

近傍超新星爆発が起こったときの 解析方法

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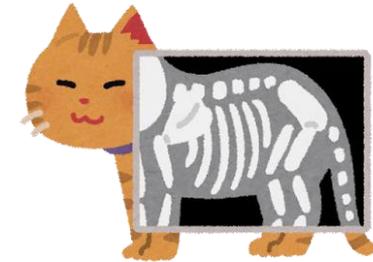
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学術変革「地下稀事象」領域研究会
7/6 大阪大学 豊中キャンパス

超新星爆発

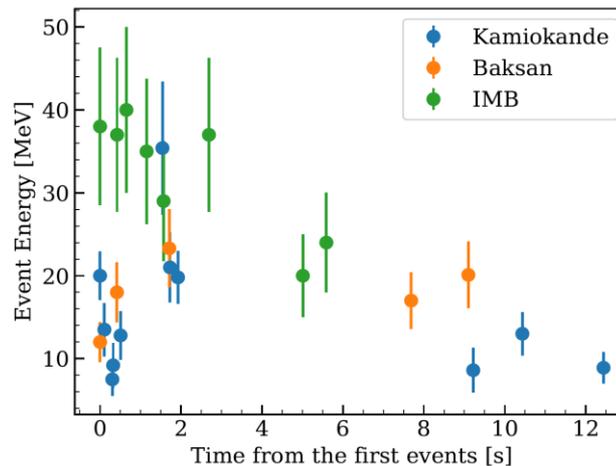
- 太陽の8倍以上の重い星の最期の大爆発
- 複雑な現象のため長時間計算が困難
- エネルギーの99%をニュートリノとして放出
 - ニュートリノは中心部を透過
 - 唯一の観測例: SN1987A



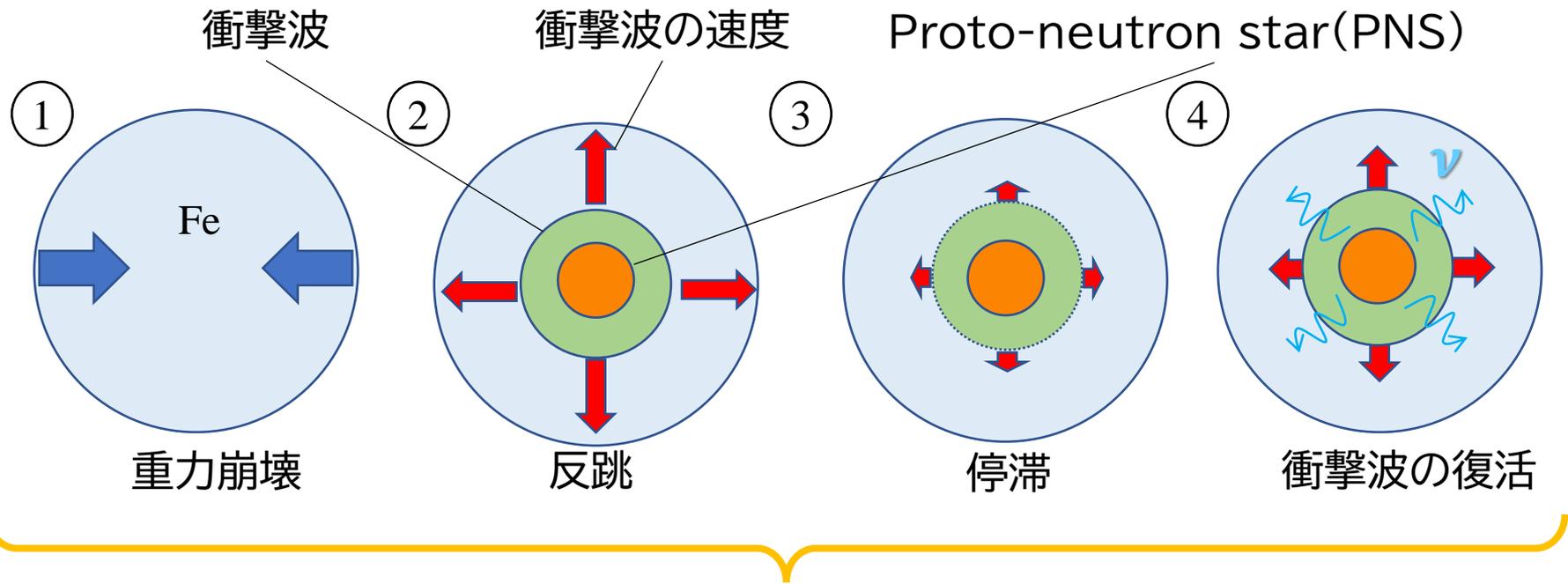
SN1987A events

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

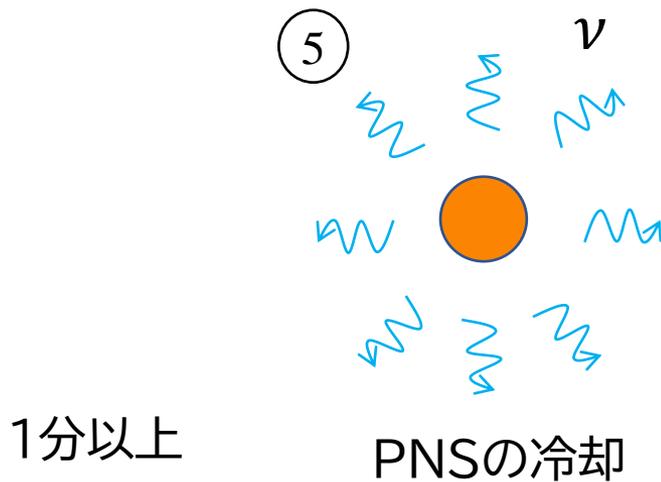
- [1] Hirata et al. 1987
- [2] Bionta et al. 1987
- [3] Alekseev et al. 1987



超新星爆発の時間発展



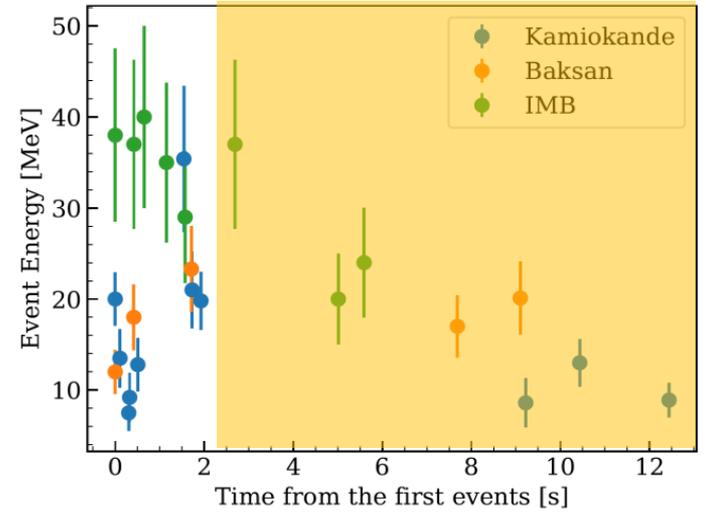
約1秒



超新星爆発は長時間計算の時代へ

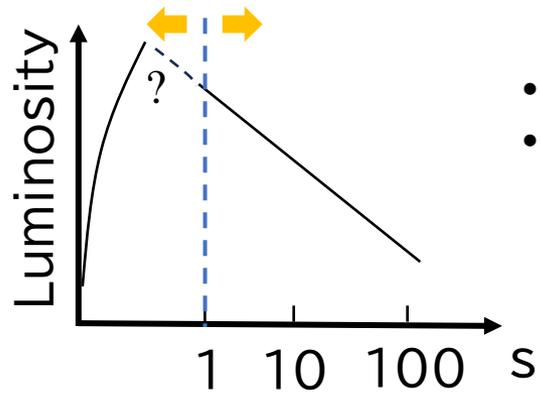
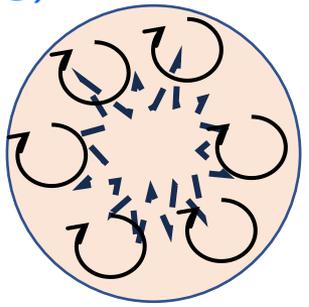
1. ニュートリノ放射は10秒以上続く
2. 後期は不定性が少ない

この時間の計算が必要



多くの不定性 (< 1s)

- 質量
- EoS
- 乱流
- ニュートリノ振動
- etc..

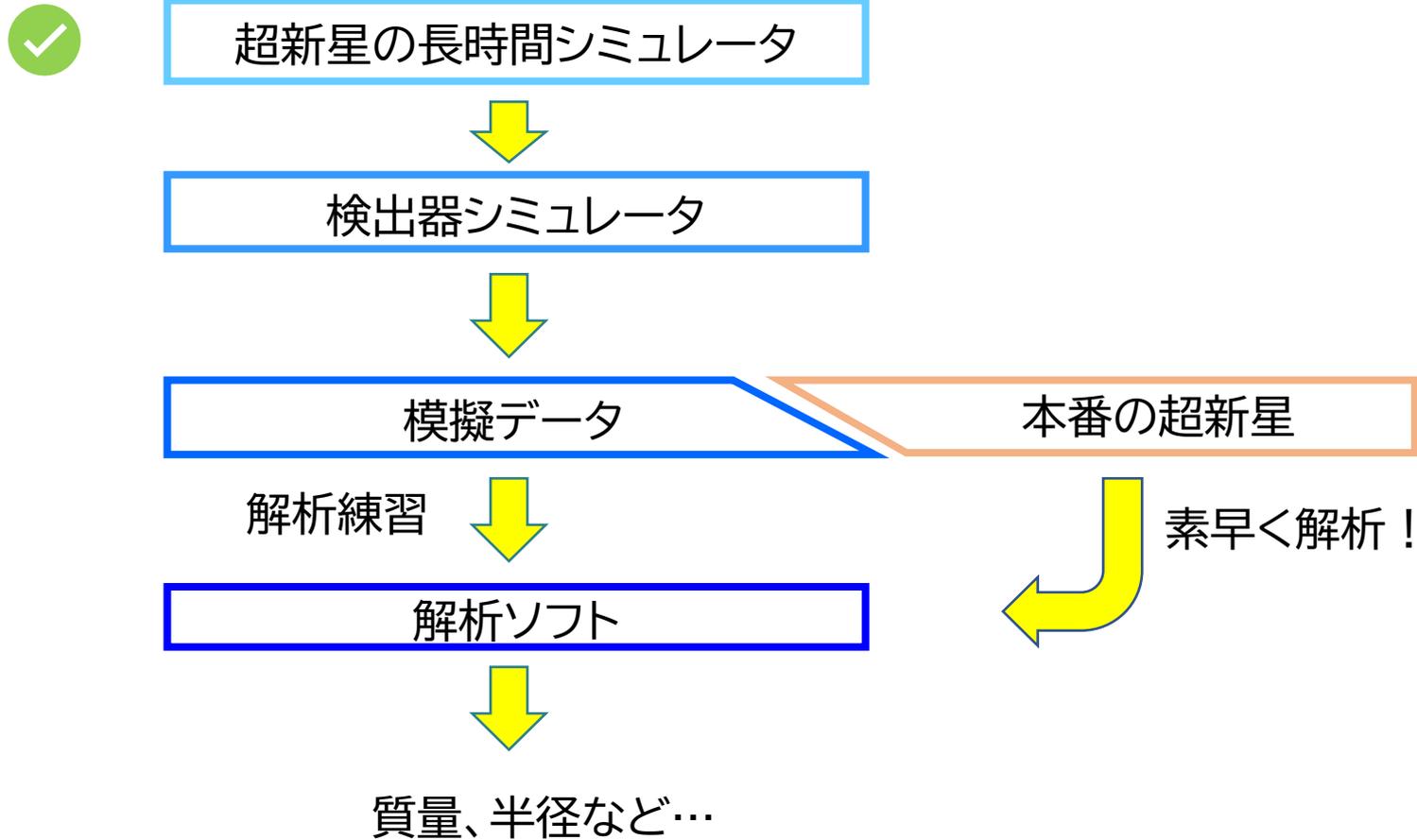


少ない不定性 (>1s)

- 質量
- EoS



超新星爆発ニュートリノフレームワーク開発



- 近い将来、系内超新星爆発が起きた場合の観測体制を構築

検出器シミュレータ



超新星の長時間シミュレータ



検出器シミュレータ



模擬データ

本番の超新星

解析練習



解析ソフト



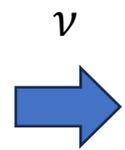
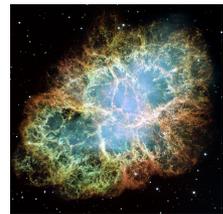
質量、半径など…

素早く解析！

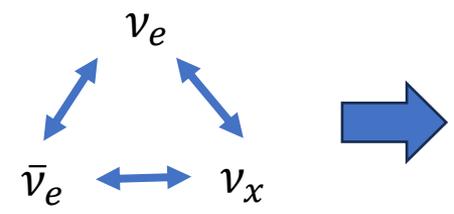


- **FOR**ecasting **E**vents from **S**upernova
Theoretical modeling (FOREST)

超新星爆発



ニュートリノ振動



検出器
例: スーパーカミオカンデ(SK)

