Microscopic equation of state for astrophysical simulations

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Outline

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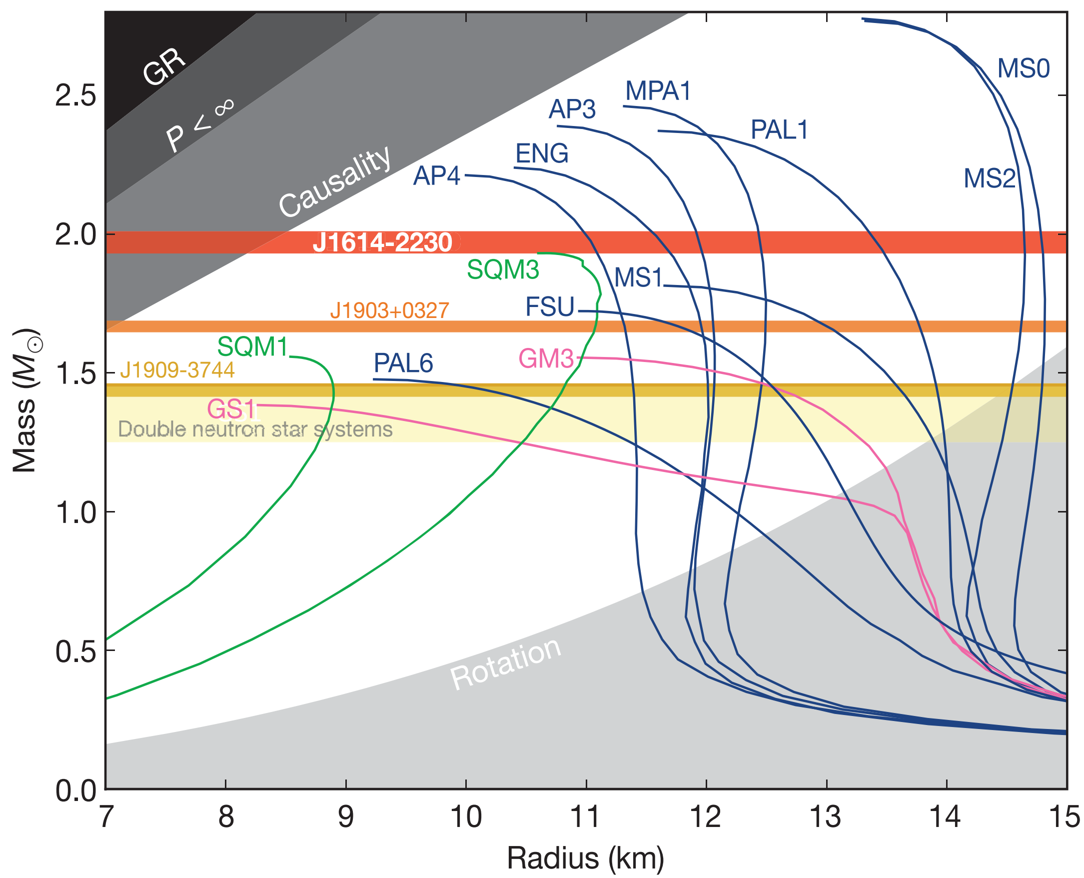
1. Introduction

Neutron Star: governed by the nuclear EOS at zero temperature

Supported against gravitational collapse by nucleon degeneracy pressure and NUCLEAR FORCE



