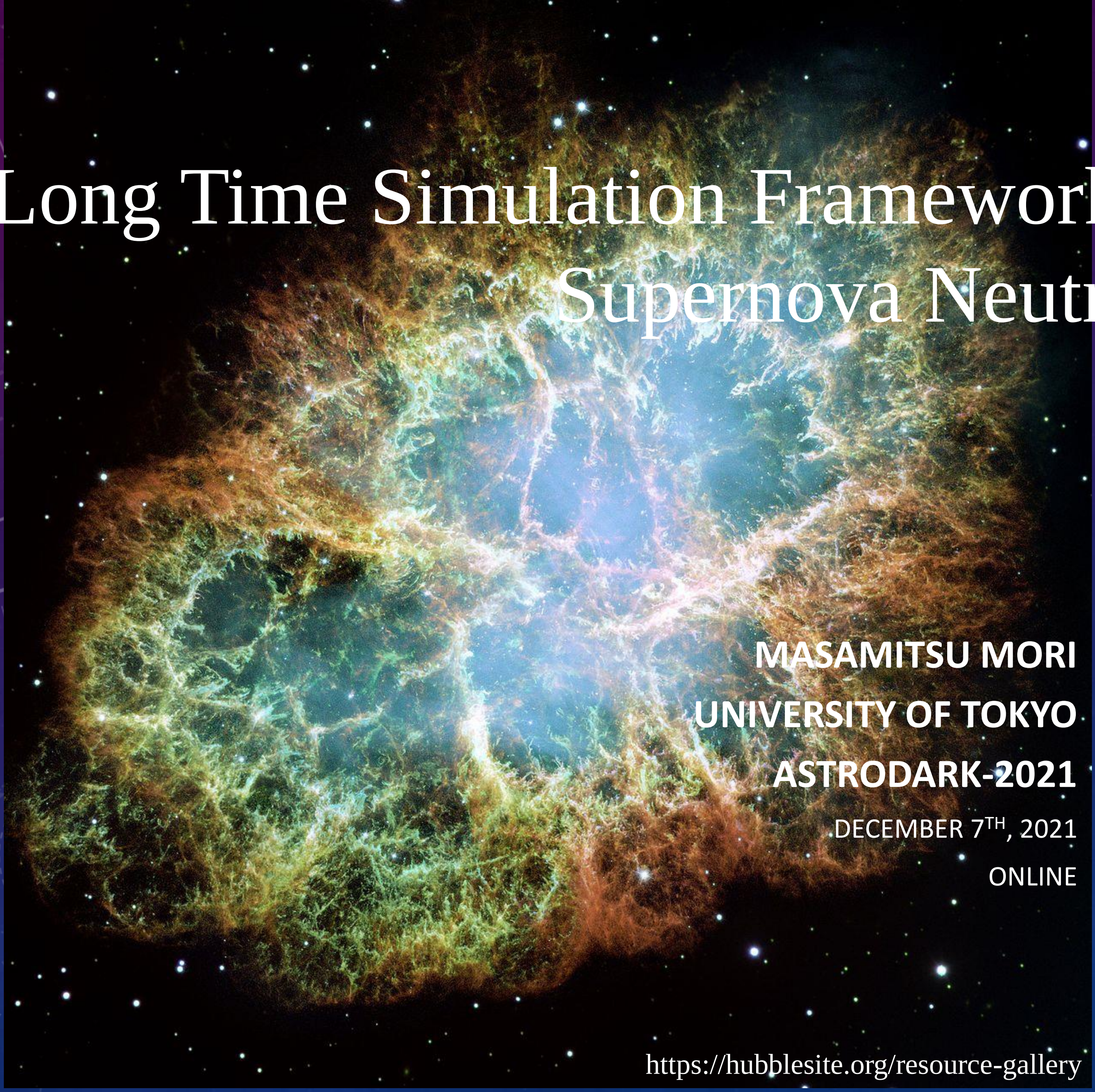
Long Time Simulation Framework of Supernova Neutrino



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ONLINE

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Overview

- Supernovae give birth to neutron stars and black holes
- Releases a lot of neutrinos

Today's theme

Long time simulation of supernovae is important

Keywords

- Supernova, neutron star, neutrino, Super-kamiokande

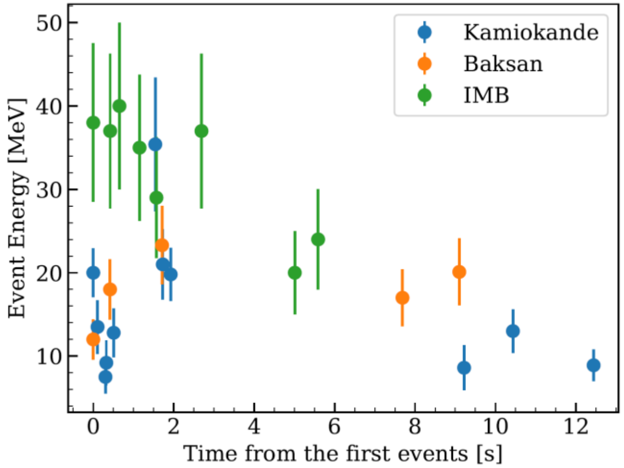
Supernova

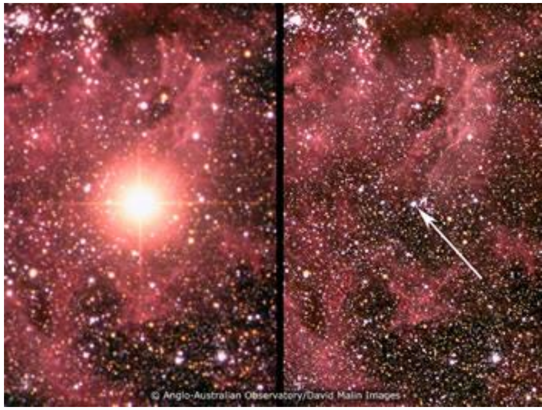
- 8 times heavier stars than the sun happen huge explosion
- Complicated phenomenon in which all the four forces of nature are related
  - ➢Not analytic calculation but heavy computation is needed
- Energy of 10^{53}erg is released as neutrino
  - ➢ Only one observation in 1987 (SN1987A)

