超新星ニュートリノの最近の話題

諏訪 雄大

（東大駒場 & 基研）

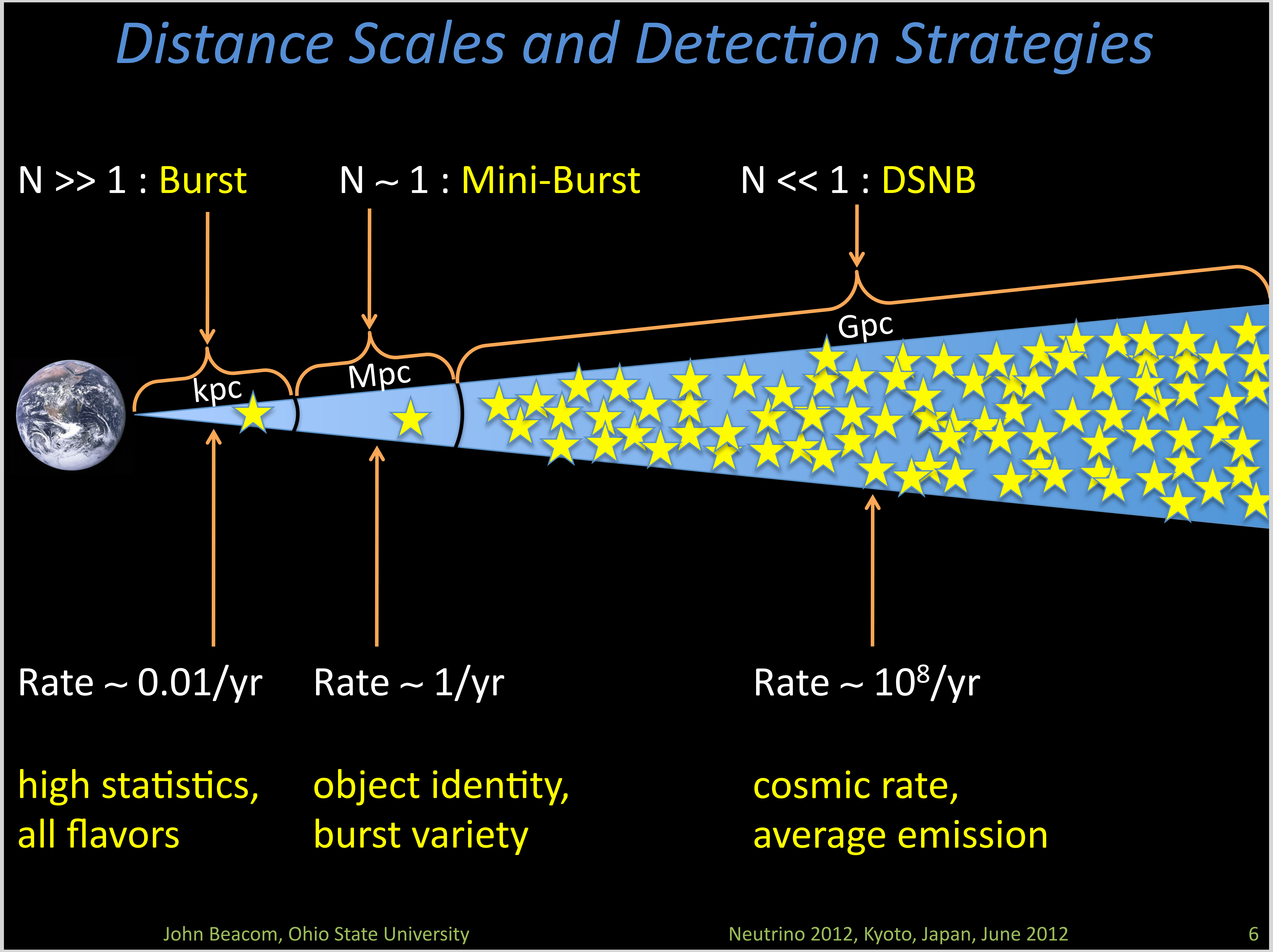
with *nuLC* collaboration

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, 925, 98 (2022)
YS, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022)

東大駒場の超新星な人々

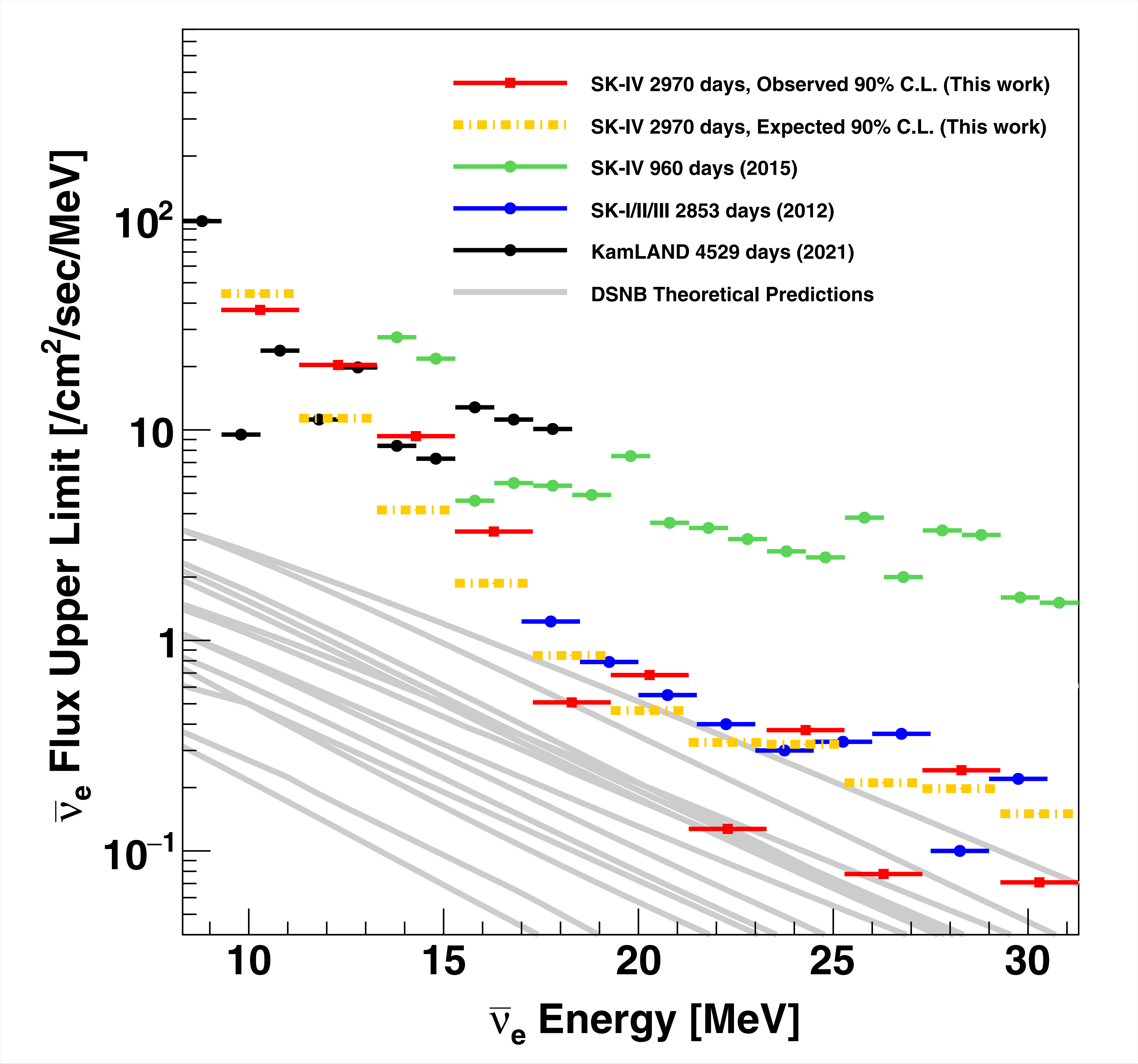
- 2021年4月から
- PD
  - 澤田涼 / Ryo Sawada：超新星元素合成（次の発表者）
  - 森正光 / Masamitsu Mori：超新星ニュートリノ（さらに次の発表者）
- M1
  - 川下大響 / Hiroki Kawashimo：対不安定型超新星（ポスター14）
  - 屈楚舒 / Chushu Qu (Sojo)：マグネター（ポスター23）
  - 篠田兼伍 / Kengo Shinoda：超新星フォールバック
  - 服部英里子 / Eriko Hattori：Ia型超新星

Supernova neutrinos



from Beacom (2012)

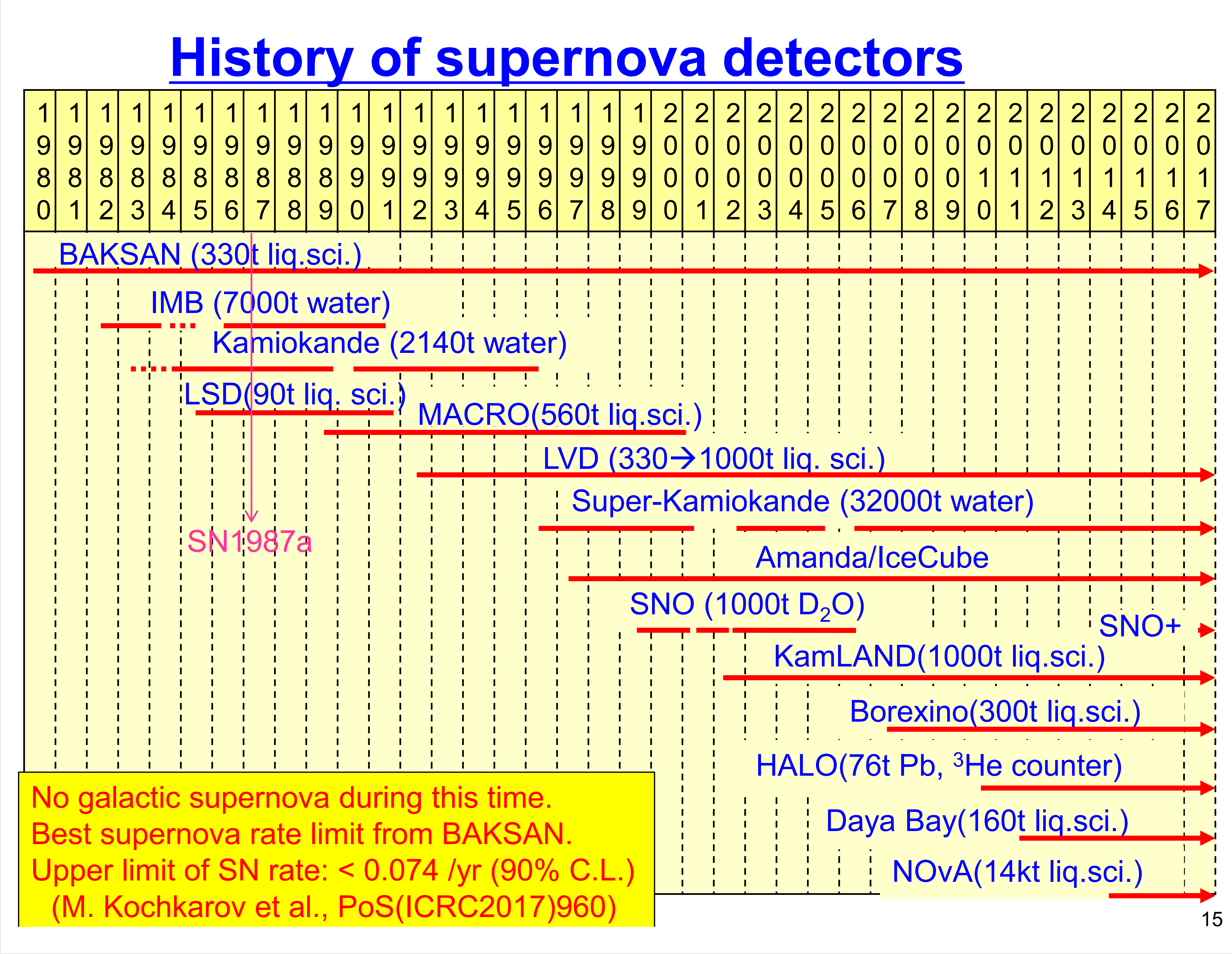
Diffuse supernova neutrino background (DSNB)



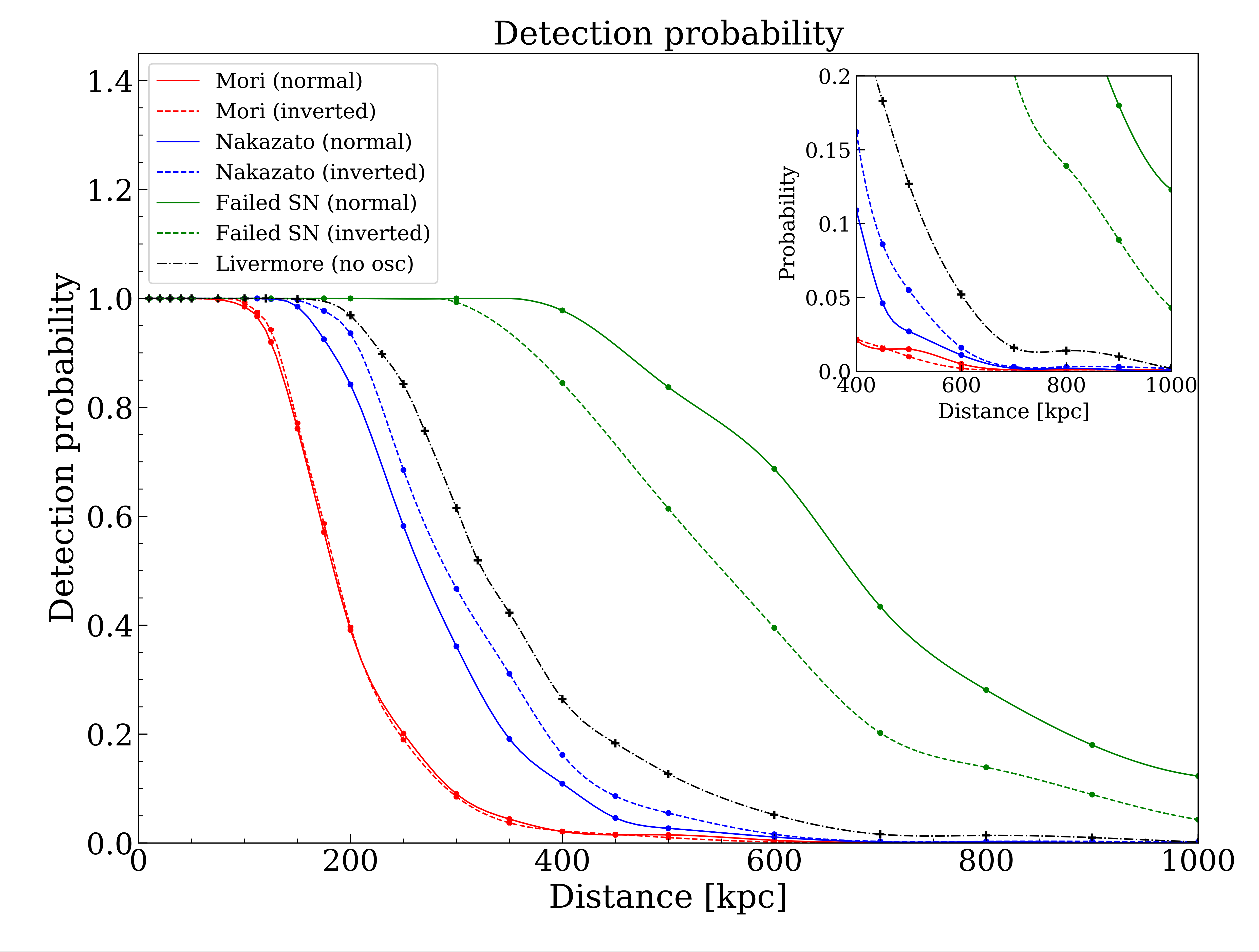
Abe et al. (2021)

Supernova neutrino (mini-)burst search

from Nakahata (2017)



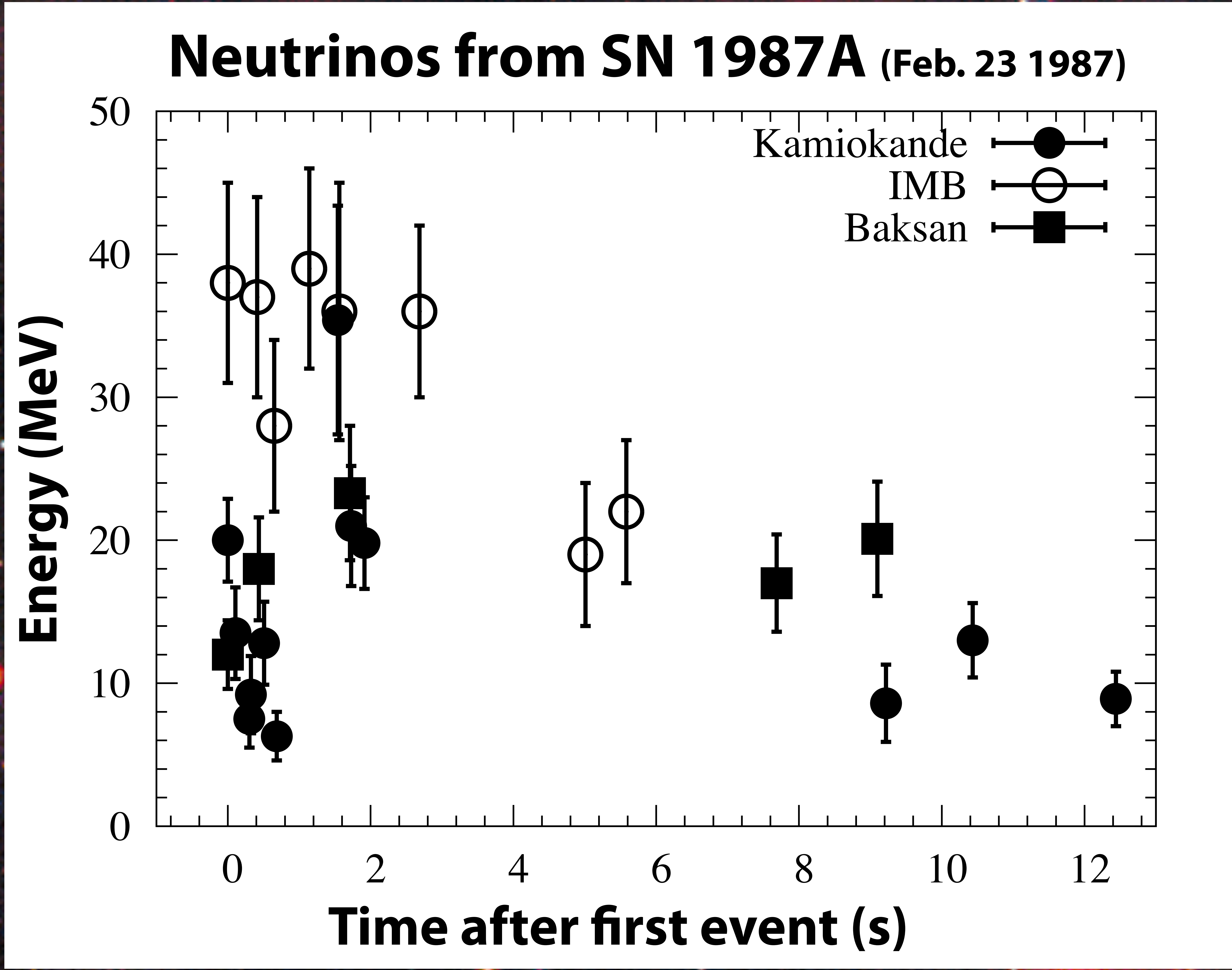
Mori et al. (2022)