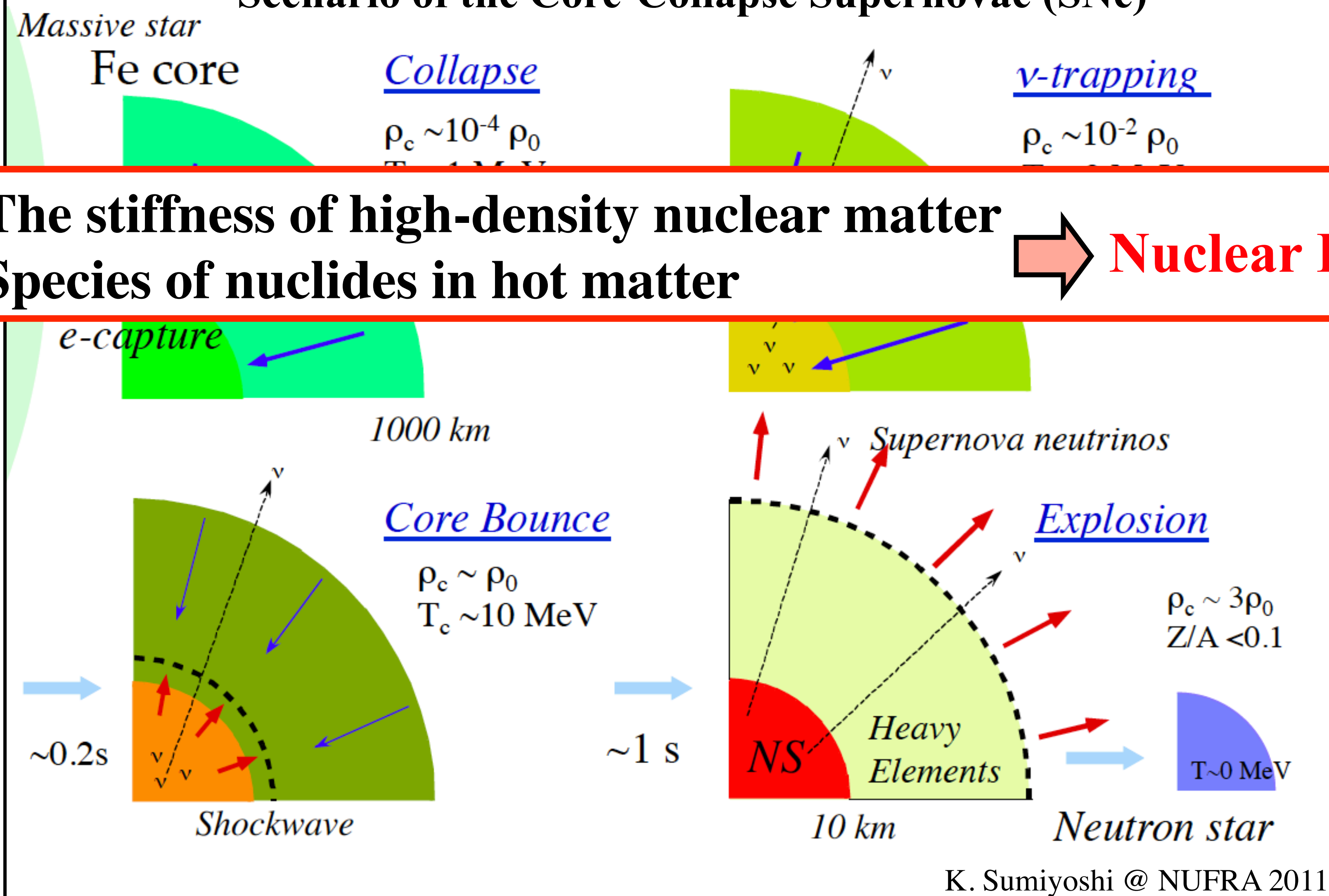
Mass-radius relation of cold neutron stars

P. B. Demorest et al., NATURE 467 (2010)

Core-Collapse Supernovae

Nuclear EOS at finite temperature *is one of the crucial ingredients for the numerical simulations of* ***Core-Collapse Supernovae***.

Scenario of the Core-Collapse Supernovae (SNe)



