Probing the nuclear equation of state in core-collapse simulations of massive stars

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Outline

1 : Introduction

2 : EOS effects on core-collapse simulations

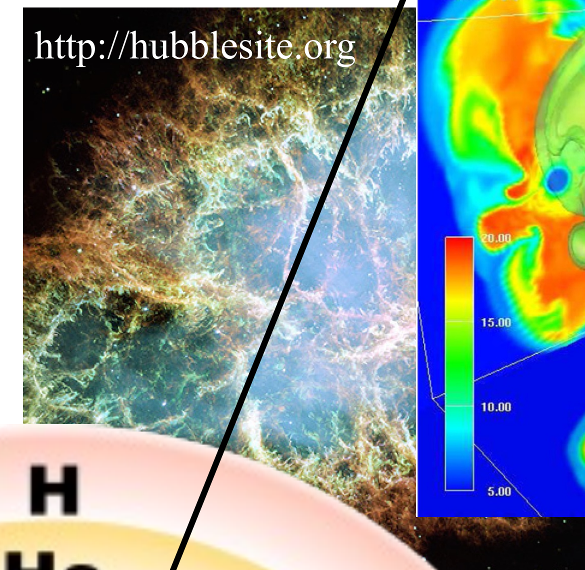
3 : Exotic phase in astrophysical phenomena

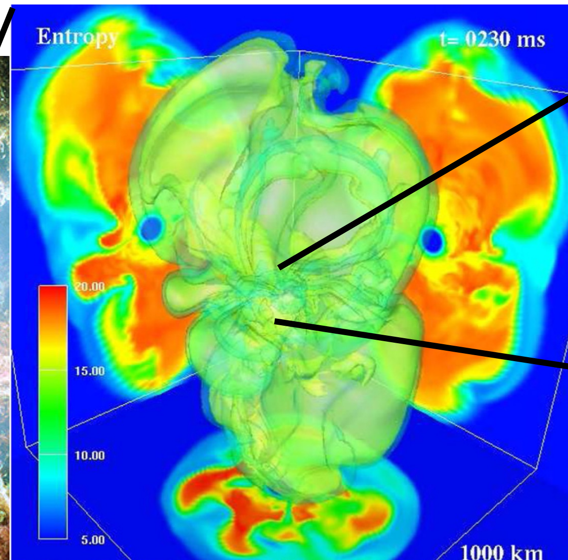
14^{th} APCTP-BLTP JINR Joint WS @ APCTP, July 14^{th}, 2023

1. Introduction

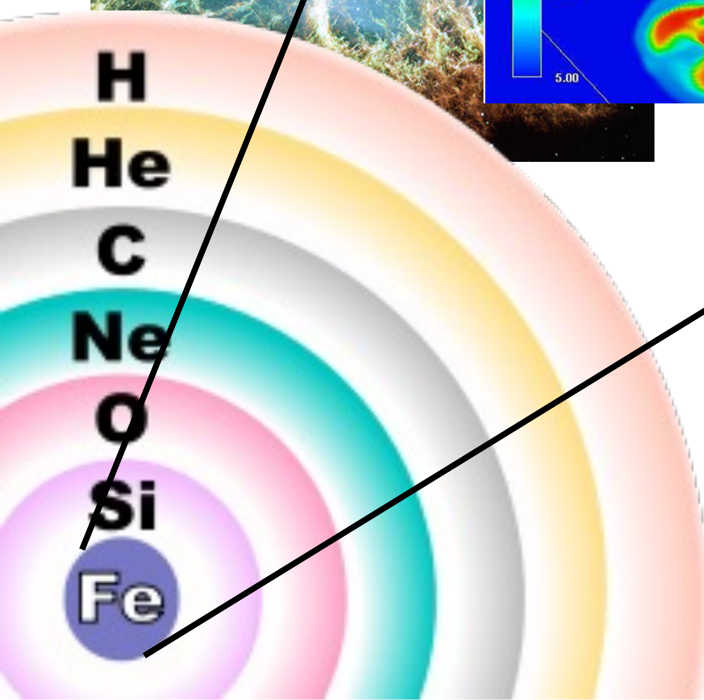
The nuclear equation of state (EOS) plays important roles for astrophysical studies.

Core-Collapse Supernovae

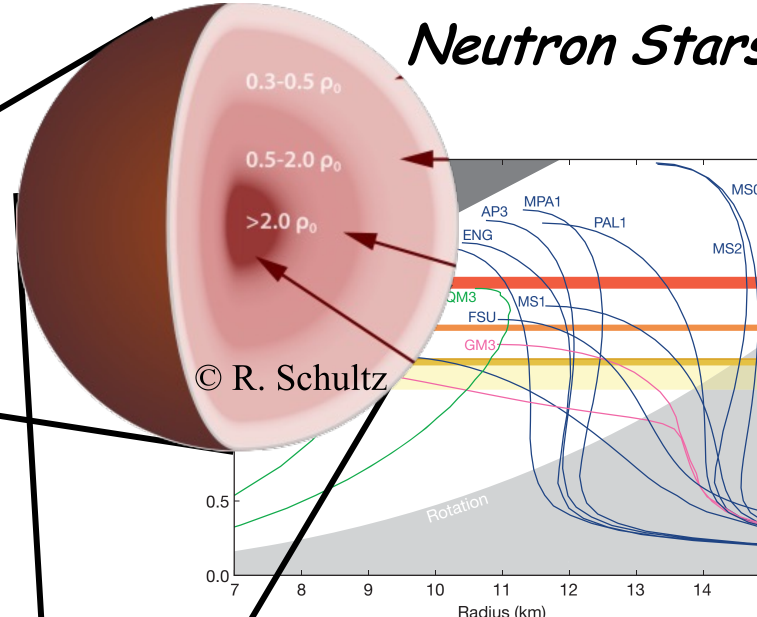




(APJ 786 (2014) 83)

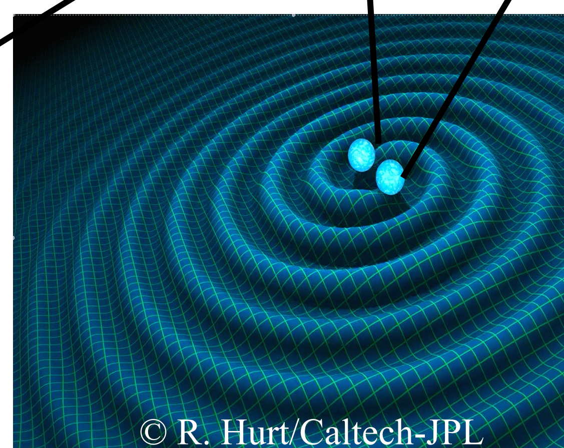


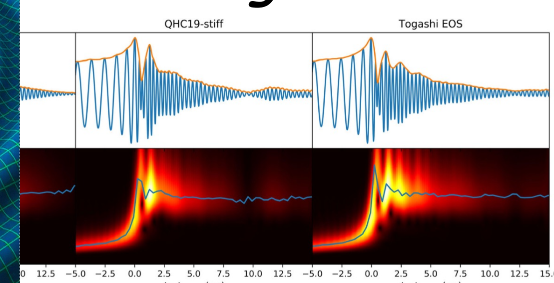
Neutron Stars



(NATURE 467 (2010) 1081)

Neutron Star Mergers

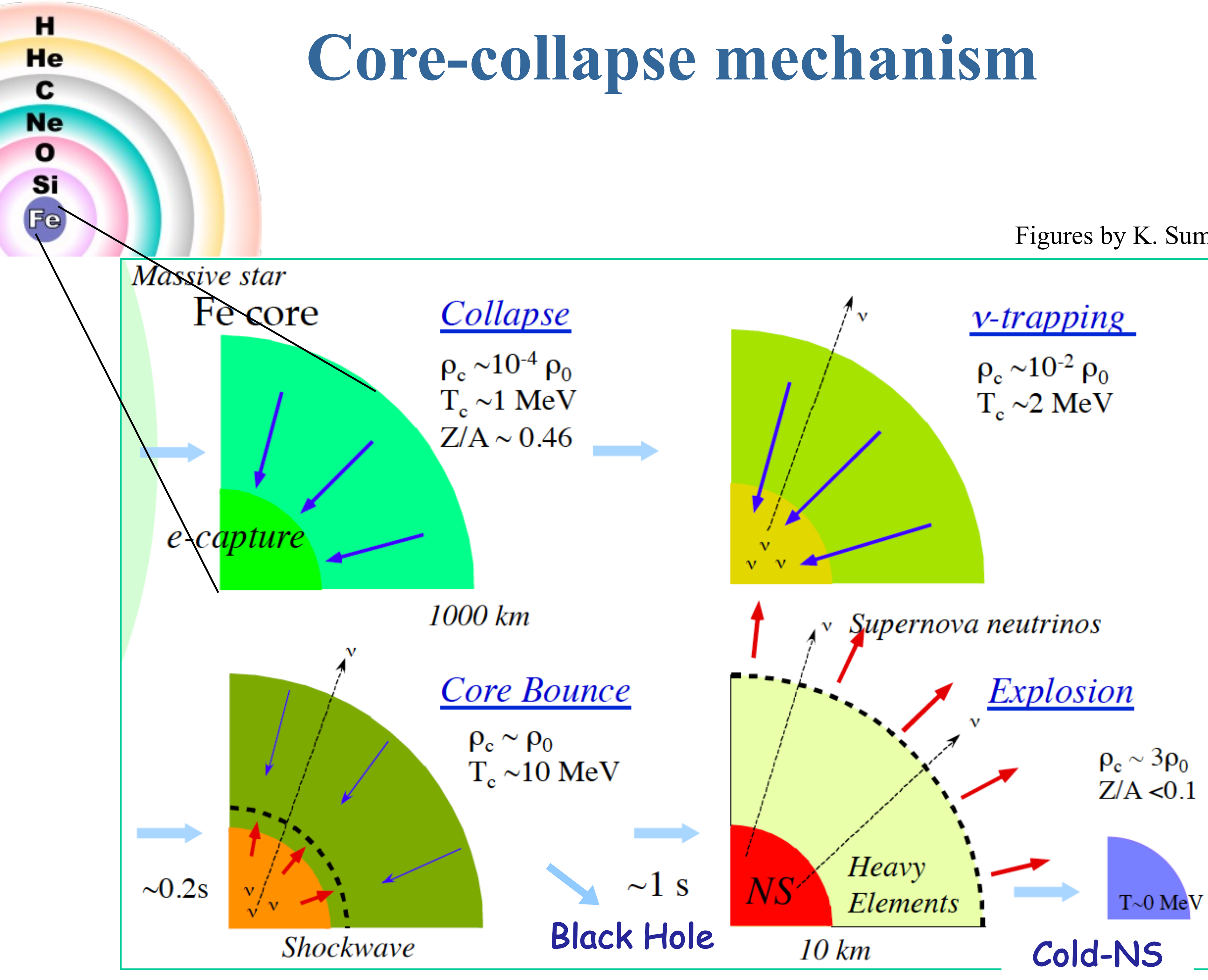




(PRL 129 (2022) 181101)

