Nuclear equation of state based on the many-body calculation with realistic nuclear forces

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Outline

1 : Introduction

2 : Supernova EOS with realistic nuclear forces

3 : Application to astrophysical objects

4 : Hyperon mixing in dense matter

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@ YITP, Kyoto, July 4, 2019

1. Introduction

Microscopic EOS with bare nuclear potentials

Uniform EOS: cluster variational method with AV18 + UIX potentials

Non-uniform EOS: Thomas-Fermi method (Single nucleus approximation)

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

Nuclear EOS for core-collapse simulations

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

Effective interactions (Skyrme or RMF model)

Model	Nuclear Interaction	Degrees	$M_{\max}$	$R_{1.4M_\odot}$	Ξ	publ.	References
H&W	SKa						); 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)
TNTYST	AV18+UIX	n, p, α, (A, Z)	2.21	11.5	0.32	y	Togashi *et al.* (2017)

Nuclear EOS with microscopic calculation

- Fermi Hypernetted Chain (FHNC) variational method

APR (A. **A**kmal, V. R. **P**andharipande, D. G. **R**avenhall, PRC 58 (1998) 1804)

Potential: AV18 two-body pot. + UIX three-body pot.

Trial wave function: Jastrow (central, tensor, spin-orbit correlations)

Nuclear Matter: Pure neutron matter and Symmetric nuclear matter

- Quantum Monte Carlo method

Auxiliary field diffusion Monte Carlo (S. Gandolfi et al., PRC 85 (2012) 032801(R))

Potential: V8 two-body pot. + UIX (or Illinois) three-body pot.

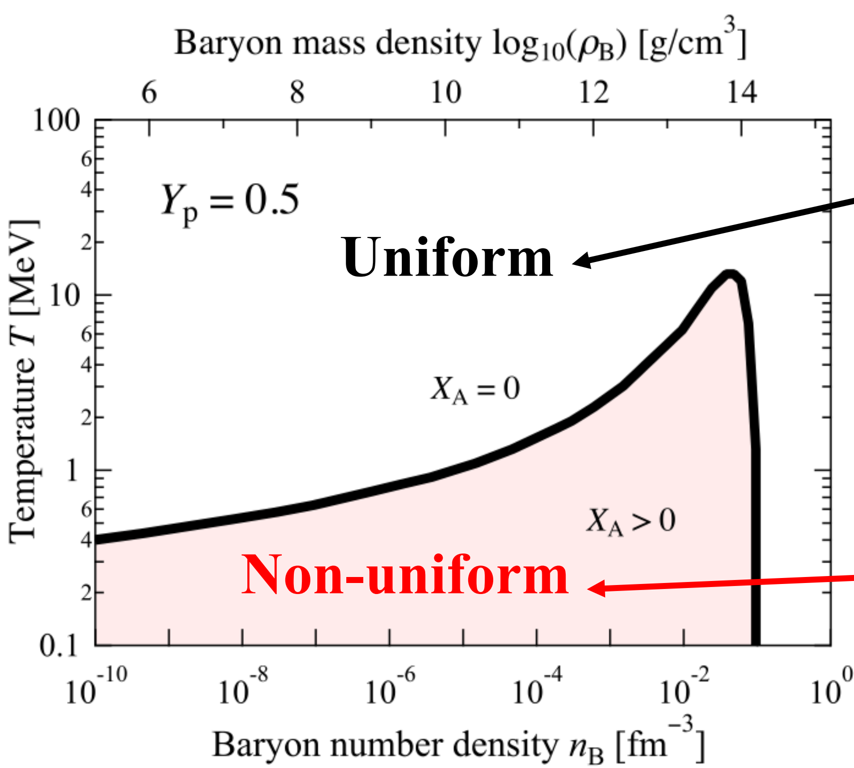
Trial wave function: Jastrow (central and tensor correlations)

Nuclear Matter: Pure neutron matter

Our procedure to construct a supernova EOS table

- EOS should provide thermodynamic quantities in the wide ranges.

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



Phase diagram of nuclear matter [based on HT *et al.*, NPA 961 (2017) 78]

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

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

2. Supernova EOS with realistic nuclear forces

Nuclear Hamiltonian

$$H = -\sum_{i=1}^{N} \frac{\hbar^2}{2m}\nabla^2 + \sum_{i<j}^{N} V_{ij} + \sum_{i<j<k}^{N} V_{ijk}$$

