Z101r

地下からのマルチメッセンジャー観測で迫る超新星爆発の最深部

諏訪雄大

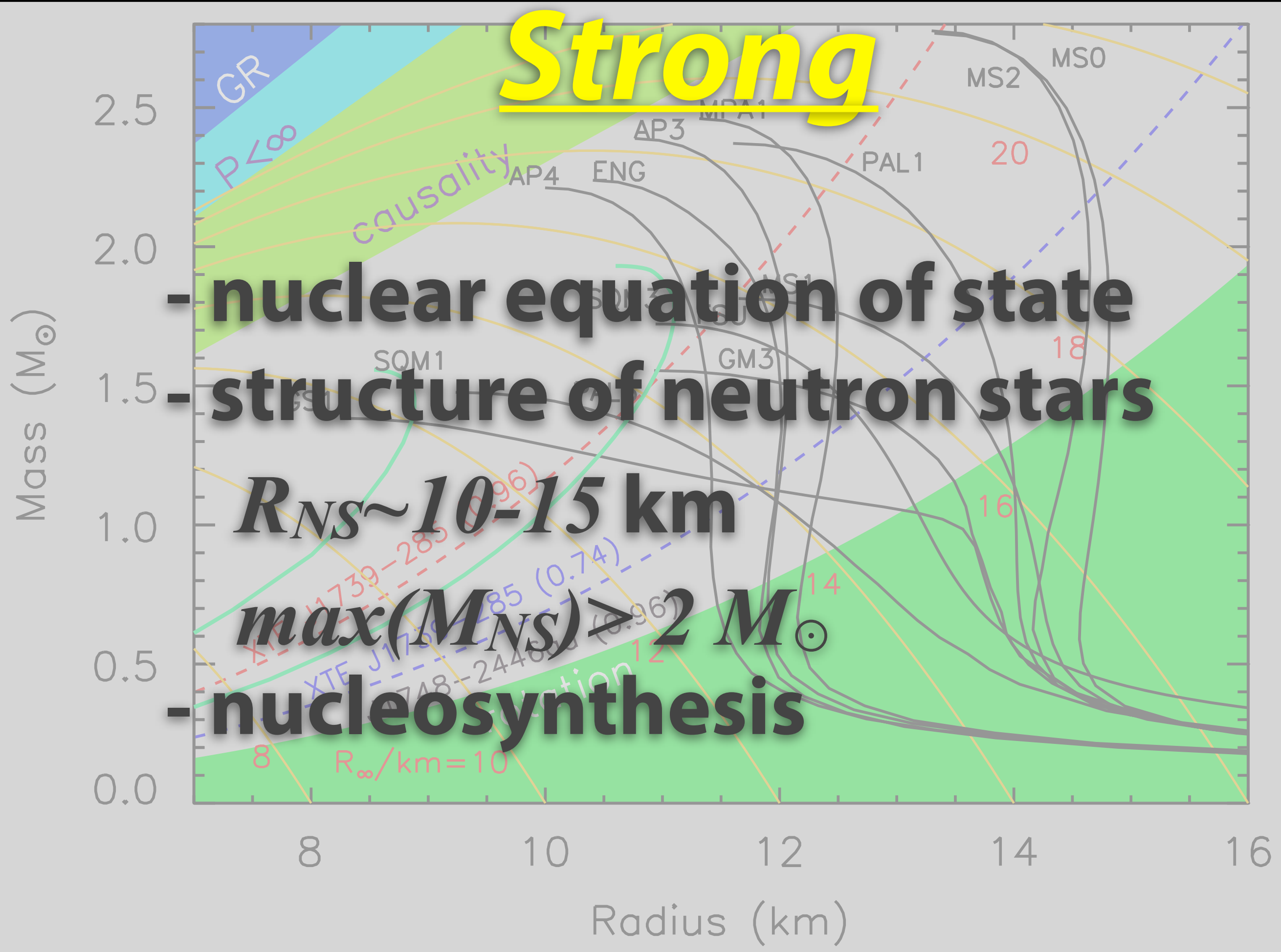
（東大総合文化 & 京大基研）

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)

Neutron star: multi-physics object

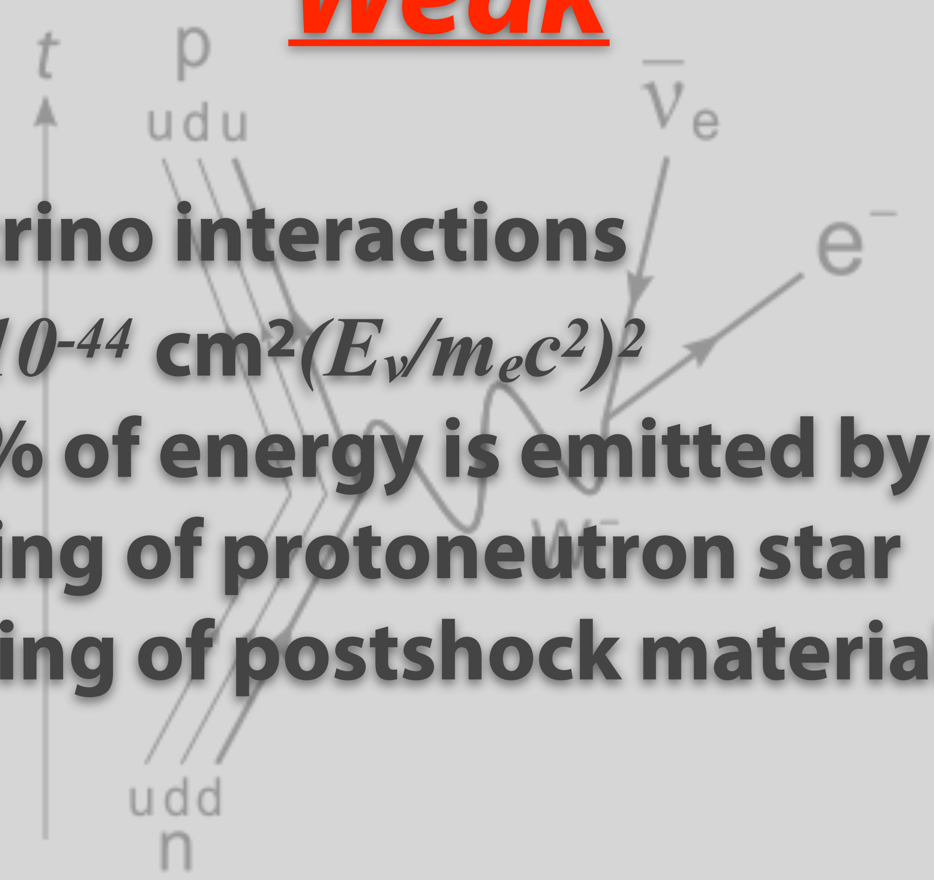
All **known interactions are involving and playing important roles**

Strong



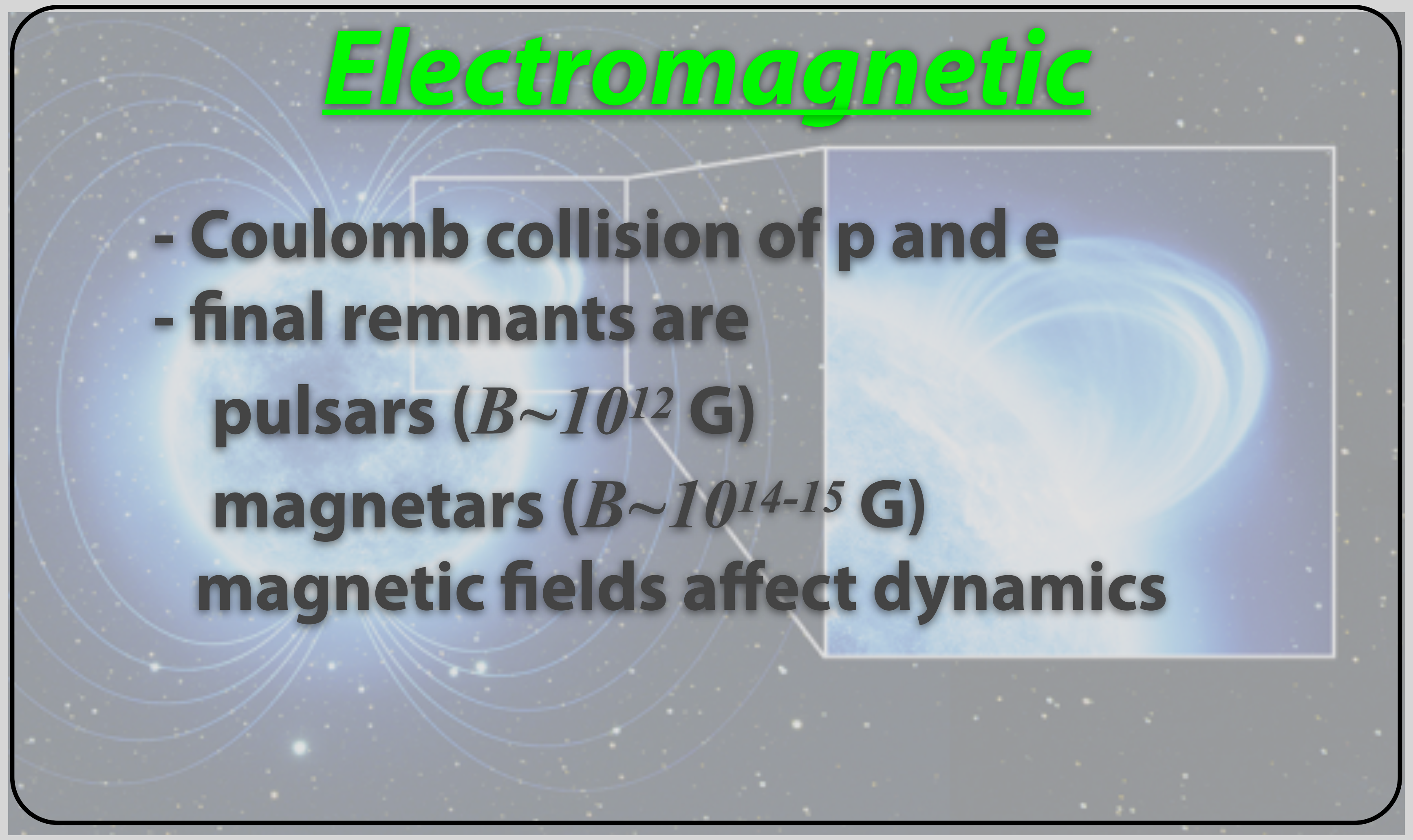
- nuclear equation of state
- structure of neutron stars
  - R_{NS}~10-15 km
  - $max(M_{NS})>2\,M_\odot$
- nucleosynthesis

Weak



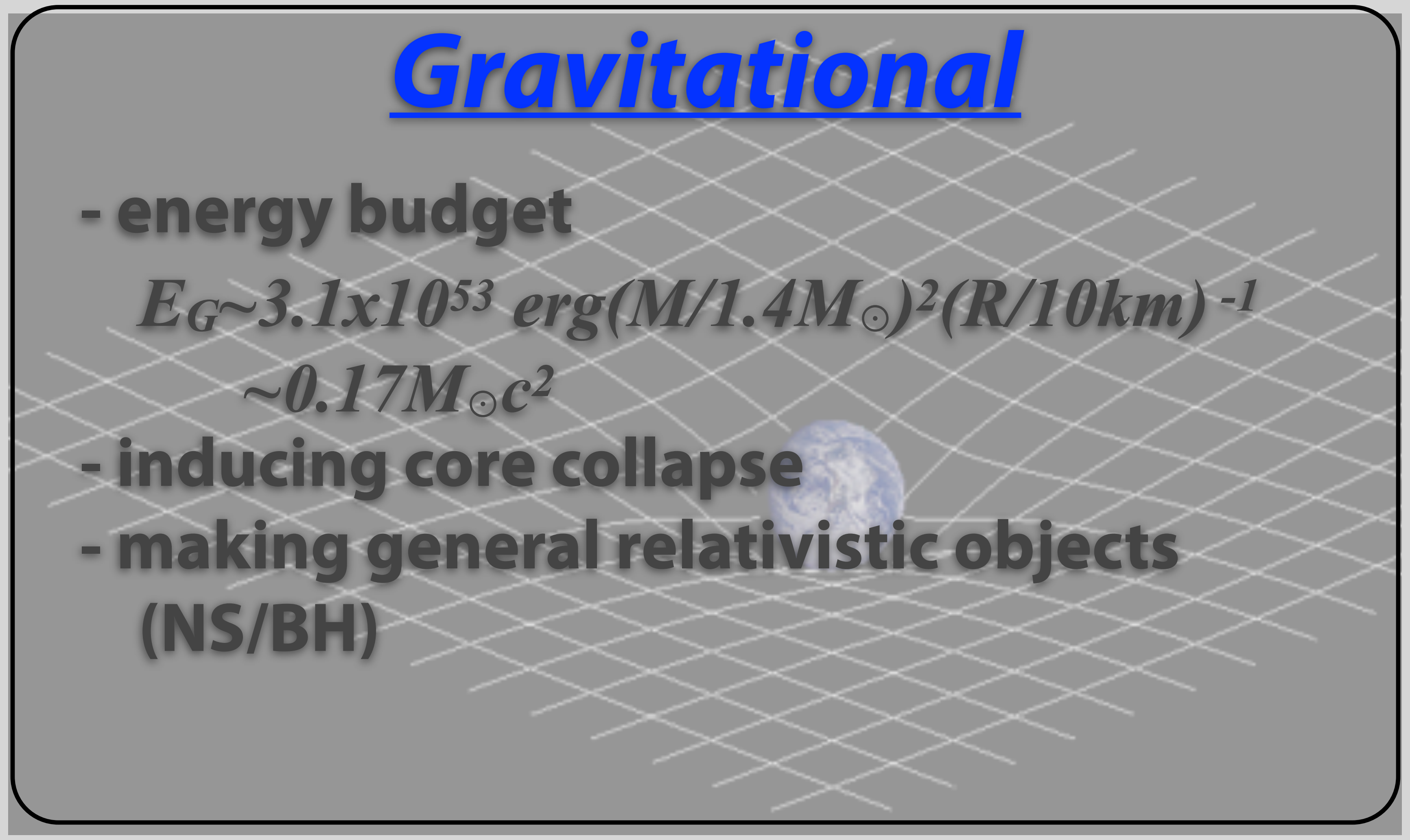
- neutrino interactions
  - $\sigma_\nu \sim 10^{-44}$ cm$^2(E_\nu/m_ec^2)^2$
- ~99% of energy is emitted by ν's
- cooling of protoneutron star
- heating of postshock material

