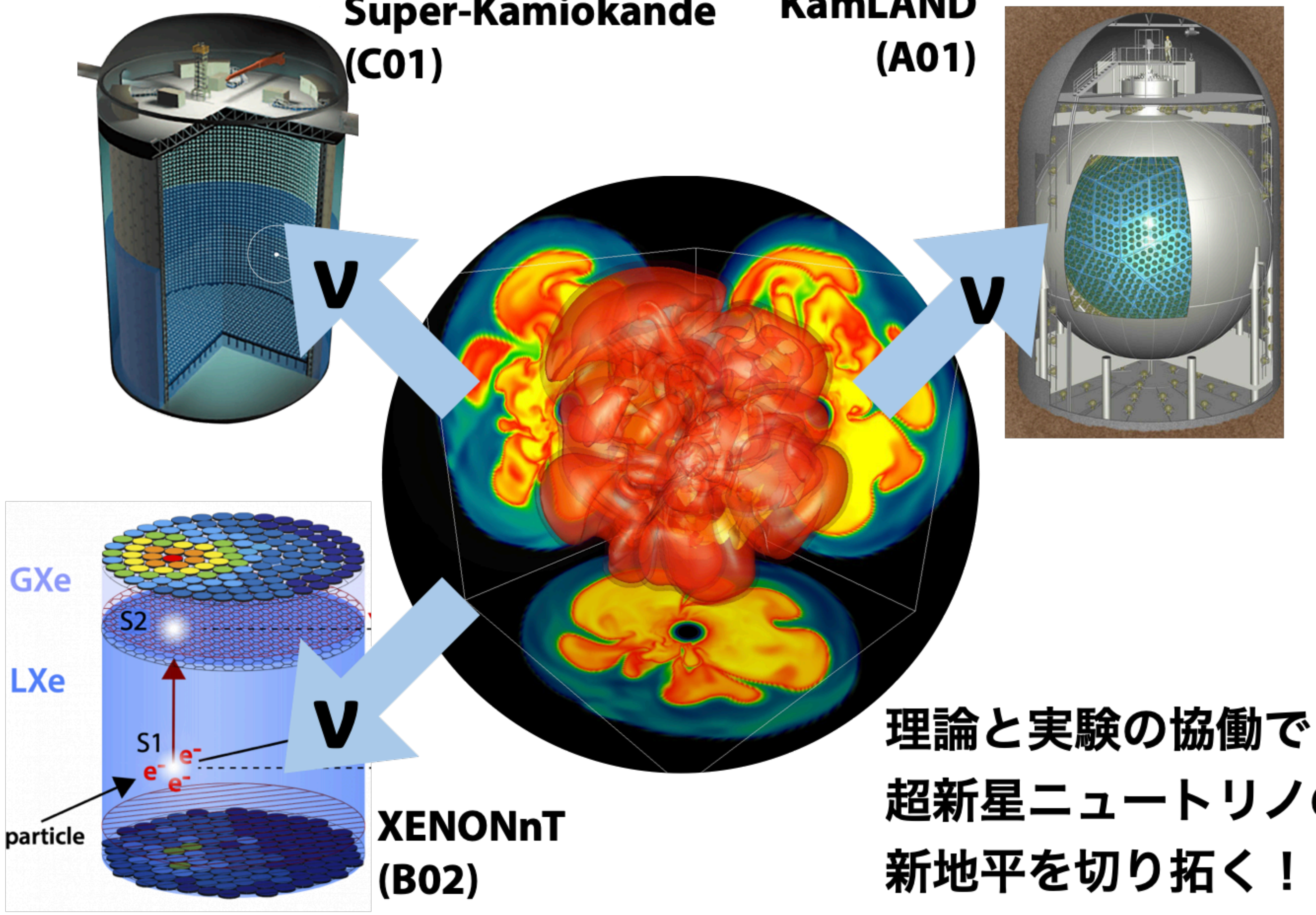
超新星ニュートリノの理論研究

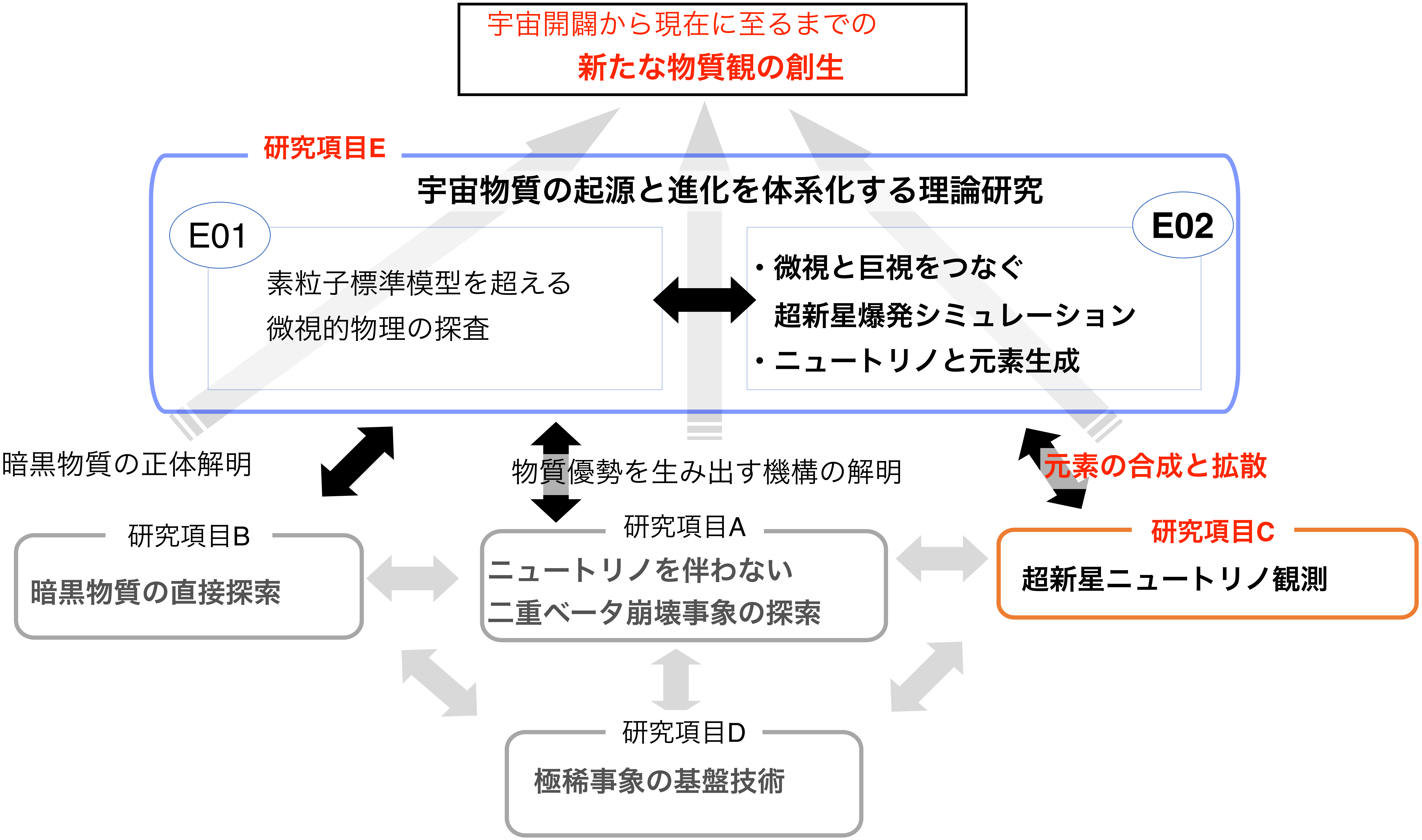
諏訪雄大（東京大学総合文化）

E02: 全ニュートリノフレーバーを用いた超新星ニュートリノの理論研究

- 重元素の起源＝超新星爆発
- 超新星爆発機構は宇宙物理学の最大の謎のひとつ
- 超新星ニュートリノの精密測定(A01/B02/C01)と詳細理論(E02)で中心に迫る
- ミクロな新物理(E01)とマクロな天体現象(E02)を結ぶ