R_{SN} < 0.074 year^{-1} in MW

R_{SN} < 0.29 year^{-1} for D<100 kpc (SN)
D<300 kpc (BH)

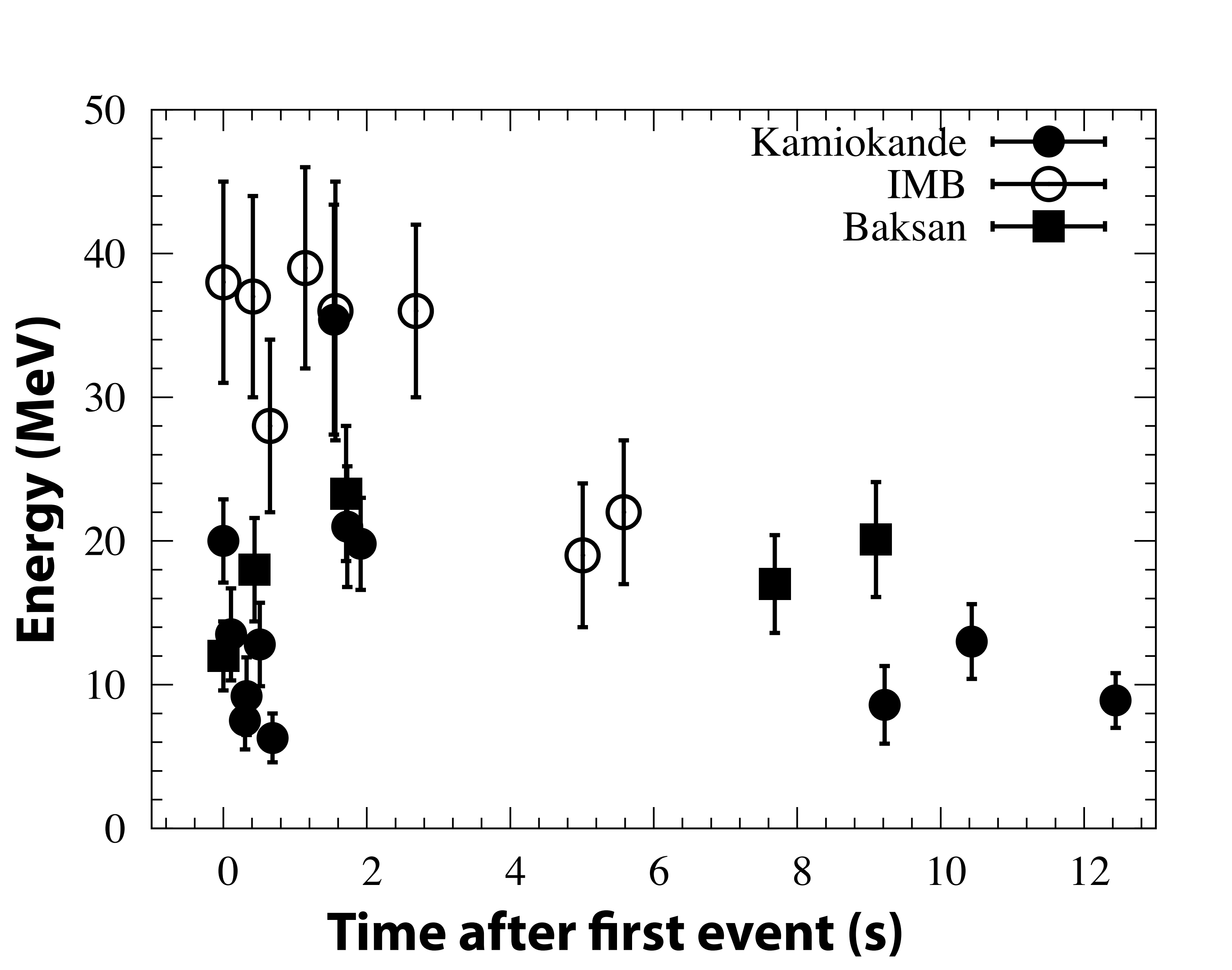
SN1987A



NASA/ESA

How many and long can we observe ν now?

- How many?
  - 11 events from SN1987A with Kamiokande
    - M=2.14 kton (full volume of inner tank)
    - D=51.2 kpc (LMC)
  - SK (M=32.5 kton), D=10 kpc => 4400 events (with *O*(10)% of statistical error)



- How long?
  - 12.4 s for SN1987A
  - How long can we observe neutrinos from a Galactic SN? No conclusive estimation so far!

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

What can we extract from neutrino observations?

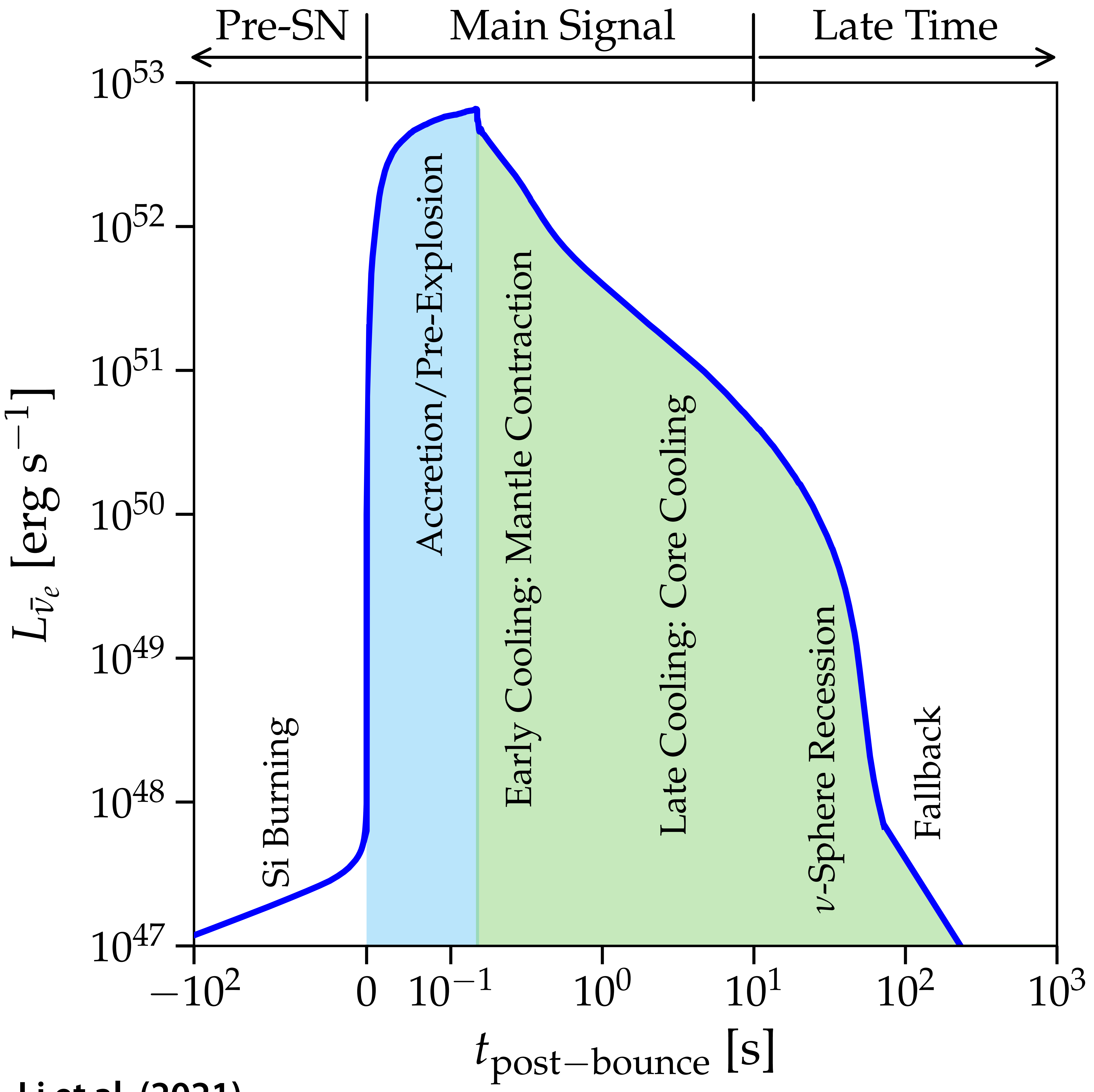
- **Properties of neutron stars**
  - **Binding energy**
    - *important for energetics, done with SN1987A*

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

  - **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

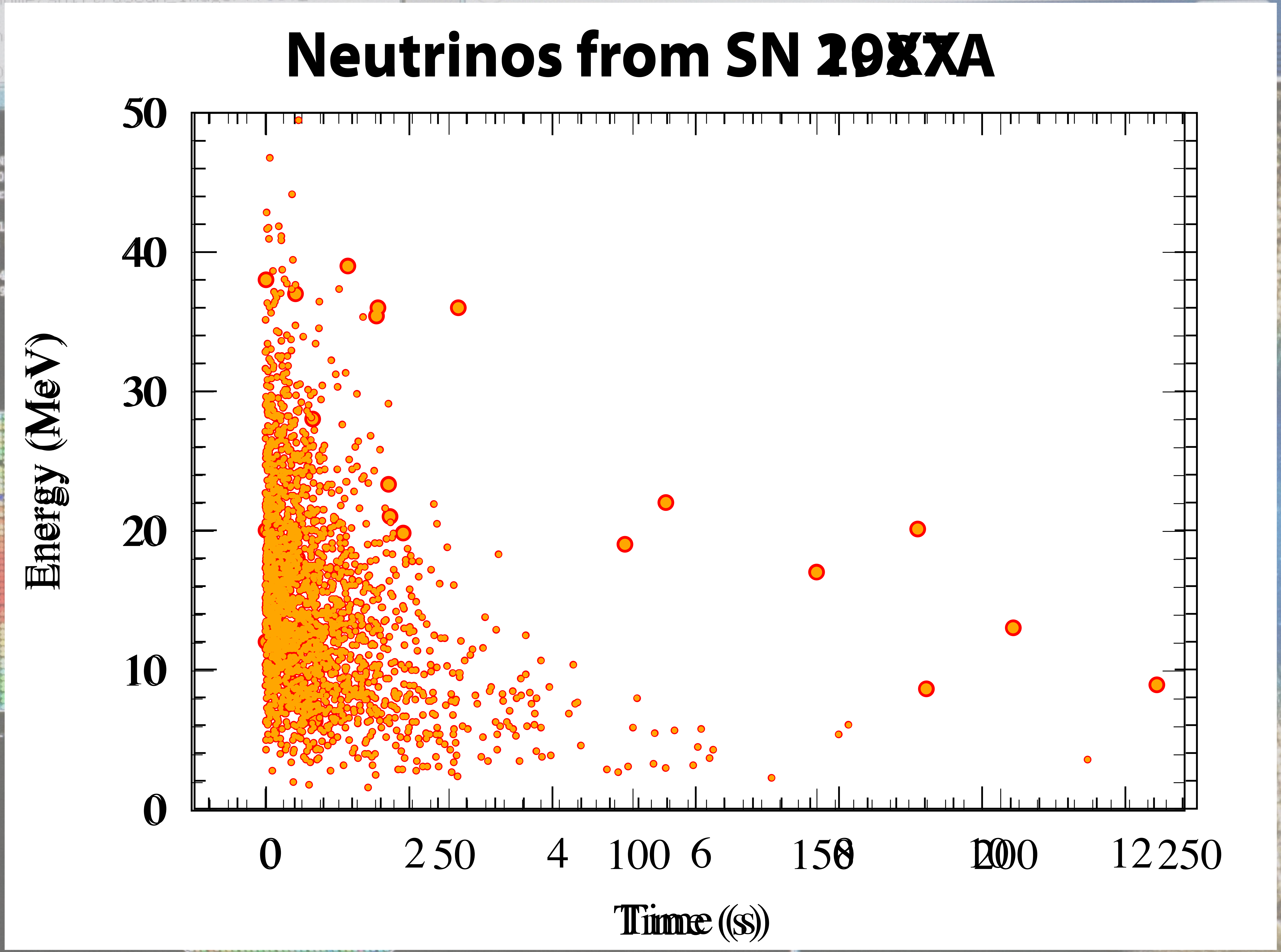
Supernova neutrinos: basics



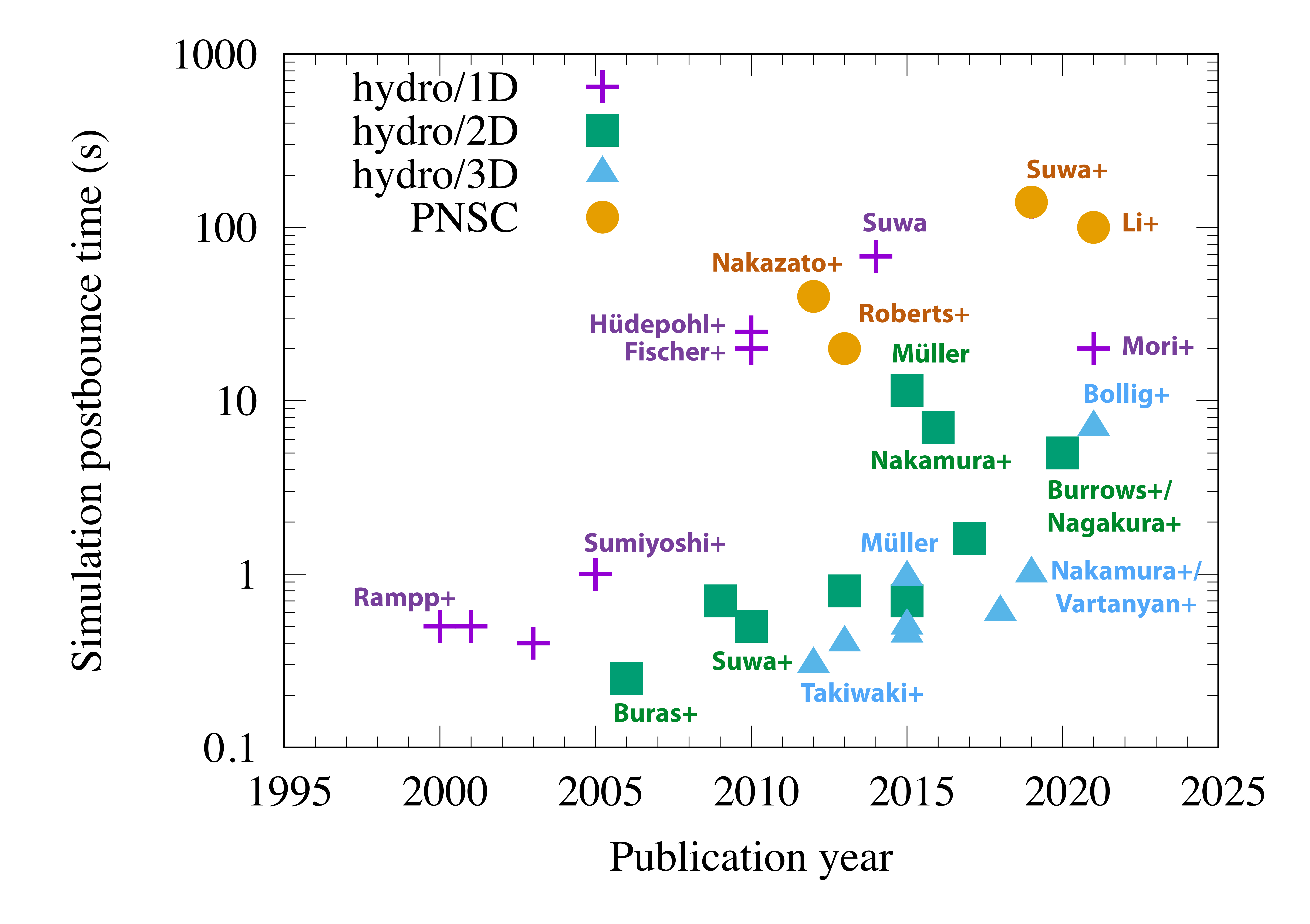
Li et al. (2021)

