Probing supernova interiors with neutrinos

Yudai Suwa *(UTokyo, 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)
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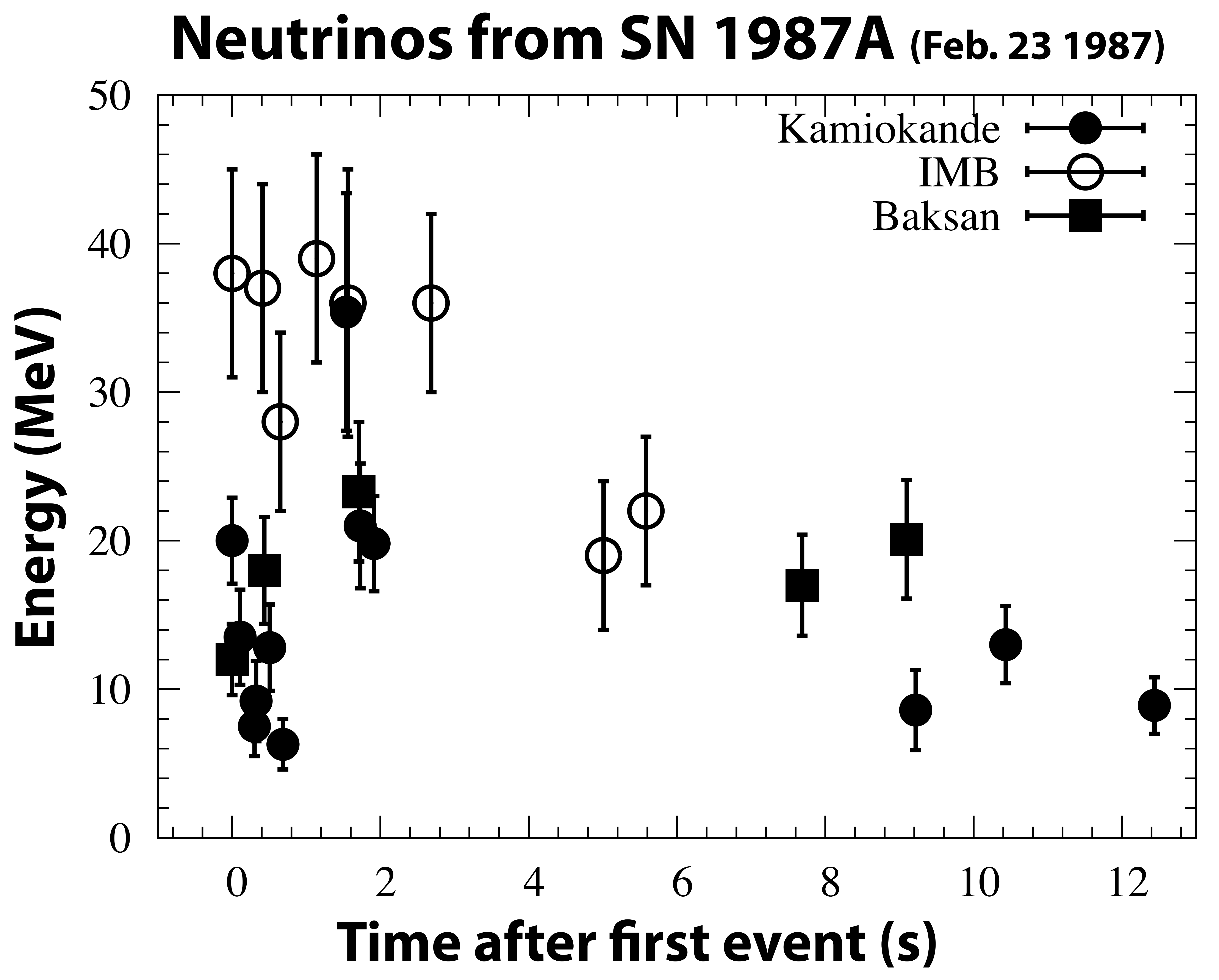
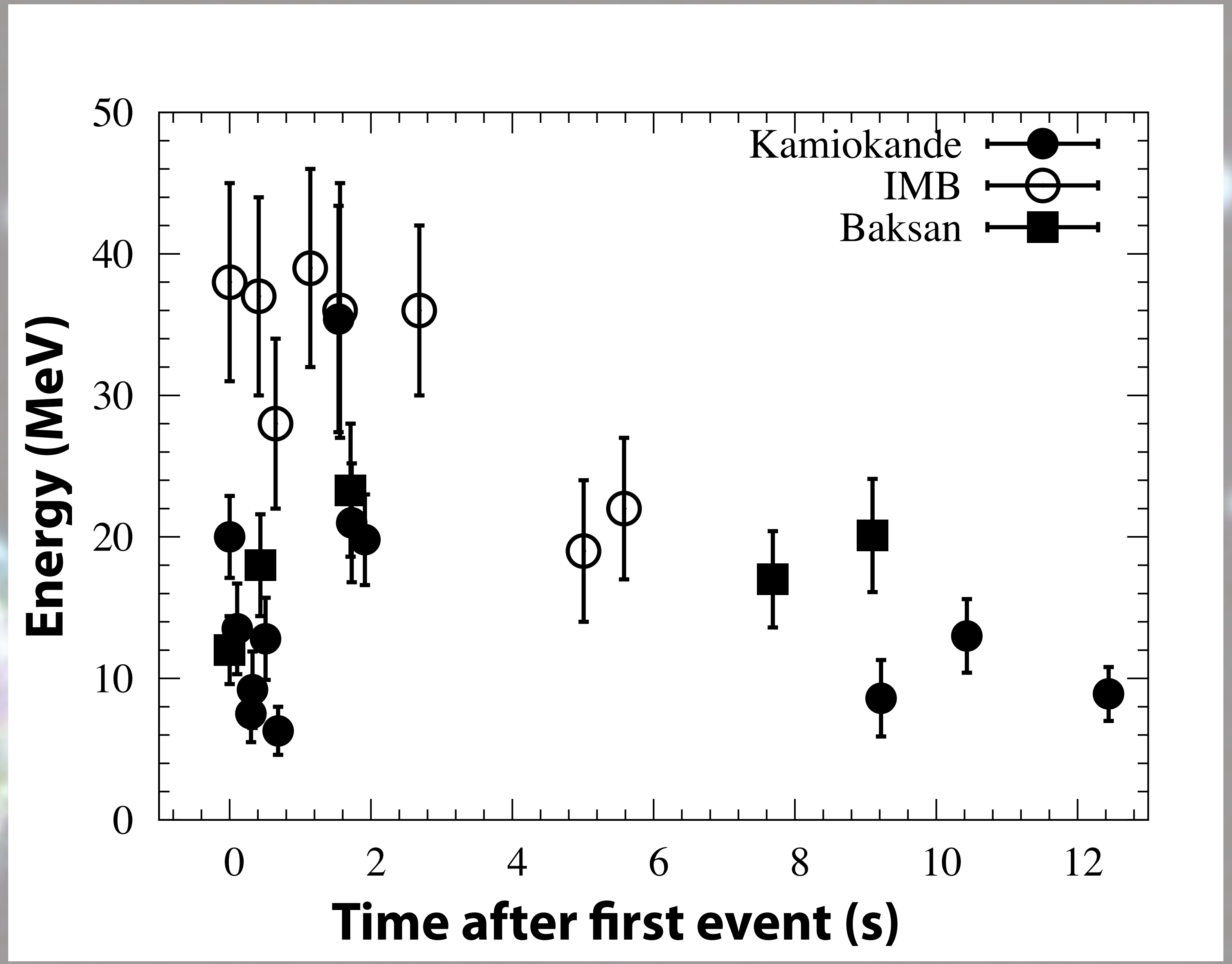
SN1987A


Neutrinos from SN 1987A (Feb. 23 1987)

