超新星シミュレーションと
マルチメッセンジャー観測で読み解く中性子星

諏訪雄大

（東大総合文化 & 京大基研）

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, ApJ, 934, 15 (2022)

Supernovae are made by neutron star formation

Remarks on Super-Novae and Cosmic Rays

5. *The super-nova process*

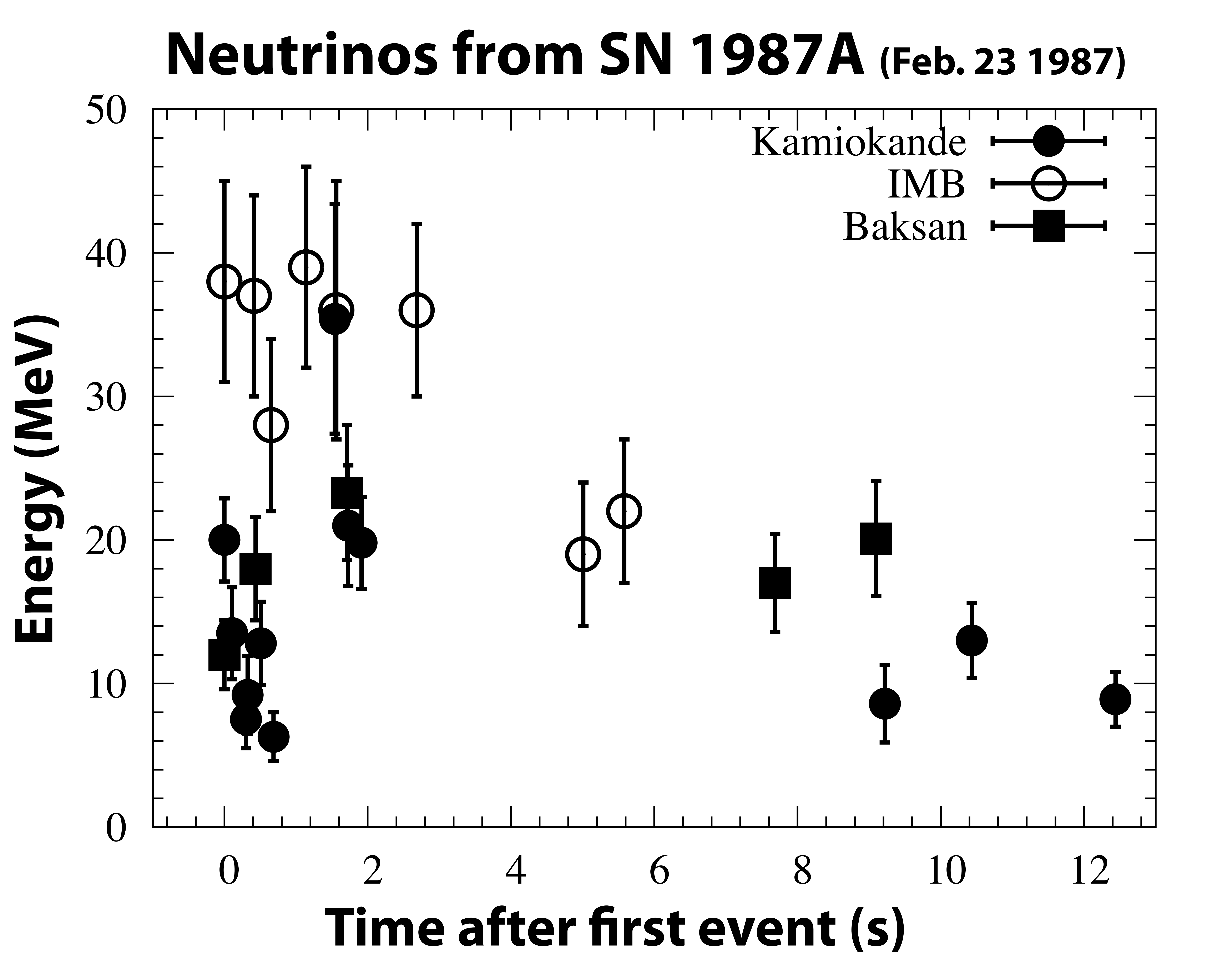
We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This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

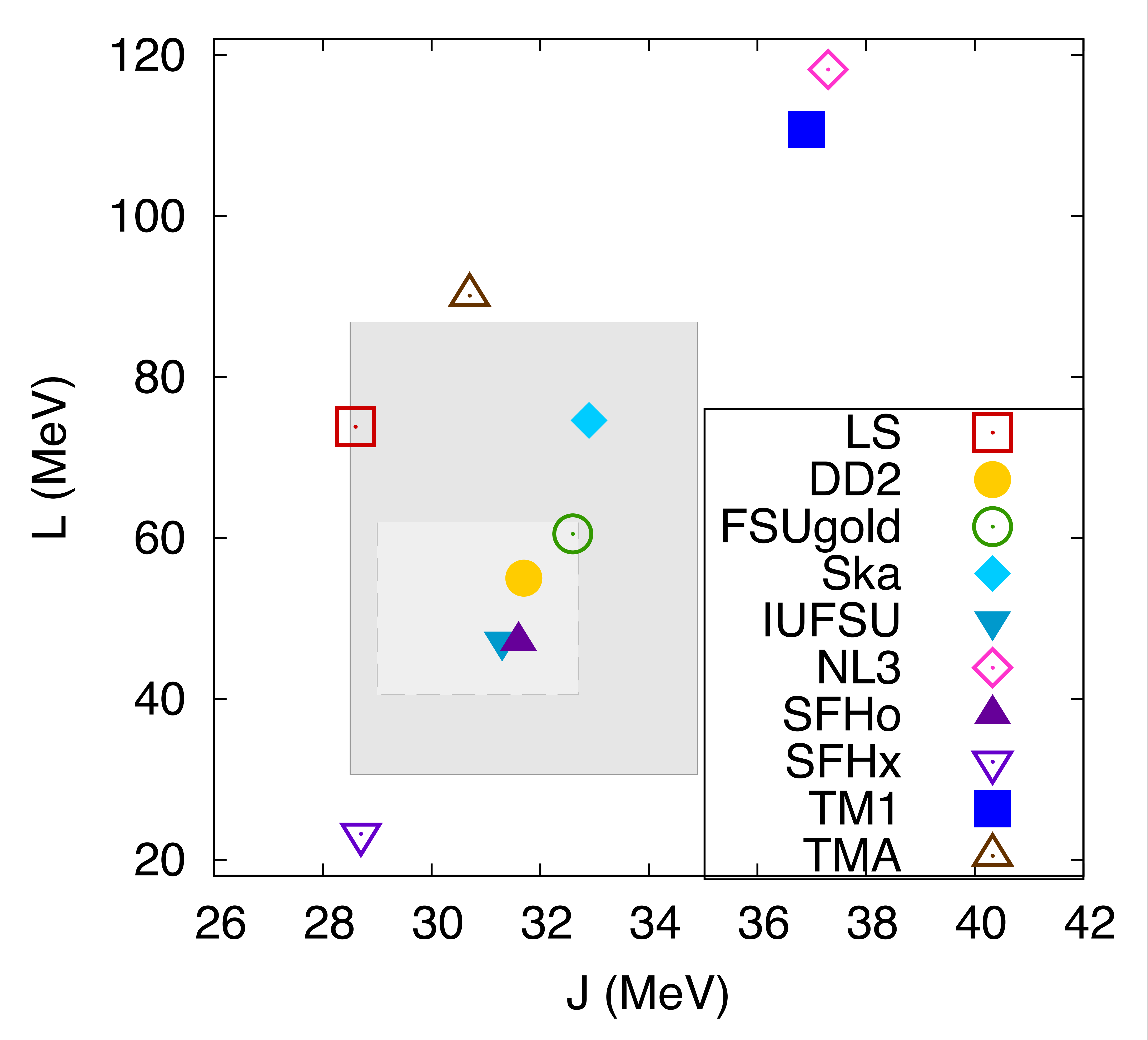
SN1987A



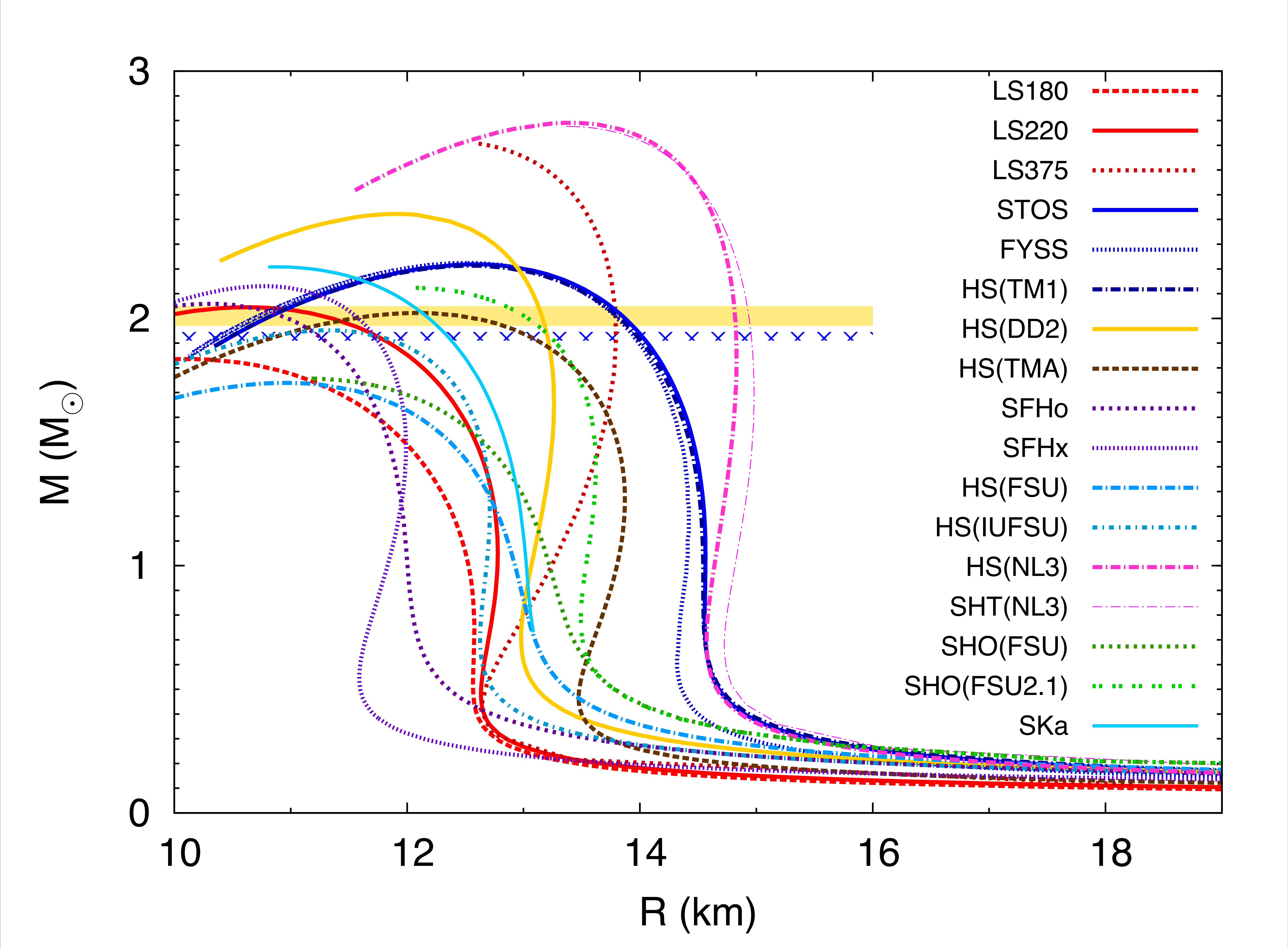
NASA/ESA

Properties of nuclear matter and neutron stars

Nuclear matter → cf. symmetry energy



Neutron-star → M-R relation



Oertel+ (2016)