Core-collapse mechanism

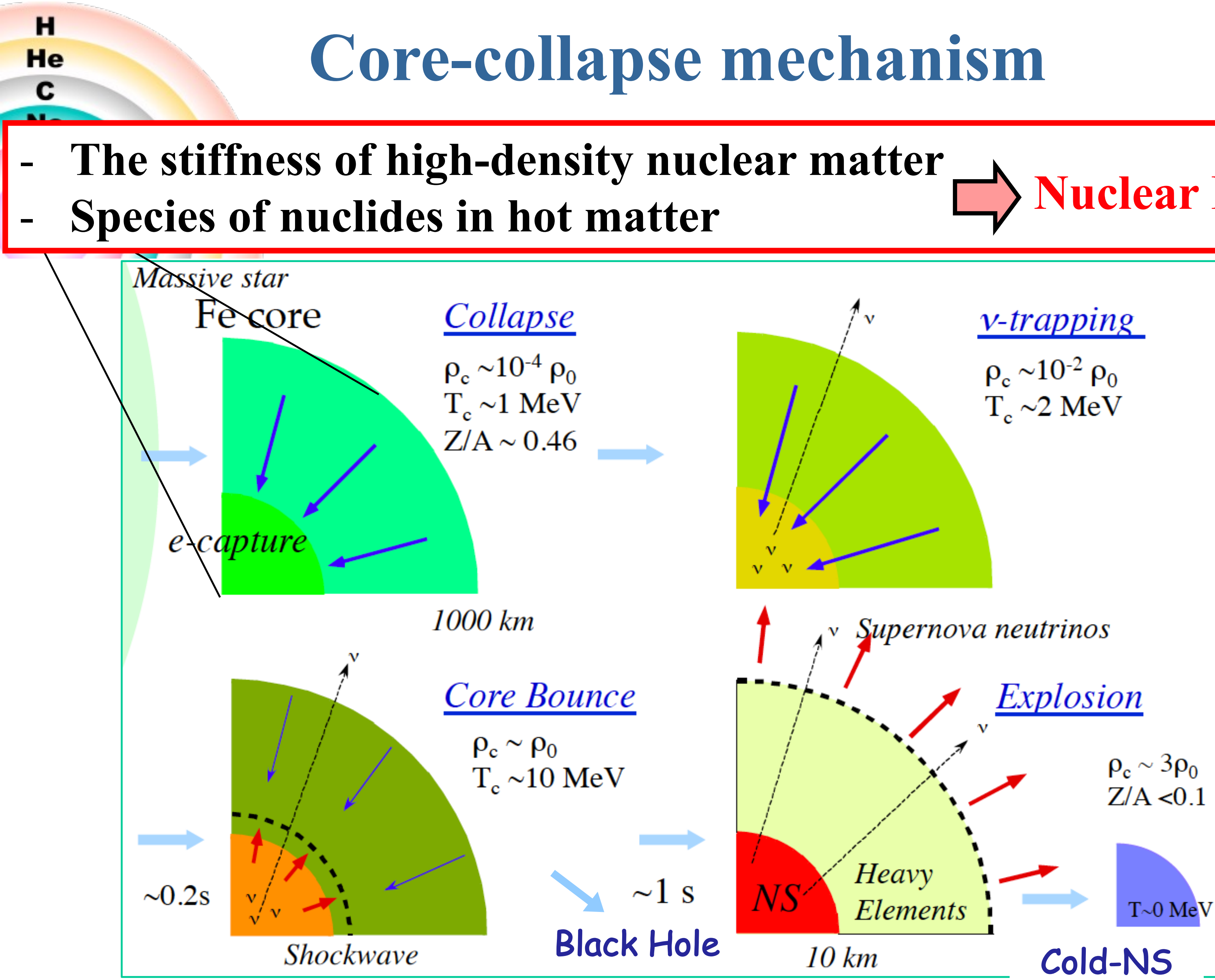
Figures by K. Sumiyoshi



Core-collapse mechanism

- **The stiffness of high-density nuclear matter**
- **Species of nuclides in hot matter**

⇨ **Nuclear EOS**

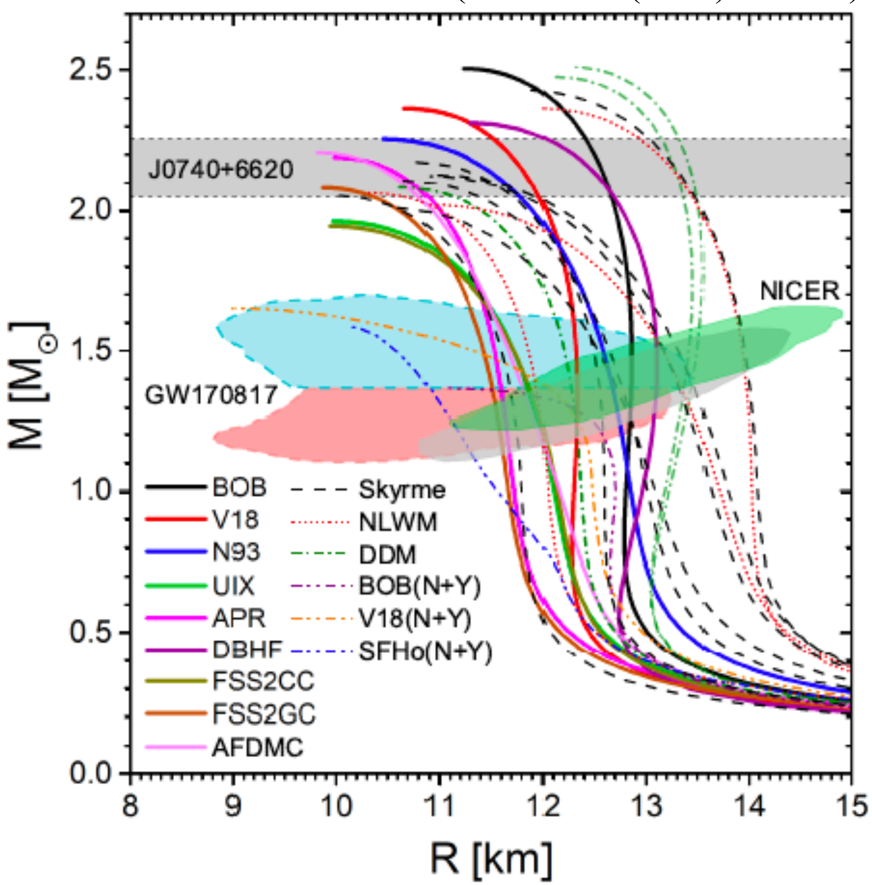


Nuclear EOS and astrophysical objects

Neutron Stars (NS)

- $T = 0$ MeV, $Y_p \sim 0.1$
- Various EOS has been proposed.

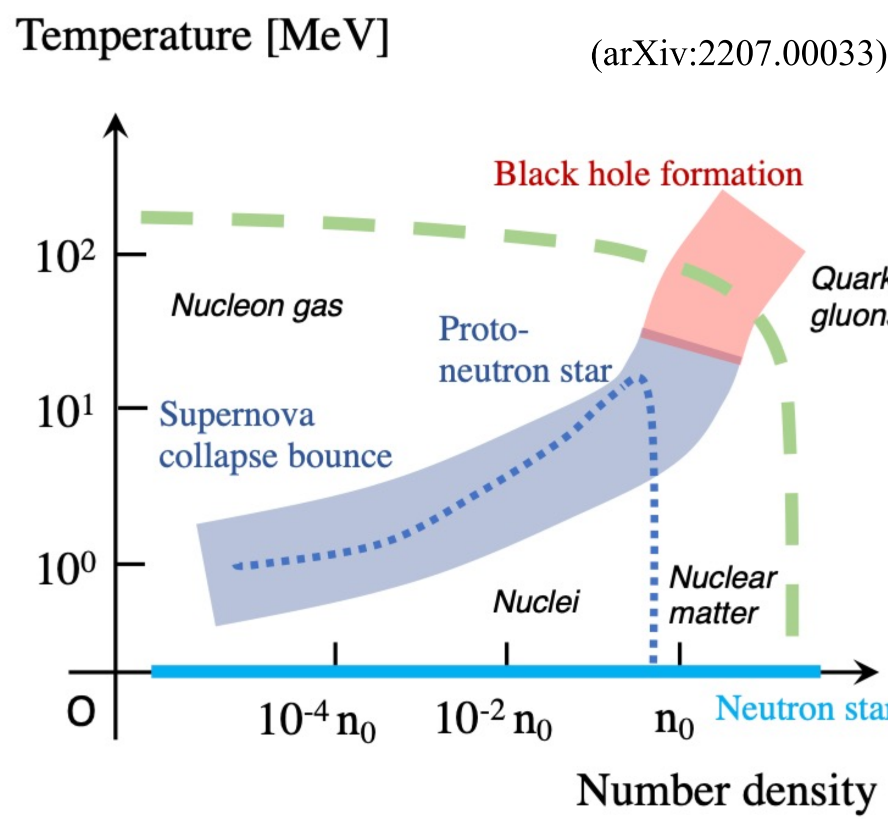
(PPNP 120 (2021) 103879)



Supernovae / NS mergers

- Wide range of T, Y_p, n_B
- Limited number of EOSs are applicable.

