ブラックホールを形成する場合の超新星爆発の計算
Calculation of a supernova in the case of BH formation

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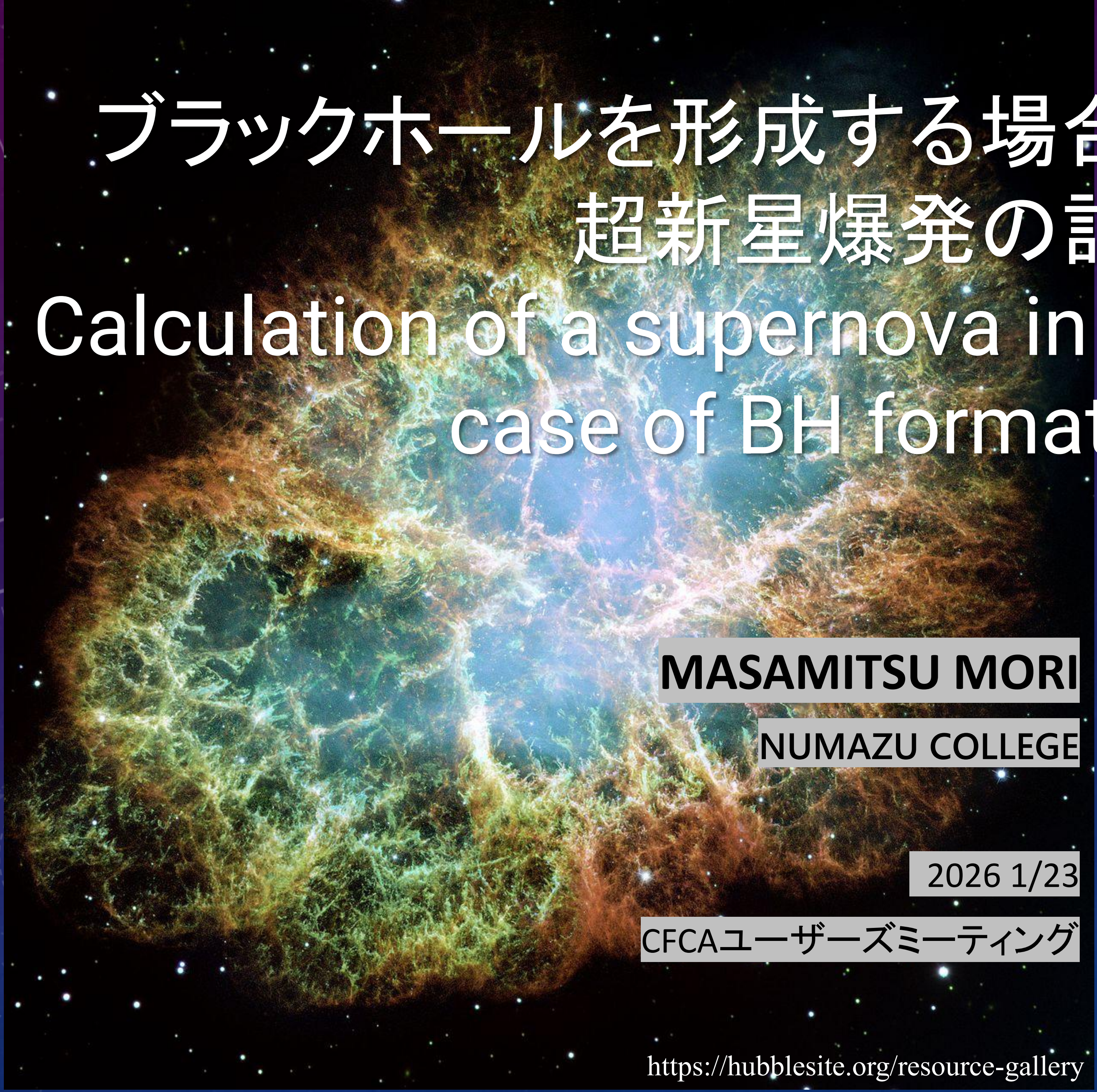
NUMAZU COLLEGE

2026 1/23

CFCAユーザーズミーティング



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Contents

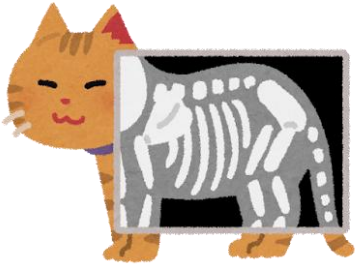
1. Supernova
2. To black holes from supernovae
3. Simulation of a failed supernova

Keywords

Supernova neutrino, Super-Kamiokande, Neutrino observation

Supernova and Neutrino

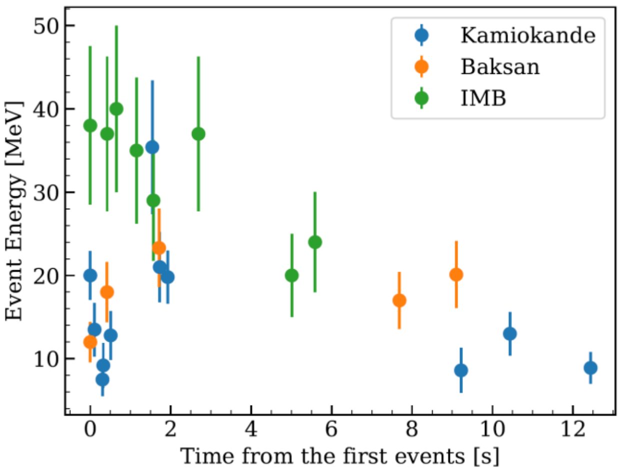
- Huge explosion of heavy stars at their death
  - Forms a neutron star or a black hole (BH)
- The "Brightest" neutrino source
- 99% of its energy released as neutrinos
  - Neutrinos can penetrate the center
  - ➤Only one observed example: SN1987A

