Long-term supernova neutrino simulation and analysis method

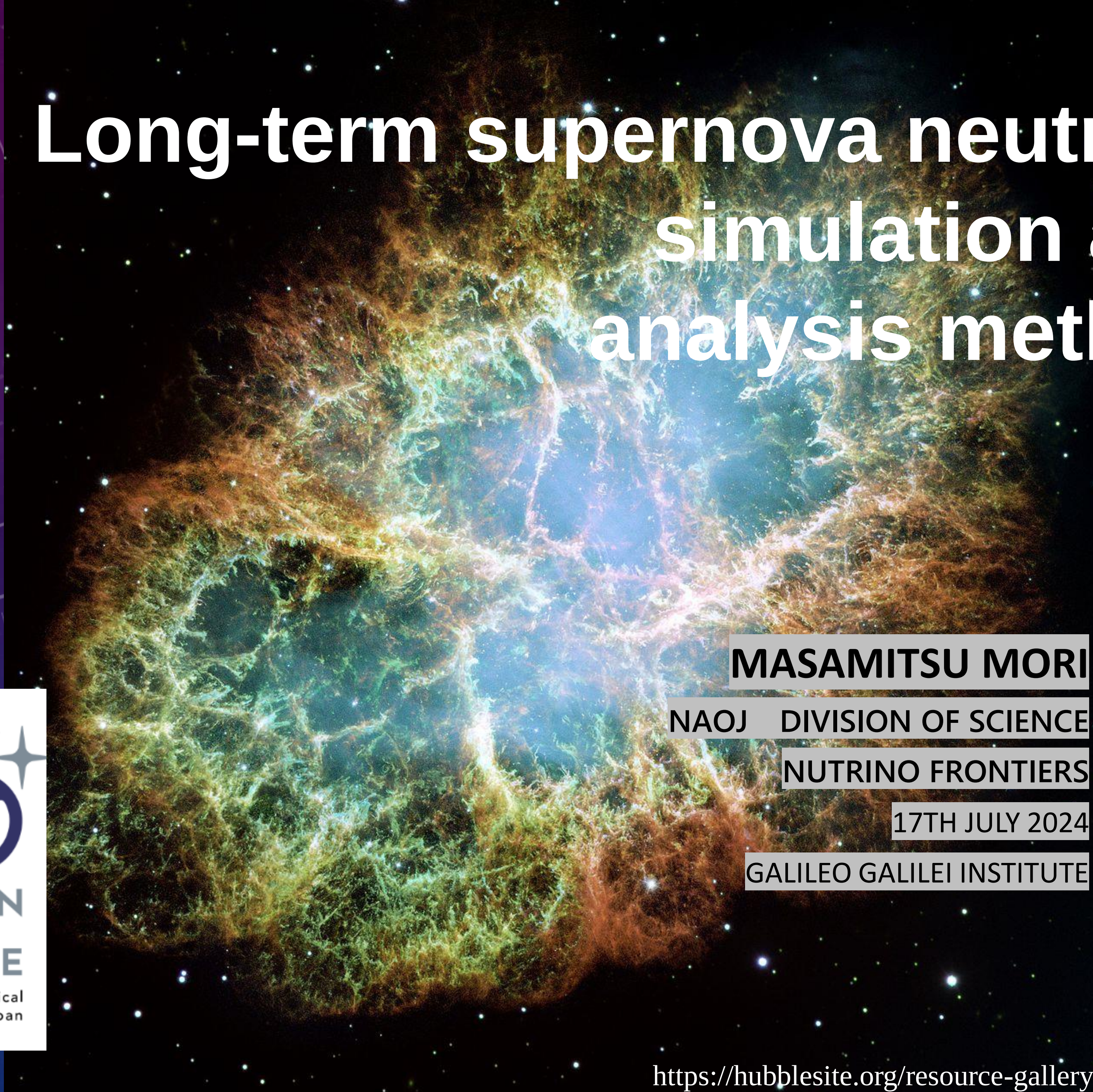
MASAMITSU MORI

NAOJ DIVISION OF SCIENCE

NUTRINO FRONTIERS

17TH JULY 2024

GALILEO GALILEI INSTITUTE



https://hubblesite.org/resource-gallery

DIVISION OF SCIENCE
National Astronomical Observatory of Japan

Contents

1. Long-term simulation of supernova neutrino
2. Neutrino signals on earth
3. Parameter estimation
4. Gravitational wave frequencies

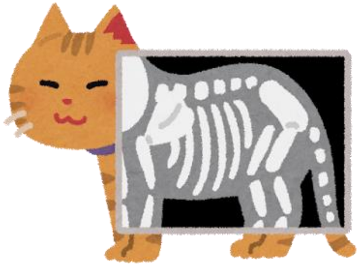
Keywords

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

Supernova

- Huge explosion of a heavy star at its end
- 99% of Its energy released as neutrinos
  - Neutrinos can penetrate the center
  - ➢Only one observed example: SN1987A

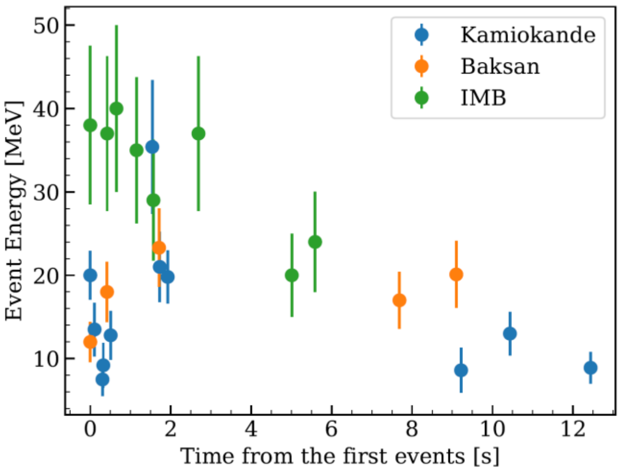
Difficult to calculate for a long term

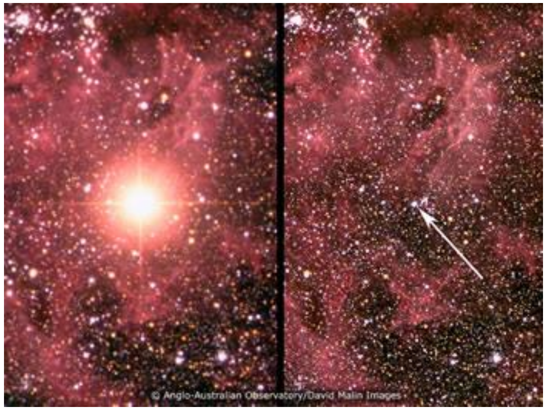


SN1987A events

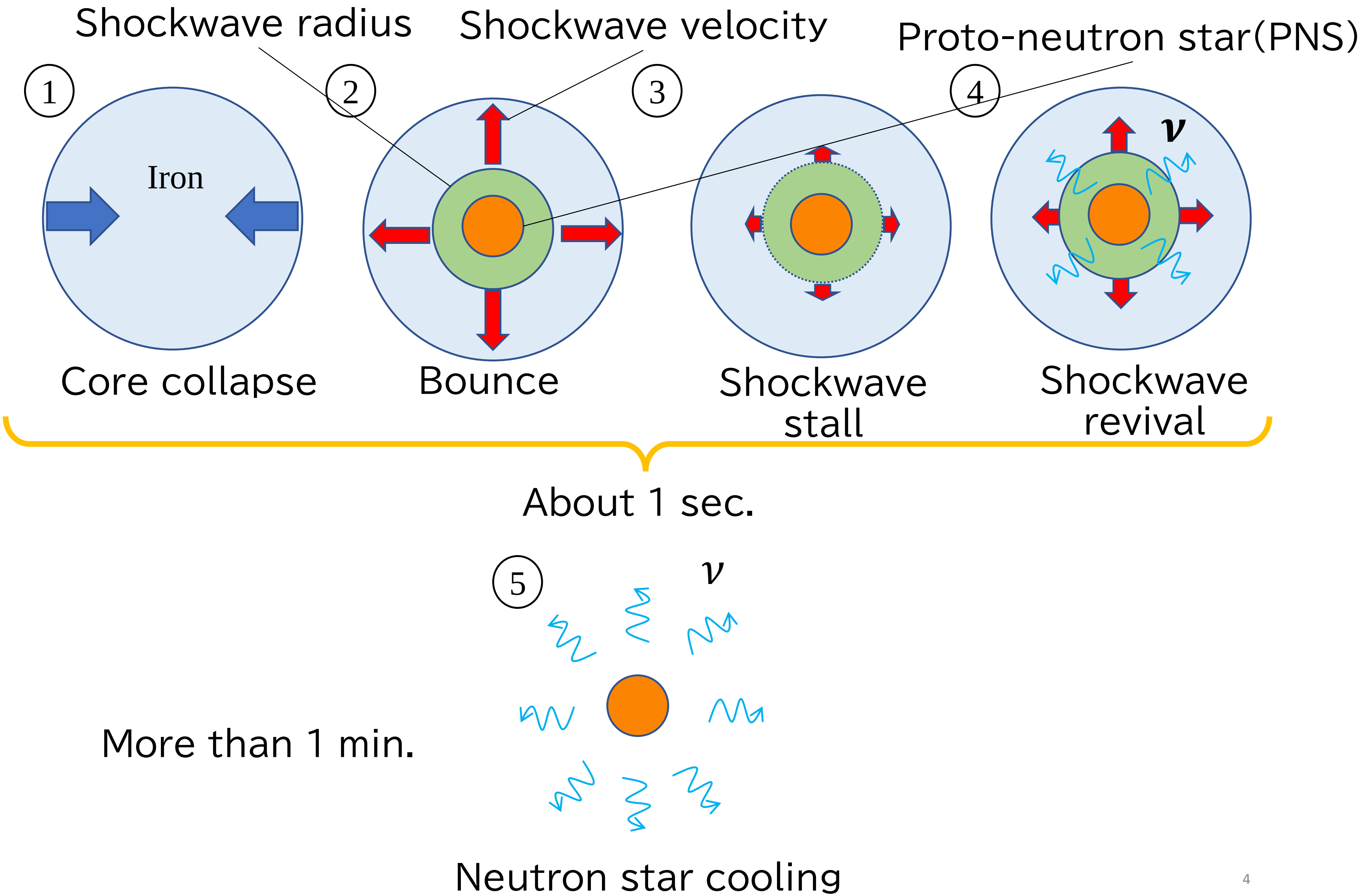
- 11: Kamiokande[1]
- 8: IMB [2]
- 5: Baksan [3]

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





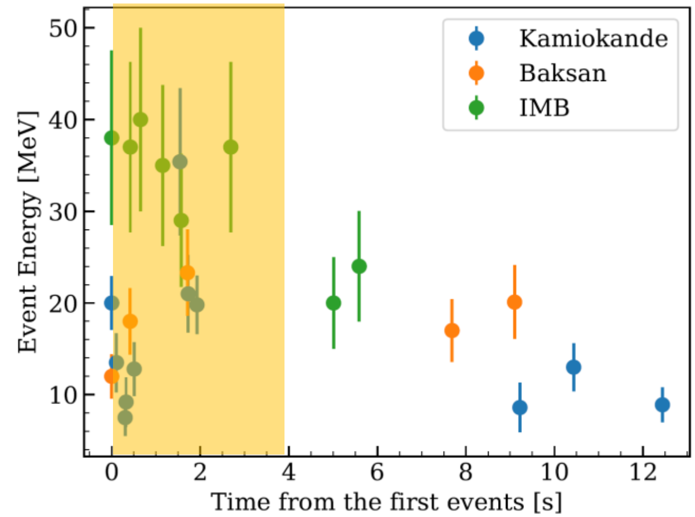
Supernova evolution



Why long-term simulation needed?