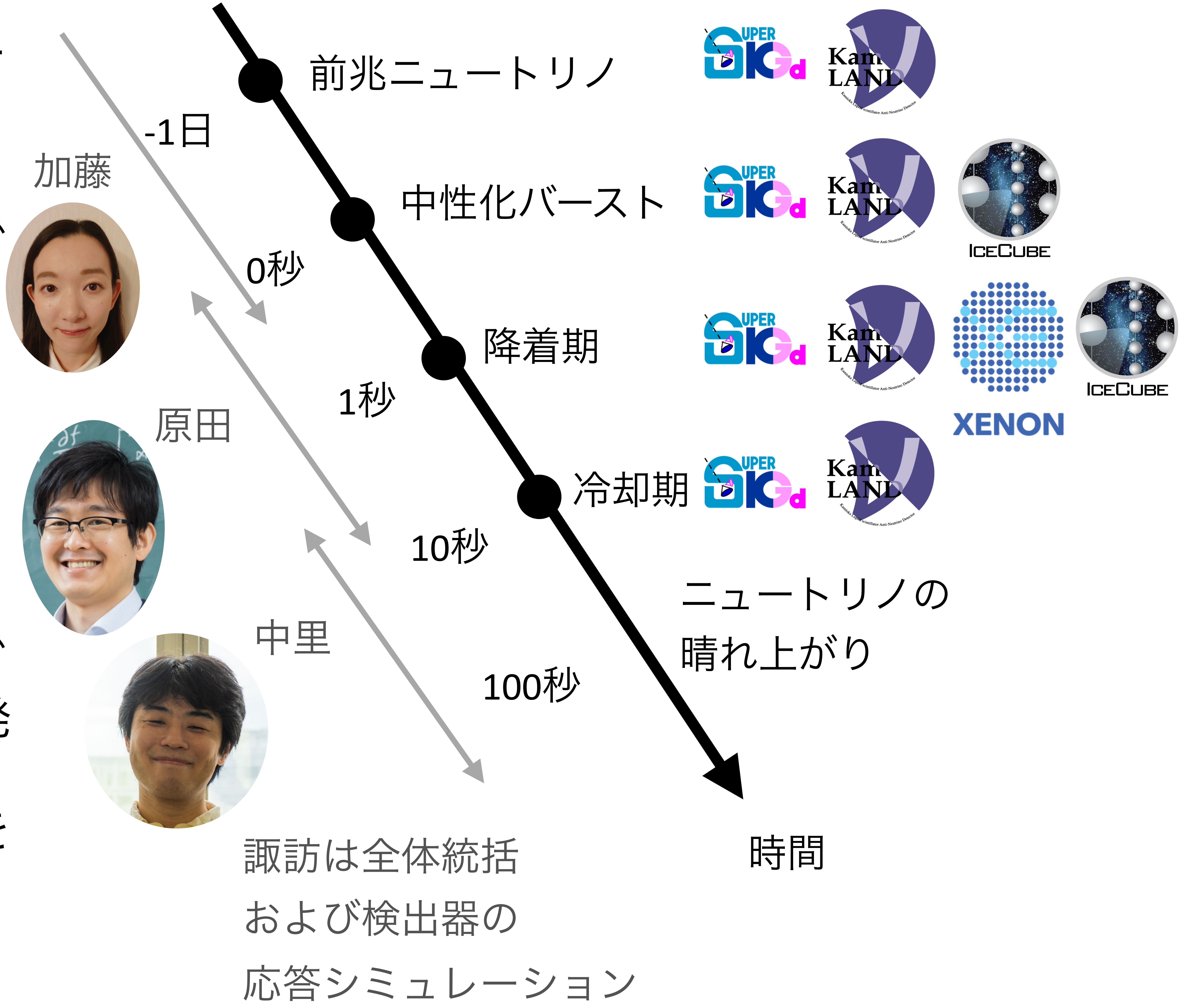
理論と実験の協働で
超新星ニュートリノの
新地平を切り拓く！



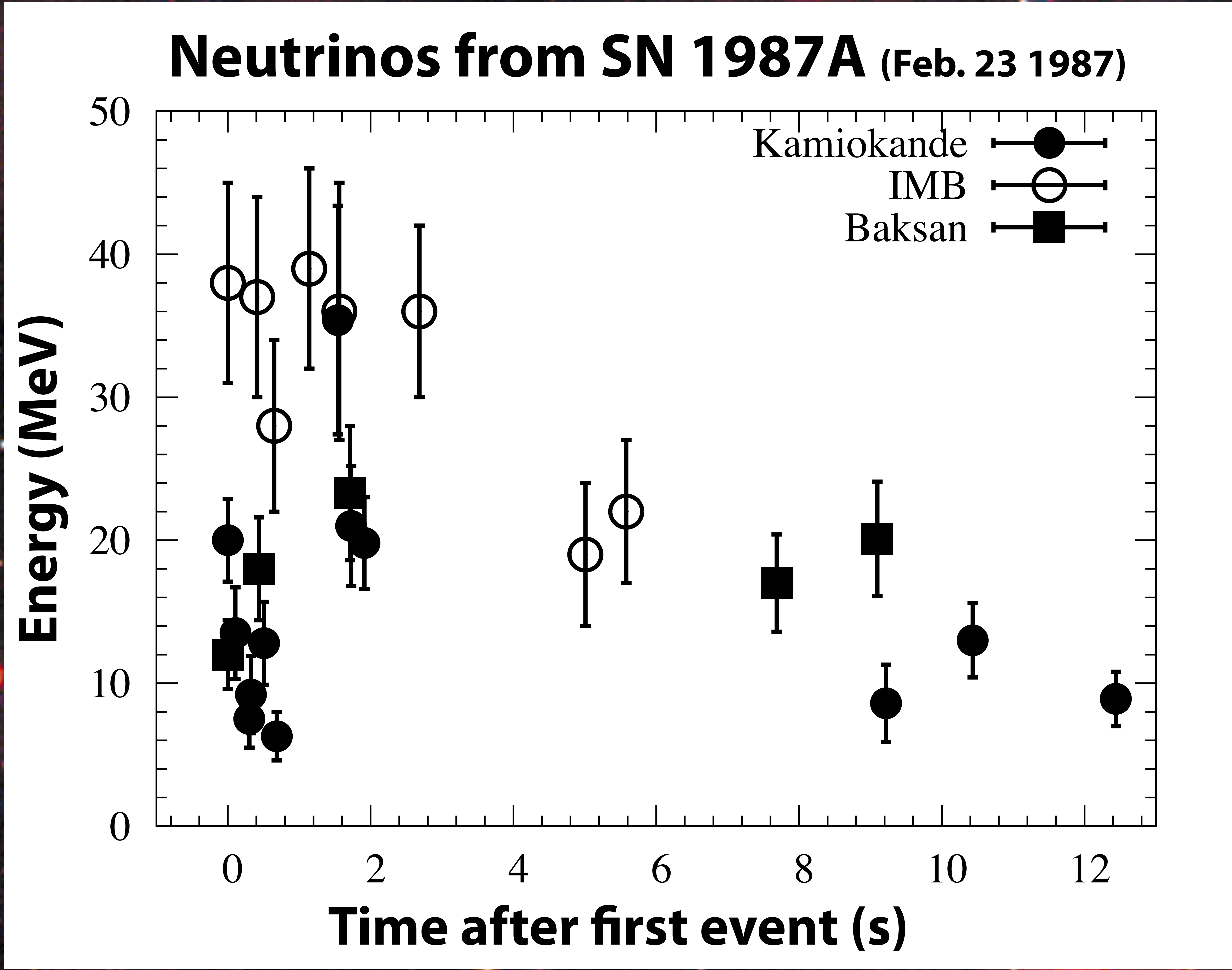
宇宙開闢から現在に至るまでの
新たな物質観の創生
研究項目E
宇宙物質の起源と進化を体系化する理論研究
E01
素粒子標準模型を超える
微視的物理の探査
E02
・微視と巨視をつなぐ
超新星爆発シミュレーション
・ニュートリノと元素生成
暗黒物質の正体解明
物質優勢を生み出す機構の解明
元素の合成と拡散
研究項目B
暗黒物質の直接探索
研究項目A
ニュートリノを伴わない
二重ベータ崩壊事象の探索
研究項目C
超新星ニュートリノ観測
研究項目D
極稀事象の基盤技術