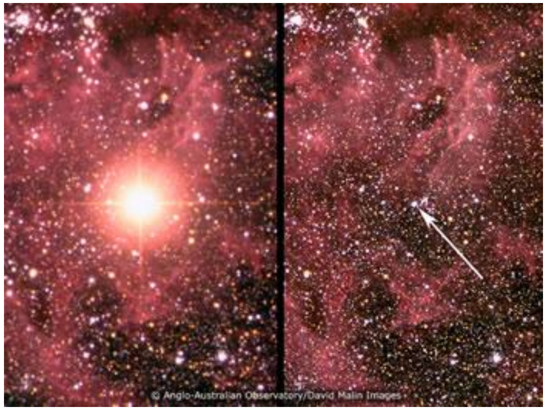


SN1987A events

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

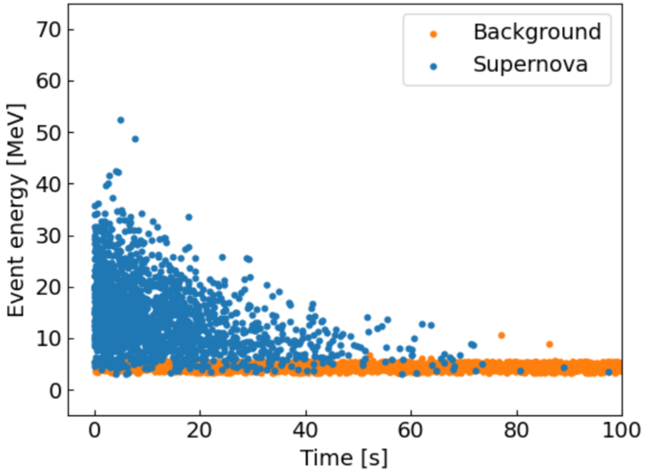
[1]Hirata et al. 1987
[2]Bionta et al. 1987
[3]Alekseev et al. 1987



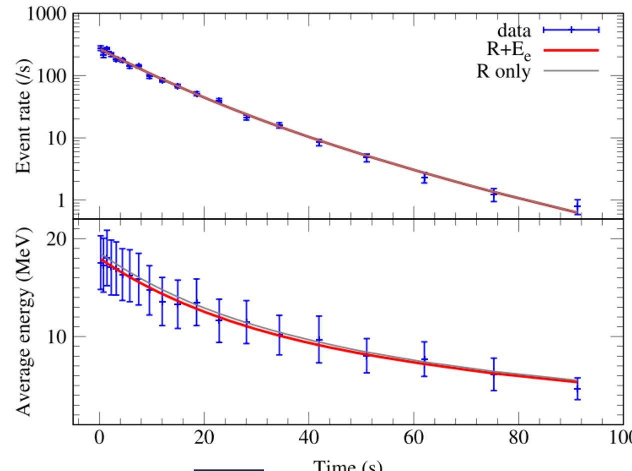


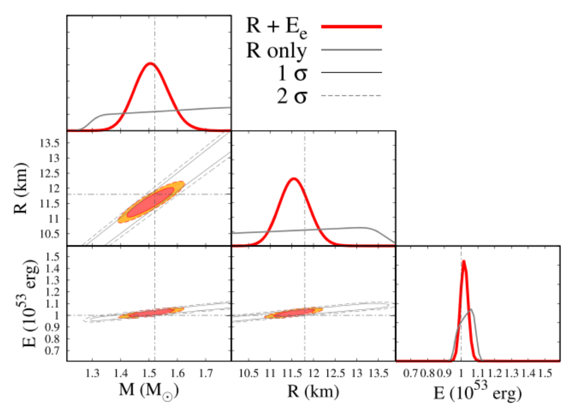
Neutrino templates and analysis of neutron stars

Supernova events



Distributed to time bins

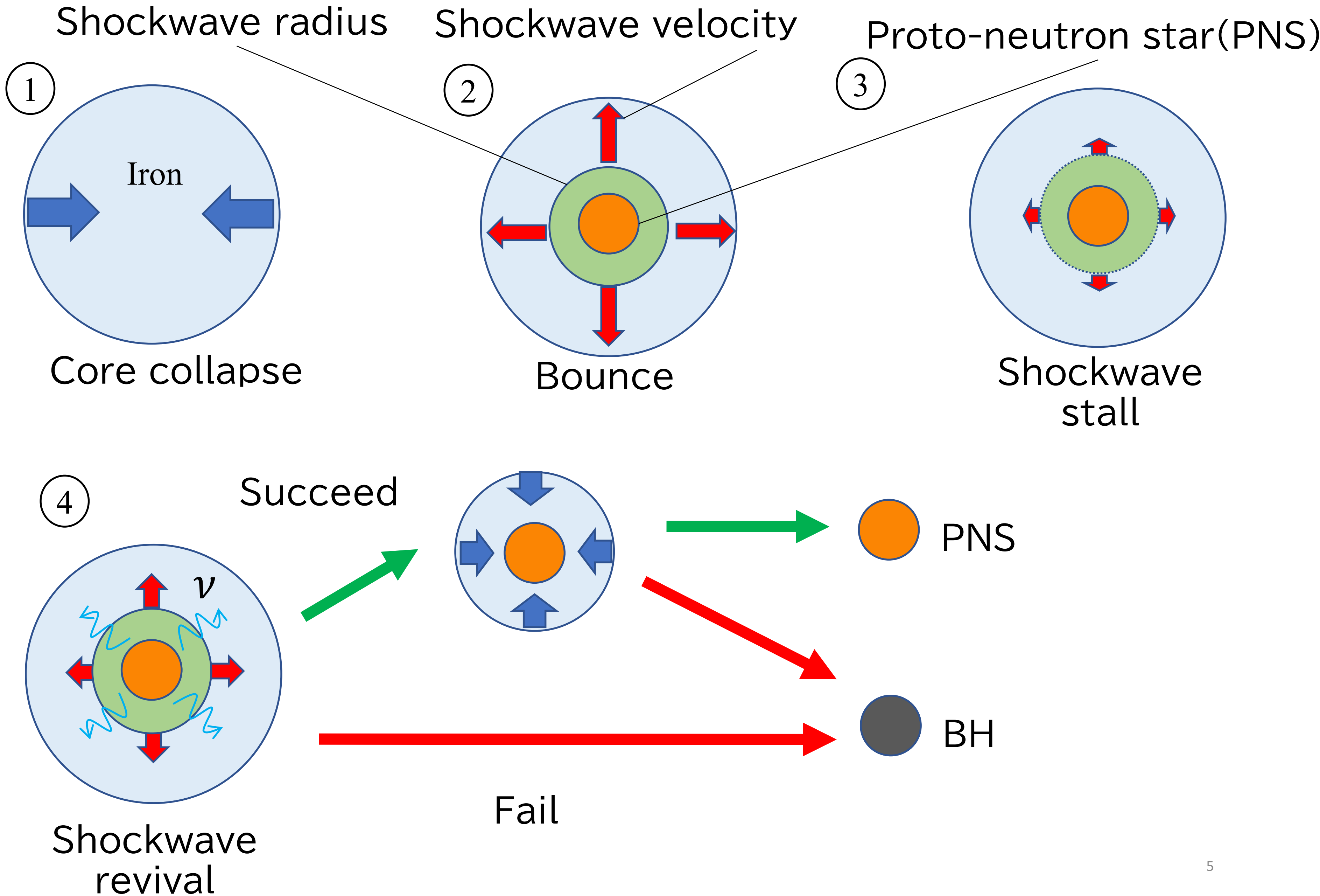




Event rate $R(t)$
and
Average energy $\langle E \rangle(t)$

- Many studies of supernova neutrinos for neutron star formation
  - Able to obtain neutron star properties from neutrinos

