ニュートリノを軸とした
超新星マルチメッセンジャー観測に向けて

Toward neutrino-based multi-messengers for SN

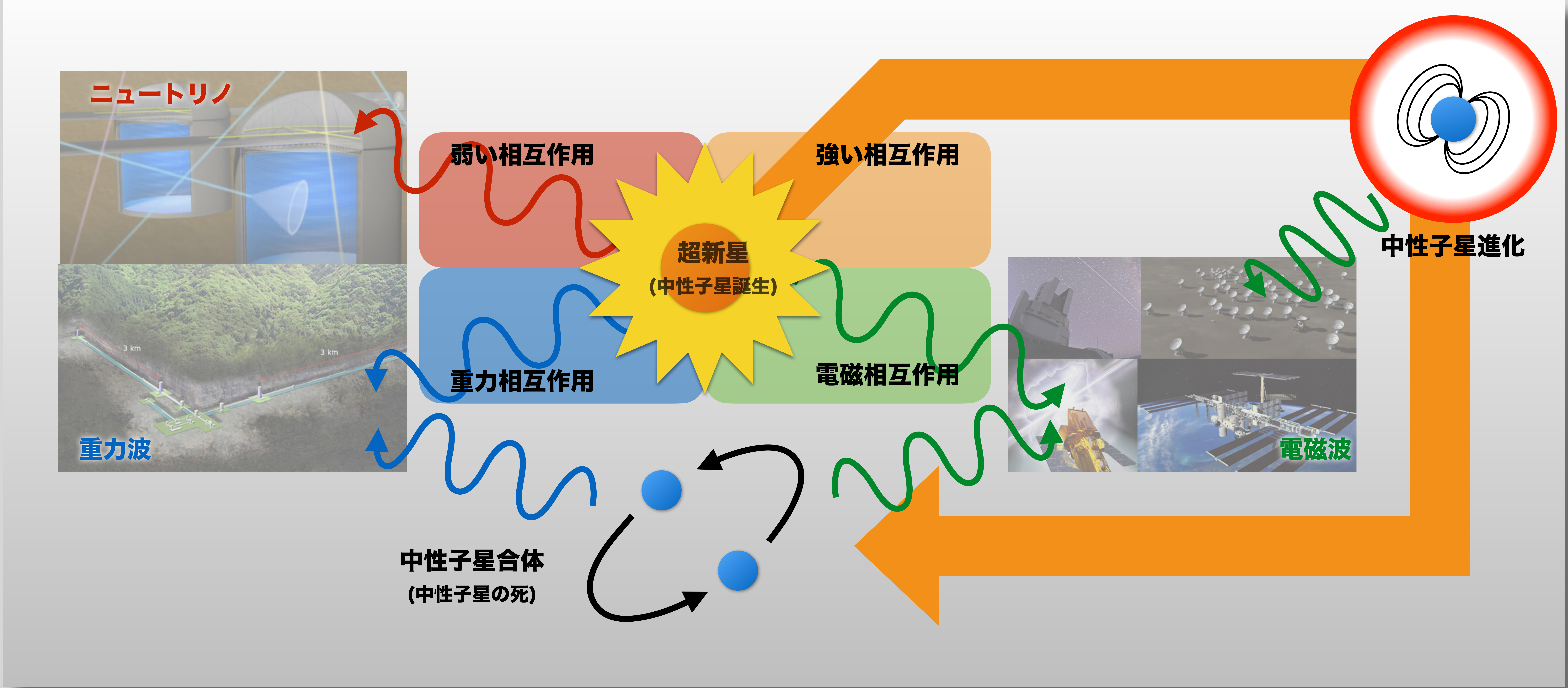
11月1日（水）
座長：中畑雅行（ICRR）
9:50-10:00 機構長・梶田隆章（ICRR）
「次世代ニュートリノ科学・マルチメ
10:00-10:25 浅野勝晃（ICRR）「マルチ
10:25-10:50 関谷洋之（ICRR）「Super-
10:50-11:15 浅岡陽一（ICRR）「ハイパ
天文学への展望」
11:15-11:45 諏訪雄大（東大総合文化）
ャー観測に向けて」
11:45-12:00 Mark Vagins（IPMU）「Mult
12:00-12:15 新谷昌人（地震研）「マル

諏訪雄大（東大総合文化 & 京大基研）

Yudai Suwa (UT, Komaba & YITP)

Yokozawa, Asano, Kayano, YS, Kanda, Koshio, Vagins, ApJ, 811, 86 (2015)
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)

Neutron star and multi-messenger observation



Energy budget

* **Gravitational energy**

$$E_g \sim \frac{GM_{\rm NS}^2}{R_{\rm NS}} = 2.6 \times 10^{53}\,{\rm erg} \left(\frac{M_{\rm NS}}{M_\odot}\right)^2 \left(\frac{R_{\rm NS}}{10{\rm km}}\right)^{-1}$$

* **Kinetic energy of ejecta**

$$E_K \sim \frac{1}{2} M_{\rm ej} v_{\rm ej}^2 = 10^{51}\,{\rm erg} \left(\frac{M_{\rm ej}}{10 M_\odot}\right) \left(\frac{v_{\rm ej}}{3000\,{\rm km/s}}\right)^2$$

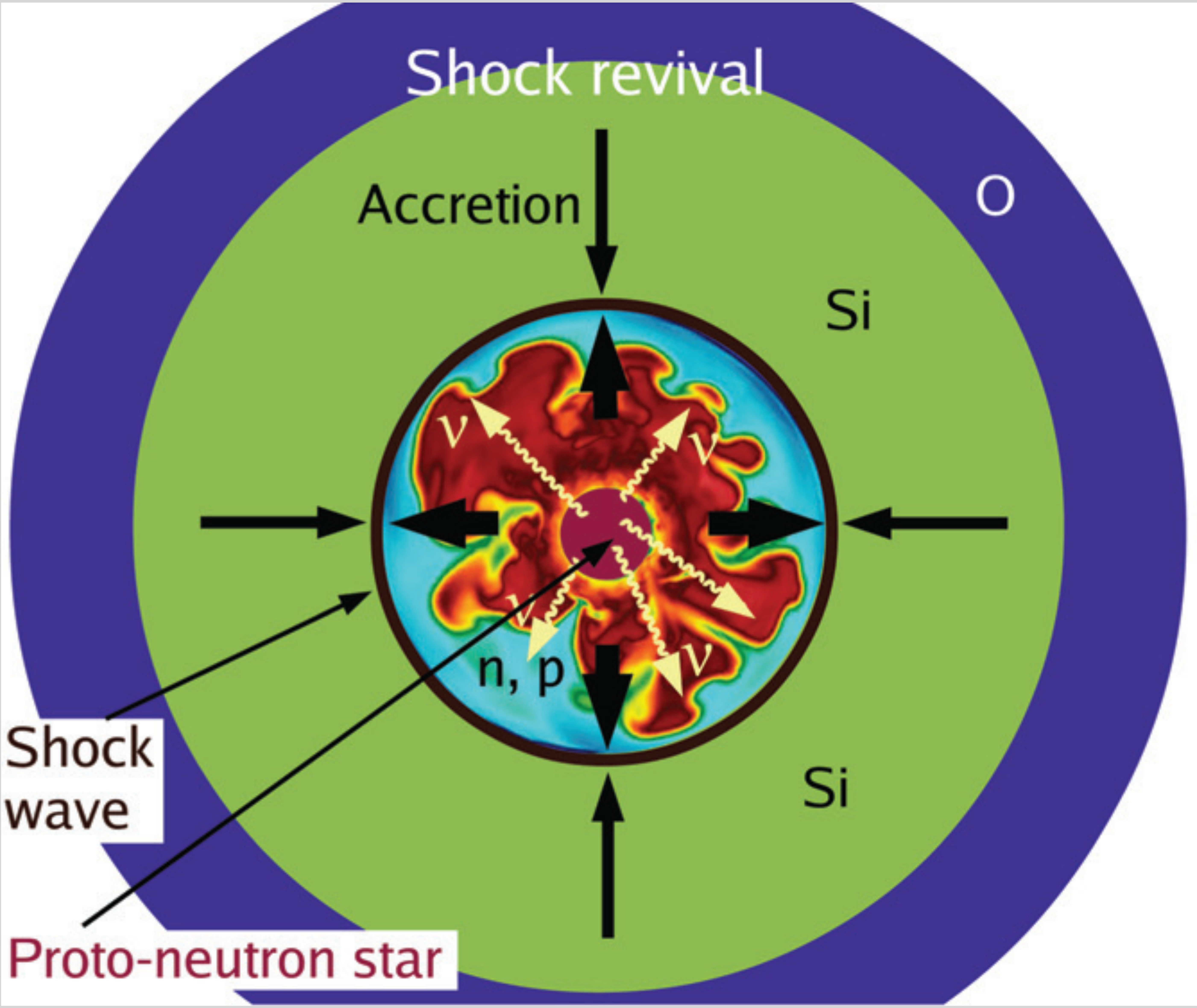
* **Radiation energy ("supernova")**

$$E_\gamma \sim M_{\rm Ni} c^2 \times f_{\rm Ni \to Fe} = 2 \times 10^{49}\,{\rm erg} \left(\frac{M_{^{56}Ni}}{0.1 M_\odot}\right) \left(\frac{f_{\rm Ni \to Fe}}{0.013\,\%}\right)$$

"Supernova"

