

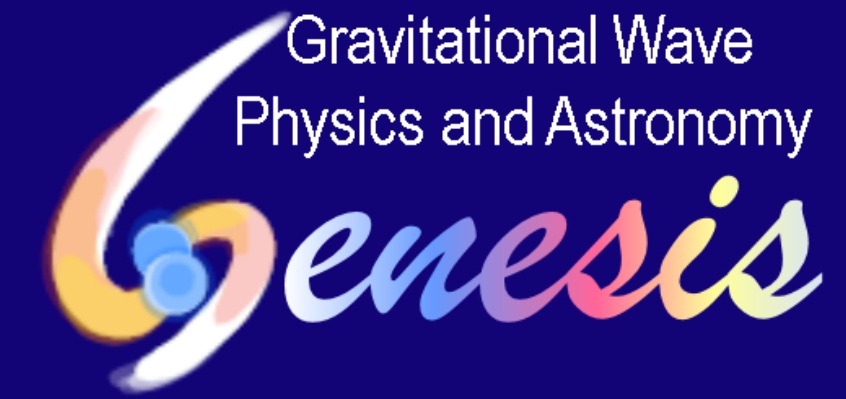
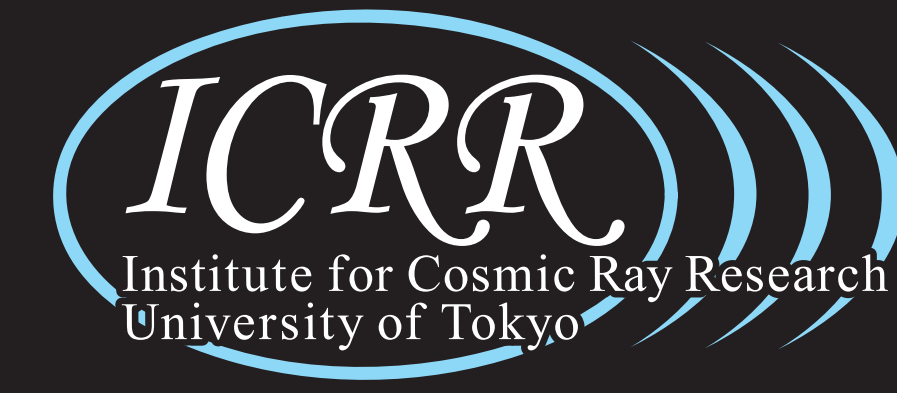
# 超新星SN1987Aからのニュートリノ信号再解析による 中性子星NS1987Aのパラメータ推定

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



Roger Wendell (Kyoto U, **exp.**)

Yusuke Koshio, Masayuki Harada, Fumi Nakanishi (Okayama U., **exp.**)

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

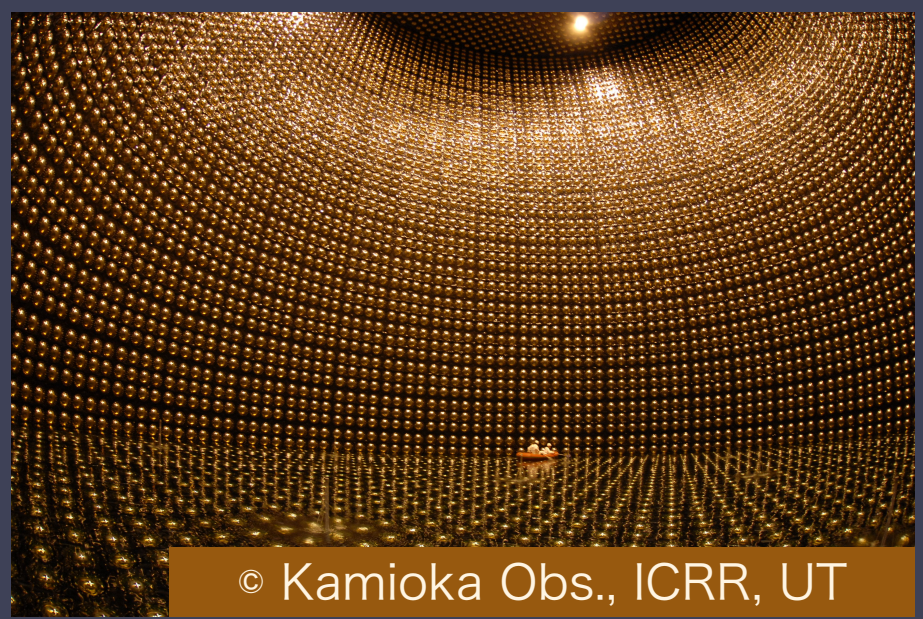
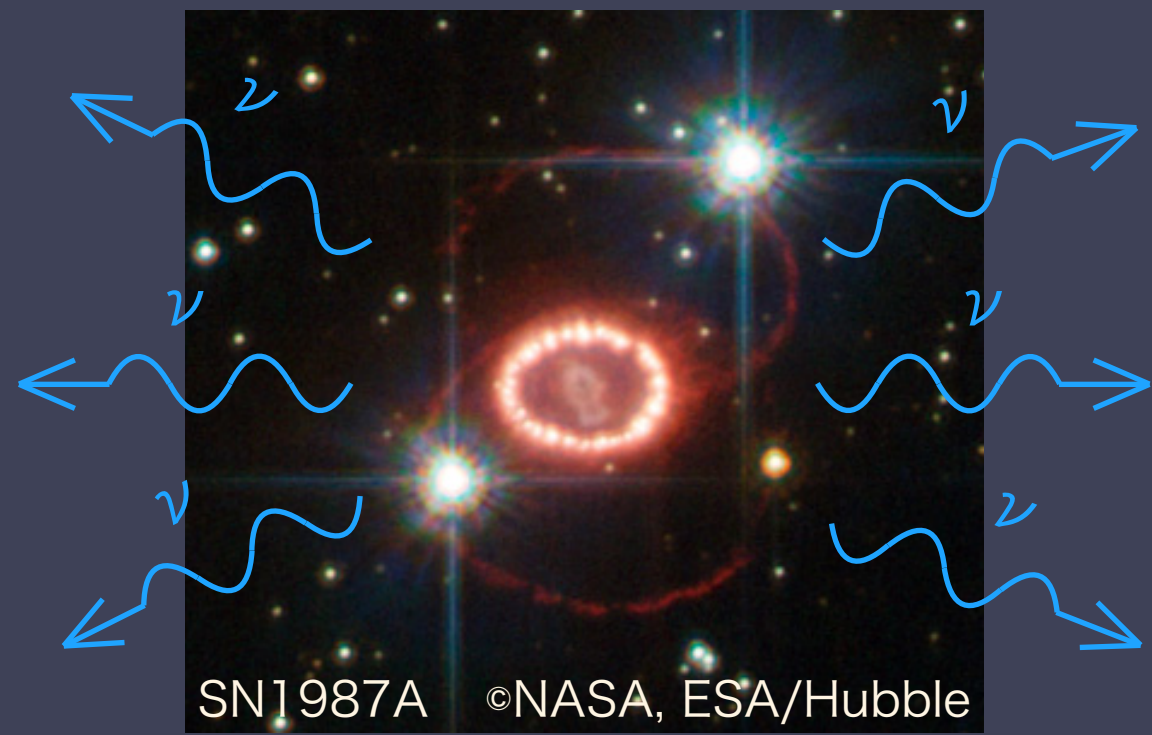
Akira Harada (me, RIKEN, **theo.**)  
Yudai Suwa (U. Tokyo, **theo.**),  
Masamitsu Mori (NAOJ, **theo./exp.**)  
Ryuichiro Akaho (Waseda U., **theo.**)

Kosuke Sumiyoshi (Numazu tech., **theo.**)

# Supernova $\nu$ -observation & theory

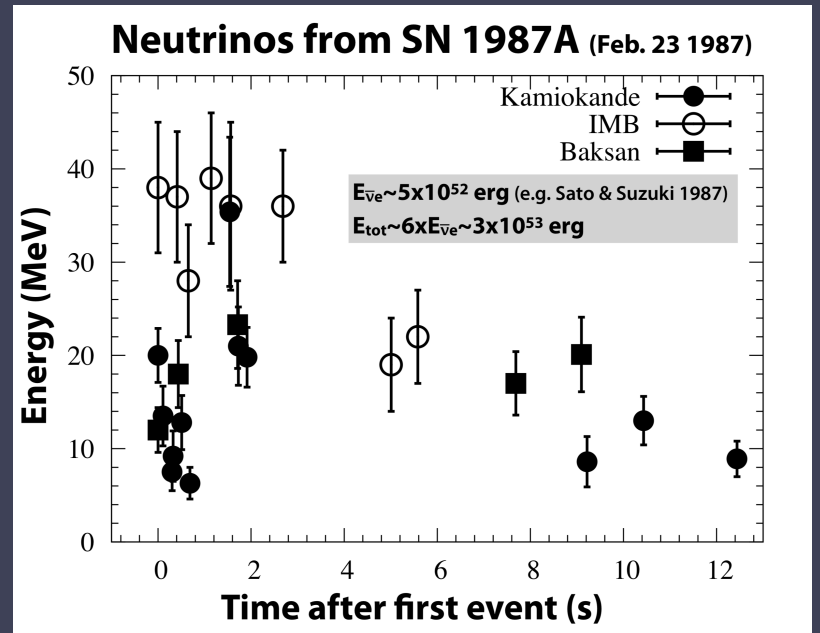
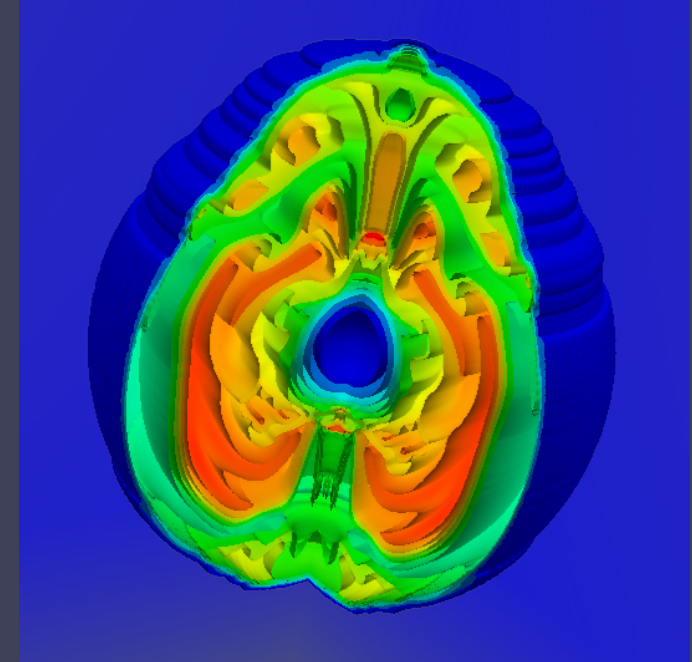
$\nu$ -emission from supernova

