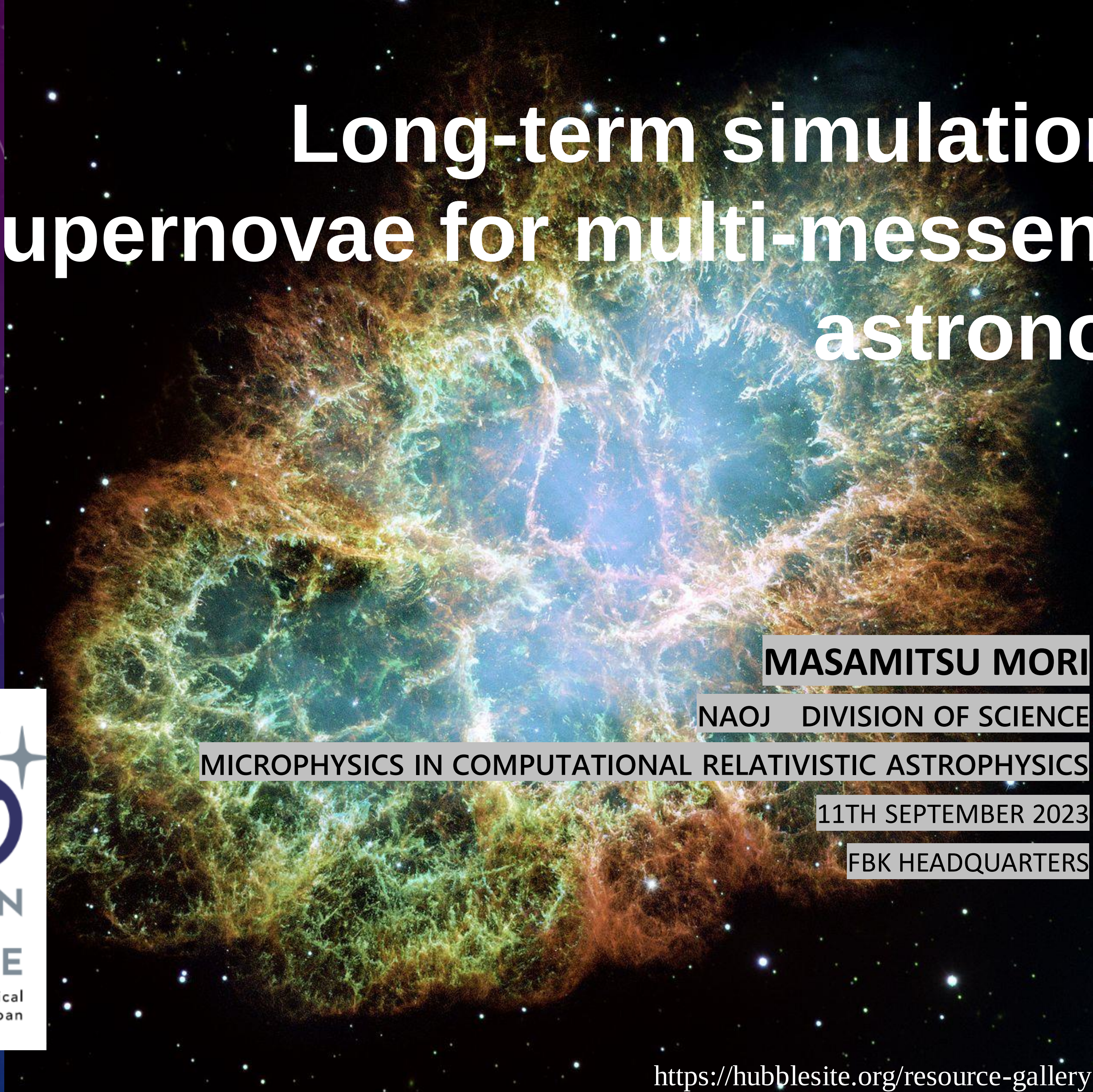
Long-term simulation of supernovae for multi-messenger astronomy



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DIVISION OF SCIENCE
National Astronomical Observatory of Japan

Contents

1. Long-term simulation of supernova neutrino
2. Estimation of neutrino signals on earth
3. Estimation of gravitational wave frequencies

Keywords

Supernova neutrino, Super-Kamiokande, Neutrino observation, gravitational wave, Multi-messenger

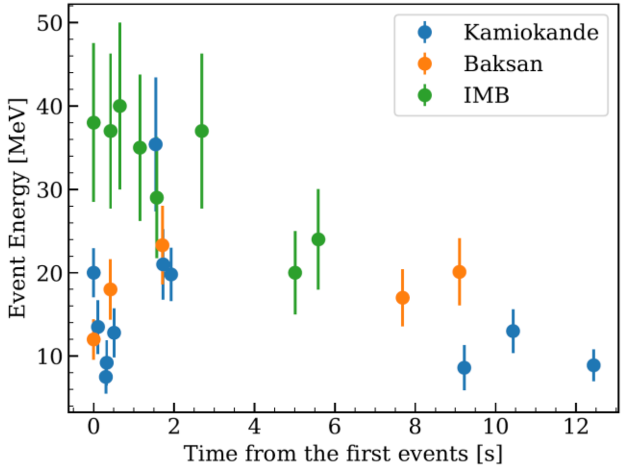
Supernova

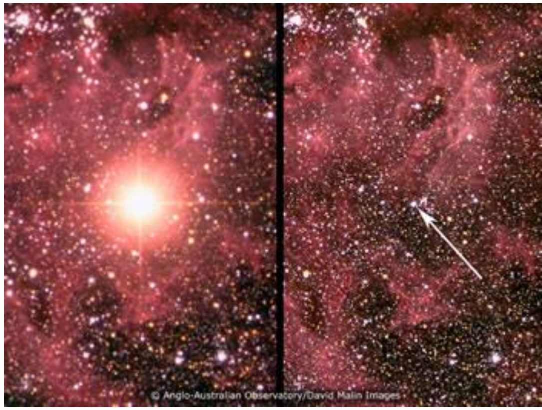
- 8 times heavier stars than the sun happen huge explosion
- Complicated phenomenon in which all the four forces of nature are related
    - ➢Not analytic calculation but heavy computation is needed
- Energy of 10^{53}erg is released as neutrinos.
    - ➢ Only one observation in 1987 (SN1987A)

SN1987A information

Distance:51.2 kpc
Number of events: Detector

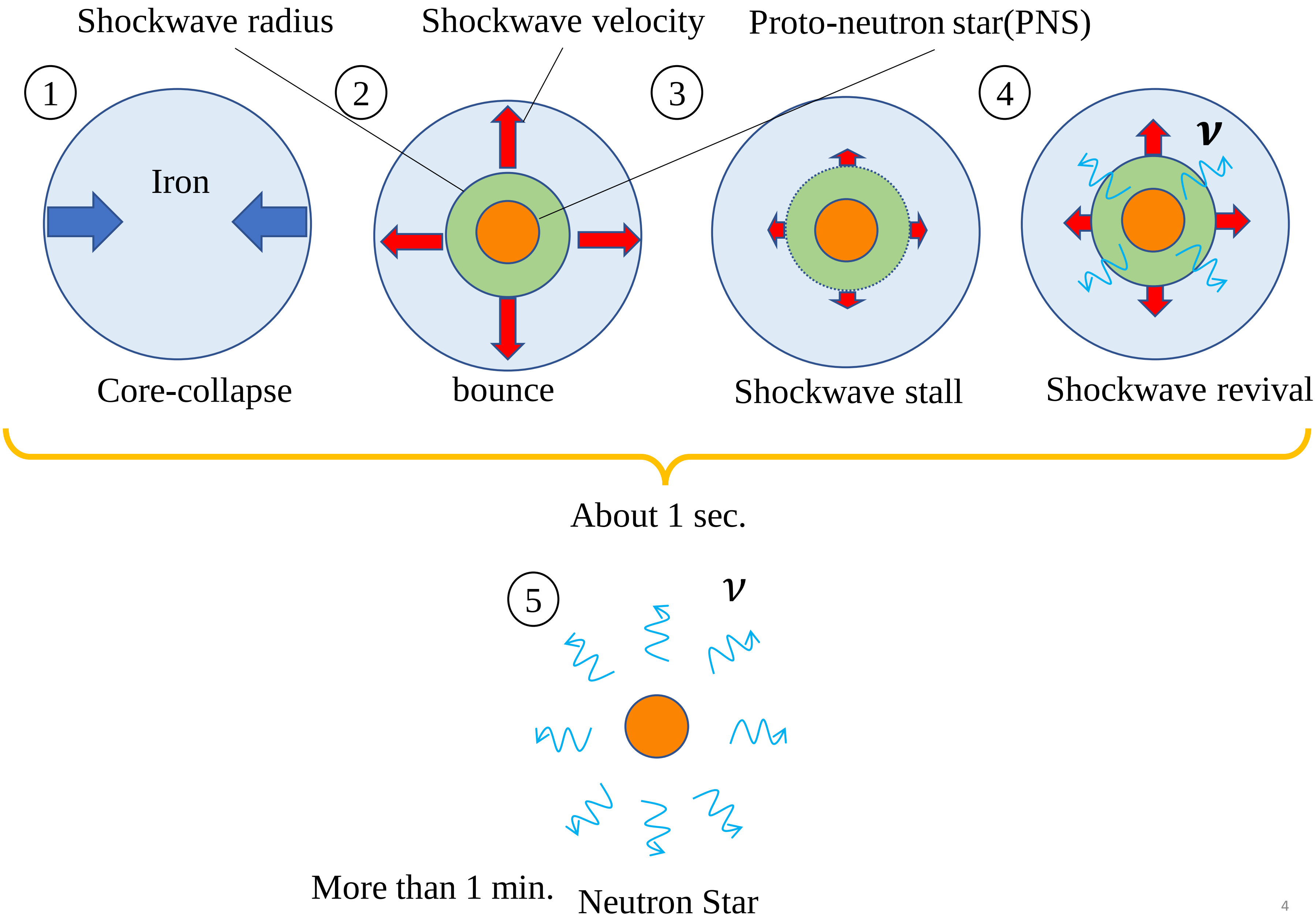
- 11: Kamiokande(2.14 kton)
- 8: IMB [2]
- 5: Baksan [3]





