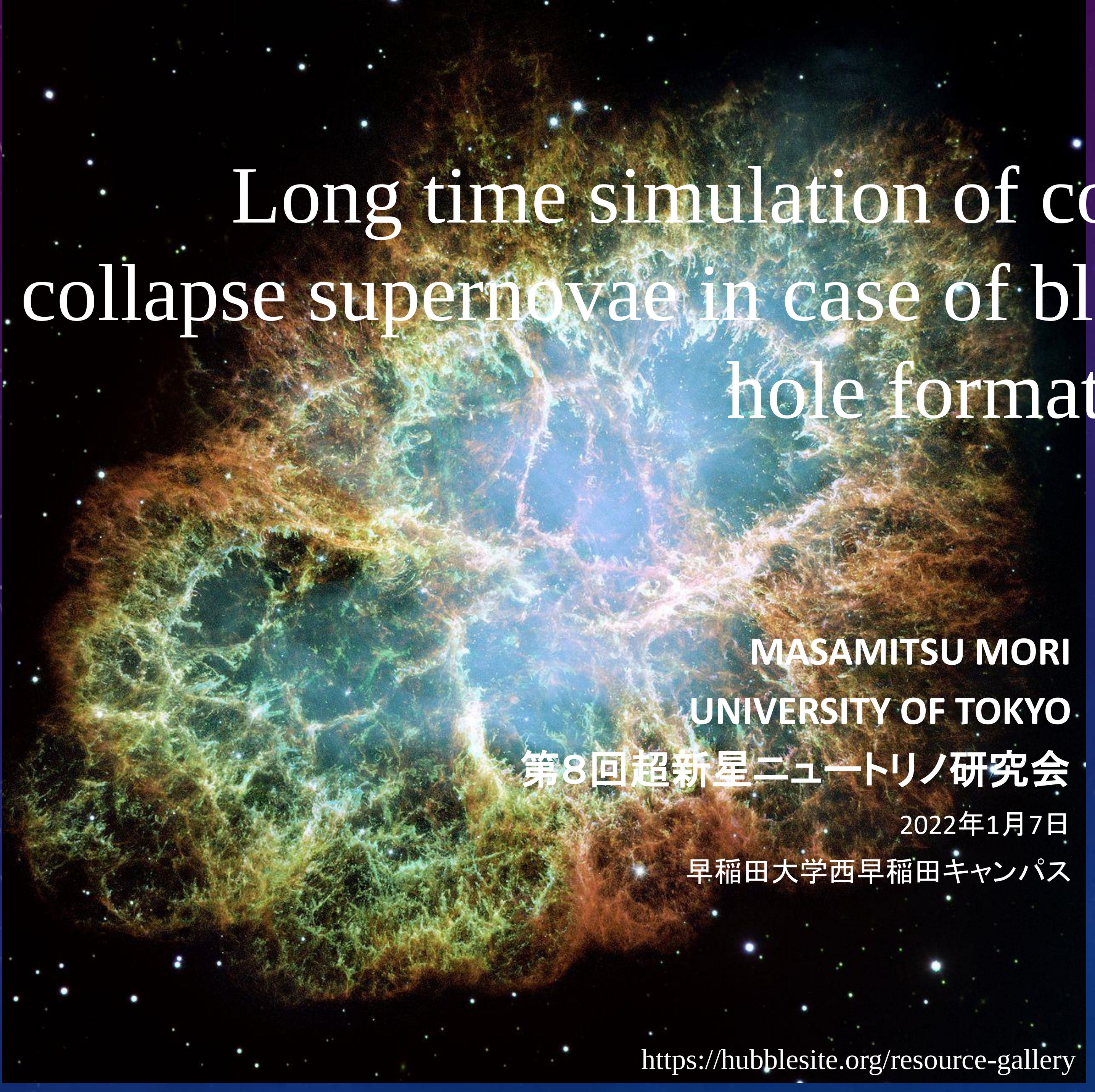
Long time simulation of core-collapse supernovae in case of black hole formation



MASAMITSU MORI
UNIVERSITY OF TOKYO

第8回超新星ニュートリノ研究会

2022年1月7日

早稲田大学西早稲田キャンパス

https://hubblesite.org/resource-gallery

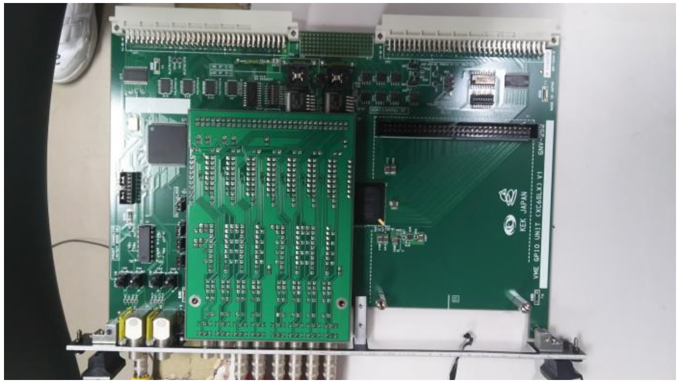
はじめに(宣伝)

昨日のSK(-Gd)のトークで

- **ベテルギウス**
- さらに、**前兆ニュートリノ**
- 加えて、**カムランドのアラーム**

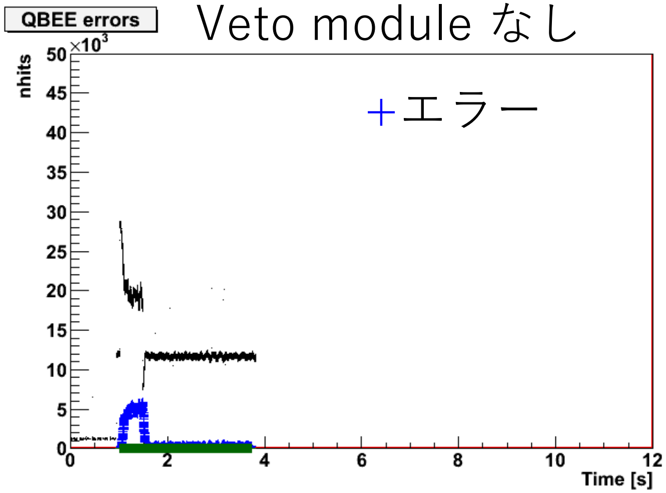
というワードが出てきたのに1ミリも僕の仕事が出てこなくて悲しかったので少し自分のSKの仕事について紹介

前兆ニュートリノが**カムランド**で観測されたらVeto moduleがオンになる。
論文執筆中

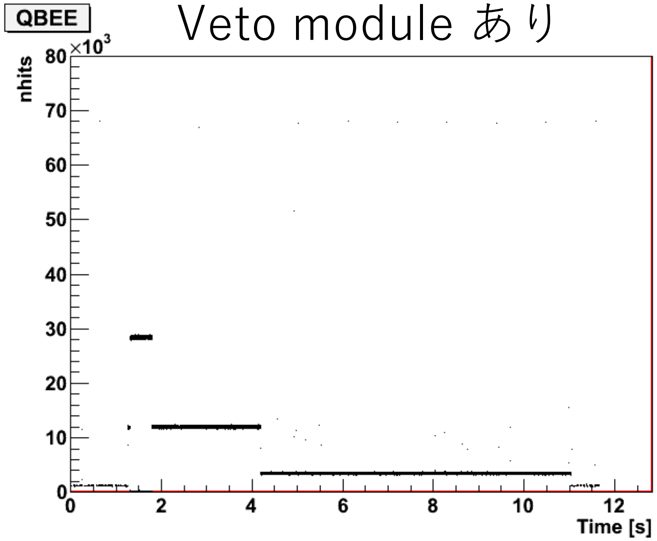


- **ベテルギウス**のような超近傍超新星爆発ではSKはイベントを処理できないので

Veto module なし



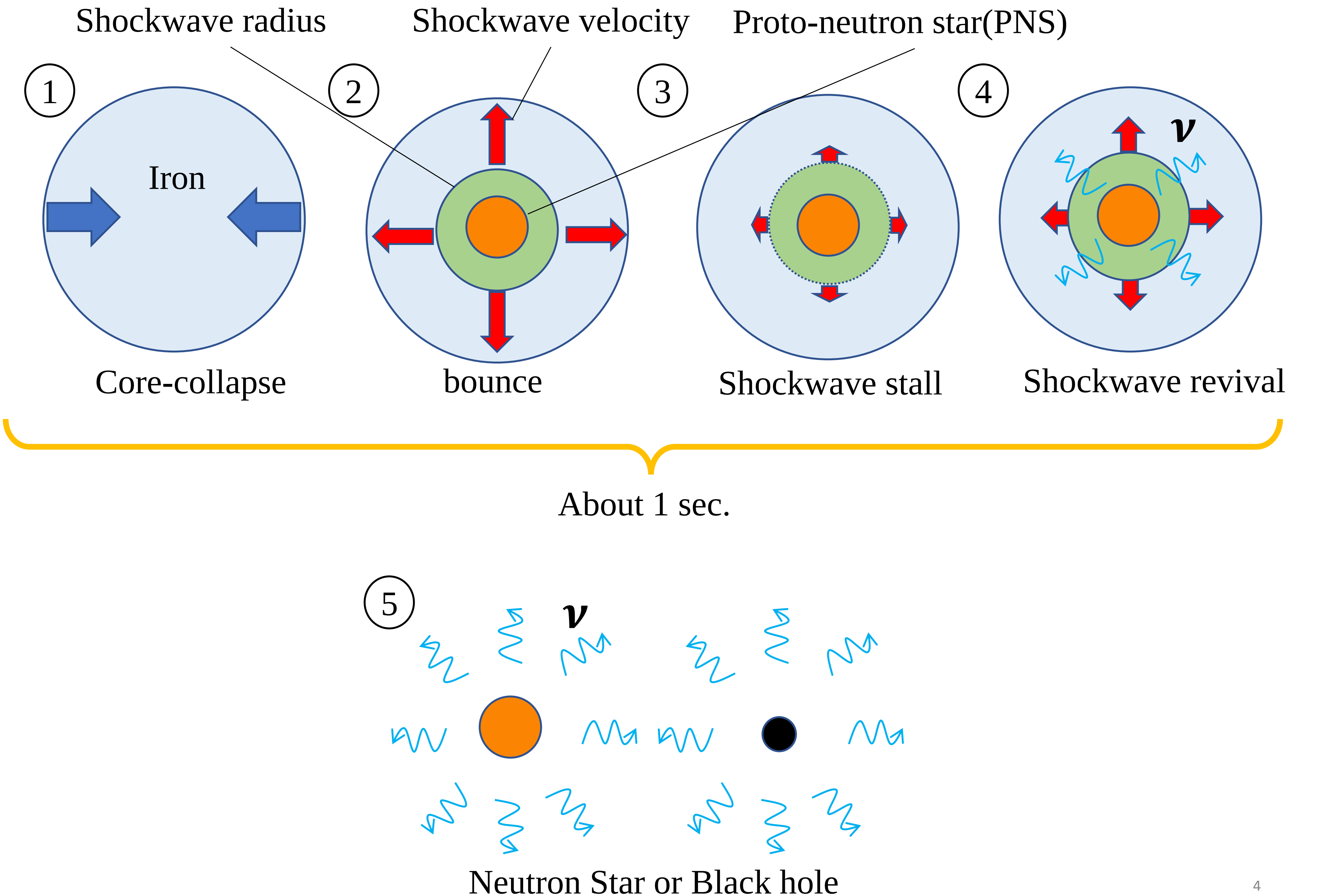
Veto module あり



Contents

1. Long time simulation of supernova neutrino
2. Estimation of signals at Super-Kamiokande
    - Have been published
    - Progress of Theoretical and Experimental Physics, Volume 2021, Issue 2, February 2021, 023E01
3. In case of black hole formation
    - Ongoing
    - Related to the title

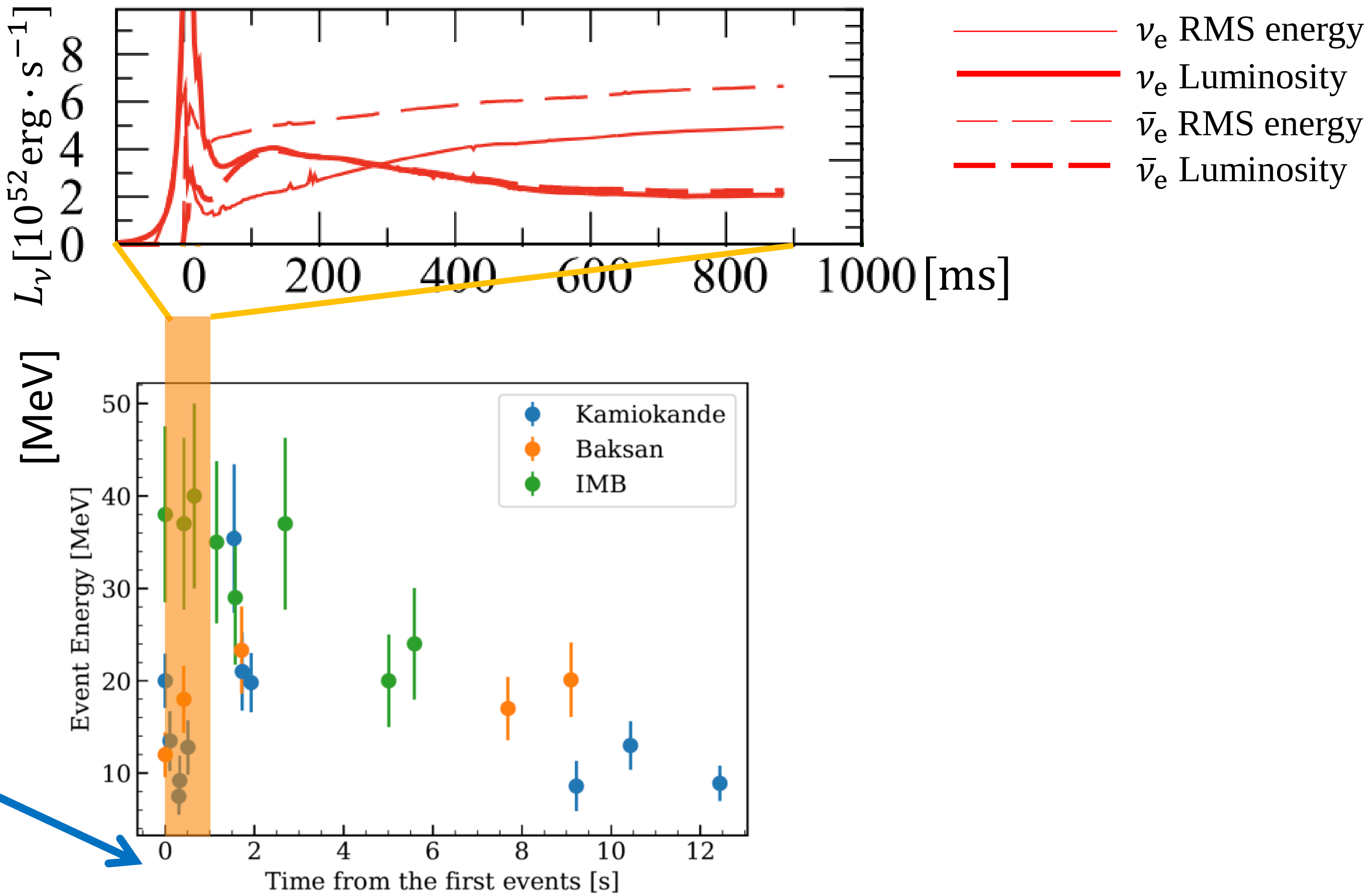
Supernova evolution



Supernova simulation problem

- Most simulations concentrates on early 1 sec.