SN1987A information

Distance:51.2 kpc
Number of events: Detector

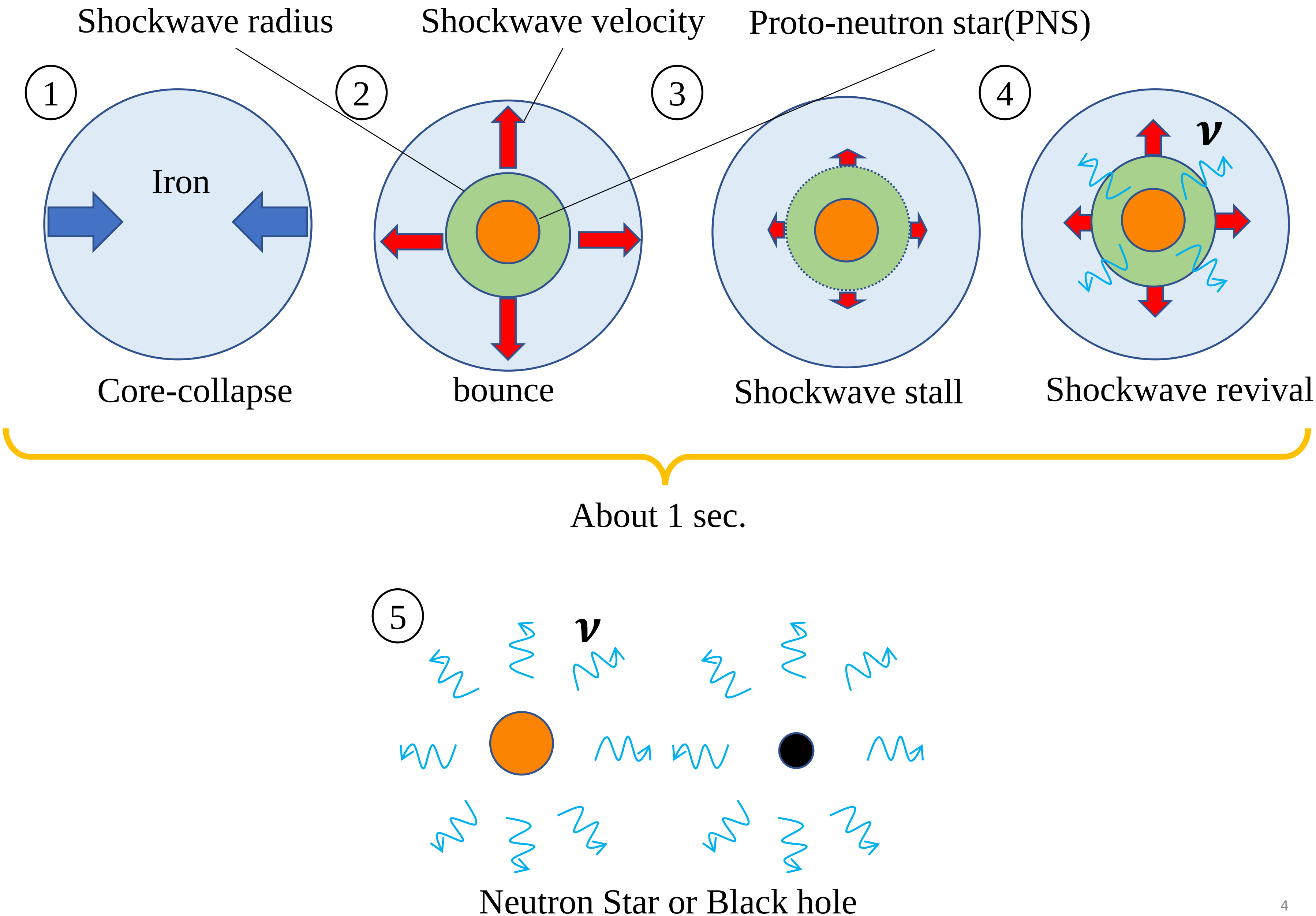
- 11: Kamiokande(2.14 kton)
- 8: IMB [2]
- 5: Baksan [3]





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

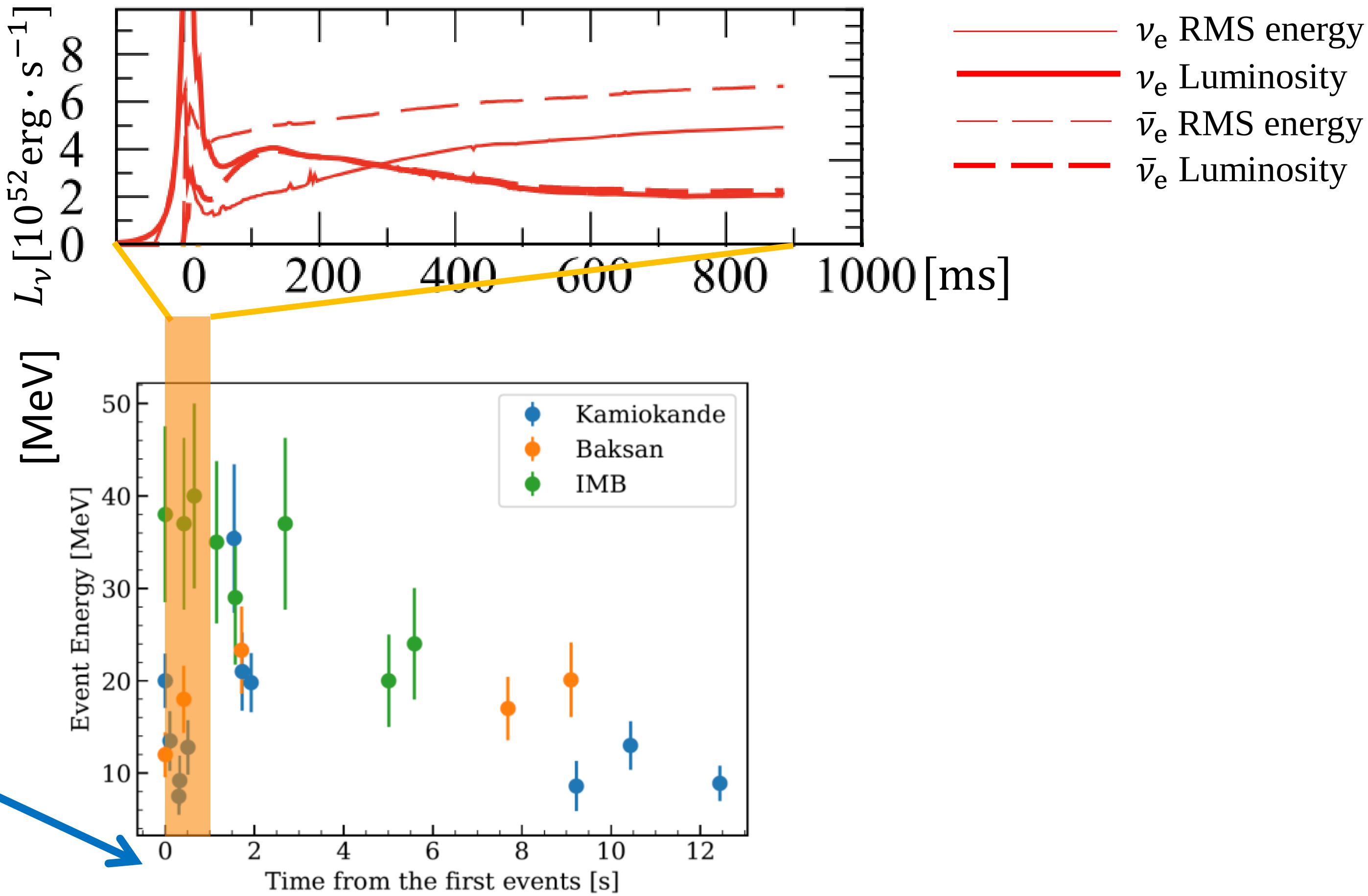
Supernova evolution



Supernova simulation problem

- Most simulations concentrate on early 1 sec.