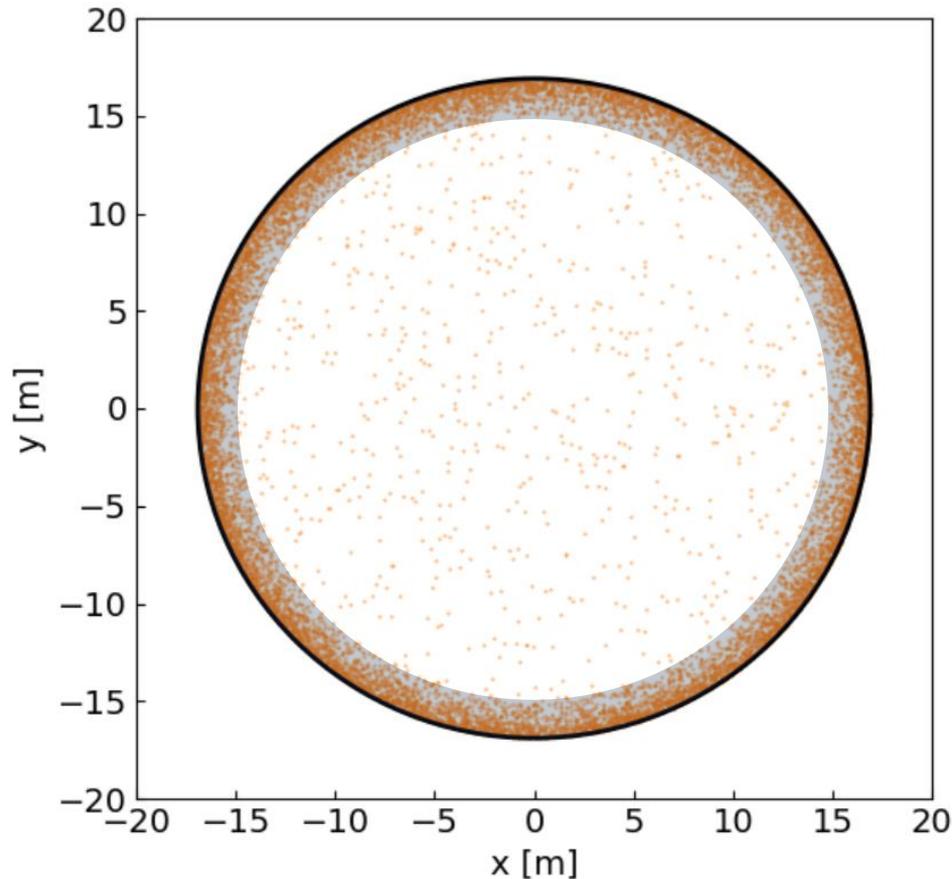


逆ベータ崩壊
 $\bar{\nu}_e + p \rightarrow e^+ + n$

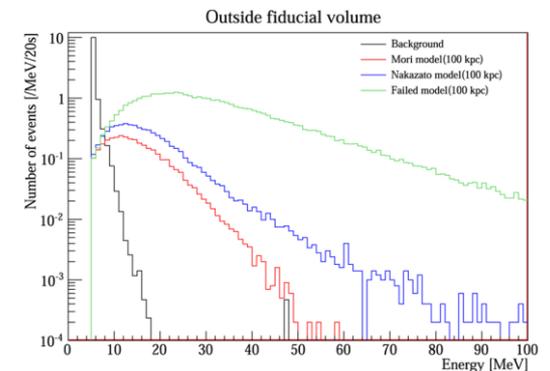
- シミュレーションデータ、解析解からニュートリノイベントを生成
- 背景事象もシミュレーションしよりリアルな状況の再現

SKの背景事象シミュレーション

FORESTでシミュレーションしたSKの1日の背景事象分布



Mori et al. (2022)



通常解析

壁際の背景事象をカット
体積: 22.5 kton

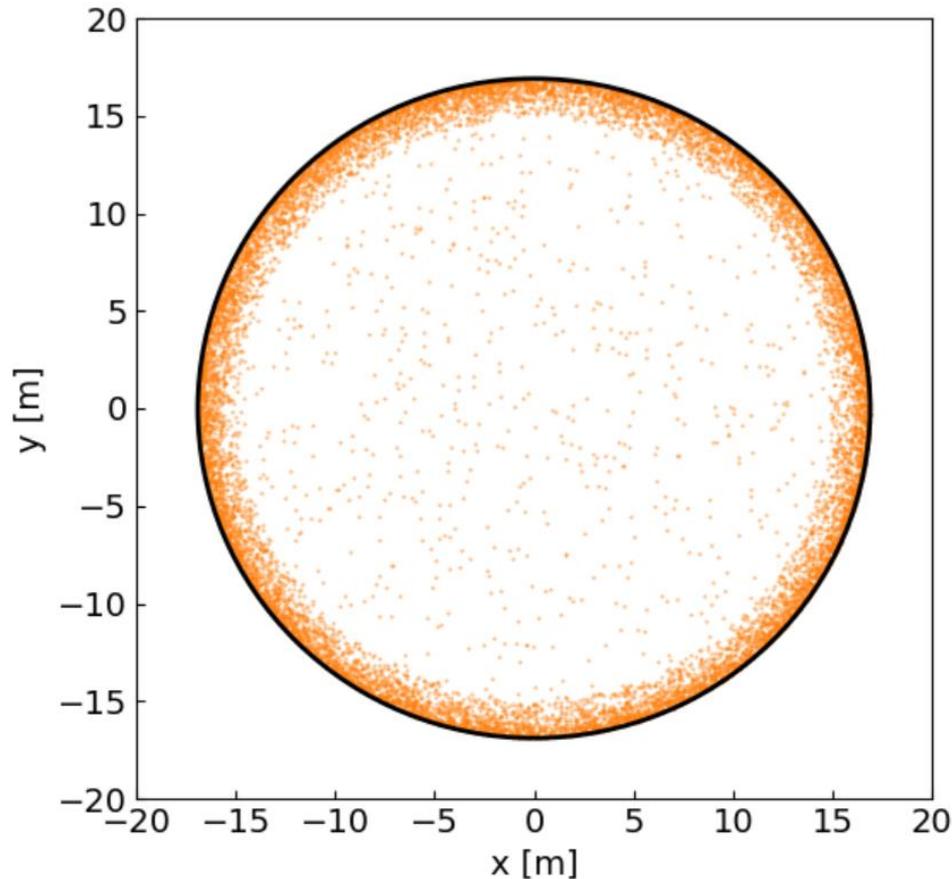
VS

超新星爆発解析

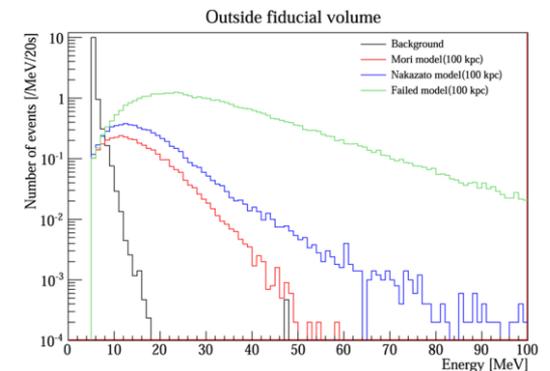
全体積を解析
体積: 32.5 kton

SKの背景事象シミュレーション

FORESTでシミュレーションしたSKの1日の背景事象分布



Mori et al. (2022)



通常解析

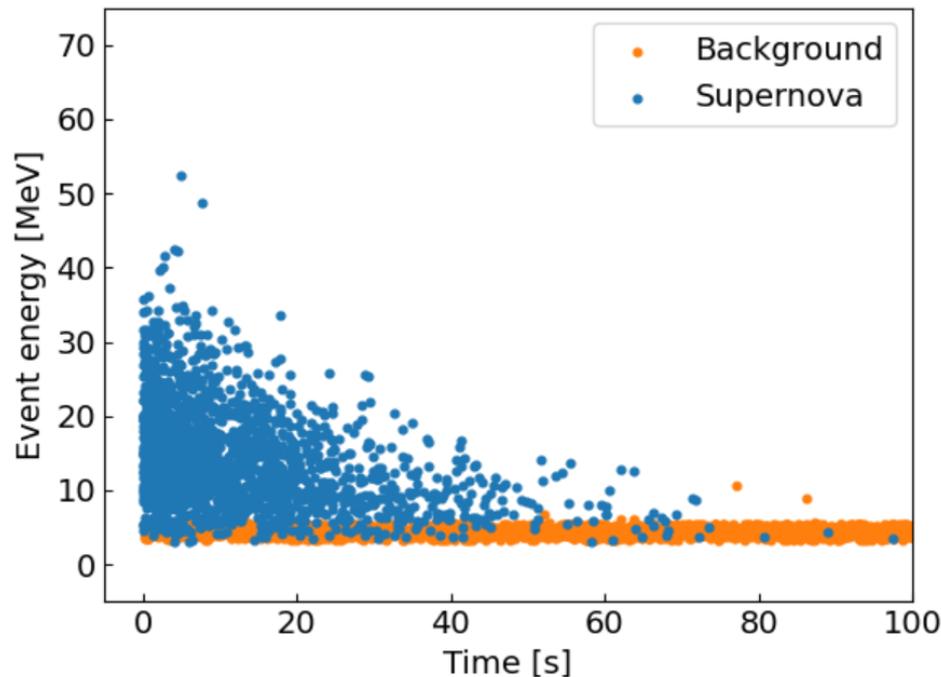
壁際の背景事象をカット
体積: 22.5 kton

VS

超新星爆発解析

全体積を解析
体積: 32.5 kton

模擬データ



- 10kpcで超新星爆発が起こったと仮定

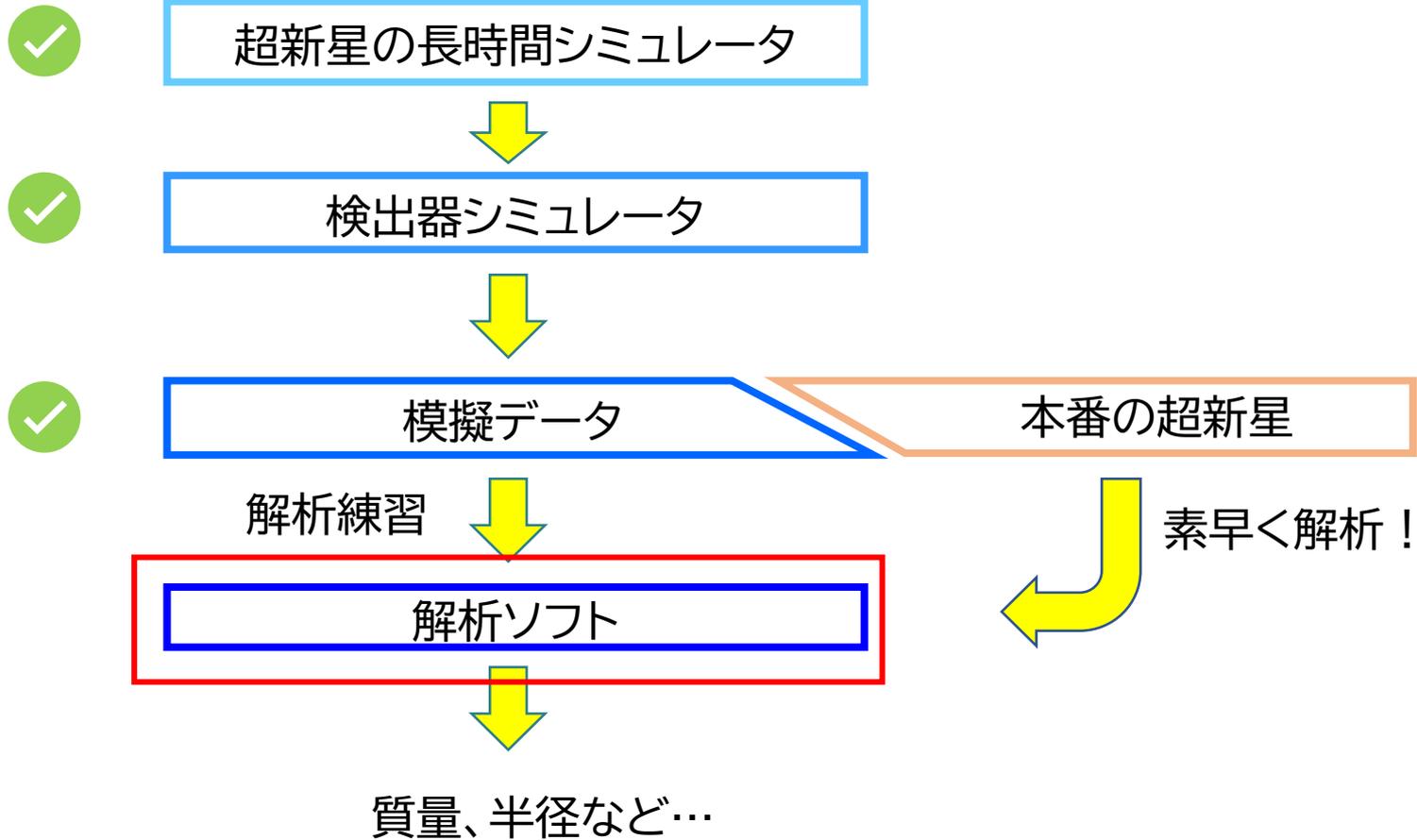
- 1分程度でもSNイベント

- 解析解

- Suwa et al. (2021)