Electromagnetic



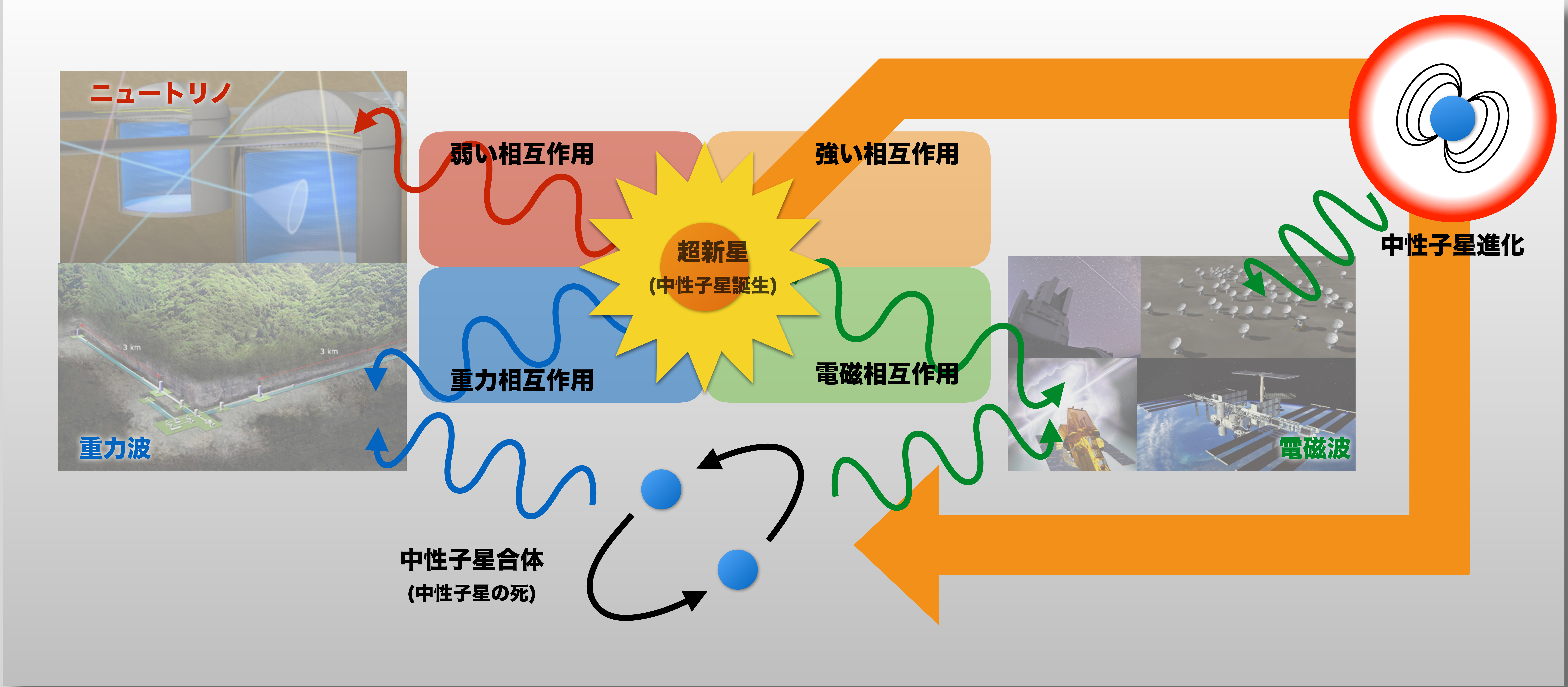
- Coulomb collision of p and e
- final remnants are
  - pulsars ($B\sim10^{12}$ G)
  - magnetars ($B\sim10^{14\text{-}15}$ G)
  - magnetic fields affect dynamics

Gravitational

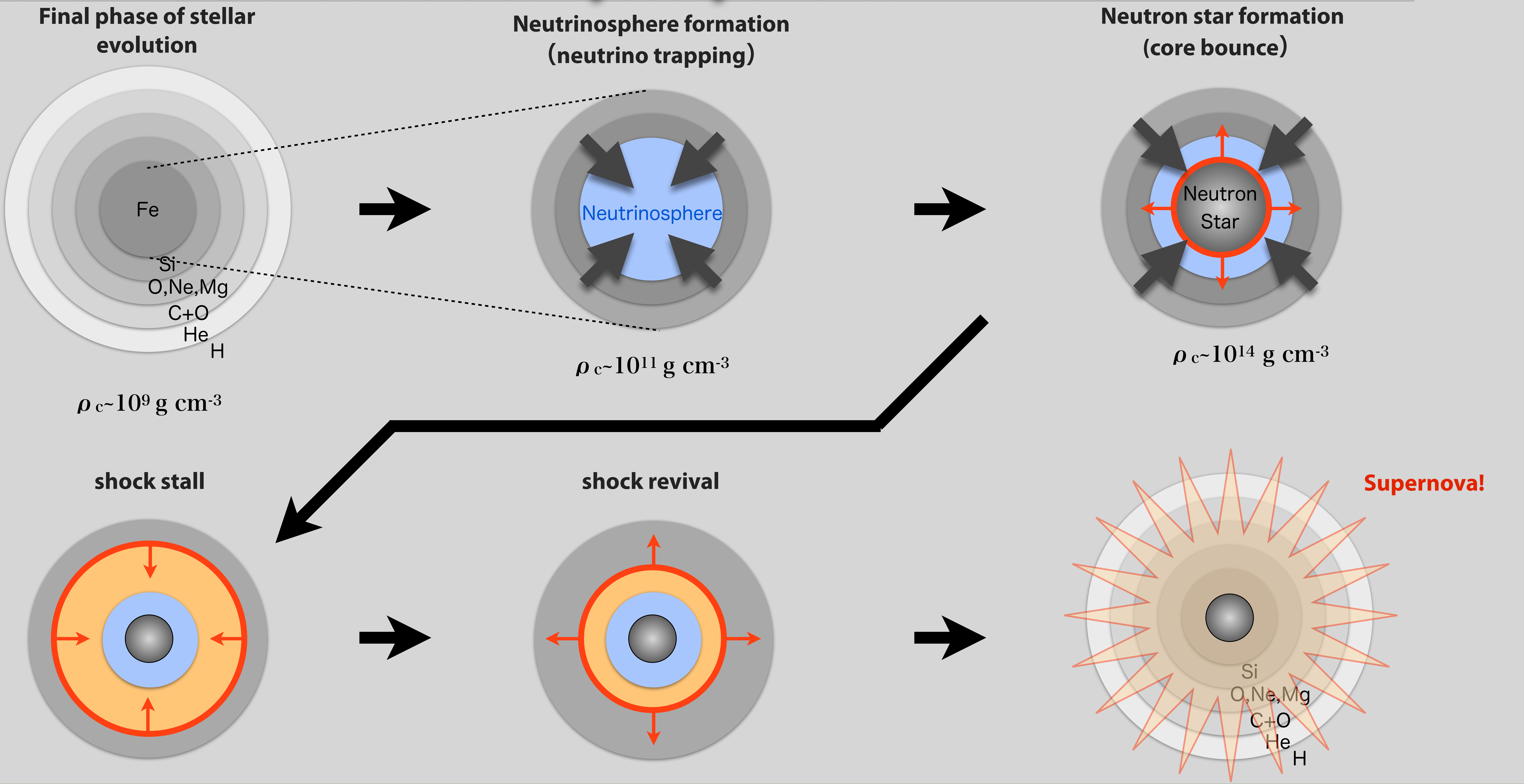


- energy budget
  - $E_G\sim3.1\times10^{53}$ erg$(M/1.4M_\odot)^2(R/10\mathrm{km})^{-1}$
  - $\sim0.17M_\odot c^2$
- inducing core collapse
- making general relativistic objects (NS/BH)

Neutron star: multi-messenger observation



Standard scenario of core-collapse supernovae



Energy budget

- **Gravitational energy**

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

- **Kinetic energy of ejecta**

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

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

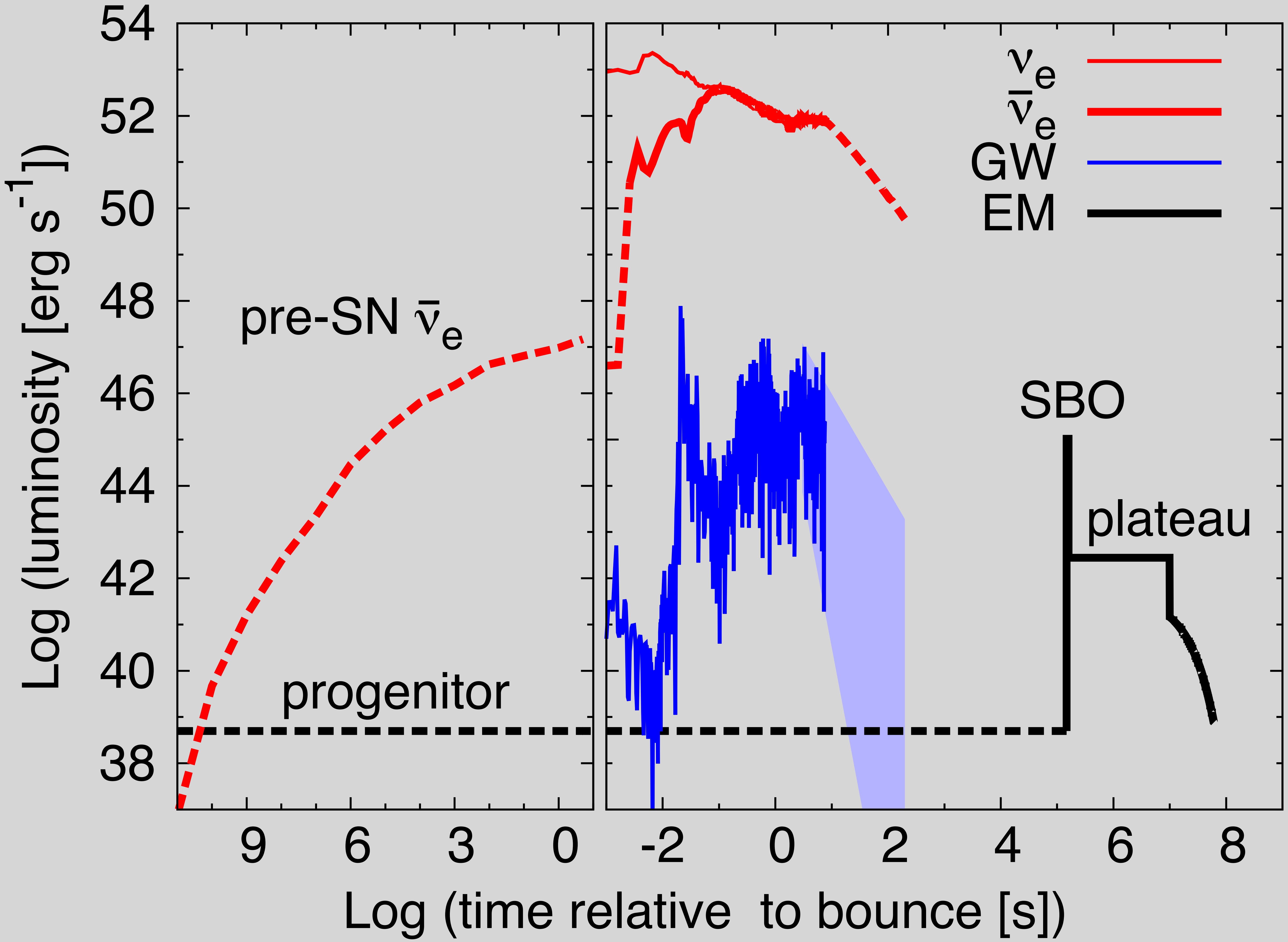
$$E_\gamma \sim M_{\rm Ni} c^2 \times f_{\rm Ni \to Fe} = 2 \times 10^{49}\,\mathrm{erg} \left(\frac{M_{56Ni}}{0.1 M_\odot}\right) \left(\frac{f_{\rm Ni \to Fe}}{0.013\,\%}\right)$$

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

"Supernova"