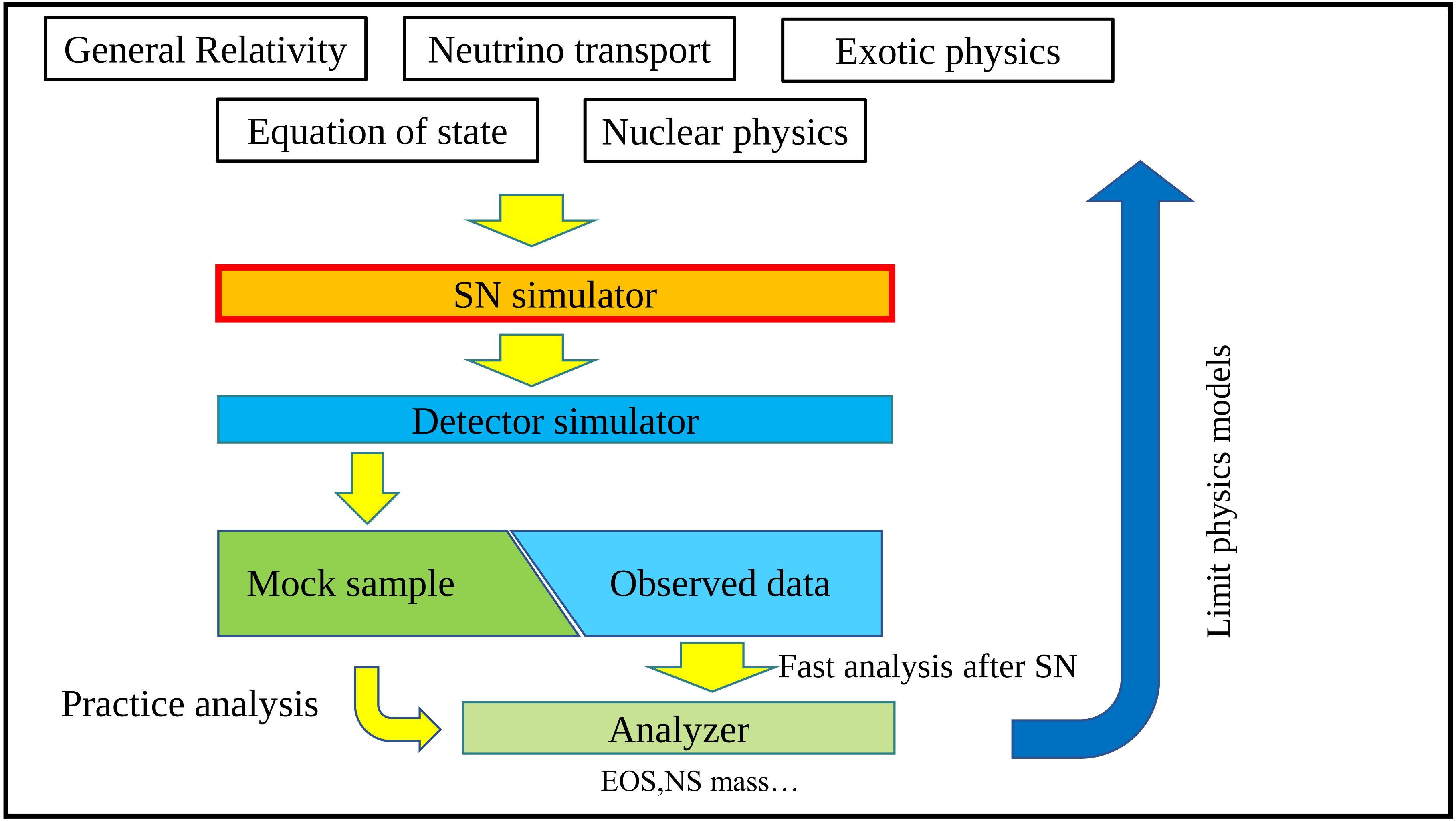
Example of simulation
Suwa et al. (2016)



We can compare theory and observation only for this time.

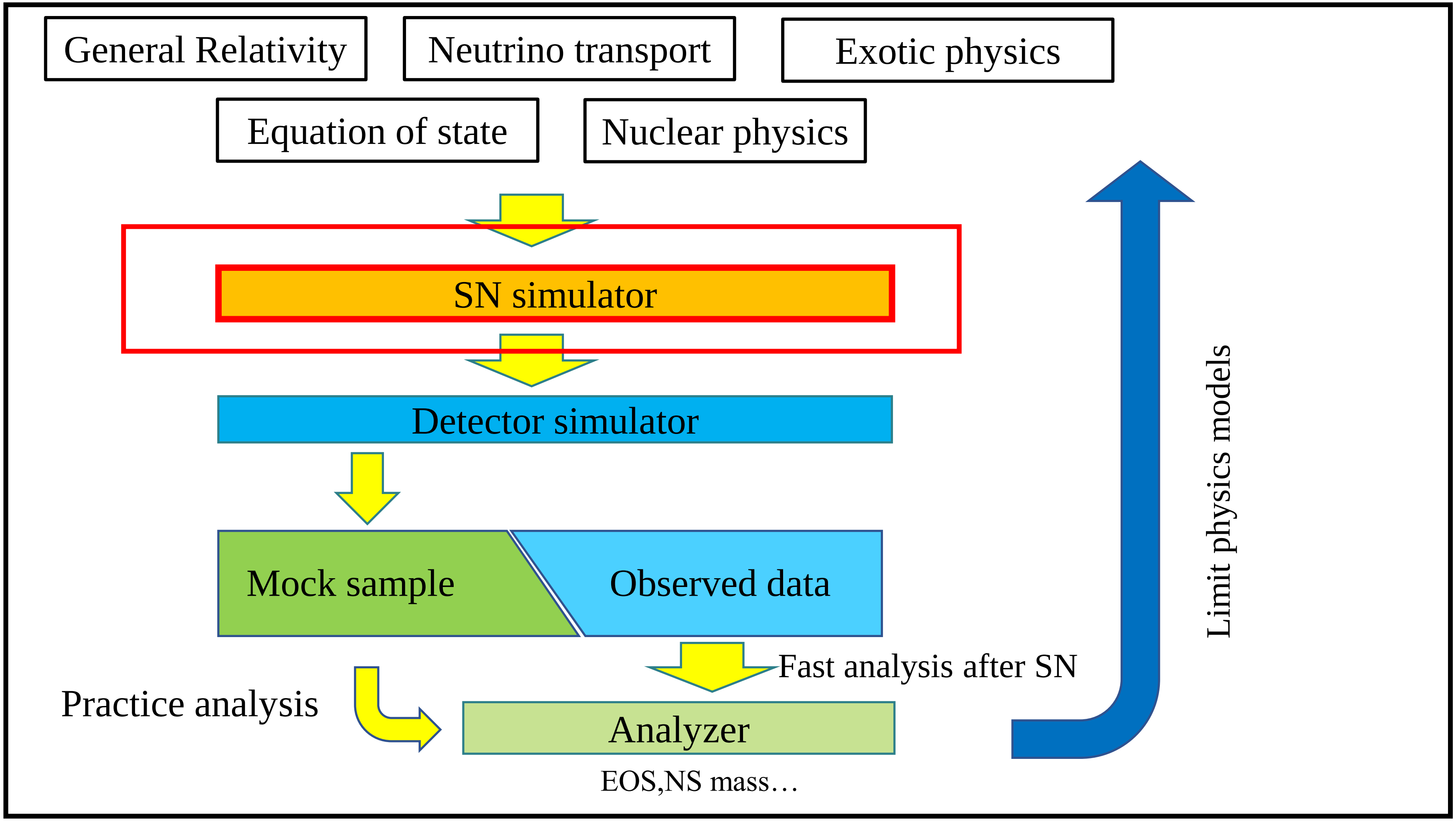
We will a long time simulation and an analysis framework.