Supernova simulations

stellar evolution

input: $\rho(r)$, $T(r)$, $Z_i(r)$, $v_r(r)$

general relativity

Gravity

electro-magnetic interaction

(Magneto-)hydrodynamics

strong interaction

Nuclear equation of state

Numerical table based on nuclear physics
e.g.) 10^3 g cm^{-3} < ρ < 10^{15} g cm^{-3}
0.1 MeV < T < 100 MeV
0.03 < Y_e < 0.56

weak interaction

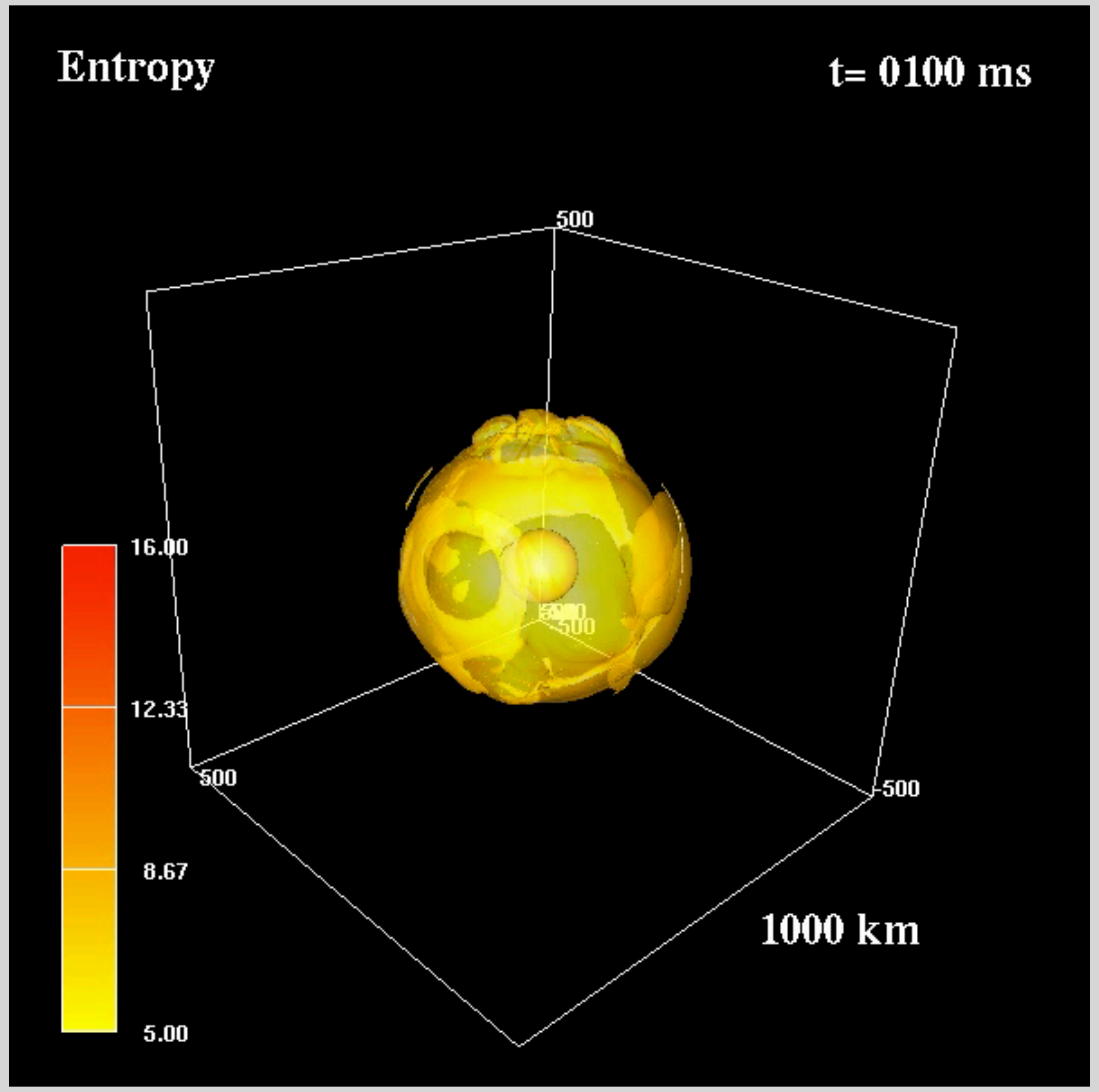
Neutrino transfer

Number of interactions;

$pe^- \leftrightarrow n\nu_e$, $ne^+ \leftrightarrow p\bar{\nu}_e$

$\nu e^\pm \leftrightarrow \nu e^\pm$, $\nu A \leftrightarrow \nu A$, $\nu N \leftrightarrow \nu N$

$\nu\bar{\nu} \leftrightarrow e^-e^+$, $NN \leftrightarrow \nu\bar{\nu}NN$, $\nu\bar{\nu} \leftrightarrow \nu\bar{\nu}$



Takiwaki, Kotake, Suwa (2014)

as first-principles as possible.
parameter free simulation!

Supernova simulations and nulear equation of state

- **Explodability**
  - success / failure of supernova explosion depends on EOS
  - "softer" EOS is better to produce explosion, since faster NS contraction
  - Marek+ (2009); Suwa+ (2013); Couch (2013); Harada+ (2020)
- **Black hole (BH) formation**
  - if a supernova fails, a BH is formed instead of a NS
  - "softer" EOS leads to faster BH formation
  - Liebendörfer+ (2004); Sumiyoshi+ (2006); O'Connor & Ott (2011); Pan+ (2018); Nakazato+ (2021)
- **QCD phase transition / crossover** (cf. Hatsuda-san's talk)
  - quark-hadron phase transition / crossover can change supernova dynamics
  - Takahara & Sato (1988); Yasutake+ (2007); Nakazato+ (2008); Fischer+ (2011, 2018); Zha+ (2020); Kuroda+ (2022); Lin+ (2022); Jakobus+ (2022)

Multimessenger observations and nuclear EOS

* **Gravitational waves (GWs)**
  - **many theoretical estimates available, but not useful to constrain EOS (too complicated)**
  - **GW asteroseismology would provide** $f(M^\alpha R^\beta)$ (cf. Sotani-san's talk)
  - Andersson & Kokkotas (1998); Sotani+ (2016+); Torres-Forné+ (2018+)

* **Neutrinos**
  - **many theoretical estimates available, but not useful to constrain EOS (too complicated)**
  - **necessary to connect observables with EOS, but no good way yet**
  - ***Q: How accurately can neutrinos alone constrain EOS?***

What can we extract from neutrino observations?

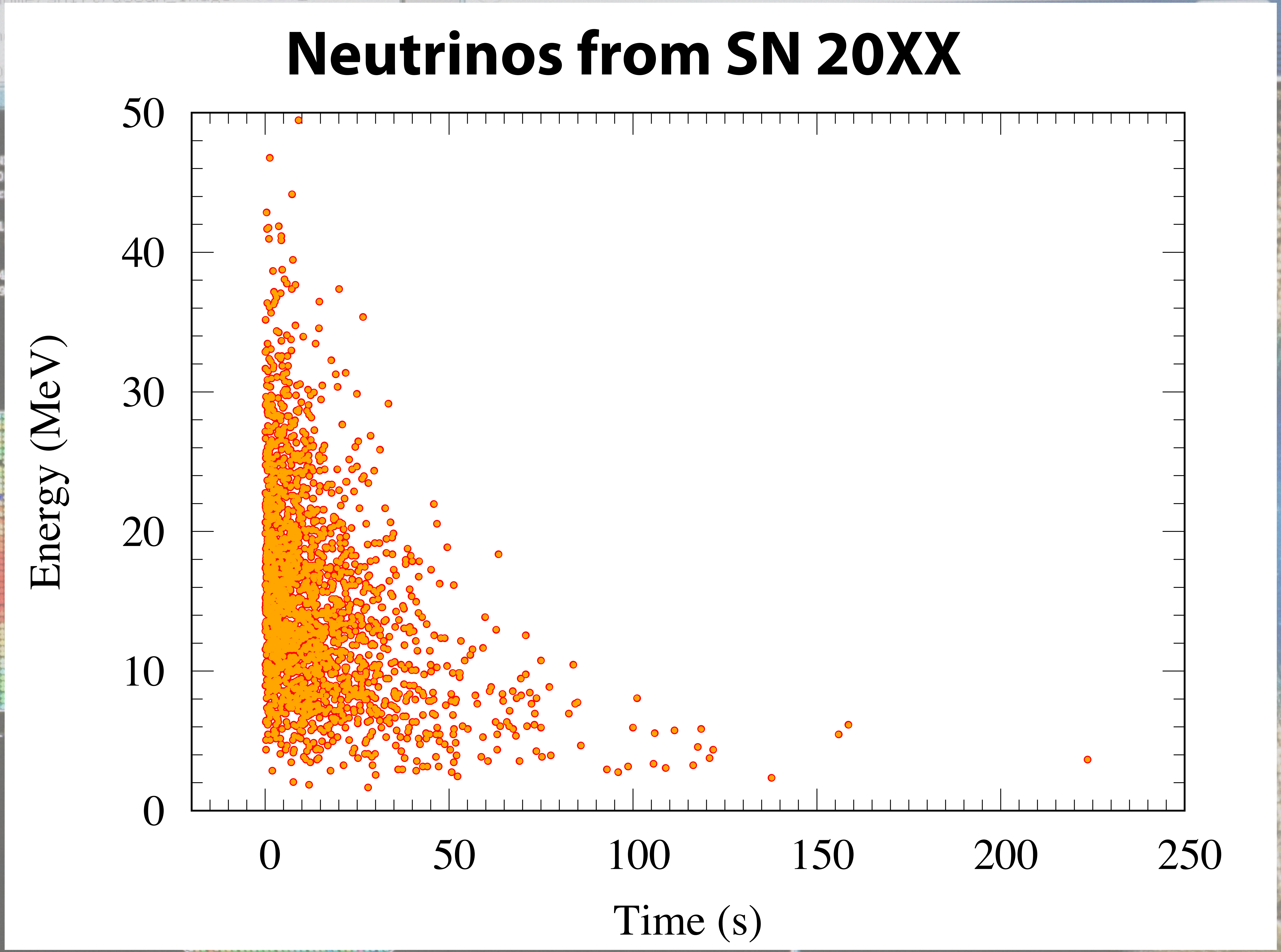
- **Properties of neutron stars**
  - **Binding energy**
    - *important for energetics, done with SN1987A*

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

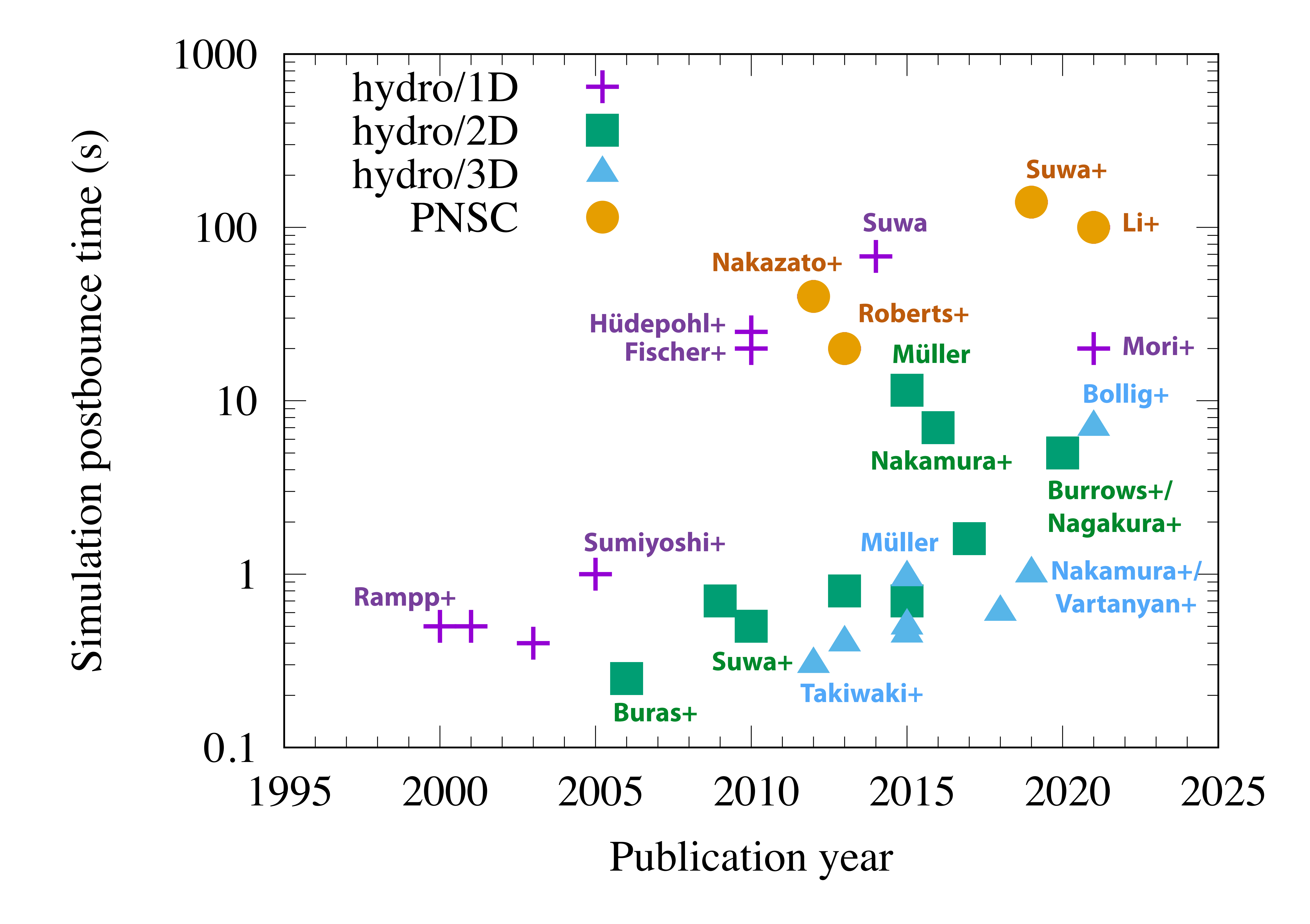
  - **Mass**
    - *important for discriminating final object (NS or BH)*
  - **Radius**
    - *important for discriminating nuclear equation of state*