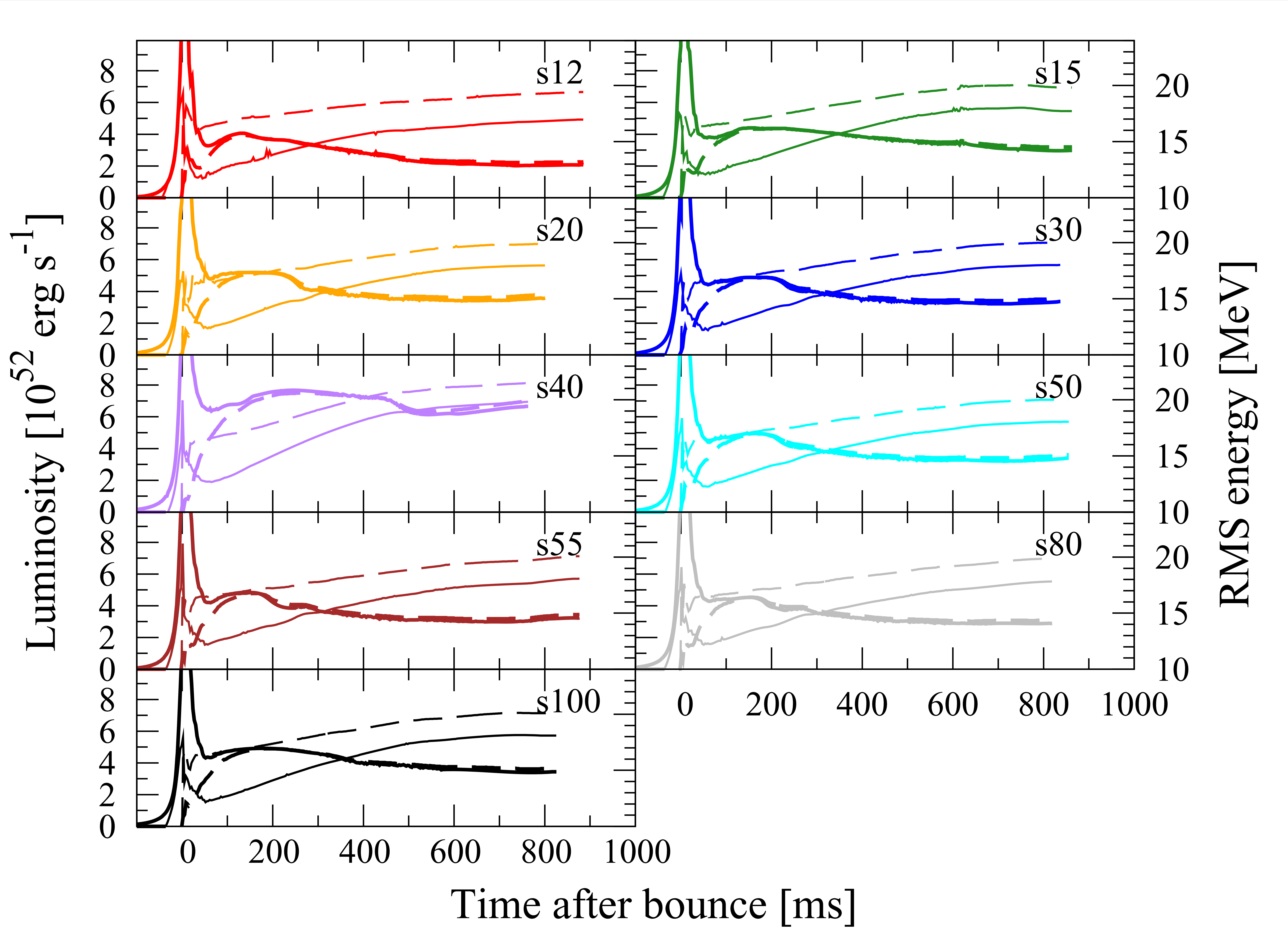
"Optical depth"

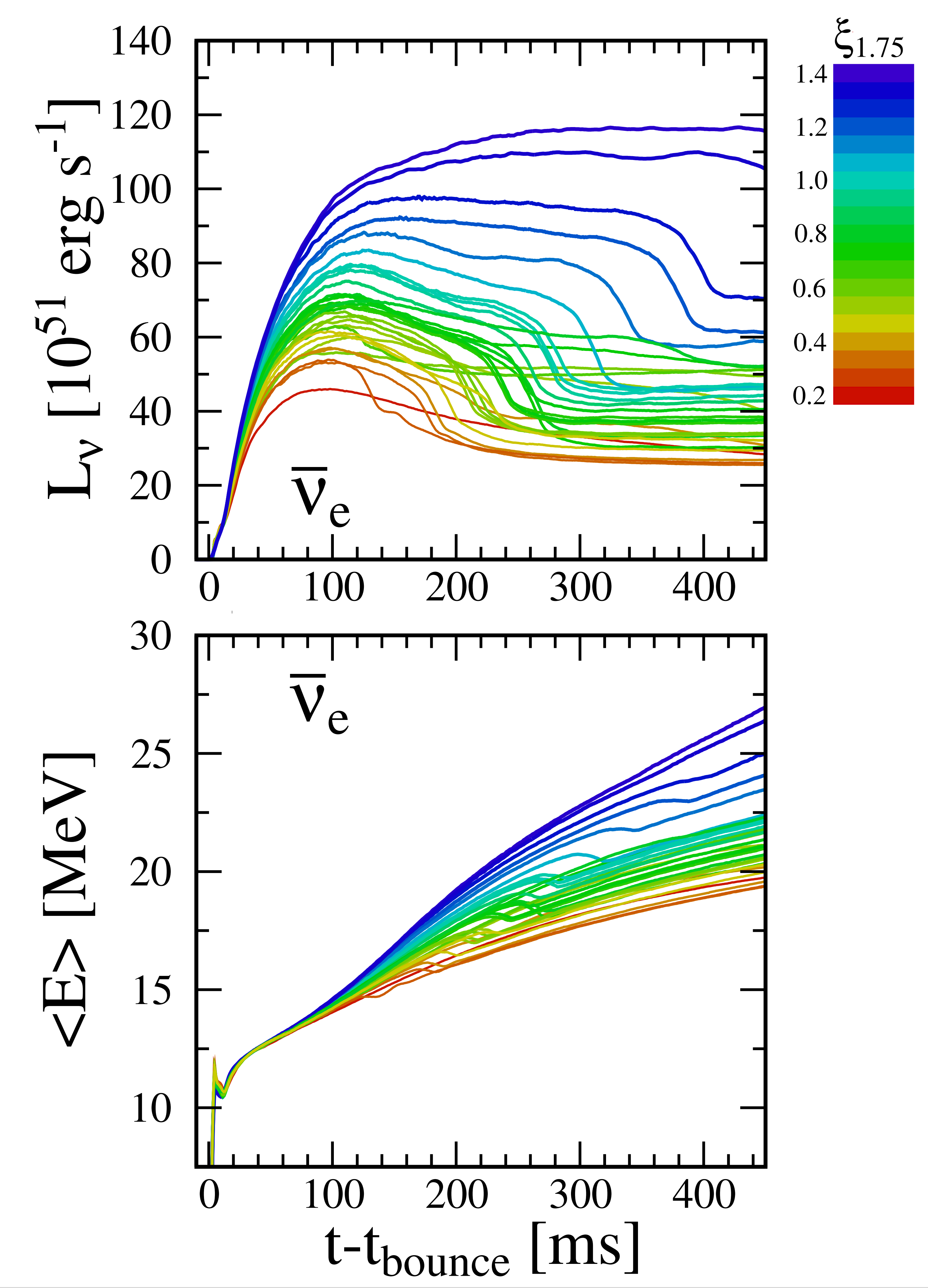
Multi-messenger time domain astronomy of CCSN



Nakamura+ 2016

Theoretical prediction: neutrino signals are robust

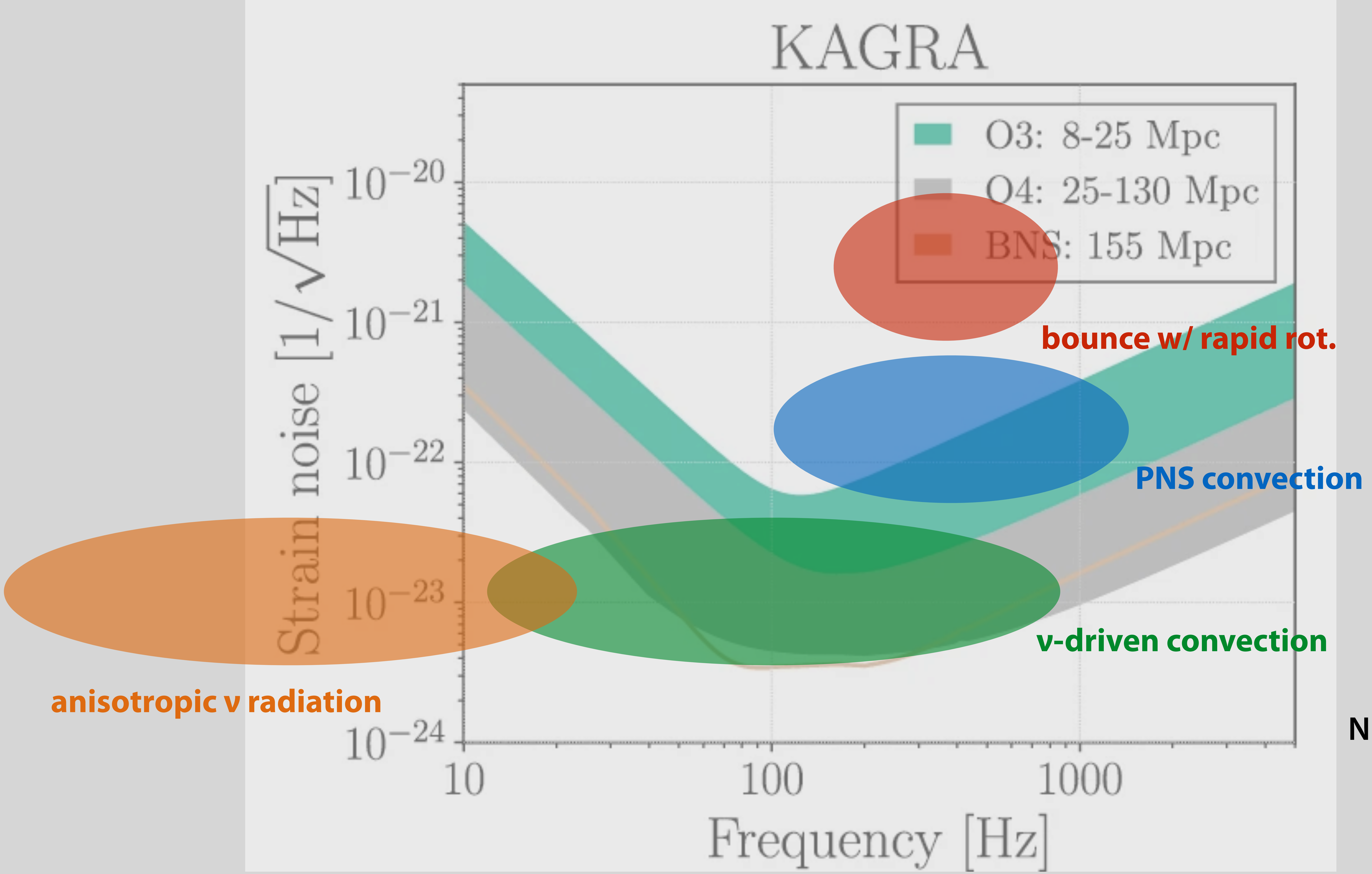




Suwa+ 2016

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)

Ideal scenario

1. **ν discovery** (Si burning phase, neutronization burst, PNS cooling phase)
   - angular resolution ~ degree
   - circulate detection worldwide
2. **γ confirm** (shock breakout, diffusion cooling, Co decay)
   - delay for ~ mins to days, depending on progenitor radius
   - follow up from radio to gamma-ray
3. **GW 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**
  - **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: KAGRA**
  - **necessary to see the innermost part**
  - smoking gun judging the explosion mechanism
  - burst search method should be improved to put a strong constraint