(arXiv:2207.00033)



Currently existing supernova EOSs

(Rev. Mod. Phys. 89 (2017) 015007)

Model	Nuclear Interaction	Degrees of Freedom	$M_{\max}$ ($M_\odot$)	$R_{1.4M_\odot}$ (km)	Ξ	publ. avail.	References
H&W	SKa	$n, p, \alpha, \{(A_i, Z_i)\}$	2.21[a]	13.9 [a]		n	El Eid and Hillebrandt (1980); Hillebrandt *et al.* (1984)
LS180	LS180	$n, p, \alpha, (A, Z)$	1.84	12.2	0.27	y	Lattimer and Swesty (1991)
LS220	LS220	$n, p, \alpha, (A, Z)$	2.06	12.7	0.28	y	Lattimer and Swesty (1991)
LS375	LS375	$n, p, \alpha, (A, Z)$	2.72	14.5	0.32	y	Lattimer and Swesty (1991)
STOS	TM1	$n, p, \alpha, (A, Z)$	2.23	14.5	0.26	y	Shen *et al.* (1998); Shen *et al.* (1998, 2011)
FYSS	TM1	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.22	14.4	0.26	n	Furusawa *et al.* (2013b)
HS(TM1)	TM1*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.21	14.5	0.26	y	Hempel and Schaffner-Bielich (2010); Hempel *et al.* (2012)
HS(TMA)	TMA*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.02	13.9	0.25	y	Hempel and Schaffner-Bielich (2010)
HS(FSU)	FSUgold*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	1.74	12.6	0.23	y	Hempel and Schaffner-Bielich (2010); Hempel *et al.* (2012)
HS(NL3)	NL3*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.79	14.8	0.31	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
HS(DD2)	DD2	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.42	13.2	0.30	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
HS(IUFSU)	IUFSU*	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	1.95	12.7	0.25	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
SFHo	SFHo	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.06	11.9	0.30	y	Steiner *et al.* (2013a)
SFHx	SFHx	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.13	12.0	0.29	y	Steiner *et al.* (2013a)
SHT(NL3)	NL3	$n, p, \alpha, \{(A_i, Z_i)\}$	2.78	14.9	0.31	y	Shen *et al.* (2011b)
SHO(FSU)	FSUgold	$n, p, \alpha, \{(A_i, Z_i)\}$	1.75	12.8	0.23	y	Shen *et al.* (2011a)
SHO(FSU2.1)	FSUgold2.1	$n, p, \alpha, \{(A_i, Z_i)\}$	2.12	13.6	0.26	y	Shen *et al.* (2011a)

+ Nuclear EOS tables based on the Liquid drop model with **Skyrme interaction** by A. S. Schneider (2017)

Currently existing supernova EOSs

(Rev. Mod. Phys. 89 (2017) 015007)

Effective interactions (Skyrme or RMF model)

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Microscopic EOS with bare nuclear potentials

Uniform EOS: cluster variational method with AV18 + UIX potentials

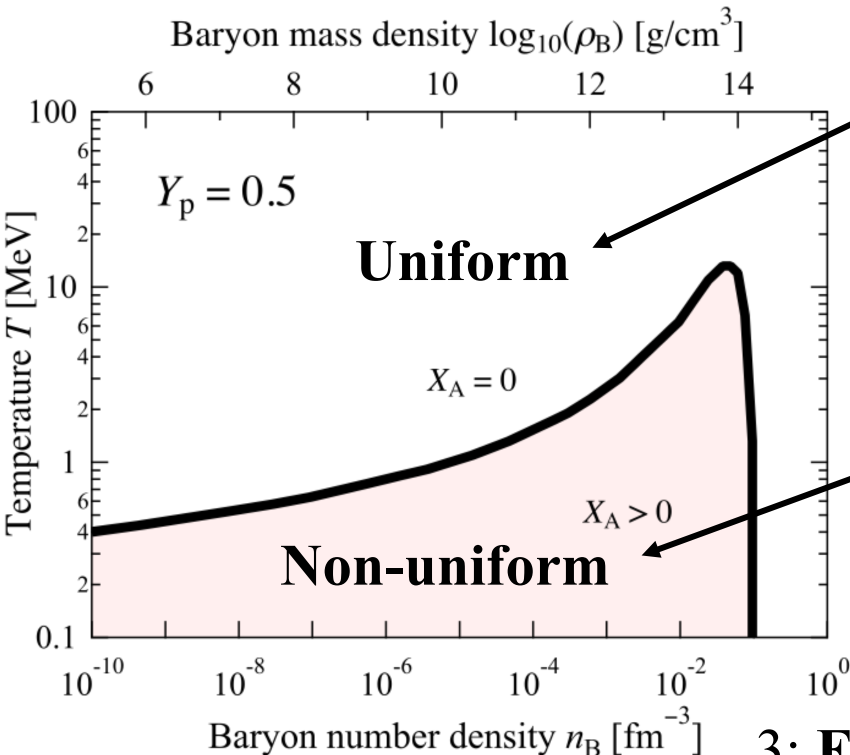
Non-uniform EOS: Thomas-Fermi method (Single spherical nuclei)

(HT, K. Nakazato, Y. Takehara, S. Yamamuro, H. Suzuki, M. Takano, NPA961 (2017) 78)

Supernova EOS table with bare nuclear forces

(HT, K. Nakazato, Y. Takehara, S. Yamamuro, H. Suzuki, M. Takano, NPA961 (2017) 78)

http://www.np.phys.waseda.ac.jp/EOS/



1: **Cluster variational method with AV18 + UIX potentials**

2: **Thomas-Fermi calculation for non-uniform matter**

3: **EOS table for astrophysical simulations**

- Temperature T : $0 \leq T \leq 400$ MeV
- Density ρ : $10^{5.1} \leq \rho_B \leq 10^{16.0}$g/cm^3
- Proton fraction Y_p : $0 \leq Y_p \leq 0.65$

2. EOS effects on core-collapse supernovae

1. Microscopic variational EOS (Togashi et al., NPA 961 (2017) 78)

- Uniform EOS: Variational method with AV18 +UIX potentials
- Non-Uniform EOS: Thomas-Fermi approximation

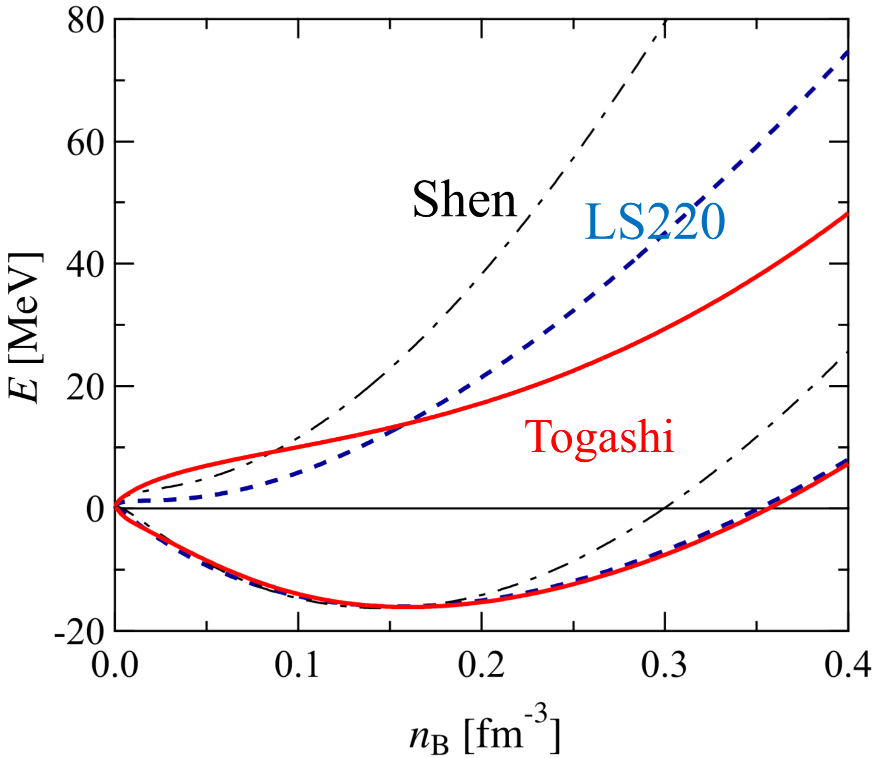
2. Phenomenological Shen EOS (Shen et al., NPA 637 (1998) 435)

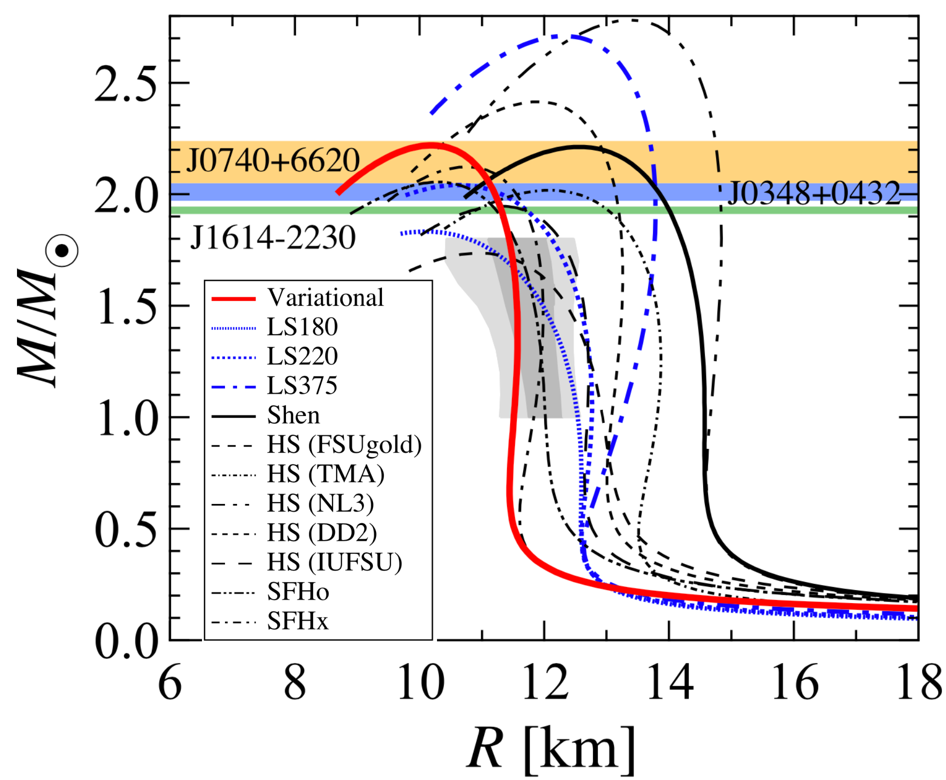
- Uniform EOS: Relativistic mean field model with TM1
- Non-Uniform EOS: Thomas-Fermi approximation