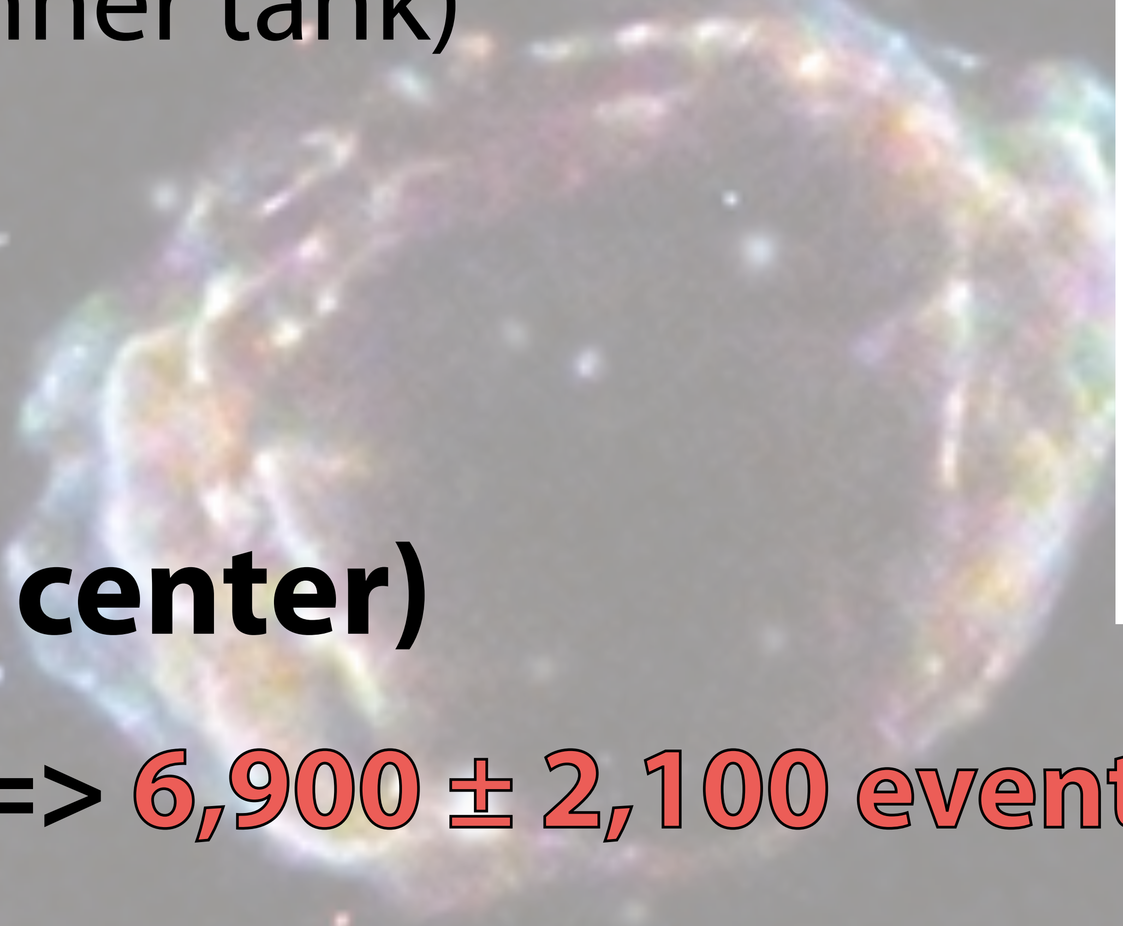
NASA/ESA

How many neutrinos can we observe now?



- **Observation of SN1987A with Kamiokande**
  - **11 events**
  - **M = 2.14 kton** (full volume of inner tank)
  - **D = 51.4 kpc** (LMC)

- **Assume D = 8 kpc (Galactic center)**
  - **with Super-K (M = 32.5 kton) => 6,900 ± 2,100 events**
  - **with Hyper-K (M = 220 kton) => 47,000 ± 14,000 events**



The latest SN found in our Galaxy, G1.9+0.3 (<170 years old) © NASA

What can we extract from neutrino observations?

- **Properties of neutron stars**
  - **Binding energy**
    - ***important for energetics, done with SN1987A*** (Sato & Suzuki 1987)

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

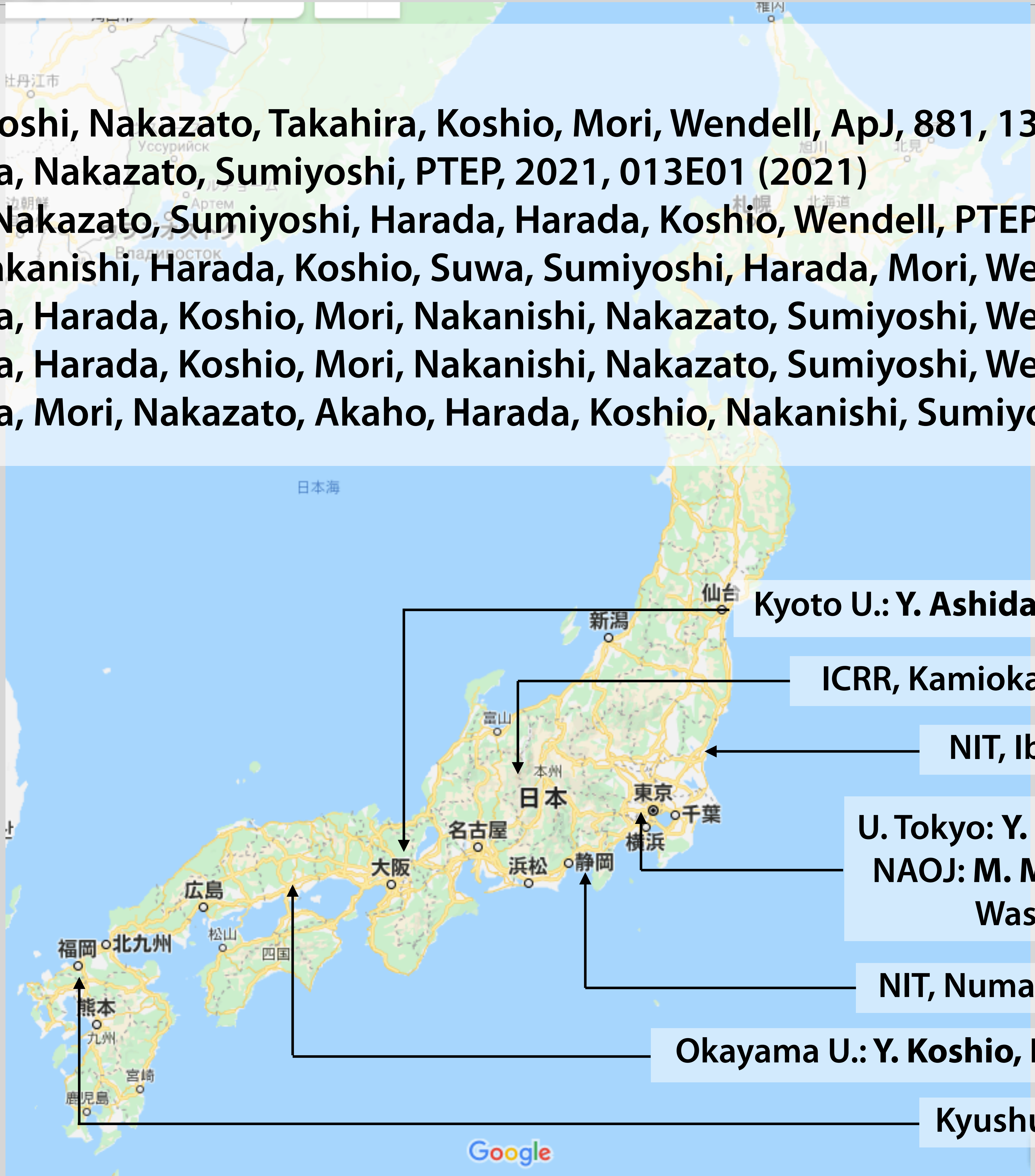
  - **Mass**
    - ***important for discriminating final object (NS or BH)***
  - **Radius**
    - ***important for discriminating nuclear equation of state***

The latest SN found in our Galaxy, G1.9+0.3 (<170 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)
7. Suwa, Harada, Mori, Nakazato, Akaho, Harada, Koshio, Nakanishi, Sumiyoshi, Wendell, ApJ, 980, 117 (2025)



Kyoto U.: **Y. Ashida, R. Wendell** (Experiment)

ICRR, Kamioka: **M. Harada** (Experiment)

NIT, Ibaraki: **A. Harada** (Theory)