Argonne v18 (AV18) two-body potential

Urbana IX (UIX) three-body potential

Jastrow wave function

$$\Psi = \mathrm{Sym}\left[\prod_{i<j} f_{ij}\right]\Phi_{\mathrm{F}}$$

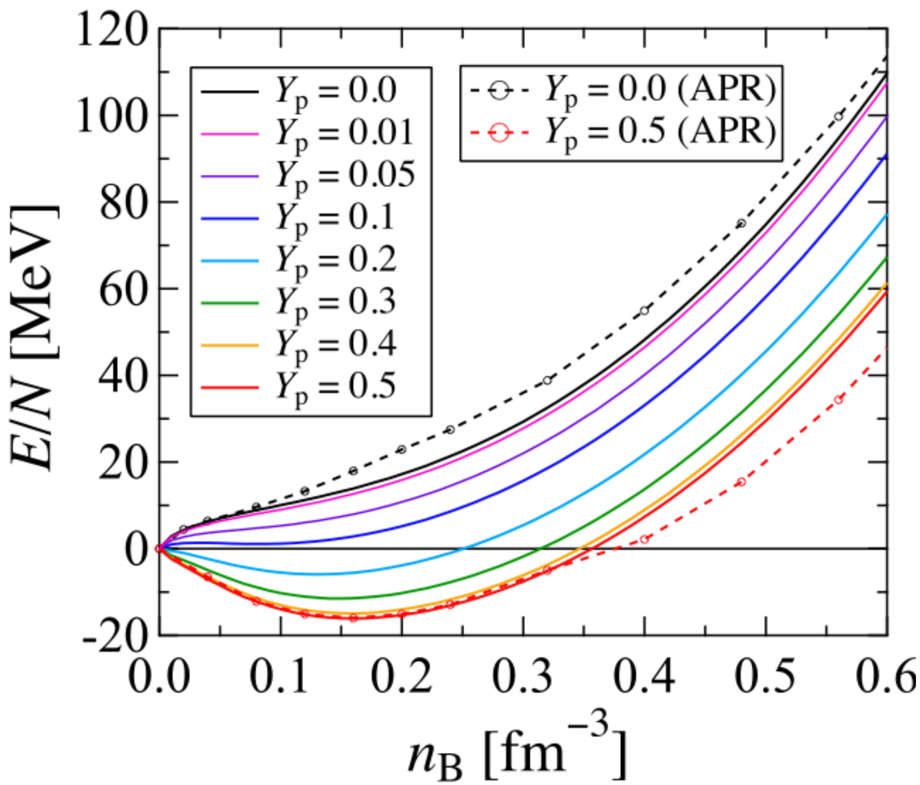
f_{ij}: Correlation function

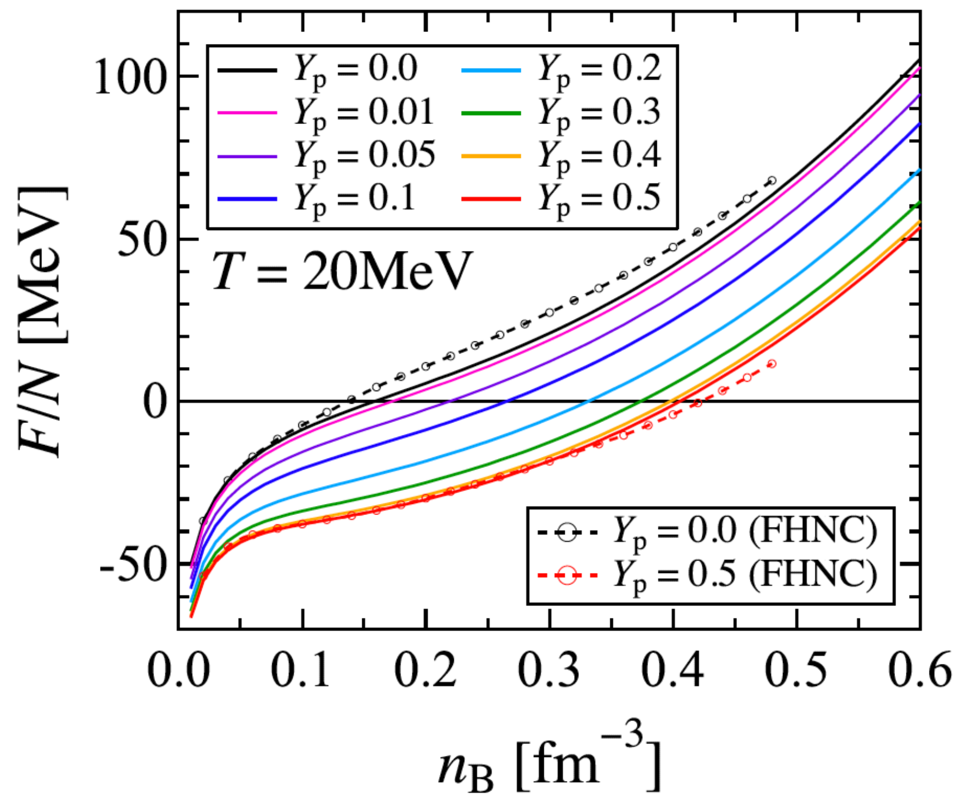
Φ_{F}: Fermi-gas wave function

- The expectation value of the Hamiltonian is calculated in ***the two-body cluster approximation***.
- The prescription by Schmidt and Pandharipande is employed to obtain the free energy ***at finite temperature***.