E02班の目指すサイエンス

- 超新星ニュートリノには複数のフェーズがある
- 各々のフェーズは異なるアプローチで計算されていた
- 今回、全フェーズの研究者を集めた
- 全員若手（42歳以下）
- 前兆ニュートリノから後期冷却期までを包括的に扱う数値計算コードを開発
- 新しい数値コードを用いた観測予言を行い、超新星ニュートリノのサイエンスを最大化するのが目標



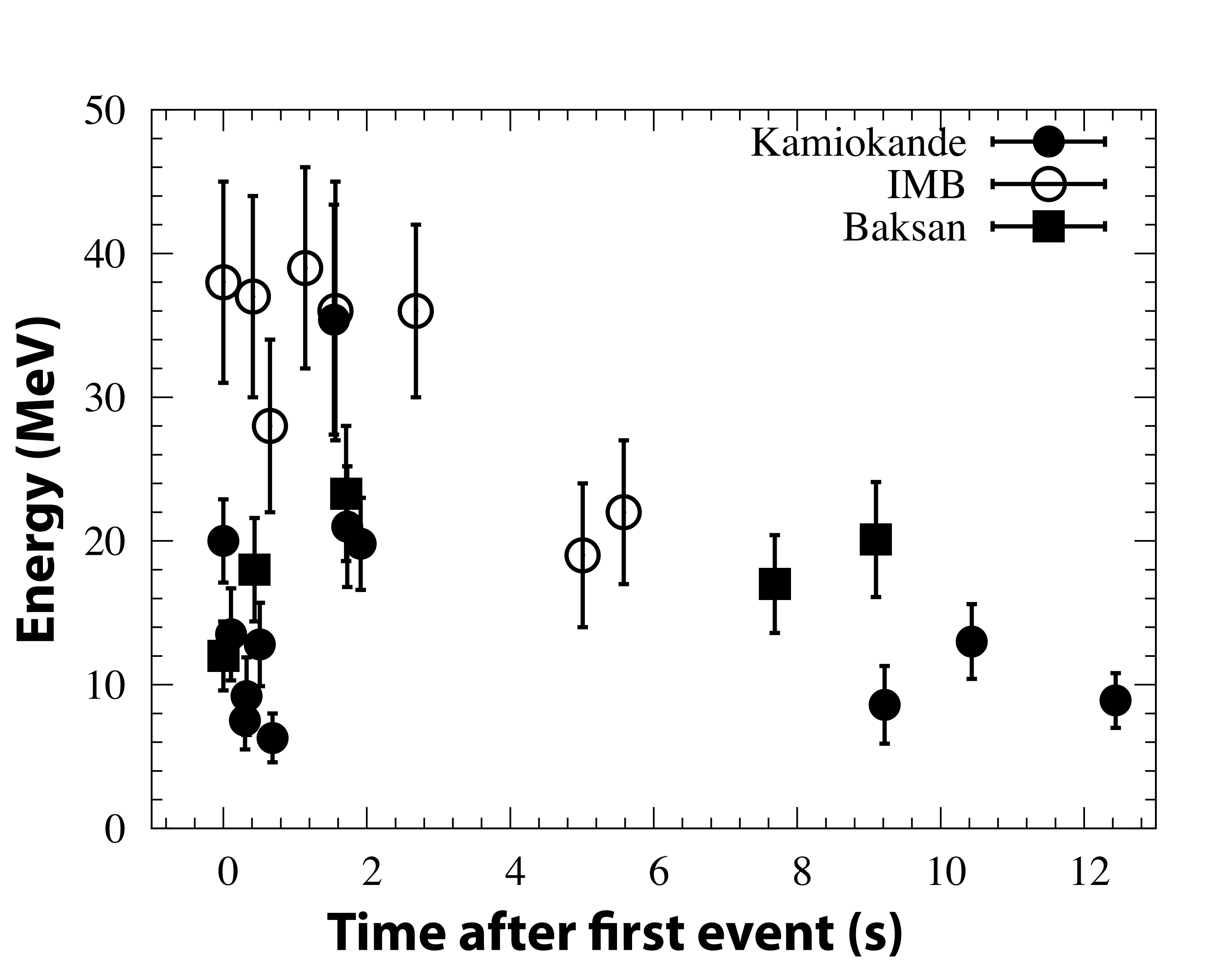
SN1987A



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?