- **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 necessary



Current status of area



focusing on long-term simulations. definitely incomplete…

Neutrino detectors: current and future

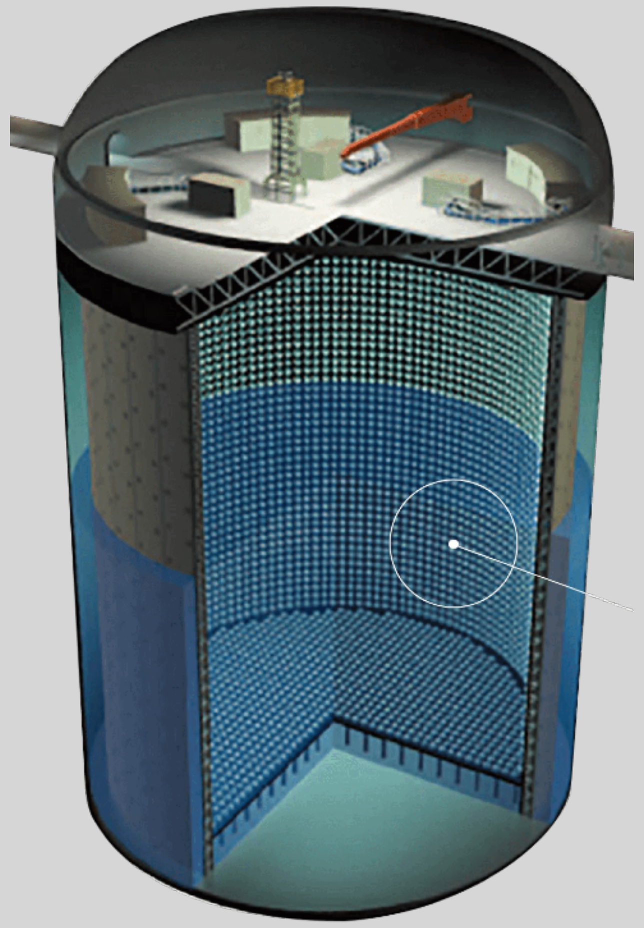
Water Cherenkov

Liquid Scintillator

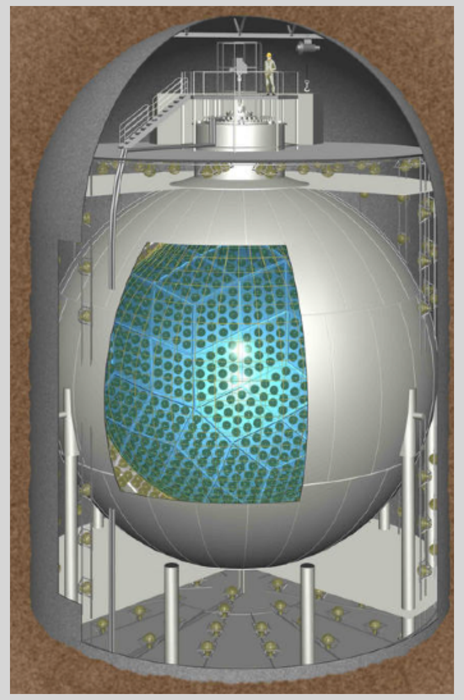
Liquid Ar

current

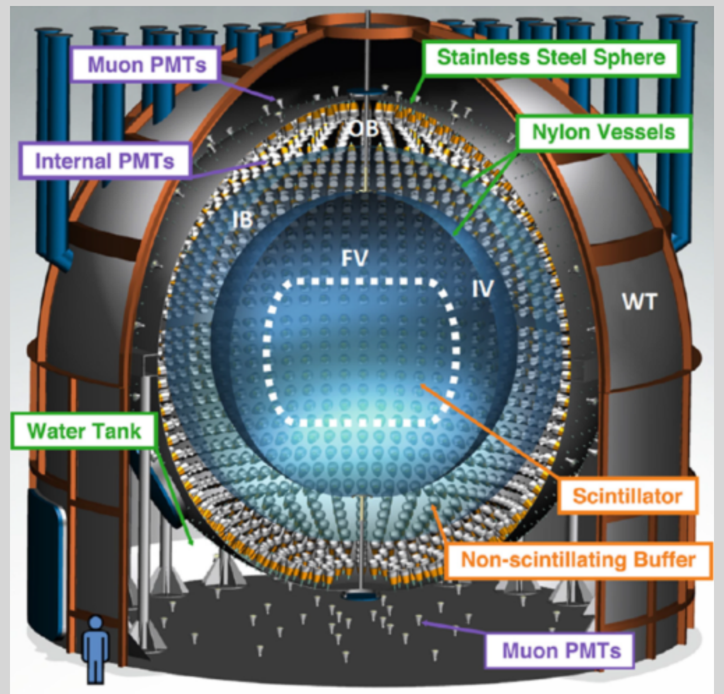
Super-Kamiokande (1996~)



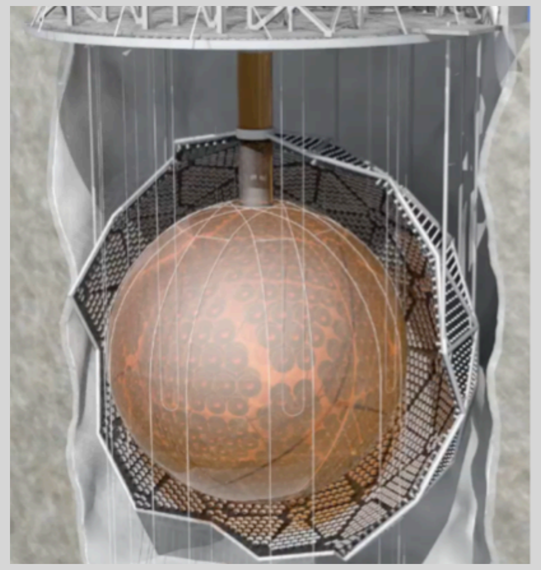
KamLAND (2002~)



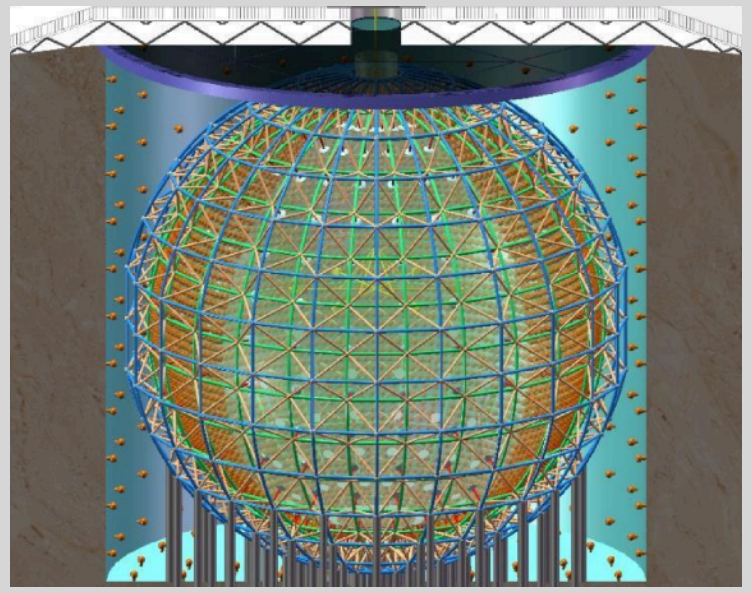
Borexino (2007~)



SNO+ (202?~)

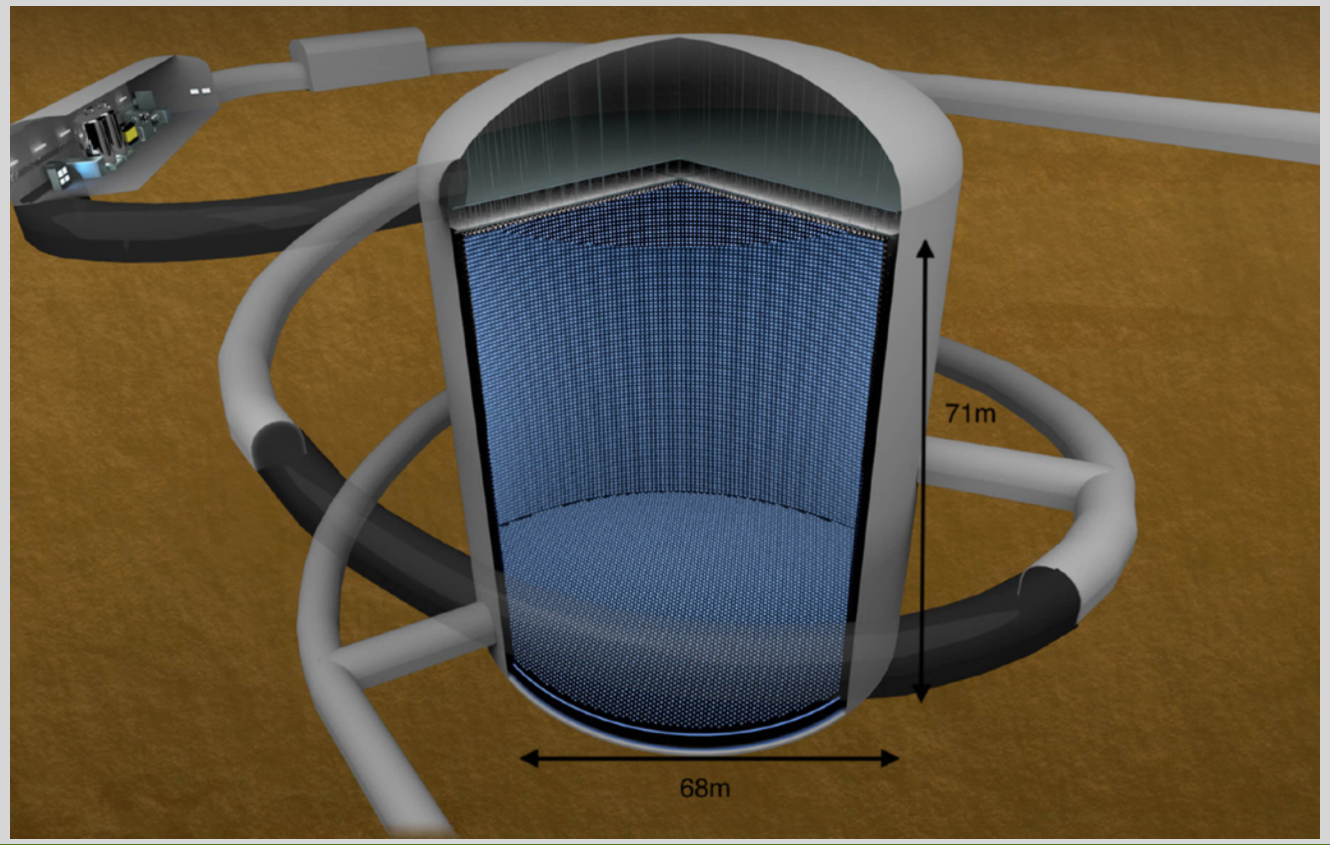


JUNO (2023~)

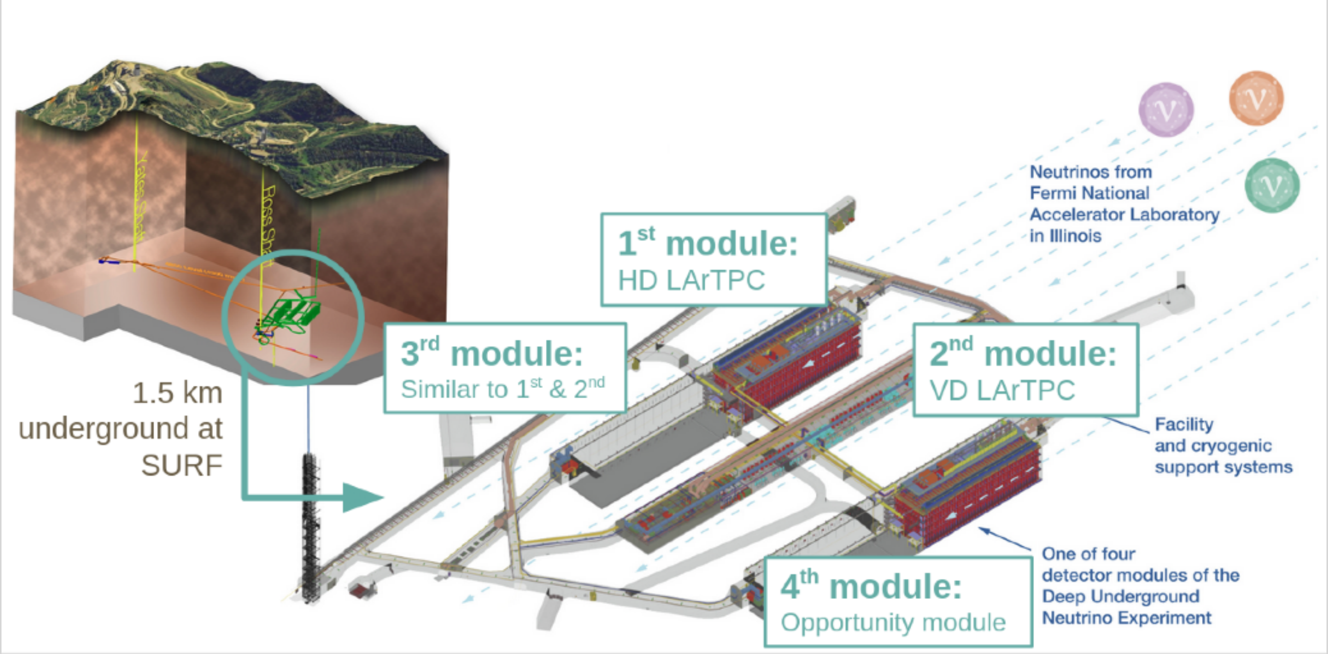


future

Hyper-Kamiokande (2027~)



DUNE (2029~)



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, ApJ, 934, 15 (2022)

Kyoto U.: R. Wendell (Experiment)

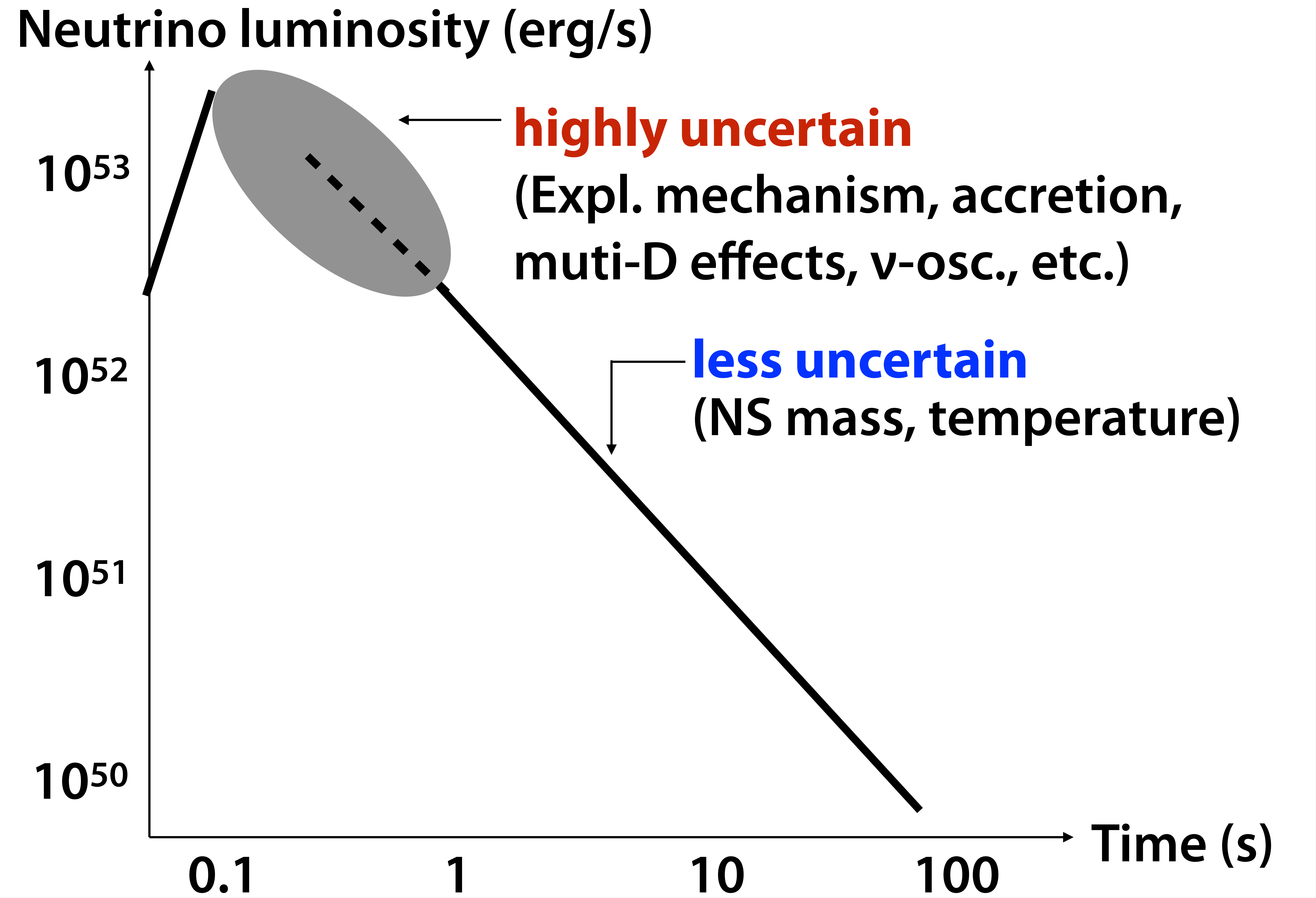
Riken: A. Harada (Theory)
U. Tokyo: Y. Suwa, M. Mori (Theory/Experiment)