(Phys. Lett. 87B(1979) 11, PRC 75(2007) 035802)

Nuclear EOS for uniform matter





n_0[fm^{-3}]	E_0[MeV]	K [MeV]	E_{sym}[MeV]
0.16	–16.1	245	30.0

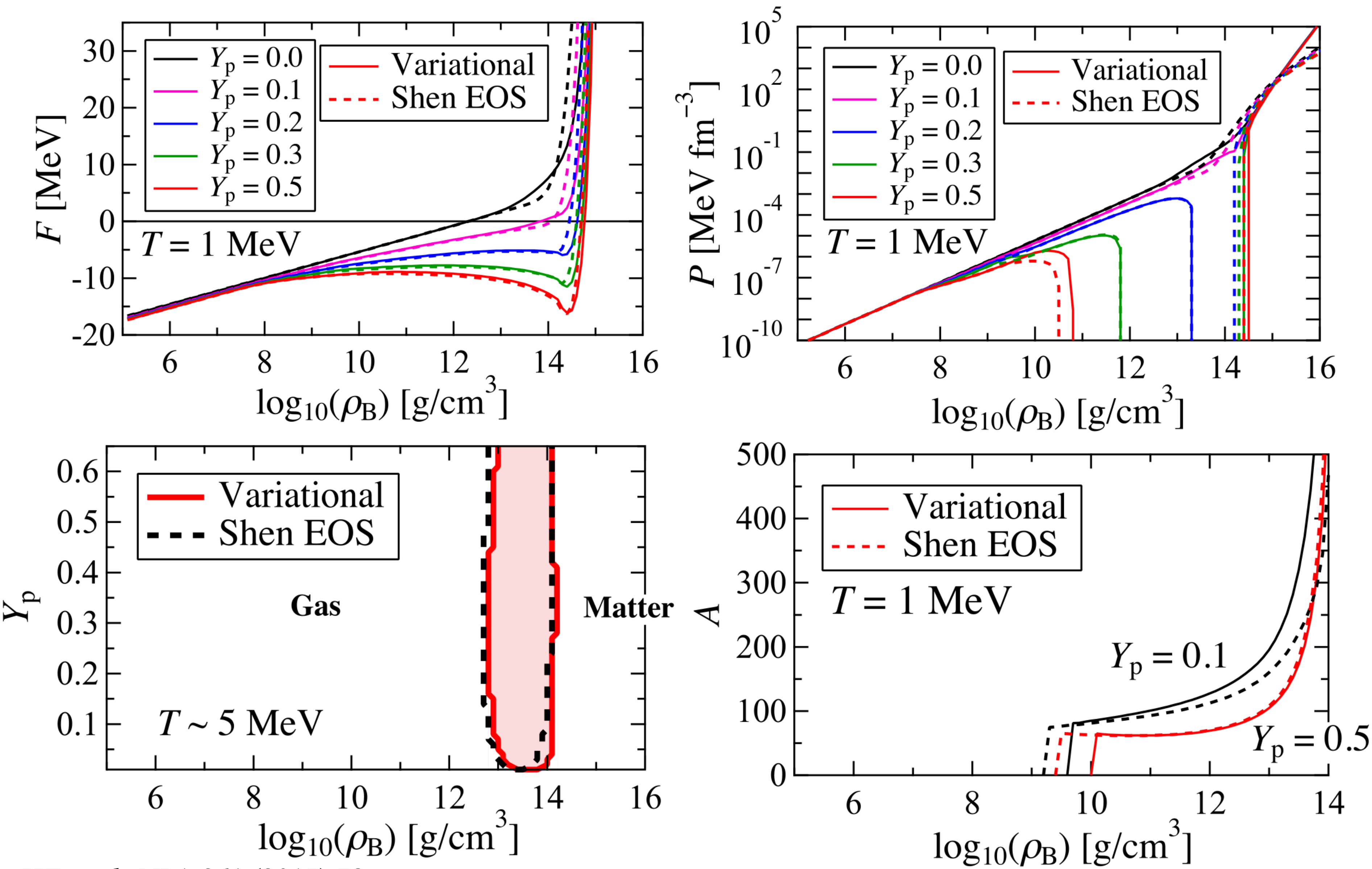
Our EOS : HT and M. Takano, NPA 902 (2013) 53

APR : A. **A**kmal, V. R. **P**andharipande, D. G. **R**avenhall, PRC 58 (1998) 1804

FHNC : A. Mukherjee, PRC 79(2009) 045811

Nuclear EOS for non-uniform matter

*We use the **Thomas-Fermi method** by Shen et al.* (PTP 100 (1998) 1013, APJS 197(2011) 20)



HT *et al.*, NPA 961 (2017) 78

Home Page of Variational EOS Table

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

Equation of state for nuclear matter with the variational method

Equation of state (EOS) based on the variational many-body theory with realistic nuclear forces is provided. For uniform matter, the EOS is constructed with the cluster variational method starting from the Argonne v18 two-body nuclear potential and the Urbana IX three-body nuclear potential. Non-uniform nuclear matter is treated in the Thomas-Fermi approximation. Alpha particle mixing is also taken into account. See Togashi et al., Nucl. Phys. A 961 (2017) 78 for details. This EOS table is open for general use in any studies for nuclear physics and astrophysics, provided that our paper is referred to in your publication.