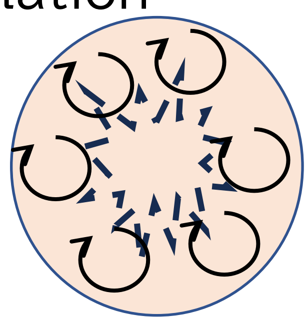
1. Observe neutrinos over 10 s from galactic supernovae
2. Fewer uncertainties at late phase

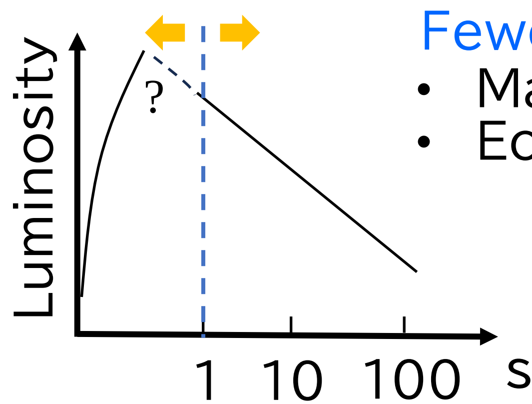
Many Multi-D simulation



More uncertainties (< 1s)

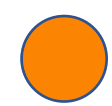
- Mass
- EoS
- Turbulence
- Neutrino oscillation
- etc..



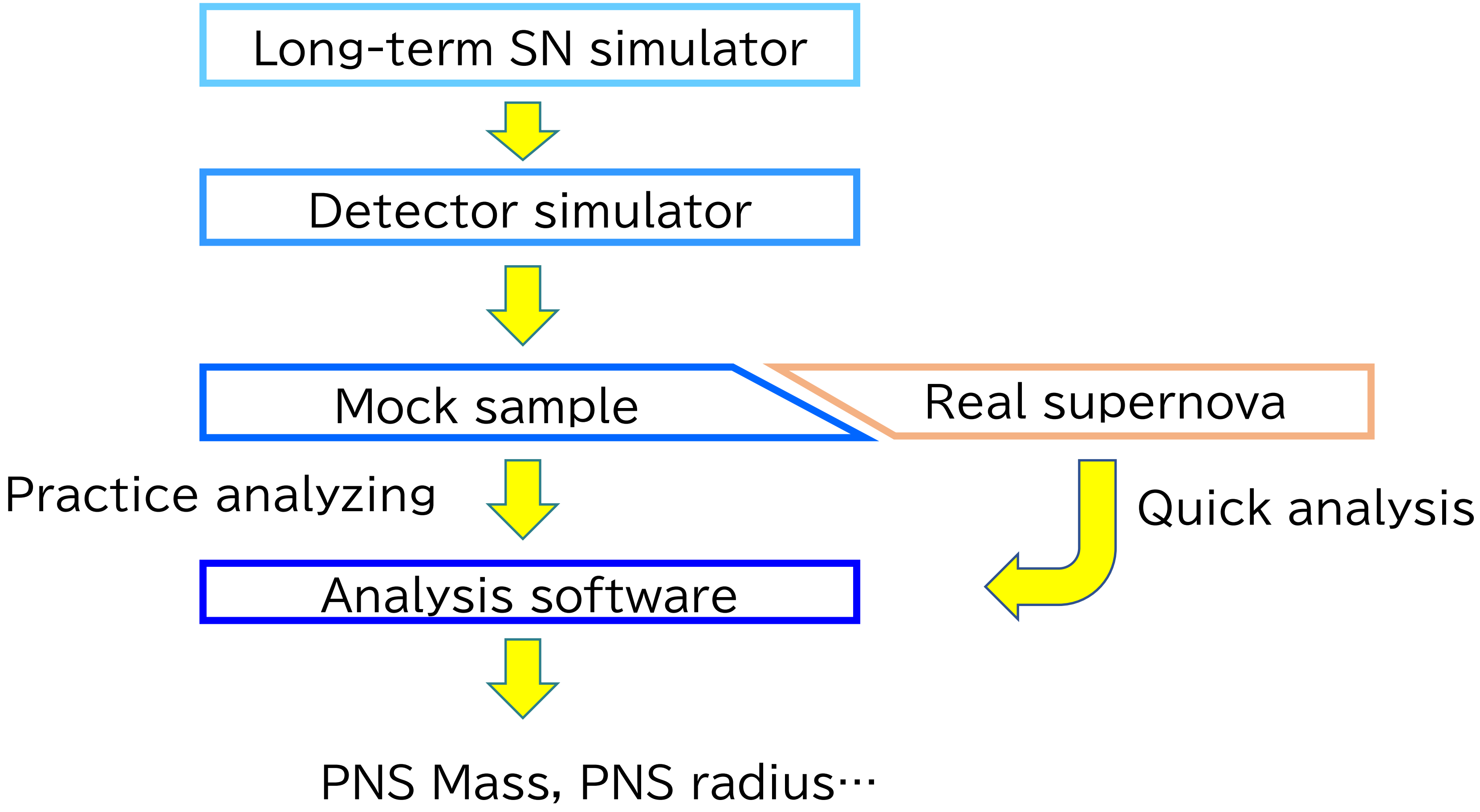


Fewer uncertainties (>1s)

- Mass
- EoS

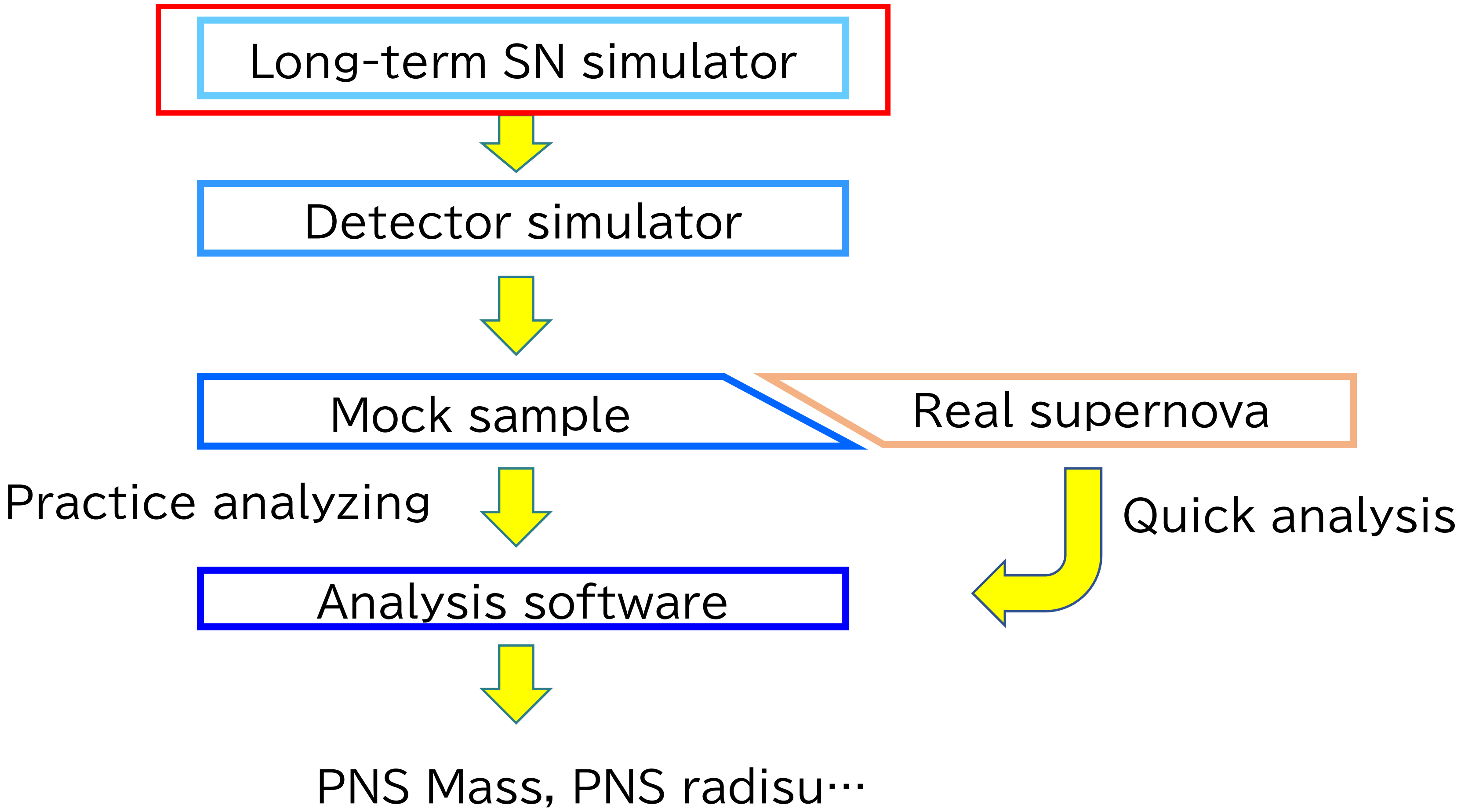


Developing supernova observation framework



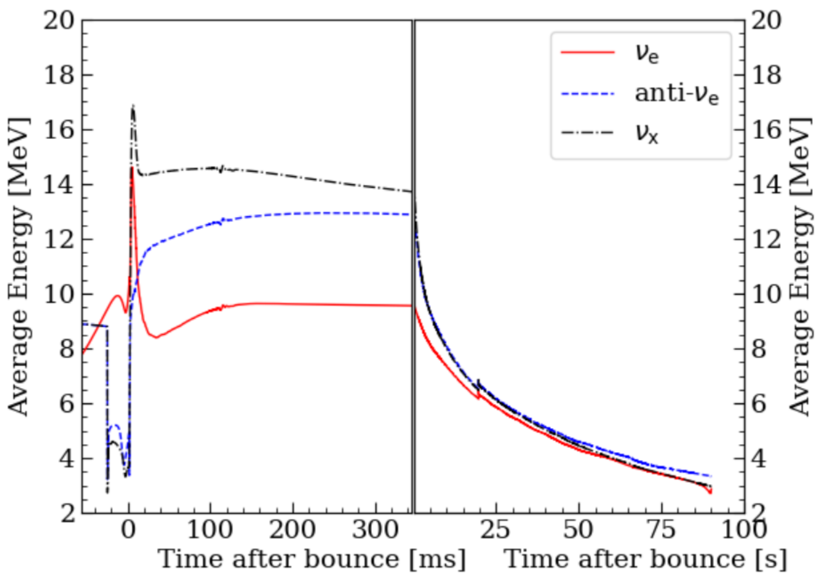
- Establish observation system of galactic supernovae in a near future