$$E_g \approx E_\nu \gg E_K \gg E_\gamma$$

Neutrino is crucial for explosion mechanism

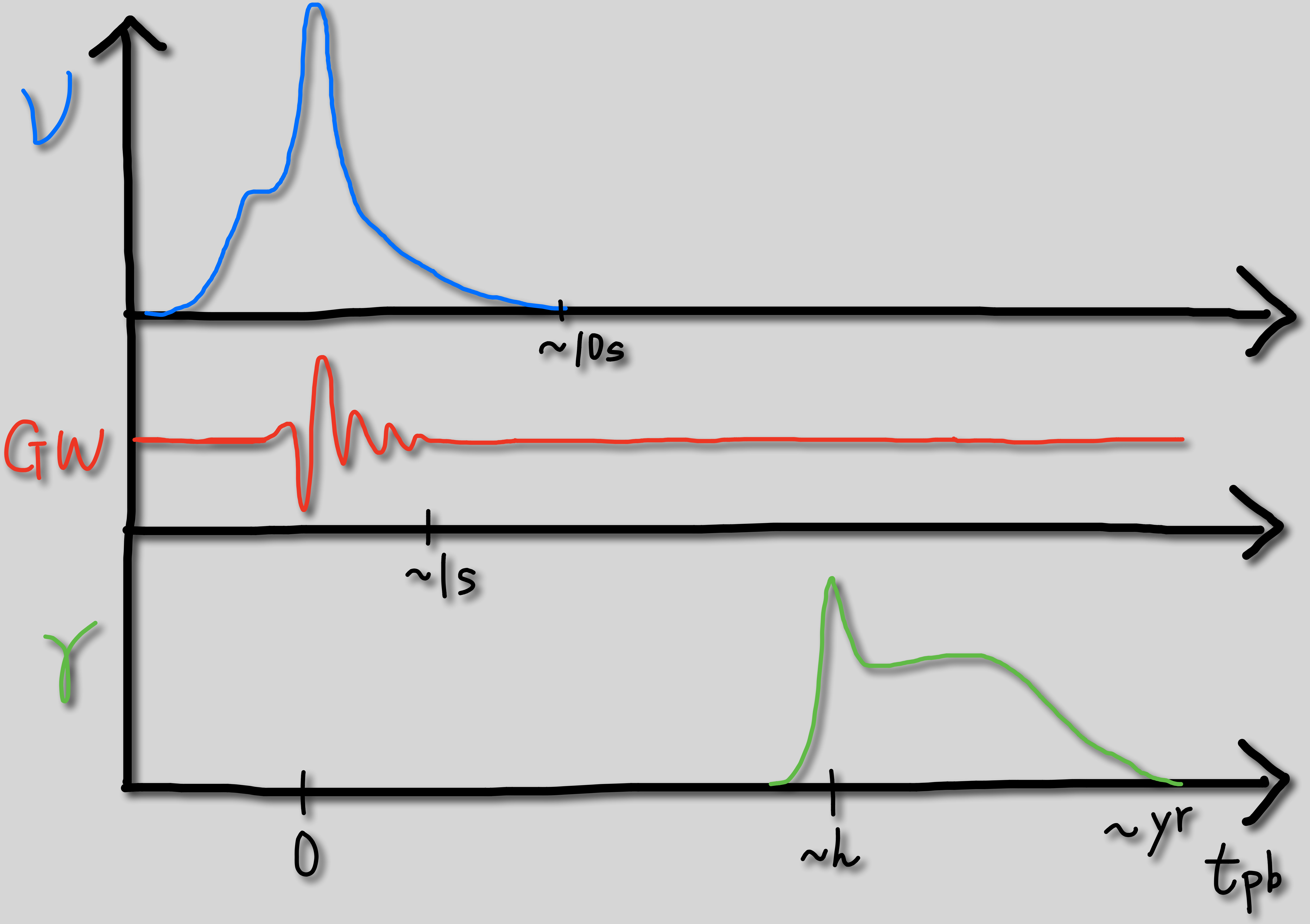


Janka 2012

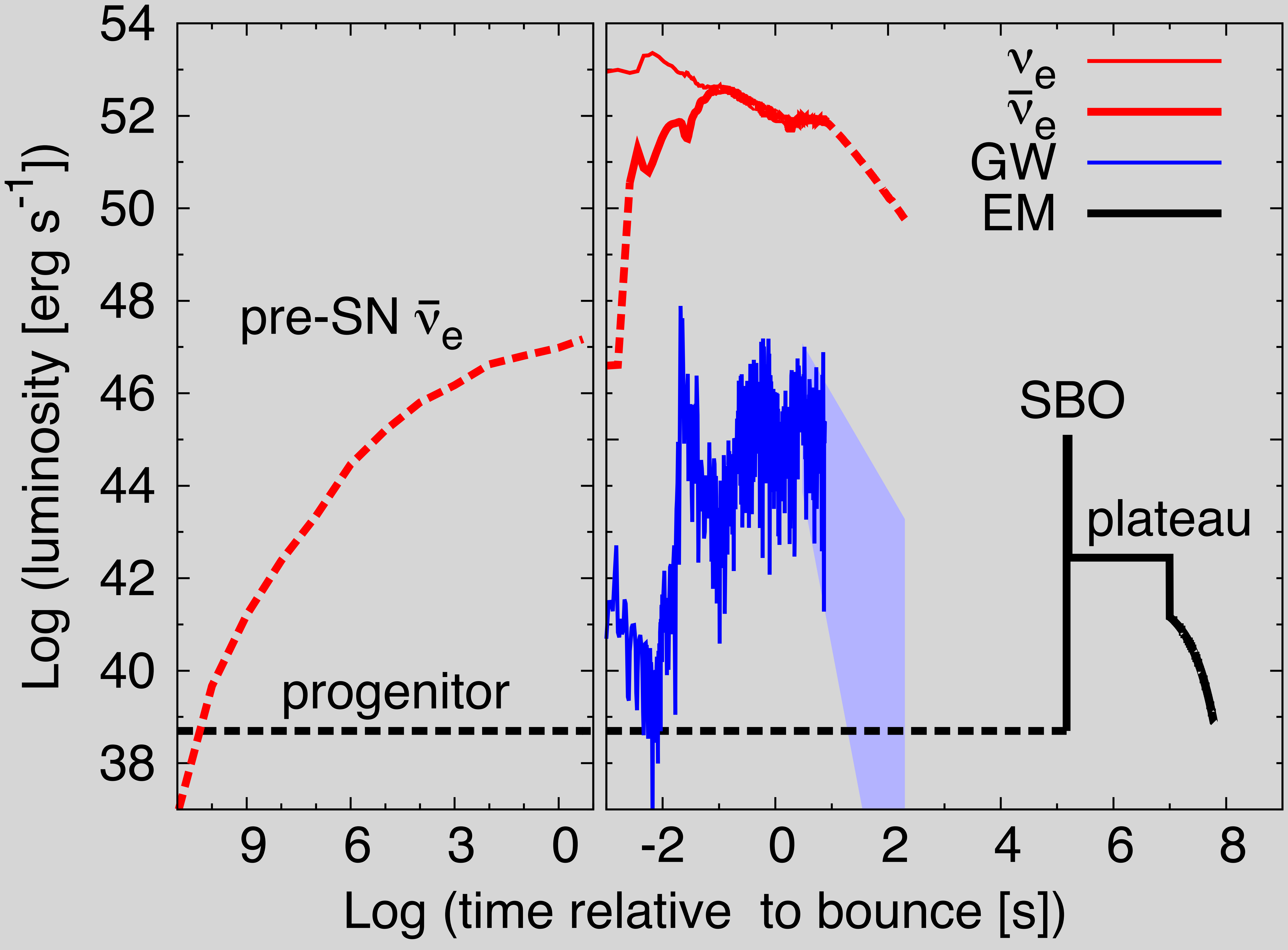
“Optical depth”

Multi-messenger time domain astronomy of CCSN

drawn by YS
(Apr. 2013)

