超新星SN1987Aからのニュートリノ信号再解析による中性子星NS1987Aのパラメータ推定

原田 了 (理研iTHEMS)

共同研究者: nuLCコラボレーション (中里健一郎 (九州大), 中西史美, 原田将之, 小汐祐介 (岡山大), 赤穂龍一郎 (早稲田大), 森正光 (国立天文台), 諏訪雄大 (東京大), 住吉光介 (沼津高専), ロジャー・ウェンデル (京都大))

nuLC collaboration

neutrino Light Curve

ICRR Institute for Cosmic Ray Research University of Tokyo

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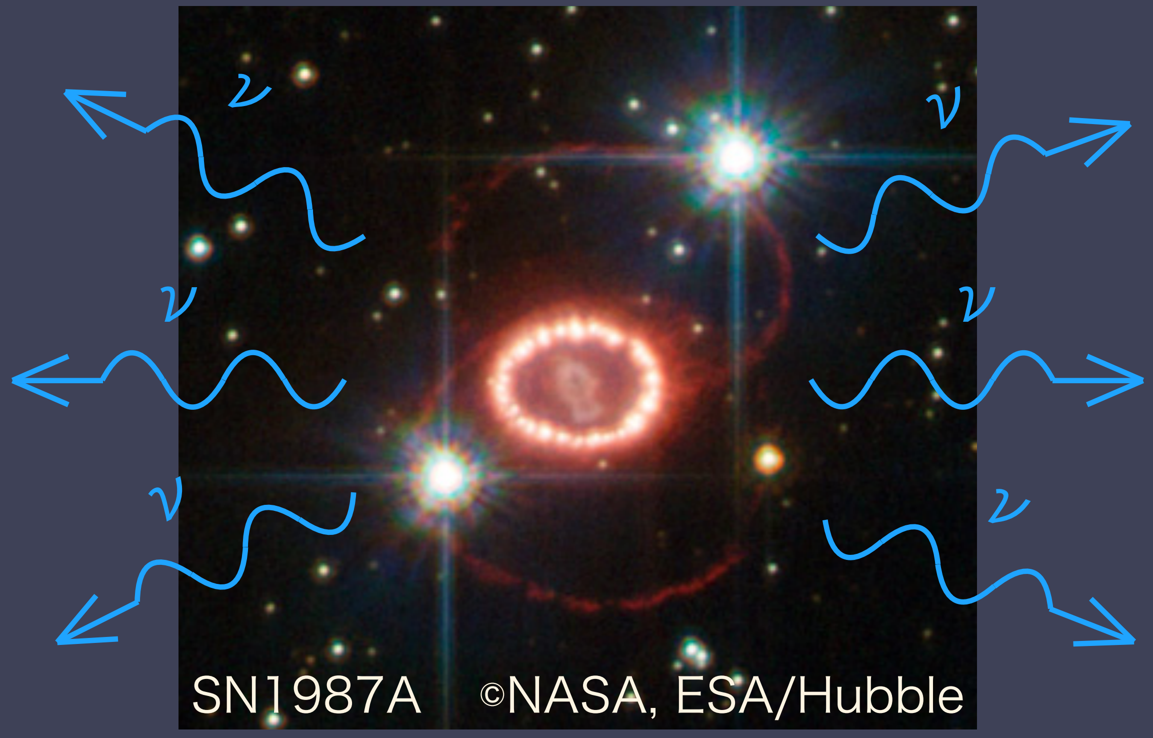
Ken'ichiro Nakazato (Kyushu U., theo.)

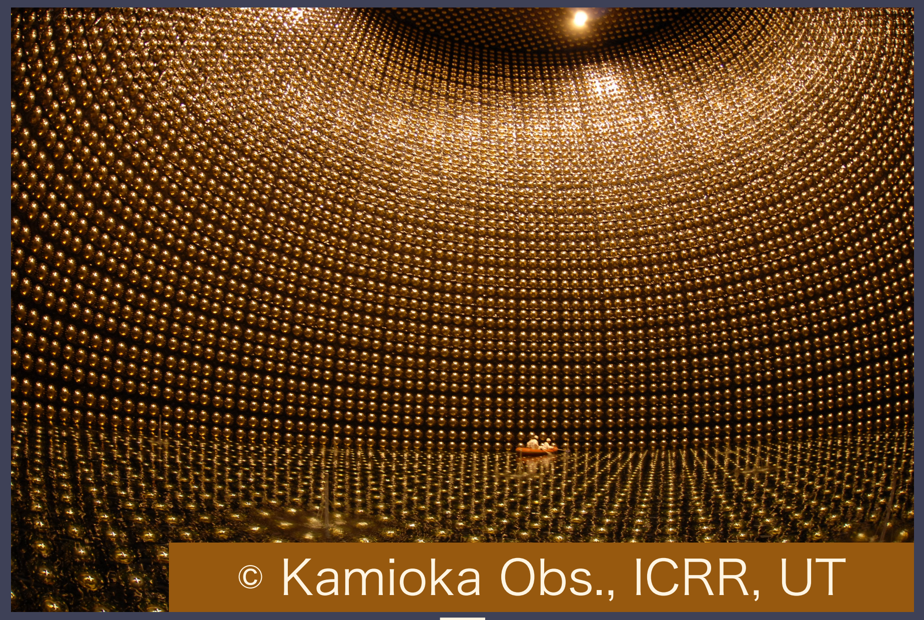
Kosuke Sumiyoshi (Numazu tech., theo.)

Supernova ν-observation & theory

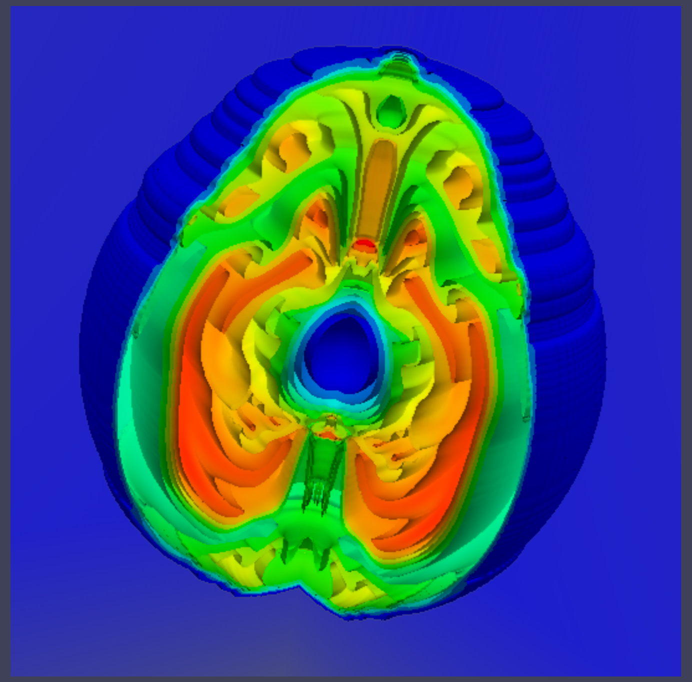
ν-emission from supernova

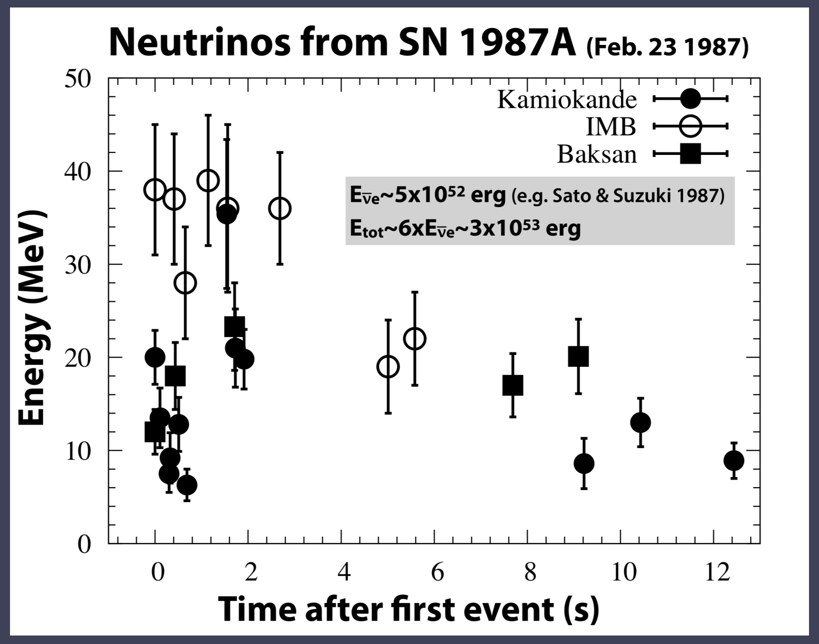
Supernova theory





State-of-the-art simulations





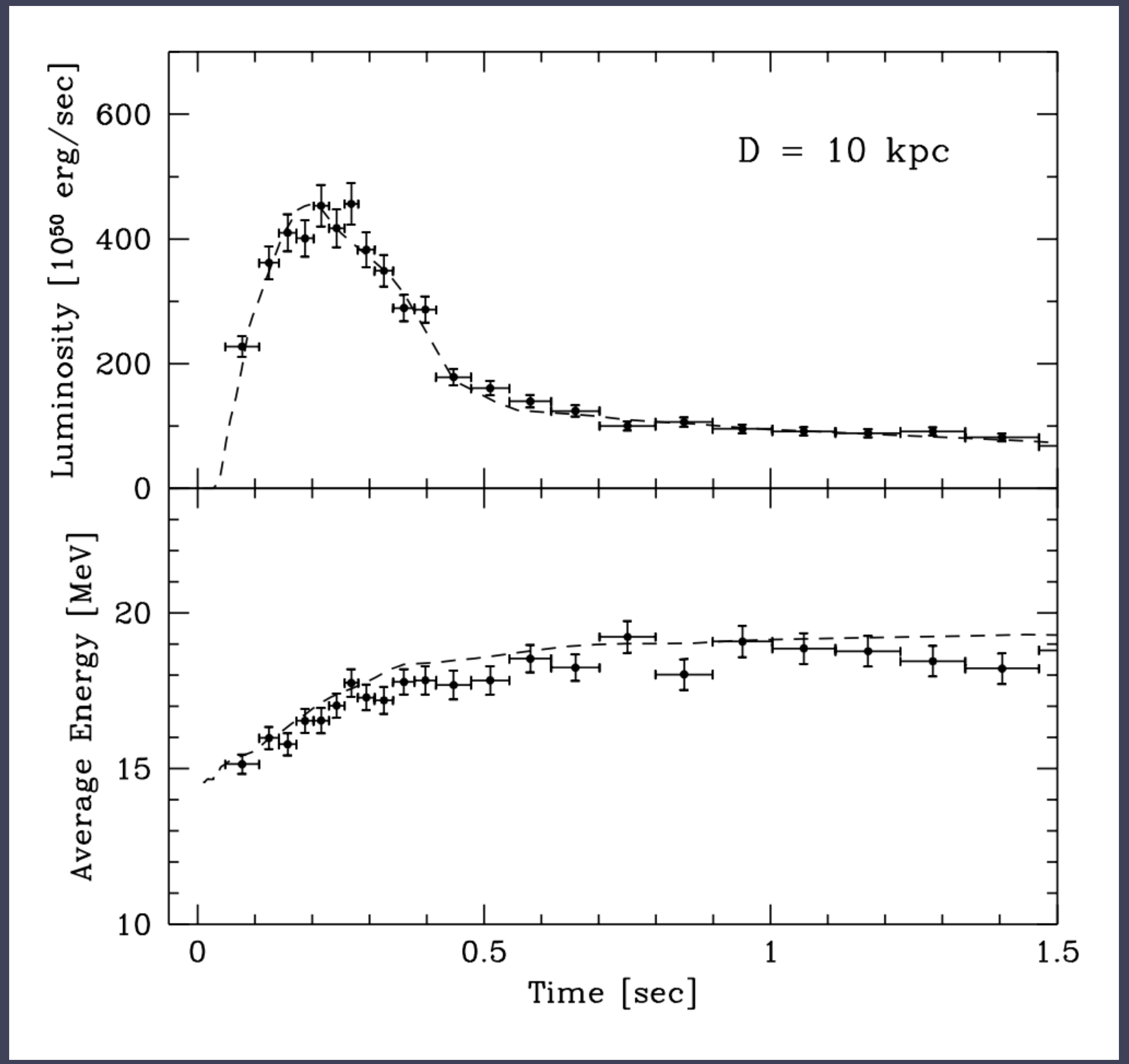
Courtesy of Suwa

Neutrino observation

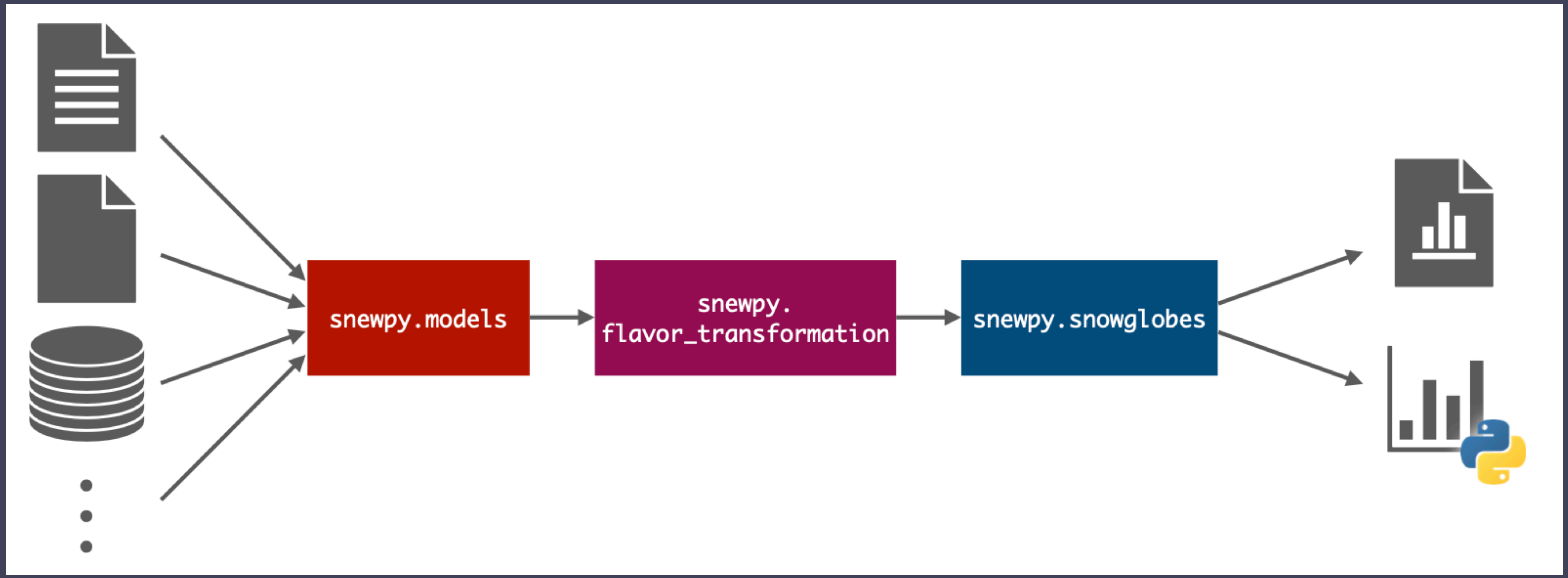
only SN1987A

Supernova ν-observation & theory

- Supernova neutrino theoretical prediction (theoretical template)
  - Totani (Levermore) model (based on Wilson's simulation)
  - SNEWPY (SNOwGLoBES/sntools) (cannot judge models)
- Close collaboration b/w supernova theorists and neutrino experimentalists is required!



