Supernova equation of state with realistic nuclear interactions and hyperon mixing in hot dense matter

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Outline

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1. Introduction

Supernova equation of state (SN-EOS)

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	[illegible]	[illegible]	[illegible]	[illegible]	y	Lattimer and Swesty (1991)
LS220	LS220	[illegible]	[illegible]	[illegible]	[illegible]	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*	[illegible]	[illegible]	[illegible]	[illegible]	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
HS(DD2)	DD2	[illegible]	[illegible]	[illegible]	[illegible]	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)

Skyrme-type effective interaction

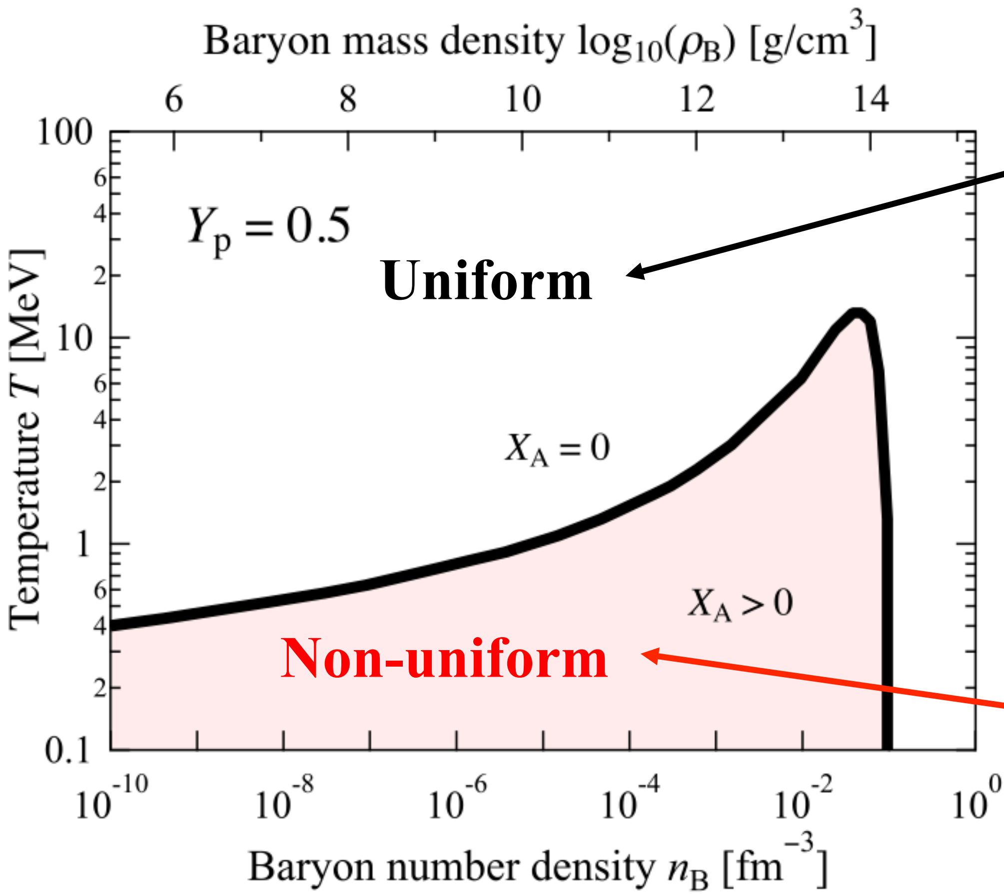
Relativistic Mean Field Theory

(M. Oertel et al., Rev. Mod. Phys. 89 (2017) 015007)

There is no SN-EOSs based on the microscopic many-body theory.

We aim to construct a new SN-EOS with the variational method starting from bare nuclear forces.

Our procedure to construct a new EOS table



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

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

- Temperature T : $0 \le T \le 100$ MeV
- Density ρ : $10^{5.1} \le \rho_B \le 10^{16.0}$ g/cm^3
- Proton fraction Y_p : $0 \le Y_p \le 0.65$

