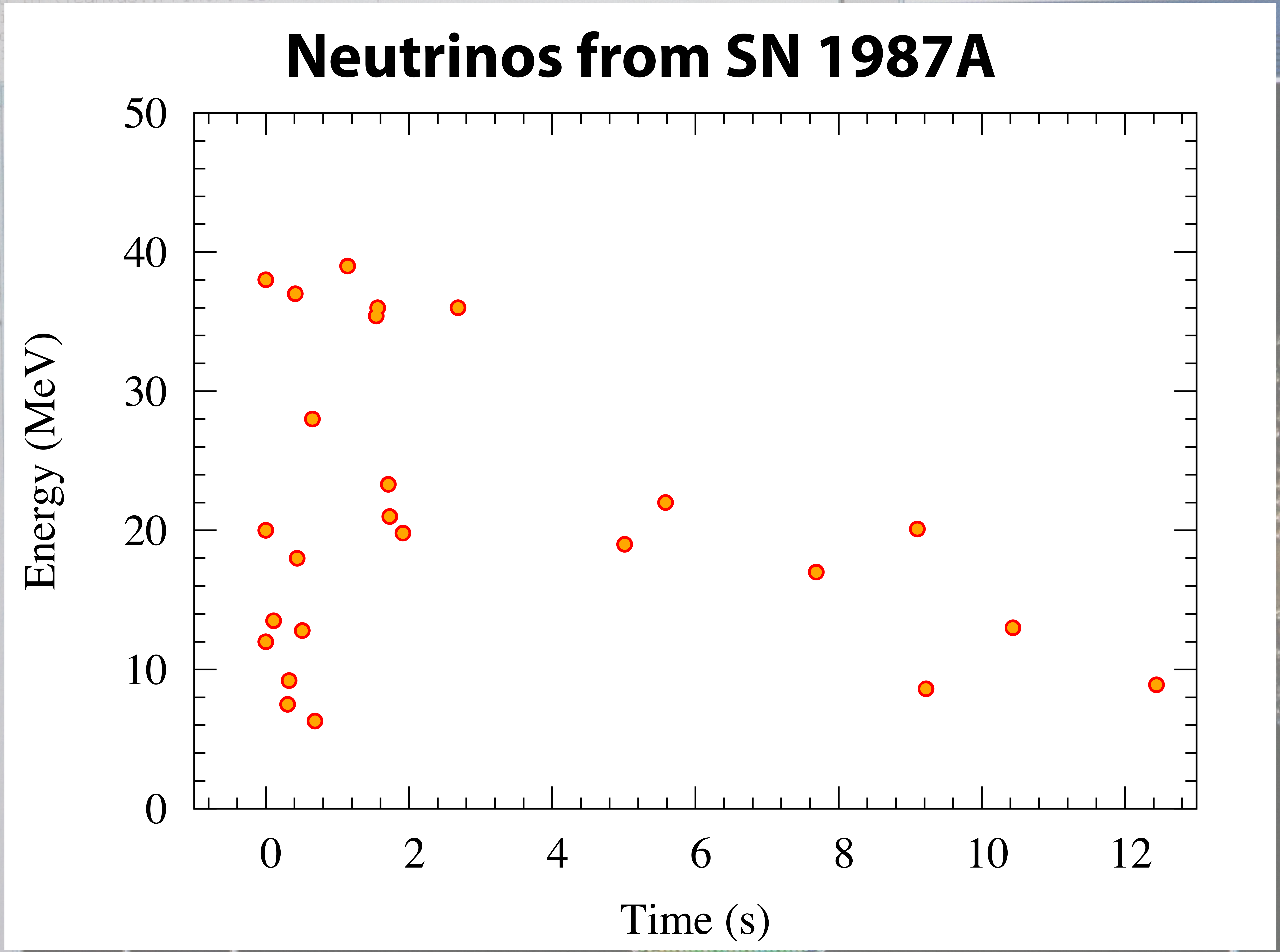
Supernova neutrinos: basics

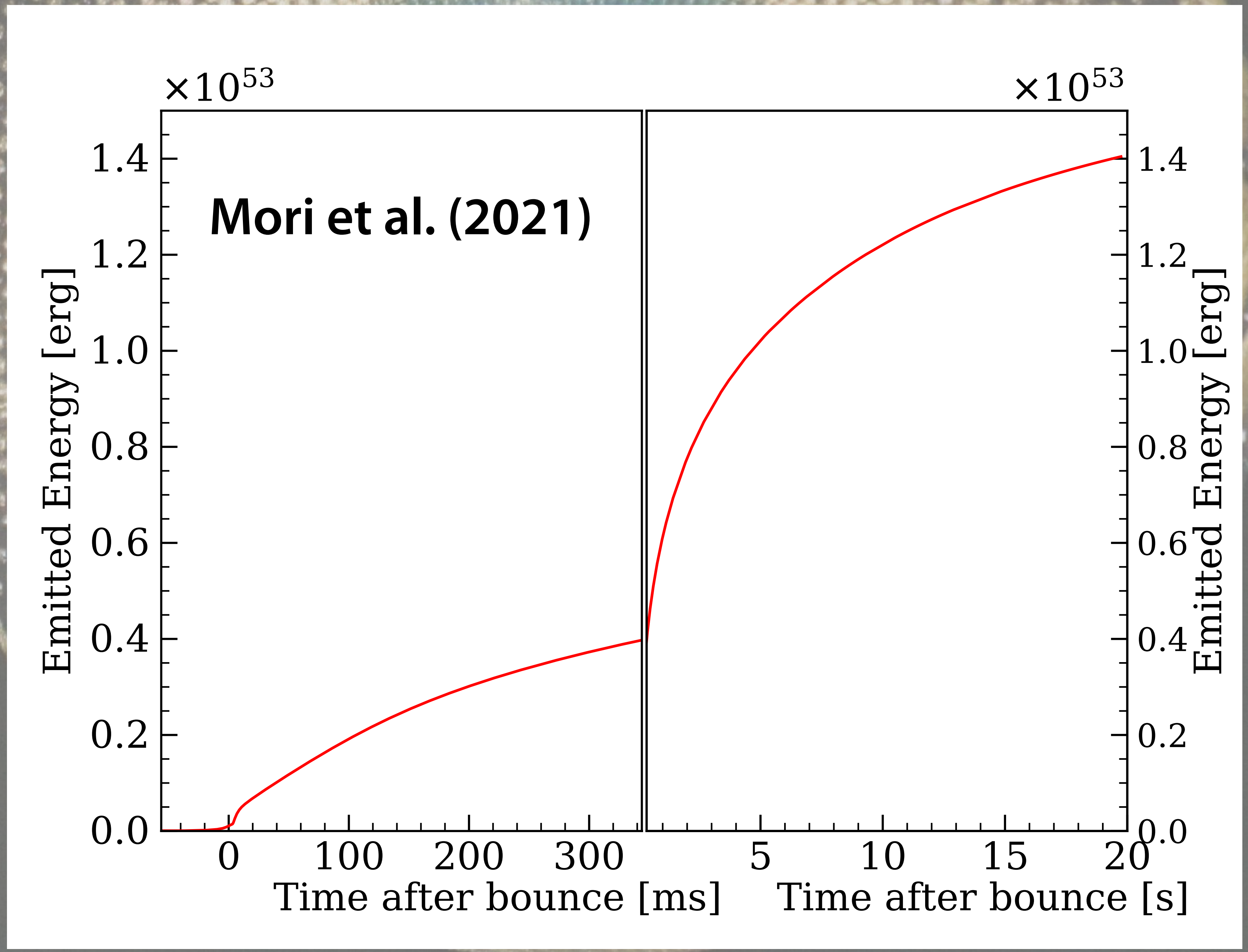


Li et al. (2021)

- **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

Long-term evolution is important





For the next Galactic supernova

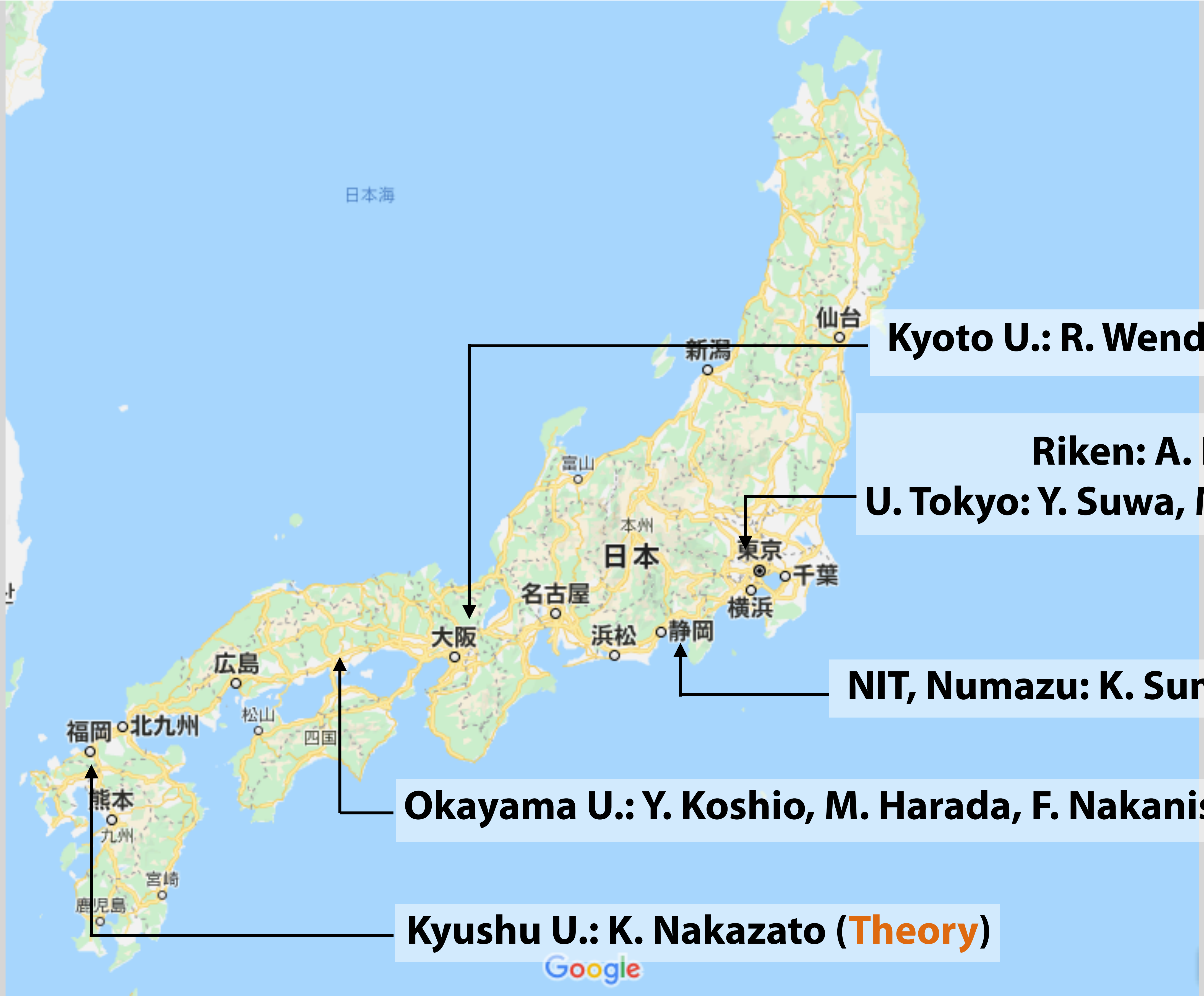
* **For optical observations of supernova explosions**
  1. building optical telescopes
  2. taking light curves with telescopes
  3. extracting physical values (ex, E_{exp}, M_{ej}, M_{Ni}) with simplified analytic model
  4. performing detailed numerical simulations for spectral analysis

