Unraveling the Supernova Interior with Super-Kamiokande

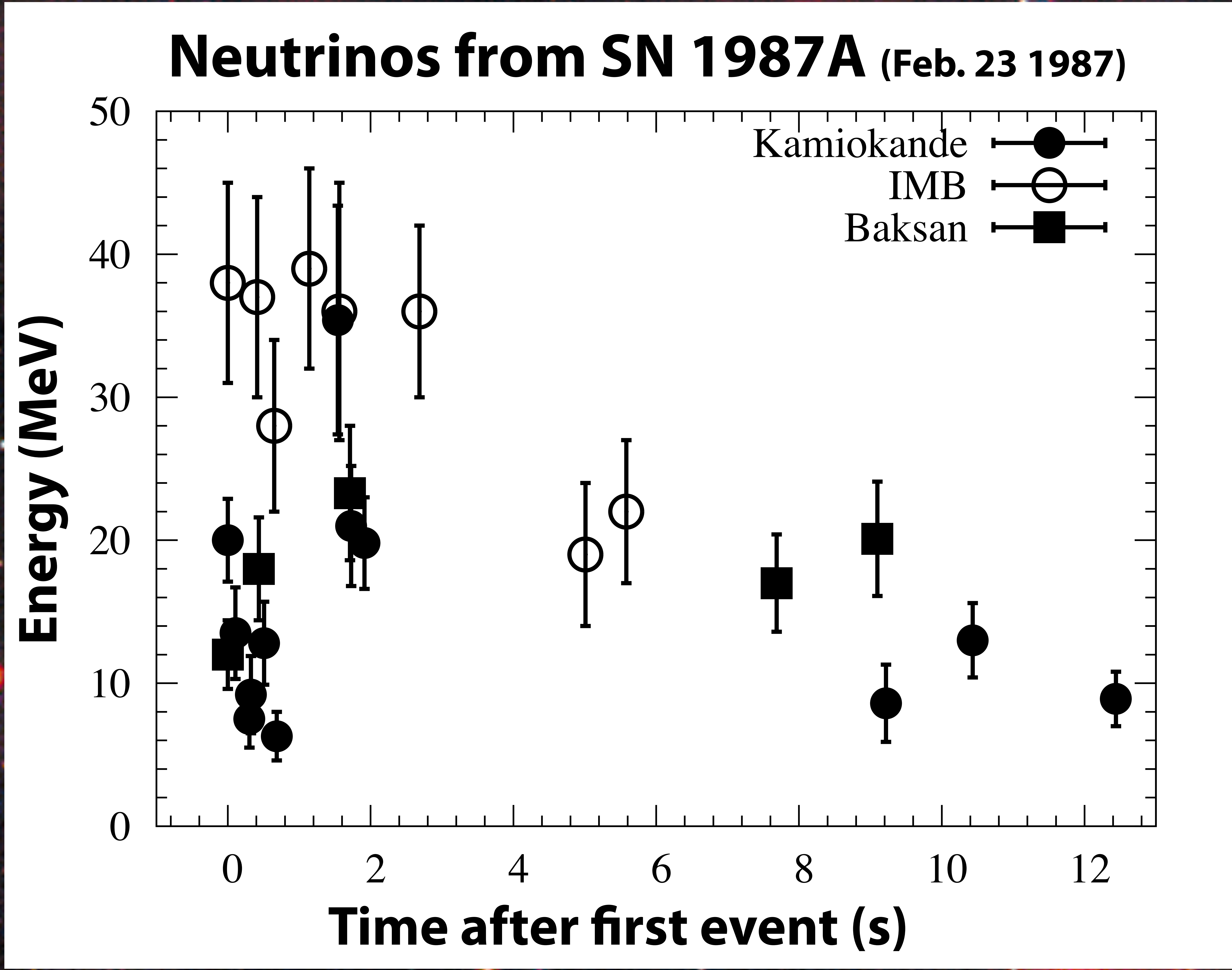
Yudai Suwa

(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, 925, 98 (2022)
YS, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, arXiv:2204.08363

SN1987A



NASA/ESA

What can we extract from neutrino observations?

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

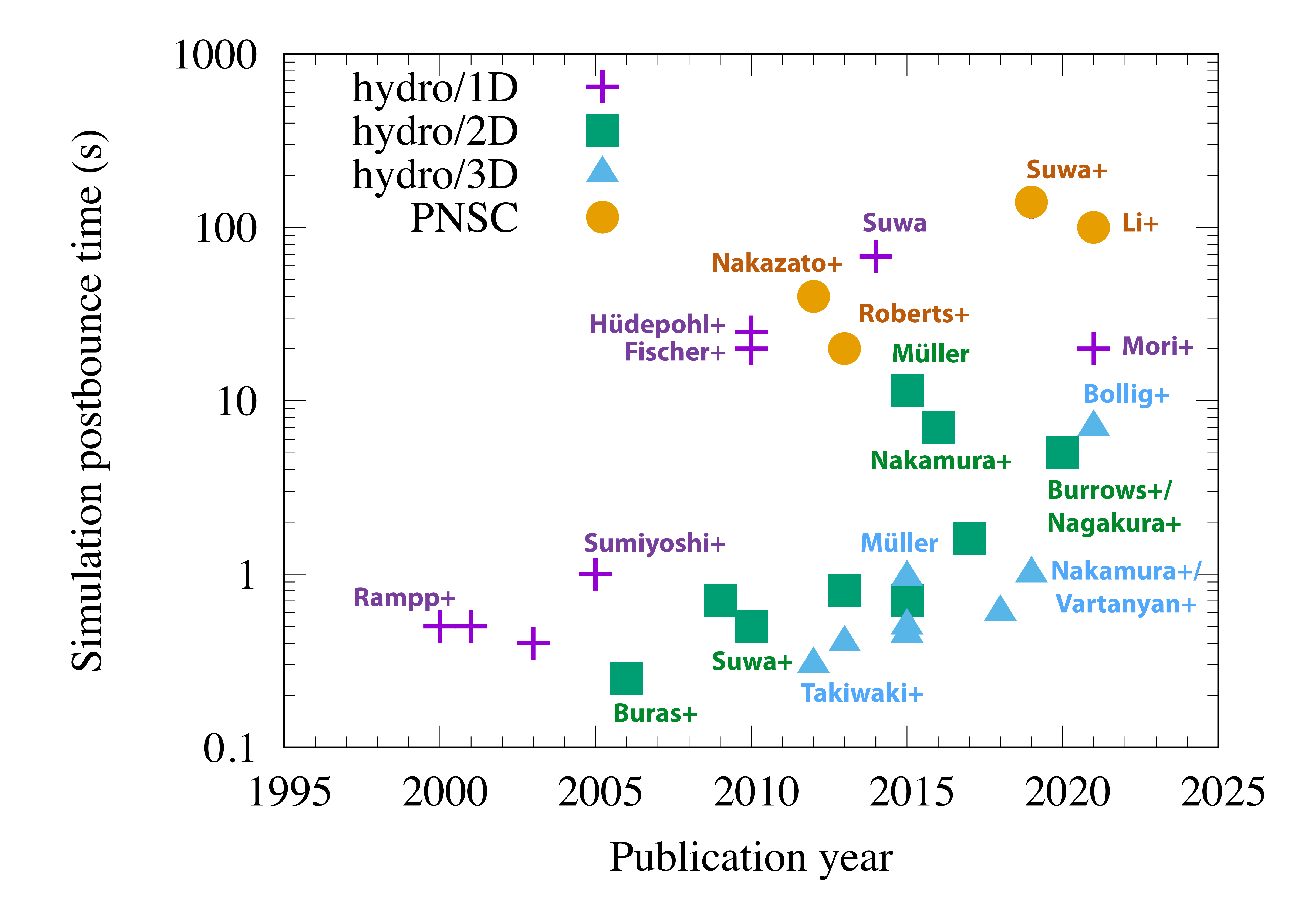
$$E_b \approx \frac{GM_{\rm NS}^2}{R_{\rm NS}} = \mathcal{O}(10^{53})\mathrm{erg}\left(\frac{M_{\rm NS}}{1.4M_\odot}\right)^2\left(\frac{R_{\rm NS}}{10\mathrm{km}}\right)^{-1}$$

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

The latest SN found in our Galaxy, G1.9+0.3 (<150 years old) © NASA

Long-term evolution is necessary

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 only short period and limited numbers)*

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, 925, 98 (2022)
5. Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, arXiv:2204.08363

Kyoto U.: R. Wendell (Experiment)

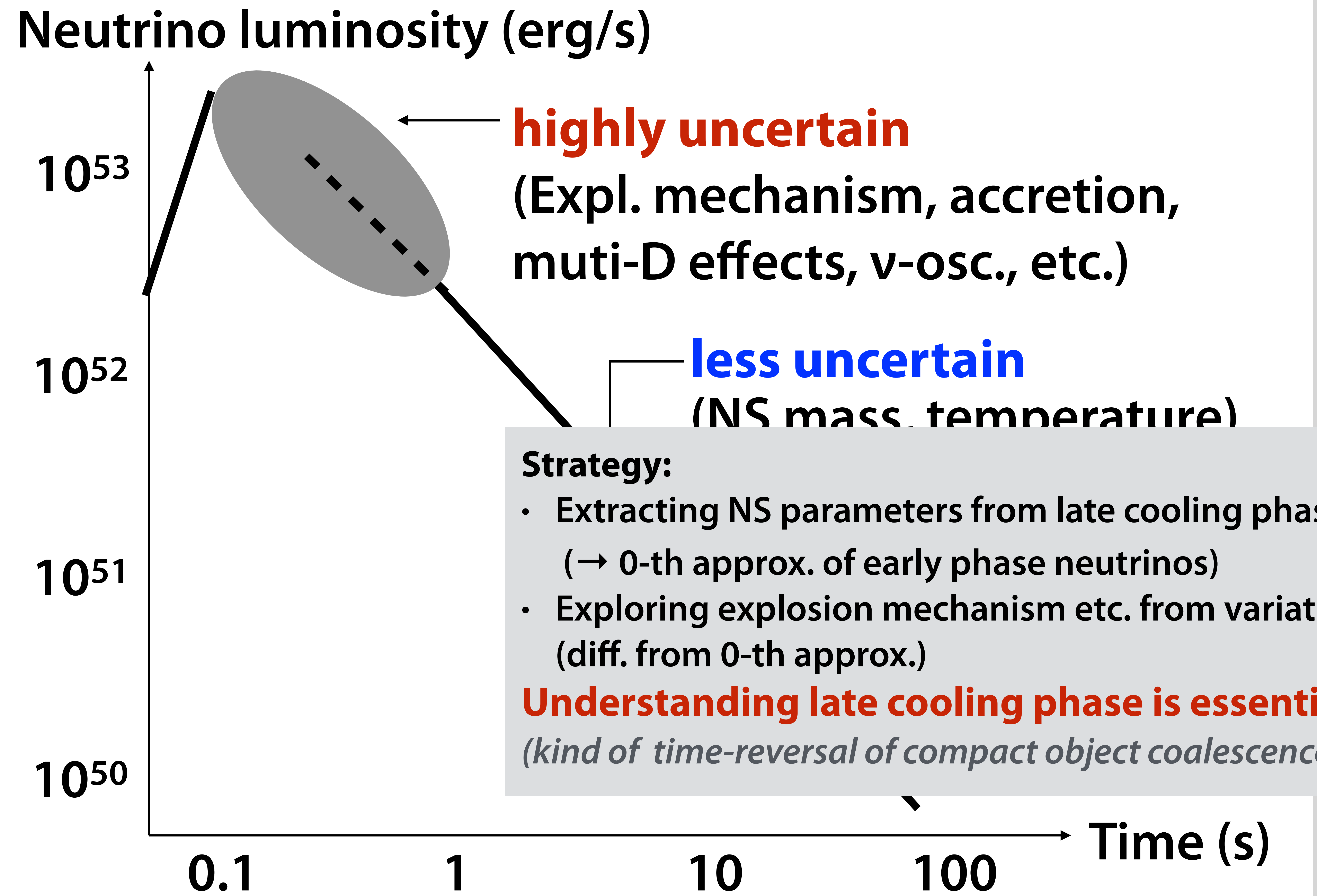
Riken: A. Harada (Theory)
U. Tokyo: Y. Suwa, M. Mori (Theory/Experiment)