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**

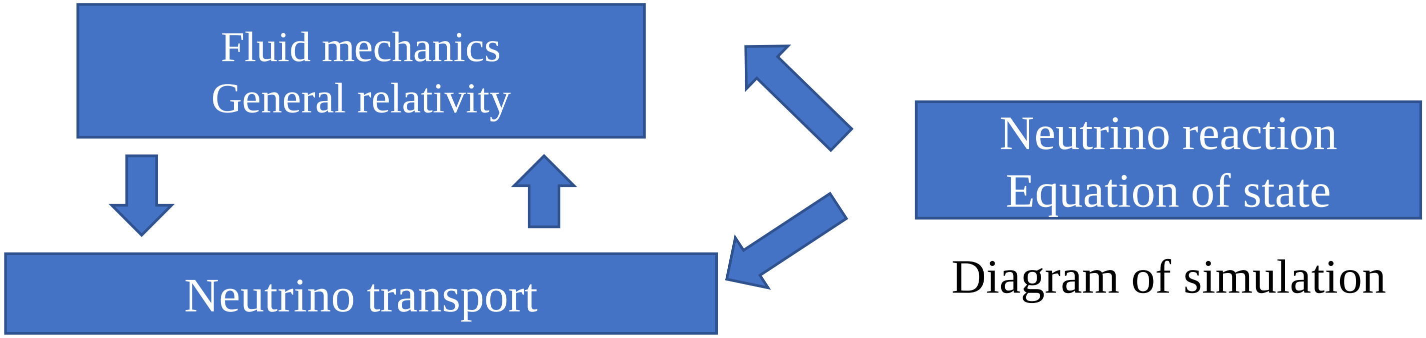
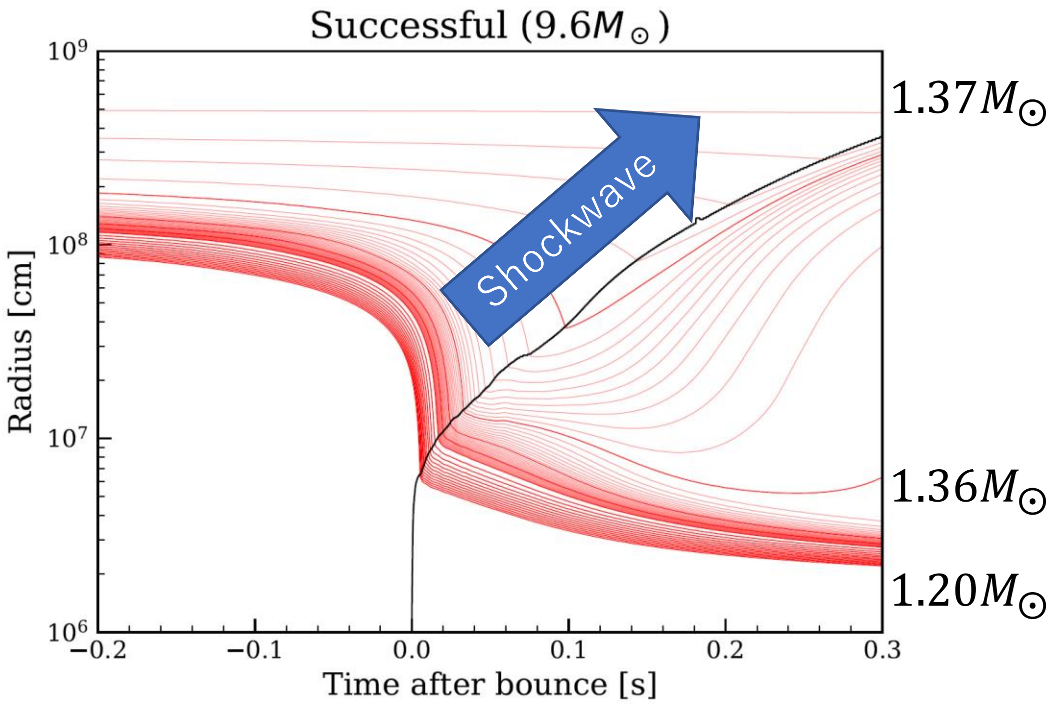
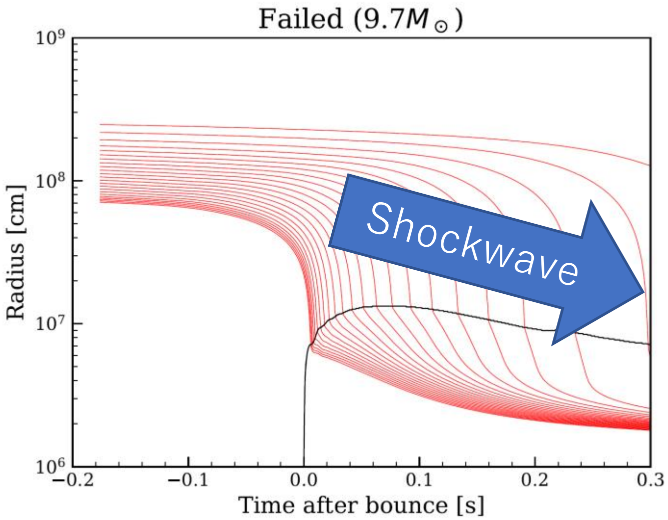


Diagram of simulation

Successful explosion

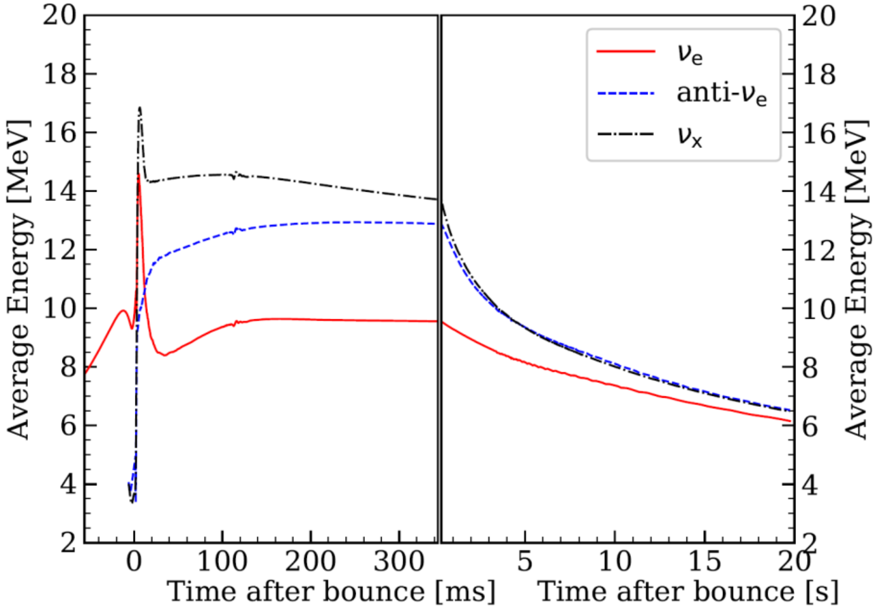




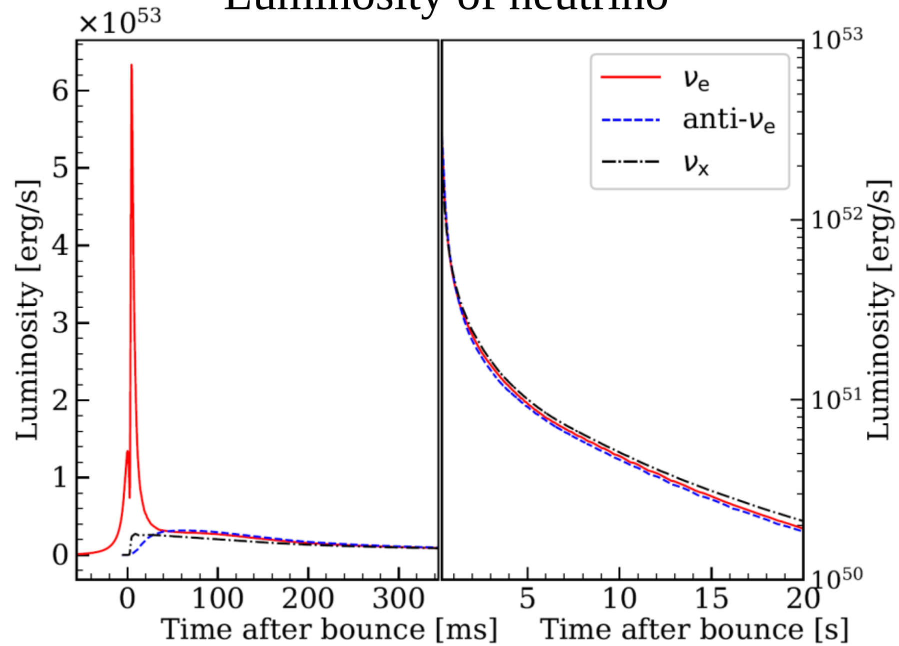
- Red：Radii at which densities are constant
- Black：Radius of a shockwave
- Succeed to explode with the suitable choice of progenitors and **without artificial methods**
  - 9.6 solar mss, initial metallicity is 0
  - Called z9.6

