Variational Study of Hyperon Effects on the Nuclear Equation of State at Finite Temperature

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Outline

1 : Introduction

2 : Variational method for hyperon matter

3 : Application to supernova matter

4 : Summary

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1: Introduction

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

1. Lattimer-Swesty EOS : *The Skyrme-type interaction* (NPA 535 (1991) 331)
2. Shen EOS : *The Relativistic Mean Field Theory* (NPA 637 (1998) 435)

SN-EOS list by M. Hempel

Nuclear Interaction	n_{sat} (fm^{-3})	BE/A (MeV)	K (MeV)	Q ($\frac{\mathrm{MeV}}{\mathrm{fm}^3}$)	J (MeV)	L (MeV)	type of int.	used in
SKa	0.155	16.0	263	-300	32.9	74.6	Skyrme	H&W
LS180	0.155	16.0	180	-451	28.6	73.8	Skyrme	LS180
LS220	0.155	16.0	220	-411	28.6	73.8	Skyrme	LS220, LS220Λ, LS220π
LS375	0.155	16.0	375	176	28.6	73.8	Skyrme	LS375
TMA	0.147	16.0	318	-572	30.7	90.1	RMF	HS(TMA)
NL3	0.148	16.2	272	203	37.3	118.2	RMF	SHT, HS(NL3)
FSUgold	0.148	16.3	230	-524	32.6	60.5	RMF	SHO(FSU1.7), HS(FSUgold)
FSUgold2.1	0.148	16.3	230	-524	32.6	60.5	RMF	SHO(FSU2.1)
IUFSU	0.155	16.4	231	-290	31.3	47.2	RMF	HS(IUFSU)
DD2	0.149	16.0	243	169	31.7	55.0	RMF	HS(DD2), BHBΛ, BHB$\Lambda\phi$
SFHo	0.158	16.2	245	-468	31.6	47.1	RMF	SFHo
SFHx	0.160	16.2	239	-457	28.7	23.2	RMF	SFHx
TM1	0.145	16.3	281	-285	36.9	110.8	RMF	STOS, FYSS, HS(TM1), STOSΛ, STOSY, STOSYπ, STOSπ, STOSπQ, STOSQ, STOSB139, STOSB145, STOSB155, STOSB162, STOSB165

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There were no supernova EOSs based on the microscopic many-body theory.

SN-EOS with the microscopic many-body theory

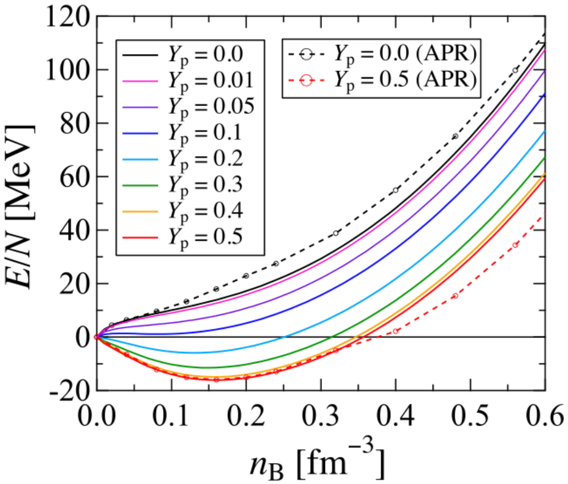
We constructed a new nuclear EOS for core-collapse simulations.