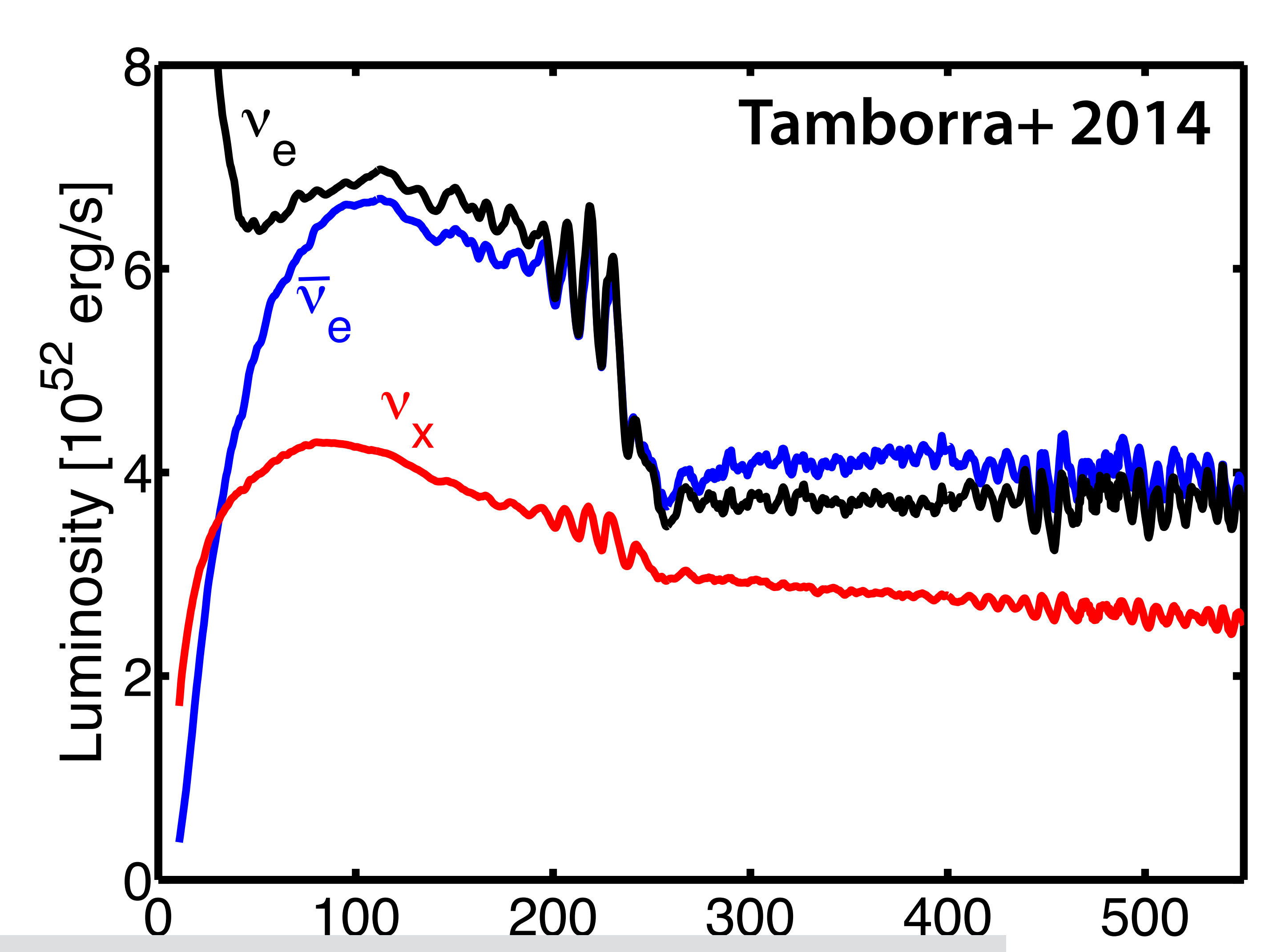
NIT, Numazu: K. Sumiyoshi (Theory)

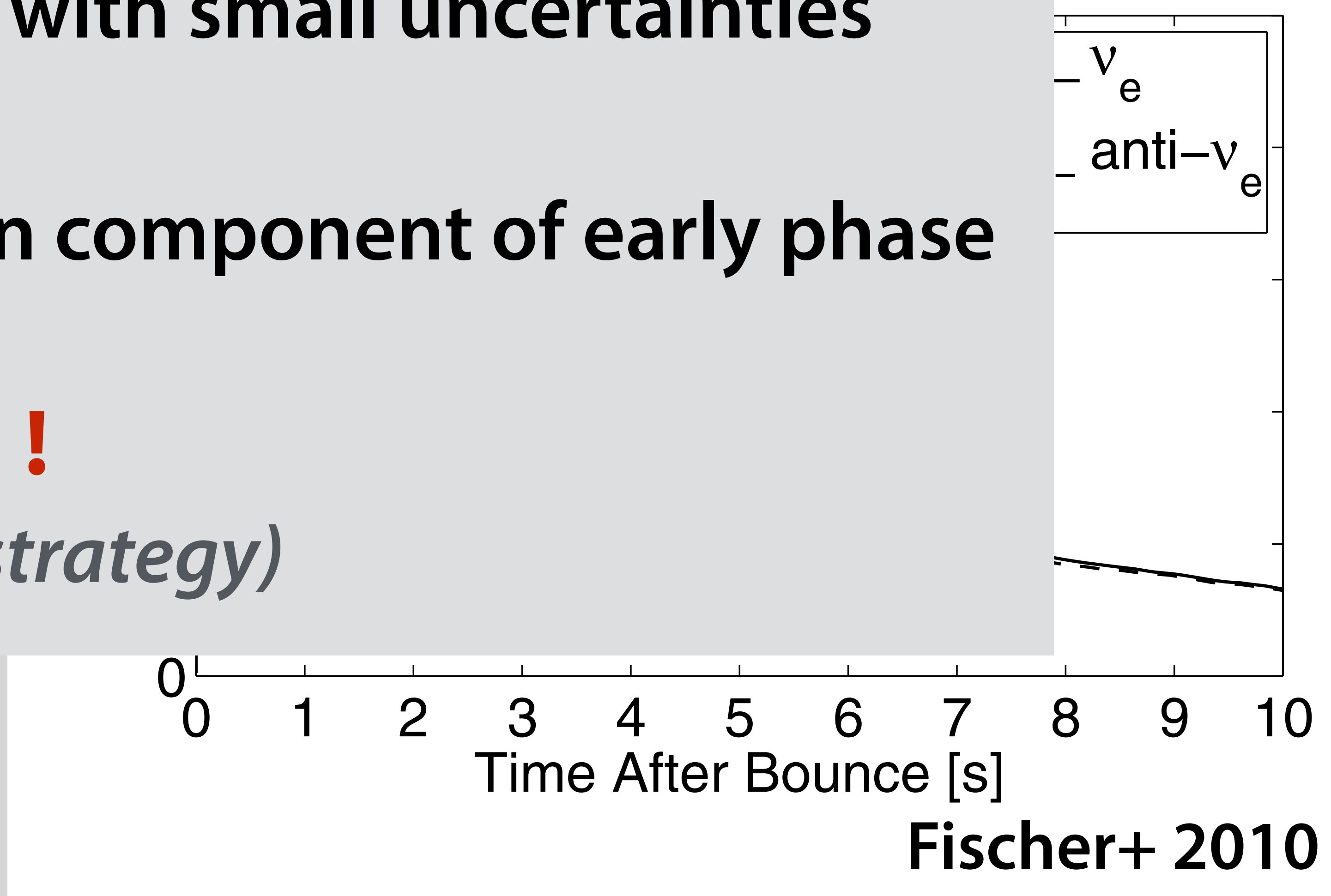
Okayama U.: Y. Koshio, M. Harada, F. Nakanishi (Experiment)

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)