3. Lattimer-Swesty EOS (Lattimer & Swesty, NPA 535 (1991) 331)

- Uniform EOS: Analytically expressed function with Skyrme
- Non-Uniform EOS: Compressible liquid drop model

Saturation properties & NS structures





EOS	n_0 [fm^{-3}]	E_0 [MeV]	K_0 [MeV]	S_0 [MeV]	L_0 [MeV]	$R_{1.4}$ [km]	M_{max} [$M_\odot$]
Togashi	0.160	16.1	245	29.1	38.7	11.6	2.21
Shen	0.145	16.3	281	36.9	110.8	14.5	2.23
LS220	0.155	16.0	220	28.6	73.8	12.7	2.06
Empirical	0.15 – 0.17	15.8 – 16.2	220 – 260	28 – 35	35 – 100	11 – 13	> 2.0

Application to Core-Collapse Supernovae

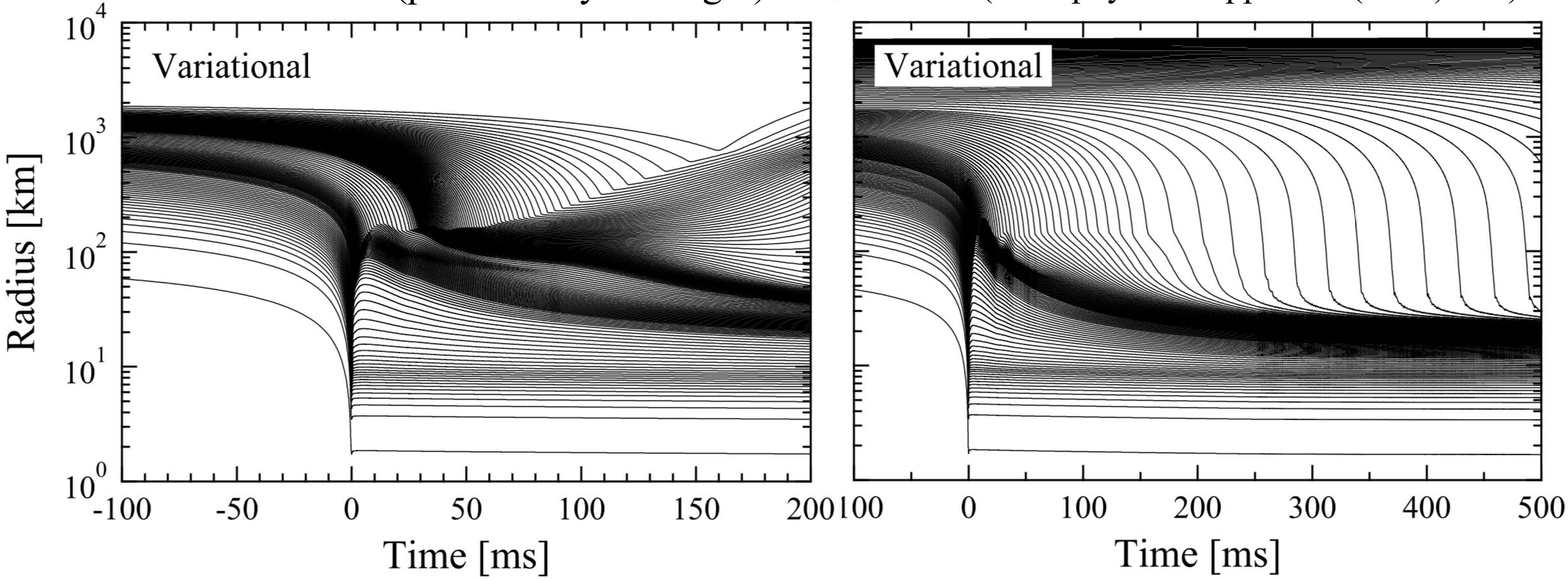
1D neutrino-radiation hydrodynamics simulations

(Nakazato, Sumiyoshi & HT, PASJ 73 (2021) 639)

- Progenitor model : 9.6 $M_\odot$, 15 $M_\odot$, 30 $M_\odot$
- Neutrino Transport: Directly solve the Boltzmann equation
- EOS: Togashi, Shen, LS220/180

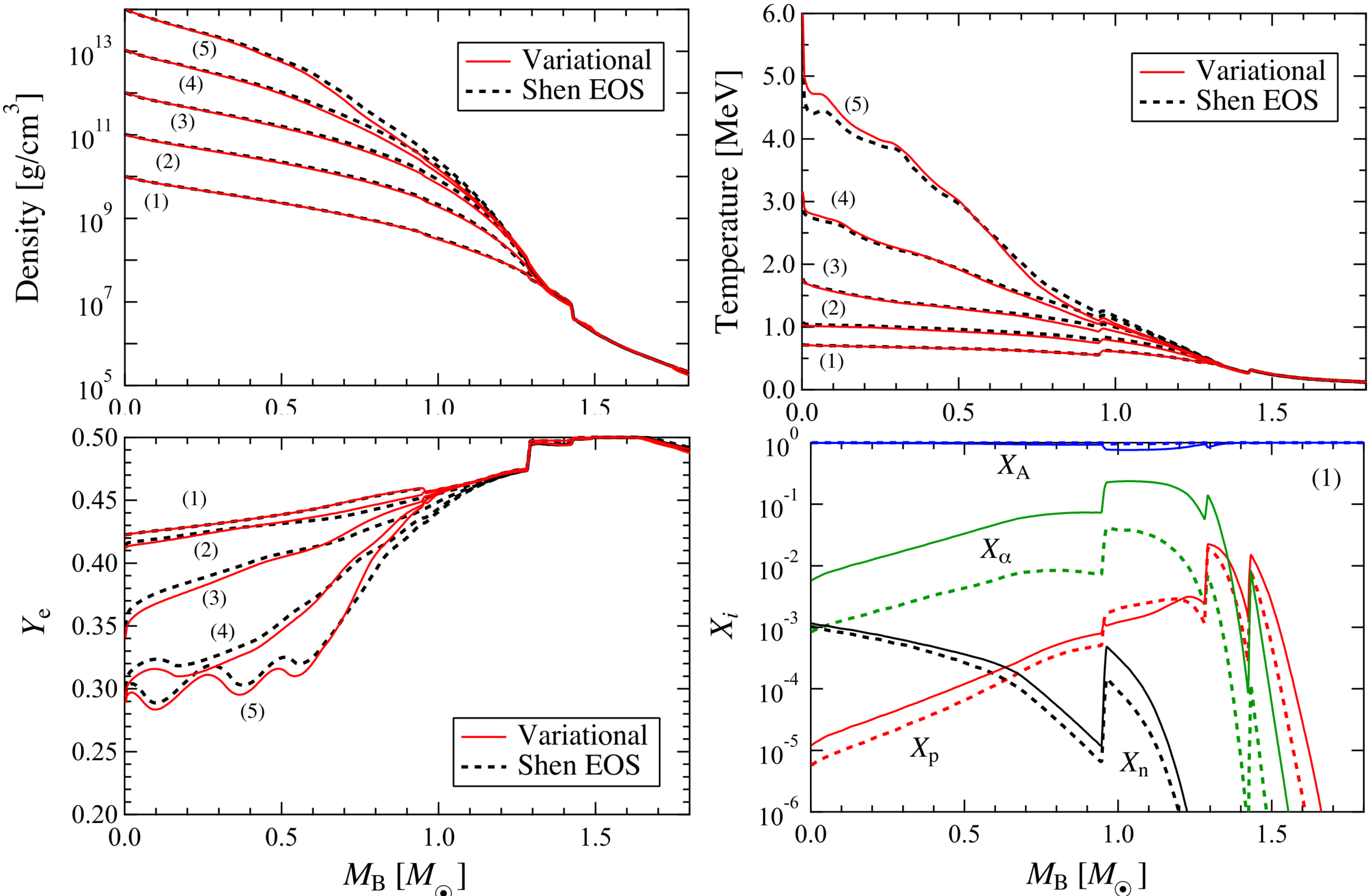
Progenitor model : 9.6 $M_\odot$
(provided by A. Heger)

Progenitor model: WW 15$M_\odot$
(Astrophys. J. Suppl. 101 (1995) 181)