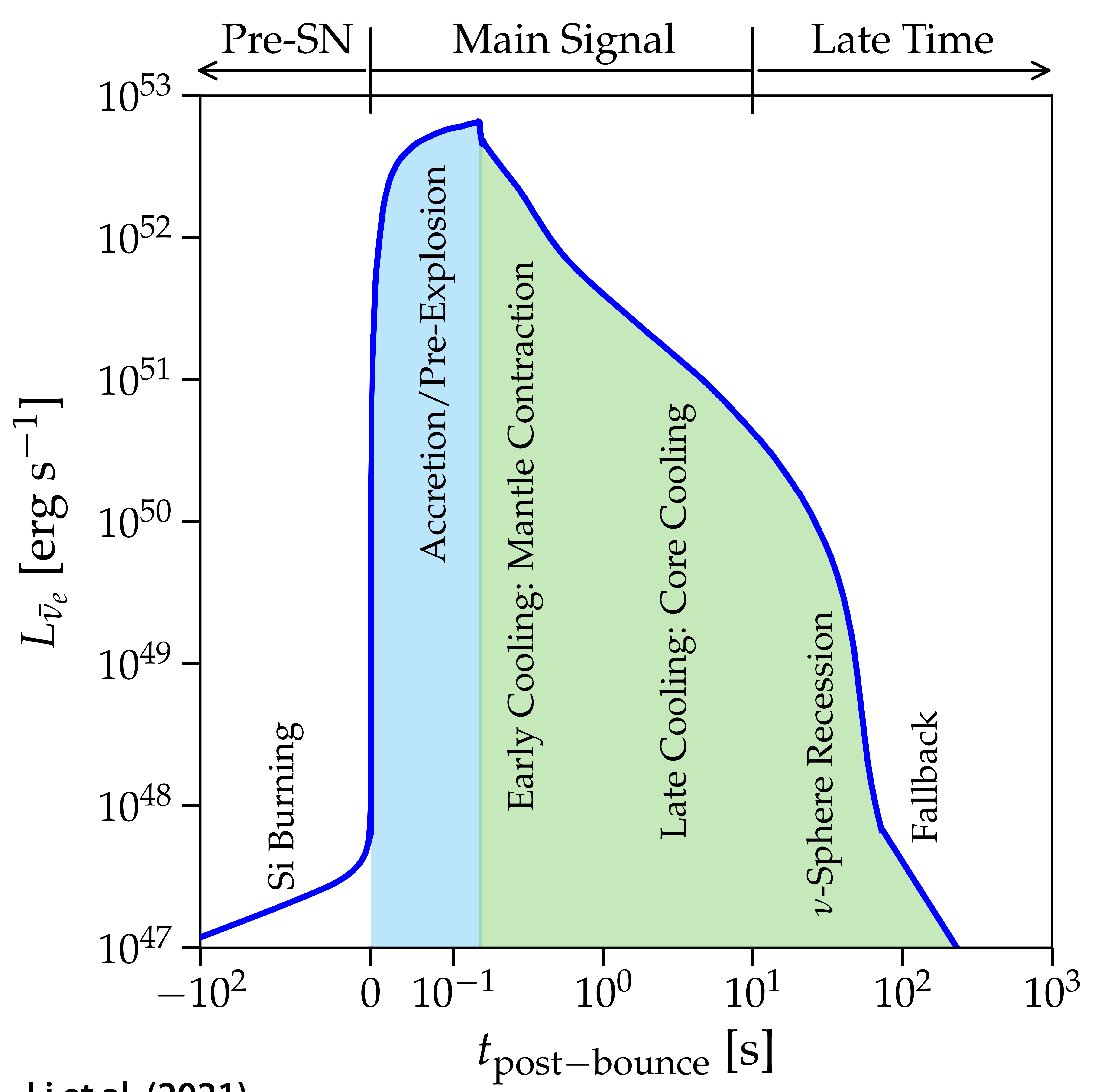
- **Properties of neutron stars**
  - **Binding energy**
    - ***important for energetics, done with SN1987A***

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

  - **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

Supernova neutrinos: basics



Li et al. (2021)

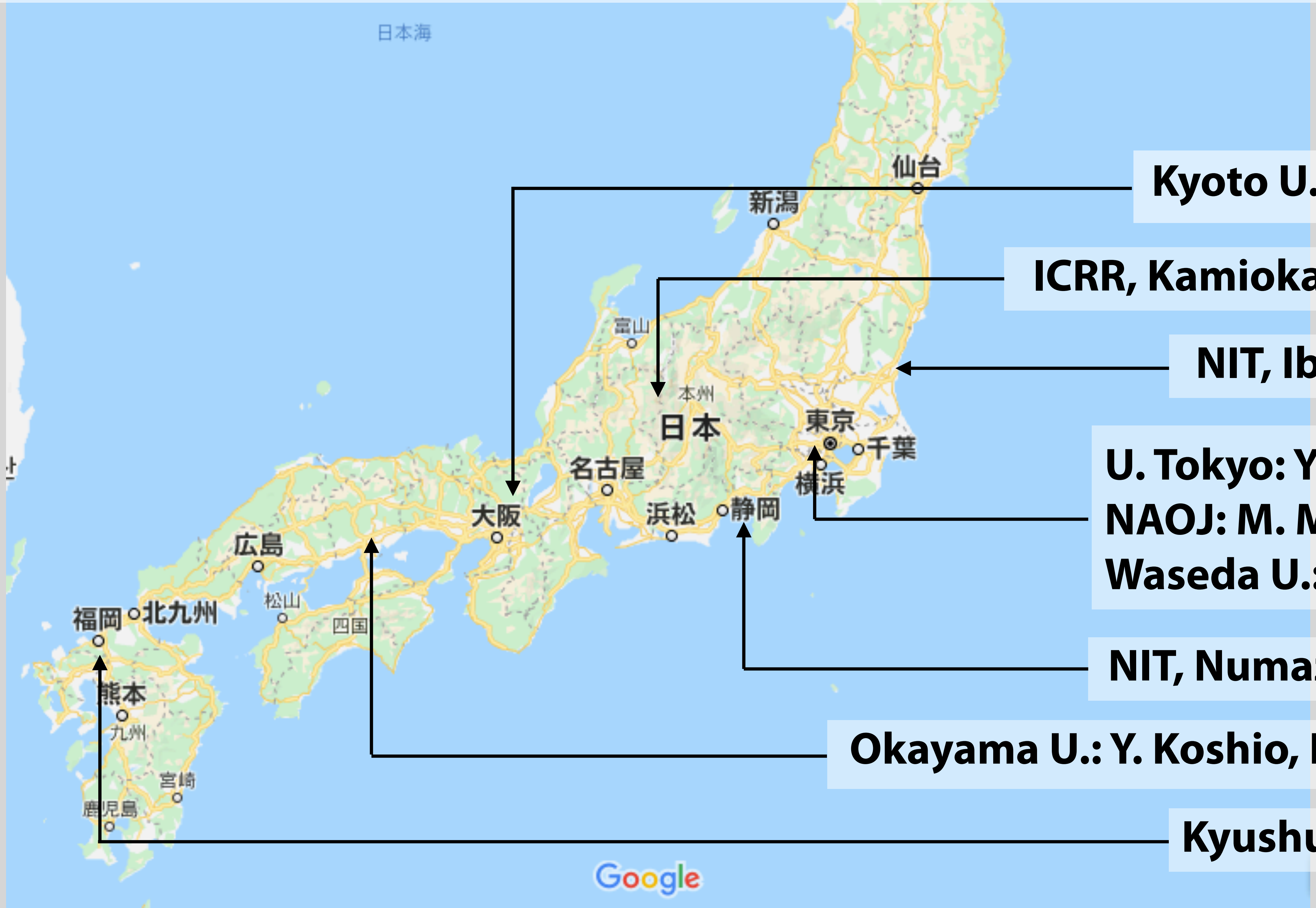
- **Si burning**
  - final phase of stellar evolution
- **Accretion/Pre-explosion**
  - neutrino trapping
  - neutronization burst
- **Cooling**
  - early phase
    - hydrodynamical instabilities, explosion mechanism, shock revival, PNS contraction…
  - late phase
    - neutrino diffusion
  - volume cooling phase
    - transparent for neutrinos