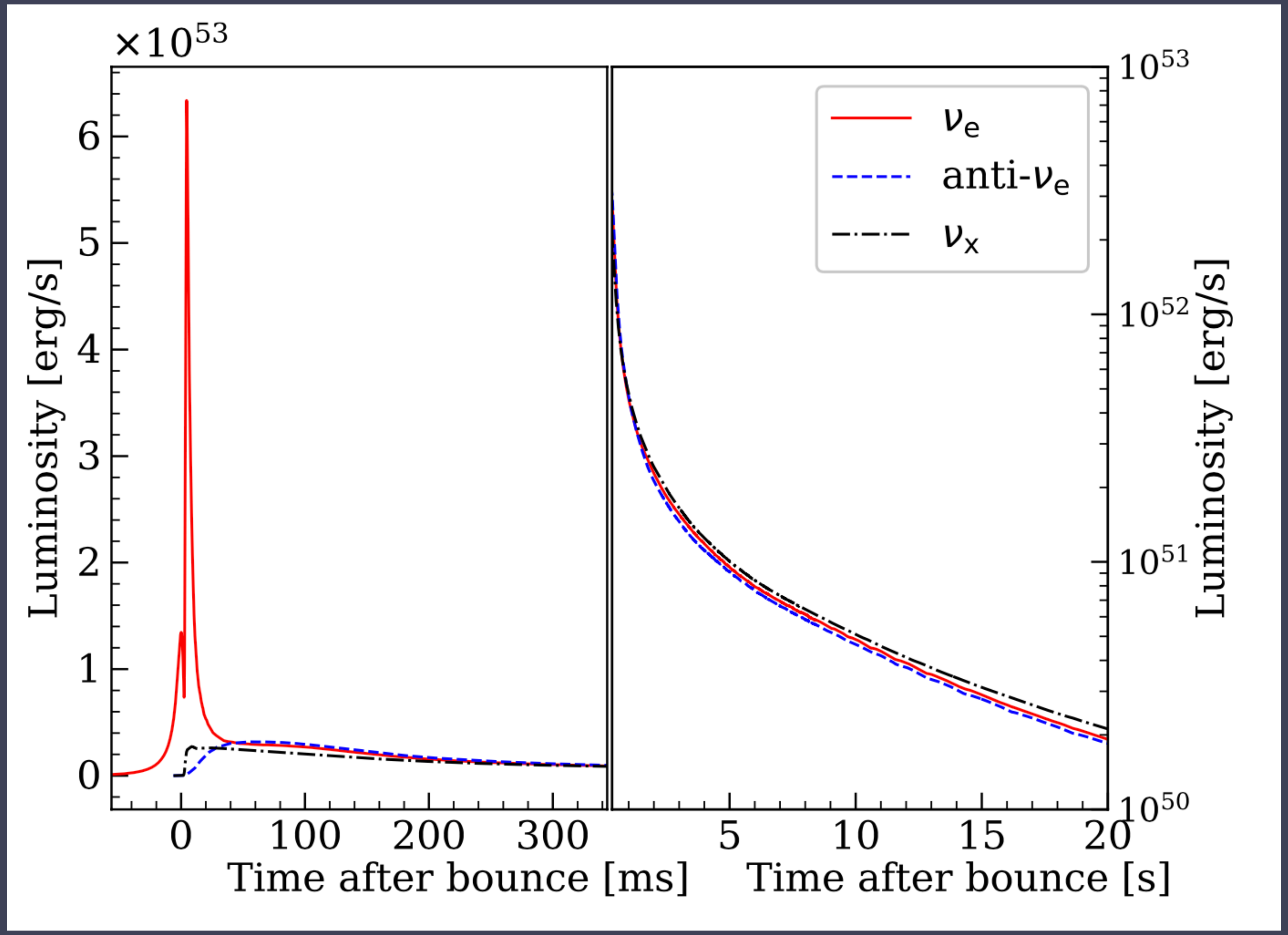
Totani+ (1997)



Bakster+ (2021)

Phases of supernova neutrino

- Explosion phase

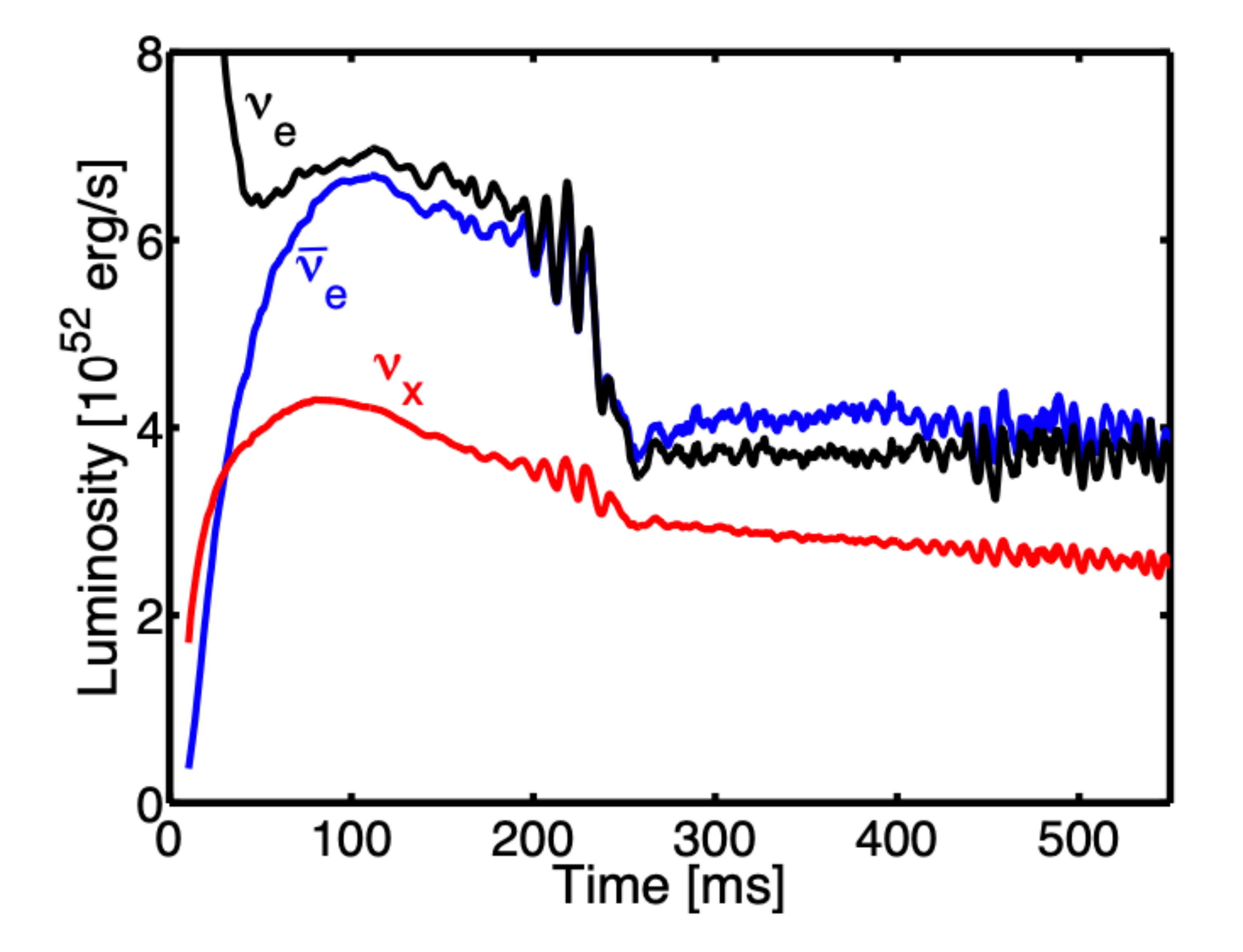


Mori+ (2021)

- PNS cooling phase

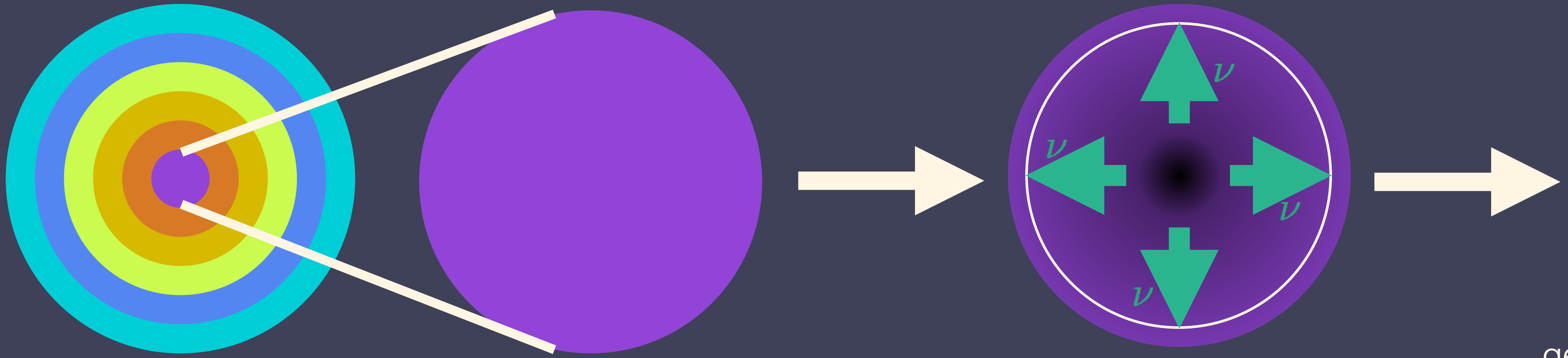
Early explosion phase

- Explosion phase
- Various physical processes involved, theoretically uncertain
- Segerlund+ (2021), Migenda+ (2021), Nagakura & Vartanyan (2022), Olsen & Qian (2022)



Tamborra+ (2014)

- PNS cooling phase



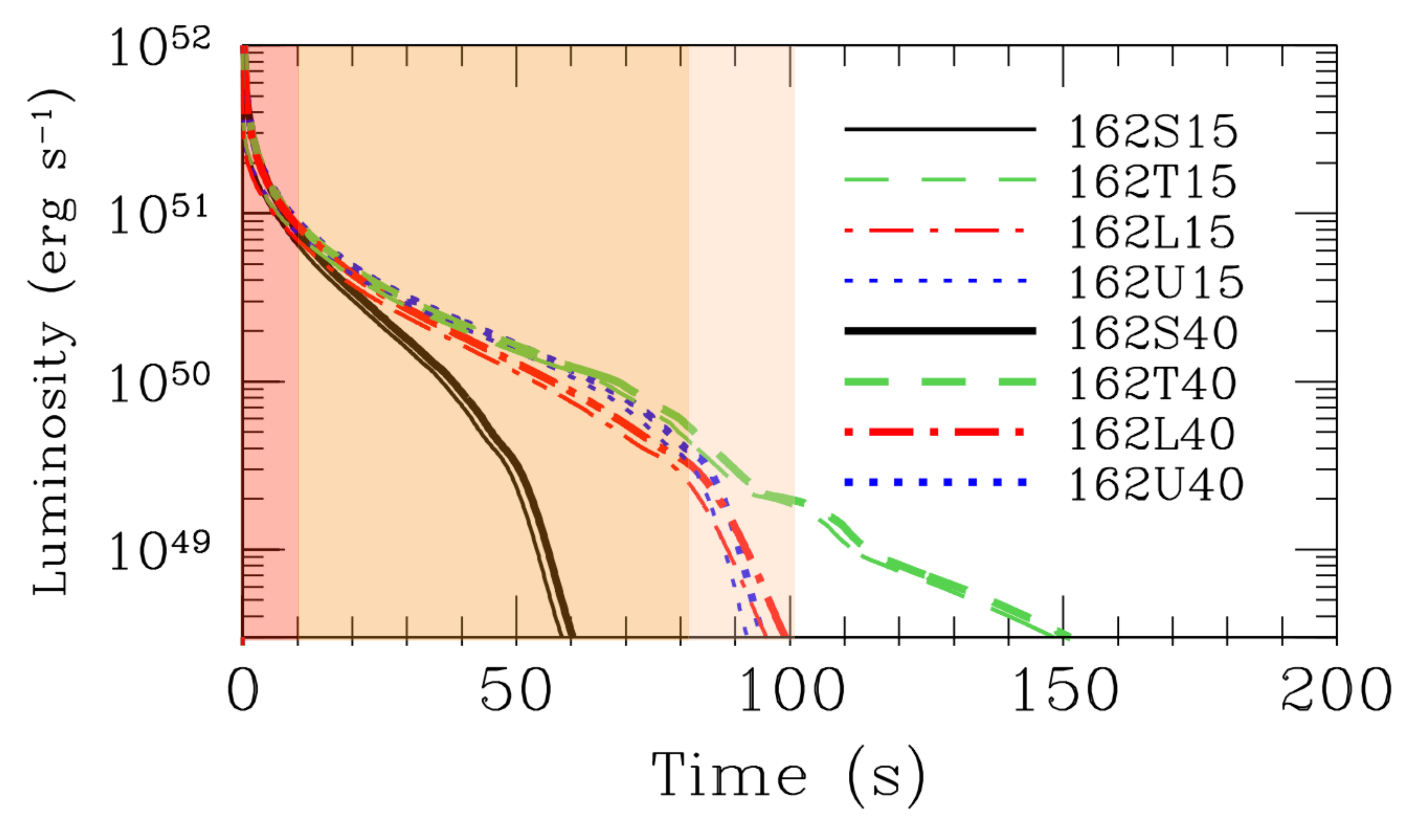
generated by DreamStudio

core collapse→core bounce→stalled shock→turbulence→shock revival

Late PNS cooling phase

- Explosion phase
- Various physical processes involved, theoretically uncertain

Nakazato+ (2022)



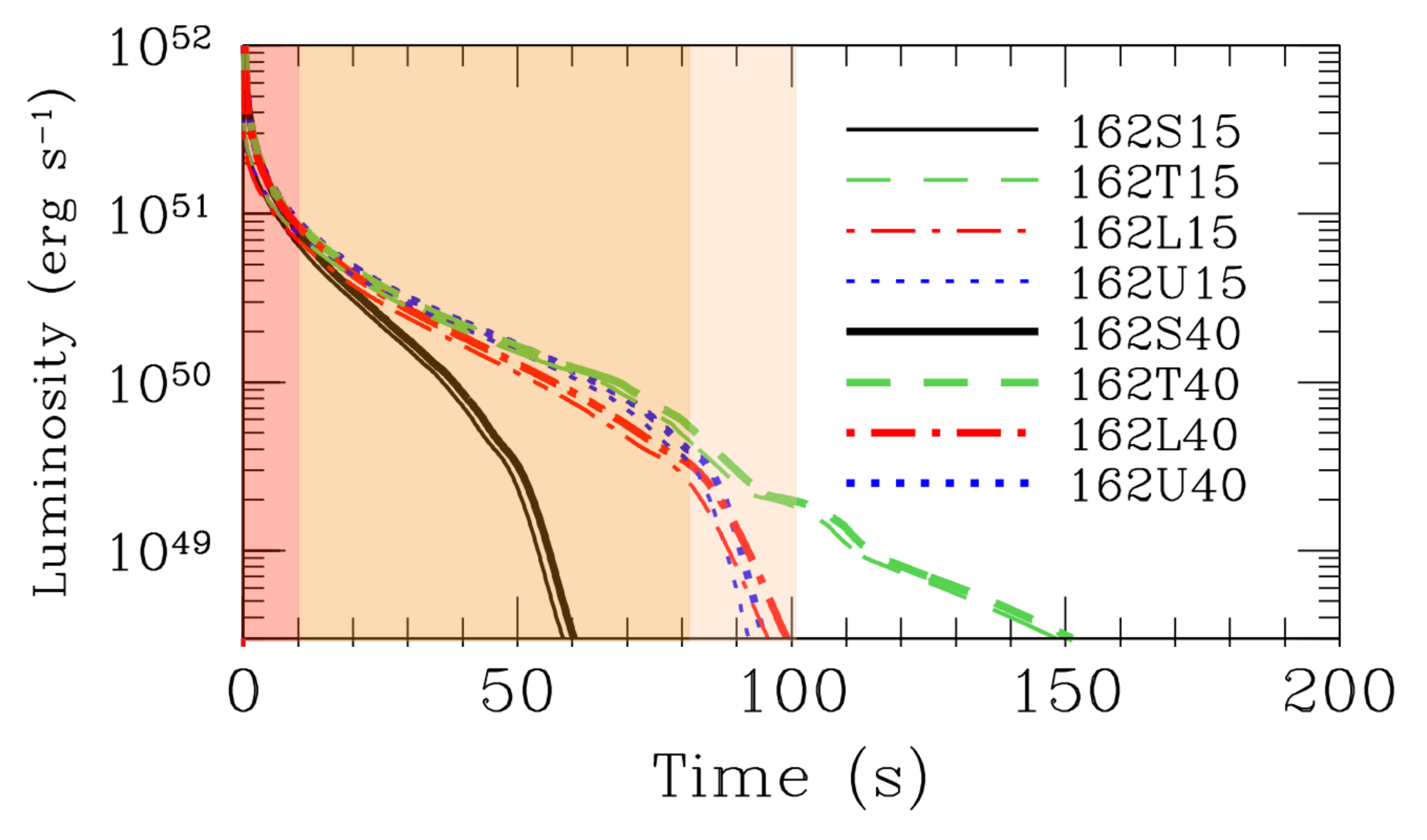
- PNS cooling phase
- Relatively simple, less uncertain
- The focus of nuLC collab.