* **The same strategy applies to neutrino observations**
  - [x] building neutrino detectors
  - [ ] taking data *(just waiting)*
  - [ ] making use of 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)

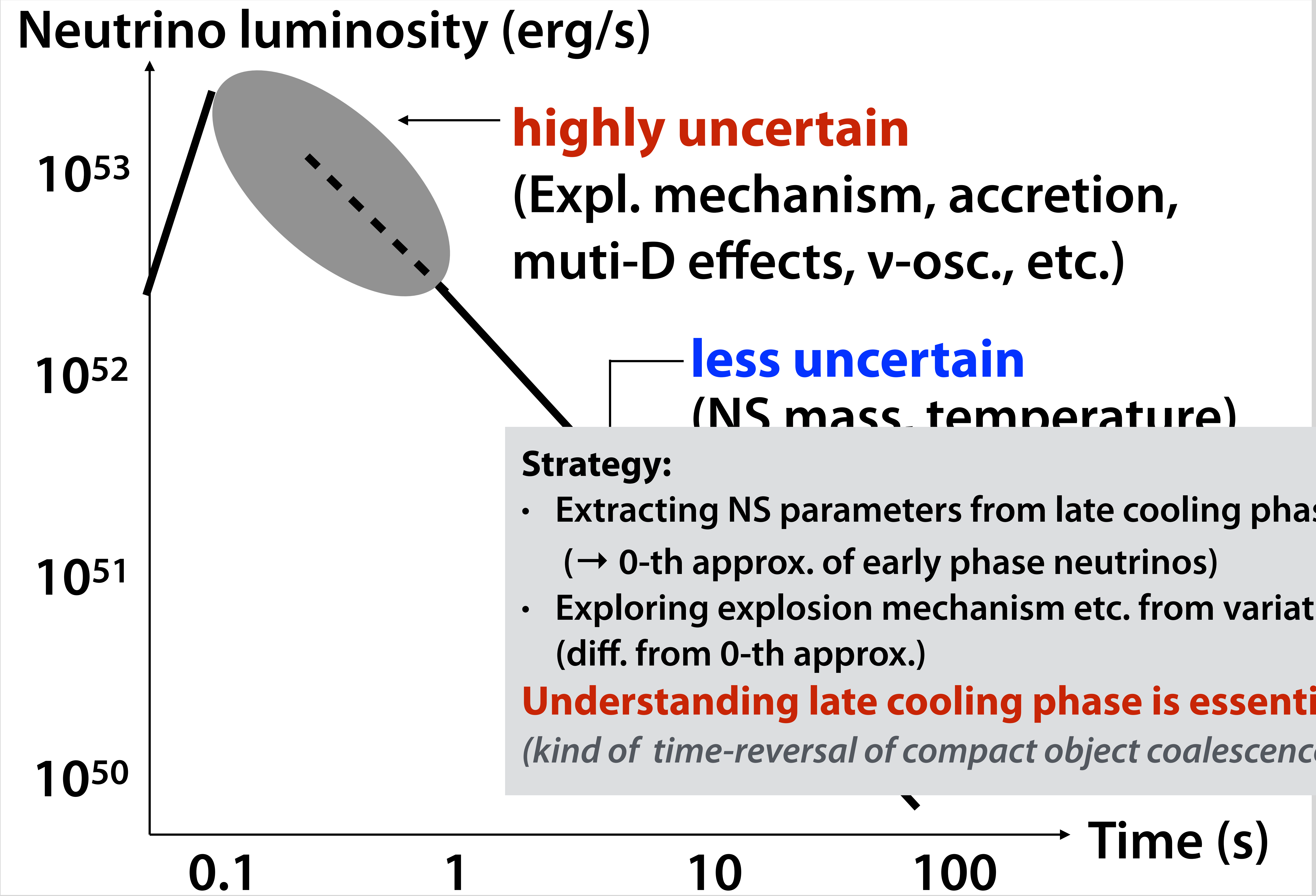
Riken: A. Harada (Theory)
U. Tokyo: Y. Suwa, M. Mori (Theory)