Long–term simulation of a supernova



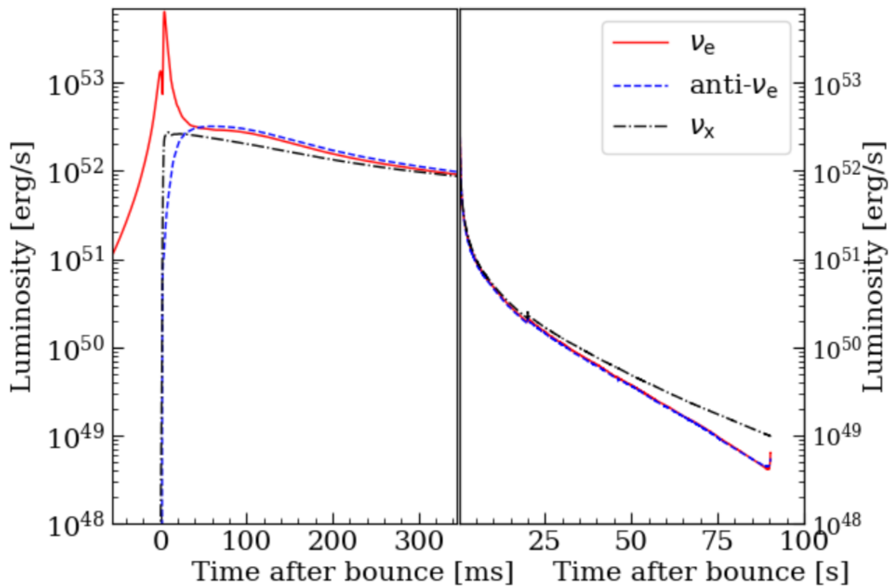
Long-term supernova neutrino simulaiton

Neutrino average energy



ν_x : μ and τ (anti) neutrinos

Neutrino luminosity

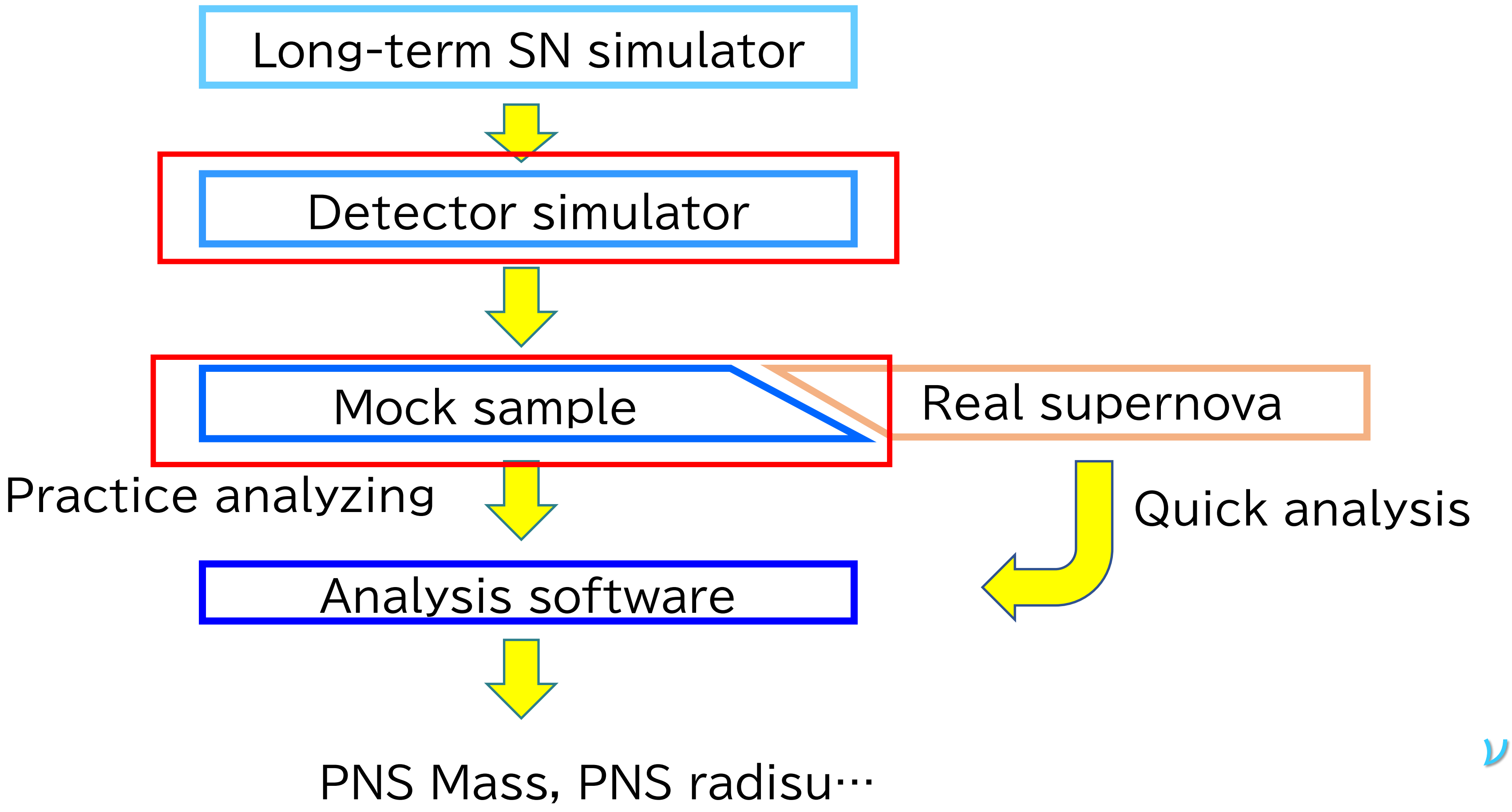


Mori et al. 2021

Features

1. General relativistic neutrino radiation hydro simulation in 1D
2. Non-artificial explosion
3. Longest general relativistic neutrino radiation hydro simulation

Long–term simulation of a supernova

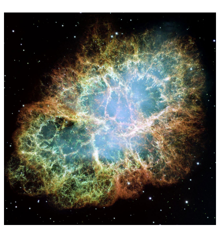


- Mock Samples are used for analysis practice and detector evaluation.

FOREST

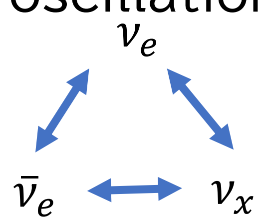
- FORcasting Events from Supernovae Theoretical modeling (FOREST)
  - Why FOREST
  - My family name: Mori = 森 in Kanji = Forest in English

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

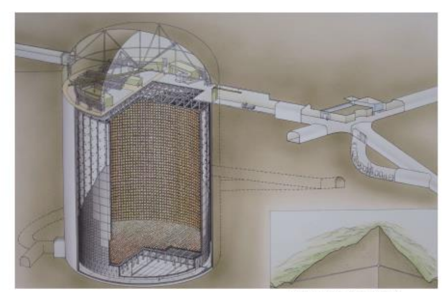


ν

Neutrino oscillation

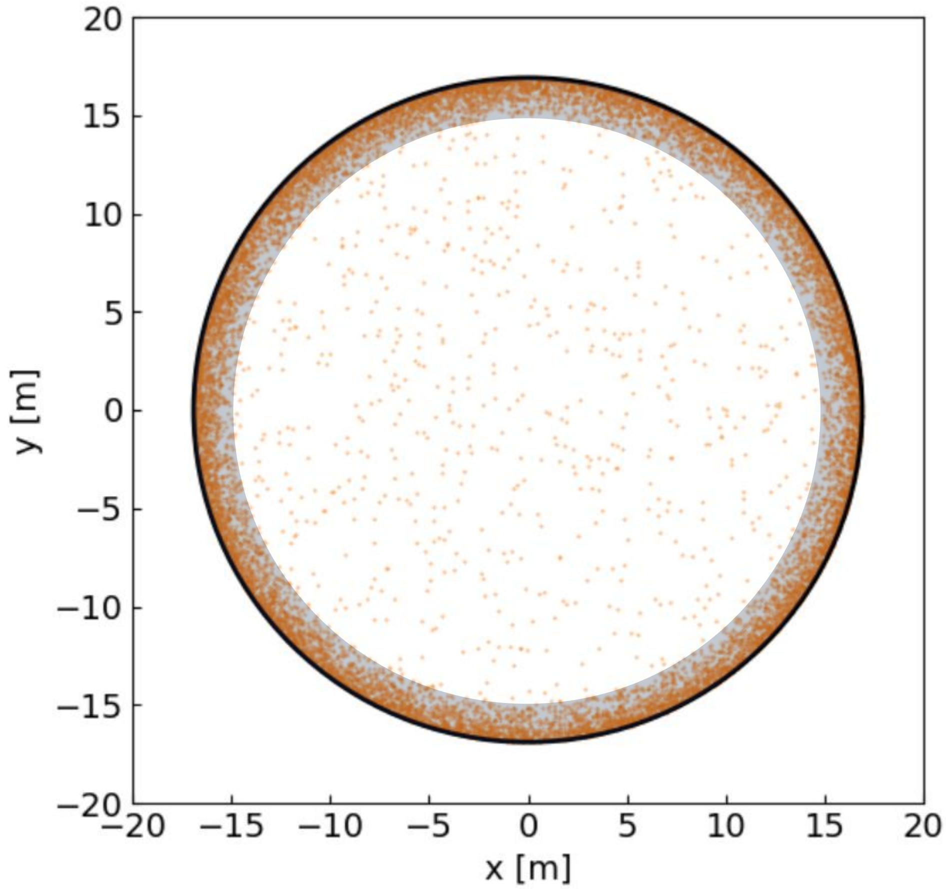


Detector



Background simulation in SK

Distribution of background in 1 day



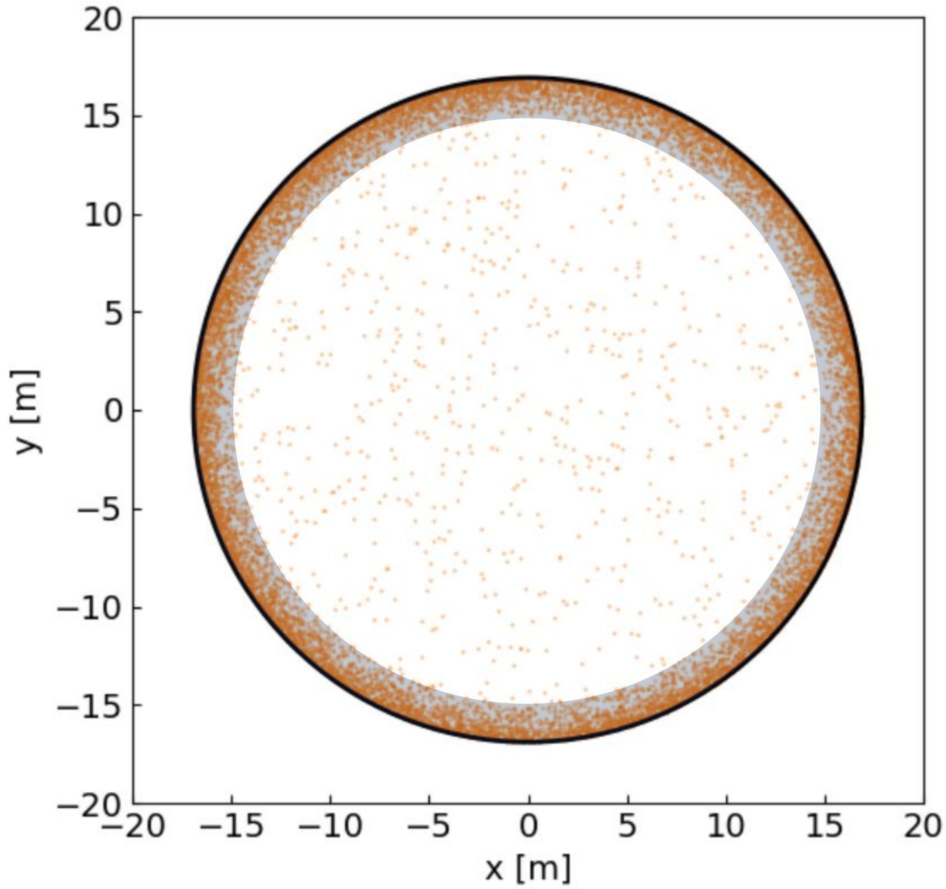
Normal analysis
Cut background near the wall
Volume:22.5 kton

vs

Supernova analysis
Use the full volume
Volume:32.5 kton

Background simulation in SK

Distribution of background in 1 day



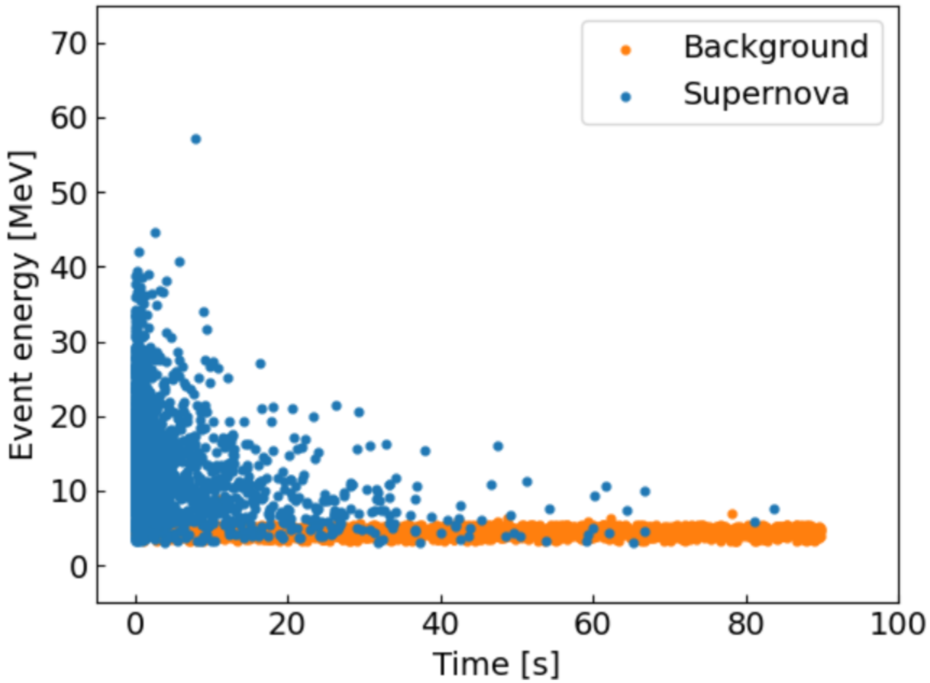
Normal analysis
Cut background near the wall
Volume:22.5 kton