→A robust estimation of the simple late phase is a clue for the complicated early phase

Late PNS cooling phase

- Explosion phase
- Various physical processes involved, theoretically uncertain

Nakazato+ (2022)



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Late PNS cooling phase

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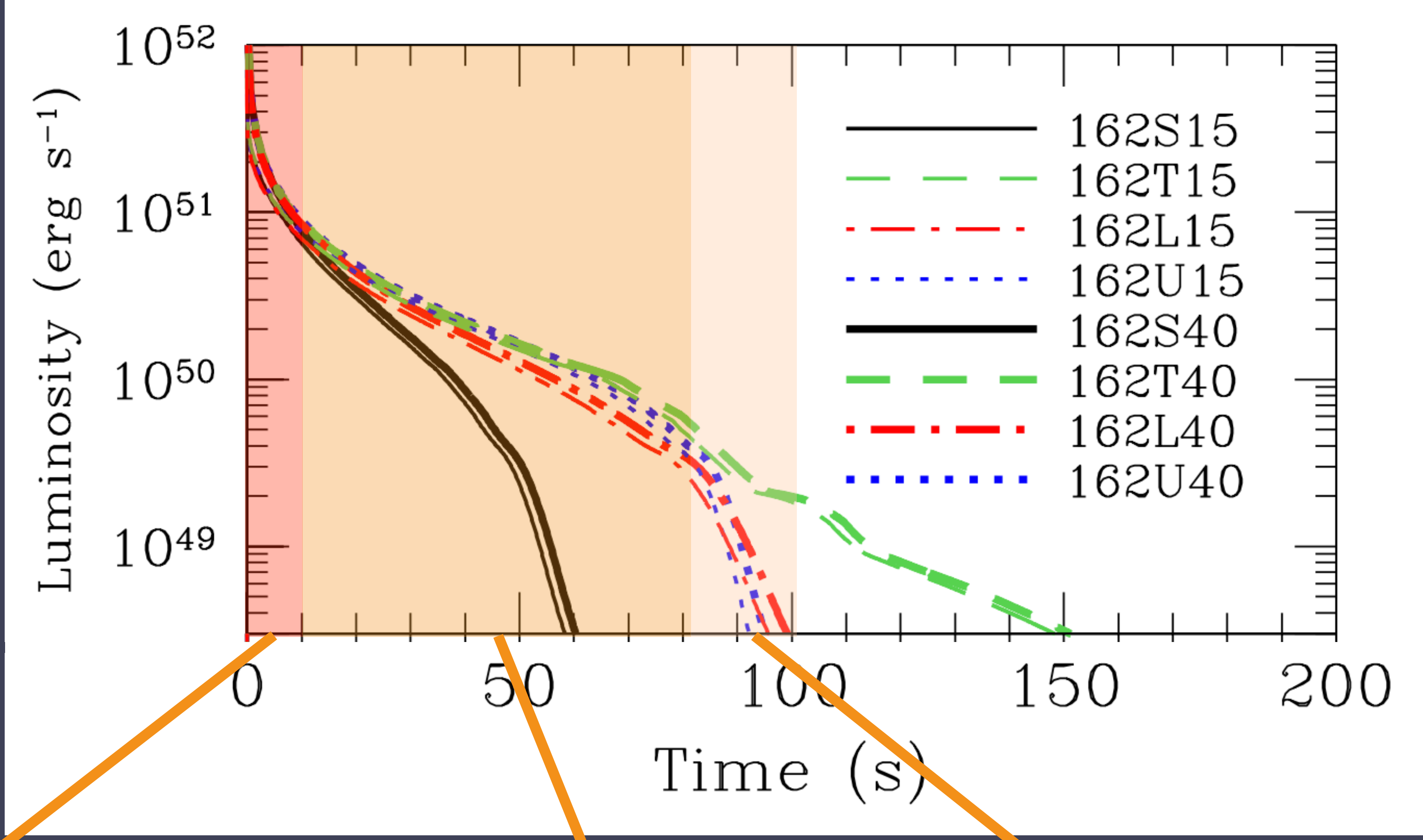
Nakazato+ (2022)



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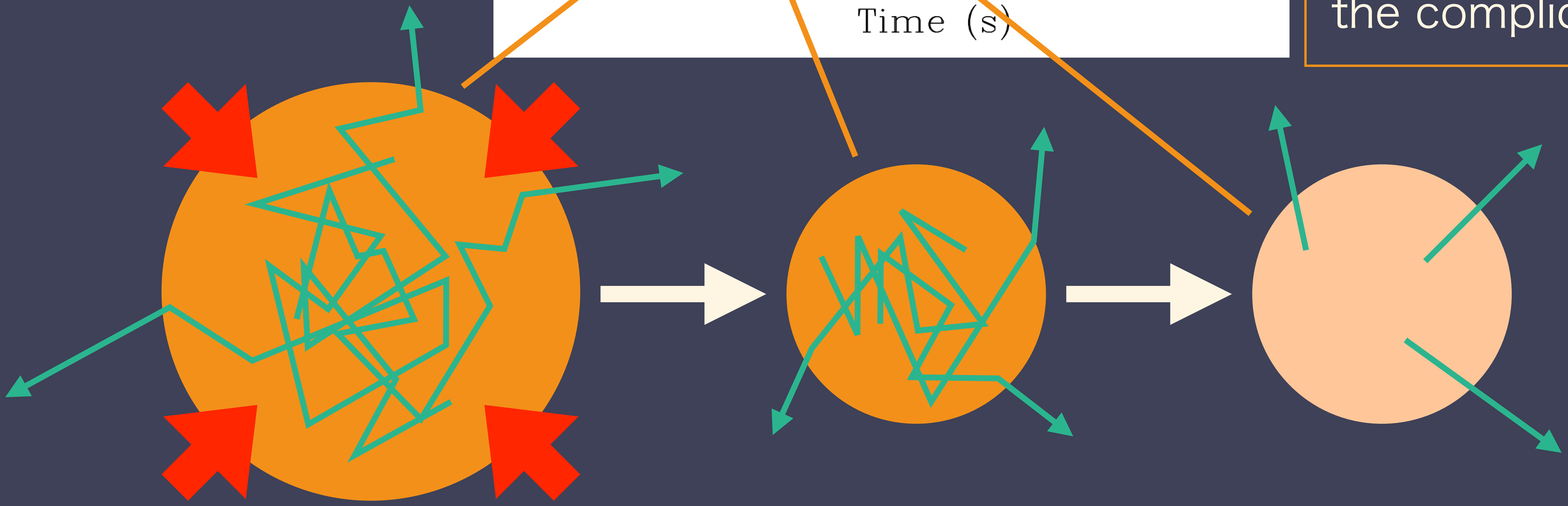


Mantle contraction→shallow decay→volume cooling

Suggestions from nuLC collab.

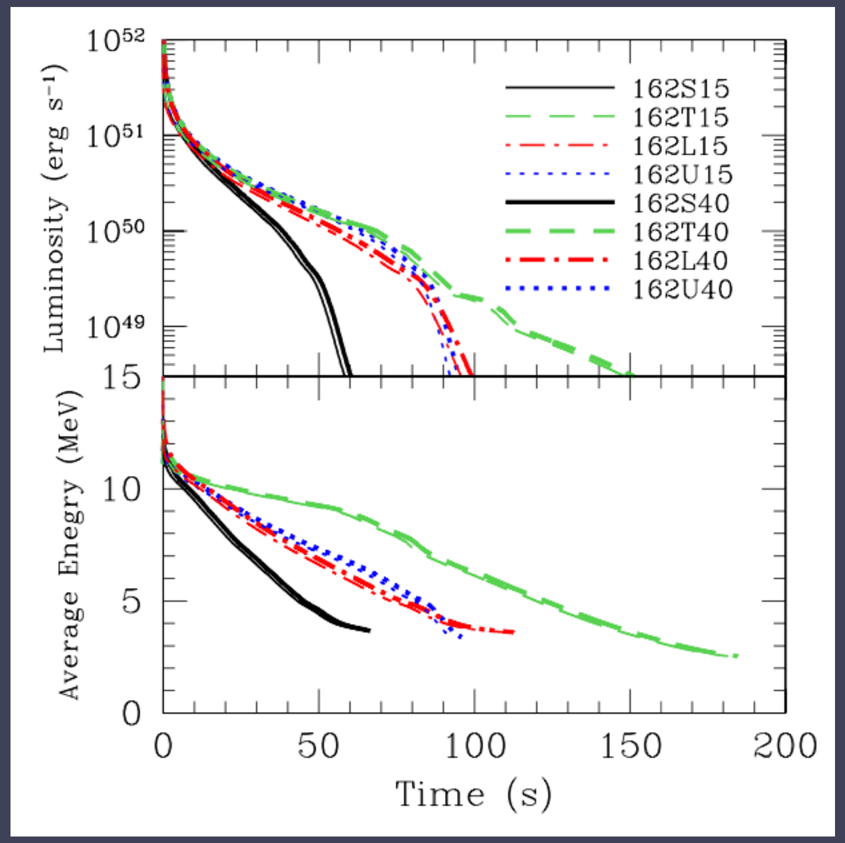
Theoretical template

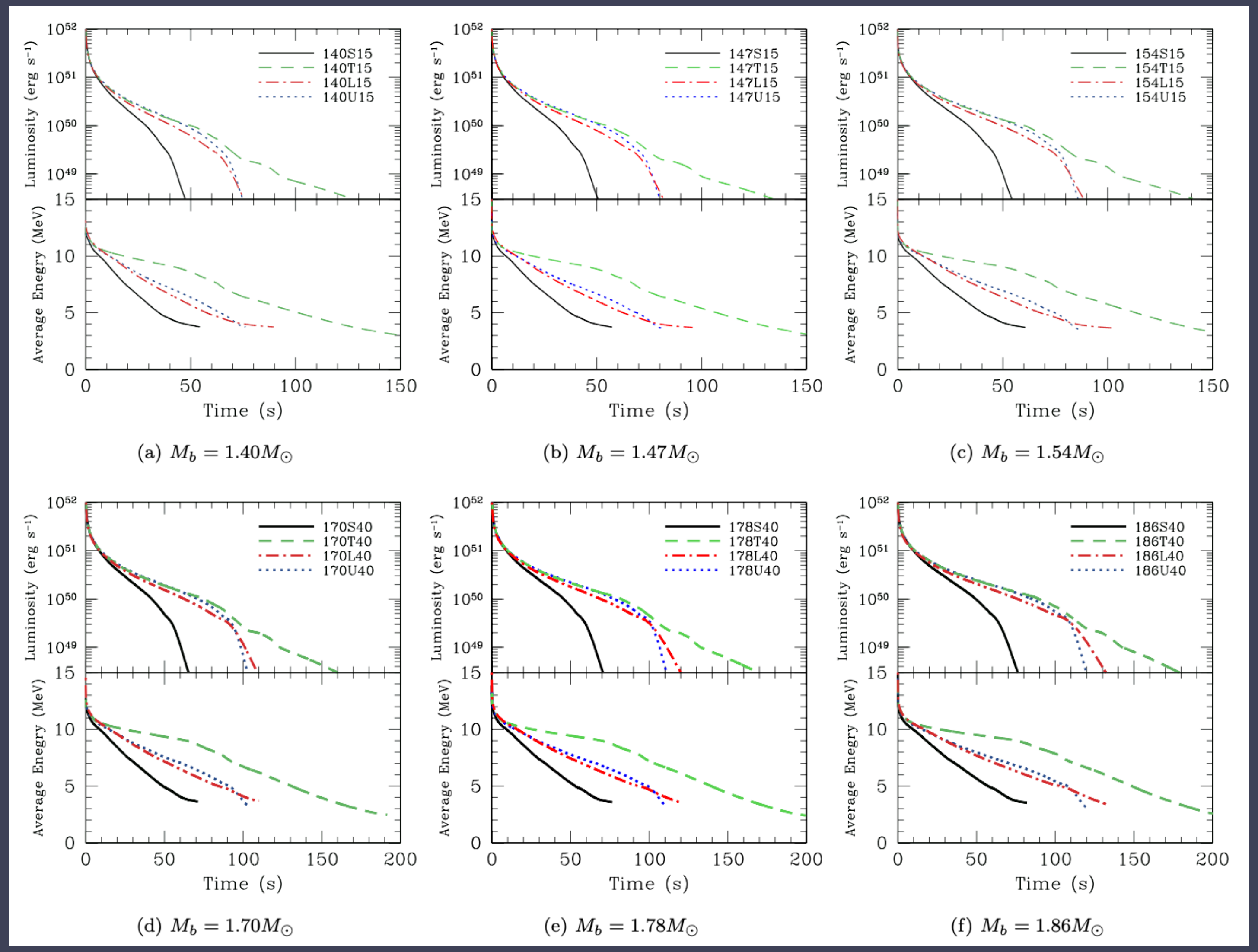
- Nakazato's database (DB)
  PNS cooling simulation with many PNS masses and EOSs
- Mori's DB
  Core collapse simulations of 1D-explodable light progenitors with improved public code, GR1D
- Analytic model
  Analytic solution with the Lane-Emden solution and neutrino diffusion approximation

Analysis method/pipeline

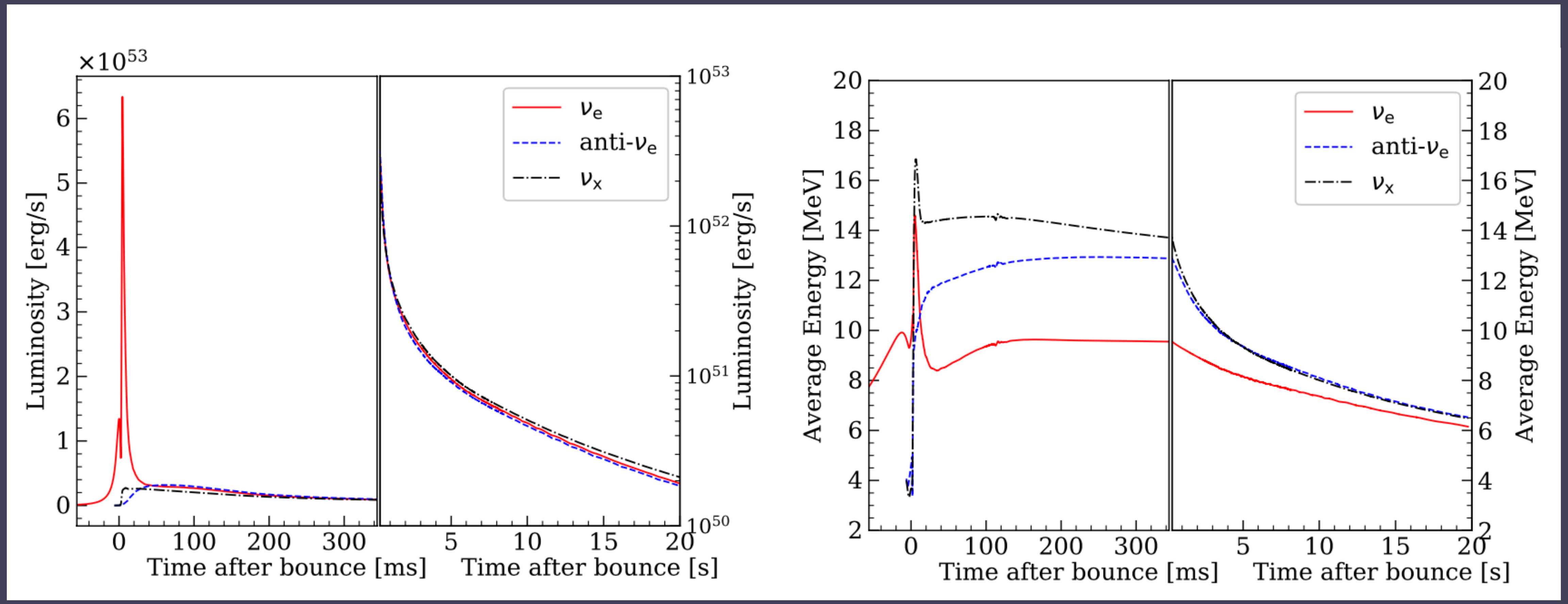
- backward time analysis
  Backward cumulative event count from last one event is useful to estimate the PNS mass
- χ-square fitting
  Obs. data fitting based on the count rates and mean energies from the analytic model
- SPECIAL BLEND
  Public analysis code using the spectral information and Poisson likelihood

Theoretical template: Nakazato's and Mori's database





Nakazato+ (2022)



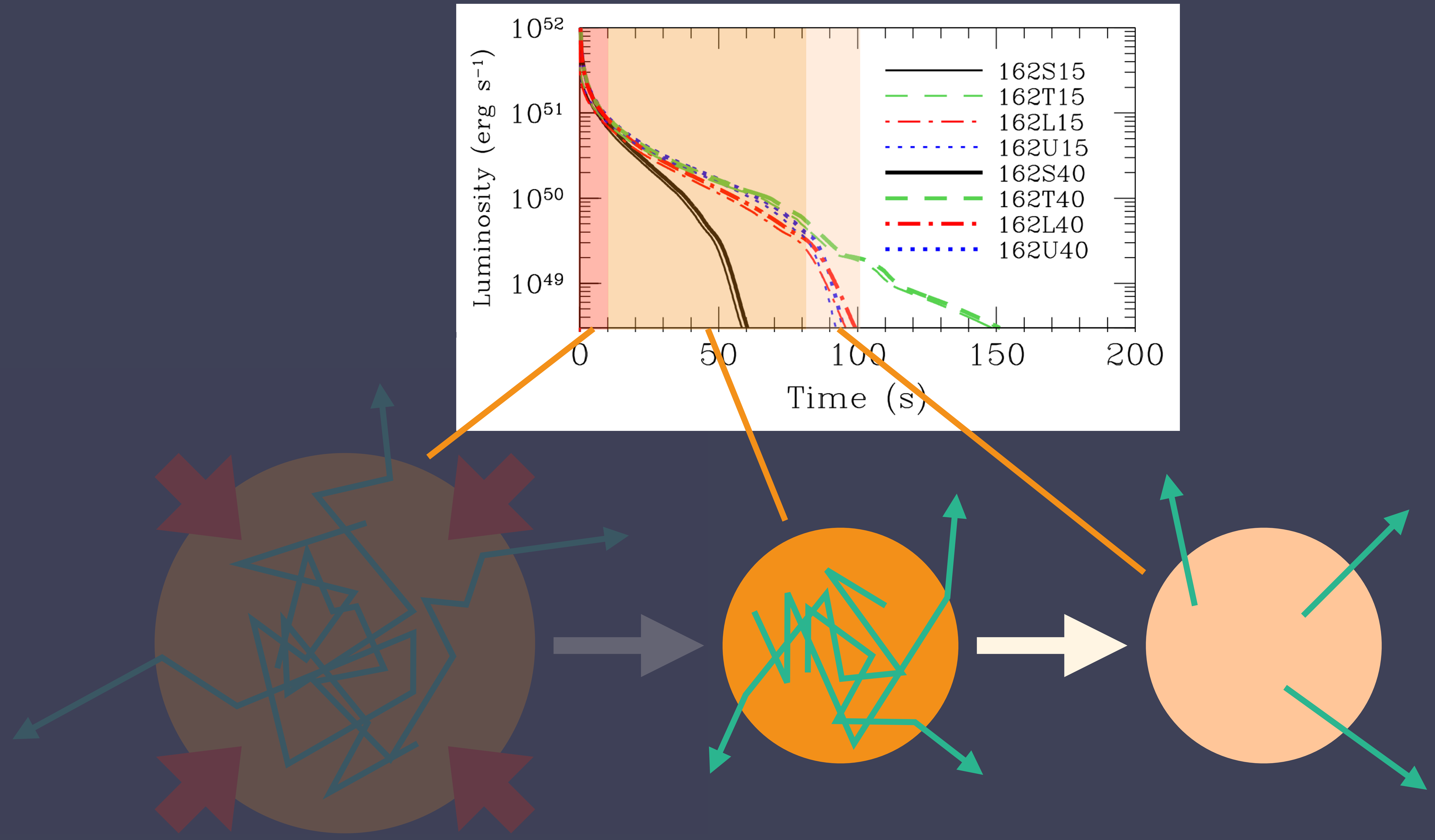
Mori+ (2021)

- Nakazato's DB
  Quasi-steady state PNS cooling simulations with diffusion approx. using various PNS masses and nuclear EOSs.