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**

☑ building neutrino detectors

☐ taking data *(just waiting)*

☐ simplified analytic model

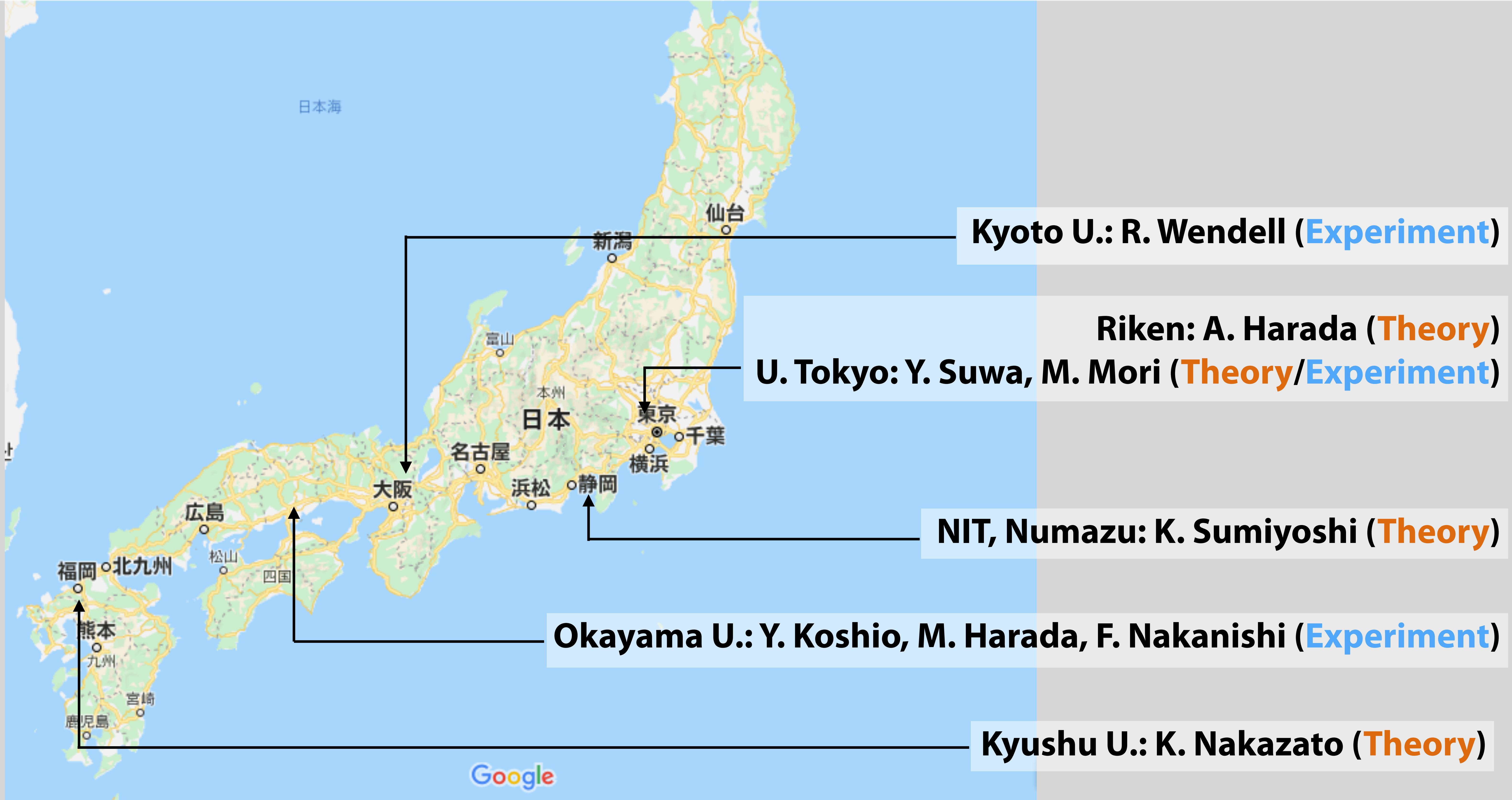
☑ detailed numerical simulations *(but only short period and limited numbers)*

nuLC collaboration

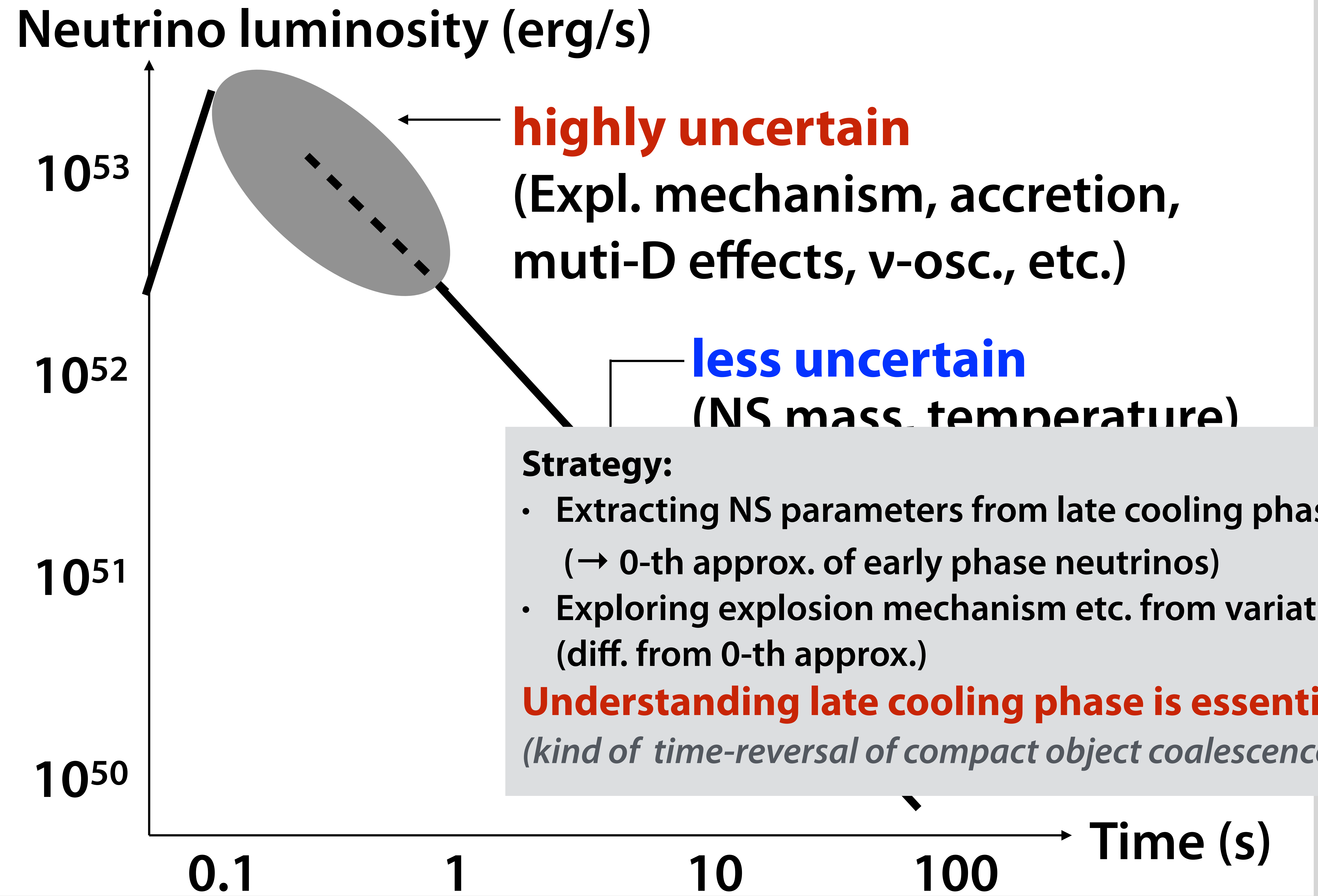
"nuLC"
=neutrino Light Curve

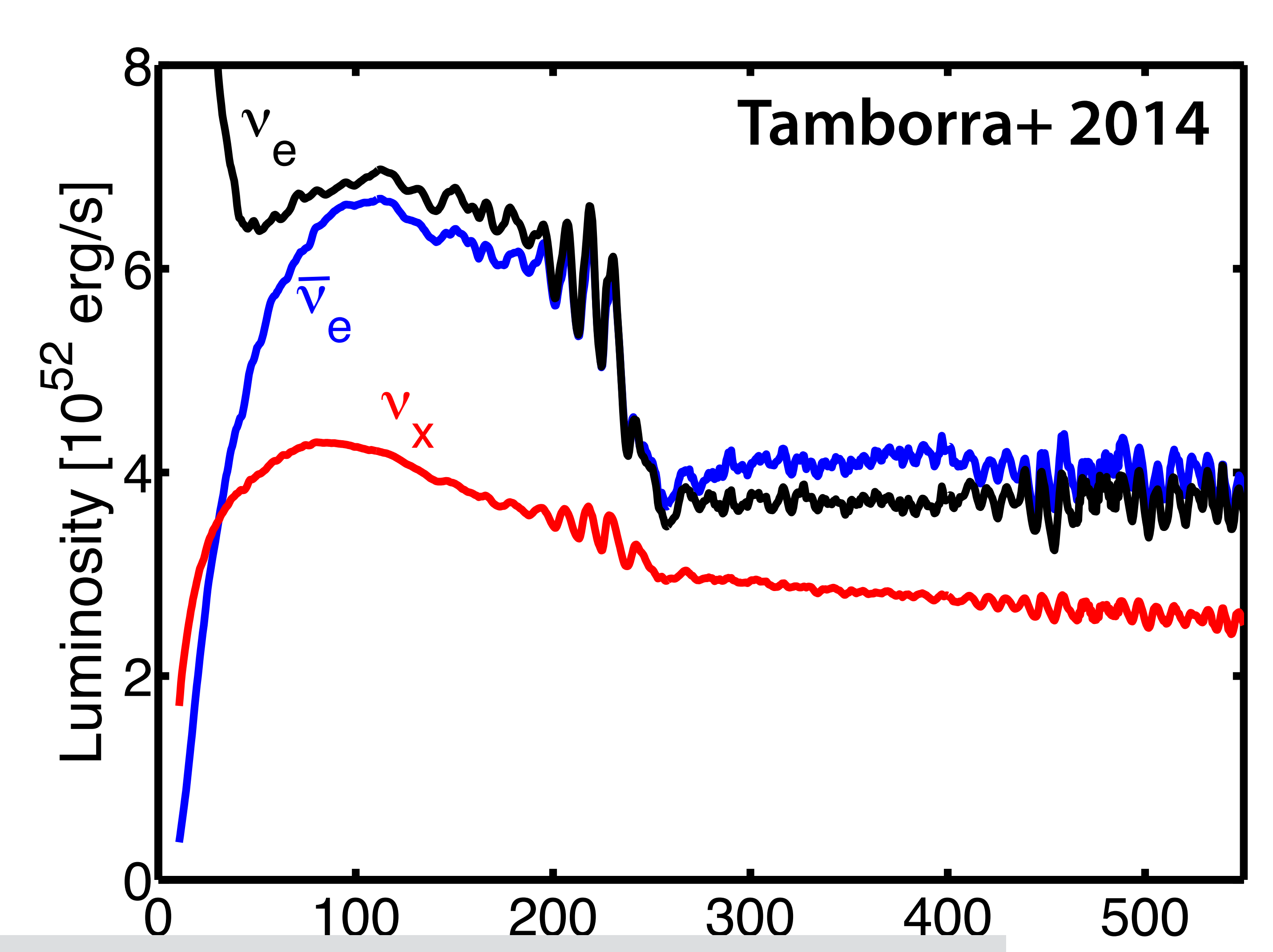
Papers:

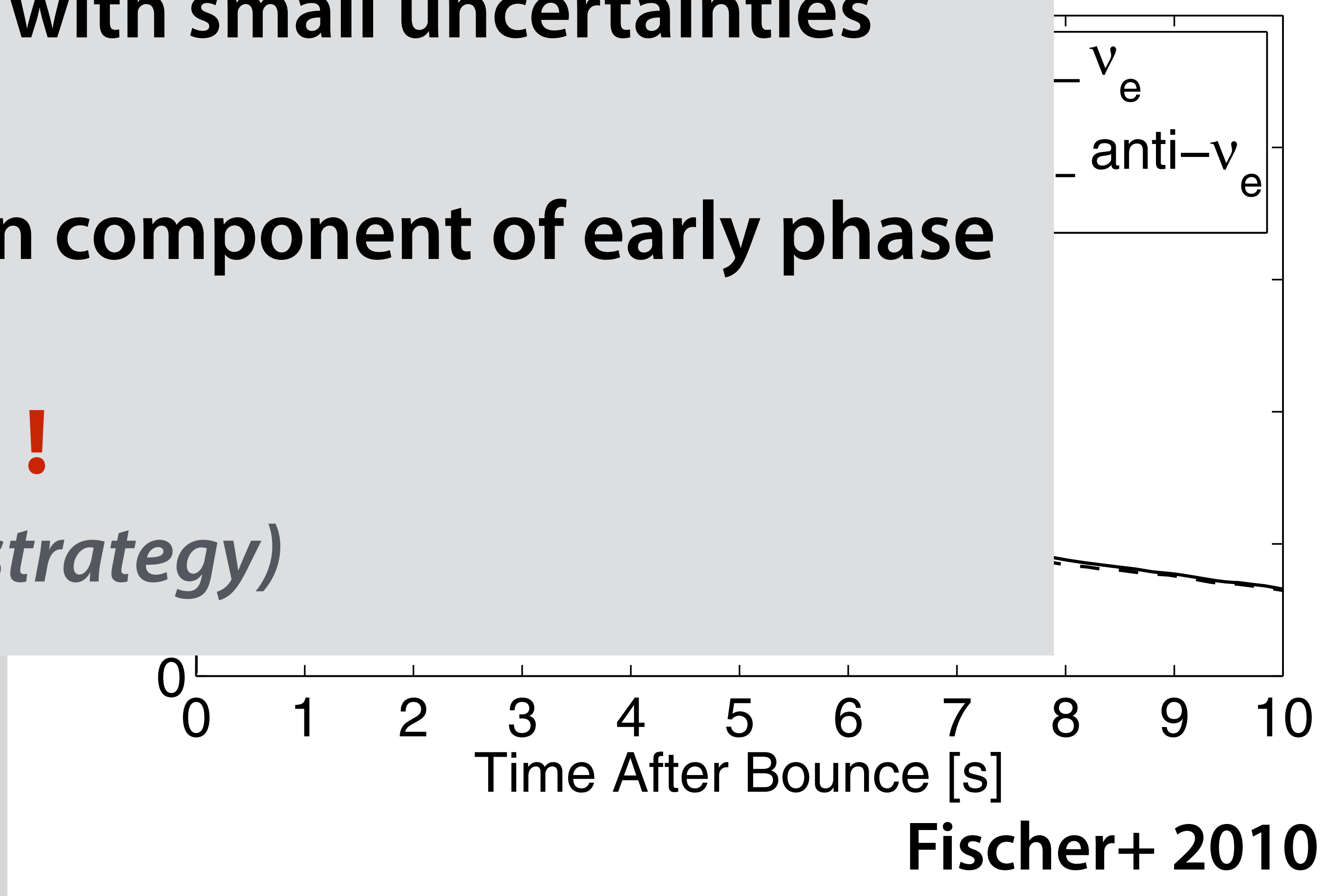
1. Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019)
2. Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 013E01 (2021)
3. Mori, Suwa, Nakazato, Sumiyoshi, Harada, Harada, Koshio, Wendell, PTEP, 2021, 023E01 (2021)
4. Nakazato, Nakanishi, Harada, Koshio, Suwa, Sumiyoshi, Harada, Mori, Wendell, ApJ, 925, 98 (2022)
5. Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022)



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

$f(x)$

ANALYTIC SOLUTIONS

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

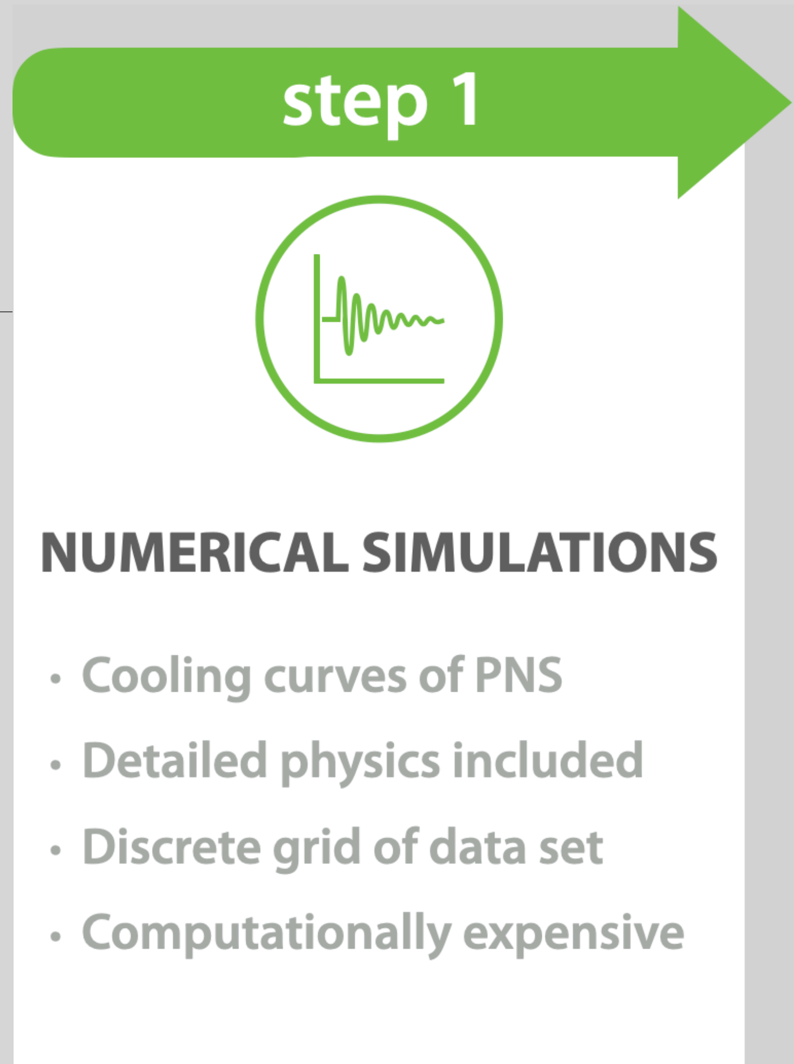
step 3

DATA ANALYSIS

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

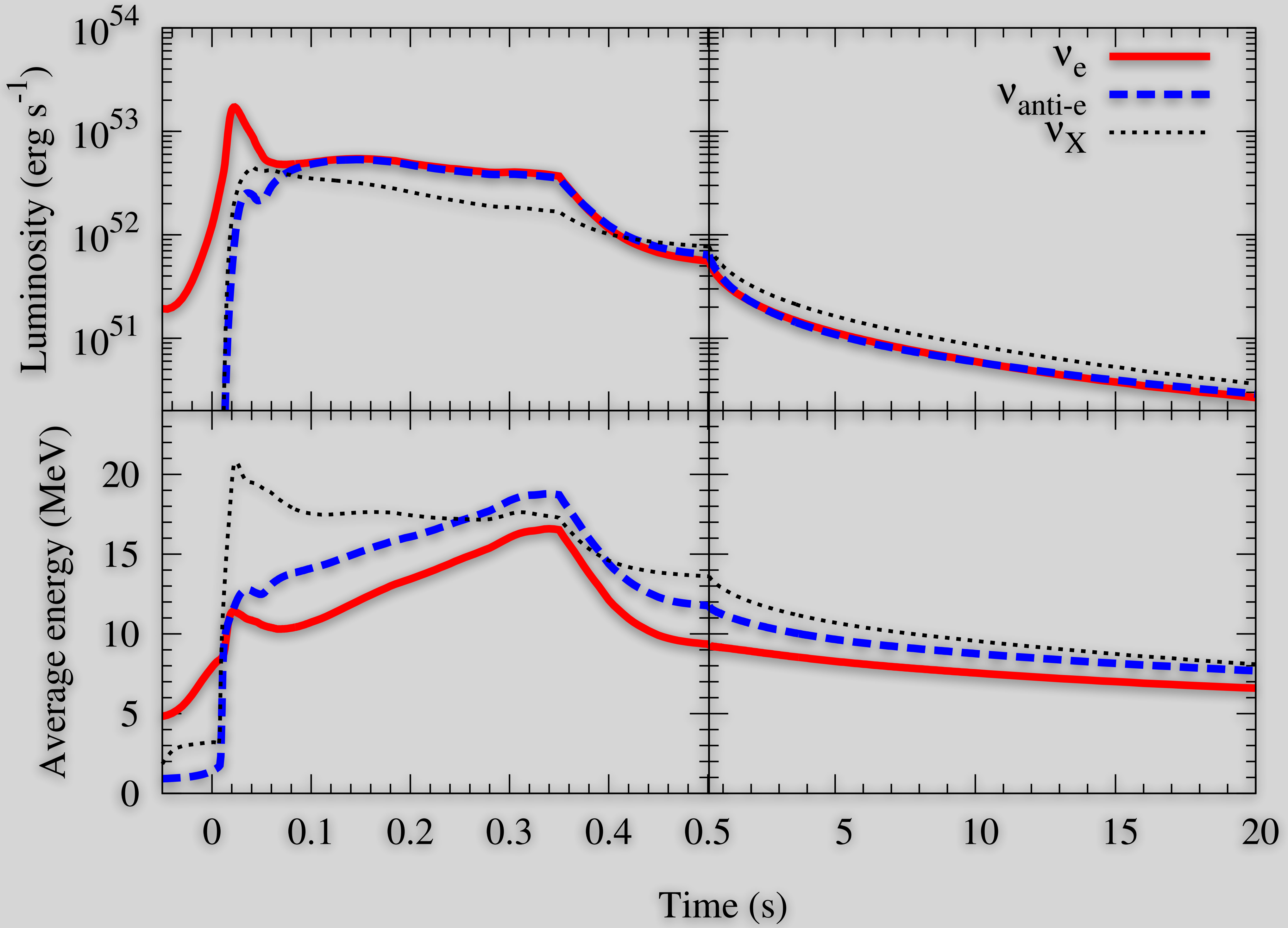
Numerical simulations

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



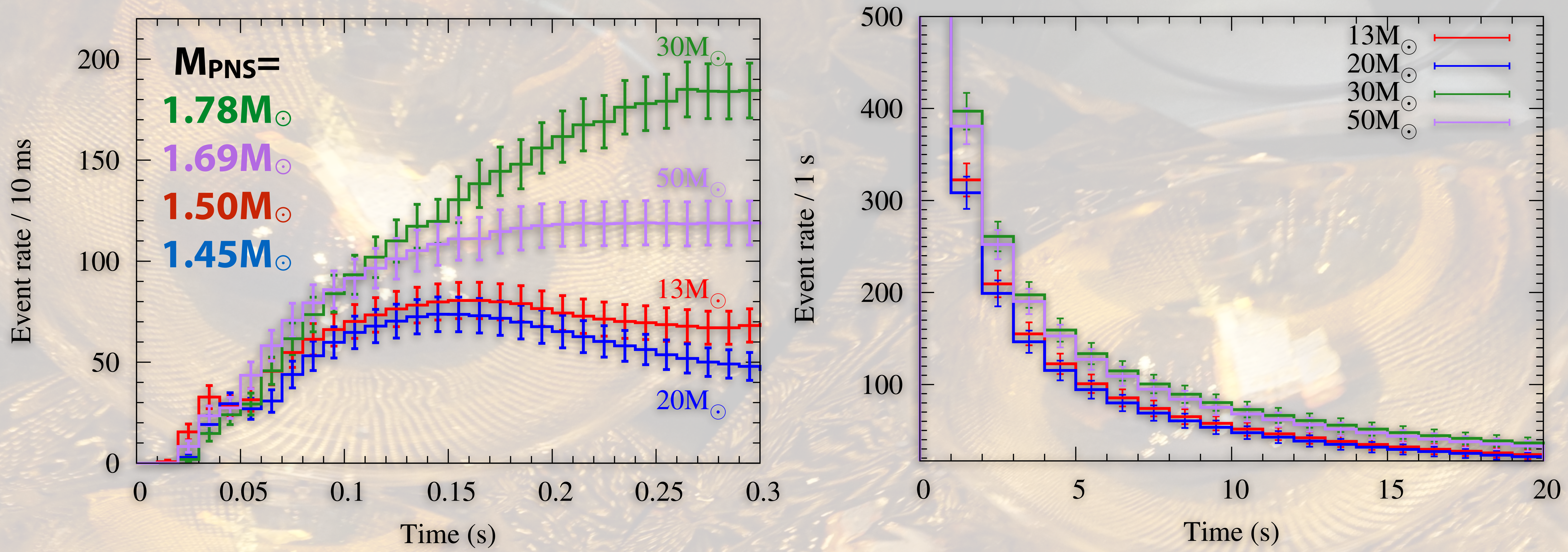
- **Hydro. simulation (t<0.3s)**
  - **dynamical, GR, Boltzmann neutrino transport, nuclear EOS, 1D**
    Yamada 1997, Sumiyoshi+ 2005
- **PNS cooling simulation (t>0.3s)**
  - **static (TOV), FLD neutrino transport, nuclear EOS, 1D**
    Suzuki 1993
- **Connection**
  - **Interpolate two results with 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**