Uniform matter : Cluster variational method (AV18 + UIX)

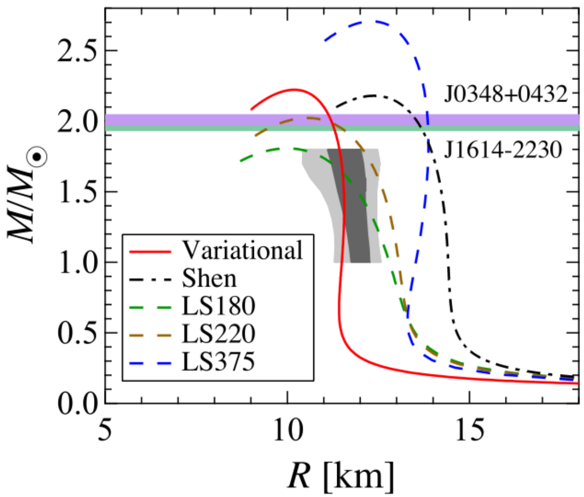
Non-uniform matter : Thomas-Fermi approximation

Collaboration with M. Takano (Waseda Univ.) , K. Sumiyoshi (Numazu College of Tech.), K. Nakazato (Kyushu Univ.), Y. Takehara, S. Yamamuro, H. Suzuki (Tokyo Univ. of Science)

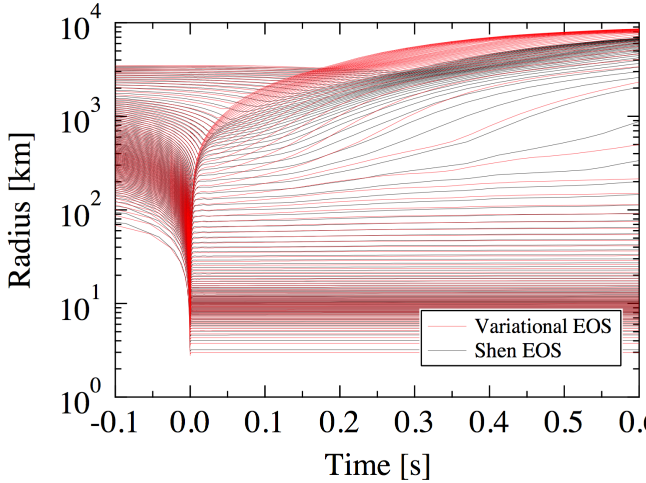
(NPA902 (2013) 53, PTEP 2014 (2014) 023D05)



Energies of uniform matter



Application to Neutron Star



Application to Supernova simulation

We aim to extend the microscopic nuclear EOS table to consider Λ hyperon mixing.

2: Variational method for hyperon matter

Two-body Hamiltonian

$$H_2 = -\sum_i \left[m_i c^2 + \frac{\hbar^2}{2m_i} \nabla_i^2 \right] + \sum_{i<j} V_{ij}$$

Two-body potential

$$V_{ij} = \sum_{N,Y} [V_{ij}^{NN} + V_{ij}^{YN} + V_{ij}^{YY}]$$

Three-body Hamiltonian

$$H_3 = \sum_{i<j<k} V_{ijk}$$

Three-nucleon potential : UIX

- *NN* potential: **AV18 two-body potential** (PRC 51 (1995) 38)
- *YN* and *YY* potentials: **Central three-range Gaussian potentials**

ΛN interaction (E. Hiyama et al., PRC 74 (2006) 054312)

$\Lambda\Lambda$ interaction (E. Hiyama et al., PRC 66 (2002) 024007)

Hyperon interactions are determined so as to reproduce the experimental data on single-and double-Λ hypernuclei.