2. Supernova EOS with realistic nuclear forces

Nuclear Hamiltonian

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

V_{ij}: Argonne v18 (AV18) two-body potential

V_{ijk}: Urbana IX (UIX) three-body potential

Jastrow wave function

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

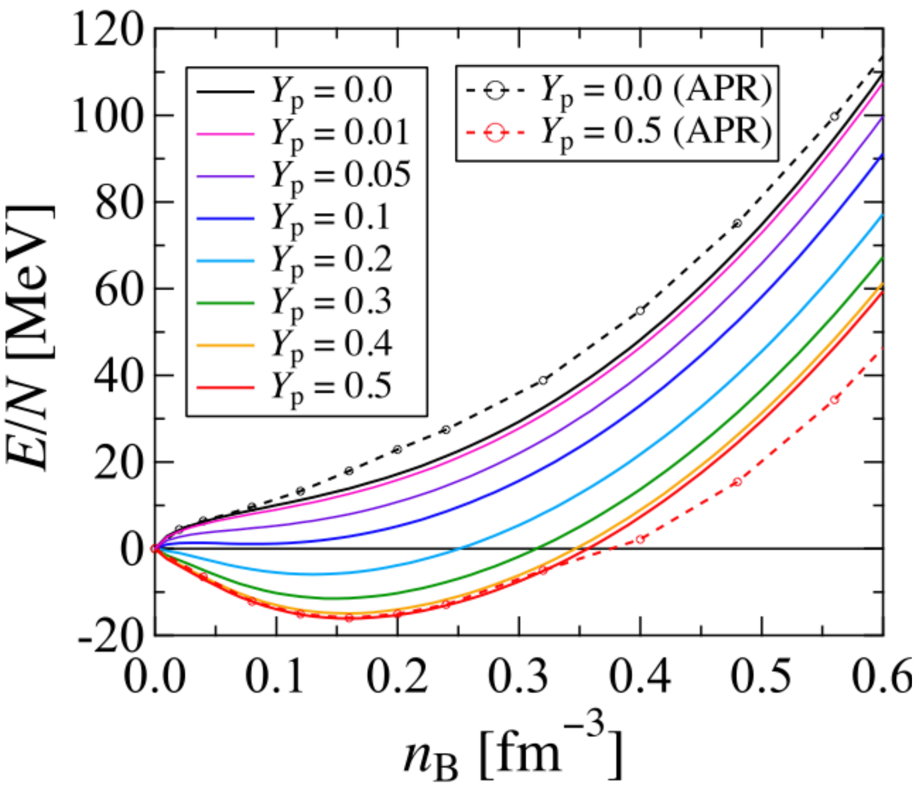
f_{ij}: Correlation function

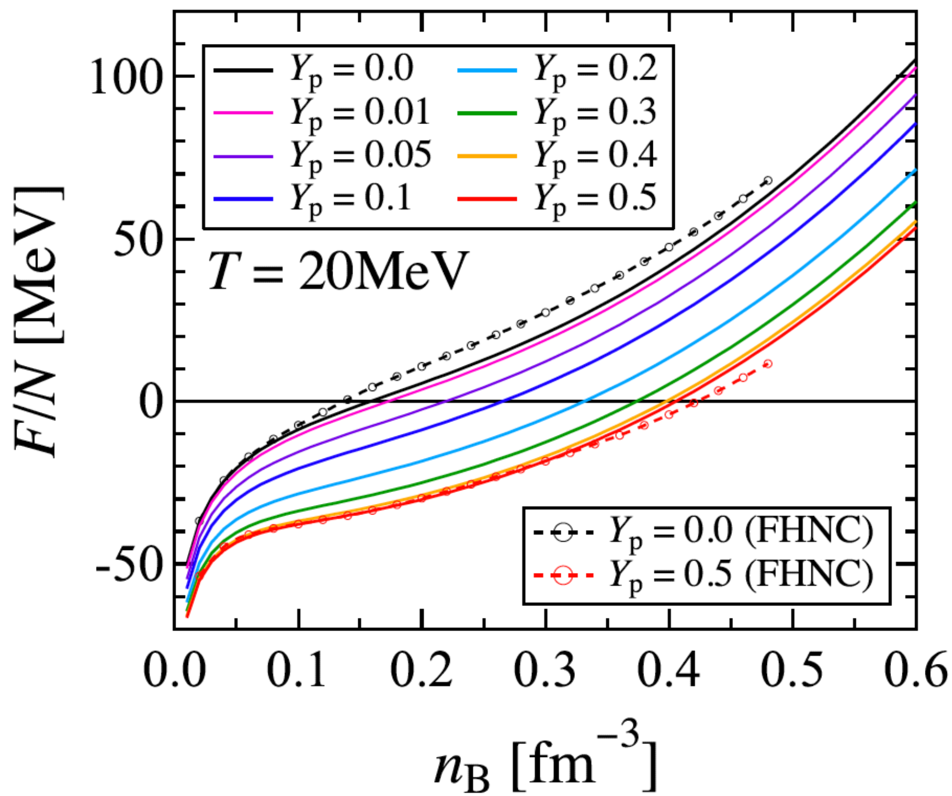
Φ_{F}: Fermi-gas wave function

- 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

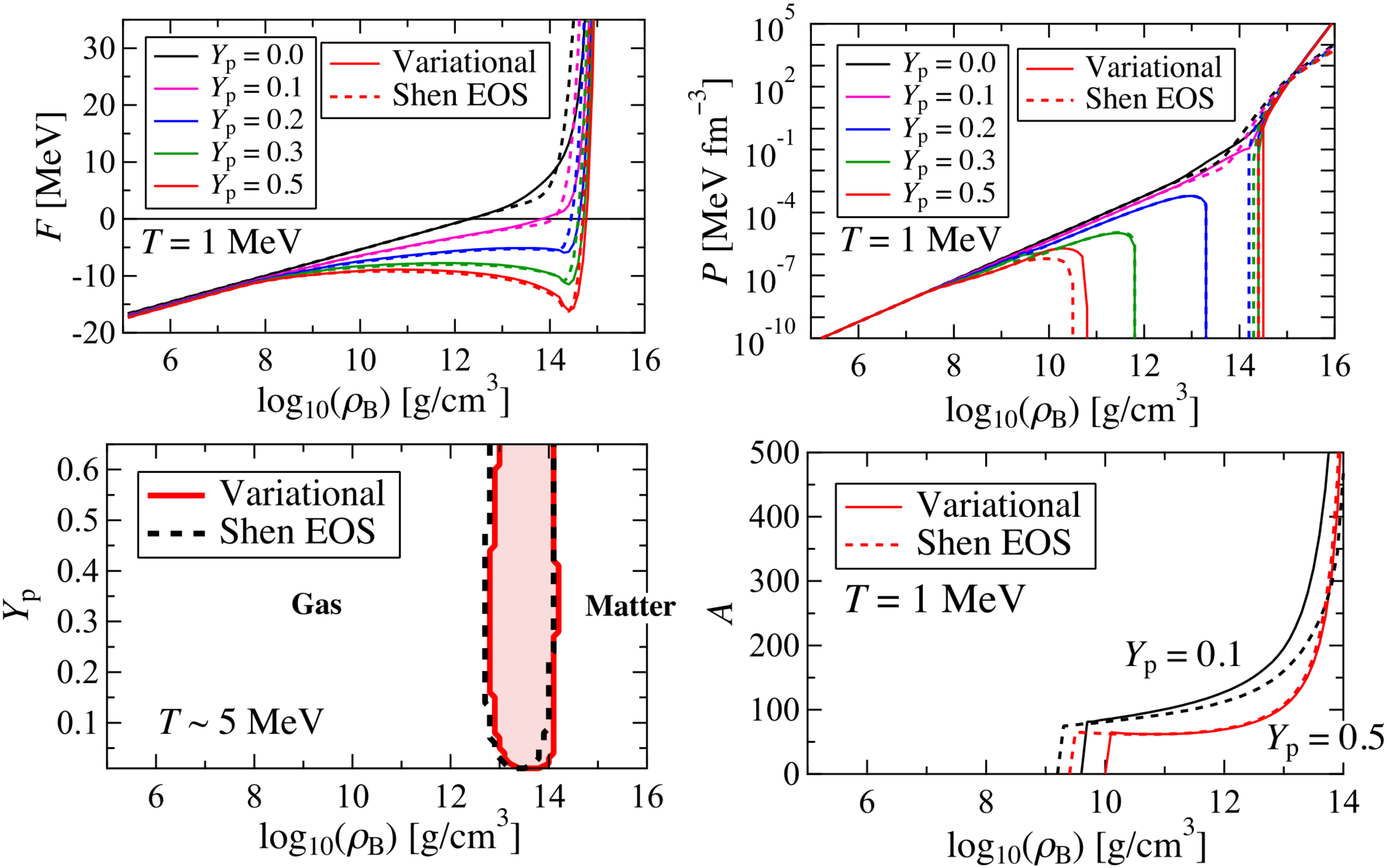
Our EOS : HT and M. Takano, NPA 902 (2013) 53

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 w

Equation of state (EOS) based on the variational man
matter, the EOS is constructed with the cluster variat
potential and the Urbana IX three-body nuclear poter
approximation. Alpha particle mixing is also taken int
This EOS table is open for general use in any studies
referred to in your publication.

User's Guide (read me first)

guide.pdf

User's Guide

User Note for the Variational EOS Table