Supernova evolution into a NS or a BH



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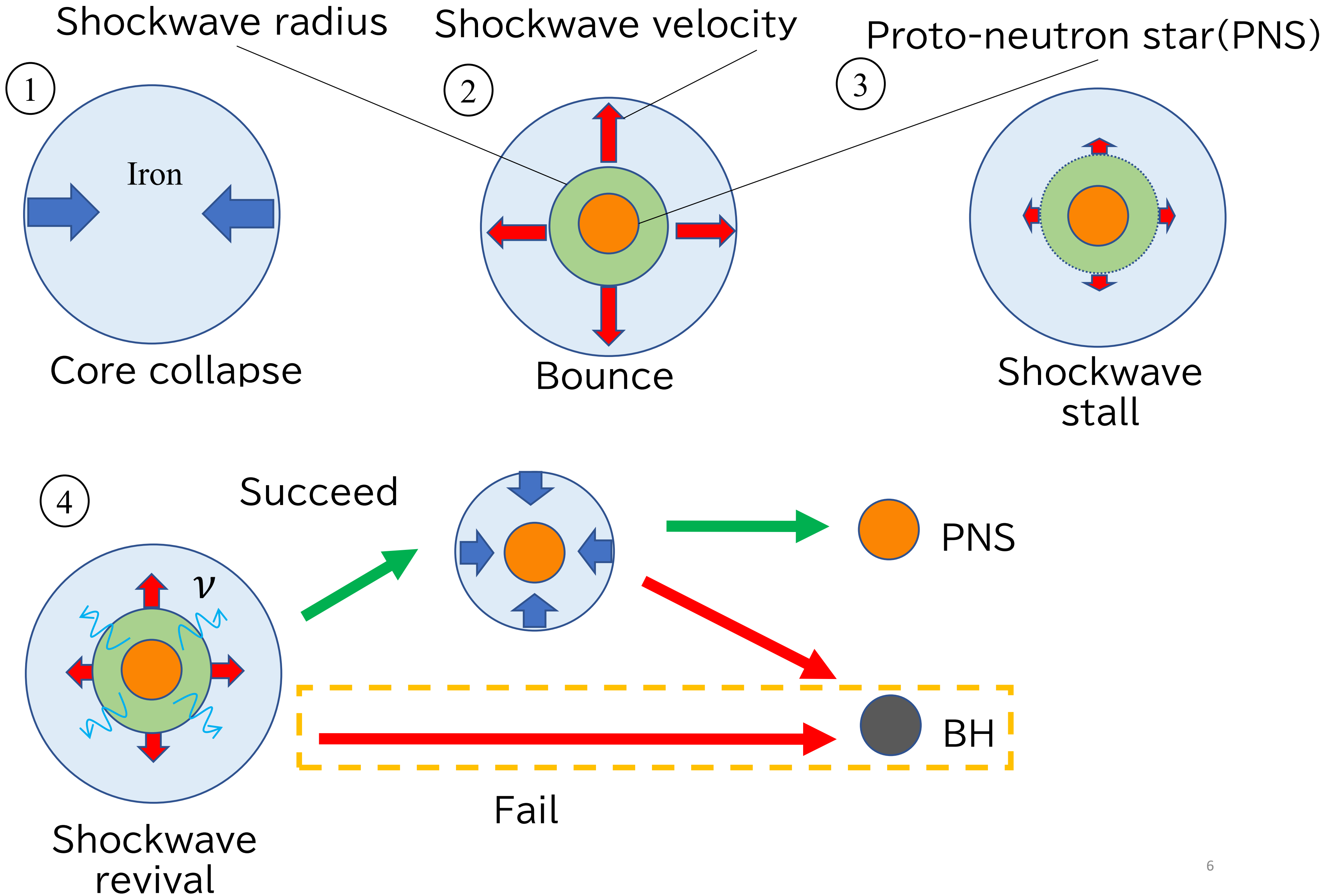
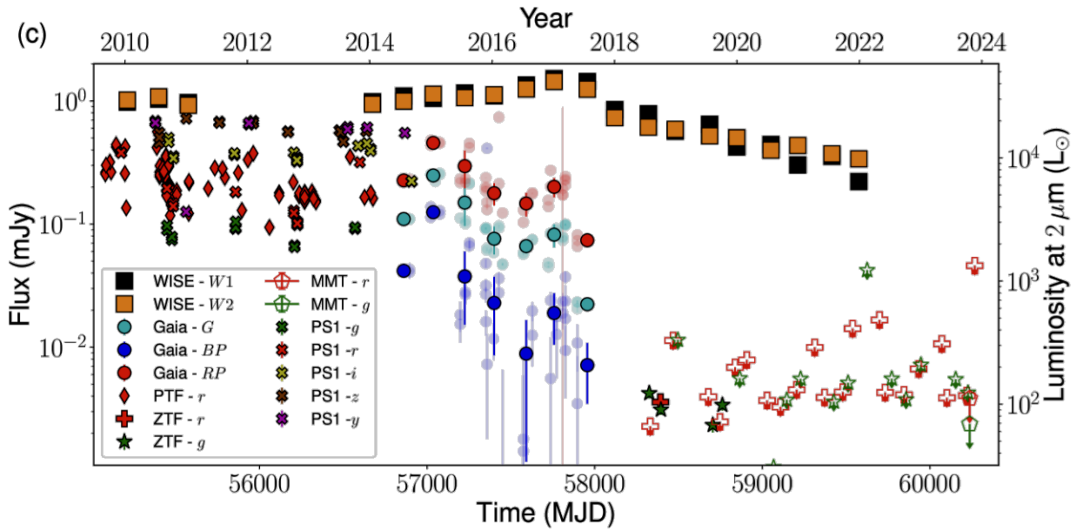
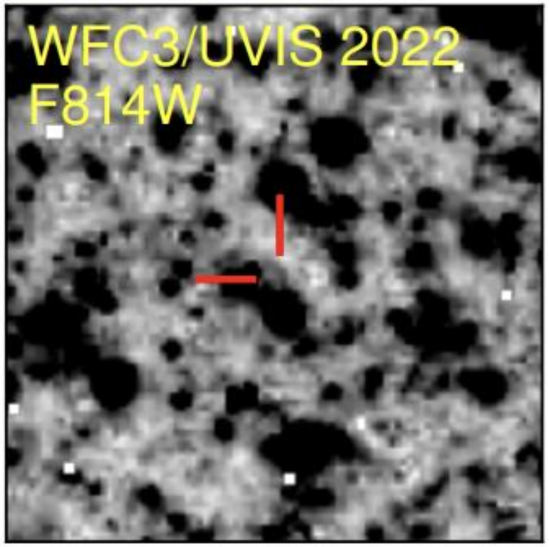