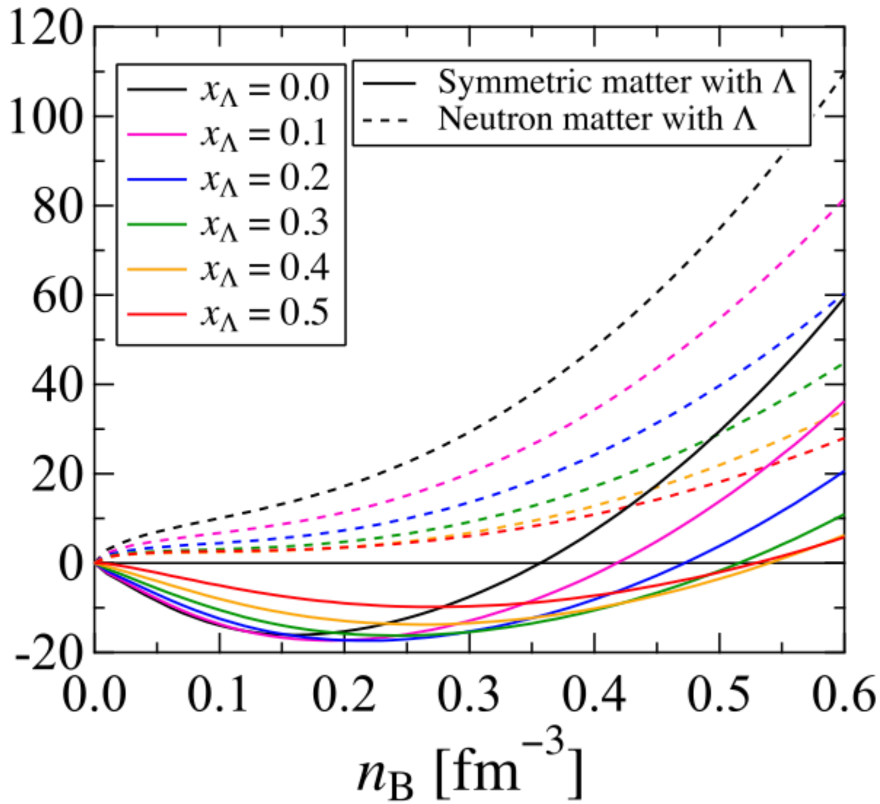
Energy of hyperon matter at zero temperature

Energy per baryon $\boxed{E(n_\mathrm{n}, n_\mathrm{p}, n_\Lambda) = E_2(n_\mathrm{n}, n_\mathrm{p}, n_\Lambda) + E_3^\mathrm{N}}$

E_2 : The expectation value of H_2 with the Jastrow wave function
in the two-body cluster approximation

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

Φ_F: Fermi-gas wave function



Energy of hyperonic nuclear matter

E_3^N : Three-nucleon energy

Based on the expectation value of H_3 with the Fermi-gas wave function

(NPA902 (2013) 53)

Free energy of hyperon matter at finite temperature

We follow the prescription proposed by Schmidt and Pandharipande.

(K. E. Schmidt et al., Phys. Lett. 87B(1979) 11)
(A. Mukherjee et al., PRC 75(2007) 035802)

Free energy F is expressed by the average occupation probabilities.