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, arXiv:2404.18248



Kyoto U.: R. Wendell (Experiment)

ICRR, Kamioka: M. Harada (Experiment)

NIT, Ibaraki: A. Harada (Theory)

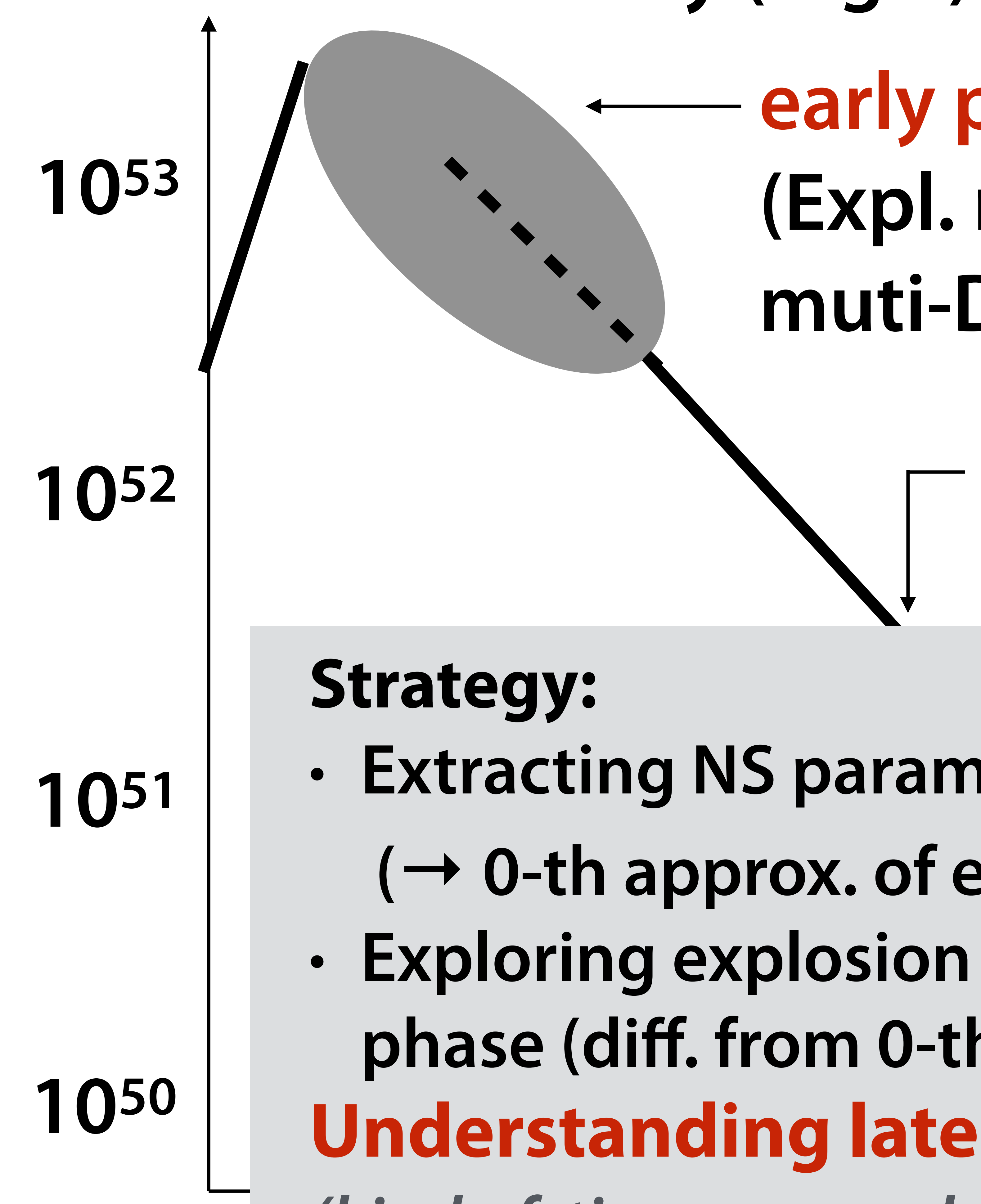
U. Tokyo: Y. Suwa (Theory)
NAOJ: M. Mori (Theory/Experiment)
Waseda U.: R. Akaho (Theory)

NIT, Numazu: K. Sumiyoshi (Theory)

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

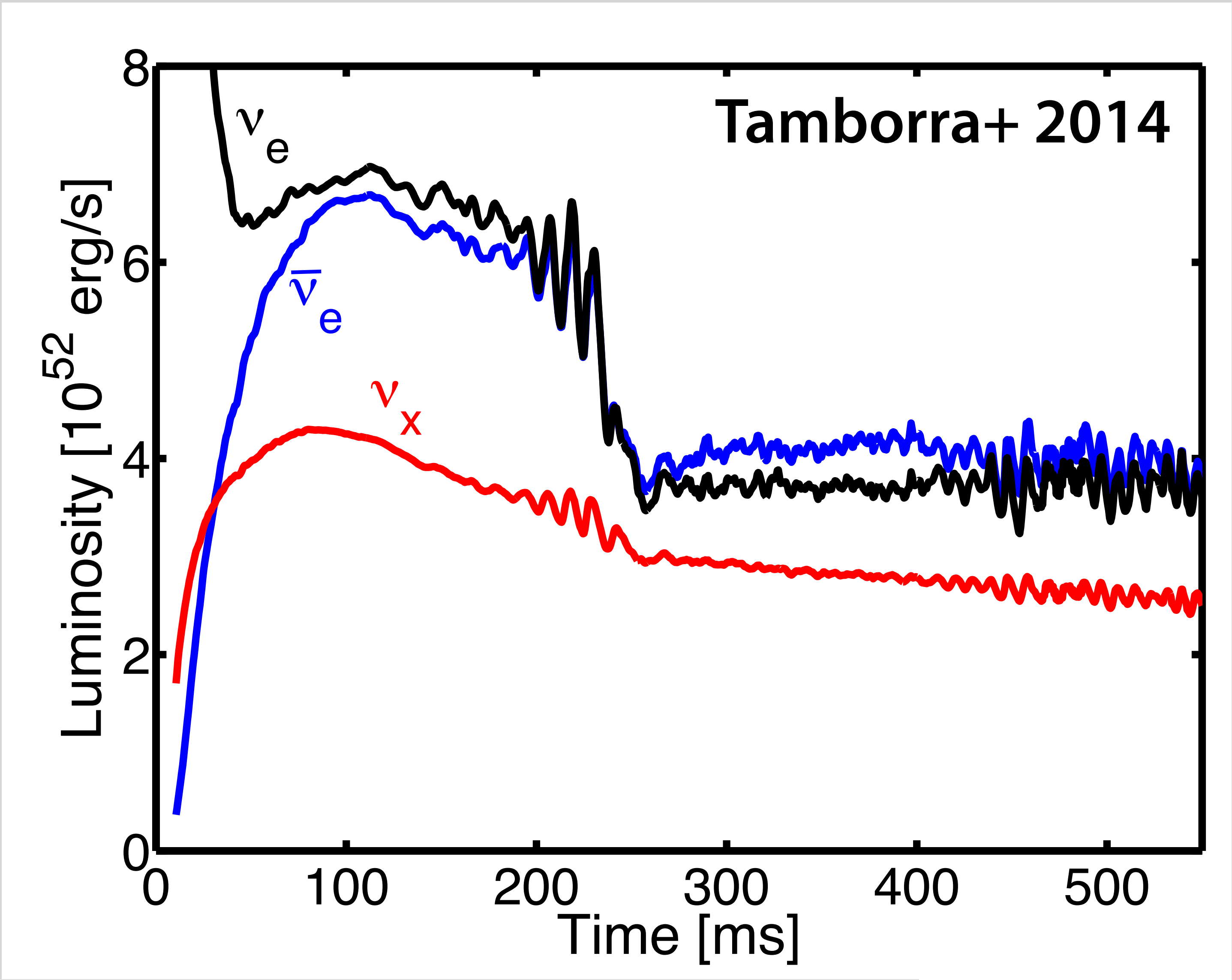
Kyushu U.: K. Nakazato (Theory)

