Probing supernova interiors with neutrinos

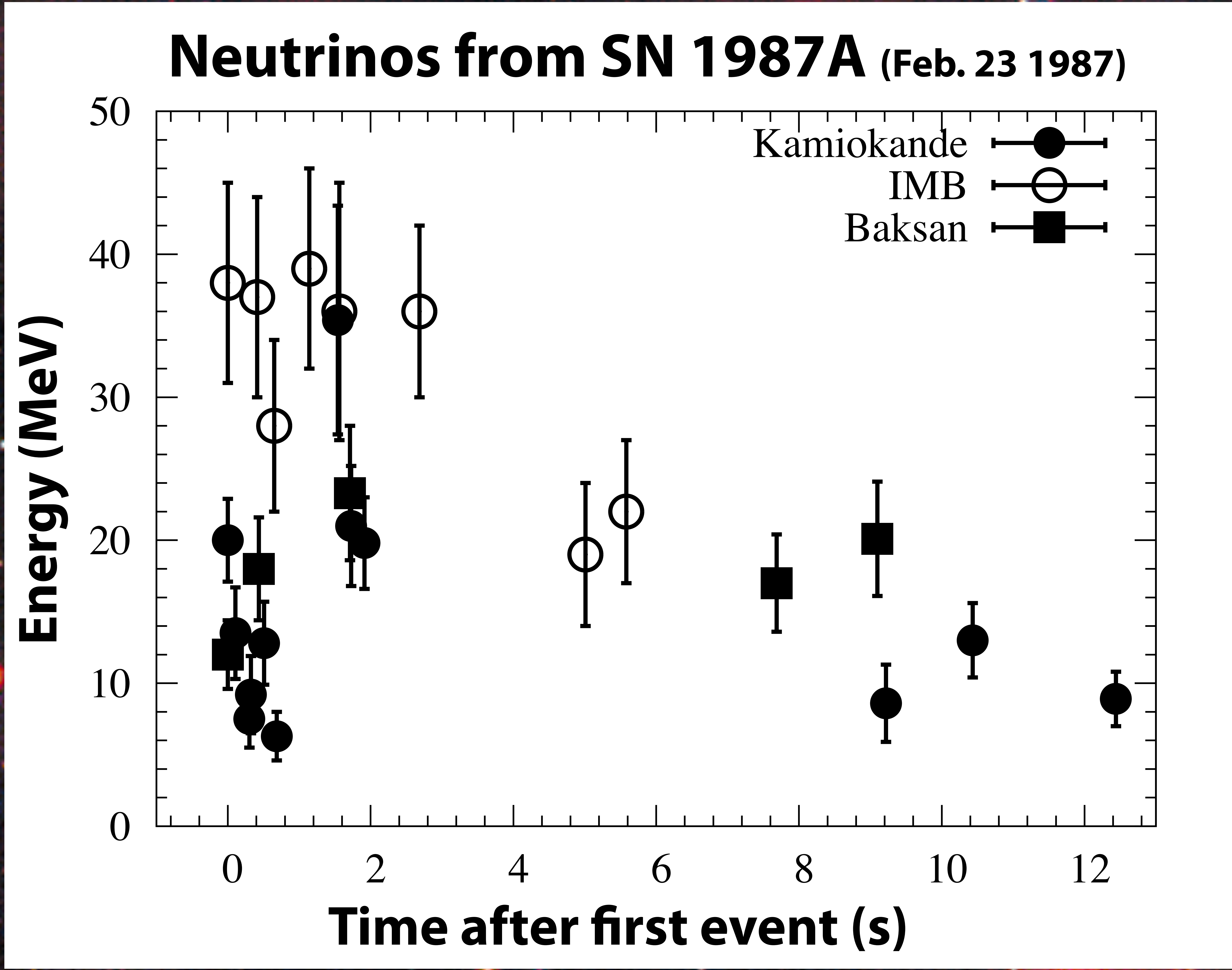
(Report of 公募研究 in FY2022-2023)

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, ApJ, 934, 15 (2022)
Harada, YS, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 954, 52 (2023)

SN1987A



NASA/ESA

What can we extract from neutrino observations?

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

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

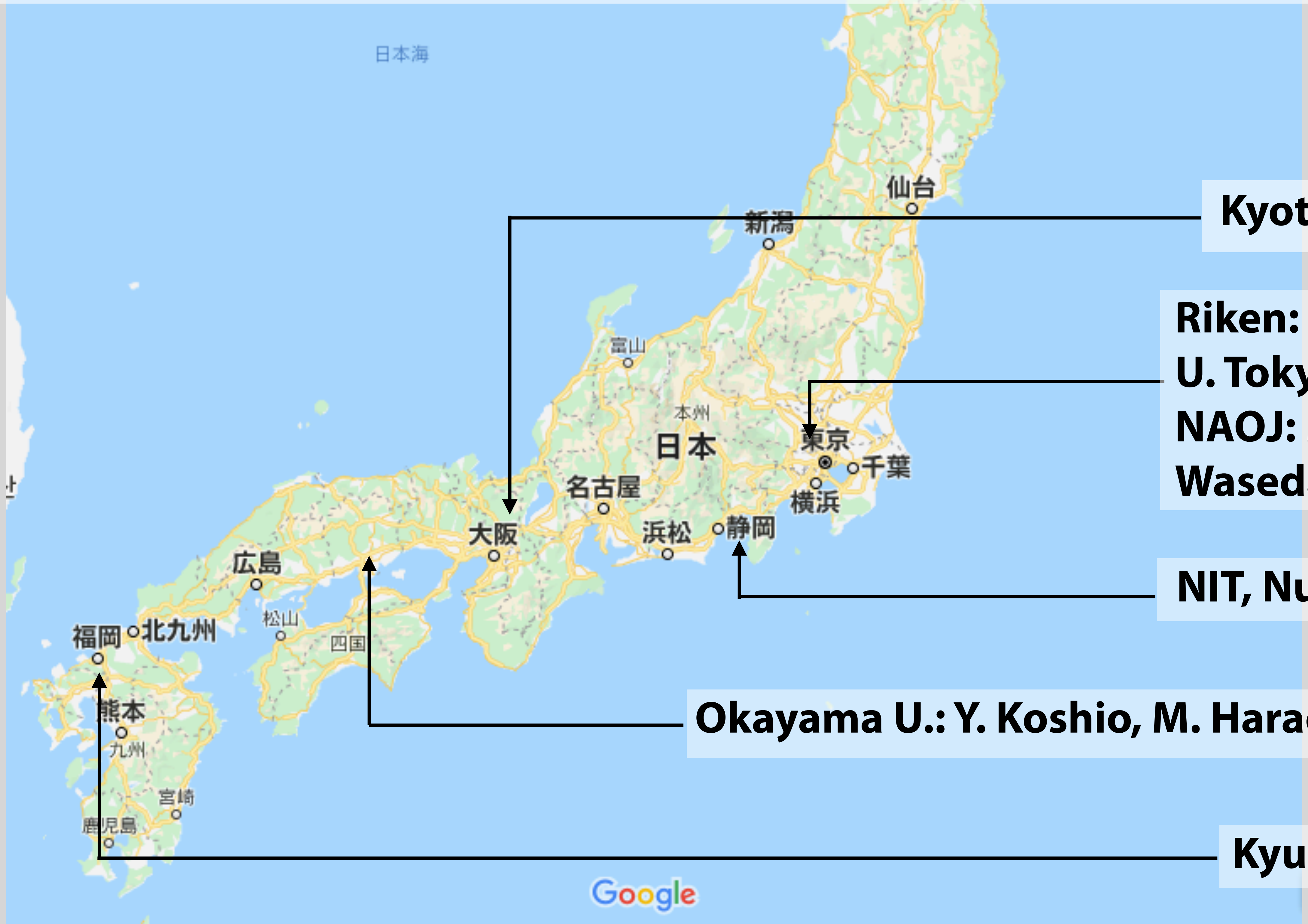
  - **Mass**
    - *important for discriminating final object (NS or BH)*
  - **Radius**
    - *important for discriminating nuclear equation of state*