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Abstract

This is a guide for users of the nuclear equation of state (EOS) table based on the Argonne v18 two-body and Urbana IX three-body potentials. We construct the nuclear EOS using the cluster variational method for uniform matter and the Thomas-Fermi calculation for non-uniform matter.

EOS tables

eos.zip

Numerical Data

```
cccccccccccc
 Log10(Temp)   Temp
-1.000000E+00  1.000000E-01
```

5.100E+00	7.581427E-11	1.000E-02	-1.516998E+00	7.968970E+00	1.427632E+01	1.004453E+02
5.200E+00	9.544451E-11	1.000E-02	-1.494684E+00	7.968916E+00	1.405264E+01	1.005867E+02
5.300E+00	1.201575E-10	1.000E-02	-1.472371E+00	7.968862E+00	1.382897E+01	1.007294E+02
5.400E+00	1.512693E-10	1.000E-02	-1.450059E+00	7.968809E+00	1.360532E+01	1.008713E+02
5.500E+00	1.904368E-10	1.000E-02	-1.427748E+00	7.968757E+00	1.338169E+01	1.010151E+02
5.600E+00	2.397458E-10	1.000E-02	-1.405439E+00	7.968705E+00	1.315807E+01	1.011550E+02
5.700E+00	3.018220E-10	1.000E-02	-1.383130E+00	7.968653E+00	1.293447E+01	1.013009E+02