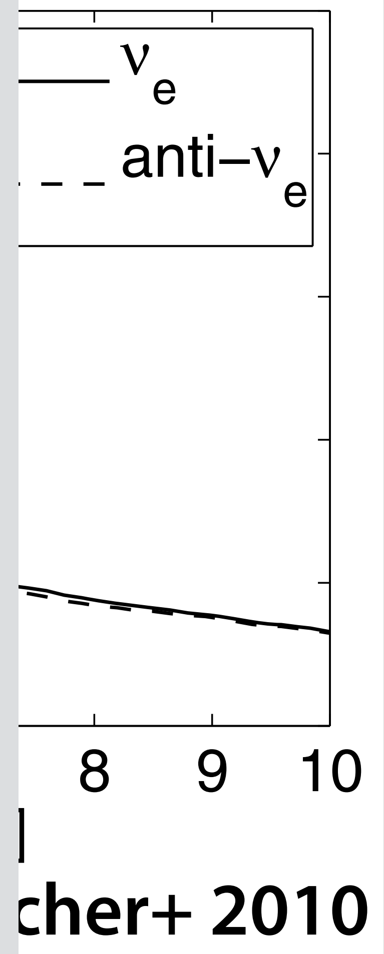
Late cooling phase is simple and understandable



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

late phase → less uncertain
(NS mass, temperature)





Strategy:

- 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)]

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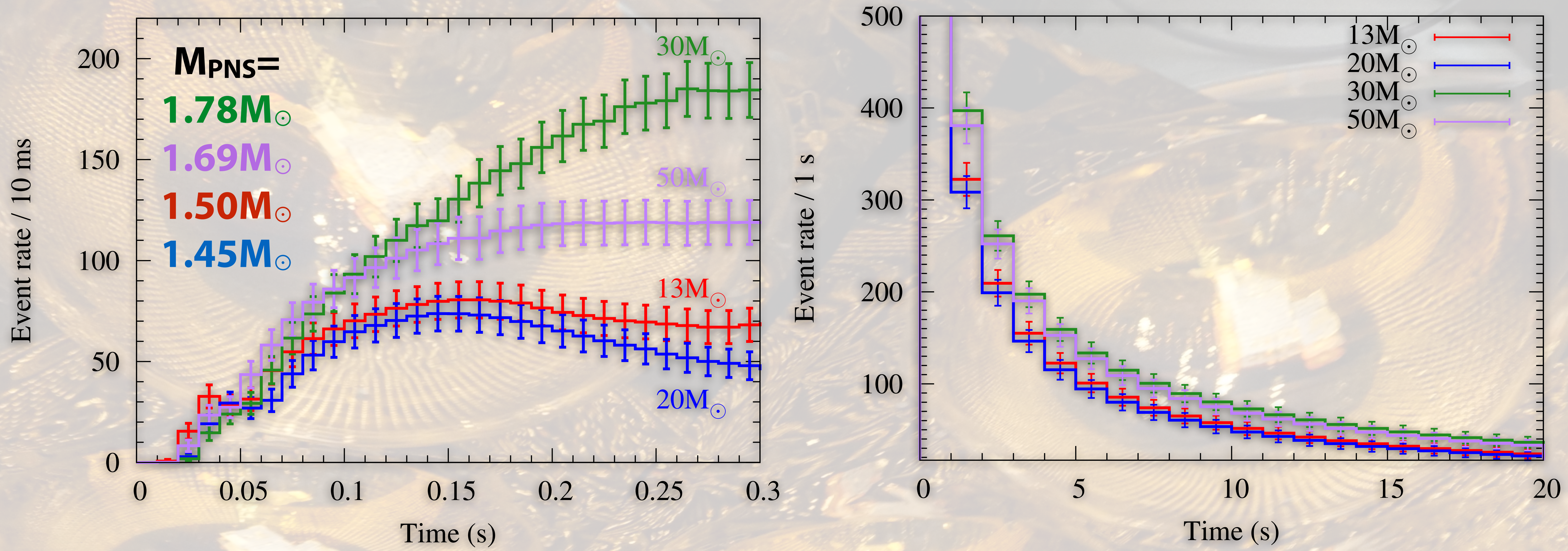


* **Event rate evolution is calculated beyond 100 s**
    - with neutrino luminosity and energy spectrum
    - with full volume of SK's inner tank (32.5 kton)
    - assuming an SN at 10 kpc
    - detector response for inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
* **Event rate is not related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