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

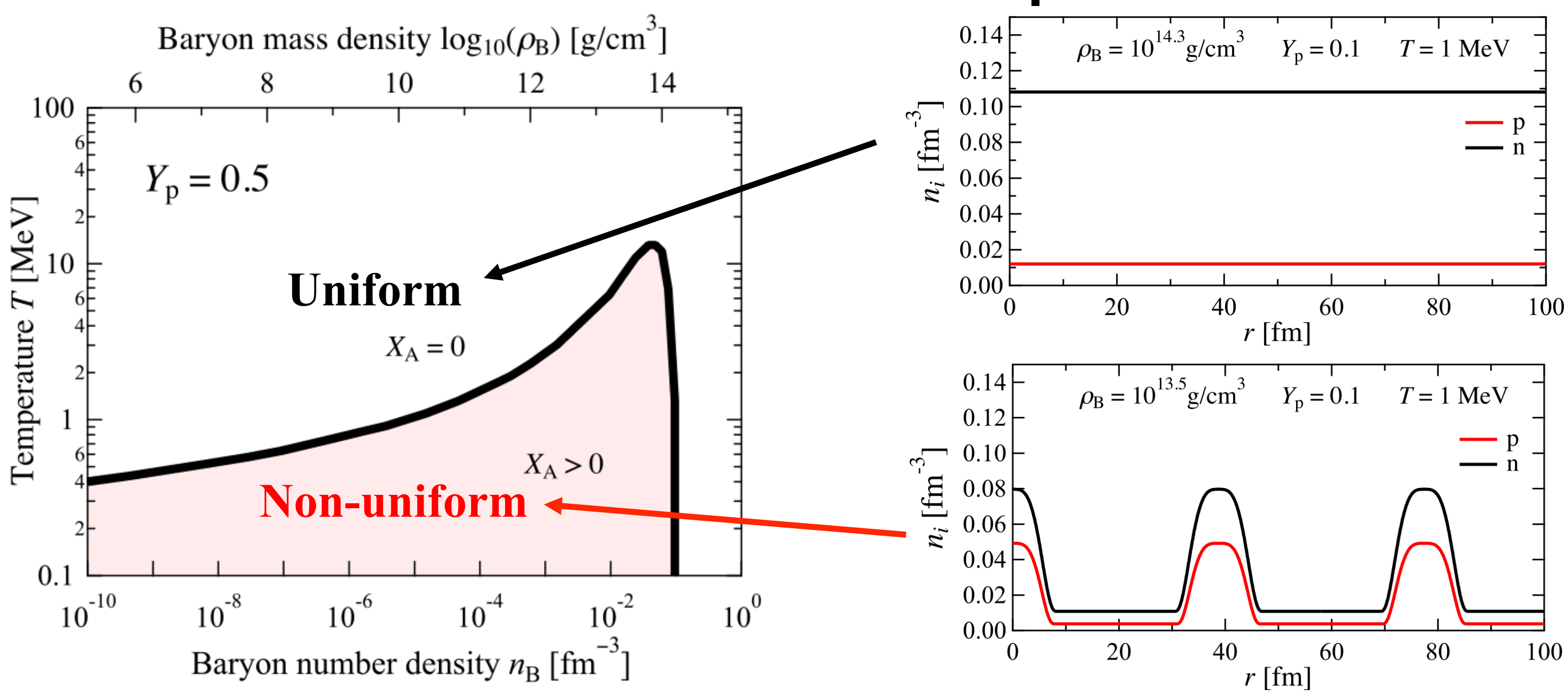
⇒ **Nuclear EOS**

Nuclear EOS for core-collapse simulations

- SN-EOS should provide thermodynamic quantities in the wide ranges.

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

- SN matter contains uniform and non-uniform phases.



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

Current Status of Nuclear EOS for Simulations

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

Effective interactions (Skyrme or RMF model)

Model	Nuclear Interaction	Degrees	M_{max}	$R_{1.4\mathrm{M}_\odot}$	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)

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)

- *Extended to Nuclear statistical equilibrium (NSE) model*

(S. Furusawa, HT, H. Nagakura, K. Sumiyoshi, S. Yamada, H. Suzuki, M. Takano, J. Phys. G 44 (2017) 094001)

Nuclear EOS with microscopic calculations

- 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

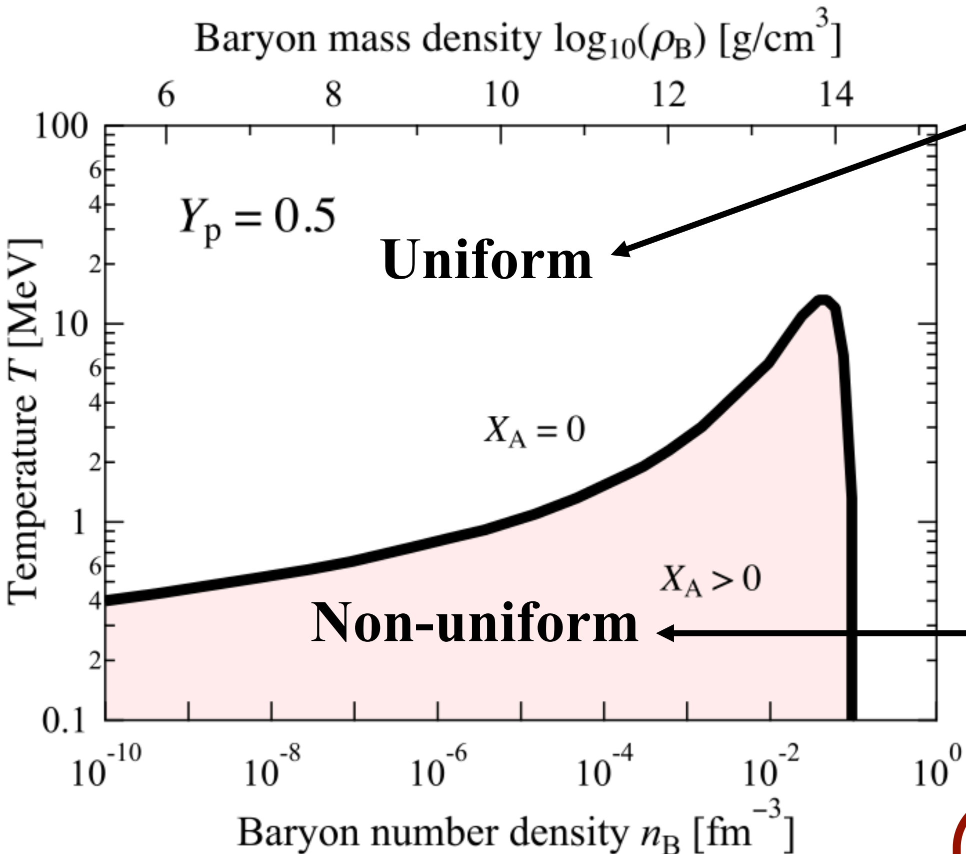
Auxiliary field diffusion Monte Carlo (S. Gandolfi et al., PRC 85 (2012) 032801(R))

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

Trial wave function: Jastrow (central and tensor correlations)

Nuclear Matter: Pure neutron matter

New EOS table for core-collapse simulations



1: **Cluster variational method**
(two-body cluster approximation)
with AV18 + UIX potentials

2: **Thomas-Fermi calculation**
(same as the Shen EOS)