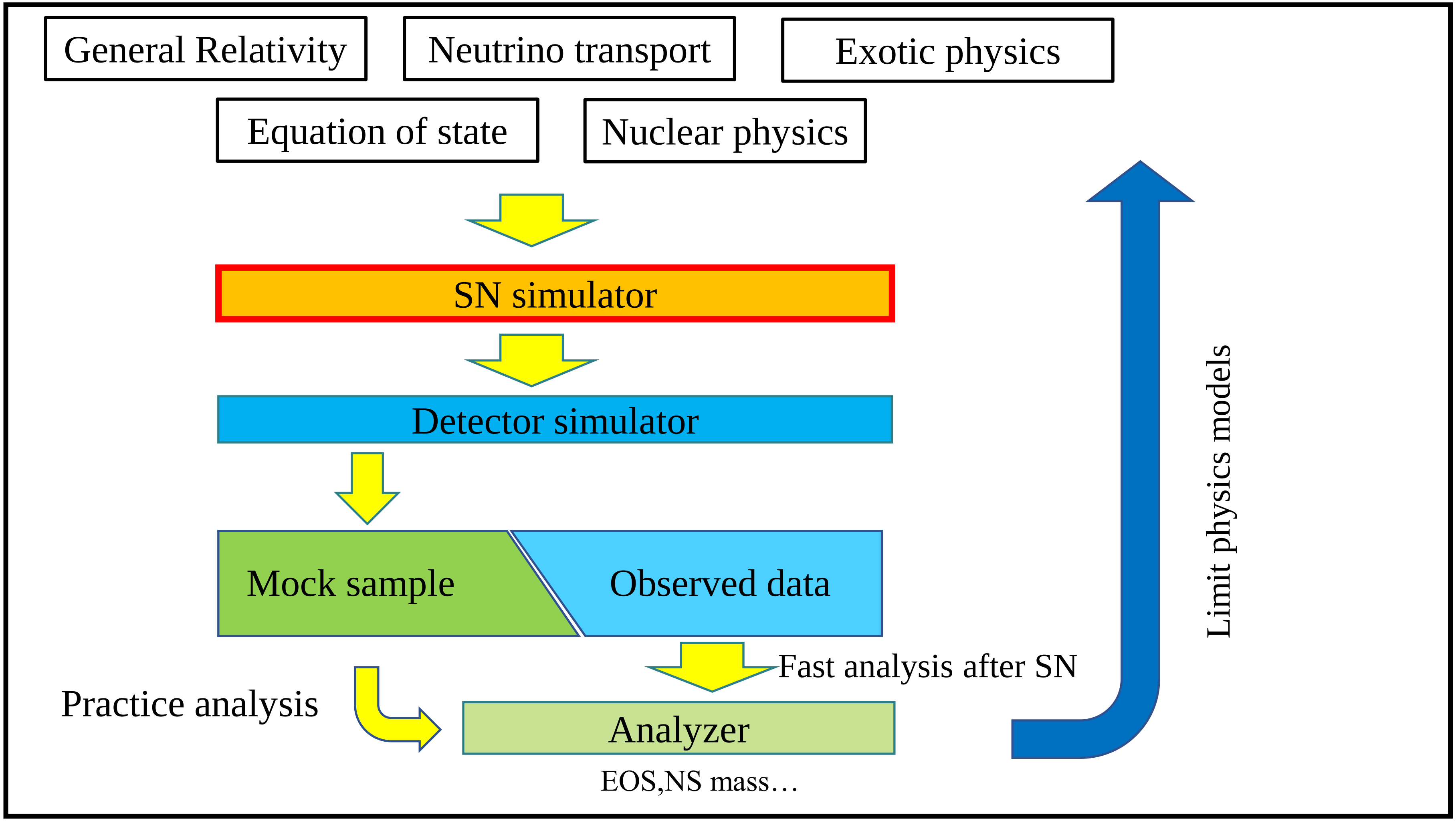
Example of simulation
Suwa et al. (2016)



We can compare theory and observation only for this time.

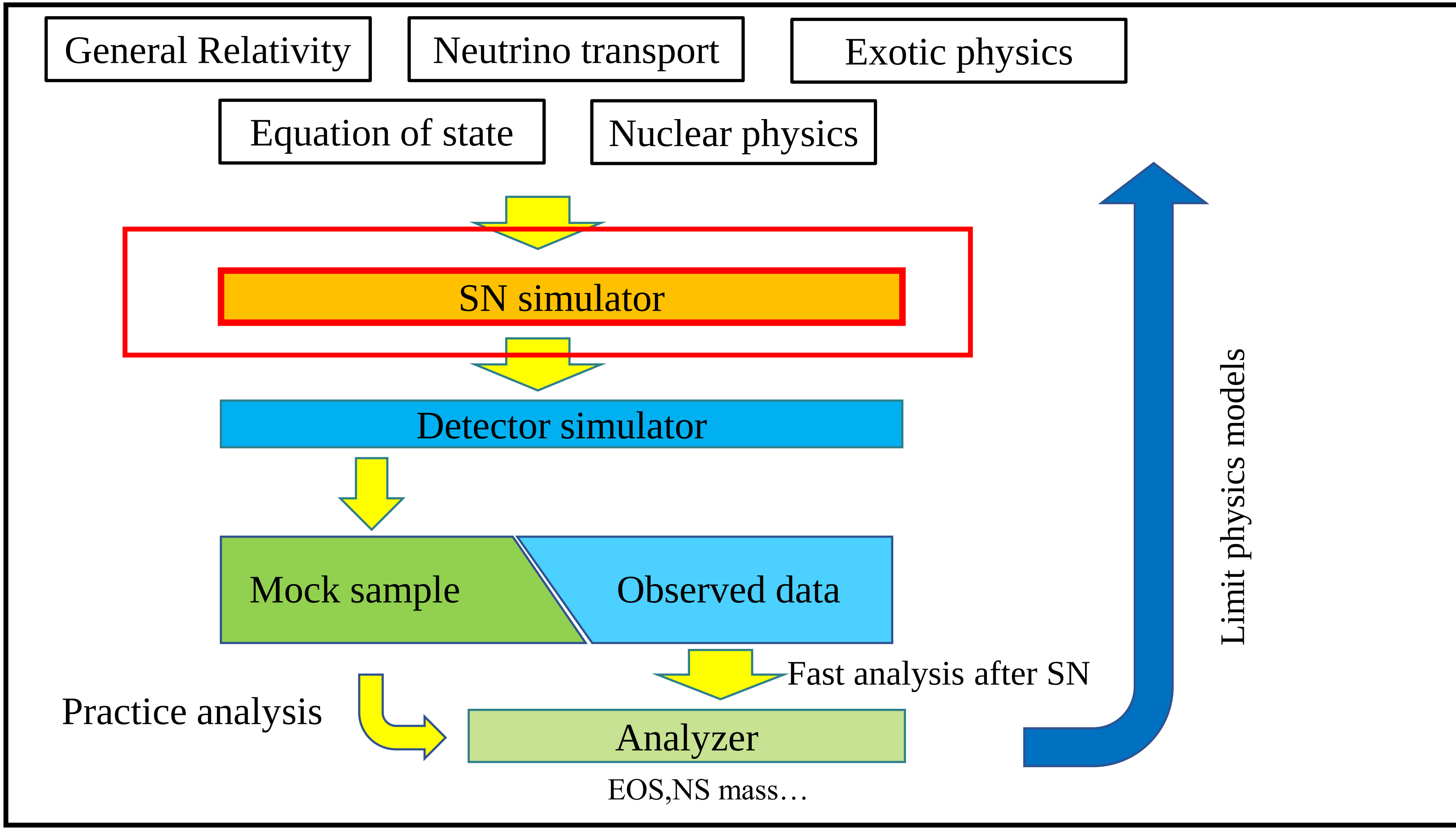
We will a long time simulation and an analysis framework.

Integrated framework



- Simulator which calculates from explosion to observation on earth.
- If a supernova is detected, the framework quickly analyze.

SN simulator



- Supernova simulation

Method of long time simulation

- Simulate supernovae in one-dimension
- Code
  - GR1Dv2 (public code: http://stellarcollapse.org)
  - O'Connor, ApJS 219 24 2015
  - Modified for long time simulation
    - ➢Resolved reference out of physics tables
    - ➢Optimized resolution of time and space
    - ➢Made a new suitable neutrino reaction table
- **Without artificial methods**

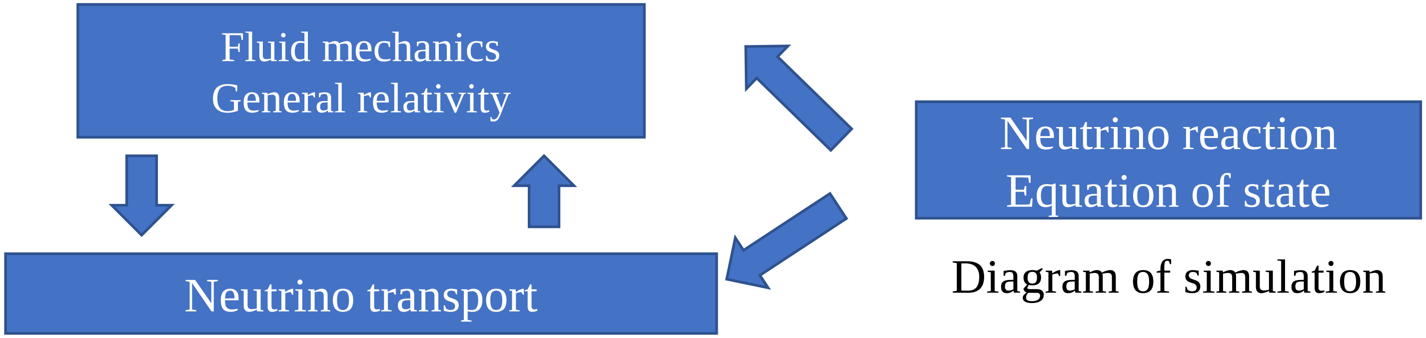
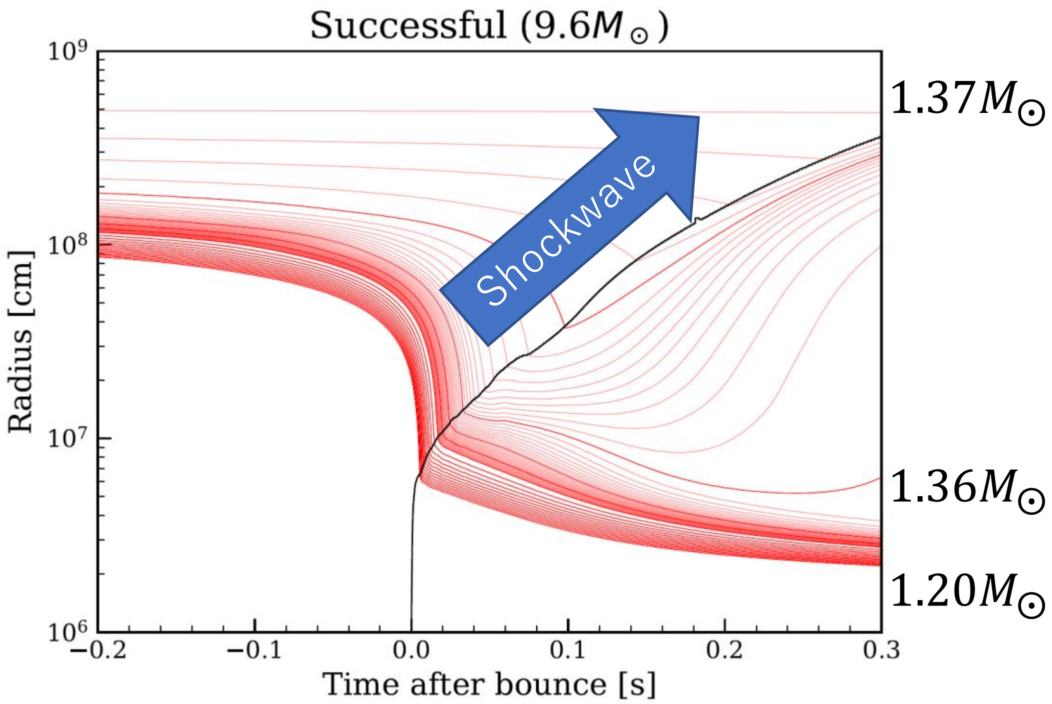
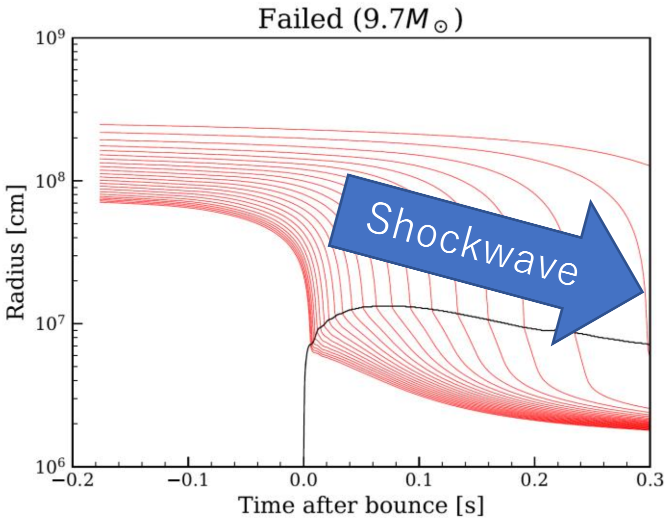