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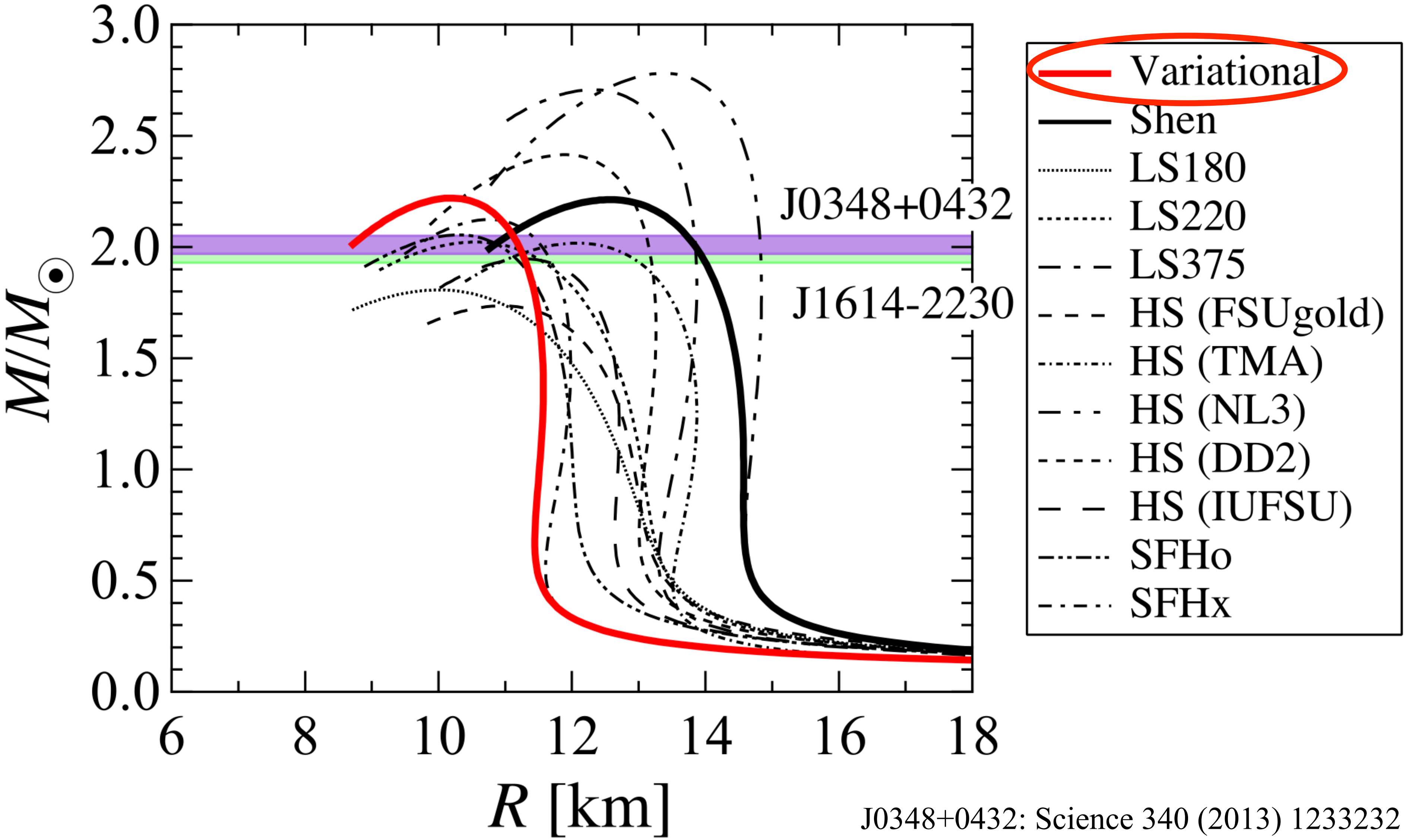
Application to neutron star