- $$R(t) = 720\text{s}^{-1} \left(\frac{M_{\text{det}}}{32.5 \text{ kton}} \right) \left(\frac{D}{10 \text{ kpc}} \right)^{-2} \left(\frac{M_{\text{PNs}}}{1.4M_{\odot}} \right)^{15/2} \left(\frac{R_{\text{PNs}}}{10 \text{ km}} \right)^{-8} \left(\frac{g\beta}{3} \right)^5 \left(\frac{t+t_0}{100 \text{ s}} \right)^{-15/2}$$

超新星ニュートリノ解析



解析方法

- バイズ推定を使って中性子星の質量を求める。
- Suwa et al. (2022), Harada et al. (2023)

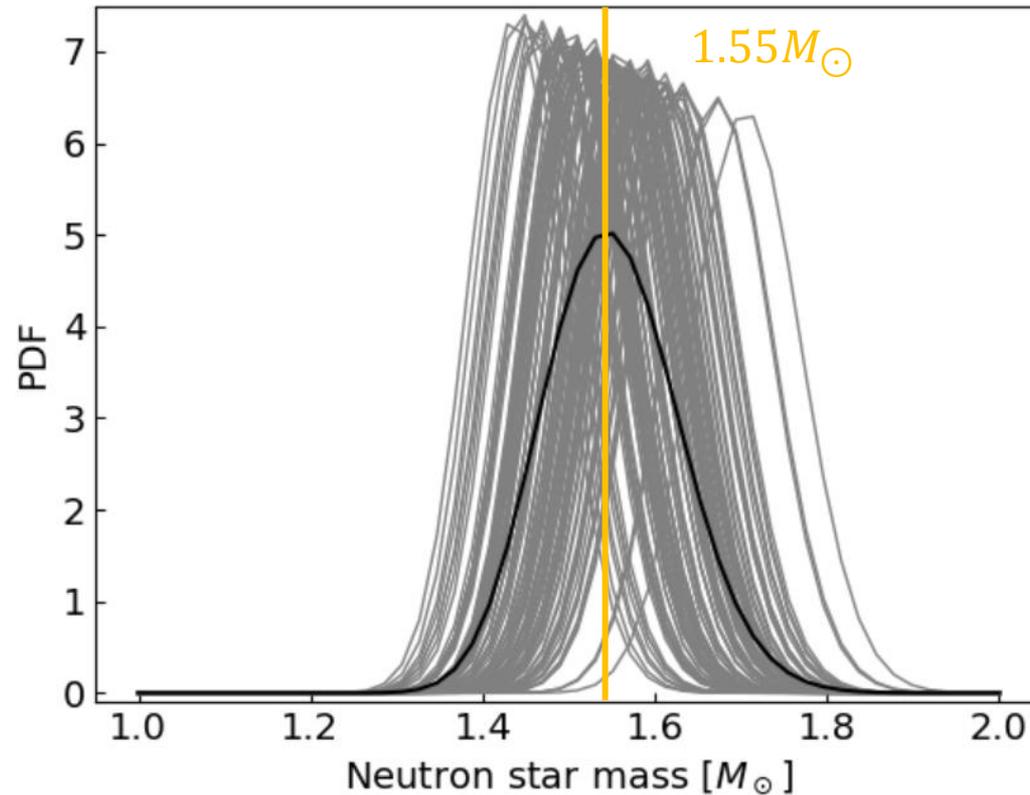
- 次の式を使って質量をフィッティング
イベントレート

- $R(t) =$
$$720\text{s}^{-1} \left(\frac{M_{\text{det}}}{32.5 \text{ kton}} \right) \left(\frac{D}{10 \text{ kpc}} \right)^{-2} \left(\frac{M_{\text{PNS}}}{1.4 M_{\odot}} \right)^{15/2} \left(\frac{R_{\text{PNS}}}{10 \text{ km}} \right)^{-8} \left(\frac{g\beta}{3} \right)^5 \left(\frac{t+t_0}{100 \text{ s}} \right)^{-15/2}$$

平均エネルギー

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

パラメータ推定



- FORESTを使って10kpcで超新星爆発が起こったと仮定
 - 正解: $1.52 M_{\odot}$
- バックグラウンドなし

バックグラウンド入り解析

- 実際はバックグラウンドイベントがニュートリノイベントに混じる
- バックグラウンドの入りの解析方法が必要

イベントレート

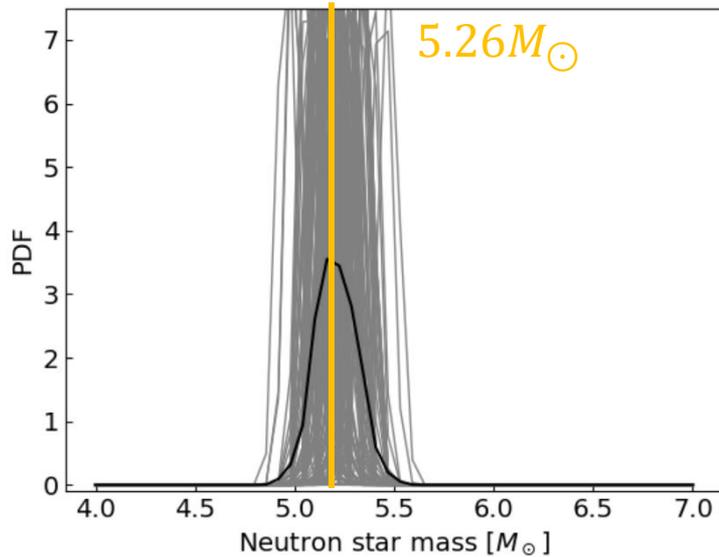
- $R(t) = R_{\text{SN}}(t) + cR_{\text{BG}}(t)$

平均エネルギー

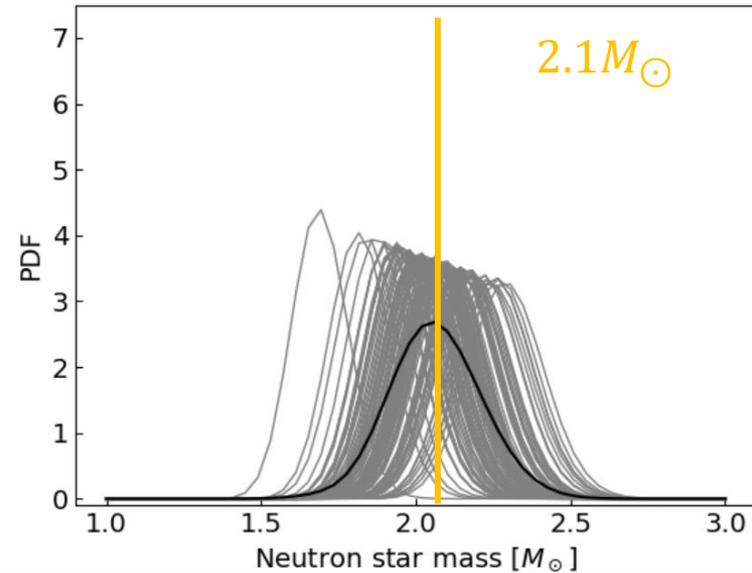
- $$\langle E \rangle(t) = \frac{R(t)_{\text{SN}} \langle E \rangle_{\text{SN}}(t) + cR_{\text{BG}}(t) \langle E \rangle_{\text{BG}}(t)}{R_{\text{SN}}(t) + cR_{\text{BG}}(t)}$$
- c はパラメータ

パラメータ推定 with バックグラウンド

バックグラウンドなしの式



バックグラウンドありの式



- 100個の模擬データを作って中性子星の質量を推定
 - 正解: $1.52M_{\odot}$
 - $c = 1$

New DAQ of SK for nearby supernovae

- 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
- **Veto module**と**SN module**という新しいDAQを開発
 - ついに論文になりました！
 - arXiv: 2404.08725