Failed SN？



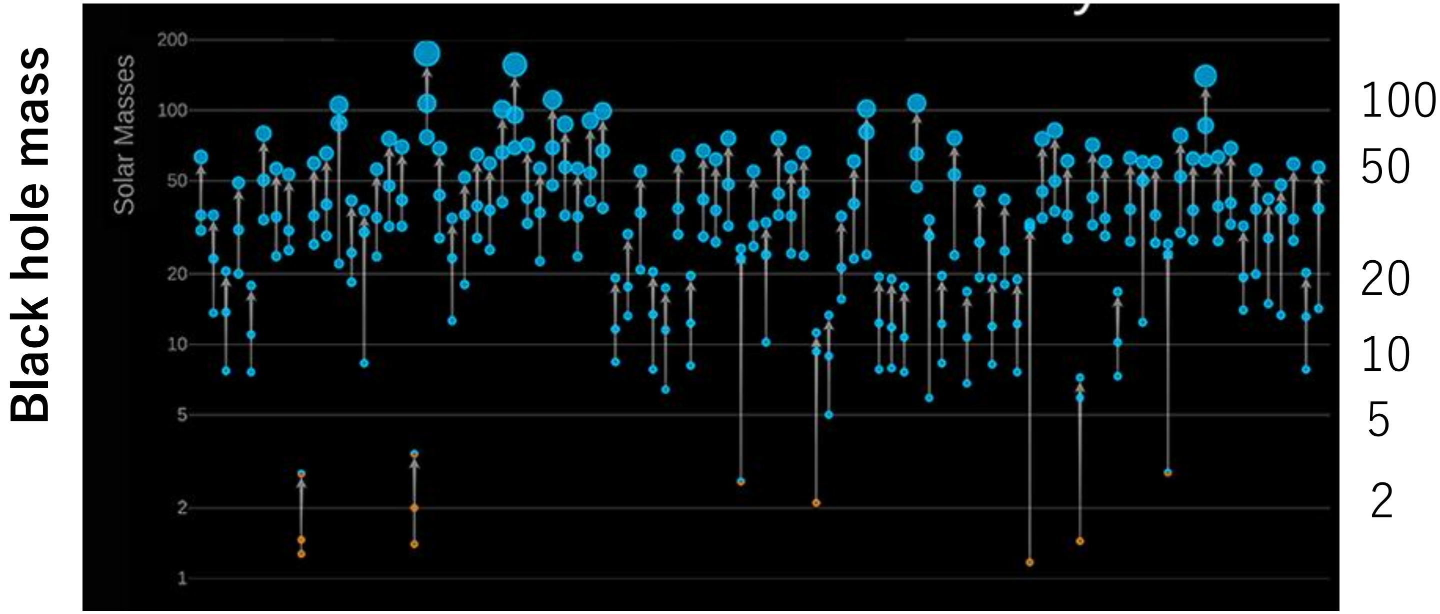


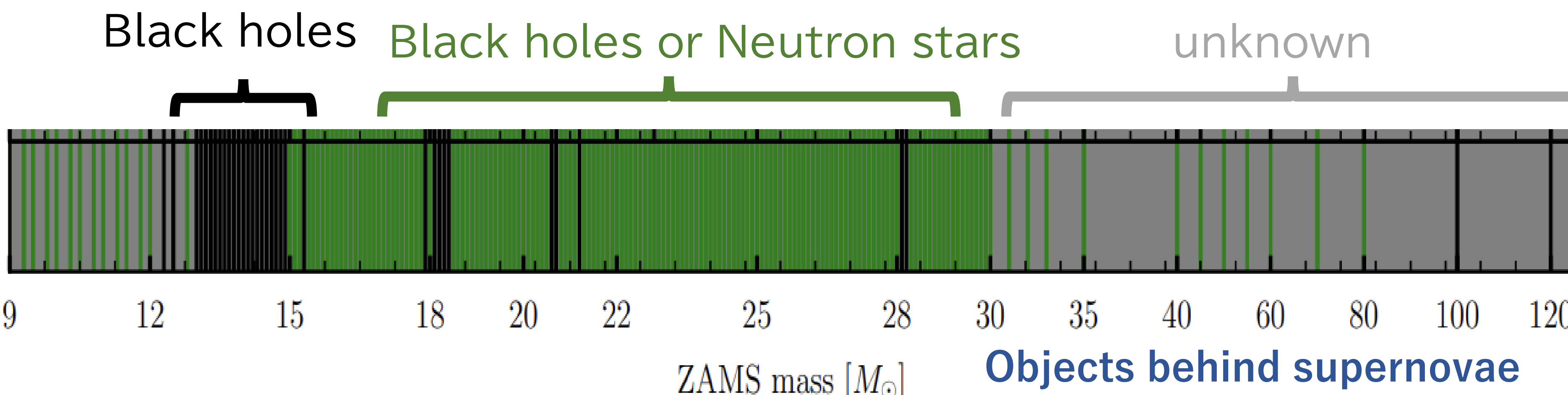
M31-2014-DS1

- A star faded into darkness in M31 in sudden.
- Failed SN?
  - Kishalay De et al. (2026)
  - Emma R. Beasor et al.(2026)

Divergence of stellar mass black hole

Mass distribution of black holes from the GW observation





Objects behind supernovae

Boccioli et al. (2024)