[1]Hirata et al. 1987
[2]Bionta et al. 1987
[3]Alekseev et al. 1987

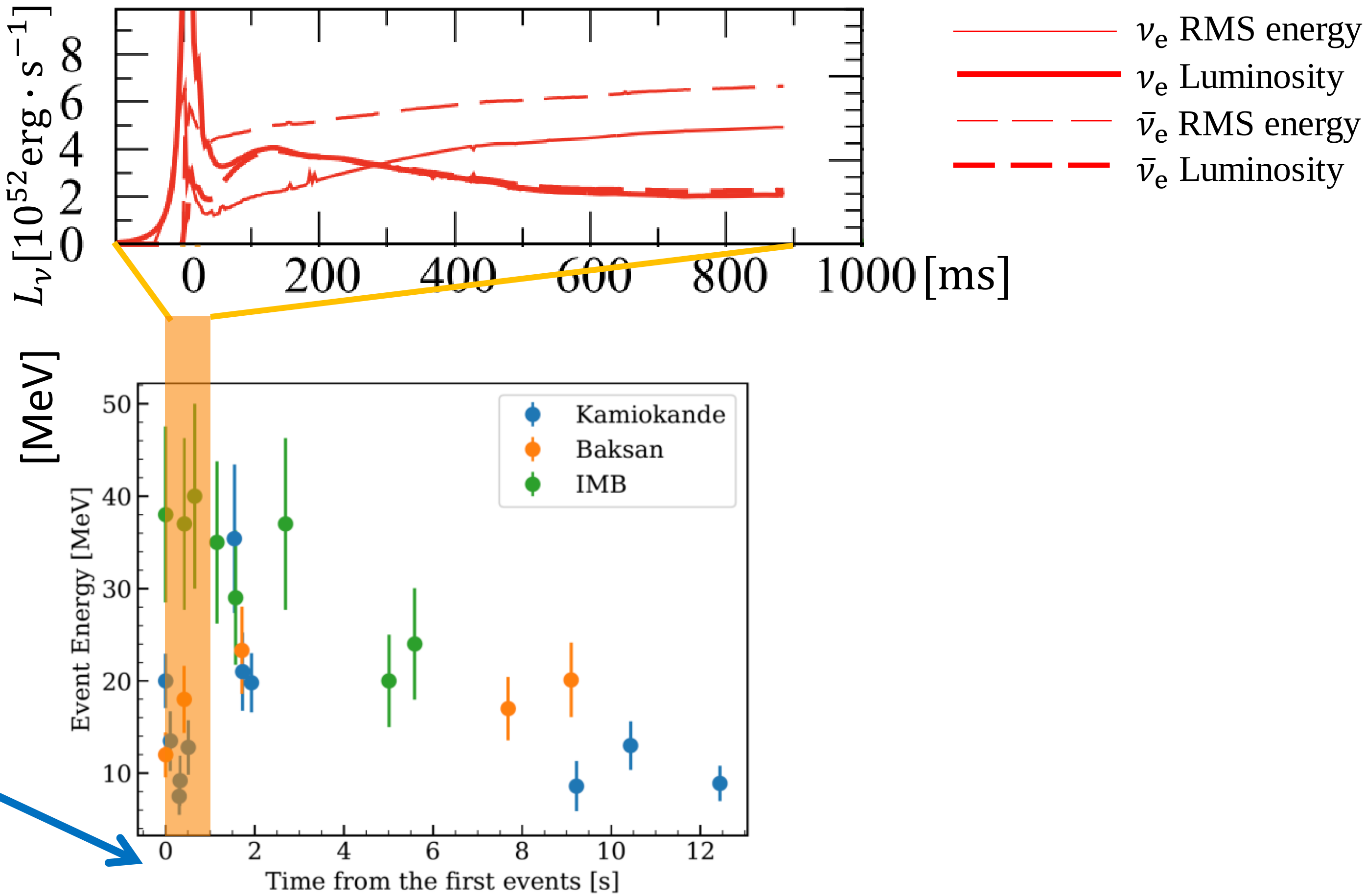
Supernova evolution



Supernova simulation problem

- Most simulations concentrate on early 1 sec.

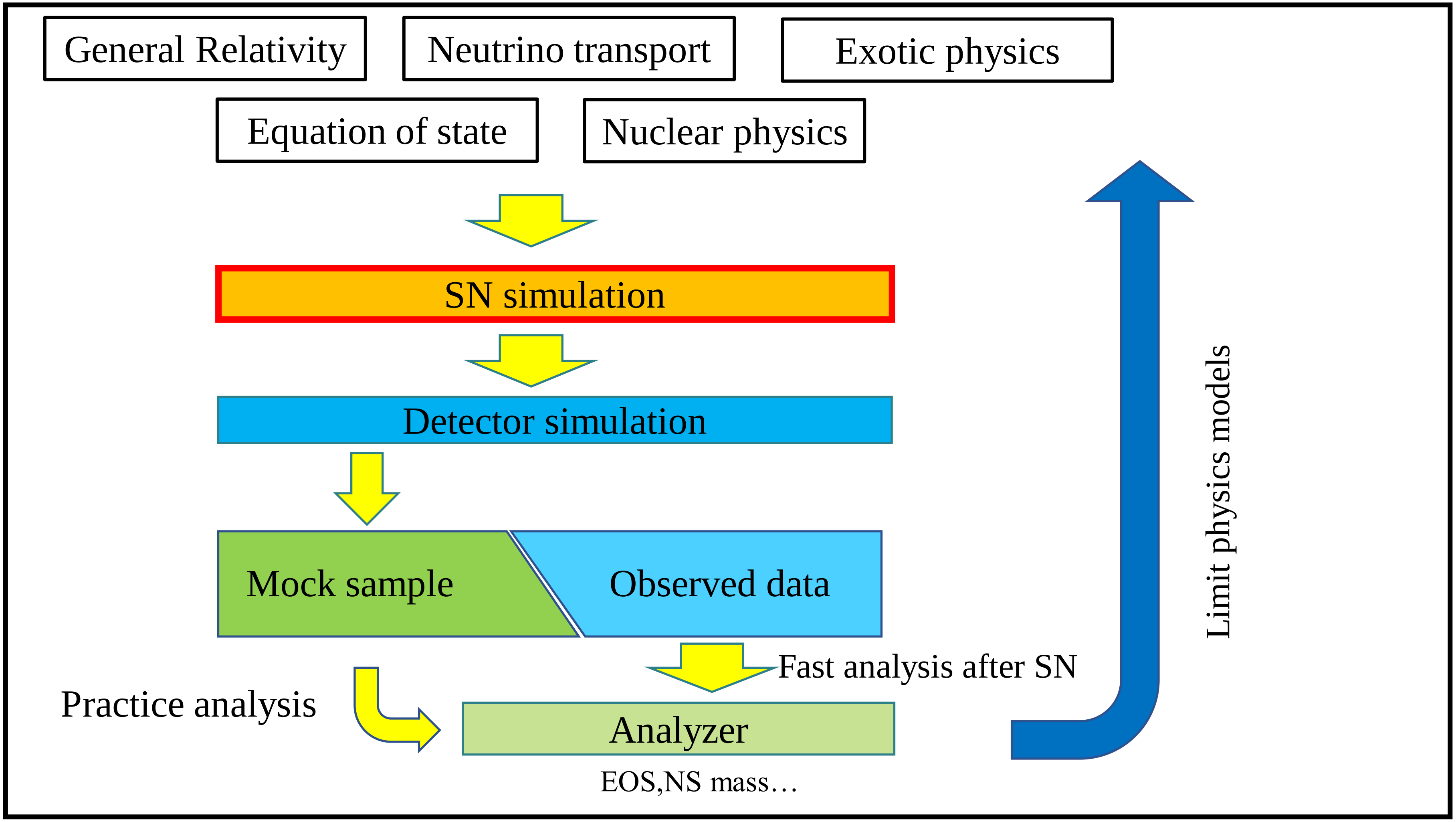
Example of simulation
Suwa et al. (2016)



We can compare theory and observation only for this time.

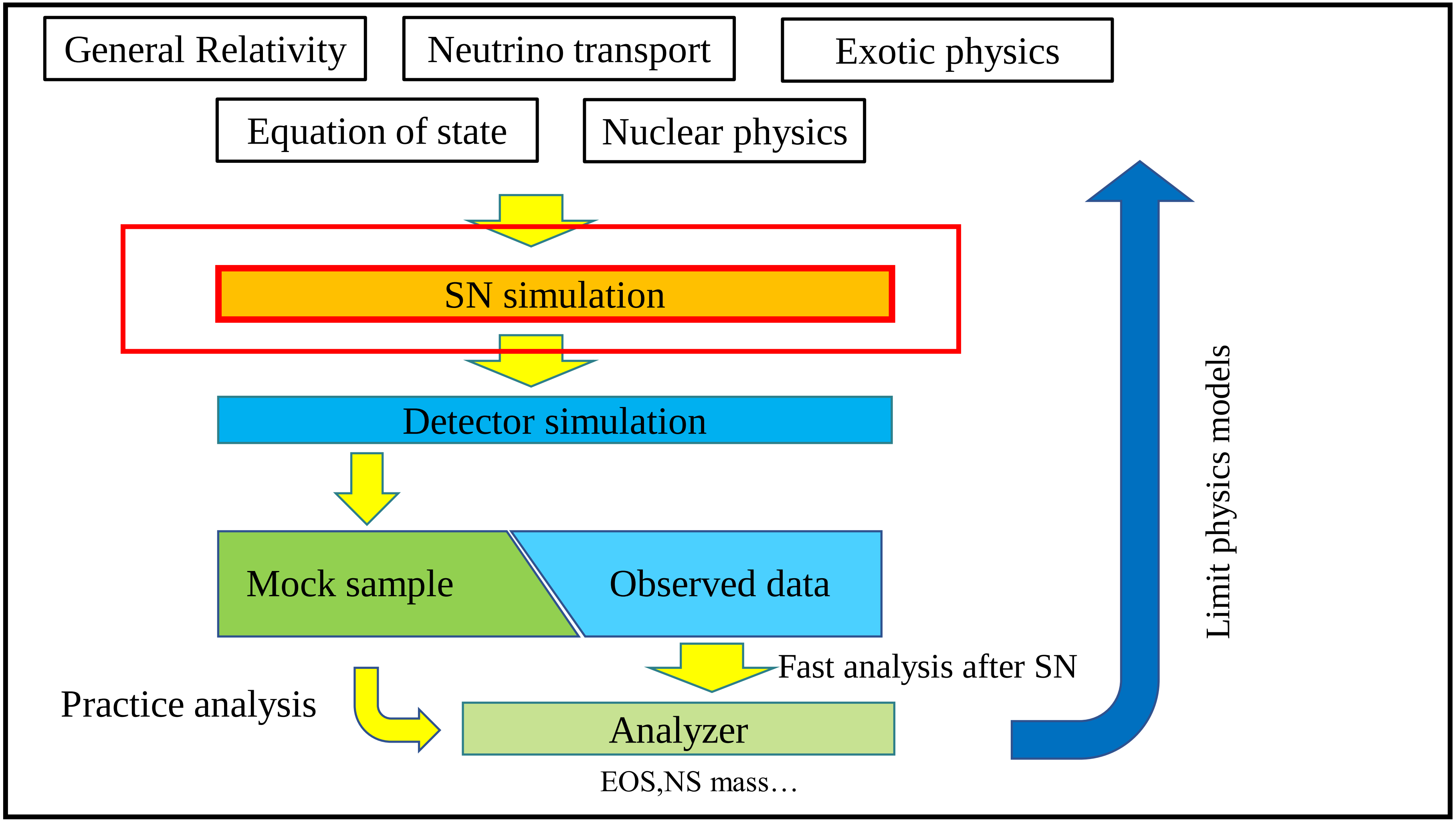
We developed a long-term simulation
and are preparing a framework.