User's Guide (read me first)

guide.pdf

(HT *et al.*, NPA961 (2017) 78)

Table A.1: Ranges of temperature T, proton fraction Y_p, and baryon mass density ρ_B in the table of the variational EOS. At the top of the last column, "+1" represents the case at $T = 0$ MeV.

Parameter	Minimum	Maximum	Mesh	Number
$\log_{10}(T)$ [MeV]	-1.00	2.60	0.04	$91+1$
Y_p	0	0.65	0.01	66
$\log_{10}(\rho_B)$ [g/cm^3]	5.1	16.0	0.10	110

EOS tables

eos.zip

Contact

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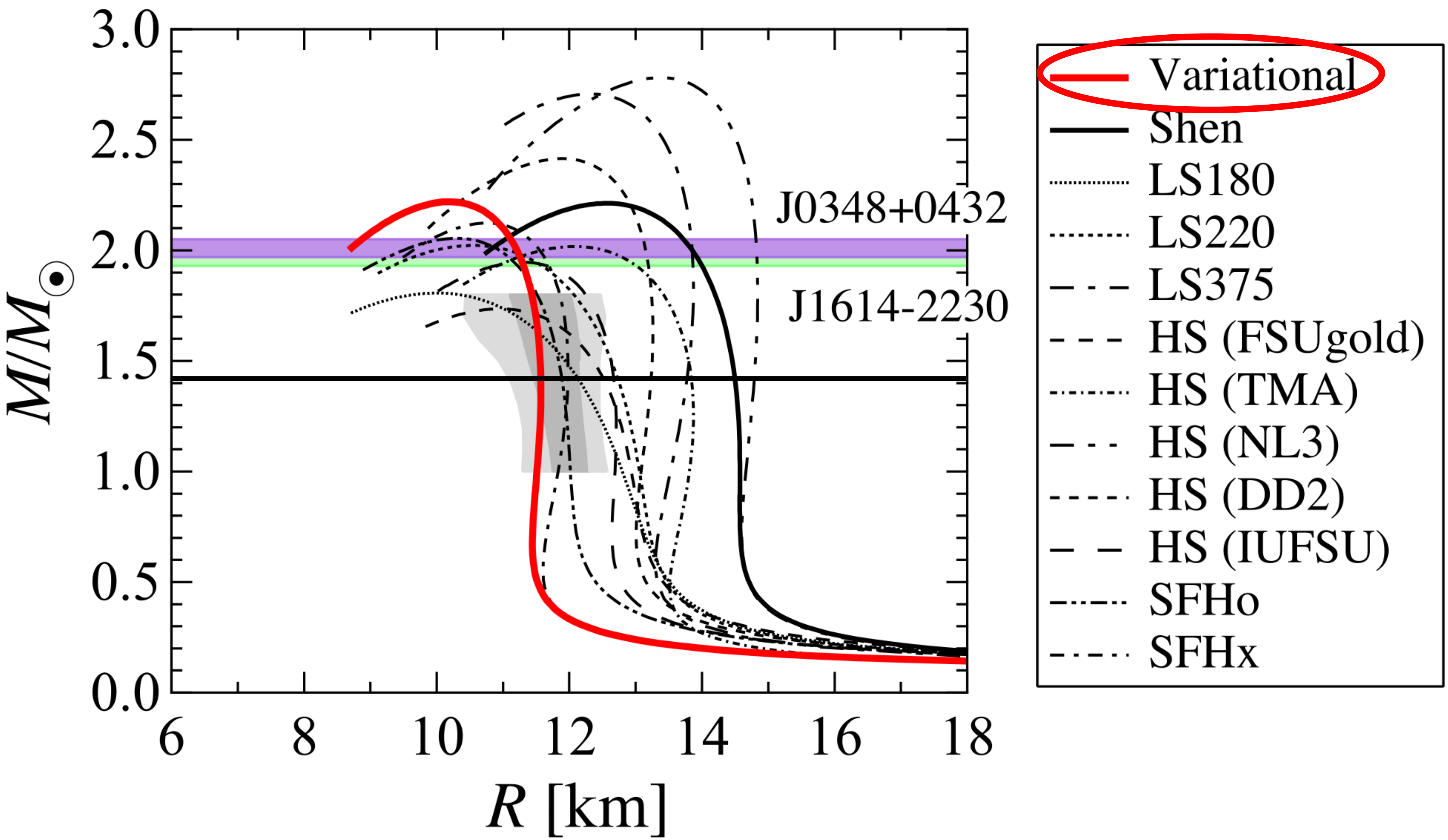
3. Application to astrophysical objects