Diagram of simulation

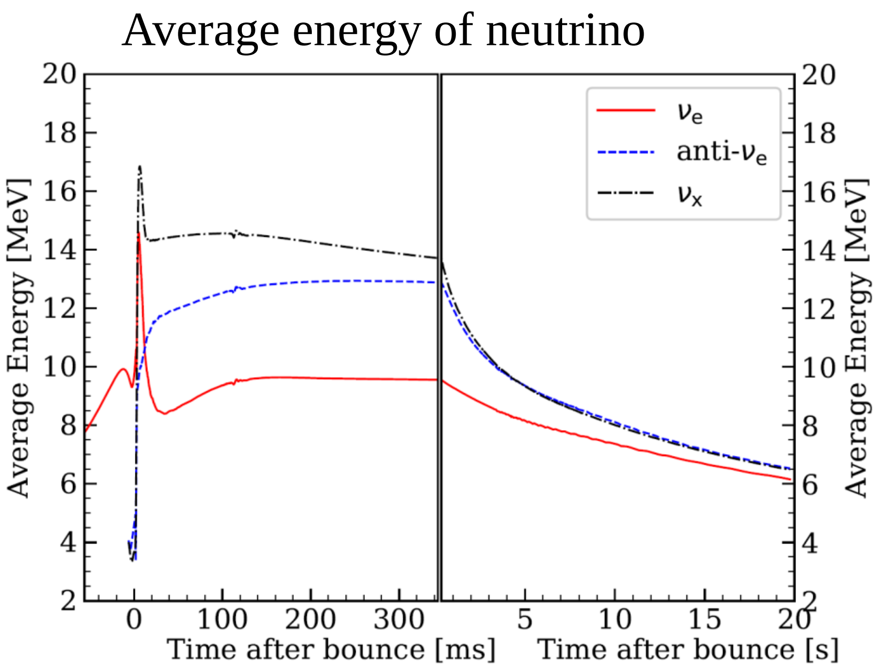
Light progenitor

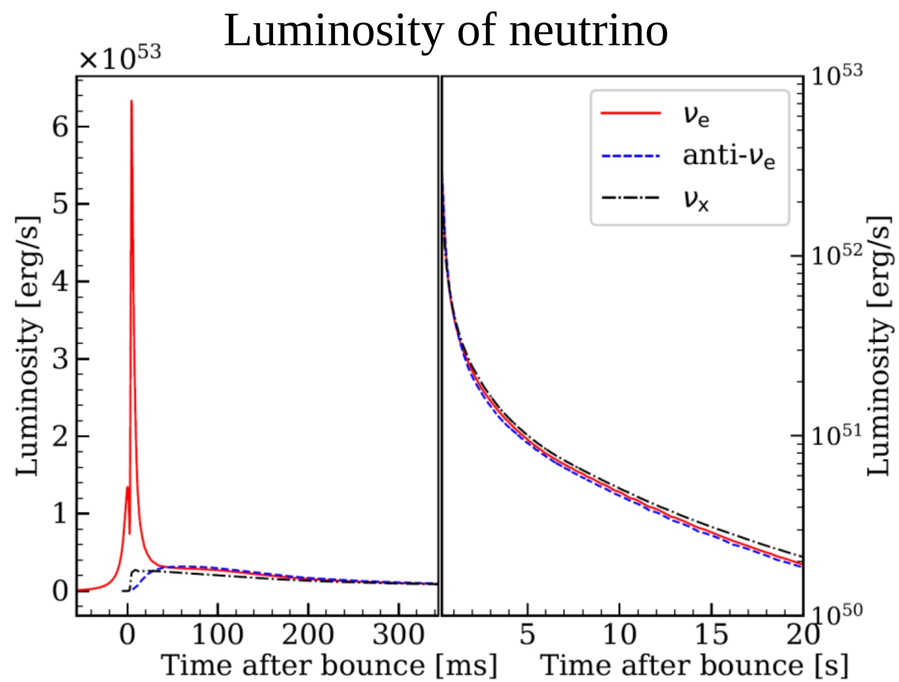




- Red：Radii at which densities are constant
- Black：Radius of a shockwave
- Succeed to explode with the suitable choice of progenitors and **without artificial methods**
  - ➢9.6 solar mss, initial metallicity is 0
  - ➢Called z9.6

Long time simulation

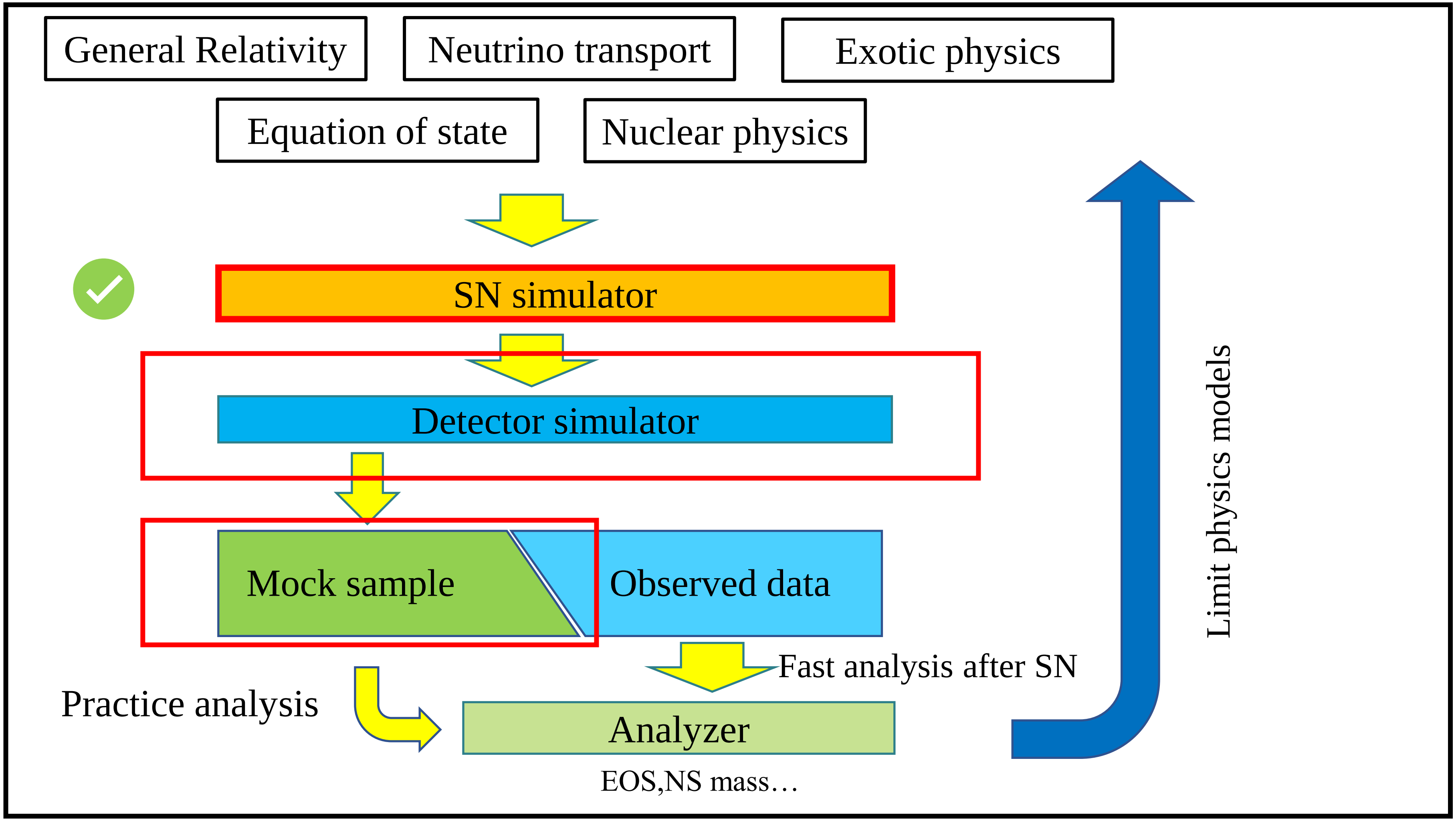




ν_x : μ and τ (anti) neutrinos

- Average energies decrease from above 10 MeV to 6 MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$
- Luminosities drecrease from 10^{53}erg/s
  - ➢These features agree with other simulations
  - ➢PNS cooling is calculated.

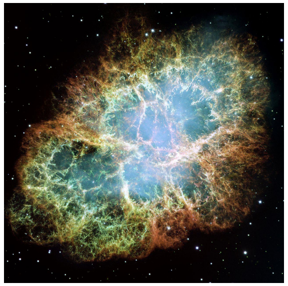
Detector simulator



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

Event simulation

Explosion



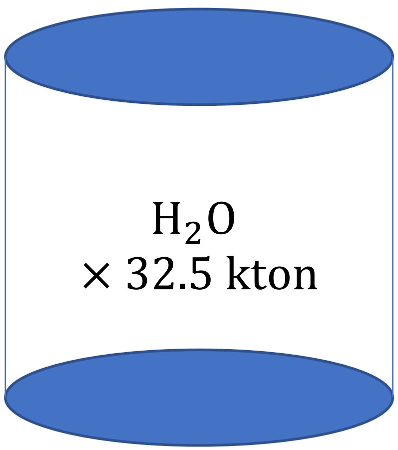
◻ Reaction channel

Inverse Beta Decay(IBD)

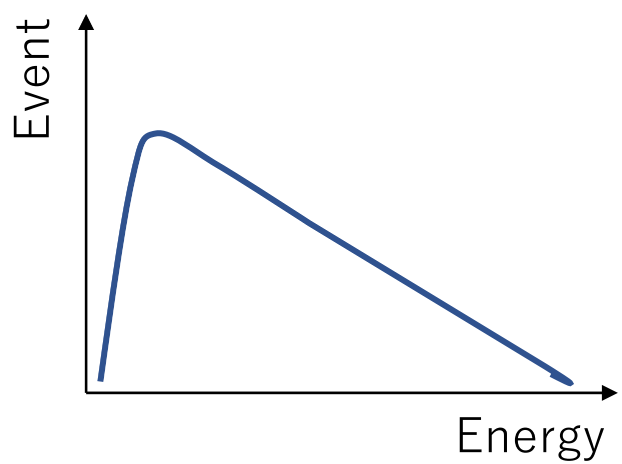
- $\bar{\nu}_e + p \rightarrow e^+ + n$
- Amount: more than 90%
- Direction sensitivity：No

Electron scattering(ES)

- $\nu + e^- \rightarrow \nu + e^-$
- Amount: 1/20 of IBD
- Direction sensitivity：Yes