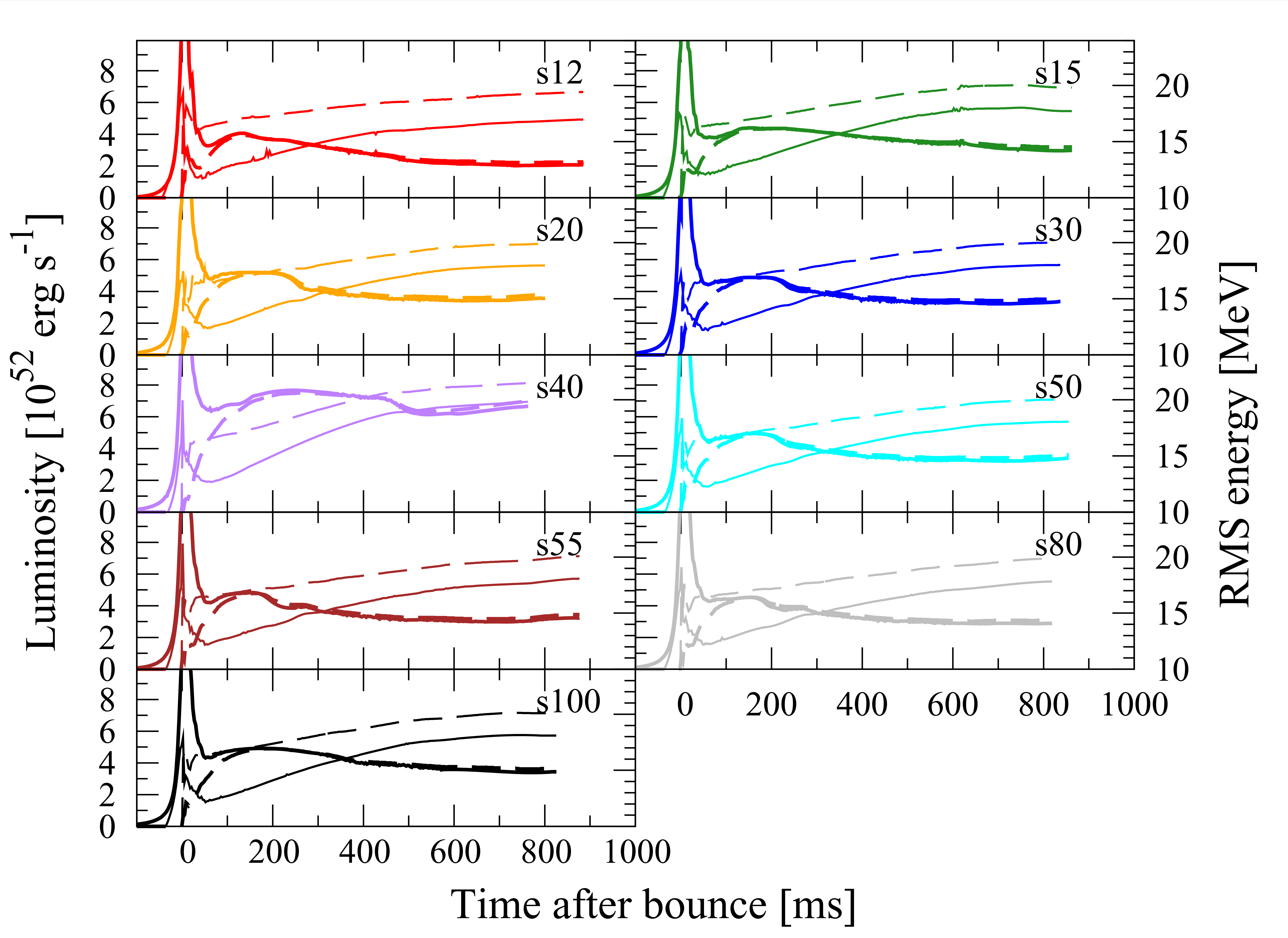


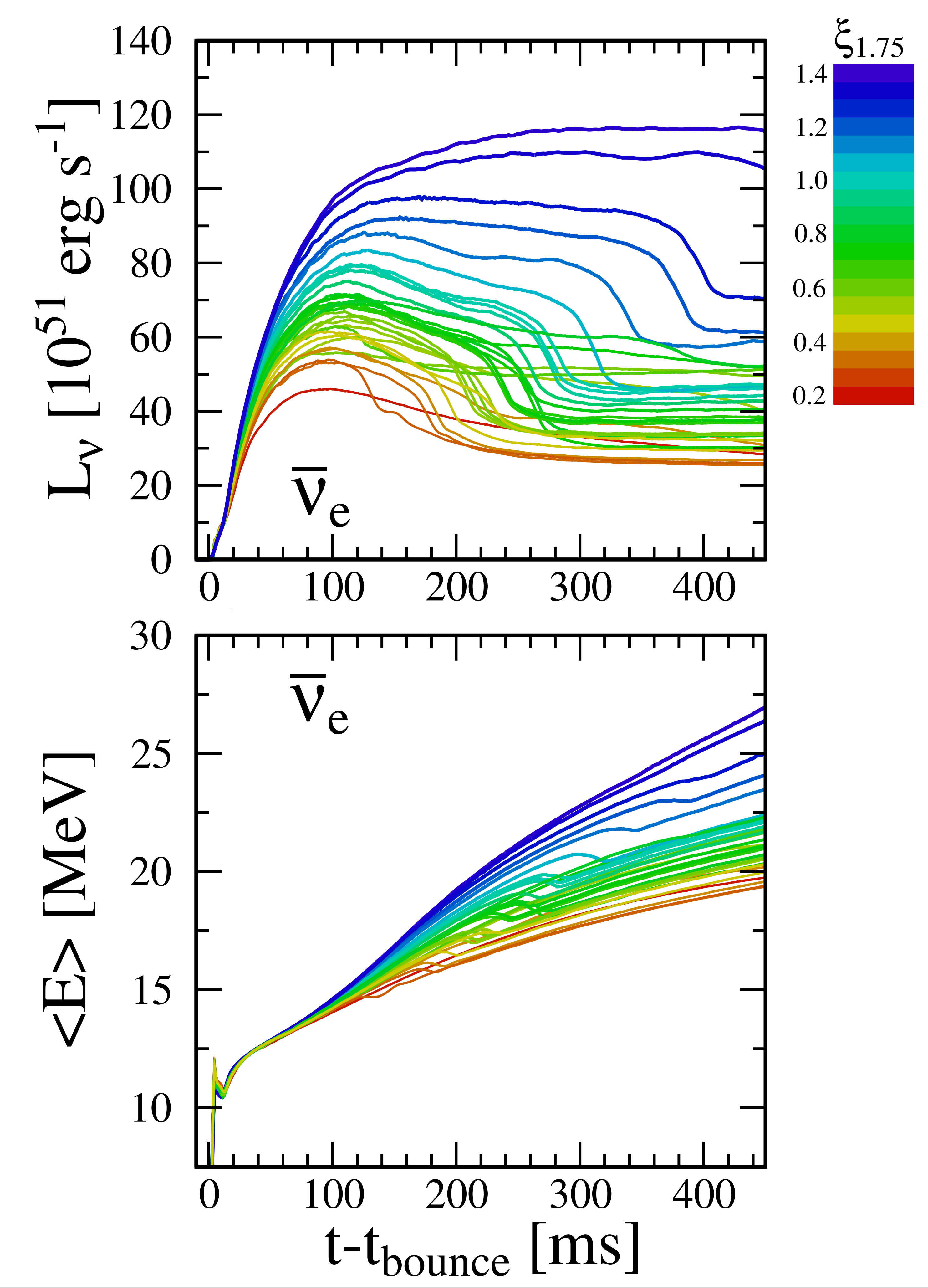
Multi-messenger time domain astronomy of CCSN



Nakamura+ 2016

Theoretical prediction: neutrino signals are robust

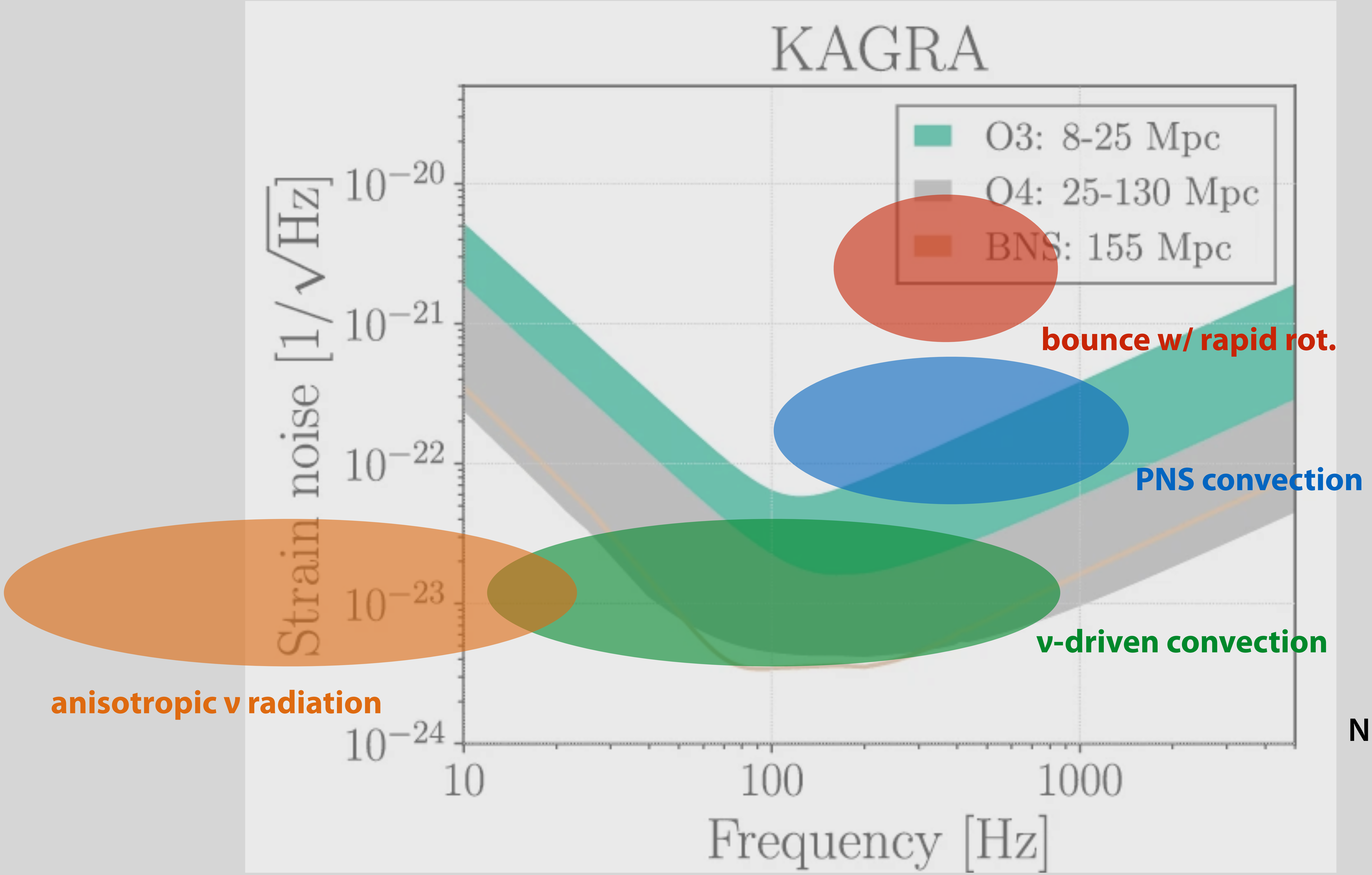




Suwa+ 2016

O'Connor & Ott (2013)

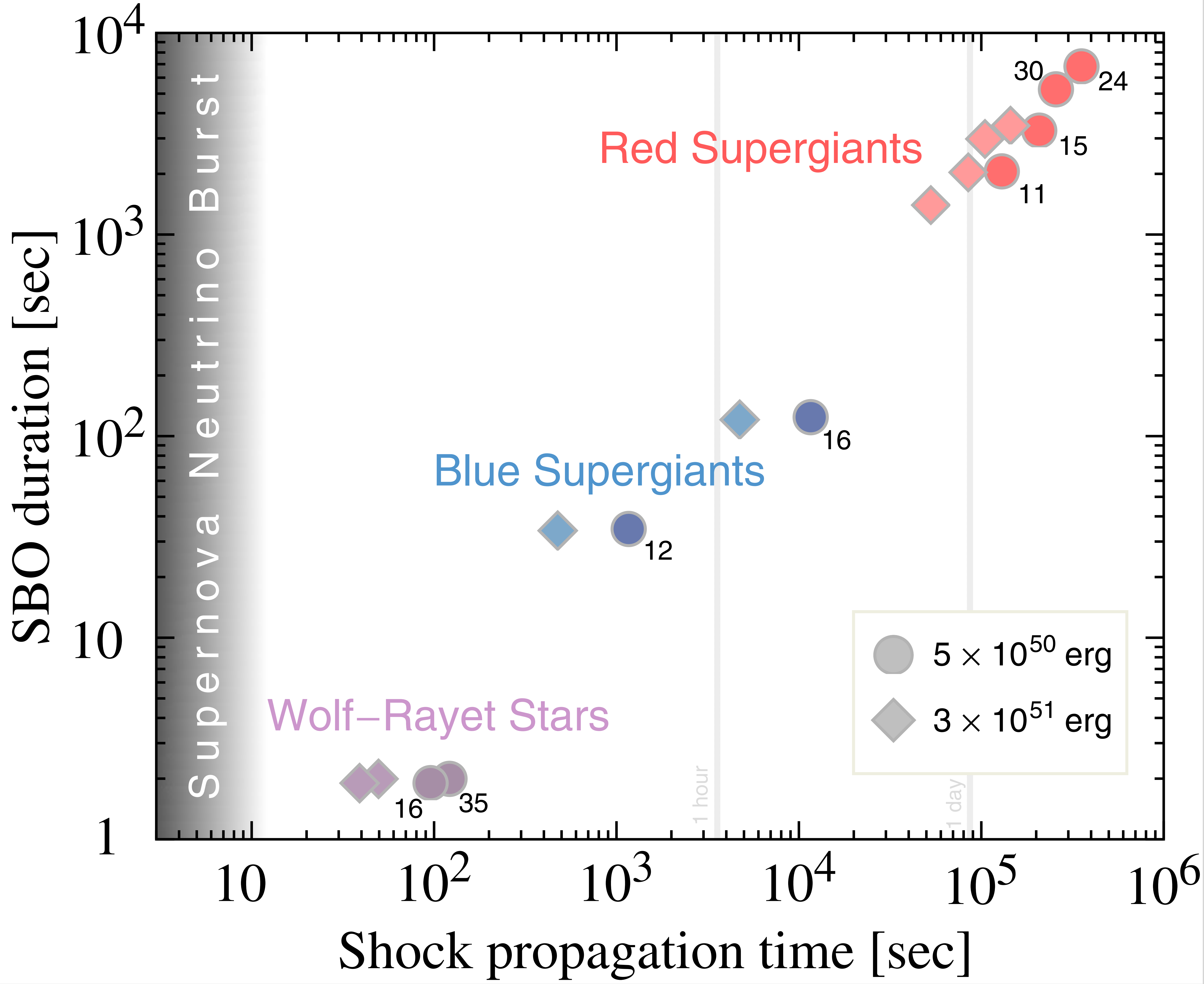
Theoretical prediction: gravitational waves are not robust



Abbott+, LRR (2020)

NB) both frequency and amplitude are highly model dependent (cf. dimensionality, EOS, neutrino interactions)