vs

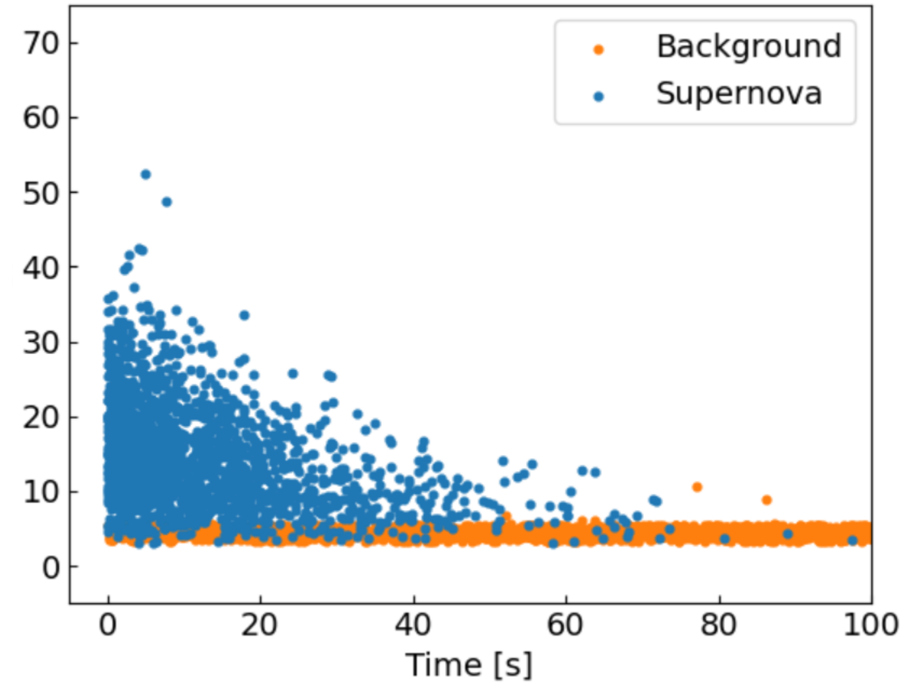
Supernova analysis
Use the full volume
Volume:32.5 kton

Mock samples

Simulation



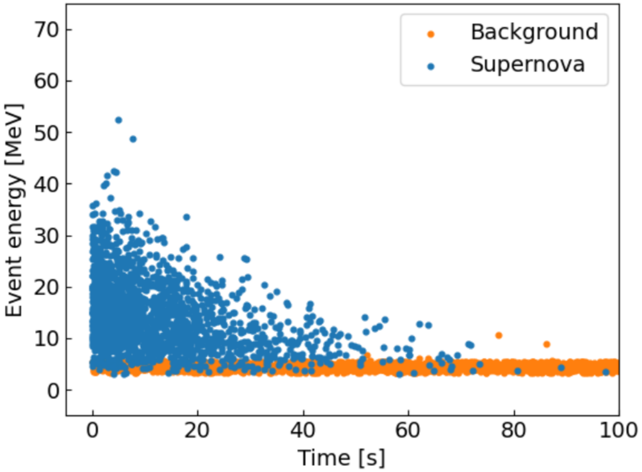
Analytic formula



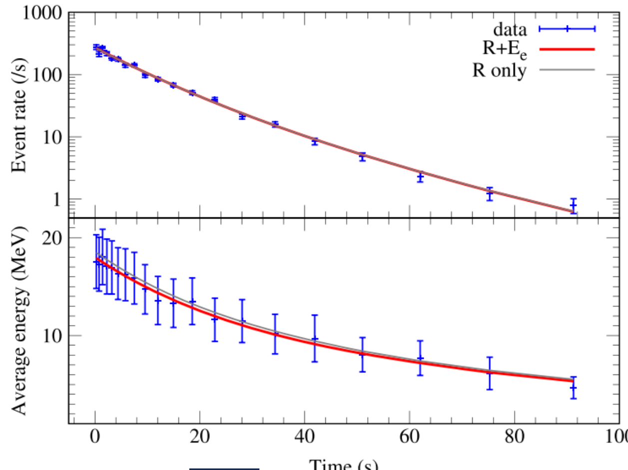
- **Assumed supernovae occurs at 10 kpc away**
  - **Some events after 1 min.**
- Analytic formula
  - Suwa et al. (2021)
  - $R(t) = 720\mathrm{s}^{-1}\left(\frac{M_{\mathrm{det}}}{32.5\ \mathrm{kton}}\right)\left(\frac{D}{10\ \mathrm{kpc}}\right)^{-2}\left(\frac{M_{\mathrm{PNS}}}{1.4M_{\odot}}\right)^{15/2}\left(\frac{R_{\mathrm{PNS}}}{10\ \mathrm{km}}\right)^{-8}\left(\frac{g\beta}{3}\right)^{5}\left(\frac{t+t_0}{100\ \mathrm{s}}\right)^{-15/2}$

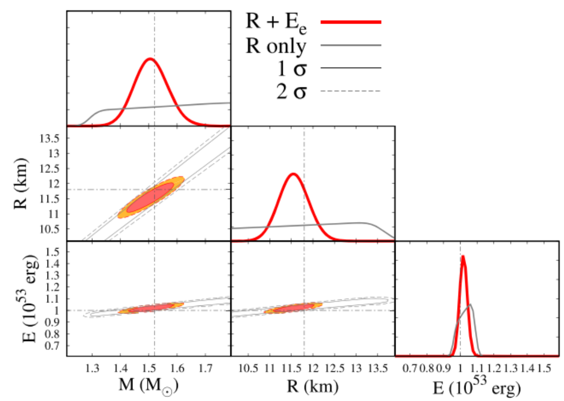
How to estimate neutron mass

Supernova events



Distributed to time bins

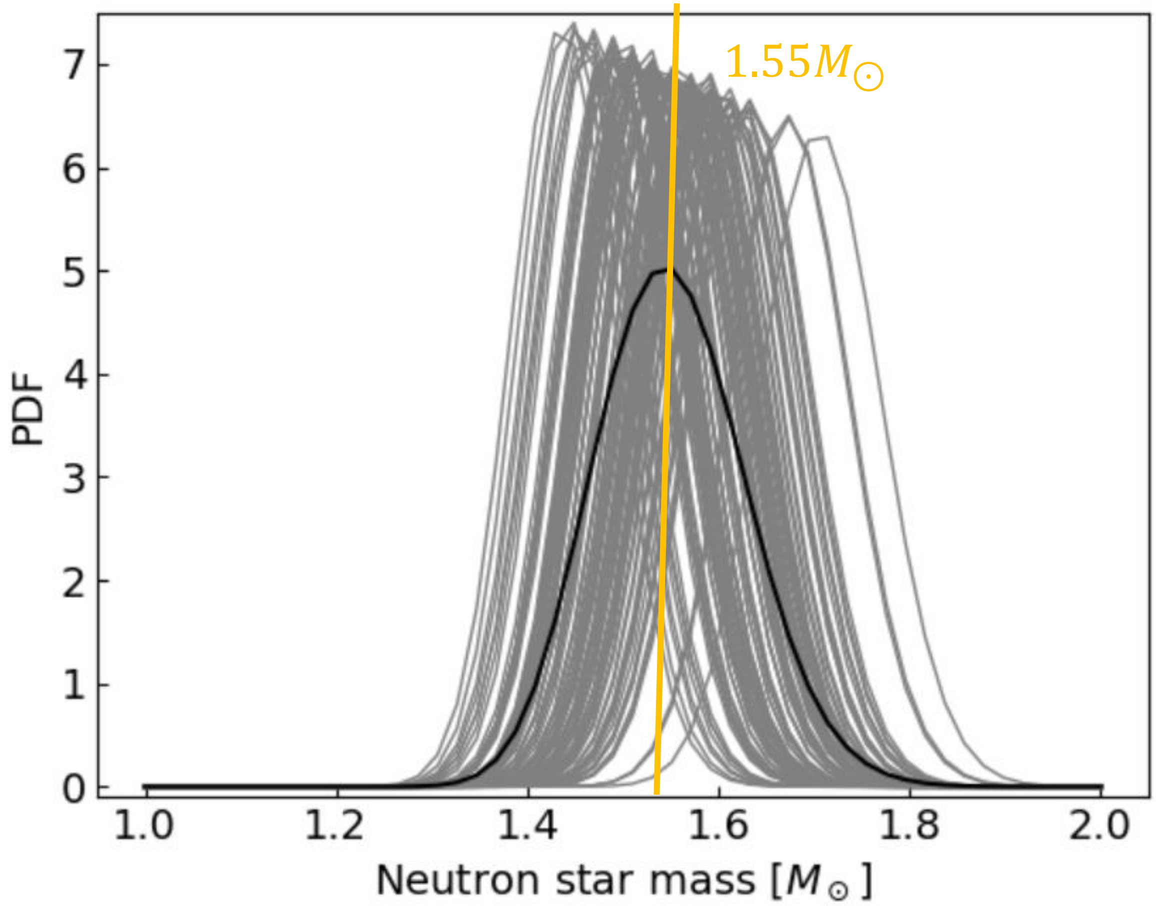




Need analytic formulas of
$R(t)$
and
$\langle E\rangle(t)$

- Bayesian analysis (Suwa et al. (2022), Harada et al. (2023))

Parameter estimation without background



- Considering pure supernova events.
- 100 realizations
  - A realization draws a gray curve.
- Estimate PNS mass
  - True value: $1.52M_\odot$

Analysis with background

- In fact, background contaminates neutrino events
- Need a new method to consider background

Event rate

- $R(t) = R_{\mathrm{SN}}(t) + \boldsymbol{cR_{\mathrm{BG}}(t)}$

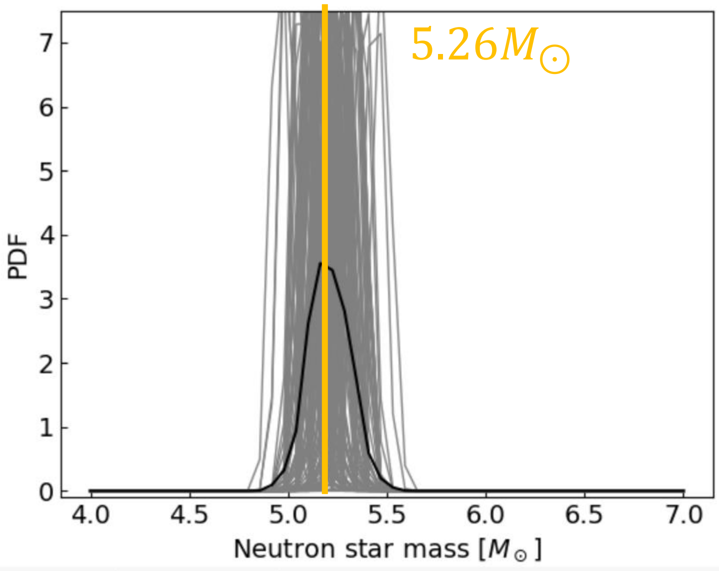
Average energy

- $\langle E\rangle(t) = \dfrac{R(t)_{\mathrm{SN}}\langle E\rangle_{\mathrm{SN}}(t)+\boldsymbol{cR_{\mathrm{BG}}(t)\langle E\rangle_{\mathrm{BG}}(t)}}{R_{\mathrm{SN}}(t)+\boldsymbol{cR_{\mathrm{BG}}(t)}}$

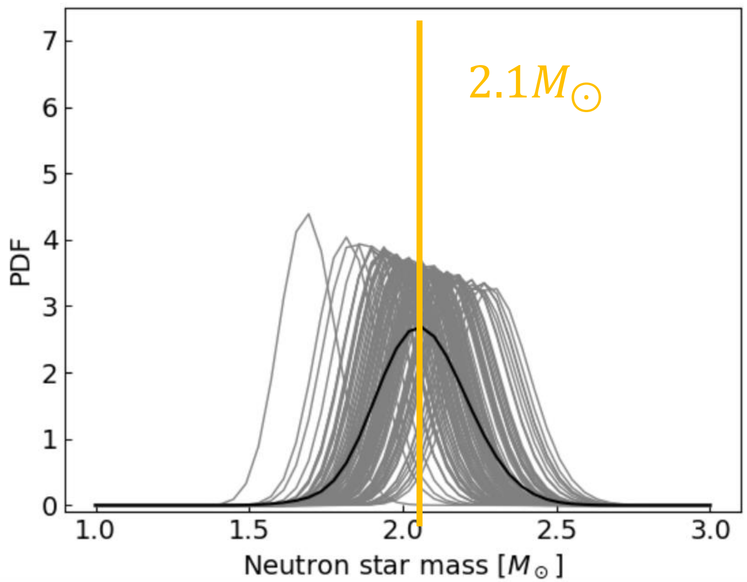
- c is a parameter

Parameter estimation with background

Formula without Background



Formula with Background



- 100 realizations
- Estimate PNS mass
- 100
  - True value: $1.52M_\odot$
  - $c = 1$

Gravitational eigenmodes

- Supernovae also emit gravitational waves.
- We estimated eigenmode frequencies with the asteroseismology approach.
  - Used GREAT (https://www.uv.es/cerdupa/codes/GREAT/)

- Linear perturbation analysis both of fluid and metric.
- Calculated eigenmodes from the result of the 20s result.