step 1

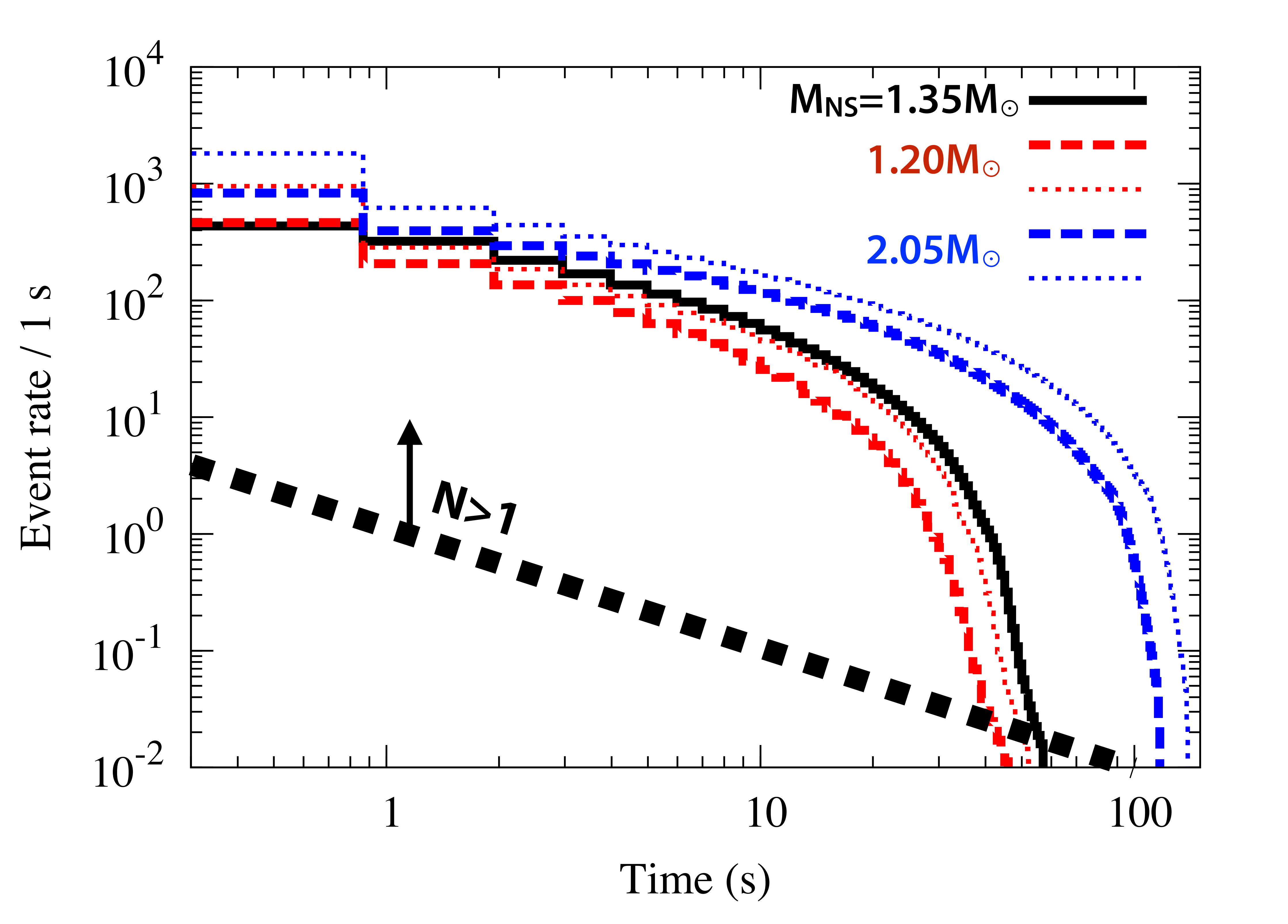
NUMERICAL SIMULATIONS

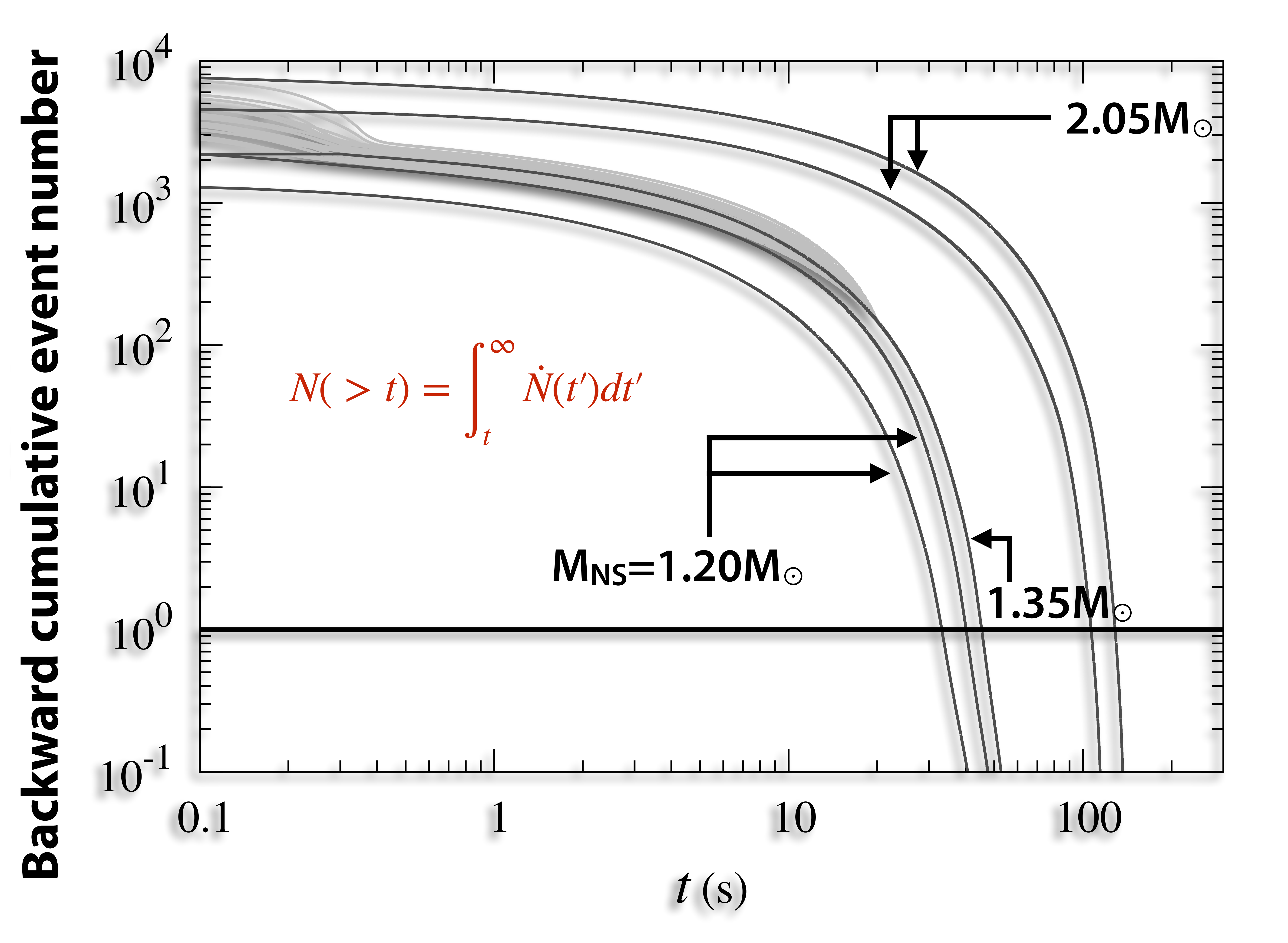
- Cooling curves of PNS
- Detailed physics included
- Discrete grid of data set
- Computationally expensive

How long can we see SN with neutrinos?

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

step 1





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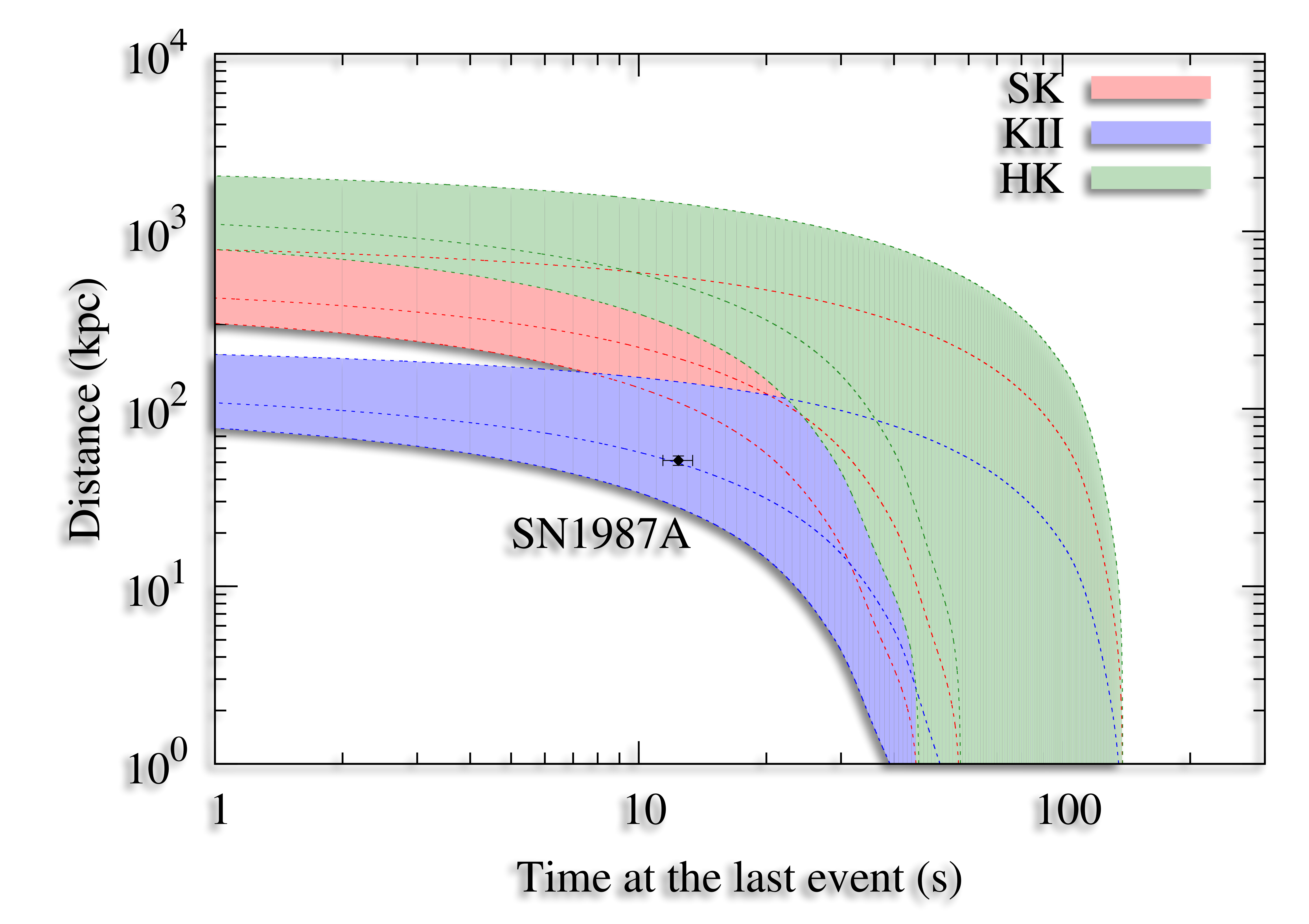