Theoretical prediction: optical emission may come early



Kistler+ 2013

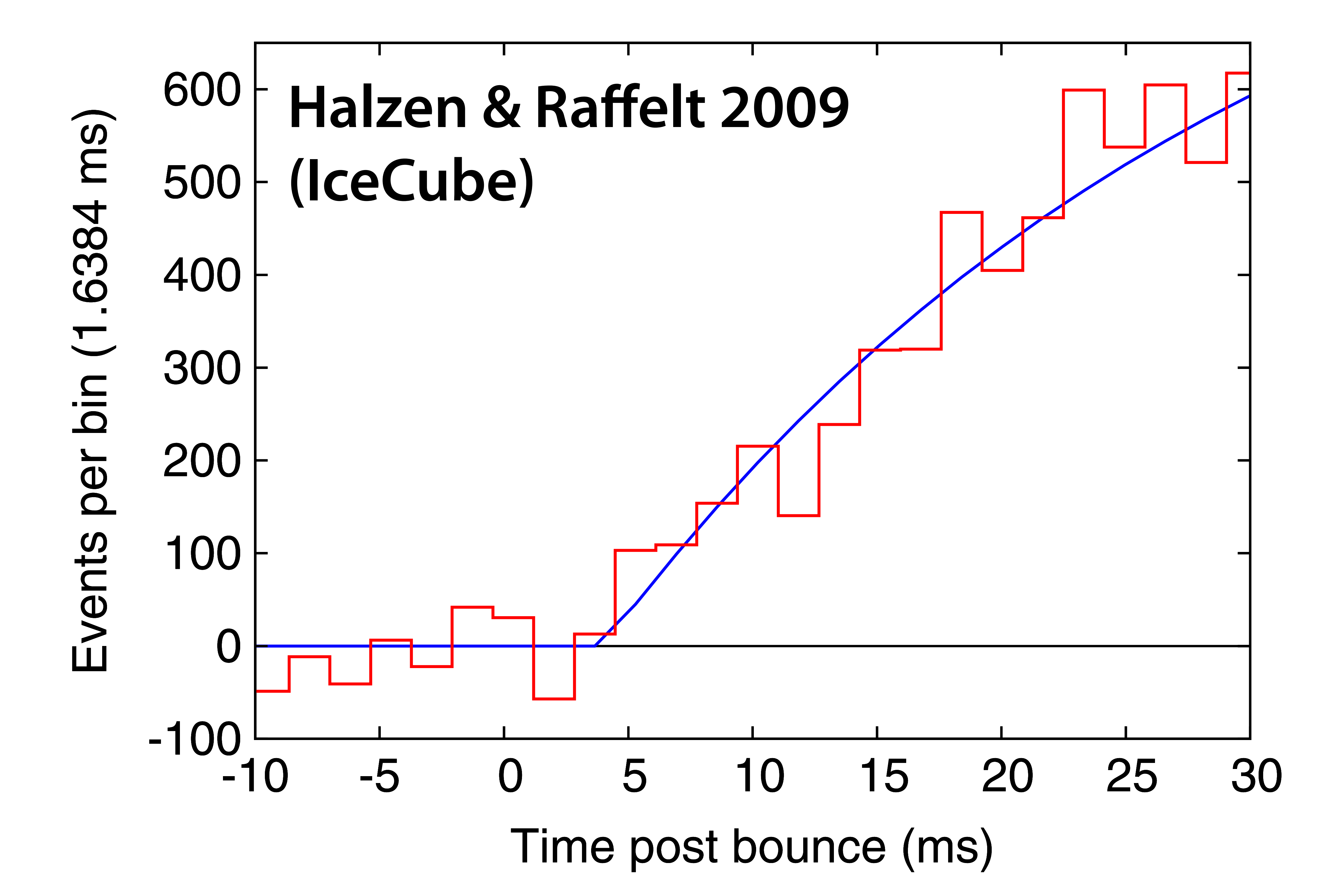
Ideal scenario

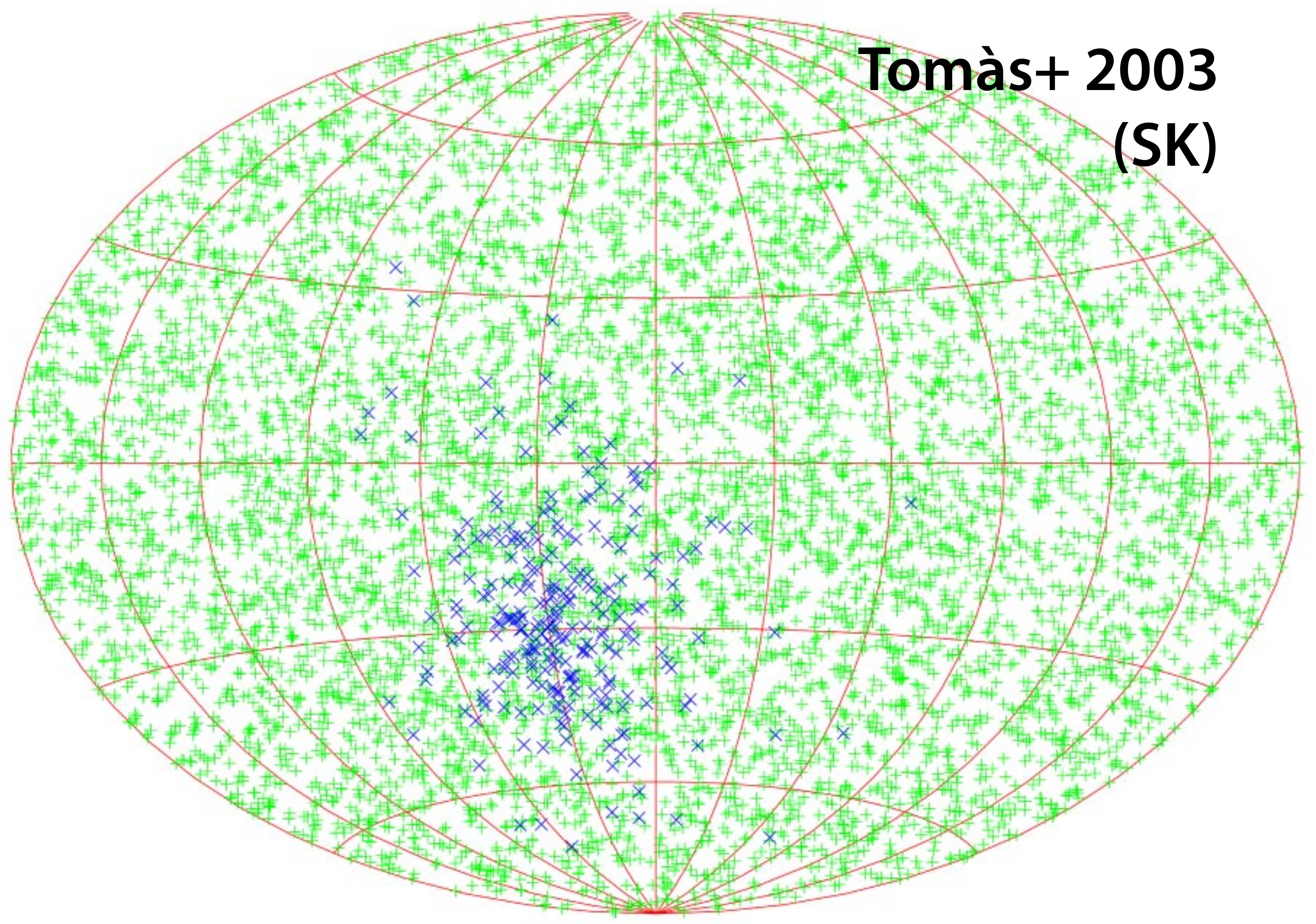
1. **ν → discovery** (Si burning phase, neutronization burst, PNS cooling phase)
   - angular resolution ~ degree
   - circulate detection worldwide
2. **EM → confirm** (shock breakout, diffusion cooling, Co decay)
   - delay for ~ mins to days, depending on progenitor radius
   - follow up observation from radio to gamma-ray
3. **GW → SN physics** (bounce, PNS convection, quasi-periodic oscillation, memory effect)
   - time coincidence with ν (and spacial coincidence?)
   - even non-detection can put constraint on explosion mechanism

Requirement for observational facilities

- **Neutrino: SK-Gd, KamLAND, IceCube, HK**
  - **promising signal !**
  - high duty cycle strongly demanded
  - good time resolution is necessary for GW
  - good position resolution is necessary for γ
- **Photon: Optical** (Subaru, etc.)**, X-ray** (MAXI, etc.)
  - **necessary to confirm as an astronomical object**
  - due to different spacial resolutions and FOV, the blind search might be necessary for large telescopes
- **Gravitational wave: LIGO, Virgo, KAGRA**
  - **necessary to see the innermost part**
  - smoking gun judging the explosion mechanism
  - burst search method should be improved to put a strong constraint

What is needed for multi-messenger observations?





time window

↓

GW

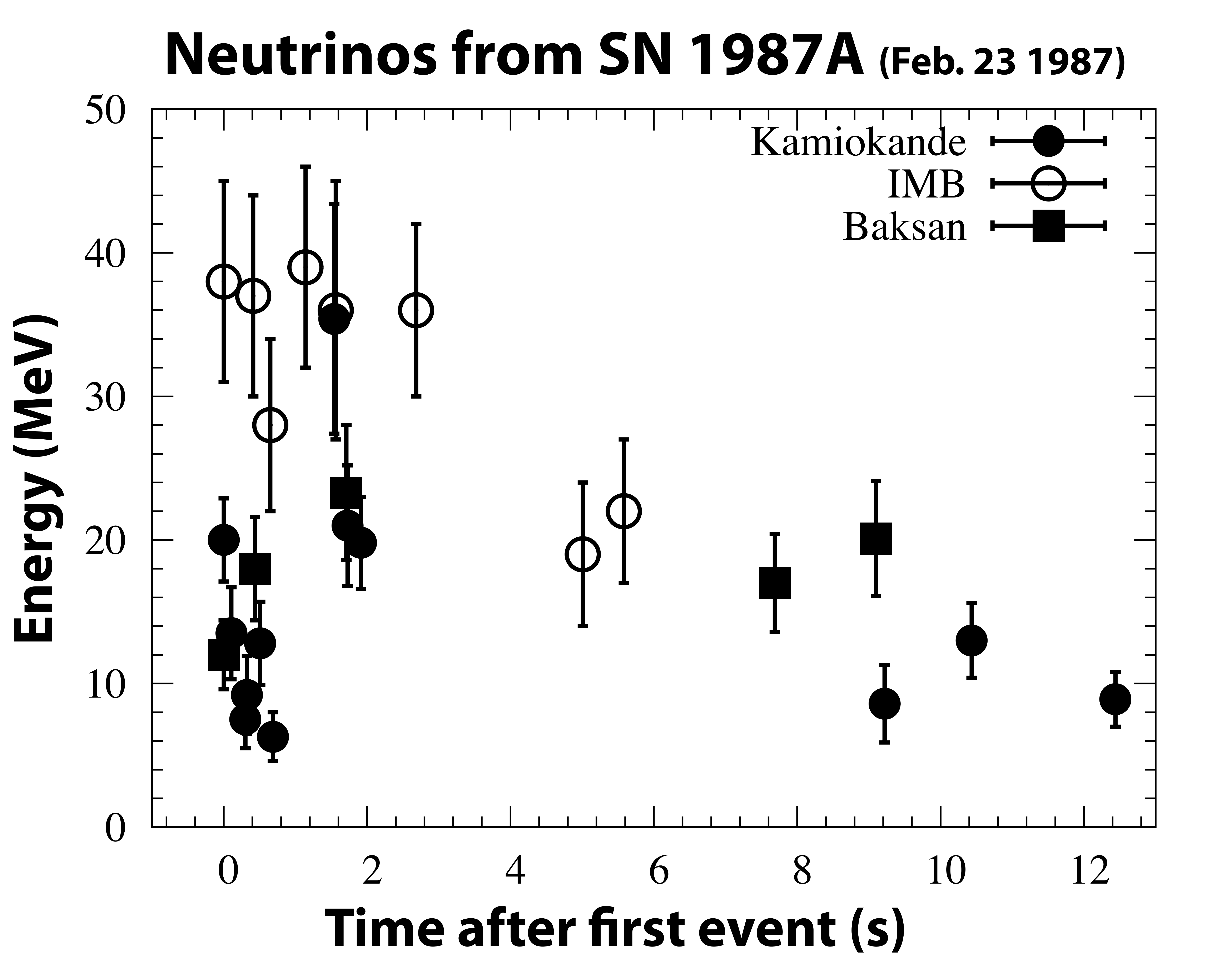
position

↓

EM

How to deal with SN neutrinos

SN1987A



NASA/ESA

What can we extract from neutrino observations?