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

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)

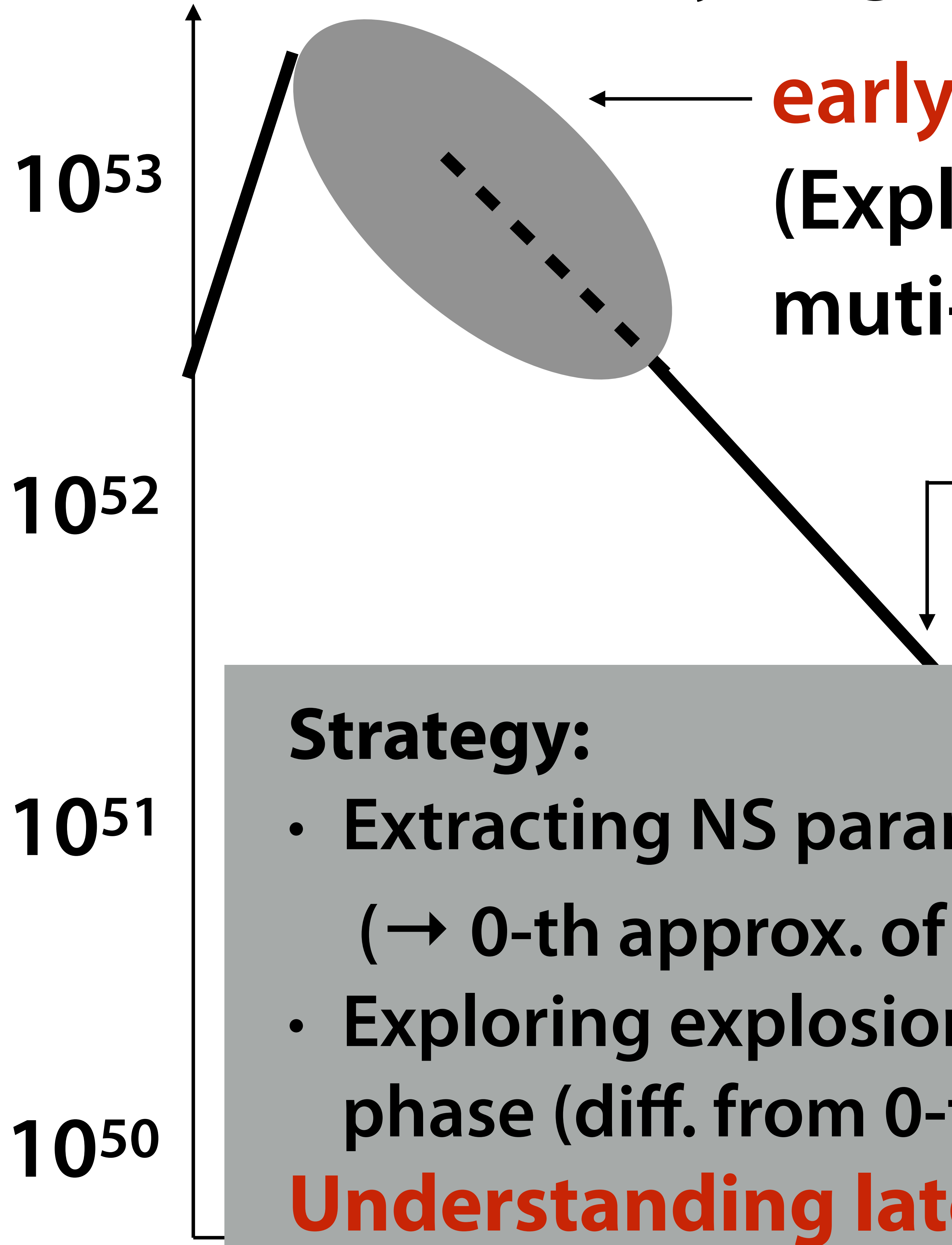
NIT, Numazu: K. Sumiyoshi (Theory)

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

Kyushu U.: K. Nakazato (Theory)