step 1

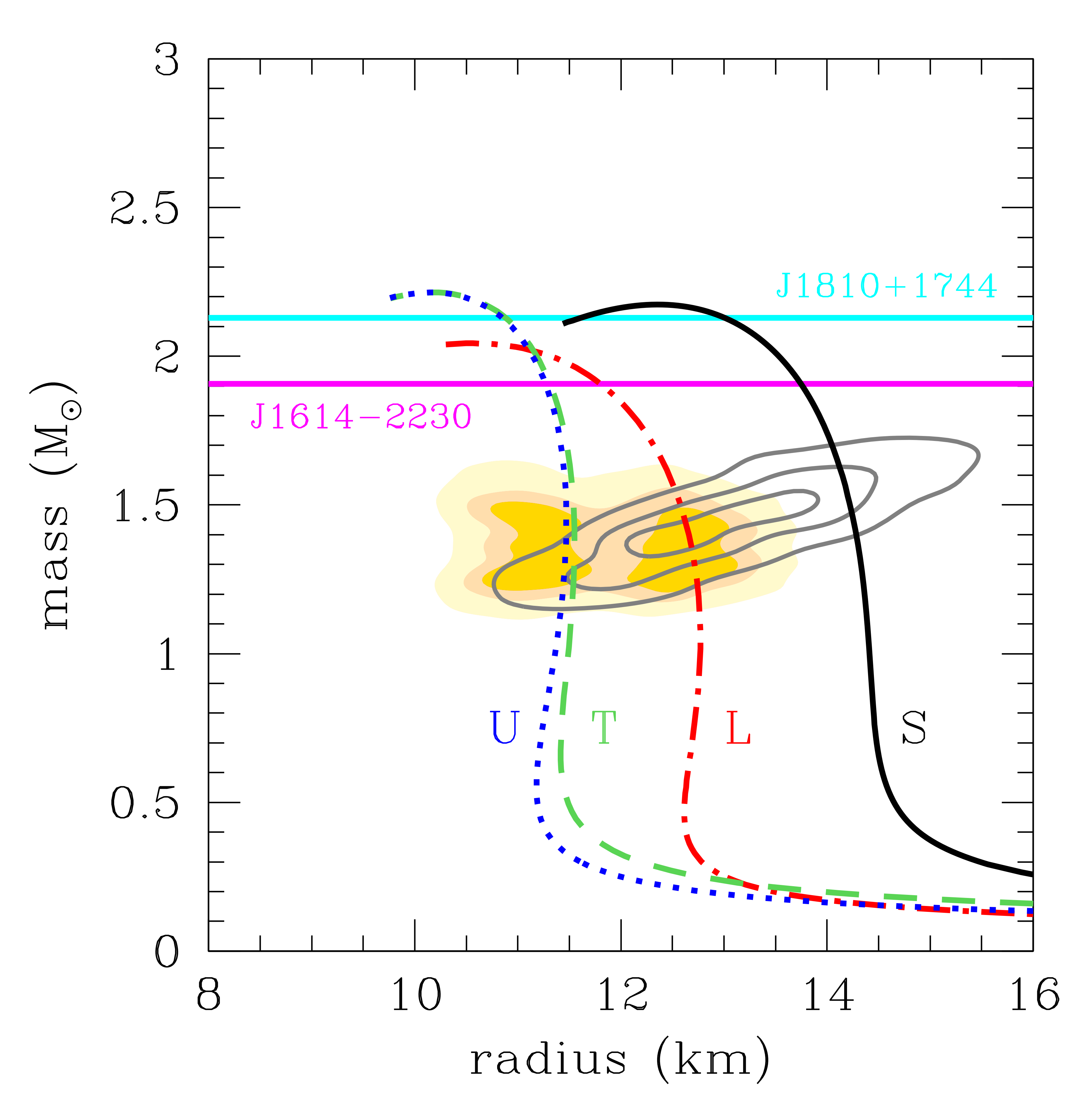
NUMERICAL SIMULATIONS

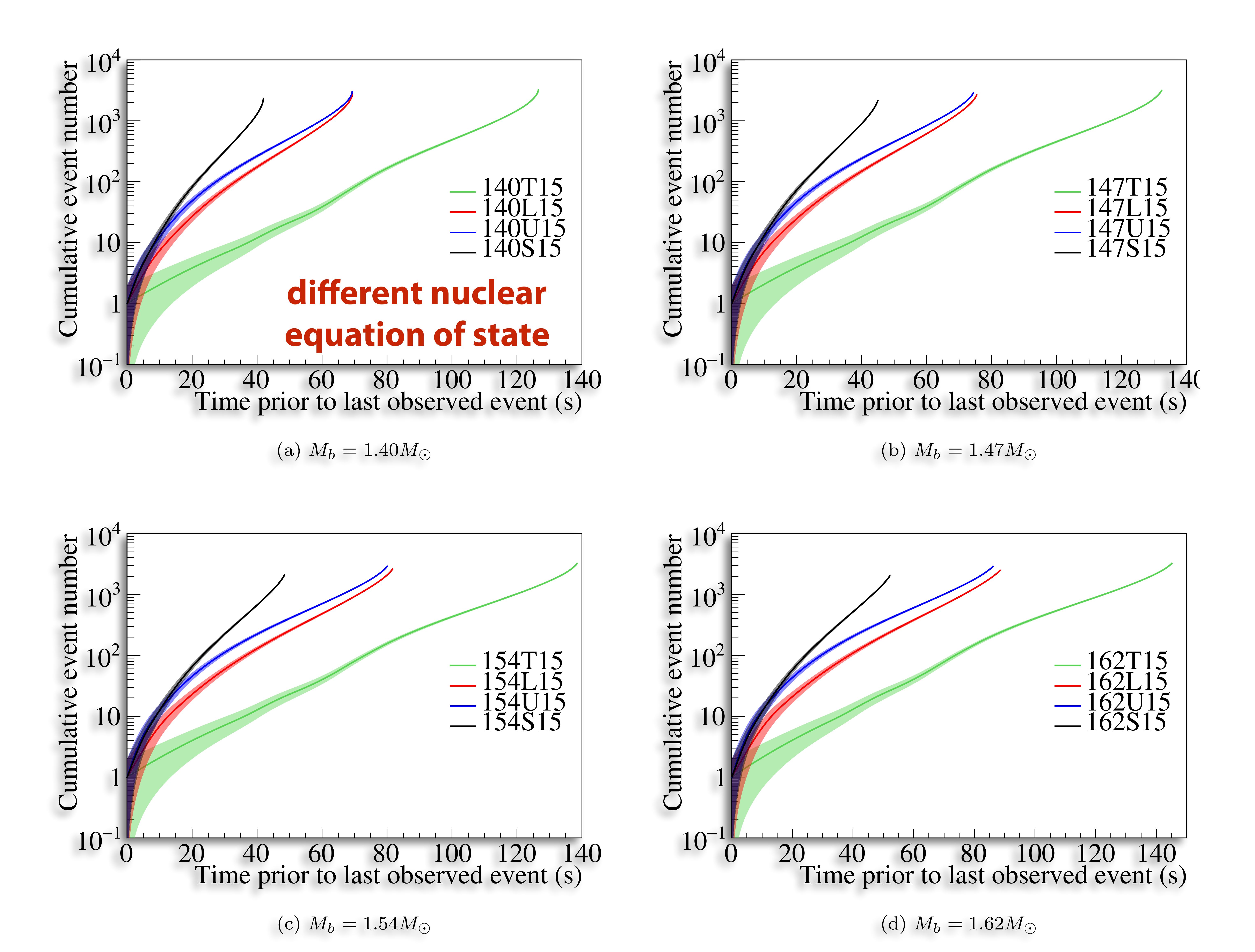
- Cooling curves of PNS
- Detailed physics included
- Discrete grid of data set
- Computationally expensive

Model grids are getting larger

step 1

[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

Analytic model

[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

* **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
$\alpha=R_{PNS}/\pi$

* **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**

$$L = 4\pi R_\nu^2 F = 1.2\times10^{50}\,\mathrm{erg\,s^{-1}}\left(\frac{M_\mathrm{PNS}}{1.4M_\odot}\right)^{4/5}\left(\frac{R_\mathrm{PNS}}{10\,\mathrm{km}}\right)^{-6/5}\left(\frac{g\beta}{3}\right)^{-4/5}\left(\frac{s}{1k_B\,\mathrm{baryon}^{-1}}\right)^{12/5}$$

* **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)]

step 2

$f(x)$

ANALYTIC SOLUTIONS

・Analytic cooling curves

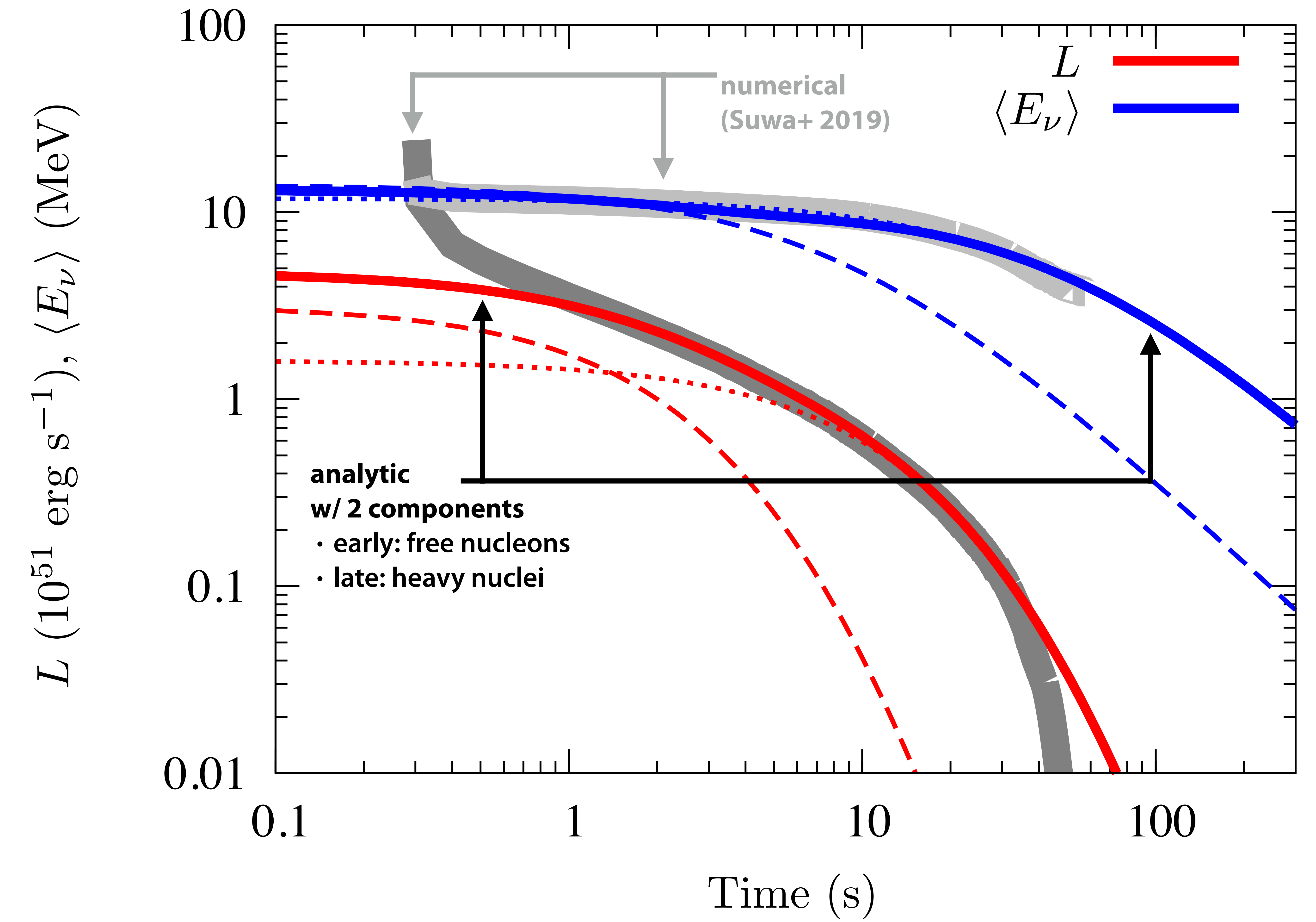
- **Solve neutrino transport eq. analytically**
  - **Neutrino luminosity**

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

  - **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)]