U. Tokyo: **Y. Suwa, M. Zaizen** (Theory)
NAOJ: **M. Mori** (Theory/Experiment)
Waseda U.: **R. Akaho** (Theory)

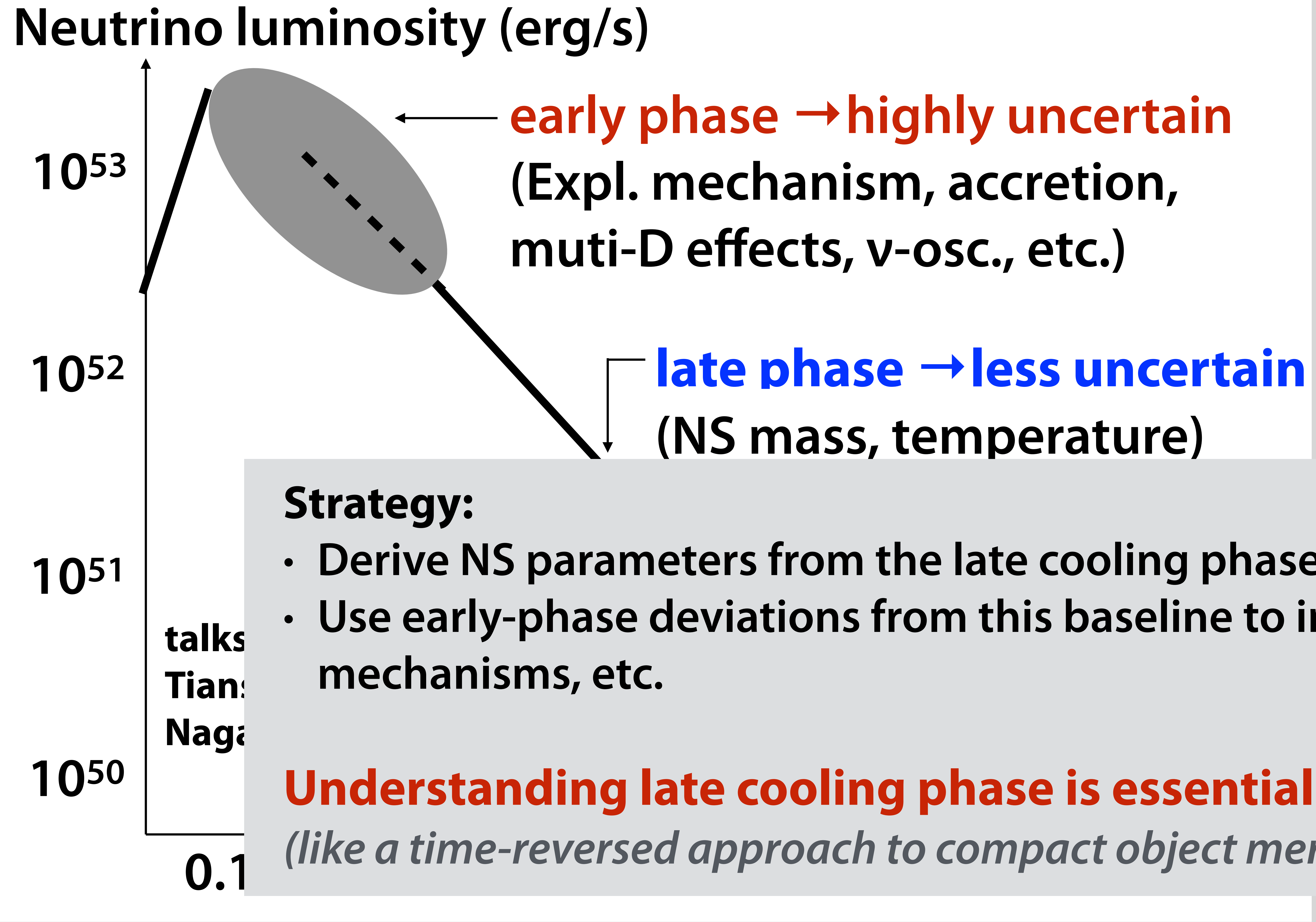
NIT, Numazu: **K. Sumiyoshi** (Theory)

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

Kyushu U.: **K. Nakazato** (Theory)

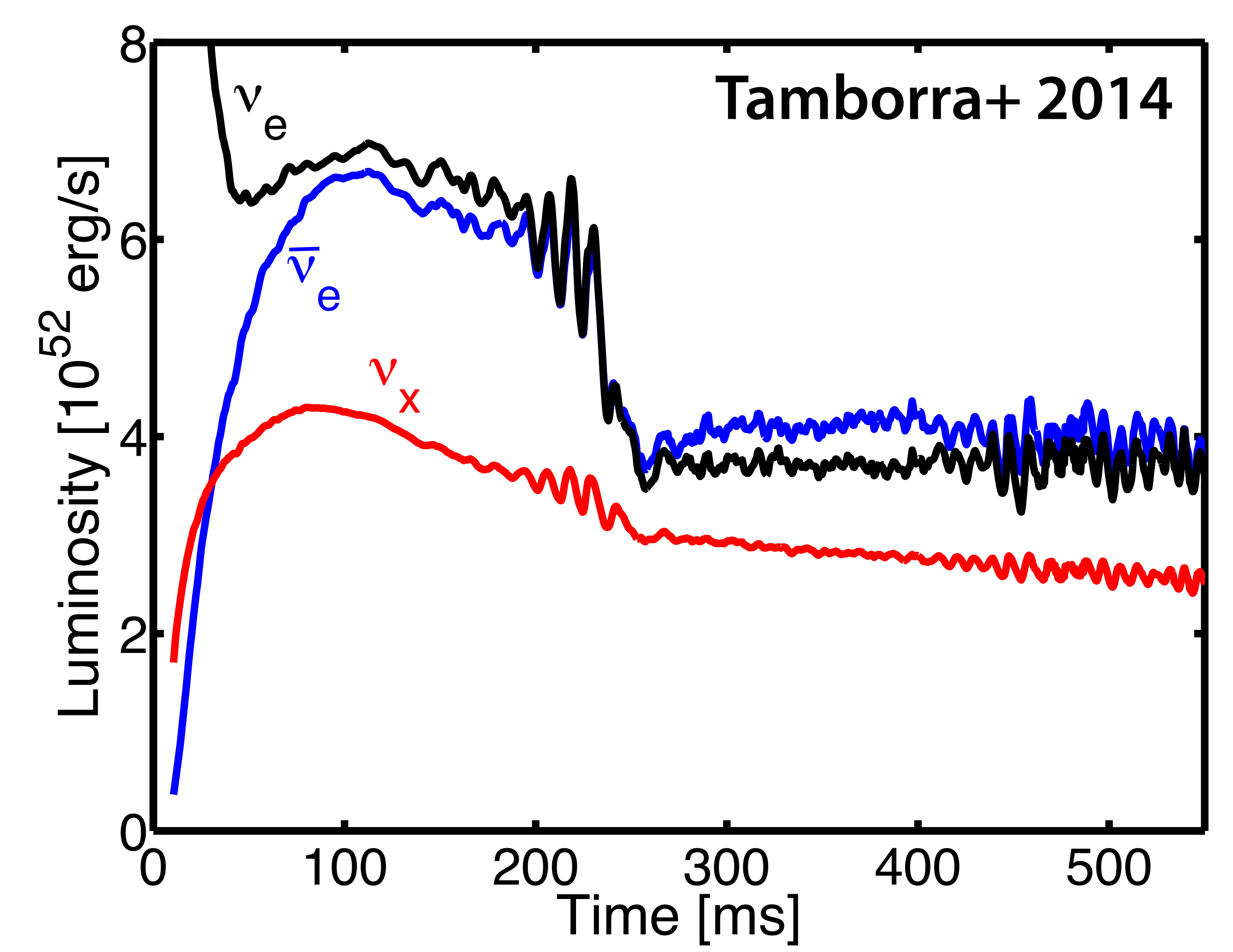
see poster by
F. Nakanishi

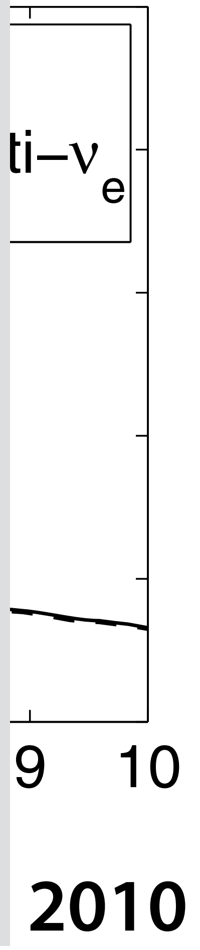
Late cooling phase is simple and understandable



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

late phase →less uncertain
(NS mass, temperature)





Strategy:
- Derive NS parameters from the late cooling phase as a 0-th order baseline
- Use early-phase deviations from this baseline to investigate explosion mechanisms, etc.

Understanding late cooling phase is essential !