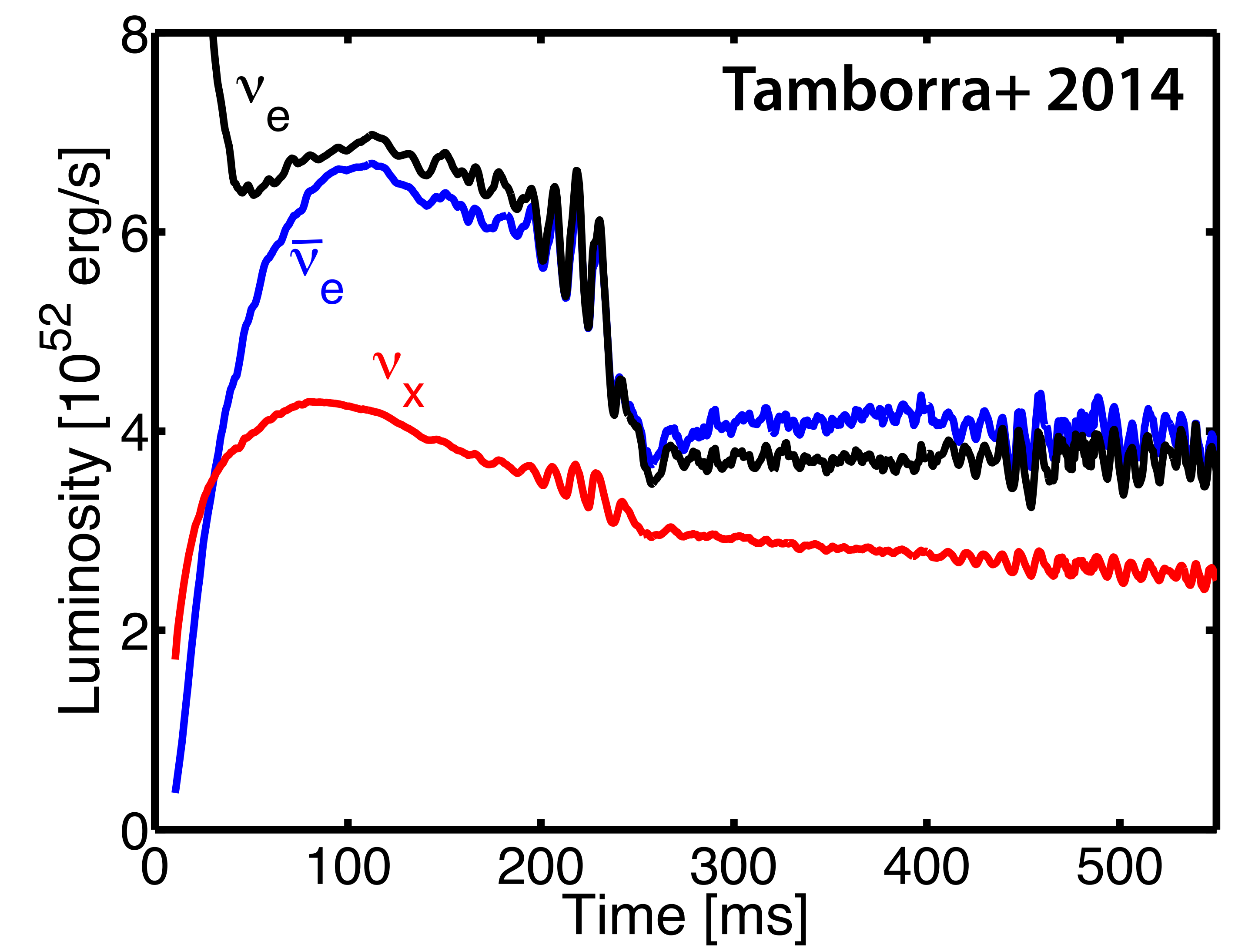
NIT, Numazu: K. Sumiyoshi (Theory)

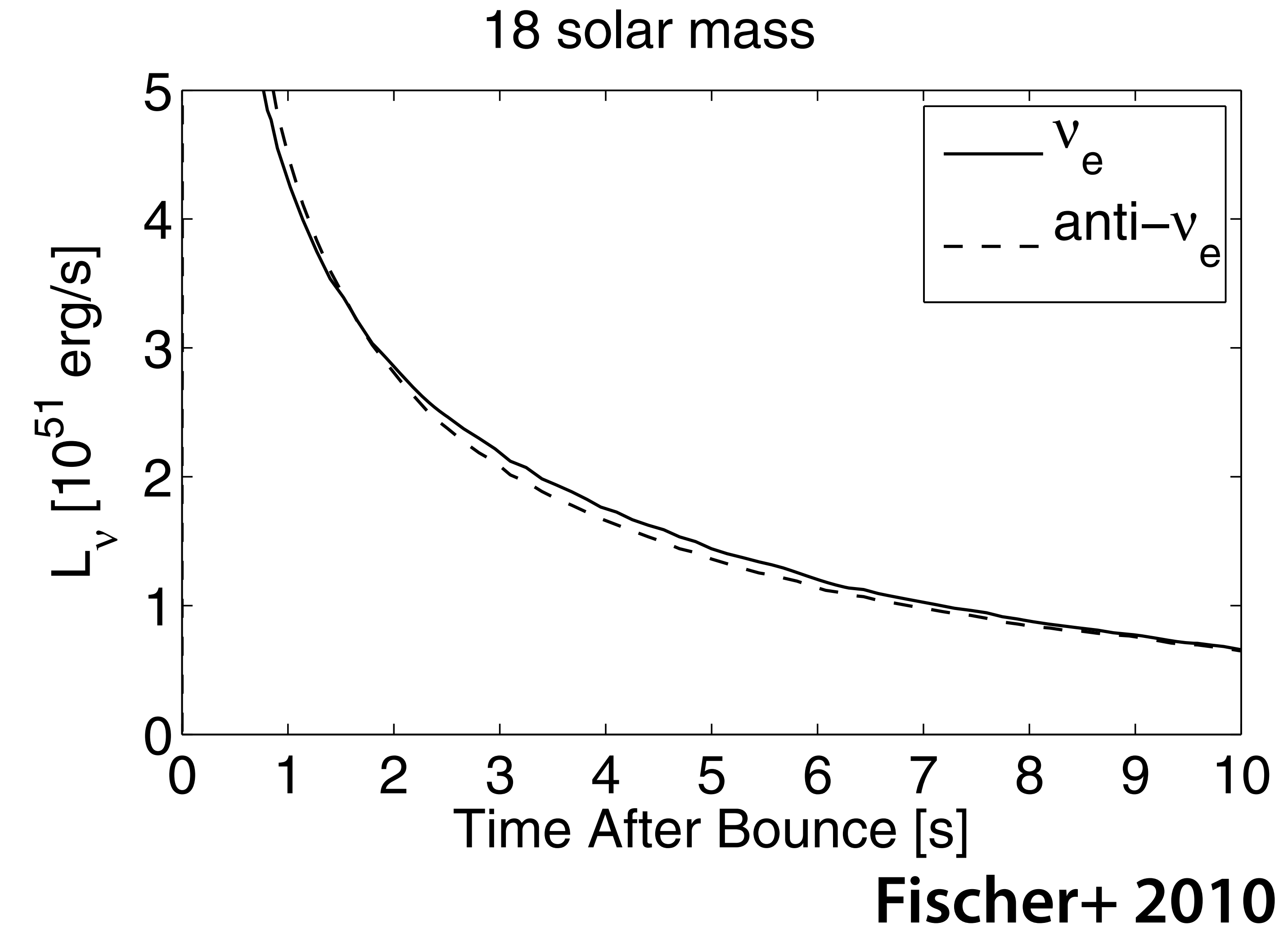
Okayama U.: Y. Koshio, M. Harada, F. Nakanishi (Experiment)

Kyushu U.: K. Nakazato (Theory)

Late cooling phase is simpler and more understandable than early phase







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/

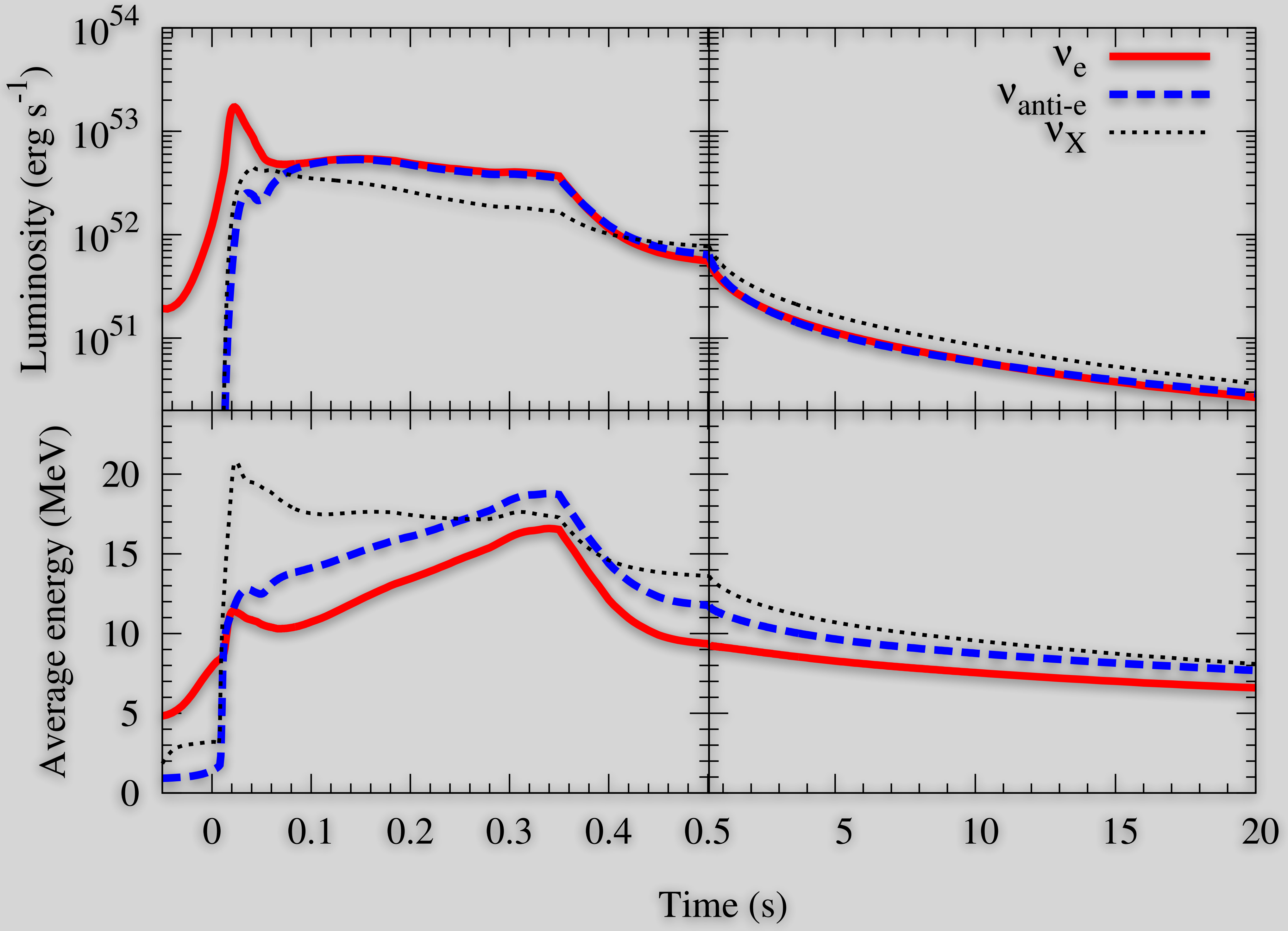
step 1

NUMERICAL SIMULATIONS

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

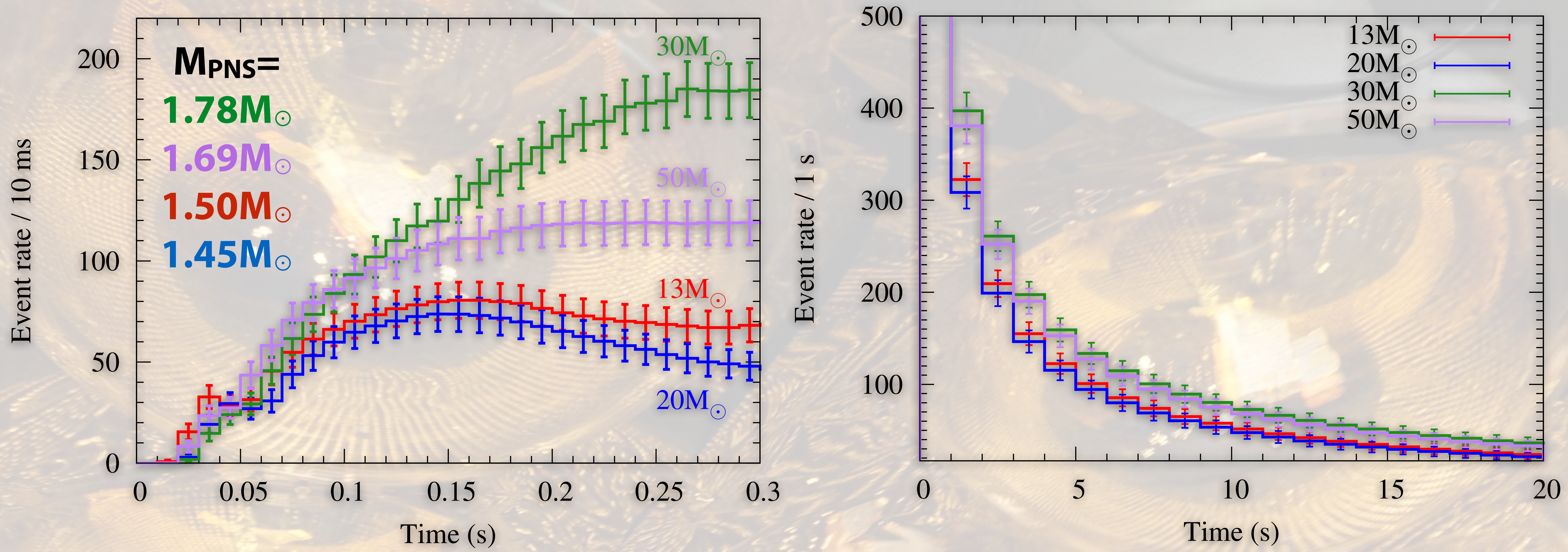
- **Hydro. simulation (t<0.3s)**
  - dynamical, GR, Boltzmann neutrino transport, nuclear EOS, 1D
    Yamada 1997, Sumiyoshi+ 2005
- **PNS cooling simulation (t>0.3s)**
  - static (TOV), FLD neutrino transport, nuclear EOS, 1D
    Suzuki 1993
- **Connection**
  - Interpolate two results with t_{revive}=100, 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 ($\bar{\nu}_e + p \rightarrow e^+ + n$)
- Event rate is not related to progenitor mass, but PNS mass

step 1

NUMERICAL SIMULATIONS

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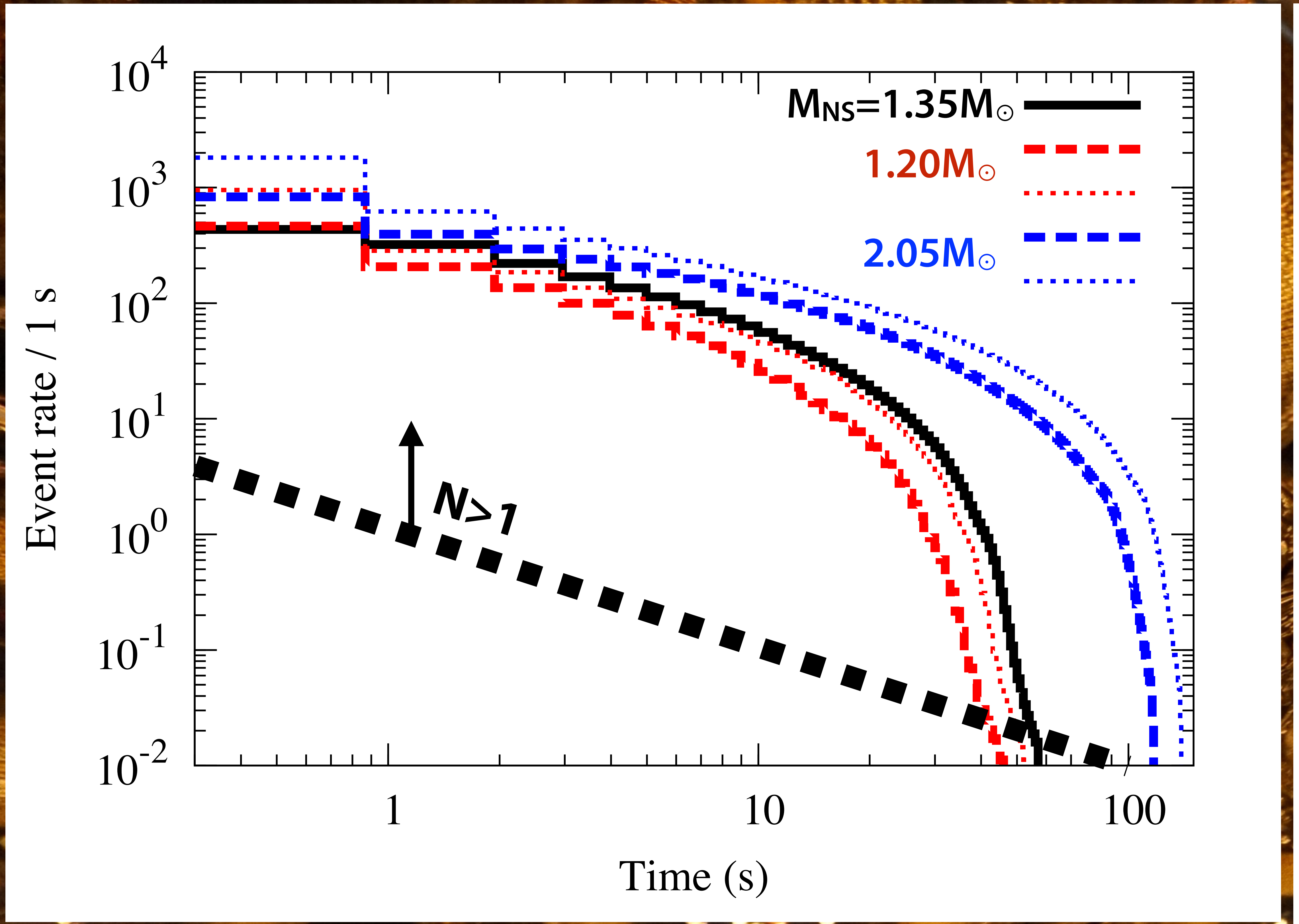
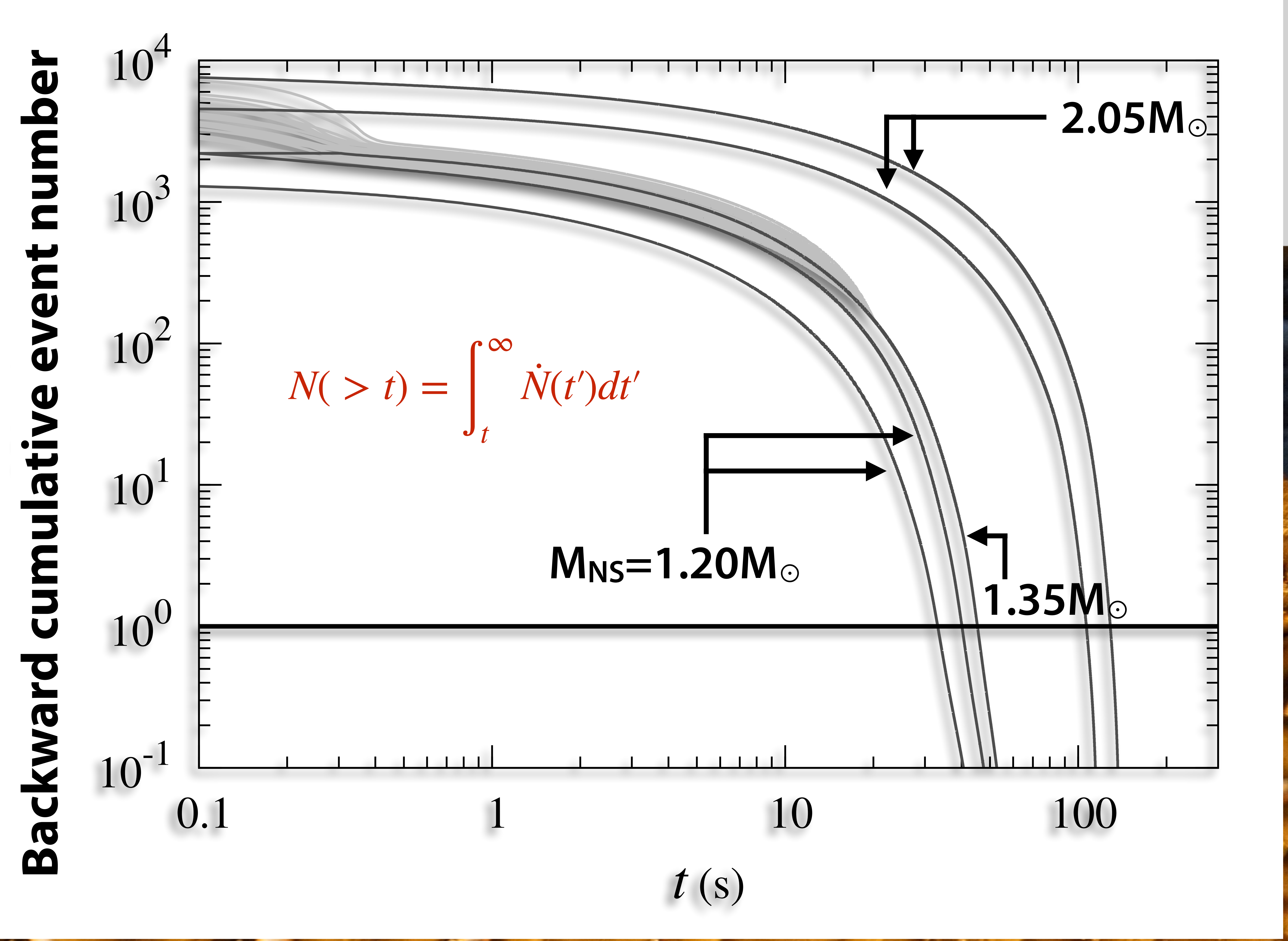
- Computationally expensive