Supernova theory



Neutrino observation

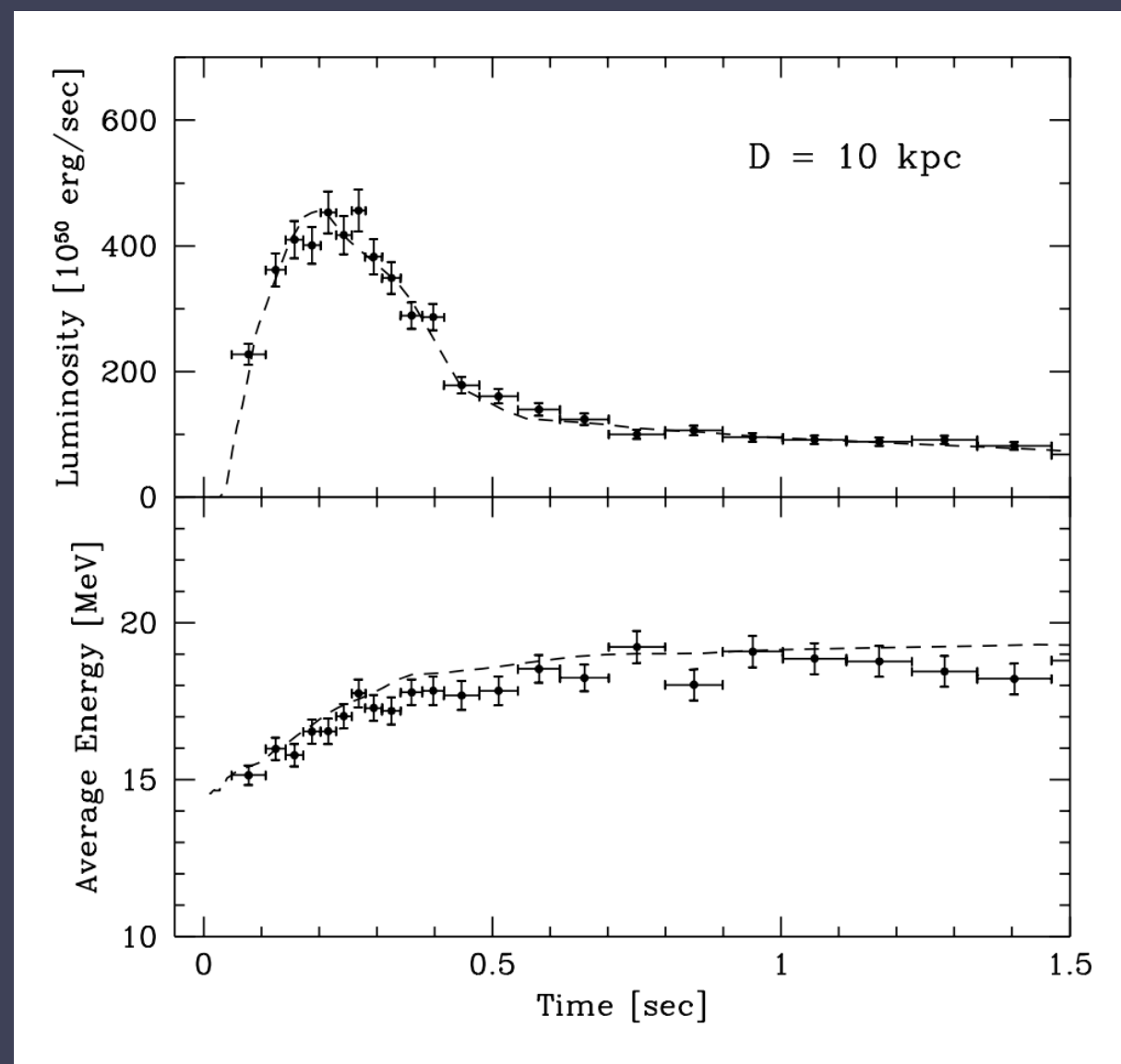
State-of-the-art simulations



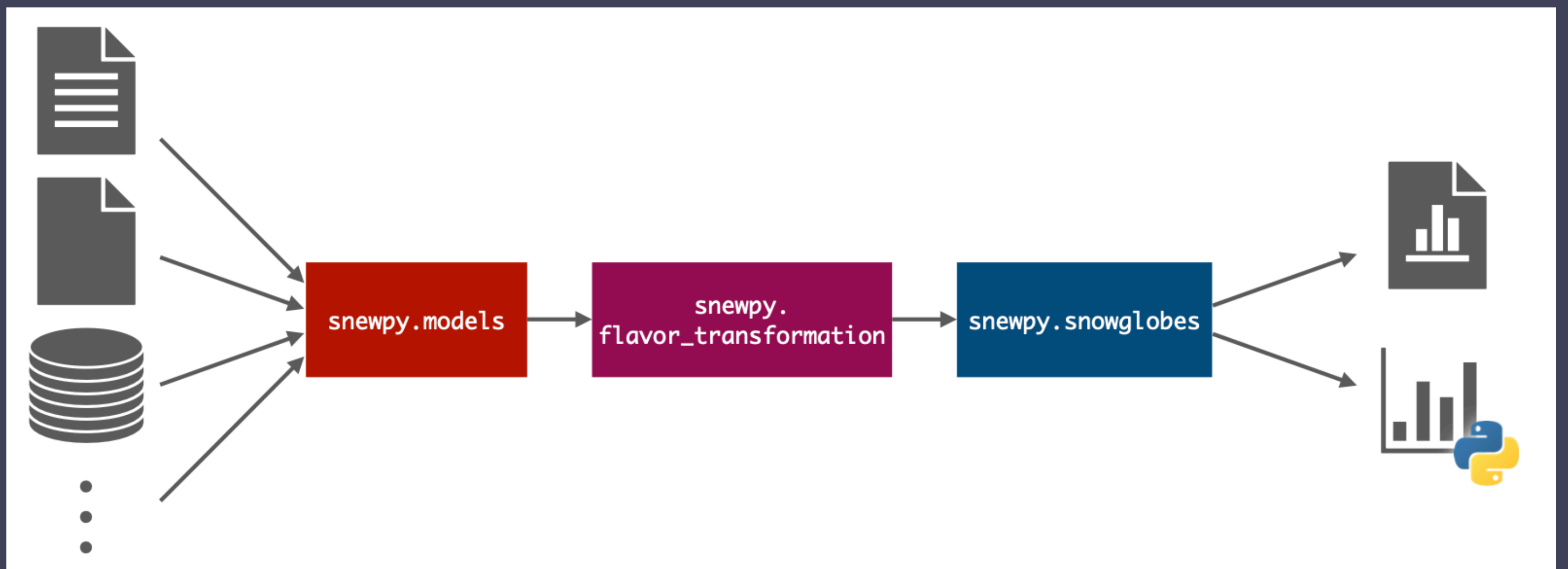
only SN1987A

# Supernova $\nu$ -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!



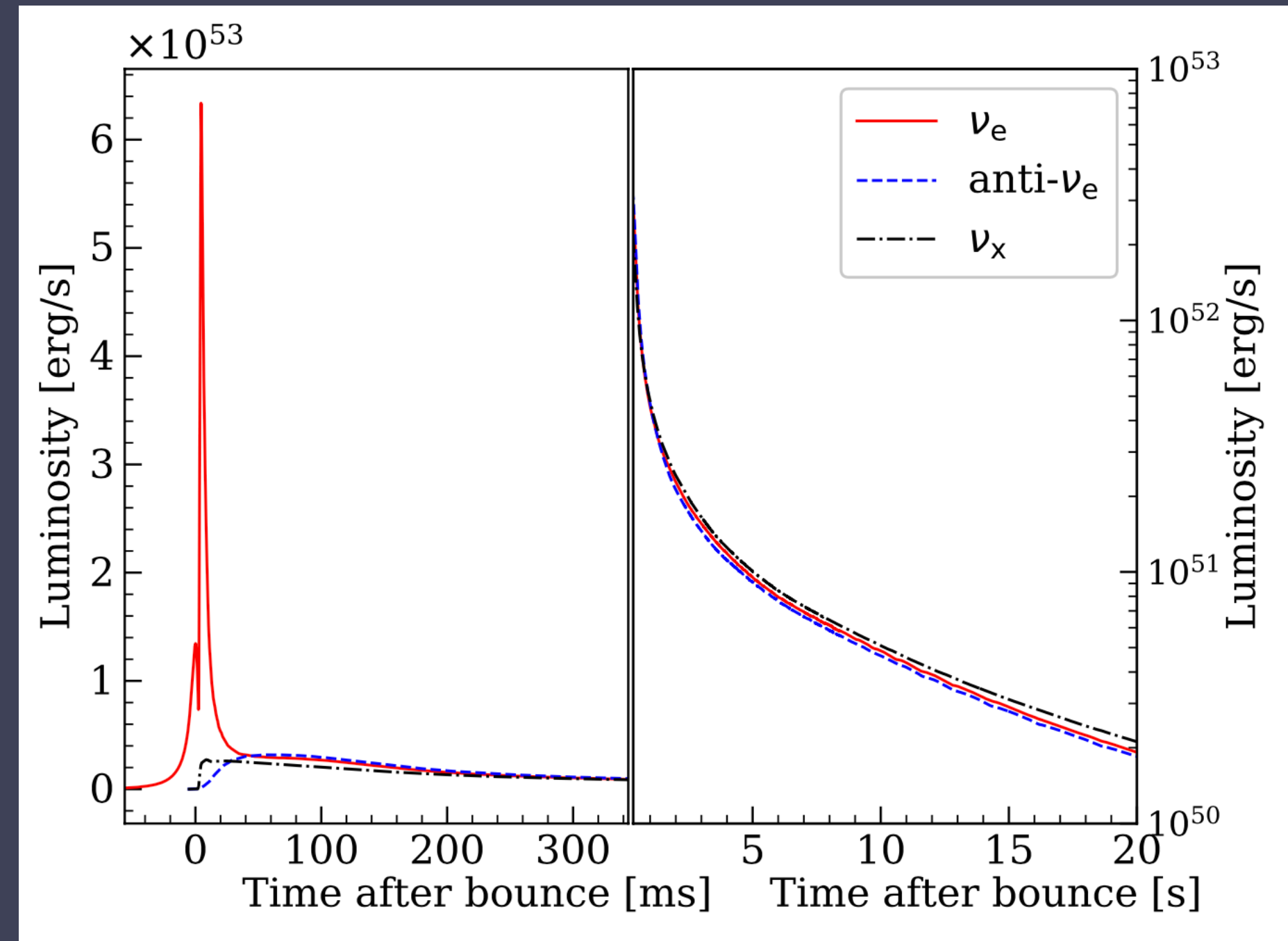
Totani+ (1997)



Bakster+ (2021)

# Phases of supernova neutrino

- Explosion phase

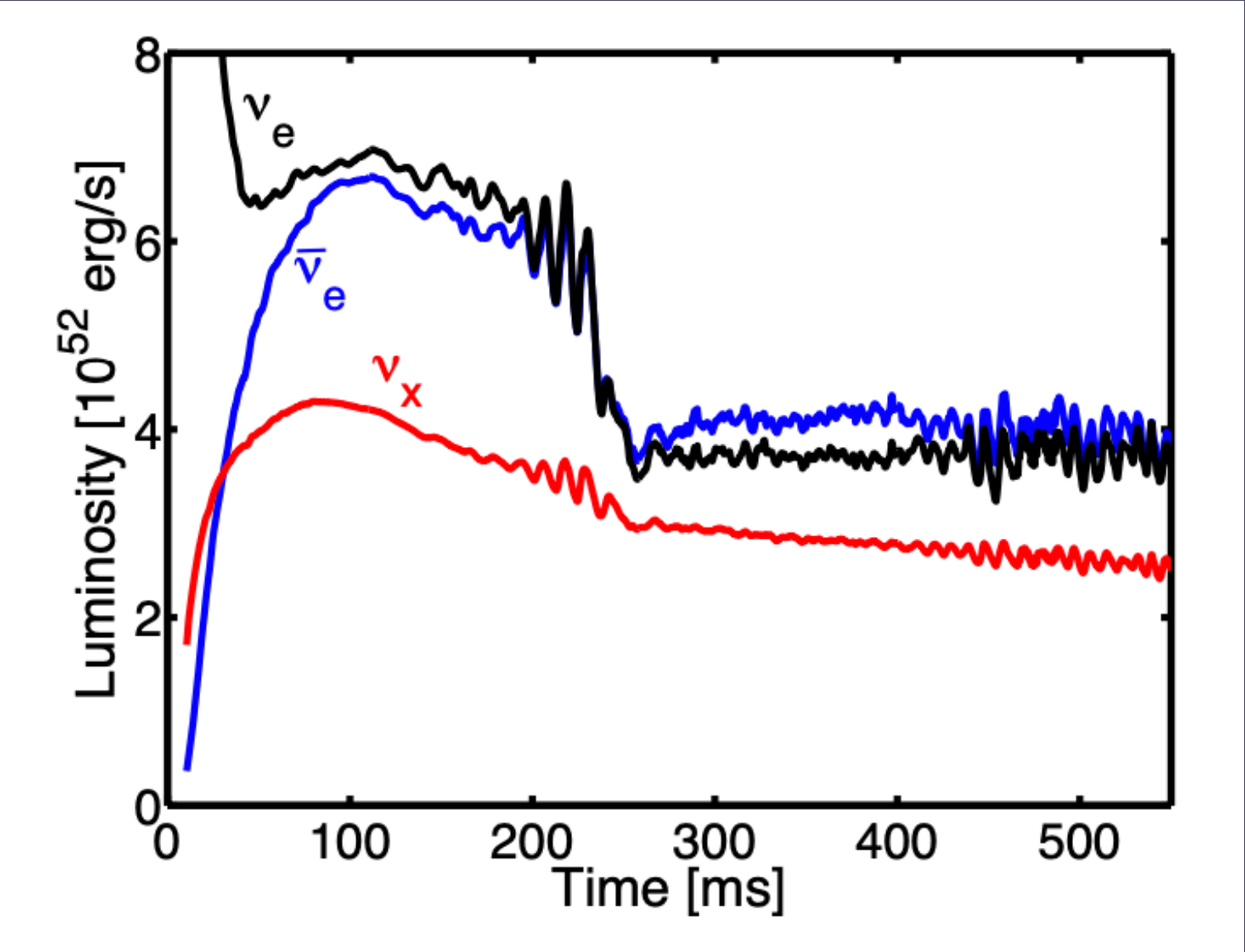


- PNS cooling phase

Mori+ (2021)

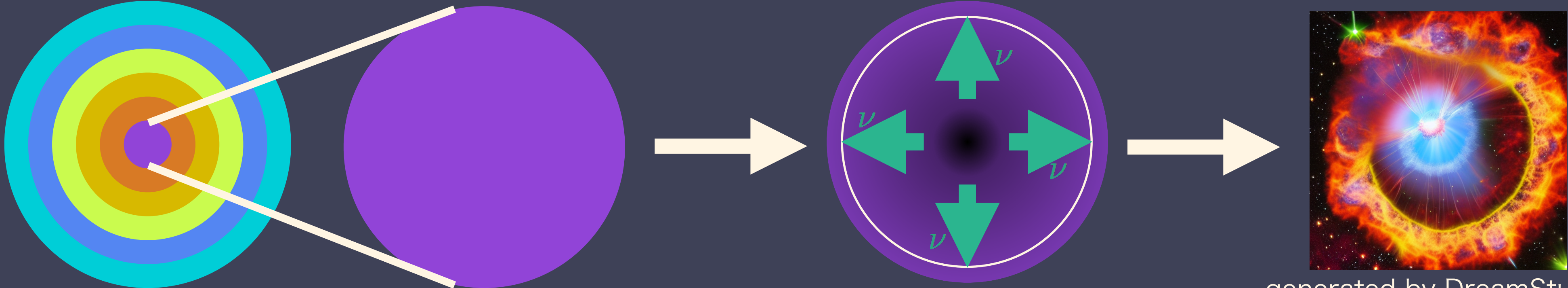
# Early explosion phase

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



Tamborra+ (2014)

- PNS cooling phase

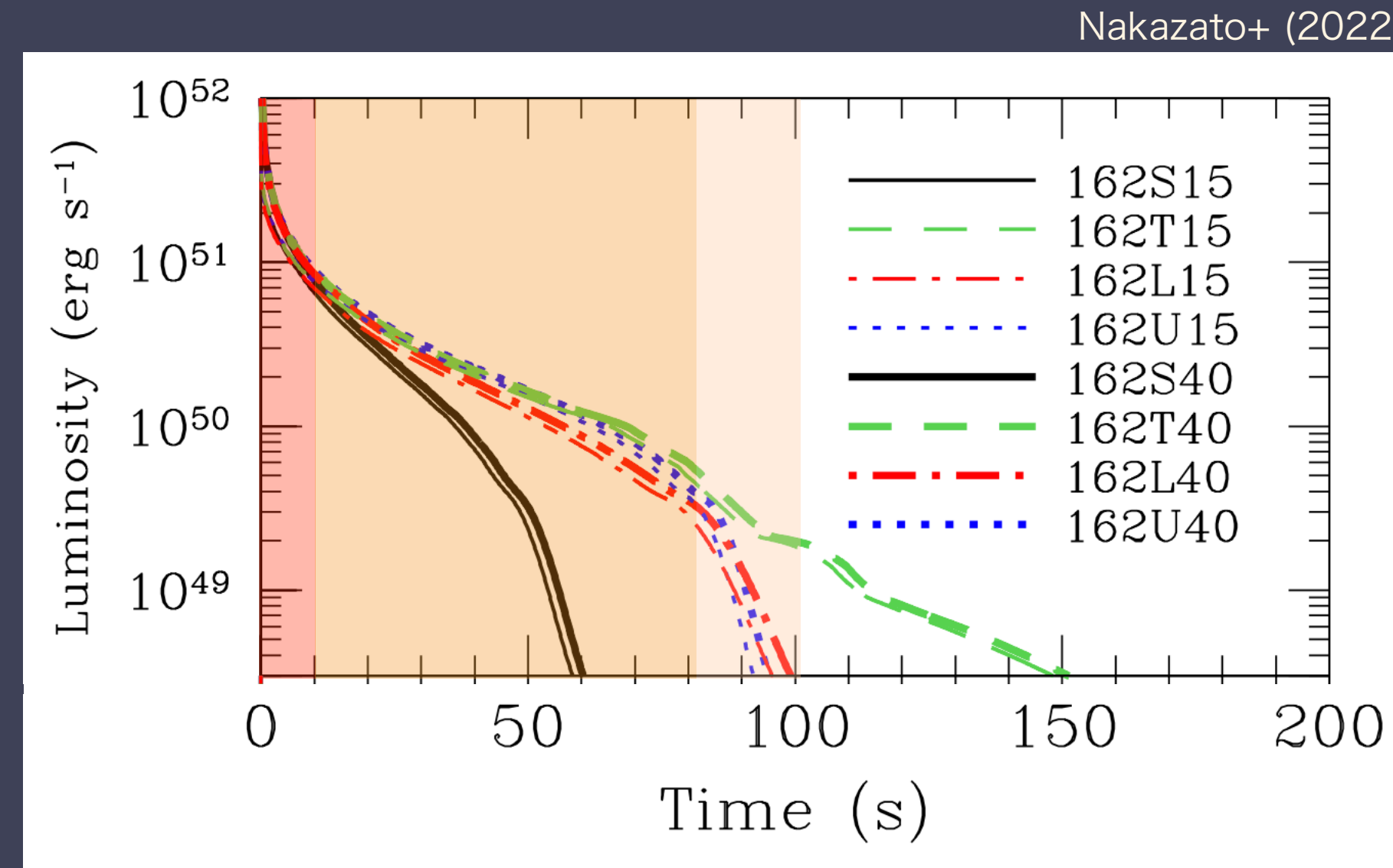


generated by DreamStudio

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

# Late PNS cooling phase

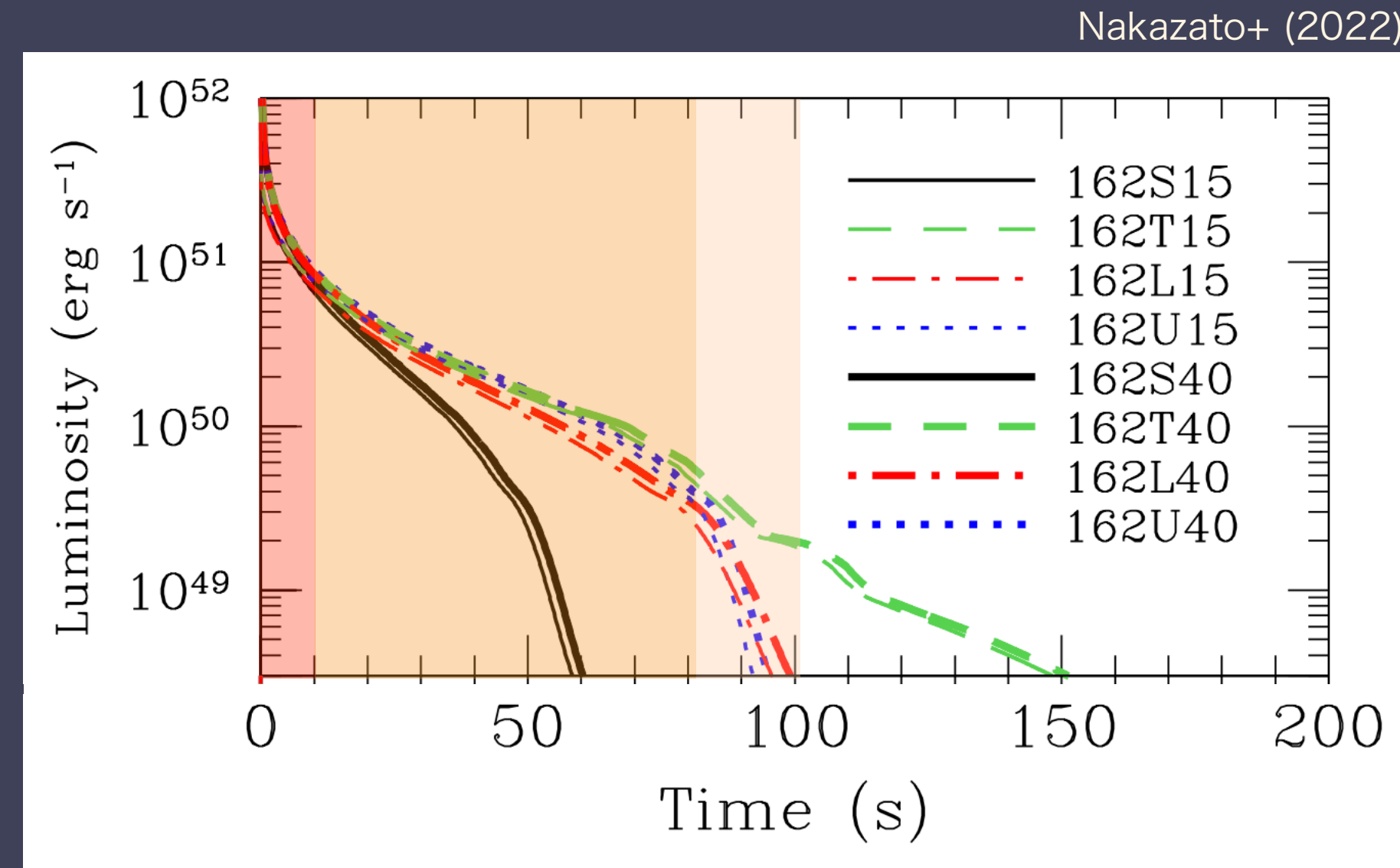
- Explosion phase
- Various physical processes involved, theoretically uncertain



- 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

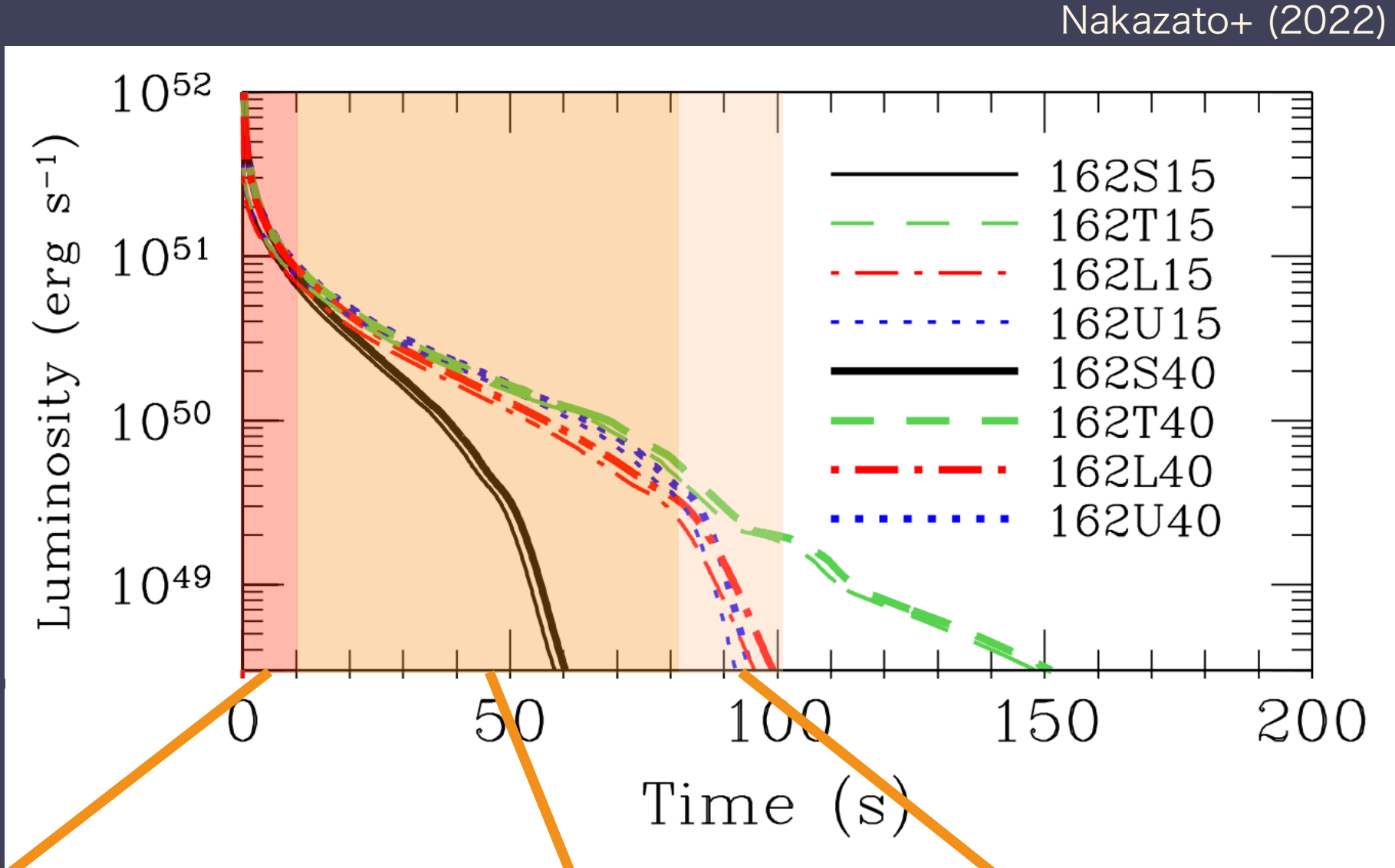


- PNS cooling phase
- Relatively simple, less uncertain
- The focus of nuLC collab.  
→ A robust estimation of the simple late phase is a clue for the complicated early phase