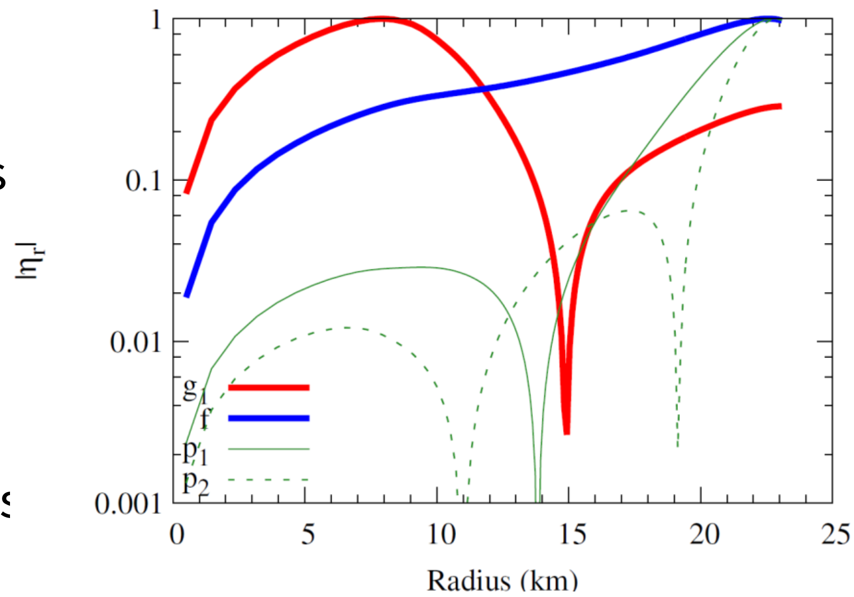
- Linear perturbation equations

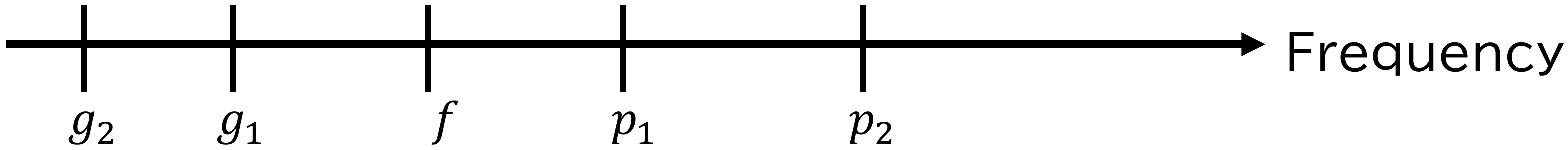
$$\partial_r \eta_r + \left[\frac{2}{r} + \frac{1}{\Gamma_1}\frac{\partial_r P}{P} + \frac{\partial_r \psi}{\psi}\right]\eta_r + \frac{\psi^4}{\alpha^2 c_s^2}\left(\sigma^2 - \mathcal{L}^2\right)\eta_\perp = \frac{1}{c_s^2}\frac{\delta\hat{Q}}{Q} - \left(6 + \frac{1}{c_s^2}\right)\frac{\delta\hat{\psi}}{\psi},$$

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

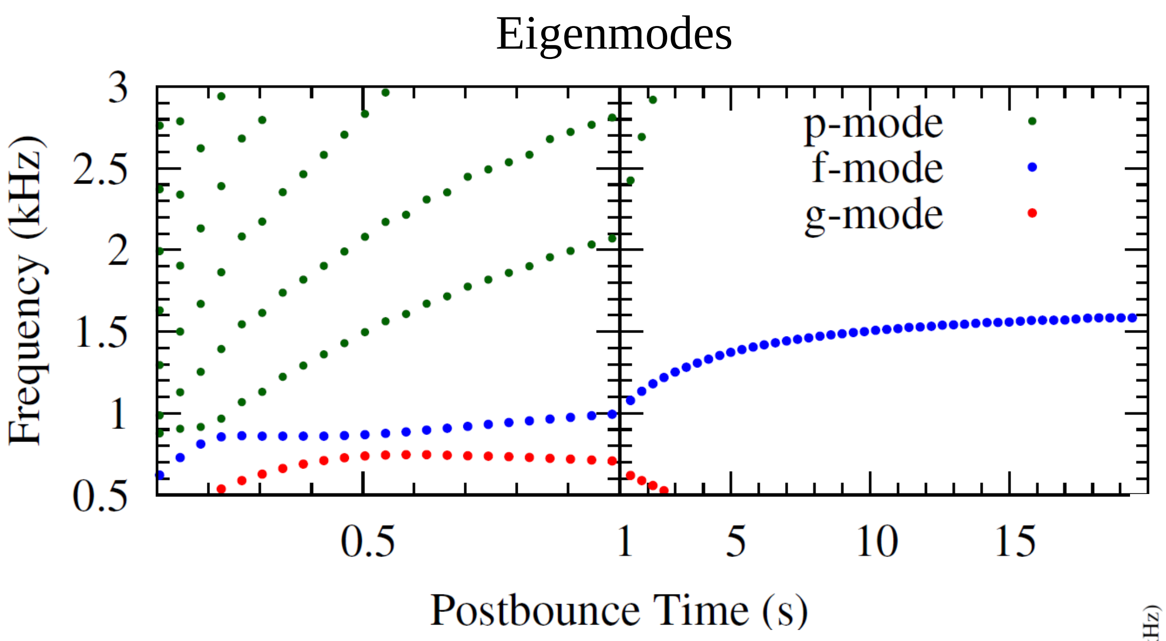
Classifications of eigenmode

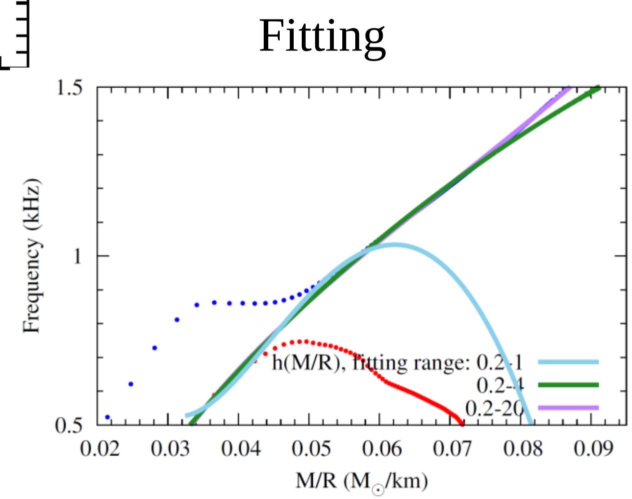
- p_{i}-mode
  - "i" is the number of nodes
  - Restoring force: pressure
  - Frequencies increase as nodes increas
- f-mode
  - Fundamental mode of the p-mode
- g_{i}-mode
  - Restoring force: buoyancy
  - Frequencies decrease as nodes increas:





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

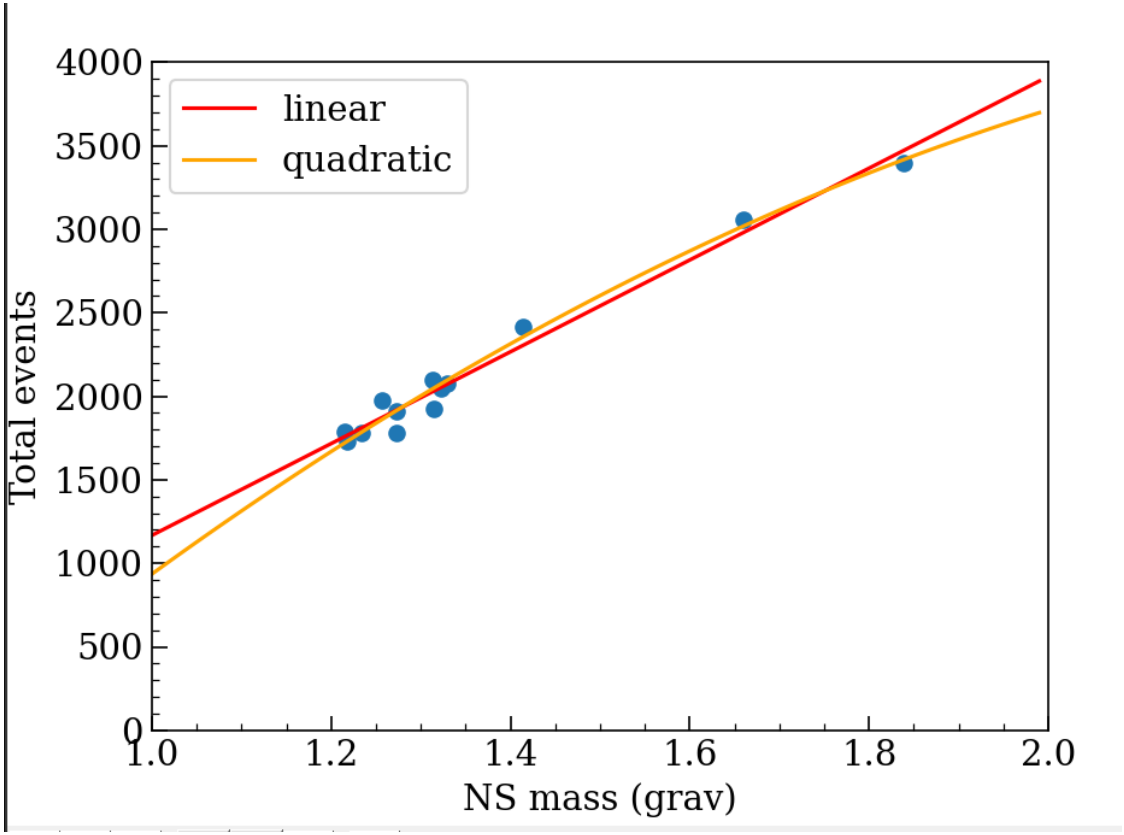
- Supernovae are promising multi-messenger targets.
- Established the long-term neutrino radiation hydro simulation
  - My long-term neutrino database: https://zenodo.org/record/5825648
- Estimated neutrino signals at Super-Kamiokande
  - We may be able to estimate neutron star mass via neutrino events.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