Neutrino detectors: current and future

	Water Cherenkov	Liquid Scintillator		Liquid Ar

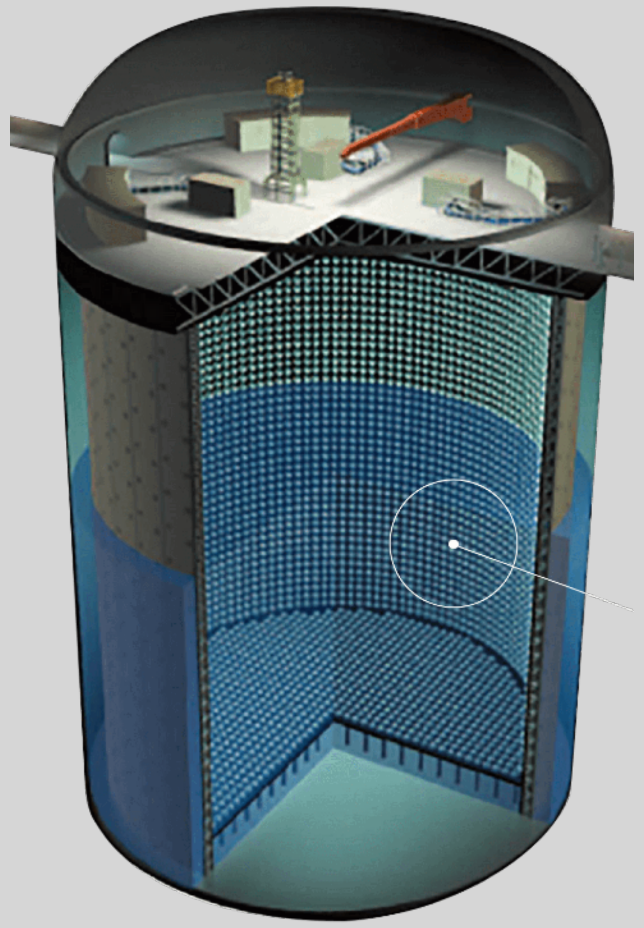
Water Cherenkov

Liquid Scintillator

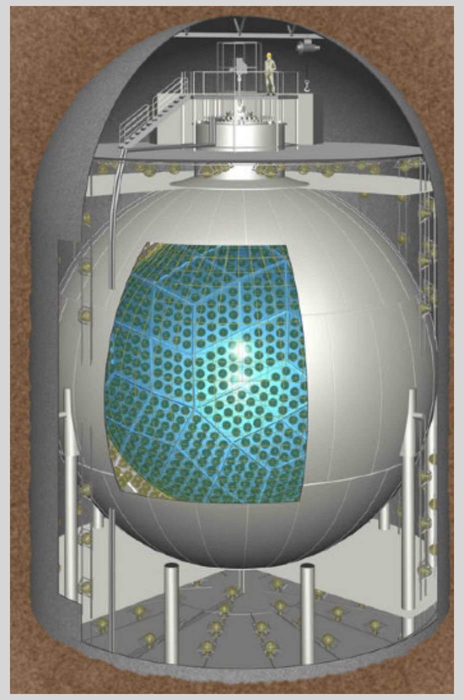
Liquid Ar

current

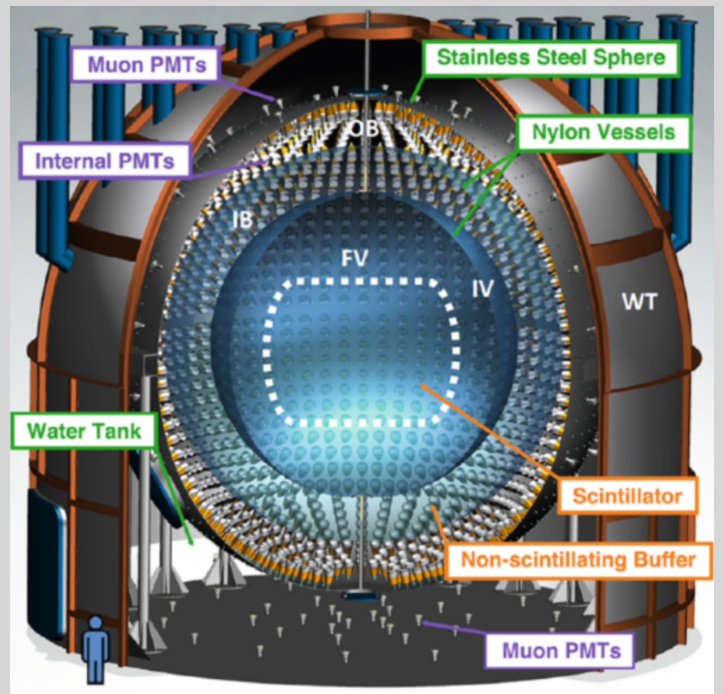
Super-Kamiokande (1996~)



KamLAND (2002~)

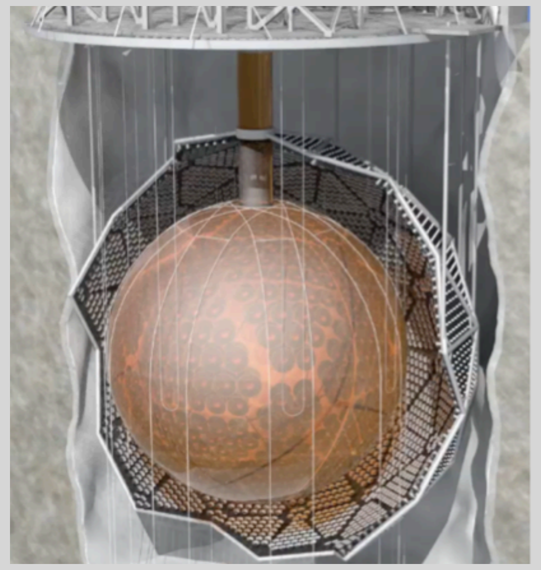


Borexino (2007~)

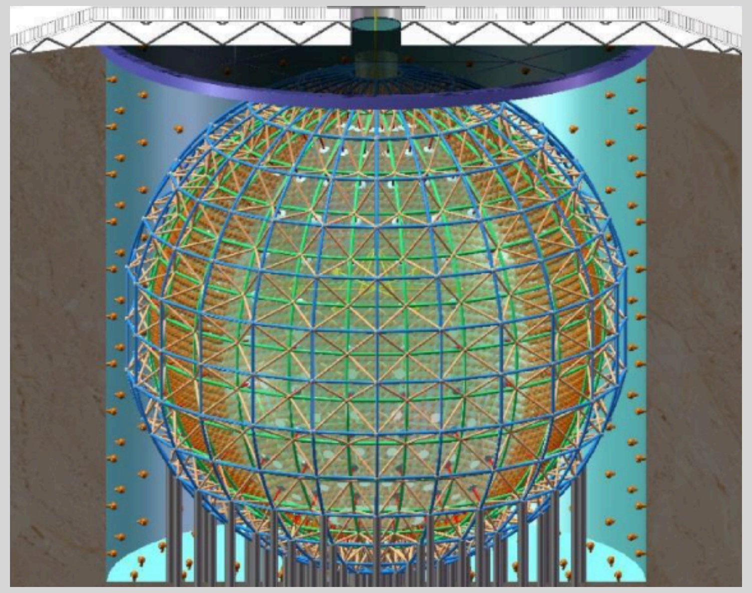


future

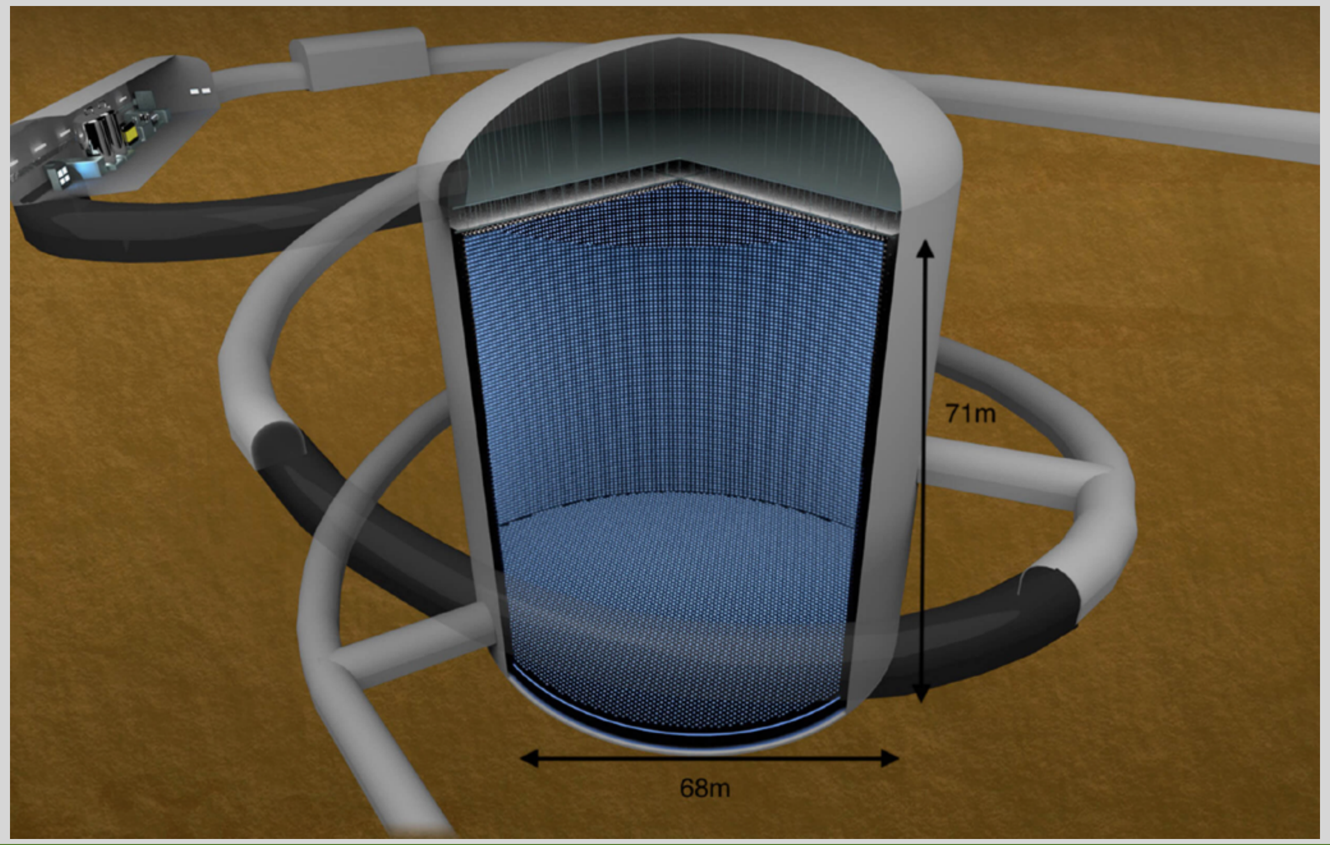
SNO+ (202?~)



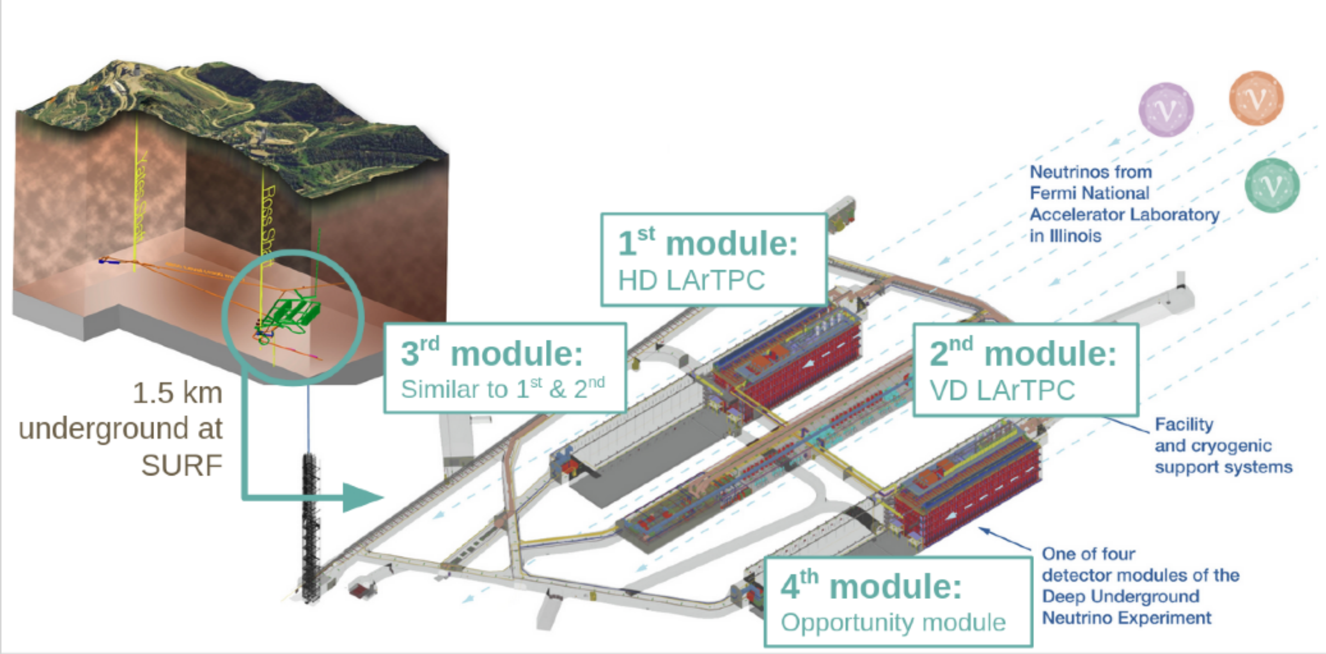
JUNO (2023~)



Hyper-Kamiokande (2027~)

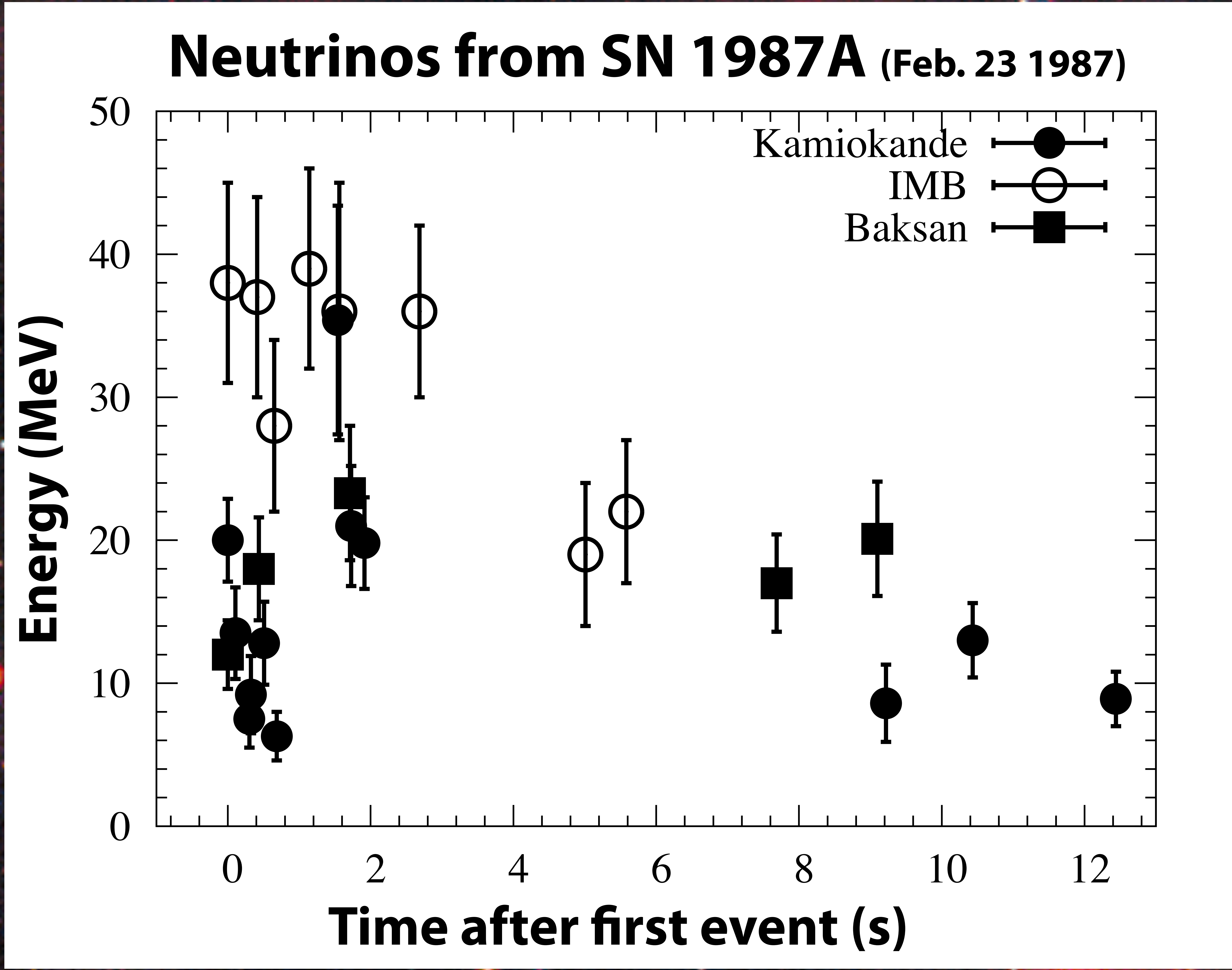


DUNE (2029~)