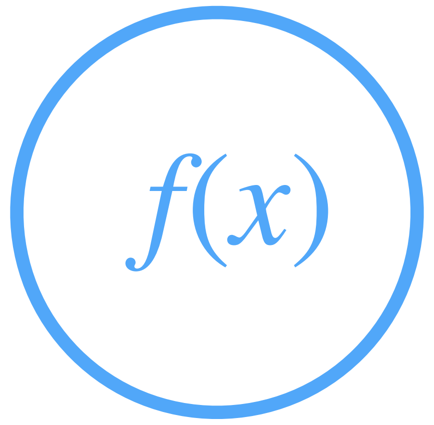
3 Steps

step 1

NUMERICAL SIMULATIONS

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

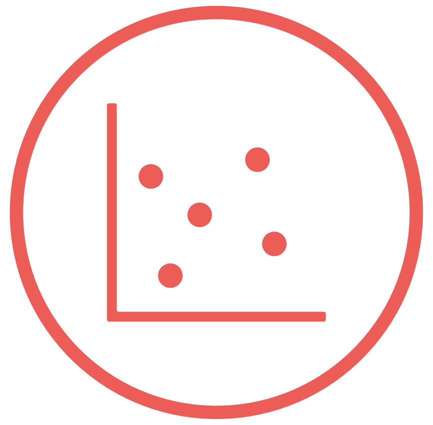
step 2



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

Numerical simulations

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

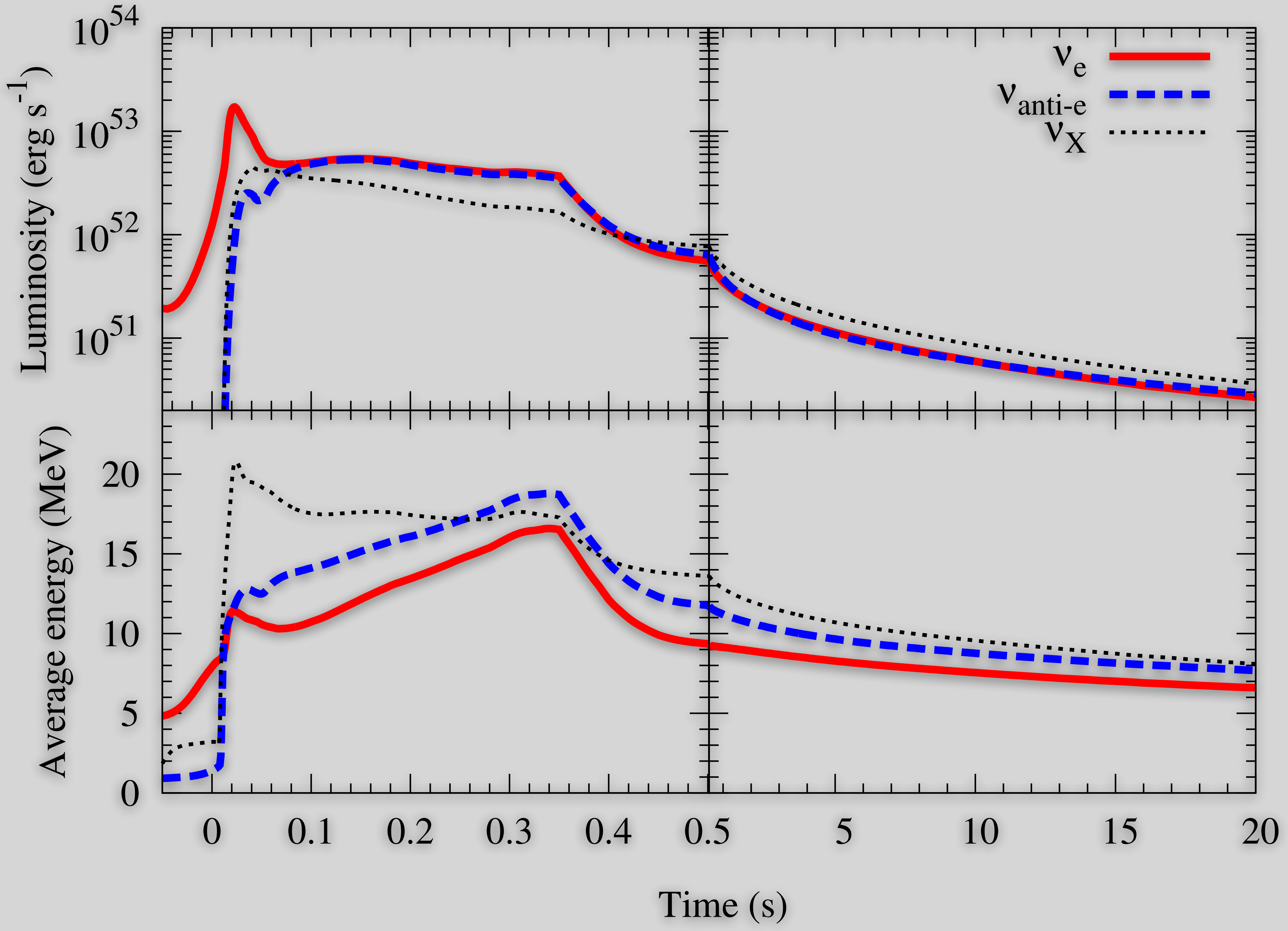
step 1

NUMERICAL SIMULATIONS

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

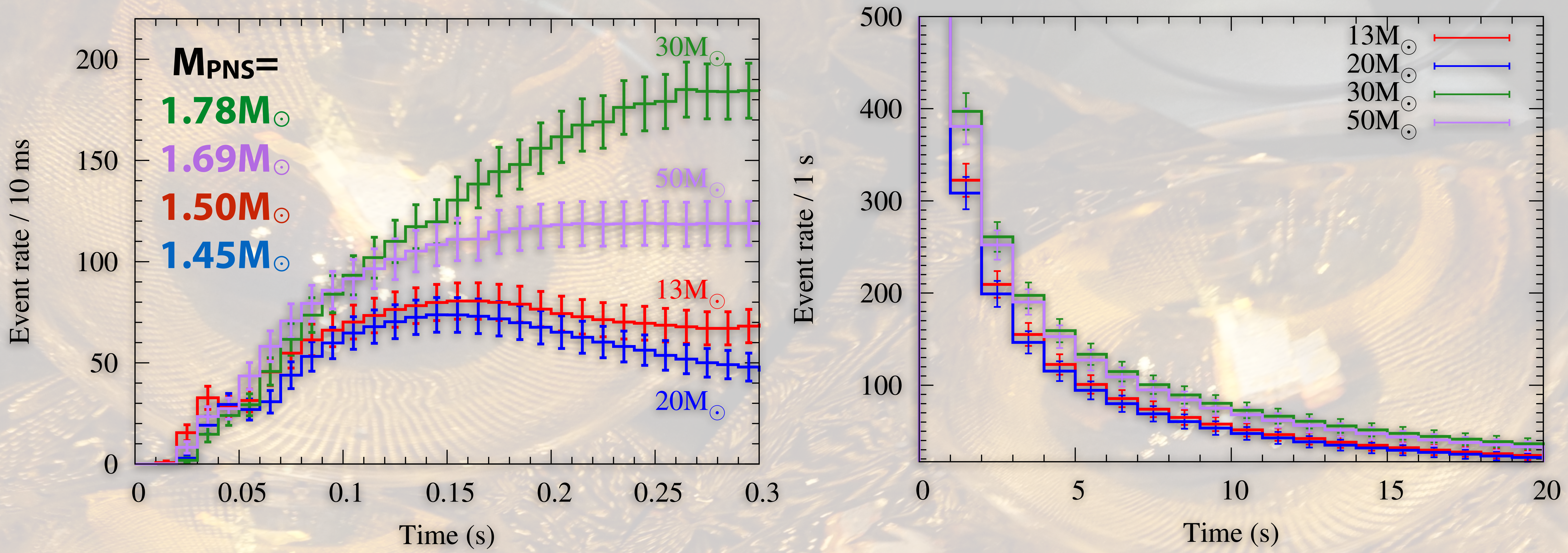
- **Hydro. simulation (t<0.3s)**
  - **dynamical, GR, Boltzmann neutrino transport, nuclear EOS, 1D**
    Yamada 1997, Sumiyoshi+ 2005
- **PNS cooling simulation (t>0.3s)**
  - **static (TOV), FLD neutrino transport, nuclear EOS, 1D**
    Suzuki 1993
- **Connection**
  - **Interpolate two results with 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 ($\bar{\nu}_e + p \to e^+ + n$)
* **Event rate is not related to progenitor mass, but PNS mass**

step 1

NUMERICAL SIMULATIONS

- Cooling curves of PNS
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- Computationally expensive

Longer simulations with broader NS mass range

step 1

NUMERICAL SIMULATIONS

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

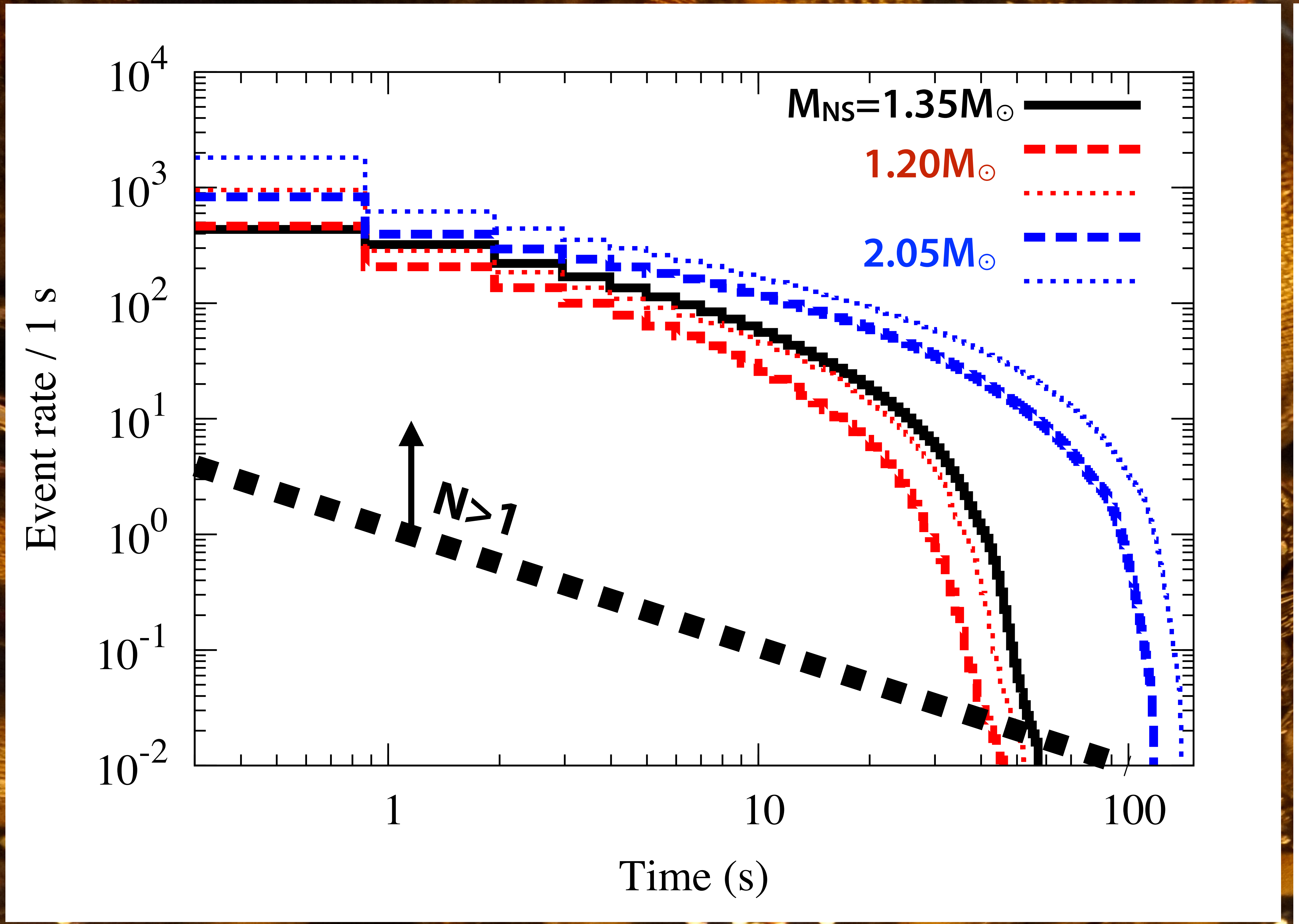
- Even 20 s after the explosion, the event rate is still high
- known mass range of NS is large: [1.17, 2.01]$M_\odot$
  Demorest+ 2010, Antoniadis+ 2013, Martinez+ 2015
  (see also Cromartie+ 2019, Romani+ 2021, for more recent update)