Mass-Radius relation of neutron stars



J0348+0432: Science 340 (2013) 1233232

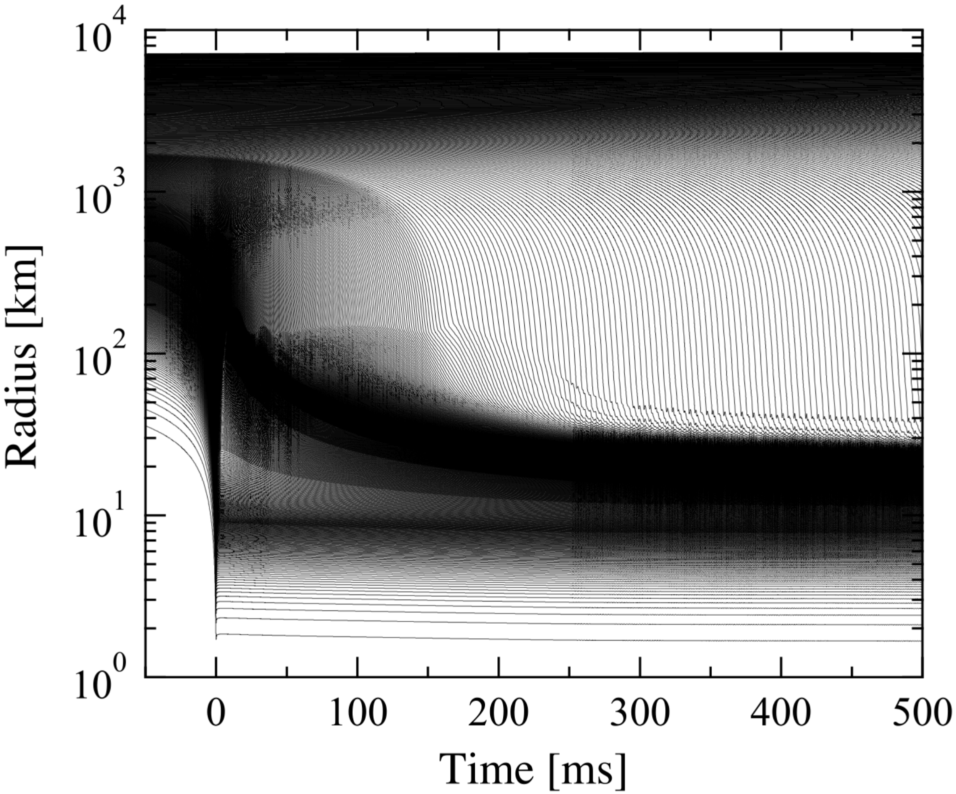
J1614-2230: Nature 467 (2010) 1081

Application to Core-Collapse Supernovae

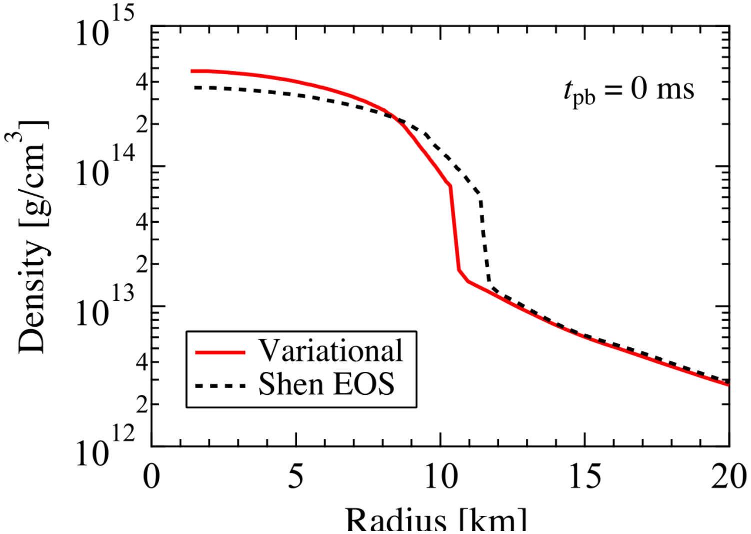
1D neutrino-radiation hydrodynamics simulations

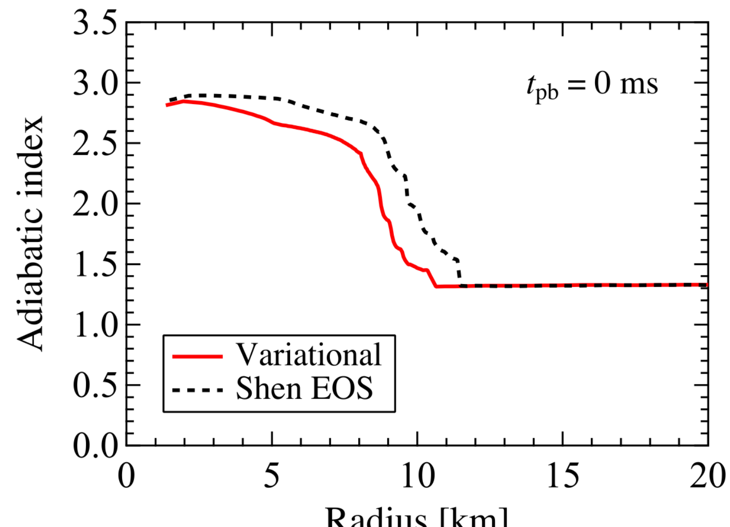
Progenitor: Woosley Weaver 1995, $15M_{\odot}$ Astrophys. J. Suppl. 101 (1995) 181

SN simulation numerical code: K. Sumiyoshi, et al., NPA 730 (2004) 227



Radial trajectories of mass elements





3. Hyperon mixing in dense matter

$$H = H_N - \frac{\hbar^2}{2m_\Lambda}\sum_i \nabla_i^2 + \sum_{i<j}\left[V_{ij}^{\Lambda N} + V_{ij}^{\Lambda\Lambda}\right]$$

H_N: **Nuclear Hamiltonian (AV18+UIX)**

Two-Body Central Potentials

$V_{ij}^{\Lambda N}$ **: Λ-Nucleon (*N*) potential** (E. Hiyama et al., PRC 74 (2006) 054312)

- Constructed so as to reproduce the experimental binding energies of light Λ hypernuclei with the Gaussian expansion method.