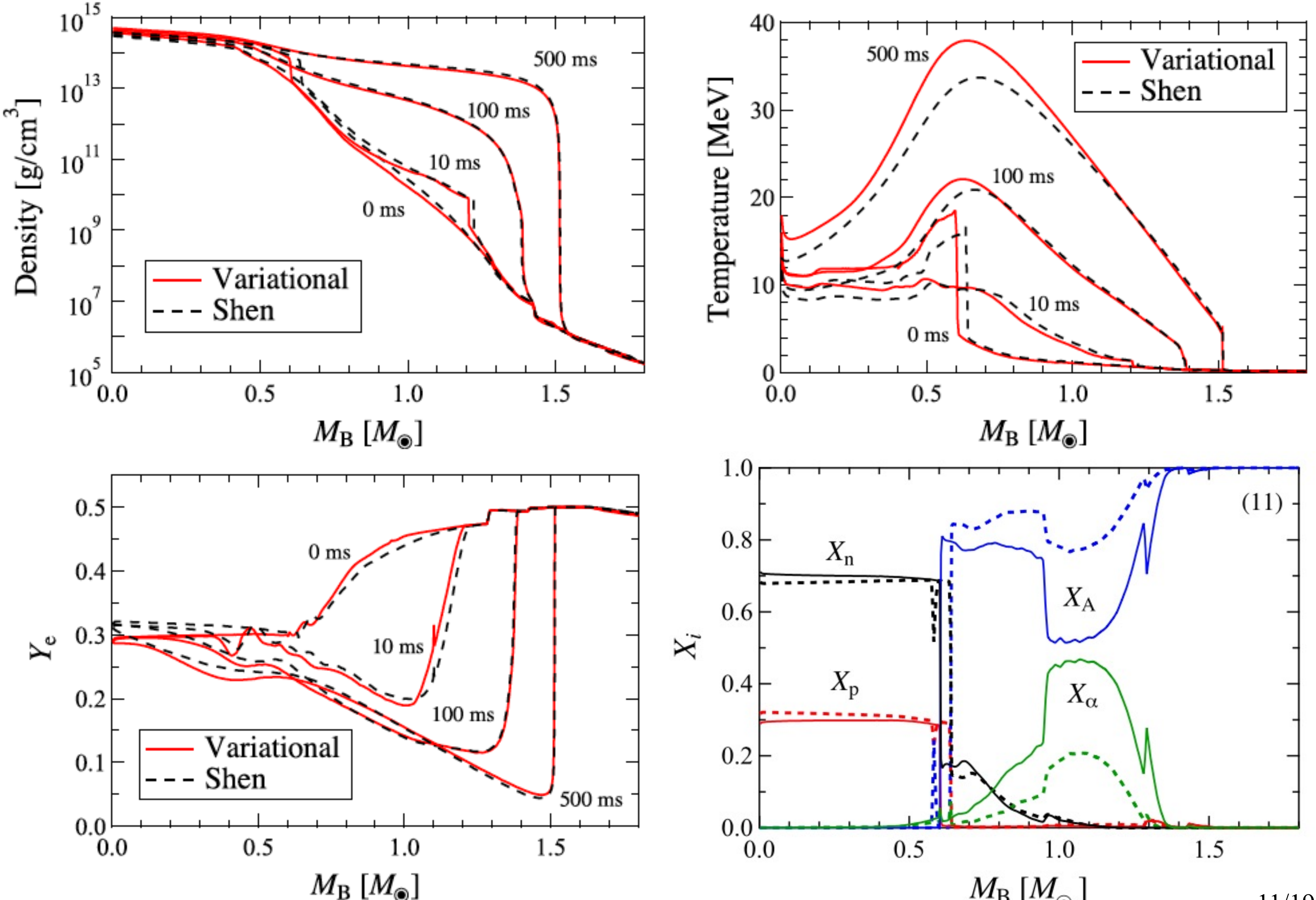
Radial trajectories of mass elements

Thermodynamic Profiles (Collapse Phase)



The numbers (1)–(5) :the times when the central density reaches 10^{10}, 10^{11}, 10^{12}, 10^{13}, 10^{14} g/cm^3

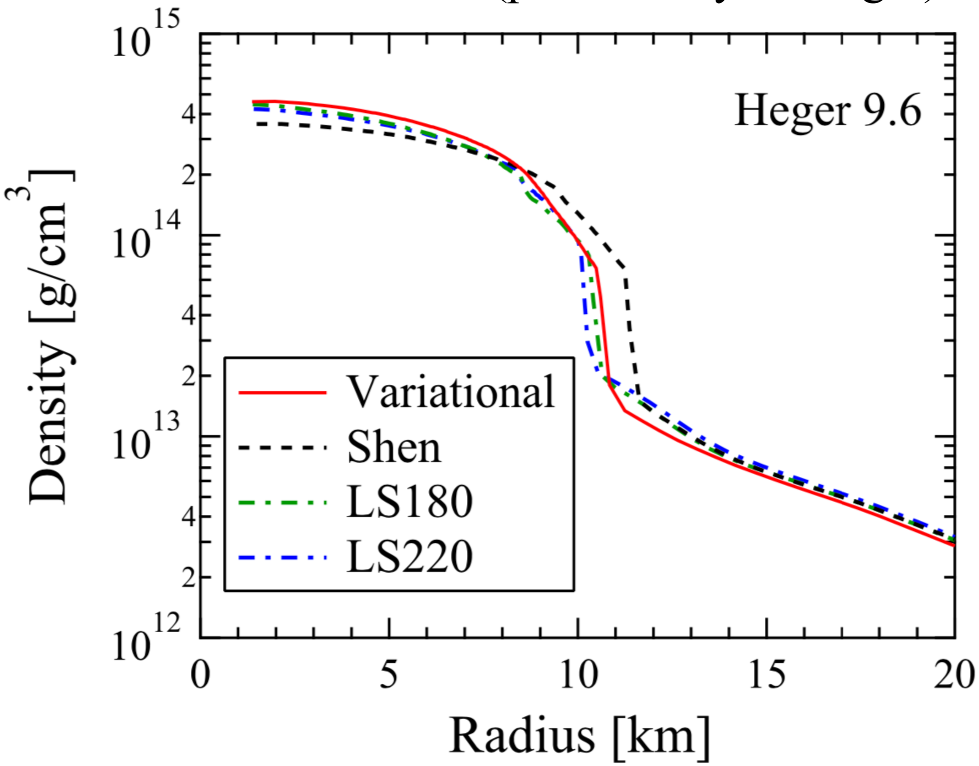
Thermodynamic Profiles (Postbounce Phase)



Density Profiles at the Bounce

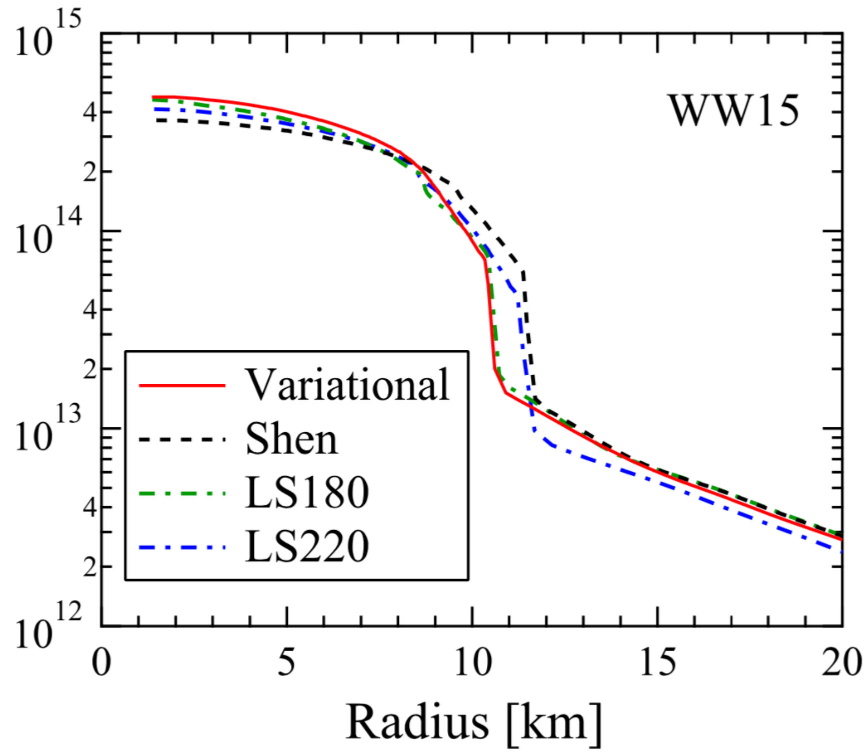
Progenitor model : 9.6 $M_\odot$

(provided by A. Heger)



Progenitor: WW 15$M_\odot$

(Astrophys. J. Suppl. 101 (1995) 181)



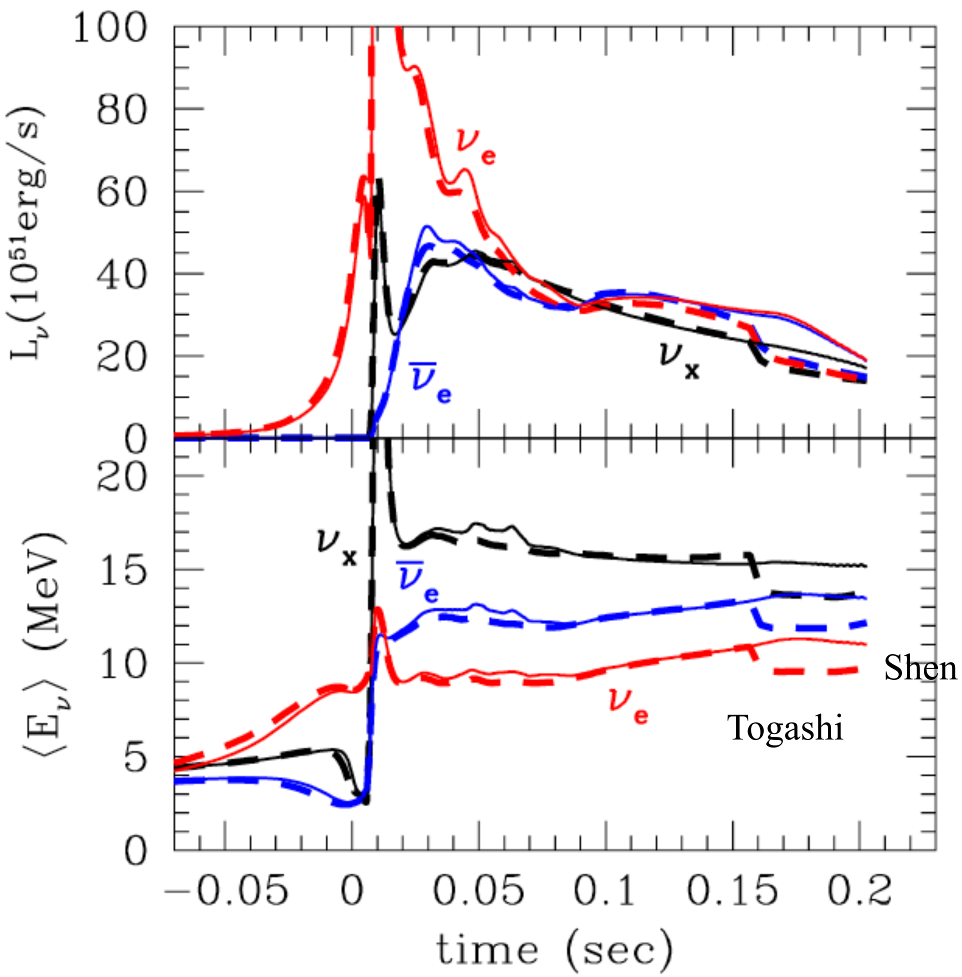
Variational : 4.59×10^{14} g/cm^3
Shen : 3.55×10^{14} g/cm^3
LS180 : 4.46×10^{14} g/cm^3
LS220 : 4.22×10^{14} g/cm^3