SN1987A
© NASA/ESA

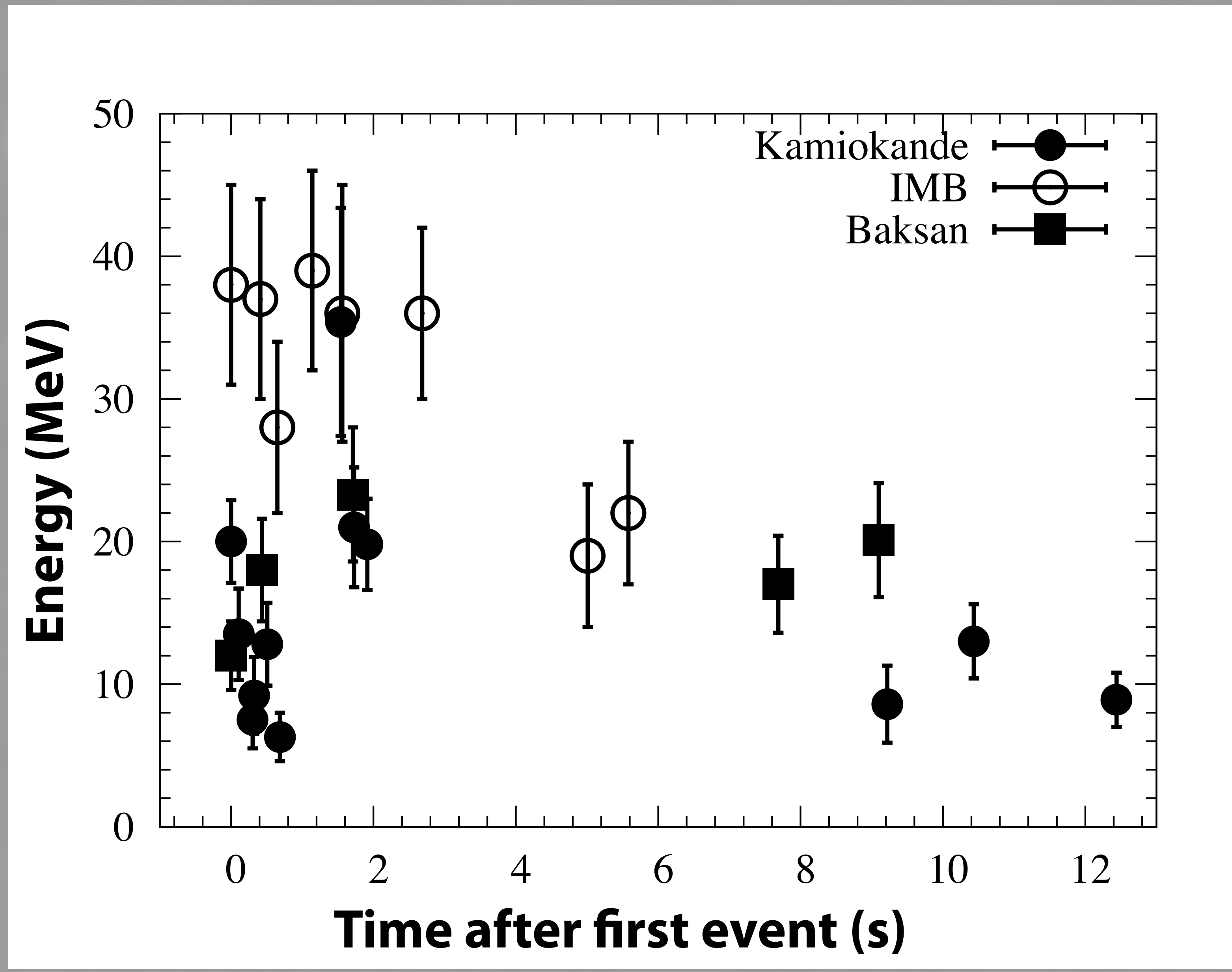
SN1987A



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

nuLC collaboration

“nuLC”
=neutrino Light Curve

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)

nuLC collaboration

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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)

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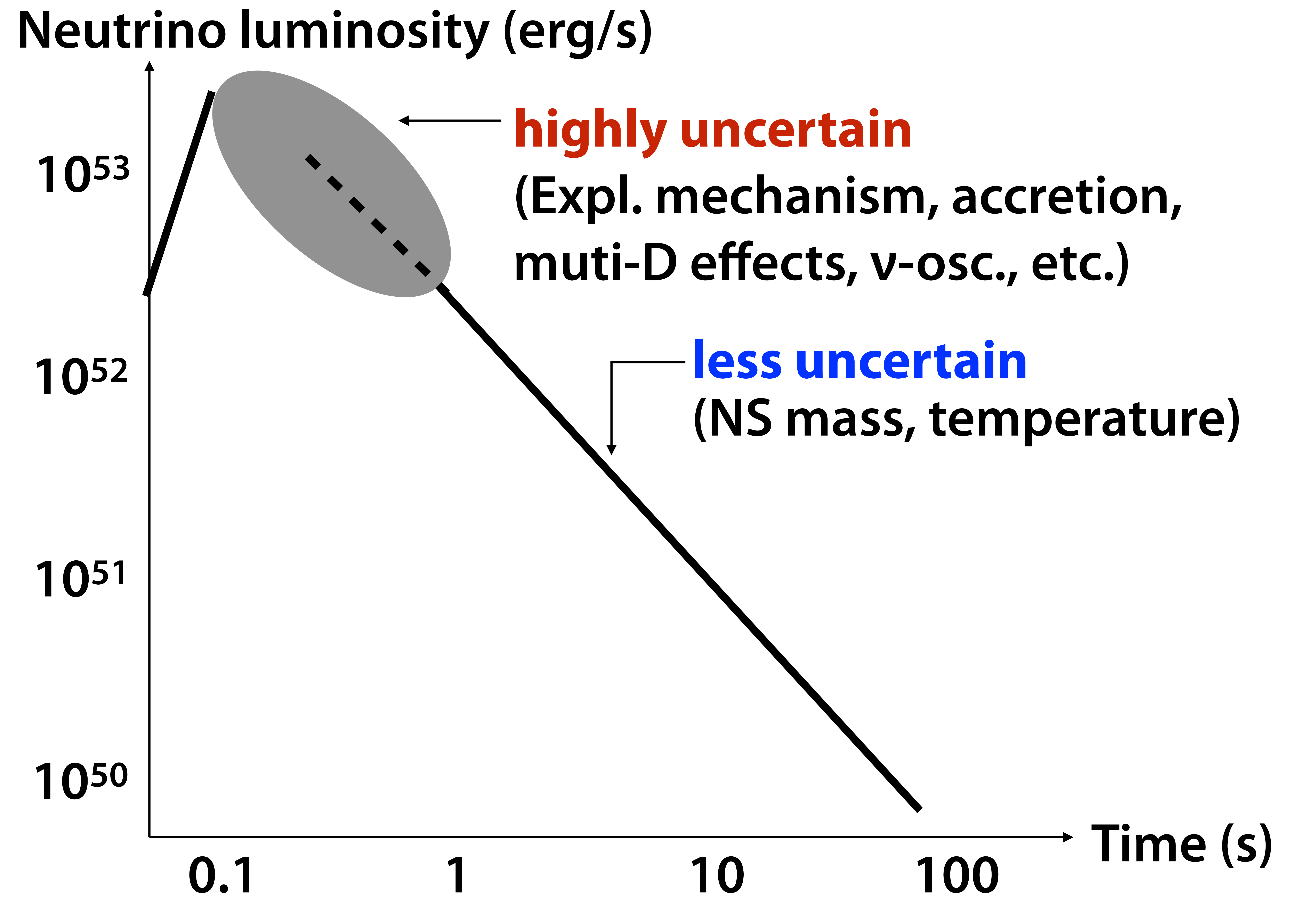
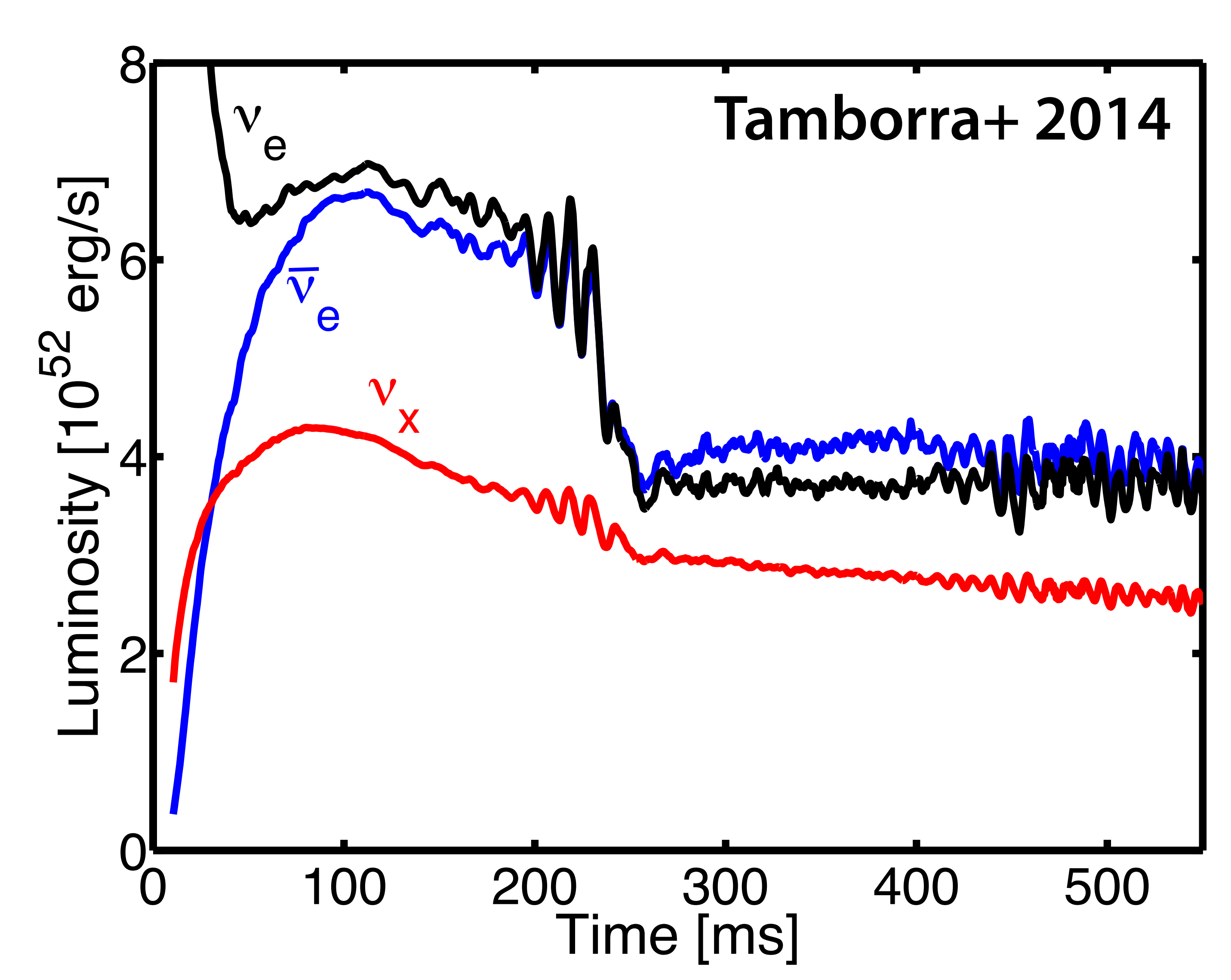
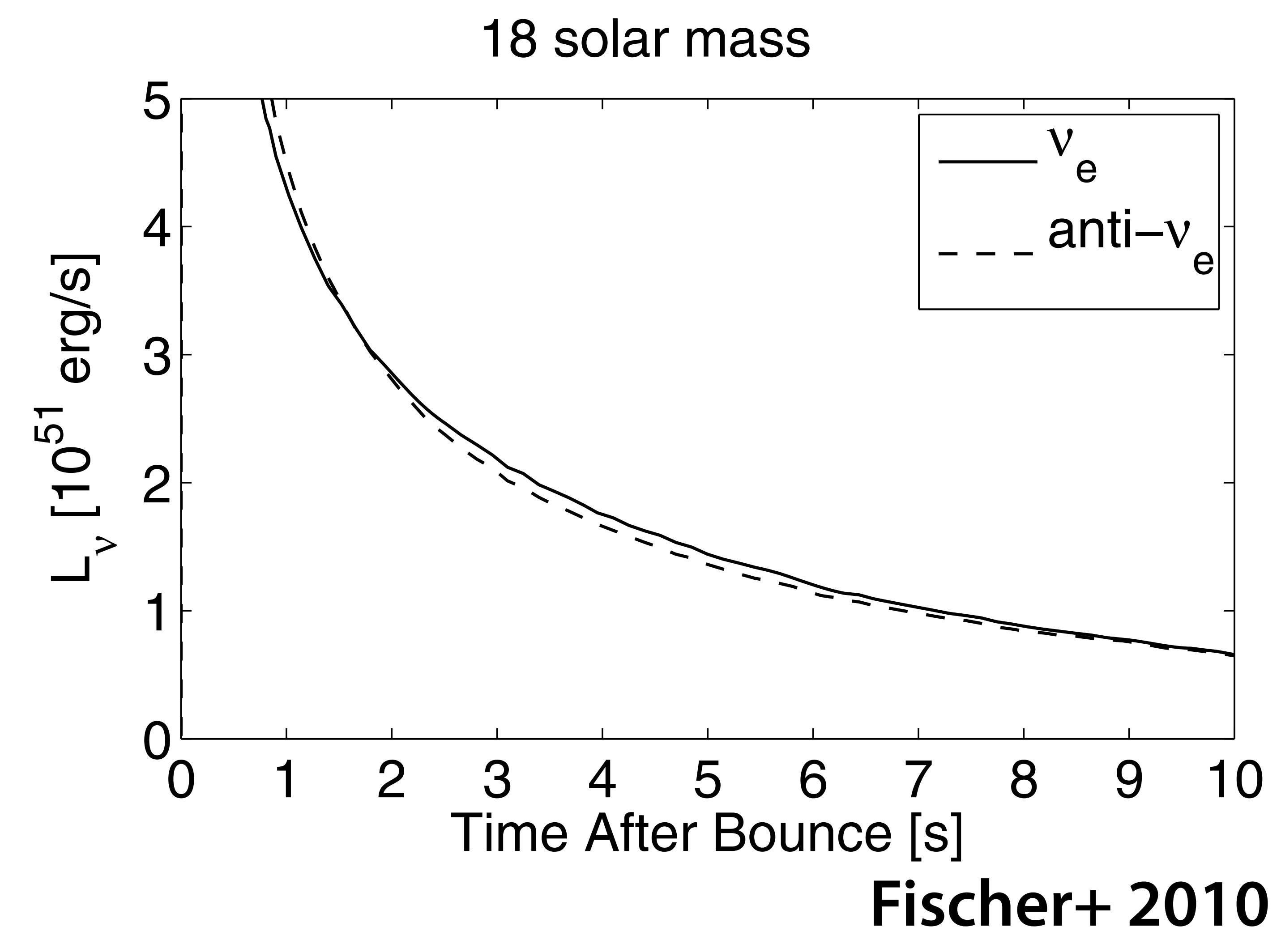
Late cooling phase is simpler and more understandable than early phase