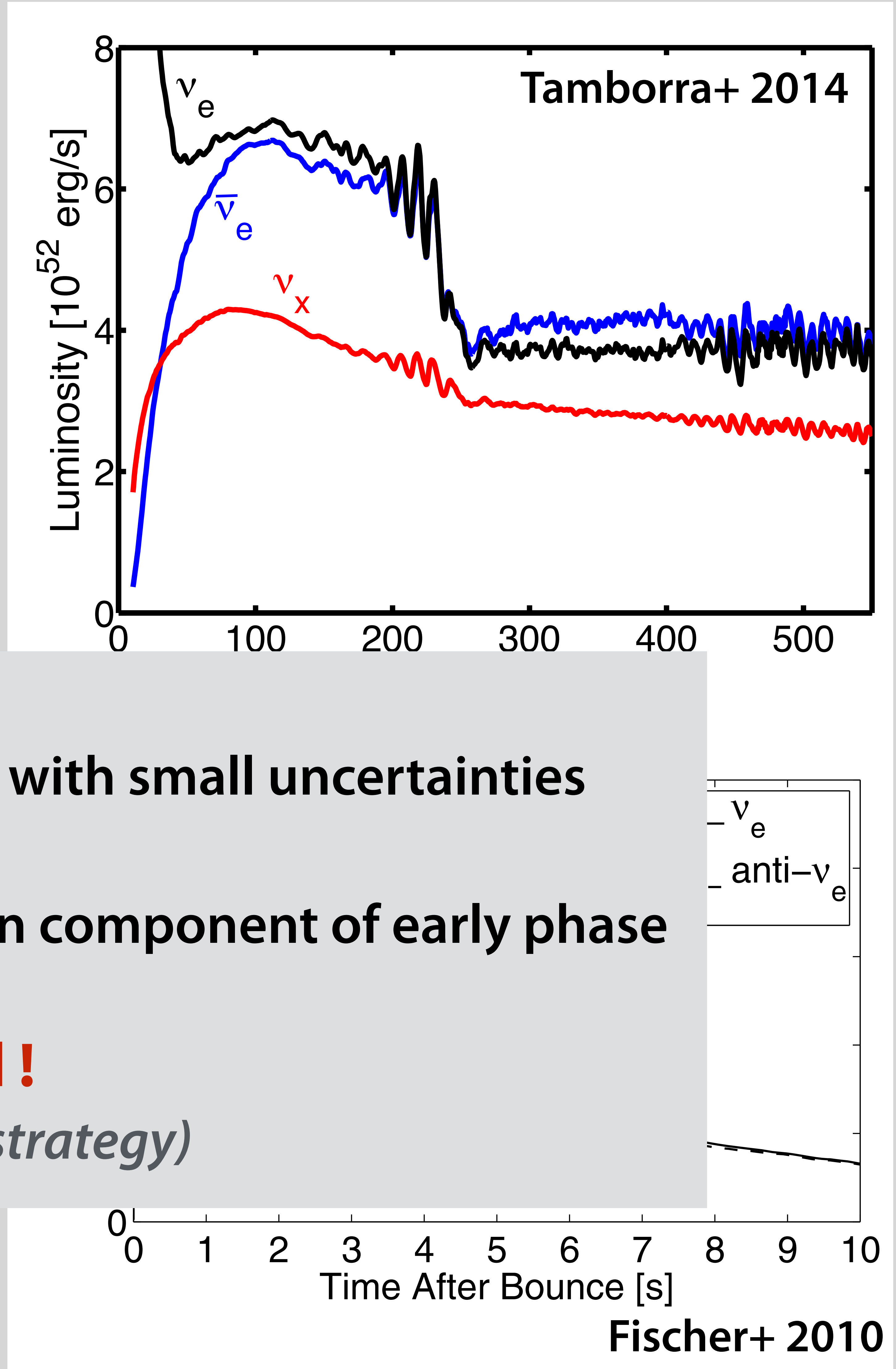
NIT, Numazu: K. Sumiyoshi (Theory)

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)

3 Steps

step 1

$f(x)$

NUMERICAL SIMULATIONS

- Cooling curves of PNS
- Detailed physics included
- Discrete grid of data set
- Computationally expensive

step 2

ANALYTIC SOLUTIONS

- Analytic cooling curves
- Calibrated w/ numerical sol.
- Simplified but essential physics included
- Fast and continuous

step 3

DATA ANALYSIS

- Mock sampling
- Analysis pipeline for real data
- Error estimate for future observations