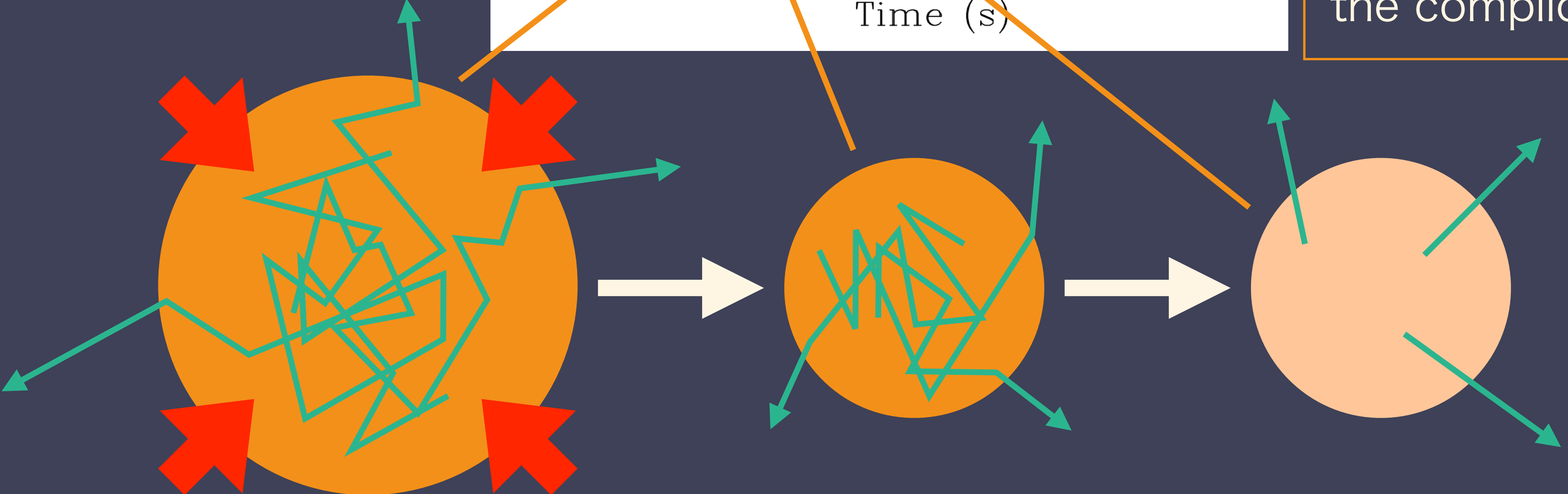


# Late PNS cooling phase

- Explosion phase
- Various physical processes involved, theoretically uncertain



- 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



Mantle contraction → shallow decay → volume cooling

# Suggestions from nuLC collab.

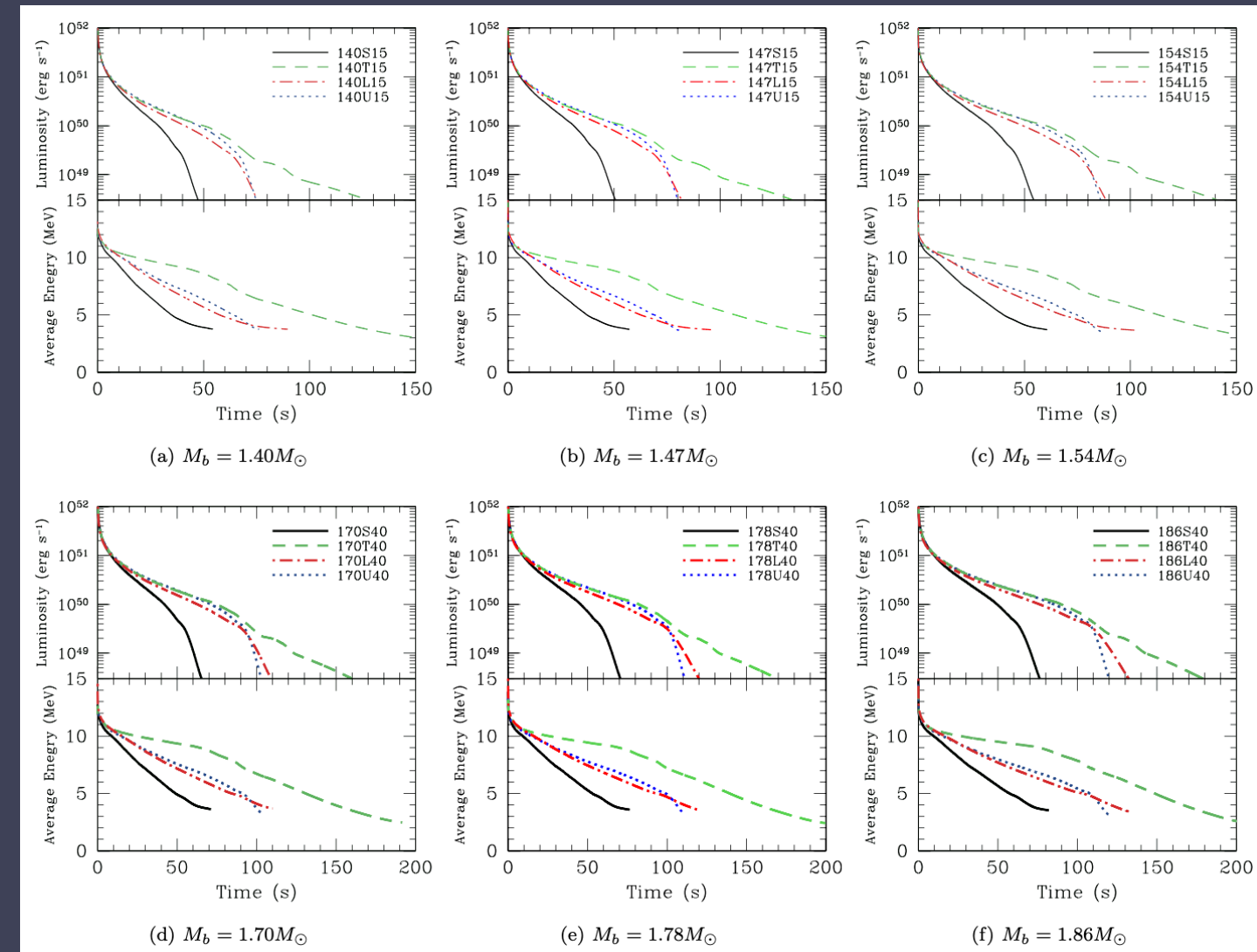
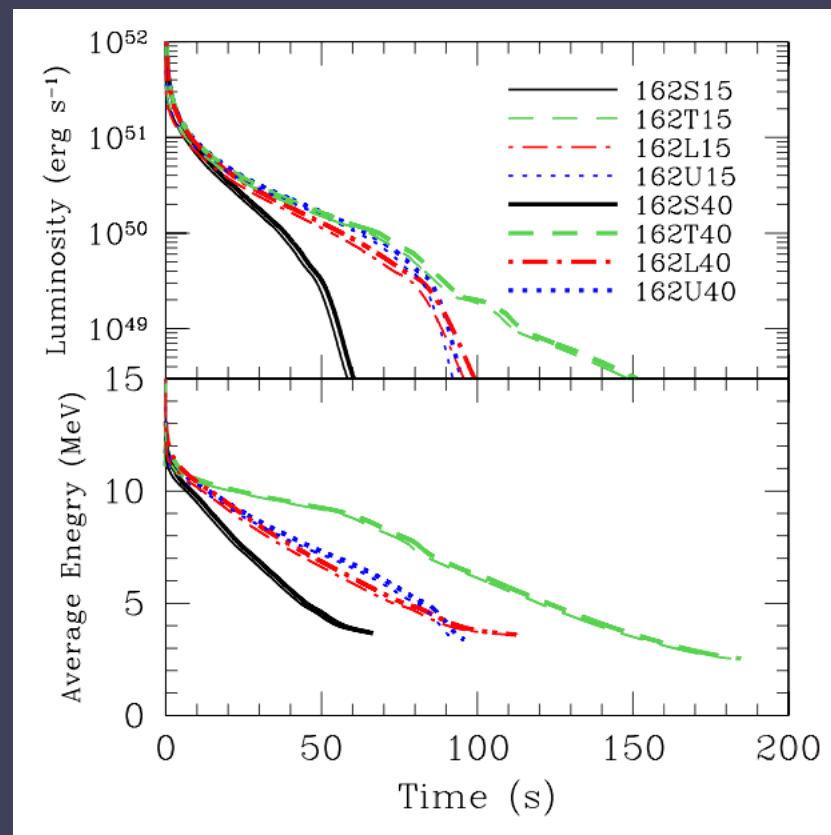
## Theoretical template

- 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

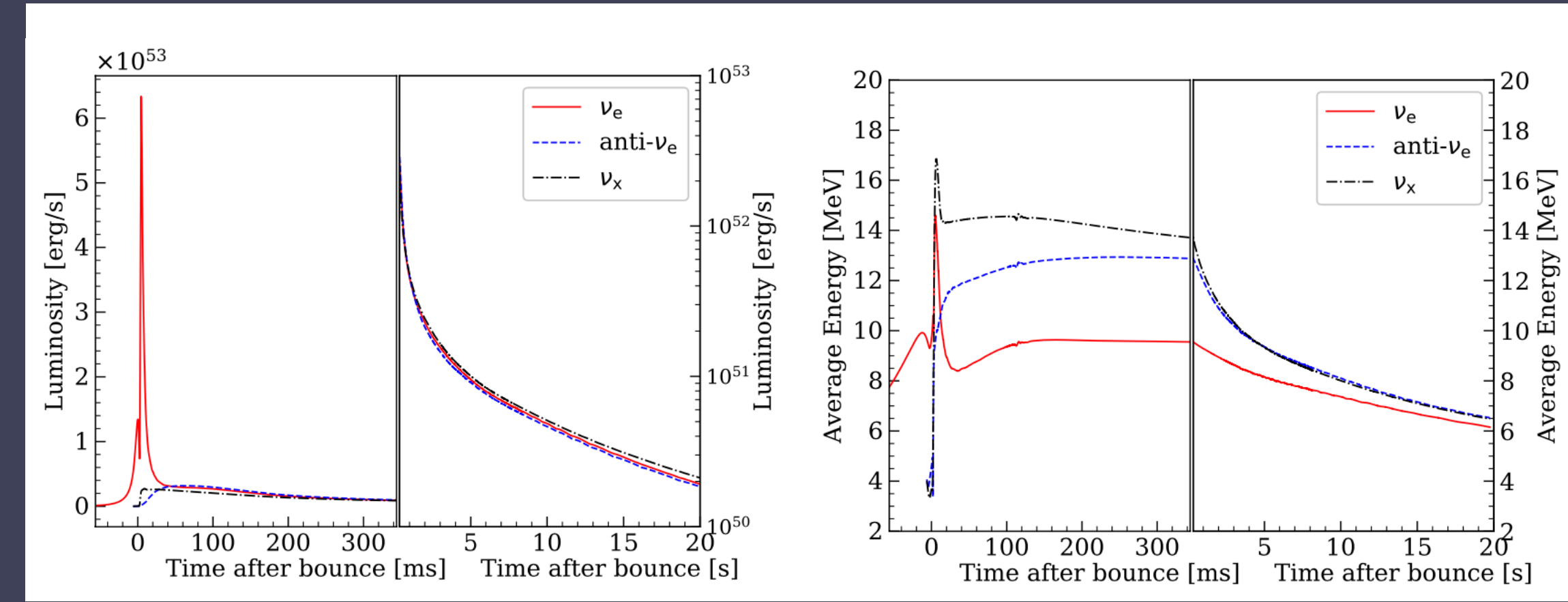
## Analysis method/pipeline

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

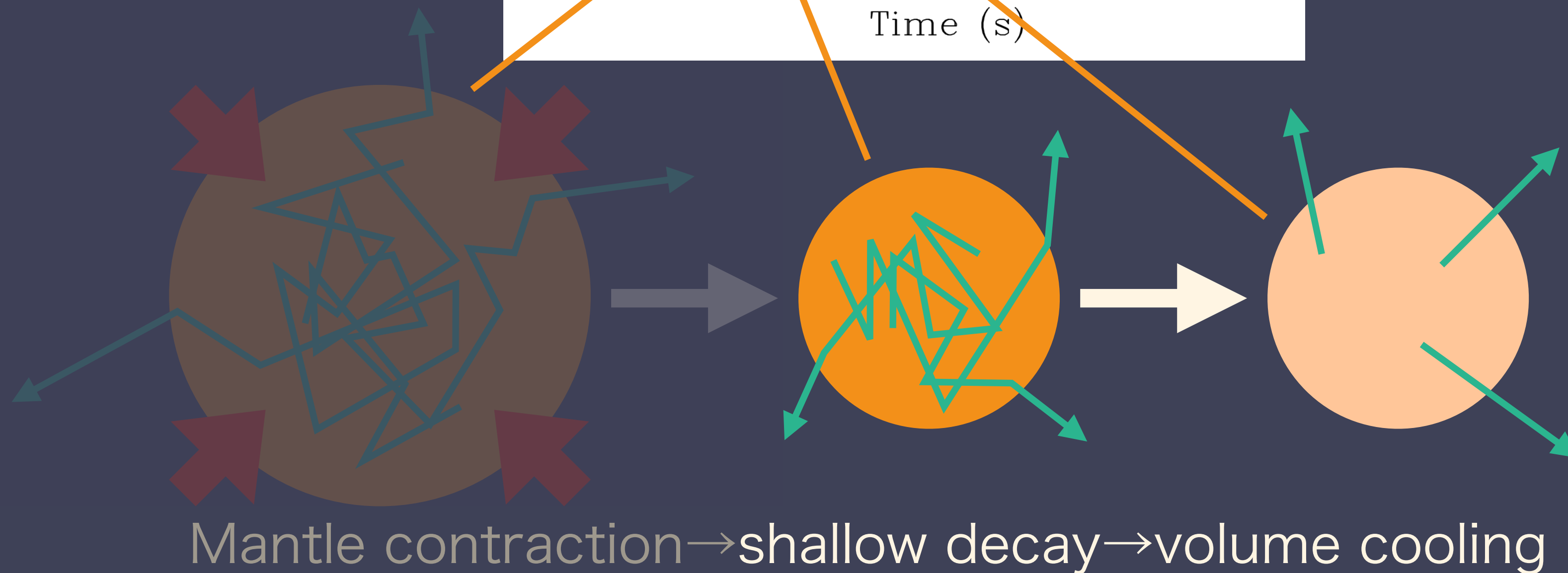
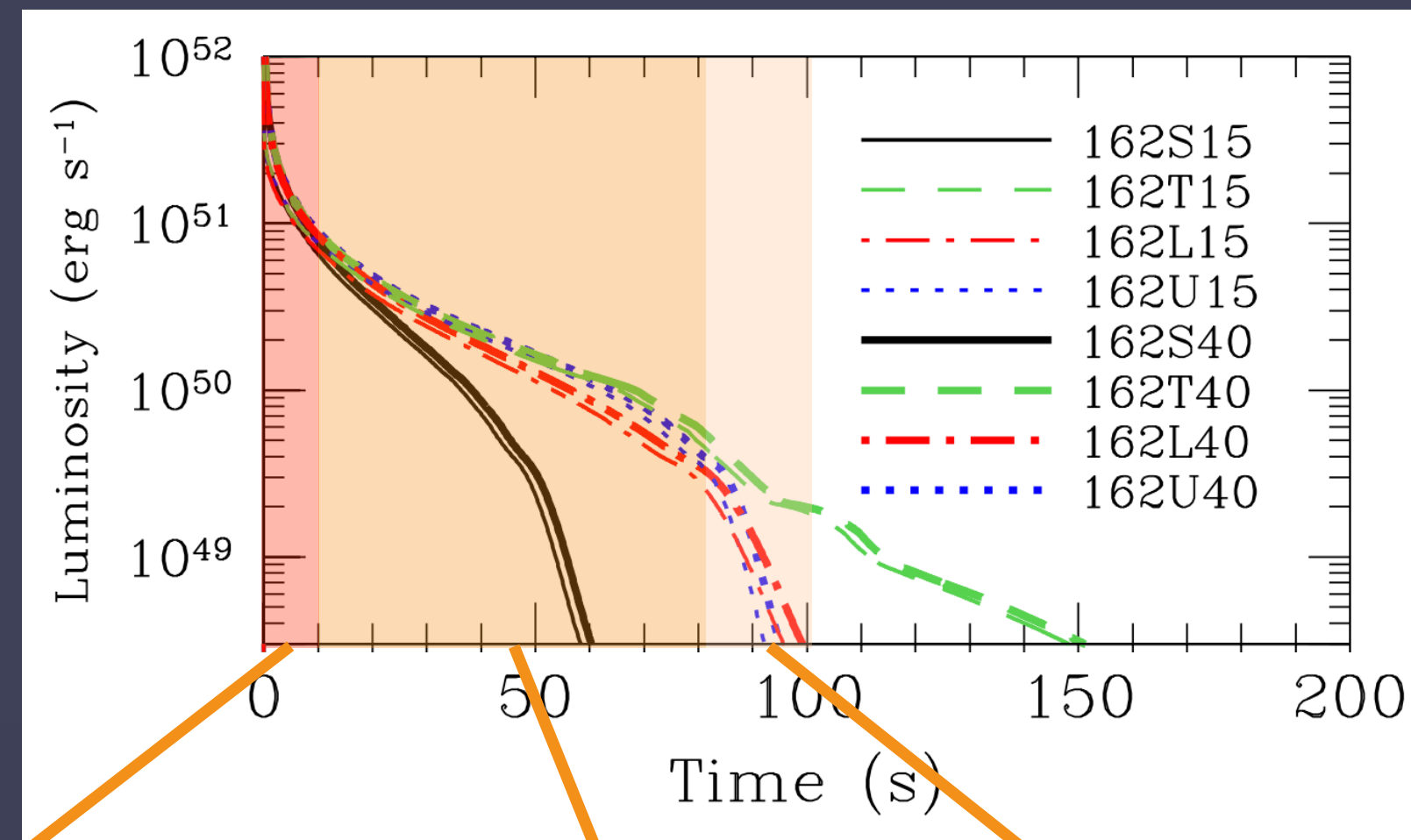
Quasi-steady state PNS cooling simulations with diffusion approx. using various PNS masses and nuclear EOSs.