Supernova neutrino framework



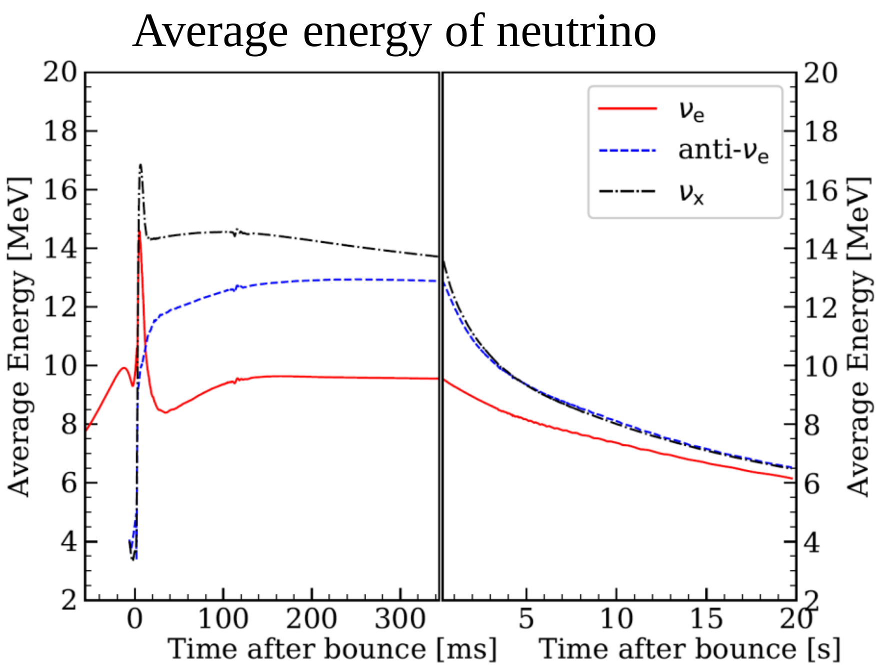
- We are developing a supernova neutrino framework.

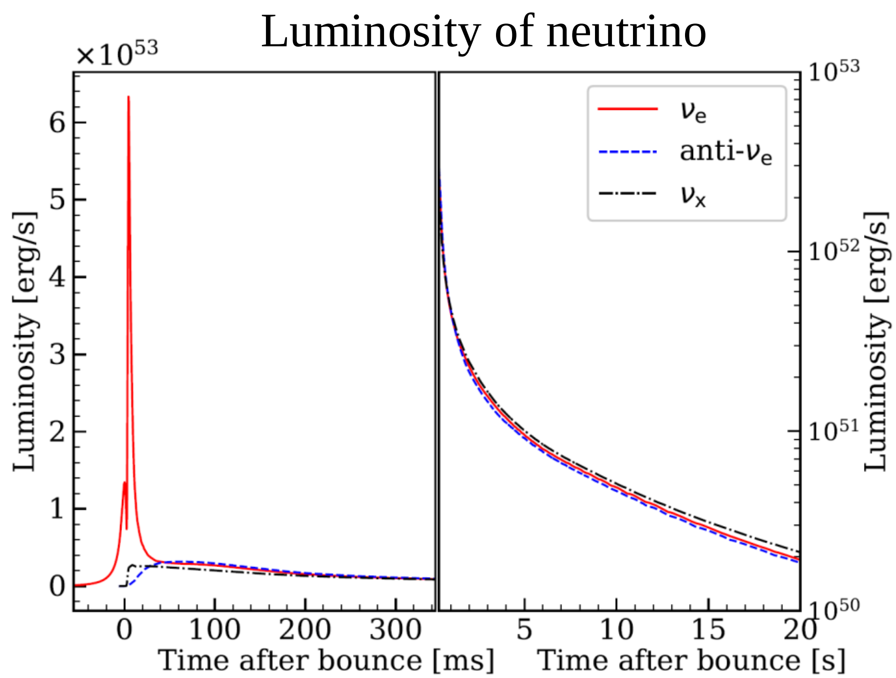
SN simulator



- Supernova simulation

Long-term neutrino emission (Mori et al. PTEP 2021 (2021) 2, 023E01)

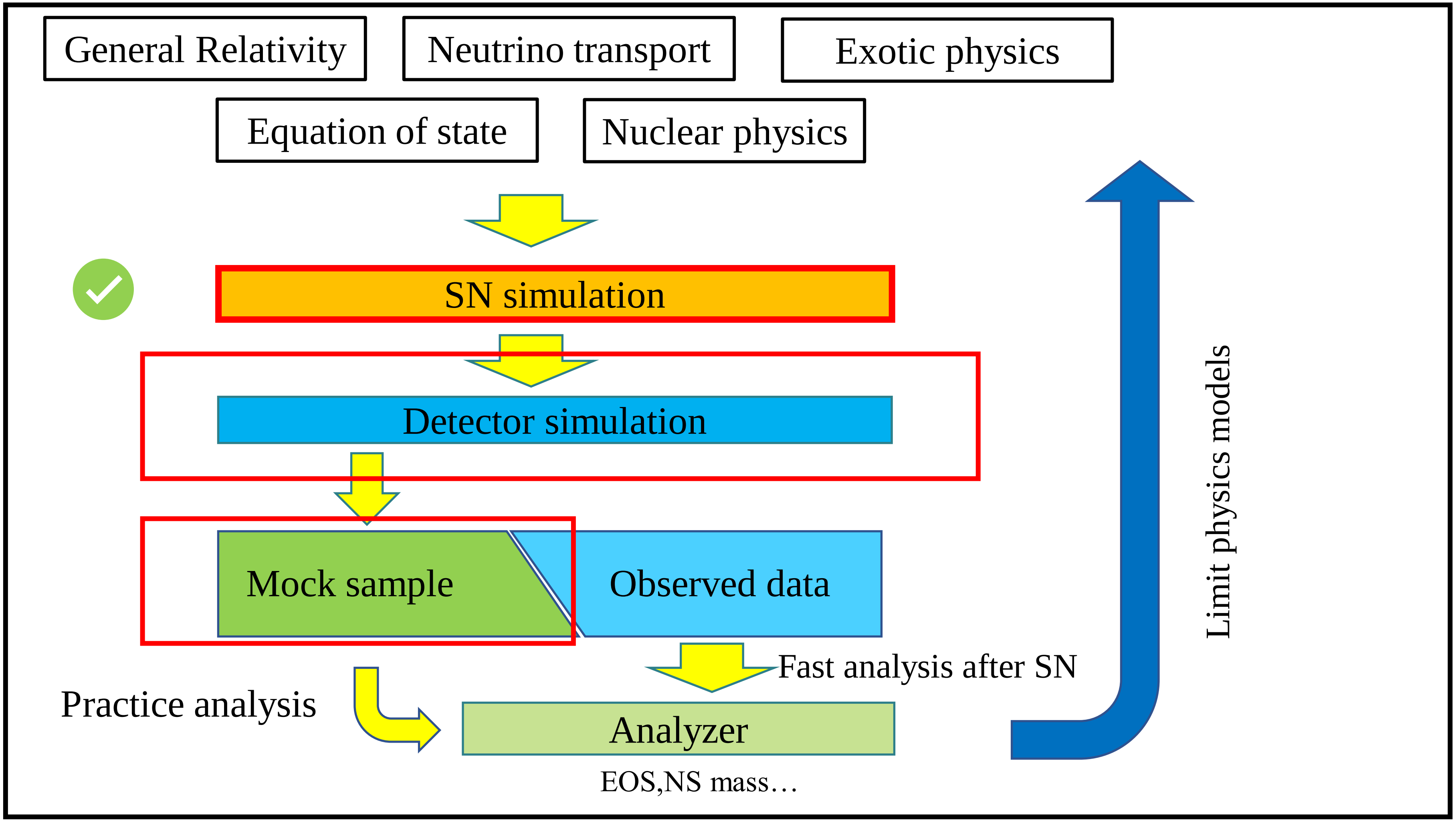




ν_x : μ and τ (anti) neutrinos

- GR1Dv2 (O'Connor, ApJS 219 24 2015)
  - General relativistic neutrino radiation hydro simulatior in 1D
- Progenitor mass: $9.6 M_{\odot}$
- Average energies decrease from above 10 MeV to 6 MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\overline{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$
- Luminosities decrease from 10^{53}erg/s
  - These features agree with other simulations.
  - PNS cooling is calculated.

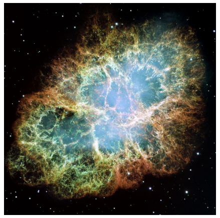
Detector simulator



- Detector simulation
- Simulates how signals of supernovae look like on earth
- Mock Samples are used for analysis practice and detector evaluation.

FOREST

- FORcasting Events from Supernovae Theoretical modeling (FOREST)
  - My family name: Mori=森 in Japanese = Forest in English
- Developing in Python
- Simulates how signals of supernovae look like on earth
- Mock Samples are used for analysis practice and detector evaluation.



