超新星ニュートリノの定量解析による距離推定

Distance Estimation of Supernovae via Quantitative Neutrino Analysis

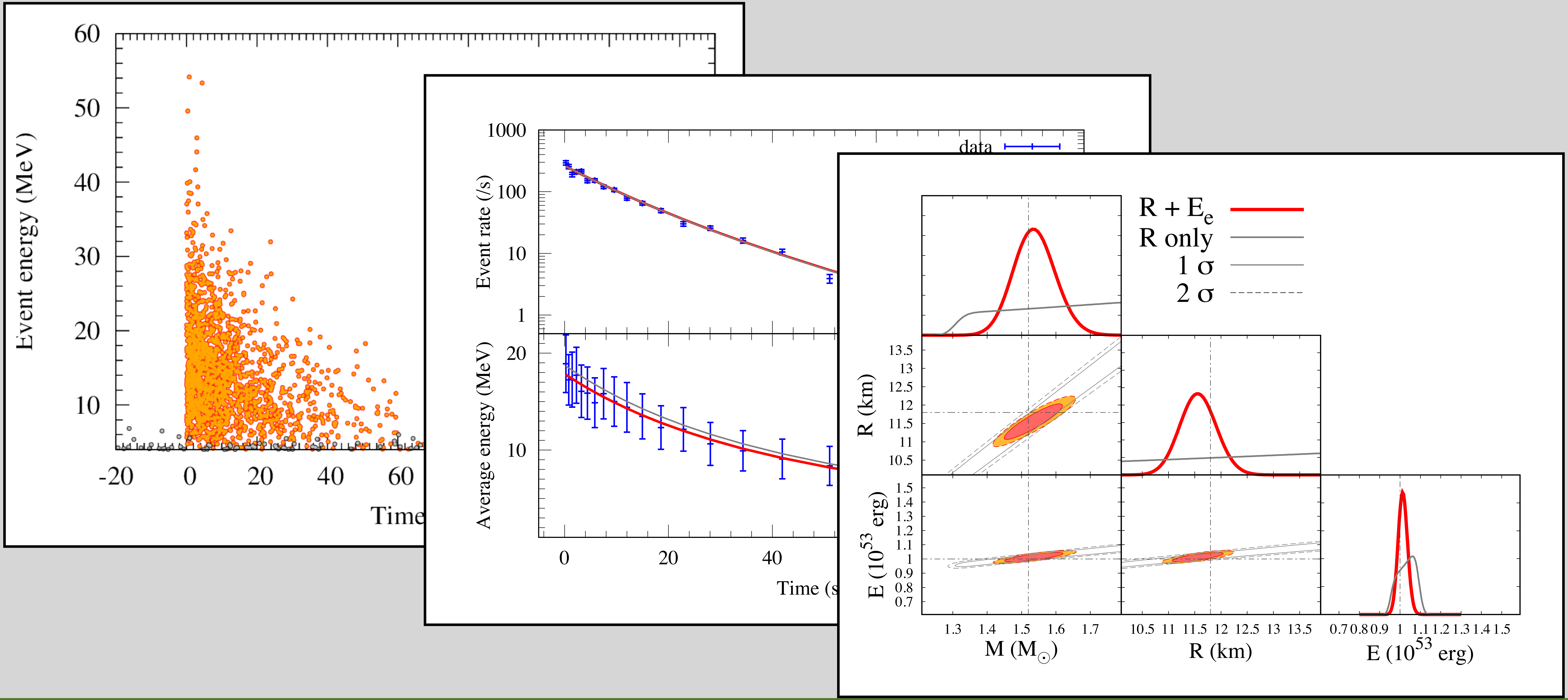
諏訪雄大（東大総合文化 & 京大基研）

Yudai Suwa (UT, Komaba & YITP)

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)
Harada, YS, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 954, 52 (2023)

Quantitative analysis of supernova neutrinos

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022);
Harada, Suwa, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 954, 52 (2023)]



37 years ago…

Volume 196, number 3 PHYSICS LETTERS B 8 October 1987

TOTAL ENERGY OF THE NEUTRINO BURST FROM THE SUPERNOVA 1987A AND THE MASS OF THE NEUTRON STAR JUST BORN

Katsuhiko SATO and Hideyuki SUZUKI
Department of Physics, Faculty of Science, The University of Tokyo, Tokyo 113, Japan

Received 25 April 1987

From the data of the neutrino burst detected by the Kamiokande-II and IMB groups we calculated the total neutrino energy carefully taking into account the efficiency of their water Čerenkov counters. By using this result, we discussed the neutron star mass which was formed by this supernova explosion. We conjectured that the mass is 1.0–1.7 $M_\odot$ and a black hole was not formed, assuming that the distance to the supernova is 50 kpc. If the distance is 56 kpc, the mass range turns into 1.0–1.8 $M_\odot$ and the possibility of black hole formation is also ruled out.