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

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

- **Positron average energy**

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

- **PNS radius**

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

- **Consistency relation of analytic model**

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

step 2

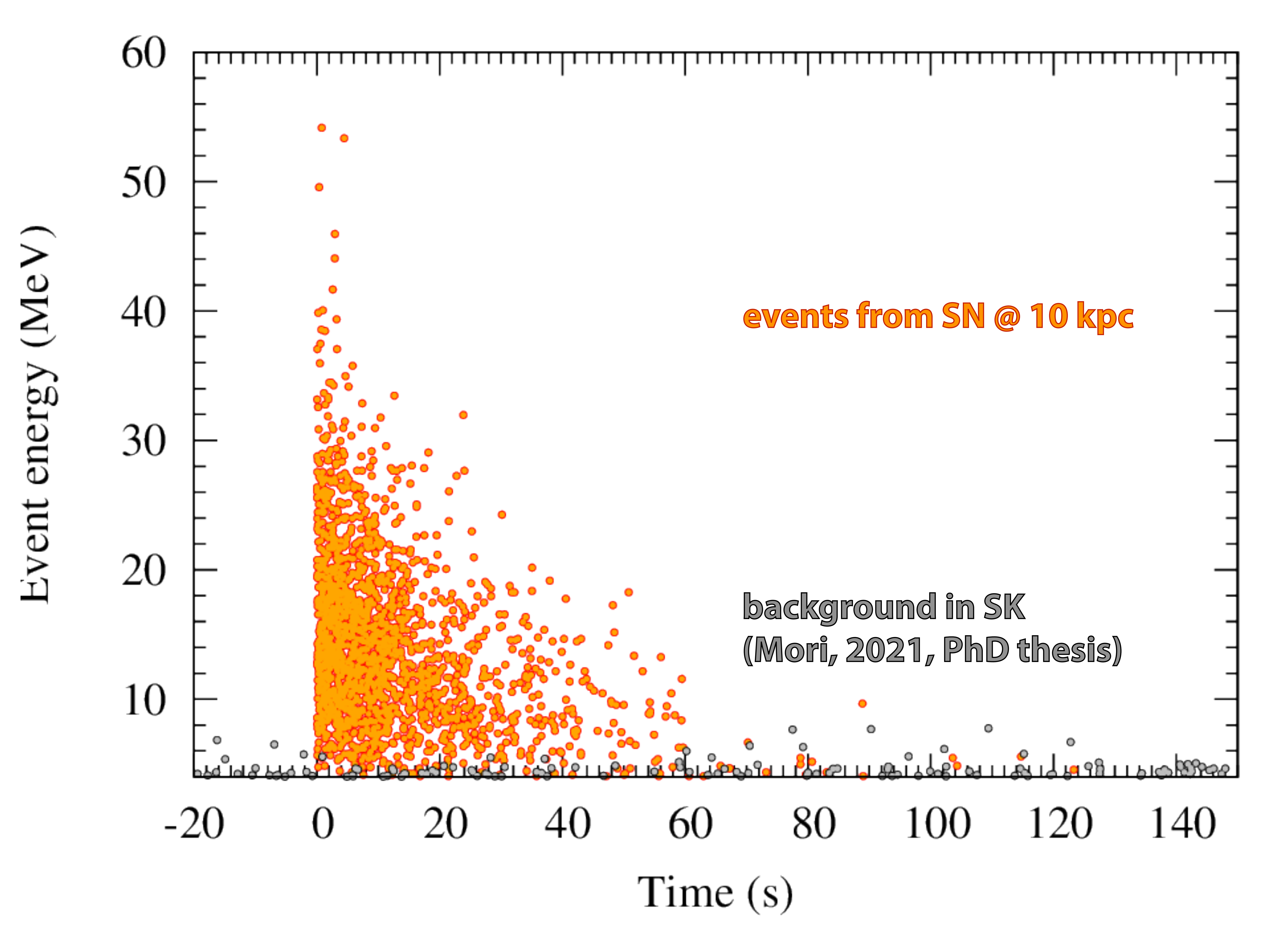
$f(x)$

ANALYTIC SOLUTIONS

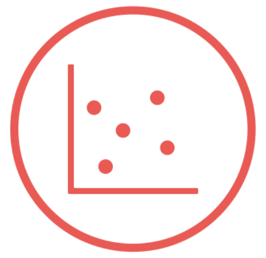
- Analytic cooling curves
- Calibrated w/ numerical sol.
- Simplified but essential physics included
- Fast and continuous

Mock sampling

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022)]



step 3



DATA ANALYSIS

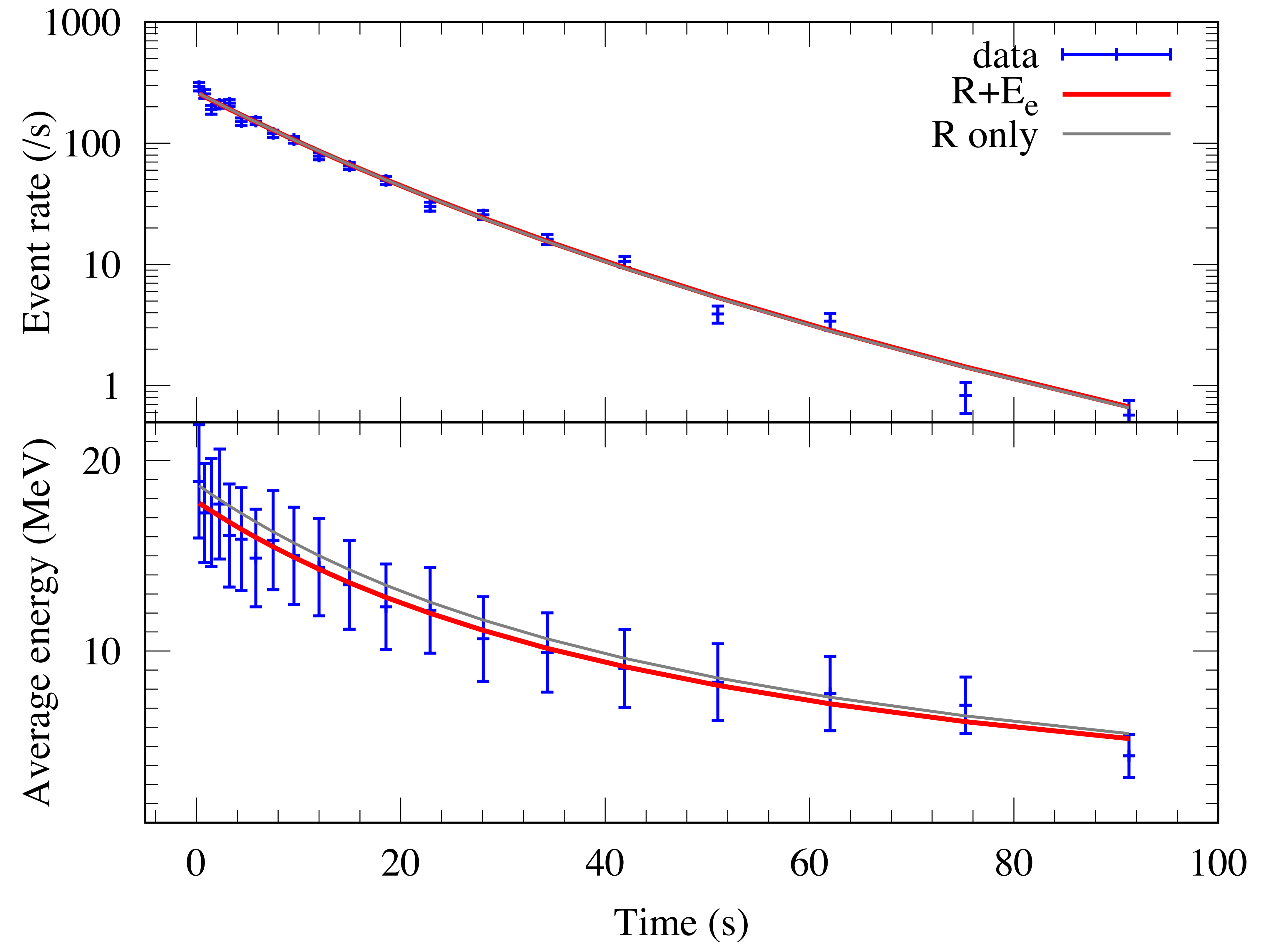
- Mock sampling
- Analysis pipeline for real data
- Error estimate for future observations

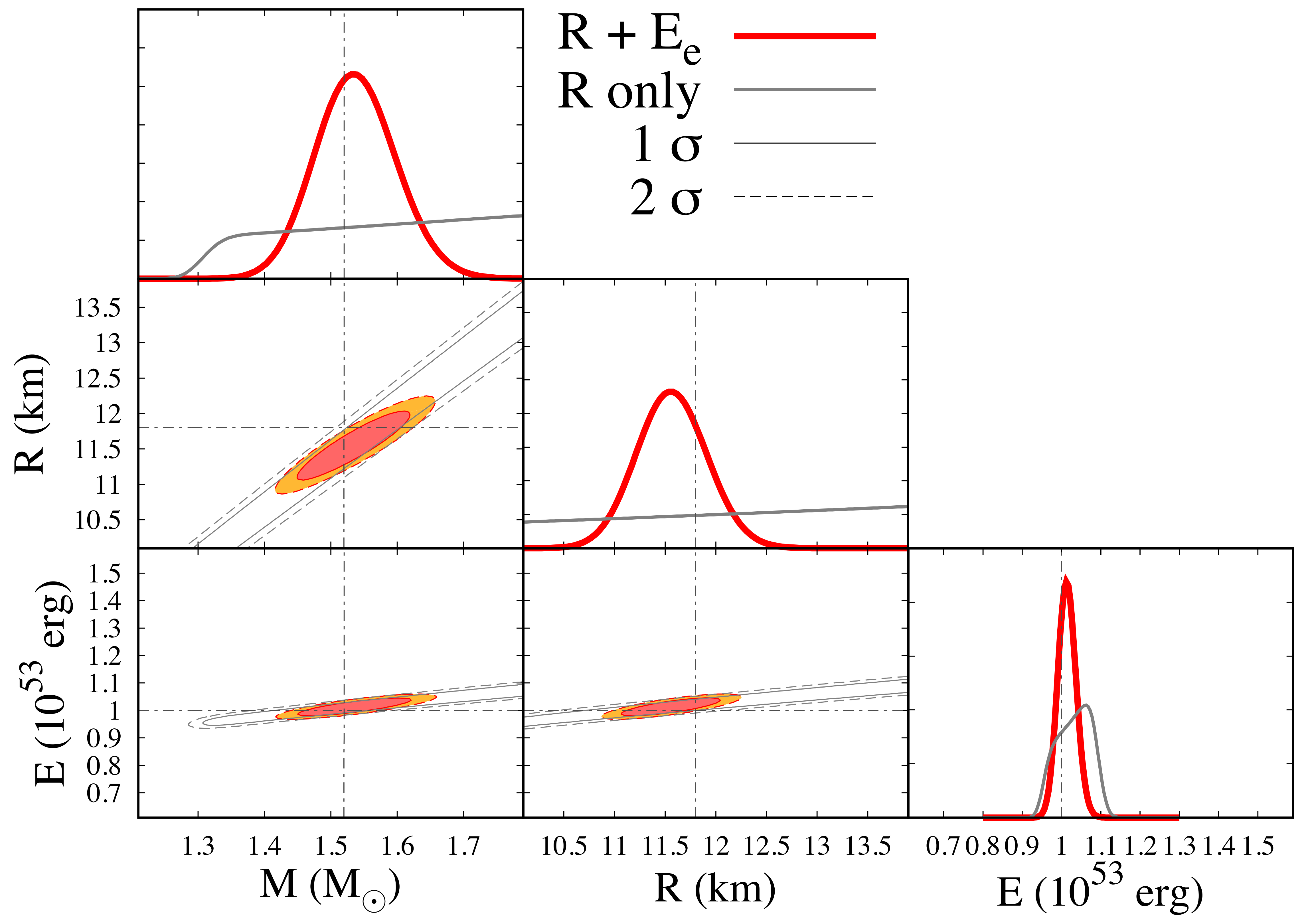
χ^2 fit and probability density function

