Equation of state for hyperonic nuclear matter and its application to compact astrophysical objects

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Outline

1 : Introduction

2 : Supernova EOS with realistic nuclear forces

3 : Supernova EOS with Λ hyperon

4 : Application to compact stars

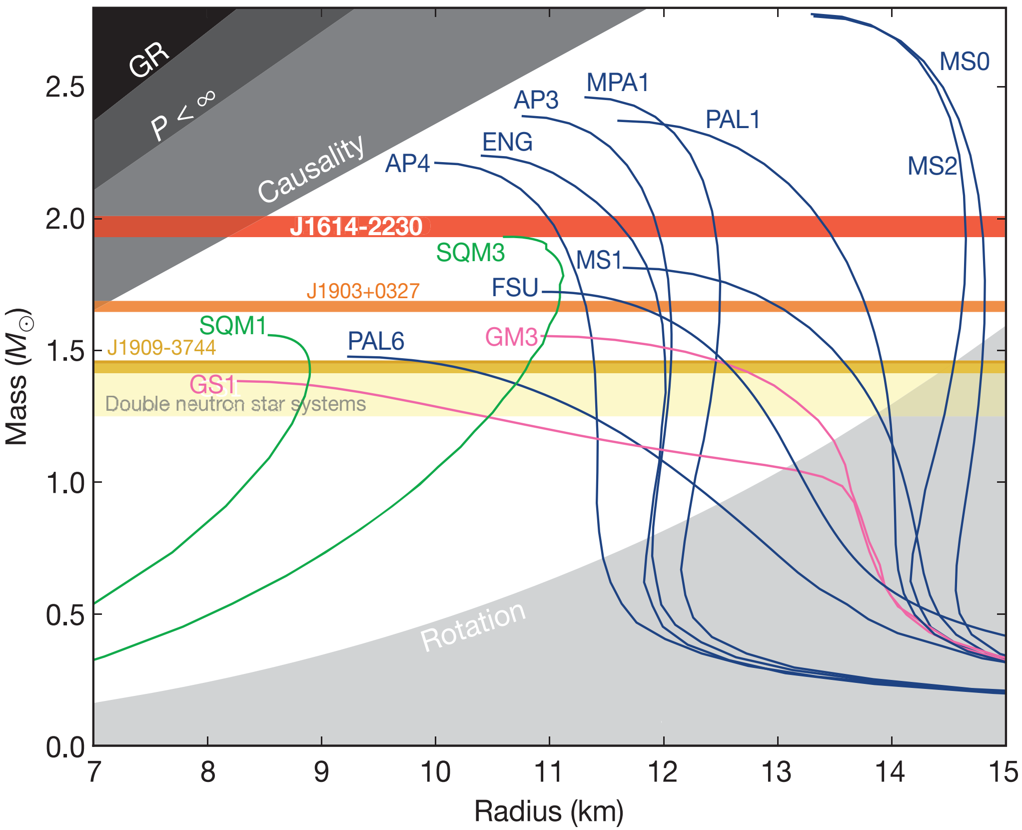
International workshop on "Hadron structure and interaction in dense matter"
@ KEK Tokai campus, November 12, 2018

1. Introduction

***Neutron star** structure is governed by*

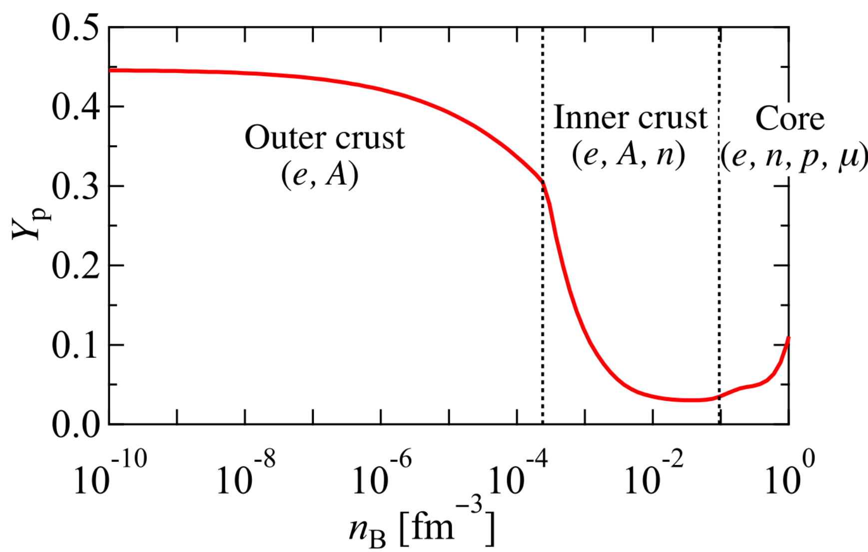
the nuclear equation of state (EOS) at zero temperature.