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

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

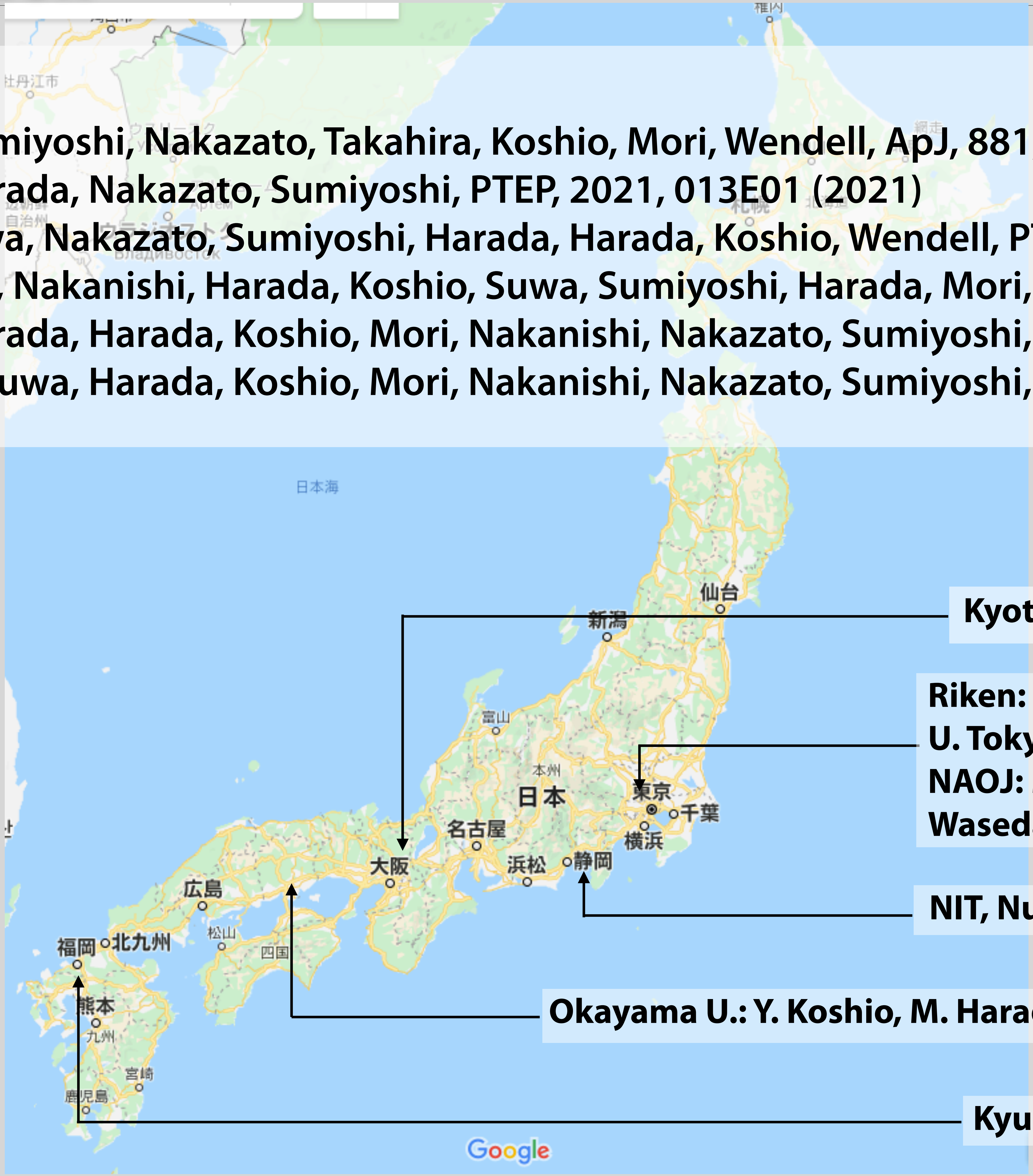
  - **Mass**
    - *important for discriminating final object (NS or BH)*
  - **Radius**
    - *important for discriminating nuclear equation of state*

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

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)

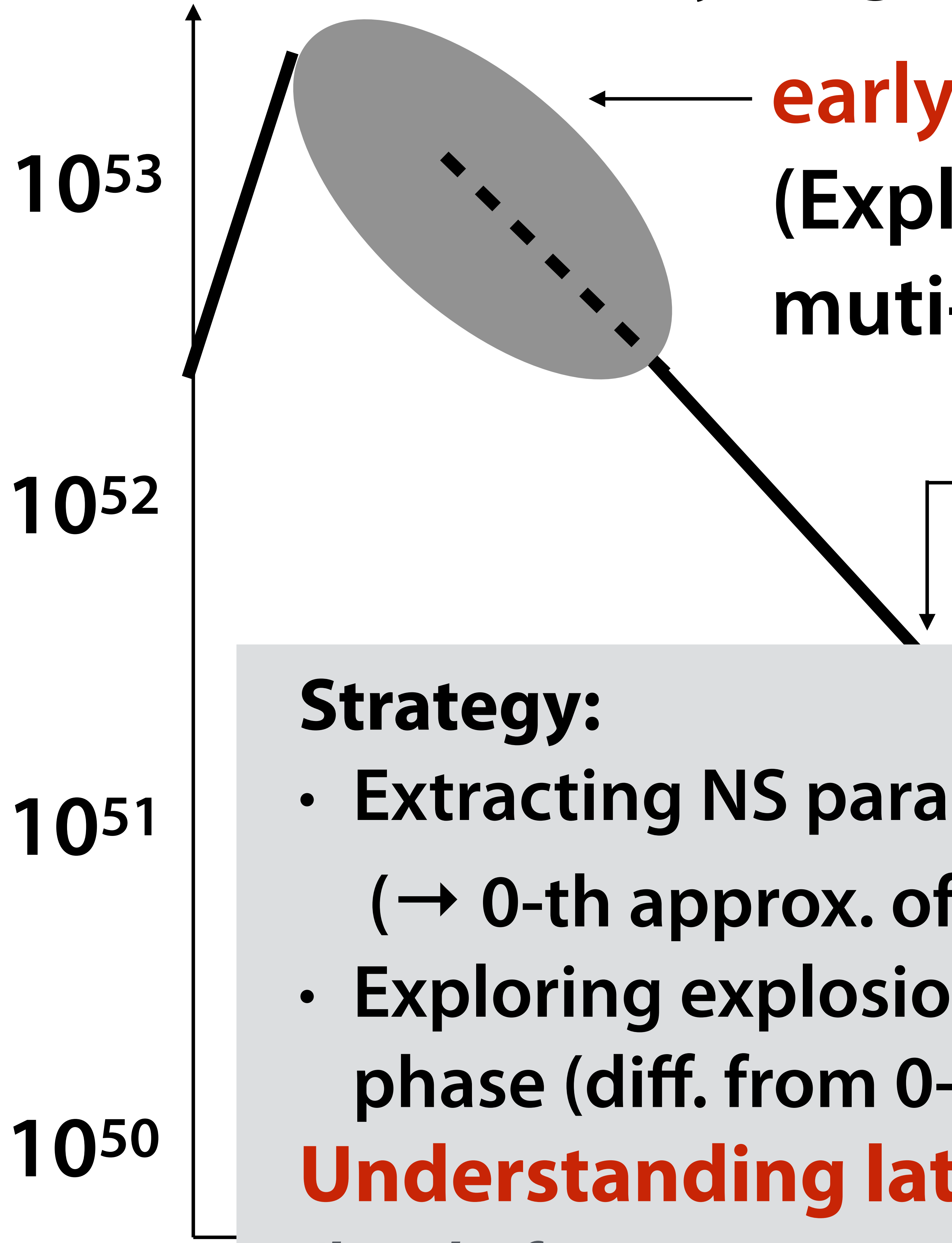
NIT, Numazu: K. Sumiyoshi (Theory)

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

Kyushu U.: K. Nakazato (Theory)

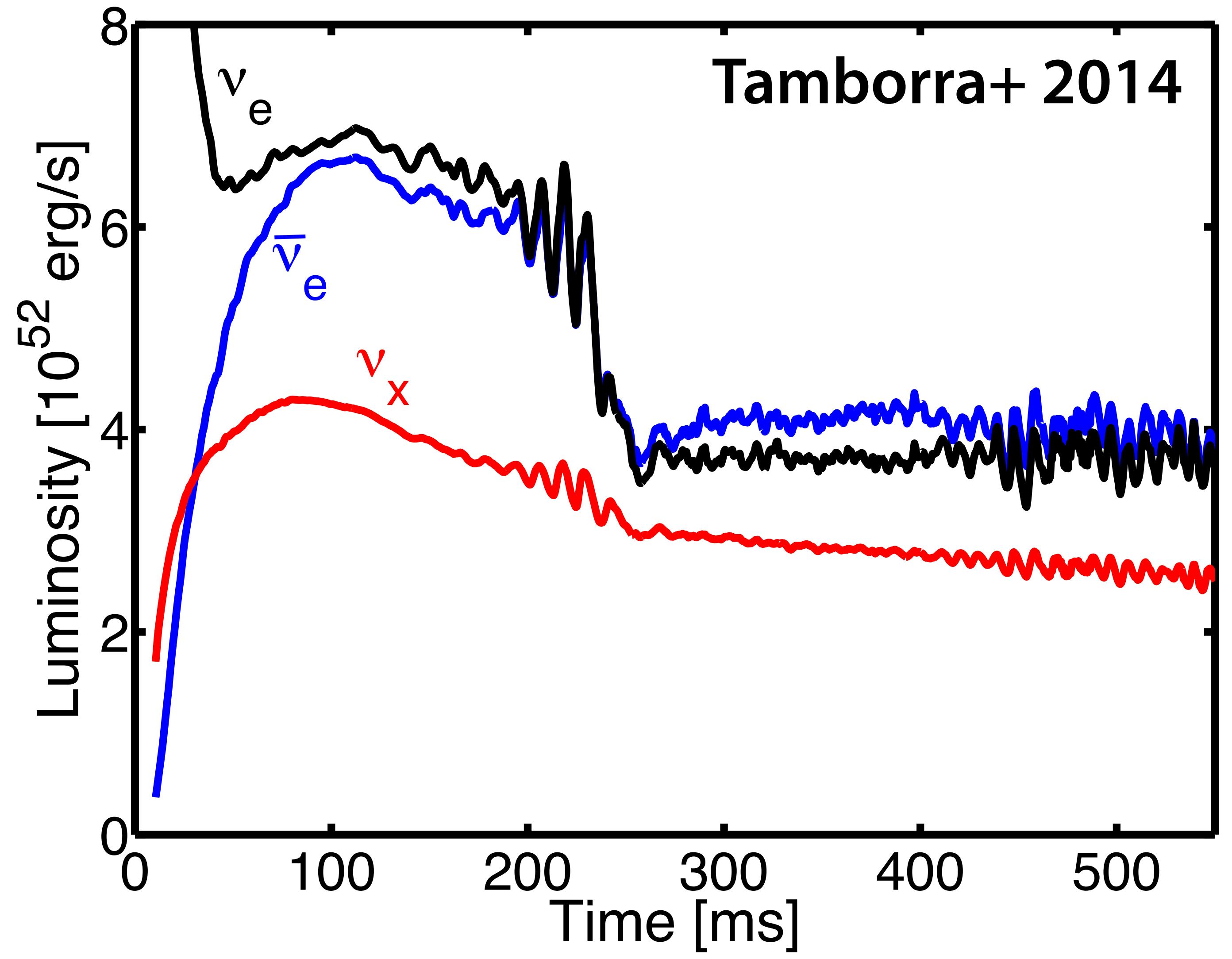
Late cooling phase is simpler and more understandable than early phase