How long can we see SN with neutrinos?

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

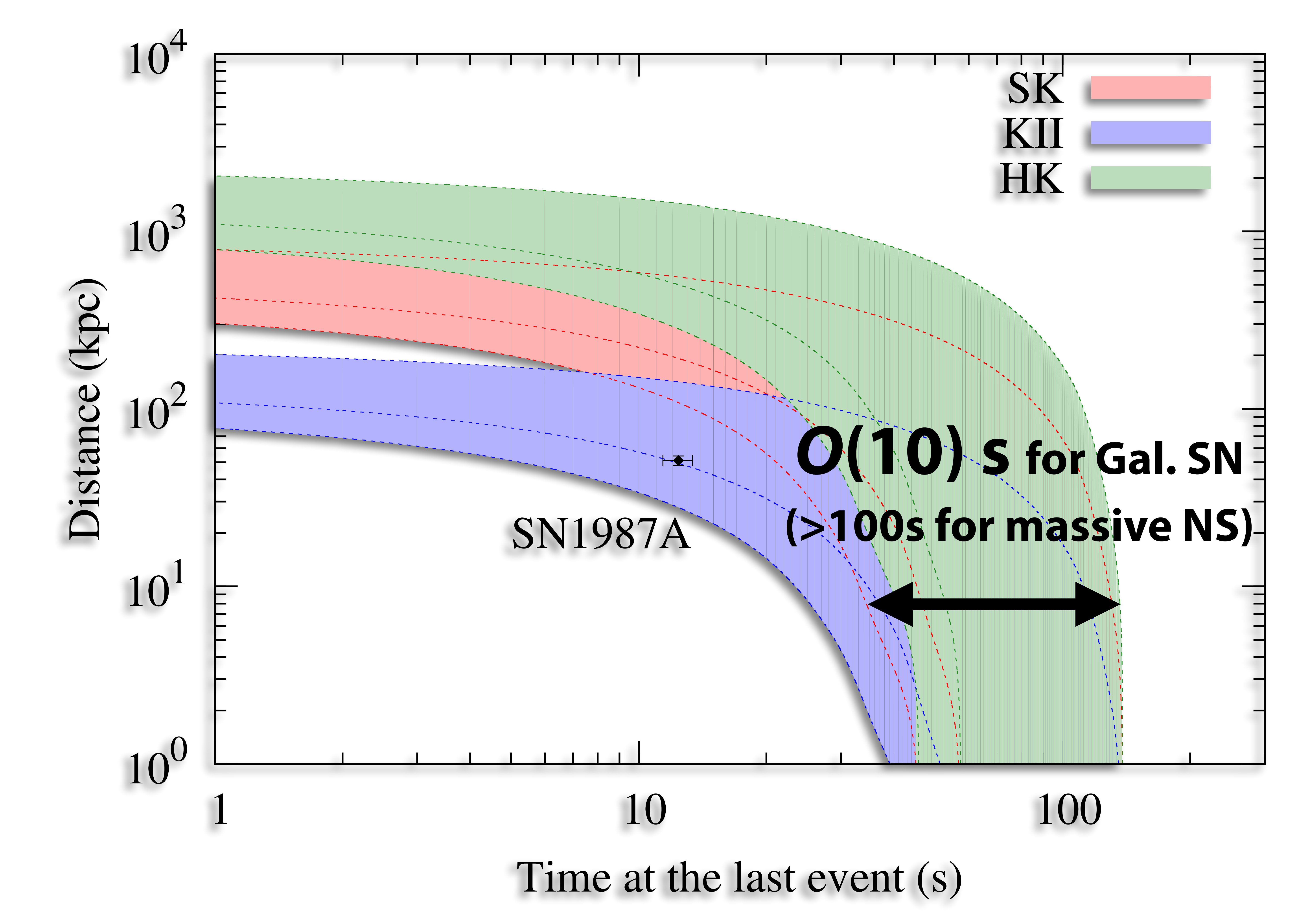
step 1

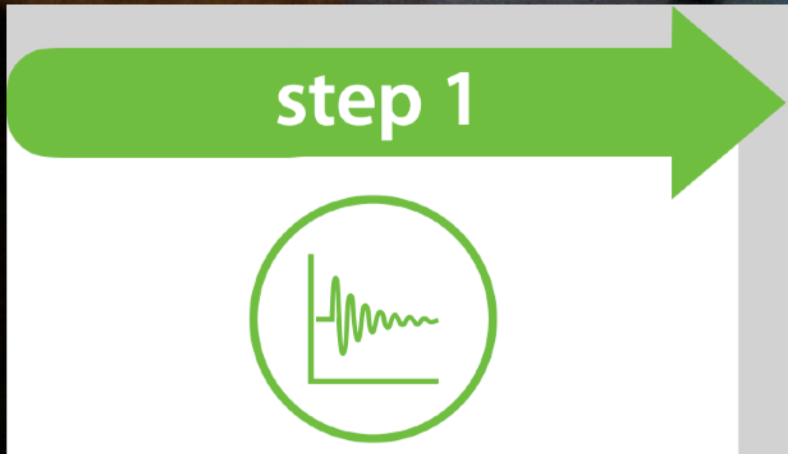




How long can we see SN with neutrinos?

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





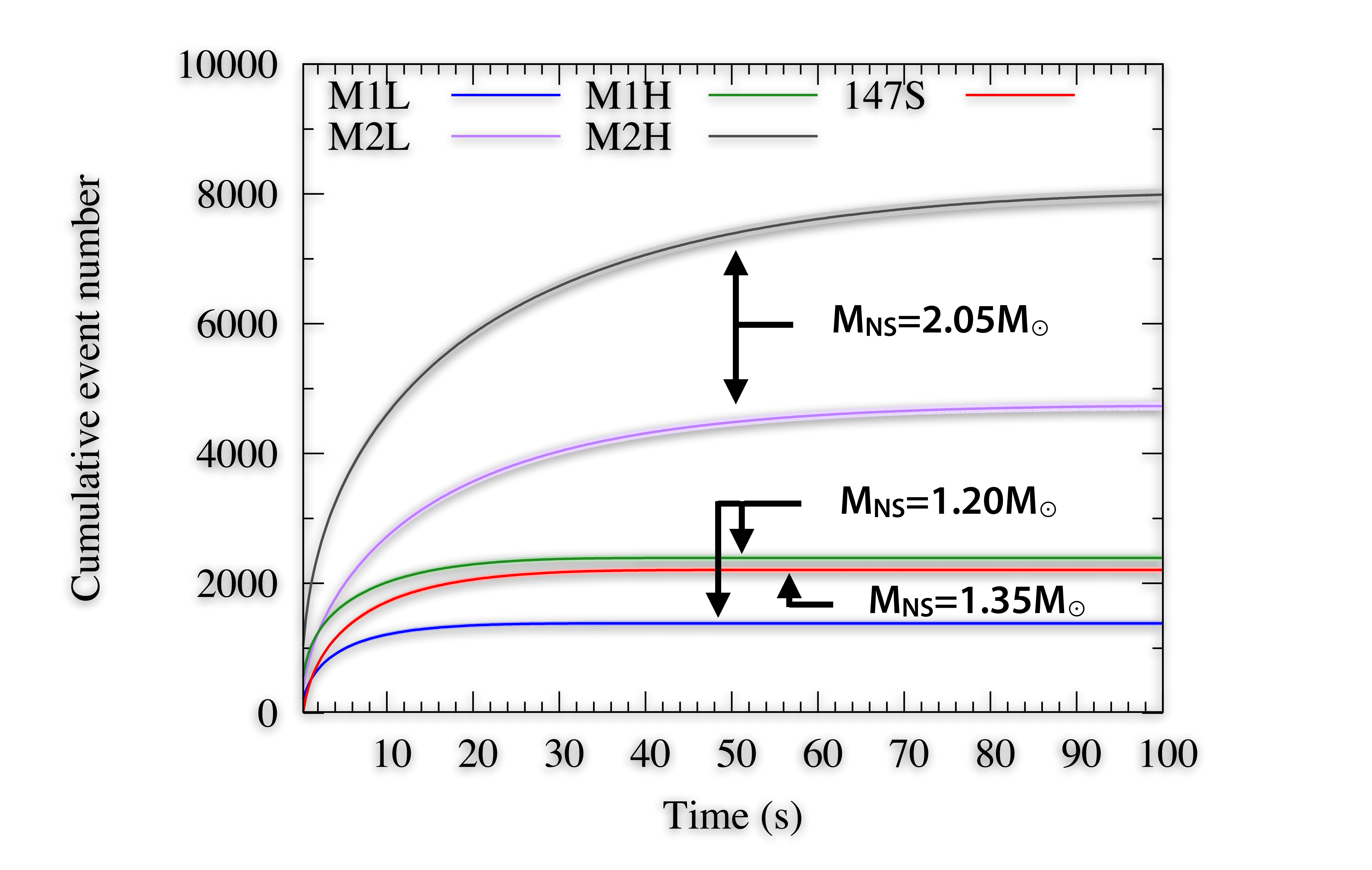
NUMERICAL SIMULATIONS

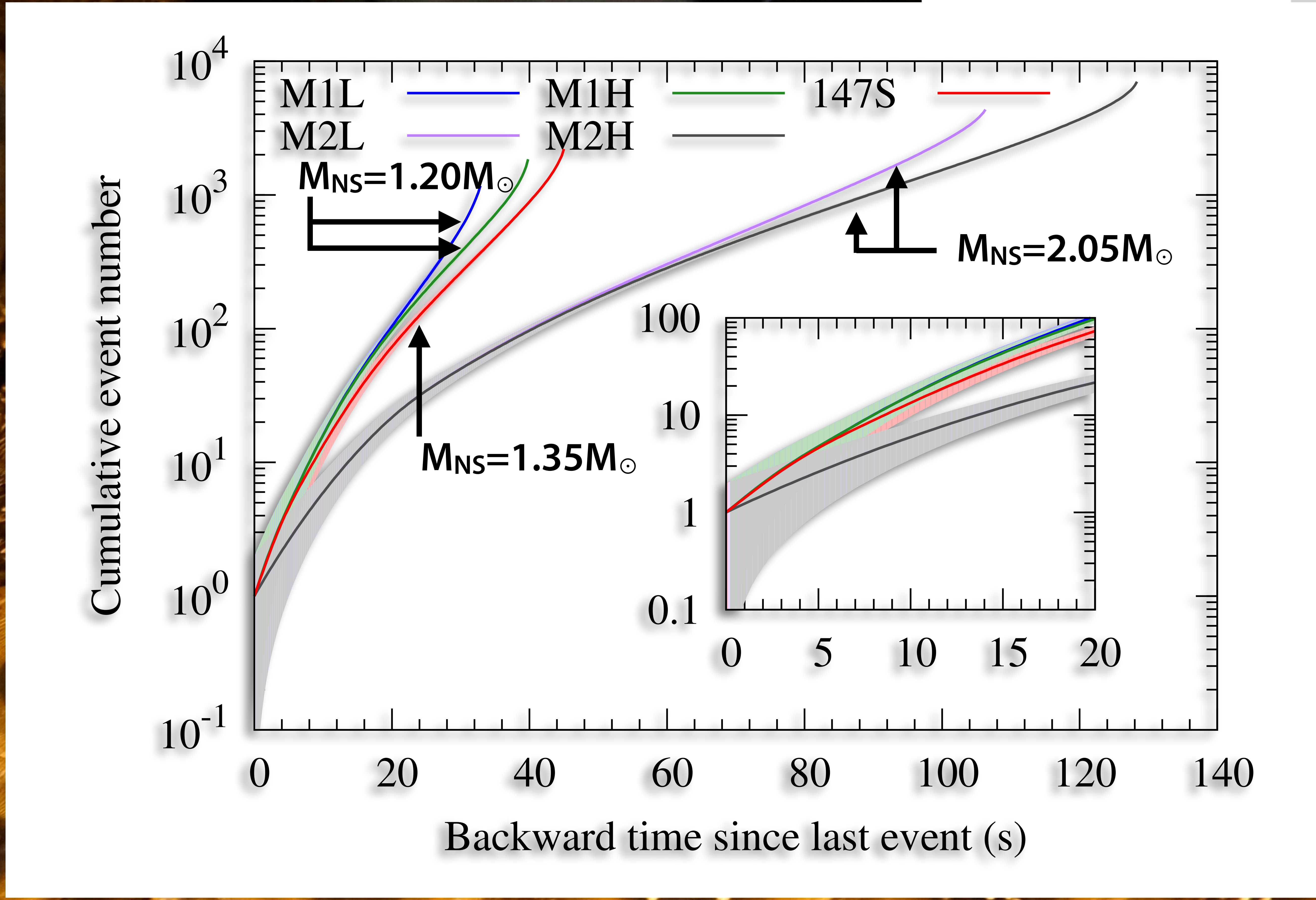
- Cooling curves of PNS
- Detailed physics included
- Discrete grid of data set
- Computationally expensive