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022)]

step 3

DATA ANALYSIS





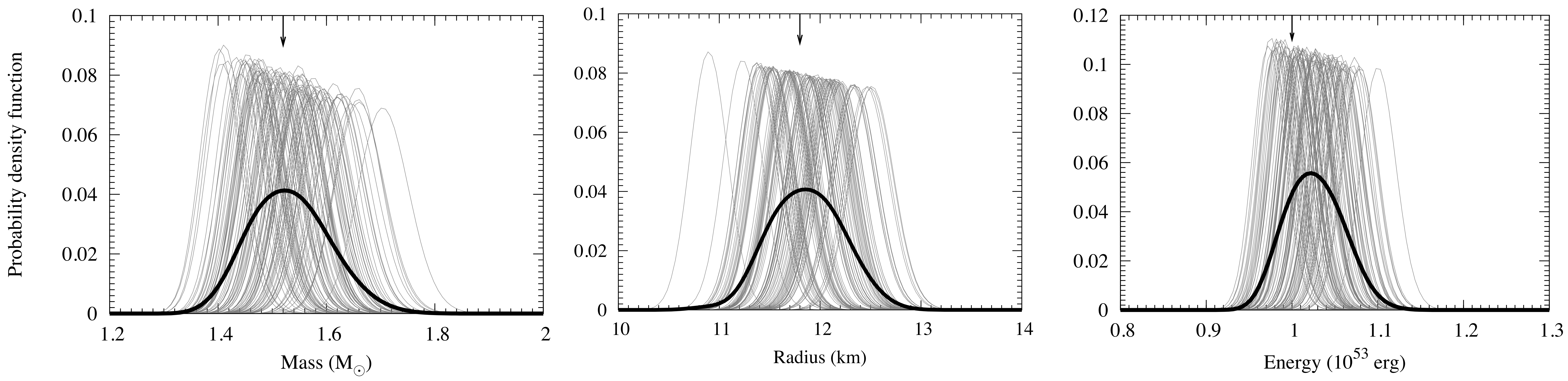
100 realizations

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022)]

step 3

DATA ANALYSIS

- Mock sampling
- Analysis pipeline for real



Parameter uncertainty

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022)]

step 3

DATA ANALYSIS

- Mock sampling
- Analysis pipeline for real data
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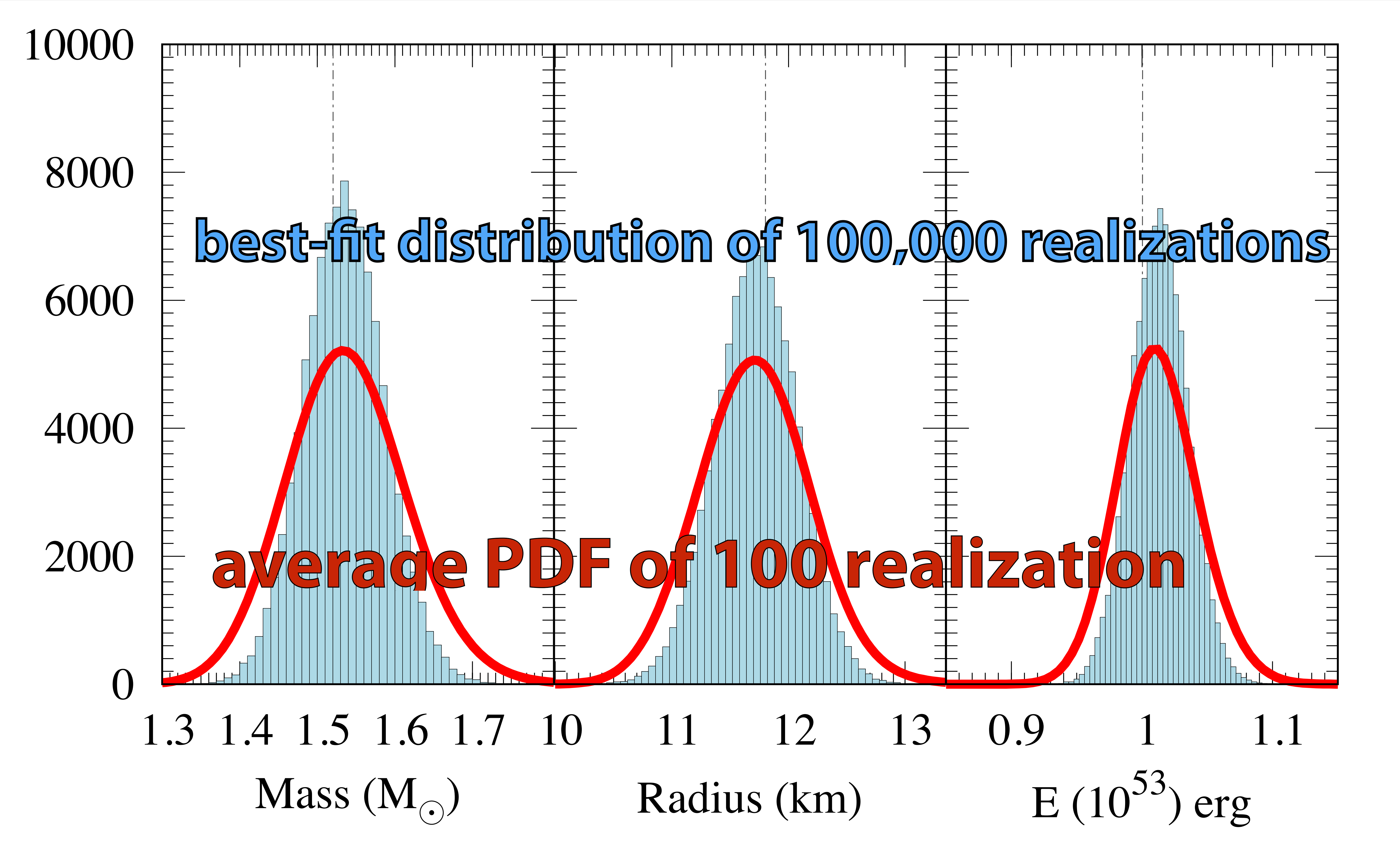


True values:

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

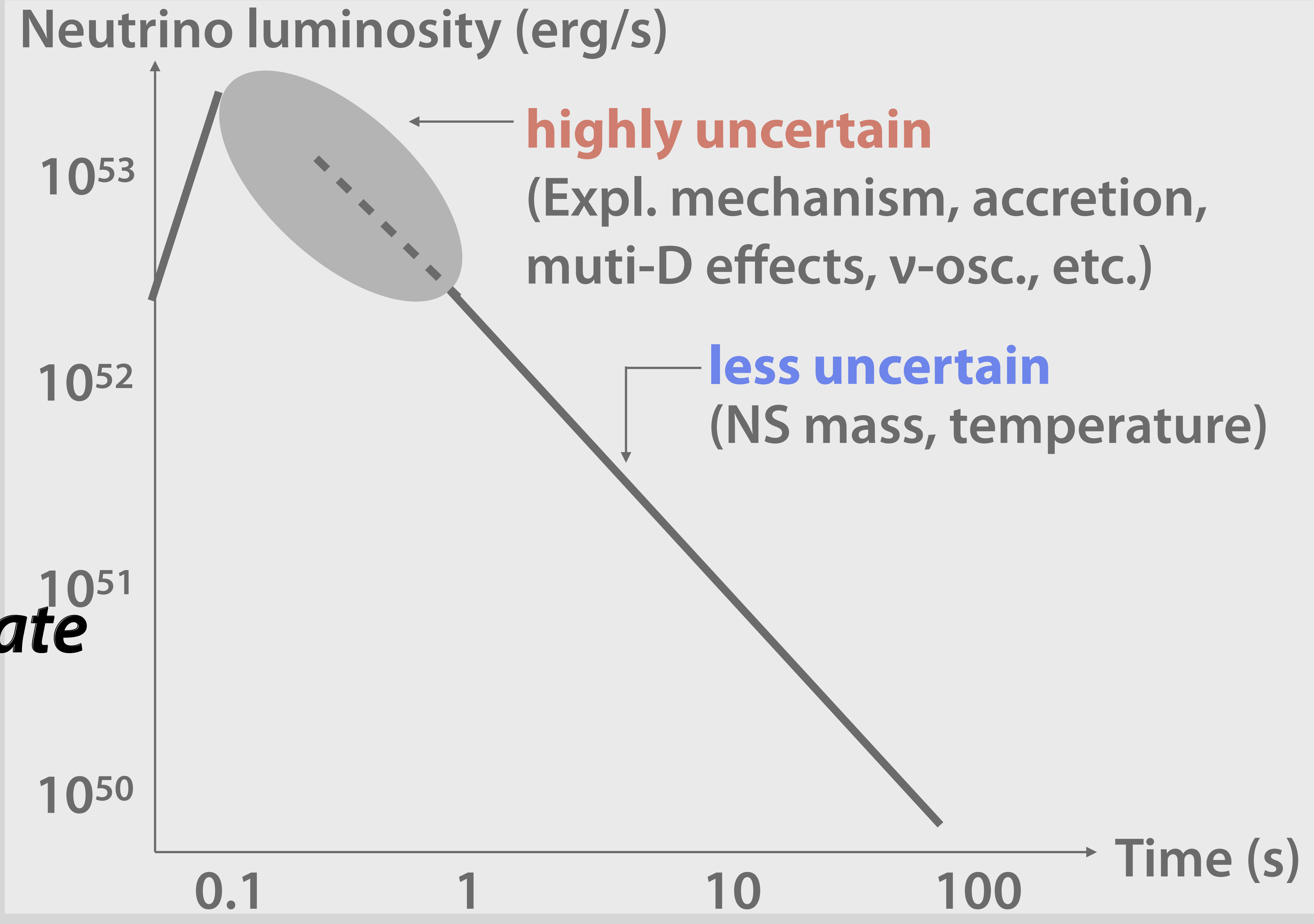
	Median	68%	95%
M_{PNS} ($M_\odot$)	1.532	$^{+0.079}_{-0.075}$	$^{+0.163}_{-0.147}$
R_{PNS} (km)	11.69	$^{+0.48}_{-0.48}$	$^{+0.98}_{-0.93}$
E_{tot} (10^{53} erg)	1.009	$^{+0.032}_{-0.030}$	$^{+0.066}_{-0.059}$

Toward physics in the next Galactic supernova

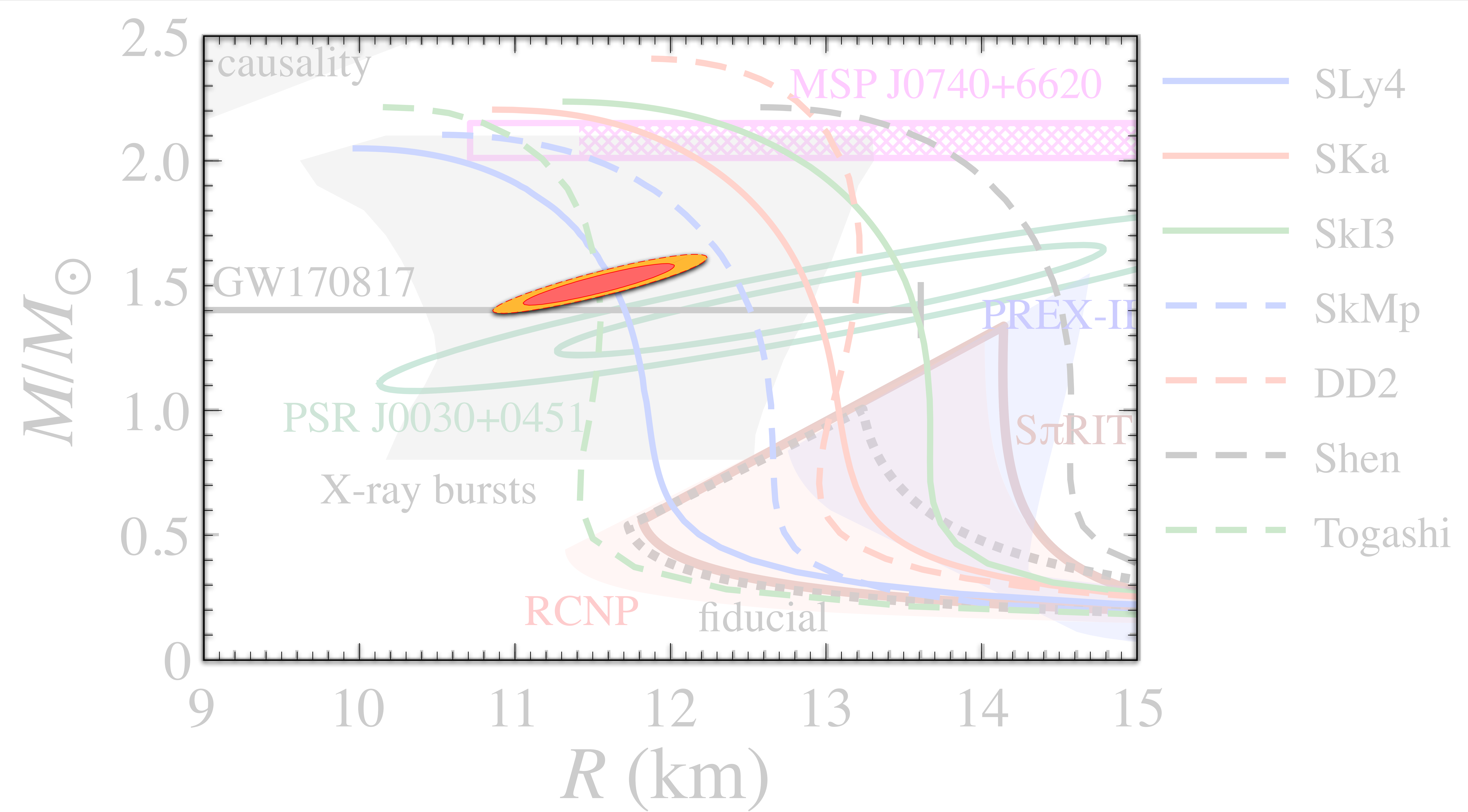
- **Properties of neutron stars**
  - **Binding energy**
    - ***important for energetics, done with SN1987A***

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

  - **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***



Neutrino constraint on M-R relation



Sotani-Nishimura-Naito (2022)

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
  - M and R can be measured independently

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