(like a time-reversed approach to compact object merger analysis)

see also Burrows 1988, Fischer+ 2009, Hüdepohl+ 2010, Roberts+ 2012, Mirizzi+ 2016, Li+ 2021

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

Numerical simulaions

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

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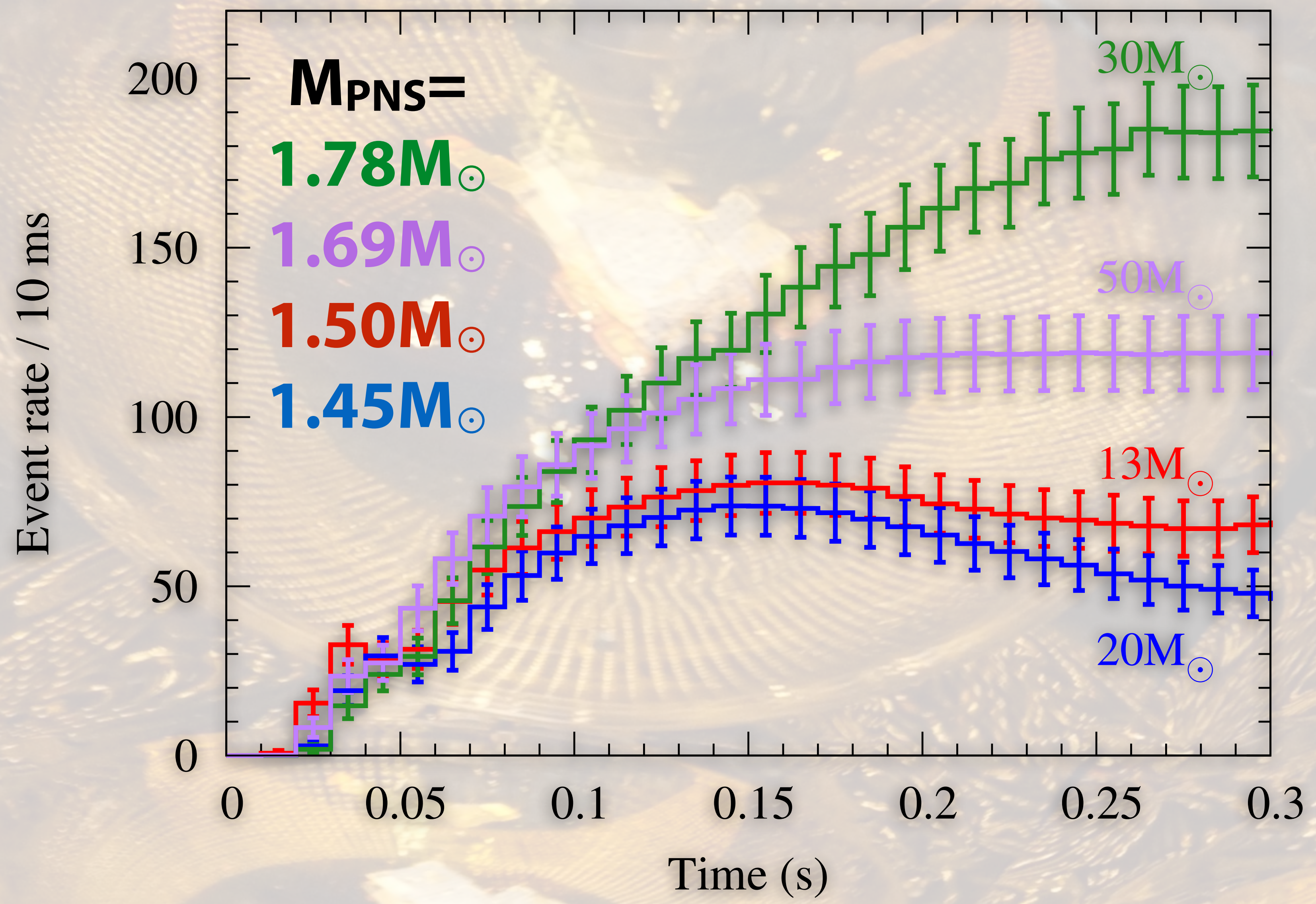
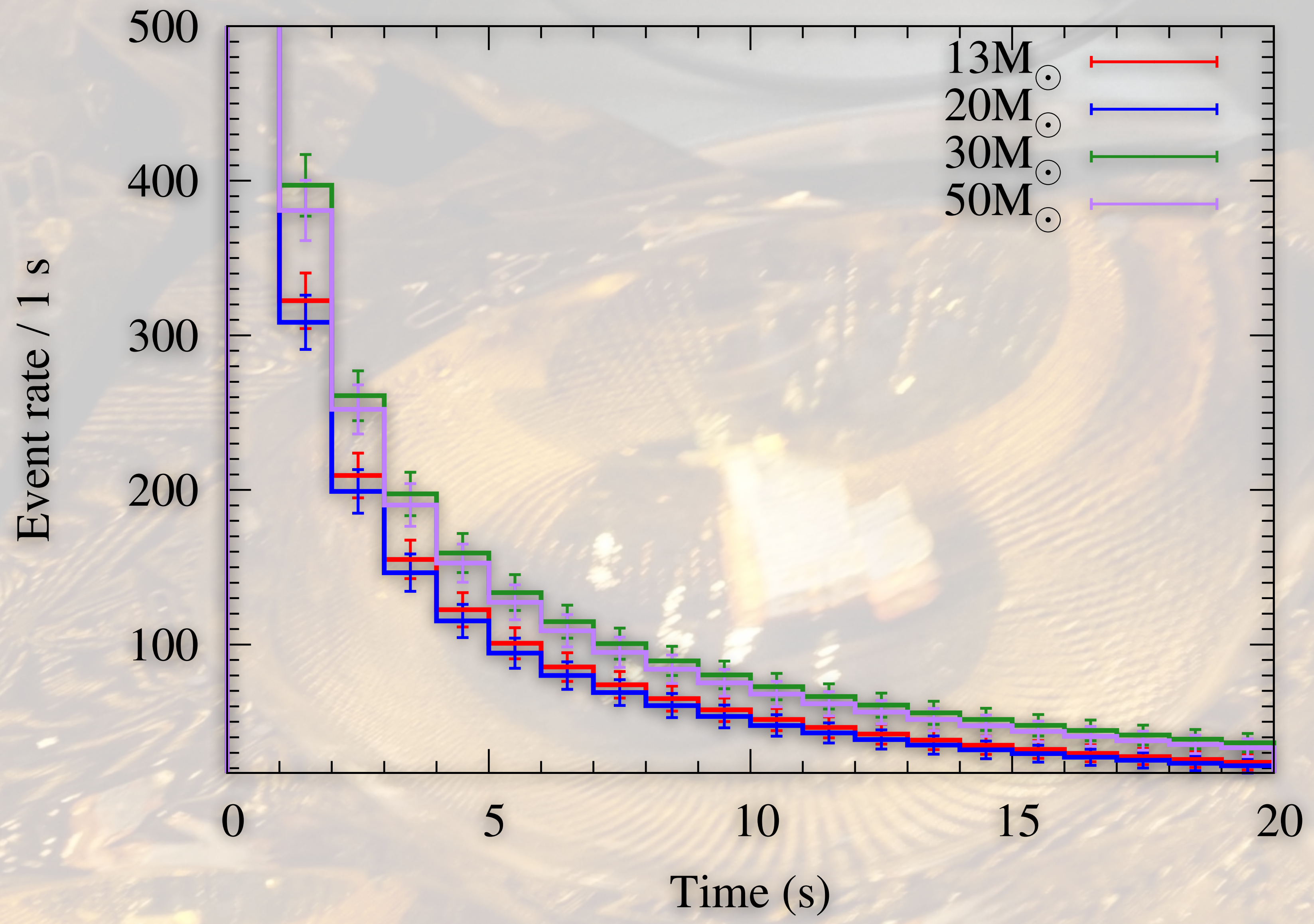




- **Event rate evolution is calculated beyond 100 s**
  - with neutrino luminosity and energy spectrum
  - with full volume of SK's inner tank (32.5 kton)
  - assuming an SN at 10 kpc
  - detector response for inverse beta decay $(\bar{\nu}_e + p \rightarrow e^+ + n)$
- **Event rate is not related to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