Simulations of neutrinos of collapse into black holes

References[a]	Progenitor mass ($M_\odot$)	EOS	Gravity	t_{BH}[b] (s)	E_{ν_e} (10^{53} erg)	$E_{\bar{\nu}_e}$ (10^{53} erg)	E_{ν_X} (10^{53} erg)	$\langle\varepsilon_{\nu_e}\rangle$ (MeV)	$\langle\varepsilon_{\bar{\nu}_e}\rangle$ (MeV)	$\langle\varepsilon_{\nu_X}\rangle$ (MeV)
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Sumiyoshi et al. (2007)	40 (WW95)	Shen-TM1	fGR	1.34	1.46	1.35	0.526	20.3	23.2	23.9
Sumiyoshi et al. (2008)	40 (H95[e])	LS180	fGR	0.36	0.334	0.271	0.160	13.5	16.8	21.9
Sumiyoshi et al. (2008)	50 (TUN07[f])	Shen-TM1	fGR	1.51	1.35	1.27	0.526	20.0	23.1	24.2
Sumiyoshi et al. (2008)	50 (TUN07)	LS180	fGR	0.507	0.450	0.372	0.191	15.7	19.0	21.2
Fischer et al. (2009)[g]	40 (WW95)	LS180	fGR	0.435	0.507	0.376	0.231	14.1	14.6	19.7
Fischer et al. (2009)	40 (WW95)	Shen-TM1	fGR	1.40	1.73	1.53	0.715	16.0	18.4	21.0
Nakazato et al. (2010)	40 (WW95)	LS220	fGR	0.780	0.729	0.627	0.382	17.3	20.1	24.1
Hüdepohl (2014)	40 (WW95)	LS180	eGR[h]	0.435	0.422	0.337	0.209	13.8	17.1	18.3
Hüdepohl (2014)	40 (WW95)	LS220	eGR	0.55	0.525	0.436	0.279	14.4	17.7	19.2
Hüdepohl (2014)	25 (WHW02[i])	LS220	eGR	1.225	0.696	0.632	0.331	15.3	18.5	17.7
Hüdepohl (2014)	40 (WHW02)	LS220	eGR	1.93	0.852	0.796	0.402	15.8	18.8	17.4
Sumiyoshi et al. (2019)	50 (TUN07)	Shen-TM1e	fGR	1.15	0.941	0.850	0.330	18.7	21.9	21.6
Sumiyoshi et al. (2019)	40 (WW95)	Shen-TM1e	fGR	1.103	1.15	1.05	0.422	19.3	22.4	23.1
Walk et al. (2020)	40 (WH07[j])	LS220	eGR	0.57	0.572	0.539	0.375	16.2	18.8	20.2
Nakazato et al. (2021)	30 (N13[k])	LS220	fGR	0.342	0.403	0.287	0.211	12.5	16.4	22.3
Nakazato et al. (2021)	30 (N13)	Togashi	fGR	0.533	0.685	0.533	0.289	16.1	20.4	23.4
Nakazato et al. (2021)	30 (N13)	Shen-TM1	fGR	0.842	0.949	0.81	0.400	17.5	21.7	23.4
Kresse et al. (2021)	40 (WW95)	LS220	eGR	0.57	0.938	0.862	0.483	15.7	18.7	17.6
Kresse et al. (2021)	40 (WHW02)	LS220	eGR	2.11	0.544	0.449	0.281	14.4	17.6	18.8
Largani et al. (2024)	40 (WHW02)	DD2F RDF-1.7	fGR	1.03	0.368	0.384	0.132	13.3	15.6	14.2
Choi et al. (2025)[l]	12.25 (S16&18[m])	SFHo	eGR	>2.09	0.563	0.511	0.297	13.9	16.3	15.5
Choi et al. (2025)	14 (S16&18)	SFHo	eGR	>2.82	0.768	0.711	0.393	15.0	17.3	15.9
Choi et al. (2025)	19.56 (S16&18)	SFHo	eGR	3.89	0.906	0.889	0.694	12.9	15.4	16.0
Choi et al. (2025)	23 (S16&18)	SFHo	eGR	6.23	0.776	0.736	0.609	12.4	14.7	14.8
Choi et al. (2025)	40 (S16&18)	SFHo	eGR	1.76	0.798	0.766	0.499	13.4	15.8	16.0
Choi et al. (2025)	100 (S16&18)	SFHo	eGR	0.44	0.529	0.462	0.246	12.9	15.1	17.1
unpublished[n]	40 (WW95)	Togashi	fGR	0.927	0.824	0.705	0.471	18.1	20.7	25.7

Many simulations?

Suwa et al. (2025)

Simulations of neutrinos of collapse into black holes

References[a]	Progenitor mass ($M_\odot$)	EOS	Gravity	$t_{\rm BH}$[b] (s)	E_{ν_e} (10^{53} erg)	$E_{\bar{\nu}_e}$ (10^{53} erg)	E_{ν_X} (10^{53} erg)	$\langle\varepsilon_{\nu_e}\rangle$ (MeV)	$\langle\varepsilon_{\bar{\nu}_e}\rangle$ (MeV)	$\langle\varepsilon_{\nu_X}\rangle$ (MeV)
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Too many $40M_\odot$ progenitors (and neighborhoods)!

Suwa et al. (2025)

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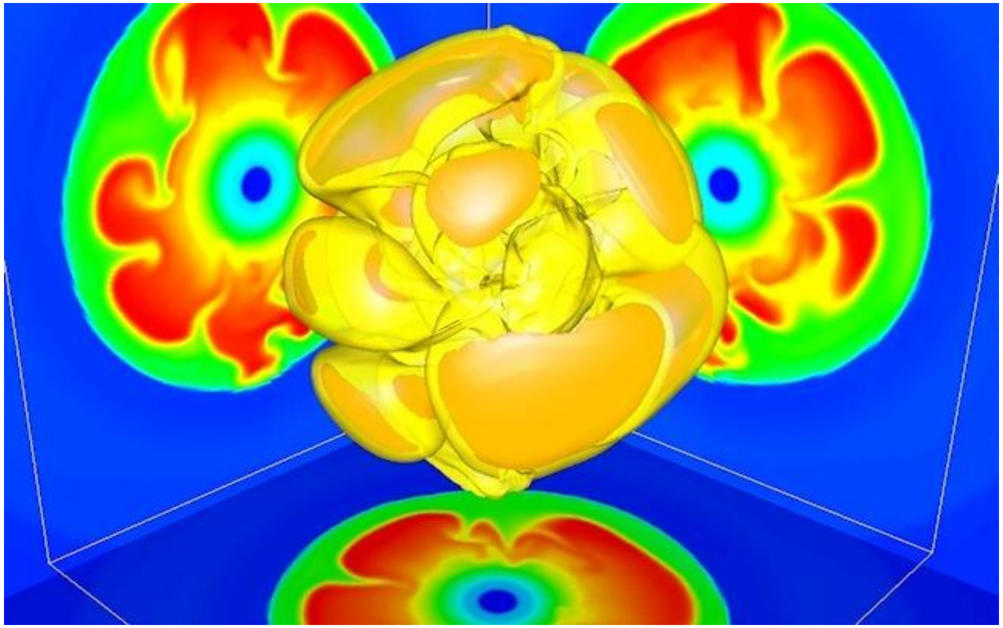
Non-full-G.R. simulations

Suwa et al. (2025)

Why are there few failed supernova simulations?

- People are interested in unveiling the supernova **explosion** mechanism.
  - Failed supernovae are just failed calculations.