Mass-Radius relation of neutron stars



J0348+0432: Science 340 (2013) 1233232 J1614-2230: Nature 467 (2010) 1081

Shaded region is the observationally suggested region by Steiner et al. (Astrophys. J. 722 (2010) 33)

HT *et al.*, NPA 961 (2017) 78

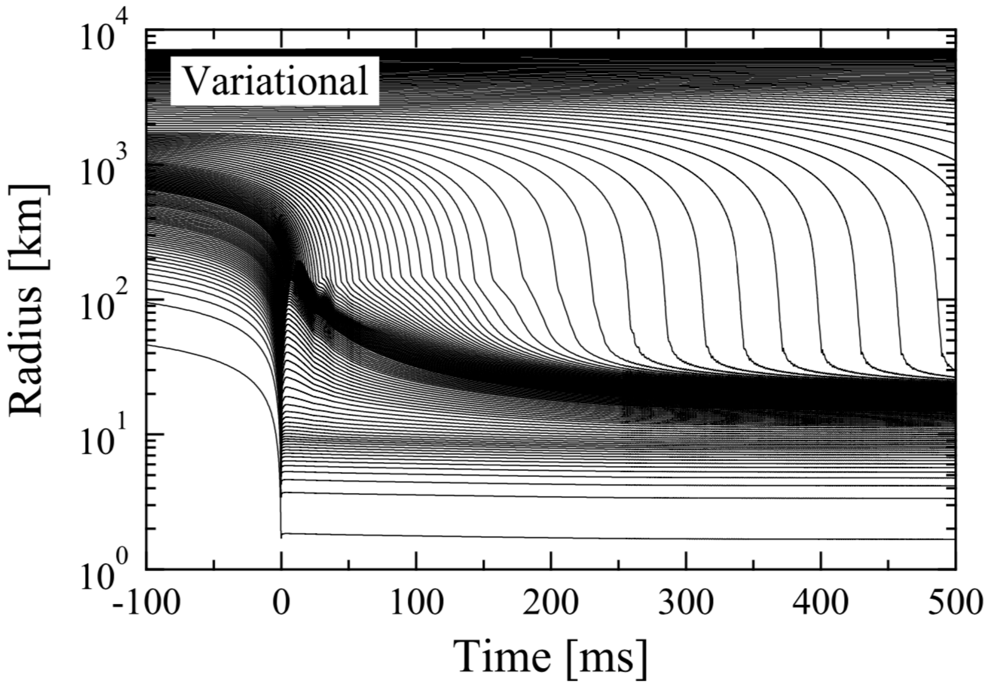
Application to Core-Collapse Supernovae

1D neutrino-radiation hydrodynamics simulations

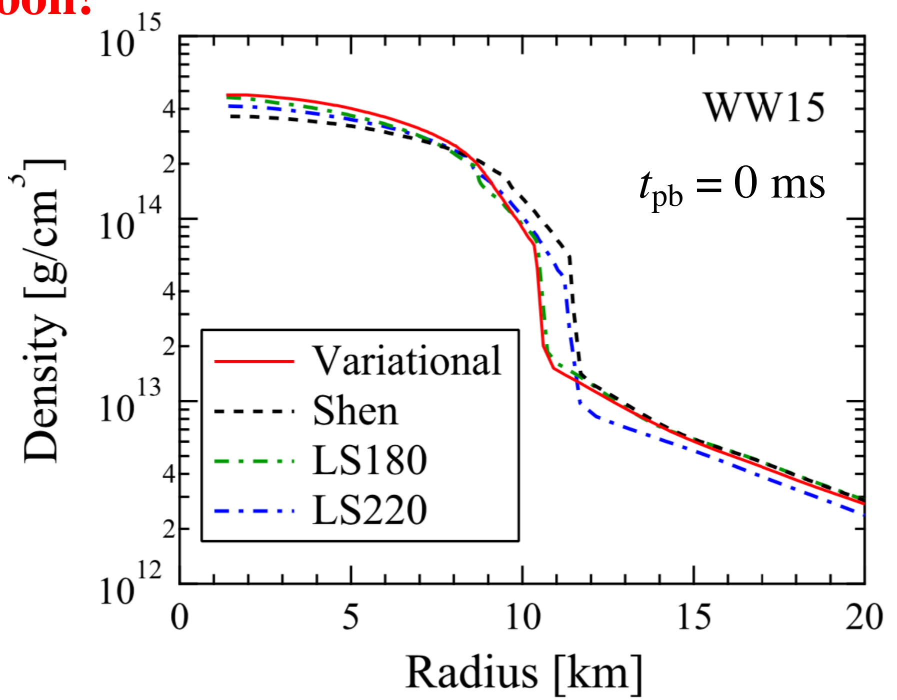
Progenitor: Woosley Weaver 1995, $15M_{\odot}$

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

More sophisticated multi-dimensional simulation
→ Takiwaki-san's talk in this afternoon!