Analytic solutions

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

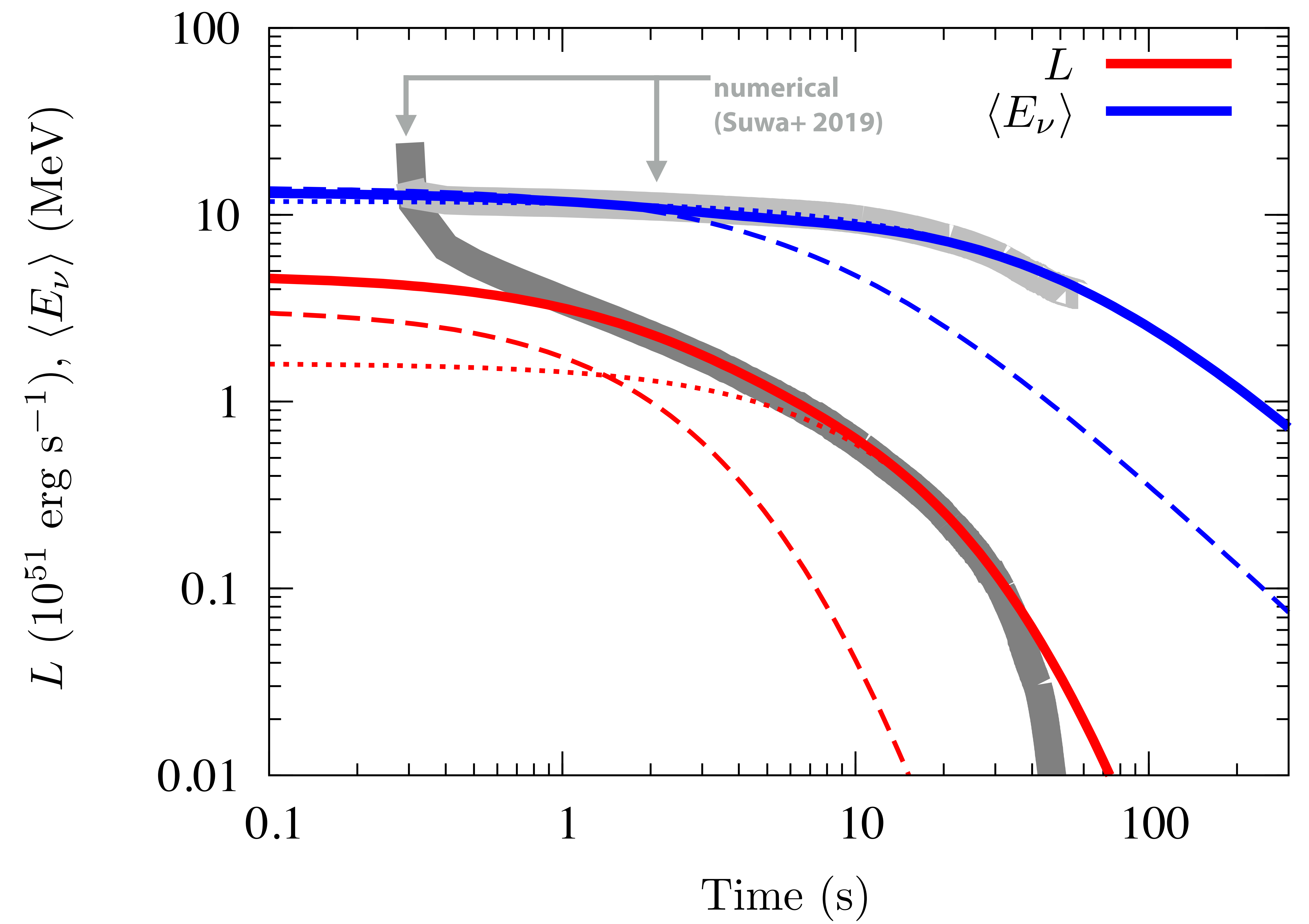
- **Solve neutrino transport eq. analytically**
  - **Neutrino luminosity**

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

  - **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))



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

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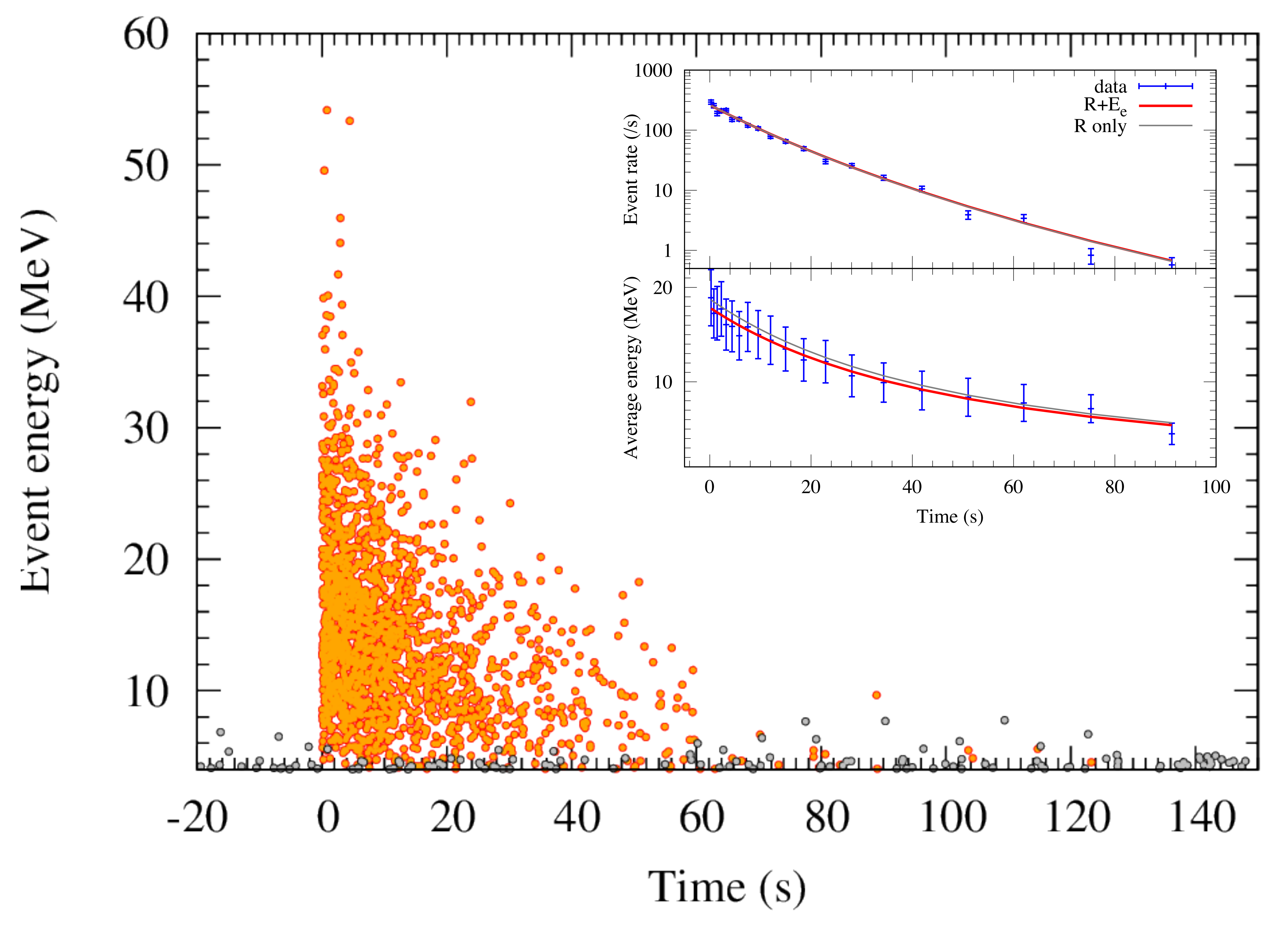
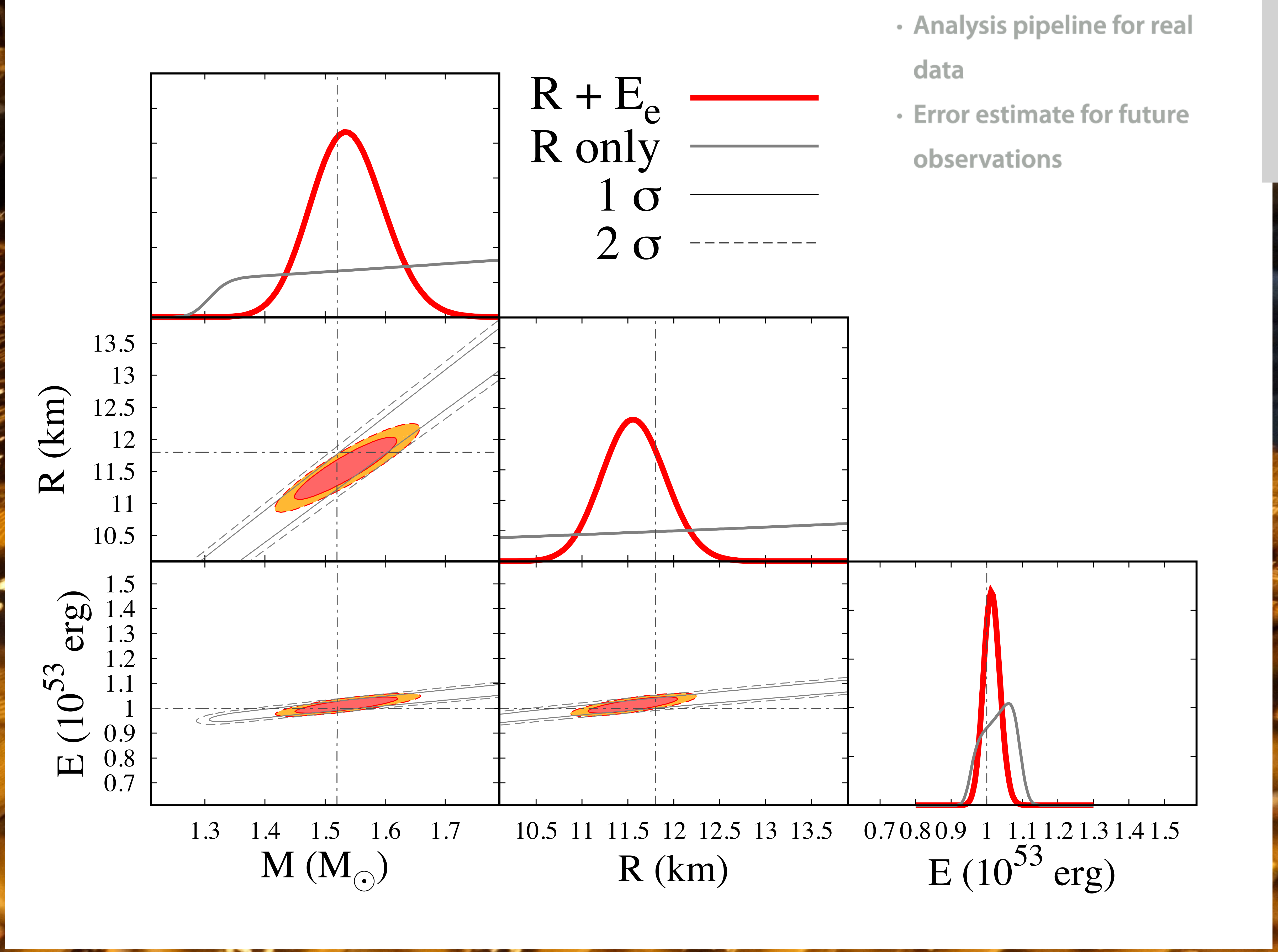