Veto module

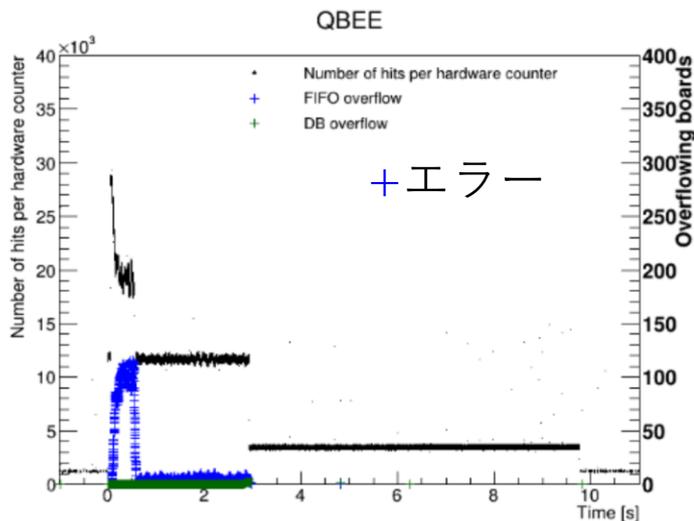
- イベントを間引いてメインDAQの負荷を減らす

SN module

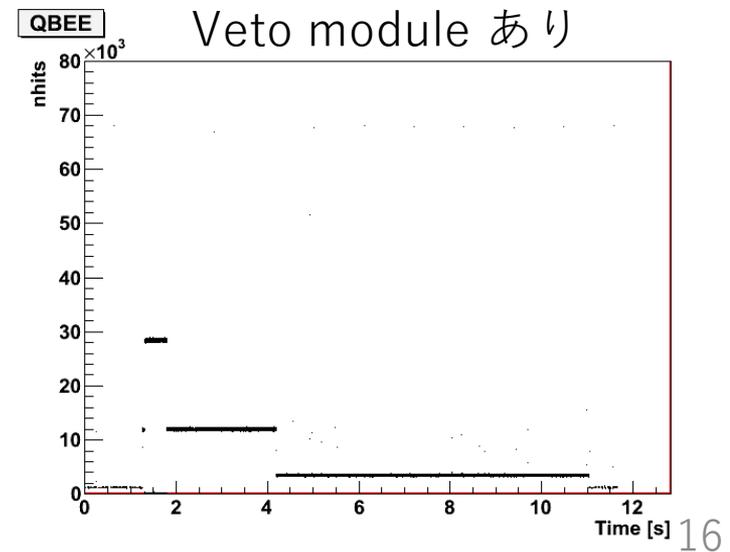
- Hit情報のみを全時間で保存
- 新しい解析方法が必要



Veto module なし



Veto module あり



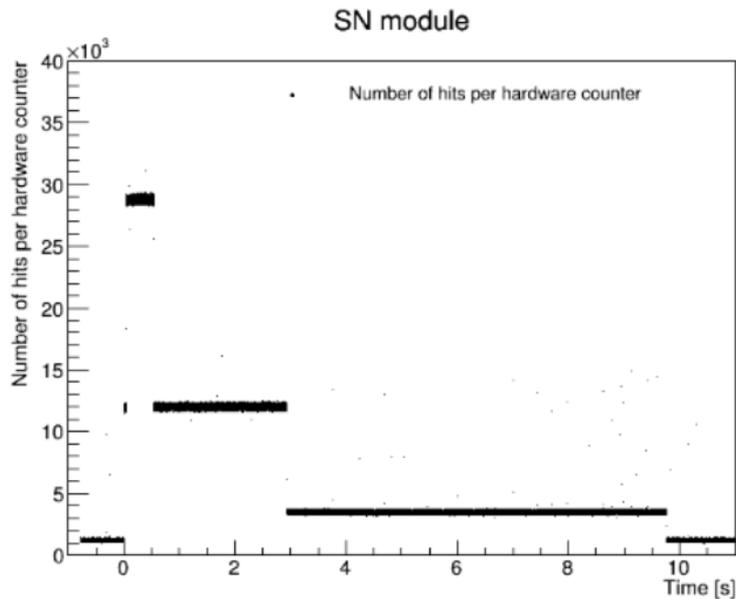
今後の展望

- c を決めてパラメータ推定の精度をよくする

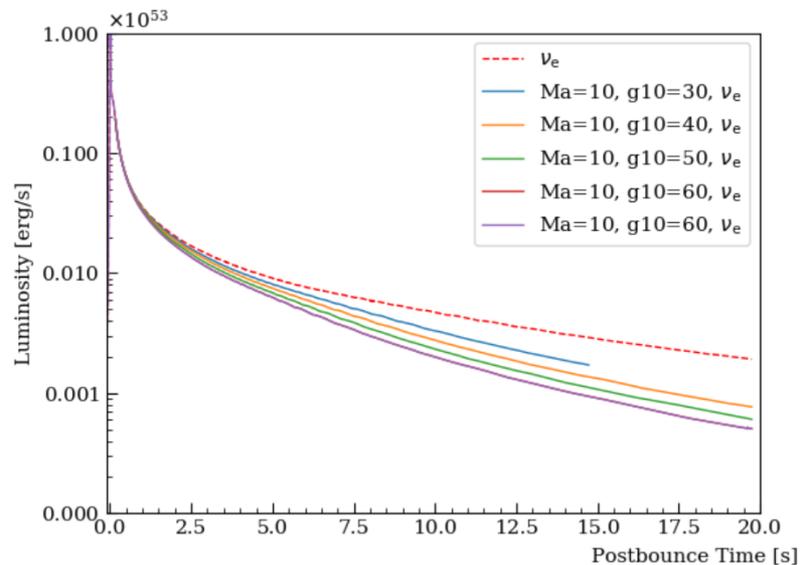
イベントレート

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

- SN moduleのヒットベースのデータの解析方法の開発
- BSM粒子を入れた計算

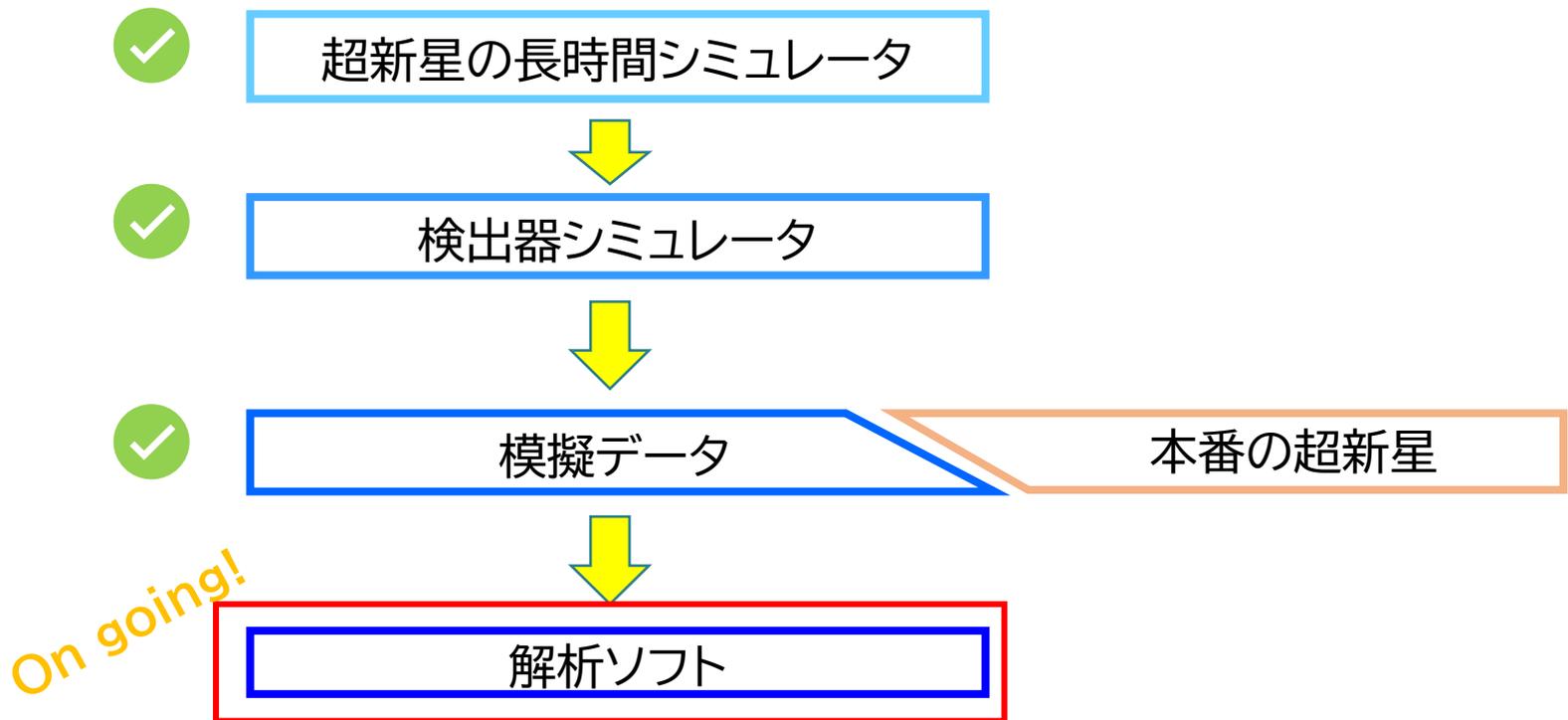


Axion 入り計算



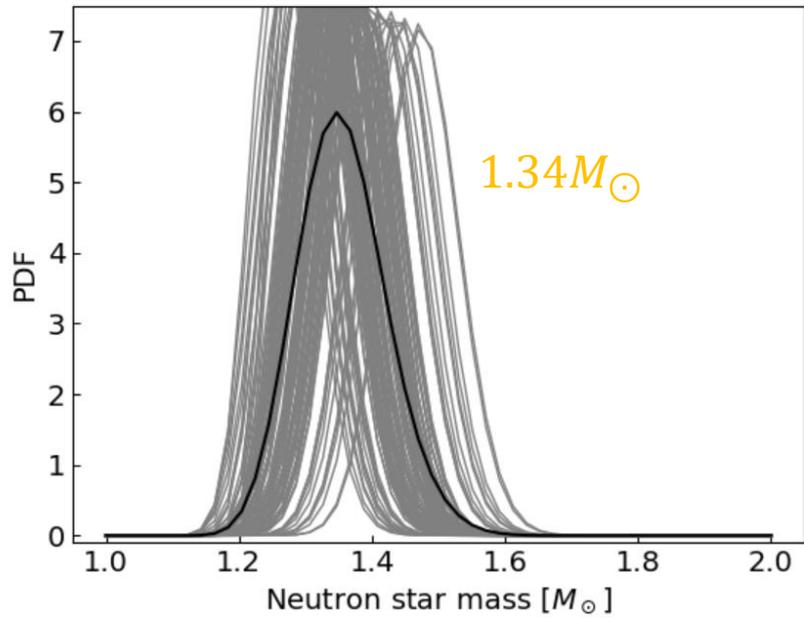
まとめ

- 超新星爆発の長時間計算を開発
- SKでの背景事象を含めた信号予測ソフト、FORESTを開発中

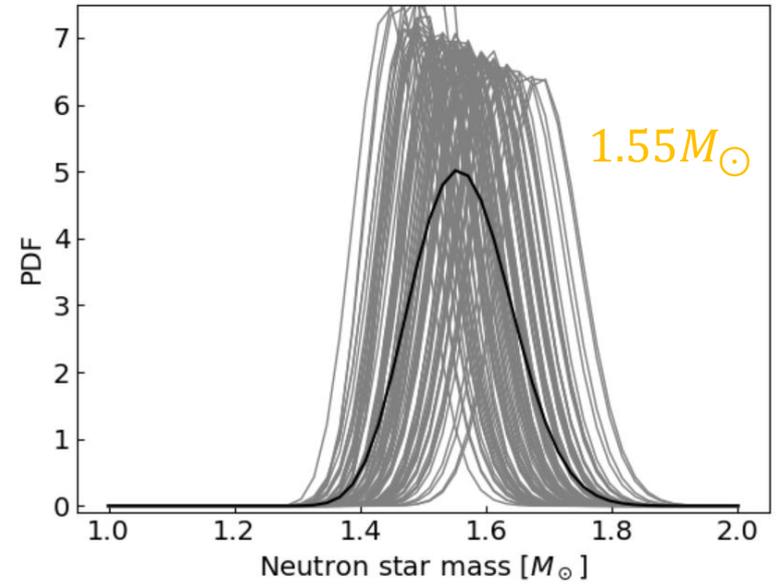


Back up

5MeV cut 全体積 BGなし



5MeV cut 全体積 BGあり



コンテンツ

1. 超新星の長時間計算
2. Super-Kamiokandeでの観測予測
3. 超新星のパラメータ推定の実演

参考文献

- Mori et al. PTEP 023E01 (2021)
Mori et al. Apj, 938, 35 (2022)
Suwa et al. PTEP 013E01 (2021)
Suwa et al. Apj, 934, 15 (2022)
Harada et al. Apj, 954, 52 (2023)

Keywords

超新星ニュートリノ、Super-Kamiokande



My 研究歴

修士

Super-Kamiokandeで
超新星ニュートリノ研究

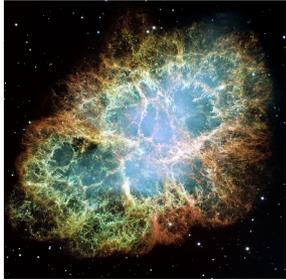
博士

超新星爆発の数値計算

ポスドク

Details of event simulation

Explosion

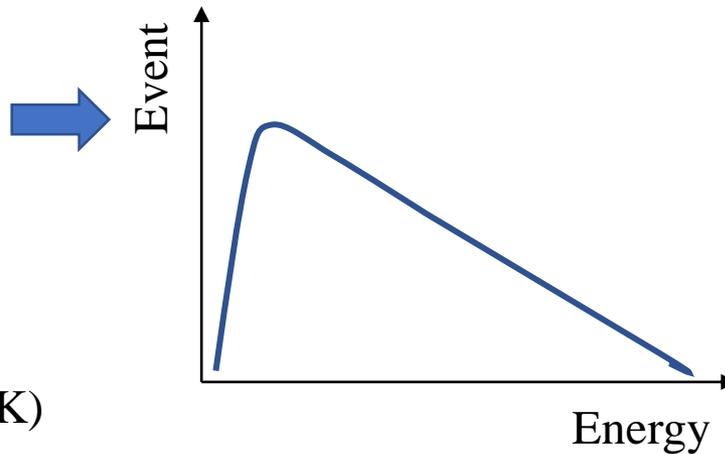


Super-Kamiokande(SK)

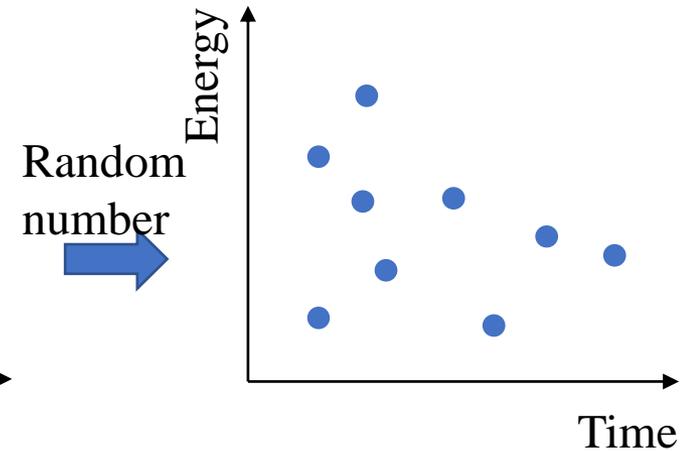
□ Reaction channel

Inverse Beta Decay(IBD)

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



Event distribution per time

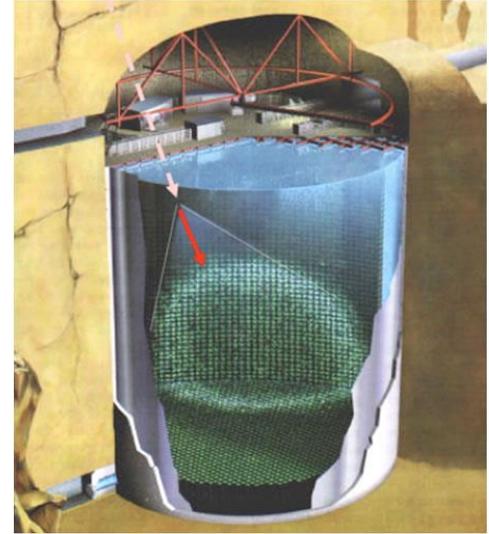


Method of long time simulation

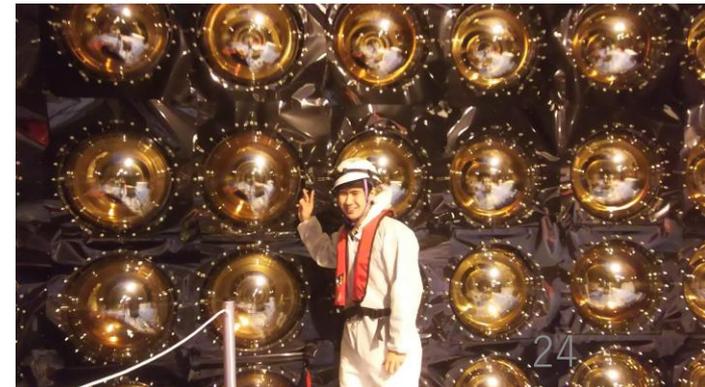
- Simulate supernovae in one-dimension
- Code
 - GR1Dv2 (public code: <http://stellarcollapse.org>)
 - O'Connor, ApJS 219 24 2015
 - Gravity: General relativity
 - M1 scheme
 - Modified for long-term simulation
 - Resolved reference out of physics tables
 - Optimized resolution of time and space
 - EOS: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

Super-Kamiokande(SK)