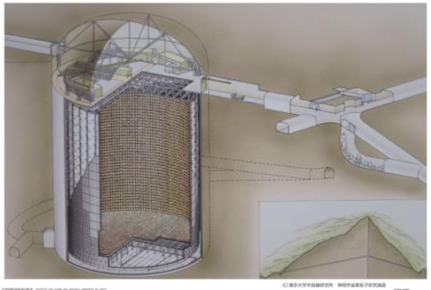
ν

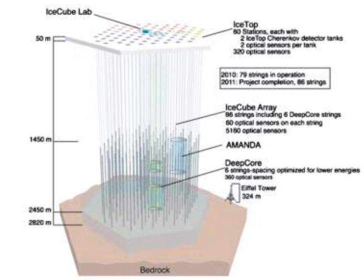
Neutrino oscillation

ν_e

$\bar{\nu}_e$ ν_x

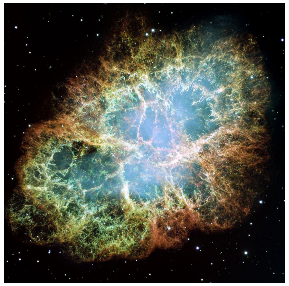
Detector





Details of event simulation

Explosion

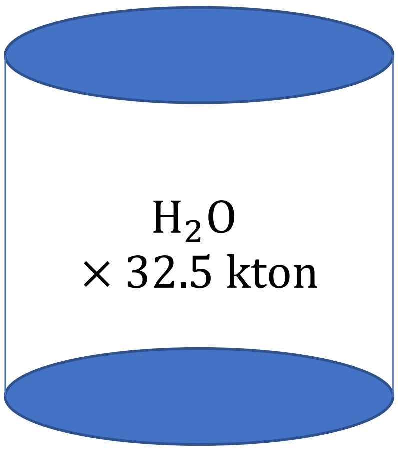


10 kpc

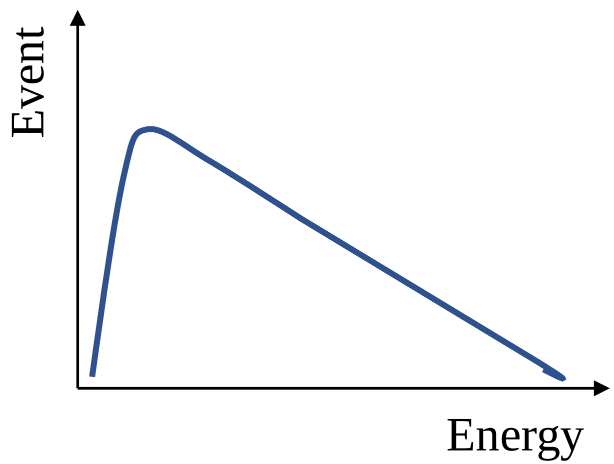
☐ Reaction channel

Inverse Beta Decay(IBD)

- $\bar{\nu}_e + p \rightarrow e^+ + n$
- Amount: more than 90%
- Direction sensitivity：No

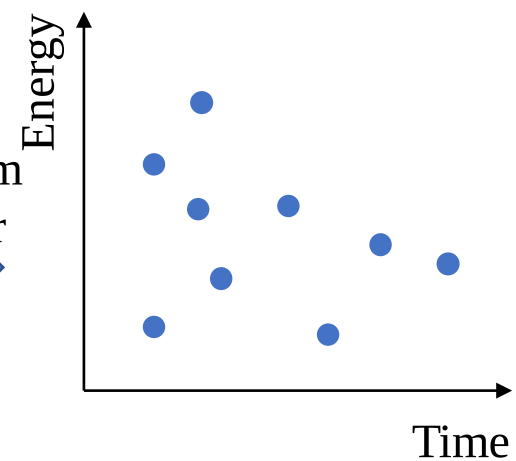


Super-Kamiokande(SK)

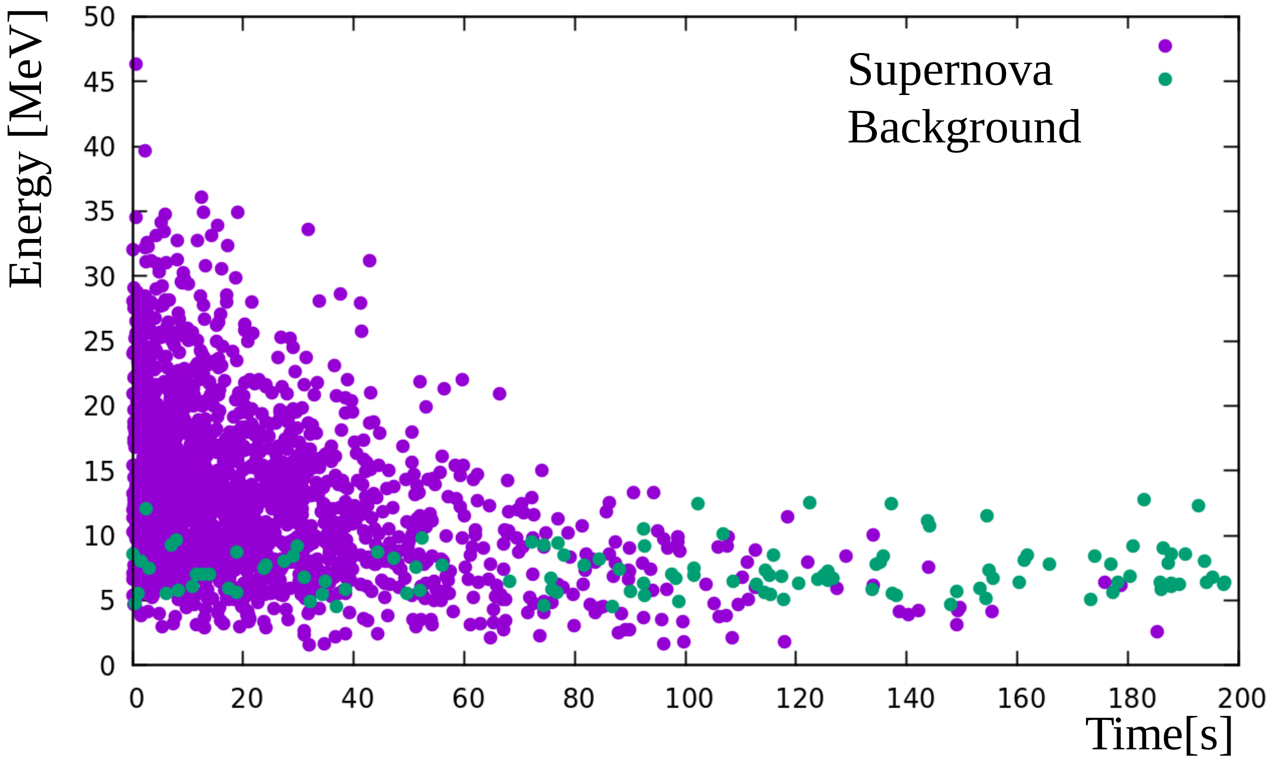


Event distribution per time

Random number



Event simulation with FOREST



- Supernova events and background events in SK.
- The analytic event rate is used.
  - [Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 0130E01 (2021)]

Gravitational eigenmodes

- Supernovae also emit gravitational waves.
- We estimated eigenmode frequencies with the asteroseismology approach.
  - Used GREAT (https://www.uv.es/cerdupa/codes/GREAT/)
  - Torres-Forné et al, MNRAS, 474, 5272 (2018)
  - Torres-Forne et al, arxiv:1806.11366 (2018)
- Linear perturbation analysis both of fluid and metric.
- Calculated eigenmodes from the result of the $9.6M_{\odot}$ progenitor in post-process

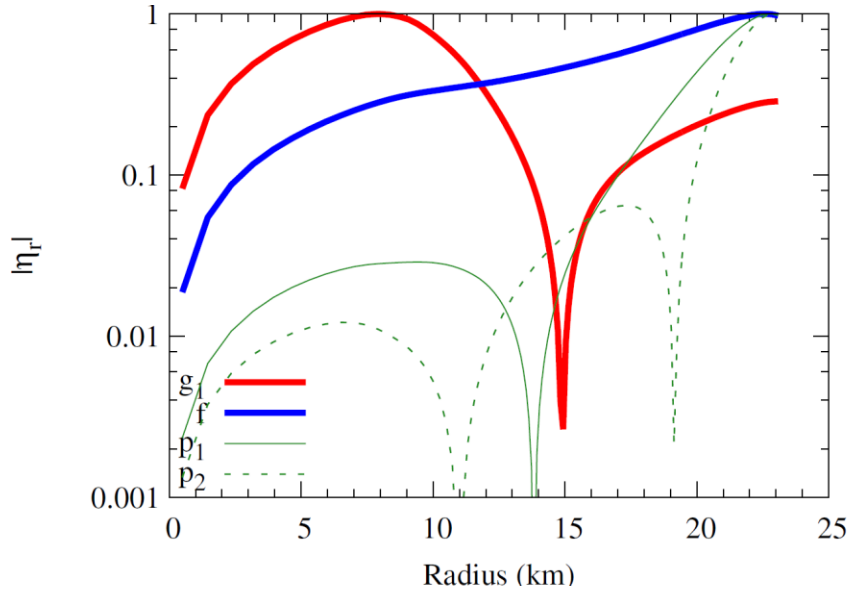
- Linear perturbation equations

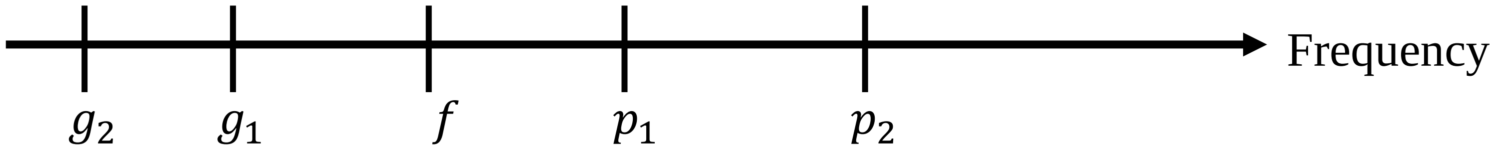
$$\partial_r \eta_r + \left[\frac{2}{r} + \frac{1}{\Gamma_1}\frac{\partial_r P}{P} + \frac{\partial_r \psi}{\psi}\right]\eta_r + \frac{\psi^4}{\alpha^2 c_s^2}\left(\sigma^2 - \mathcal{L}^2\right)\eta_\perp = \frac{1}{c_s^2}\frac{\delta\hat{Q}}{Q} - \left(6 + \frac{1}{c_s^2}\right)\frac{\delta\hat{\psi}}{\psi},$$

$$\partial_r \eta_\perp - \left(1 - \frac{\mathcal{N}^2}{\sigma^2}\right)\eta_r + \left[\partial_r \ln q - \mathcal{G}\left(1 + \frac{1}{c_s^2}\right)\right]\eta_\perp = \frac{\alpha^2}{\psi^4 \sigma^2}\left[\partial_r(\ln \rho h)\left(1 + \frac{1}{c_s^2}\mathcal{G}\right)\right]\left(\frac{\delta\hat{Q}}{Q} - \frac{\delta\hat{\psi}}{\psi}\right),$$