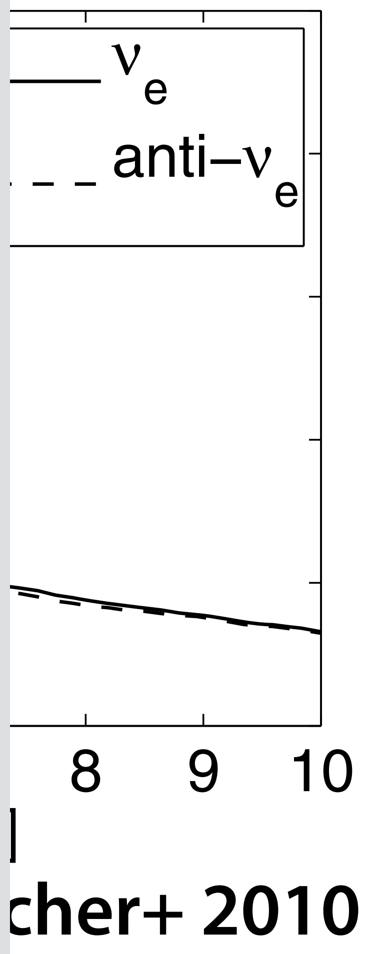
Neutrino luminosity (erg/s)



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)