Temperature T : $0 \leq T \leq 400$ MeV

Density ρ : $10^{5.1} \leq \rho_B \leq 10^{16.0}$g/cm^3

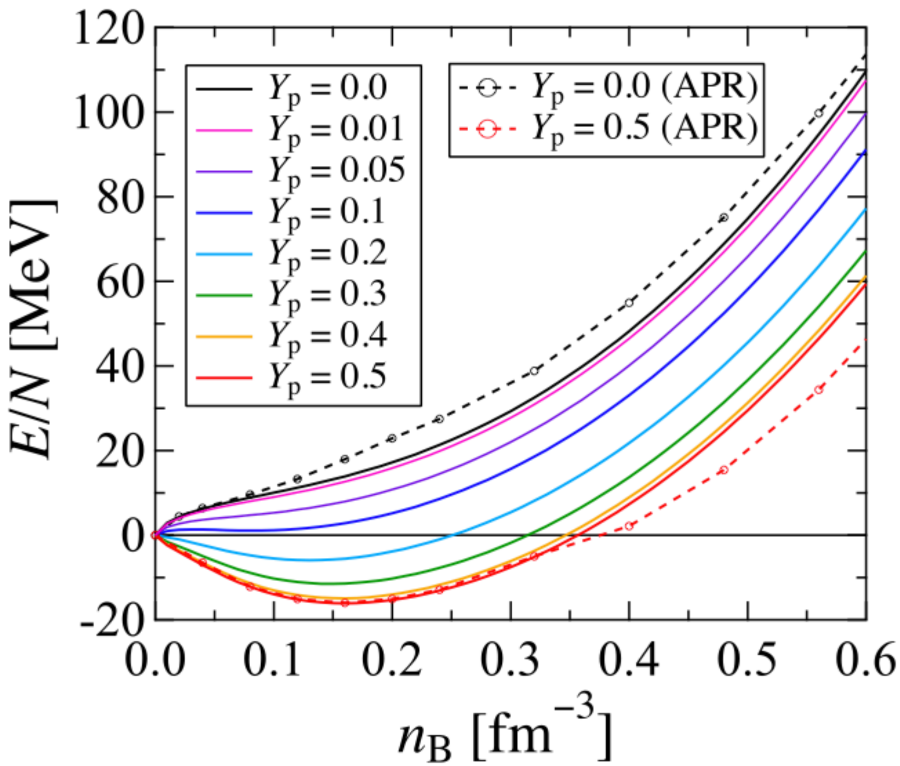
Proton fraction Y_p : $0 \leq Y_p \leq 0.65$

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

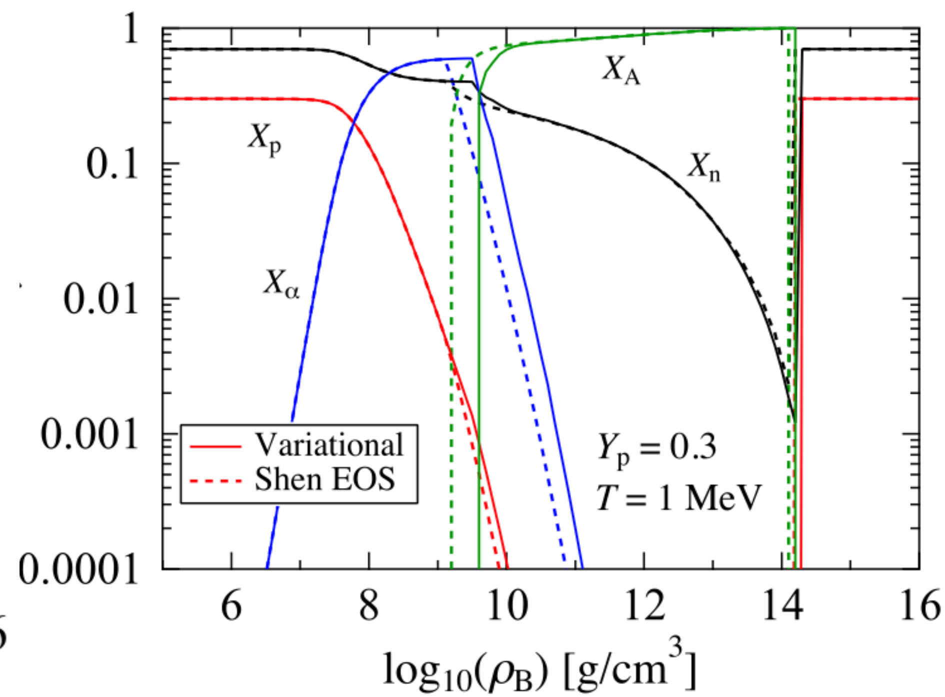
2. Supernova EOS with realistic nuclear forces