Detector	$\bar{E}$ [MeV]	Temperature [MeV]	Total energy ($\times 10^{53}$ [erg])	Neutron star mass [$M_\odot$]		
				P	BJ I	PS
Kamiokande	16.7+1.1	2.8+0.3	2.9−0.4	1.2	1.4	1.6
	−1.1	−0.2	+0.6	1.4	1.6	1.8
IMB	33.8+2.9	4.6+0.7	1.5−0.6	0.8	1.0	1.0
	−2.9	−0.7	+1.2	1.2	1.5	1.7
Kamiokande	18.7+1.4	3.3+0.3	1.6−0.2	1.0	1.1	1.2
(8 events)	−1.4	−0.3	+0.3	1.1	1.3	1.4
IMB	37.3+3.7	5.4+0.9	0.7−0.3	0.6	0.7	0.7
(6 events)	−3.7	−0.9	+0.4	0.9	1.0	1.1

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)
6. Harada, Suwa, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 954, 52 (2023)

Kyoto U.: R. Wendell (Experiment)

Riken: A. Harada (Theory)
U. Tokyo: Y. Suwa (Theory)
NAOJ: M. Mori (Theory/Experiment)
Waseda U.: R. Akaho (Theory)

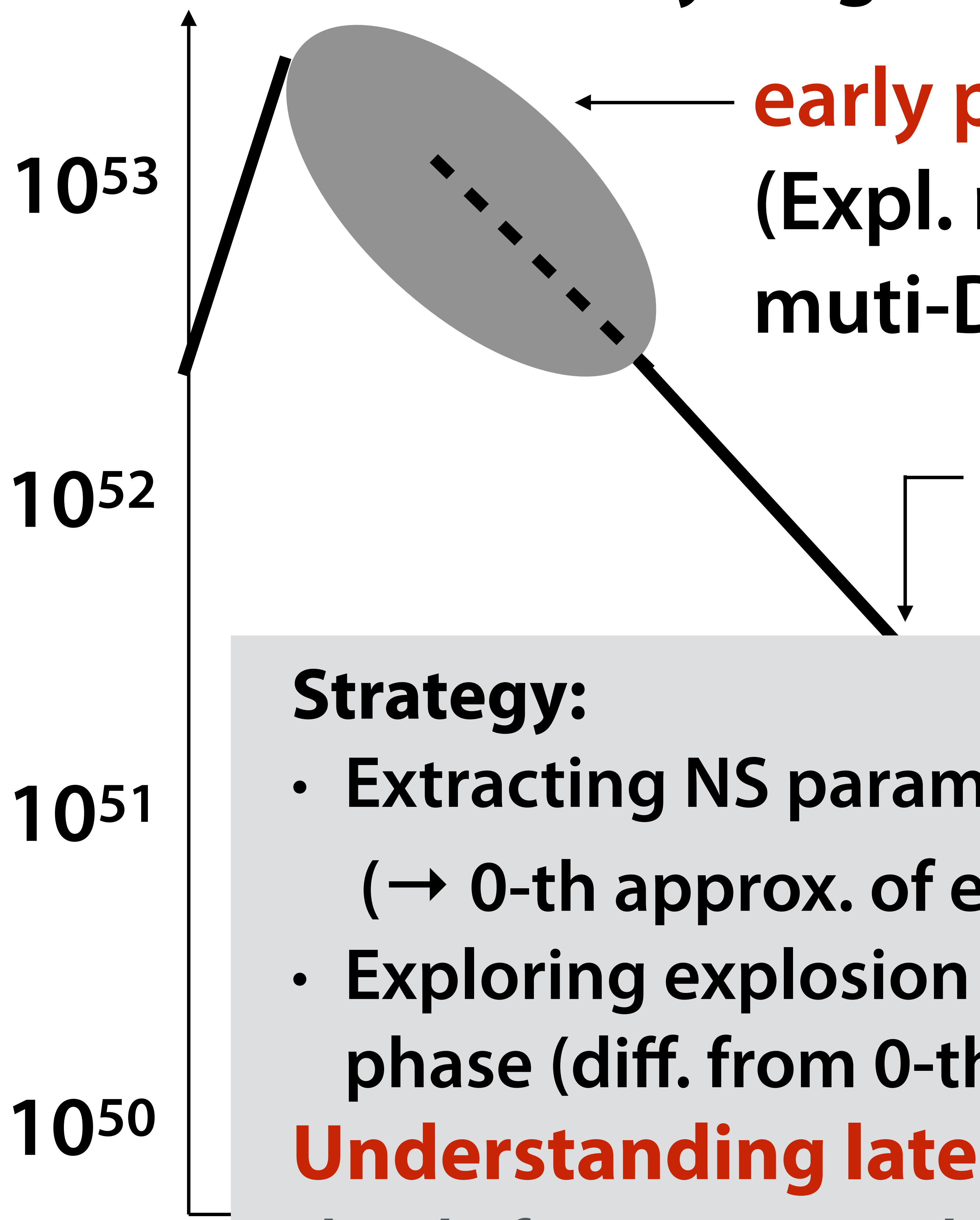
NIT, Numazu: K. Sumiyoshi (Theory)