Back up

Method of long time simulation

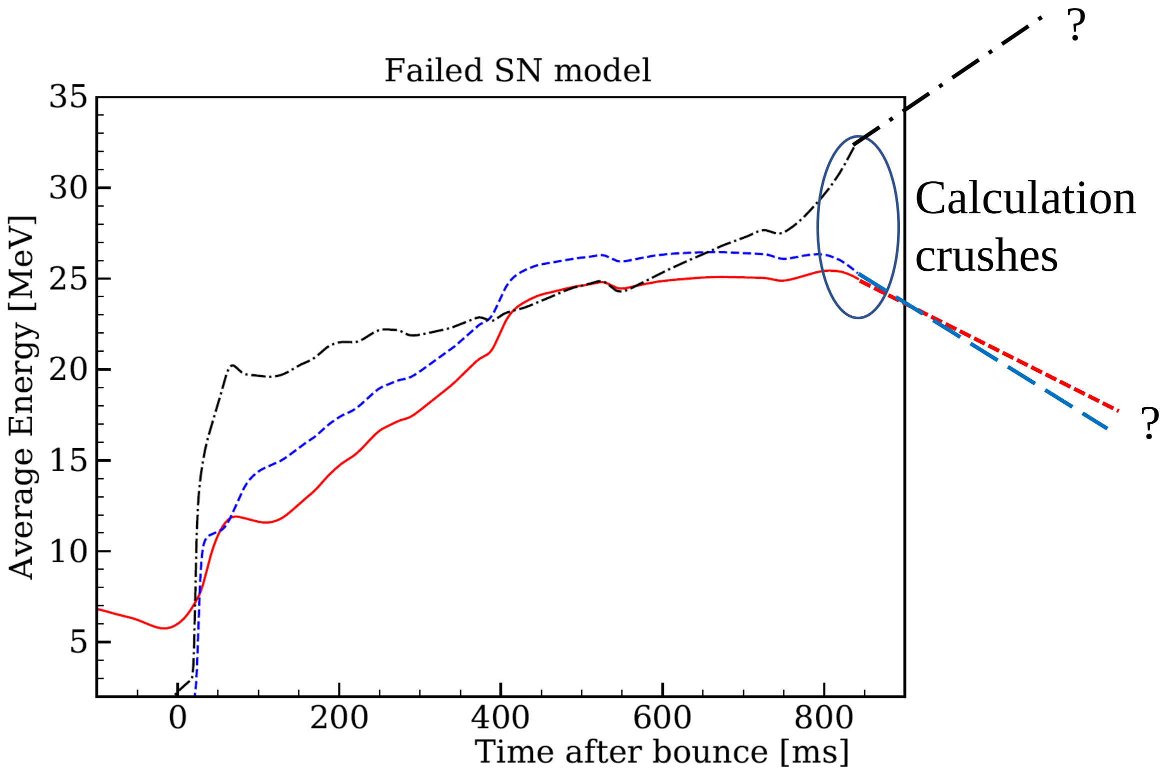
- Simulate supernovae in one-dimension
- Code
  - GR1Dv2 (public code: http://stellarcollapse.org)
    - ➢ O'Connor, ApJS 219 24 2015
  - Gravity: General relativity
  - M1 scheme
  - Modified for long-term simulation
    - ➢ Resolved reference out of physics tables
    - ➢ Optimized resolution of time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



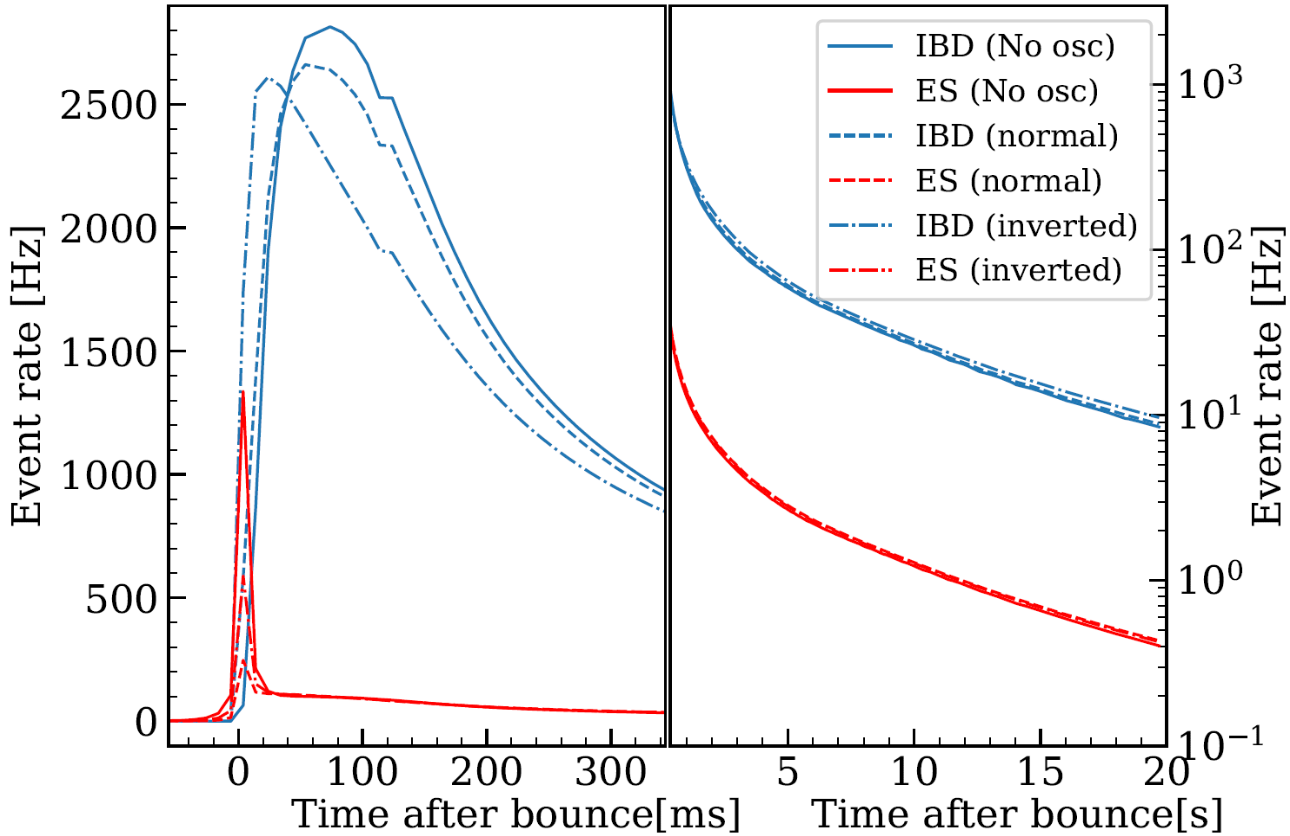
Misner-Sharp metric

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

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

- 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

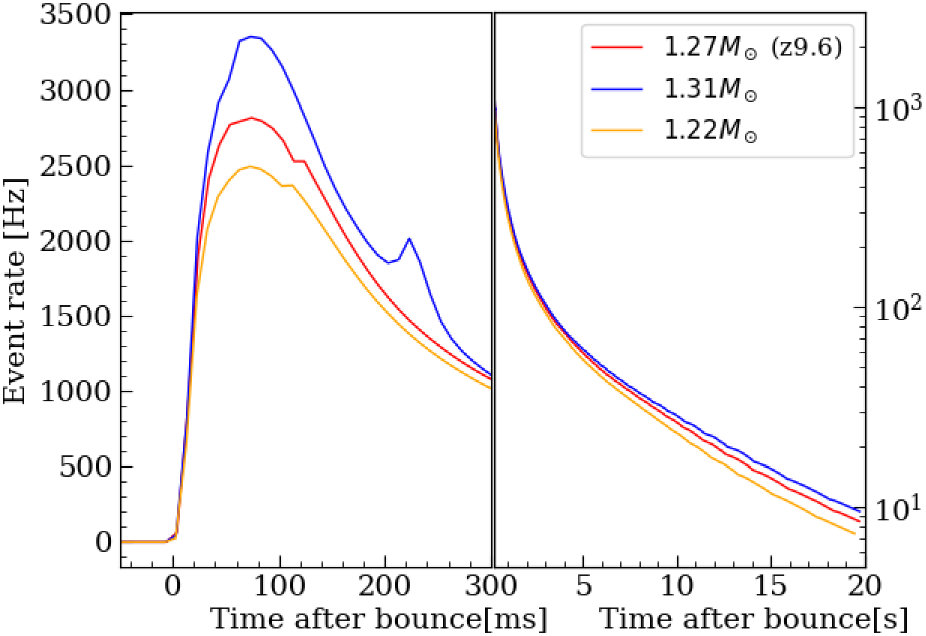
Recent simulations

	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**

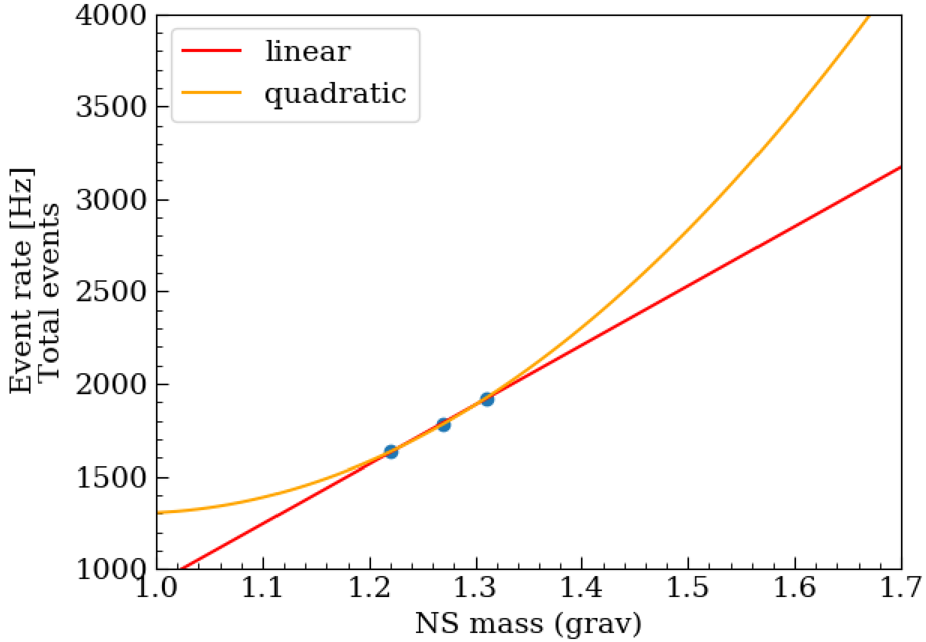
- To explode without artificial methods in one-dimension is difficult
  - ➢ Enhancement of neutrino reaction rates
  - ➢ Removal of material accreting
- Long time simulation in multi-dimension is impossible
- We do long time simulation in one-dimension without artificial methods

Neutrino and neutron star mass

Event rate at 10 kpc



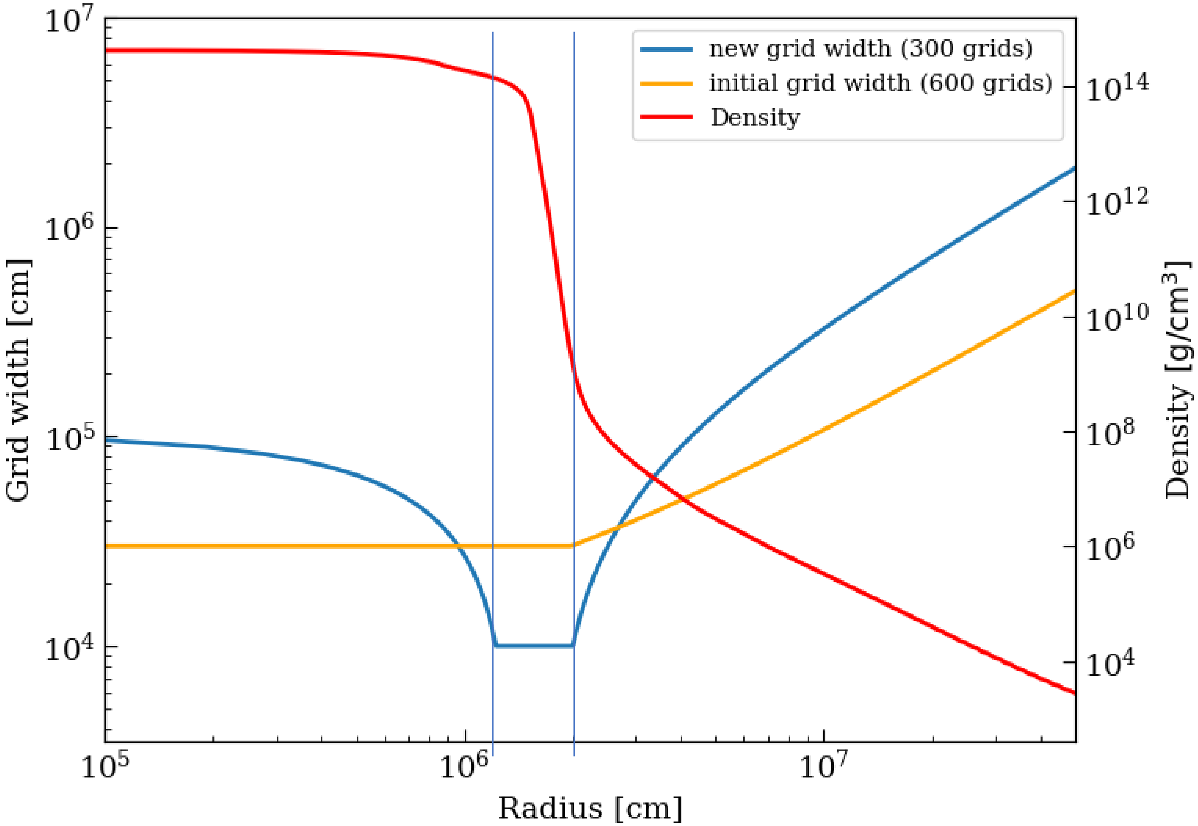
Relation between the number of events and neutron star mass

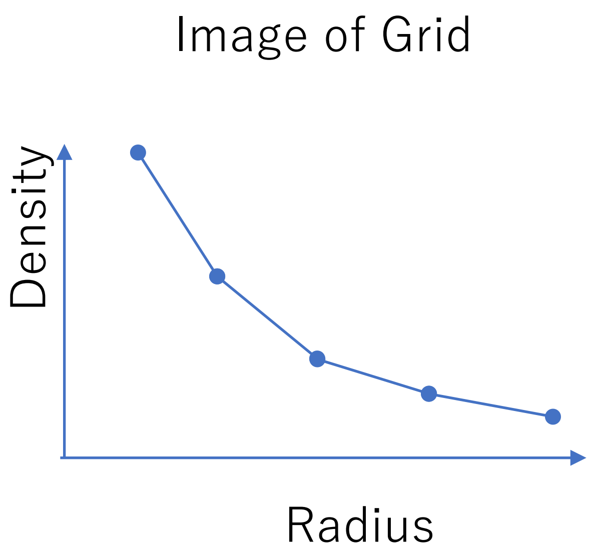


- Three simulations which lead to different neutron star mass
- If distance is determined, neutron star mass is maybe determined.
    - ➢More simulations are needed.