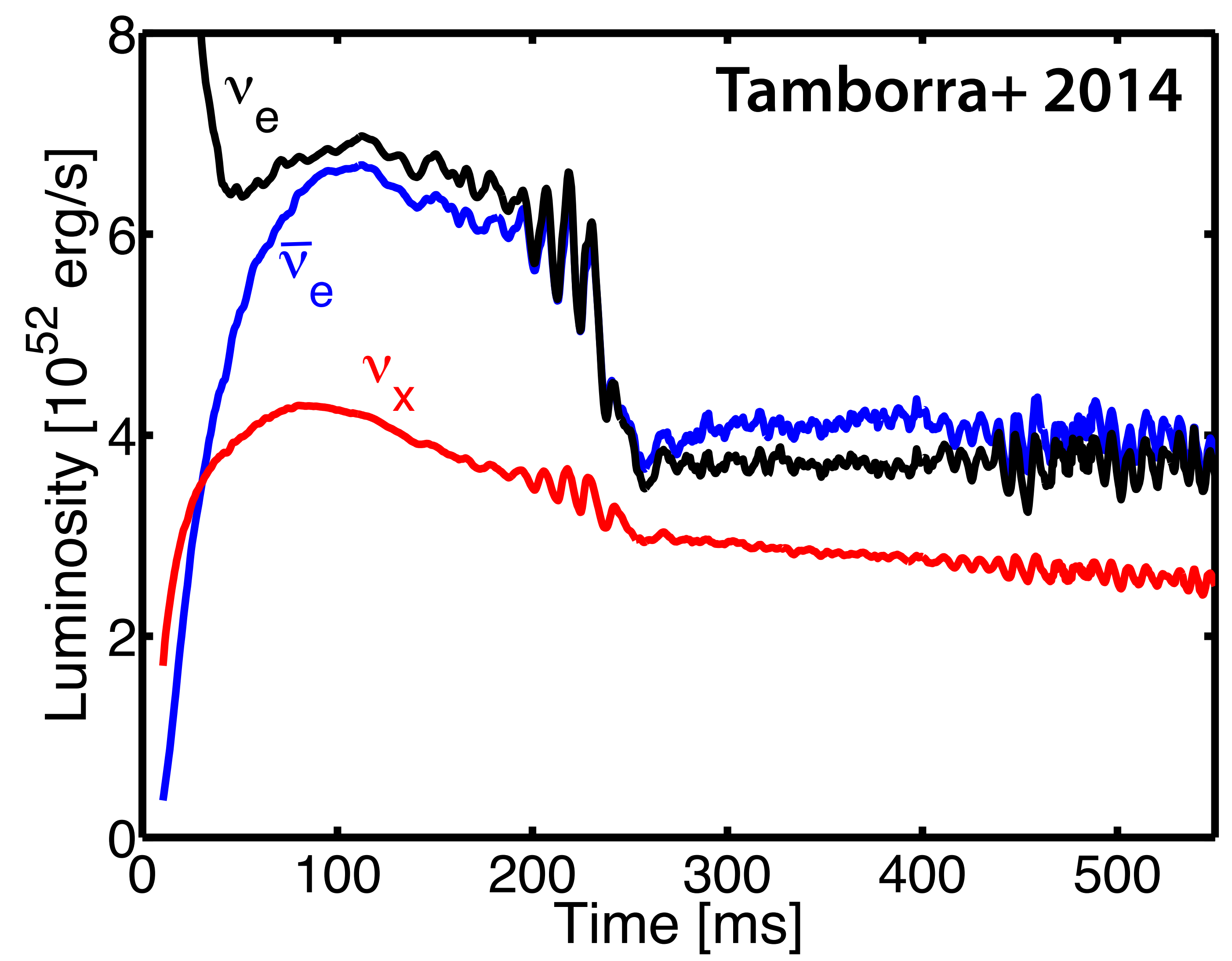
Late cooling phase is simple and understandable

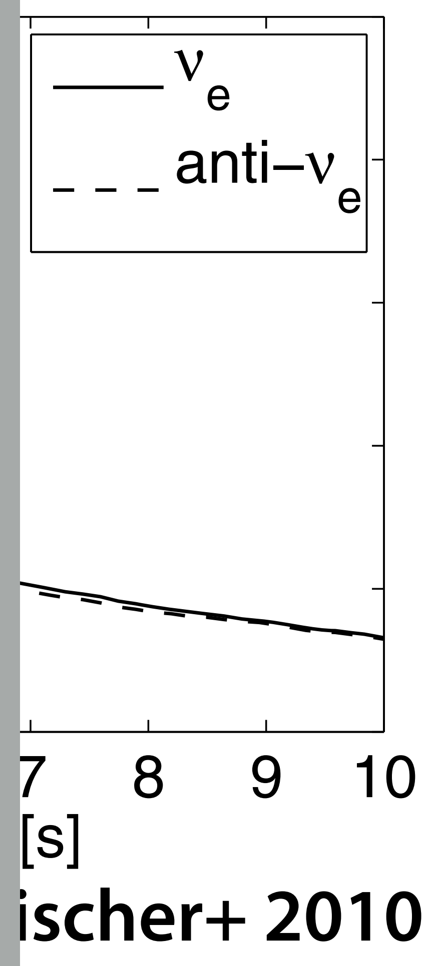
Neutrino luminosity (erg/s)



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)