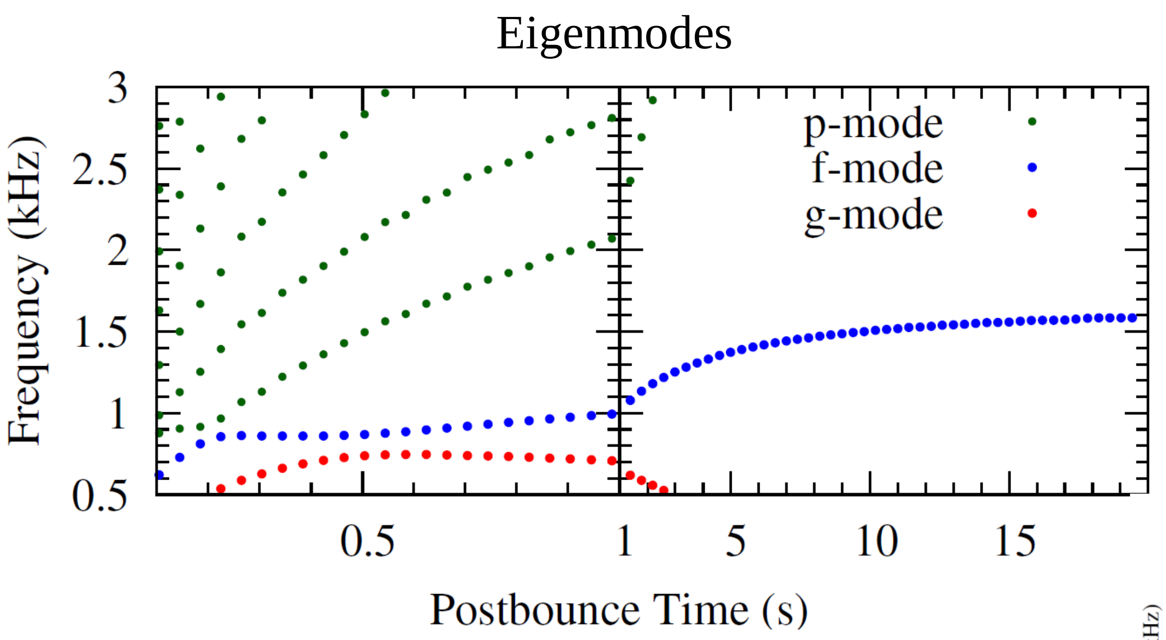
Kinds of eigenmode

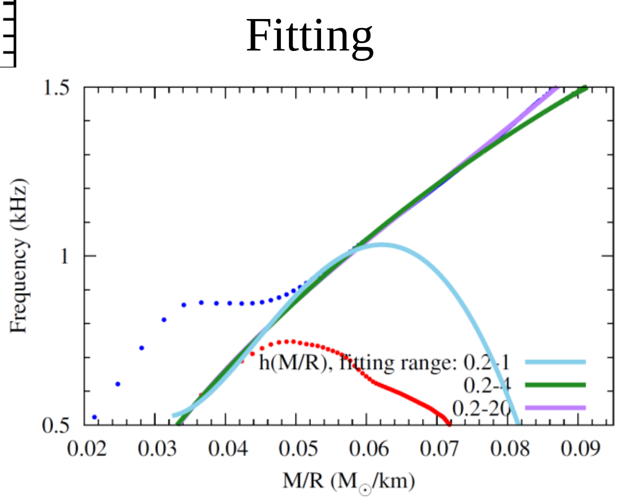
- p_{i}-mode
  - "i" is the number of nodes
  - Restoring force: pressure
  - Frequencies increase as nodes increase
- f-mode
  - Fundamental mode of the p-mode
- g_{i}-mode
  - Restoring force: buoyancy
  - Frequencies decrease as nodes increase





Gravitational wave frequency (Mori et al. Phys.Rev.D 107 (2023) 8, 083015)





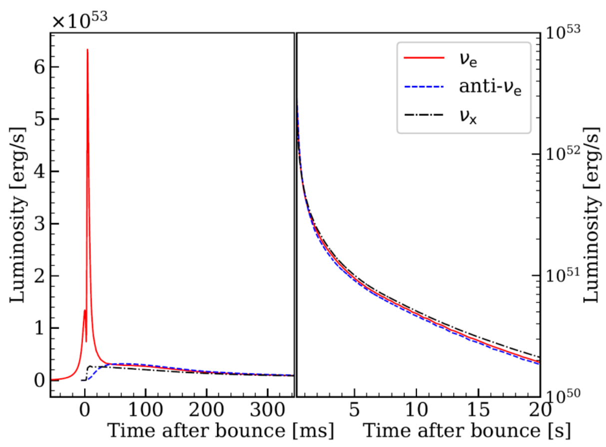
- Calculated eigenfrequencies up to 20 seconds.
- Differences of frequencies increase with time.
- We developed the fitting.
  -

Summary

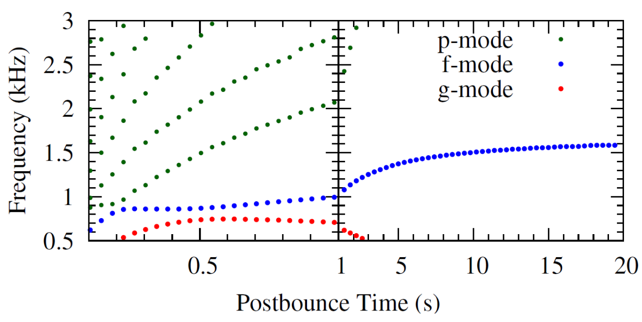
Summary

- Supernovae are promising multi-messenger targets.
- Established the long-term neutrino radiation hydro simulation
  - My long-term neutrino database: https://zenodo.org/record/5825648
- Estimated neutrino signals at Super-Kamiokande
  - We may be able to estimate neutron star mass via neutrino events.
- Estimated long-term gravitational wave eigemodes

Neutrino



Gravitational waves

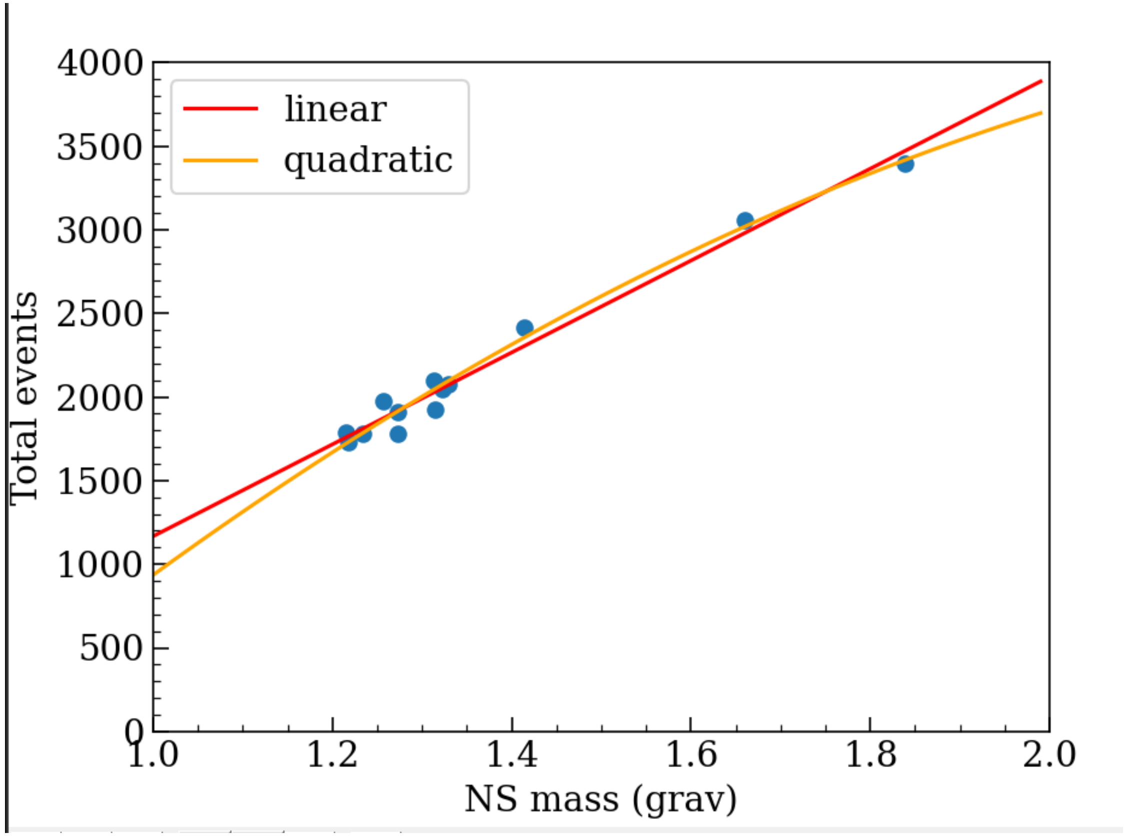


Back up

Method of long time simulation

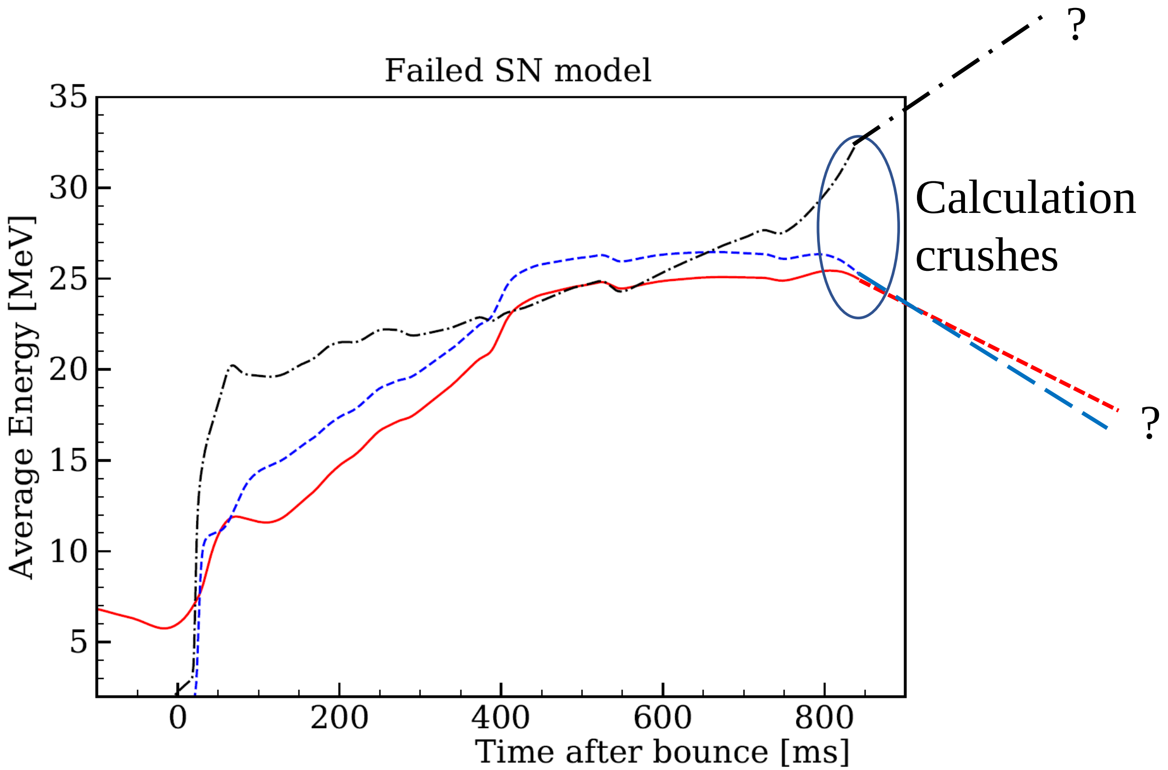
- Simulate supernovae in one-dimension
- Code
  - GR1Dv2 (public code: http://stellarcollapse.org)
    - ➢O'Connor, ApJS 219 24 2015
  - Gravity: General relativity
  - M1 scheme
  - Modified for long-term simulation
    - ➢Resolved reference out of physics tables
    - ➢Optimized resolution of time and space
  - EOS: DD2

Total events and neutron star masses



- Vertical axis: the number of events at SK for 10 s.
- Horizontal axis: neutron star mass
- It seems that heavier neutron stars lead to more neutrino events.
  - It possible to estimate neutron star mass from neutrino events.