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

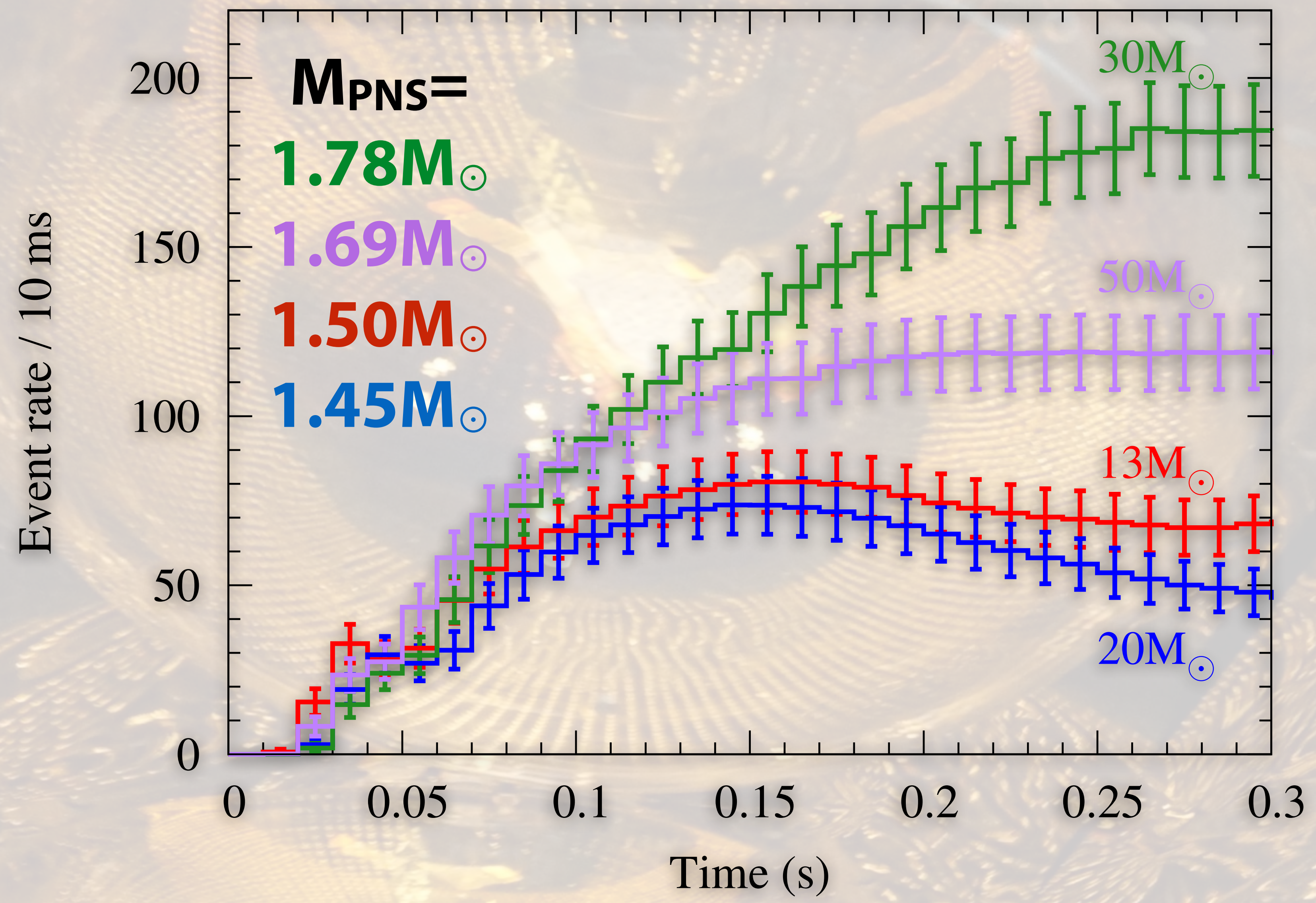
step 3

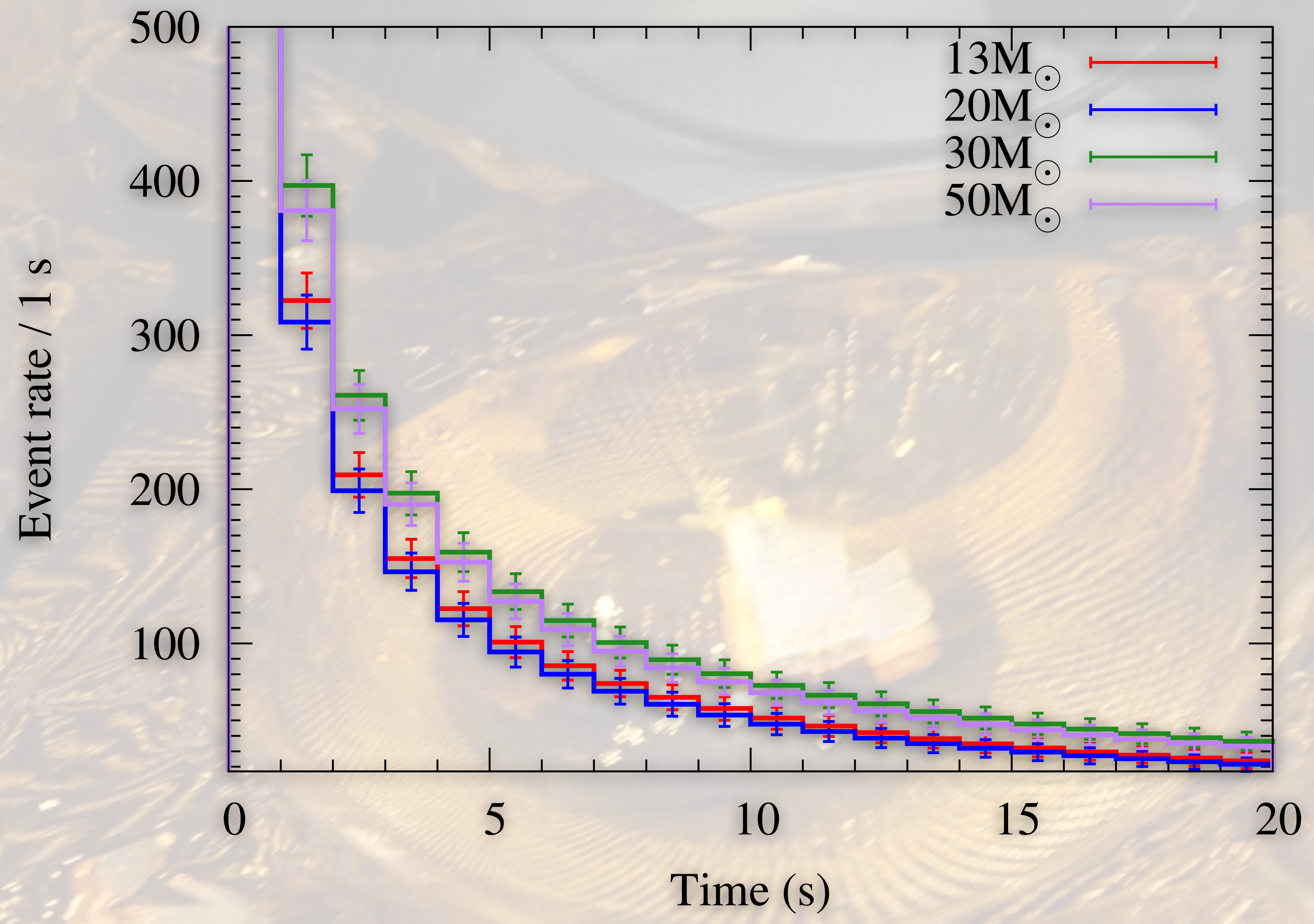
DATA ANALYSIS

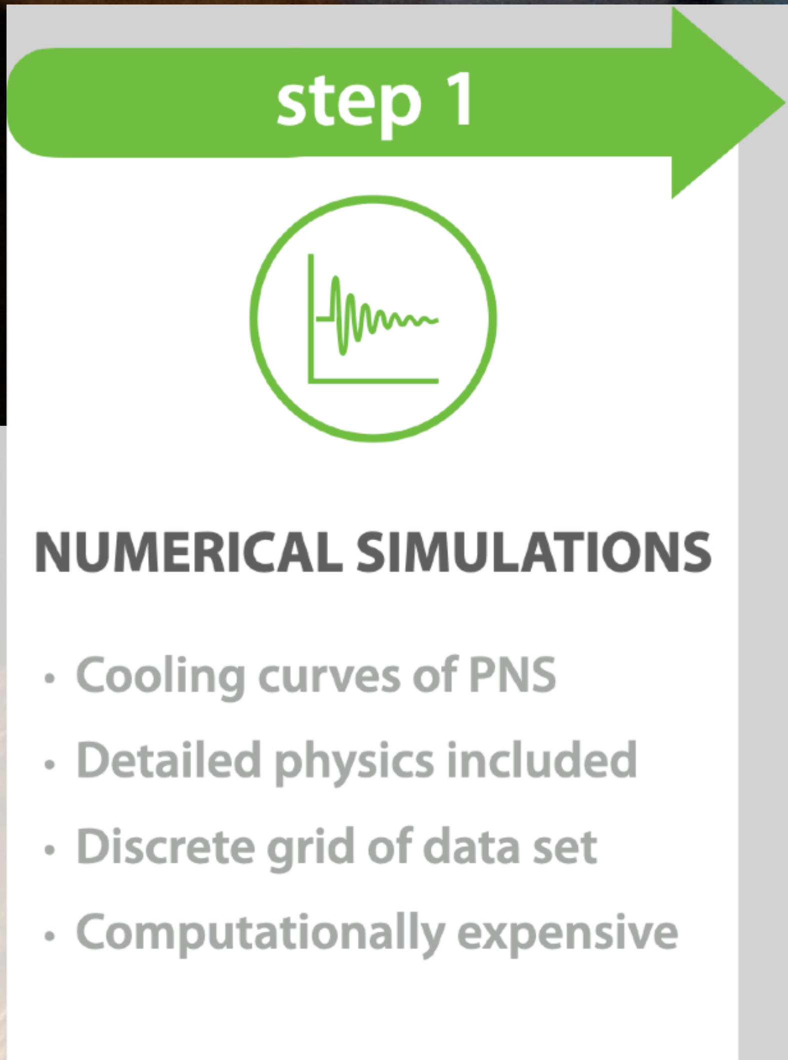
- Mock sampling
- Analysis pipeline for real data
- Error estimate for future observations

Event rate evolution

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







* **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)]

step 2

ANALYTIC SOLUTIONS

- Analytic cooling curves

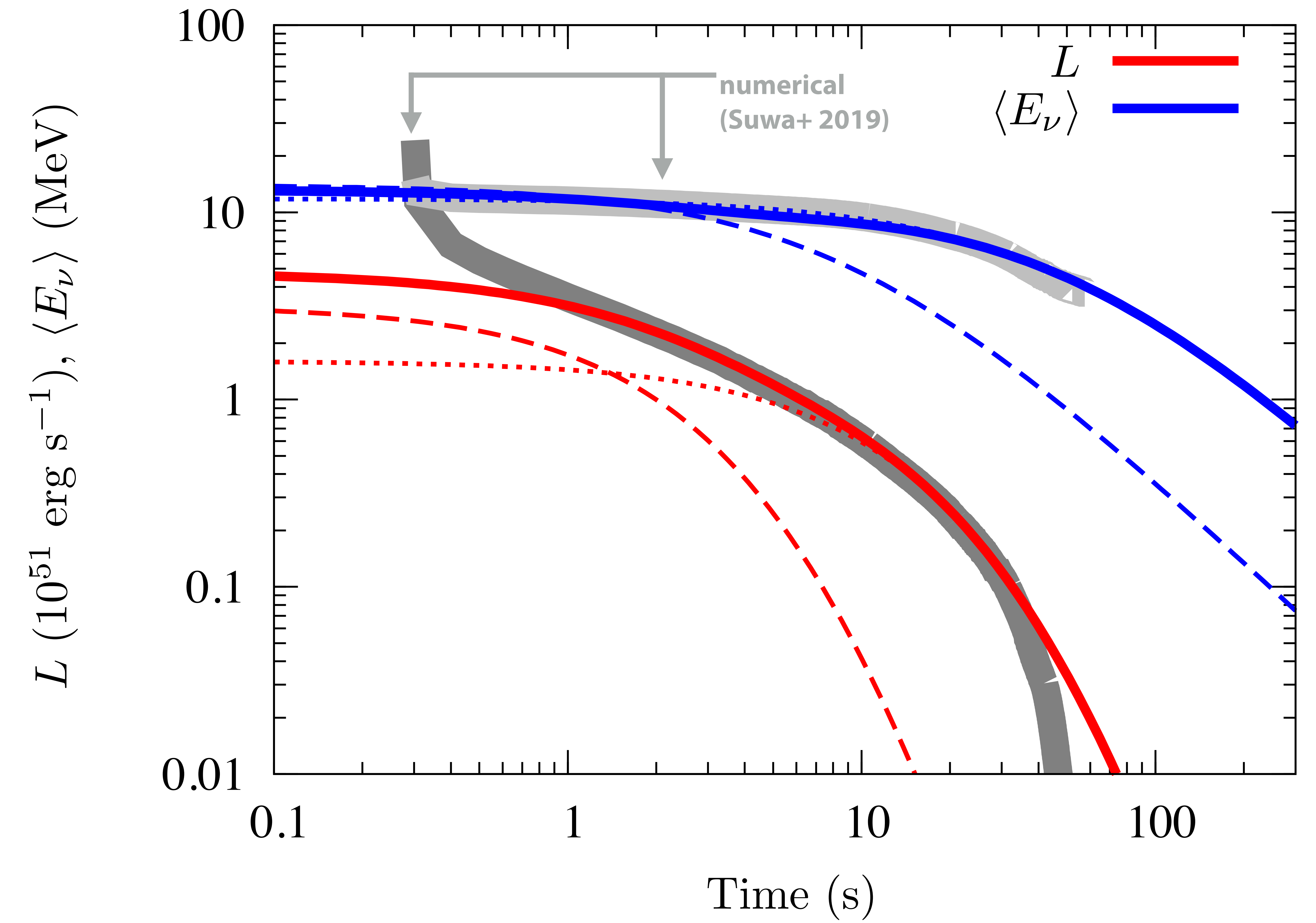
- Solve neutrino transport eq. analytically
  - **Neutrino luminosity**

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

  - **Neutrino average energy**

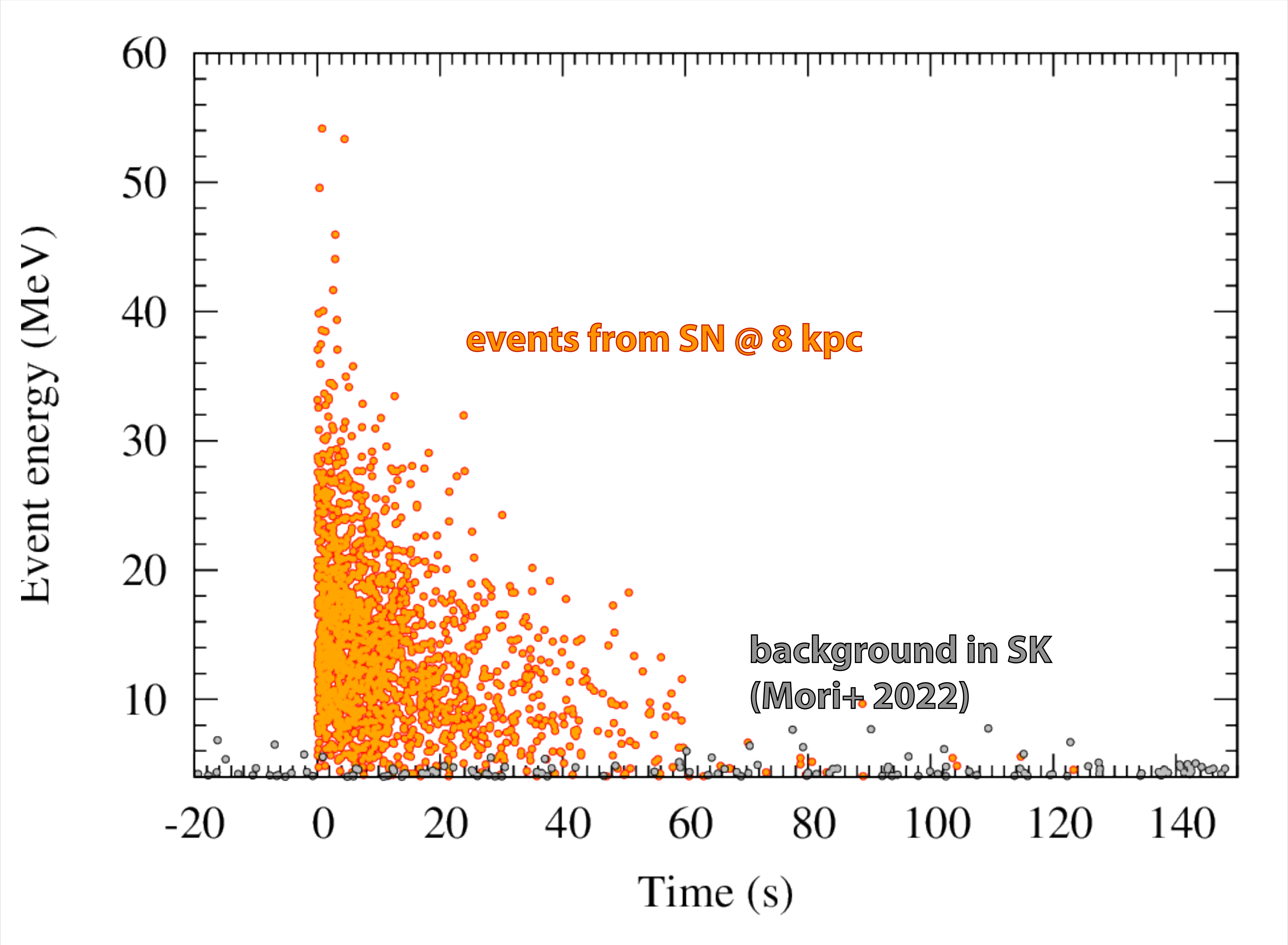
$$\langle E_\nu\rangle = 16\,\mathrm{MeV}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{3/2}\left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-2}\left(\frac{g\beta}{3}\right)\left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-3/2}$$

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



Mock sampling

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



See also Mori-san's talk !