Variational : 4.76×10^{14} g/cm^3
Shen : 3.62×10^{14} g/cm^3
LS180 : 4.61×10^{14} g/cm^3
LS220 : 4.12×10^{14} g/cm^3

Neutrino Luminosity and average energy

Progenitor model : 9.6 $M_\odot$

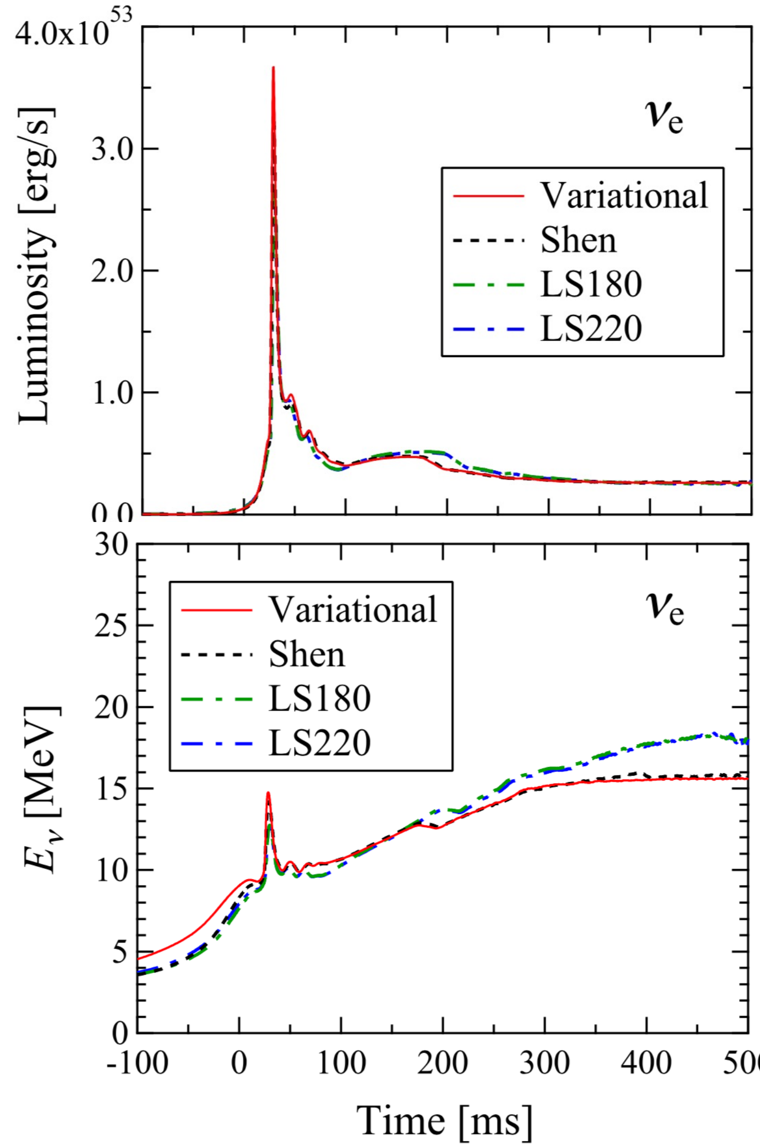
(provided by A. Heger)



(Nakazato, Sumiyoshi & HT, PASJ 73 (2021) 639)

Progenitor: WW 15$M_\odot$

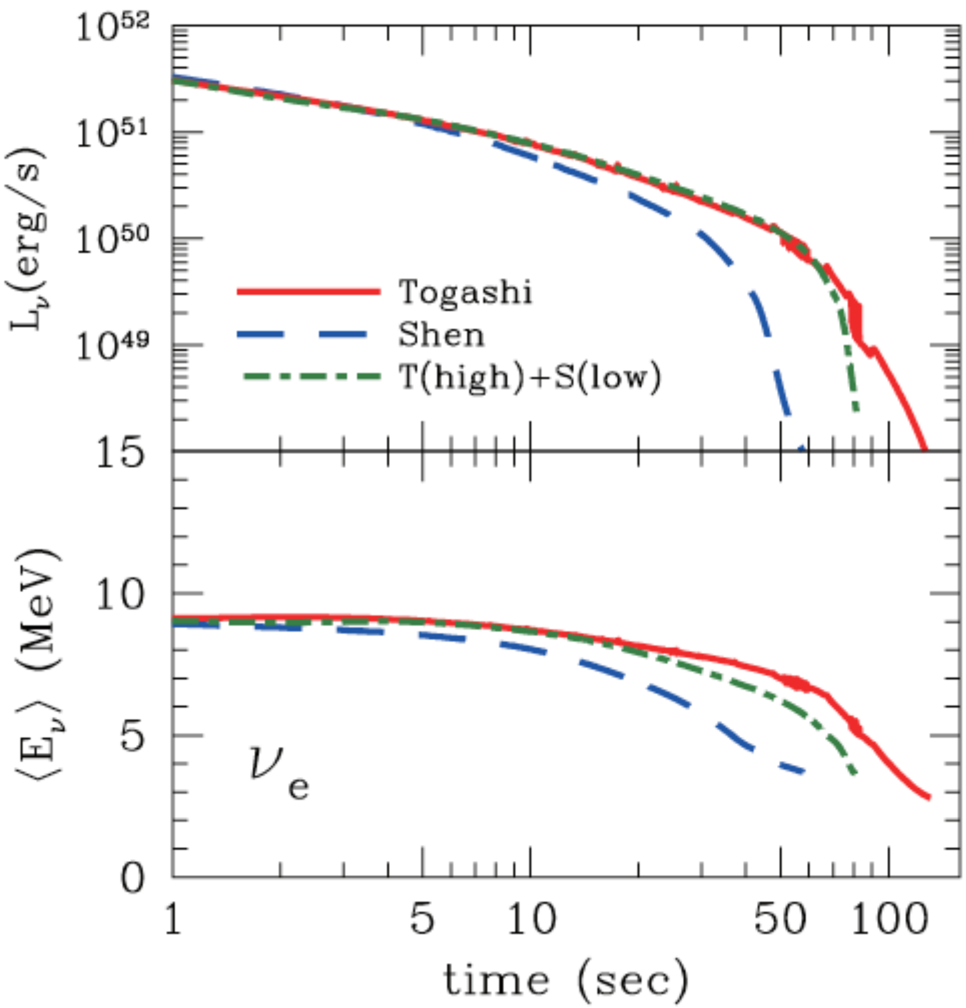
(Astrophys. J. Suppl. 101 (1995) 181)

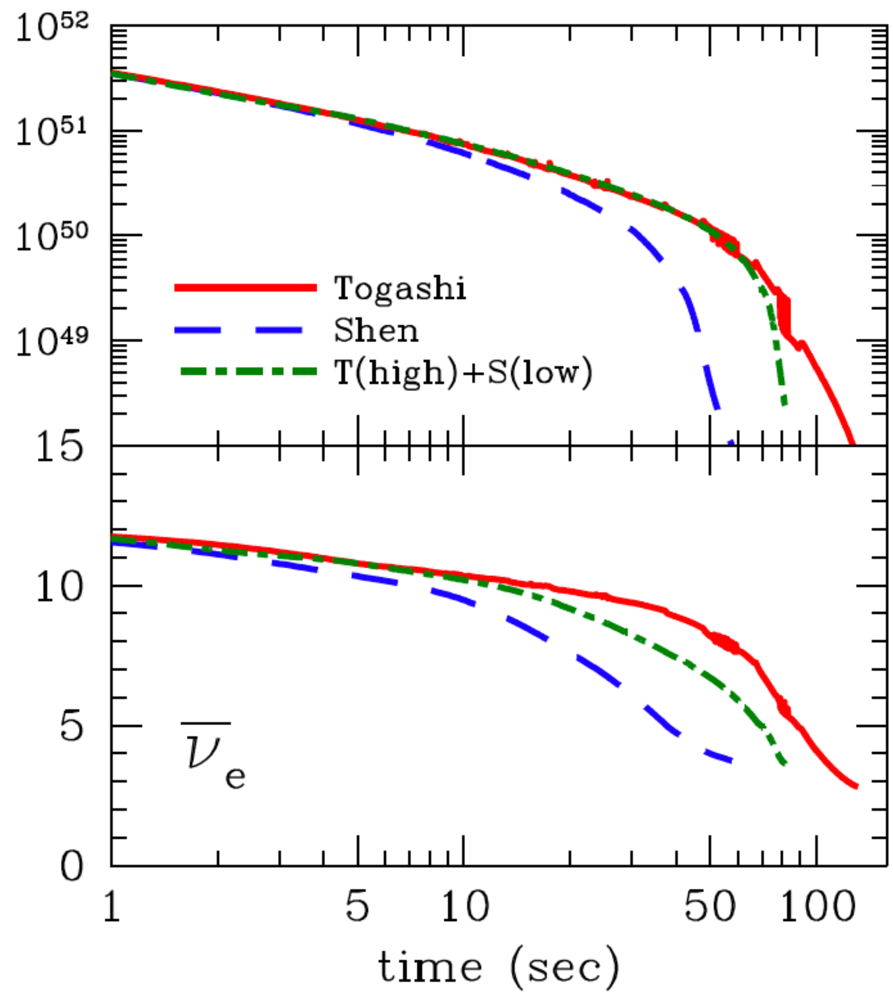


Application to Proto-Neutron Star Cooling

(Nakazato, Suzuki &HT, Phys. Rev. C 97 (2018) 035804)