Radial trajectories of mass elements



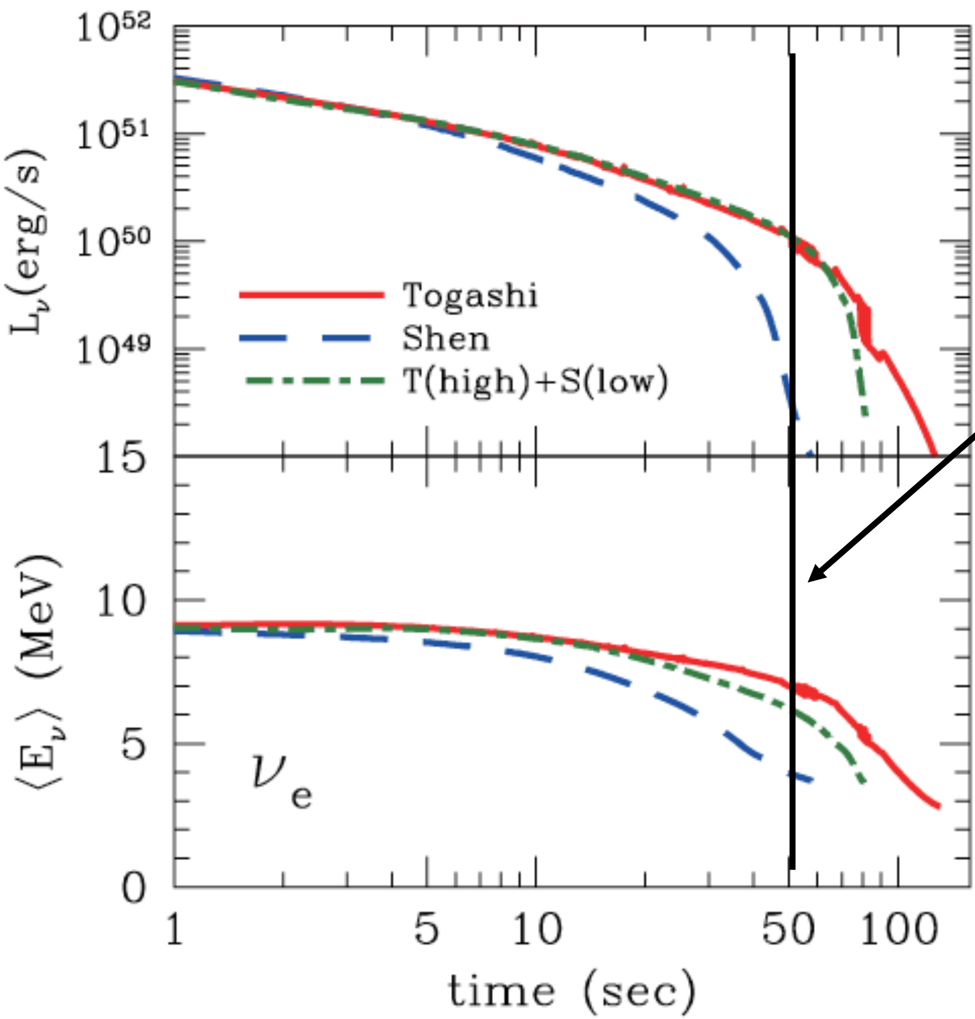
Central density: 0.30 fm^{-3}
Temperature: ~10 MeV
Proton fraction: ~0.3

HT *et al.*, in preparation

Application to Proto-Neutron Star Cooling

K. Nakazato, H. Suzuki, and HT, Phys. Rev. C 97 (2018) 035804

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



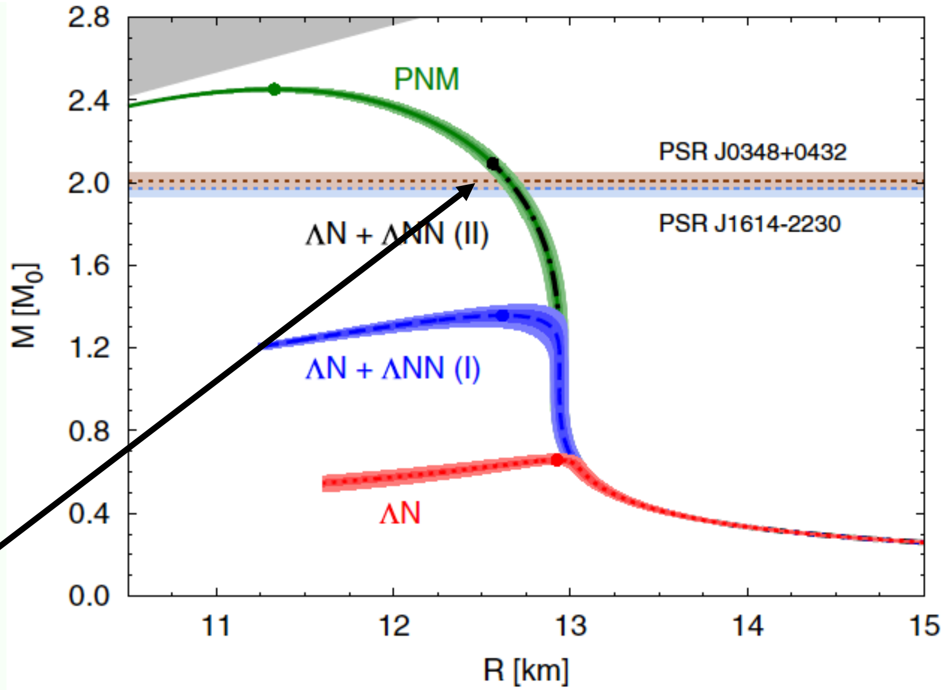
Central density: 0.47 fm^{-3}
Temperature: ~10 MeV
Proton fraction: ~0.1