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

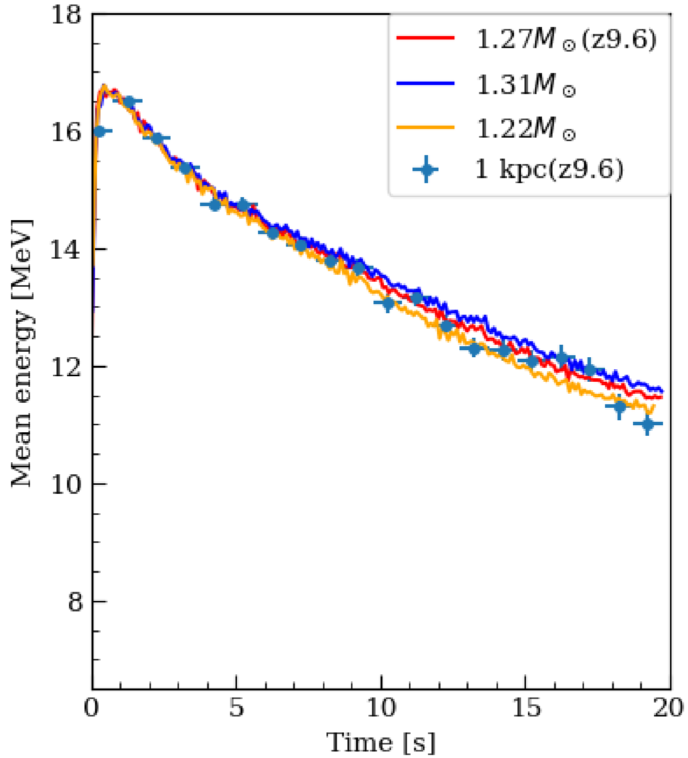
Device of grids

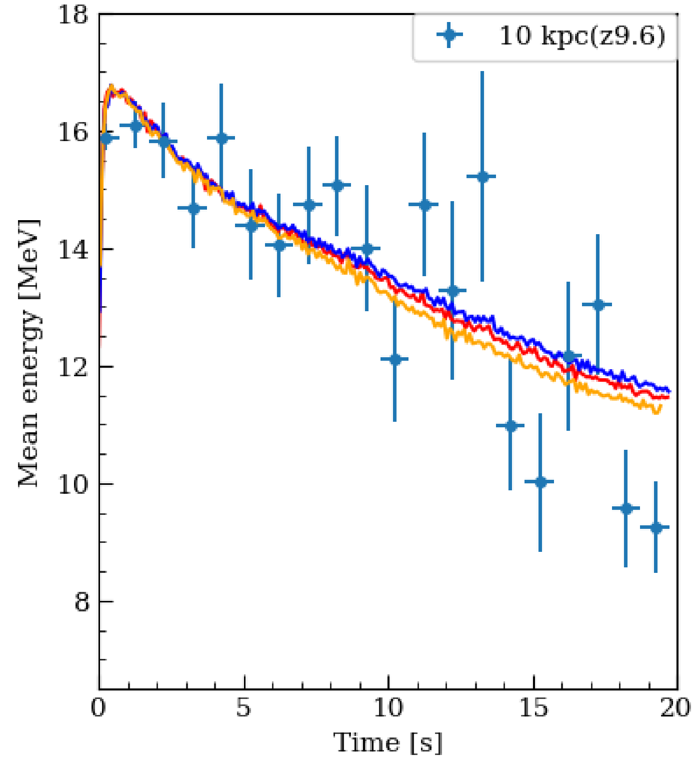




- Red ： Density structure of PNS
- Yellow ： Initial grids (600 grids)
- Blue ： Optimized grids (300 grids)
- The region in which the density drastically changes is finely resolved.
  - Initial grids make calculation stop at about 5 sec.
  - Cost is also too high

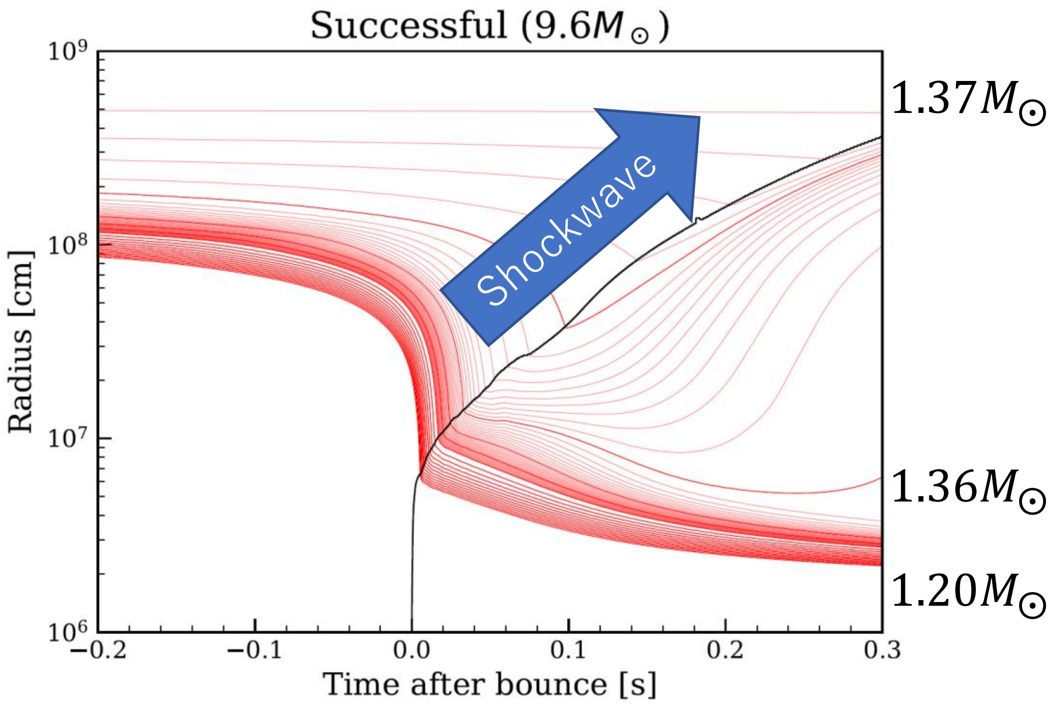
平均エネルギーの発展

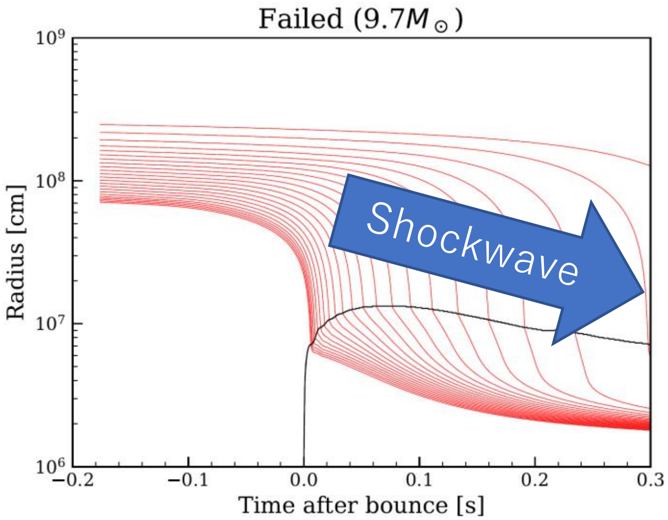




- **実線**:無限個のイベントの平均エネルギー
- **マーカー**:有限個のイベントの平均エネルギー(z9.6)
  - エラーバー: $\sqrt{\frac{1/N_{\mathrm{bin}}\times\sum_{i=1}^{N_{\mathrm{bin}}}(E_i-\bar{E})^2}{N_{\mathrm{bin}}}}$
- 個数だけでなく、エネルギー情報も使った比較が可能
- エネルギーの時間発展からのモデルの分別を目指す。