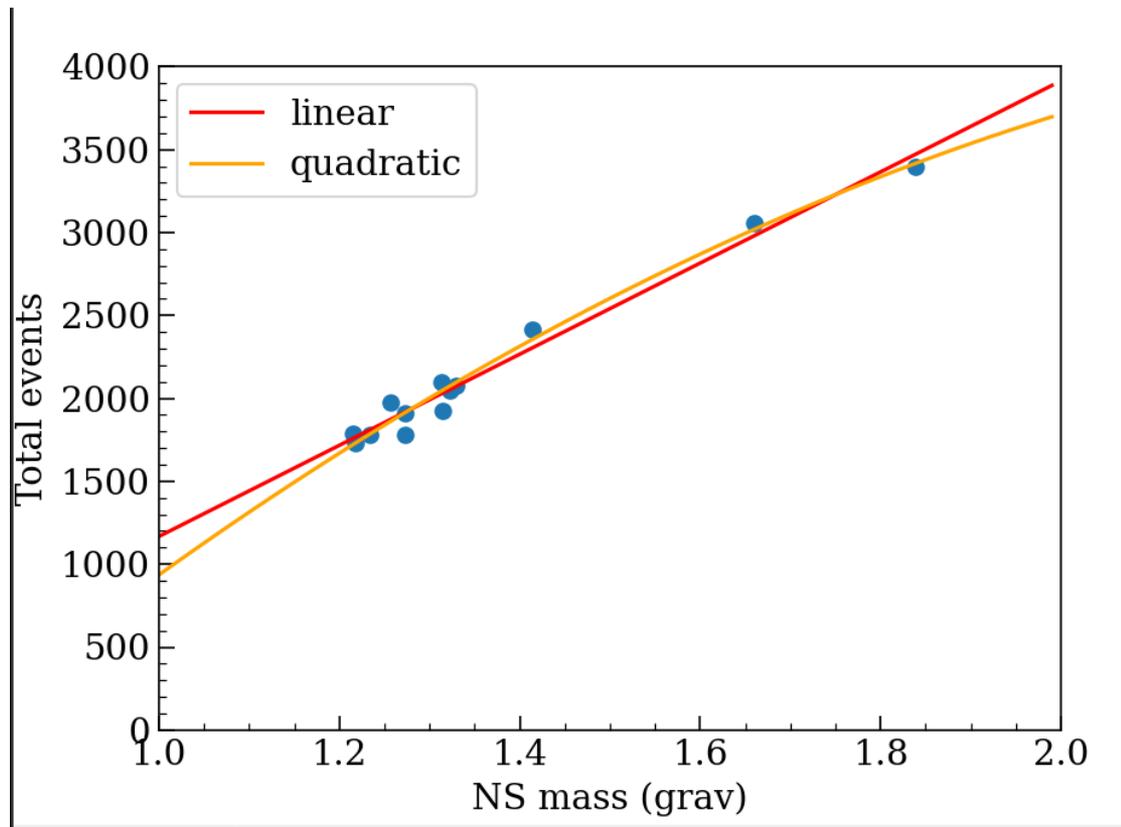
- Water Cherenkov detector in the Gifu prefecture.
 - Height: 41.4 m
 - Diameter: 39.3 m
 - Inner detector: 32.5 kton
 - Number of PMTs: 11,129
 - Energy threshold: 5MeV
- Various neutrino studies
 - atmosphere, solar , accelerator...
- Monitoring supernovae for 24 hours
 - If galactic supernovae happen, it is predicted to detect from 2,000 to 7,000 events.



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

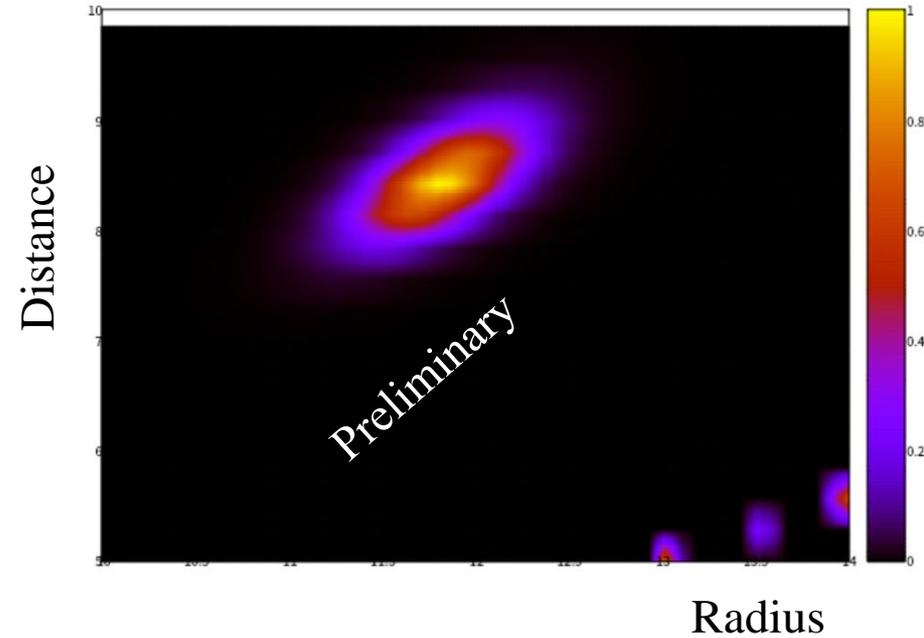
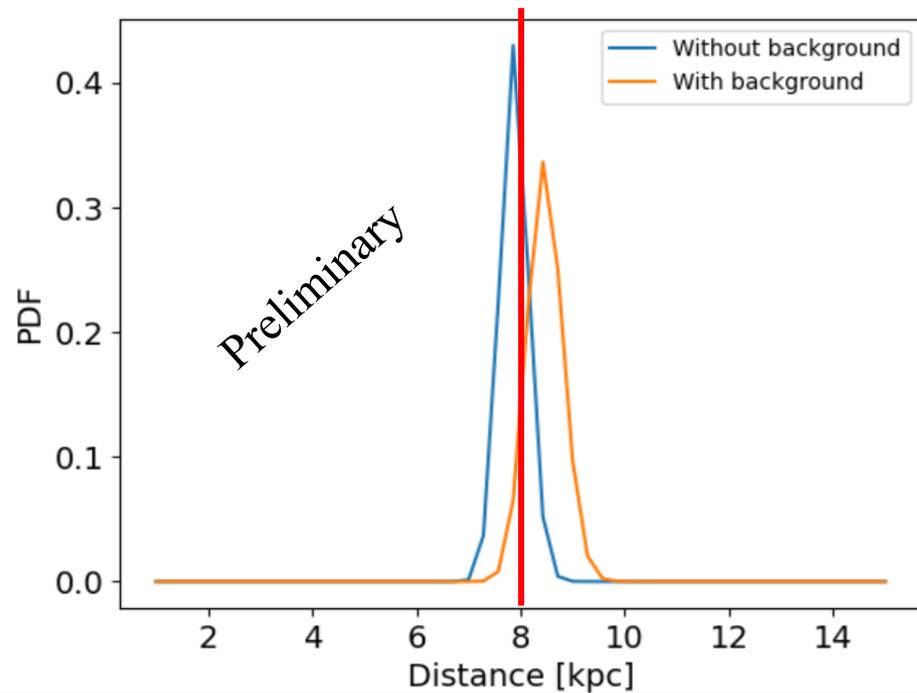


Total events and neutron star masses



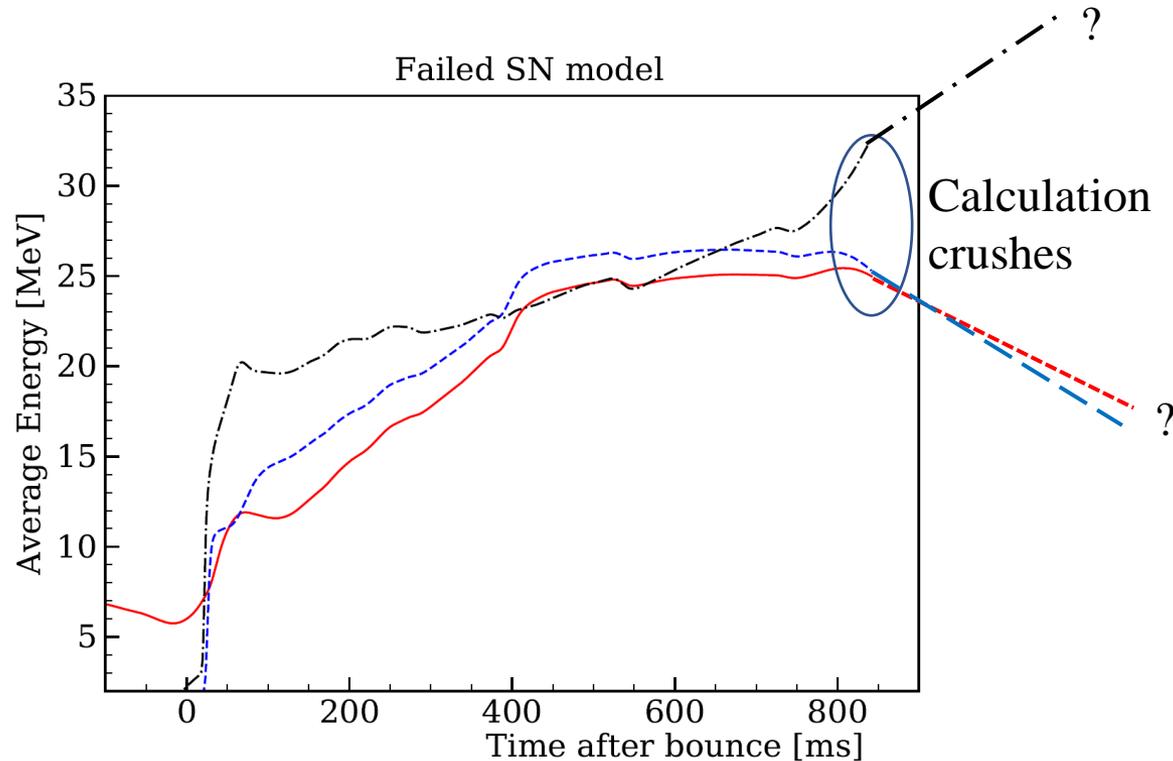
- Vertical axis: the number of events at SK for 10 s.
- Horizontal axis: neutron star mass
- It seems that heavier neutron stars lead to more neutrino events.
 - It possible to estimate neutron star mass from neutrino events.

Distance estimation (Preliminary)



- Developing the distance estimation.
 - Want to know mass, radius, energy and distance