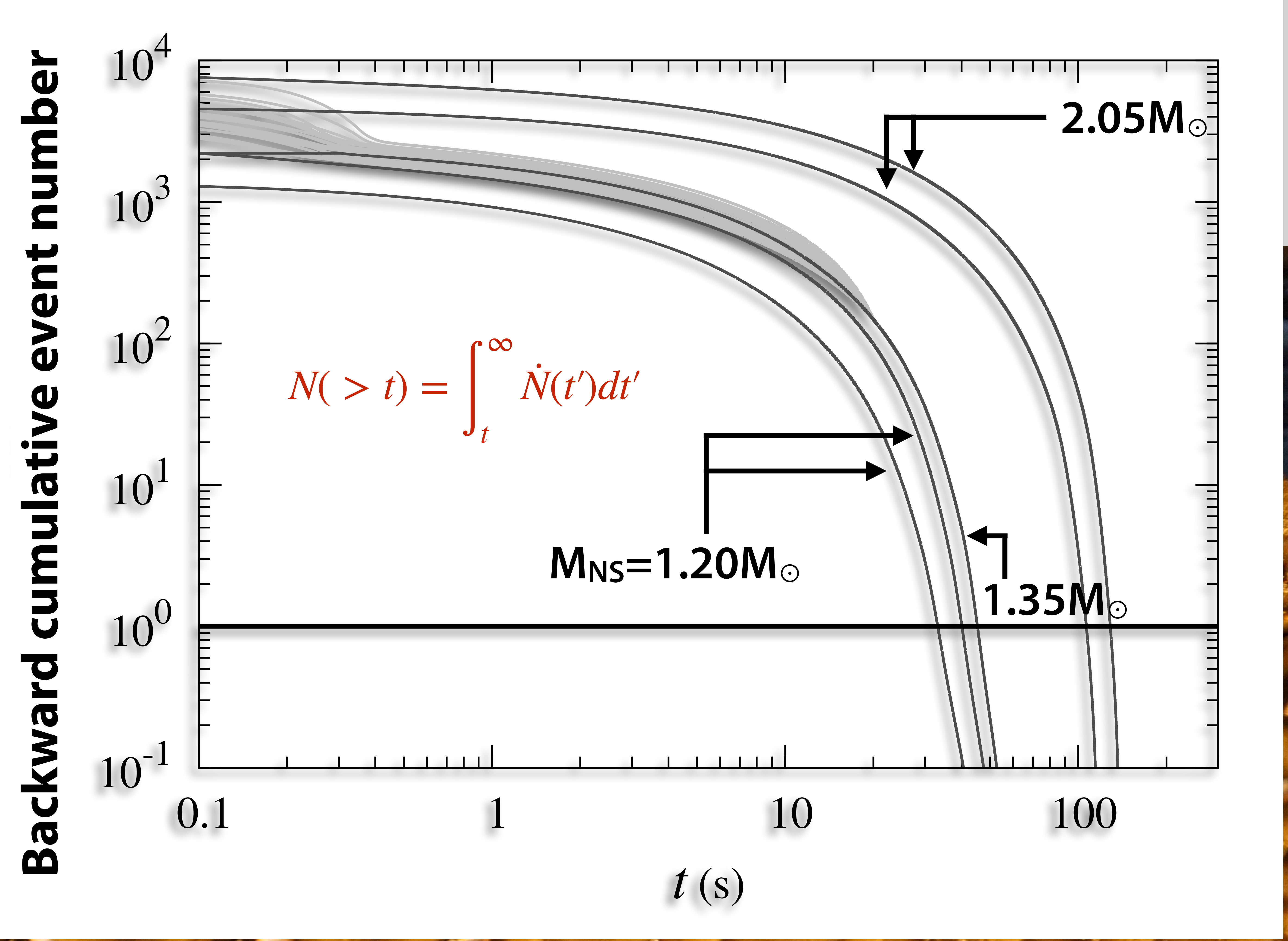
- Additional long-term simulations for PNS cooling
  - canonical model has M_{NS}=1.35$M_\odot$
  - parametric models
    - with M_{NS}=1.20$M_\odot$ and 2.05$M_\odot$
    - with two extreme entropy profiles (low and high)
  - up to the *last* detectable event

How long can we see SN with neutrinos?

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

step 1





How long can we see SN with neutrinos?

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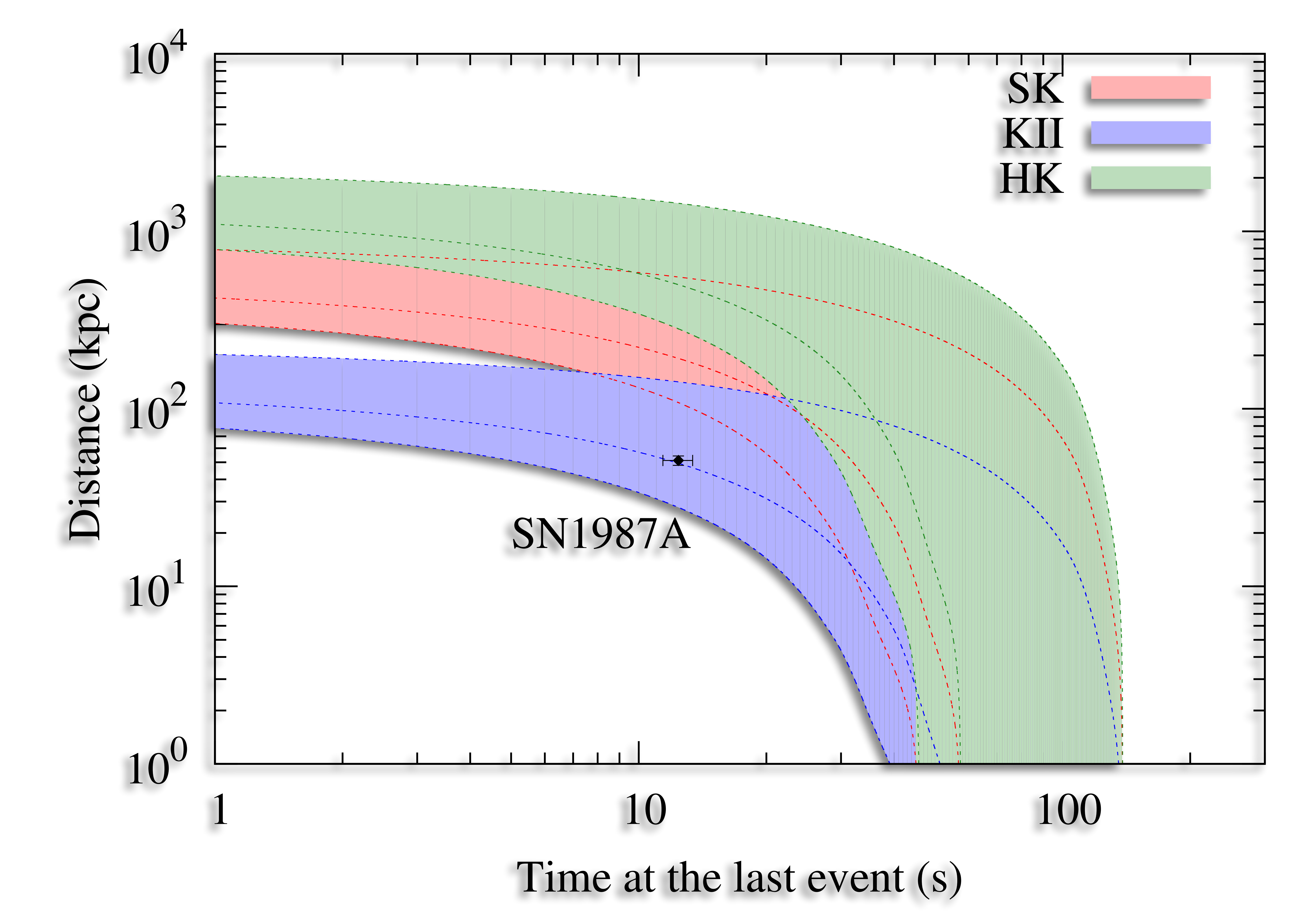