Analysis code *SPECIAL BLEND* is available on github

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

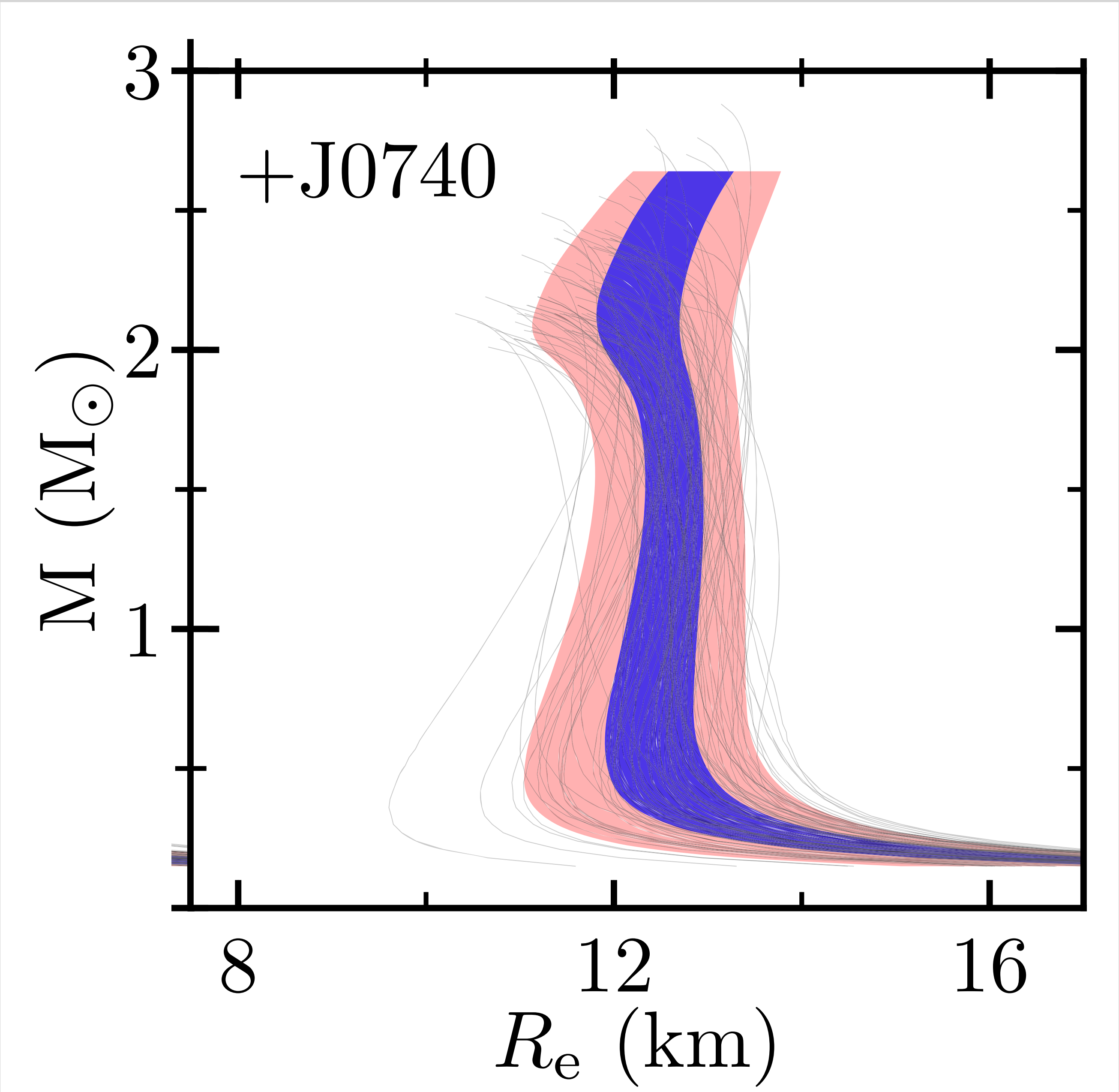
Distance estimation with neutrinos

[Suwa, Harada, Mori, Nakazato, Akaho, Harada, Koshio, Nakanishi, Sumiyoshi, Wendell, ApJ, 980, 117 (2025)]

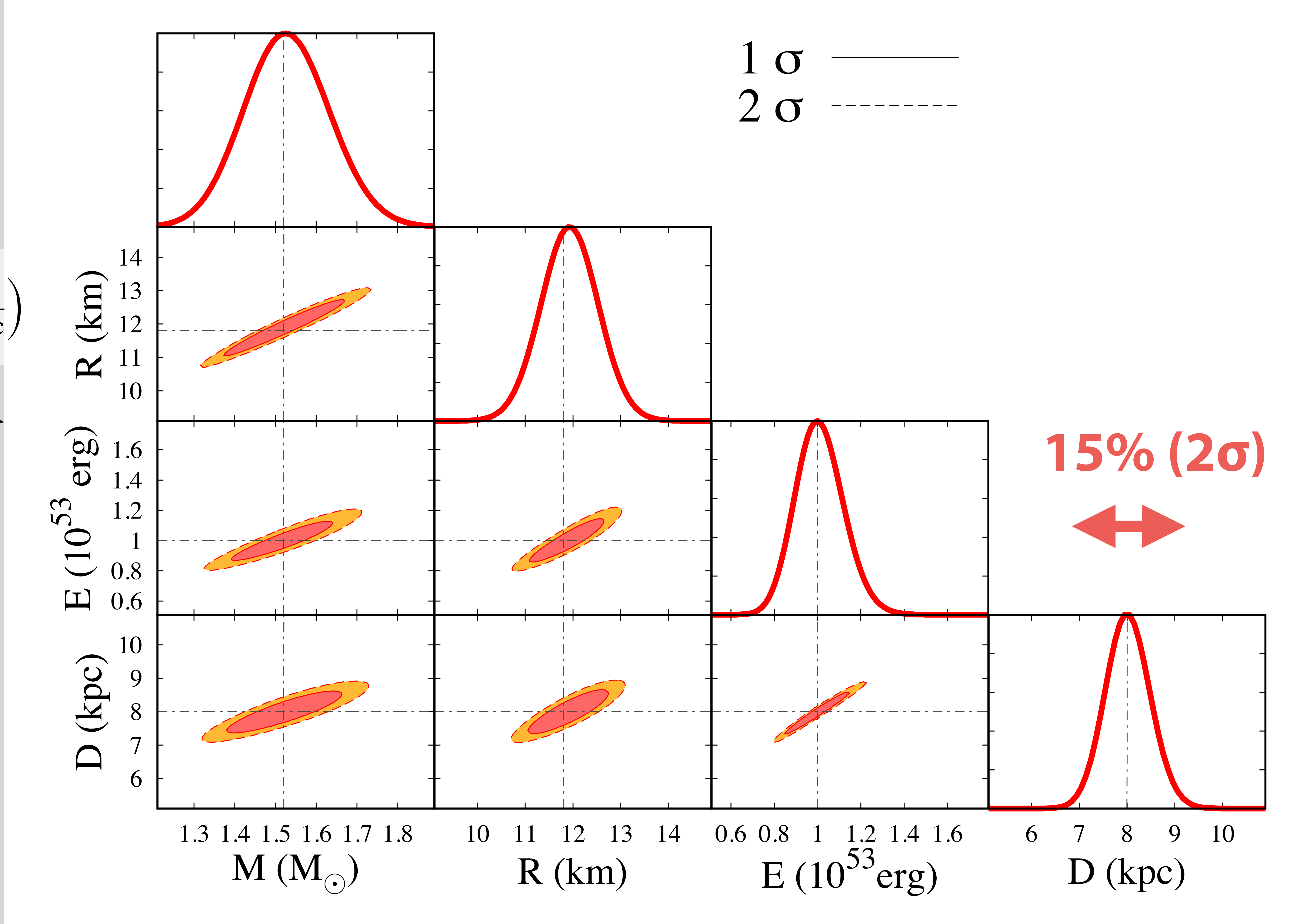
Analytic solution tells us (measured) PNS radius and source distance are correlated