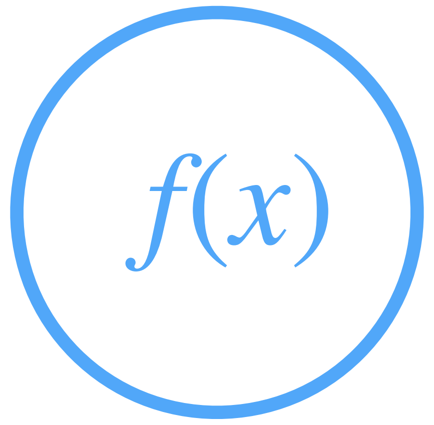
What we have done so far: 3 steps

step 1

NUMERICAL SIMULATIONS

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

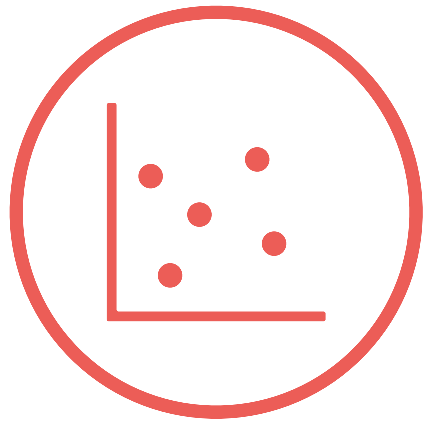
step 2



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

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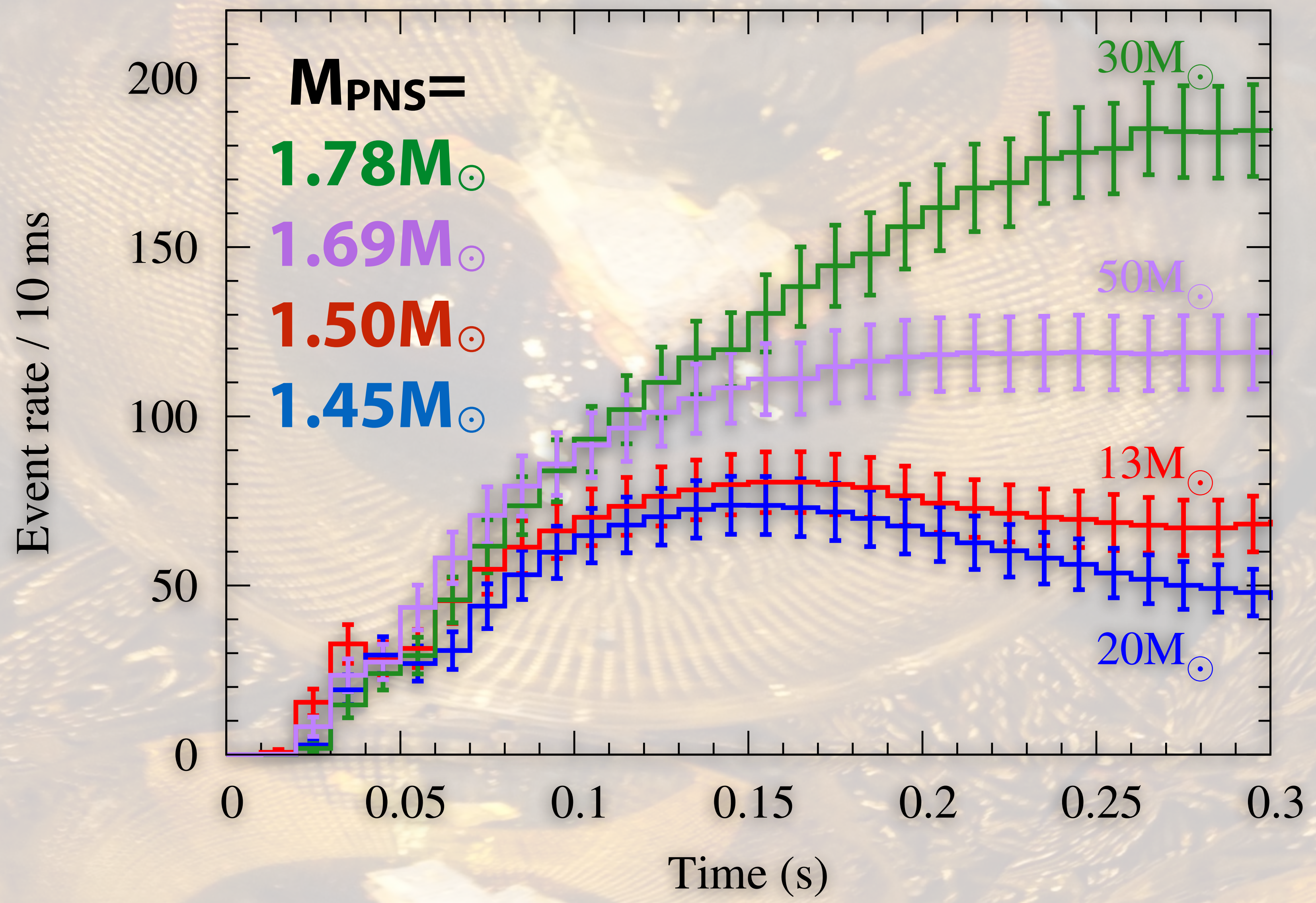
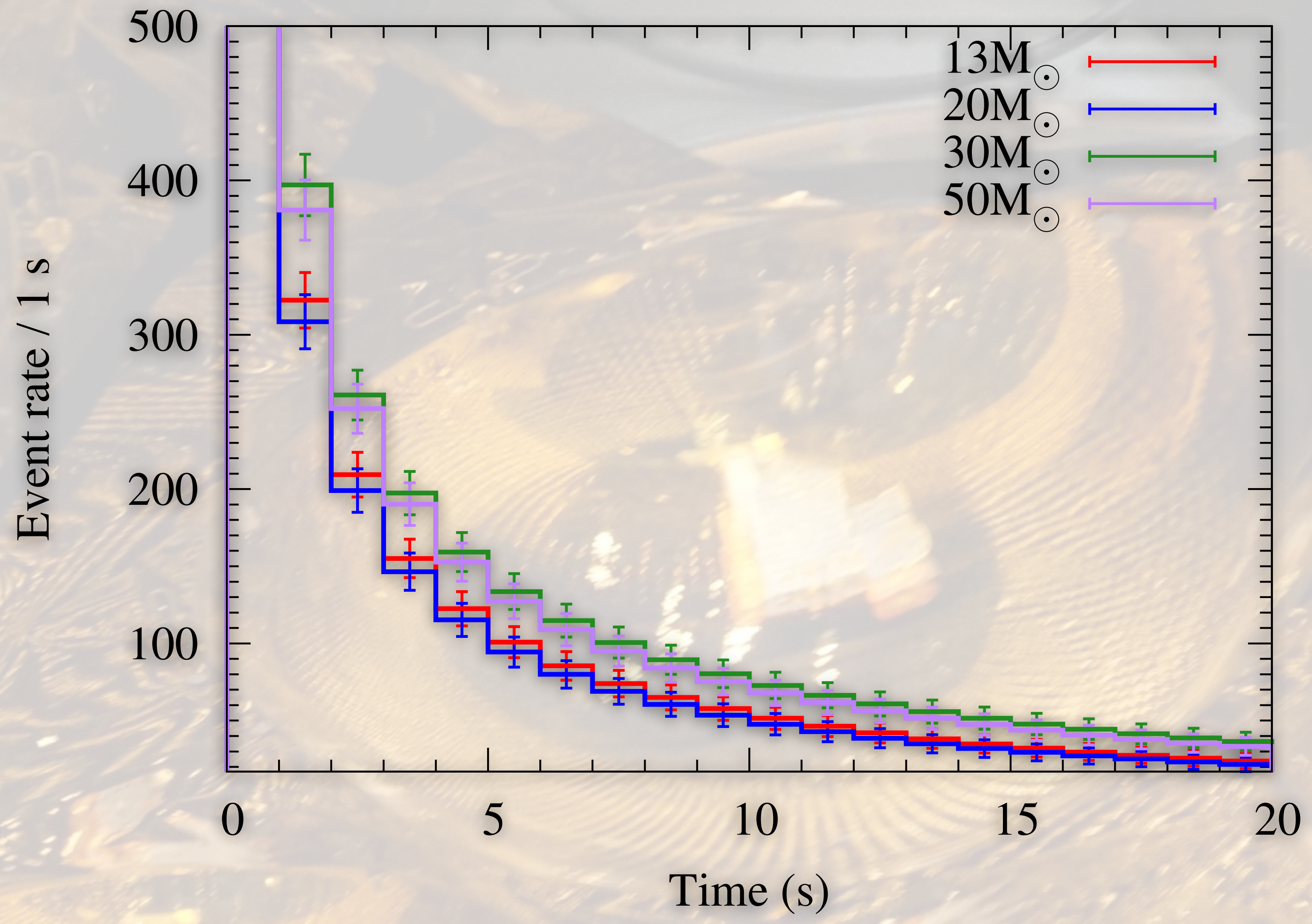




- **Event rate evolution is calculated beyond 100 s**
  - with neutrino luminosity and energy spectrum
  - with full volume of SK's inner tank (32.5 kton)
  - assuming an SN at 10 kpc
  - detector response for inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
- **Event rate is not related to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