## • 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



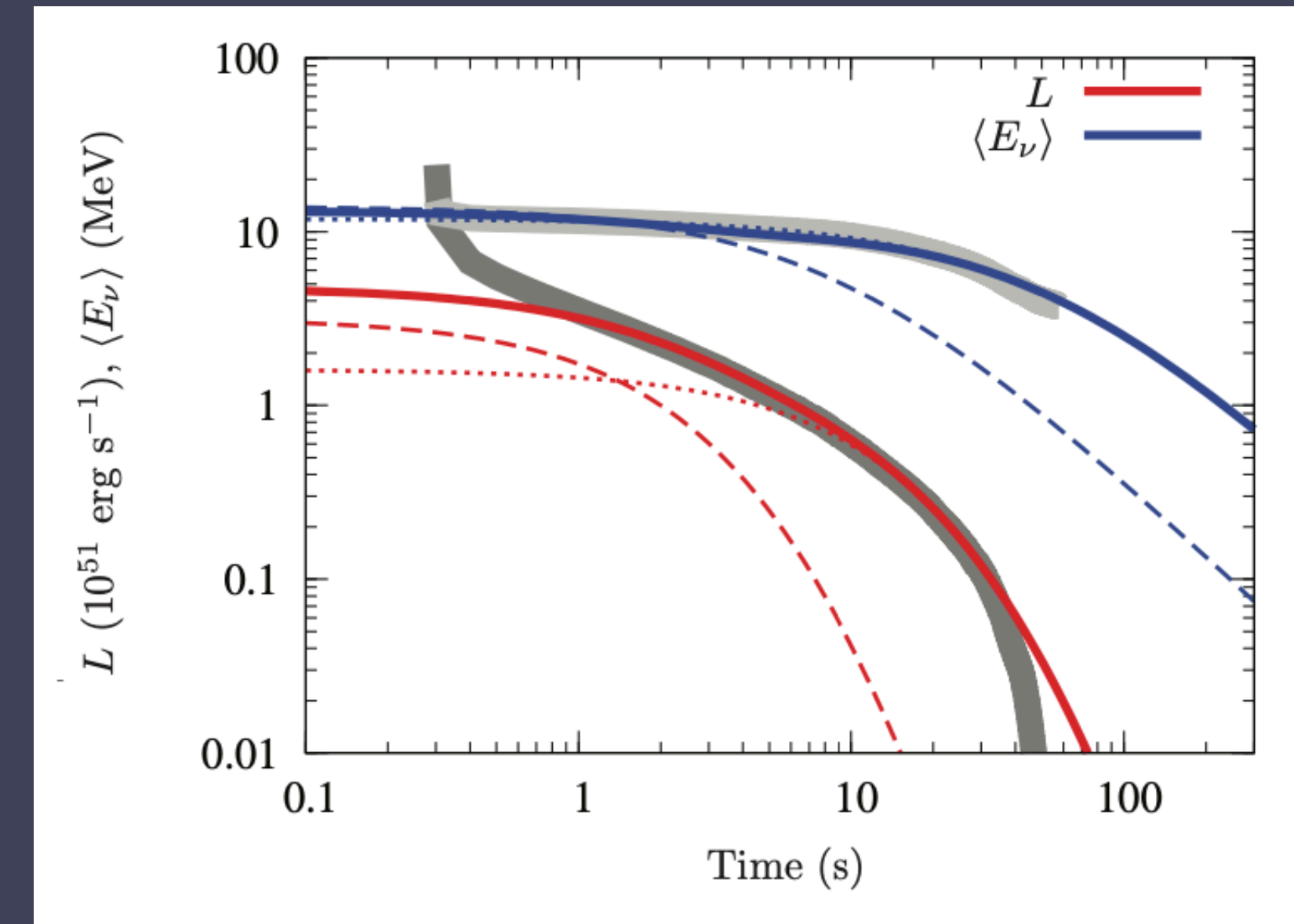
# Theoretical template: Analytic model

- Target: after the shallow decay phase when the mass and radius are fixed
  - PNS structure is determined by  $\gamma=2$  Lane-Emden equation
- neutrino luminosity and mean energy

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

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

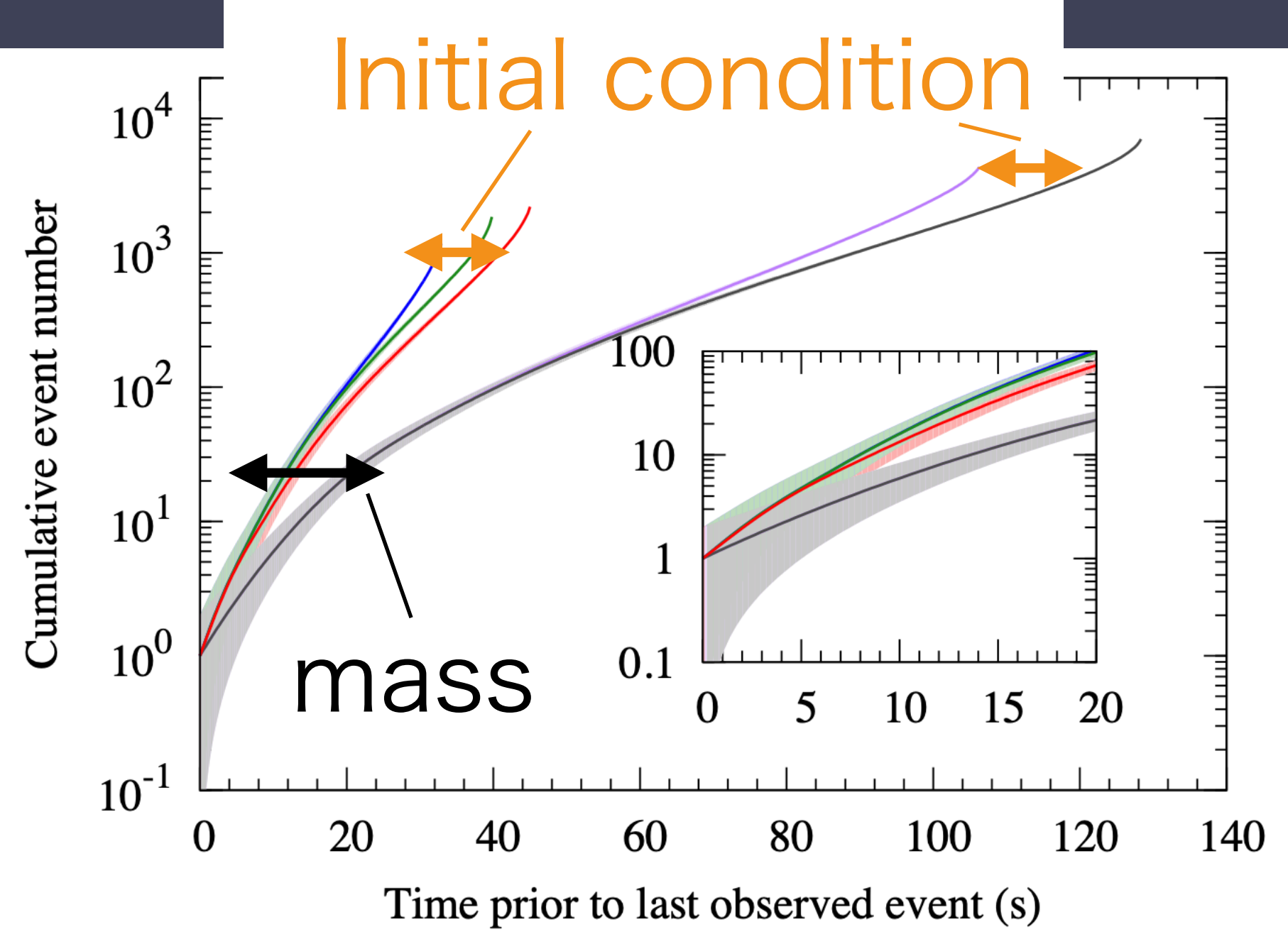
$$t_0 = 210 \text{ s} \left( \frac{M_{\text{PNS}}}{1.4 M_{\odot}} \right)^{6/5} \left( \frac{R_{\text{PNS}}}{10 \text{ km}} \right)^{-6/5} \left( \frac{g\beta}{3} \right)^{4/5} \left( \frac{E_{\text{tot}}}{10^{52} \text{ erg}} \right)^{-1/5}$$



Suwa+ (2021)

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

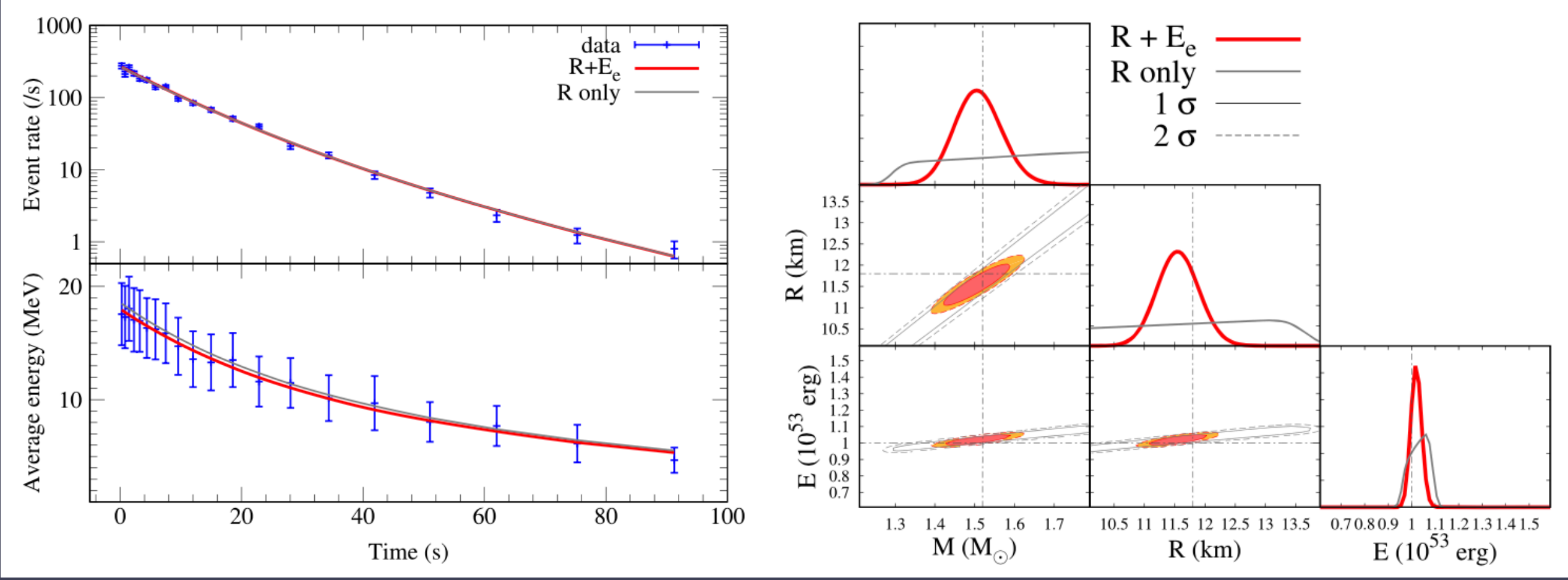
# Proposal of analysis methods



Suwa+ (2019)

- backward time analysis

Backward cumulative event count from last one event is useful to estimate the PNS mass.



Suwa+ (2022)

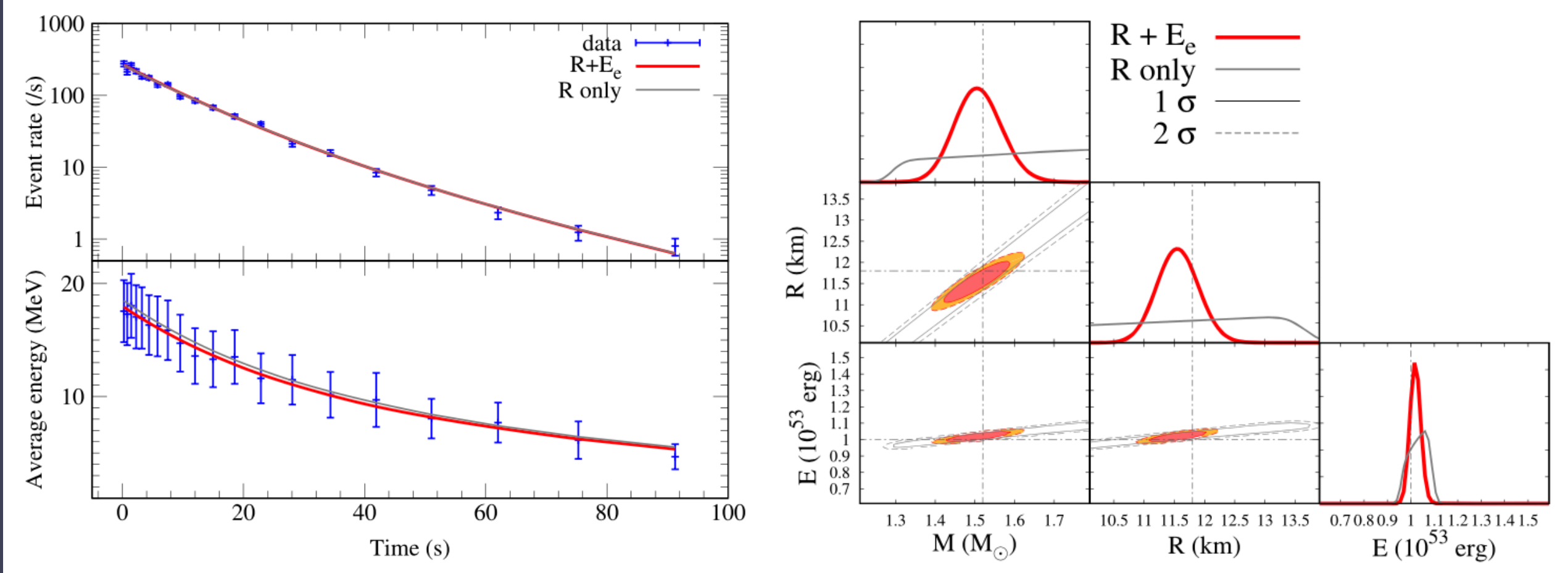
$$\chi^2 = \sum_{i \in \text{time bin}} \left( \frac{(N_i / \Delta t_i - \mathcal{R}_i)^2}{\mathcal{R}_i^2 / N_i} + \frac{(\langle \epsilon \rangle_i - E_{e^+,i})^2}{(0.05 E_{e^+,i})^2} \right)$$

Theo. rate                      Obs. mean ene.  
 Obs. rate                      Theo. mean ene.

- $\chi$ -square fitting

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

# Proposal of analysis methods



Suwa+ (2022)

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

Labels for the equation: 'Theo. rate' points to  $\mathcal{R}_i$ , 'Obs. rate' points to  $N_i / \Delta t_i$ , 'Obs. mean ene.' points to  $\langle \epsilon \rangle_i$ , and 'Theo. mean ene.' points to  $E_{e+,i}$ .