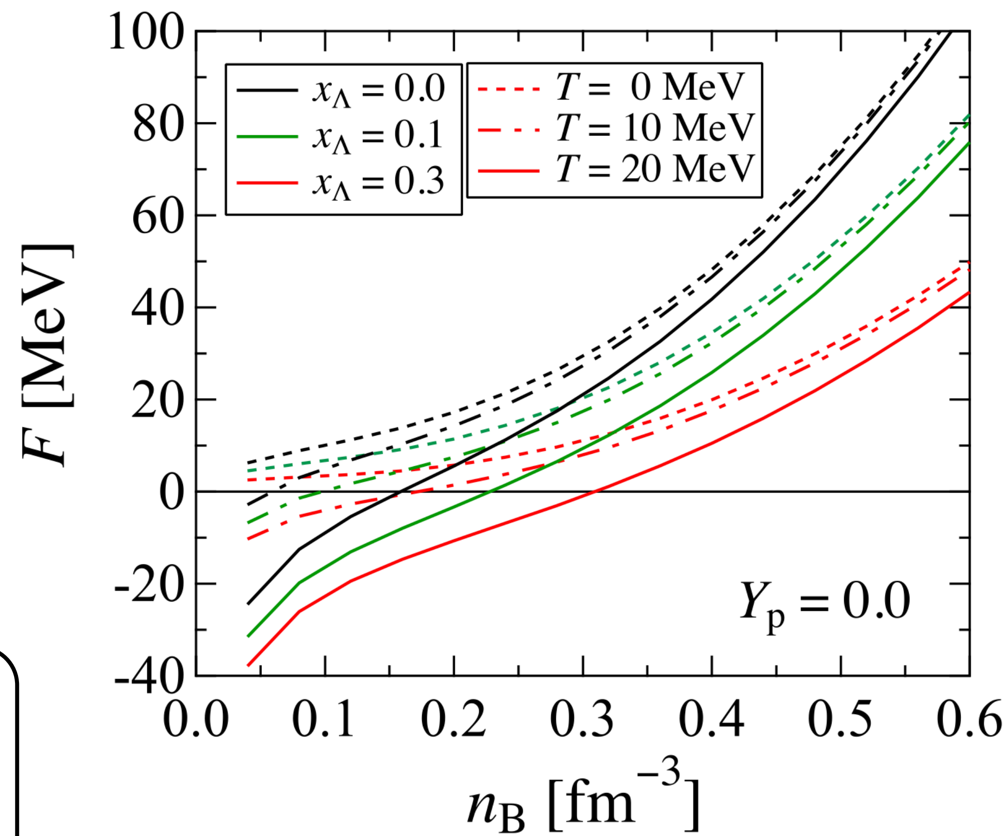
$$\boxed{n_{\mathrm{T}i}(k) = \left\{1 + \exp\left[\frac{\varepsilon_i(k) - \mu_{0i}}{k_{\mathrm{B}}T}\right]\right\}^{-1}}$$

$\varepsilon_i(k)$: Single particle energy

$$\varepsilon_i(k) = \frac{\hbar^2 k^2}{2m_i^*} \quad (i = \mathrm{p, n}, \Lambda)$$