step 1

NUMERICAL SIMULATIONS

- Cooling curves of PNS
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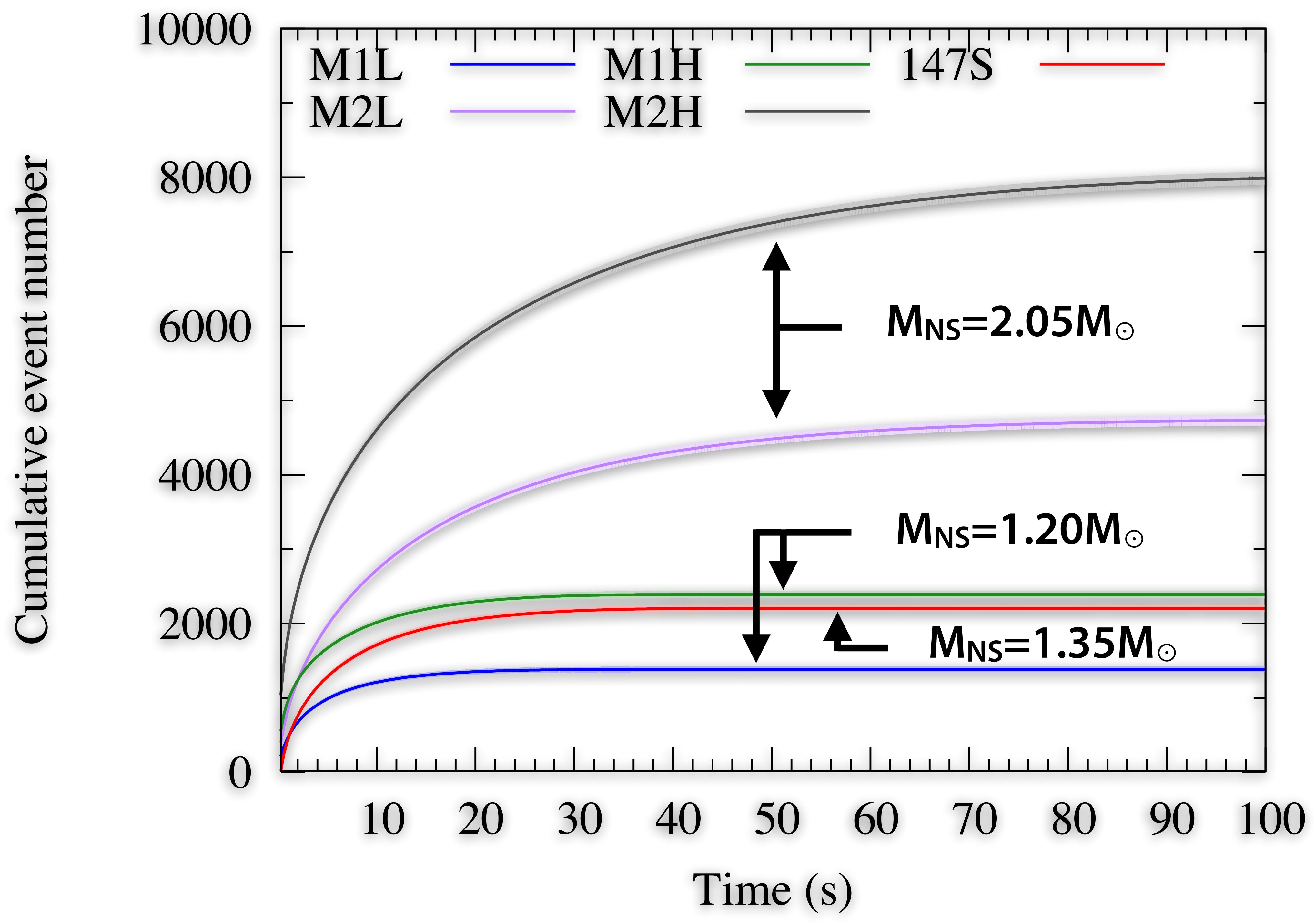
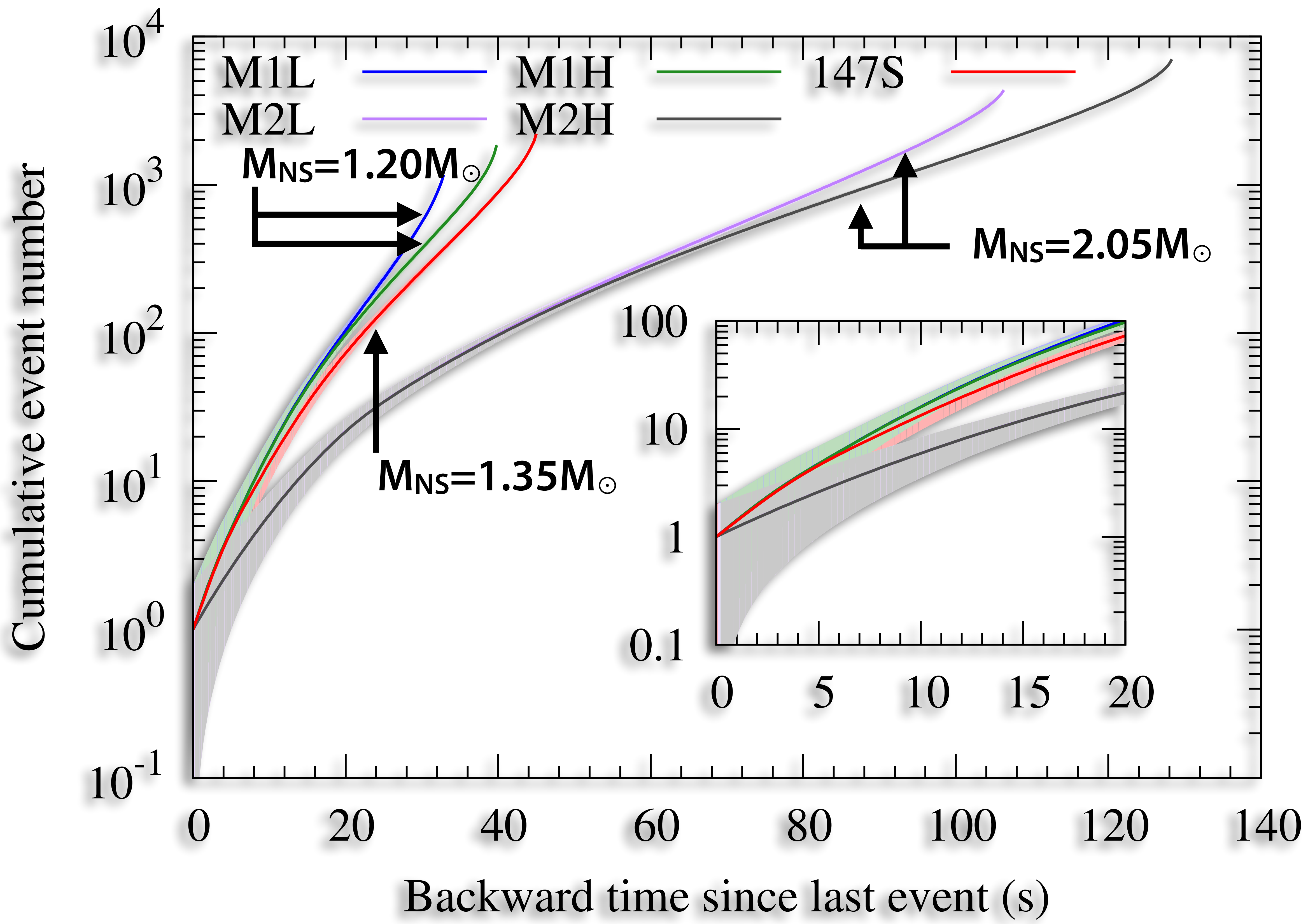
- Computationally expensive