Analytic solutions

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

- Solve neutrino transport eq. analytically
  - Neutrino luminosity

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

  - Neutrino average energy

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

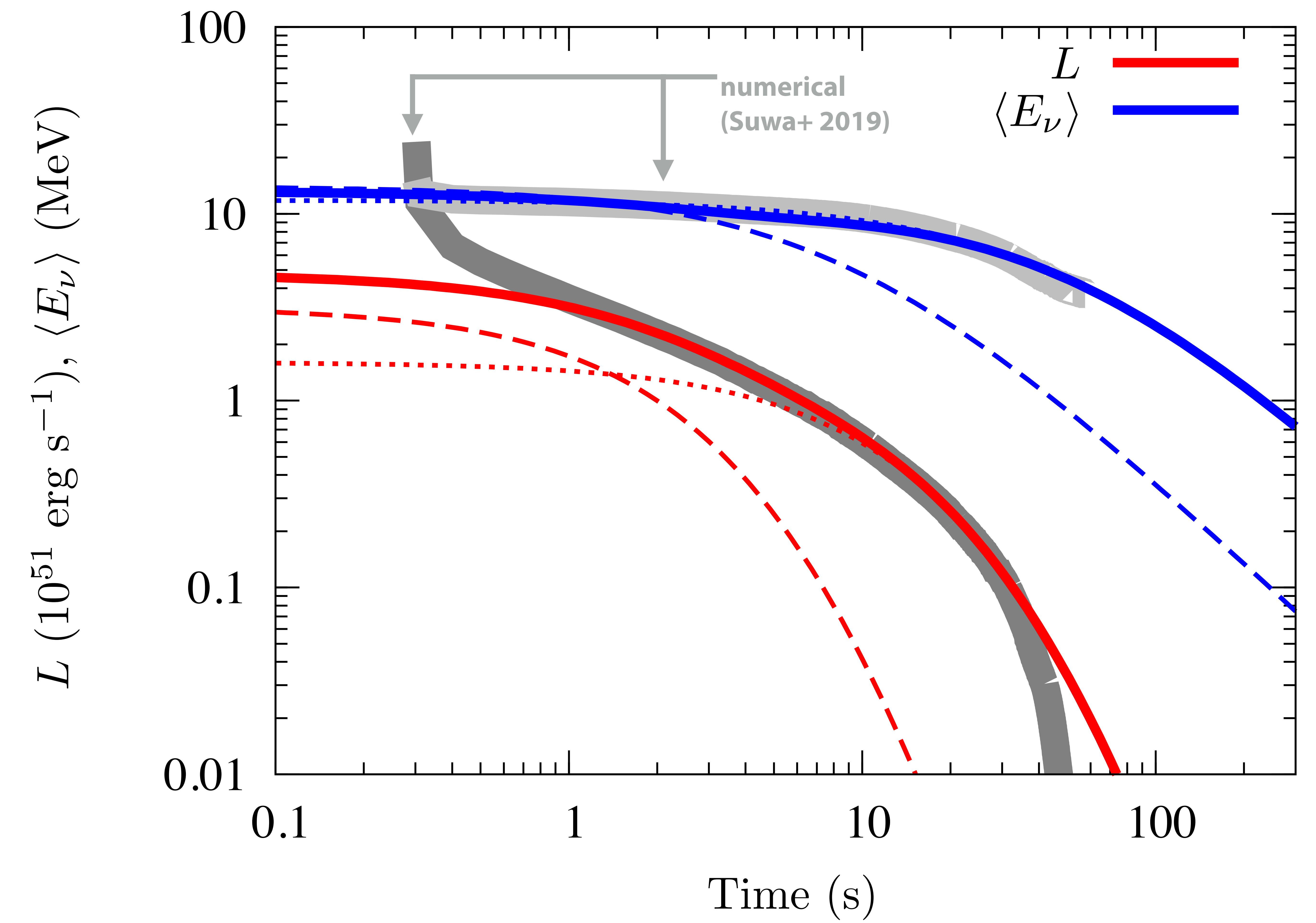
  - two-component model
    - early cooling phase (β=3)
    - late cooling phase (β=O(10))

step 2

$f(x)$

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)]