Uniform EOS: Cluster variational method with AV18 + UIX potentials

Non-uniform EOS: Thomas-Fermi method



Energy per nucleon for uniform matter



Particle fractions for non-uniform matter

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

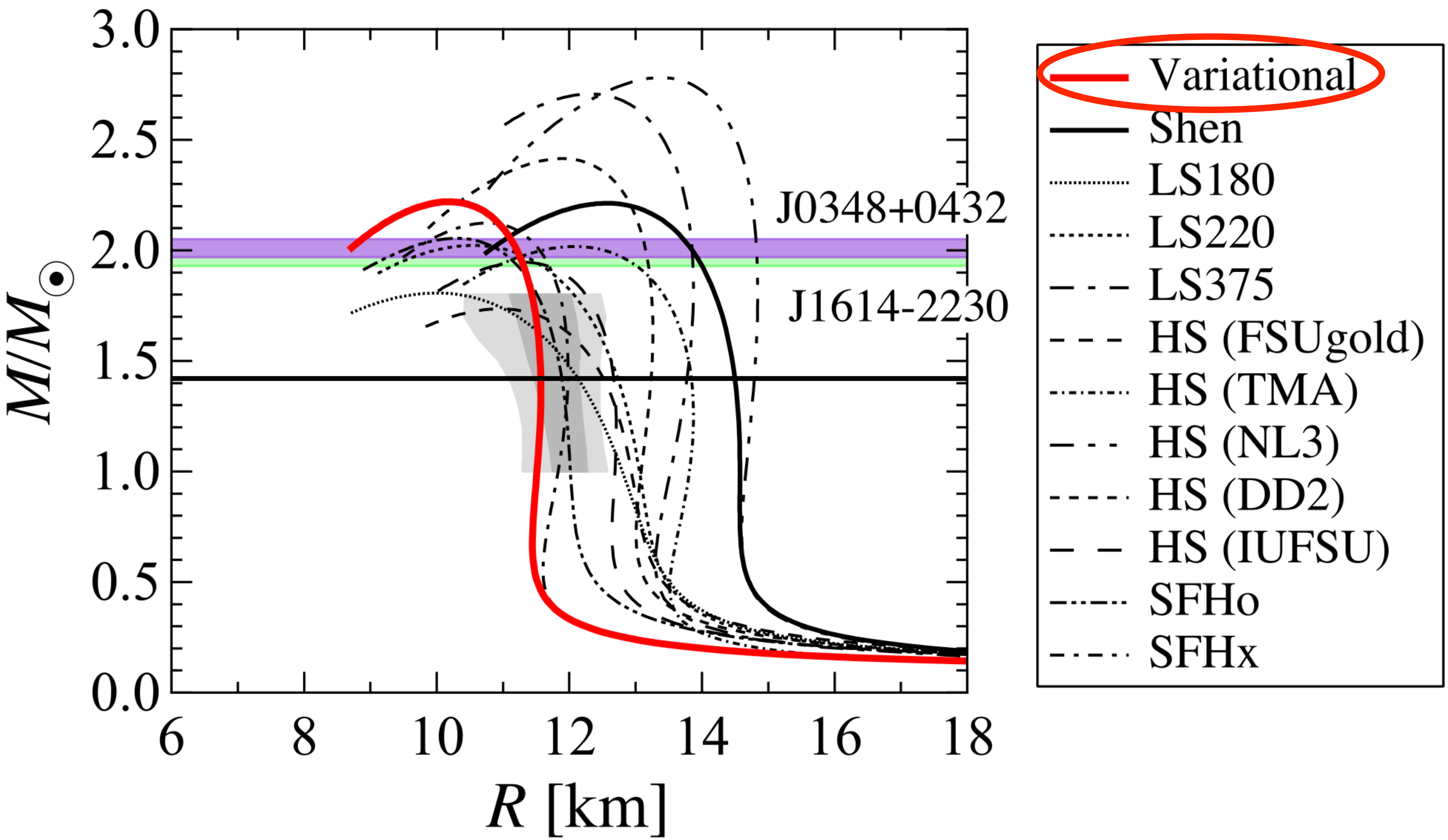
Our EOS : HT and M. Takano, NPA 902 (2013) 53

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

Shen EOS : APJS 197 (2011) 20

Application to Neutron Star

Mass-Radius relation of neutron stars



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

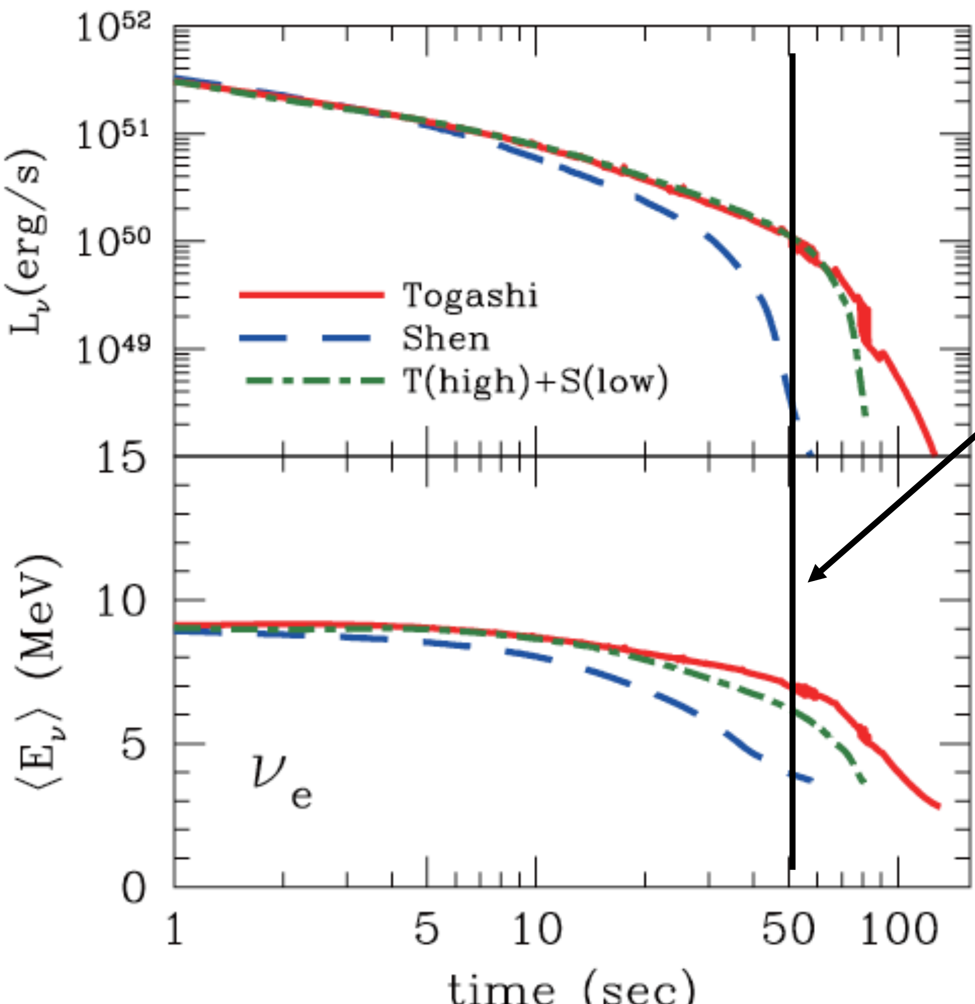
Shaded region is the observationally suggested region by Steiner et al. (Astrophys. J. 722 (2010) 33)