- Using  $\chi^2$  is ad hoc, appropriate only for the Gaussian distribution
- Poisson distribution is appropriate → applicable to the distant supernovae

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

# Analysis Pipeline : SPECIAL BLEND

- Supernova Parameter Estimation Code based on Insight on Analytic Late-time Burst Light curve at Earth Neutrino Detector (SPECIAL BLEND)
- Public analysis code that works on Google colaboratory
- Everyone can easily use!

```
!git clone https://[user_name]:{access_token}@github.com/akira-harada/SPECIAL_BLEND.git

Cloning into 'SPECIAL_BLEND'...
remote: Enumerating objects: 54, done.
remote: Counting objects: 100% (54/54), done.
remote: Compressing objects: 100% (37/37), done.
remote: Total 54 (delta 24), reused 35 (delta 14), pack-reused 0
Unpacking objects: 100% (54/54), done.

import os, sys

!{sys.executable} -m numpy.f2py --quiet -c /content/SPECIAL_BLEND/SPECIAL_BLEND.f90 -m SPECIAL_BLEND

!%run /content/SPECIAL_BLEND/event_generator.py

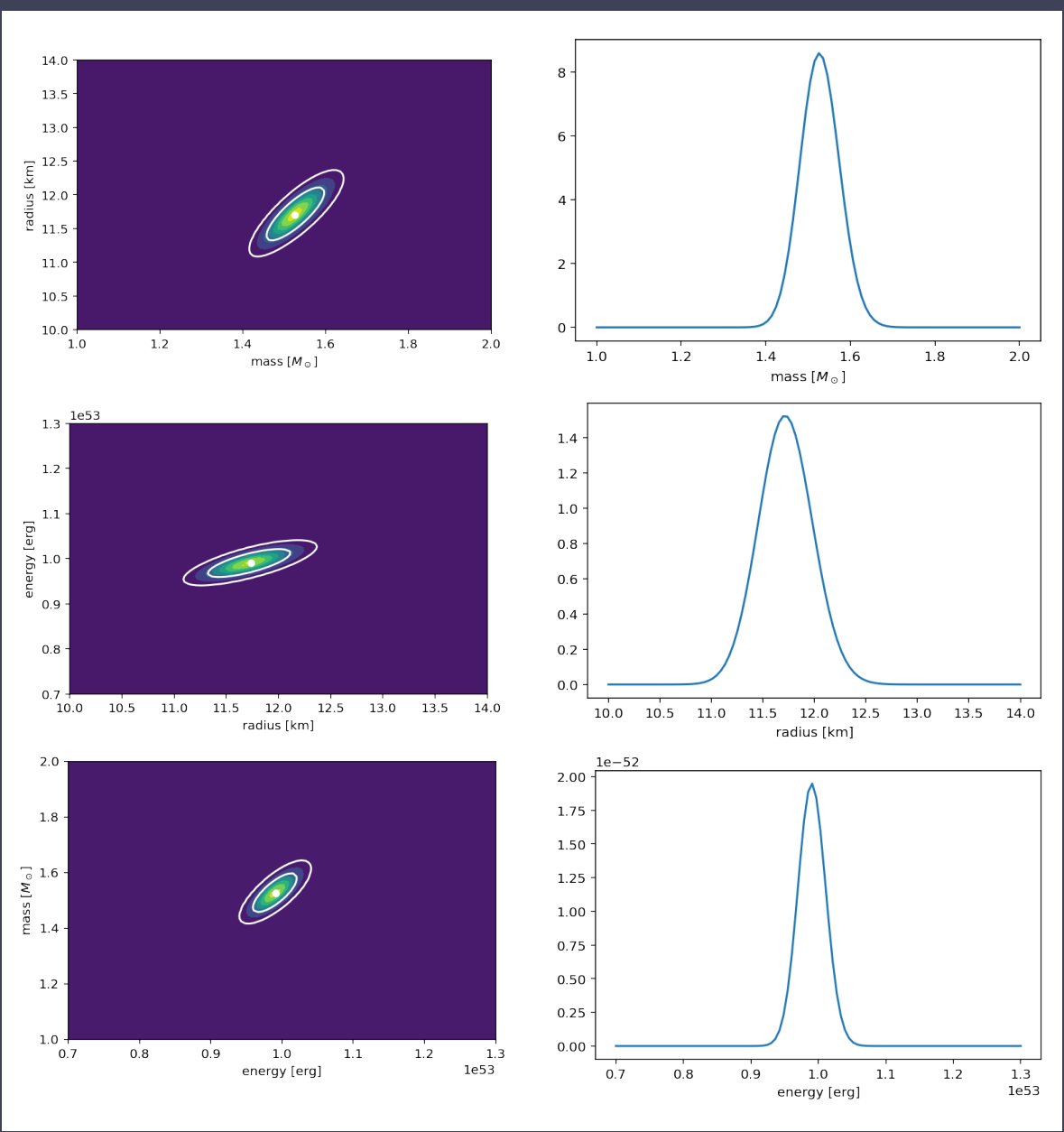
# define functions
%config InlineBackend.figure_format = 'retina'
import numpy as np
import csv
import matplotlib.pyplot as plt
import SPECIAL_BLEND as SB

def main():
    params = np.loadtxt('/content/SPECIAL_BLEND/parameters.dat') # 'parameters.dat' file has the following contents: assumed gbeta, distance to the SN [kpc], detector mass [kton], parameter
    origdata = np.loadtxt('/content/time_energy.dat') # 'time_energy.dat' file has the time and energy of each event: first column is time, second column is energy
    analysis_mode = int(params[10]) # 1:unbinned, 2:full-binned (mode 3 and 4 work only in fortran version, not implemented in this Google Colaborator version)
    tmin = params[13]
    tmax = params[14]
    data = loaddata(tmin, tmax, origdata)
    if analysis_mode == 1:
        print("unbinned analysis")
        mlogLH, mass, rad, et = unbinned_likelihood(data, params)
        print("likelihood calculation completed")
    elif analysis_mode == 2:
        print("binned analysis")
        mlogLH, mass, rad, et = binned_likelihood(data, params)
        print("likelihood calculation completed")
```

```
1D marginalized result
mass = 1.526519e+00 +4.92e-02/-4.78e-02 (68%) +9.14e-02/-8.68e-02 (95%)
radius = 1.171508e+01 +2.65e-01/-2.60e-01 (68%) +5.25e-01/-5.04e-01 (95%)
energy = 9.901252e+52 +1.90e+51/-1.88e+51 (68%) +4.30e+51/-4.16e+51 (95%)

2D marginalized result
M-R: the best fit is (M,R)=(1.53e+00,1.17e+01), and the levels of CI is 7.36e+00 (68%) and 1.12e+00 (95%)
R-E: the best fit is (R,E)=(1.17e+01,9.91e+52), and the levels of CI is 1.39e-52 (68%) and 2.21e-53 (95%)
E-M: the best fit is (E,M)=(9.91e+52,1.53e+00), and the levels of CI is 8.32e-52 (68%) and 1.29e-52 (95%)

[1]: # visualize likelihood
visualize(mass, rad, et, mlogLH, LH_MR, MRvals, LH_RE, REvals, LH_EM, EMvals, LHLM, LHLMR, LHLE)
```





# Analysis Pipeline : SPECIAL BLEND

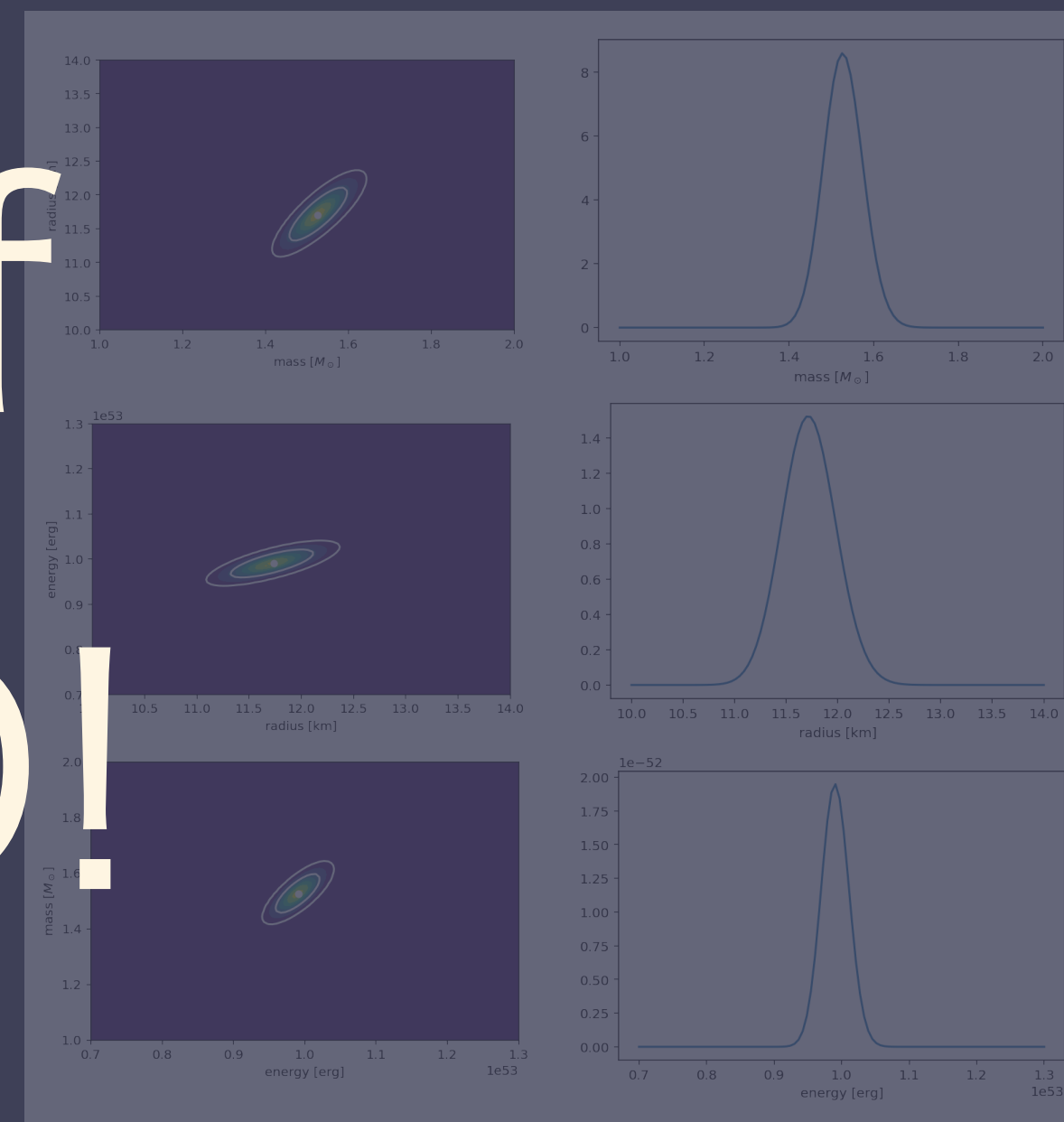
- Supernova Parameter Estimation Code based on Insight on Analytic Late-time Burst Light curve at Earth Neutrino Detector (SPECIAL BLEND)
- Public analysis code that works on Google colaboratory
- Everyone can easily use!

I'll do a demo of  
SPECIAL BLEND!

```
SPECIAL_BLEND_pyinterface.ipynb
ファイル 編集 表示 挿入 ランタイム ツール ヘルプ すべての変更を保存しました
+ コード + テキスト
RAM 100% ディスク 100%
[1] !git clone https://[user_name]:[access_token]@github.com/akira-harada/SPECIAL_BLEND.git
Cloning into 'SPECIAL_BLEND'...
remote: Enumerating objects: 54, done.
remote: Counting objects: 100% (54/54), done.
remote: Compressing objects: 100% (37/37), done.
remote: Total 54 (delta 24), reused 35 (delta 14), pack-reused 0
Unpacking objects: 100% (54/54), done.
[2] import os, sys
[3] !{sys.executable} -m numpy.f2py --quiet -c /content/SPECIAL_BLEND/SPECIAL_BLEND.F90 -m SPECIAL_BLEND
[4] %run /content/SPECIAL_BLEND/event_generator.py
[5] # define Functions
%config InlineBackend.figure_format = 'retina'
import numpy as np
import csv
import matplotlib.pyplot as plt
import SPECIAL_BLEND as SB

def main():
    params = np.loadtxt('/content/SPECIAL_BLEND/parameters.dat') # 'parameters.dat' file has the following contents: distance to SN [kpc], detector mass [kton], parameter
    origdata = np.loadtxt('/content/time_energy.dat') # 'time_energy.dat' file has the time and energy of each event: first column is time, second column is energy
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    tmin = params[13]
    tmax = params[14]
    data = loaddata(tmin, tmax, origdata)
    if analysis_mode == 1:
        print("unbinned analysis")
        mlogLH, mass, rad, et = unbinned_likelihood(data, params)
        print("likelihood calculation completed")
    elif analysis_mode == 2:
        print("binned analysis")
        mlogLH, mass, rad, et = binned_likelihood(data, params)
        print("likelihood calculation completed")
```

```
SPECIAL_BLEND_pyinterface.ipynb
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RAM 100% ディスク 100%
[1] 1D marginalized result
mass = 1.526519e+00 +4.92e-02/-4.78e-02 (68%) +9.14e-02/-8.68e-02 (95%)
radius = 1.171508e+01 +2.65e-01/-2.60e-01 (68%) +5.25e-01/-4.94e-01 (95%)
energy = 9.901252e+52 +1.90e+51/-1.88e+51 (68%) +4.30e+51/-4.16e+51 (95%)
[2] 2D marginalized result
N-R: the best fit is (1.53e+00, 1.17e+01) and the 68% and 95% CIs are (1.36e+00, 1.70e+01) and (1.17e+01, 9.91e+52) and the likelihood is 0.000188
R-E: the best fit is (1.17e+01, 9.91e+52) and the 68% and 95% CIs are (1.39e+52, 1.17e+53) and (9.91e+52, 1.53e+53) and the likelihood is 0.000188
E-M: the best fit is (9.91e+52, 1.53e+53) and the 68% and 95% CIs are (1.33e+52, 9.91e+52) and (9.91e+52, 1.53e+53) and the likelihood is 0.000188
[3] # visualize likelihood
visualize_likelihood(mlogLH, LH_MR, MRvols, LHvols, MRvols, LHvols)
[4] # visualize likelihood
visualize_likelihood(mlogLH, LH_MR, MRvols, LHvols, MRvols, LHvols)
```



# 解析パイプライン：SPECIAL BLEND

- Supernova Parameter Estimation Code based on Insight on Analytic Late-time Burst Light curve at Earth Neutrino Detector (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

```
SPECIAL_BLEND_pyinterface.ipynb
ファイル 編集 表示 挿入 ランタイム ツール ヘルプ すべての変更を保存しました
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Cloning into 'SPECIAL_BLEND'...
remote: Enumerating objects: 54, done.
remote: Compressing objects: 100% (54/54), done.
remote: Total 54 (re-used 0): 1.18 MB, 39.00 KB/s, done.
Unpacking objects: 100% (54/54), done.

import os
import sys

!system('ls -l')
!system('ls -l SPECIAL_BLEND/SPECIAL_BLEND_F90 -m SPECIAL_BLEND')

!xrun /content/SPECIAL_BLEND/event_generator.py

# define function
def generate_data():
    # generate 100 random data
    import numpy as np
    import csv
    import matplotlib.pyplot as plt
    import SPECIAL_BLEND

    # generate 100 random data
    origdata = np.loadtxt('content/time_energy.dat') # 'time_energy.dat' file has the time and energy of each event: first column is time, second column is energy
    analysis_mode = int(params[10]) # 1:unbinned, 2:full-binned (mode 3 and 4 work only in fortran version, not implemented in this Google Colaborator version)
    tmin = params[11]
    tmax = params[12]
    data = origdata[(origdata[:,0] > tmin) & (origdata[:,0] < tmax)]

    # analyze data
    print('analyze data')
    mlogLH, mass, rad, et = unbinned_likelihood(data, params)
    print('likelihood calculation completed')

    elif analysis_mode == 2:
        print('binned analysis')
        mlogLH, mass, rad, et = binned_likelihood(data, params)
        print('likelihood calculation completed')
```

```
SPECIAL_BLEND_pyinterface.ipynb
ファイル 編集 表示 挿入 ランタイム ツール ヘルプ すべての変更を保存しました
+ コード + テキスト
[1] 1D marginalized result
mass = 1.526519e+00 +4.92e-02/-4.78e-02 (68%) +9.14e-02/-8.68e-02 (95%)
radius = 1.171508e+01 +2.65e-01/-2.60e-01 (68%) +5.25e-01/-5.04e-01 (95%)
energy = 9.981252e+52 +1.98e+52/-1.91e+52 (68%) +3.96e+52/-3.82e+52 (95%)
M: the best fit is (E,M)=(1.17e+01, 9.91e+52), and the levels of CI is 1.39e-52 (68%) and 2.21e-52 (95%)
E-M: the best fit is (E,M)=(9.91e+52, 1.53e+00), and the levels of CI is 8.32e-52 (68%) and 1.29e-52 (95%)

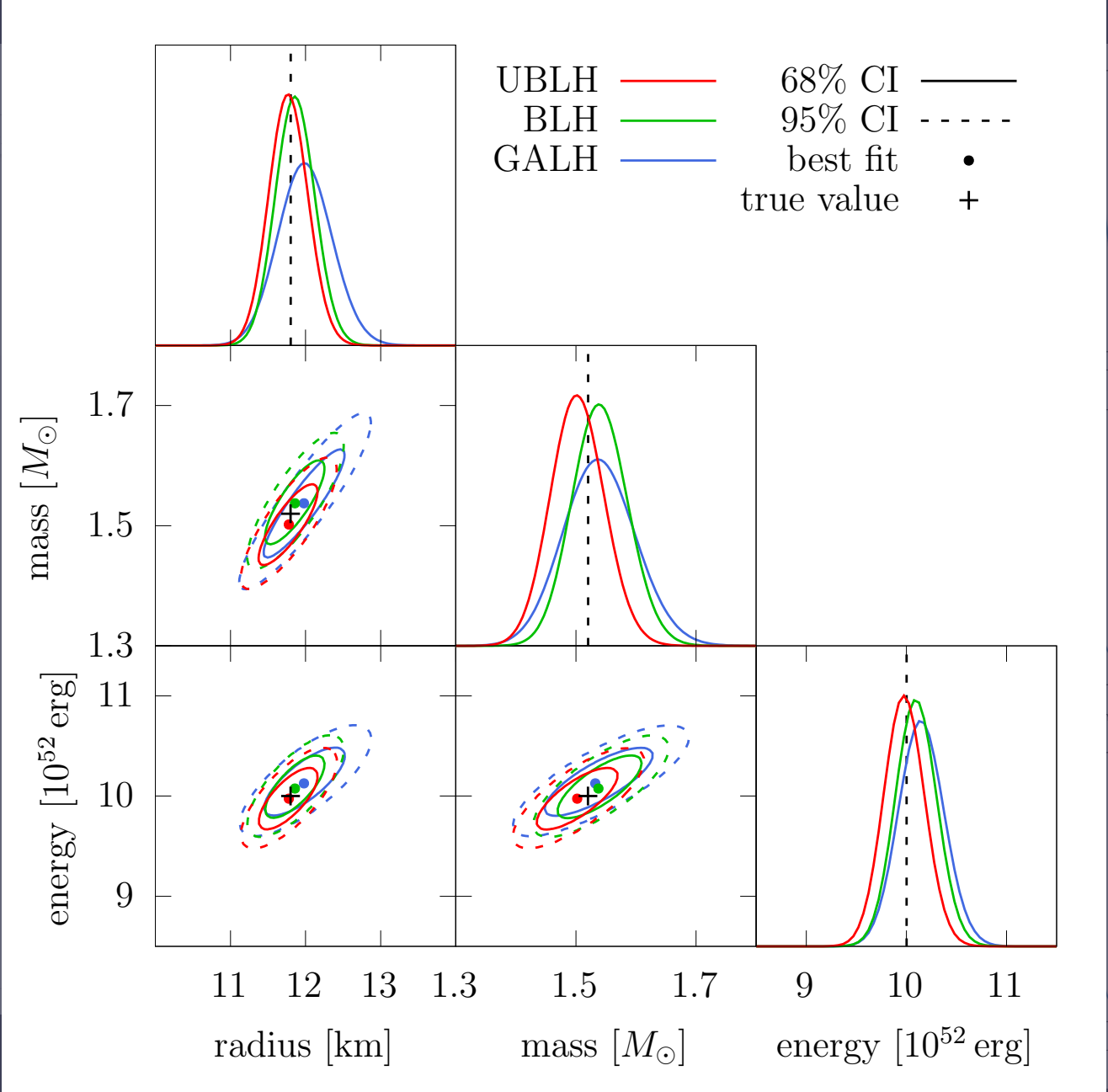
[3] # visualize likelihood
visualize(mass, rad, et, mlogLH, LH_MR, MRvals, LH_RE, REvals, LH_EM, EMvals, LHM, LHR, LHE)
```