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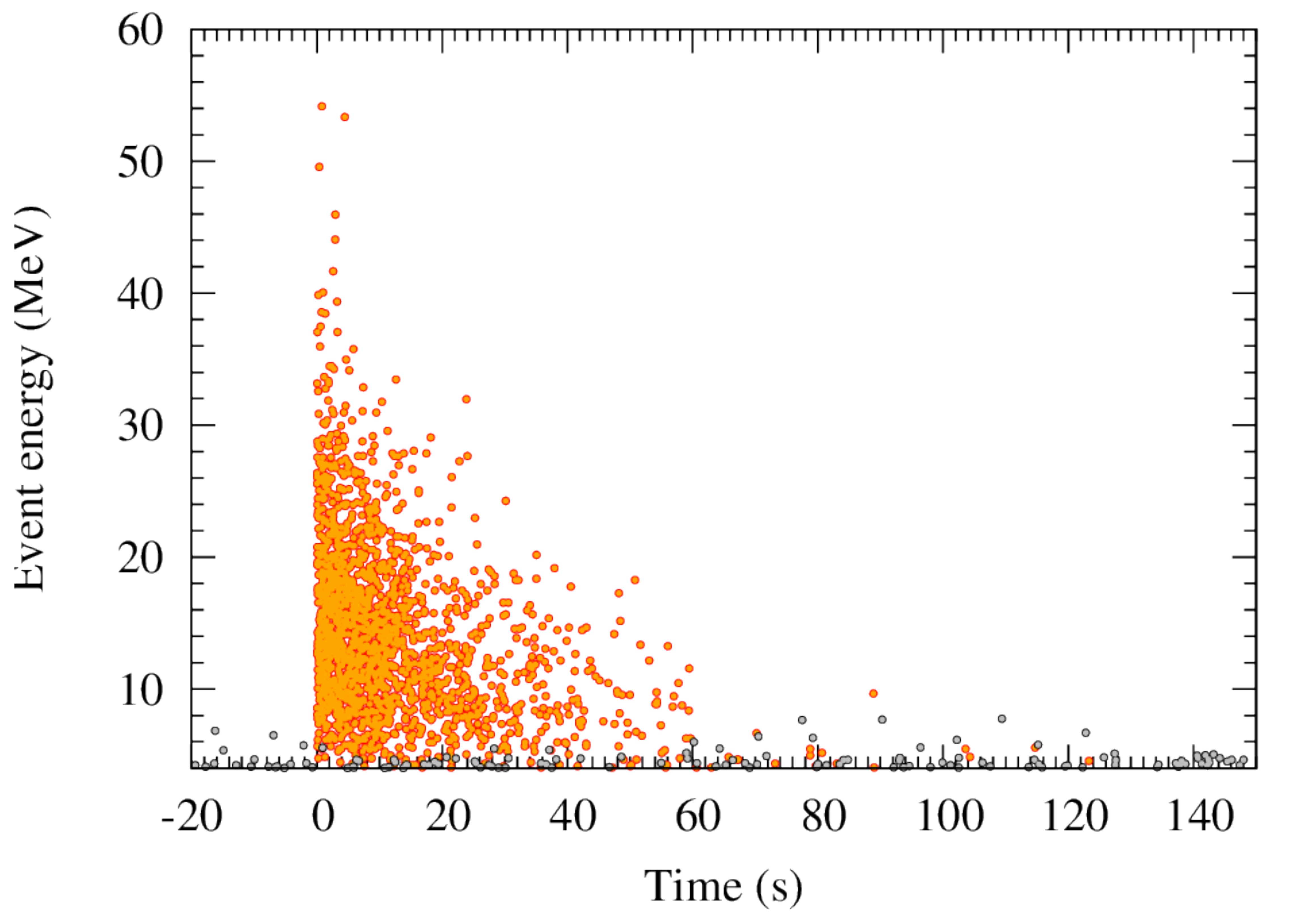
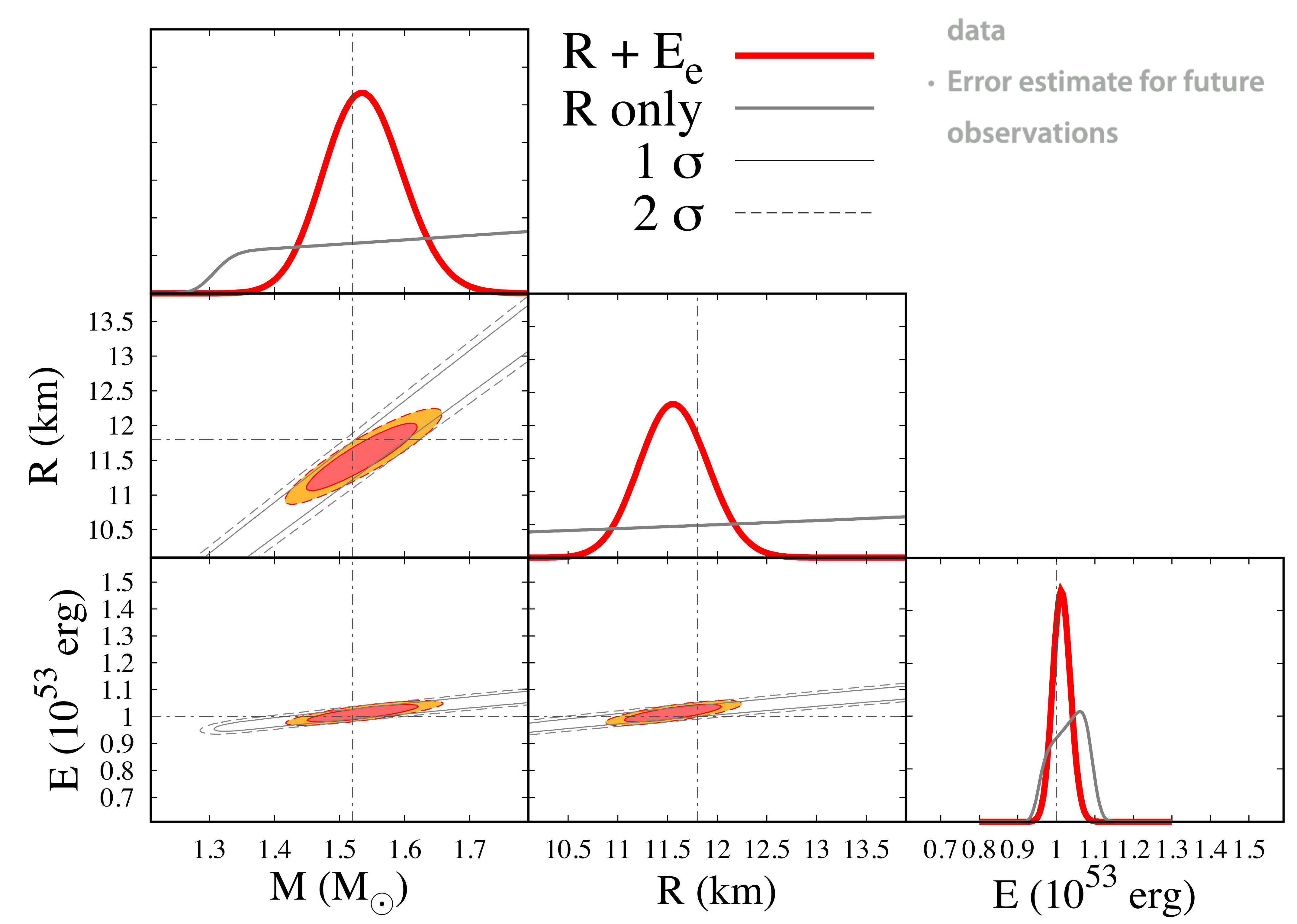




Analysis code *SPECIAL BLEND* is available from github

Next steps

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

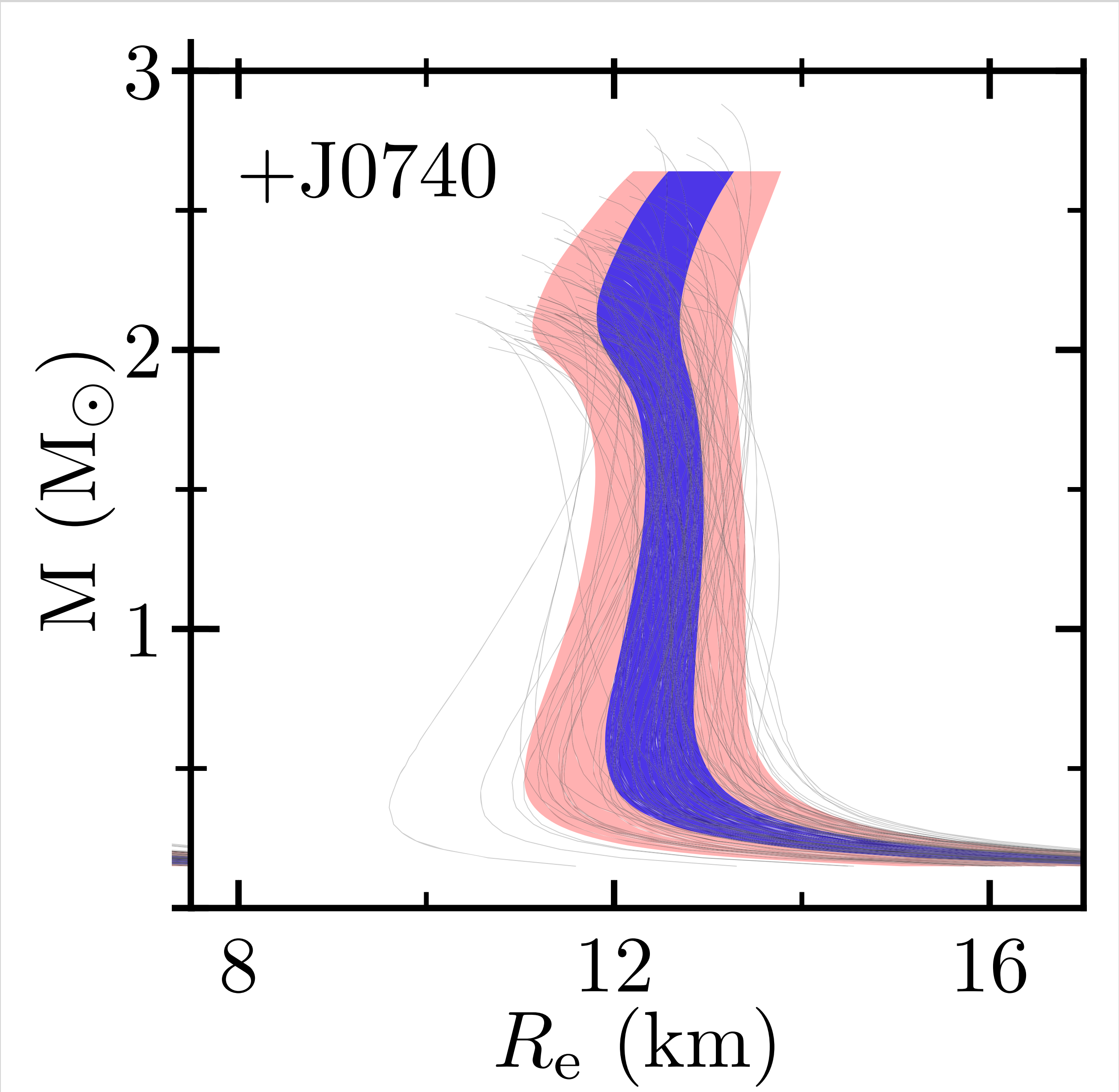
* **Up Next: Exploring applications**
  - Measuring distances using only neutrinos
  - Gathering insights on nuclear matter at neutron star surfaces
  - Probing for new physics