How to analyze neutrinos? Backward cumulative plot is useful

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

step 1

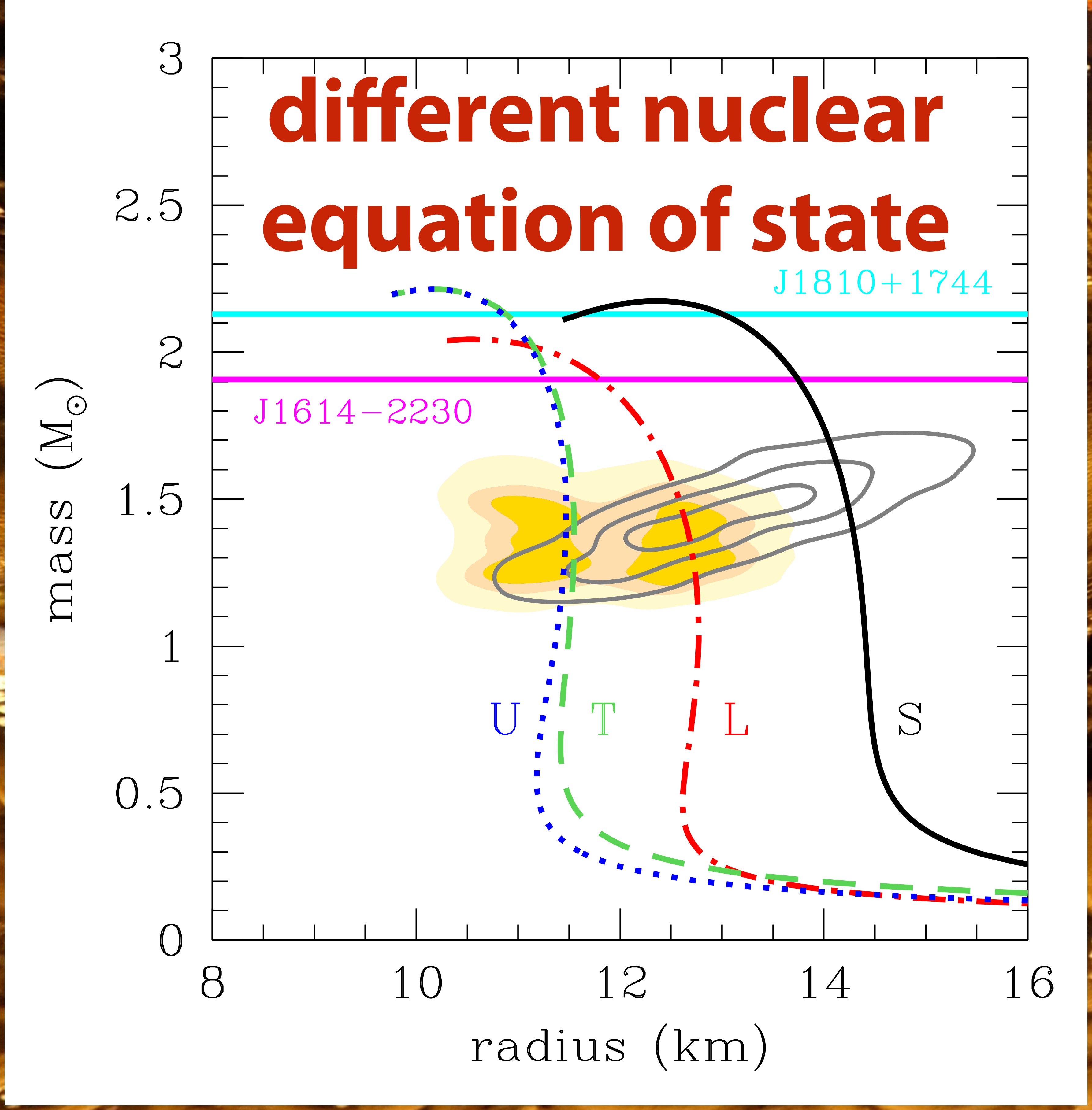


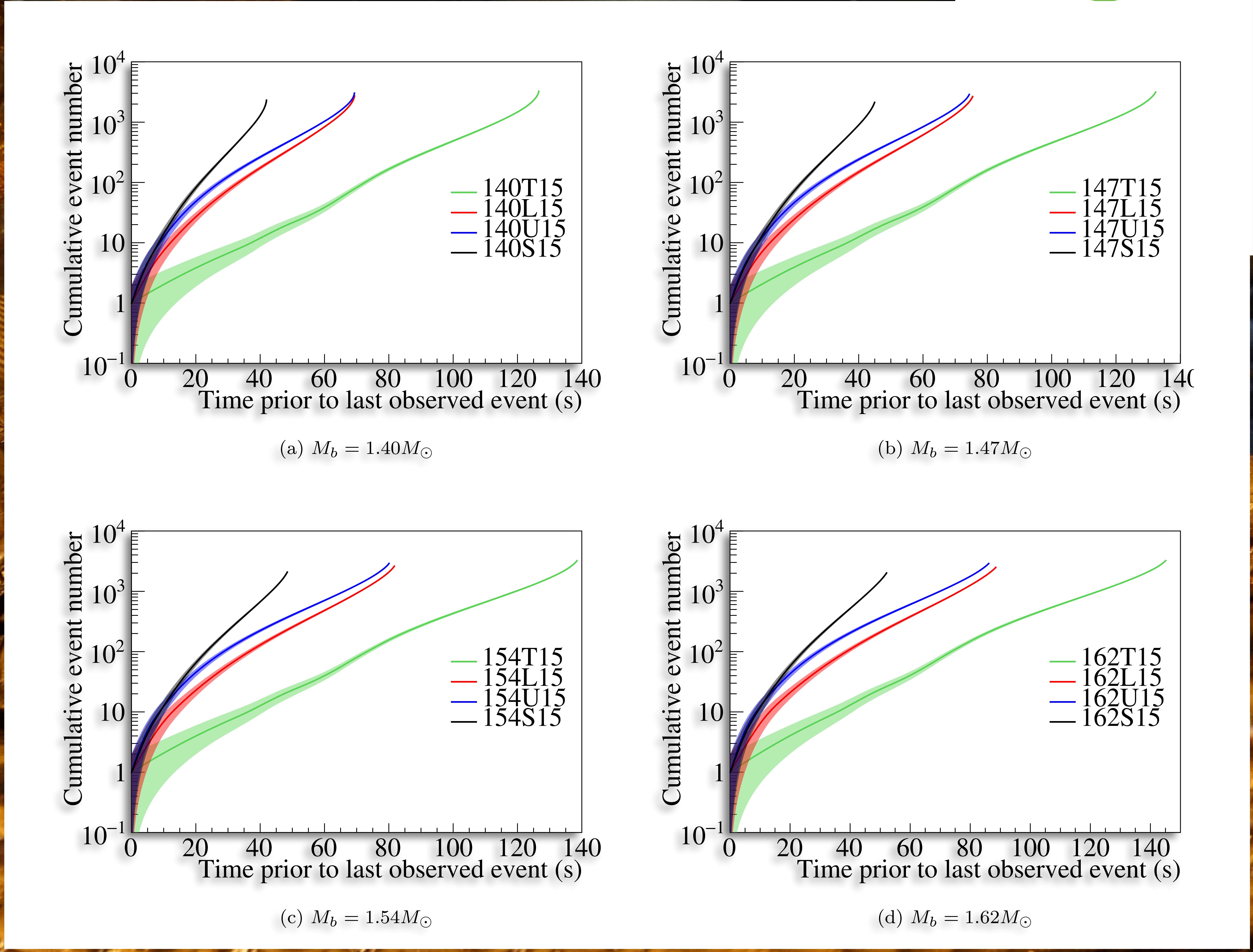


Model grids are getting larger

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) $M_b = 1.62 M_\odot$

Next is analytic expression

- A Grid of PNS cooling simulations is getting broader
- Good

- 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)]

* **PNS is assumed as Lane-Emden solution with n=1 (γ=2)**

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

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

* **Neutrino transport with diffusion approximation**

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

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

step 2

$f(x)$

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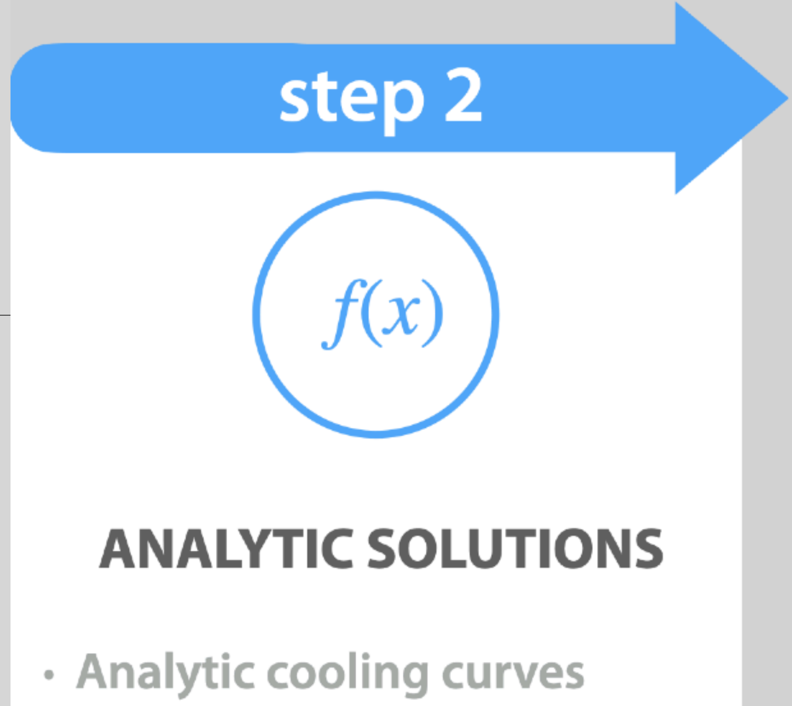
Analytic solutions



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

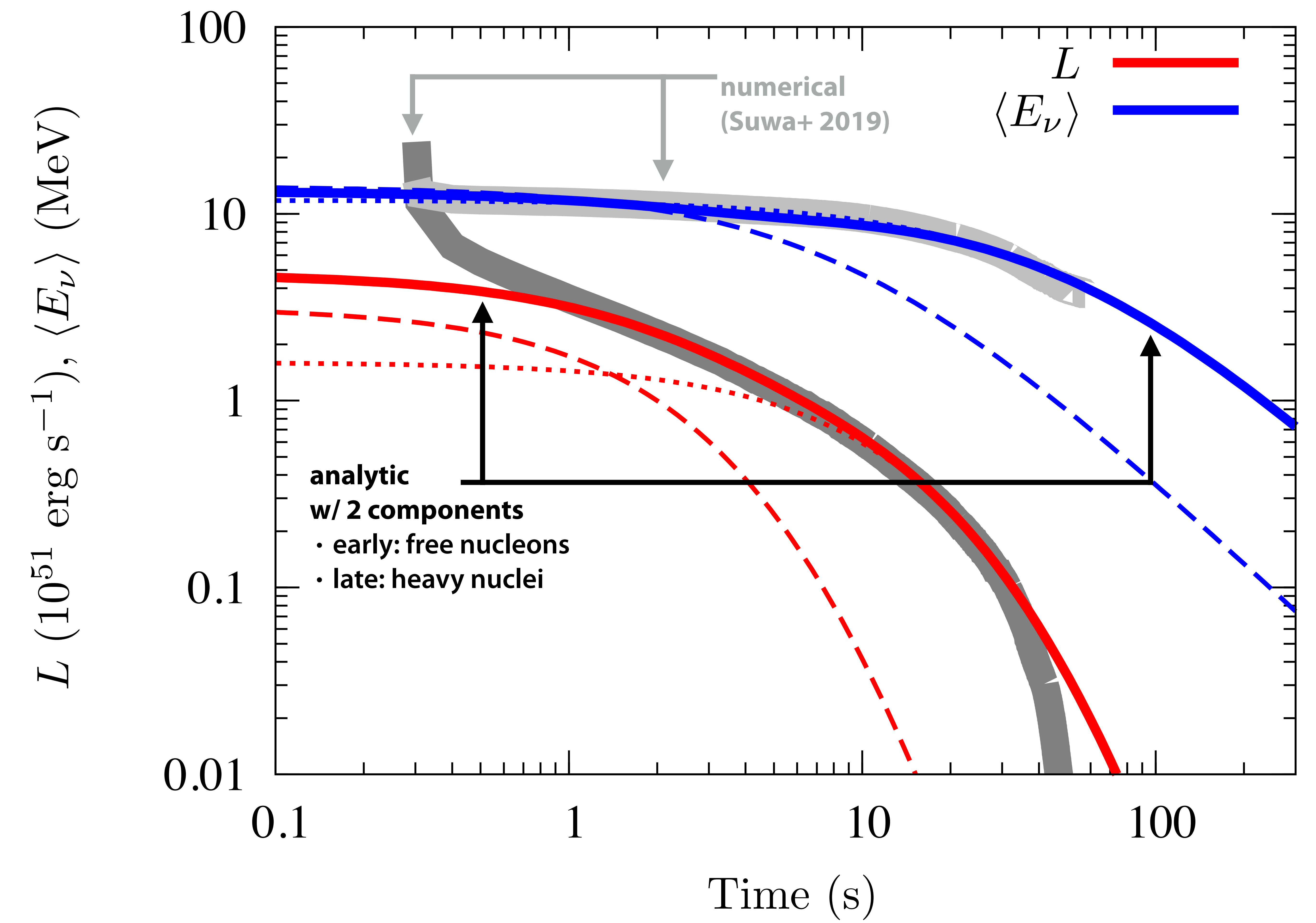
- Solve neutrino transport eq. analytically
  - Neutrino luminosity

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

  - 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))



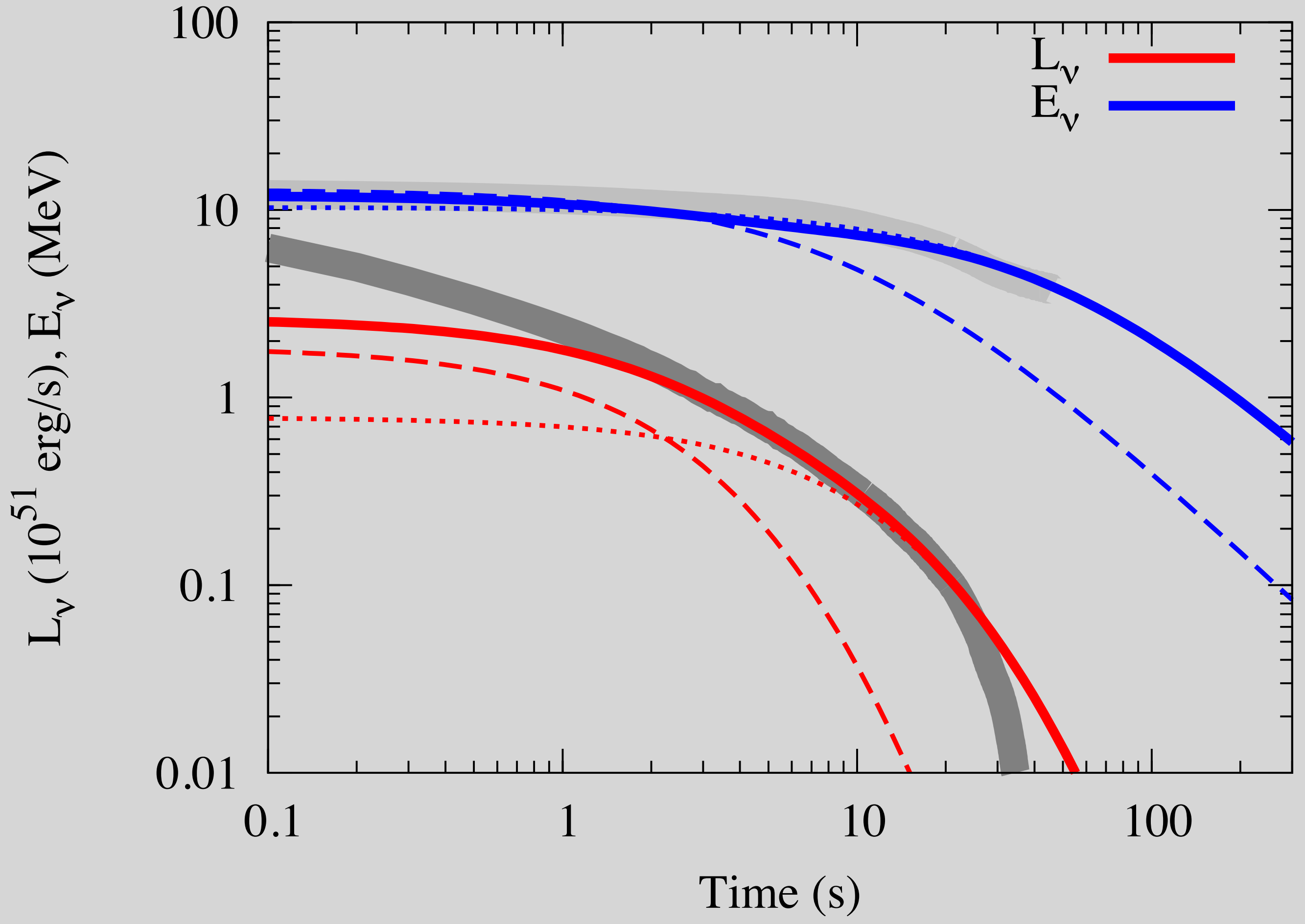
Other models

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

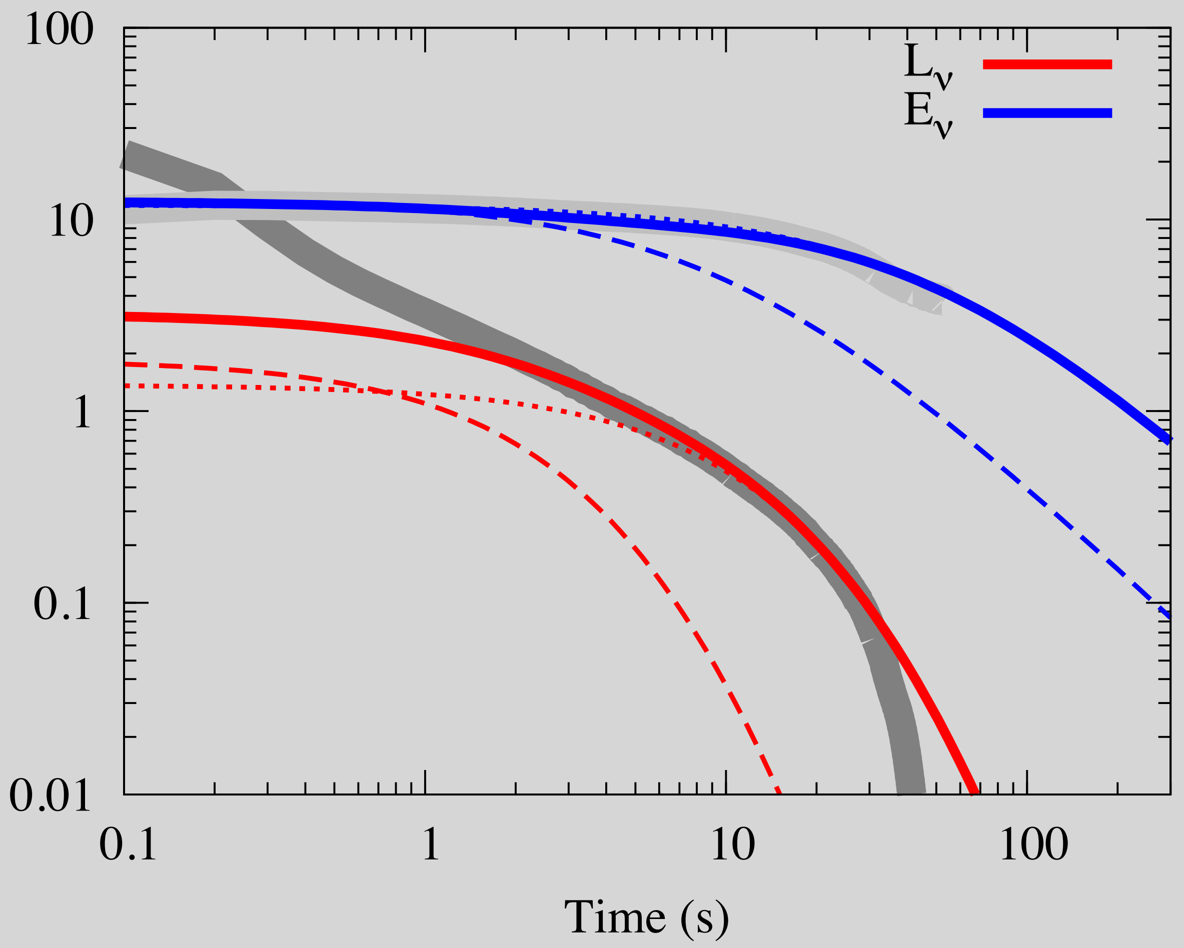
Table 1. Model parameters reproducing numerical solutions presented in Ref. [12].