4. Hyperon mixing in dense matter

HYPERON PUZZLE

- **EOS becomes softer due to hyperon mixing.**
- **Maximum mass tends to be lower than the observational data.**

Hyperon Three-Body Force (ΛNN TBF)



D. Lonardoni *et al*., PRL 114 (2015) 092301

Hyperon Interactions for the variational method

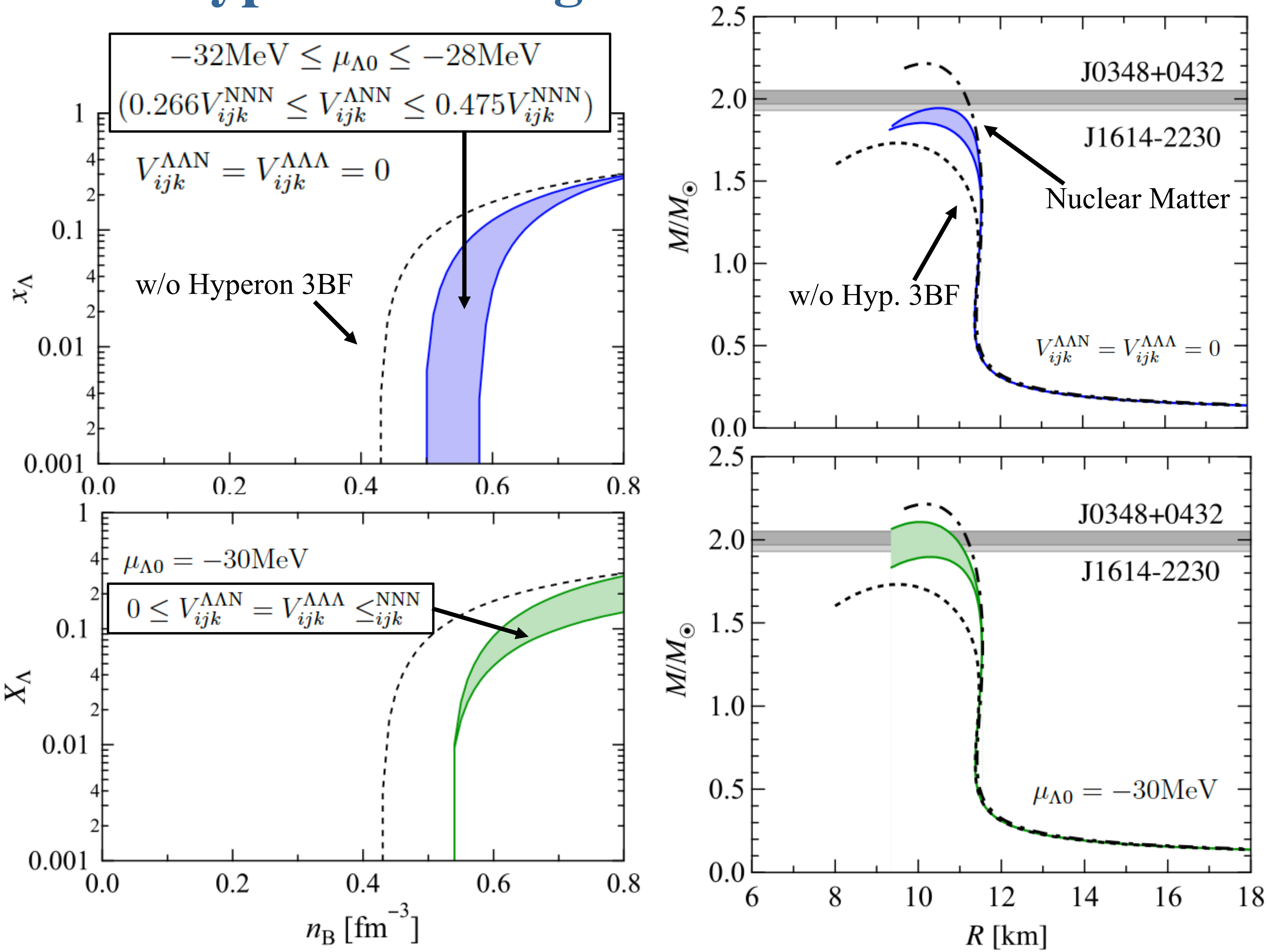
$V_{ij}^{\Lambda N}$, $V_{ij}^{\Lambda\Lambda}$: two-body potential (E. Hiyama et al., PRC 74 (2006) 054312) (E. Hiyama et al., PRC 66 (2002) 024007)