1D neutrino-radiation hydrodynamics simulations (until 300 ms)
→ Quasi-static evolutionary calculation of PNS cooling



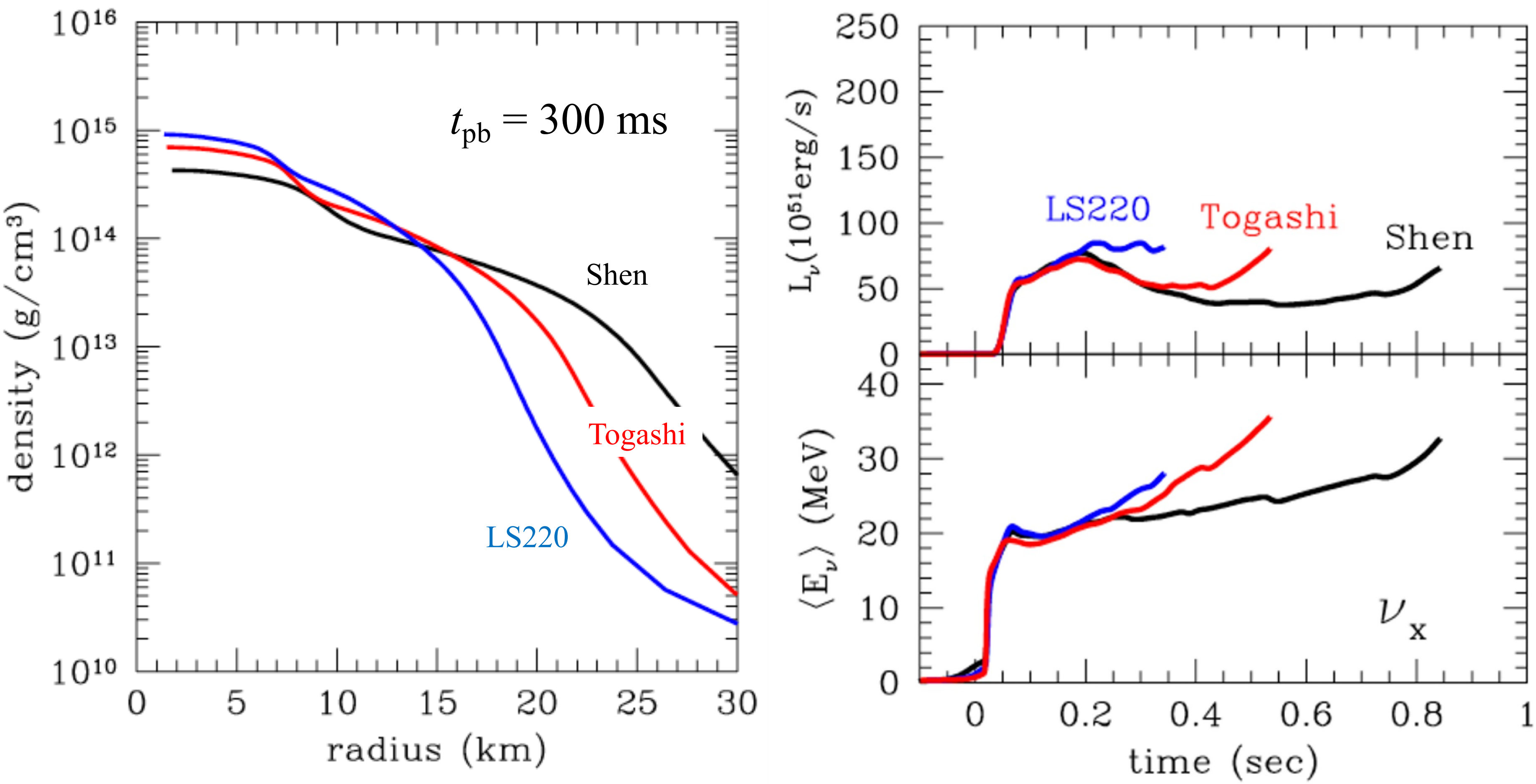


Application to Black Hole Formation

Black hole formation after failed core-collapse supernovae

(Nakazato, Sumiyoshi & HT, PASJ 73 (2021) 639)

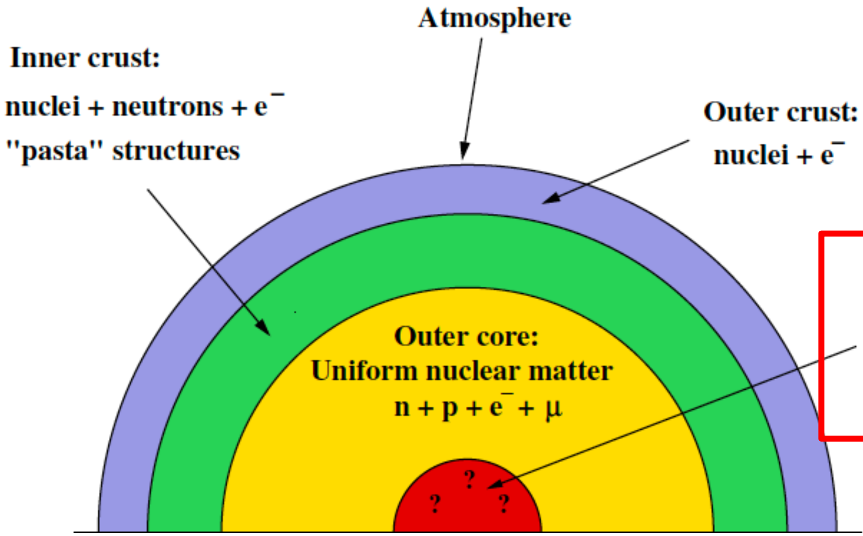
Progenitor model : 30 $M_\odot$ star (K. Nakazato et.al., APJS 205 (2013) 2)



3. Exotic phase in dynamical phenomena

- **Hyperon must appear in NSs**
- **EOS with hyperons is too soft**

→ cannot support massive NSs (~2$M_\odot$)



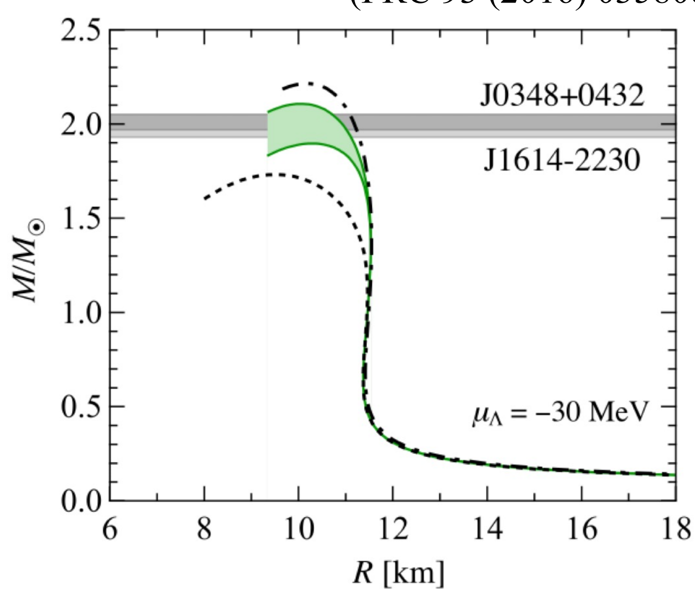
Inner core:
Meson condensates ?
Hyperons ?
Quarks ?

(Universe 6 (2020) 119)

Possible Solutions of the Hyperon Puzzle

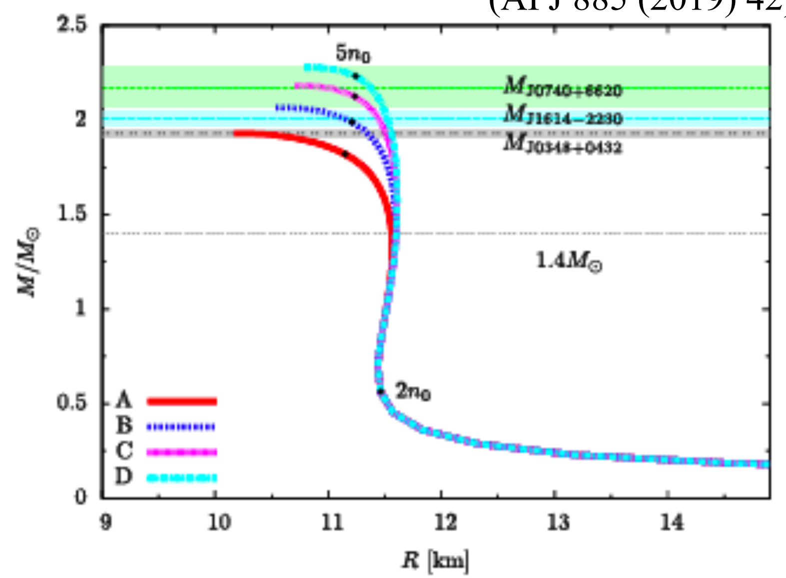
- Hyperonic three-body forces

(PRC 93 (2016) 035808)



- Quark-Hadron Crossover transition

(APJ 885 (2019) 42)