m_i^*: Effective mass of baryons

Free energy is minimized with respect to m_i^*

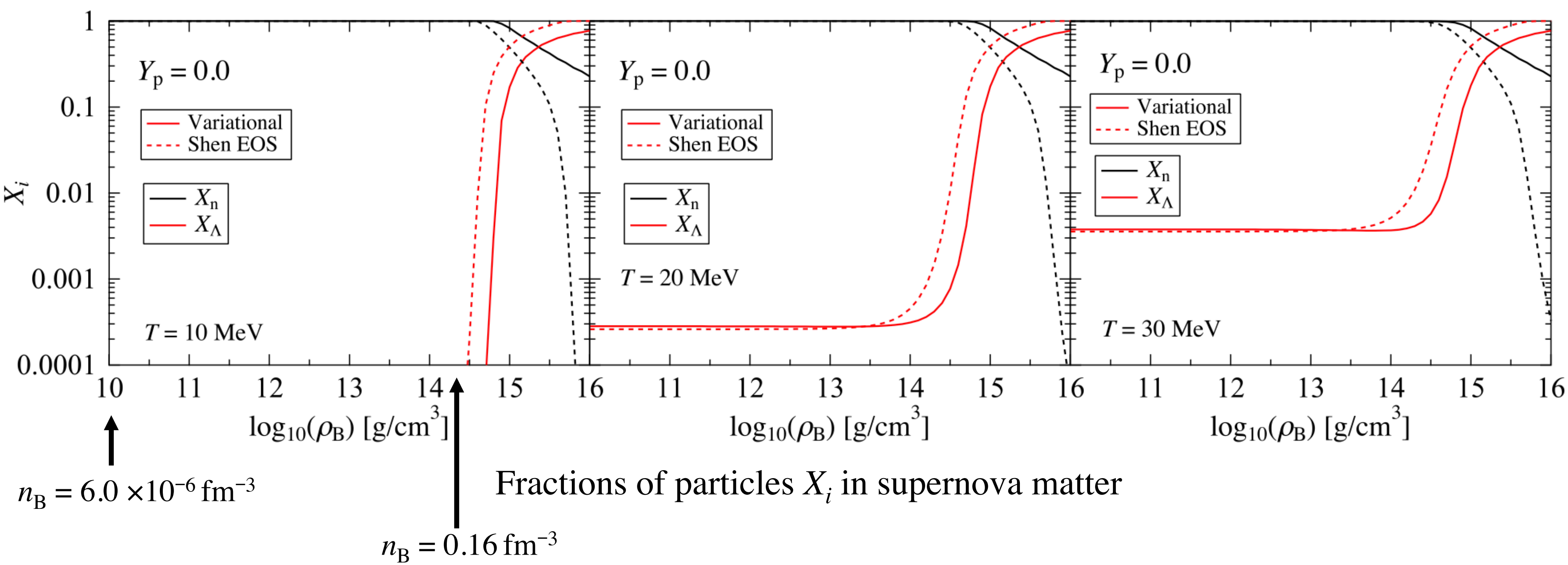


Free energy of hyperonic nuclear matter

3: Application to supernova matter

Using the obtained EOS of hot hyperon matter,

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

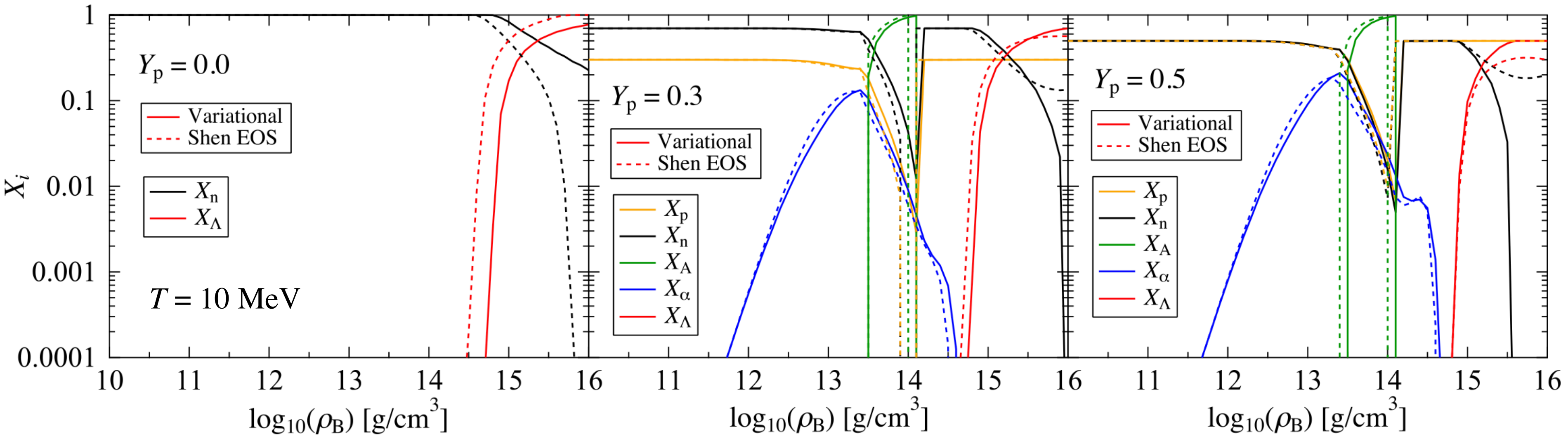


Fractions of particles X_i in supernova matter

The effect of Λ hyperons on SN matter becomes larger at higher temperatures.