- *Constructed so as to reproduce the experimental binding energies of light hypernuclei*

$V_{ijk}^{\Lambda NN}$, $V_{ijk}^{\Lambda\Lambda N}$, $V_{ijk}^{\Lambda\Lambda\Lambda}$: three-body potential

- *Repulsive part of the UIX pot. is employed*

Hyperon mixing in neutron-star matter

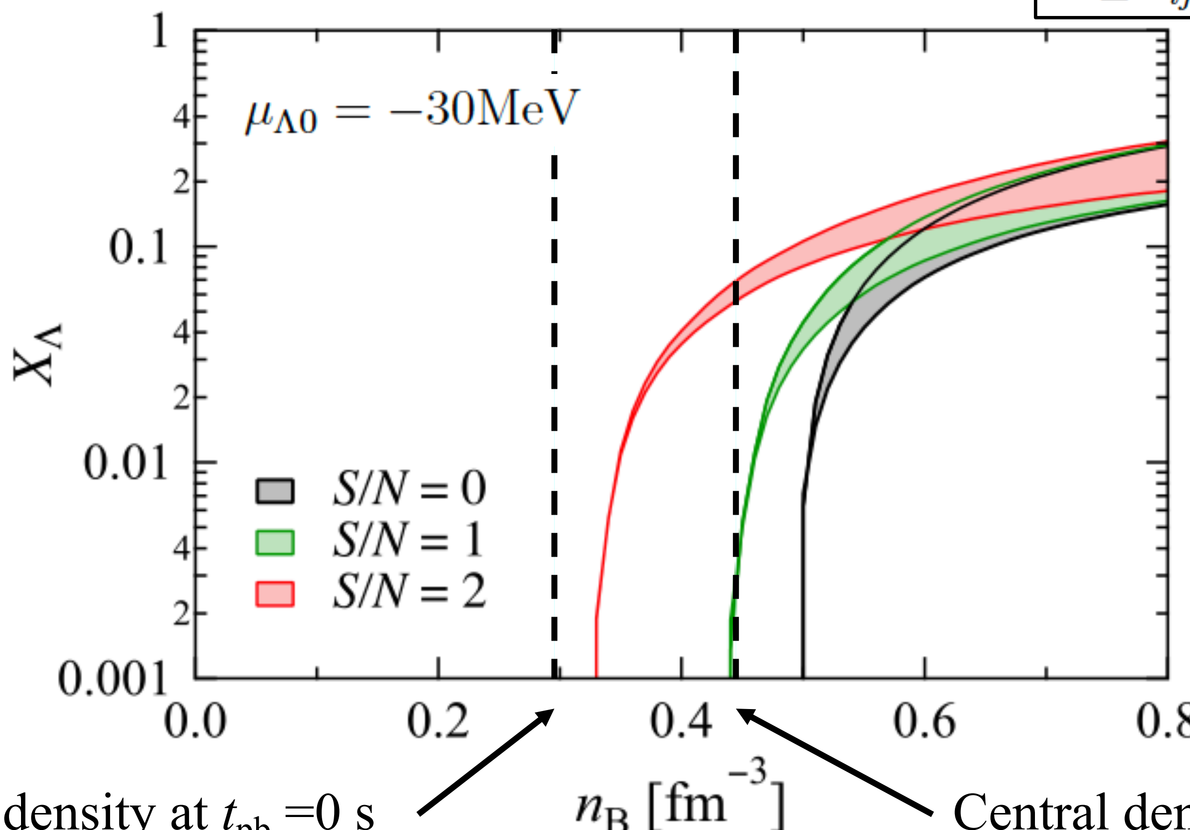


Hyperon mixing in supernova matter

Supernova matter

- Charge neutral and Isentropic matter (The entropy per baryon S ~ 1-2)
- Neutrino-free β-stable matter

$0 \leq V_{ijk}^{\Lambda\Lambda N} = V_{ijk}^{\Lambda\Lambda\Lambda} \leq_{ijk}^{NNN}$



Central density at t_{pb} =0 s (Core-collapse supernova)

Central density at t_{pb} =50 s (PNS cooling)

Summary

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

Uniform nuclear matter : Cluster variational method

Non-uniform nuclear matter : Thomas-Fermi approximation

→ We are extending our microscopic EOS table to consider Λ hyperon mixing in dense nuclear matter.

Our SN-EOS is available at

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

Future Plans

- Construction of the hyperon EOS table for simulations
- Taking into account mixing of other hyperons (Σ^-, Σ^0, Σ^+, Ξ^0, Ξ^-)
- Employing more sophisticated baryon interactions (e.g. Nijmegen)