• 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 $\chi^2$ の結果

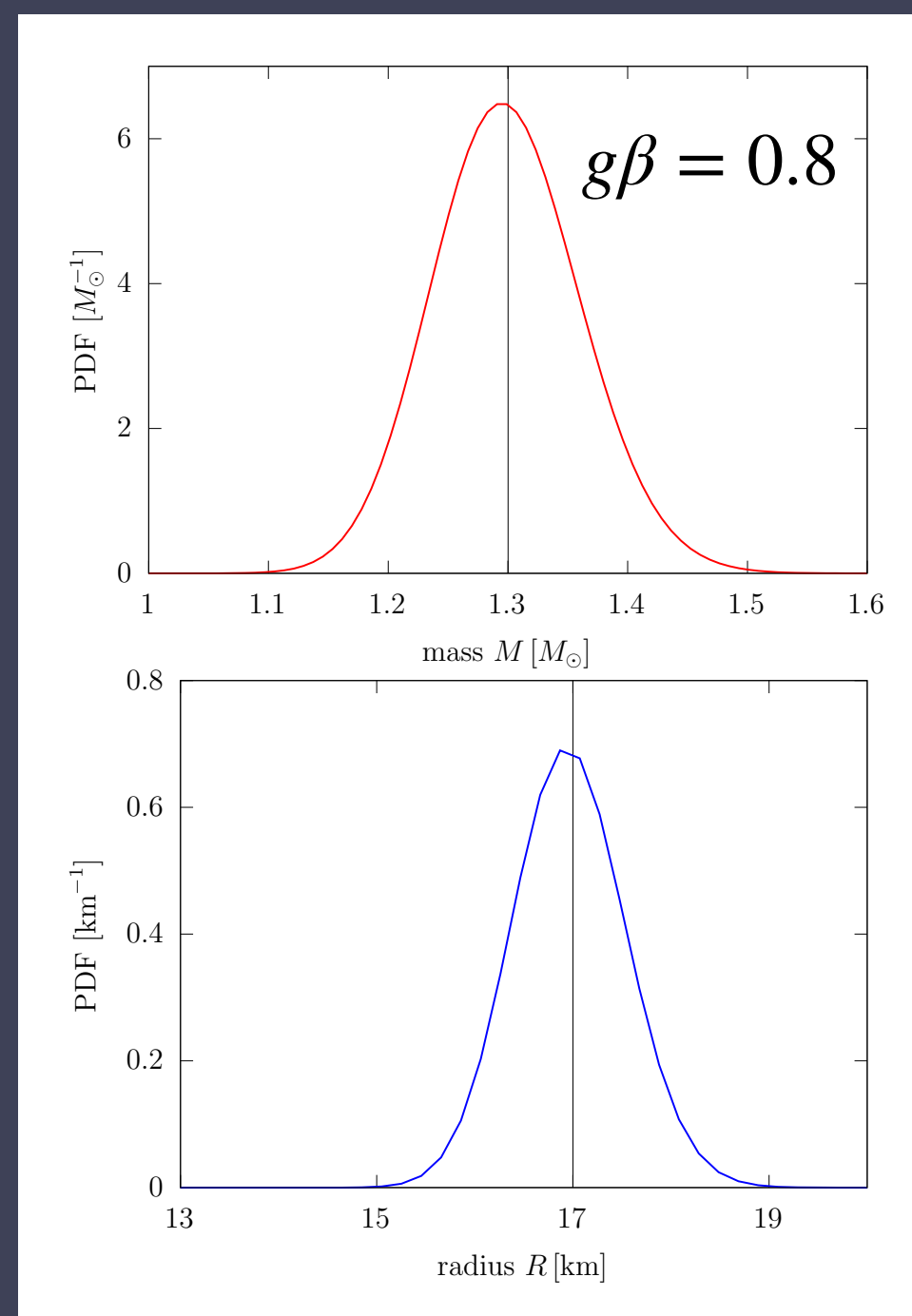
• 典型的には真の値をまあよく再現できる



# How about realistic data?

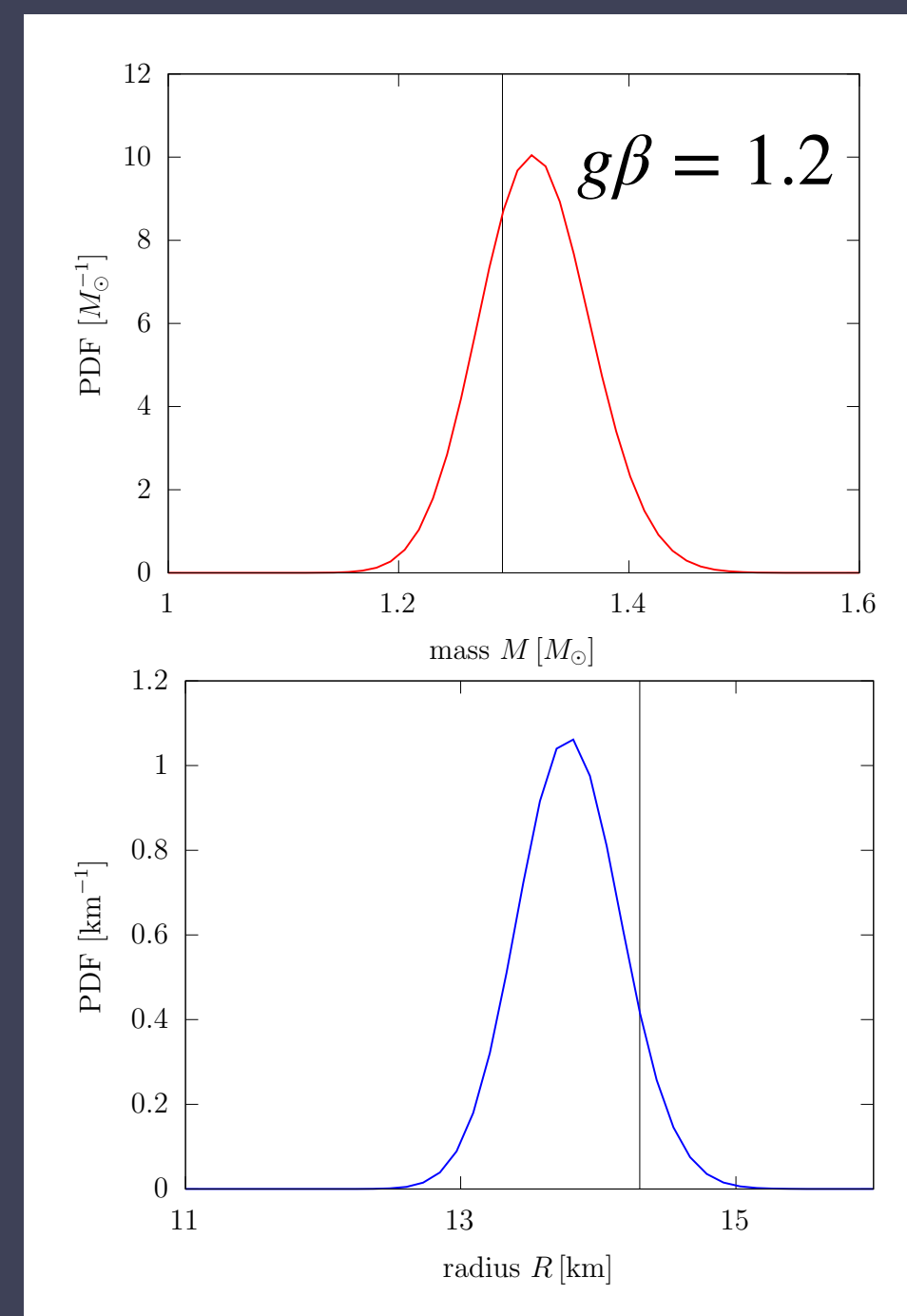
- Analyze the mock observational data based on theoretical template of Nakazato's and Mori's database: supernova is at the Galactic center, the detector is Super Kamiokande
- By focusing on the shallow decay phase with cutting first 0.5 s events, SPECIAL BLEND reproduces the parameters of the realistic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

Mori's DB



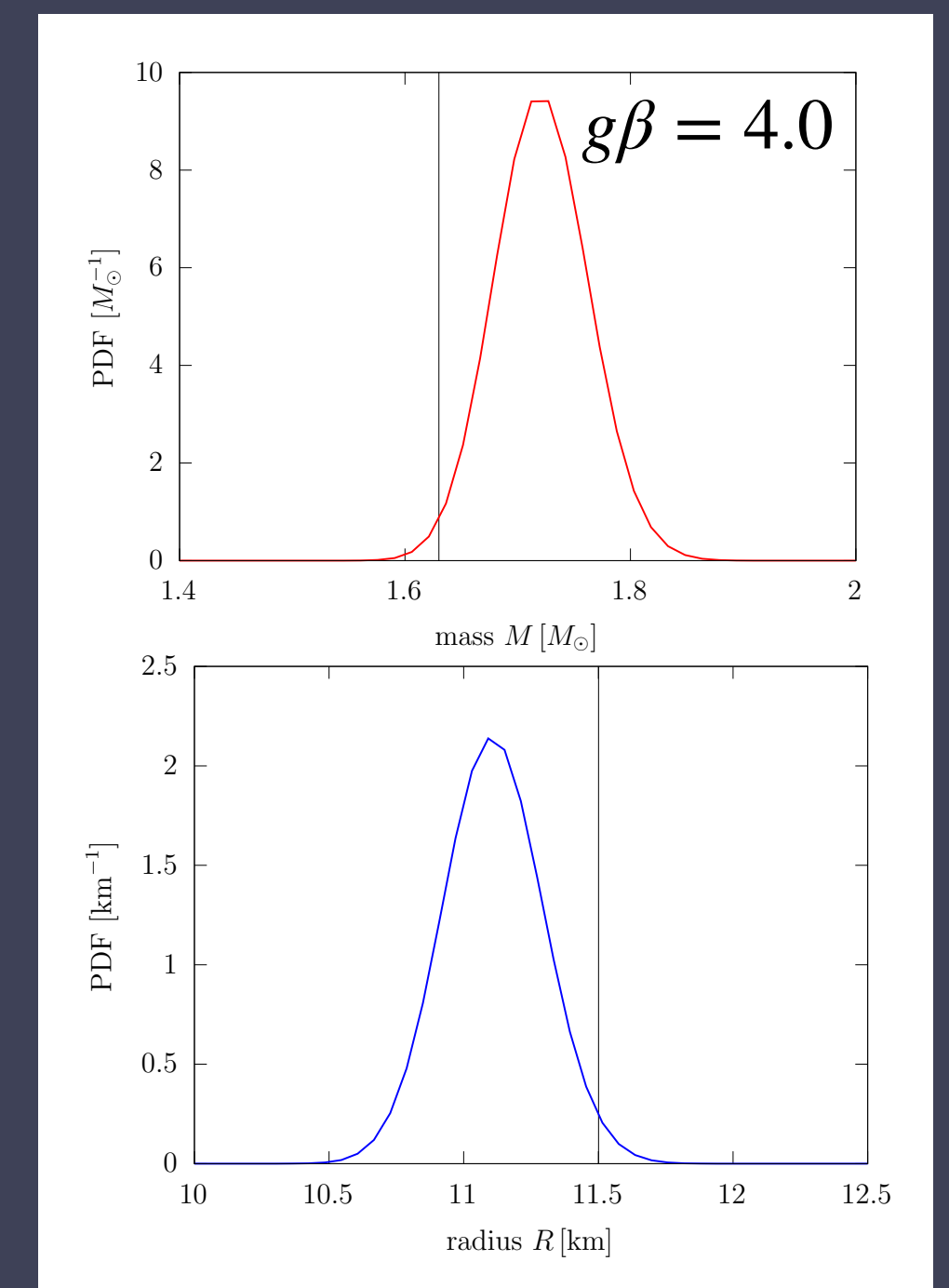
AH+ in prep.

Nakazato's DB-1



AH+ in prep.

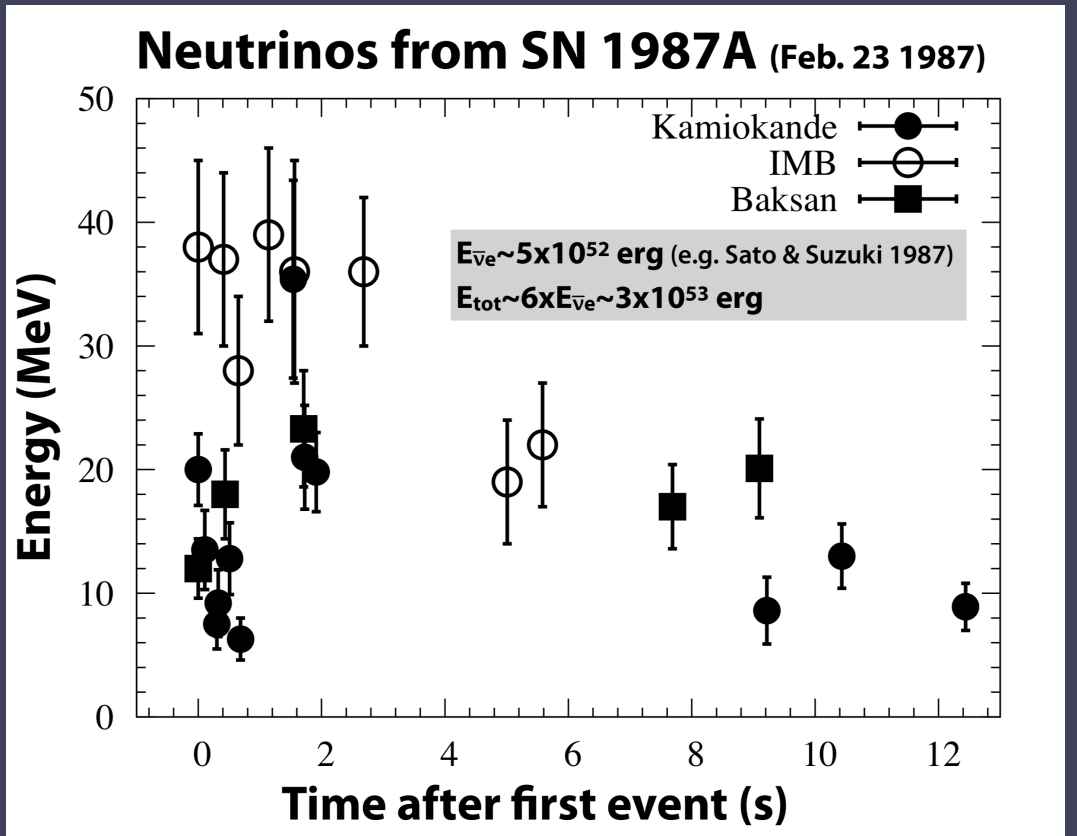
Nakazato's DB-2



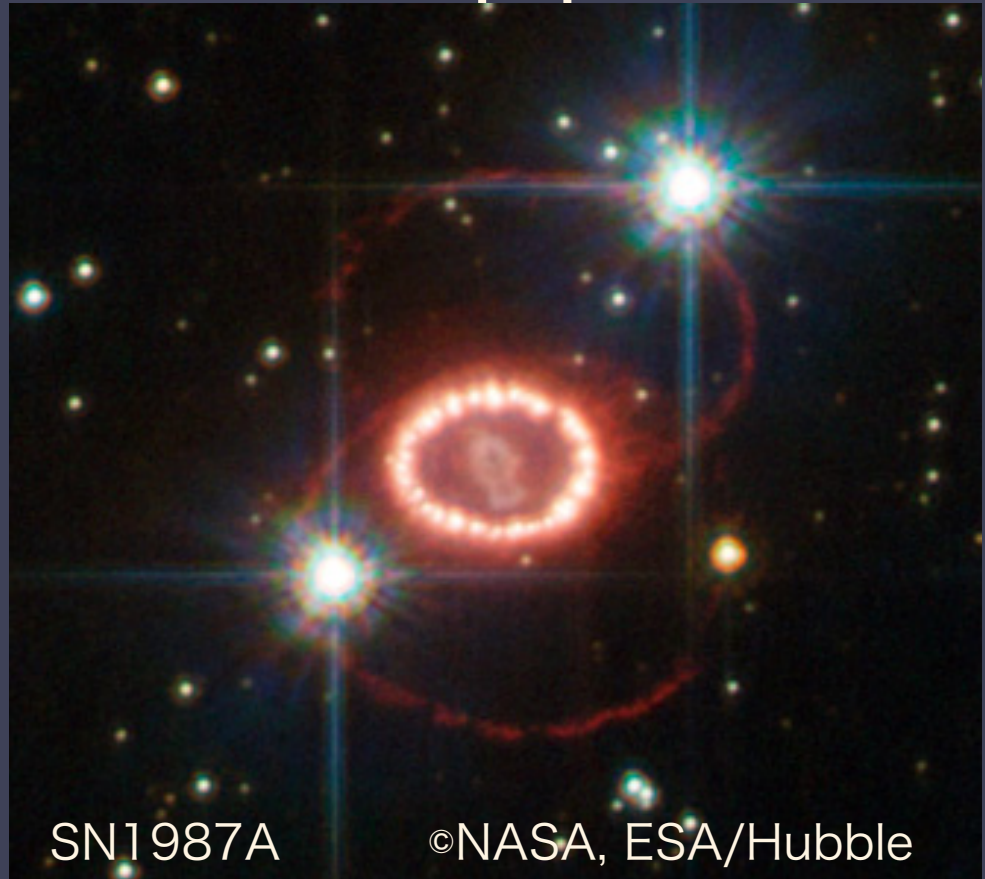
AH+ in prep.