- More difficult than calculation of neutron stars.
  - General relativity
  - Too extreme environment



By Takiwaki

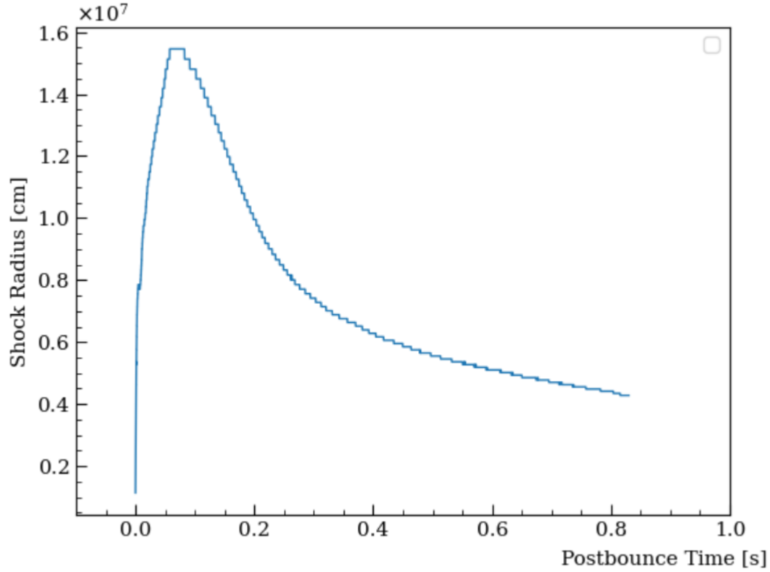
Black hole simulation

- Motivation
  - Make neutrino templates of failed supernovae
  - Calculate various progenitors and situations.

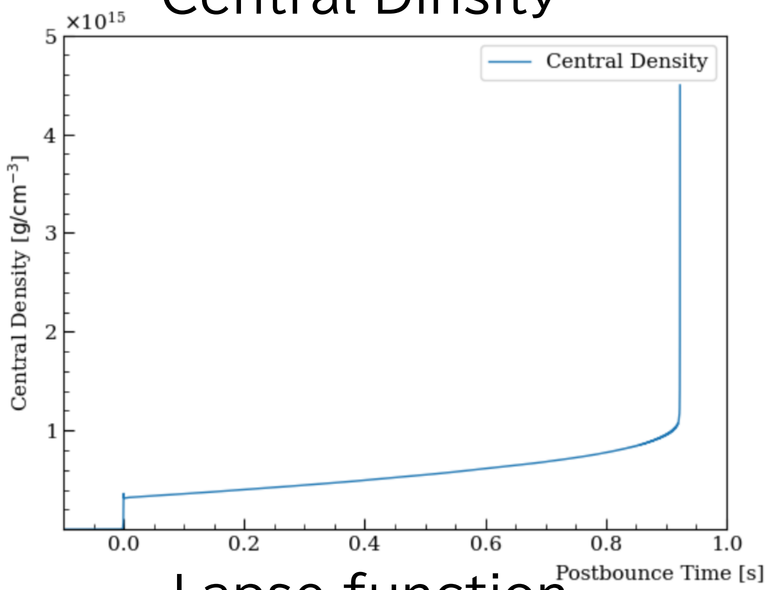
- Method
  - Computers
    - Personal Computer Cluster (PCC)
    - Open MP
  - GR1D (O'Connor et al. 2015)
    - **modified for black hole simulations**
    - General relativity
    - Neutrino radiation transport
    - 1D
  - EOS
    - Shen EOS (2020)
    - Wide-ranged parameters
      - Density: $\sim 10^{16}$g/cc
    - Maximum mass: $2.12 M_\odot$
  - Progenitor
    - $40 M_\odot$
    - Woosely and Weaver 1995