step 1

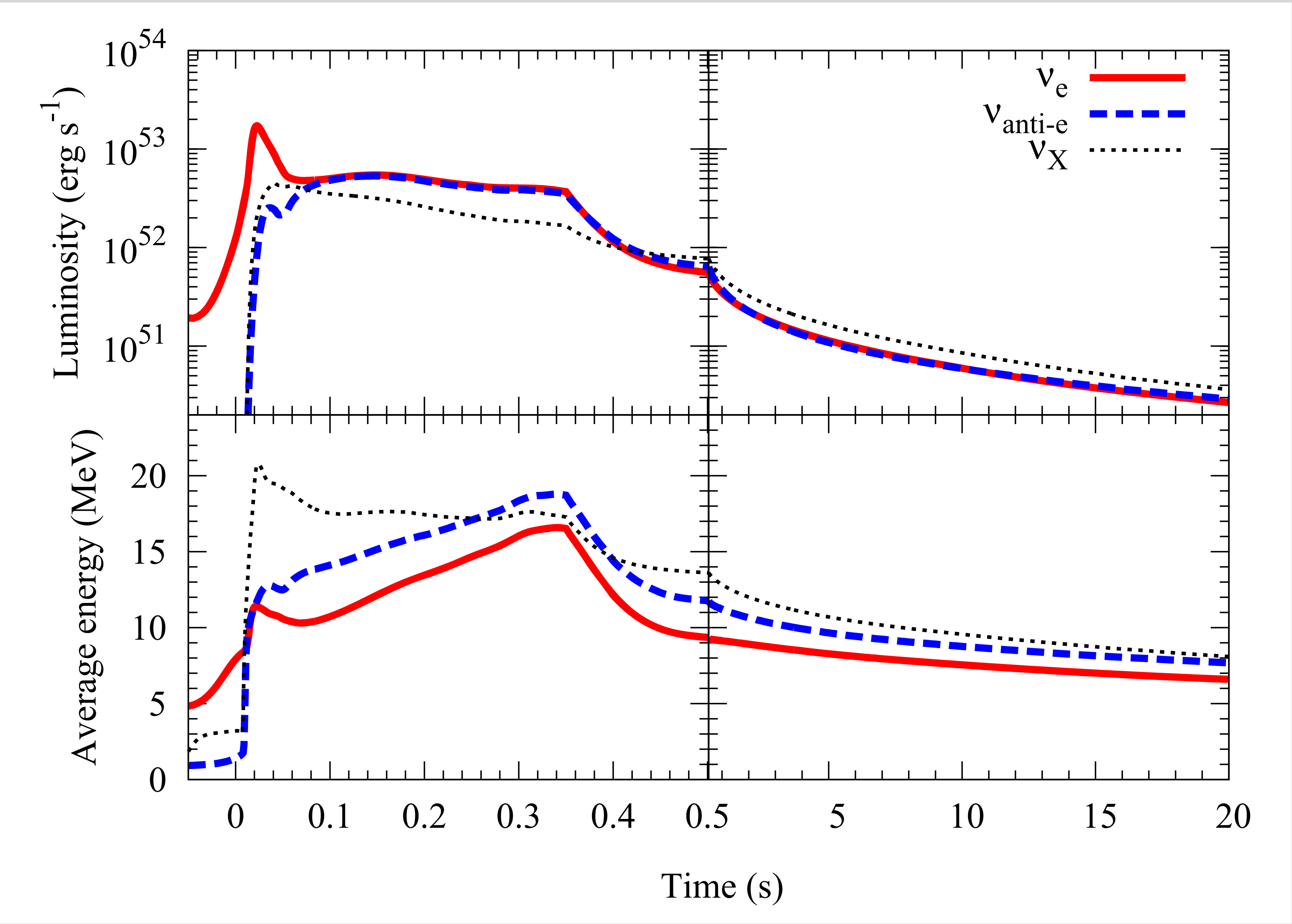
NUMERICAL SIMULATIONS

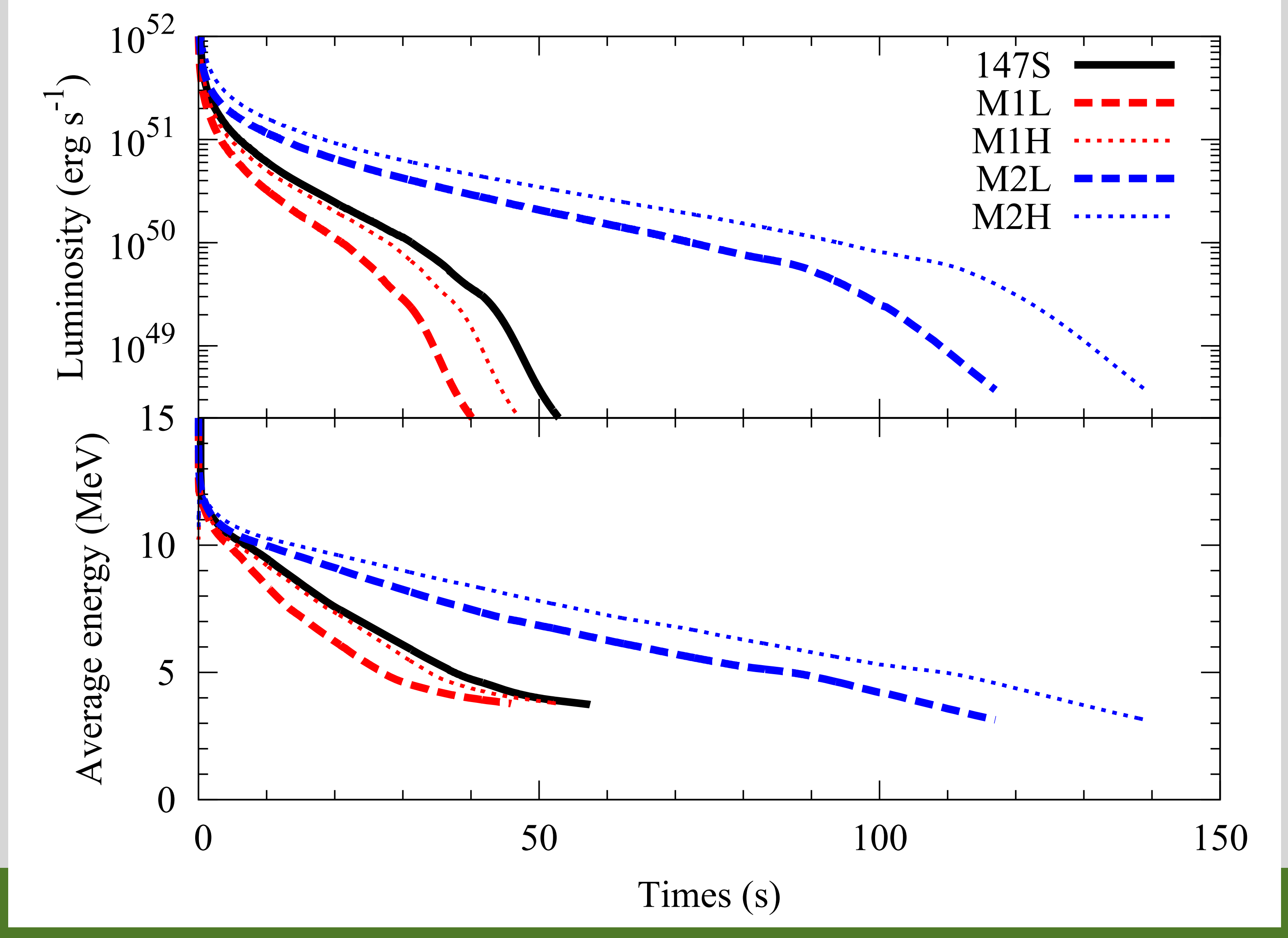
- Cooling curves of PNS
- Detailed physics included
- Discrete grid of data set
- Computationally expensive

Numerical simulations

[Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, **881**, 139 (2019)]
[Nakazato, Nakanishi, Harada, Koshio, Suwa, Sumiyoshi, Harada, Mori, Wendell, arXiv:2108.03009]