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

Kyushu U.: K. Nakazato (Theory)

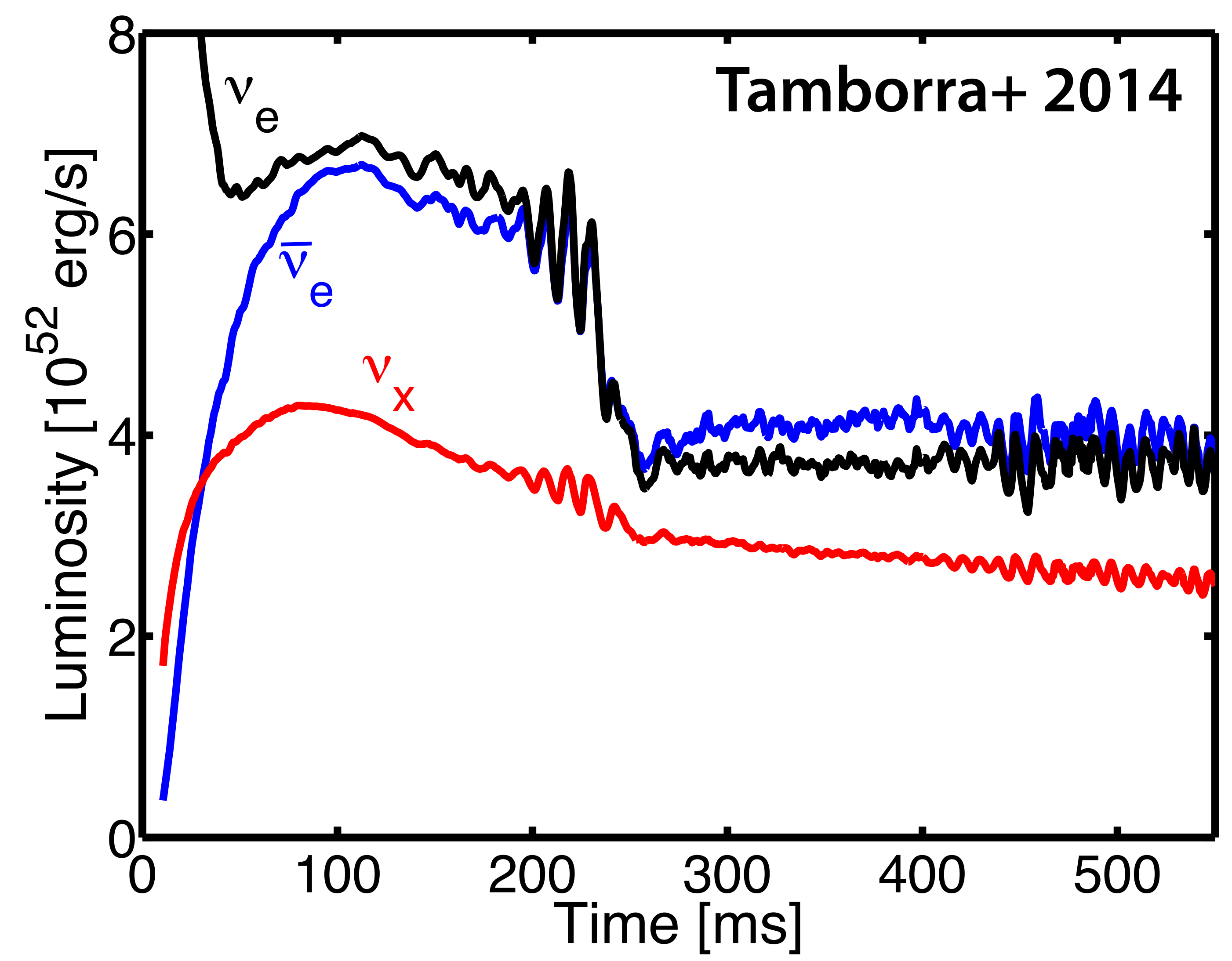
Late cooling phase is simple and understandable