First idea



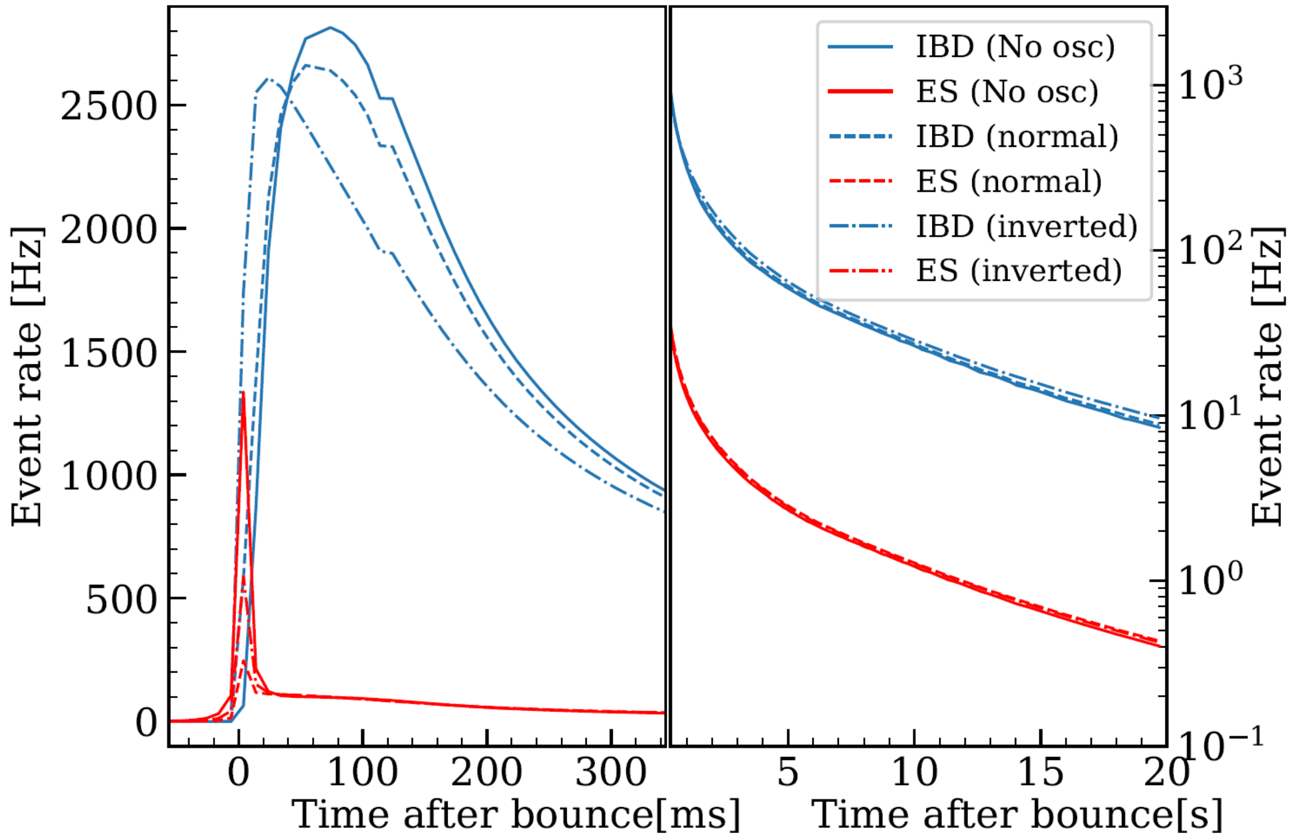
Misner-Sharp metric

$$ds^2 = -e^{2\phi}dt^2 + X^2dr^2 + d\Omega^2$$

$$X = 1/\sqrt{1 - \frac{2M}{R}}$$

- Calculation in case of black hole formation is more difficult
- Because metric diverges at an event horizon.

Reaction rate



- Assumed a supernova happen at 10 kpc（Distance to the galactic enter: 8kpc）
- About 2,000 events at 20 seconds
- In the later time, neutrino oscillation has little influence

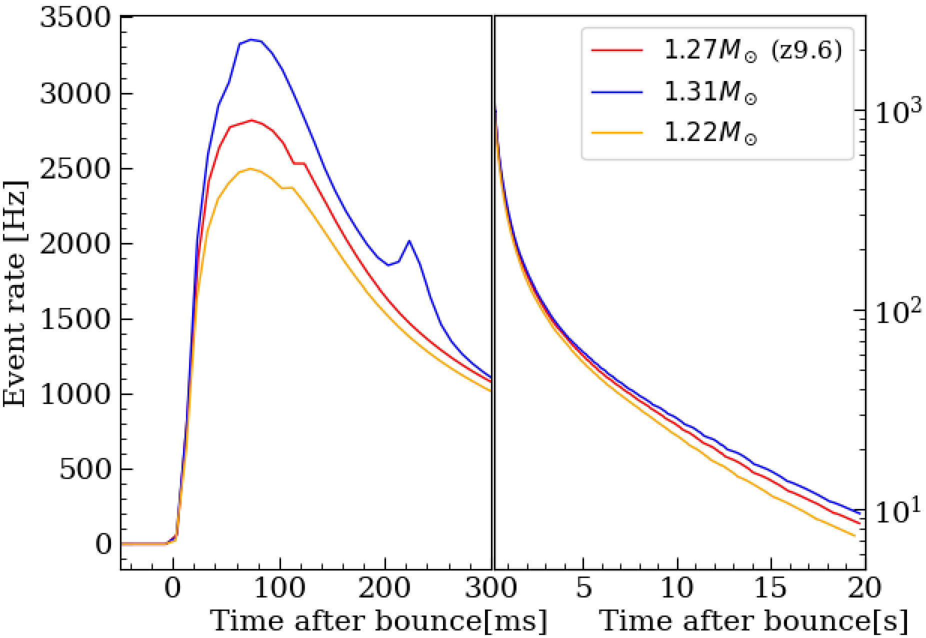
Recent simulations

	Huedepohl (1D)	Fischer (1D)	Multi-dimension Takiwaki(2016), Suwa(2016)… etc	This study
Iron core	×	○	○	**○**
Natural explosion	○	×	○	**○**
Max time	20 s	20 s	< 1 s	**20 s**

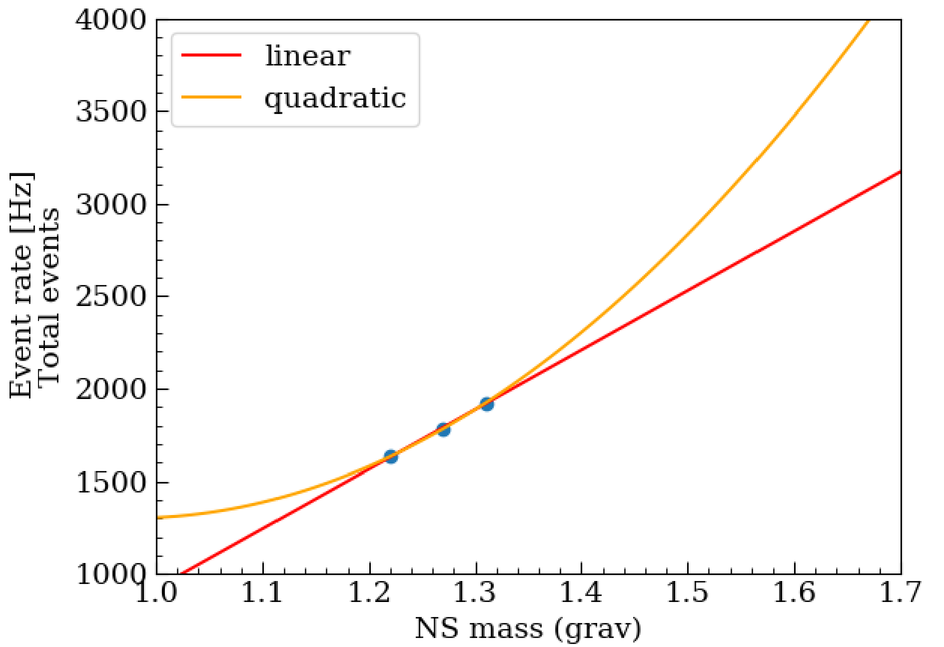
- To explode without artificial methods in one-dimension is difficult
  - ➢ Enhancement of neutrino reaction rates
  - ➢ Removal of material accreting
- Long time simulation in multi-dimension is impossible
- We do long time simulation in one-dimension without artificial methods

Neutrino and neutron star mass

Event rate at 10 kpc



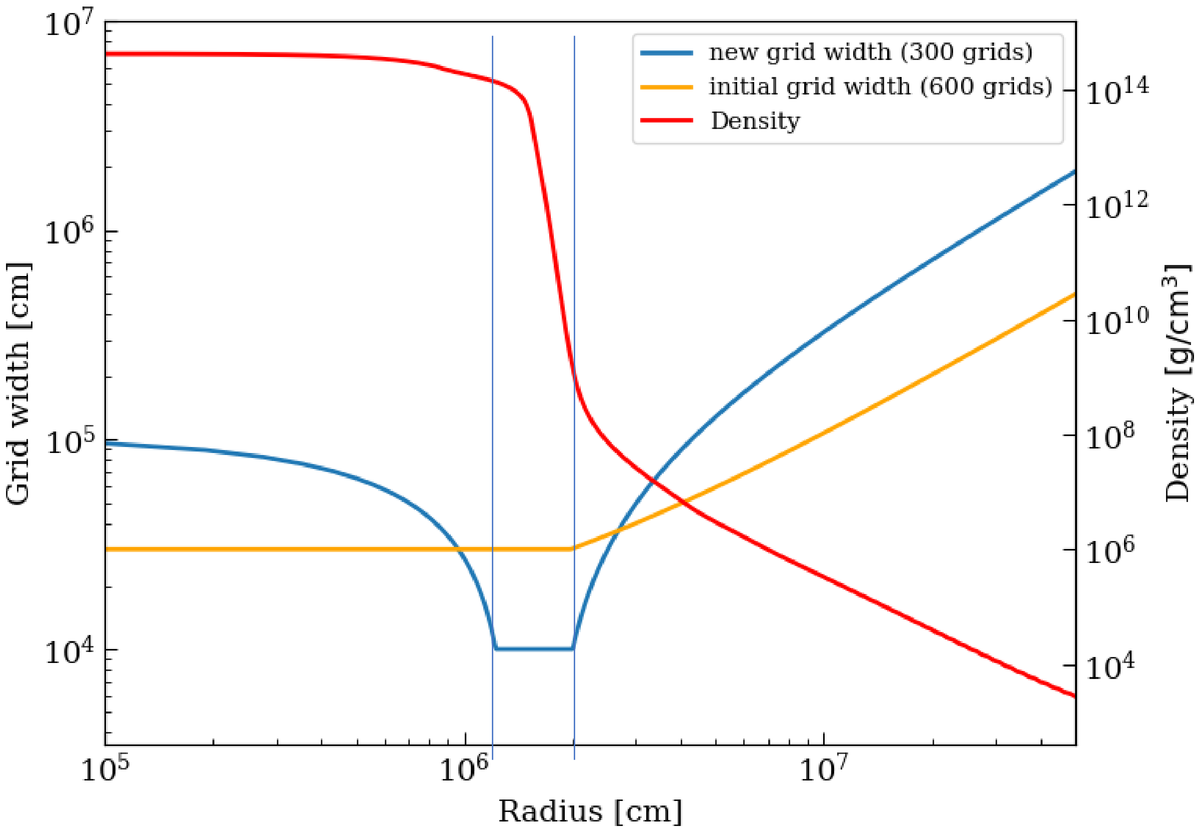
Relation between the number of events and neutron star mass