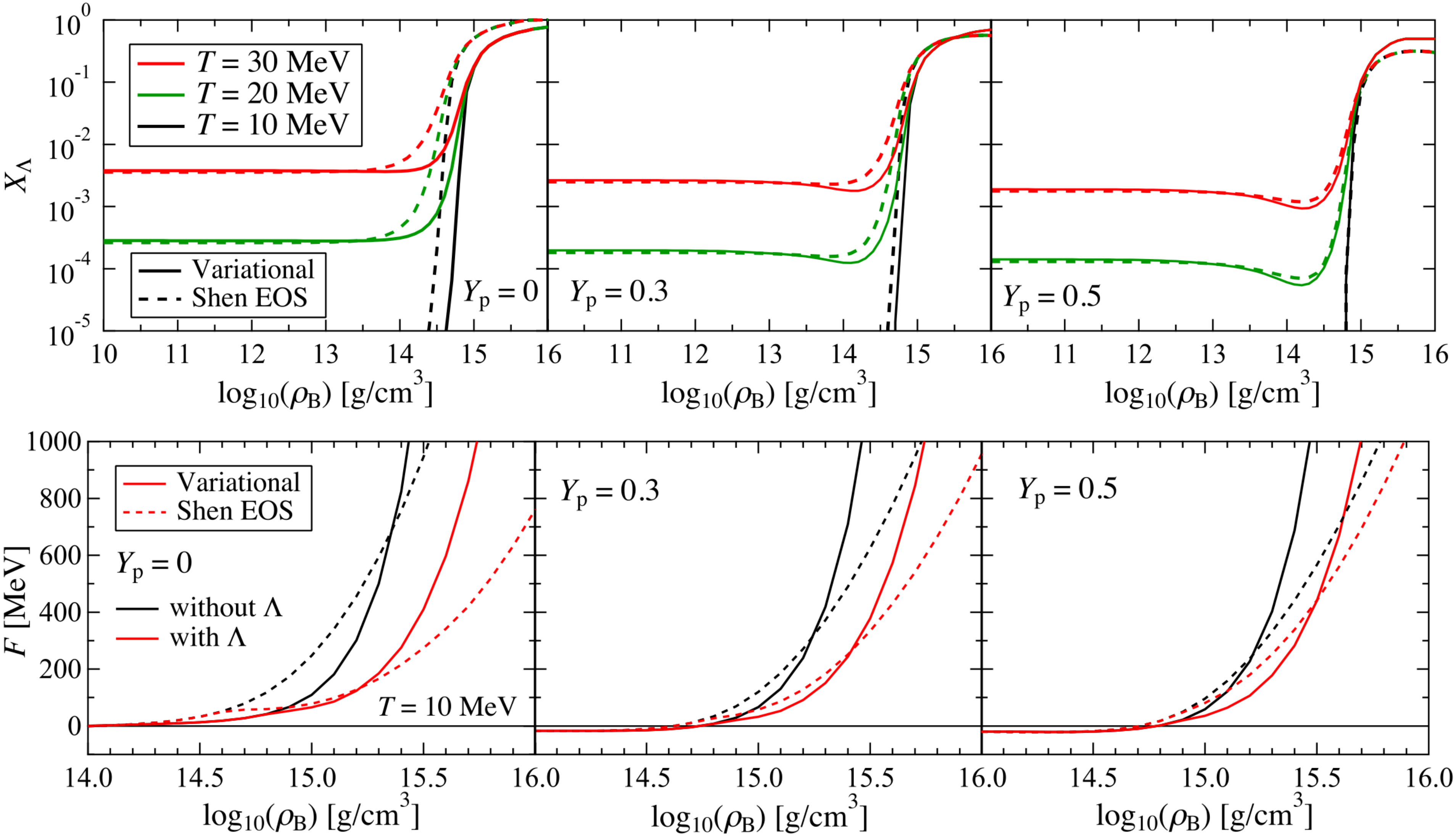
$V_{ij}^{\Lambda\Lambda}$ **: Λ-Λ potential** (E. Hiyama et al., PRC 66 (2002) 024007)

- the experimental double-Λ binding energy from $^{6}_{\Lambda\Lambda}He$ (NAGARA event)