Long time simulation

Average energy of neutrino



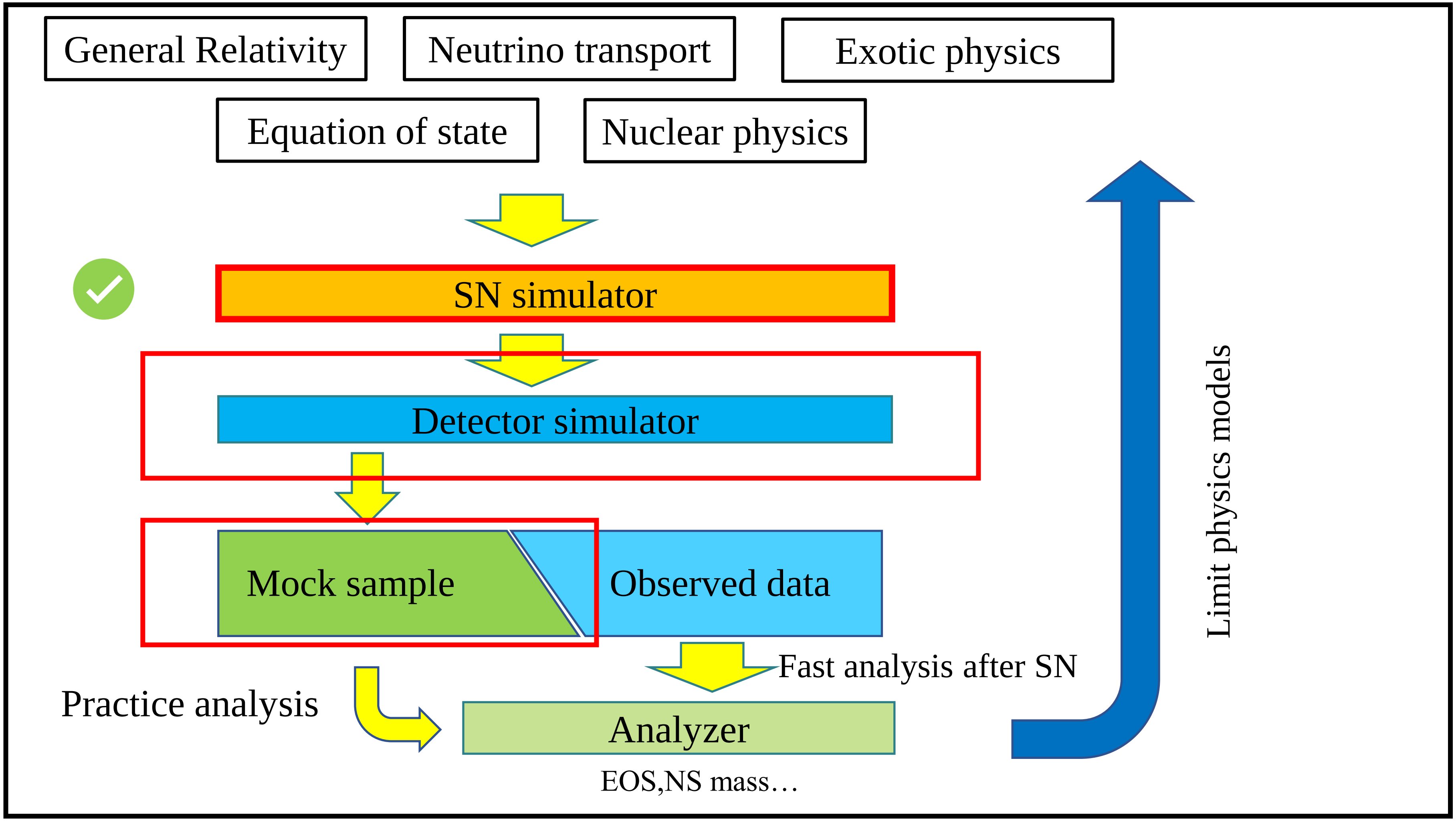
Luminosity of neutrino



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.

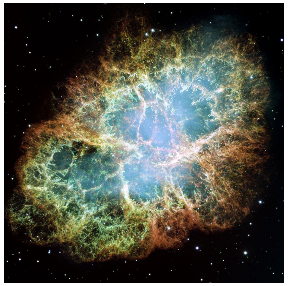
Detector simulator



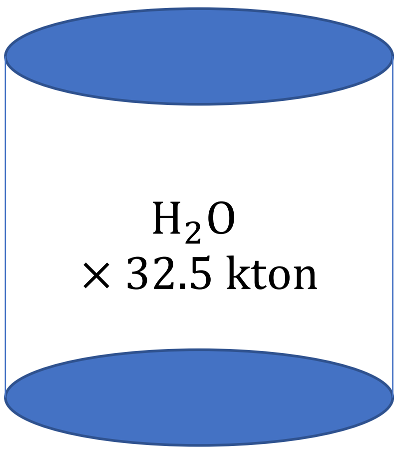
- Detector simulation
- Simulates how signals of supernovae look like on earth
- Mock Sample is used for analysis practice and detector evaluation.

Event simulation

Explosion



10 kpc



Assumed Super-Kamioknde

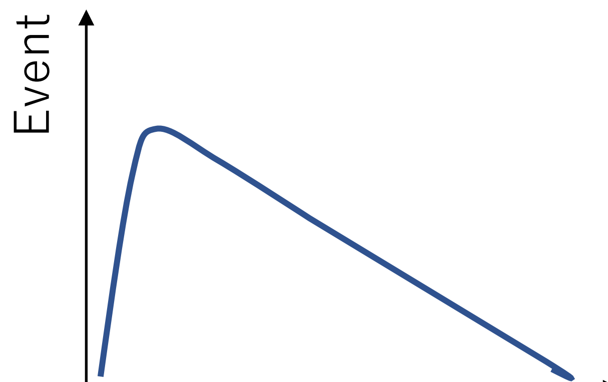
Reaction channel

Inverse Beta Decay(IBD)

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

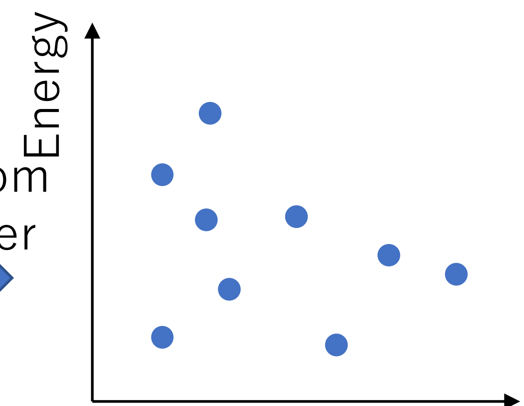
Electron scattering(ES)

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

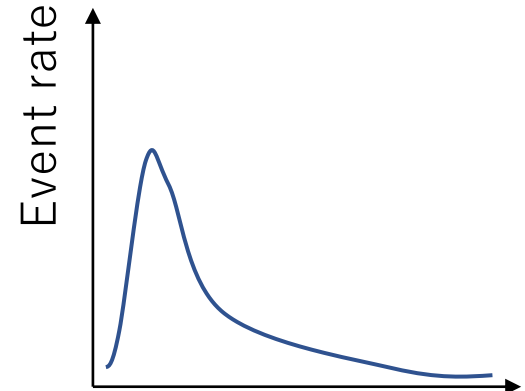


Event distribution per a time

Random number

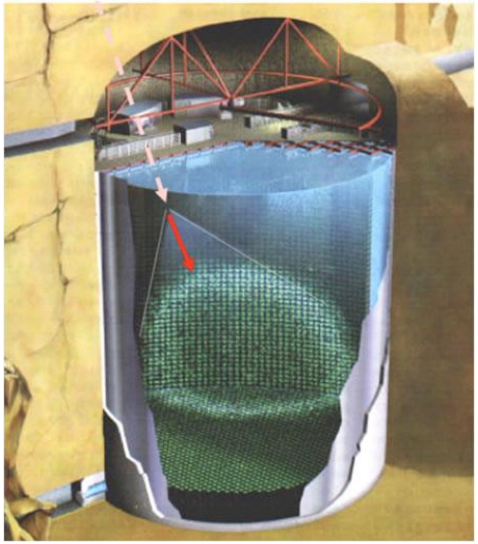


Integrate



Super-Kamiokande(SK)