How to analyze neutrinos? Backward cumulative plot is useful

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

step 1

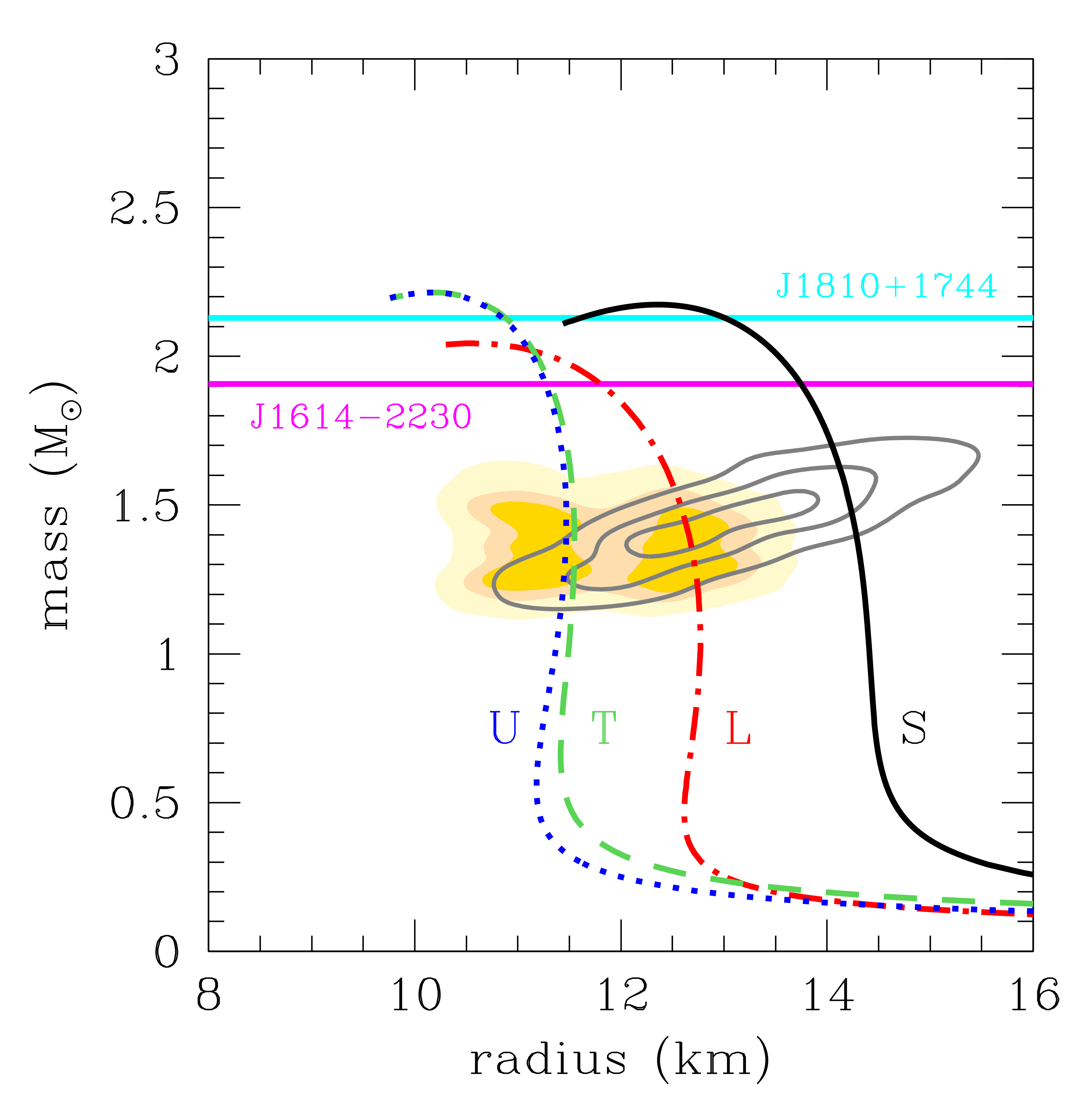


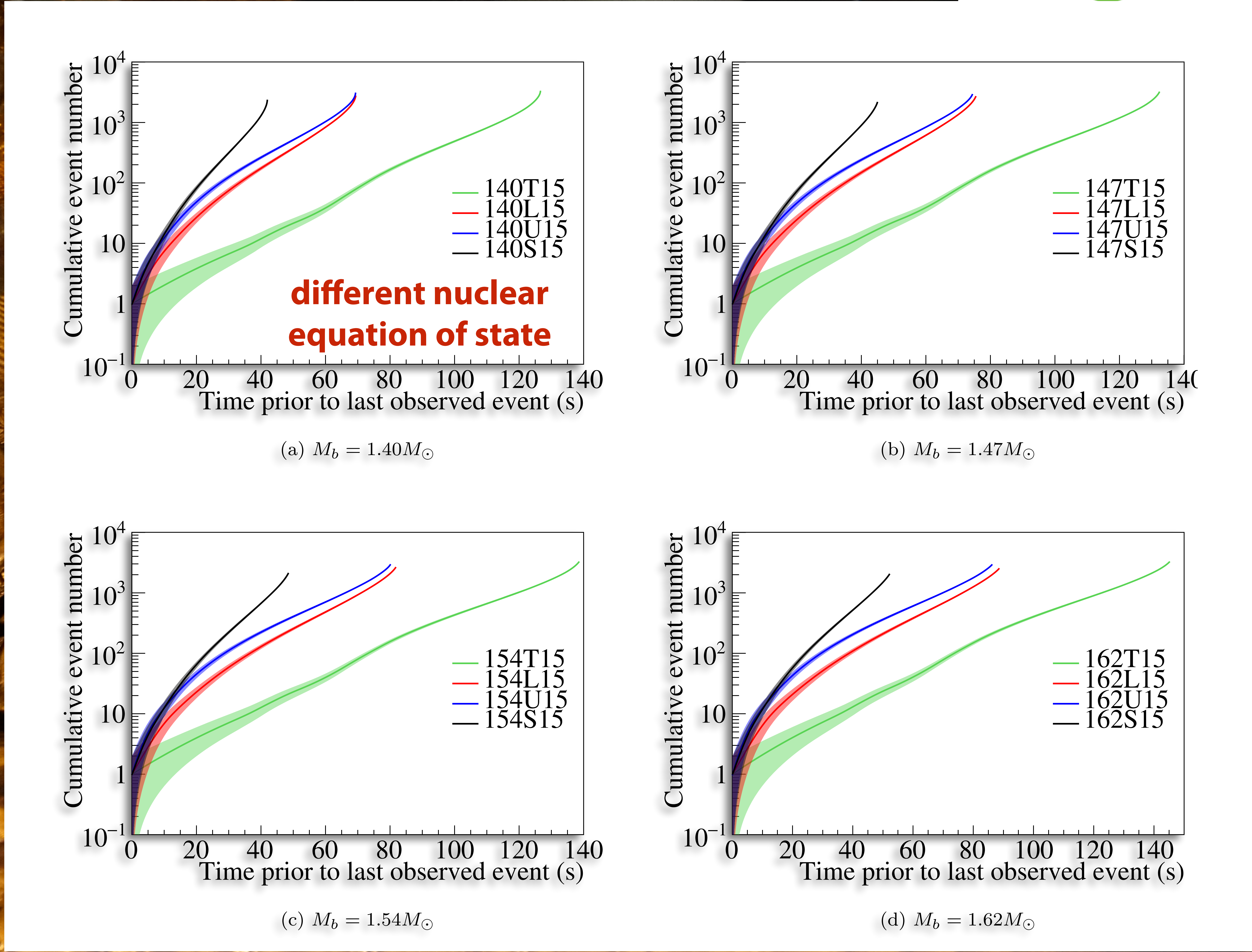


step 1

Model grids are getting larger

[Nakazato, Nakanishi, Harada, Koshio, Suwa, Sumiyoshi, Harada, Mori, Wendell, ApJ, 925, 98 (2022)]





(a) $M_b = 1.40 M_\odot$

(b) $M_b = 1.47 M_\odot$

(c) $M_b = 1.54 M_\odot$

(d) $M_b = 1.62 M_\odot$

Data is available from zenodo:

Paper I → zenodo.4632494

Paper II → zenodo.5778223

Next is analytic expression

- A Grid of PNS cooling simulations is getting broader

- Next step is simplified analytic model
- How?

step 2

$f(x)$

ANALYTIC SOLUTIONS

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

Simplified analytic model

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

step 2

$f(x)$

ANALYTIC SOLUTIONS

- Analytic cooling curves
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* **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**

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

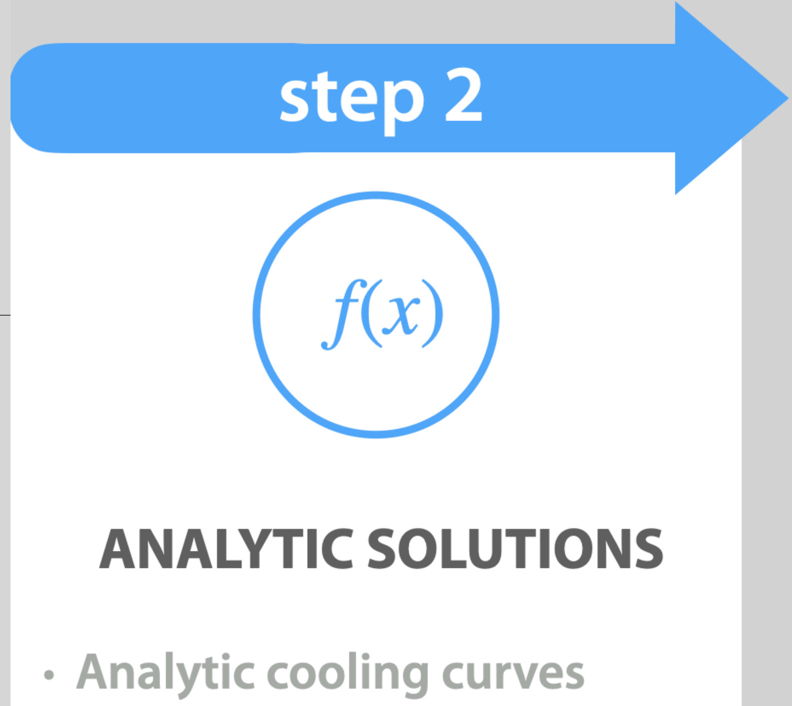
* **Time evolution**

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

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)]



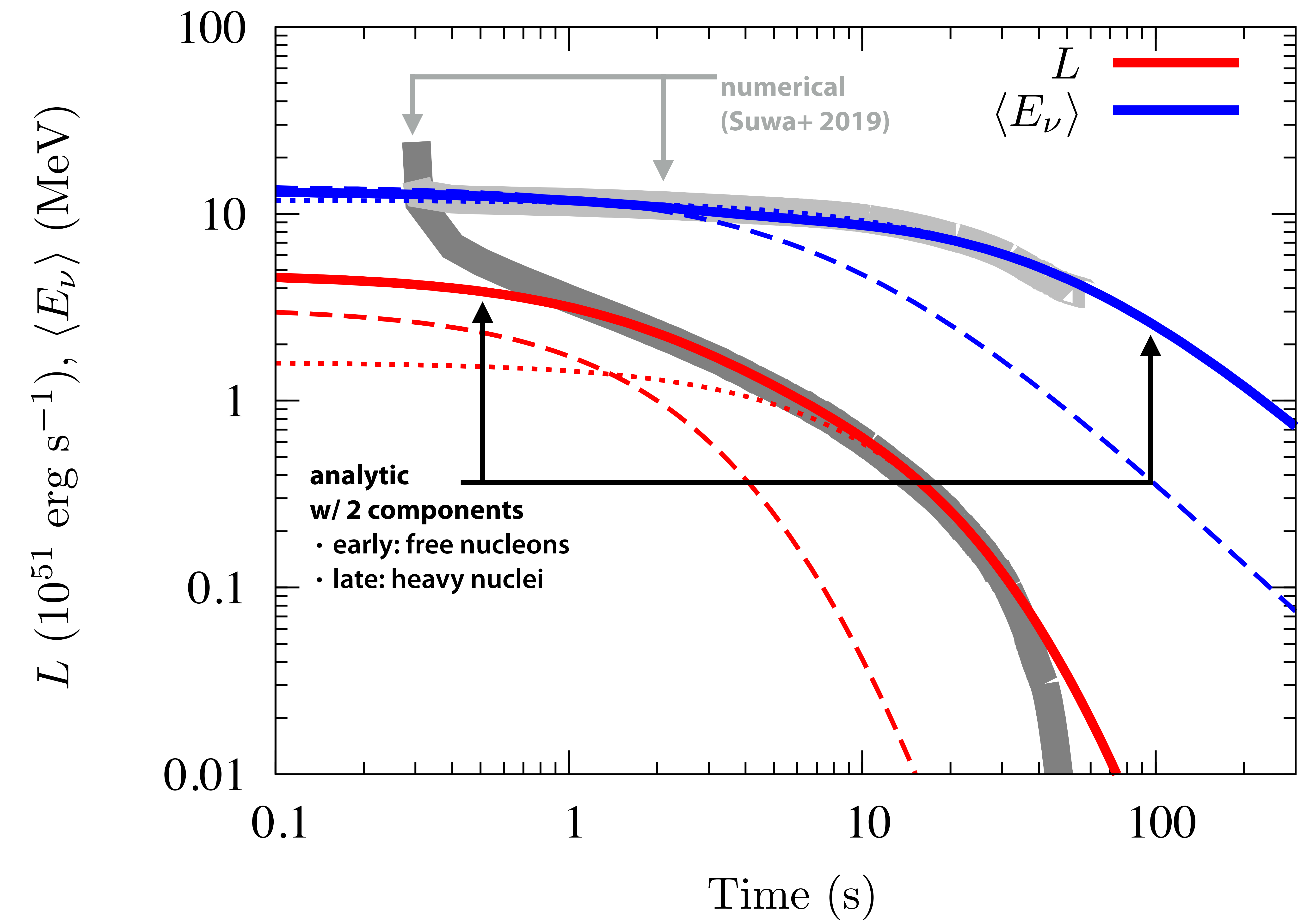
- **Solve neutrino transport eq. analytically**
  - **Neutrino luminosity**

$$L = 3.3\times10^{51}\,\mathrm{erg\,s^{-1}}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{6}\left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-6}\left(\frac{g\beta}{3}\right)^{4}\left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-6}$$