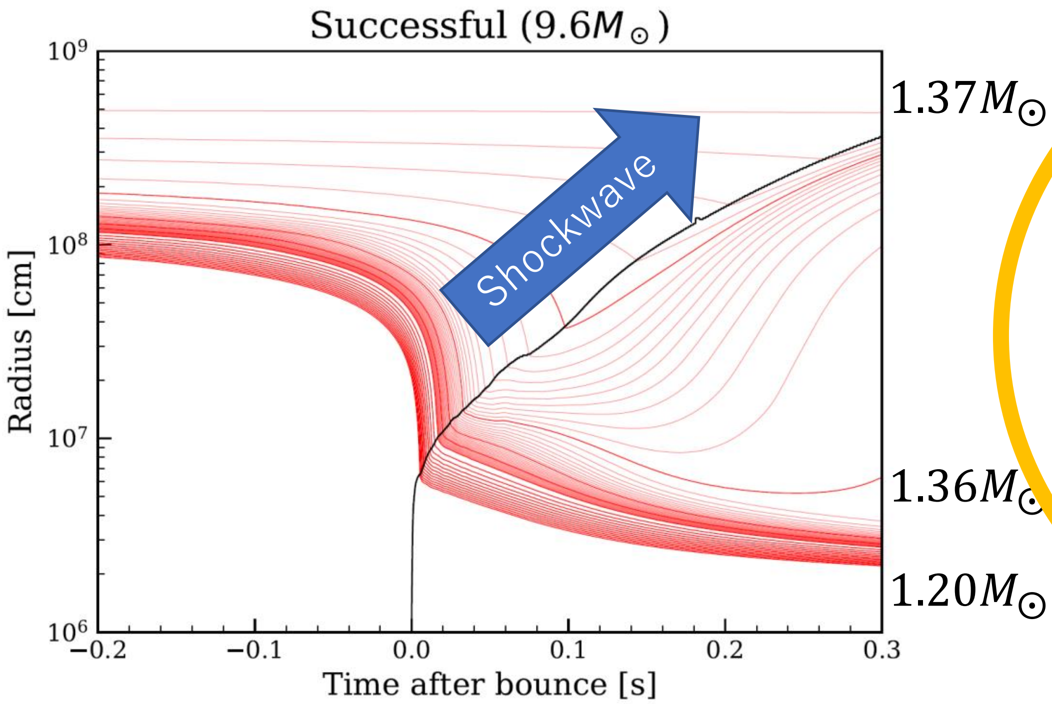
Light progenitor

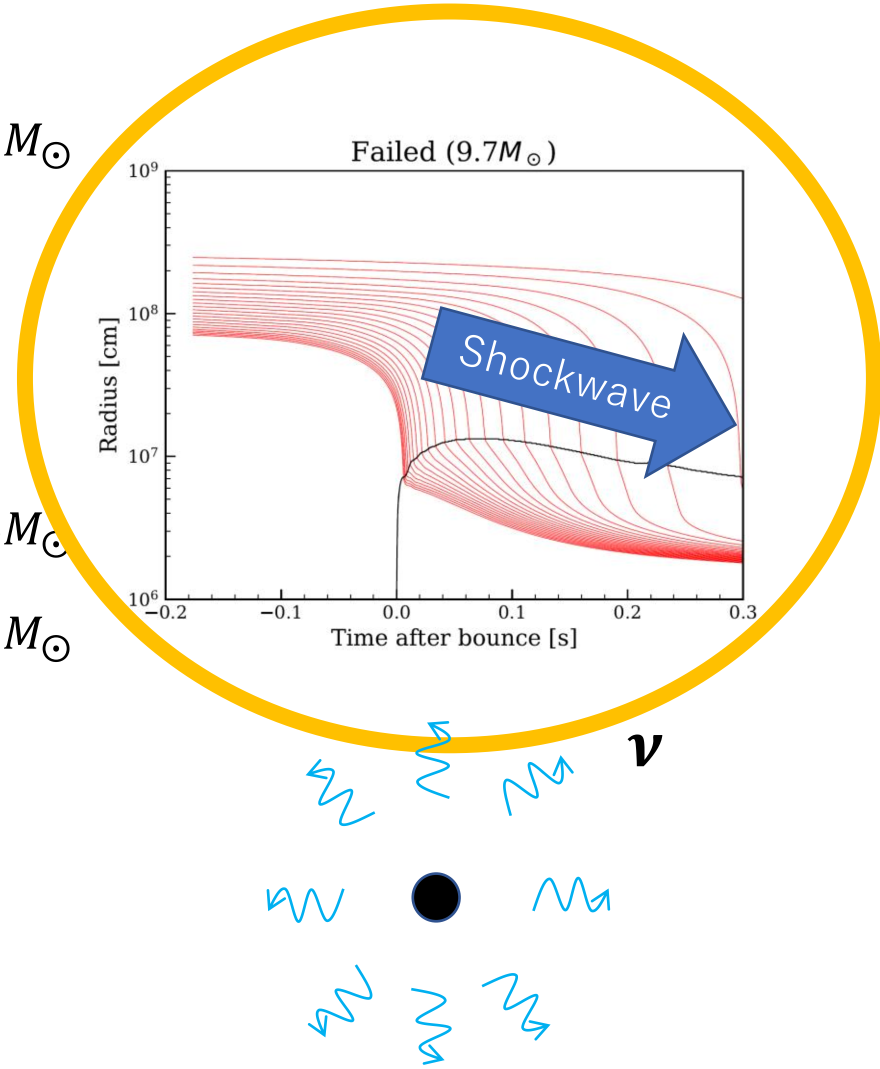




- Red：Radii at which densities are constant
- Black：Radius of a shockwave
- Succeed to explode with the suitable choice of progenitors and **without artificial methods**
  - 9.6 solar mss, initial metallicity is 0
  - Called z9.6

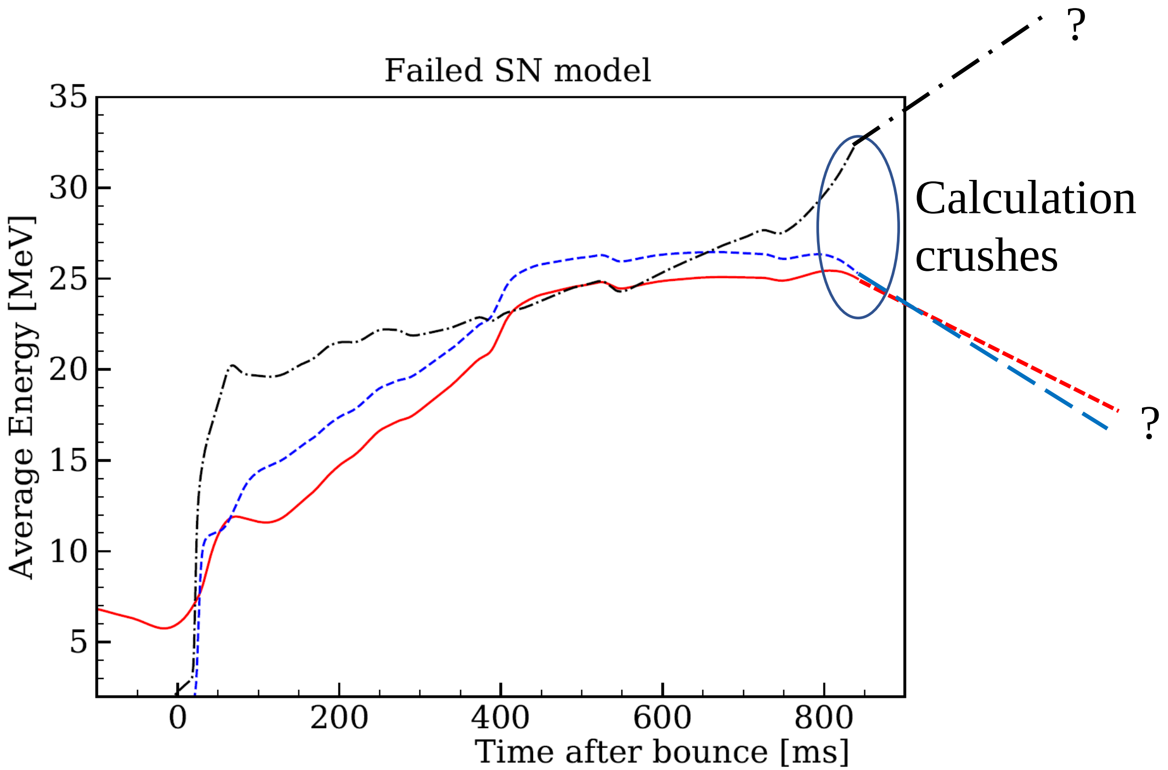
Black hole formation





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

Calculation crush



Misner-Sharp metric

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

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

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

Hernandez–Misner metric

- Misner-Sharp metric

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

- Introduce new time u

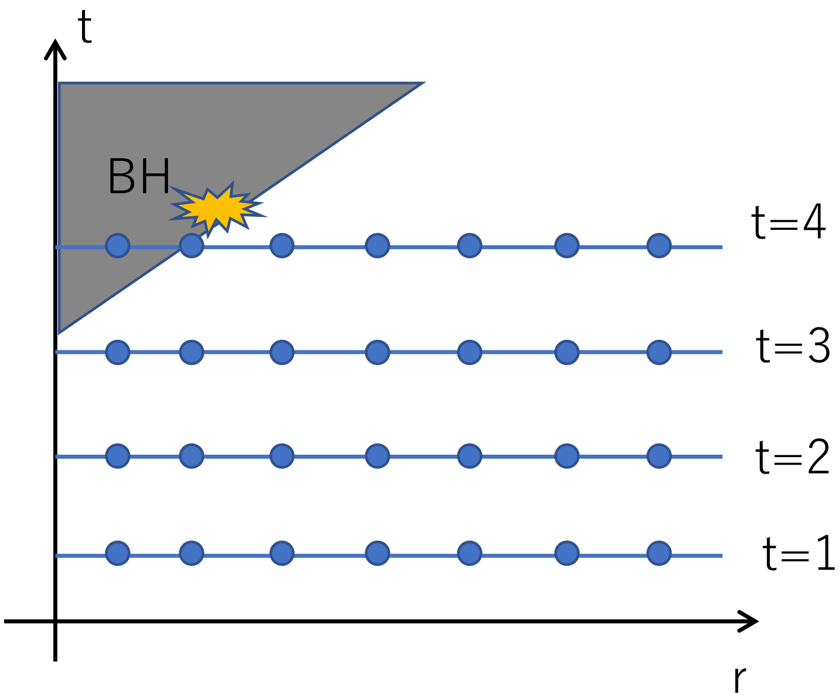
$$e^{\psi}du = e^{\phi}dt - Xdr$$

- Hernandez-Misner metric

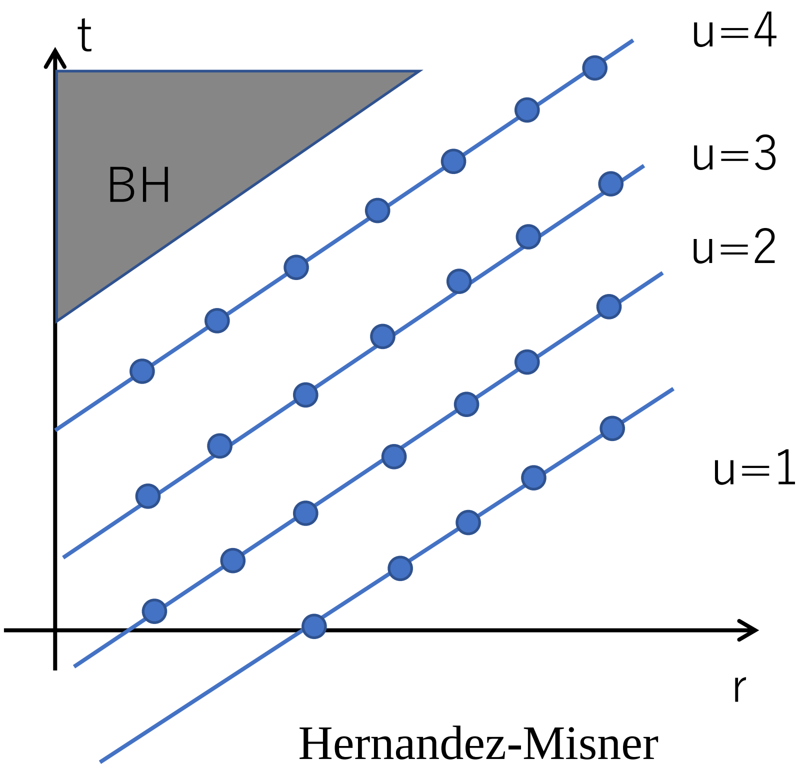
$$ds^2 = -e^{2\psi}du^2 - 2e^{\psi}Xdrdu + d\Omega^2$$

- The “u” is called observer time.

Difference between two metrics



Misner-Sharp

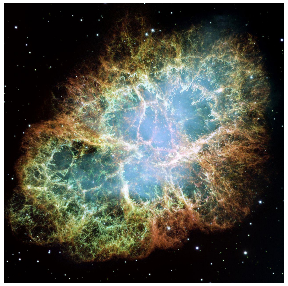


Hernandez-Misner

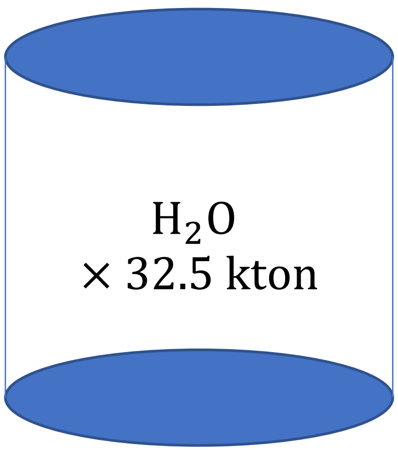
- Evolute time so that it avoids a black hole surface.
  - ➢Time is slower, closer to the center.

Details of event simulation

Explosion



10 kpc

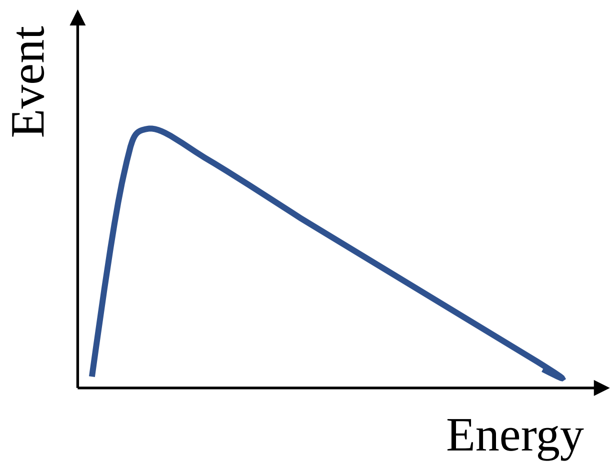


Super-Kamiokande(SK)

Reaction channel

Inverse Beta Decay(IBD)

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



Event distribution per time

Random number