Model	$M_{\rm PNS}$ ($M_\odot$)	$R_{\rm PNS}$ (km)	g	β_1	$E_{\rm tot,1}$ (10^{52} erg)	β_2	$E_{\rm tot,2}$ (10^{52} erg)
147S	1.5	12	0.04	3	4.0	40	10
M1L	1.3	11	0.04	3	2.5	25	5.0
M1H	1.3	11	0.04	3	2.5	30	9.0
M2L	2.3	13	0.1	3	8.0	30	22
M2H	2.3	13	0.1	3	11	40	35

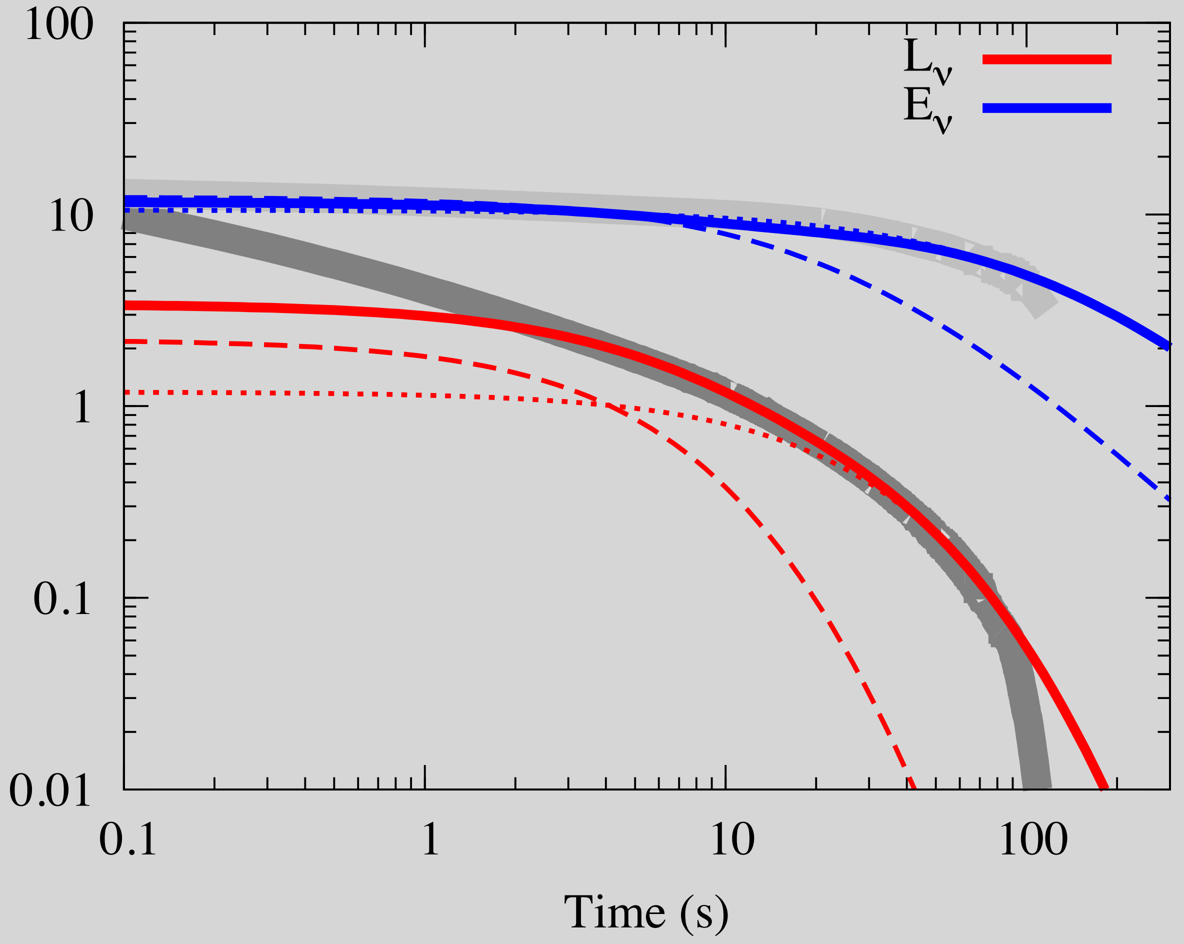
M1L
(1.2M⊙, low-entropy)



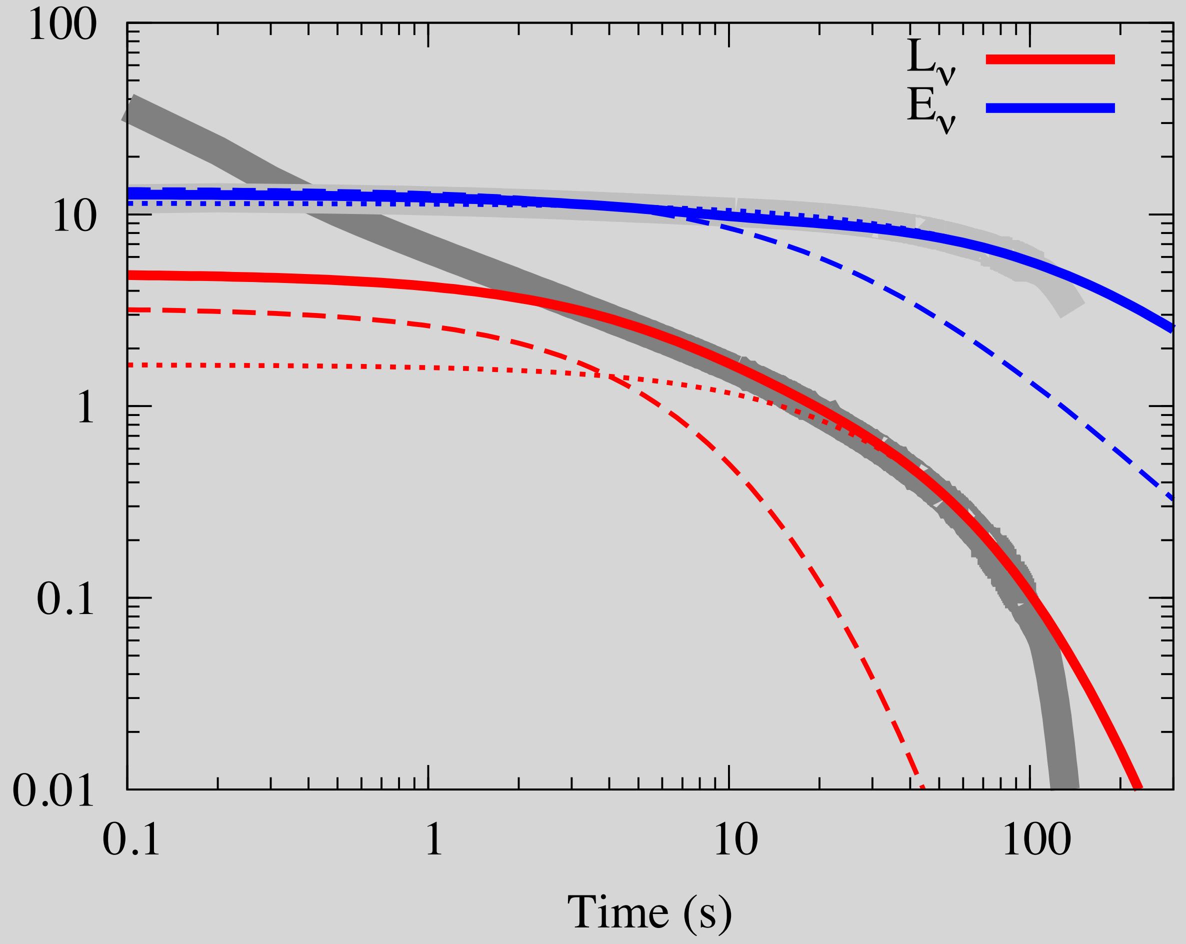
M1H
(1.2M⊙, high-entropy)



M2L
(2.0M⊙, low-entropy)



M2H
(2.0M⊙, high-entropy)



step 2

$f(x)$

ANALYTIC SOLUTIONS

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Observables with analytic solutions

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

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

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

* **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**

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

* **Consistency relation of analytic model**

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

step 2

$f(x)$

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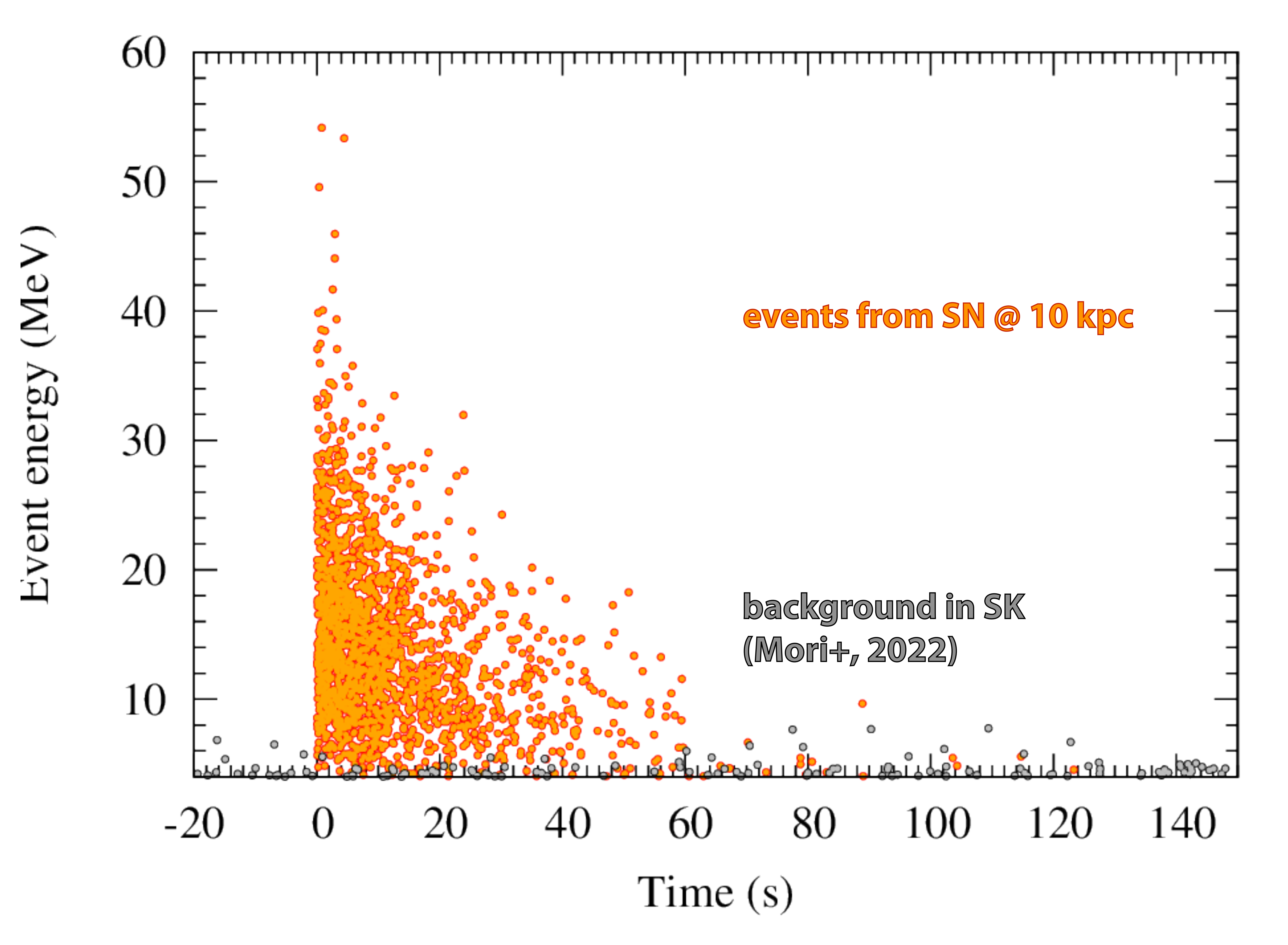
Mock sampling

[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

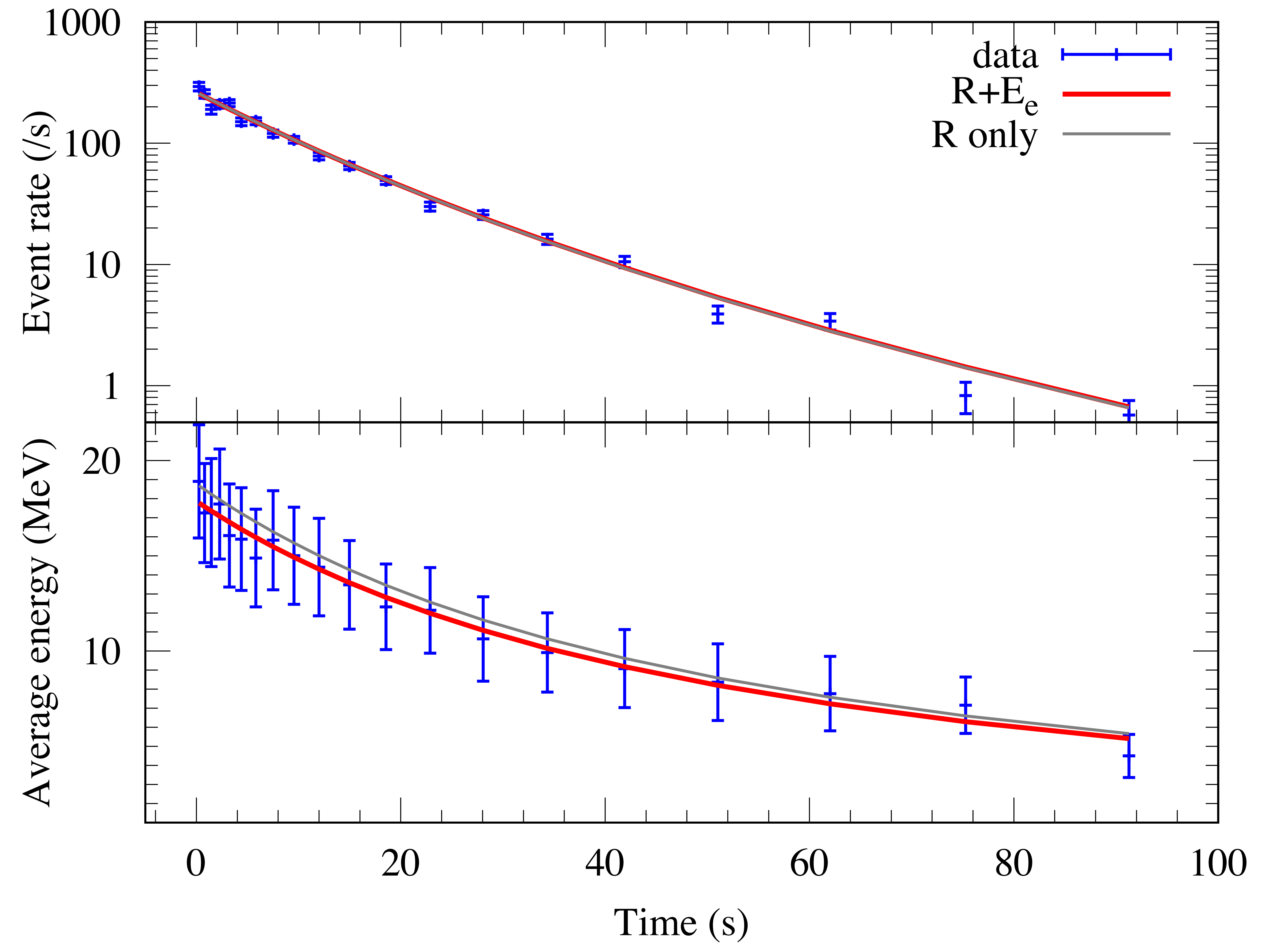
χ^2 fit and probability density function