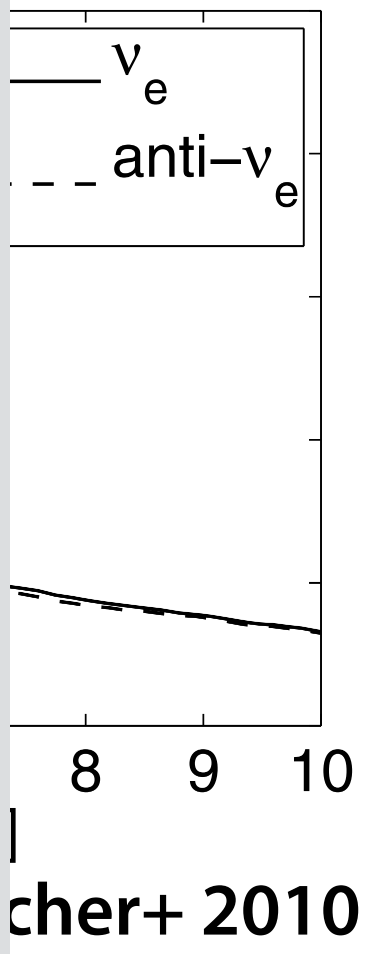
Neutrino luminosity (erg/s)



early phase →highly uncertain
(Expl. mechanism, accretion, muti-D effects, ν-osc., etc.)

late phase →less uncertain
(NS mass, temperature)





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)

What we have done so far: 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

Event rate evolution

[Suwa, Sumiyoshi, Nakazato, Takahira, Koshio, Mori, Wendell, ApJ, 881, 139 (2019);
Nakazato, Nakanishi, Harada, Koshio, Suwa, Sumiyoshi, Harada, Mori, Wendell, ApJ, 925, 98 (2022)]

step 1

NUMERICAL SIMULATIONS

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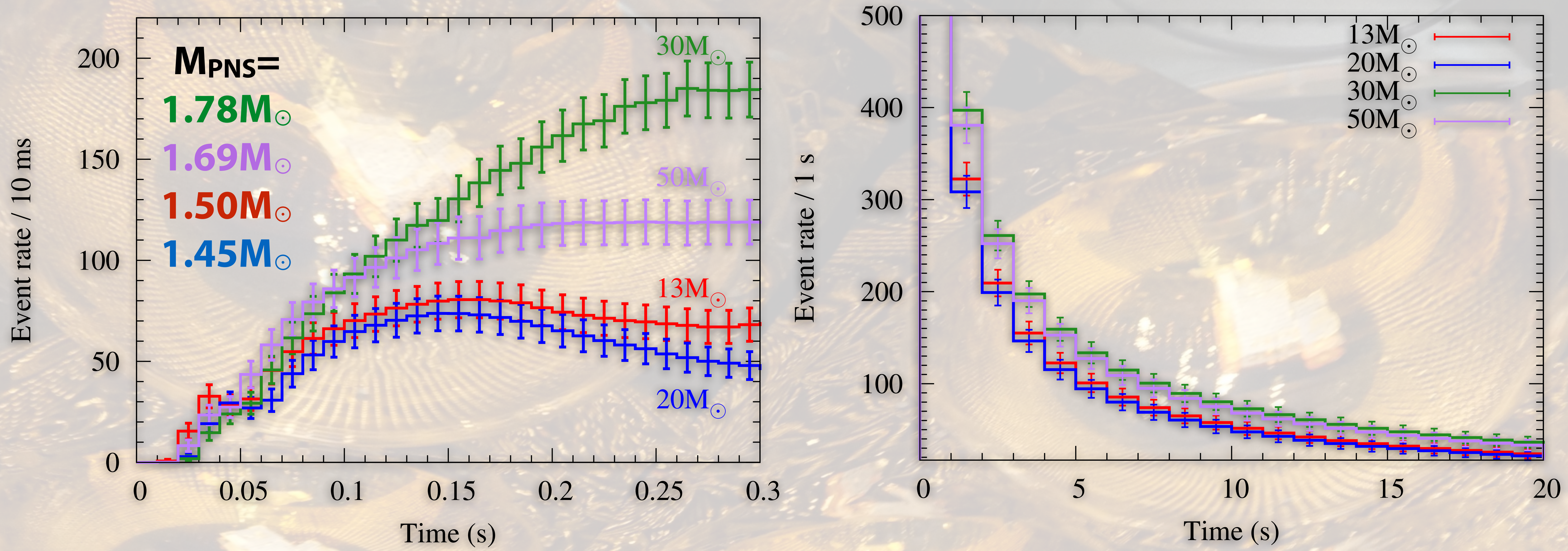