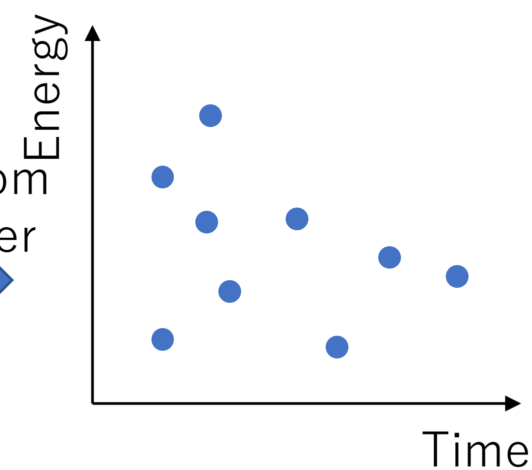


Assumed Super-Kamioknde

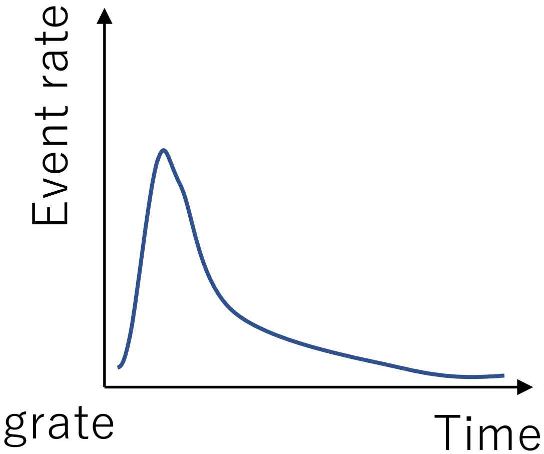


Event distribution per a time

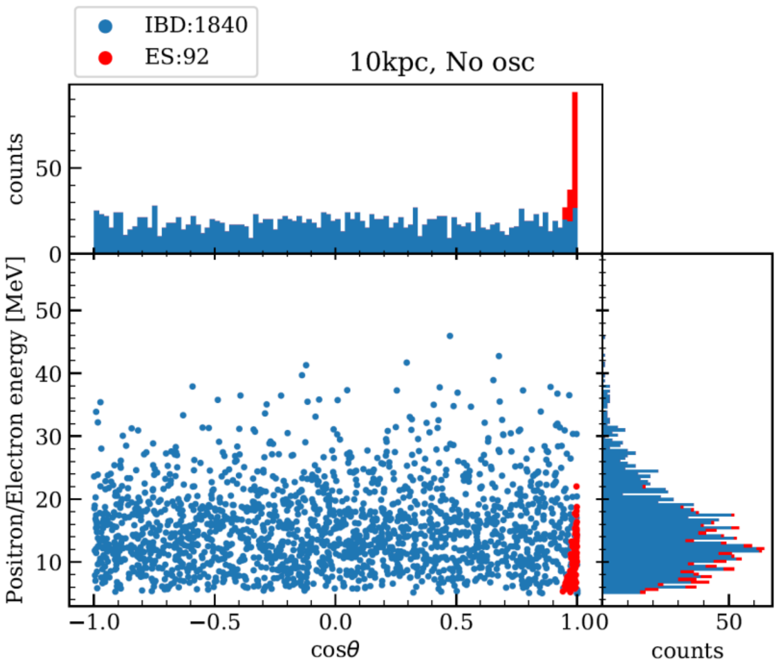
Random number

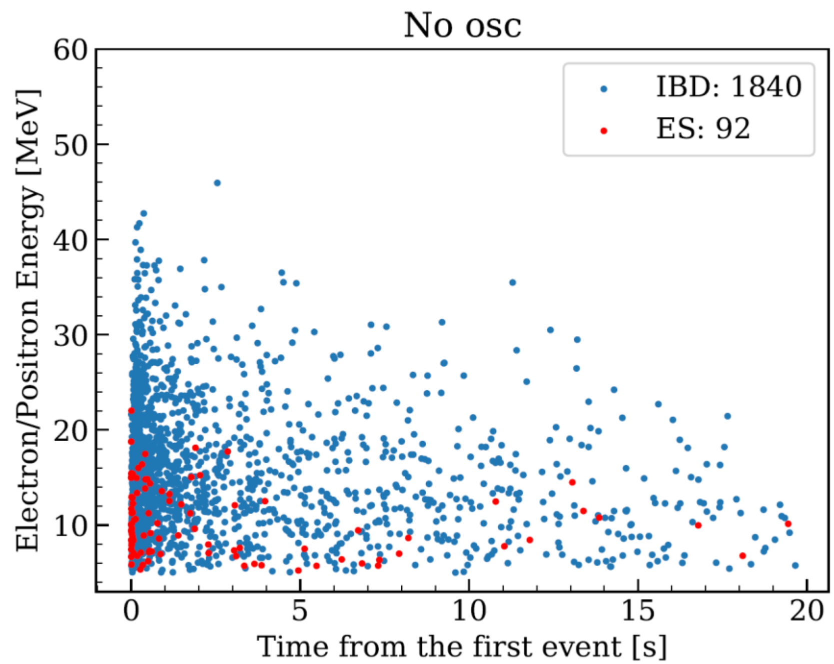


Integrate



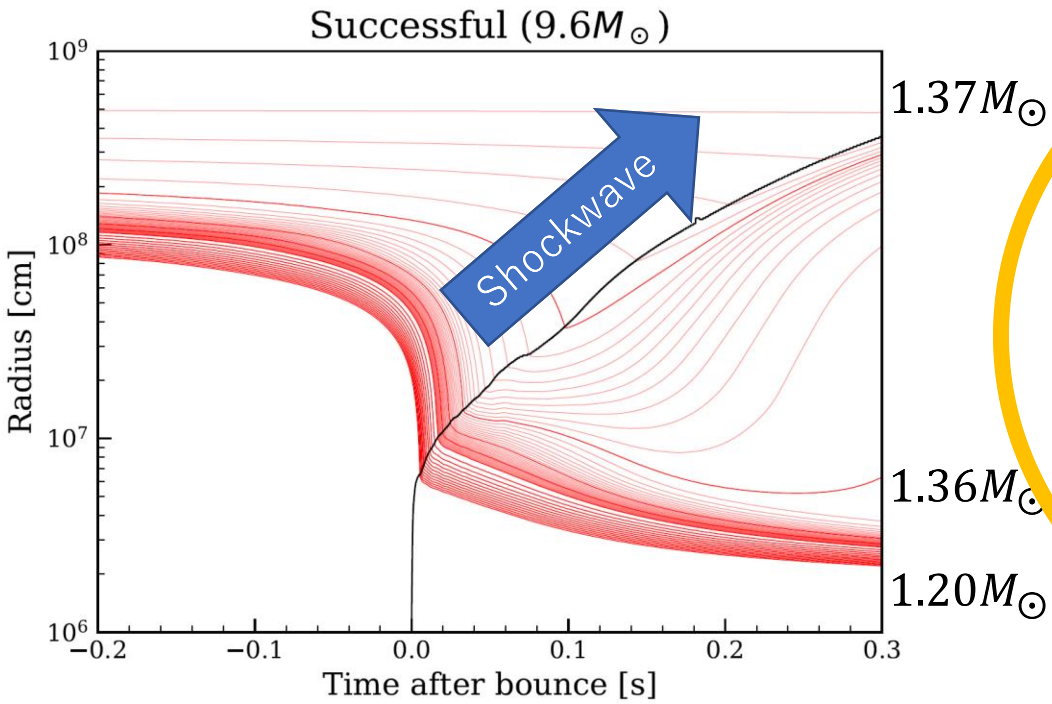
Scatter plot (Mock sample)

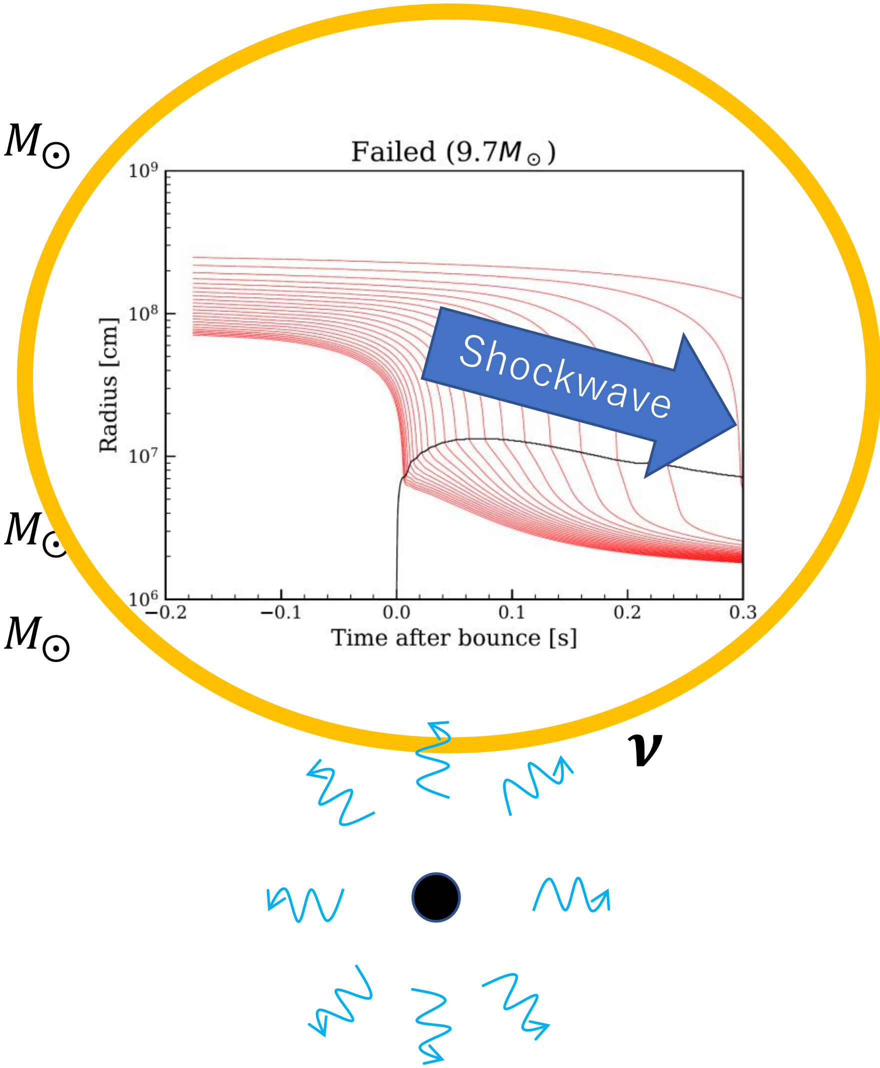




- Each event is simulated with random number (10kpc)
- Left：cosine distribution between neutrinos and charged leptons.
- Right：Time evolution of energy
  - ➢Almost all IBD, ES scatters forward.
- **Mock samples are applied for various studies**
  - ➢Development and practice of analysis methods
  - ➢Evaluation of SK

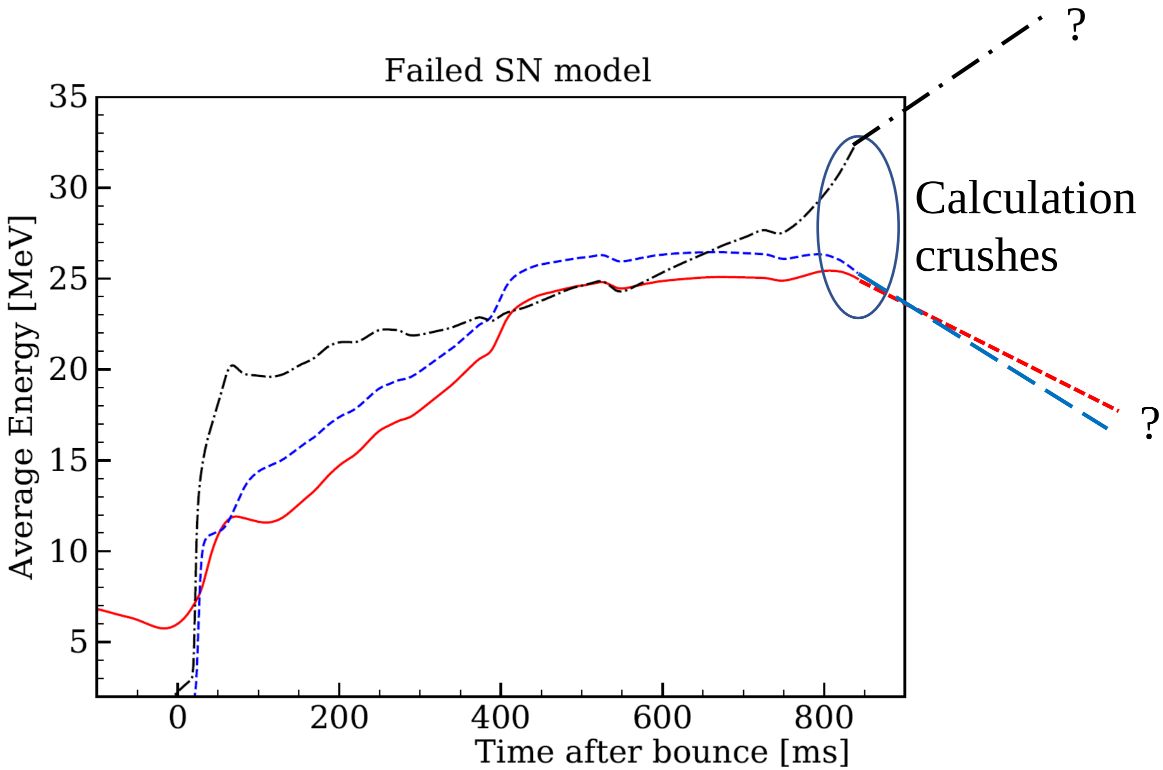
Black hole formation





- 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

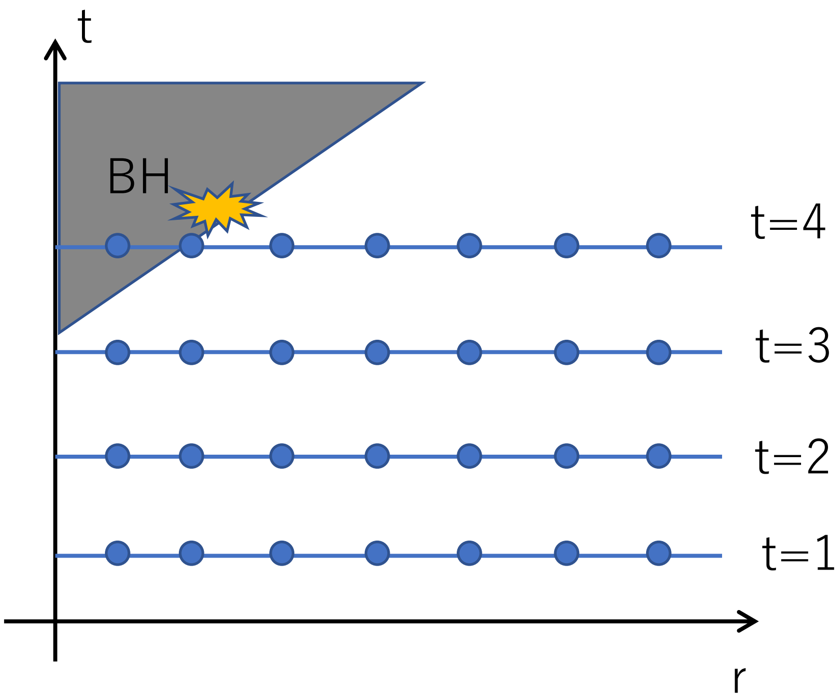
$$e^{\psi}du = e^{\phi}dt - Xdr$$

- Hernandez-Misner metric

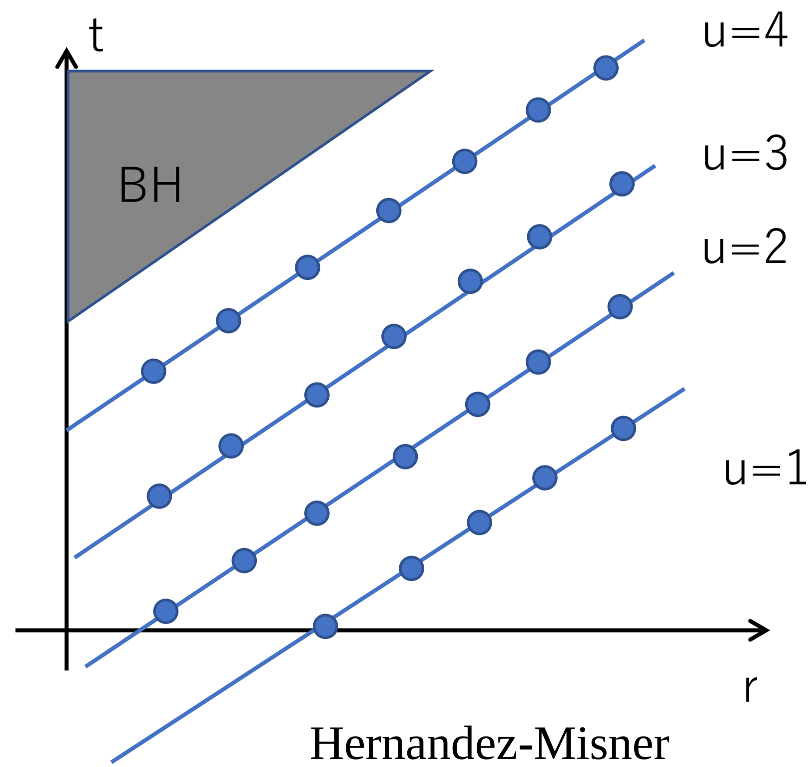
$$ds^2 = -e^{2\psi}du^2 - 2e^{\psi}Xdrdu + d\Omega^2$$

- 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.