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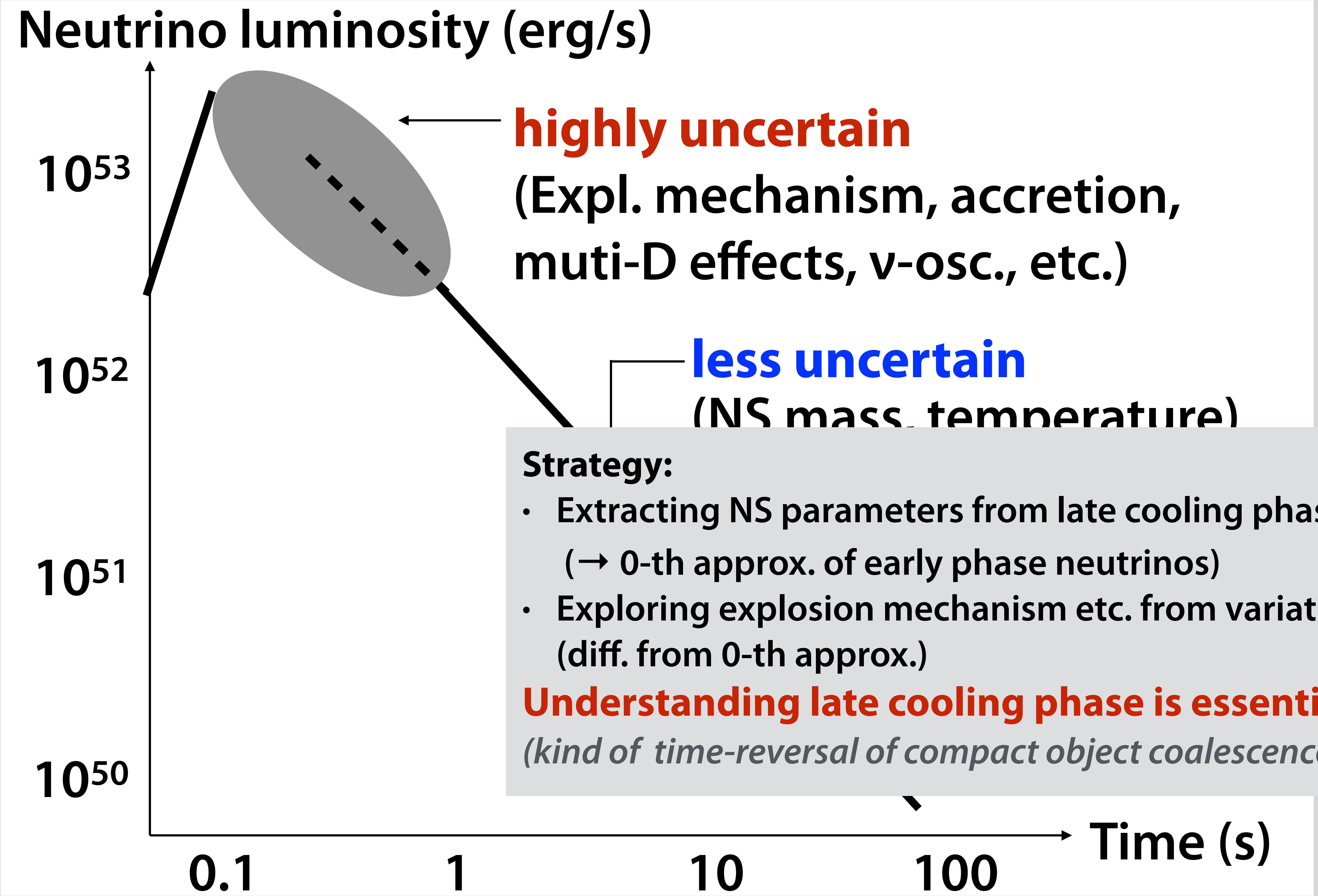
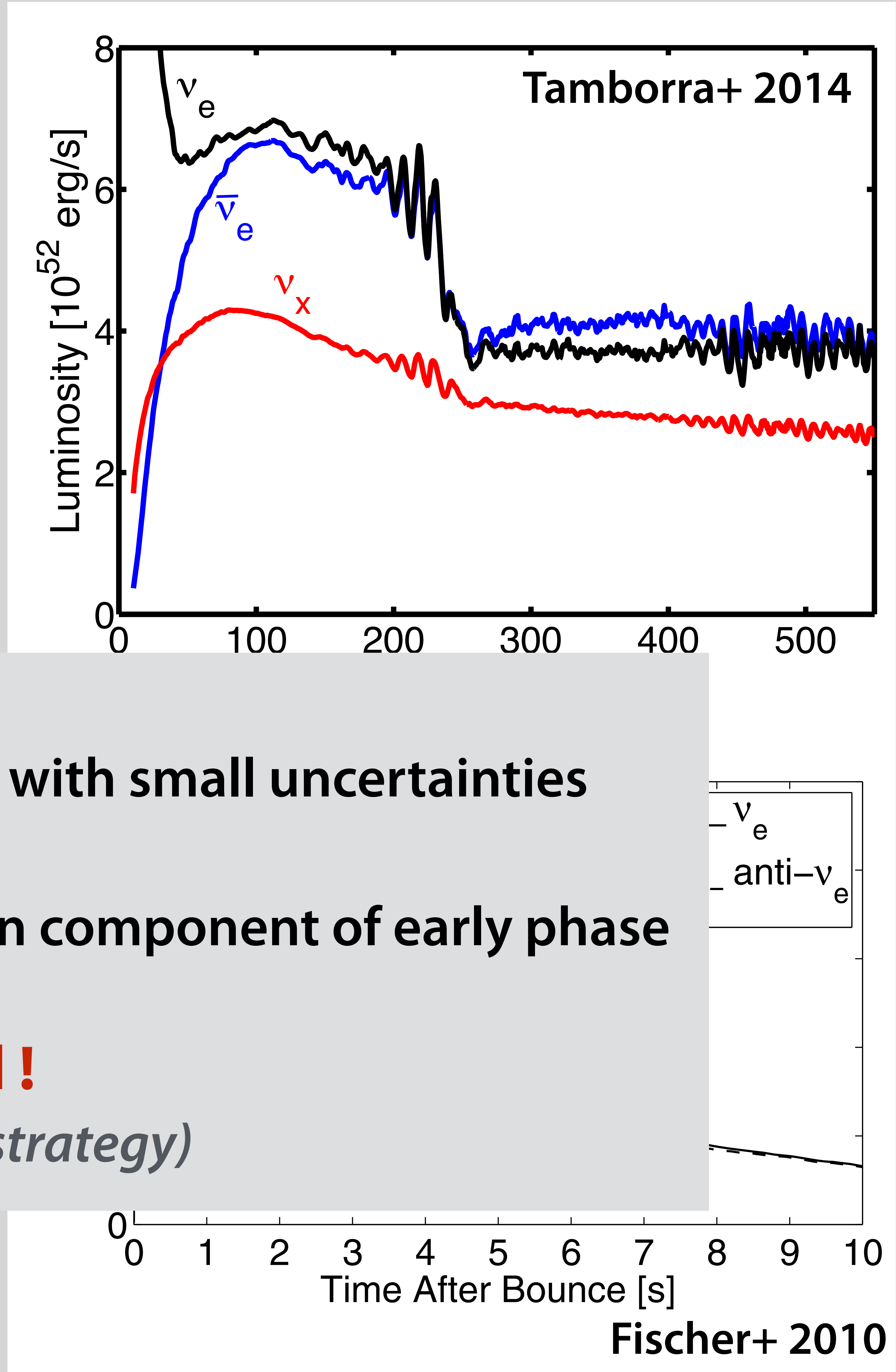




Strategy:

- 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

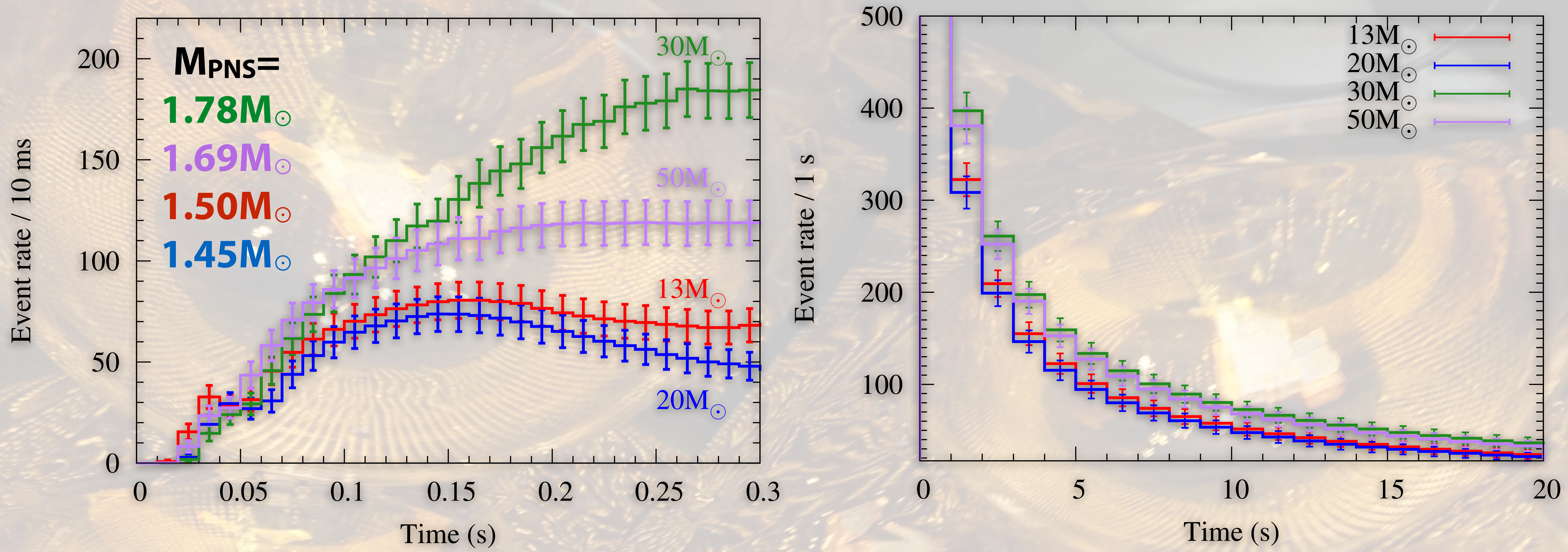
step 3

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)]