* **Event rate evolution is calculated beyond 100 s**
  - with neutrino luminosity and energy spectrum
  - with full volume of SK's inner tank (32.5 kton)
  - assuming an SN at 10 kpc
  - detector response for inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
* **Event rate is not related to progenitor mass, but PNS mass**

Analytic solutions

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

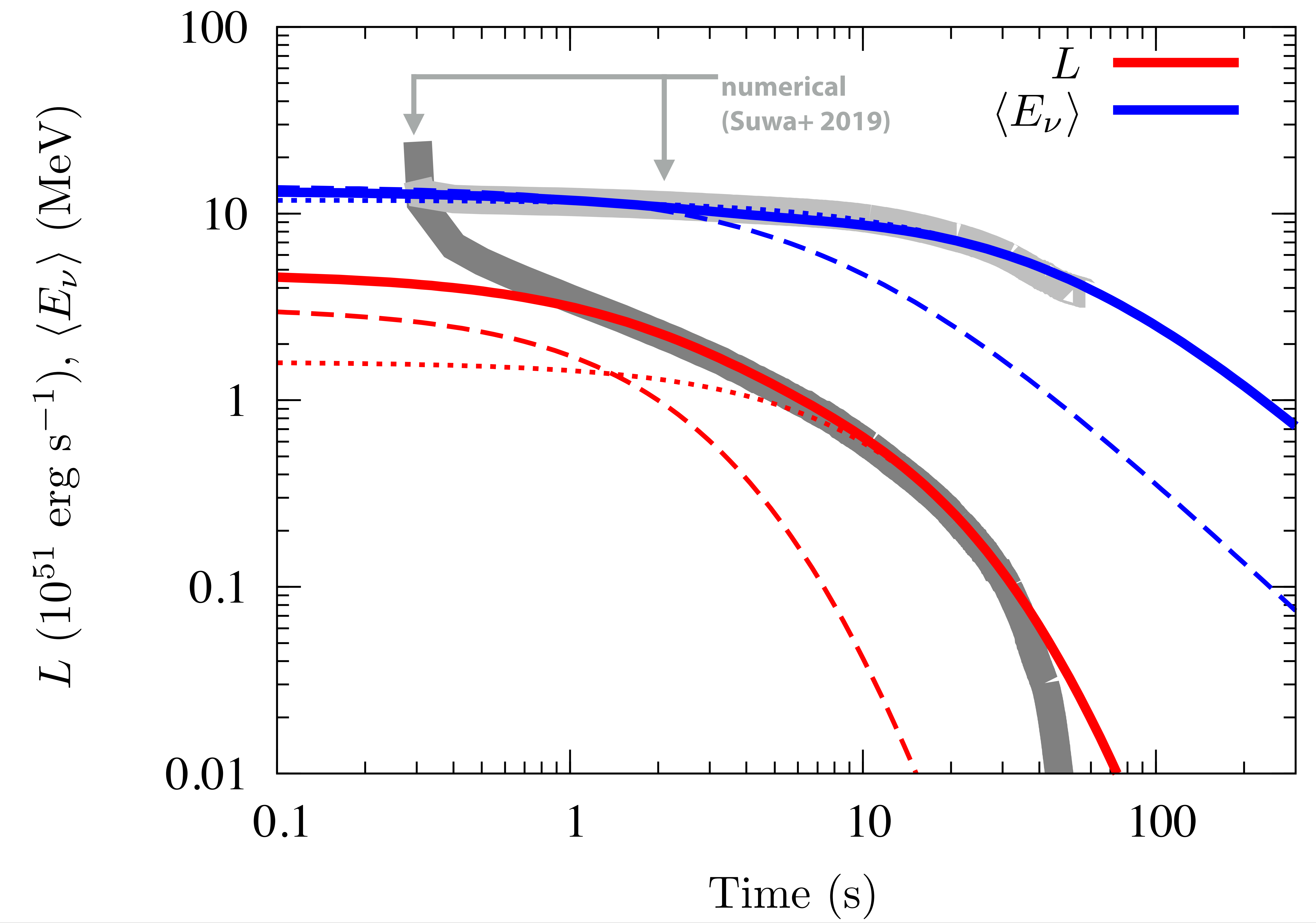
- Solve neutrino transport eq. analytically
  - Neutrino luminosity