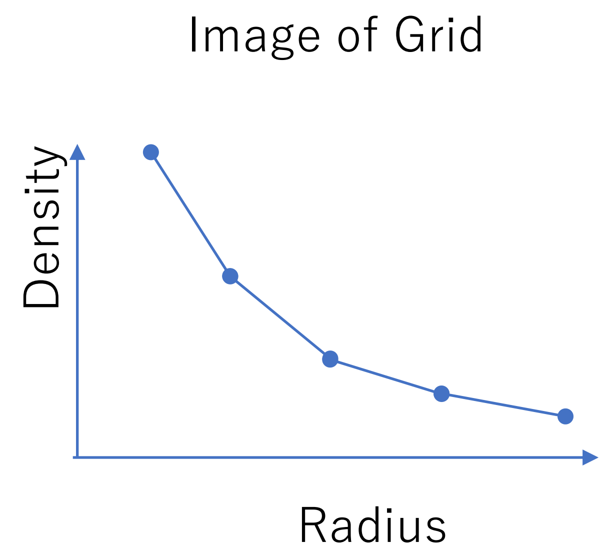


- Three simulations which lead to different neutron star mass
- If distance is determined, neutron star mass is maybe determined.
  - ➢More simulations are needed.

➢In addition, I'm developing simulation in the case of BH formation.

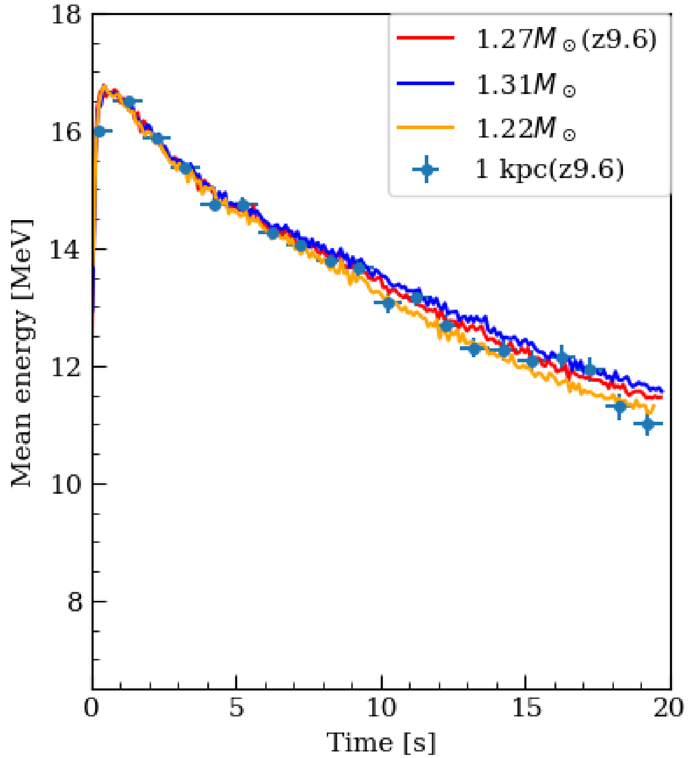
Device of grids

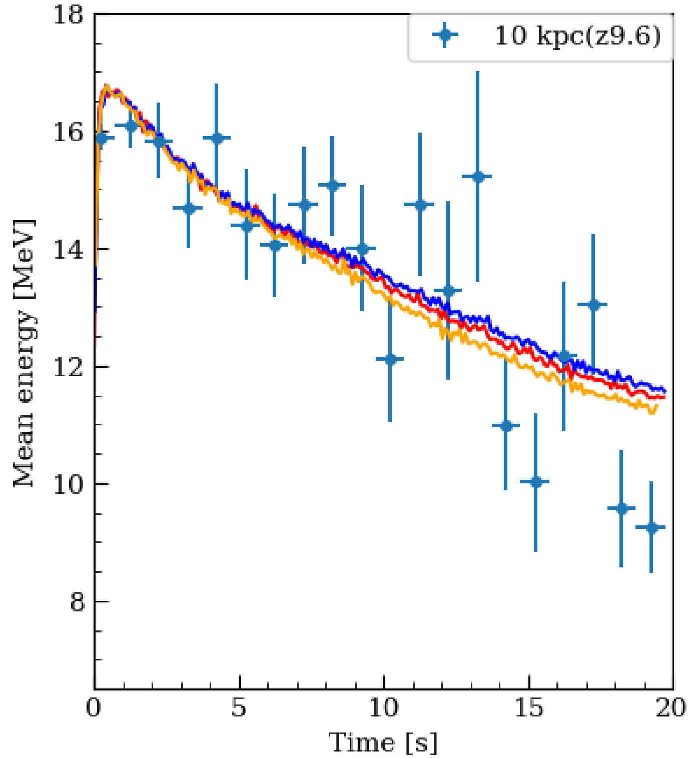




- Red：Density structure of PNS
- Yellow：Initial grids (600 grids)
- Blue：Optimized grids (300 grids)
- The region in which the density drastically changes is finely resolved.
  - ➢Initial grids make calculation stop at about 5 sec.
  - ➢Cost is also too high

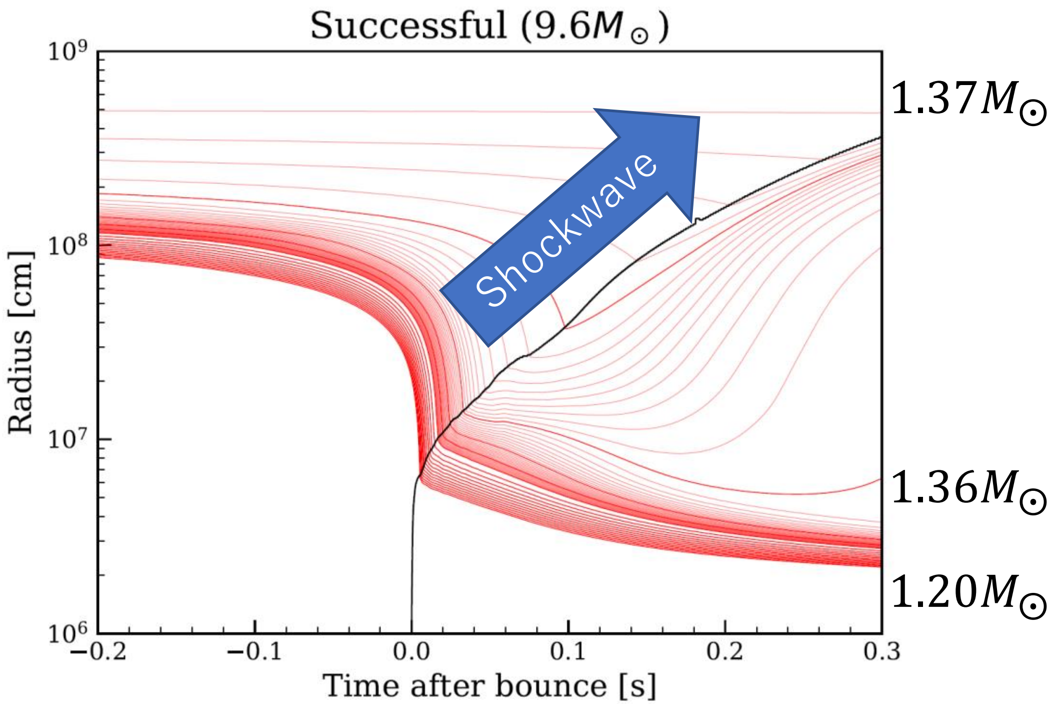
平均エネルギーの発展

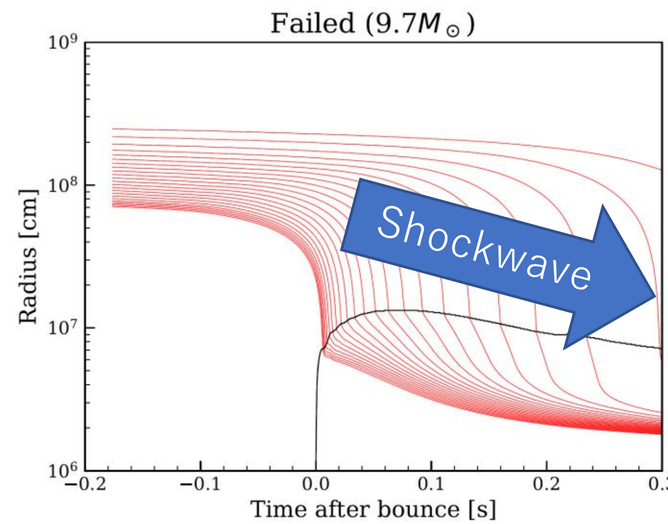




- **実線**:無限個のイベントの平均エネルギー
- **マーカー**:有限個のイベントの平均エネルギー(z9.6)
  - ➢エラーバー: $\sqrt{\dfrac{1/N_{\mathrm{bin}}\times\sum_{i=1}^{N_{\mathrm{bin}}}(E_i-\bar{E})^2}{N_{\mathrm{bin}}}}$
- 個数だけでなく、エネルギー情報も使った比較が可能
- エネルギーの時間発展からのモデルの分別を目指す。