- Mori's DB
  Dynamical Simulations of core collapse, explosion, and PNS cooling using the improved GR1D
  (Progenitors are light enough to explode under 1D)

Theoretical template: Analytic model

- Target: after the shallow decay phase when the mass and radius are fixed



Mantle contraction→shallow decay→volume cooling

Theoretical template: Analytic model

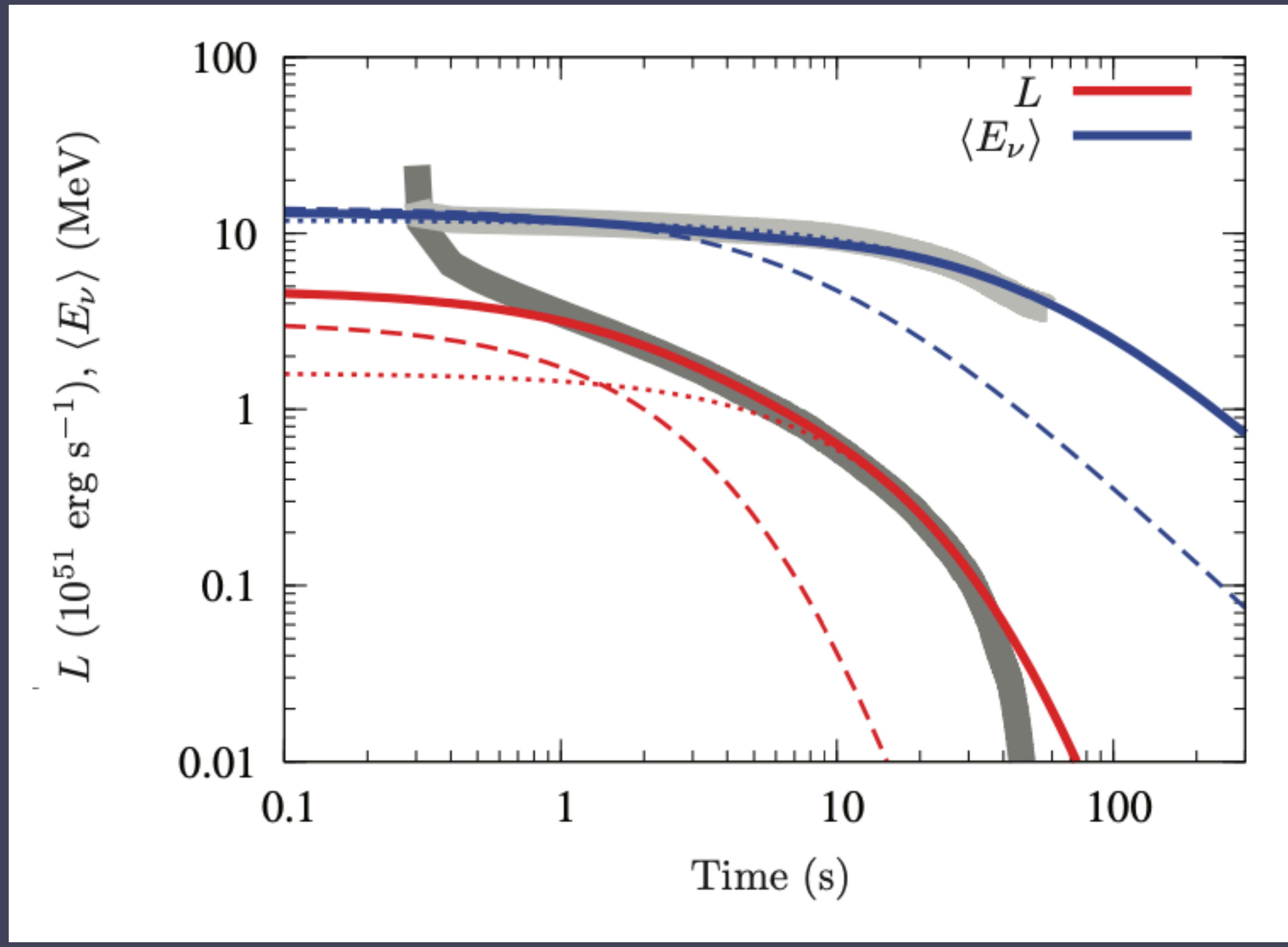
- Target: after the shallow decay phase when the mass and radius are fixed
- PNS structure is determined by γ=2 Lane-Emden equation

→neutrino luminosity and mean energy

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

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

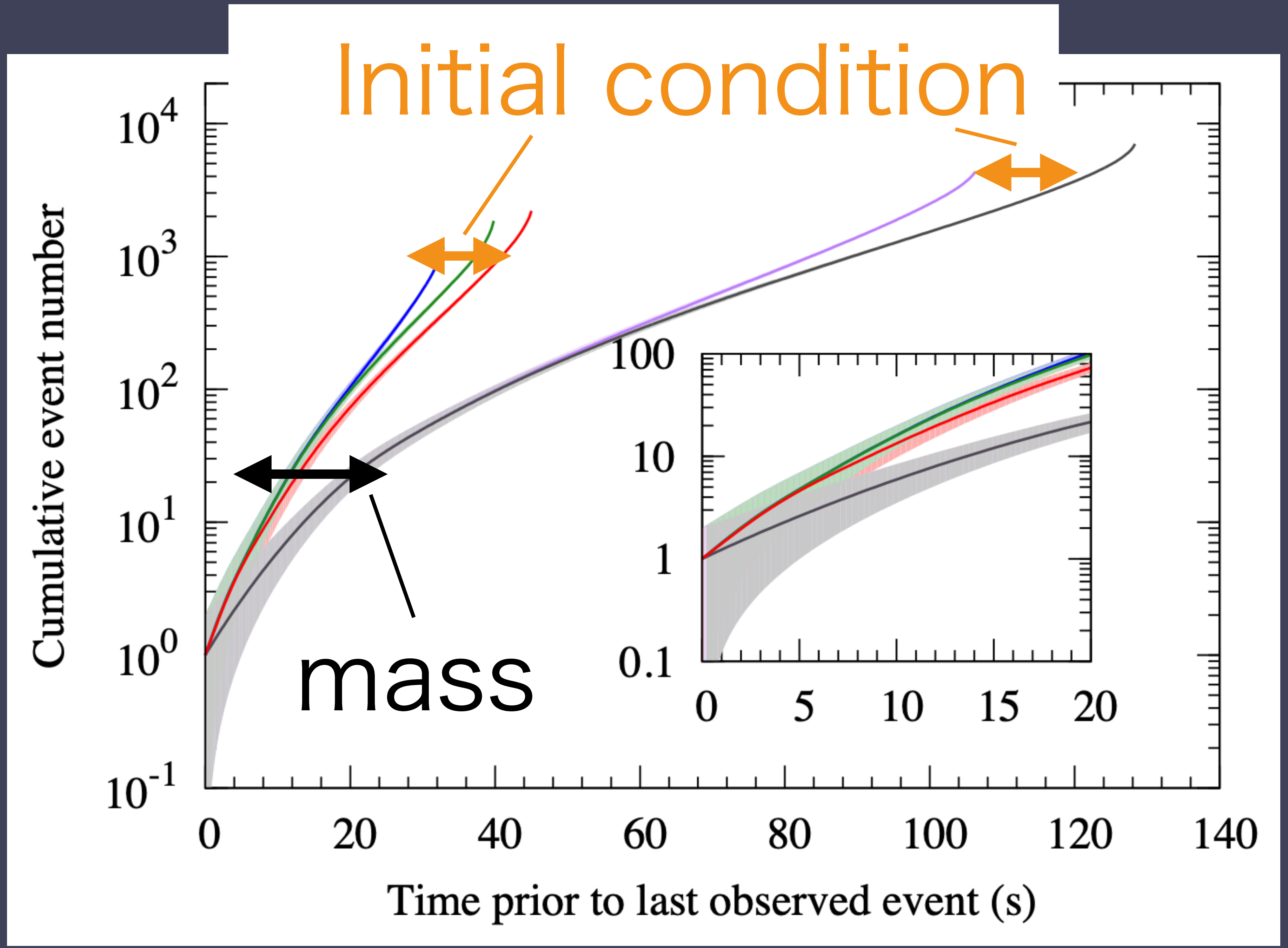
$$t_0 = 210\,\mathrm{s} \left(\frac{M_{\rm PNS}}{1.4\,M_\odot}\right)^{6/5} \left(\frac{R_{\rm PNS}}{10\,\mathrm{km}}\right)^{-6/5} \left(\frac{g\beta}{3}\right)^{4/5} \left(\frac{E_{\rm tot}}{10^{52}\,\mathrm{erg}}\right)^{-1/5}$$



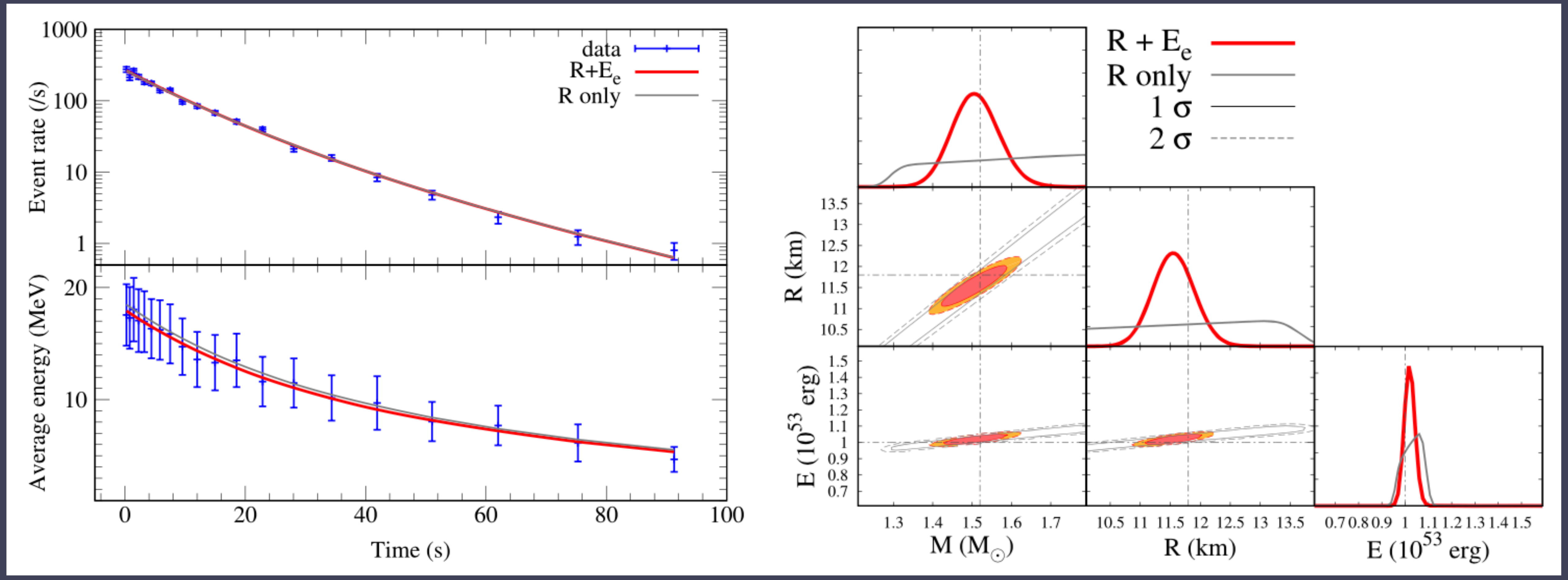
Suwa+ (2021)

- The analytic model has three parameters: $M_{\rm PNS}$、$R_{\rm PNS}$、$E_{\rm tot}$ (total emitted neutrino energy during the shallow decay phase; not the total binding energy of the neutron star)

Proposal of analysis methods



Suwa+ (2019)



Suwa+ (2022)

- backward time analysis
  Backward cumulative event count from last one event is useful to estimate the PNS mass.

Theo. rate

Obs. mean ene.

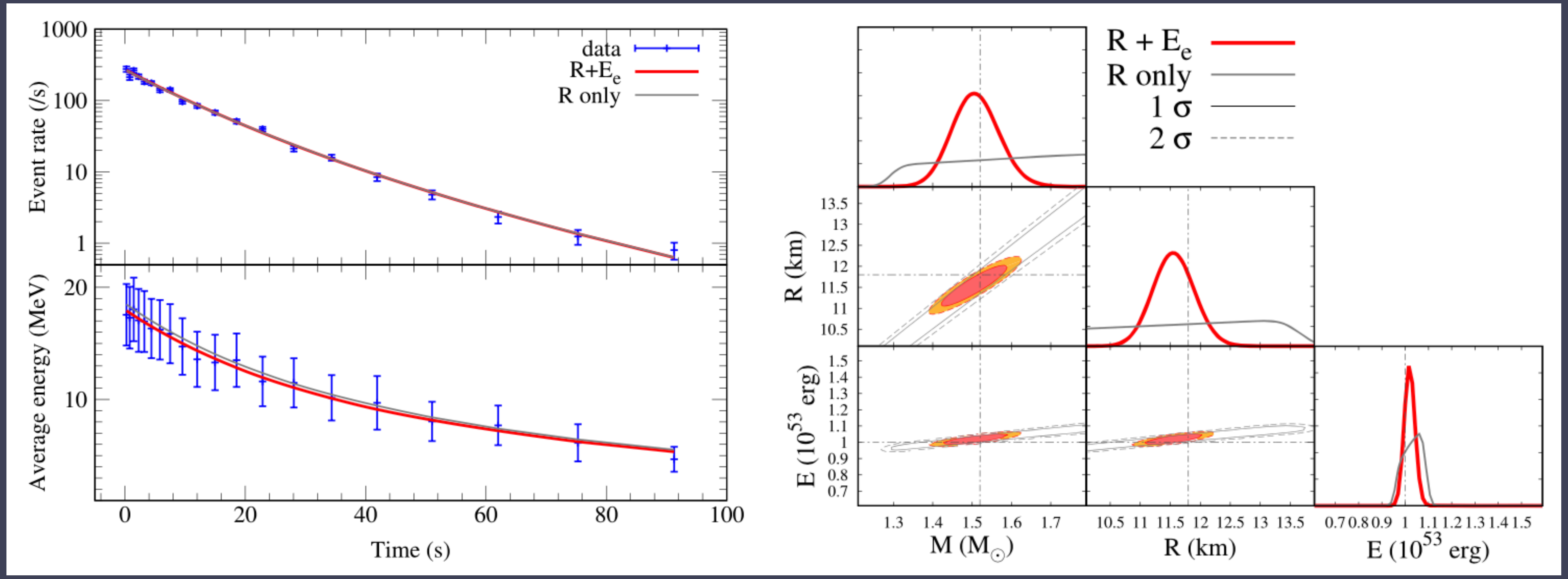
Theo. mean ene.

Obs. rate

$$\chi^2 = \sum_{i \in \text{time bin}} \left(\frac{(N_i/\Delta t_i - \mathscr{R}_i)^2}{\mathscr{R}_i^2/N_i} + \frac{(\langle \epsilon \rangle_i - E_{e^+,i})^2}{(0.05E_{e^+,i})^2} \right)$$

- χ-square fitting
  Search for the parameters that minimize χ^2 defined with the count rate and mean energy of the analytic model

Proposal of analysis methods



Suwa+ (2022)

Obs. rate

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Theo. mean ene.

$$\chi^2 = \sum_{i \in \text{time bin}} \left(\frac{(N_i/\Delta t_i - \mathscr{R}_i)^2}{\mathscr{R}_i^2/N_i} + \frac{(\langle \epsilon \rangle_i - E_{e+,i})^2}{(0.05E_{e+,i})^2} \right)$$

- χ-square fitting

  Search for the parameters that minimize χ^2 defined with the count rate and mean energy of the analytic model