- **PNS cooling simulations beyond 10 s**
  - up to 20 s for models based on hydro. simulations (Nakazato et al. 2013)
  - up to > 100 s for models based on parametric PNS with broad mass range (1.20 to 2.05$M_\odot$)
- **Nuclear equation of state dependence**
- **Detector response of Super-Kamiokande**
  - event rate
  - positron spectrum
  - complete data up to the last detectable event





Simplified analytic model

step 2

$f(x)$

ANALYTIC SOLUTIONS

- Analytic cooling curves
- Calibrated w/ numerical sol.
- Simplified but essential physics included
- Fast and continuous

[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**

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

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

* **Neutrino luminosity with given entropy**

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

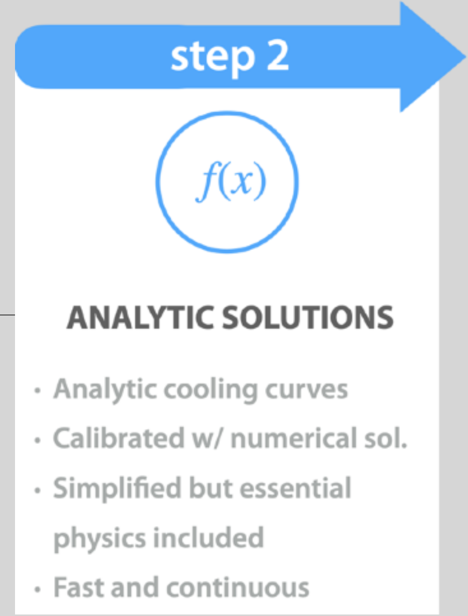
* **Time evolution**

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

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

Analytic solutions of neutrino light curves

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



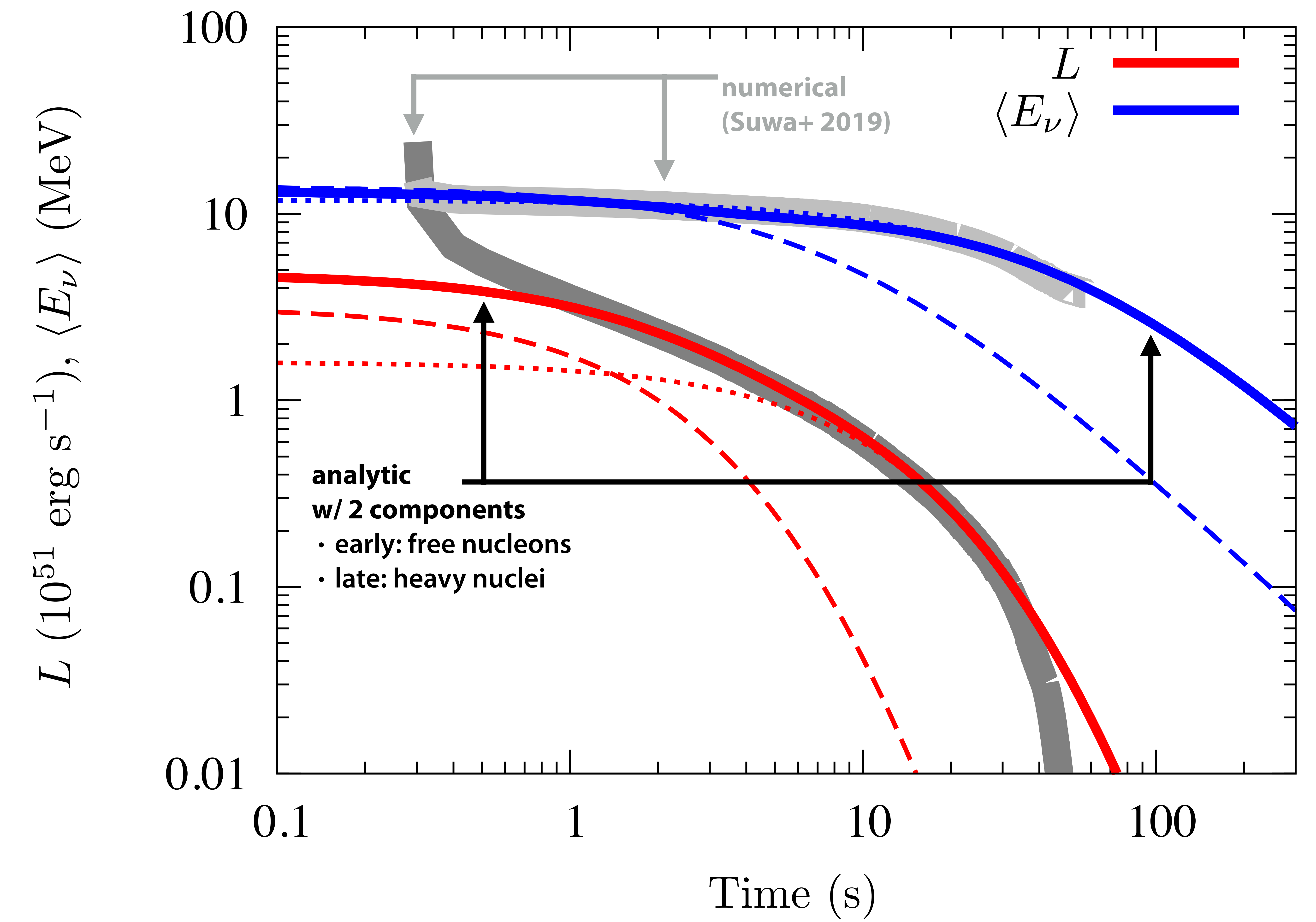
- Solve neutrino transport eq. analytically
  - **Neutrino luminosity**