Composition of supernova matter

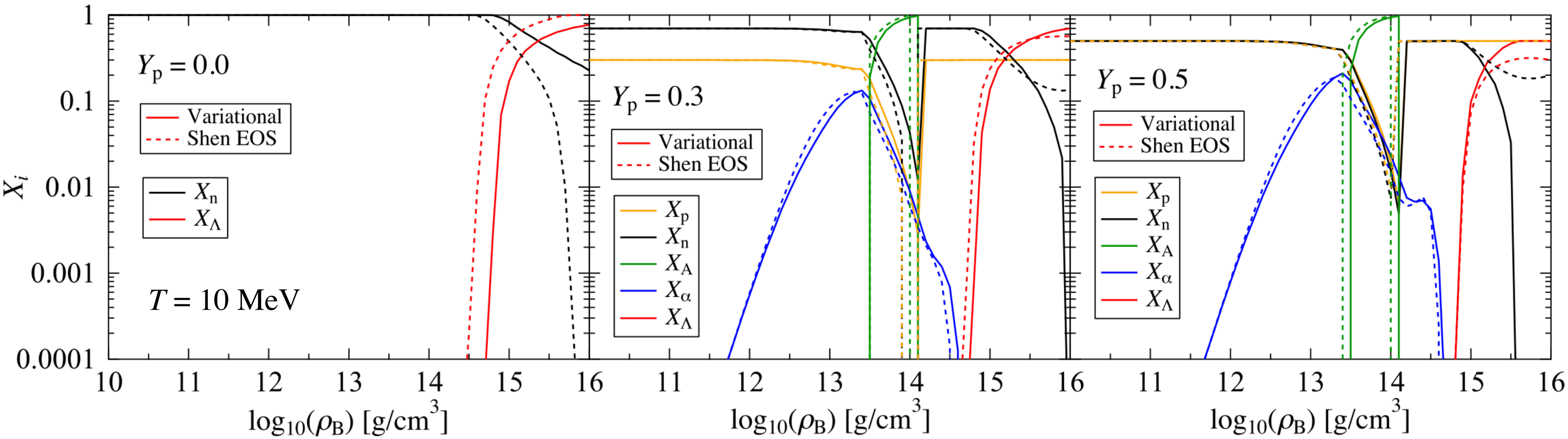
Equilibrium condition: $\mu_n = \mu_\Lambda$



The effect of Λ hyperons on SN matter