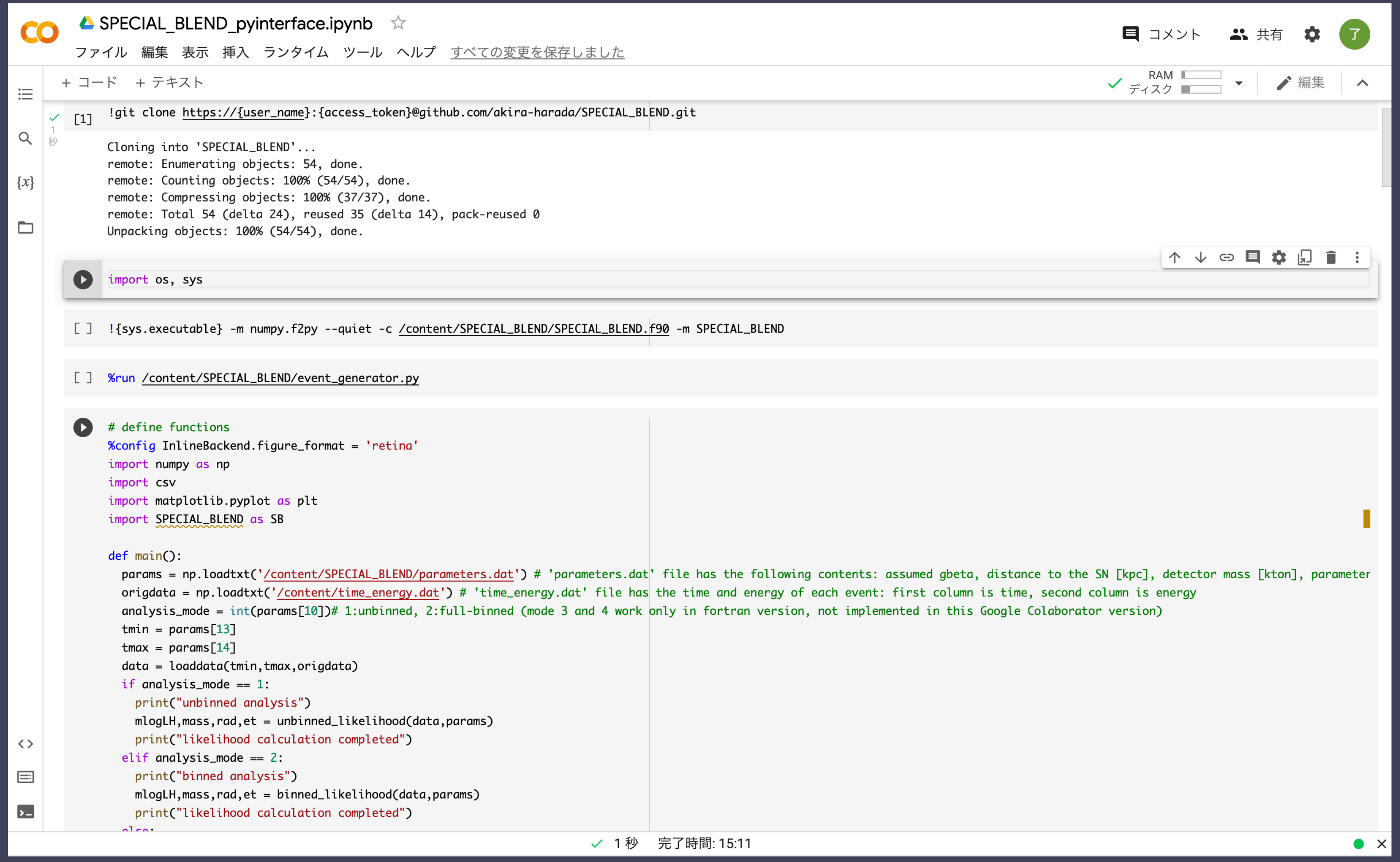
- Using χ^2 is ad hoc, appropriate only for the Gaussian distribution

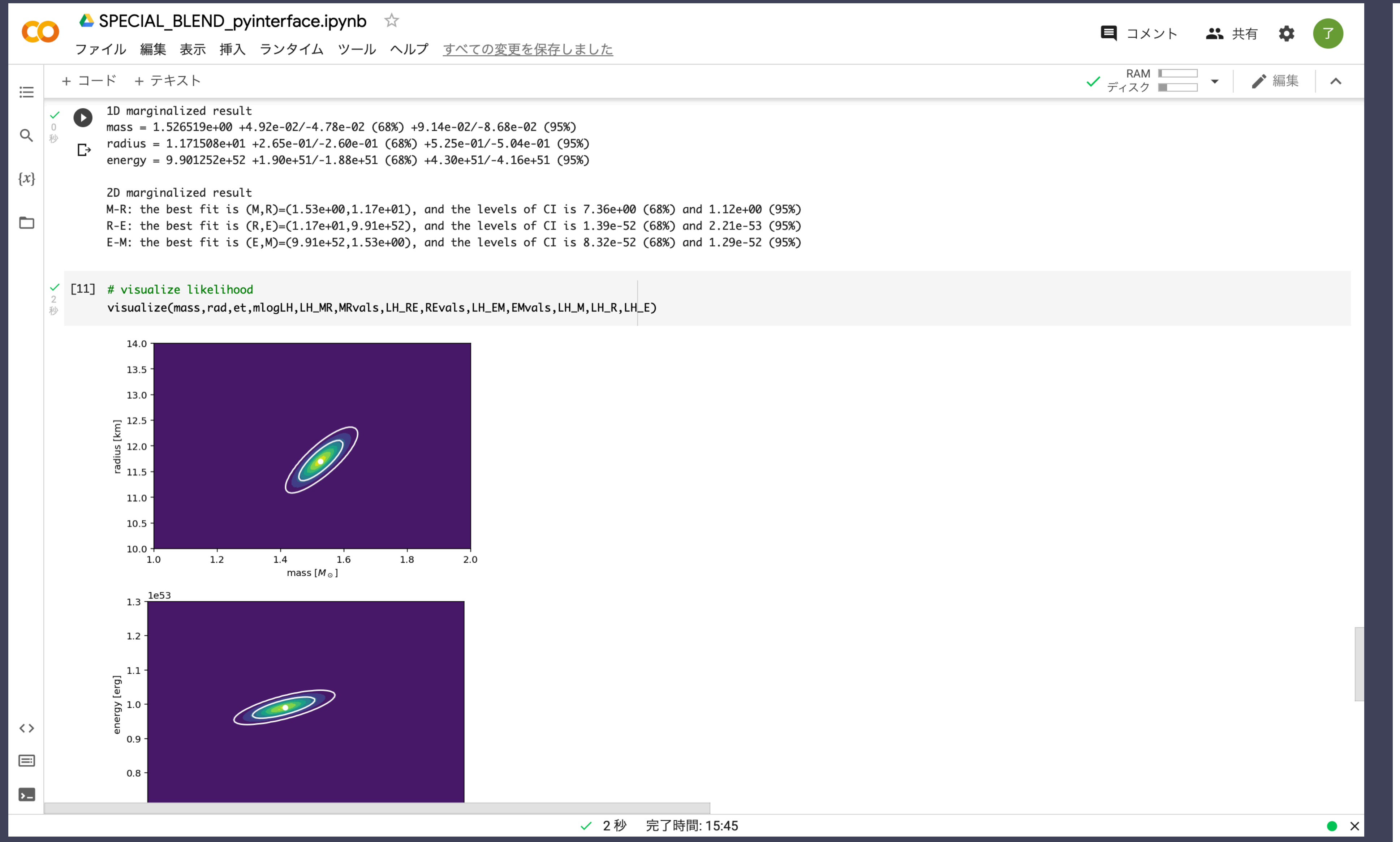
- Poisson distribution is appropriate

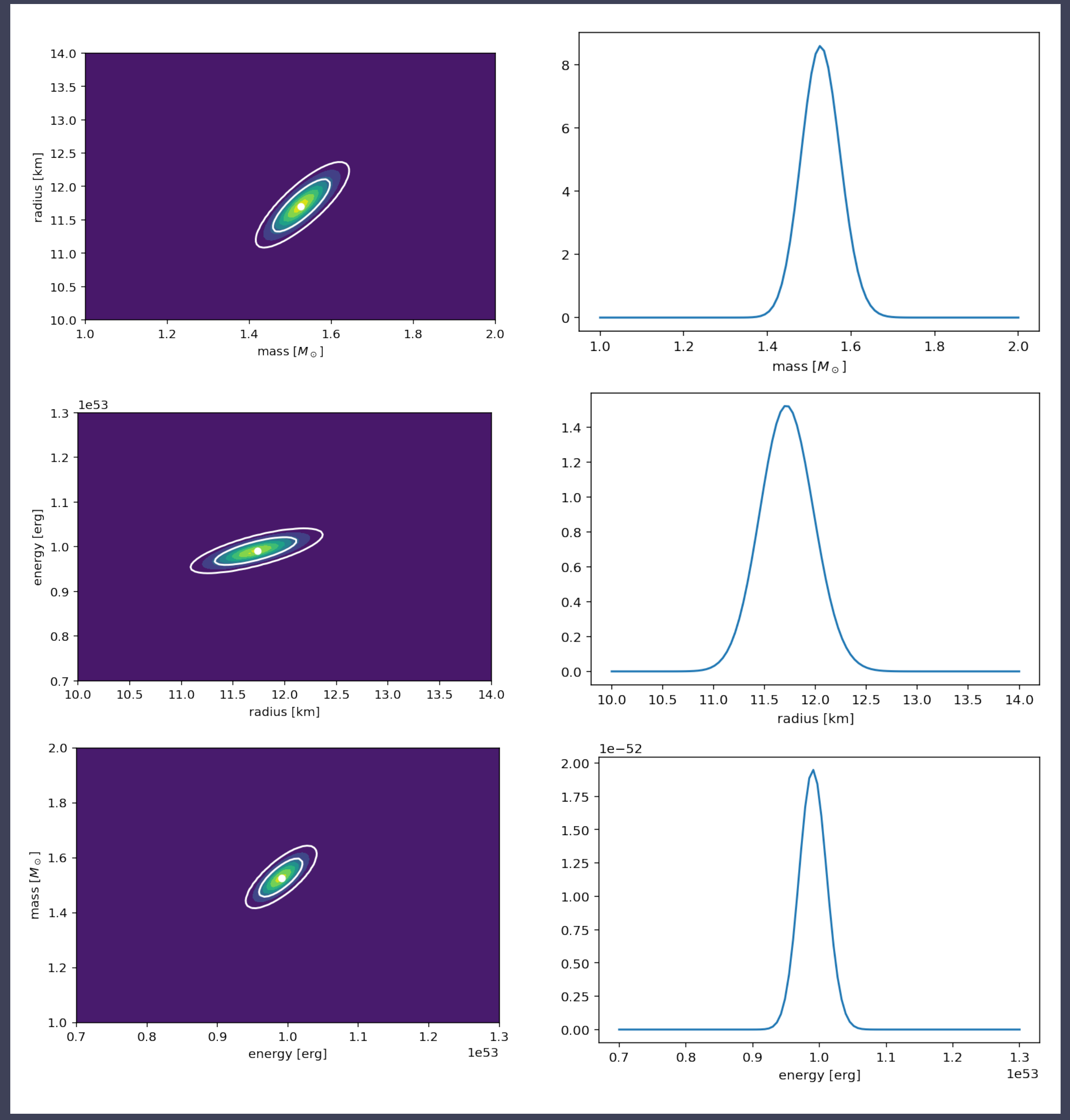
  →applicable to the distant supernovae

Analysis Pipeline : SPECIAL BLEND

- **S**upernova **P**arameter **E**stimation **C**ode based on **I**nsight on **A**nalytic **L**ate-time **B**urst **L**ight curve at **E**arth **N**eutrino **D**etector (SPECIAL BLEND)
- Public analysis code that works on Google colaboratory
- Everyone can easily use!







Analysis Pipeline : SPECIAL BLEND

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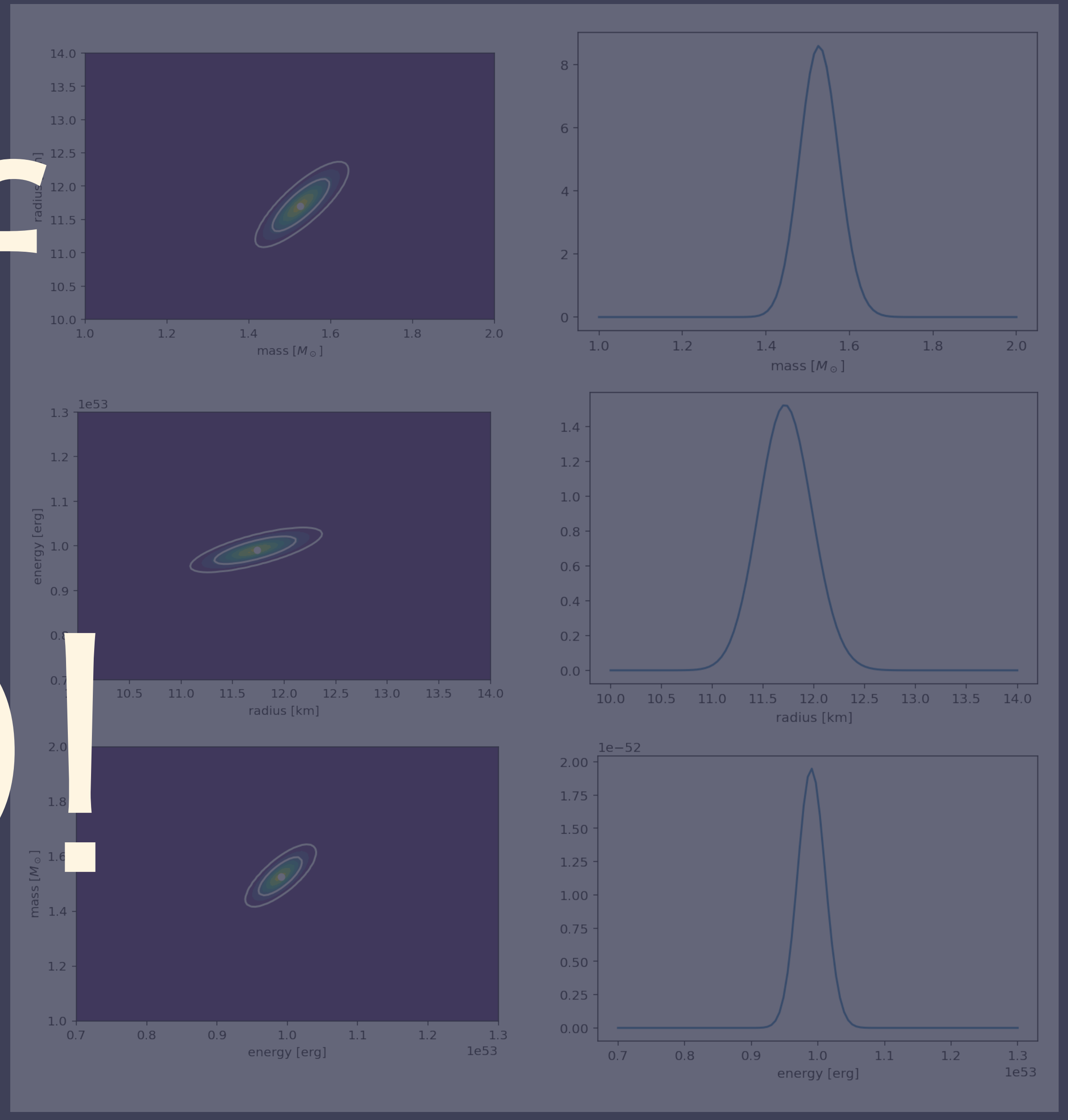
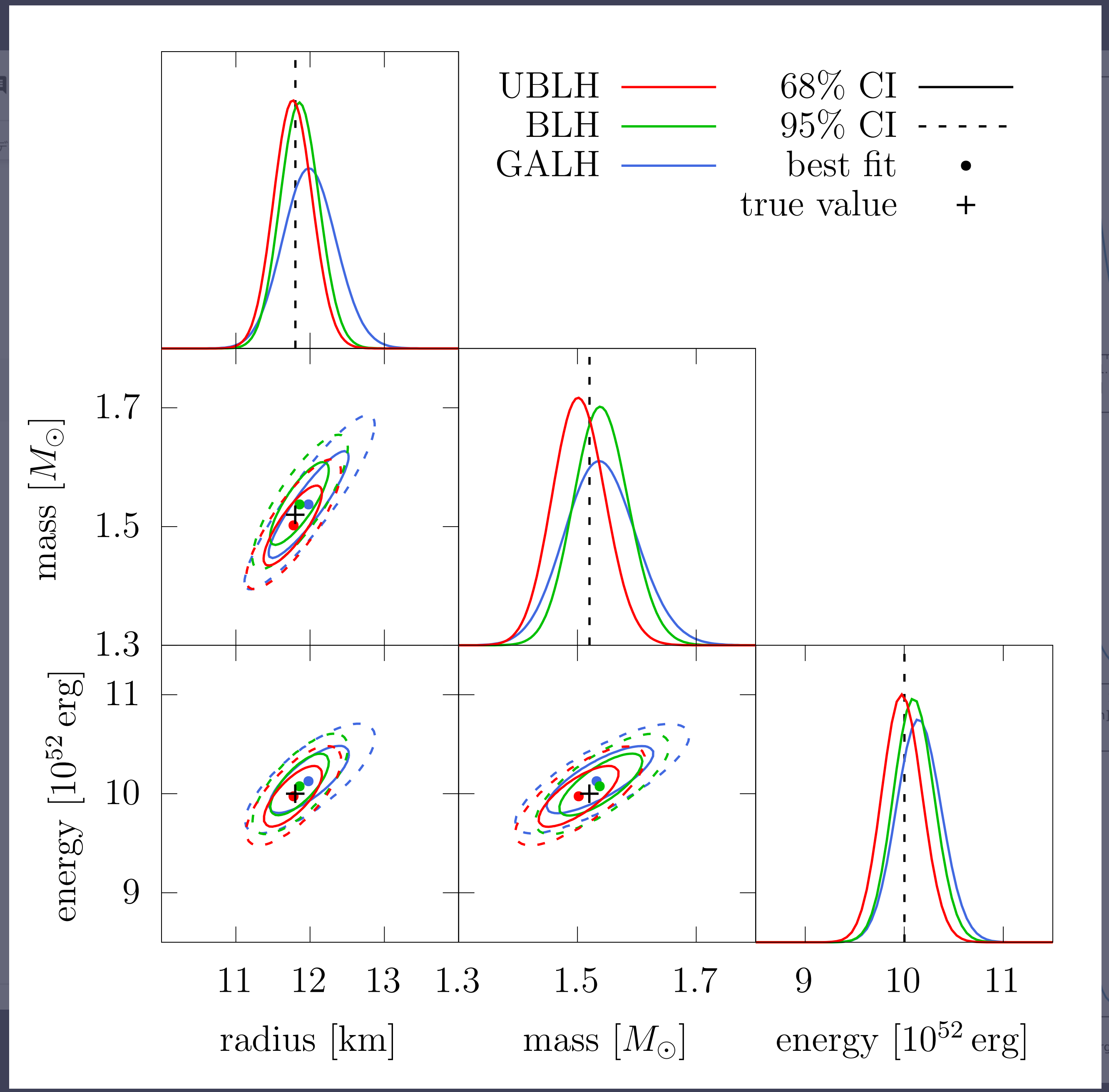


I'll do a demo of SPECIAL BLEND!