Fluid equations in the Hernandez–Misner metric

Baryon

$$\partial_u(X\rho W(1-v)) + \frac{1}{r^2}\partial_r\left(\frac{e^\psi r^2}{X}\rho W v X\right) = 0$$

Lepton

$$\partial_u(Y_e X\rho W(1-v)) + \frac{1}{r^2}\partial_r\left(\frac{e^\psi r^2}{X}Y_e\rho W v X\right) = e^\psi X R^0_{Y_e}$$

Momentum

$$\partial_u[\rho h W^2 v(1-v) - P] + \frac{1}{r^2}\partial_r\left[\frac{e^\psi r^2}{X}(\rho h W^2 v^2 + P)\right] =$$

$$e^\psi[8\pi P^2 r + 8\pi P W^2\rho(v-1) + 8\pi W^4\rho^2 h^2 r(v^2 - v) + \frac{m}{r^2}(2P - \rho h) + 8\pi r P^2 + \frac{2P}{X^2 r}] + e^\psi X q^r$$

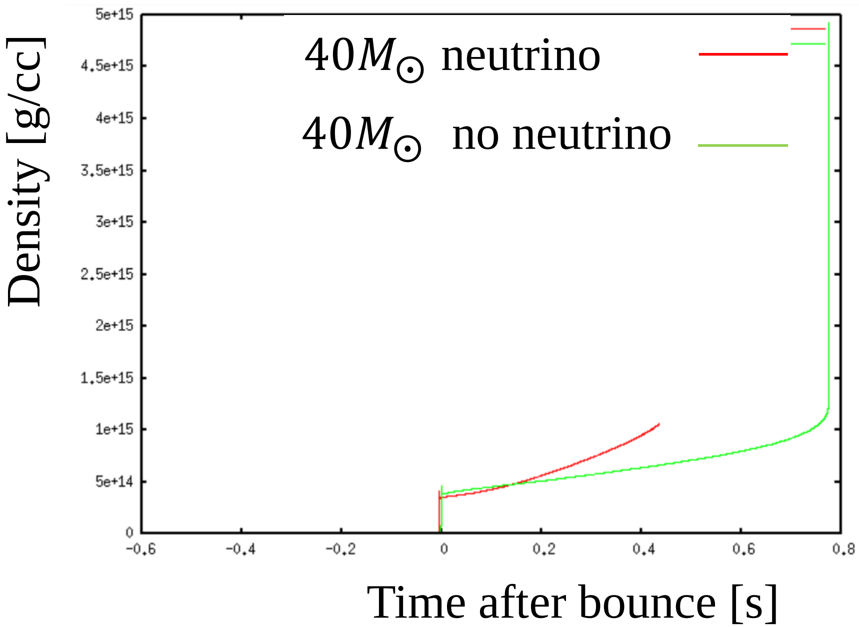
Energy

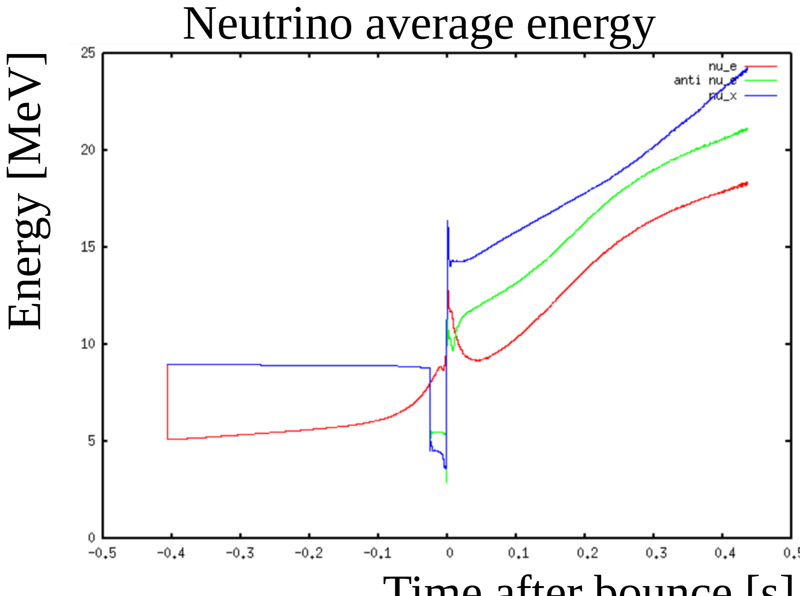
$$\partial_u[\rho h W^2(1-v)^2] + \frac{1}{r^2}\partial_r\left[\frac{e^\psi r^2}{X}(\rho h W^2 v(1-v) - P)\right] =$$

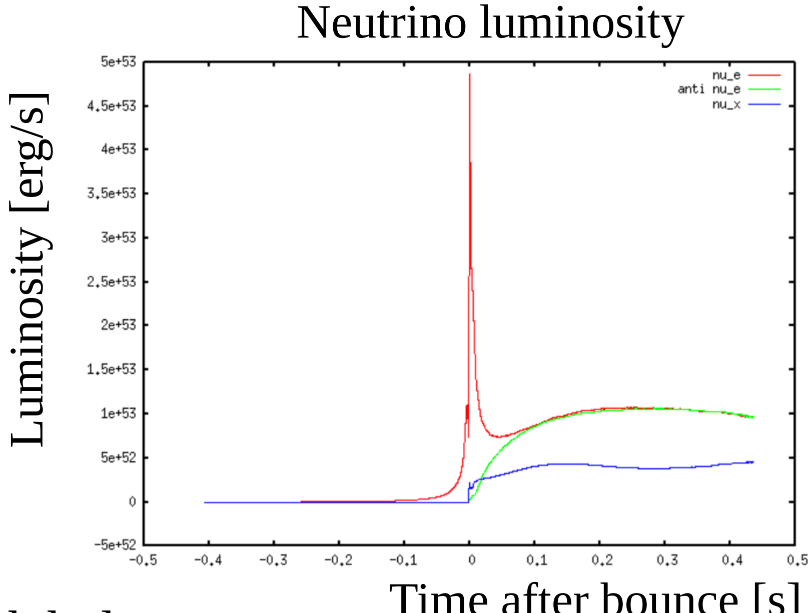
$$q^u e^{2\psi} - 8\pi P^2 r X e^\psi - 8\pi P W^2\rho h r v X e^\psi + 8\pi P W^2 \rho h r X e^\psi - \frac{2Pe^\psi}{rX} - \frac{2PXme^\psi}{r^2}$$

$$-8\pi W^4\rho^2 h^2 r v^3 e^\psi - 16\pi W^4\rho^2 h^2 r v^2 X e^\psi + 8\pi W^4\rho^2 h^2 r v X e^\psi - \frac{W^2\rho h v^2 X m e^\psi}{r^2} + \frac{W^2\rho h X m e^\psi}{r^2}$$

Current status of development







- Caculation stops close to formation of black holes

Summary

Summary

- Supernovae give birth to neutron stars and black holes
- Established the long time simulation
- Estimated neutrino signals at Super-Kamiokande
- Developing the new method for black hole formation

To do

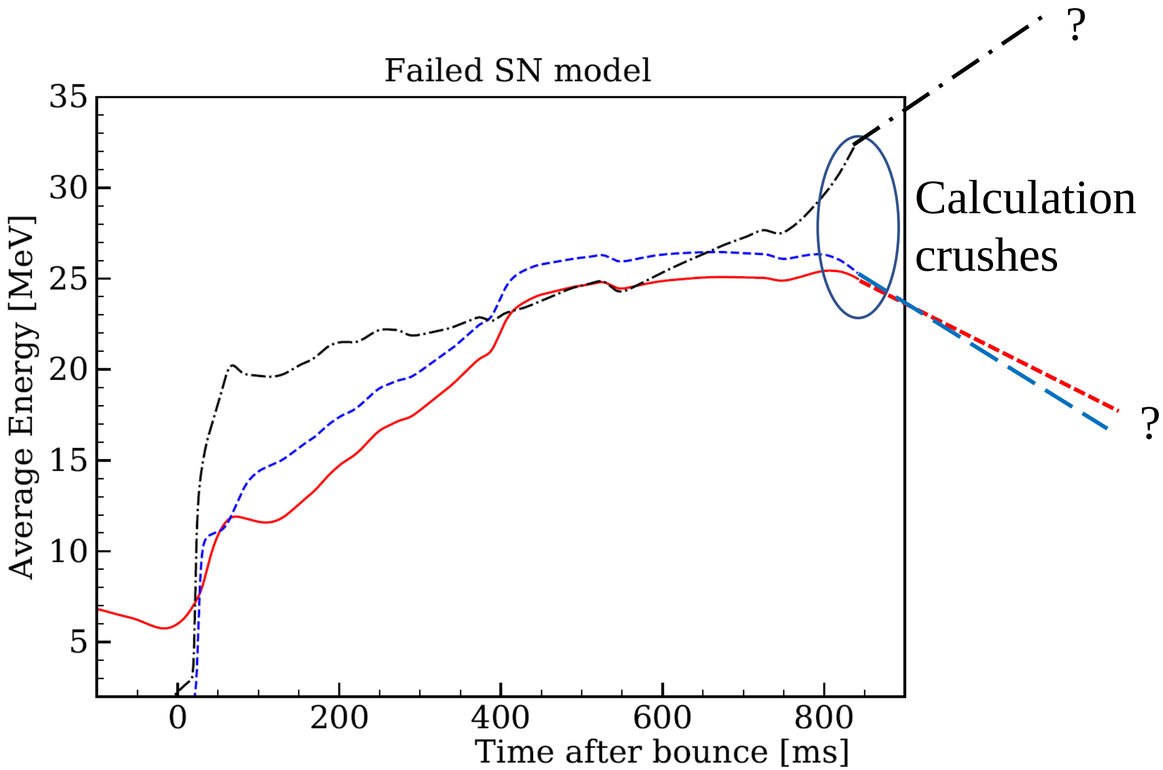
- More progenitors will be simulated
- Develop an analysis method

My model is available

https://zenodo.org/record/5825648

Back up

First idea



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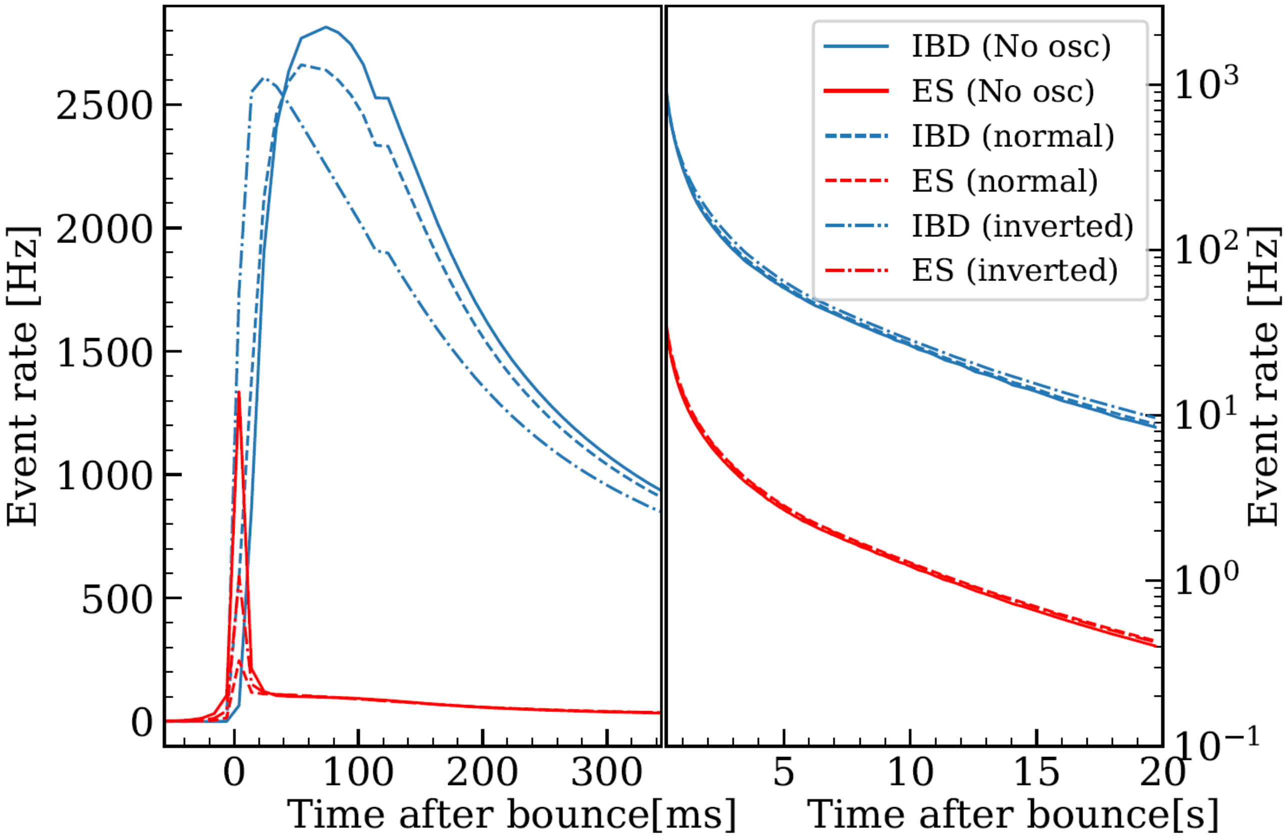
- Because metric diverges at an event horizon.

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

Supernova

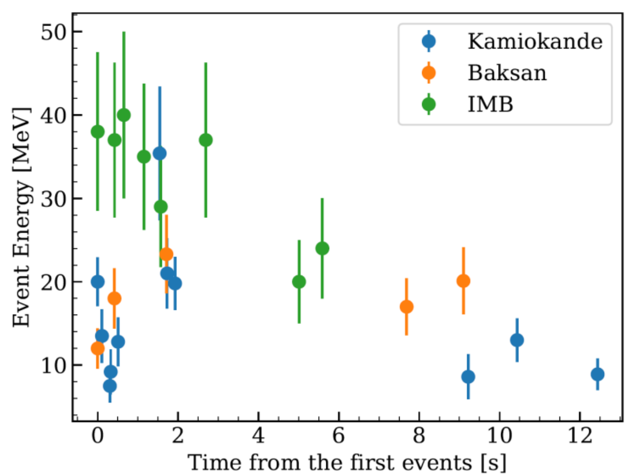
- 8 times heavier stars than the sun happen huge explosion
- Complicated phenomenon in which all the four forces of nature are related
  - ➢Not analytic calculation but heavy computation is needed
- Energy of 10^{53}erg is released as neutrino
  - ➢ Only one observation in 1987 (SN1987A)

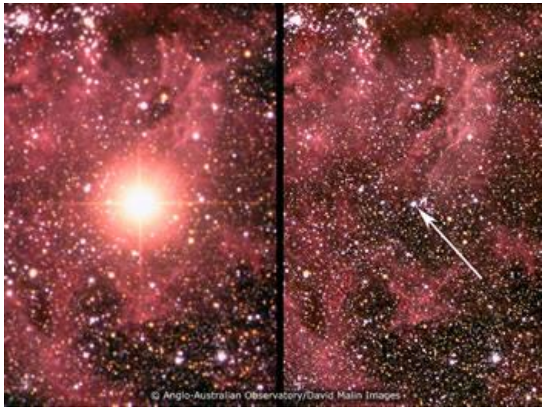
SN1987A information

Distance:51.2 kpc
Number of events: Detector

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

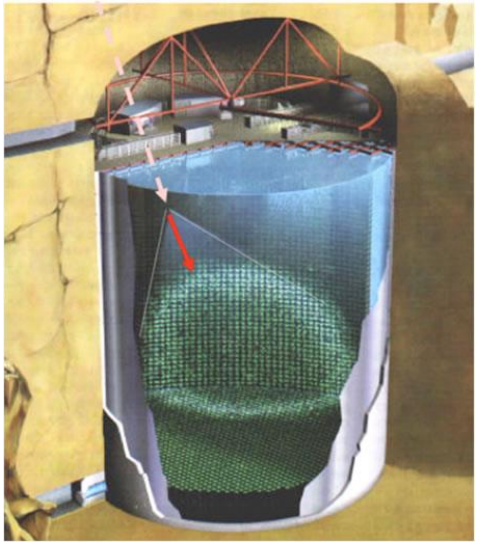
[1]Hirata et al. 1987
[2]Bionta et al. 1987
[3]Alekseev et al. 1987





Super-Kamiokande(SK)

- Water Cherenkov detector in the Gifu prefecture.
  - Height: 41.4 m
  - Diameter: 39.3 m
  - Inner detector: 32.5 kton
  - Number of PMTs:11,129
  - Energy threshold: 5MeV
- Various neutrino studies
  - atmosphere, solar , accelerator…



http://www-sk.icrr.u-tokyo.ac.jp

- Monitoring supernovae for 24 hours
  - If galactic supernovae happen, it is predicted to detect from 2,000 to 7,000 events.