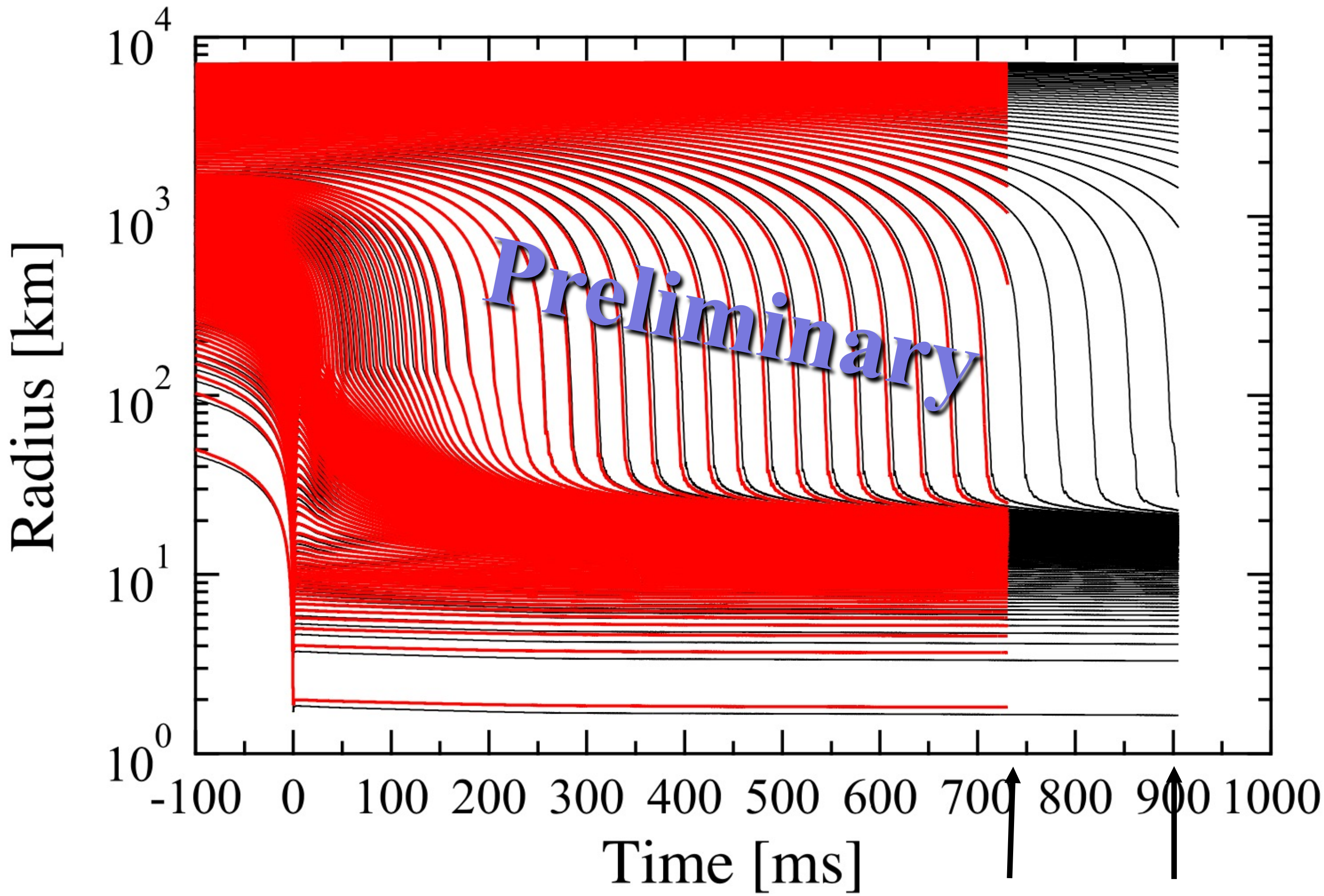


Hyperon mixing in black hole formation

1D hydrodynamics simulations without neutrinos

Progenitor: Woosley Weaver 1995, $40M_\odot$

(K. Sumiyoshi, et al., NPA 730 (2004) 227)
(Astrophys. J. Suppl. 101 (1995) 181)



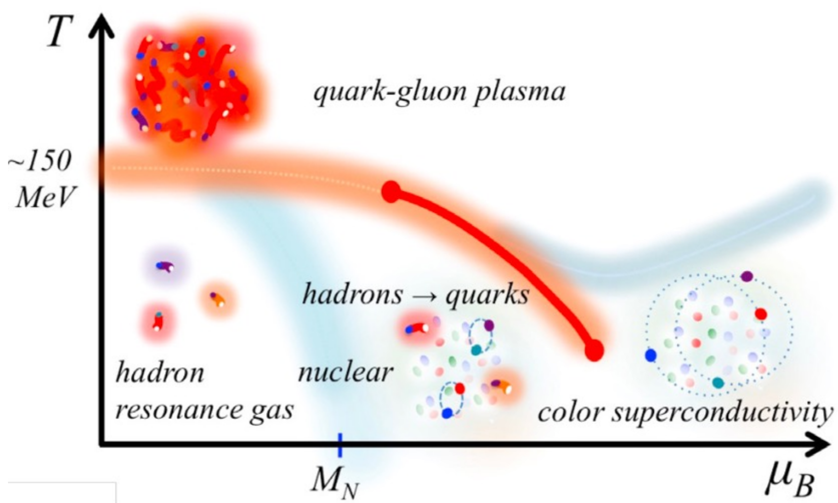
t_{pb} =730 ms (with Λ hyperon)

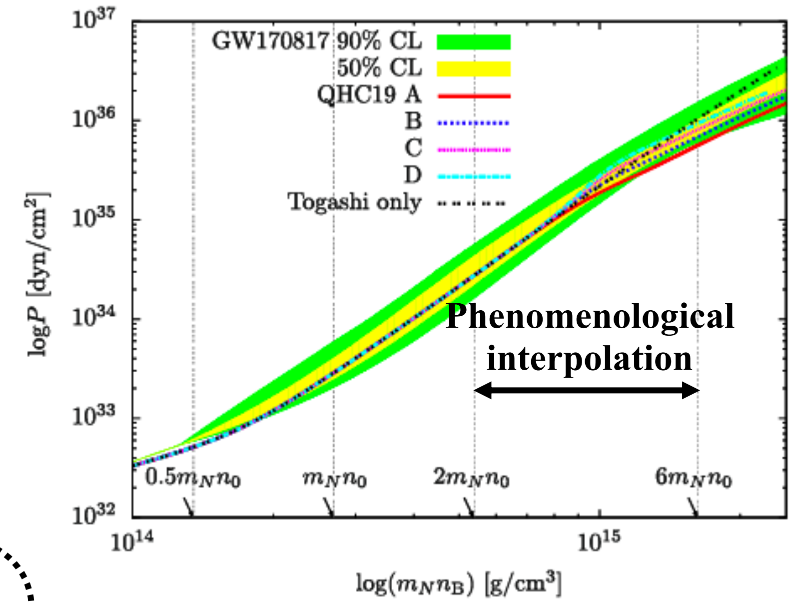
t_{pb} =910 ms (without Λ hyperon)

Quark-Hadron Crossover in Dense Matter

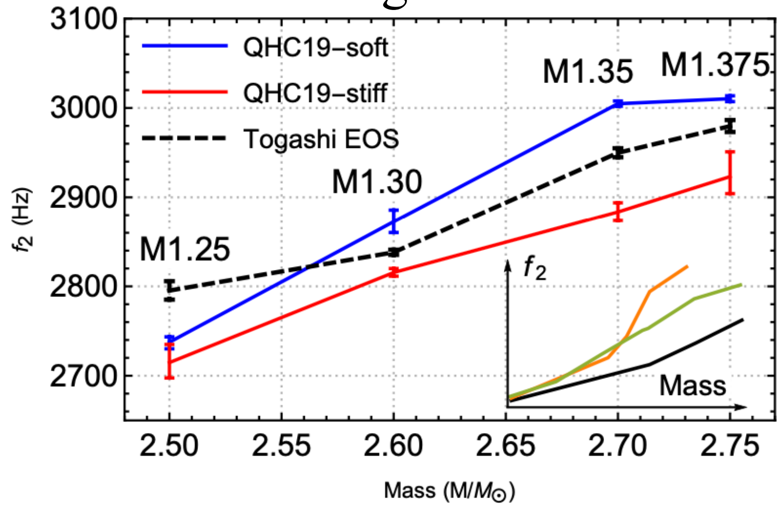
Hadron: Togashi EOS   Quark: NJL

(APJ 885 (2019) 42)

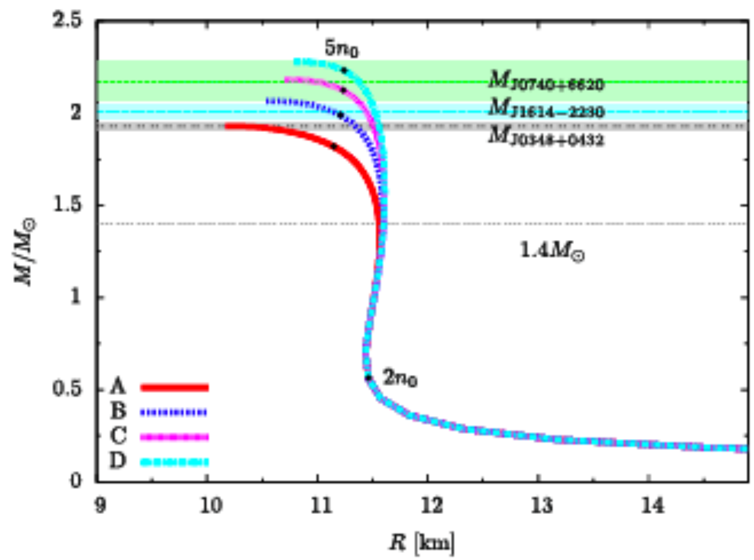




NS-NS merger simulations



(PRL 129 (2022) 181101)



Summary

Nuclear EOS for astrophysical simulations is constructed with realistic nuclear forces (AV18 + UIX).

Uniform nuclear matter : Cluster variational method

Non-uniform nuclear matter : Thomas-Fermi approximation

Our EOS is available at

`http://www.np.phys.waseda.ac.jp/EOS/`

- Nuclear EOS affects on thermodynamic profiles at center of a star.
- The impact of the EOS is not significant to the neutrino signals at $t_{pb} < 500$ms.
- The impact of the EOS is rather significant to the neutrino signals at $t_{pb} > 10$ s.
- Black hole formation time is affected by the EOS stiffness.
- Hyperon mixing & QHC transition also affects the astrophysical phenomena.