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

Application to 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

3. Hyperon mixing in hot dense matter

SN-EOS list by M. Hempel

Hyperon EOS

Nuclear Interaction	n_{sat} (fm^{-3})	BE/A (MeV)	K (MeV)	Q ($\frac{MeV}{fm^3}$)	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, BHBΛϕ
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

- **Shen EOS with Λ, Σ, Ξ** [M_{max} = 1.67 $M_\odot$] (C. Ishizuka et al., JPG 35 (2008) 085201)
- **Shen EOS with Λ** [M_{max} = 1.75 $M_\odot$] (H. Shen et al., APJS 197 (2011) 20)
- **LS EOS with Λ** [M_{max} = 1.91 $M_\odot$] (M. Oertel et al., PRC 85 (2012) 055806)
- **DD2 EOS with Λ** [M_{max} = 2.11 $M_\odot$] (S. Banik et al., APJS 214 (2014) 22)
- **DD2 EOS with Λ, Σ, Ξ** [M_{max} = 2.04 $M_\odot$] (M. Marques et al., PRC 96 (2017) 045806)

Free energy for Λ hyperon matter

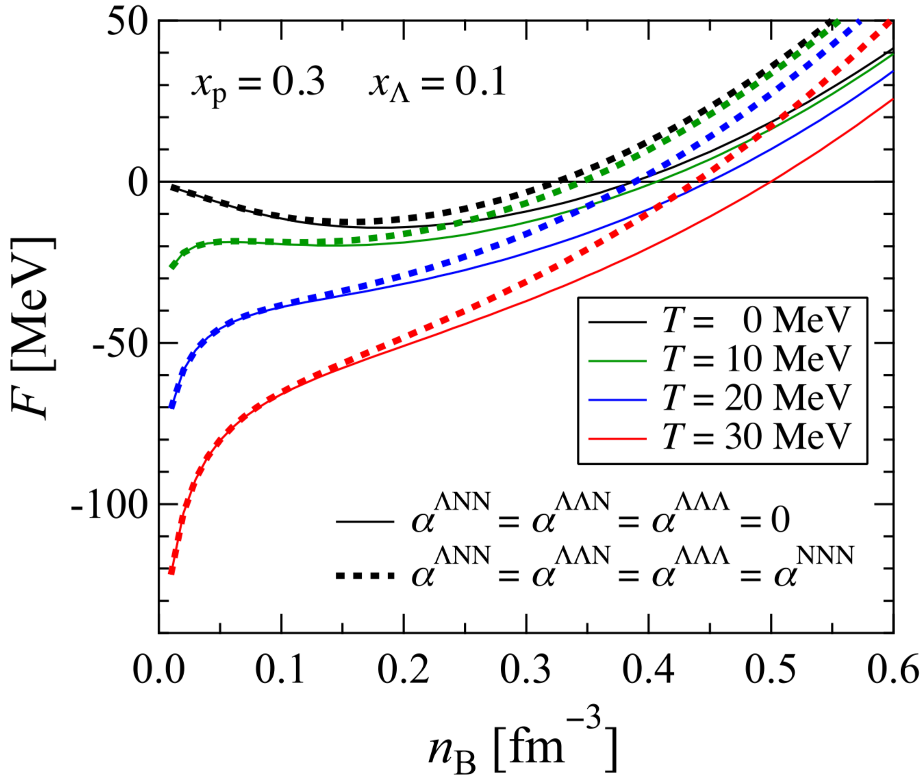
$V_{ij}^{\Lambda N}$, $V_{ij}^{\Lambda\Lambda}$: **two-body potential** (E. Hiyama et al., PRC 74 (2006) 054312) (E. Hiyama et al., PRC 66 (2002) 024007)