step 1

NUMERICAL SIMULATIONS

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

* **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**

Analytic solutions

step 2

$f(x)$

ANALYTIC SOLUTIONS

- Analytic cooling curves

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

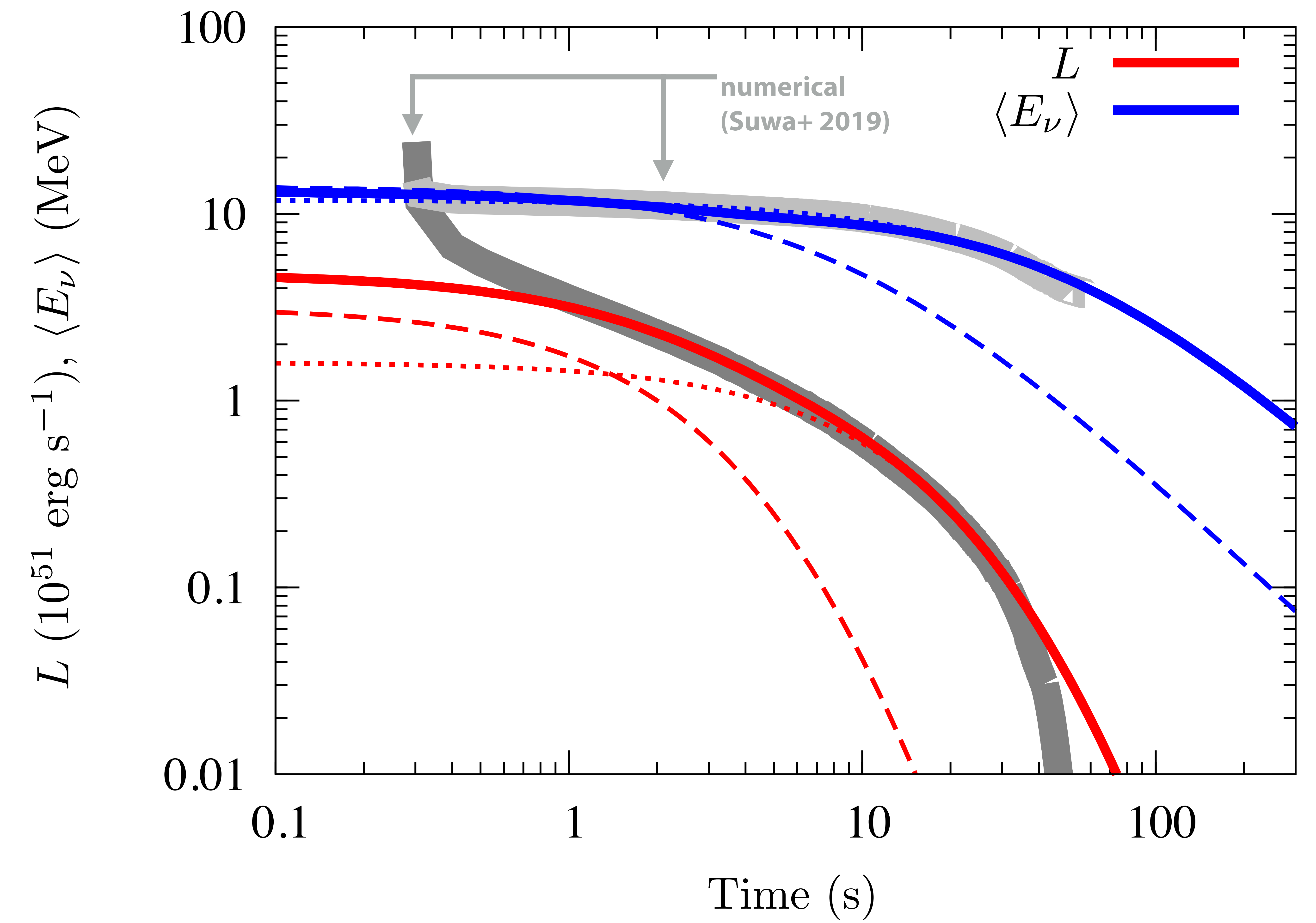
- Solve neutrino transport eq. analytically
  - Neutrino luminosity

$$L = 3.3\times10^{51}\,\mathrm{erg\,s^{-1}}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{6}\left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-6}\left(\frac{g\beta}{3}\right)^{4}\left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-6}$$

  - Neutrino average energy

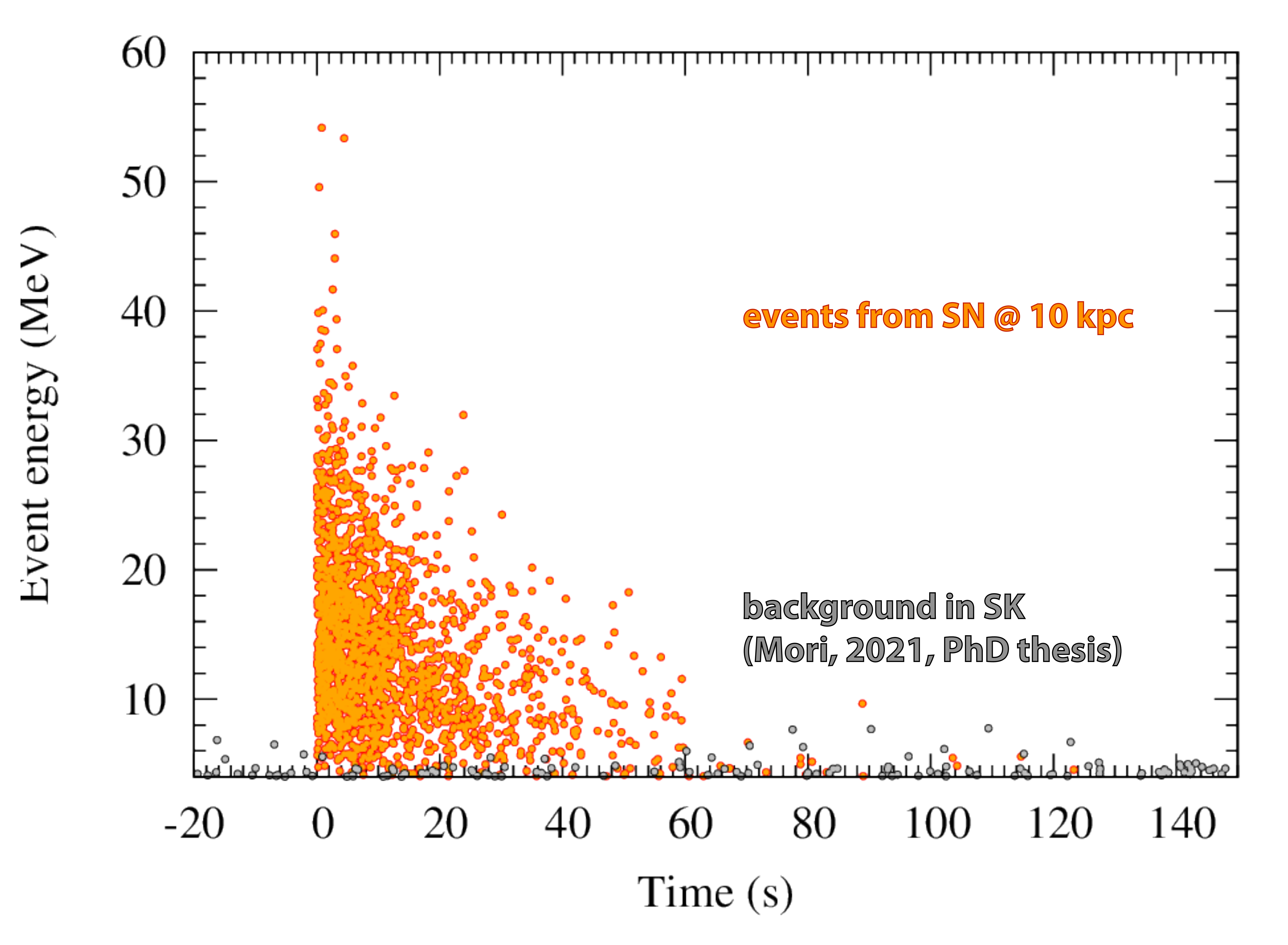
$$\langle E_\nu\rangle = 16\,\mathrm{MeV}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{3/2}\left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-2}\left(\frac{g\beta}{3}\right)\left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-3/2}$$

  - 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)]



step 3

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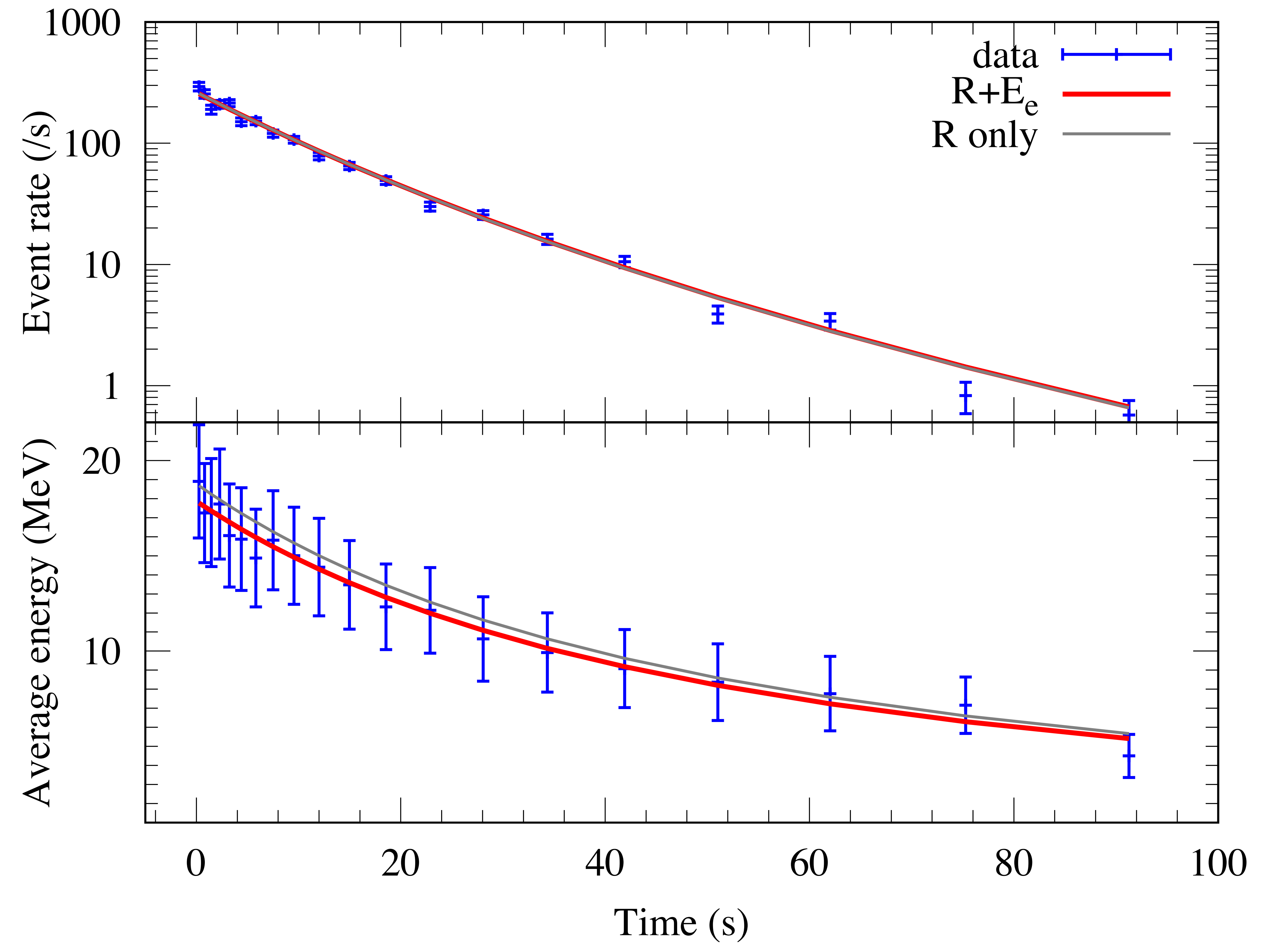
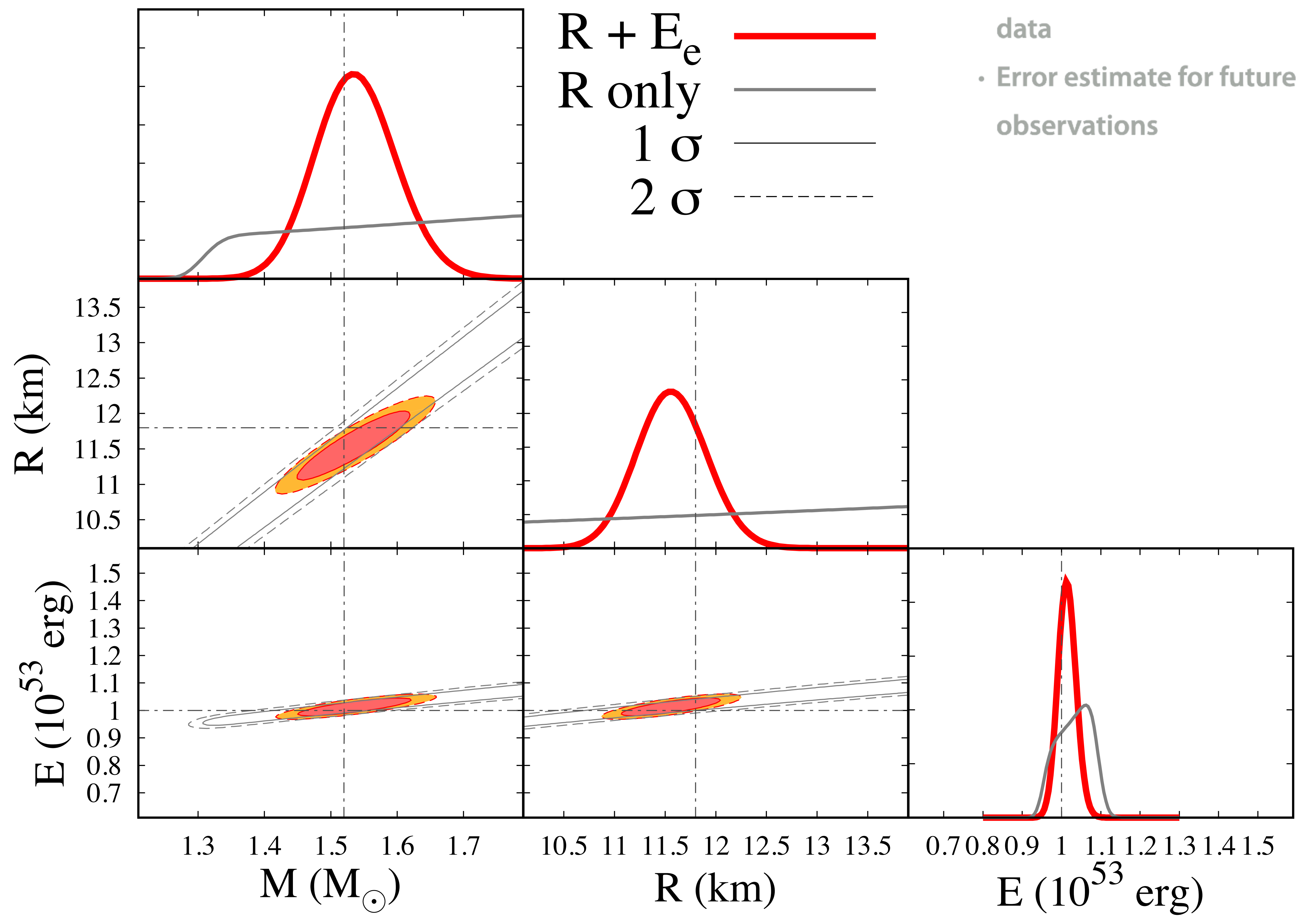
χ^2 fit and probability density function