First idea



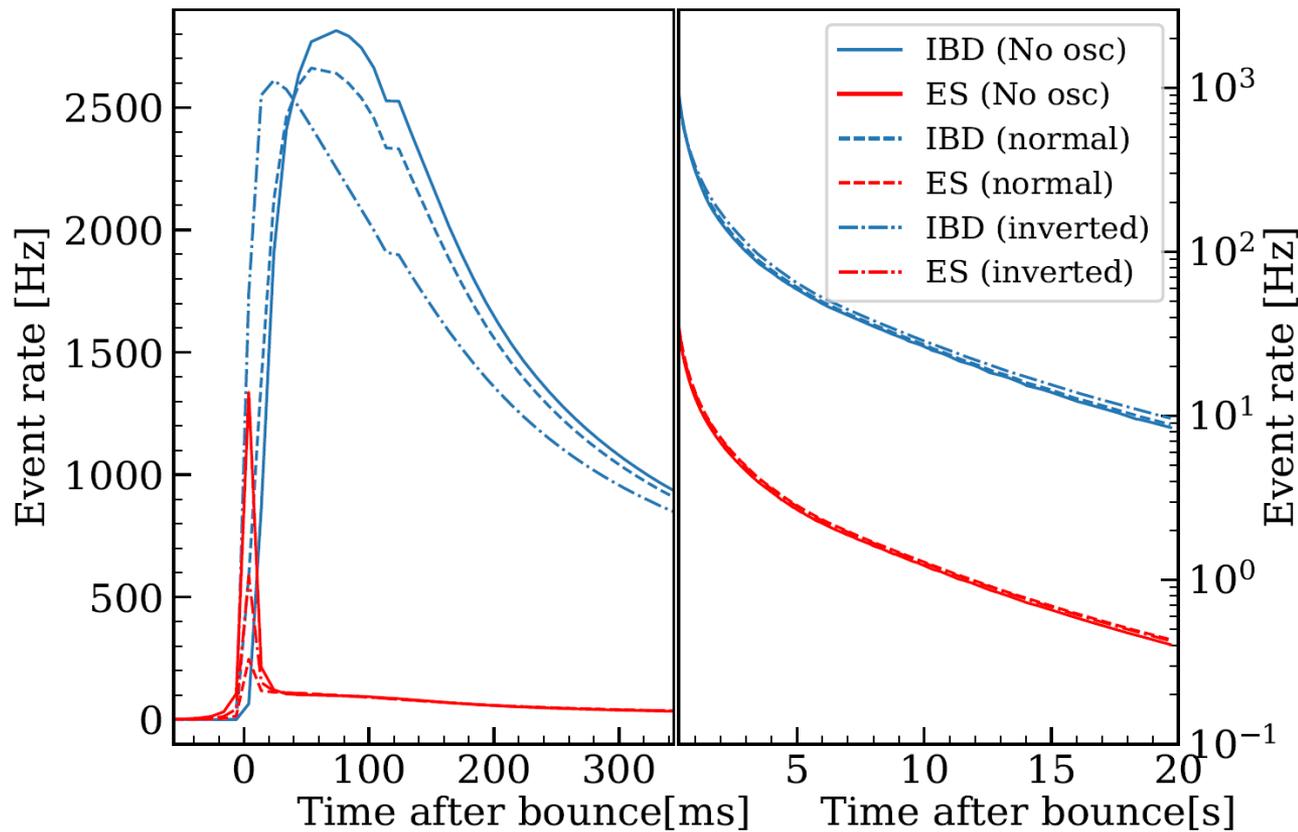
Misner-Sharp metric

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

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

- 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

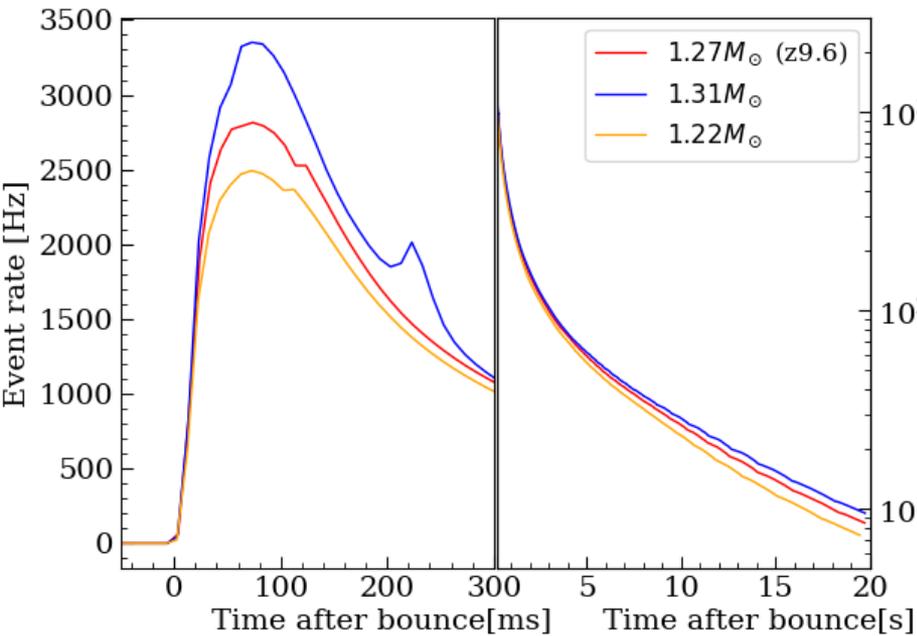
Recent simulations

| | 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 |

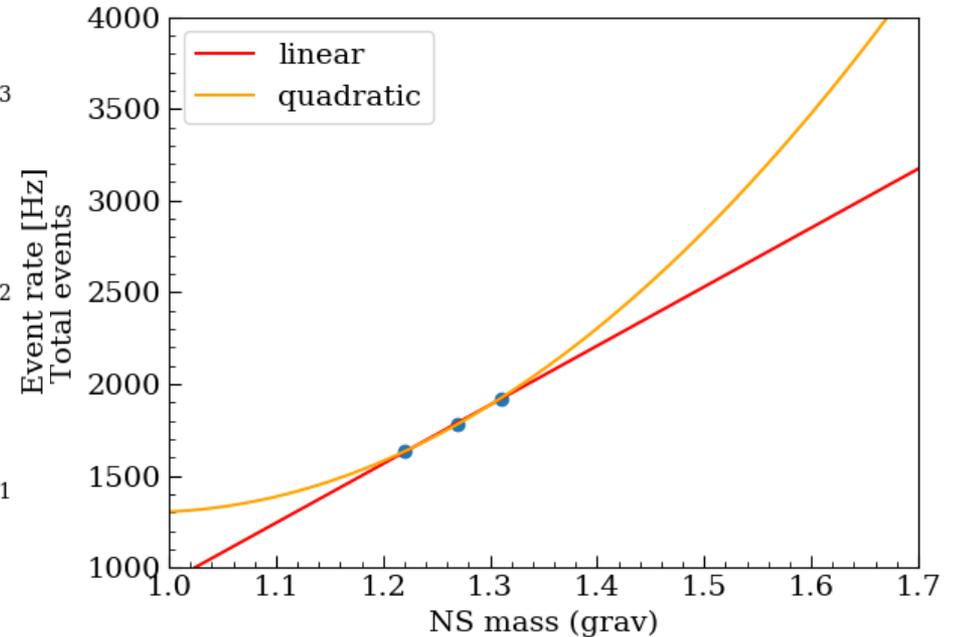
- To explode without artificial methods in one-dimension is difficult
 - Enhancement of neutrino reaction rates
 - Removal of material accreting
- Long time simulation in multi-dimension is impossible
- We do long time simulation in one-dimension **without artificial methods**

Neutrino and neutron star mass

Event rate at 10 kpc

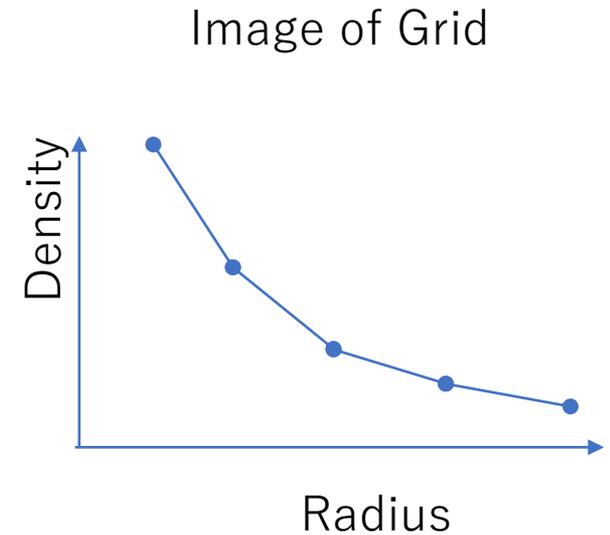
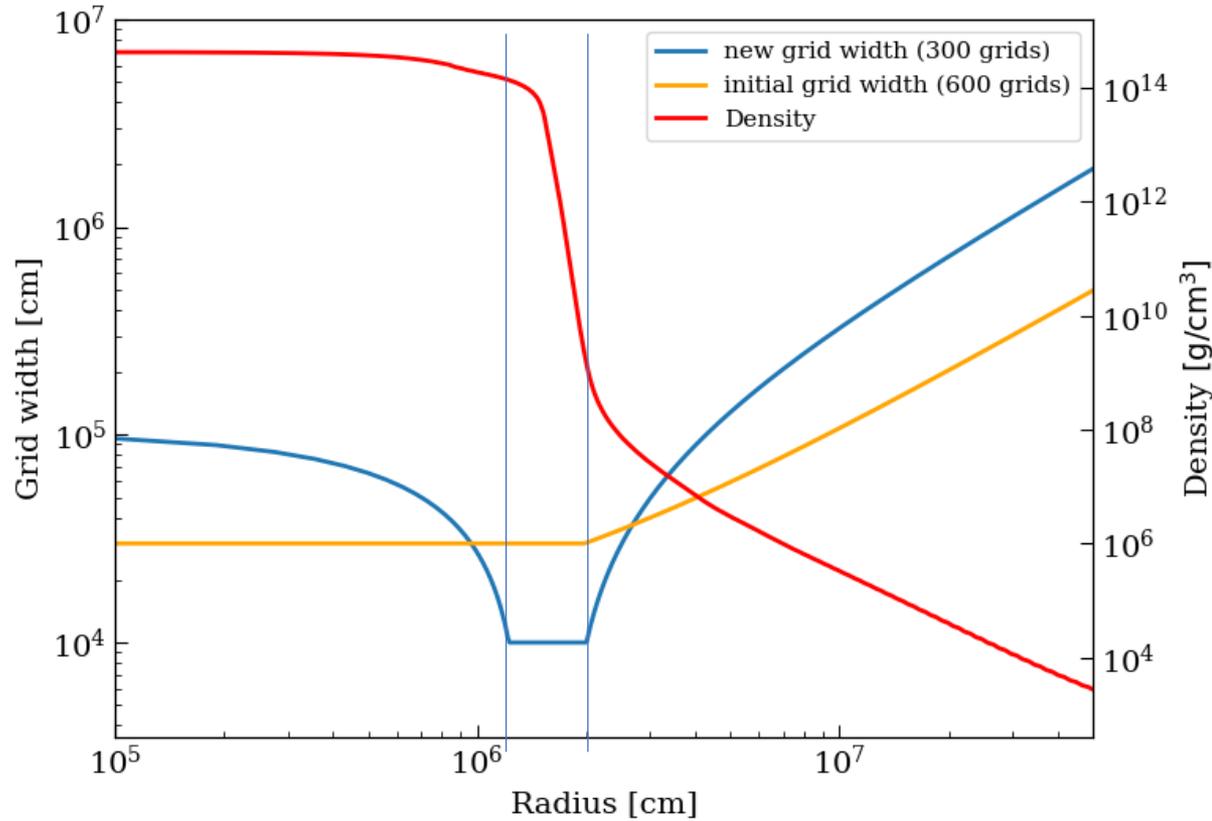


Relation between the number of events and neutron star mass



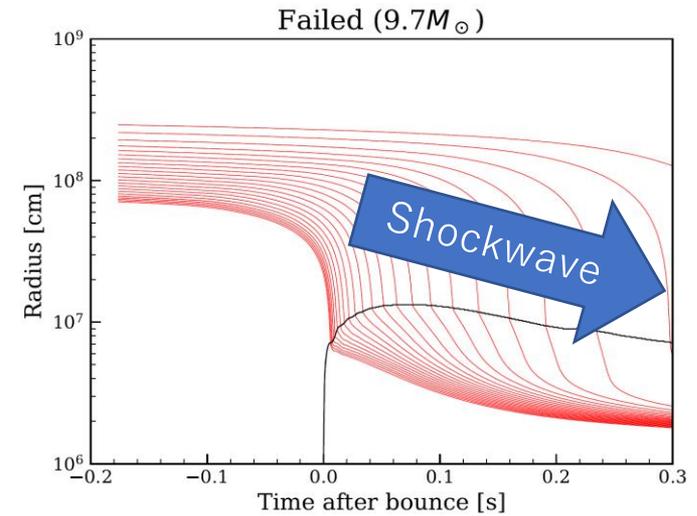
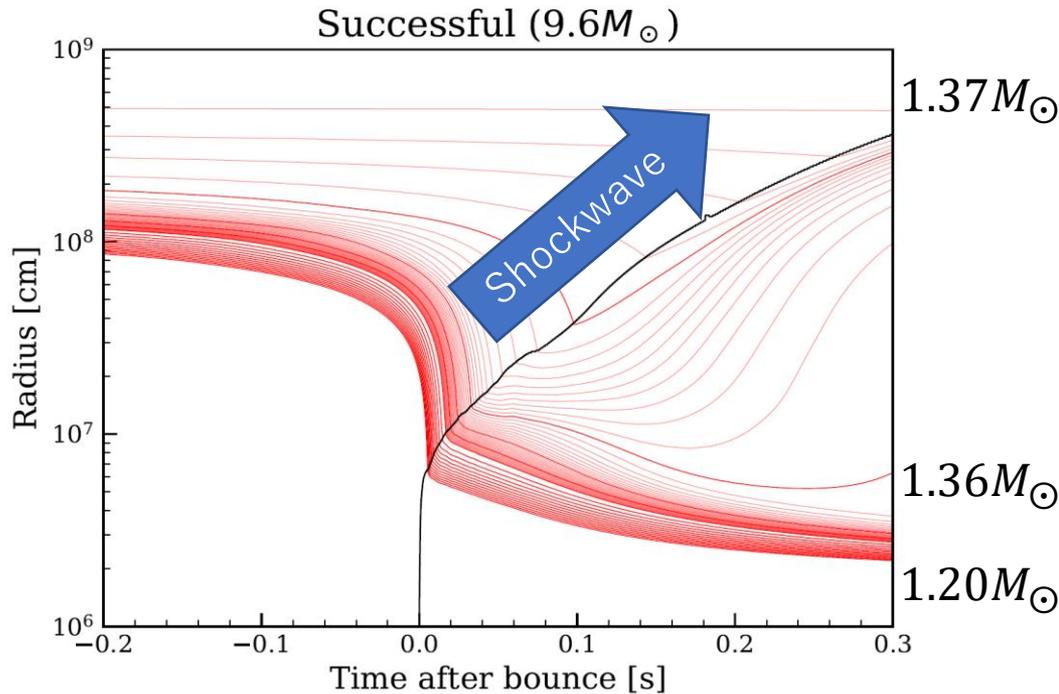
- Three simulations which lead to different neutron star mass
- If distance is determined, neutron star mass is maybe determined.
 - More simulations are needed.
 - In addition, I'm developing simulation in the case of BH formation.