Fluid properties and metric

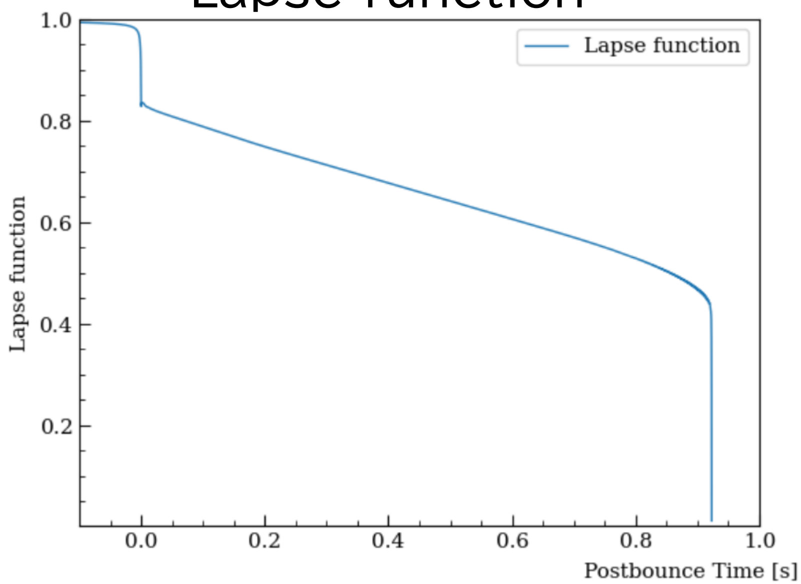
Shockradius



Central Dinsity



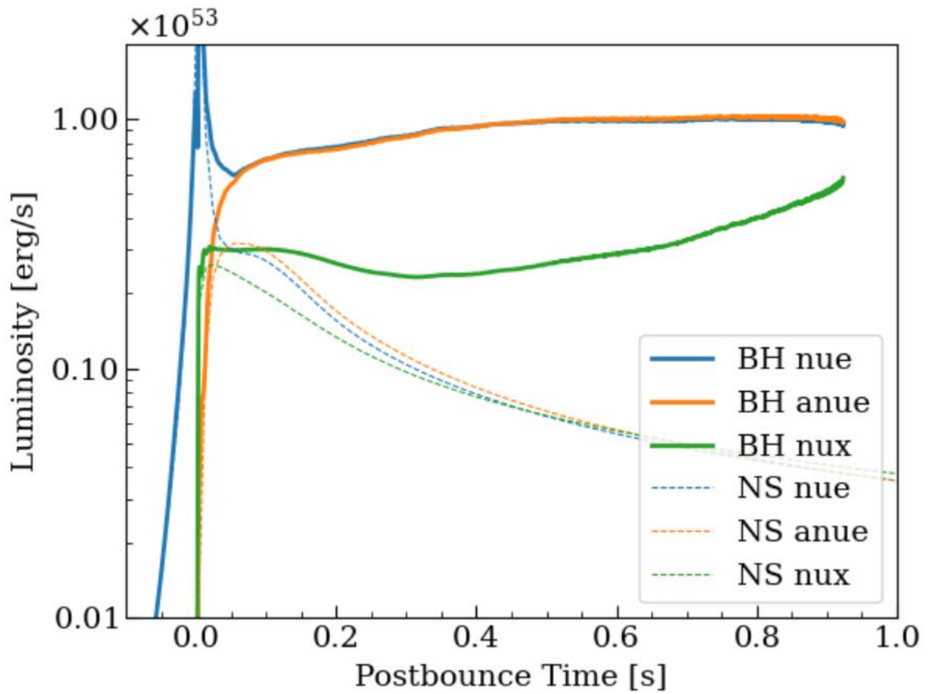
Lapse function

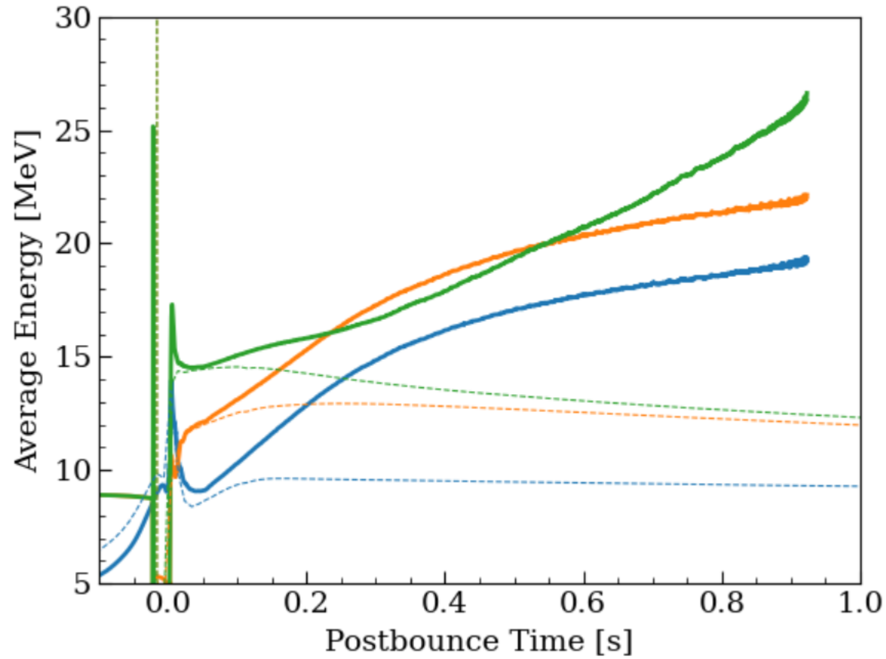


- Failed SN
- The central density suddenly rises at 0.92 s
- The lapse function drops 0.01.

  Metric
  - $ds^2 = -\alpha^2 dt^2 + X^2 dr^2$
  - $\alpha = \alpha_0 \exp\left(\int X^2 \left[\frac{m}{r^2} + 4\pi r(\rho h W^2 v^2 + P + \tau)\right] \mathrm{dr}\right)$