becomes larger at lower proton fraction.

Composition of supernova matter

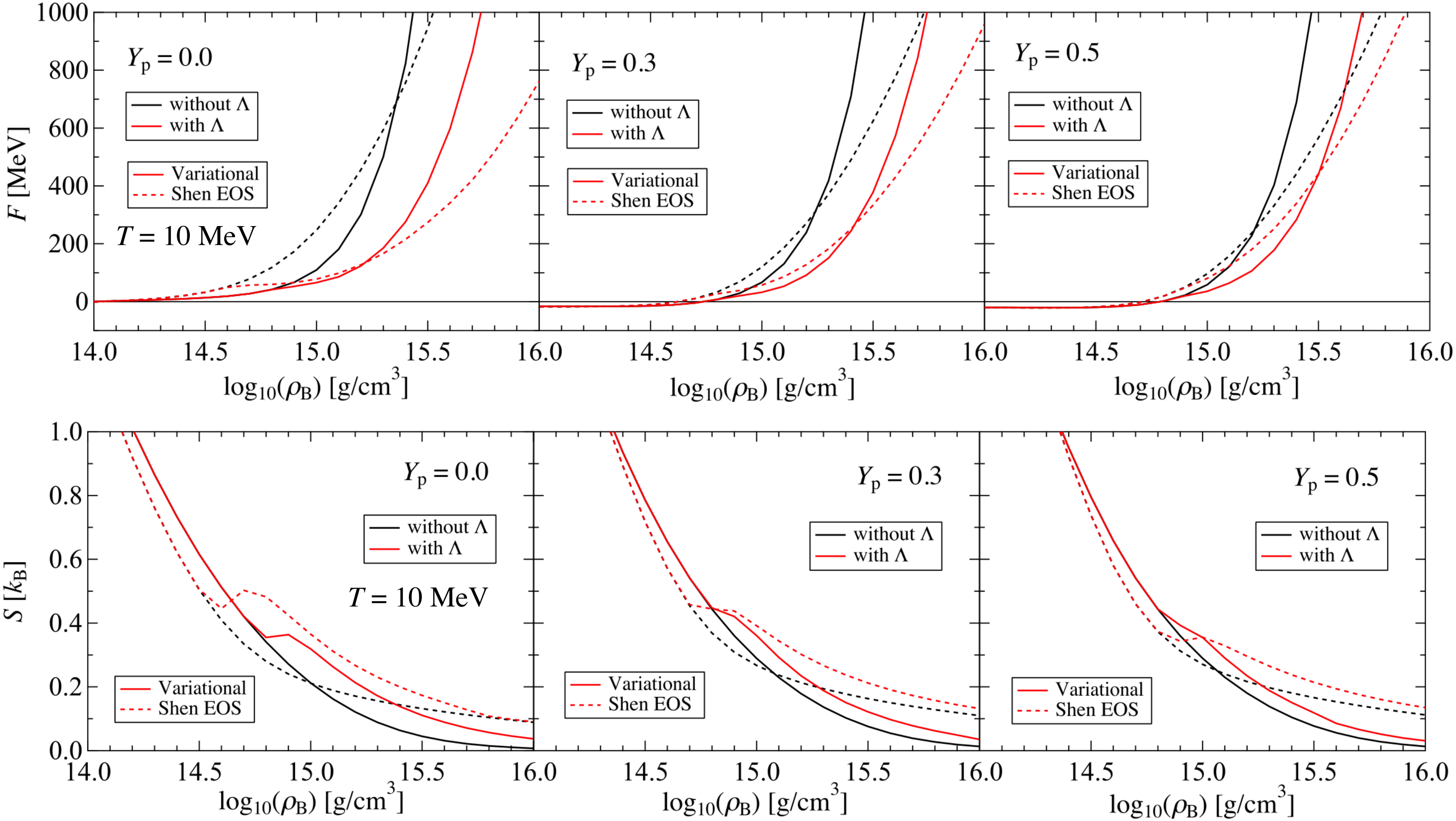
Equilibrium condition: $\mu_n = \mu_\Lambda$