Device of grids



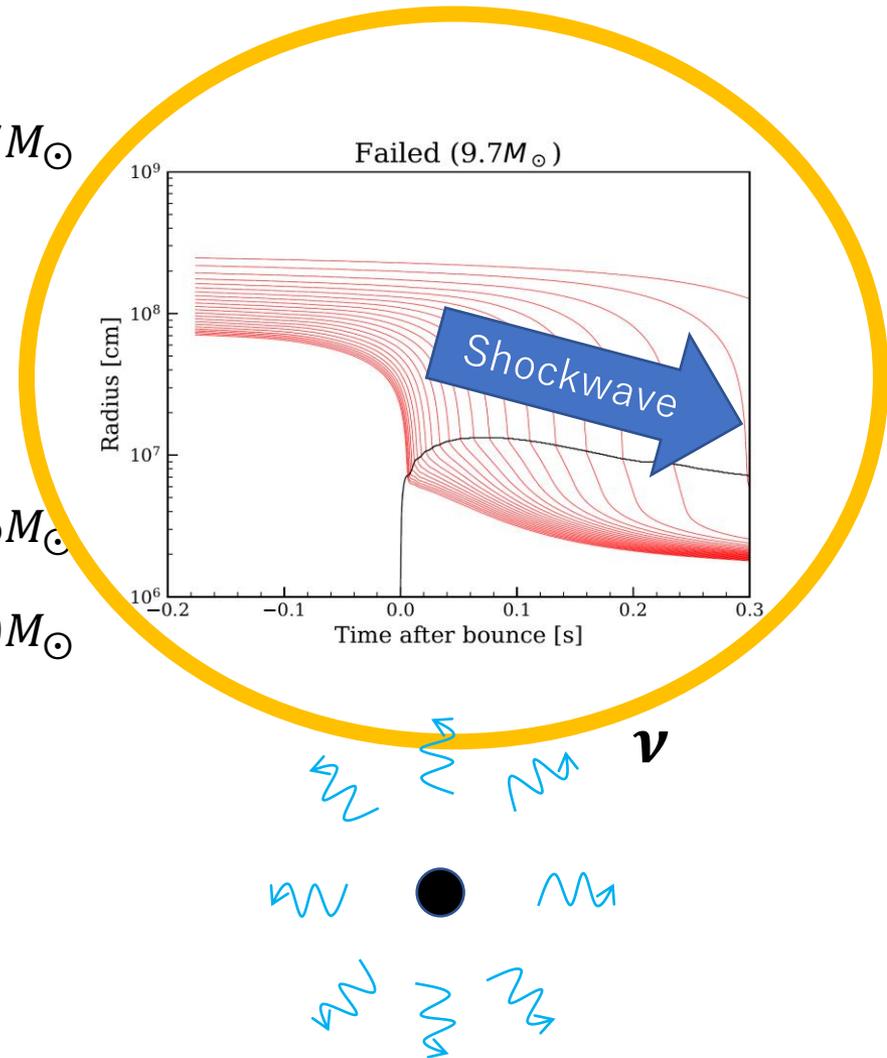
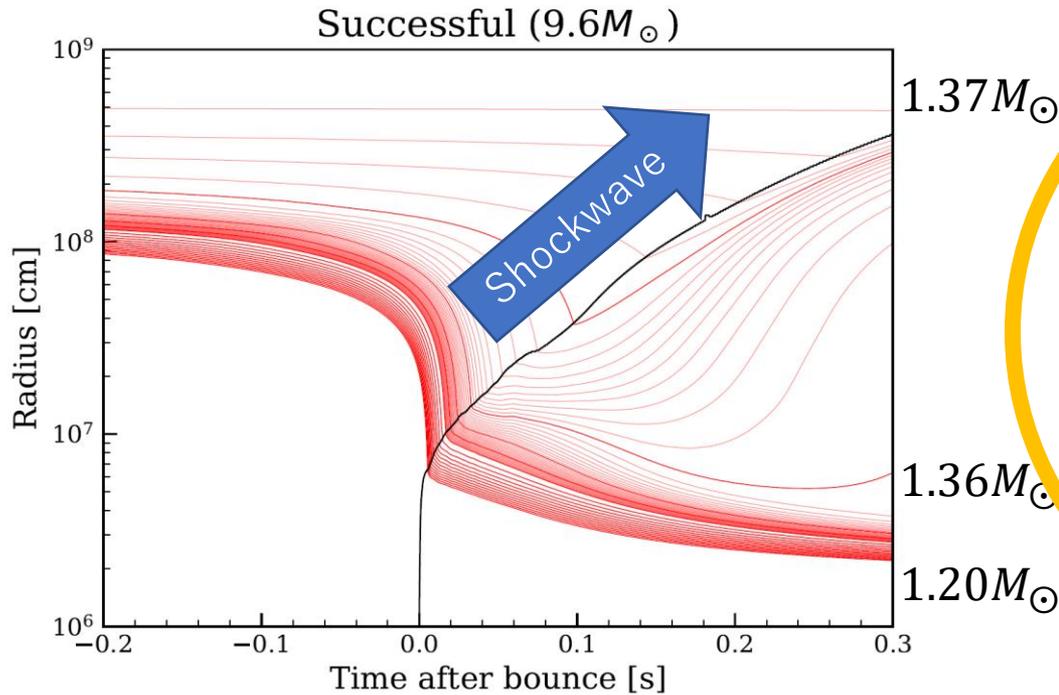
- **Red** : Density structure of PNS
- **Yellow** : Initial grids (600 grids)
- **Blue** : Optimized grids (300 grids)
- The region in which the density drastically changes is finely resolved.
 - Initial grids make calculation stop at about 5 sec.
 - Cost is also too high

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 mass, initial metallicity is 0
 - Called z9.6

Black hole formation



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

Hernandez–Misner metric

- Misner-Sharp metric

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

- Introduce new time u

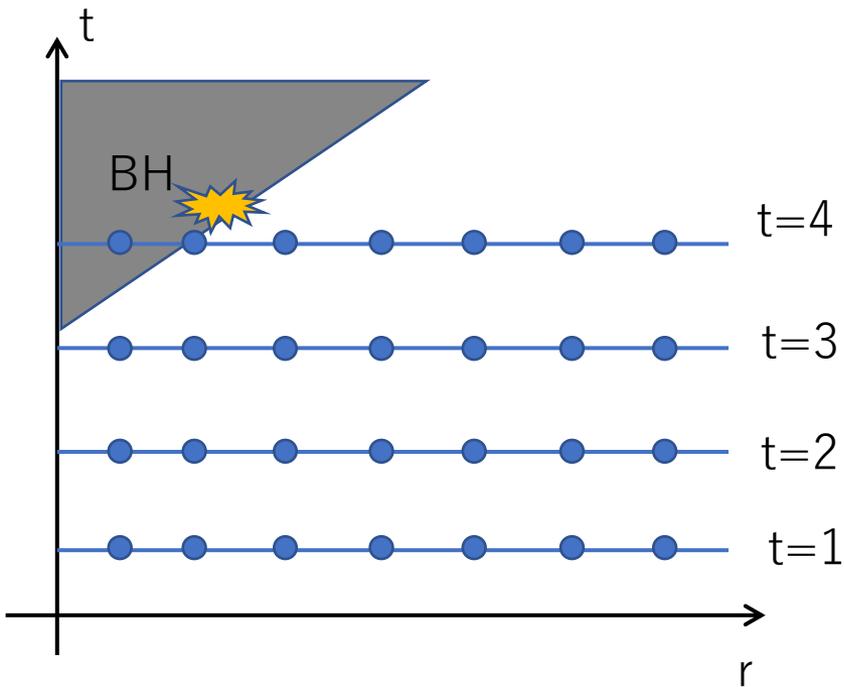
$$e^\psi du = e^\phi dt - Xdr$$

- Hernandez-Misner metric

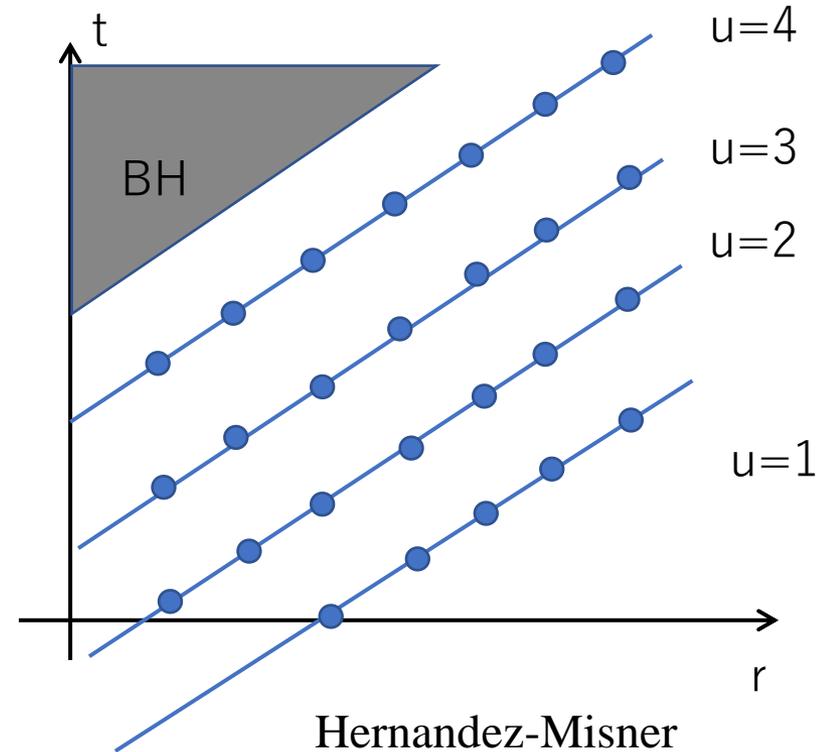
$$ds^2 = -e^{2\psi} du^2 - 2e^\psi Xdrdu + d\Omega^2$$

- 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.

Gravitational eigenmodes

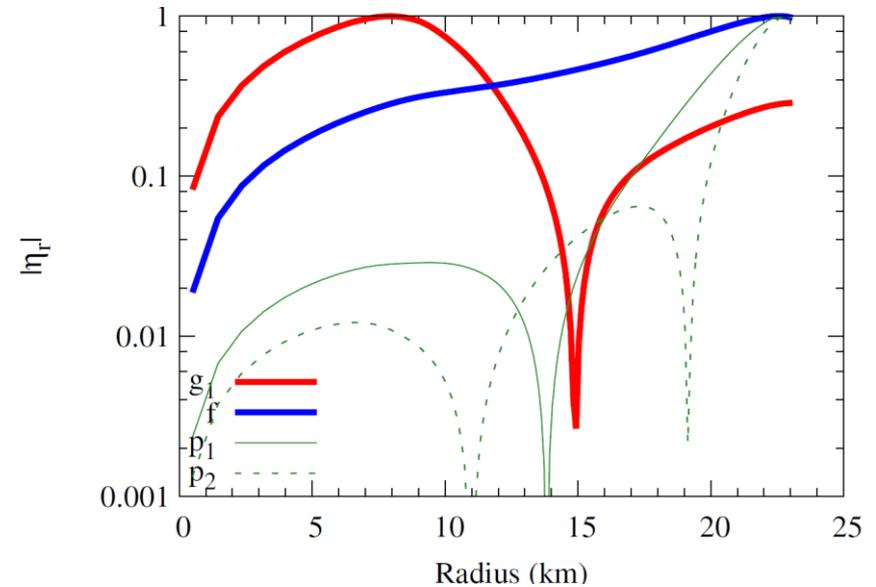
- Supernovae also emit gravitational waves.
- We estimated eigenmode frequencies with the asteroseismology approach.
 - Used GREAT (<https://www.uv.es/cerdupa/codes/GREAT/>)
 - Torres-Forné et al, MNRAS, 474, 5272 (2018)
 - Torres-Forne et al, arxiv:1806.11366 (2018)
- Linear perturbation analysis both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

- Linear perturbation equations

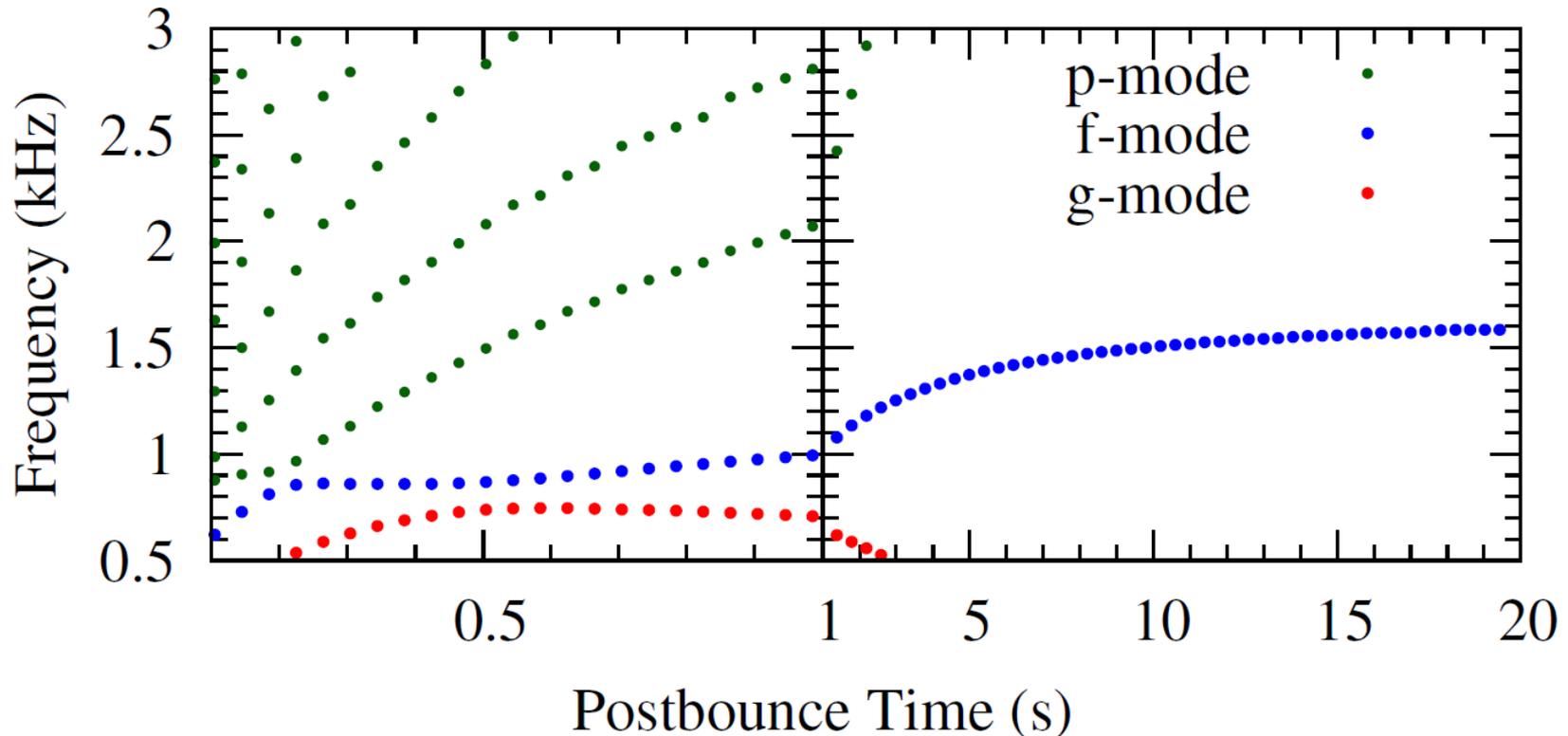
$$\partial_r \eta_r + \left[\frac{2}{r} + \frac{1}{\Gamma_1} \frac{\partial_r P}{P} + \frac{\partial_r \psi}{\psi} \right] \eta_r + \frac{\psi^4}{\alpha^2 c_s^2} (\sigma^2 - \mathcal{L}^2) \eta_{\perp} = \frac{1}{c_s^2} \frac{\delta \hat{Q}}{Q} - \left(6 + \frac{1}{c_s^2} \right) \frac{\delta \hat{\psi}}{\psi},$$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