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

  - **Neutrino average energy**

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

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



Observables with analytic solutions

step 2

$f(x)$

ANALYTIC SOLUTIONS

- Analytic cooling curves
- Calibrated w/ numerical sol.
- Simplified but essential physics included
- Fast and continuous

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

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

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

- **Positron average energy**

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

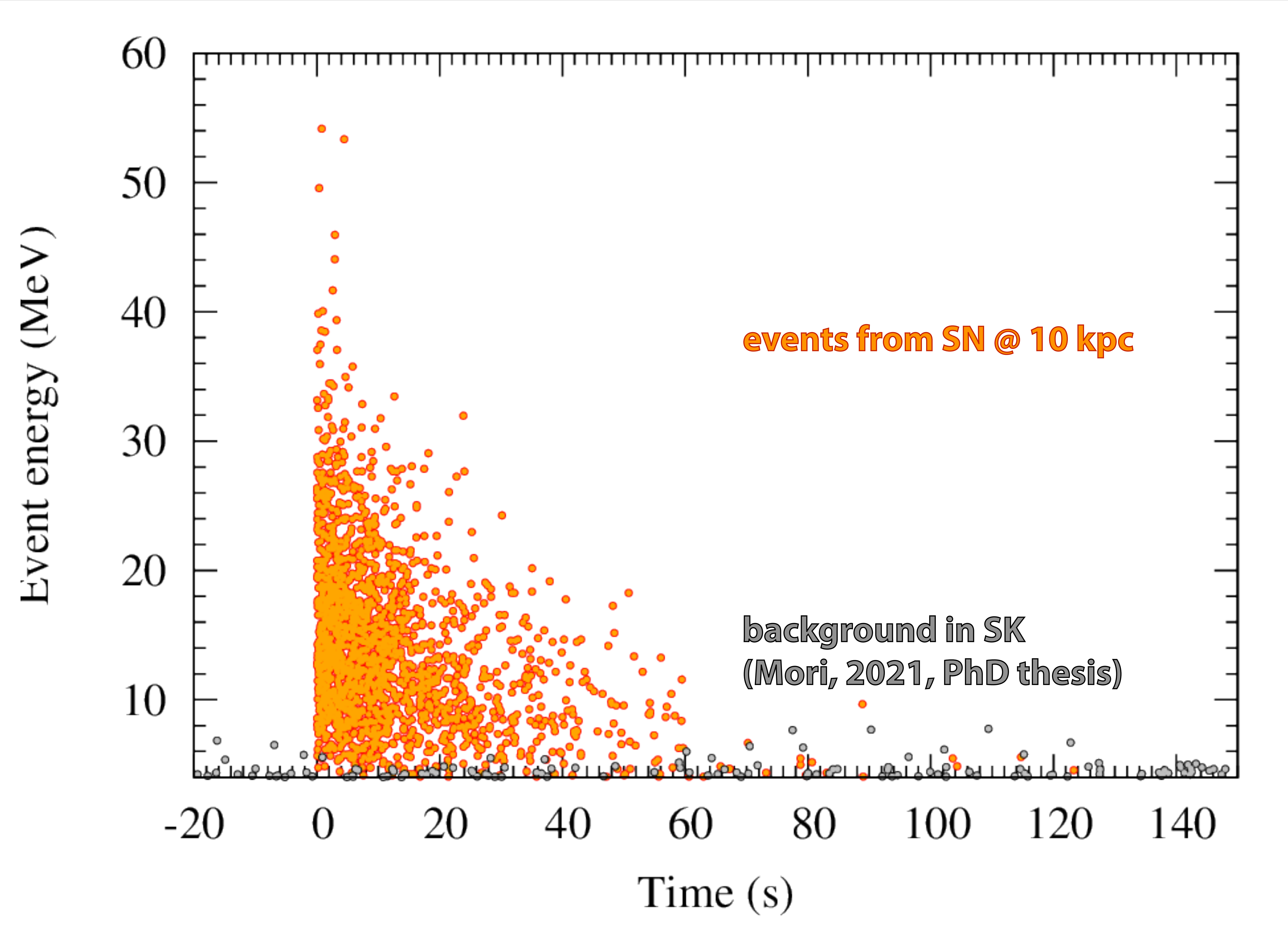