  - **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)]

step 2

$f(x)$

ANALYTIC SOLUTIONS

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

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

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

* **Positron average energy**

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

* **PNS radius**

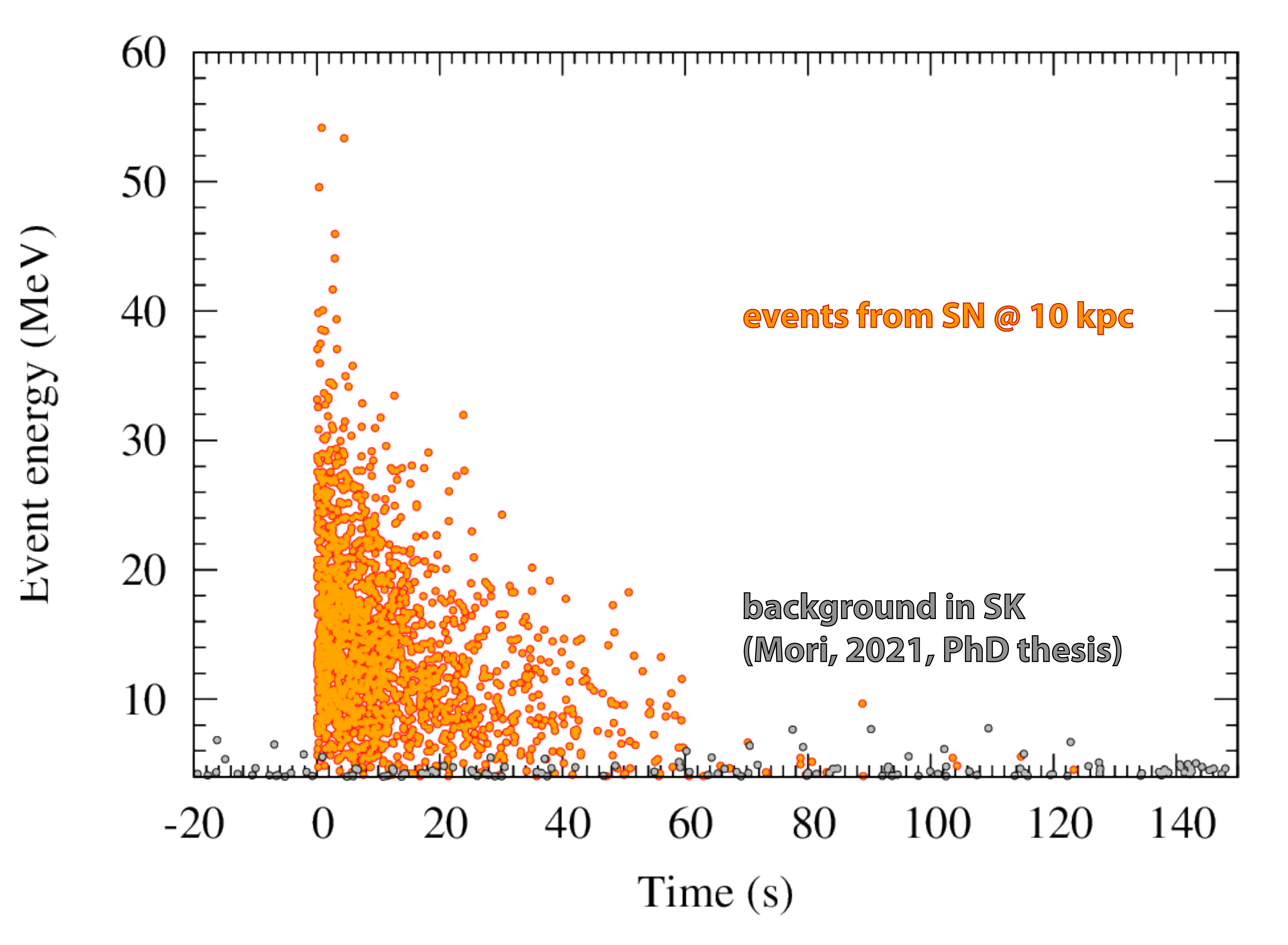
$$R_{\rm PNS} = 10\,\mathrm{km} \left(\frac{\mathscr{R}}{720\,\mathrm{s}^{-1}}\right)^{1/2} \left(\frac{E_{e^+}}{25\,\mathrm{MeV}}\right)^{-5/2} \left(\frac{M_{\rm det}}{32.5\,\mathrm{kton}}\right)^{-1/2} \left(\frac{D}{10\,\mathrm{kpc}}\right)$$

* **Consistency relation of analytic model**

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

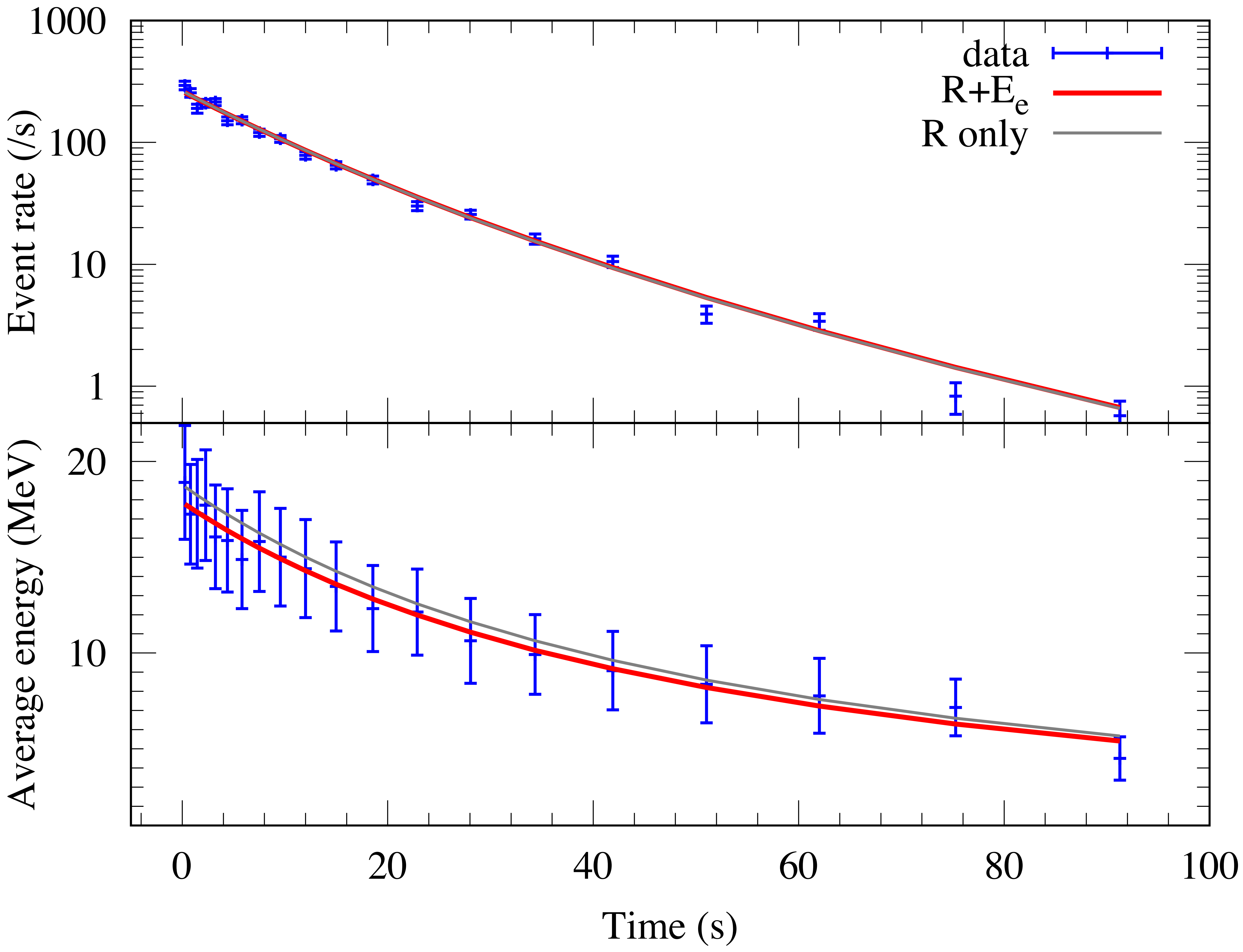
Mock sampling

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, arXiv:2204.08363]



χ^2 fit

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, arXiv:2204.08363]



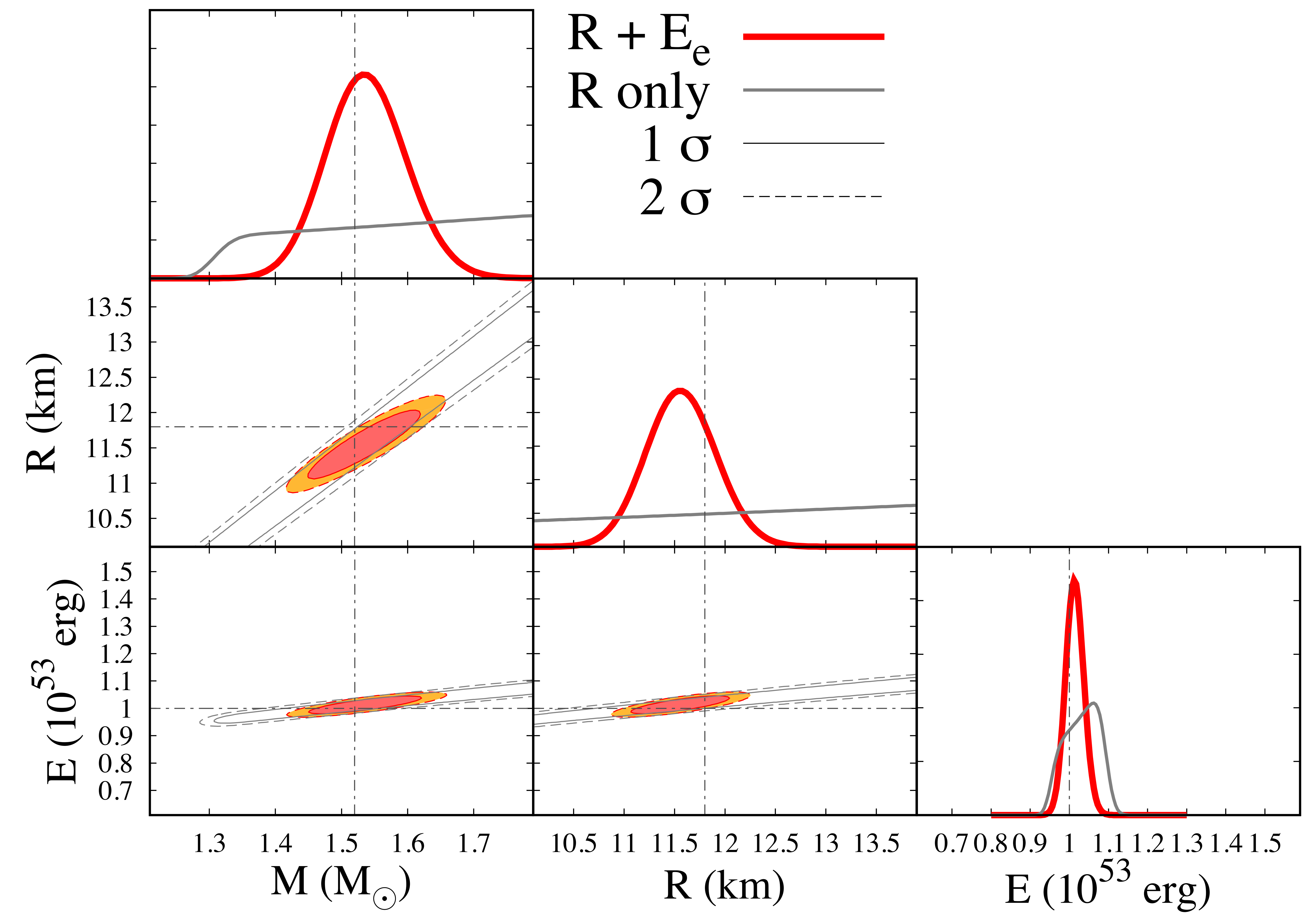
step 3

DATA ANALYSIS

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

Probability density functions (PDF)