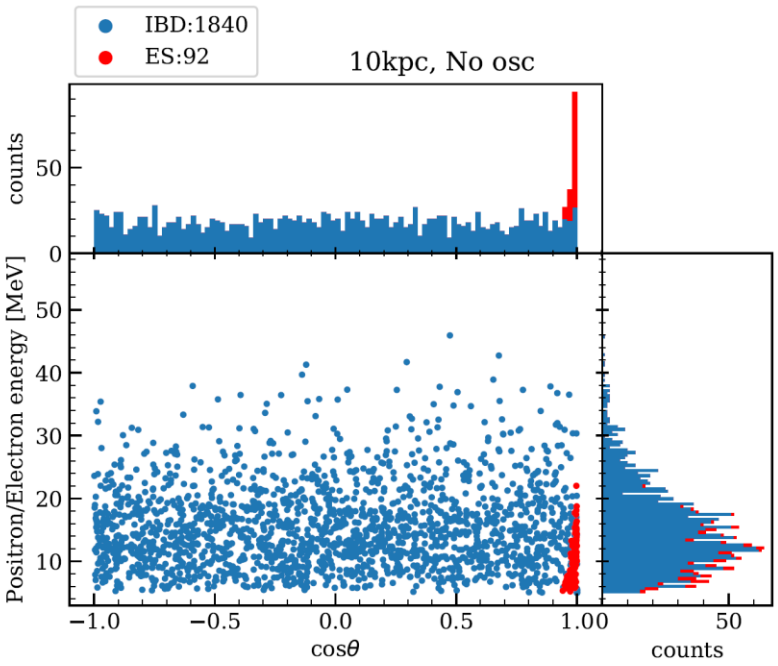
- Water Cherenkov detector in the Gifu prefecture.
  - ➢Height: 41.4 m
  - ➢Diameter: 39.3 m
  - ➢Volume for SN burst: 32.5 kton
  - ➢Number of PMTs:11,129
  - ➢Energy threshold: 5MeV
- Various neutrino studies
  - ➢atmosphere, solar , accelerator…

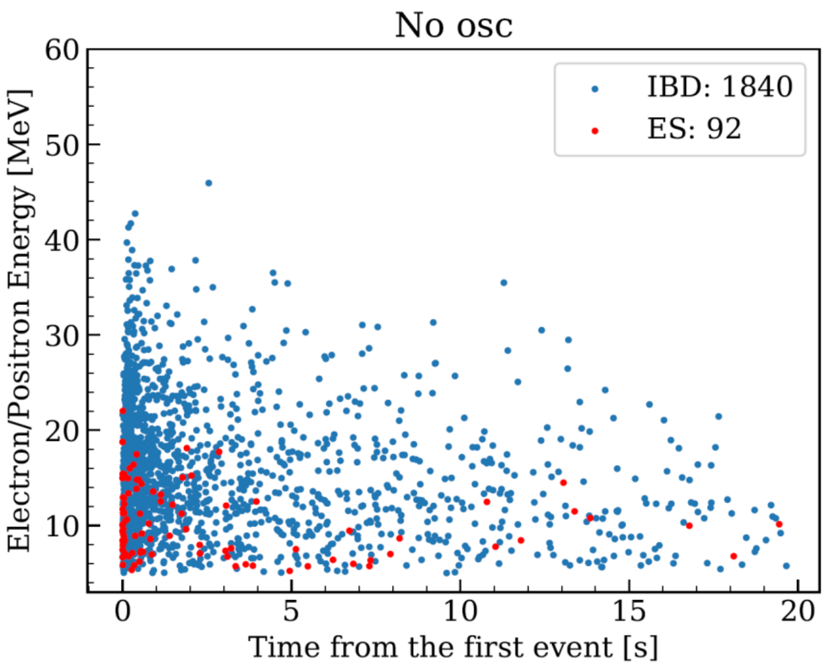


http://www-sk.icrr.u-tokyo.ac.jp

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

Scatter plot (Mock sample)

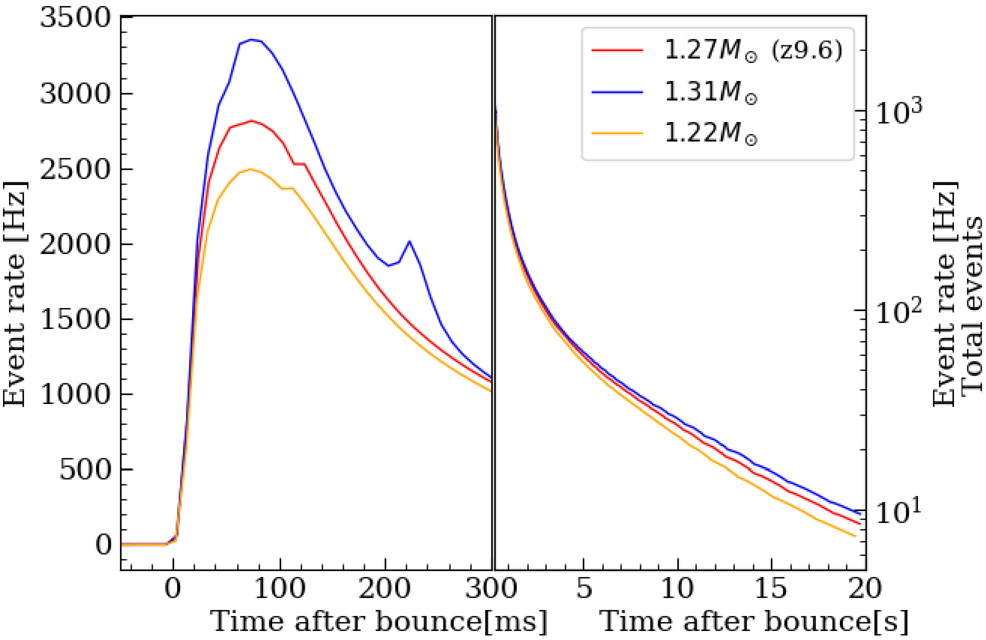




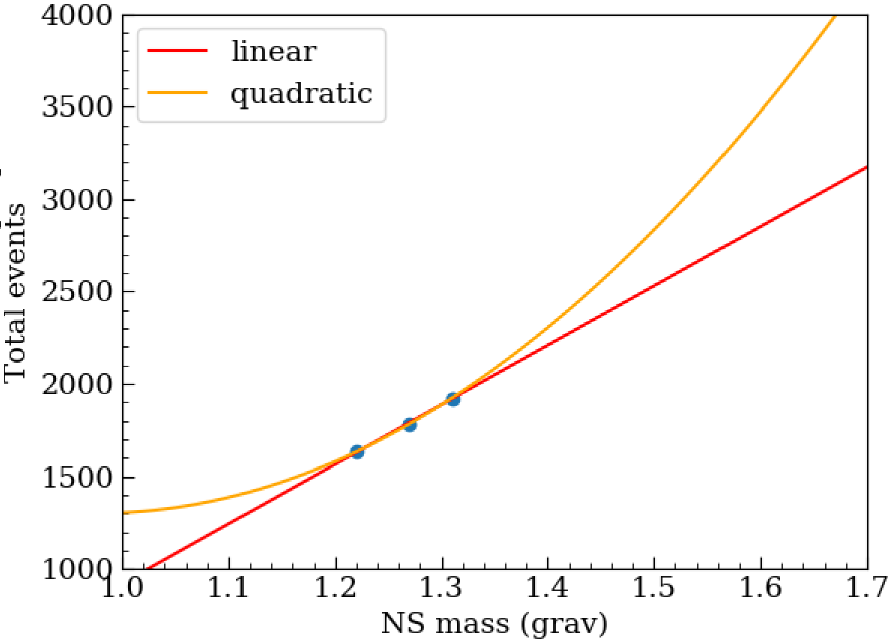
- Each event is simulated with random number (10kpc)
- Left：cosine distribution between neutrinos and charged leptons.
- Right：Time evolution of energy
  - ➢Almost all IBD, ES scatters forward.
- **Mock samples are applied for various studies**
  - ➢Development and practice of analysis methods
  - ➢Evaluation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

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.