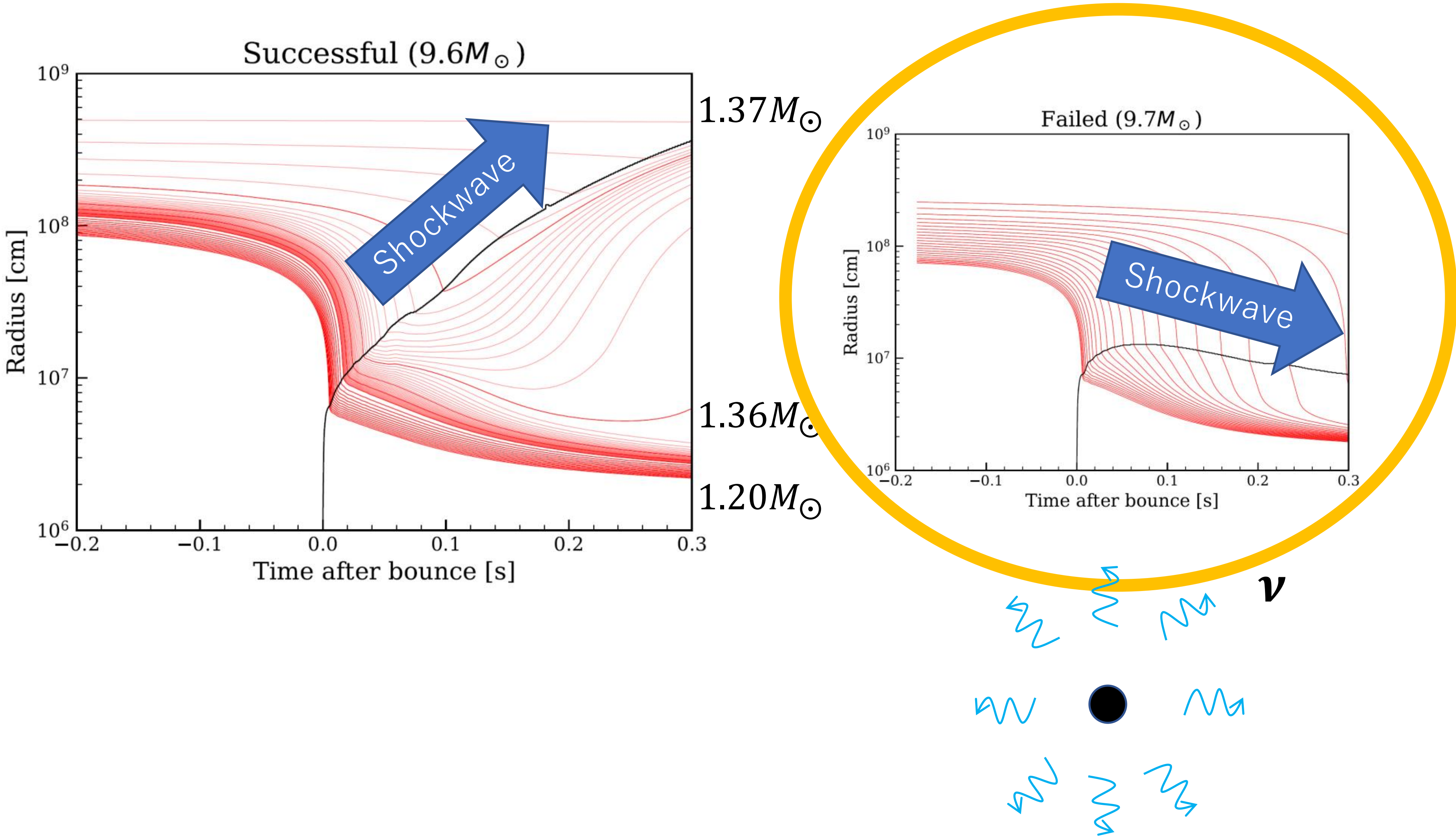
Light progenitor





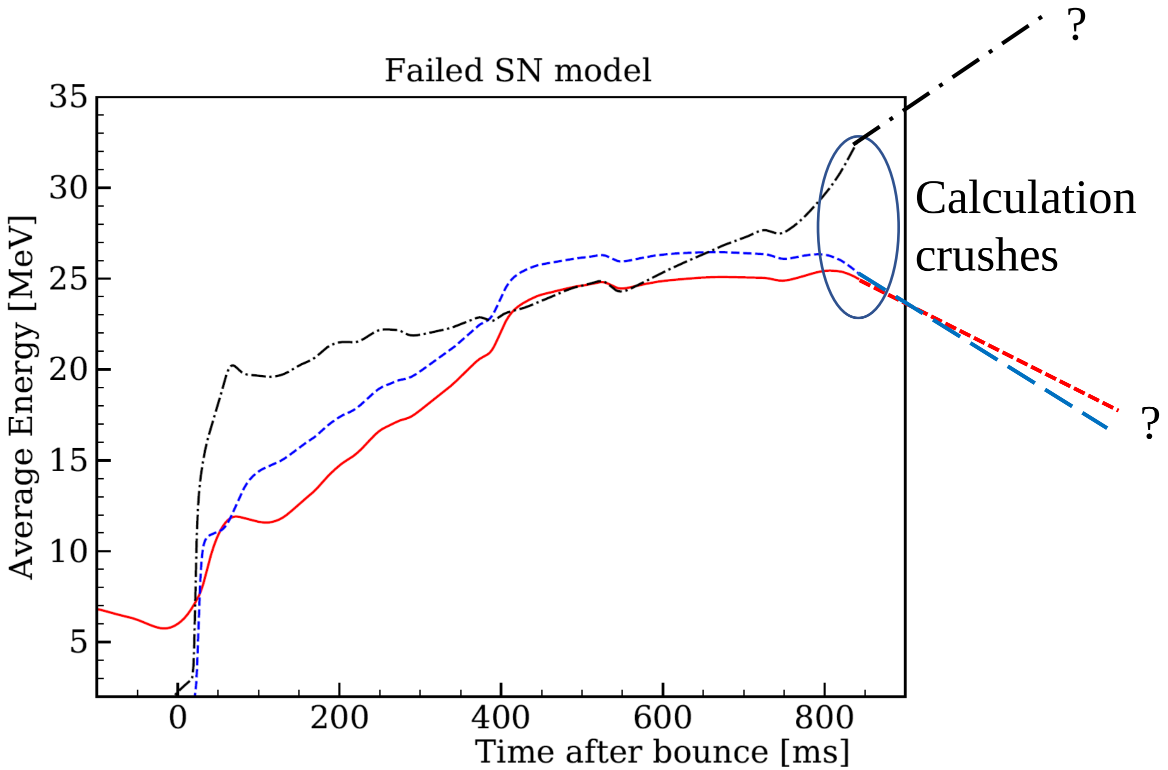
- Red：Radii at which densities are constant
- Black：Radius of a shockwave
- Succeed to explode with the suitable choice of progenitors and **without artificial methods**
  - ➢9.6 solar mss, initial metallicity is 0
  - ➢Called z9.6

Black hole formation



- I want to also calculate the case of failed supernovae and black hole formation.

Calculation crush



Misner-Sharp metric

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- Calculation in case of black hole formation is more difficult
- Because metric diverges at an event horizon.

Hernandez–Misner metric

- Misner-Sharp metric

$$ds^2 = -e^{2\phi}dt^2 + X^2dr^2 + d\Omega^2$$

- Introduce new time u

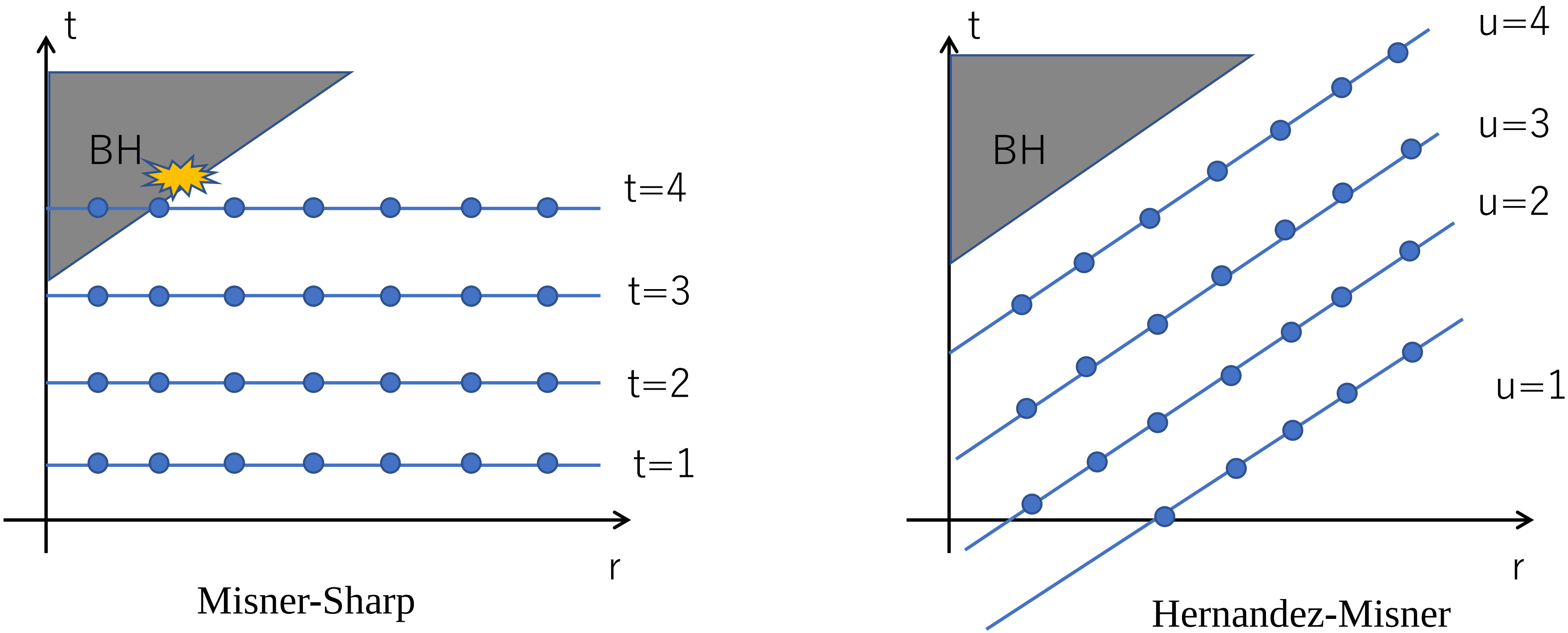
$$e^{\psi}du = e^{\phi}dt - Xdr$$

- Hernandez-Misner metric

$$ds^2 = -e^{2\psi}du^2 - 2e^{\psi}Xdrdu + d\Omega^2$$

- The “u” is called observer time.

Difference between two metrics



- Evolute time so that it avoids a black hole surface.
  - ➢Time is slower, closer to the center.