解析パイプライン：SPECIAL BLEND

- **S**upernova **P**arameter **E**stimation **C**ode based on **I**nsight on **A**nalytic **L**ate-time **B**urst **L**ight curve at **E**arth **N**eutrino **D**etector (SPECIAL BLEND)
- Google colaboratoryやFortranをコンパイルできるPCで動かせる公開コード(準備中)
- 誰でも簡単に使えるようにしています

- 真のパラメータが68%信用区間に入らないのは3回に1回くらいはありうる
- 100回模擬観測データを生成して、典型的な推定結果が右図
- 赤線と緑線は遠方用と近傍用の解析結果、青線はχ^2の結果
- 典型的には真の値をまあよく再現できる

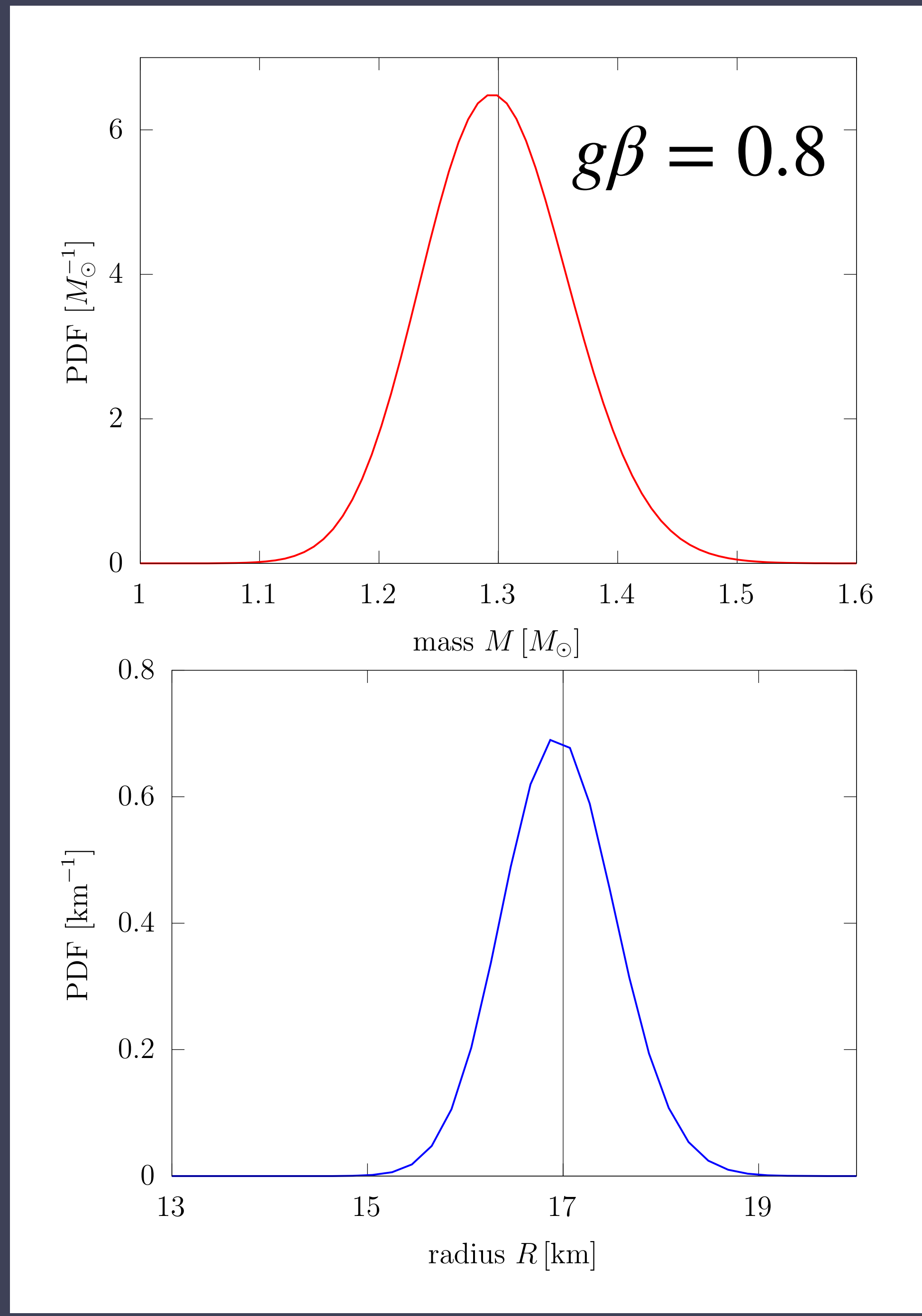


AH+ in prep.

How about realistic data?

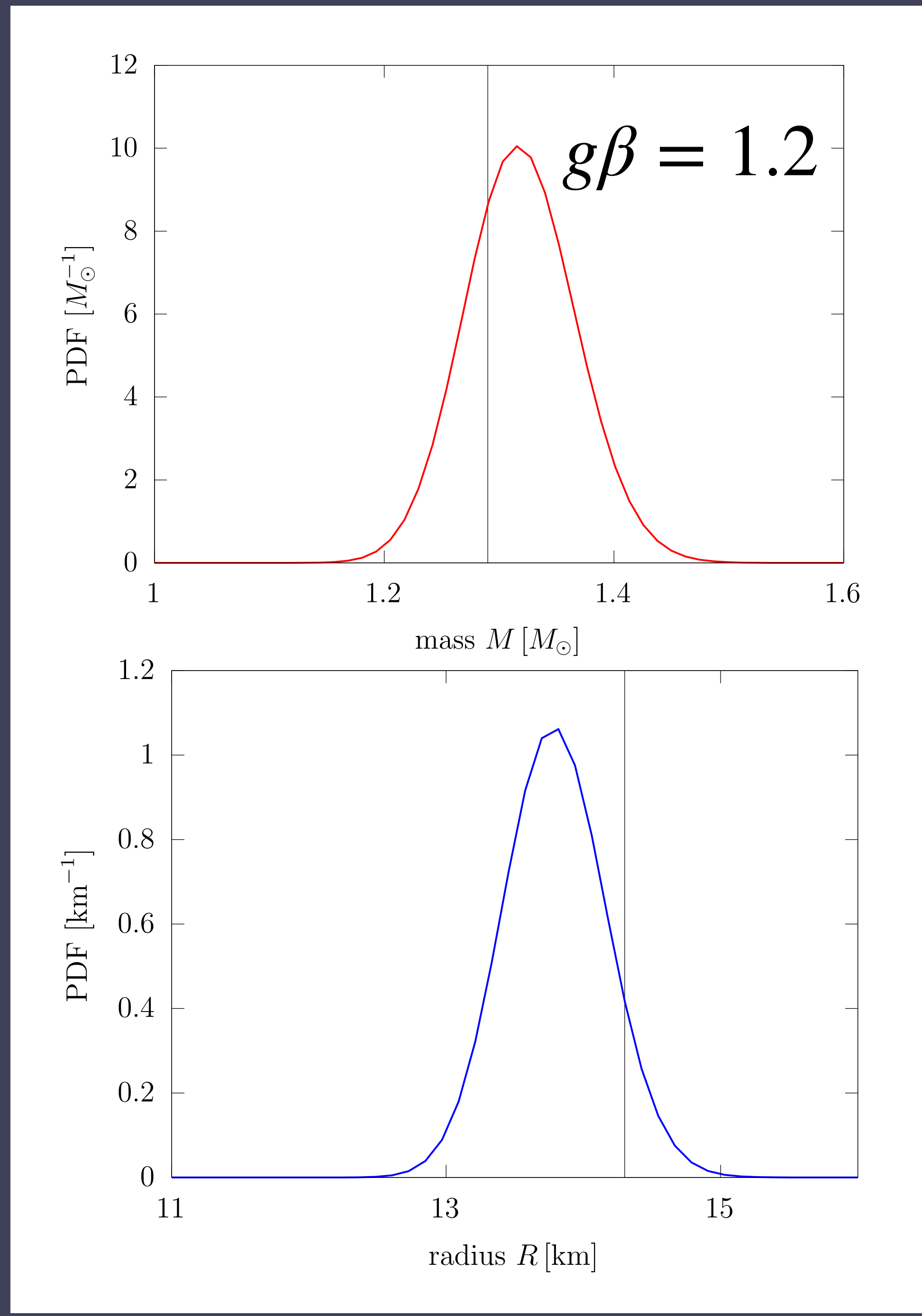
- Analyze the mock observational data based on theoretical template of Nakazato's and Mori's database: supernova is at the Galactic center, the detector is Super Kamiokande
- By focusing on the shallow decay phase with cutting first 0.5 s events, SPECIAL BLEND reproduces the parameters of the realistic models relatively well

Mori's DB



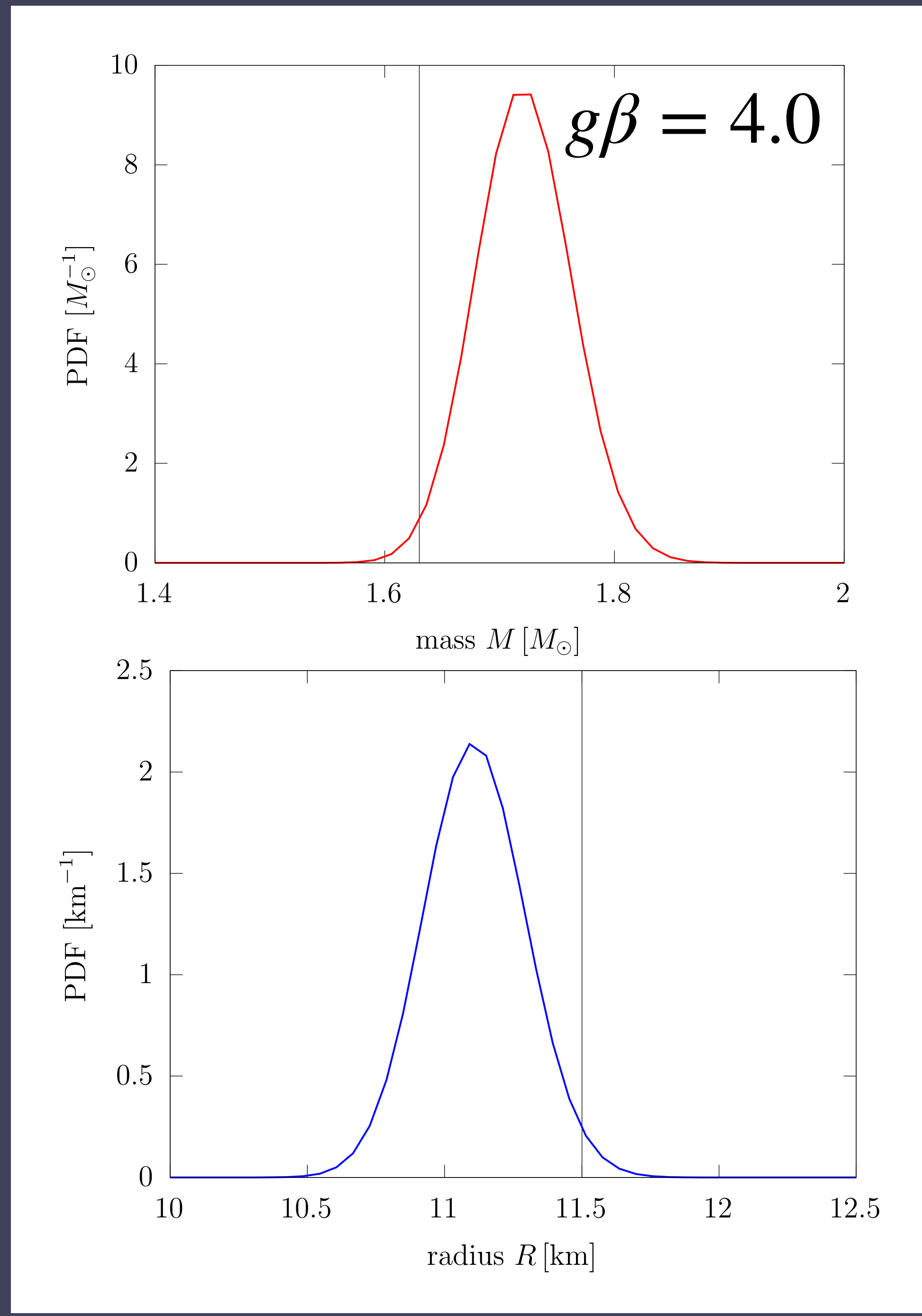
AH+ in prep.

Nakazato's DB-1



AH+ in prep.

Nakazato's DB-2

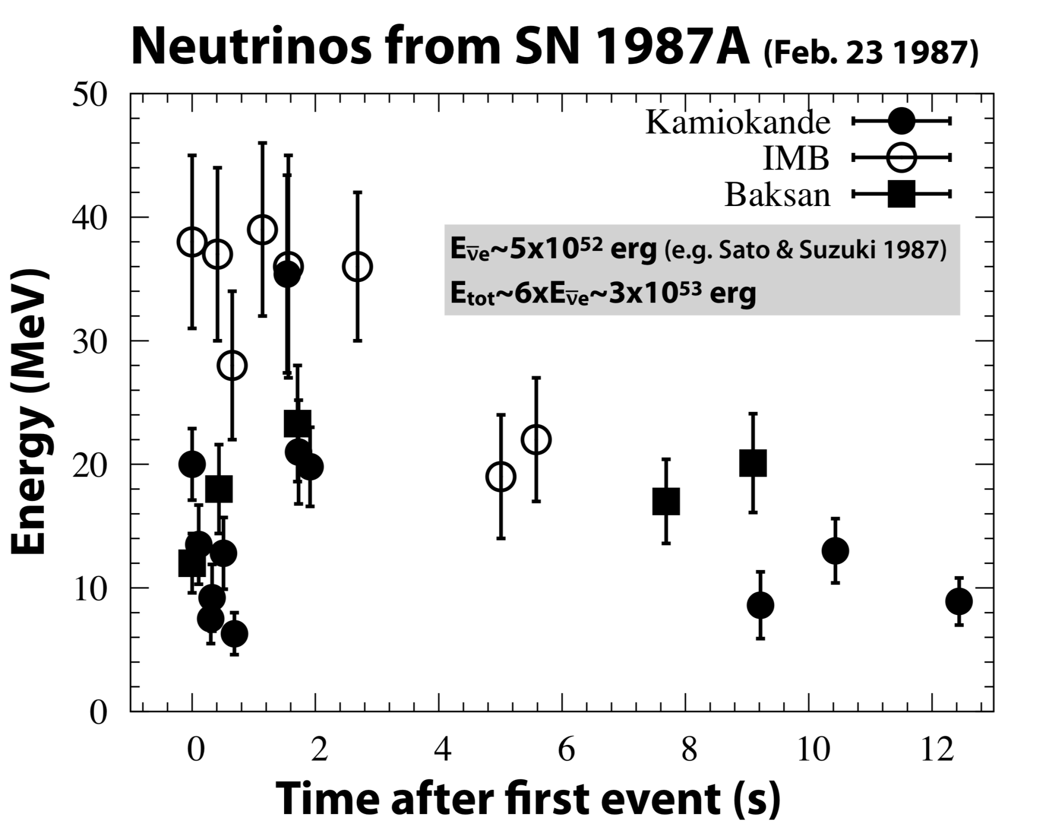


AH+ in prep.

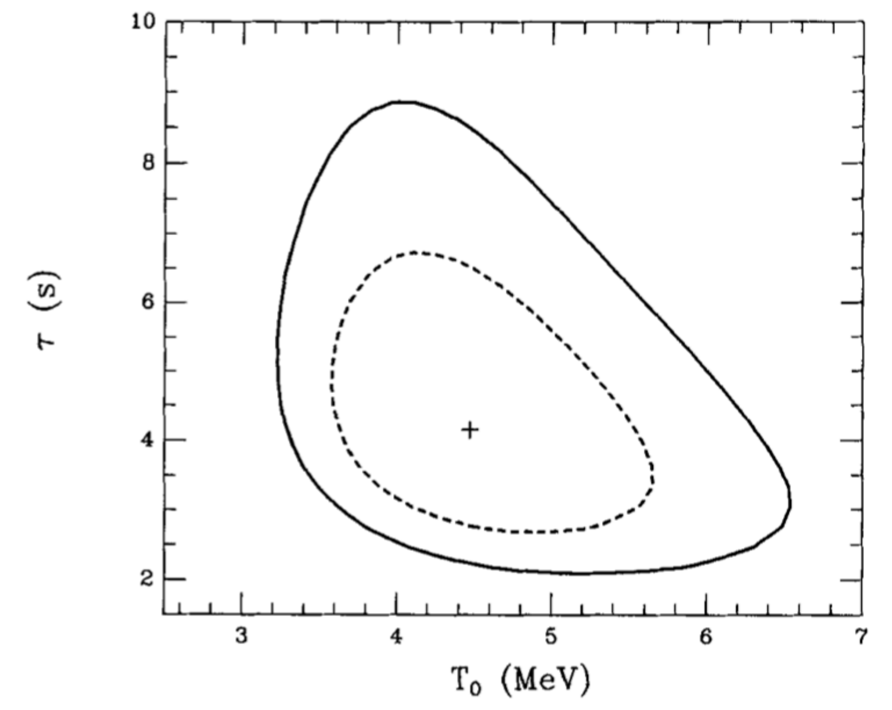
SN1987A neutrinos and NS1987A(?)