Summary

Summary

- Supernovae give birth to neutron stars and black holes
- Established the long time simulation
- Estimated neutrino signals at Super-Kamiokande

To do

- More progenitors will be simulated
- Calculate black hole formation
- Develop an analysis method

Back up

Device of grids

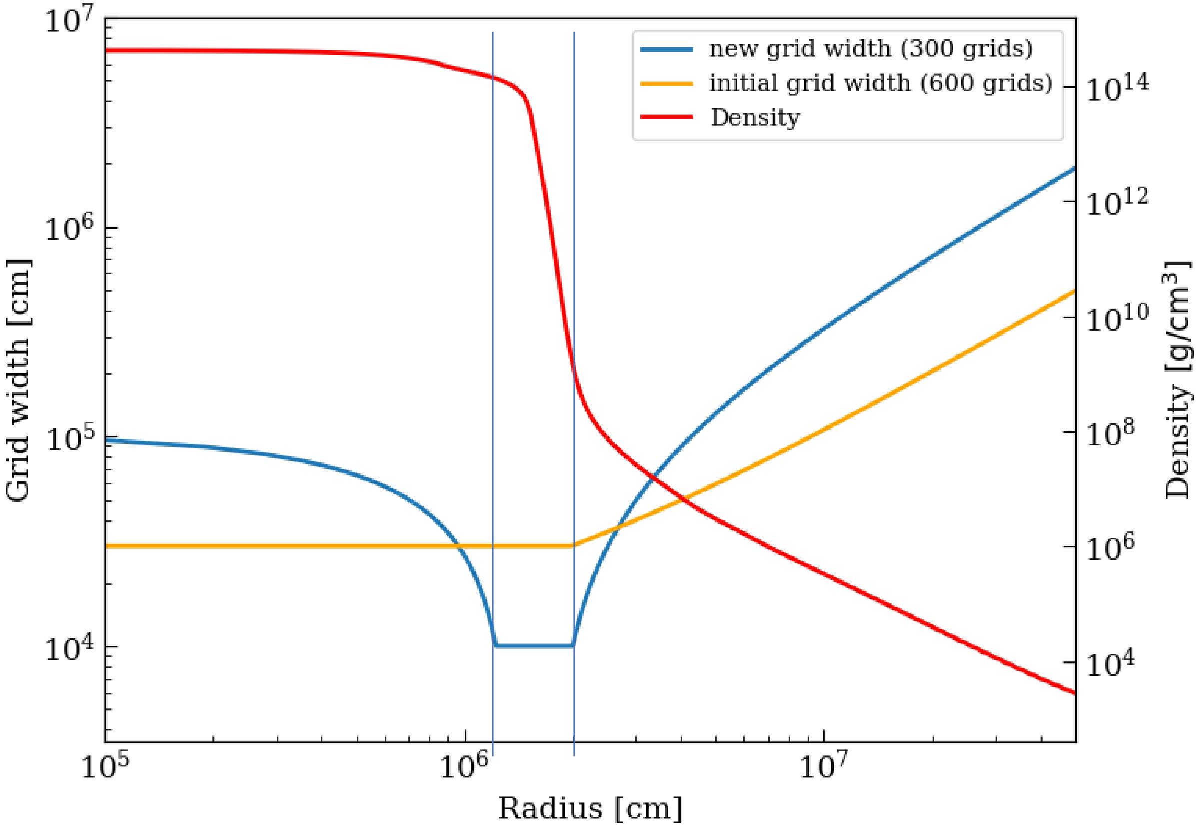
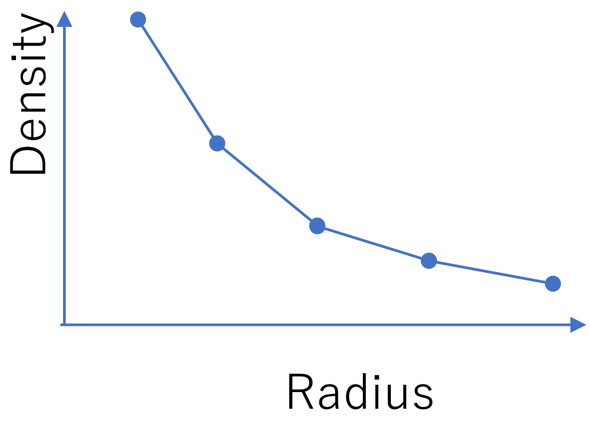


Image of Grid



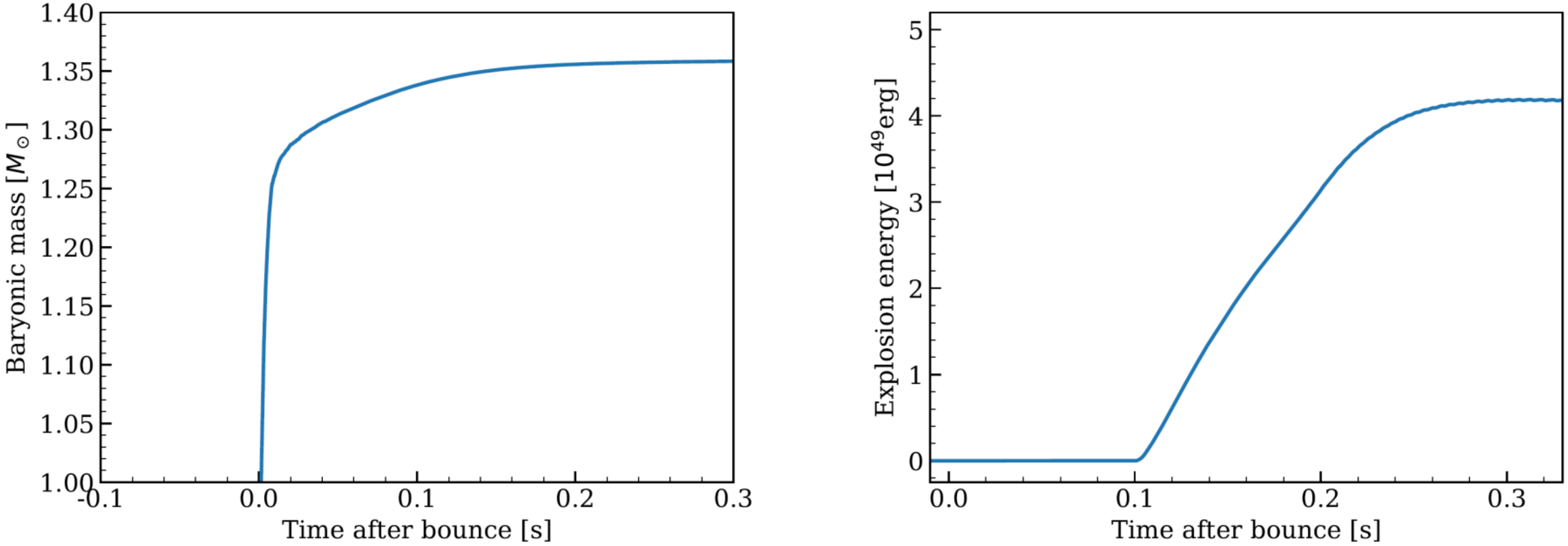
- Red：Density structure of PNS
- Yellow：Initial grids (600 grids)
- Blue：Optimized grids (300 grids)
- The region in which the density drastically changes is finely resolved.
  - ➢Initial grids make calculation stop at about 5 sec.
  - ➢Cost is also too high