Distance measurement using only neutrinos

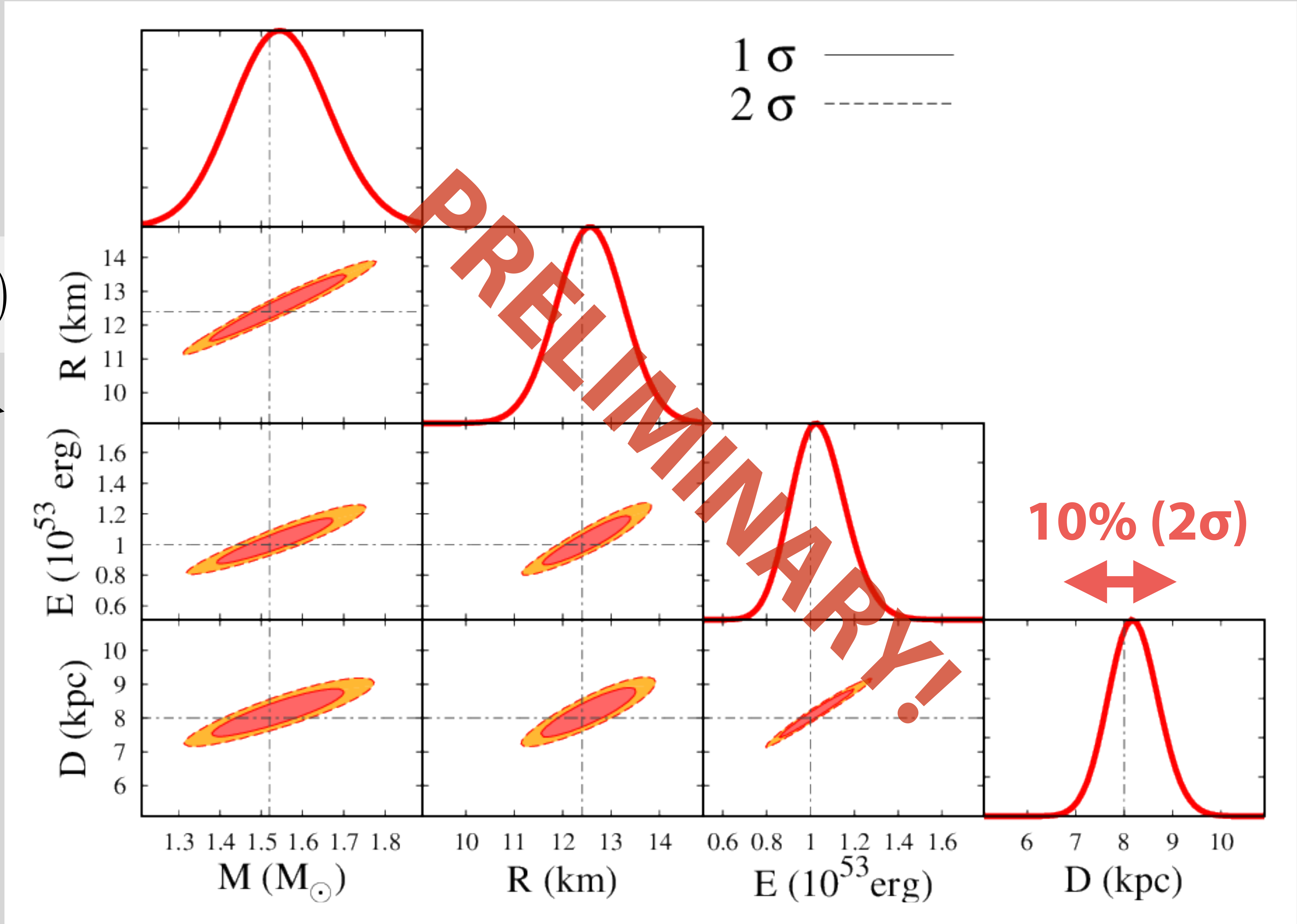
Analytic solution tells us (measured) PNS radius and source distance are correlated