Analytic solutions

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

step 2

$f(x)$

ANALYTIC SOLUTIONS

- Analytic cooling curves

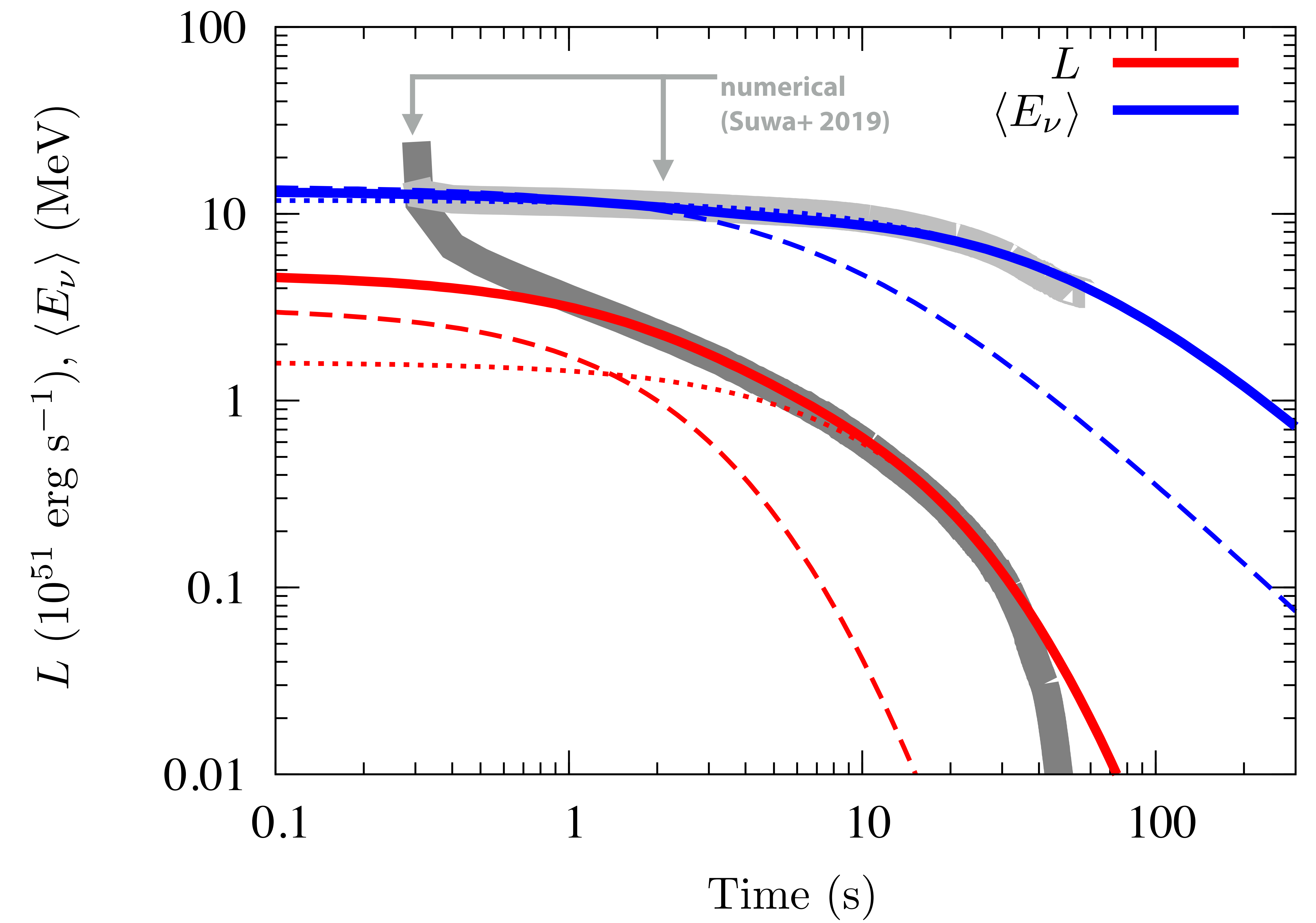
- **Solve neutrino transport eq. analytically**
  - **Neutrino luminosity**