Data fitting and measuring physical quantities

[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
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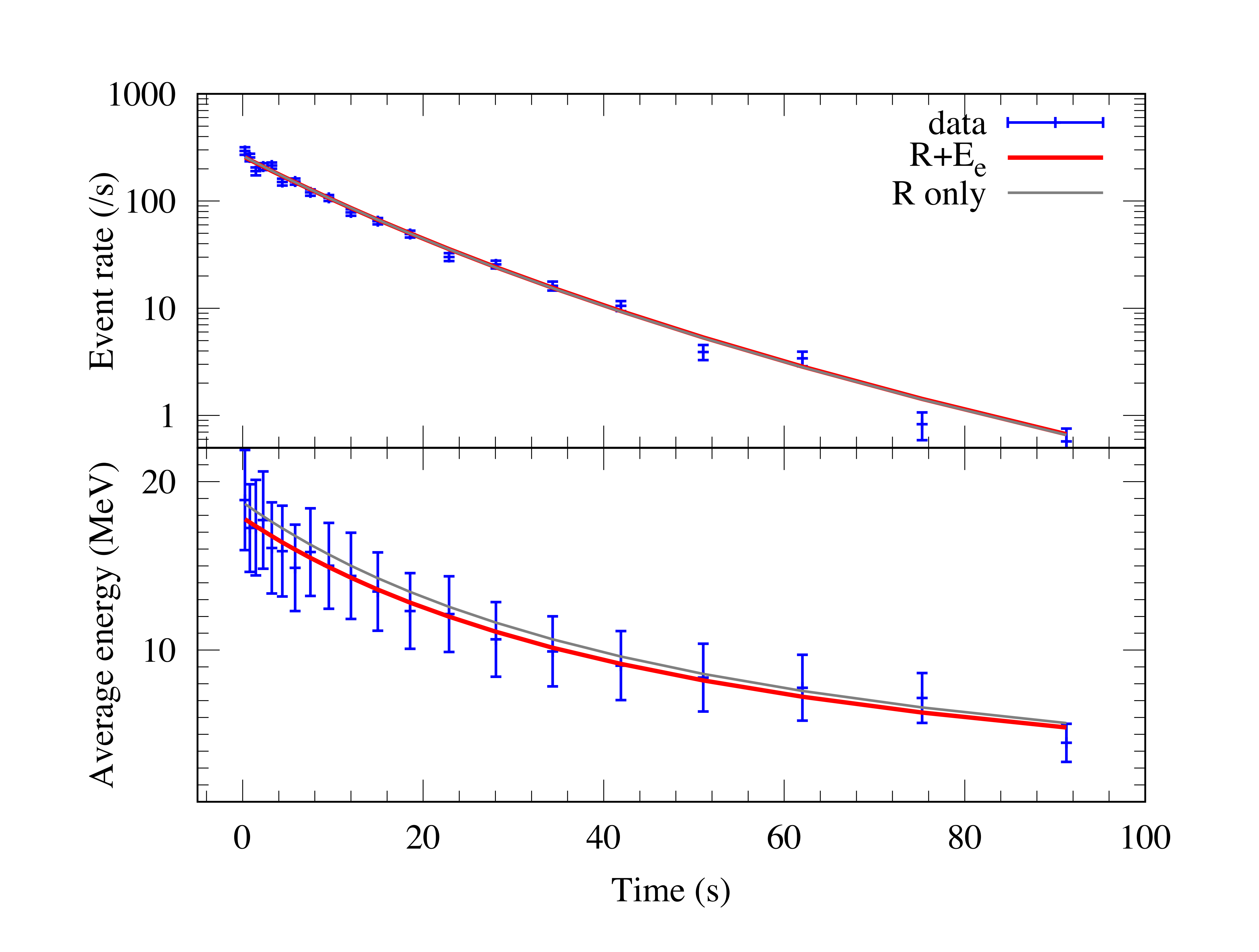
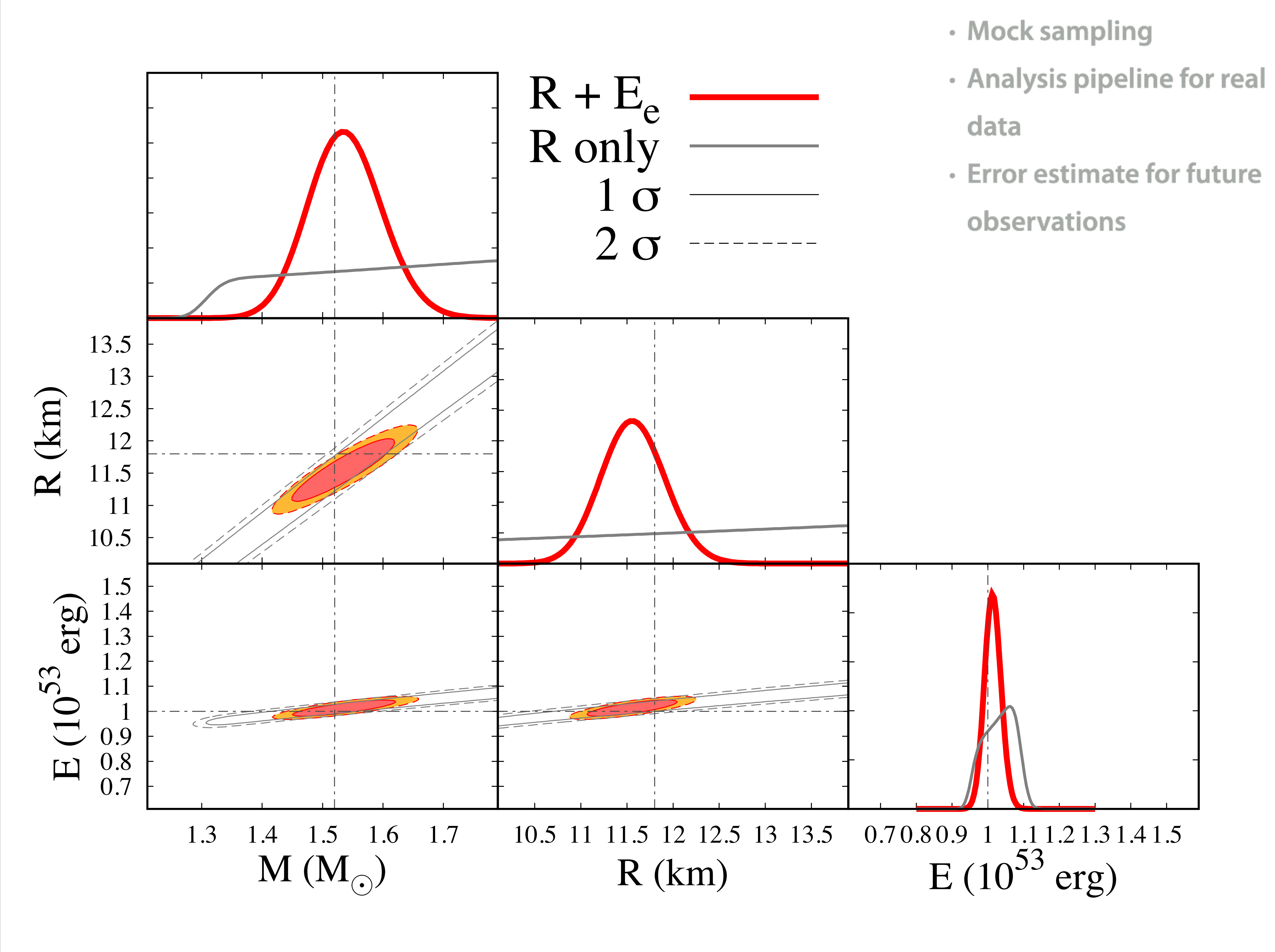


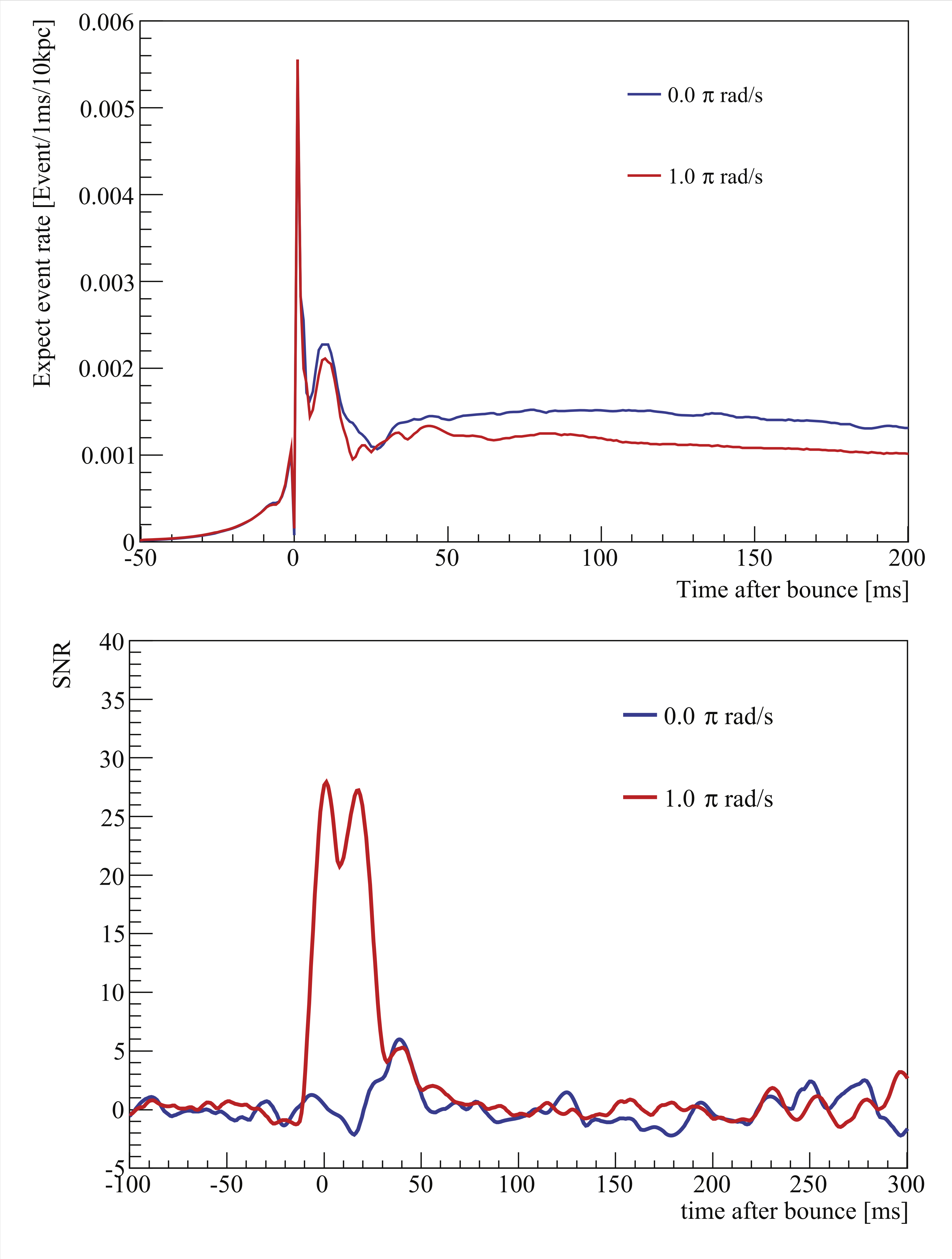


Analysis code *SPECIAL BLEND* (developed by A. Harada) is now publicly available!

https://github.com/akira-harada/SPECIAL_BLEND

Combining neutrinos and GWs

[Yokozawa, Asano, Kayano, Suwa, Kanda, Koshio, Vagins, ApJ, 811, 86 (2015)]



- **Neutrinos**
  - luminosity and average energy don't depend on rotation of the iron core
    → expected event rate evolution are same
- **Gravitational waves**
  - onset time strongly depends on rotation (existence of bounce signal)
- **Onset time of ν and GW tells rotation**
  - $\tau_\nu > \tau_{\rm GW}$ → rotating
  - $\tau_\nu < \tau_{\rm GW}$ → non-rotating
- **Timing accuracy is essential, detectors at the same place (Kamioka) is perfect**

Summary

* **Supernovae are optimal targets of multi-messenger observations**
* **Neutrinos are robust**
    * promising signal
    * late cooling phase is critical for parameter estimate
* **Photons are needed to confirm**
    * counter part search in huge sky is a key
    * distance information from neutrino may be helpful
* **Gravitational waves are physics probe (smoking gun!)**
    * highly model dependent, difficult to predict
    * even non-detection constrains physics, but time window from neutrinos are crucial

* **Be prepared for the next nearby SN !**