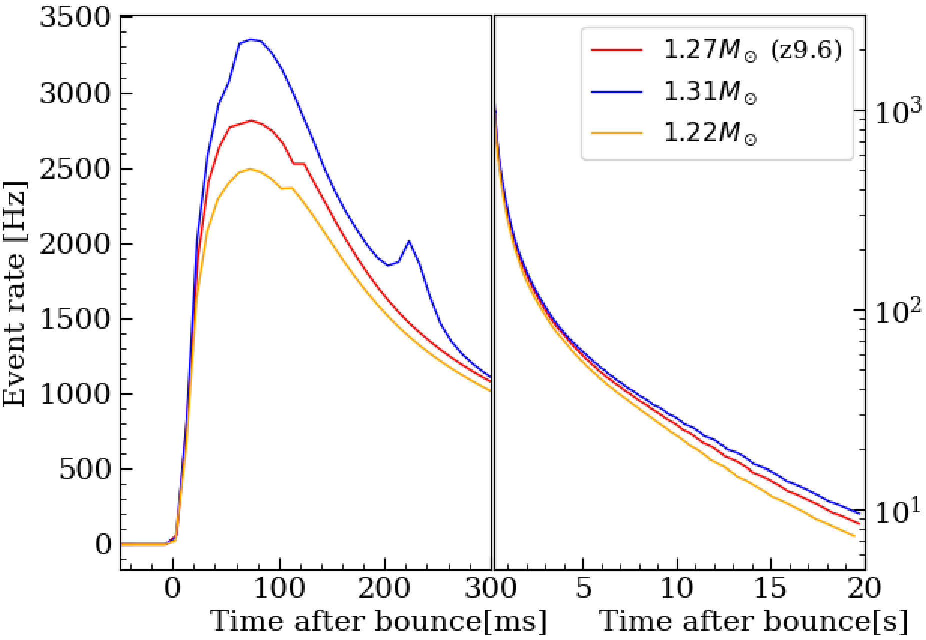
Recent simulations

	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**

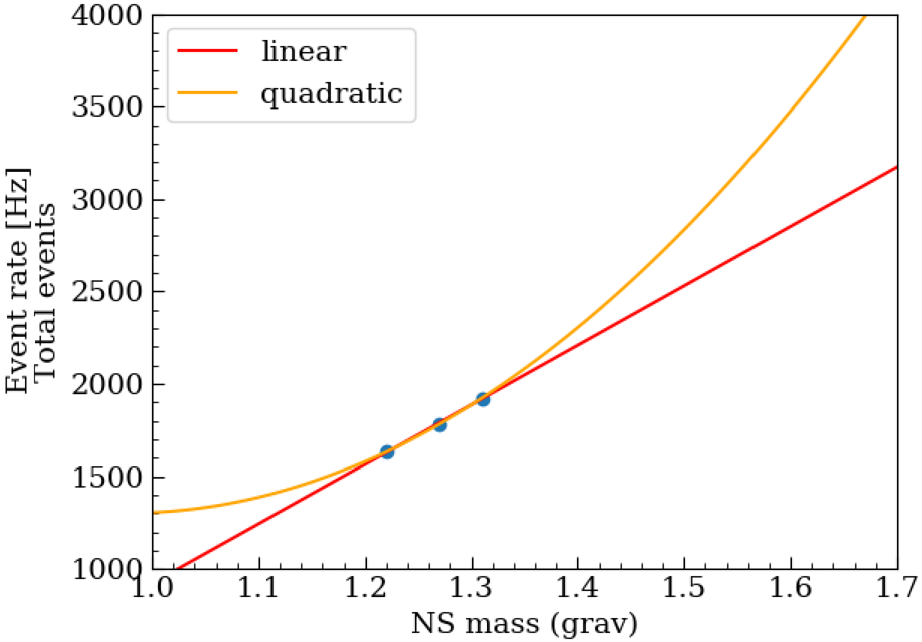
- To explode without artificial methods in one-dimension is difficult
  - ➢ Enhancement of neutrino reaction rates
  - ➢ Removal of material accreting
- Long time simulation in multi-dimension is impossible
- We do long time simulation in one-dimension without artificial methods

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

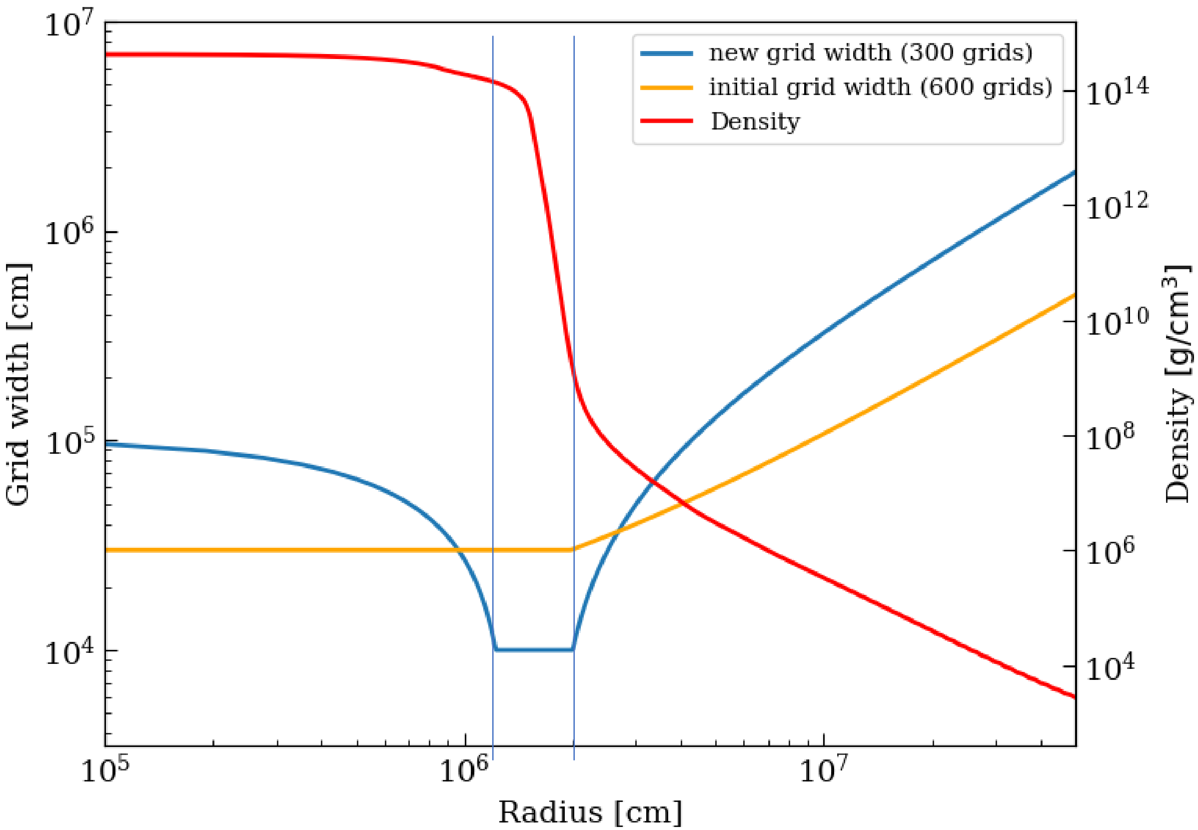
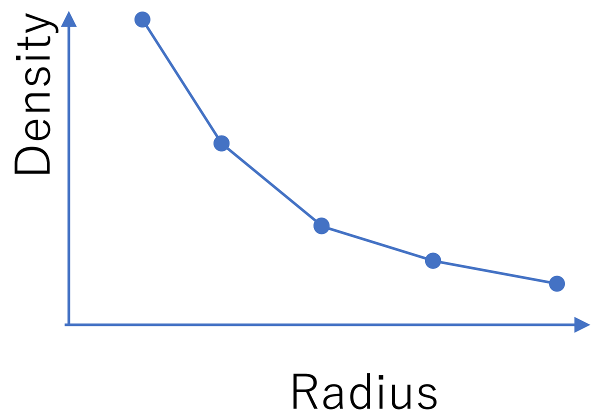
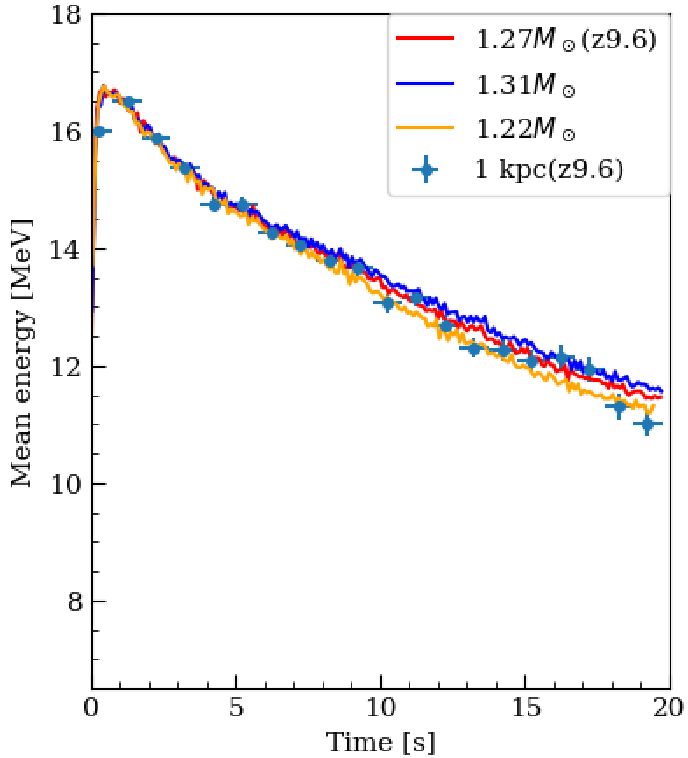


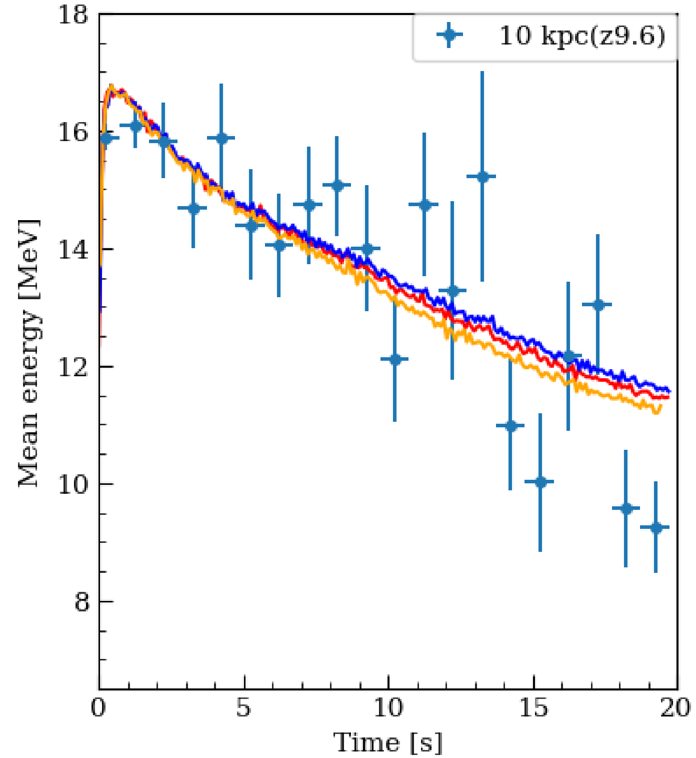
Image of Grid



- 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

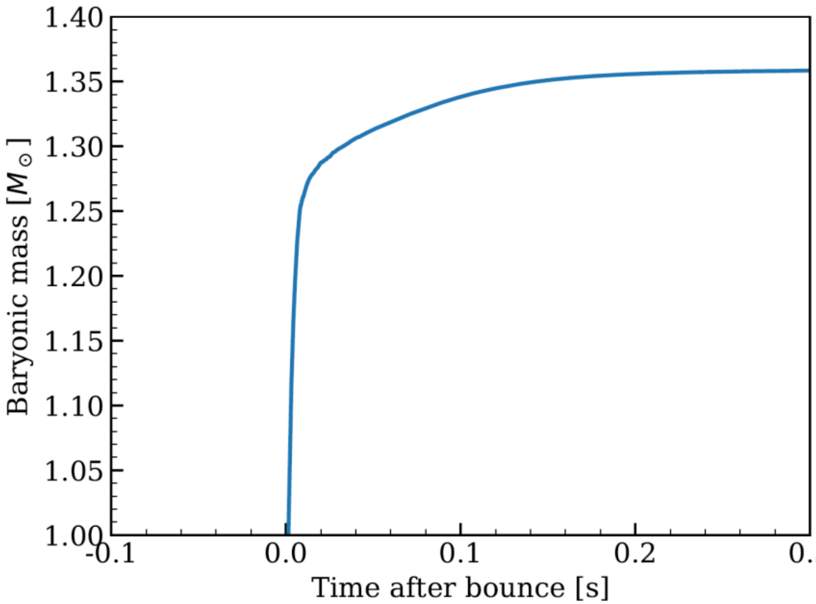
平均エネルギーの発展

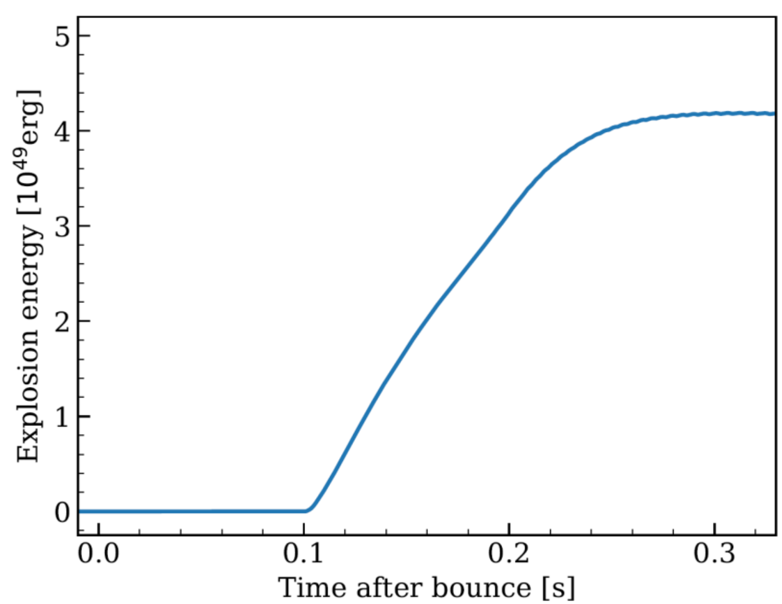




- **実線**:無限個のイベントの平均エネルギー
- **マーカー**:有限個のイベントの平均エネルギー(z9.6)
  - エラーバー: $\sqrt{\dfrac{1/N_{\mathrm{bin}} \times \sum_{i=1}^{N_{\mathrm{bin}}} (E_i - \bar{E})^2}{N_{\mathrm{bin}}}}$
- 個数だけでなく、エネルギー情報も使った比較が可能
- エネルギーの時間発展からのモデルの分別を目指す。