Using the variational method for hot hyperon matter,

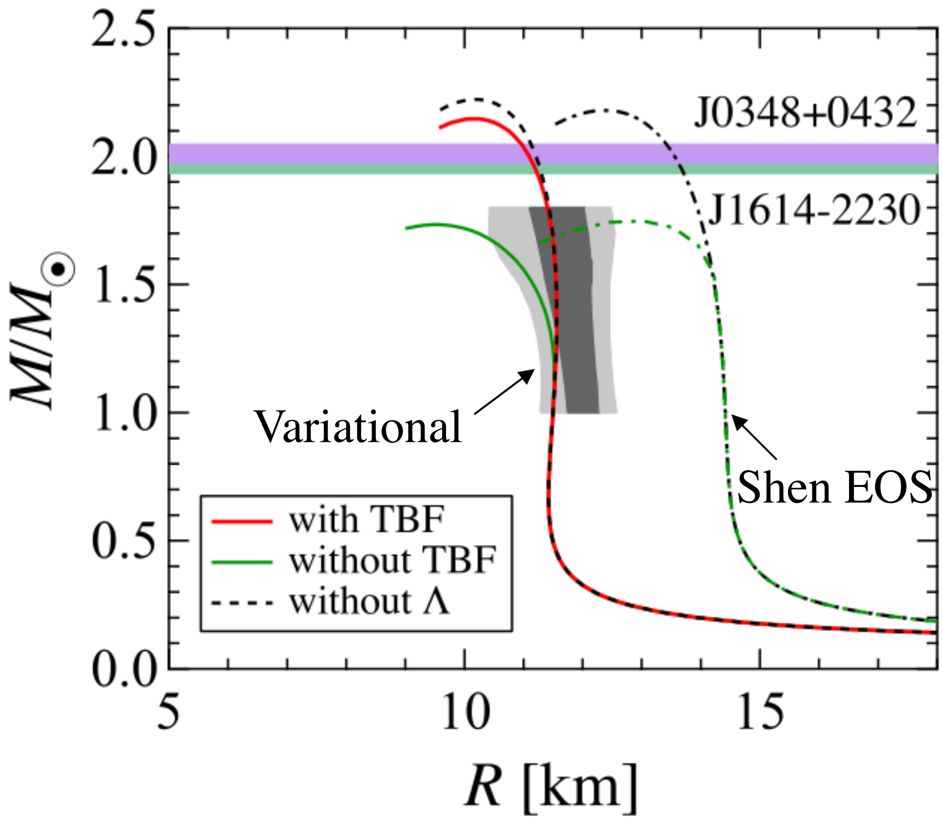
We calculate the thermodynamic quantities of hot dense matter **under the equilibrium condition $\mu_n = \mu_\Lambda$** at fixed baryon number density n_B, proton fraction Y_p, and temperature T.

Supernova EOS with Λ hyperon

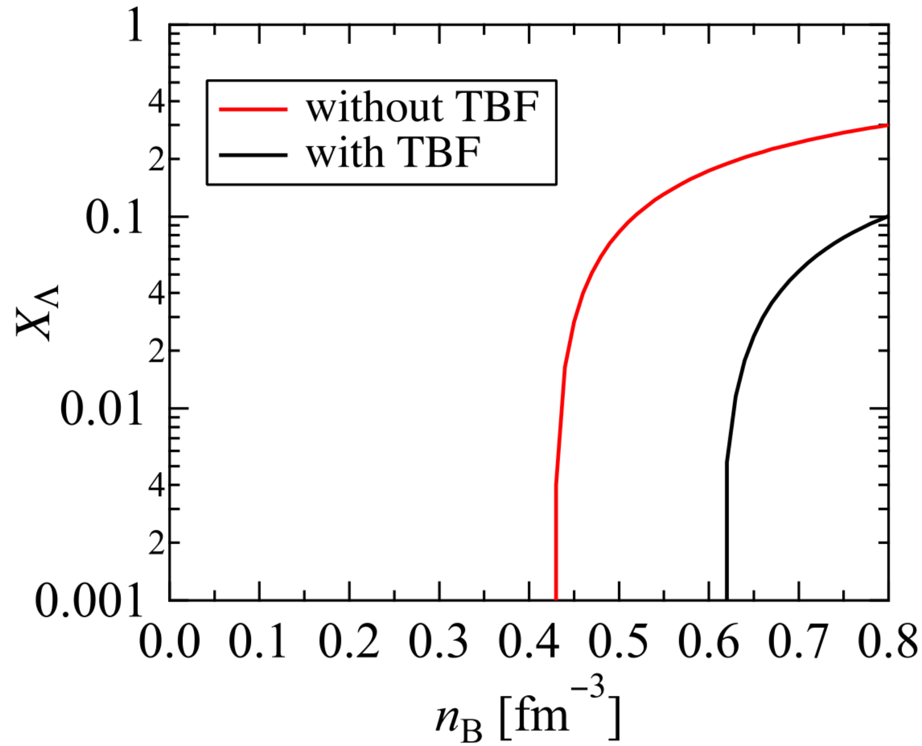


Thermodynamic quantities of our EOS at smaller Y_p are less affected by the Λ hyperon mixing than in the case of the Shen EOS.