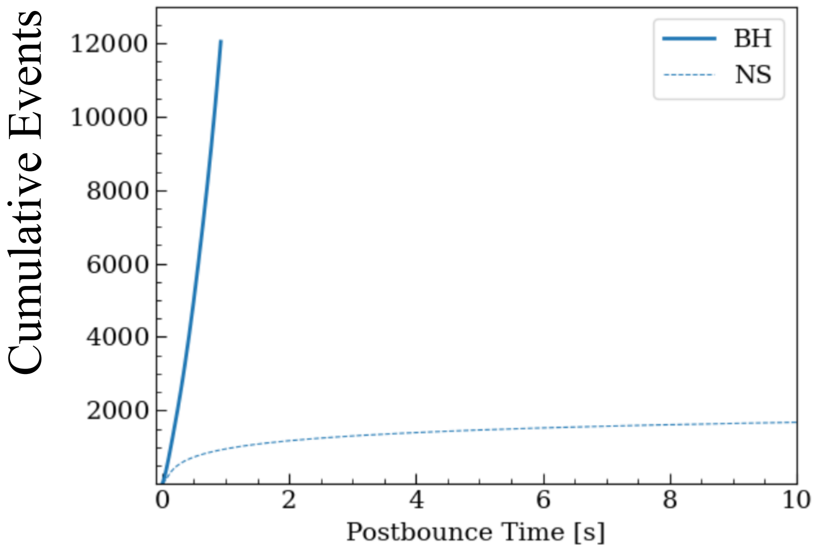
Neutrino properties

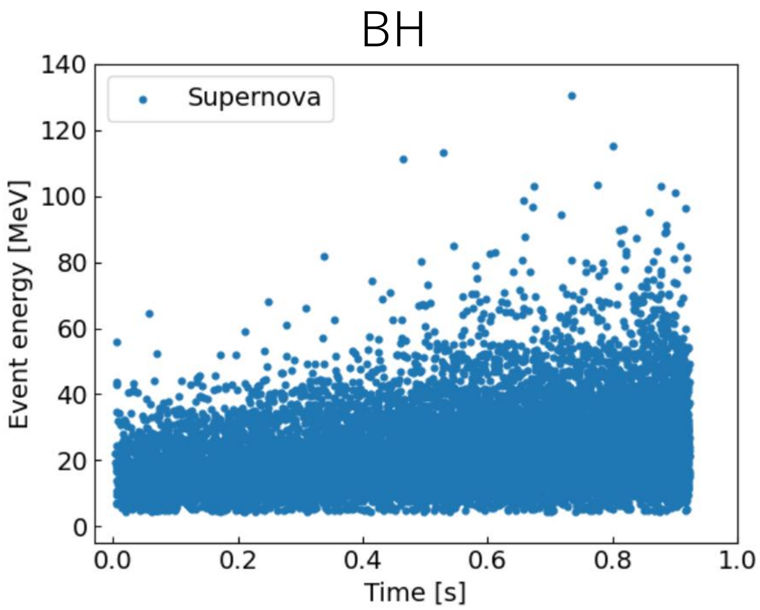


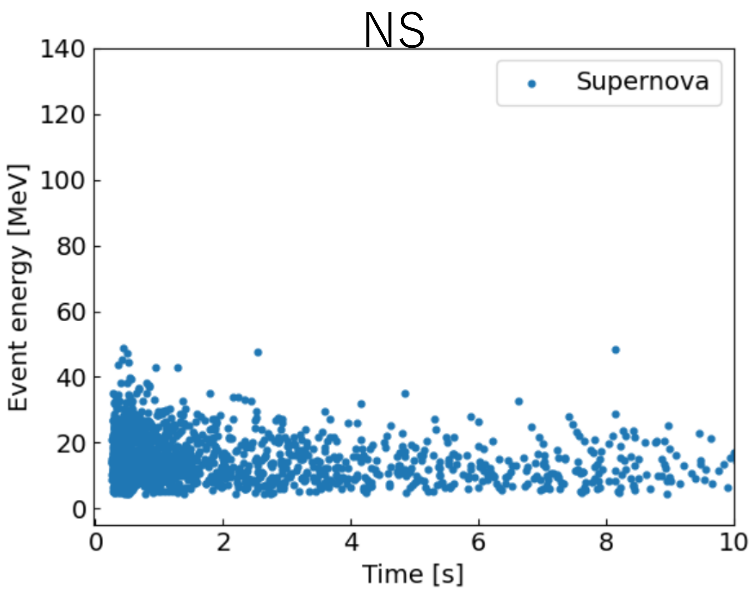


- Average energy and luminosity
- Reference NS model (Dashed lines)
  - Mass: 9.6$M_\odot$
  - EOS: DD2
  - Mori et al. (2021)
- Higher energy and luminosity

Neutrino observation



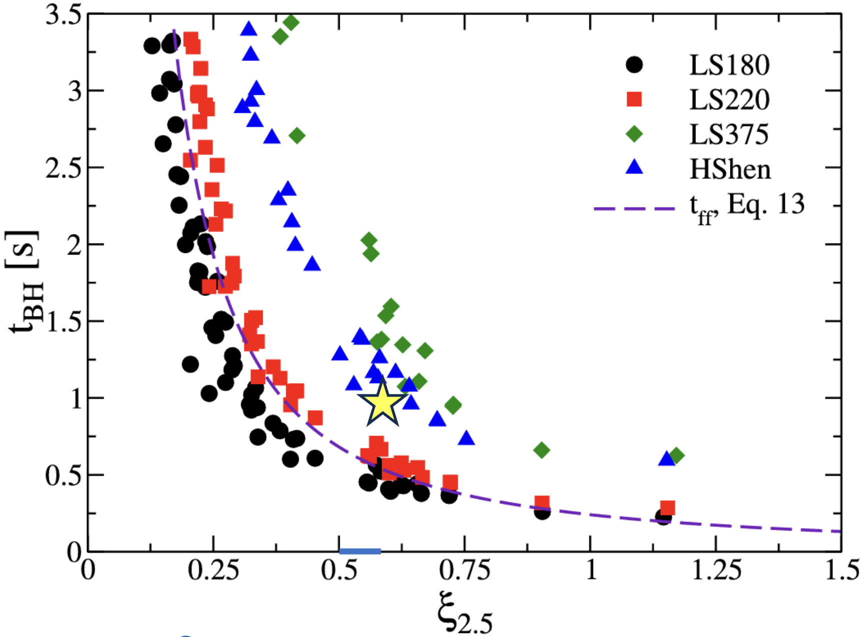




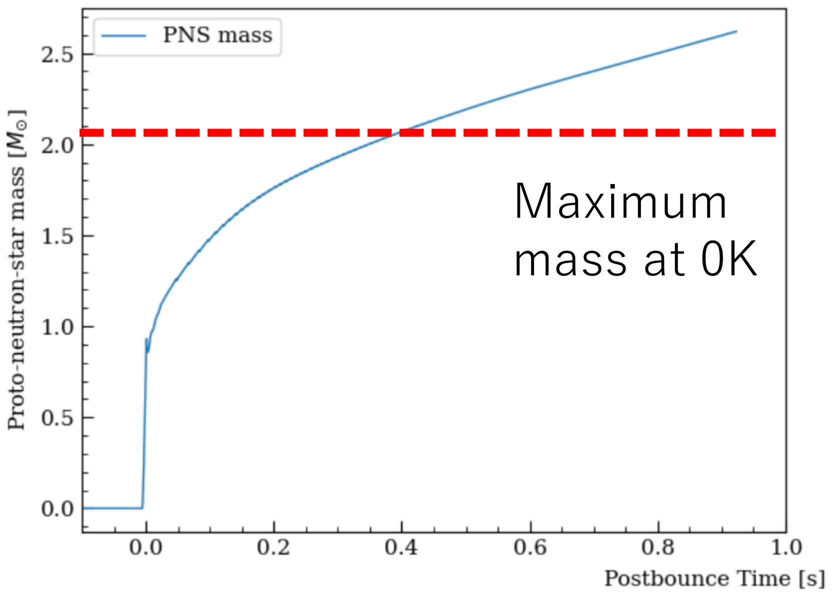
- 10 kpc supernovae with Super-kamiokande
  - BH: 12000 at 0.92 s
  - NS: 1700 at 10 s
- Higher events above 100MeV in BH

Discussion

O'Connor et al. (2011)



NS mass



- BH formation time vs compactness
  - Compactness $\xi_{2.5}$: 0.583
  - $\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\mathrm{km}}$ $M = 2.5M_\odot$
- PNS mass of BH formation
  - $2.6M_\odot$
  - Need to consider finite temperature

Summary

Summary

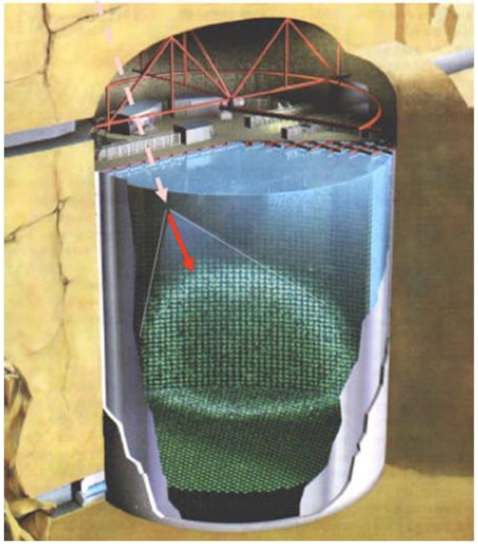
- Motivation
  - Want to make a neutrino database for collapse to black holes
- Succeeded code development
  - Calculated $40M_{\odot}$
  - Stabilized M1 scheme
- Result
  - Higher average energy and more neutrinos

To do

- Increase progenitors and EOSs.

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
- Can detect BH formation in M31
  - Main interaction channel
    - Inverse beta decay
    - $\bar{\nu}_e + p \rightarrow e^+ + n$



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