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, arXiv:2204.08363]



step 3

DATA ANALYSIS

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

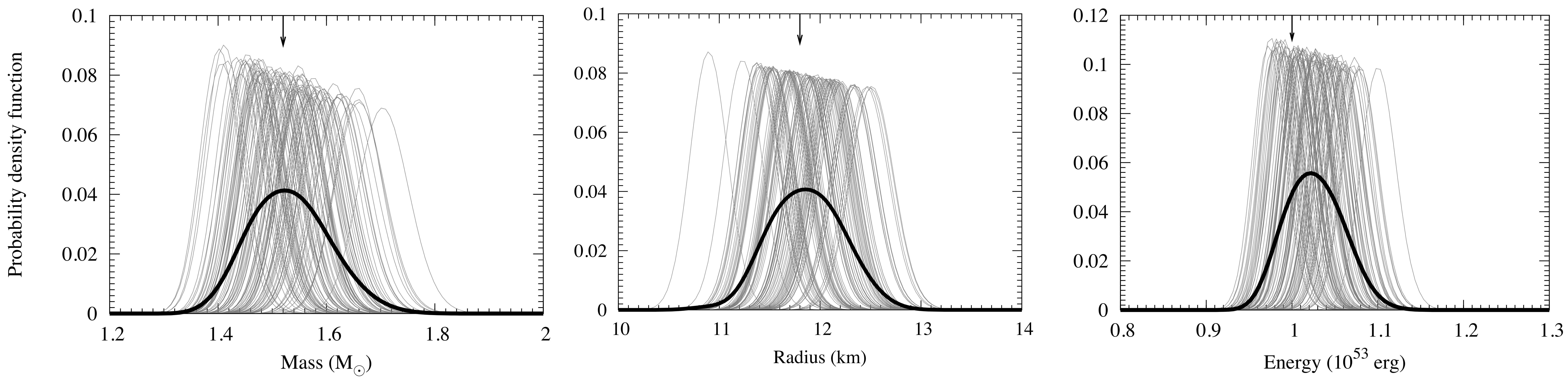
100 realizations

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, arXiv:2204.08363]

step 3

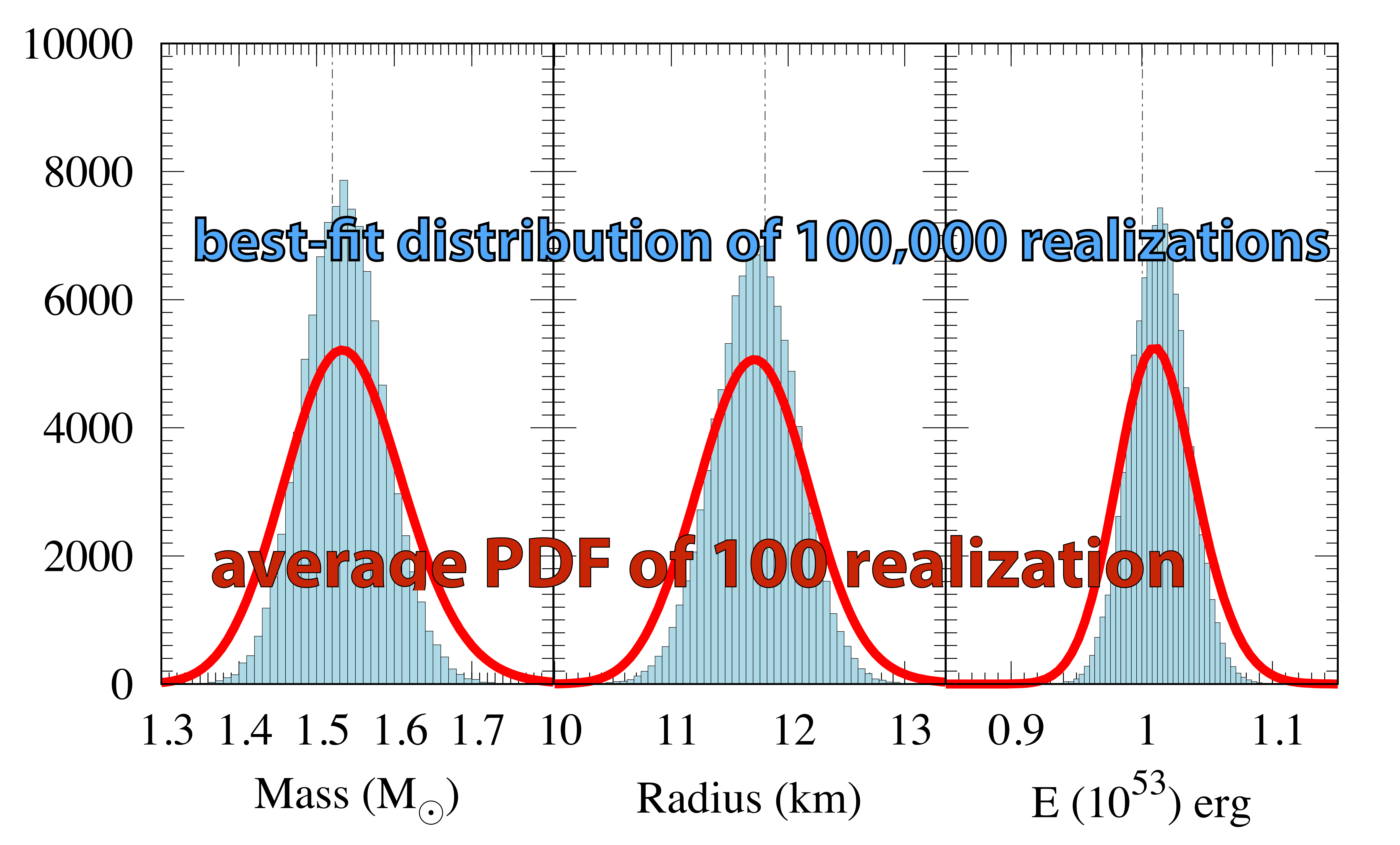
DATA ANALYSIS

- Mock sampling
- Analysis pipeline for real



Parameter uncertainty

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, arXiv:2204.08363]



step 3

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True values:

- $M_{PNS} = 1.52 M_\odot$
- $R_{PNS} = 11.8$ km
- $E_{tot} = 10^{53}$ erg

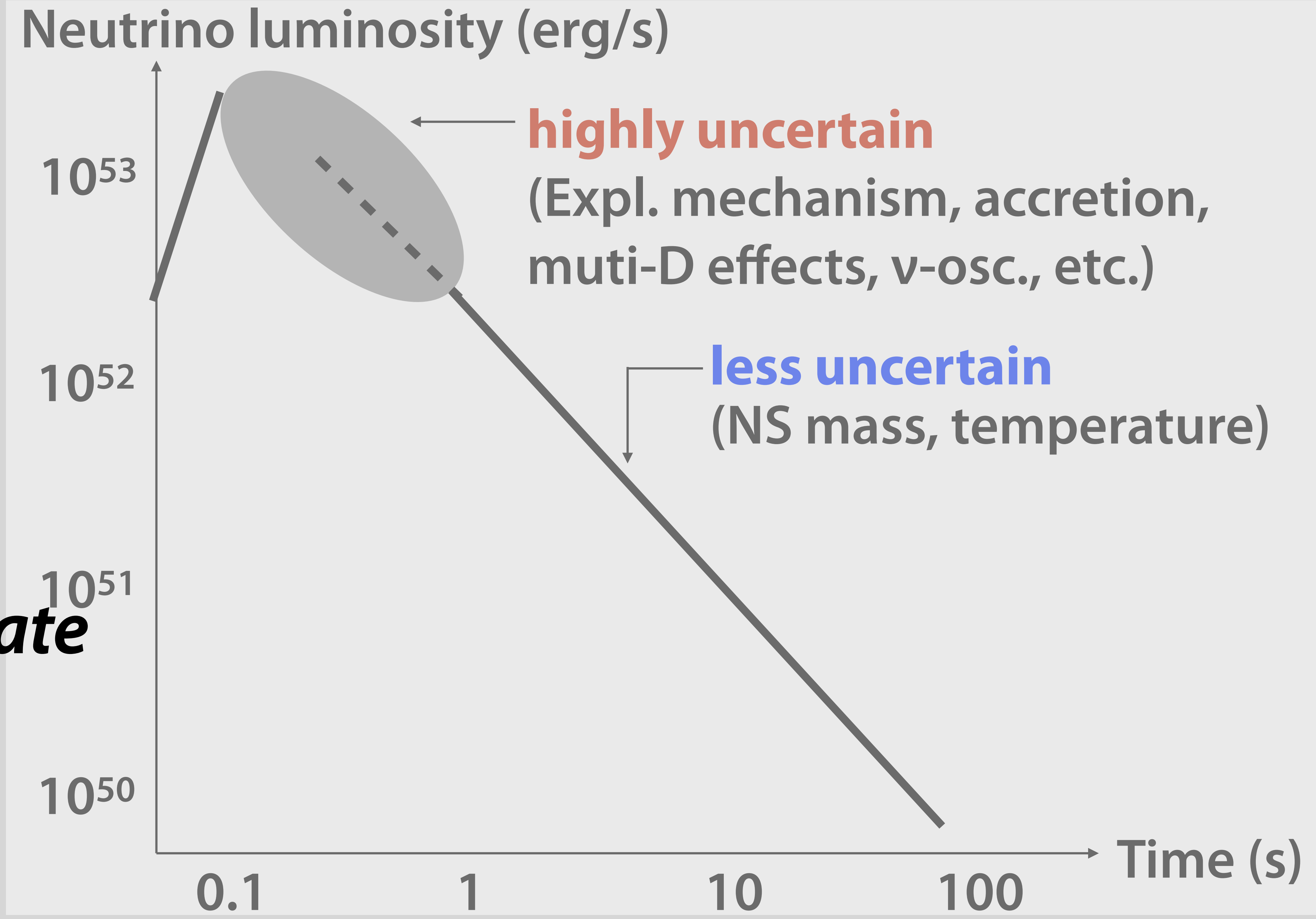
	Median	68%	95%
$M_{\rm PNS}$ $(M_\odot)$	1.532	$^{+0.079}_{-0.075}$	$^{+0.163}_{-0.147}$
$R_{\rm PNS}$ (km)	11.69	$^{+0.48}_{-0.48}$	$^{+0.98}_{-0.93}$
$E_{\rm tot}$ $(10^{53}$ erg)	1.009	$^{+0.032}_{-0.030}$	$^{+0.066}_{-0.059}$

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

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