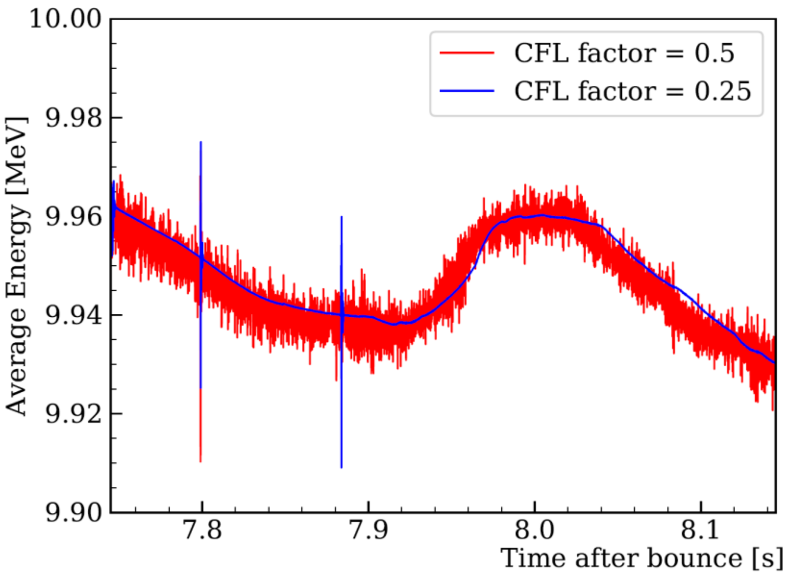
中性子星の質量と爆発エネルギー



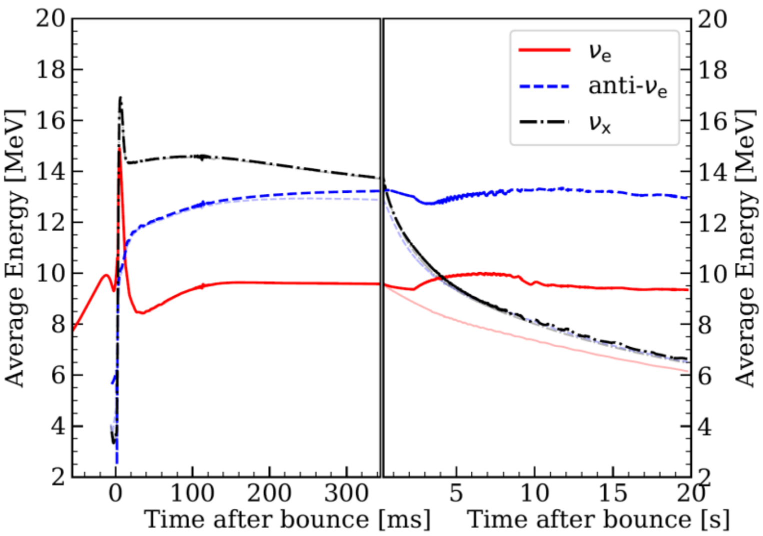


- 中性子星の質量は$1.36M_\odot$
  - 典型的な質量は　$1M_\odot$~$2M_\odot$
- 爆発エネルギーは4×10^{49}erg
  - 典型的は10^{50}erg
  - 少し小さいが、10^{49}erg程度の超新星爆発も見つかっている。

長時間計算用の修正

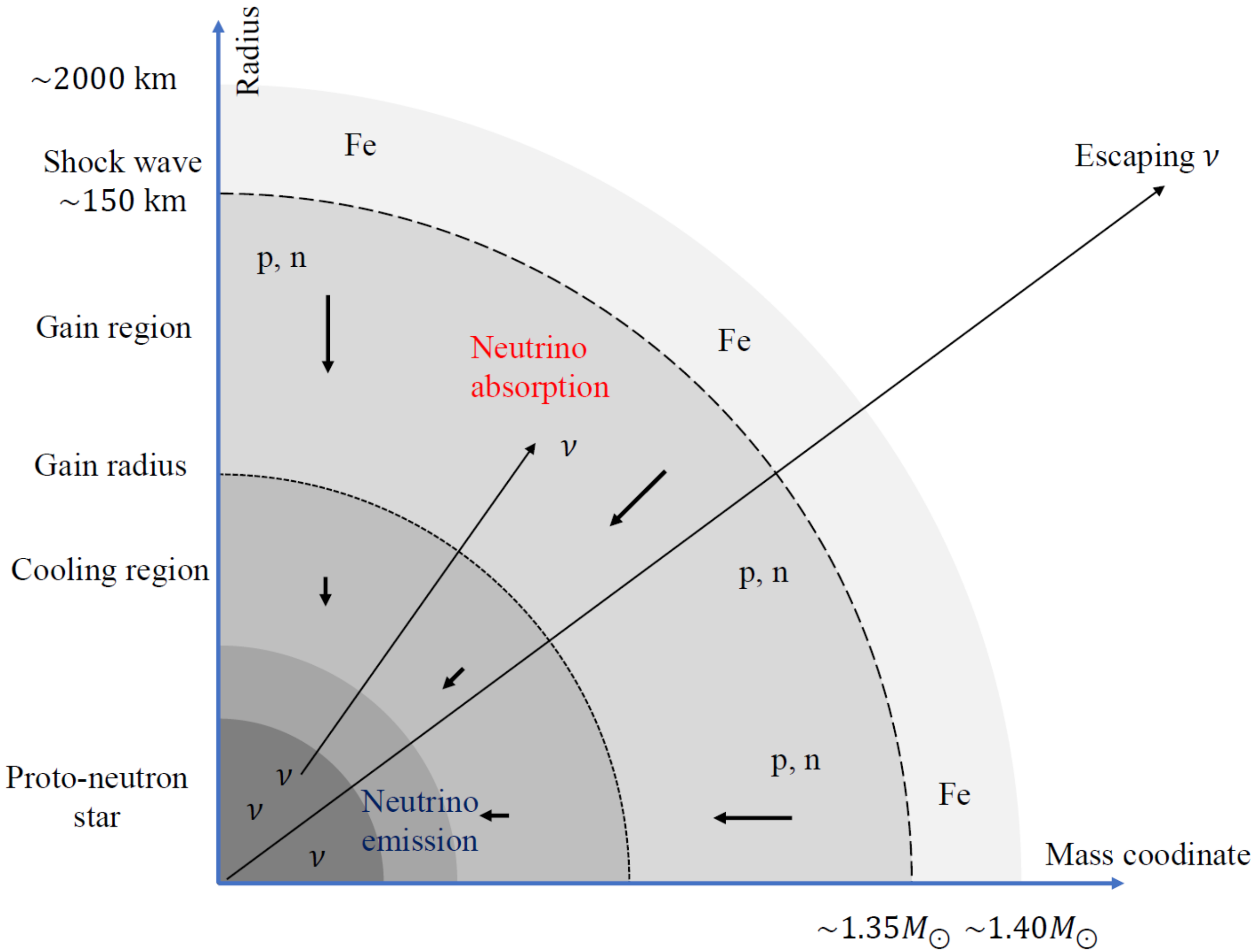


CFL factor = 0.5
CFL factor = 0.25
Average Energy [MeV]
Time after bounce [s]



ν_e
anti-ν_e
ν_x
Average Energy [MeV]
Time after bounce [ms]
Time after bounce [s]

エネルギーの階層性



Radius
~2000 km
Fe
Shock wave
~150 km
p, n
Gain region
Neutrino
absorption
Fe
Escaping ν
Gain radius
ν
Cooling region
p, n
p, n
Proto-neutron
star
ν
ν
Neutrino
emission
ν
Fe
Mass coodinate
~1.35$M_\odot$ ~1.40$M_\odot$

GR1Dのニュートリノ反応

生成・消滅

$$\nu_{\mathrm{e}} + n \leftrightarrow p + e^-,$$
$$\bar{\nu}_{\mathrm{e}} + p \leftrightarrow n + e^+,$$
$$\nu_{\mathrm{e}} + (A, Z) \leftrightarrow (A, Z+1) + e^-,$$

弾性散乱

$$\nu + \alpha \rightarrow \nu + \alpha,$$
$$\nu_{\mathrm{i}} + p \rightarrow \nu_{\mathrm{i}} + p,$$
$$\nu_{\mathrm{i}} + n \rightarrow \nu_{\mathrm{i}} + n,$$
$$\nu + (A, Z) \rightarrow \nu + (A, Z),$$

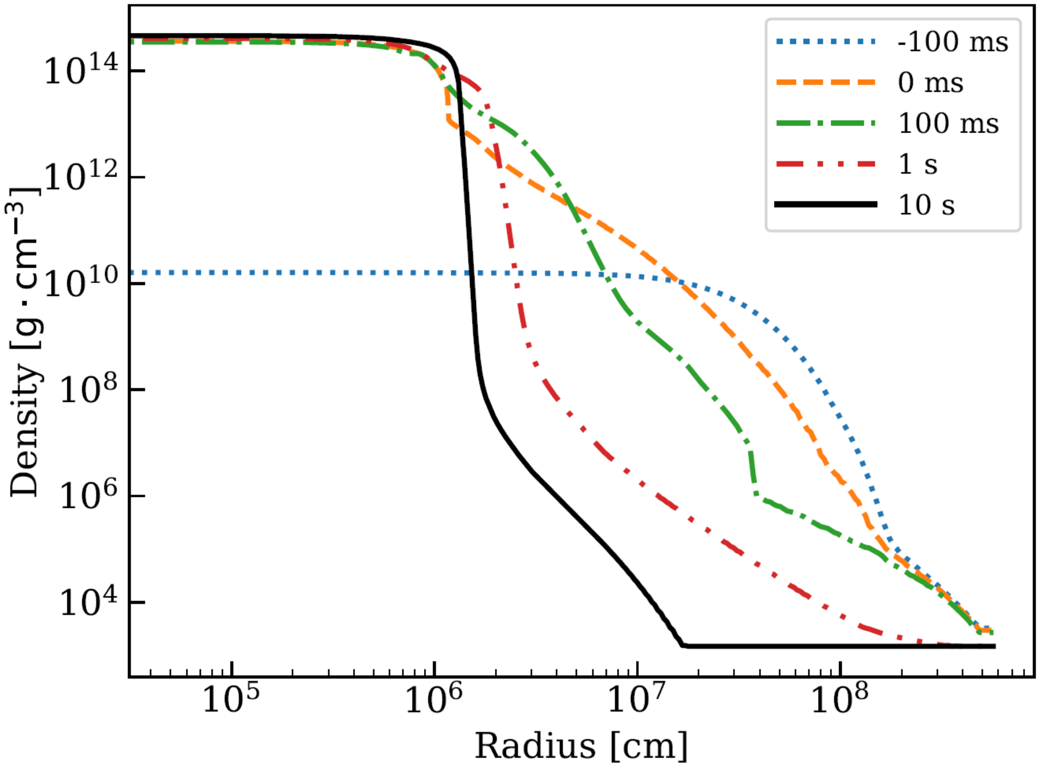
非弾性散乱

$$\nu_{\mathrm{i}} + e^- \rightarrow \nu_{\mathrm{i}}' + e^{-\prime},$$

熱化過程

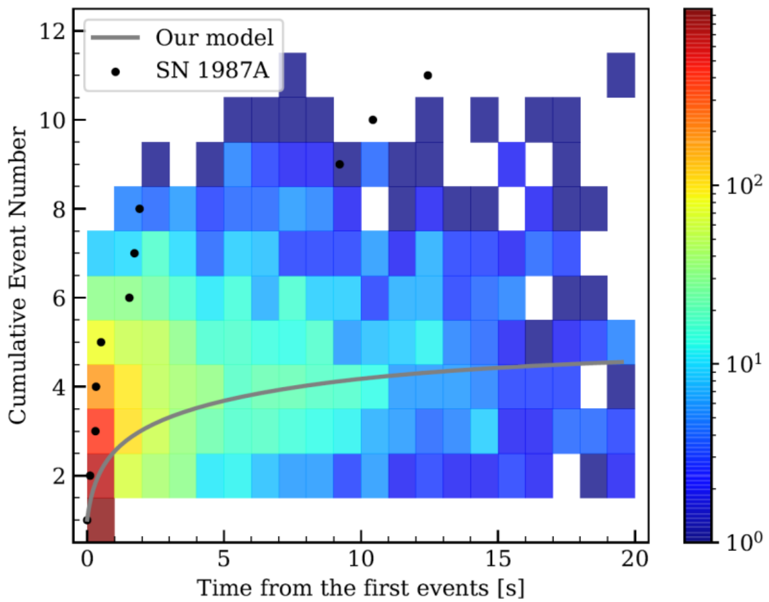
$$e^- + e^+ \rightarrow \nu_{\mathrm{x}} + \bar{\nu}_{\mathrm{x}},$$
$$N + N \rightarrow N + N + \nu_{\mathrm{i}} + \bar{\nu}_{\mathrm{i}},$$

バリオン密度プロファイル

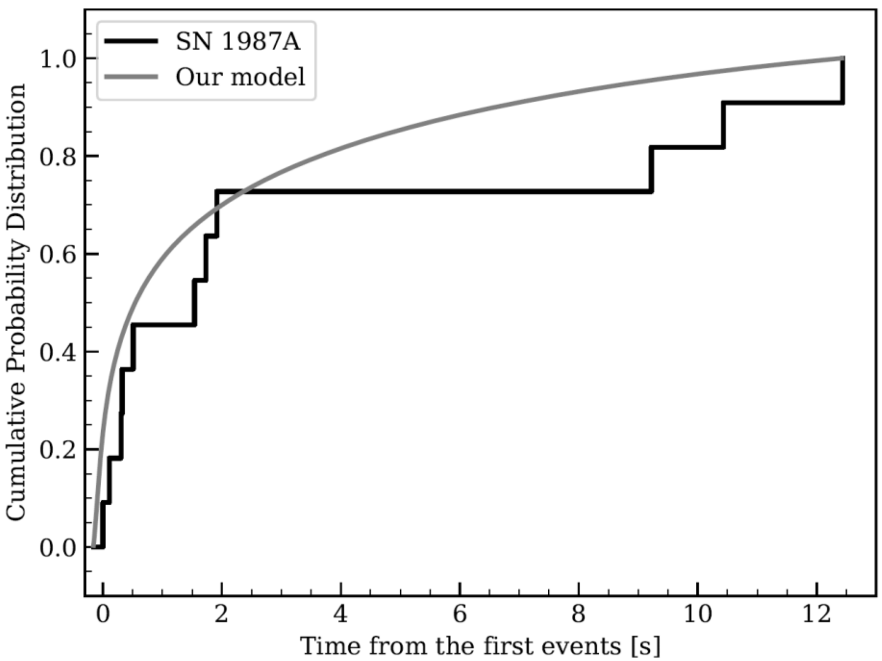


イベント数によらない解析(KSテスト)