Neutrinos

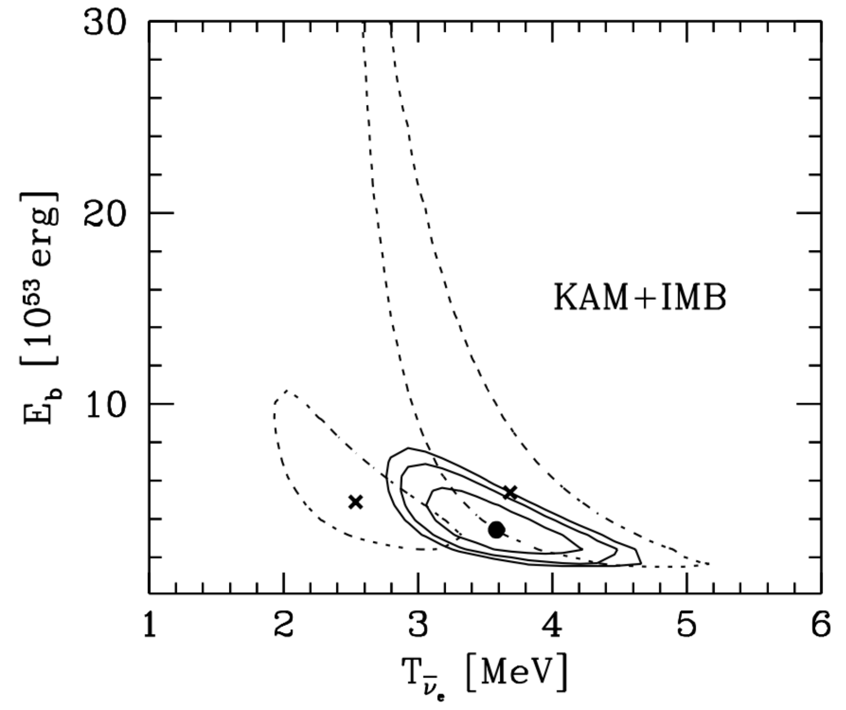
Optical
(~30 yrs. later)



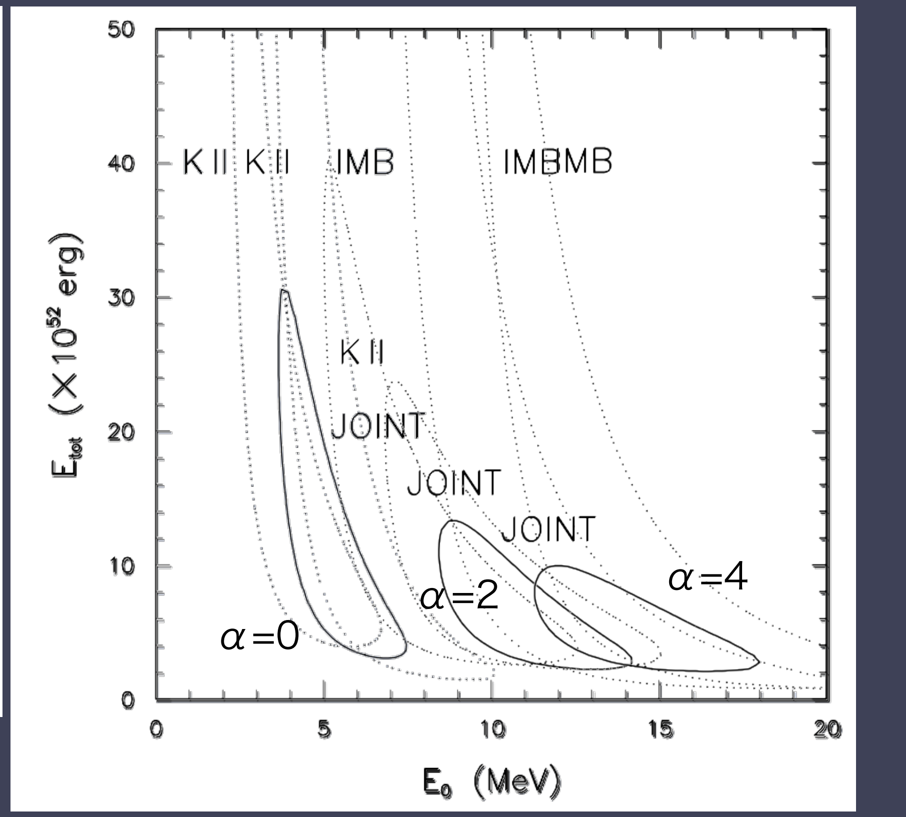
Courtesy of Suwa



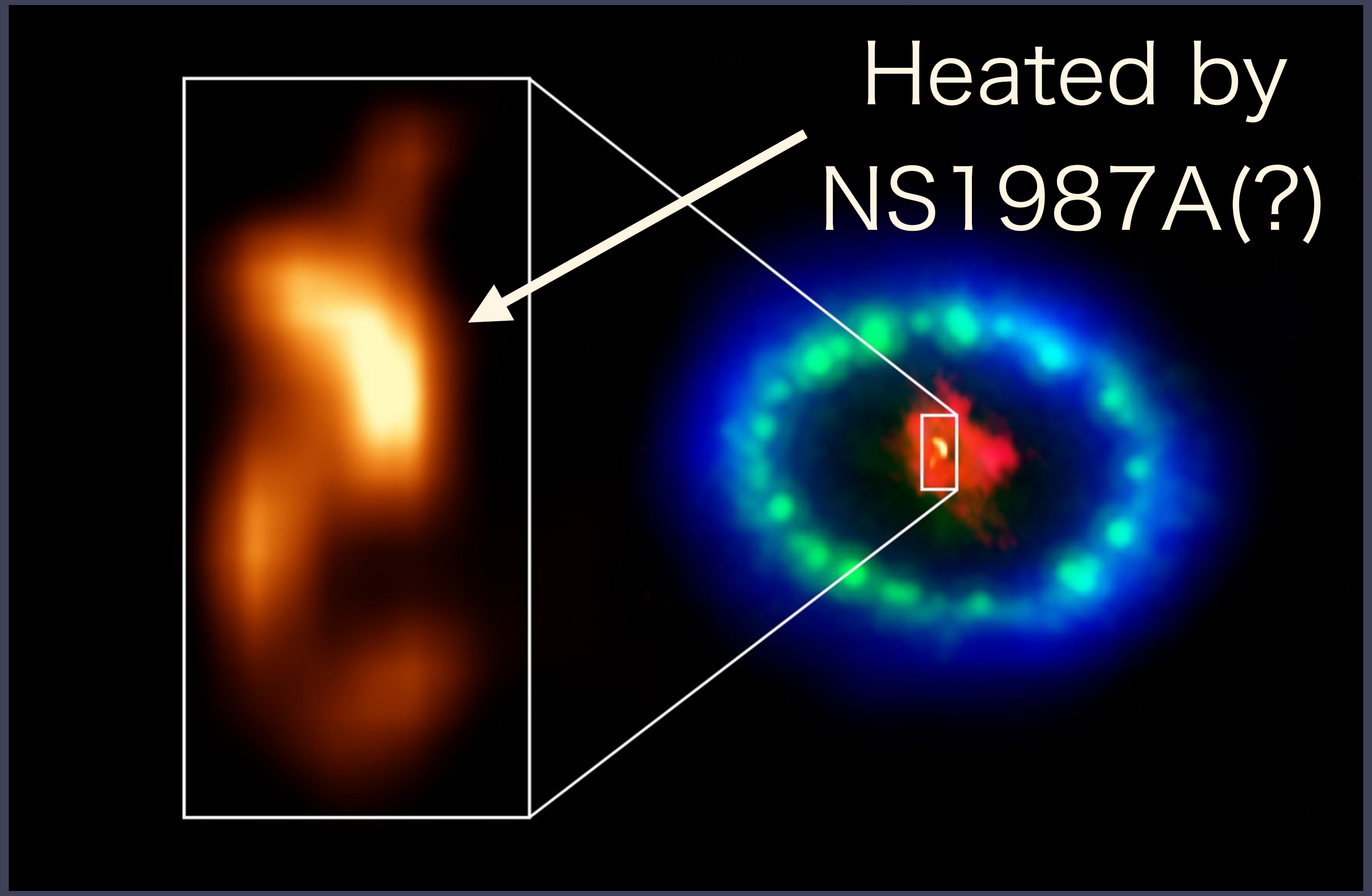
Loredo & Lamb (1989)
Time-dep. model
Joint analysis only



Jegerlehner et al. (1996)
Time-ave. model
Joint and individual analysis



Mirizzi et al. (2006), Fig. 4 superposed

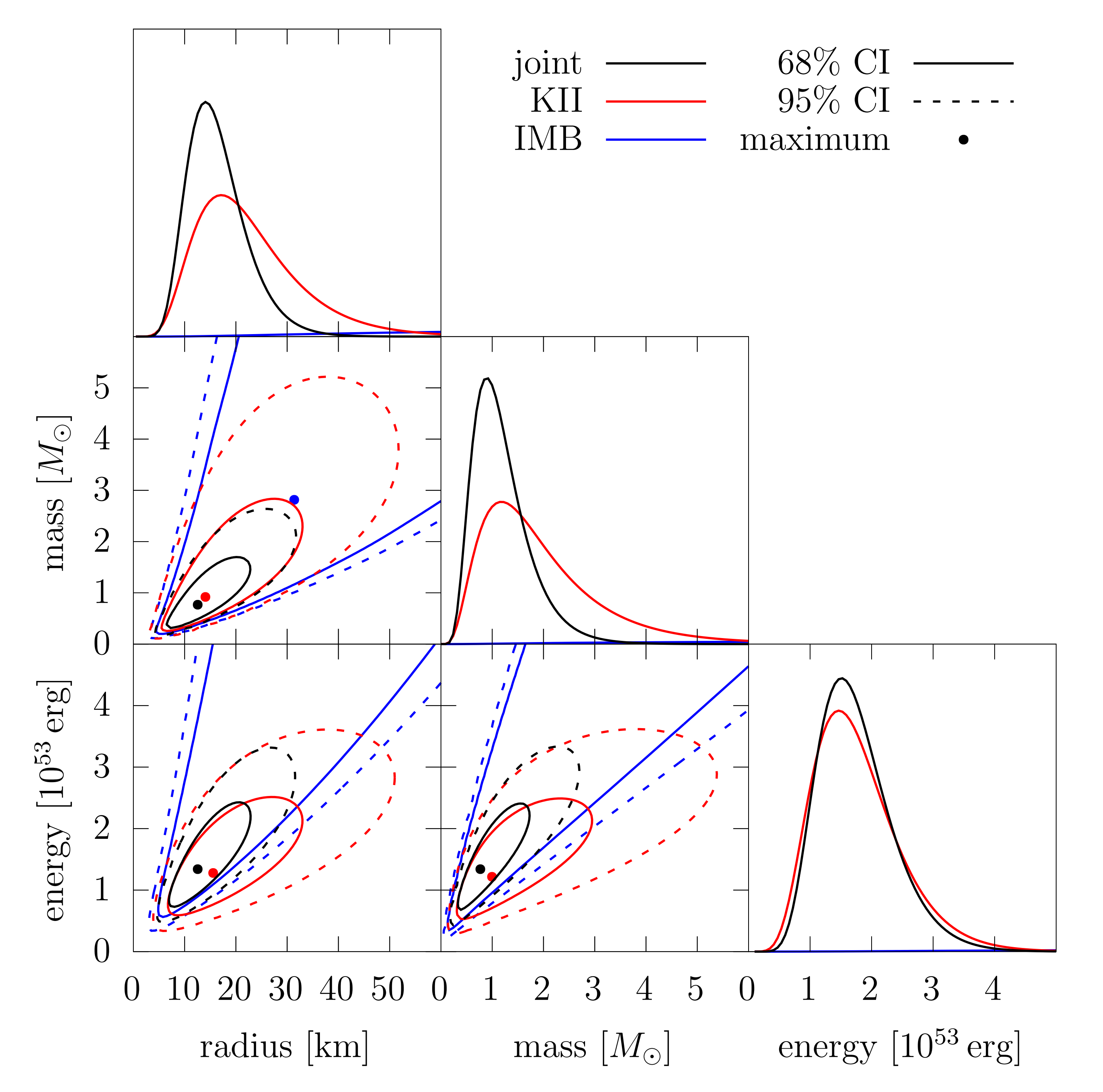


Credit: ALMA (ESO/NAOJ/NRAO), P. Cigan and R. Indebetouw;
NRAO/AUI/NSF, B. Saxton; NASA/ESA

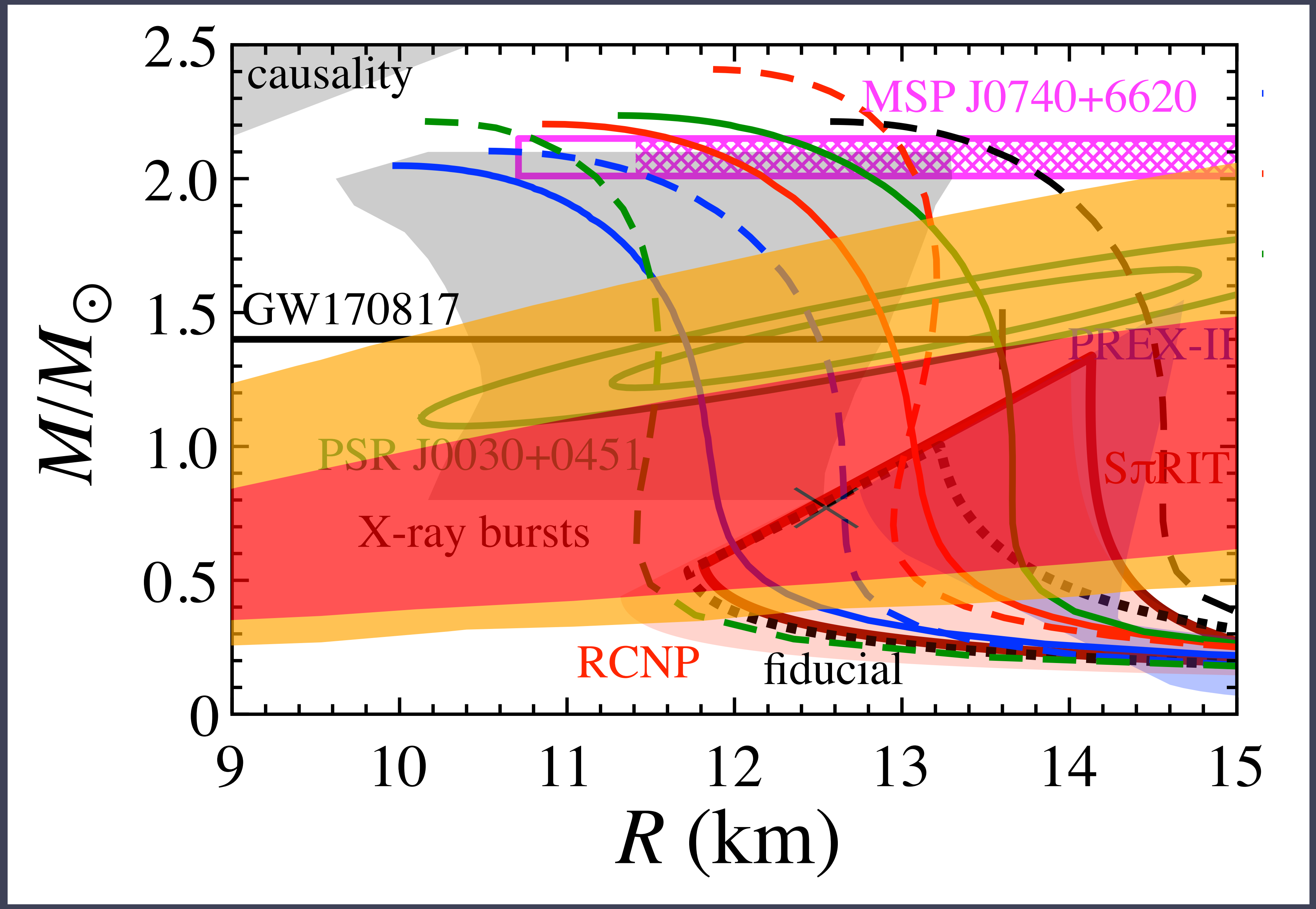
- Analysis of SN1987A has relied on phenomenological models: discrepancy between KII and IMB
- ALMA found a hot spot in SN1987A remnant→evidence of NS1987A?
- Properties are still unknown.