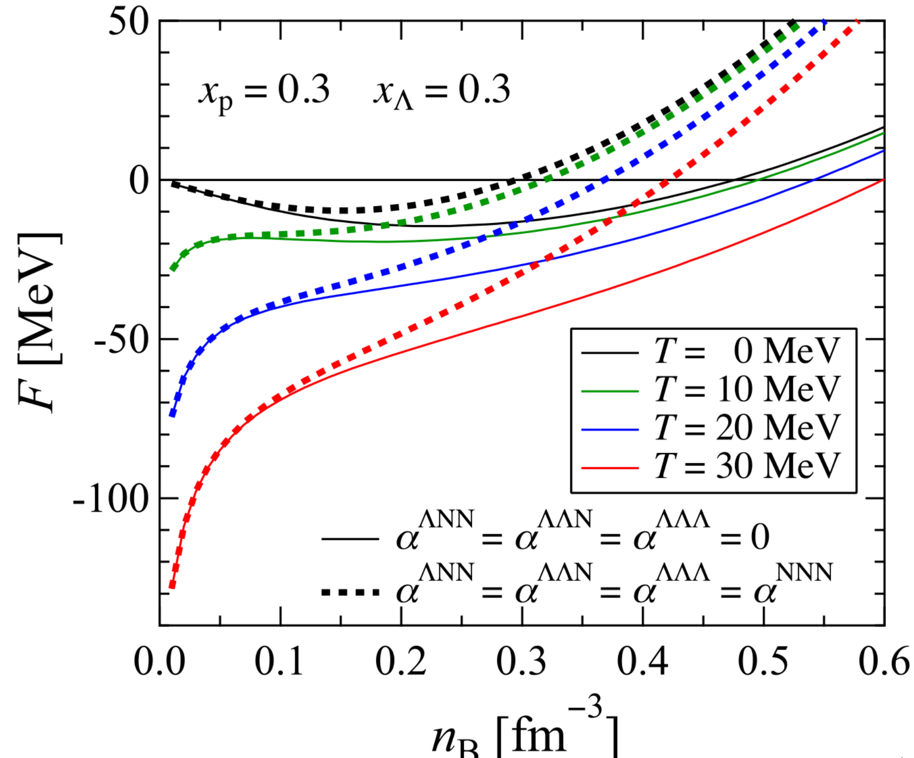
$V_{ijk}^{\Lambda NN}$, $V_{ijk}^{\Lambda\Lambda N}$, $V_{ijk}^{\Lambda\Lambda\Lambda}$: *Repulsive part of UIX is extended*

$$V_{ijk}^{\mu} = \sum_{\mu} \alpha^{\mu} V_{ijk}^{R} P_{ijk}^{\mu}$$

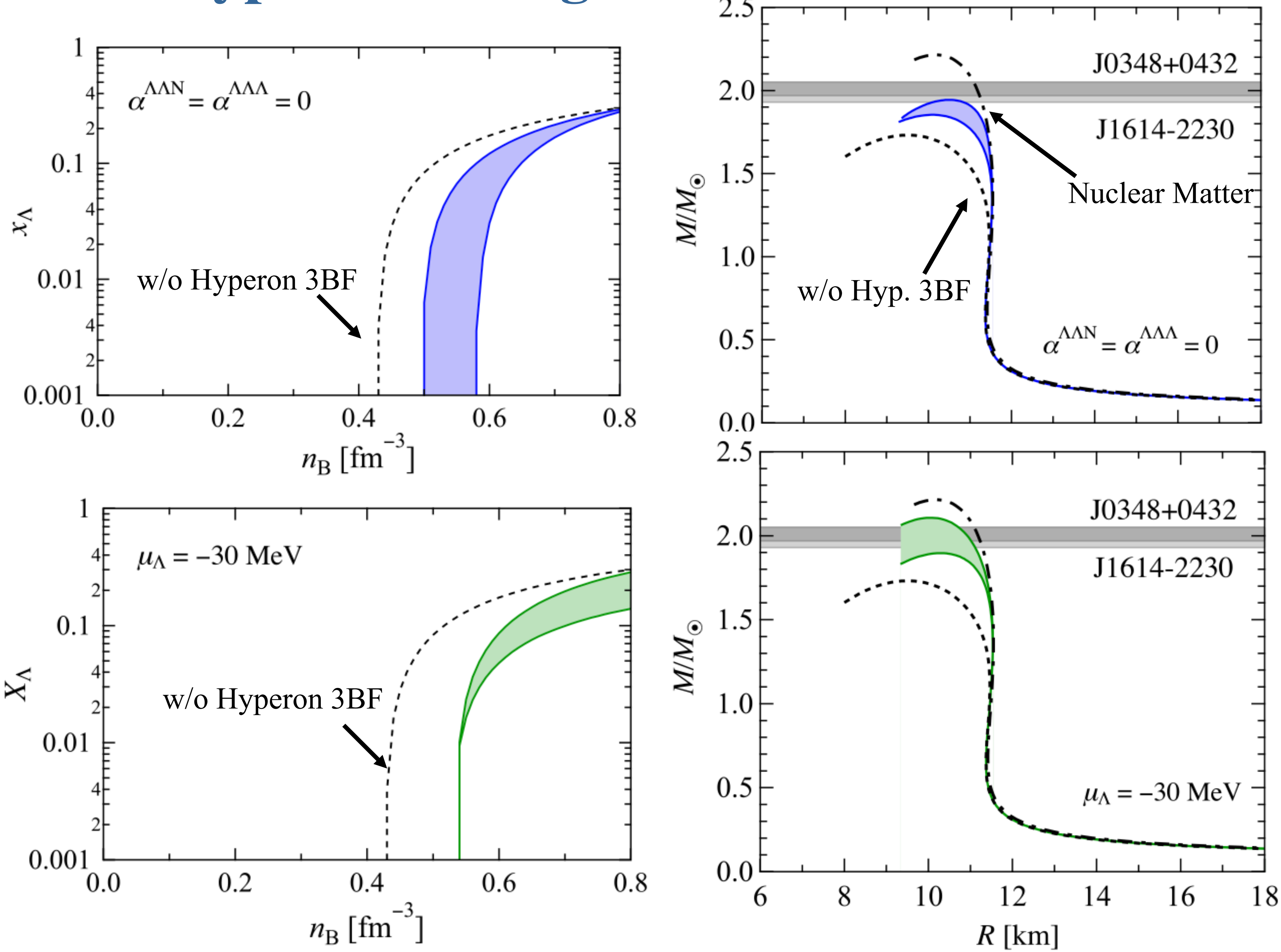
(μ = NNN, ΛNN, ΛΛN, ΛΛΛ)