Neutron star matter with Λ hyperon



Mass-radius relations of neutron stars



Λ fractions in neutron star matter

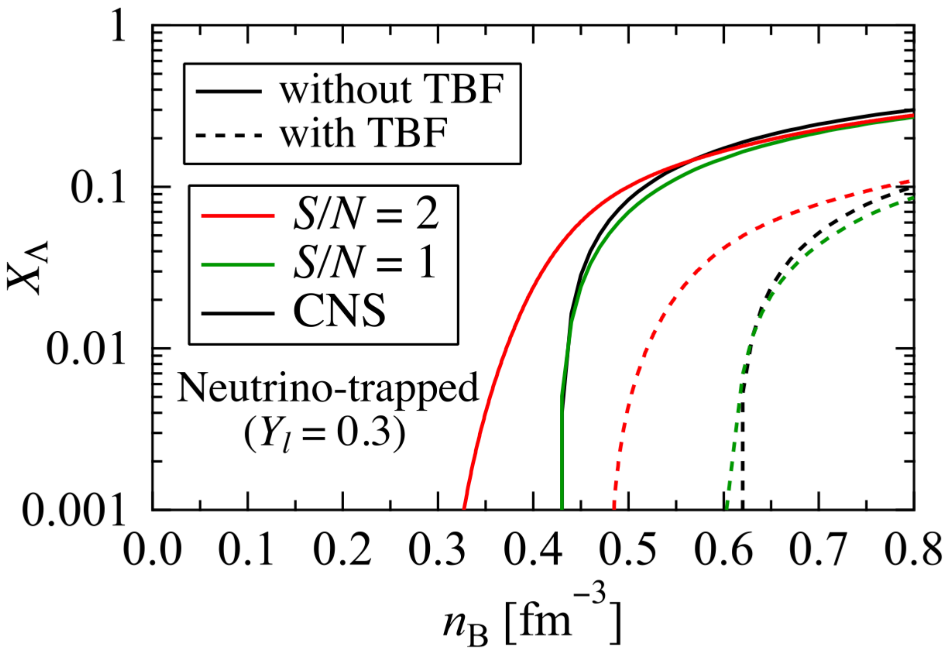
We consider an effective potential based on
Three-Baryon Force (TBF) for Λ*NN*, ΛΛ*N*, ΛΛΛ systems.

(Y. Yamamoto et al., PRC 90 (2014) 04580, HT et al., PRC 93 (2016) 035808)

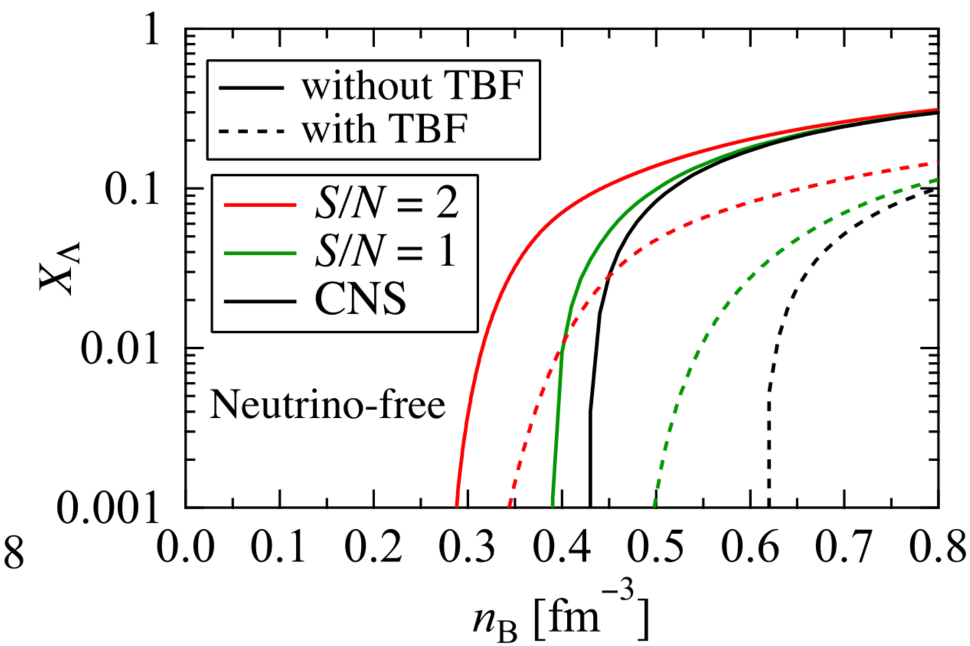
Supernova matter with Λ hyperon

Supernova matter

- Charge neutral and Isentropic matter (The entropy per baryon $S \sim$ 1-2)
- Neutrino-free or neutrino-trapped ($Y_l = Y_e + Y_{\nu e} = 0.3$) β-stable matter



X_Λ in neutrino-trapped supernova matter
($Y_p \sim 0.25$)



X_Λ in neutrino-free supernova matter
($Y_p \sim 0.1$)

Summary

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

- ***uniform nuclear matter : the cluster variational method***
- ***Non-uniform nuclear : the Thomas-Fermi calculation***

Our SN-EOS is available at

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

NSE model based on the variational EOS for uniform matter

https://sites.google.com/site/furusawashun/eosdata

Variational EOS is being extended to consider Λ hyperon mixing in nuclear matter.

- Trapped neutrino reduces Λ mixing in supernova cores.
- Hyperon three-body force shifts the onset density of Λ hyperon to higher density region.