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

with NS radius constraint

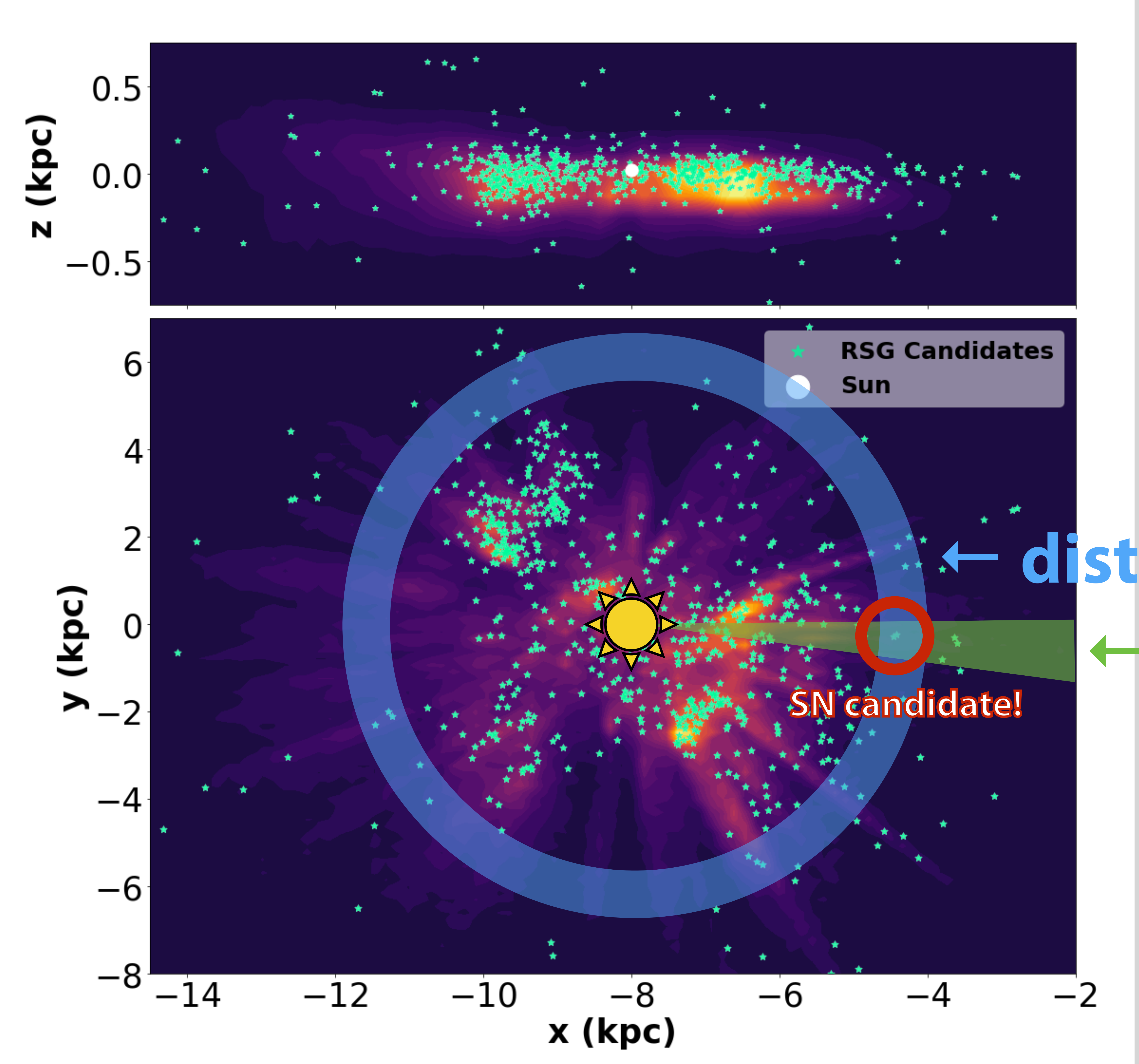


Miller+ 2021



NS mass NS radius total energy distance

Targeting an RSG based on neutrino observables



← distance constraint (~kpc)

← angle constraint (~degree)

Healy+ 2023

Why can we measure distance?

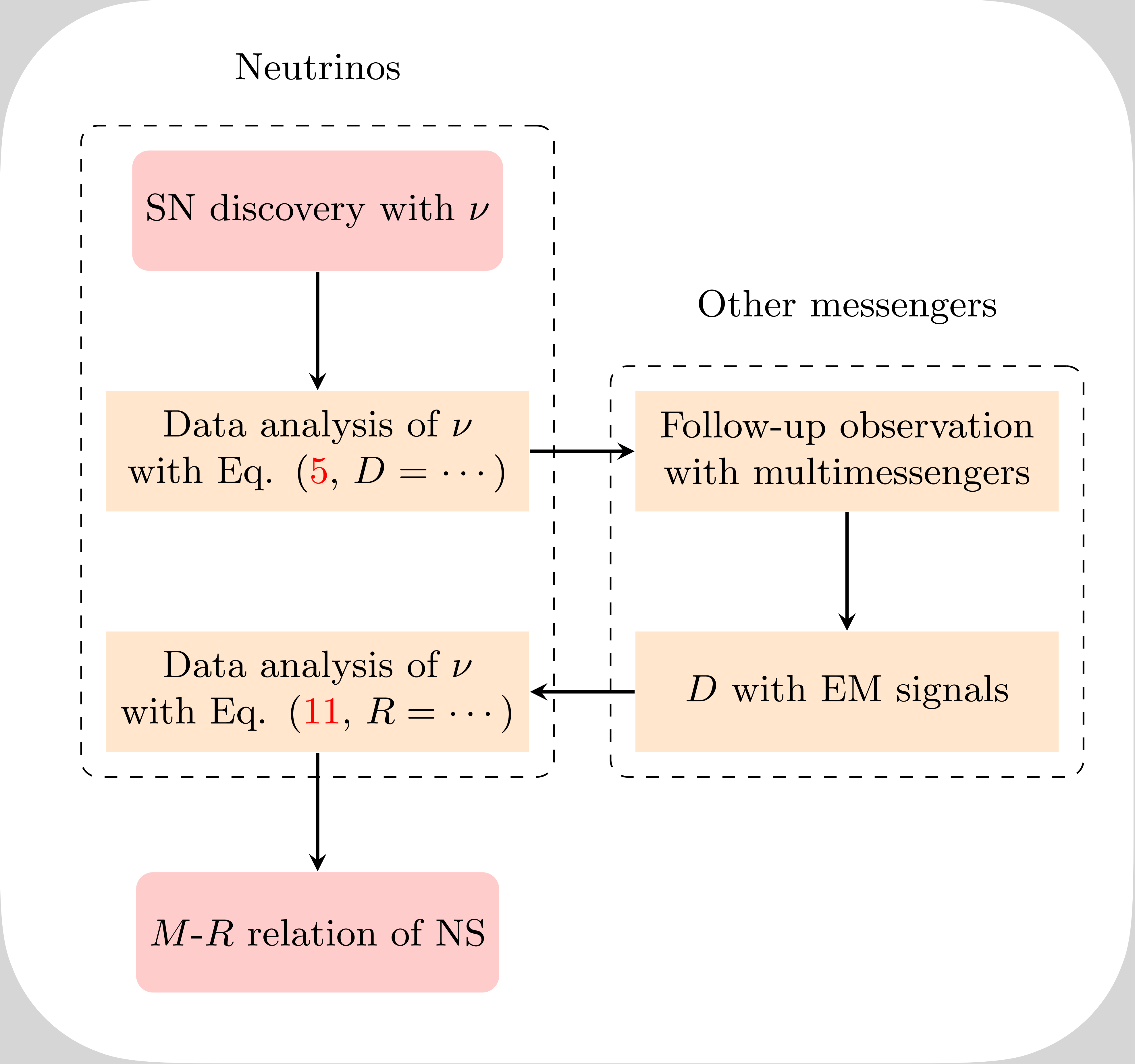
- **Analogous to distance measurement with main sequence stars**
  (aka. main sequence fitting or spectroscopic parallax)