累積イベント数

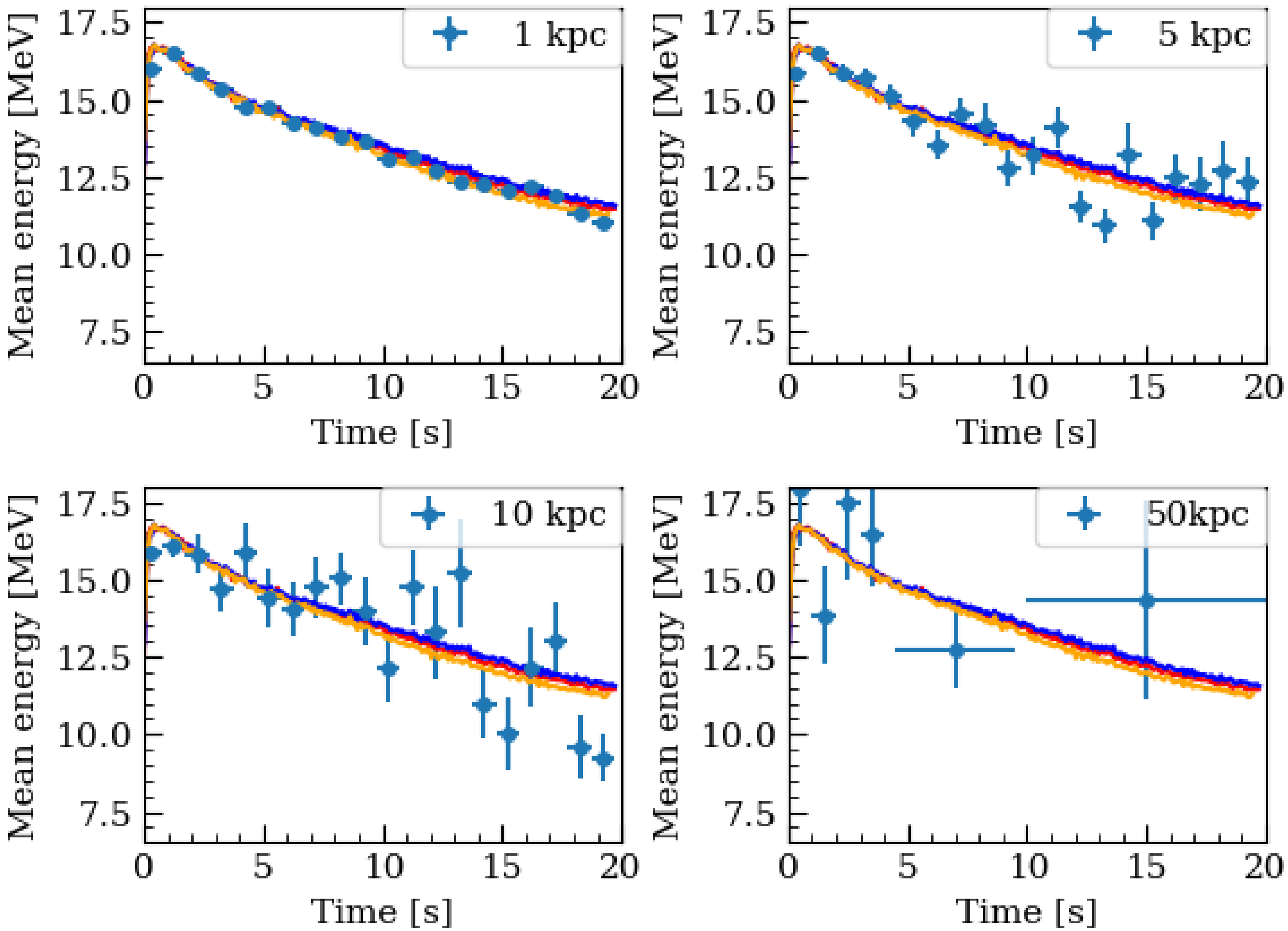


KSテスト

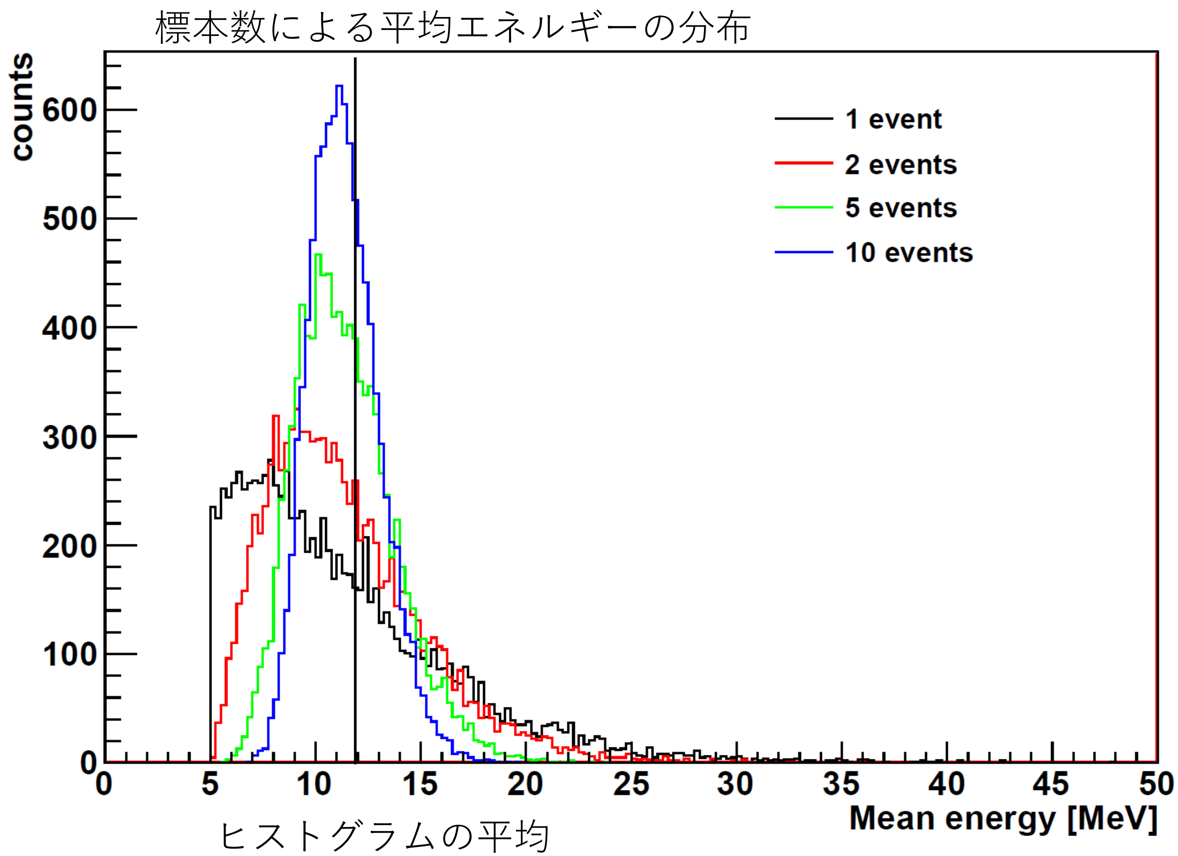


- 規格化したイベント数の発展を比べると距離によらない比較が可能
  - 例としてSN1987Aと比較を行っている。

平均エネルギーの発展


1 kpc
5 kpc
10 kpc
50kpc
Mean energy [MeV]
17.5
15.0
12.5
10.0
7.5
0
5
10
15
20
Time [s]

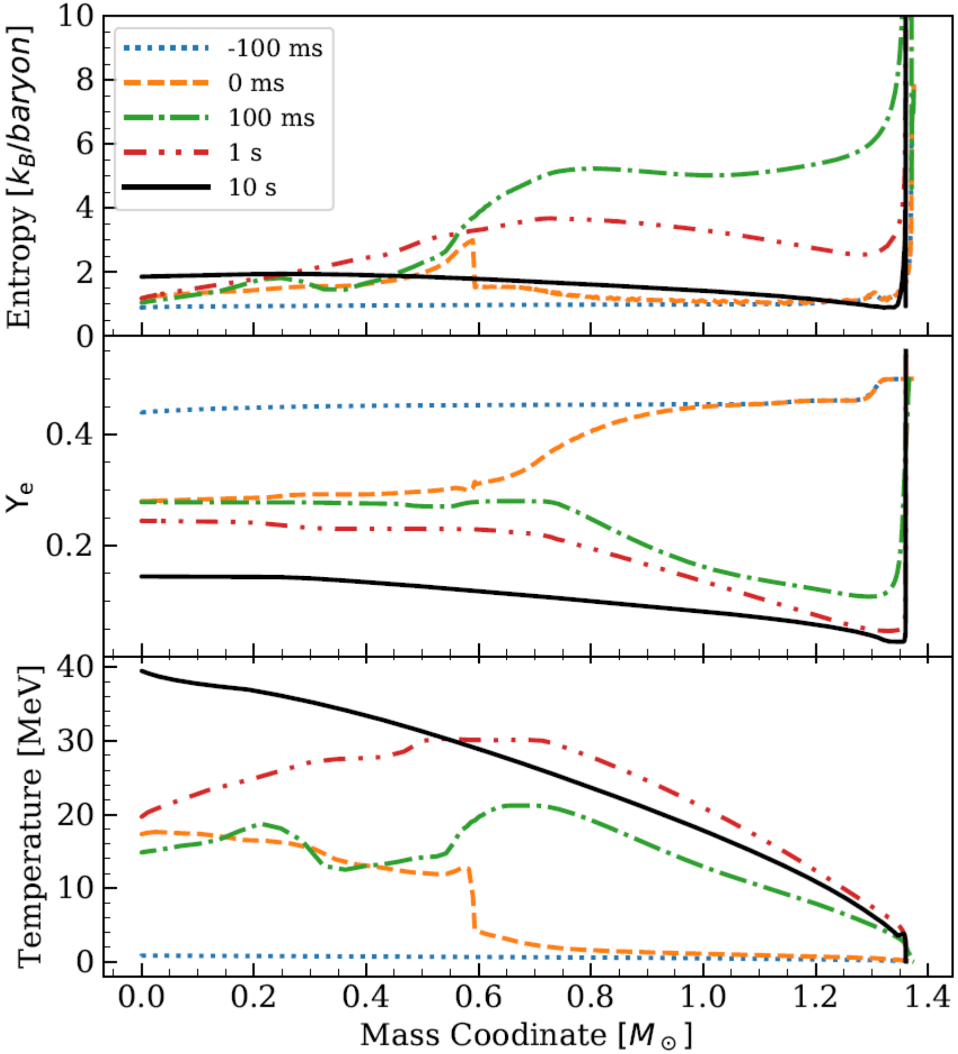
Timeビンに入る個数による平均値の分布



平均よりも下と上の比率

- 1 event　59:41
- 2 events　57:43
- 5 events　54:46
- 10 events 53:47

他の流体量



-100 ms
0 ms
100 ms
1 s
10 s
Entropy [k_B/baryon]
Y_e
Temperature [MeV]
Mass Coodinate [$M_\odot$]
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

ニュートリノ振動

- MSW効果,
- Normal hierarchy

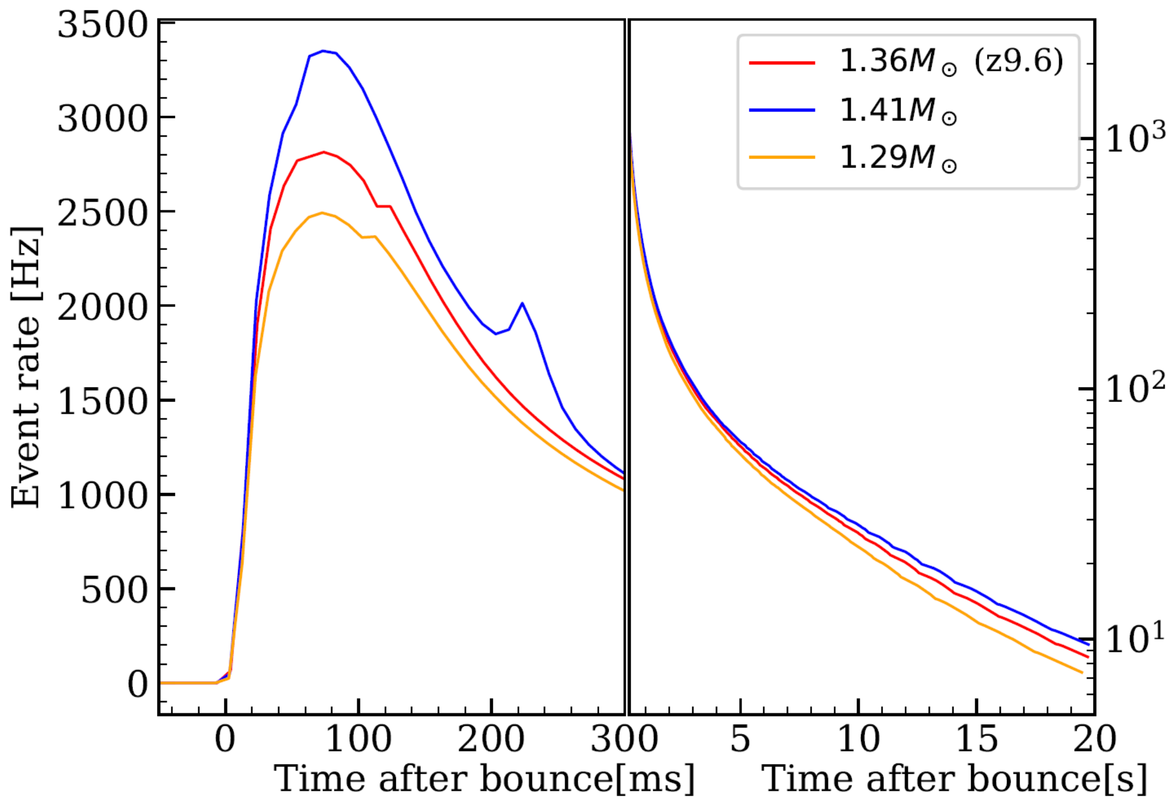
$$
\begin{aligned}
F'_{\nu_e} &= F_{\nu_x}\,, \\
F'_{\bar{\nu}_e} &= pF_{\bar{\nu}_e} + (1-p)F_{\nu_x}\,, \\
4F'_{\nu_x} &= F_{\nu_e} + (1-p)F_{\bar{\nu}_e} + (2+p)F_{\nu_x}\,,
\end{aligned}
$$

- Inverted hierarchy

$$
\begin{aligned}
F'_{\nu_e} &= (1-p)F_{\nu_e} + pF_{\nu_x}\,, \\
F'_{\bar{\nu}_e} &= F_{\nu_x}\,, \\
4F'_{\nu_x} &= pF_{\nu_e} + F_{\bar{\nu}_e} + (3-p)F_{\nu_x}\,,
\end{aligned}
$$

- $p = 0.69$

中性子星質量によるイベントレートの違い



- 中性子星の質量が多くなるほど、イベントレートが高くなる傾向にある。