P_{ijk}^{μ}: Three-particle projection operator





Hyperon mixing in neutron-star matter

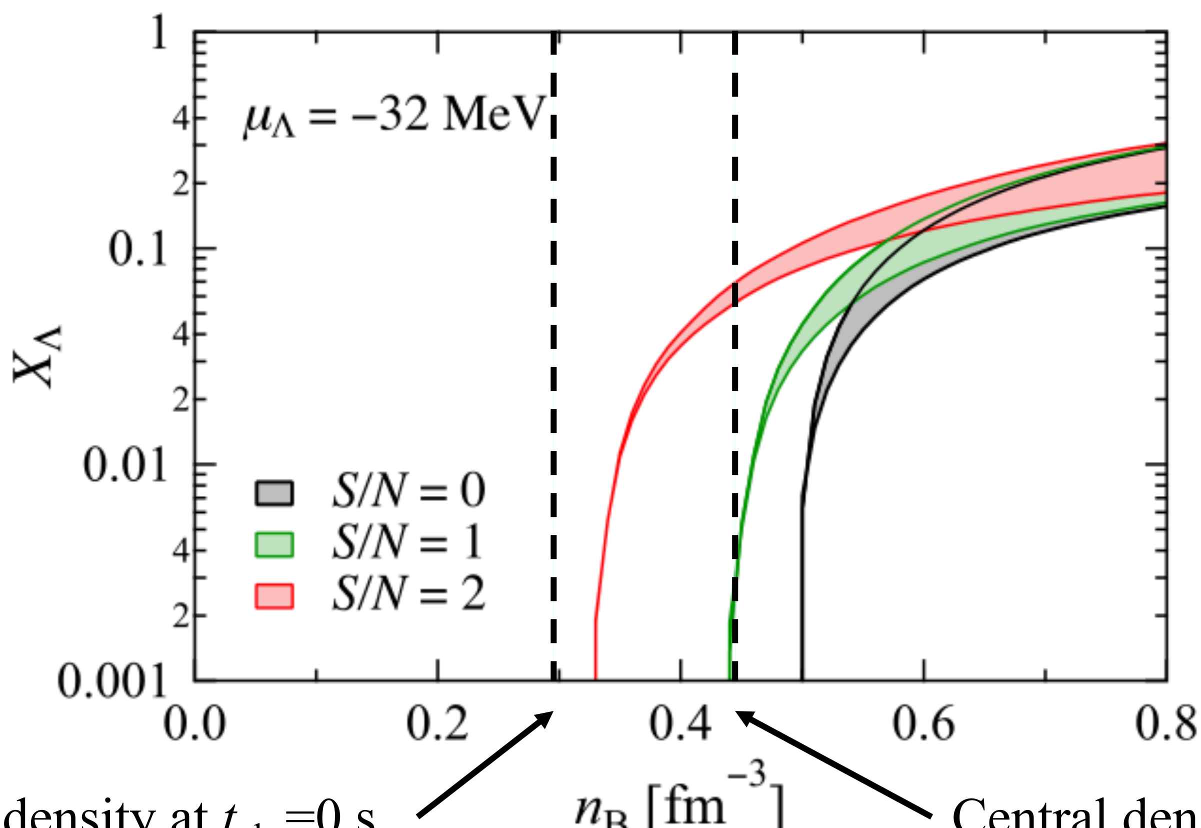


Hyperon mixing in supernova matter

Supernova matter

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

$(0 \leq \alpha^{\Lambda\Lambda N} = \alpha^{\Lambda\Lambda\Lambda} \leq \alpha^{NNN})$



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)