- X_Λ with our EOS is considerably smaller than that of the Shen EOS for $Y_p = 0$.
- X_Λ with our EOS is close to that of the Shen EOS for $Y_p = 0.5$.

→ Symmetry energy of our EOS (E_{sym} = 30.0 MeV) is smaller than that of the Shen EOS (E_{sym} = 36.9 MeV).

Free energy and entropy of hot hyperon matter



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.

Summary

We construct the EOS of nuclear matter including Λ hyperons at zero and finite temperatures by <u>the variational method</u>.

Variational method for hyperon matter

- The obtained thermodynamic quantities are reasonable.

Application of the EOS to supernova matter

- The effect of Λ hyperons on supernova matter becomes larger at higher temperatures and lower proton fractions.

Comparison with the Shen EOS

- Our EOS at smaller Y_p are less affected by the Λ hyperon mixing due to the smaller symmetry energy.

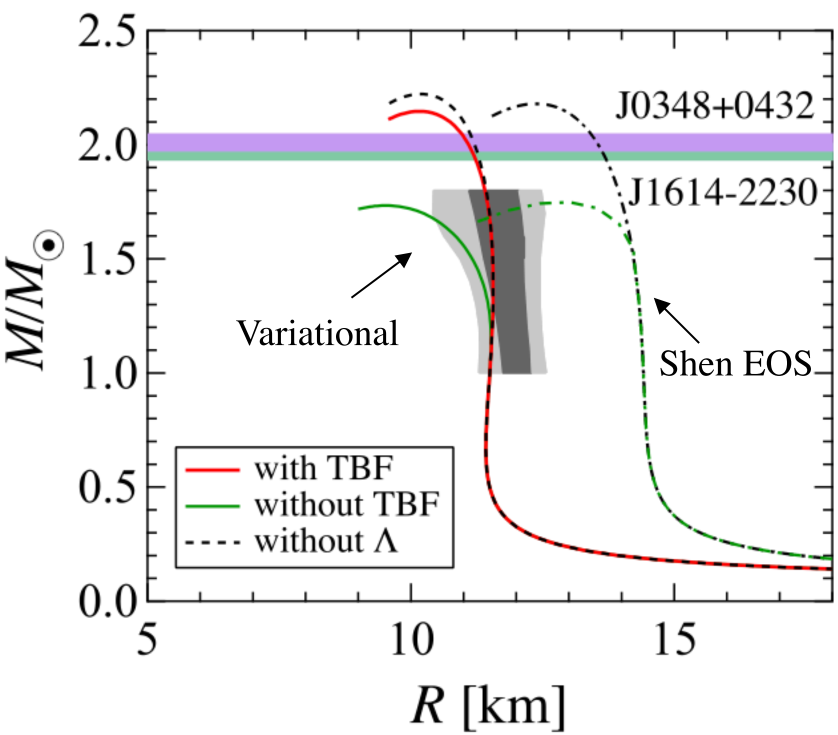
Future Plans

- Construction of the hyperon EOS table for core-collapse simulations
- Contribution of the hyperon three-baryon force

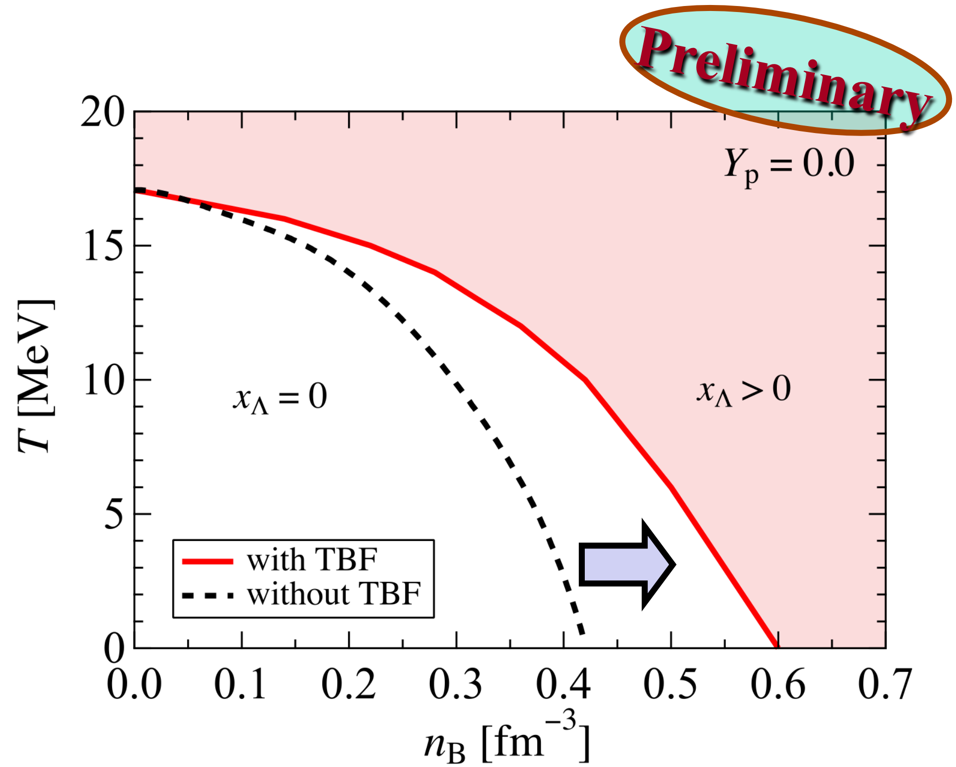
Hyperon Matter with Three-Baryon Force

We consider a phenomenological three-baryon repulsive force (TBF)
as a density dependent two-body effective potential.

(Y. Yamamoto et al., PRC 90 (2014) 045805)
(HT et al., PRC 93 (2016) 035808)



Mass-radius relations of neutron stars



Phase diagram of hot hyperon matter