- **PNS radius**

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

- **Consistency relation of analytic model**

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

Mock sampling

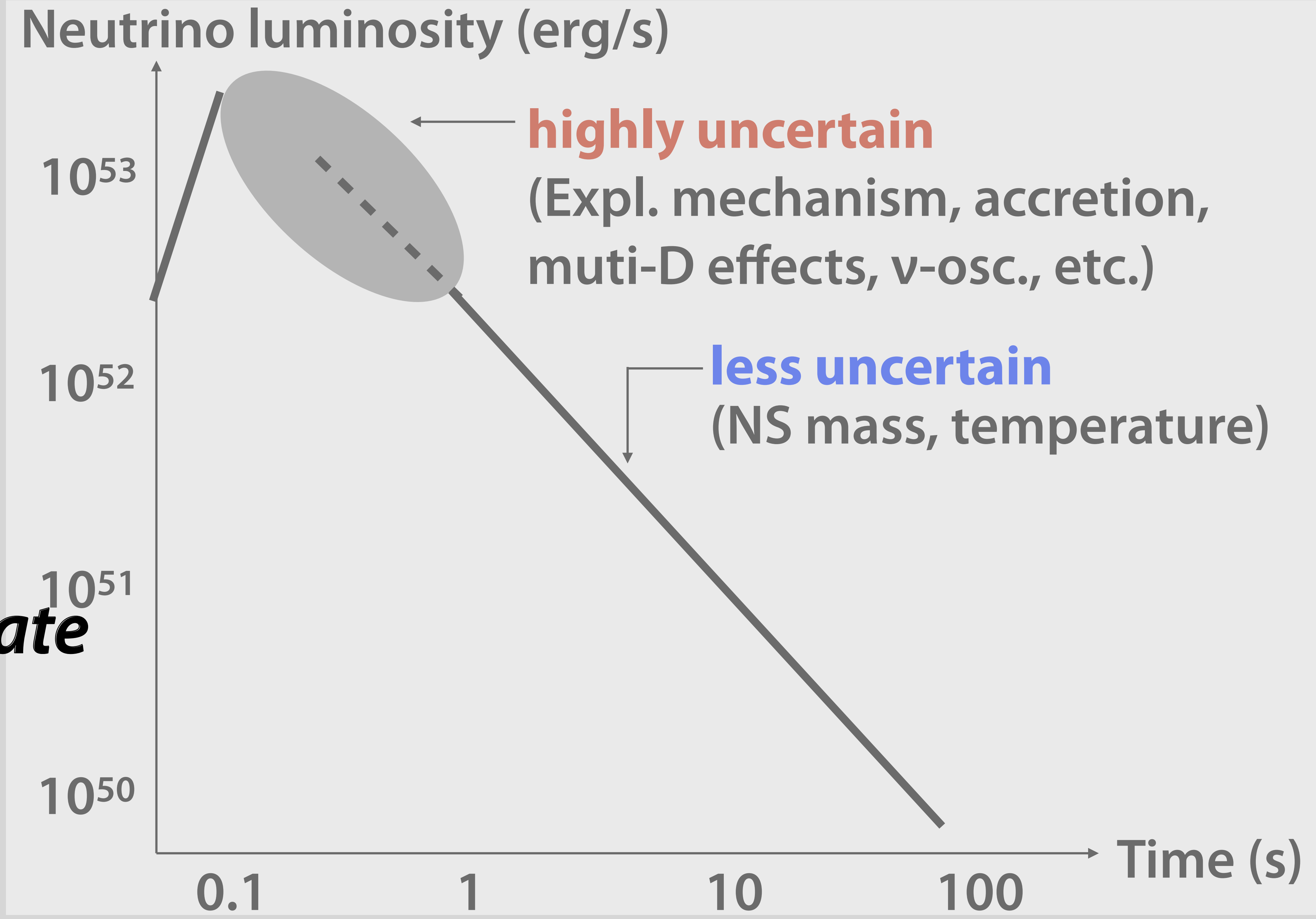


Toward physics in the next Galactic supernova

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

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

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

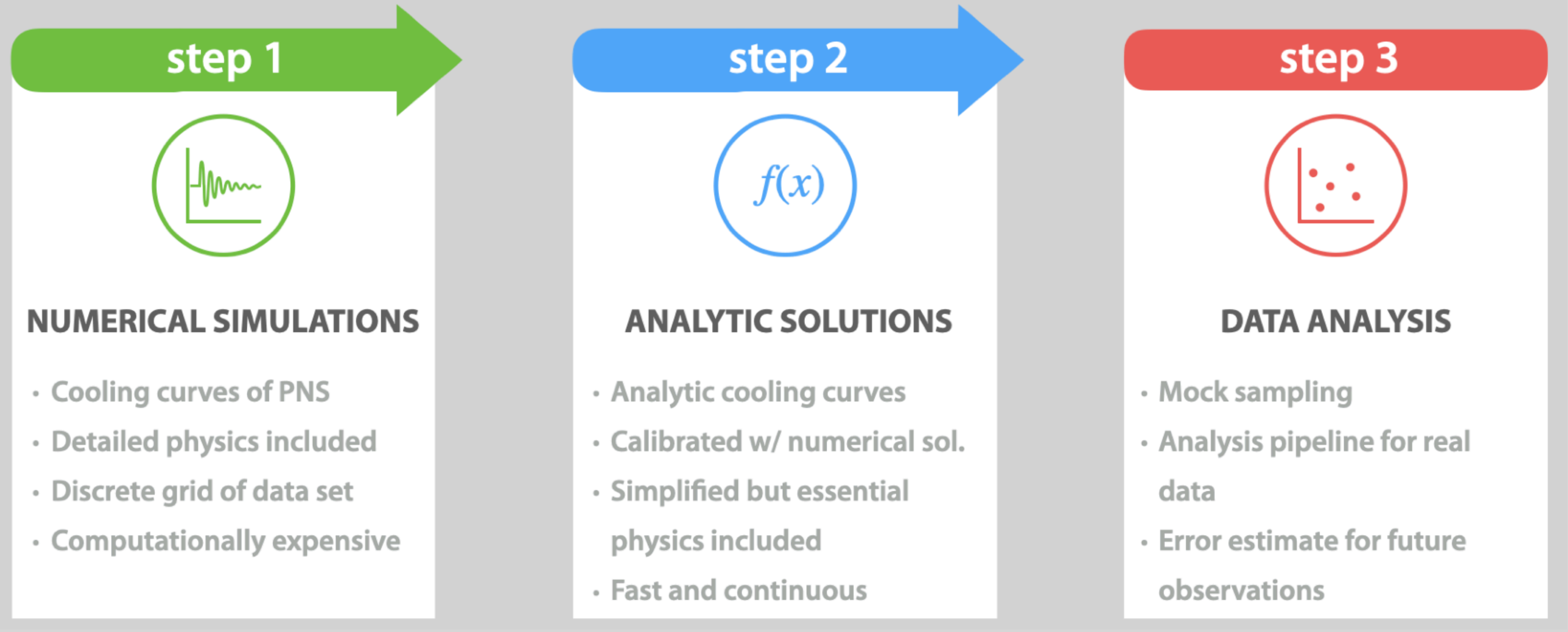


Summary

* 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)*
  - ☑ making use of simplified analytic model
  - ☑ detailed numerical simulations



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