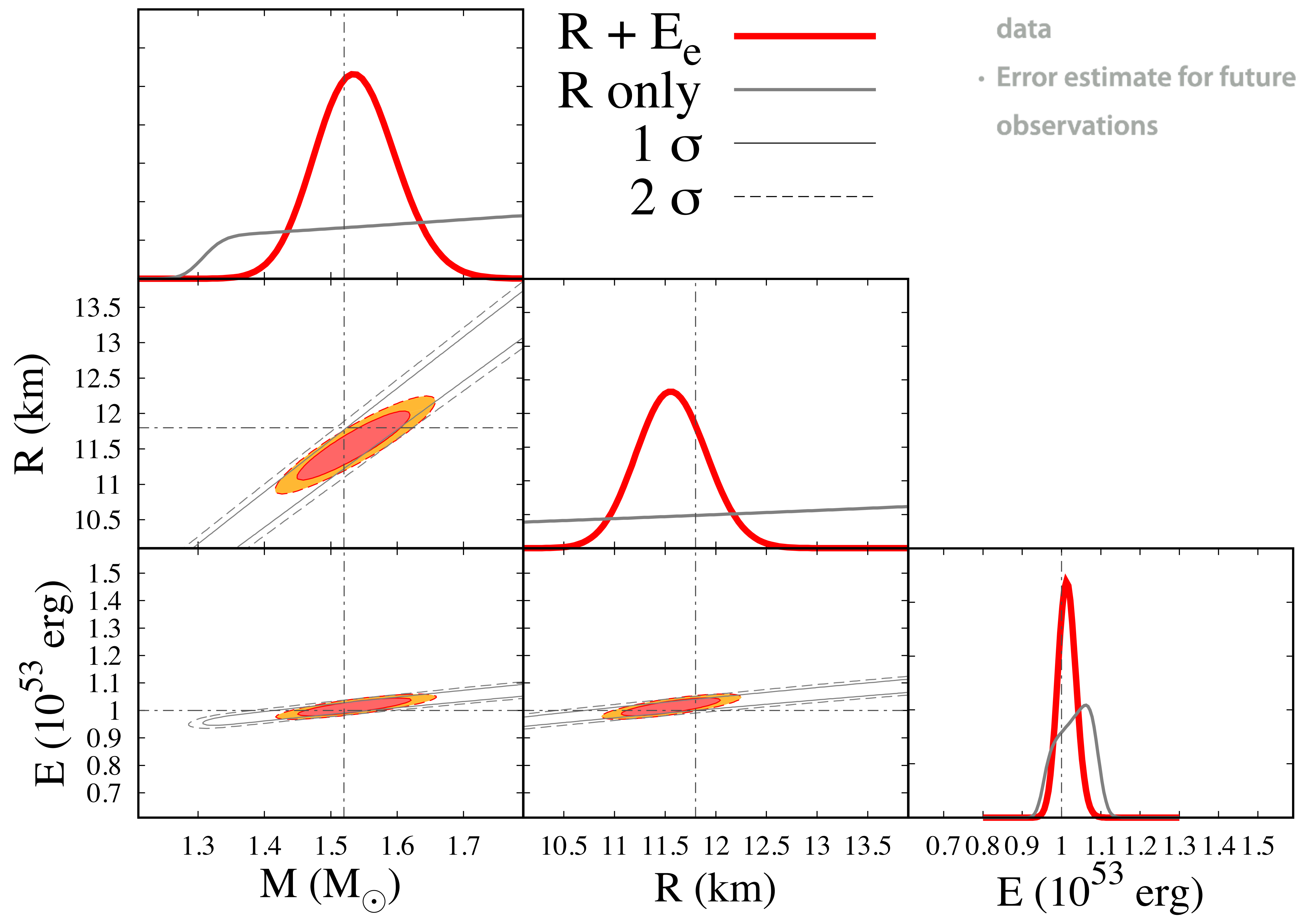
[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022)]

step 3

DATA ANALYSIS

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





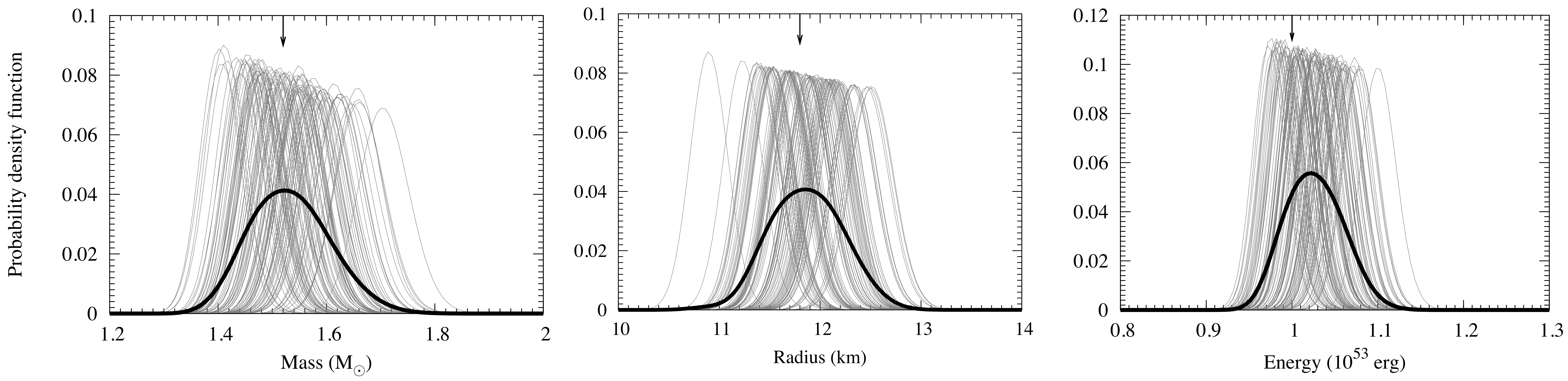
100 realizations

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

step 3

DATA ANALYSIS

- Mock sampling
- Analysis pipeline for real



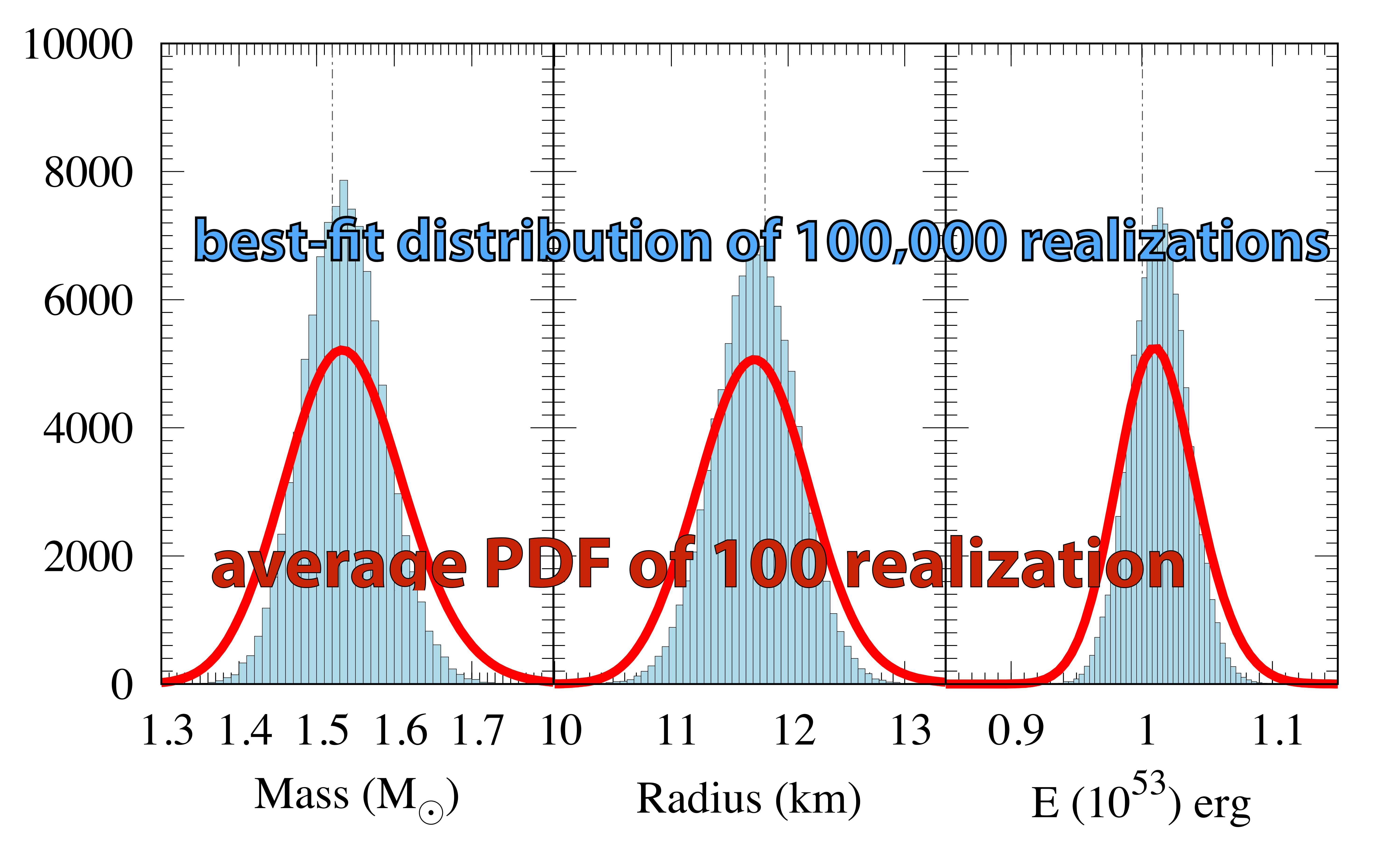
Parameter uncertainty

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

step 3

DATA ANALYSIS

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

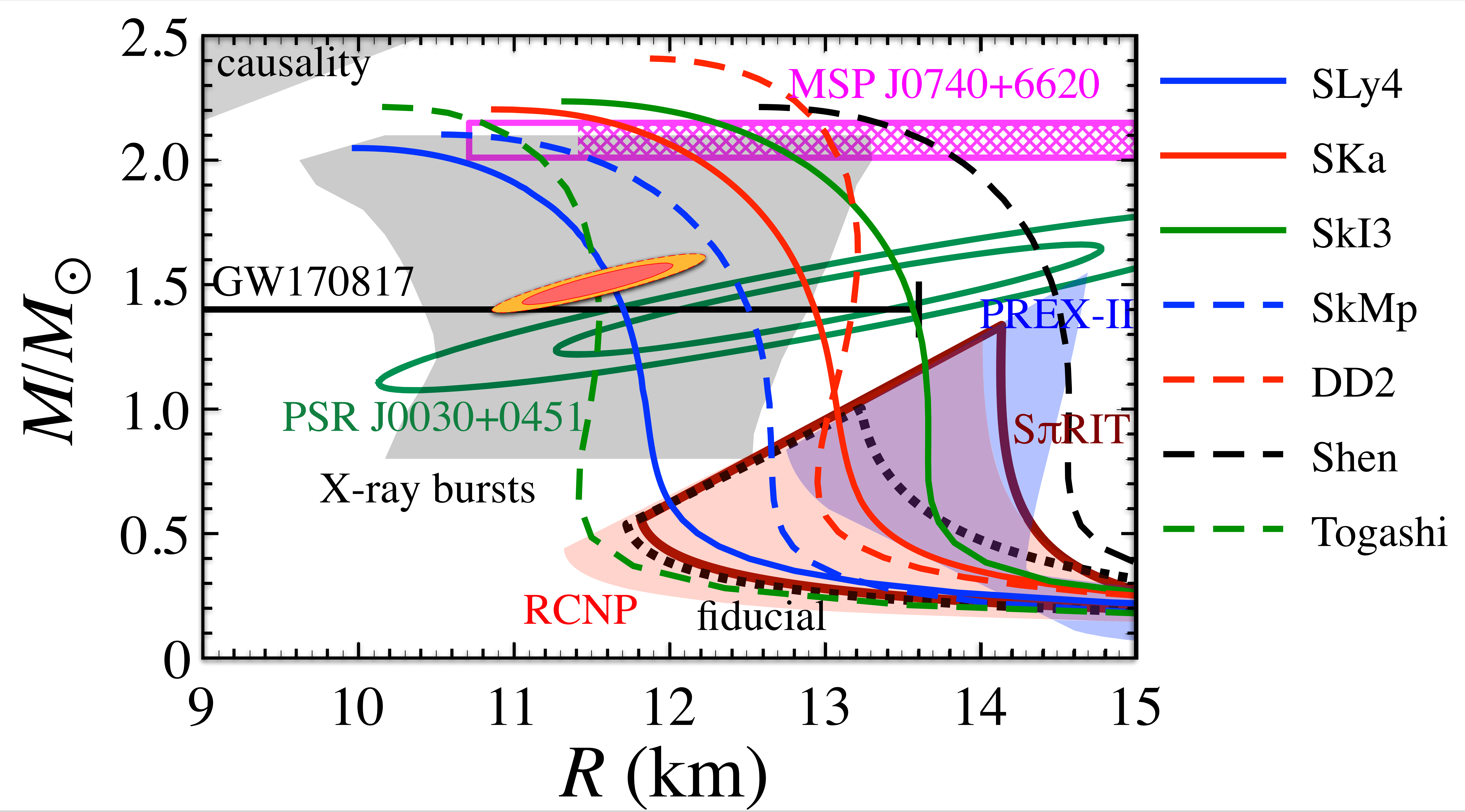


True values:

- $M_{PNS} = 1.52 M_\odot$
- $R_{PNS} = 11.8$ 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	$^{+0.032}_{-0.030}$	$^{+0.066}_{-0.059}$

Neutrino constraint on M-R relation



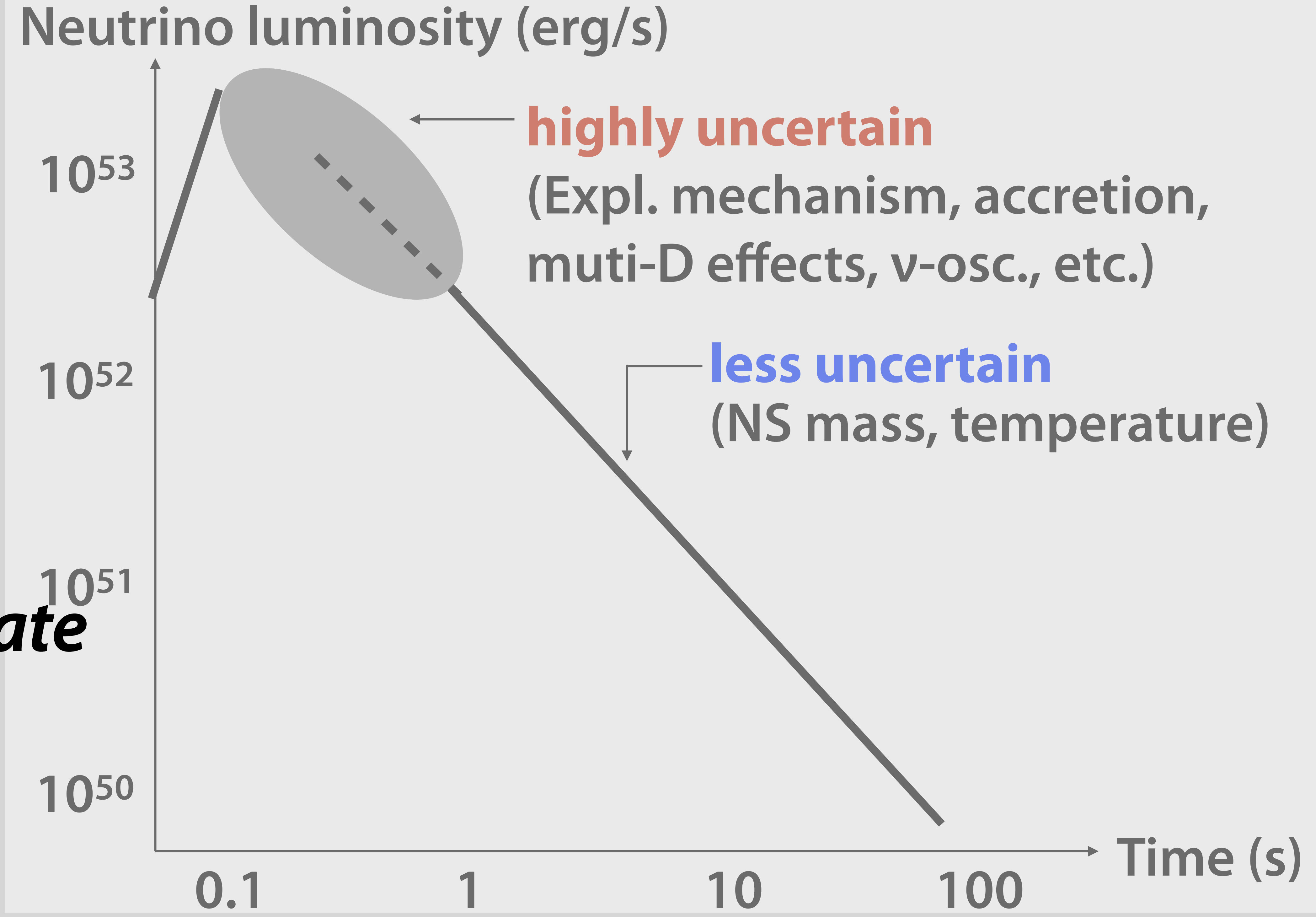
Sotani-Nishimura-Naito (2022)

Toward physics in the next Galactic supernova

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

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

  - **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***

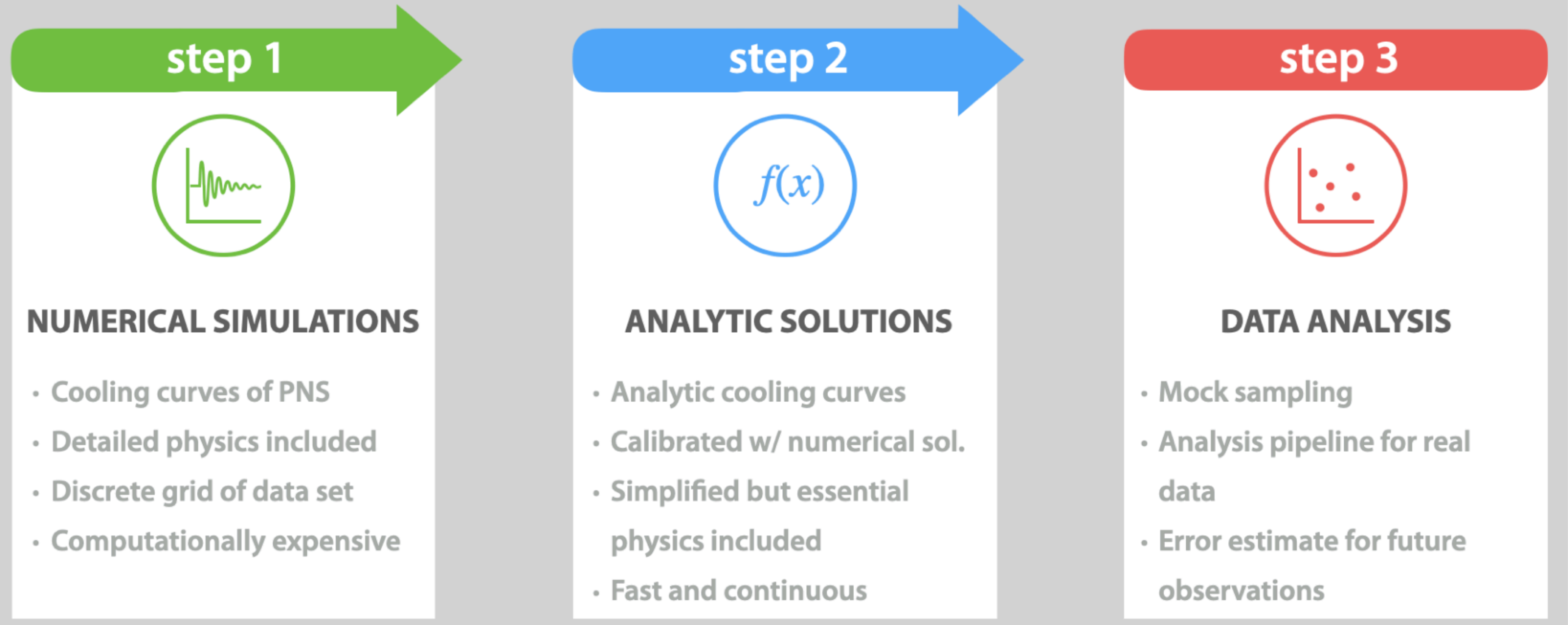


Summary

* 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