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

  - Neutrino average energy

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

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



step 2

ANALYTIC SOLUTIONS

- Analytic cooling curves

Mock sampling and data analysis

[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (2022); Harada, Suwa, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 954, 52 (2023)]

step 3

DATA ANALYSIS

- Mock sampling
- Analysis pipeline for real data
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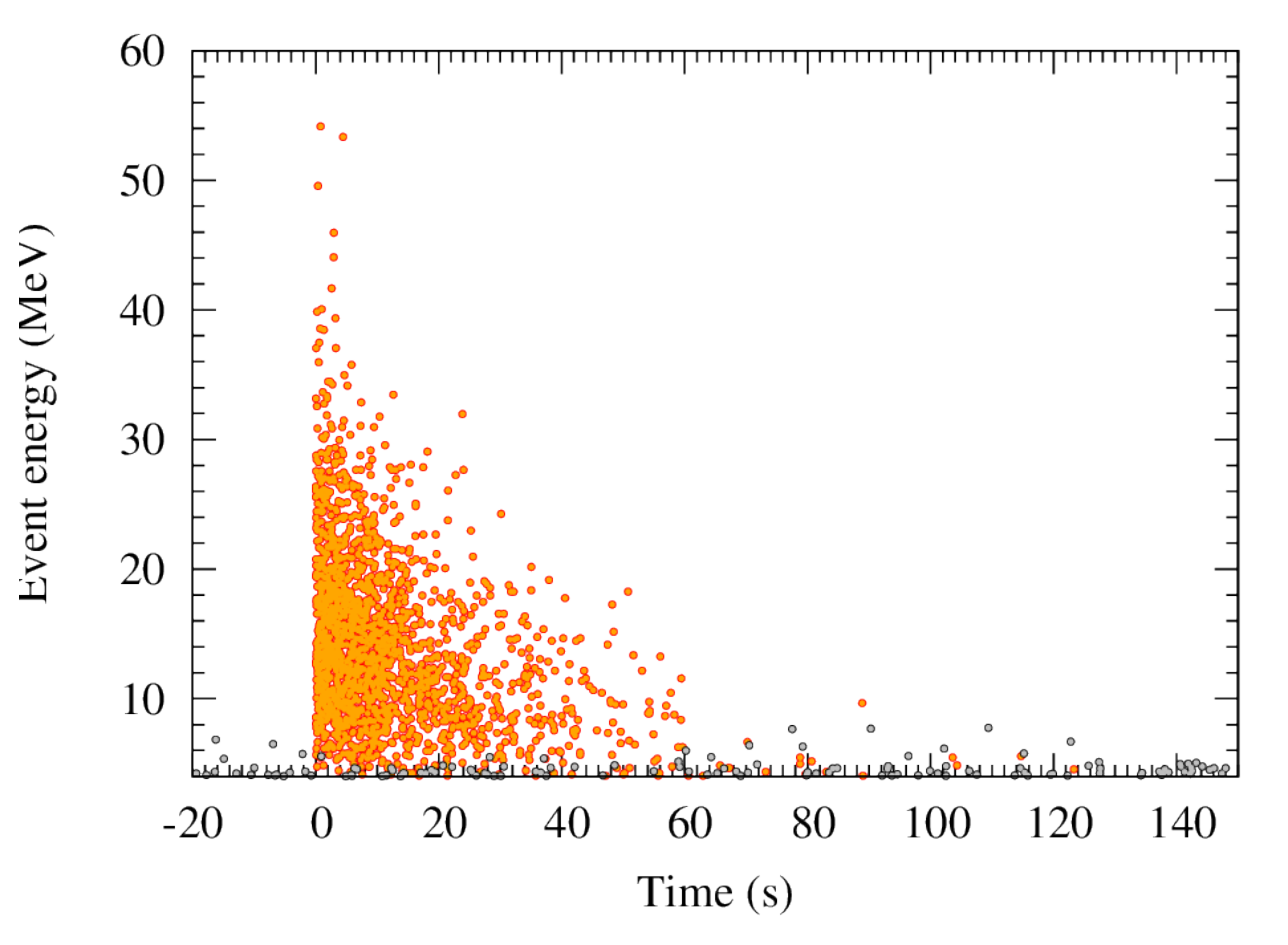
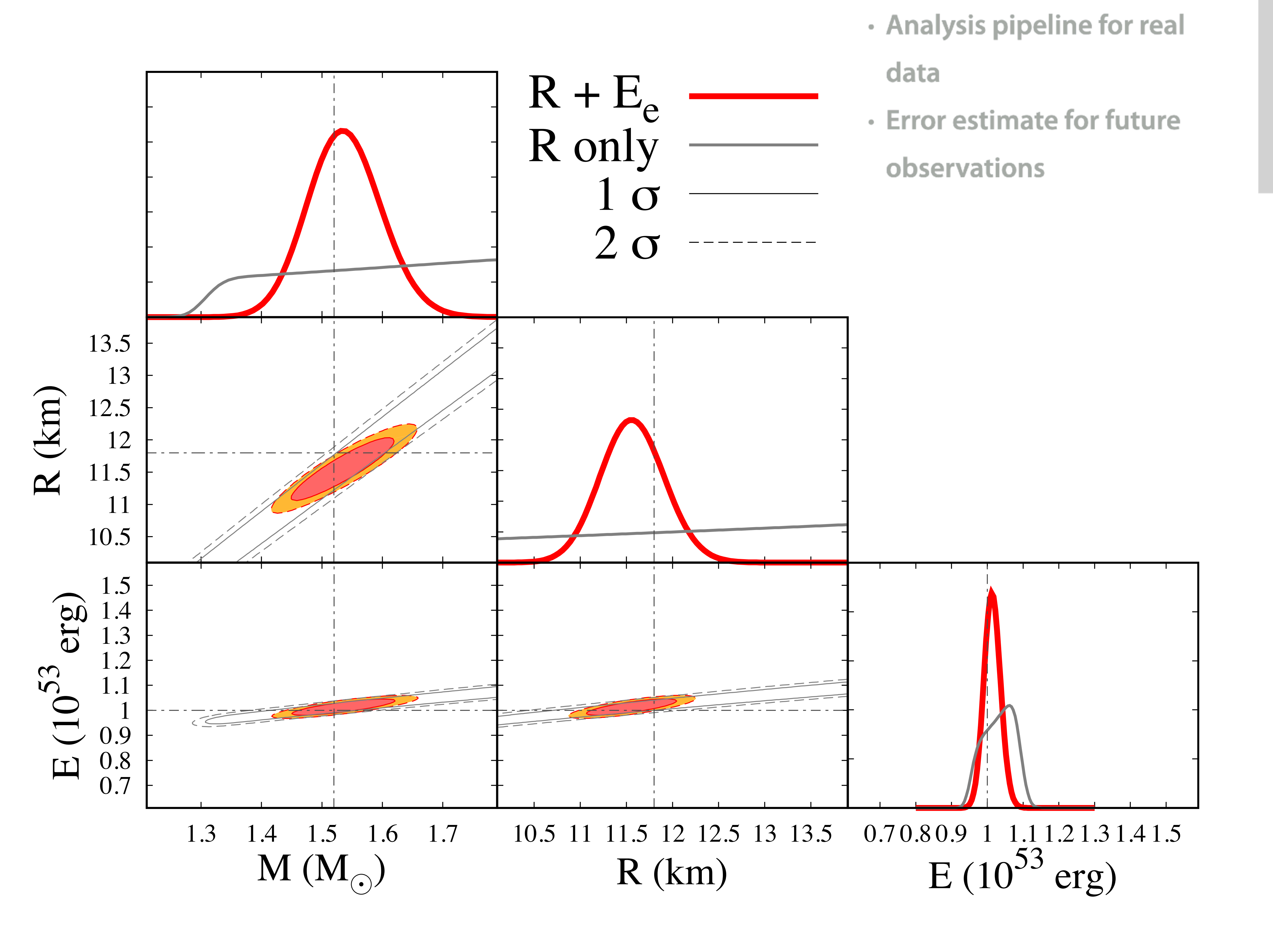