- **Essence**
  - Luminosity: $L = 4\pi R_*^2 \sigma T_*^4$ (absolute magnitude for main sequence)
  - Energy flux: $F = L/(4\pi D^2) = (R_*/D)^2 \sigma T_*^4$ (apparent magnitude for main sequence)
  - Spectrum: $F(E) \rightarrow T_*$ (color for main sequence)
  - If R_* is given, we can estimate the distance D

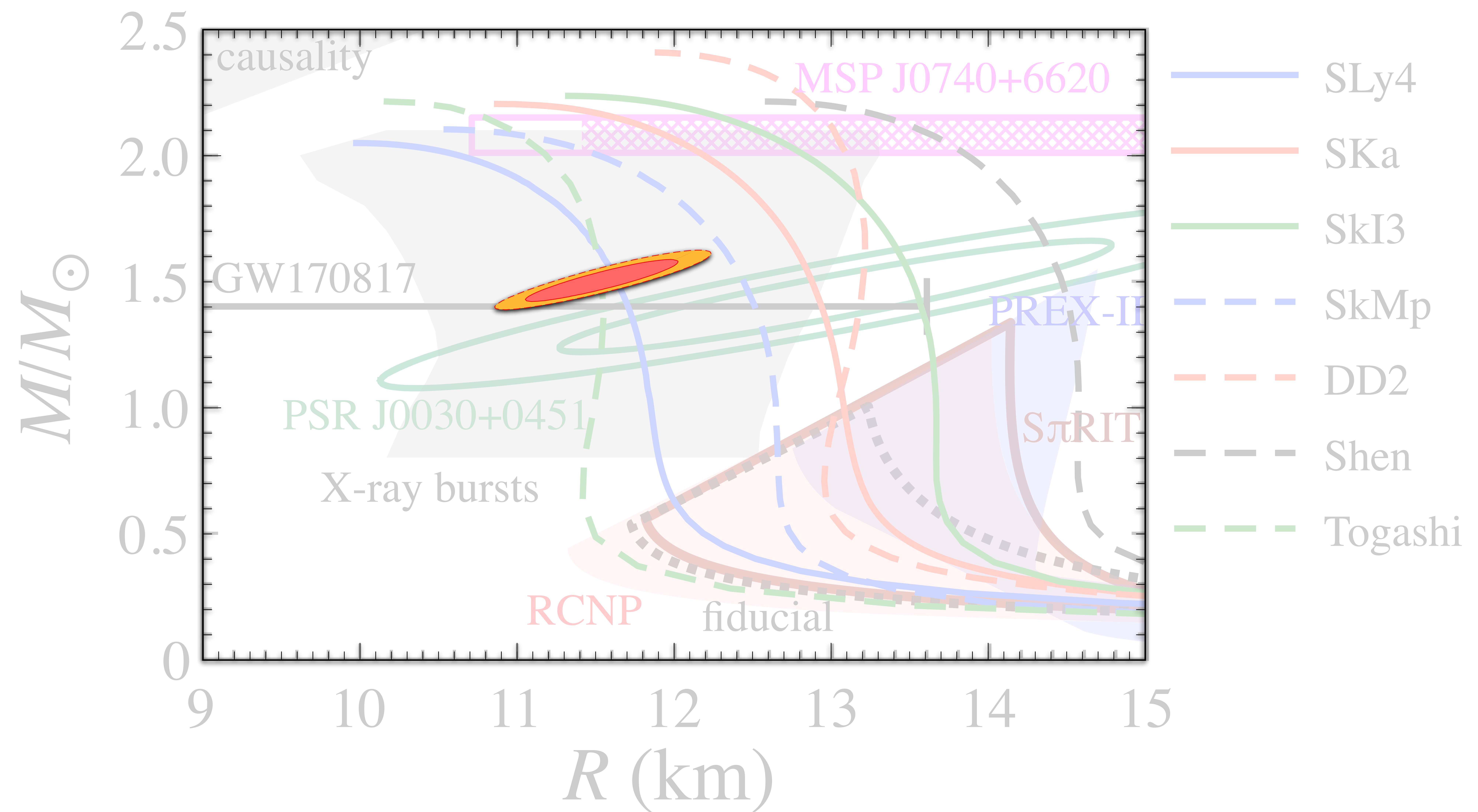
Usage of neutrinos before and after discorvery of SN

- ***Before* finding SN**:
  - Neutrinos tell us **distance to SN with O(10)% error**
  - **Multi-messenger followup observation** become possible with 3D localization
  - 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**

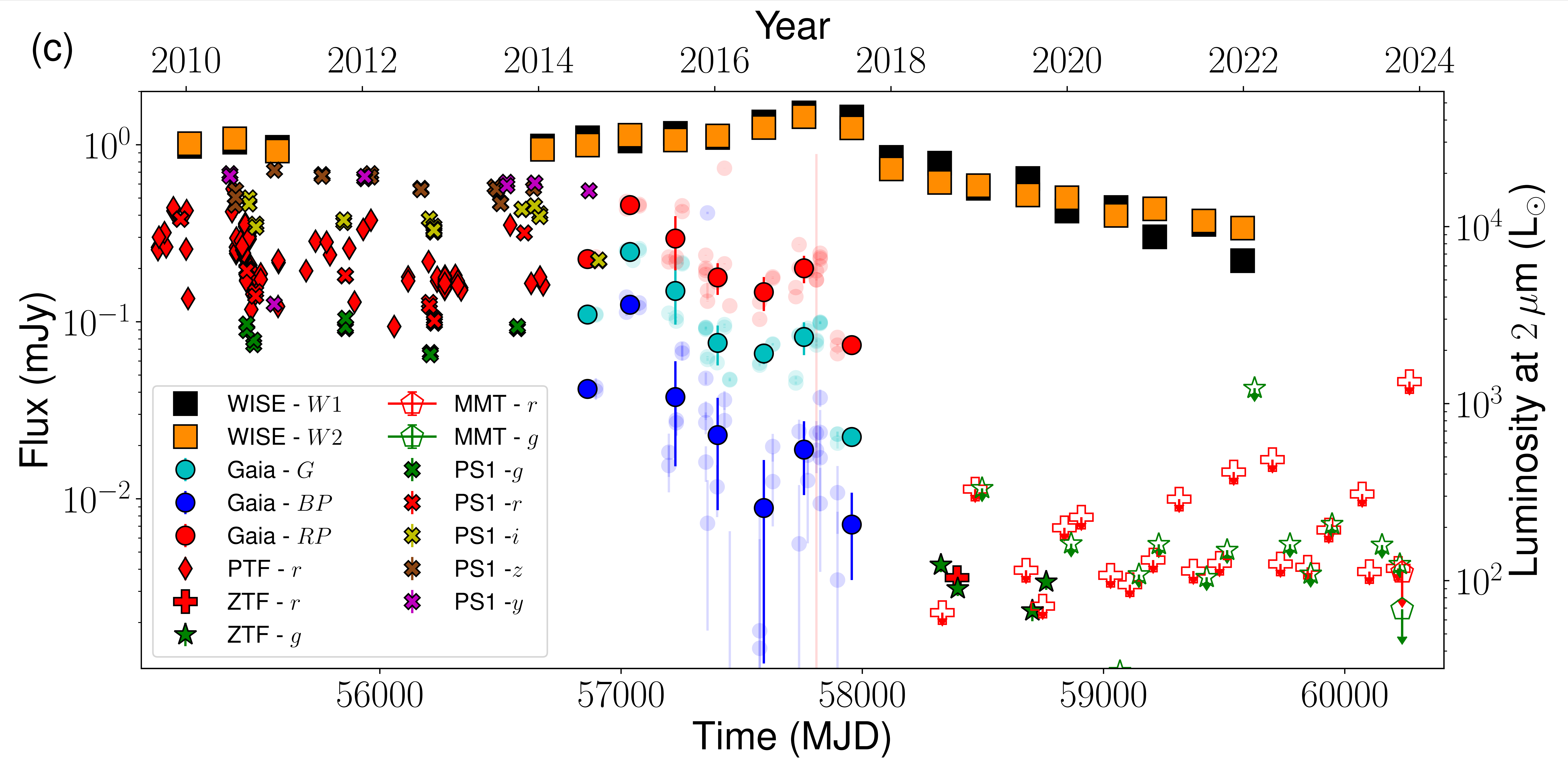


Neutrino constraint on M-R relation



Sotani-Nishimura-Naito (2022)

Appendix: Constraints on BH-forming simulations with neutrinos



De+ 2024

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 multi-messenger astronomy
  - Integrating neutrinos with electromagnetic signals and gravitational waves providing better understanding supernova mechanism