Parameter estimation of NS1987A

- Modify SPECIAL BLEND to apply to the data of KII/IMB era
- KII best fit is inside the 68% CI of IMB ← previous works might overestimate the data quality of IMB
- Result of the joint analysis: $M_{\rm PNS} = 0.89^{+0.60}_{-0.38}\,M_\odot$ $R_{\rm PNS} = 14.1^{+6.3}_{-4.6}\,{\rm km}$ $E_{\rm tot} = 1.51^{+0.66}_{-0.49} \times 10^{53}{\rm erg}$



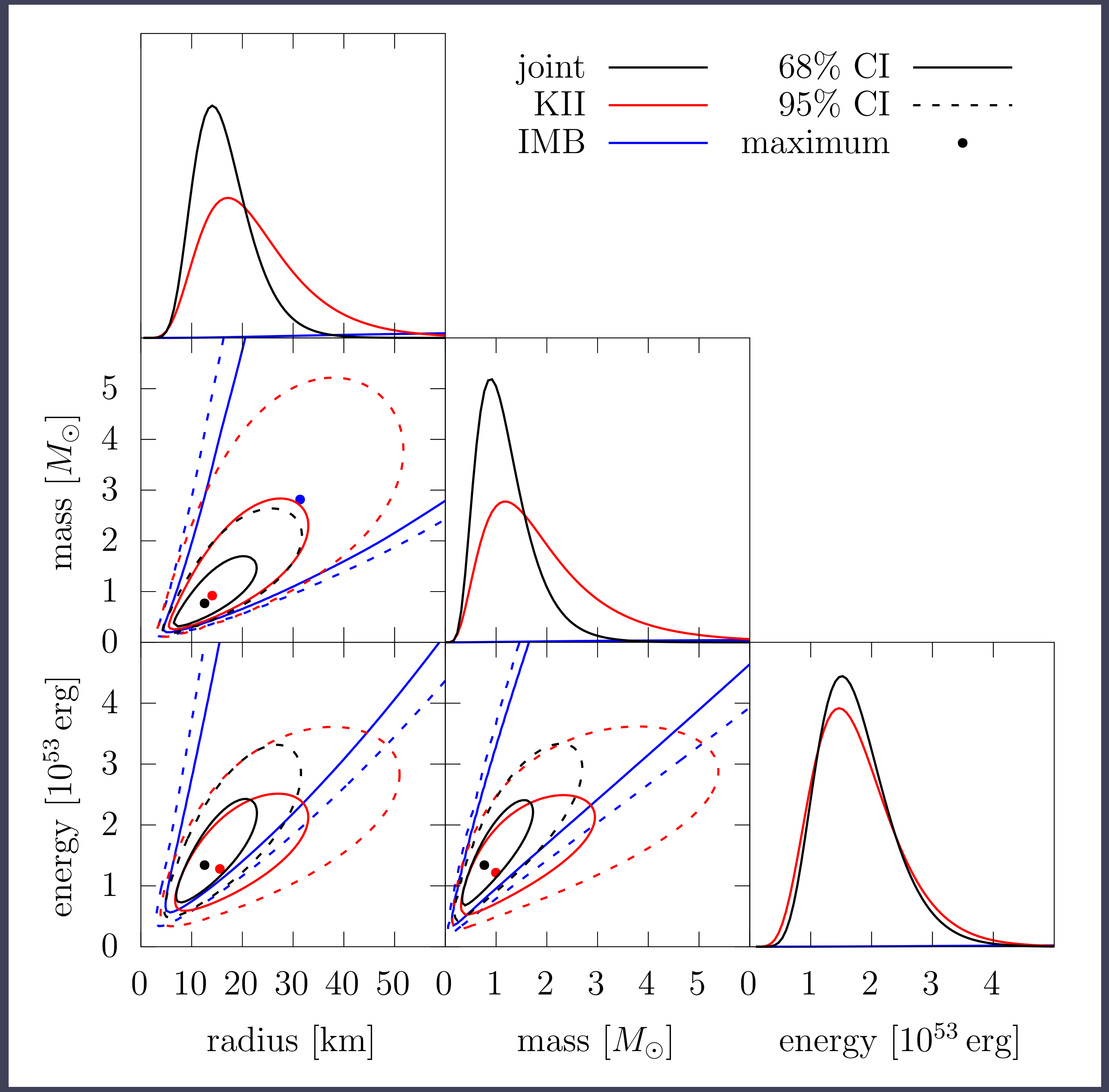
AH+ in prep.



M-R relation diagram (Superimposed to Sotani+ 2022 Fig. 2)

Parameter estimation of NS1987A

- Caution 1: observational data is stochastic, and small mass may be due to the statistical fluctuation
- Caution 2: mass is degenerate with the phenomenological parameter gβ
- Caution 3: typical (?) NS mass in simulations (~1.6 $M_\odot$) may be too large



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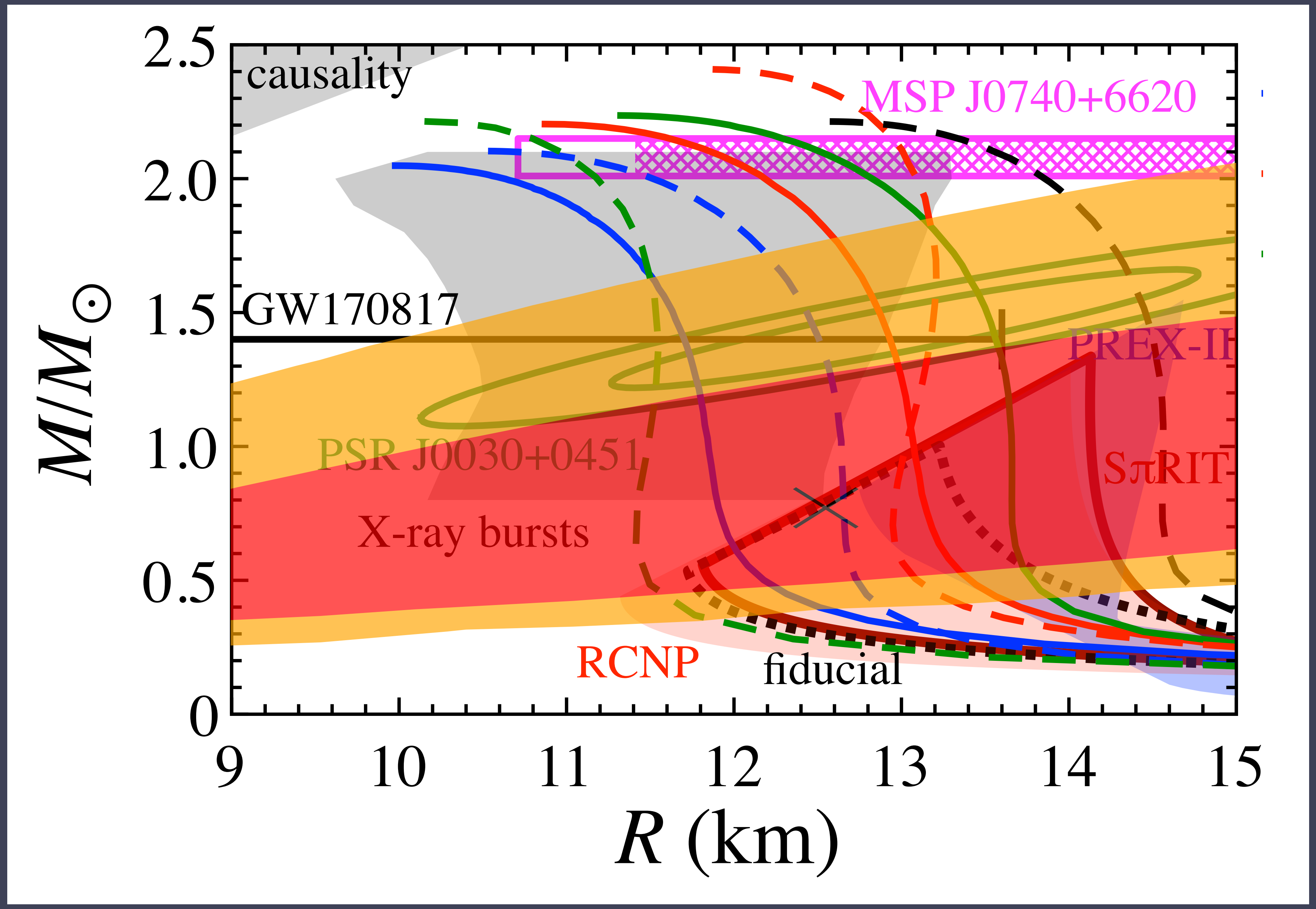
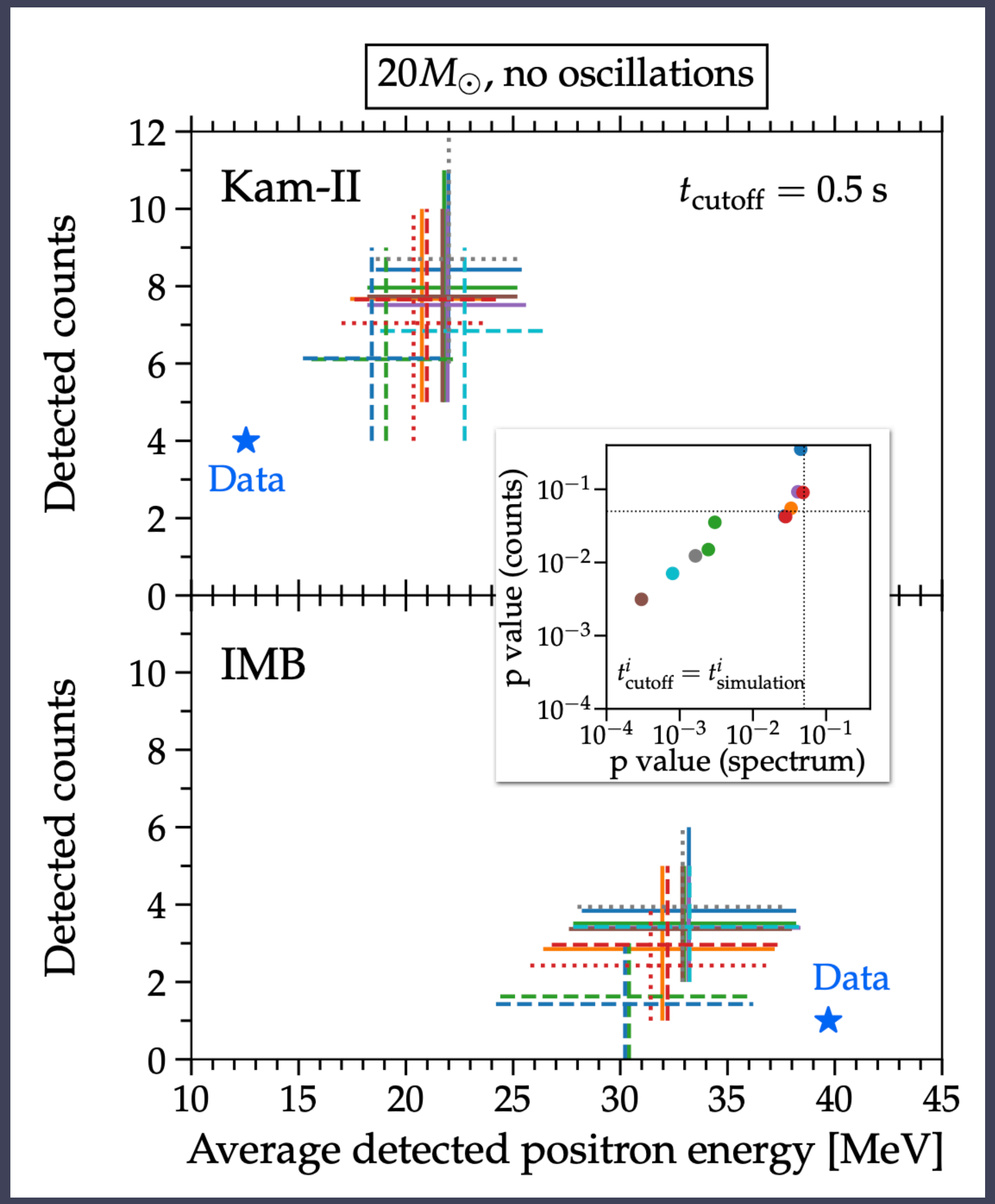


M-R relation diagram (Superimposed to Sotani+ 2022 Fig. 2)

Li+ arXiv:2306.08024

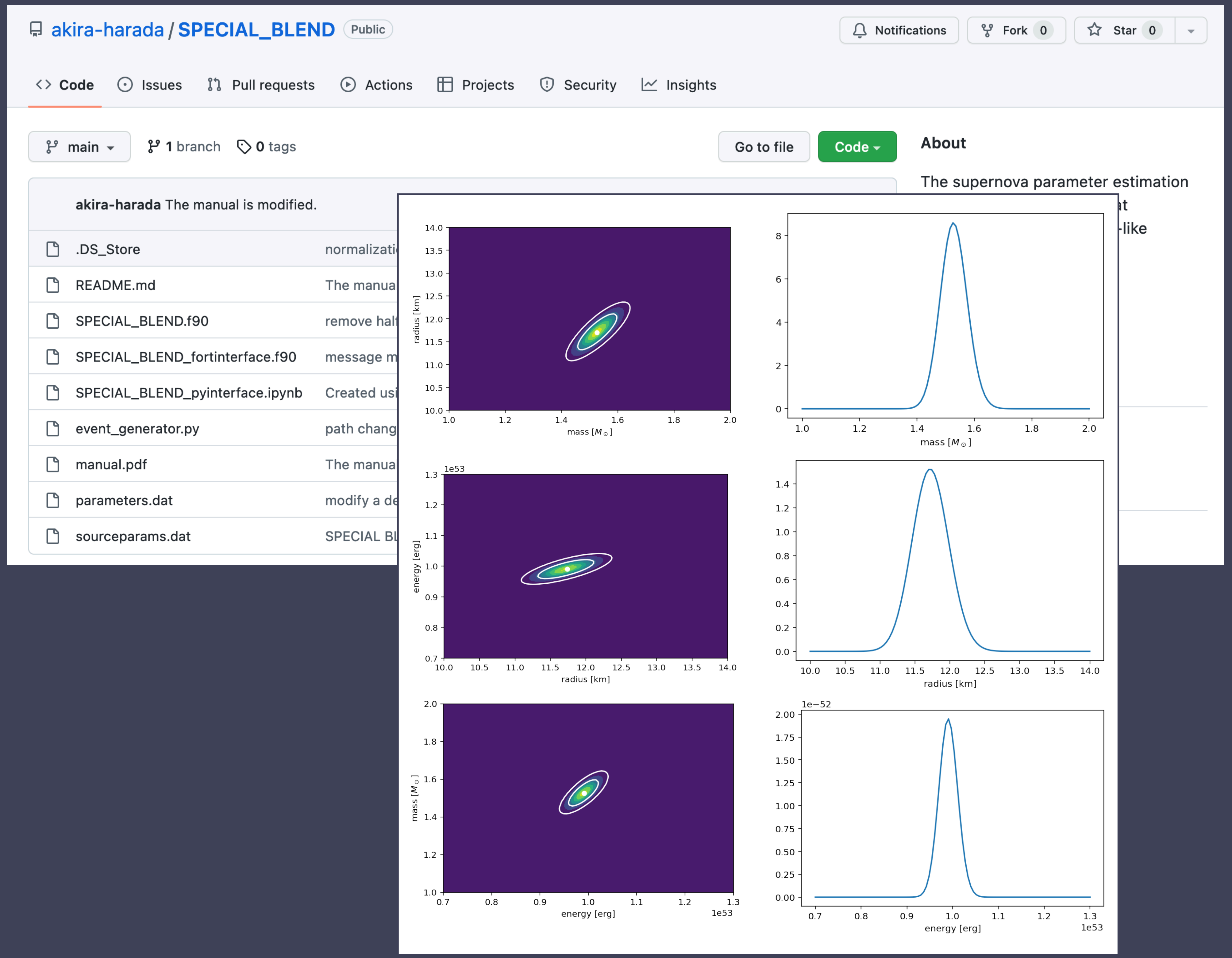


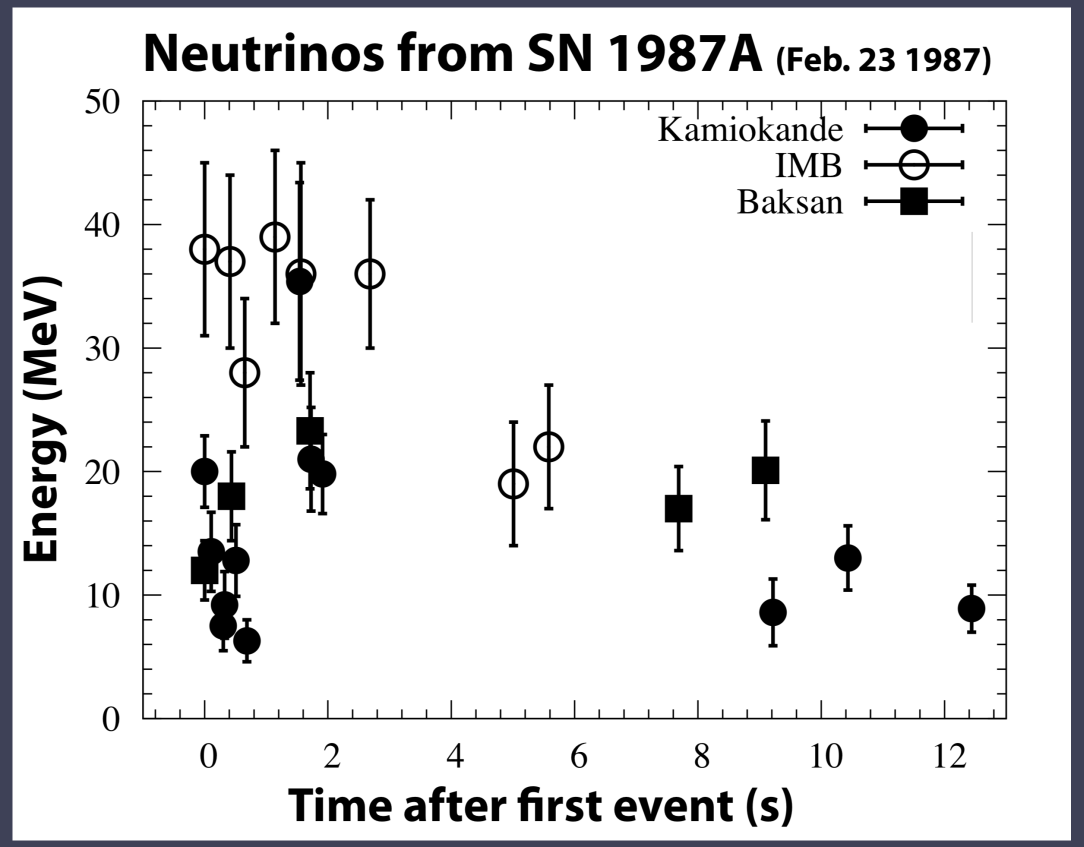
Li+ (2023)

Summary

- We developed a public analysis code, SPECIAL BLEND for the future supernova neutrino detection
- SPECIAL BLEND can be used easily and estimates parameters well.
- We estimated the parameters of NS1987A from SN1987A neutrinos:

$$M_{\rm PNS} = 0.89^{+0.60}_{-0.38}\, M_\odot \quad R_{\rm PNS} = 14.1^{+6.3}_{-4.6}\,{\rm km} \quad E_{\rm tot} = 1.51^{+0.66}_{-0.49} \times 10^{53}{\rm erg}$$





Courtesy of Suwa