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**

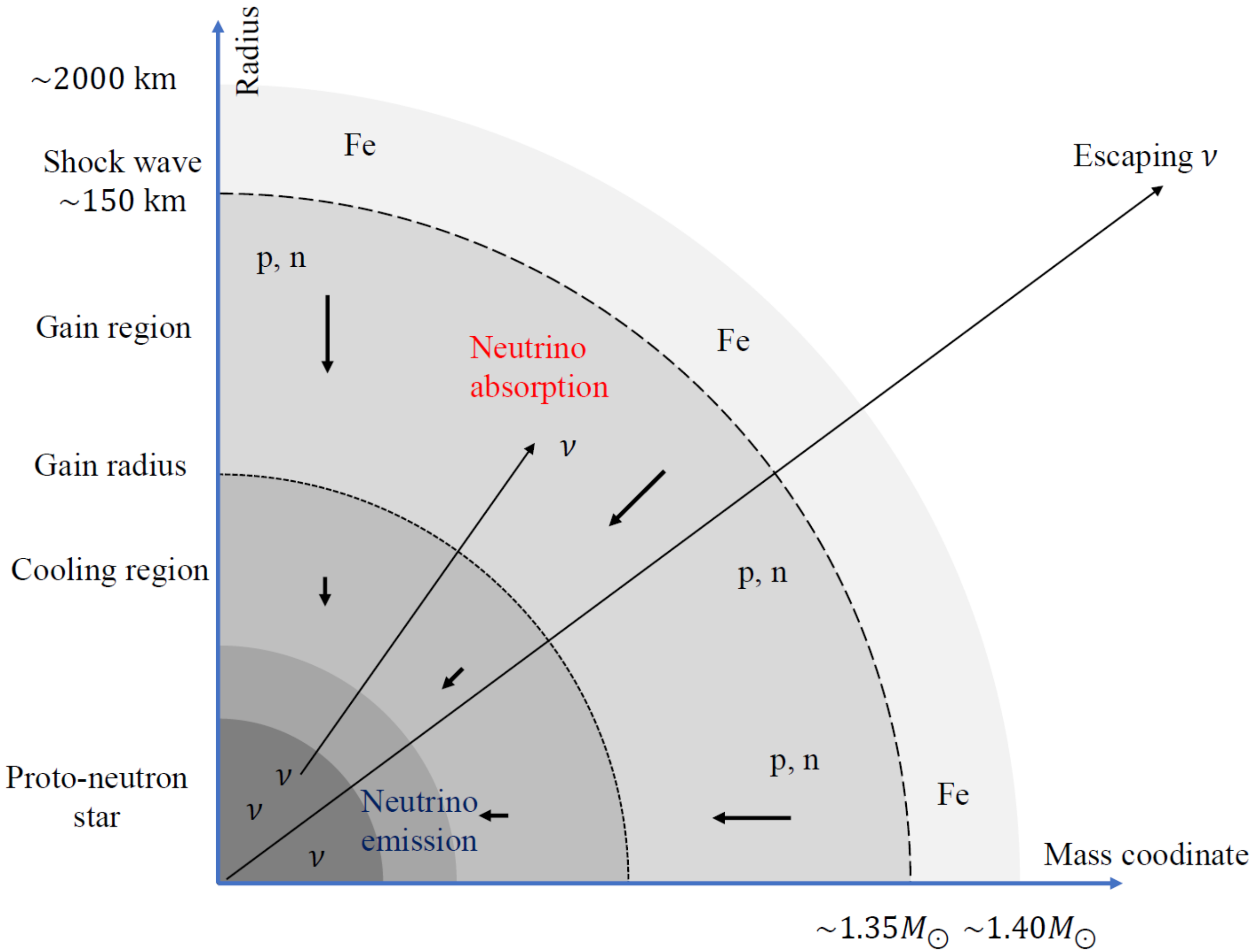
- To explode without artificial methods in one-dimension is difficult
  - ➢ Enhancement of neutrino reaction rates
  - ➢ Removal of material accreting
- Long time simulation in multi-dimension is impossible
- We do long time simulation in one-dimension without artificial methods

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。

エネルギーの階層性



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

GR1Dのニュートリノ反応

生成・消滅

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

弾性散乱

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

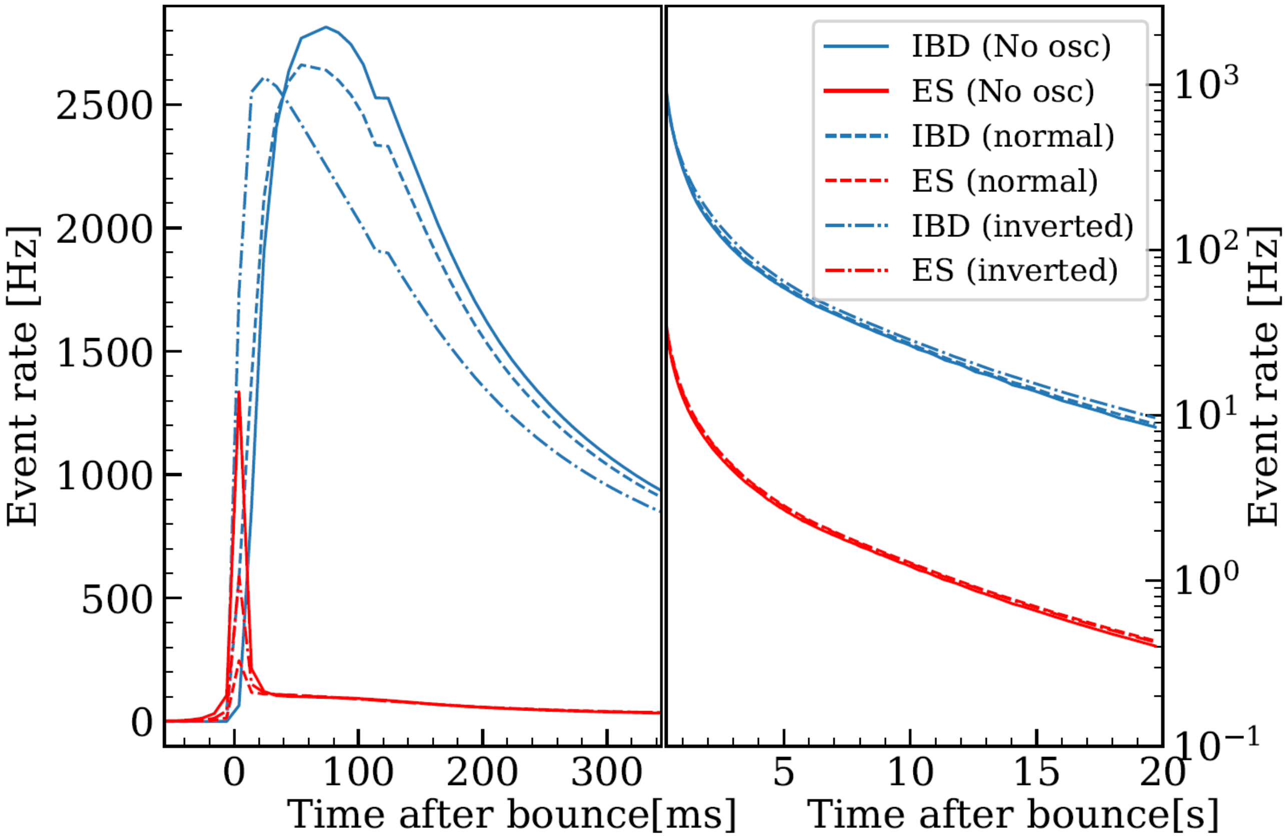
非弾性散乱

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

熱化過程

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

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