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

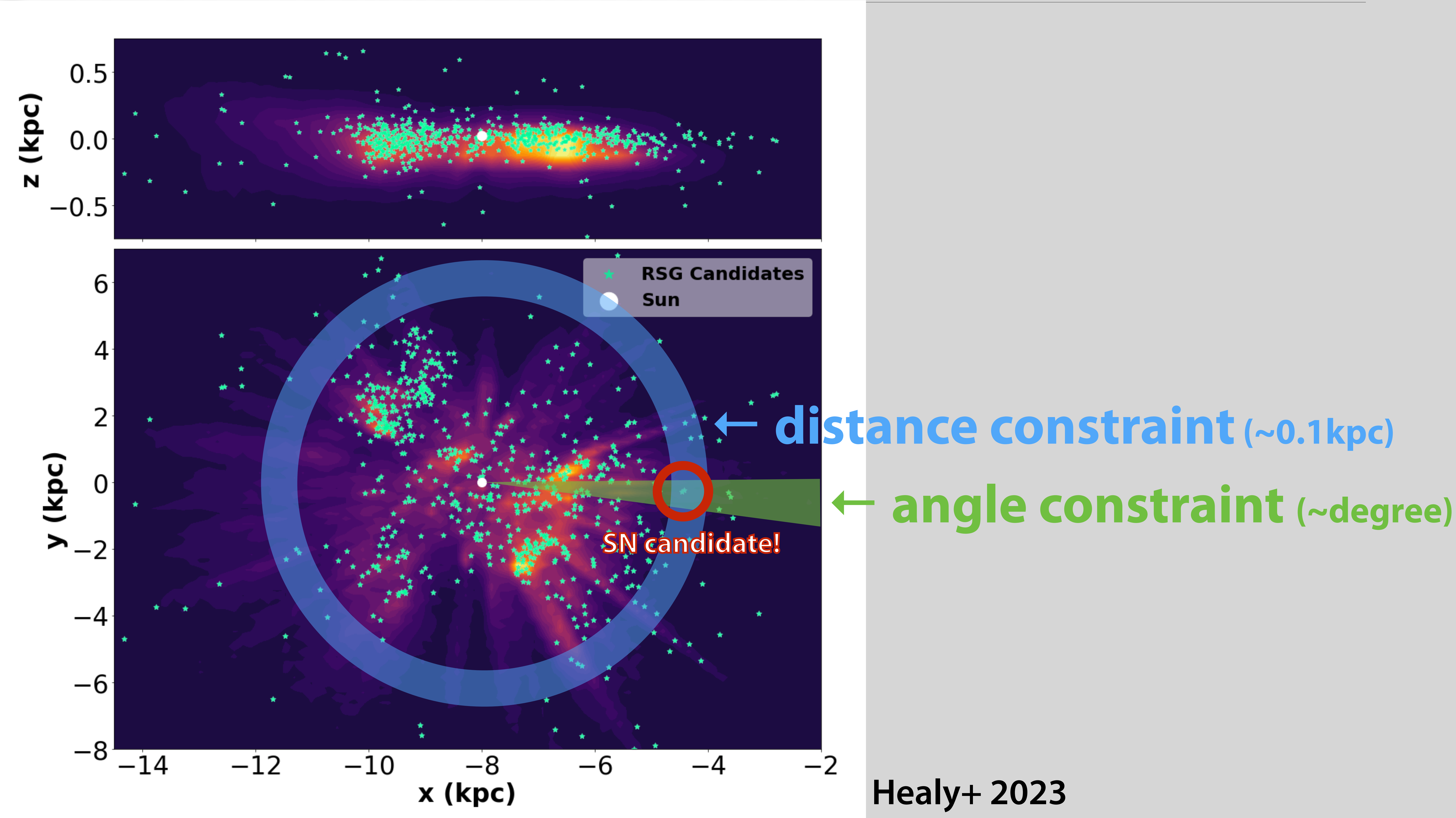
with NS radius constraint



Miller+ 2021



Targeting an RSG based on neutrino observables



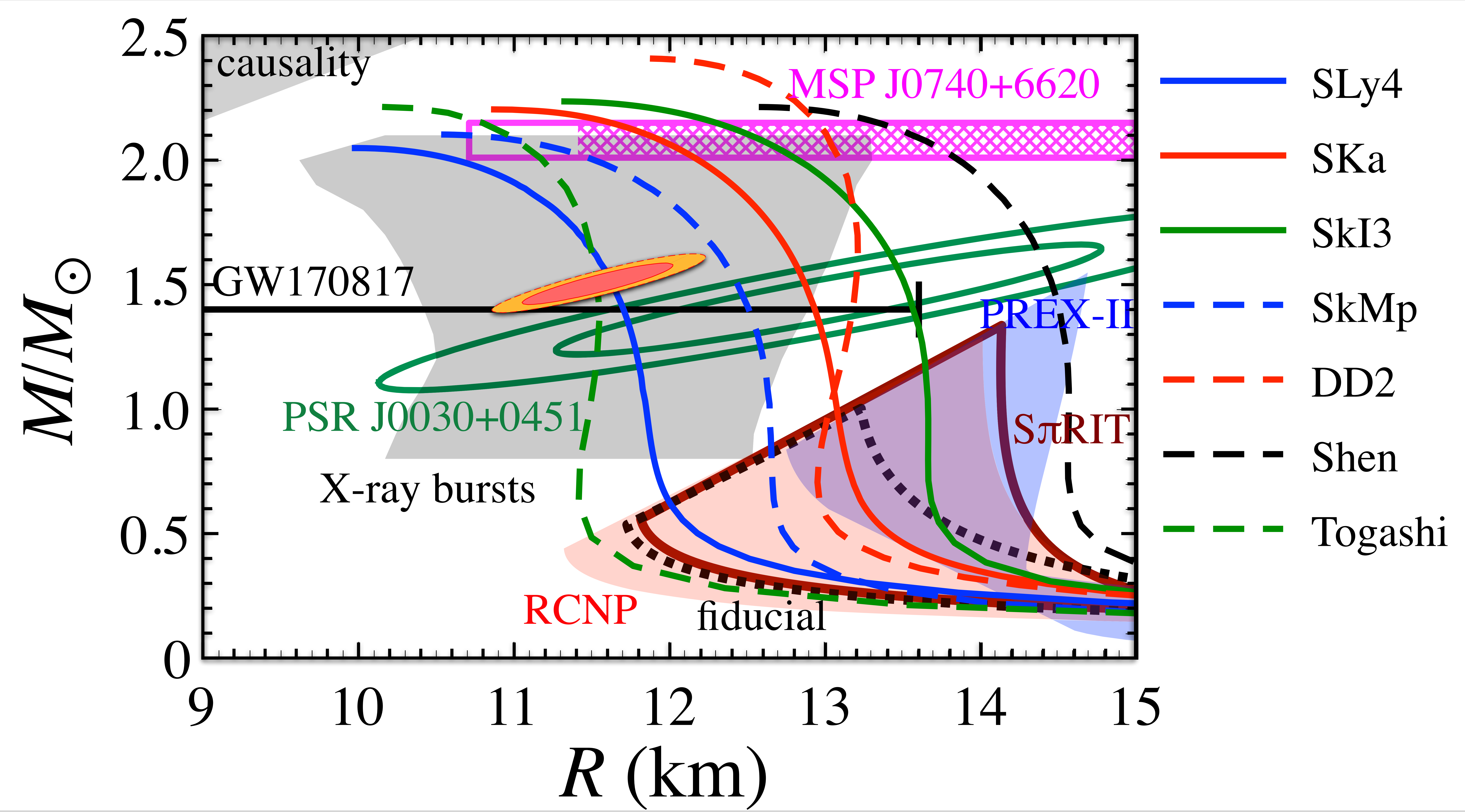
Healy+ 2023

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