# SN1987A neutrinos and NS1987A(?)

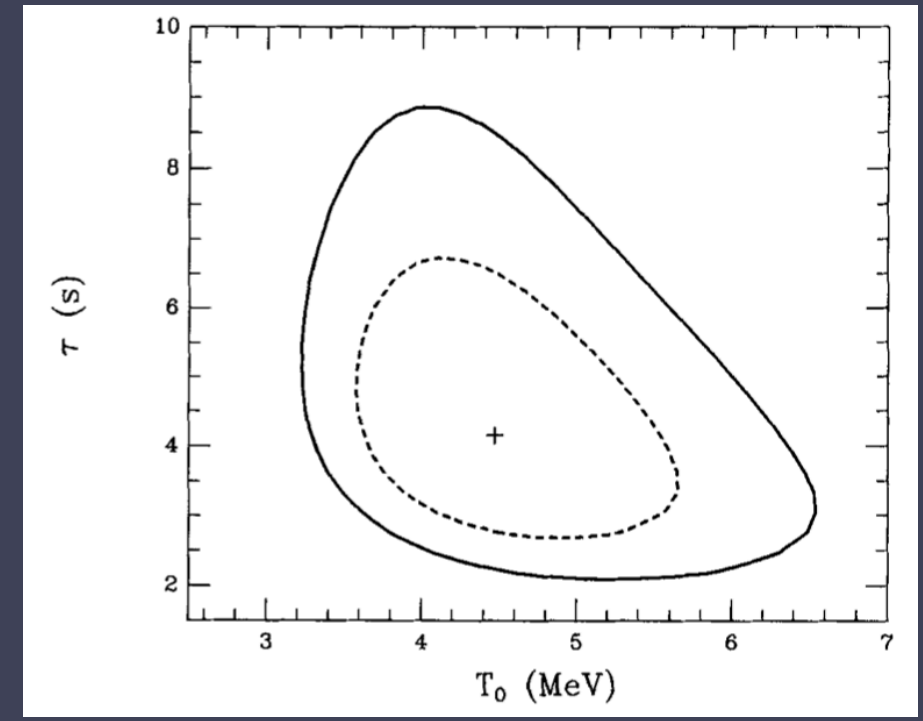
Neutrinos



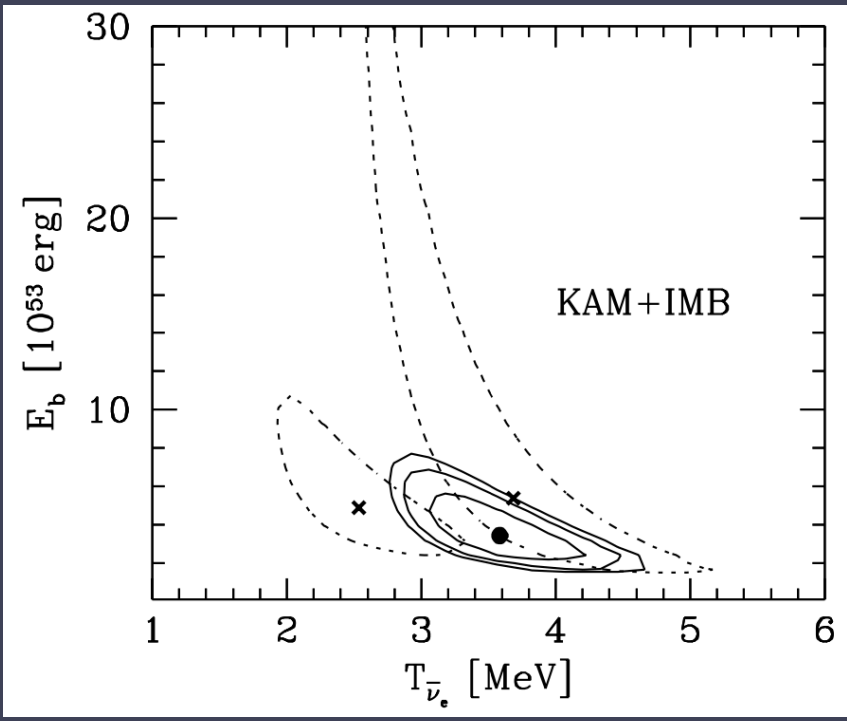
Courtesy of Suwa



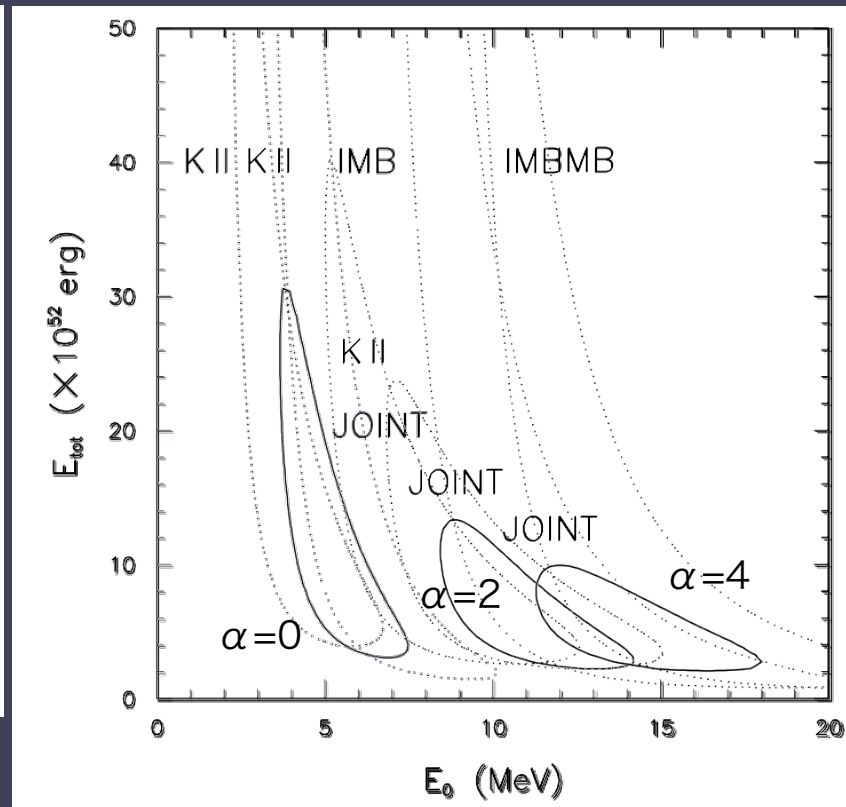
SN1987A ©NASA, ESA/Hubble



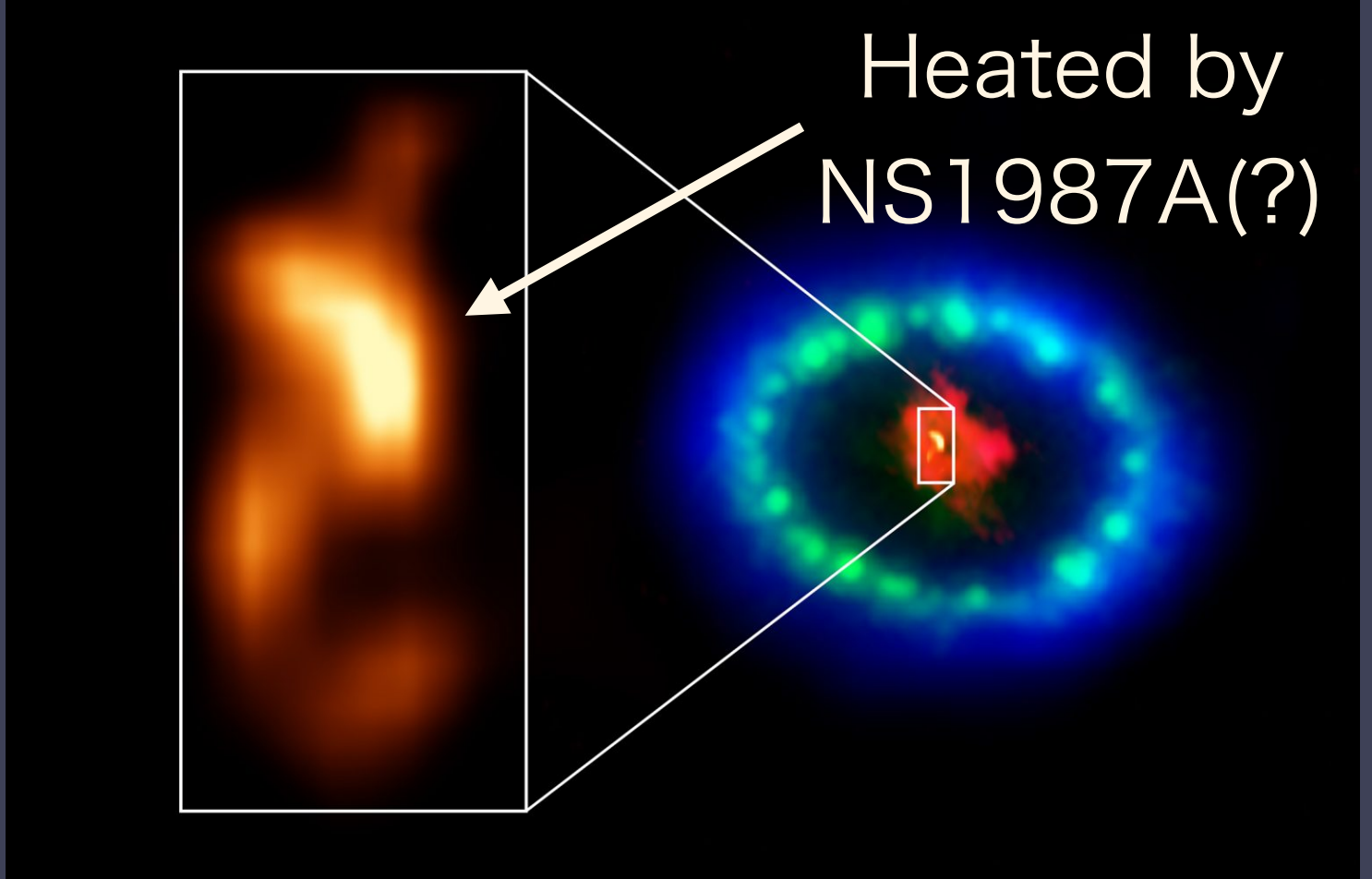
Loredo & Lamb (1989)  
Time-dep. model  
Joint analysis only



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

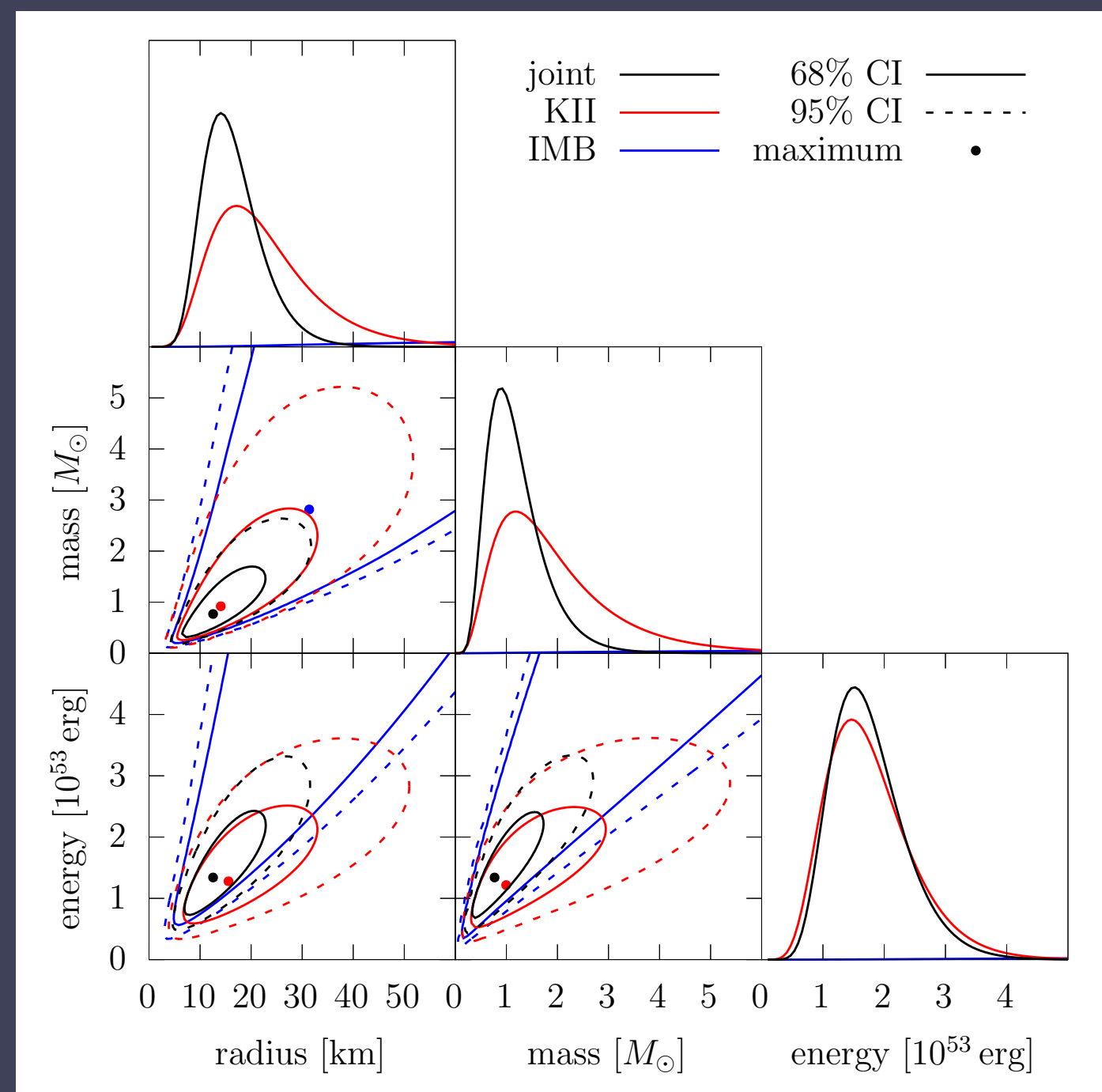
- Analysis of SN1987A has relied on phenomenological models: discrepancy between KII and IMB
- ALMA found a hot spot in SN1987A remnant → evidence of NS1987A?
- Properties are still unknown.

Optical

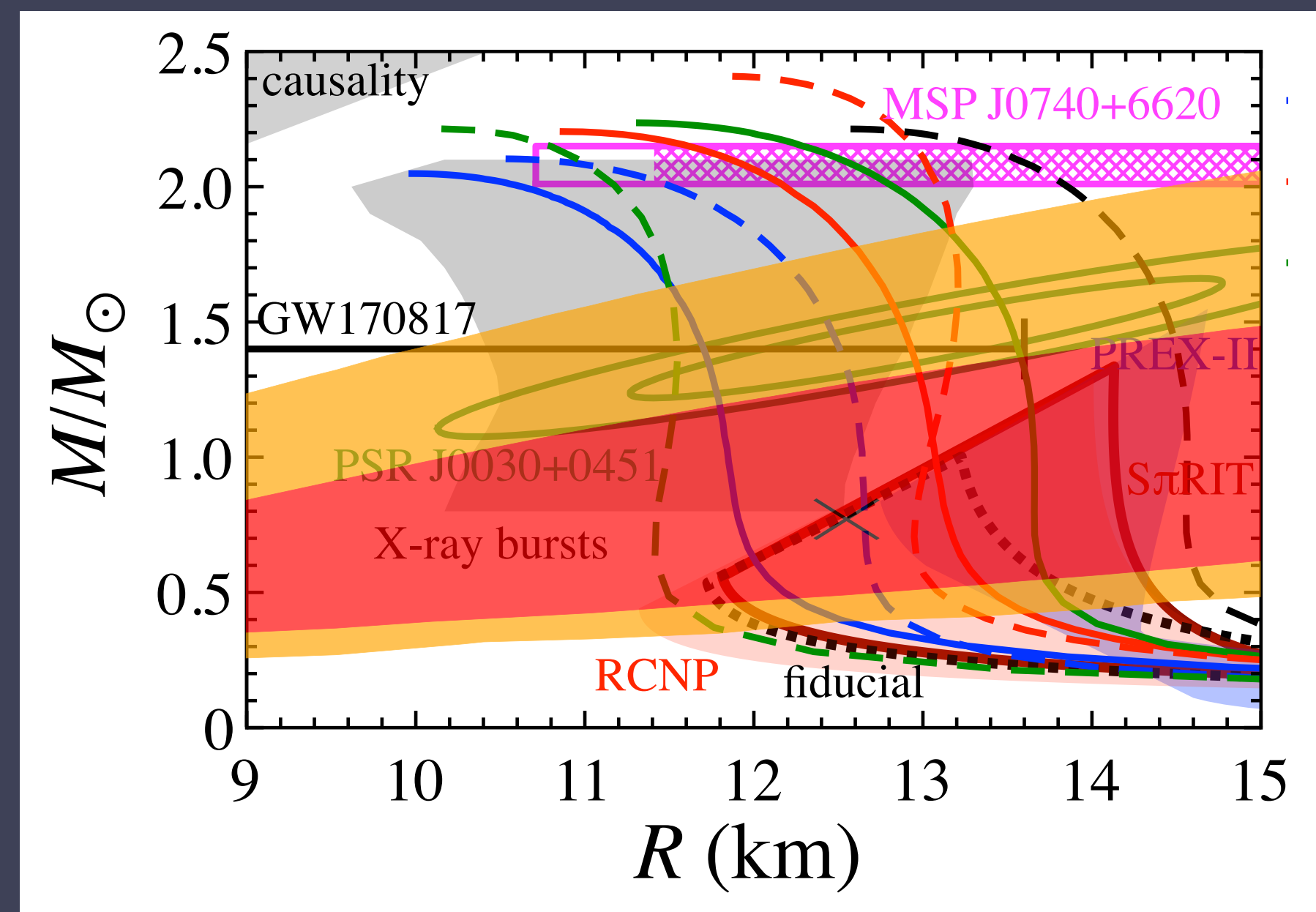
(~30 yrs. later)

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



AH+ in prep.