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

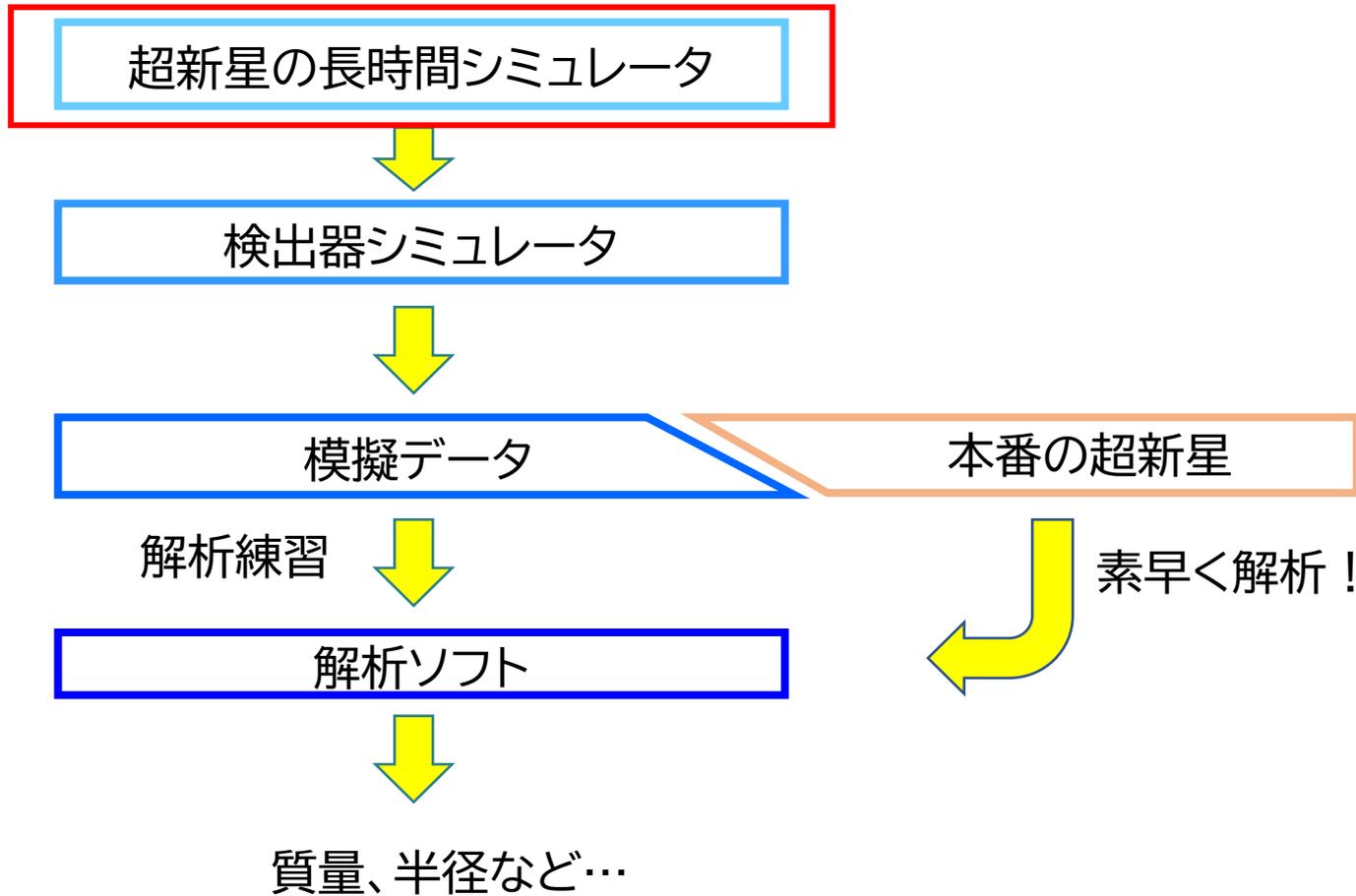


Gravitational wave frequency



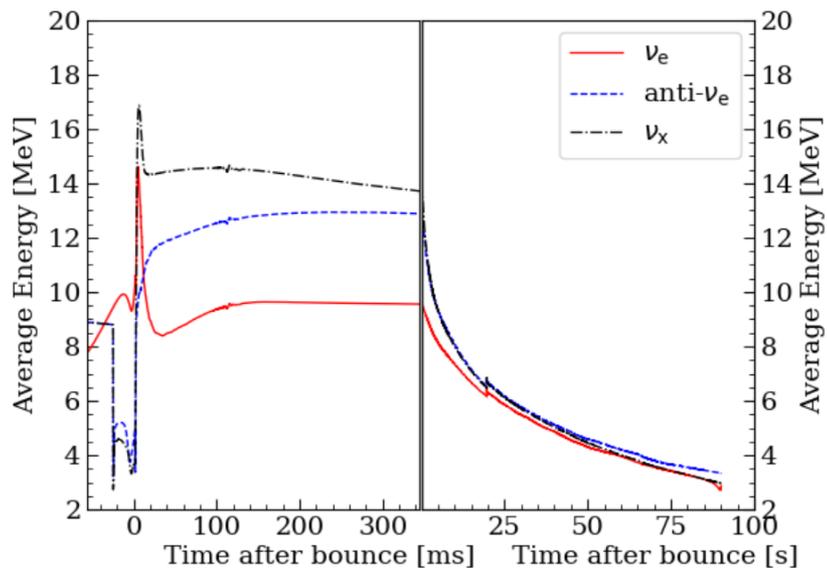
- Calculated eigenfrequencies up to 20 seconds.
- Differences of frequencies increase with time.
- Next, we make fitting functions.

超新星の長時間シミュレータ

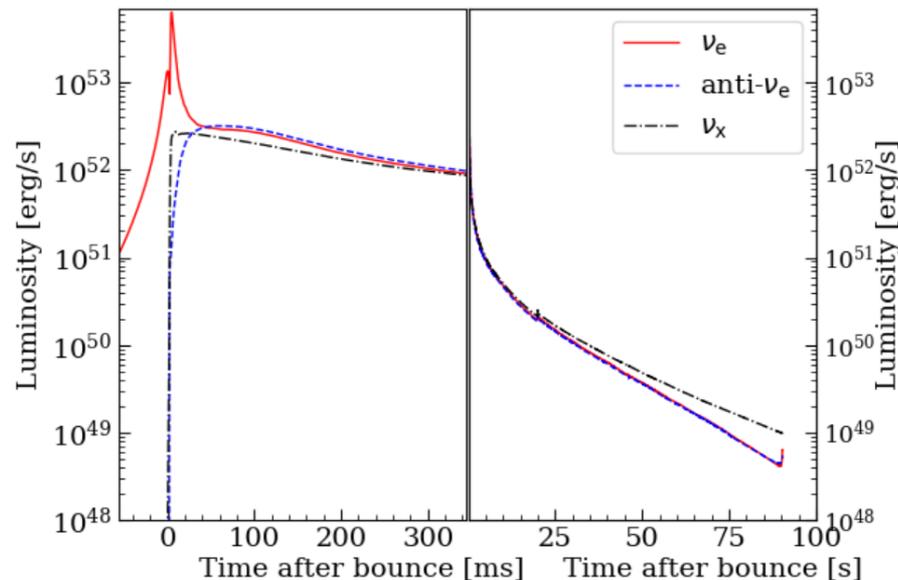


長時間の超新星ニュートリノ計算

ニュートリノ平均エネルギー



ニュートリノルミノシティ



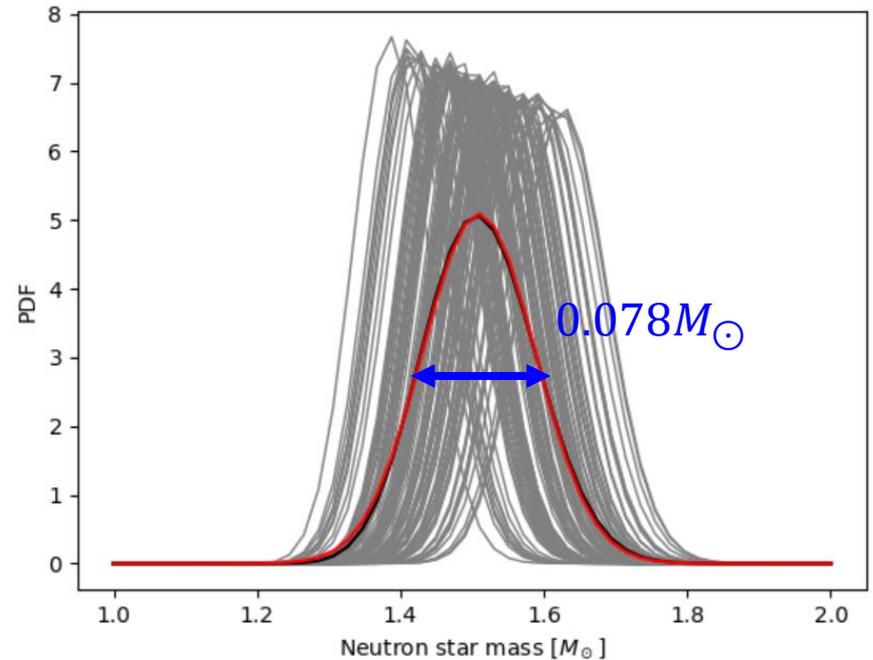
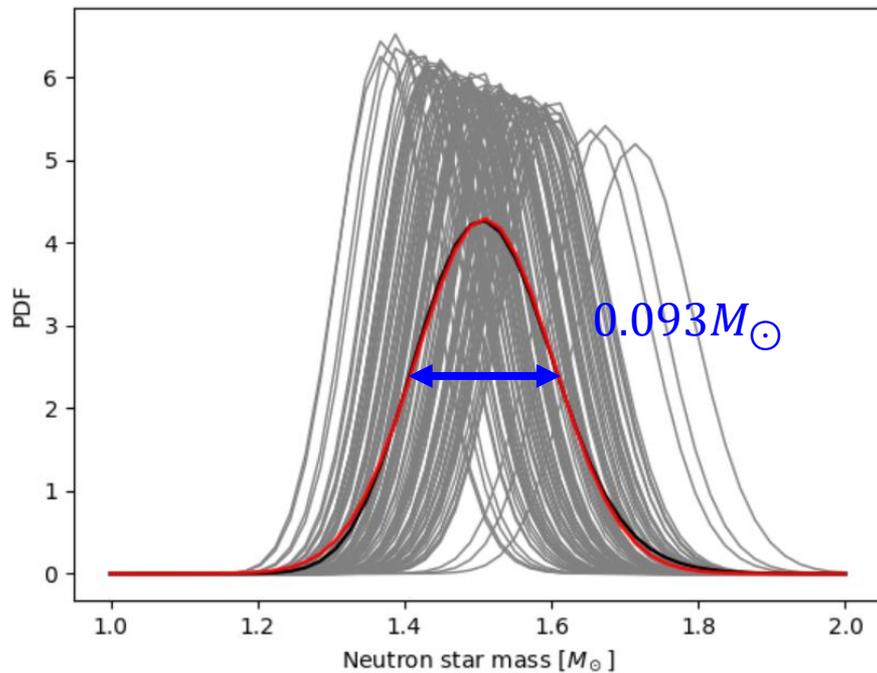
ν_x : μ and τ (anti) neutrinos

Mori et al. 2021

特長

1. 1次元一般相対論ニュートリノ輻射輸送流体計算
2. Non-artificial explosion
3. 一般相対論ニュートリノ輻射輸送流体計算では世界最長

パラメータ推定の誤差



- ガウシアンでフィッティングして分散を求める
 - イベント数が多くなるので分散は小さい