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

  - **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 and data analysis

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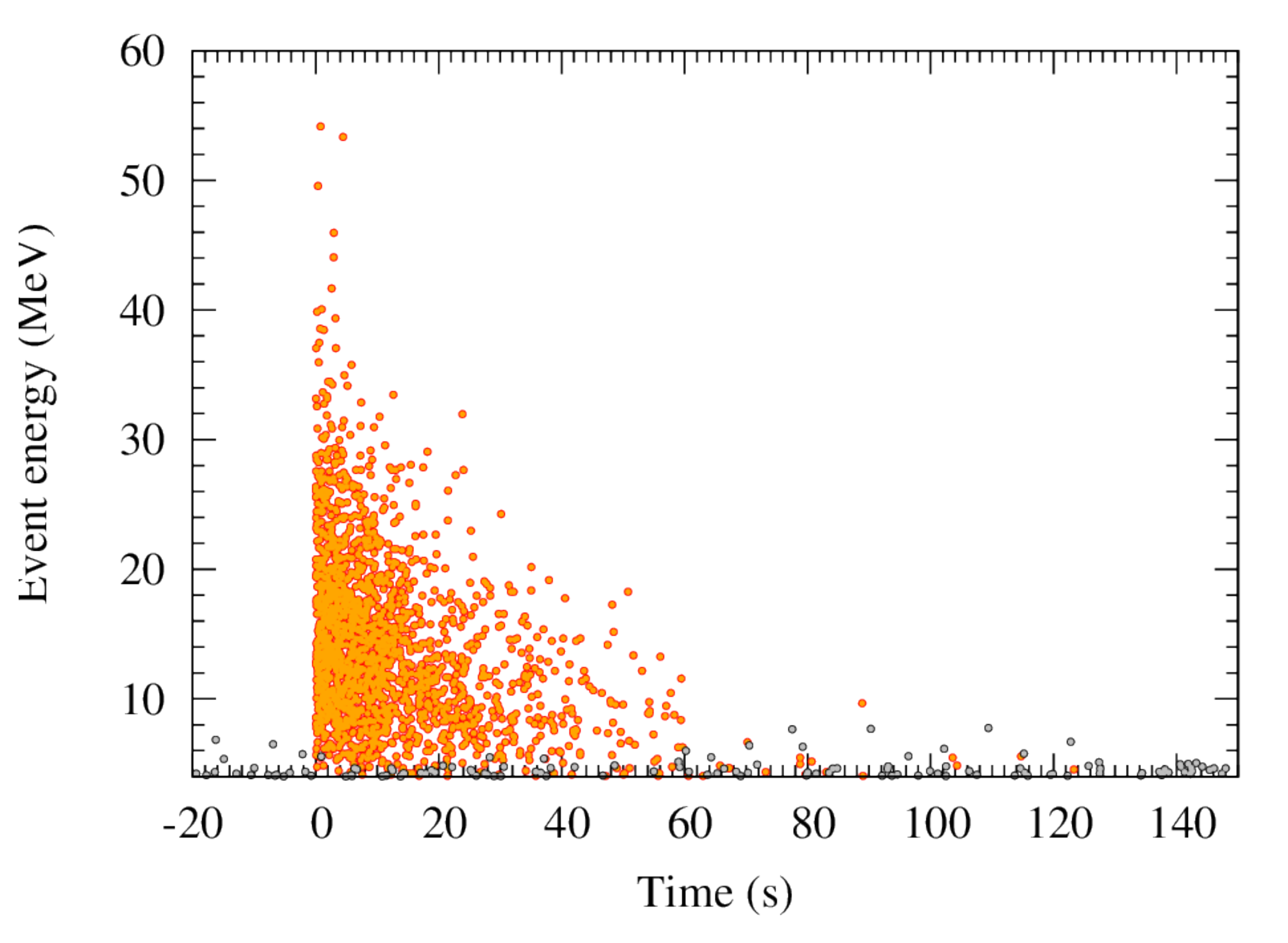
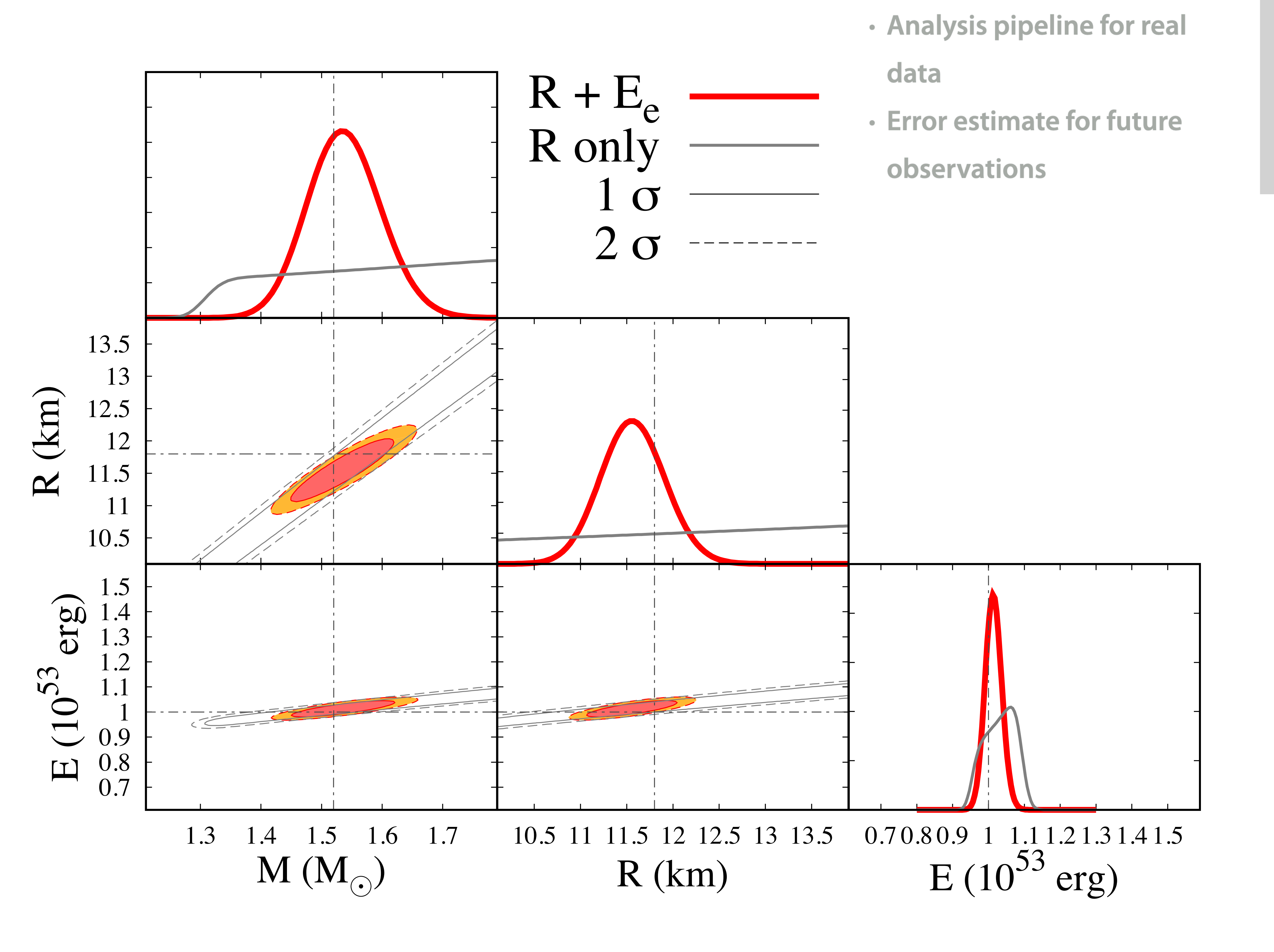
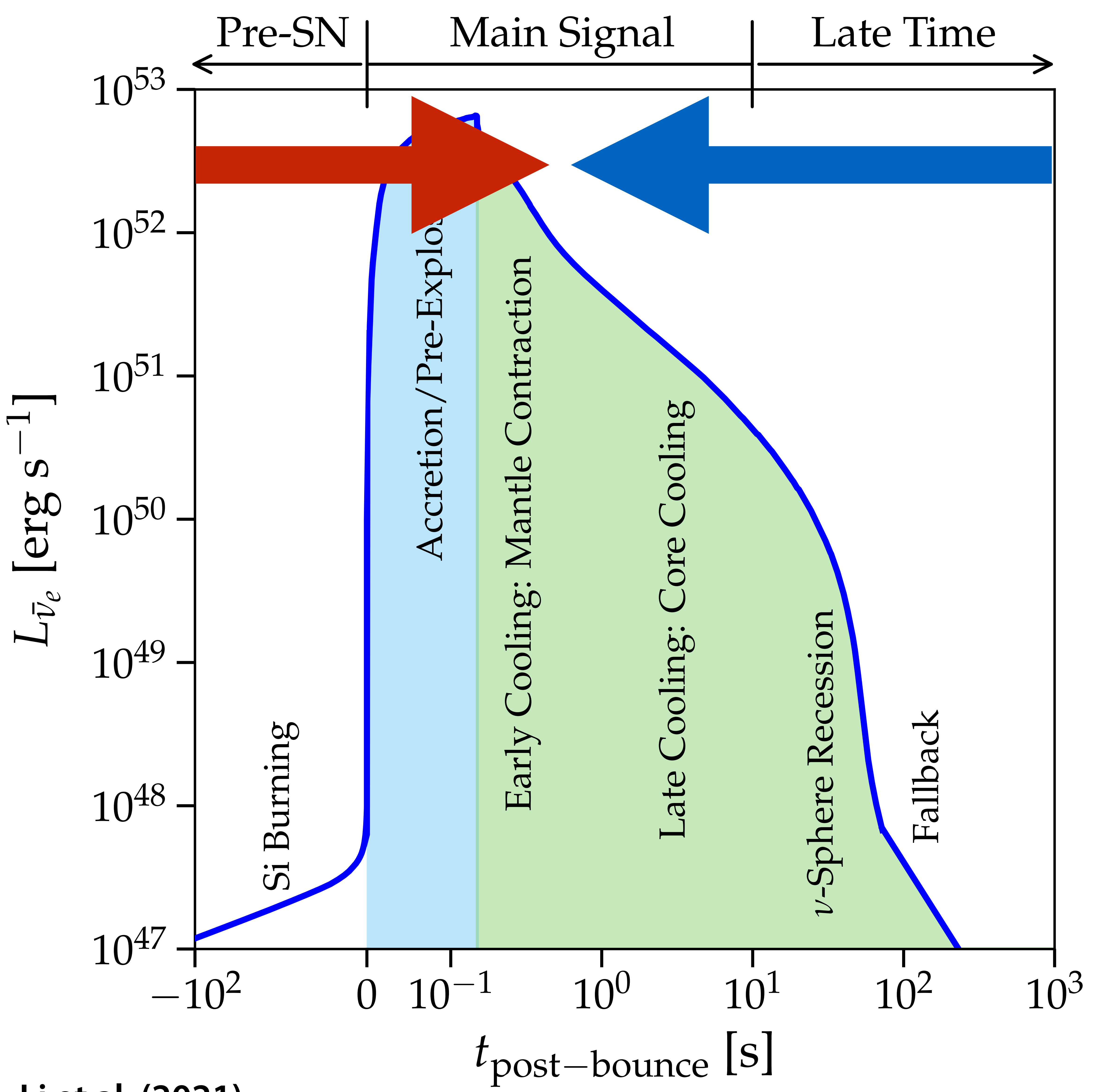




See also Mori-san's talk

Analysis code *SPECIAL BLEND* is available from github

Toward a comprehensive model



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