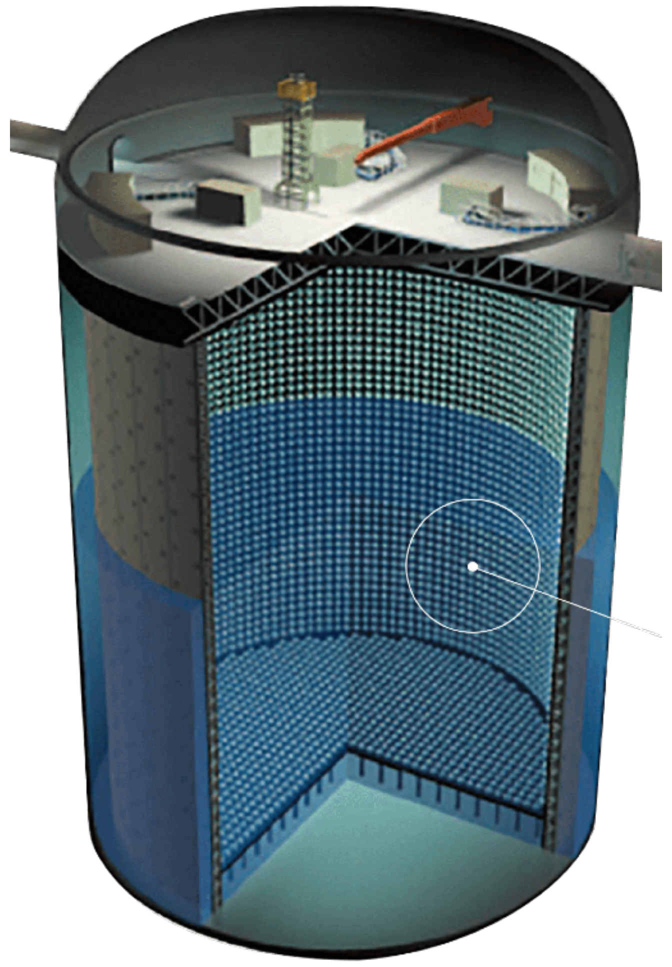
[Suwa, Harada, Harada, Koshio, Mori, Nakanishi, Nakazato, Sumiyoshi, Wendell, ApJ, 934, 15 (202





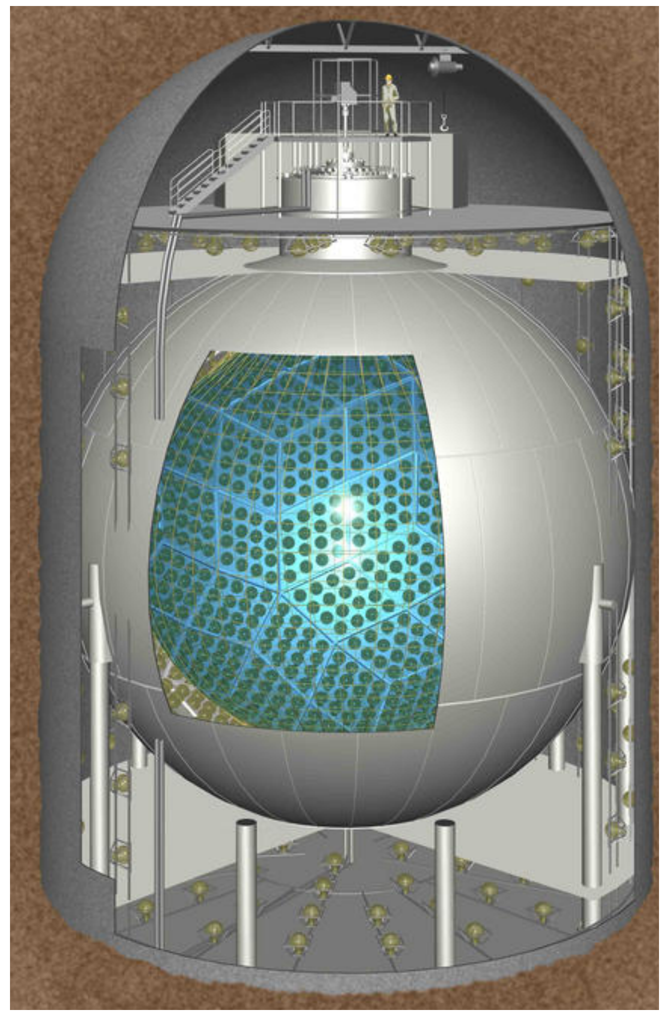
Combining Super-Kamiokande and KamLAND

Super-Kamiokande



- $\bar{\nu}_\mathrm{e} + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$
  → sensitive to $\bar{\nu}_\mathrm{e}$
- large statistics
- good for late phase (flavor independent)

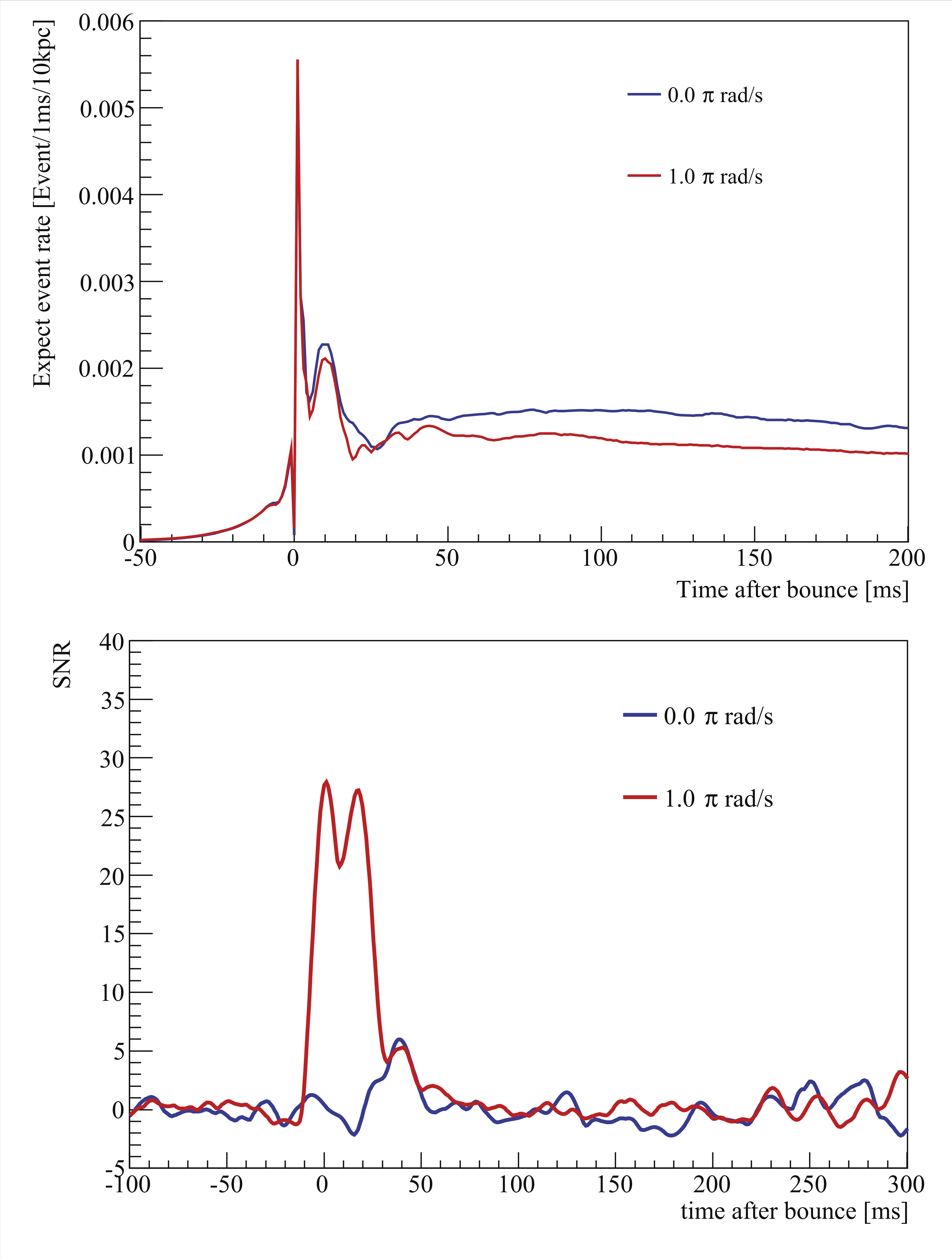
KamLAND



- $\nu + \mathrm{p} \rightarrow \nu + \mathrm{p}$
  → flavor independent
- low threshold energy
- good for early phase (strong flavor dependency)

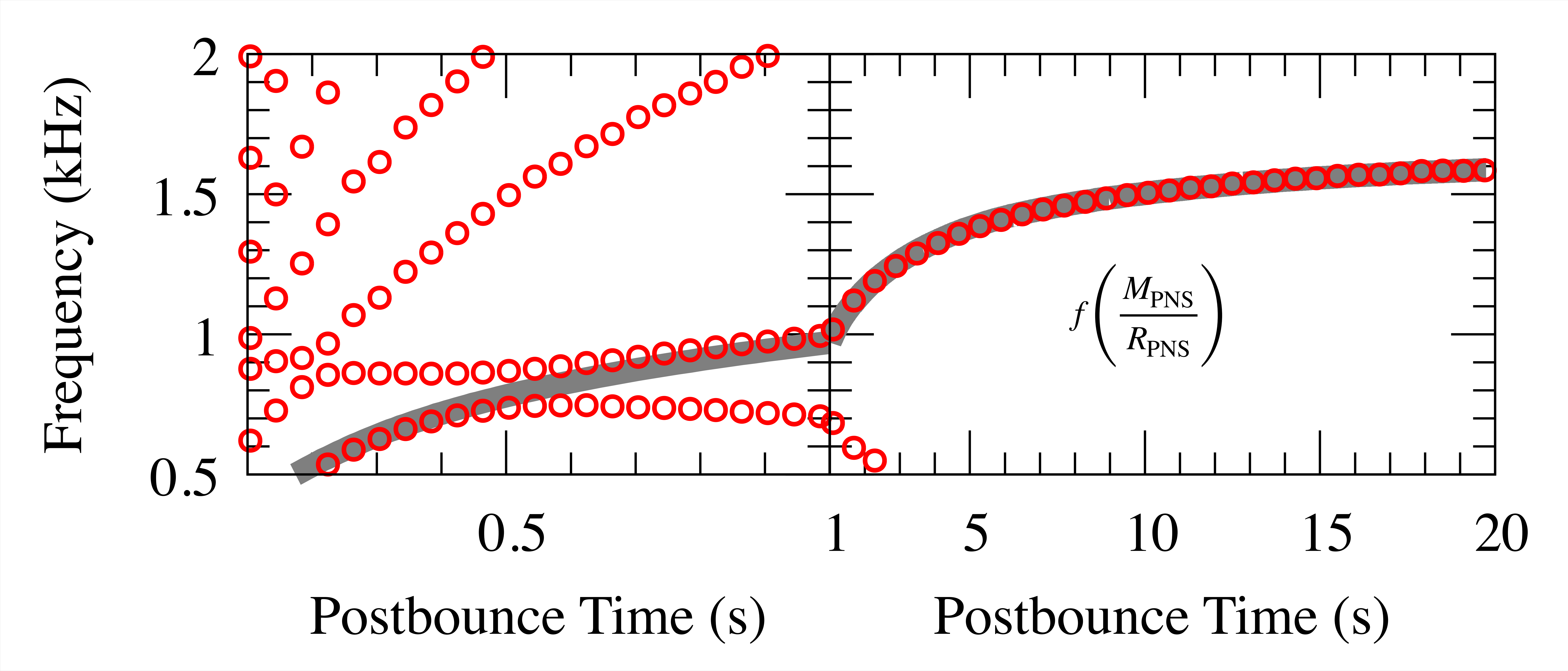
Combining neutrinos and GWs

[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**

Crosscheck with GW asteroseismology



Mori, YS, Takiwaki, in prep.
see poster (Z114b) for simulation details

Summary

- **Supernovae are optimal targets of multi-messenger observations**
- **Neutrinos are robust**
  - promising signal
  - late cooling phase is critical for parameter estimate
  - SK and KamLAND are complementary
- **Gravitational waves are physics probe (smoking gun!)**
  - highly model dependent, difficult to predict
  - even non-detection constrains physics
  - Many possible synergies with neutrinos (not much discussed)

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