Analysis code *SPECIAL BLEND* is available from github

Next steps

- **Completed: Basics of quantifying supernova neutrinos (cf. $M_{\rm NS}, R_{\rm NS}, E_\nu$).**

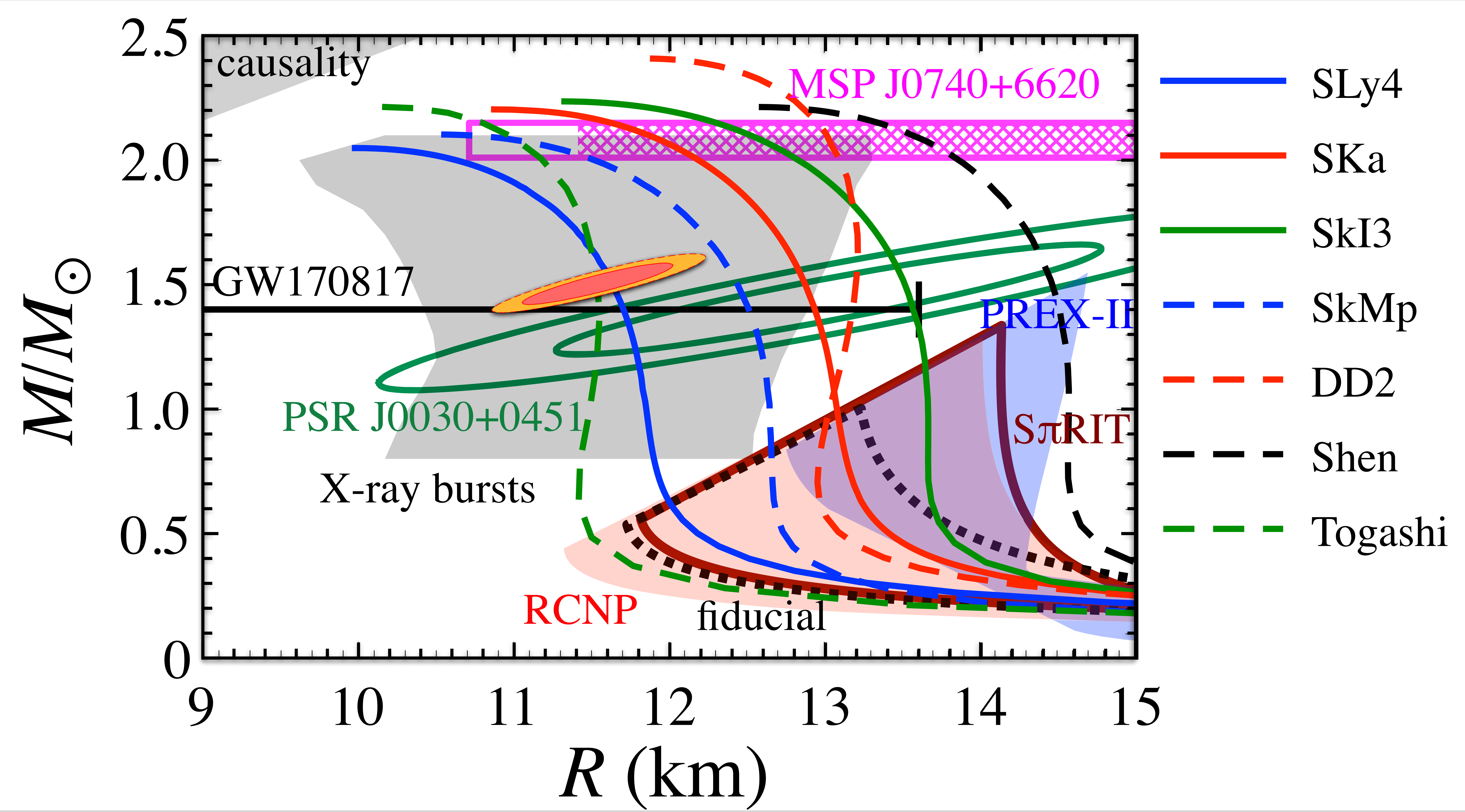
- **Up Next: Exploring applications**
  - Measuring distances using only neutrinos
  - Gathering insights on nuclear matter at neutron star surfaces
  - Probing for new physics

Usage of neutrinos before and after discorvery of SN

- ***Before* finding SN:**
  - Neutrinos tell us distance to SN with O(10)% error
  - Multimessenger followup observation become possible
  - Position determination is essential for multi wavelength obs. of shock breakout

- ***After* finding SN:**
  - Suppose that distance is measured by other (optical/IR) observation with O(1)% error
  - Neutrinos can be used to measure NS radius
  - Combining with the mass, we can constrain M-R relation of NS

Neutrino constraint on M-R relation



Sotani-Nishimura-Naito (2022)

Summary: take-home messages

- **Supernova Neutrinos: A New Era of Quantitative Science**
  - Understanding the basics
  - Measuring key features: mass, radius, and energy
- **Practical Uses of Supernova Neutrinos**
  - Measuring distances of SN
  - Exploring nuclear and new physics
- **Improving Astronomy with Neutrinos**
  - Better pointing accuracy for multimessenger astronomy
  - Integrating neutrinos with electromagnetic signals and gravitational waves providing better understanding supernova mechanism