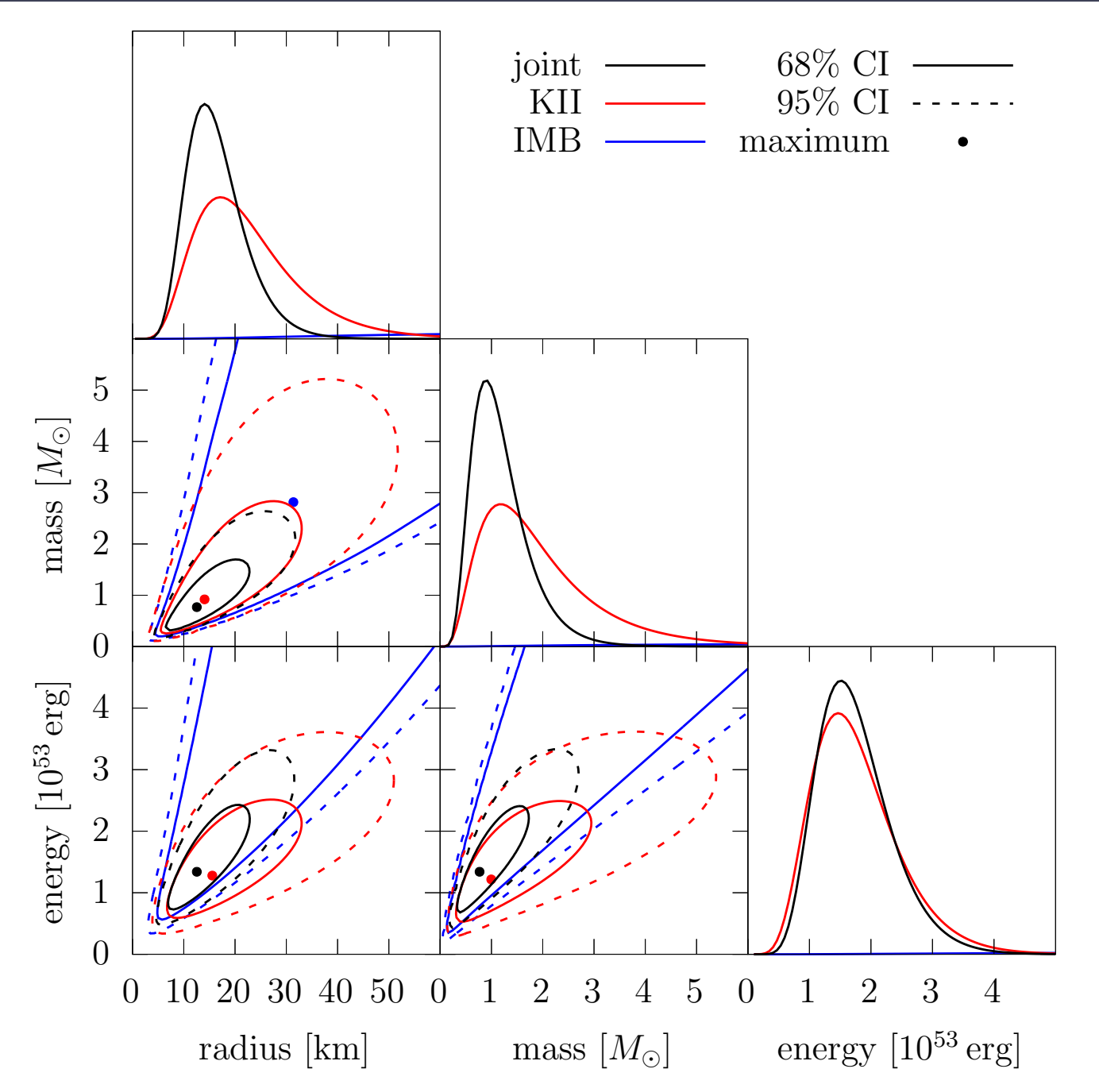


M-R relation diagram (Superimposed to Sotani+ 2022 Fig. 2)

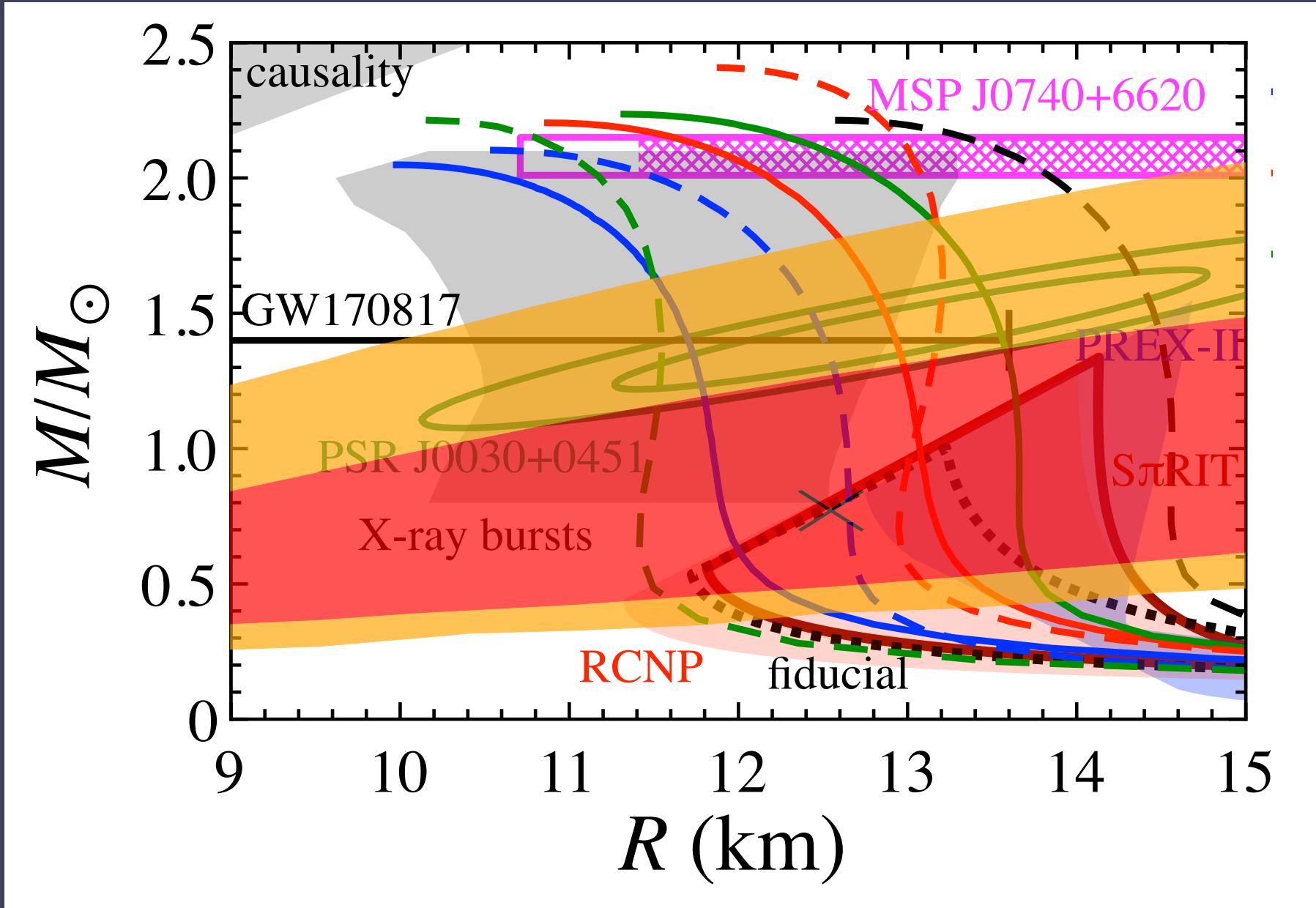
# Parameter estimation of NS1987A

- 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  $g\beta$
- Caution 3: typical (?) NS mass in simulations ( $\sim 1.6 M_{\odot}$ ) may be too large

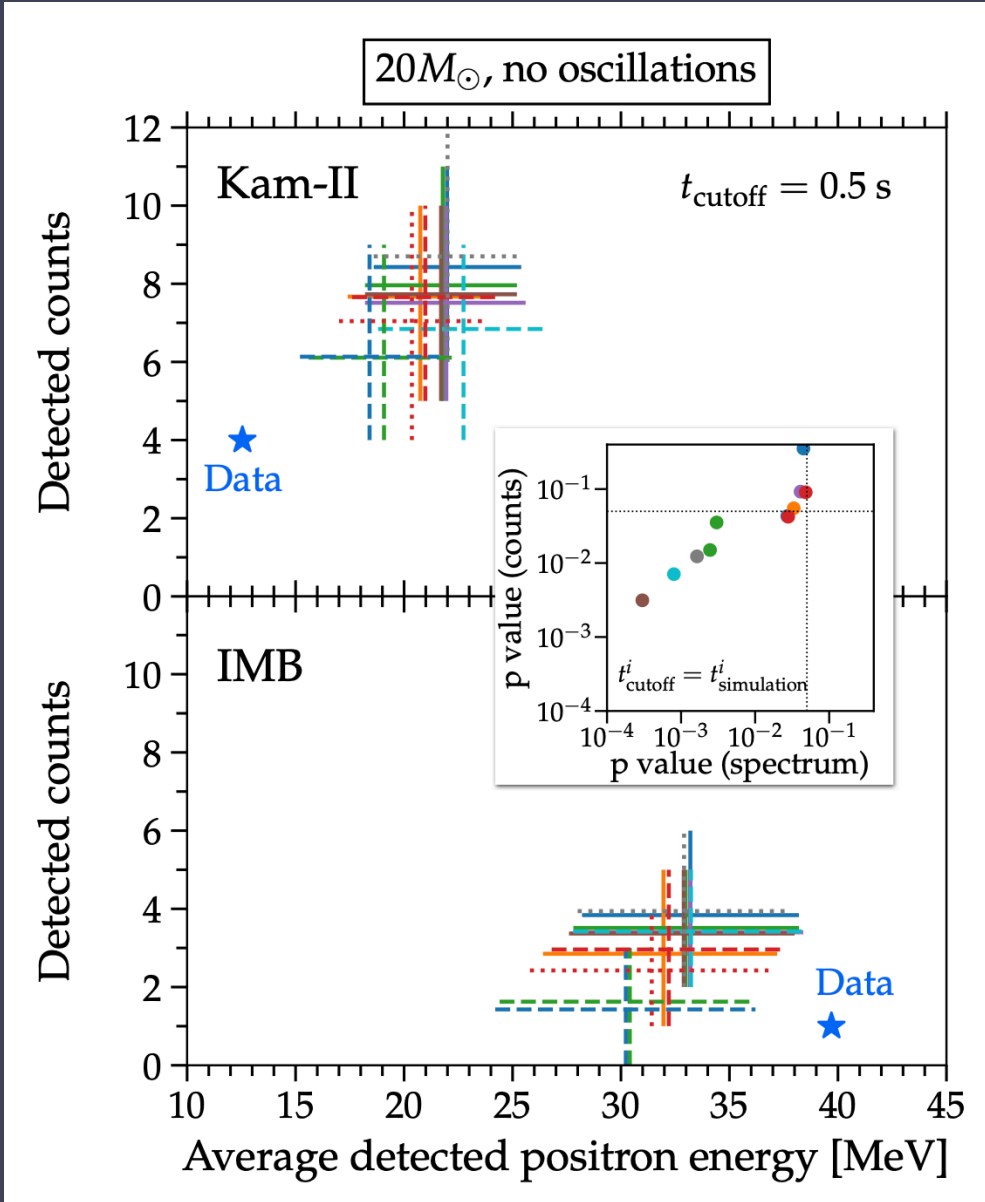
Li+ arXiv:2306.08024



AH+ in prep.



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

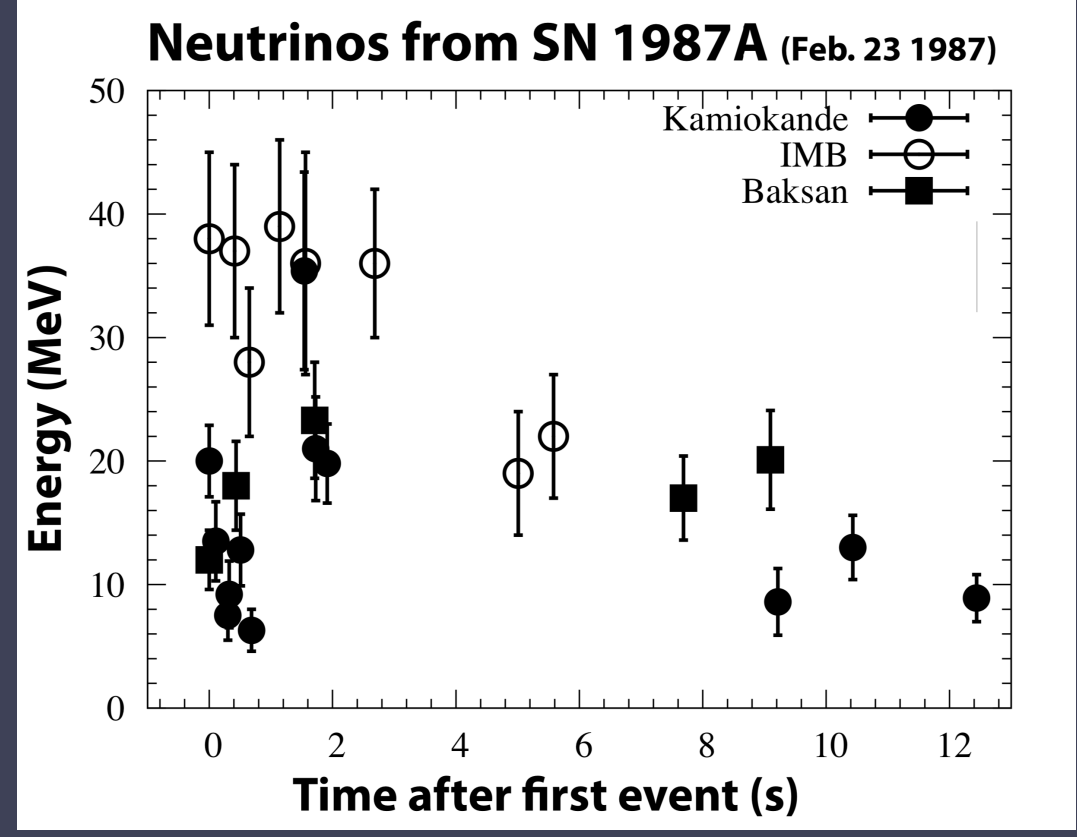
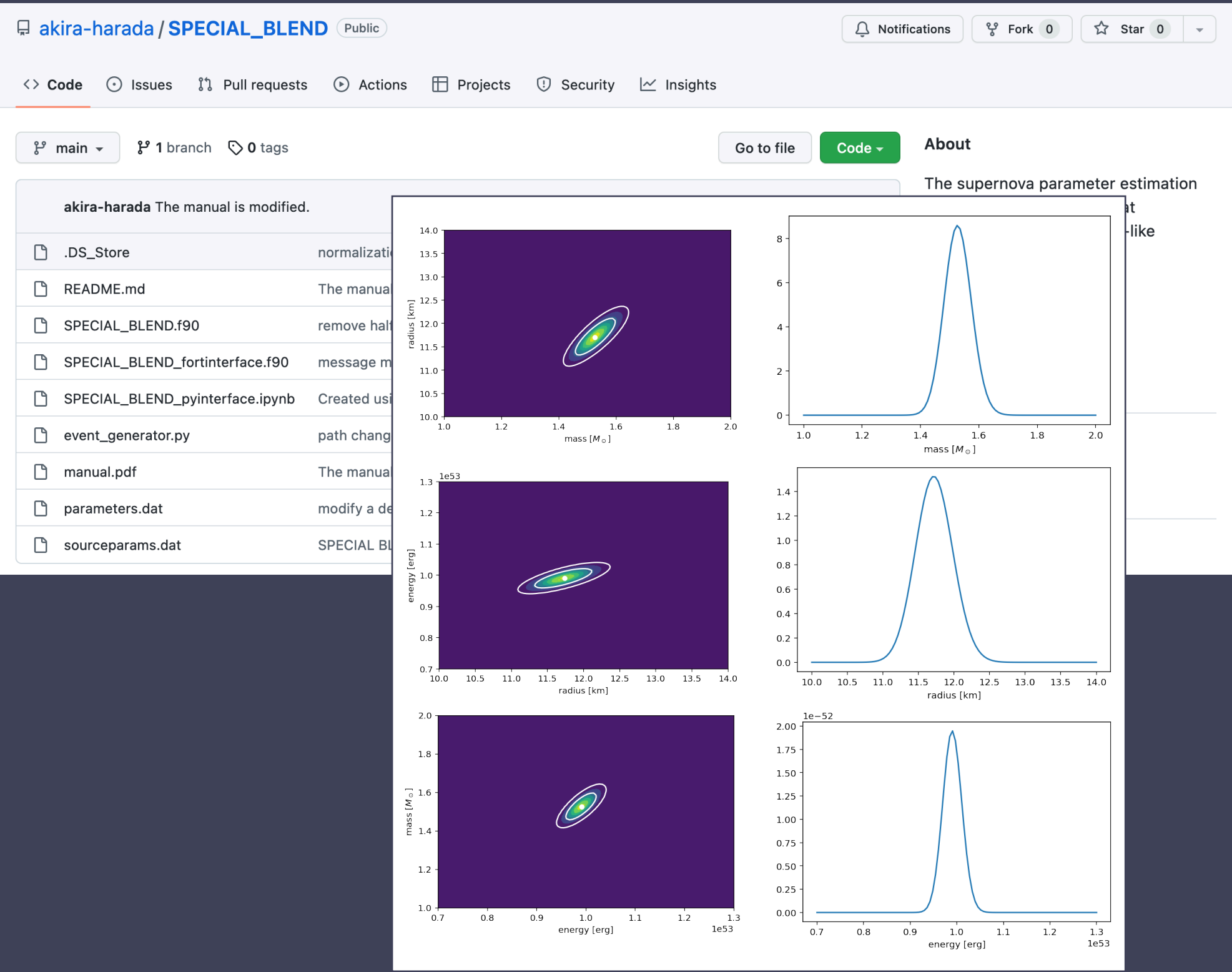


Li+ (2023)

# 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:

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



Courtesy of Suwa