Neutron Stars: Stiffness (EOS at 0 MeV) ⇔ Self-gravity



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

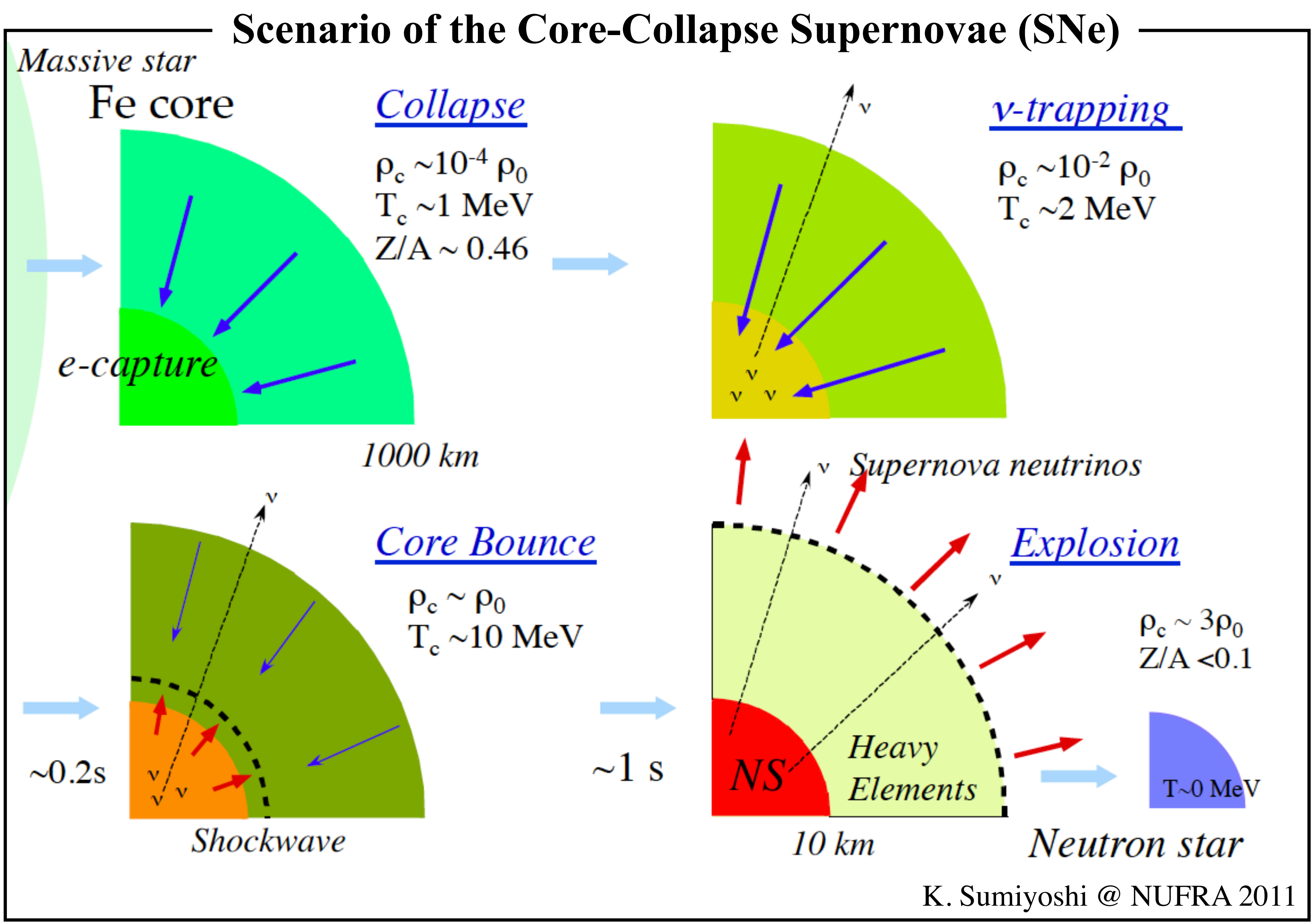
Mass-radius relation of cold neutron stars



Phase diagram of cold nuclear matter

Nuclear EOS and Core-Collapse Supernovae

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

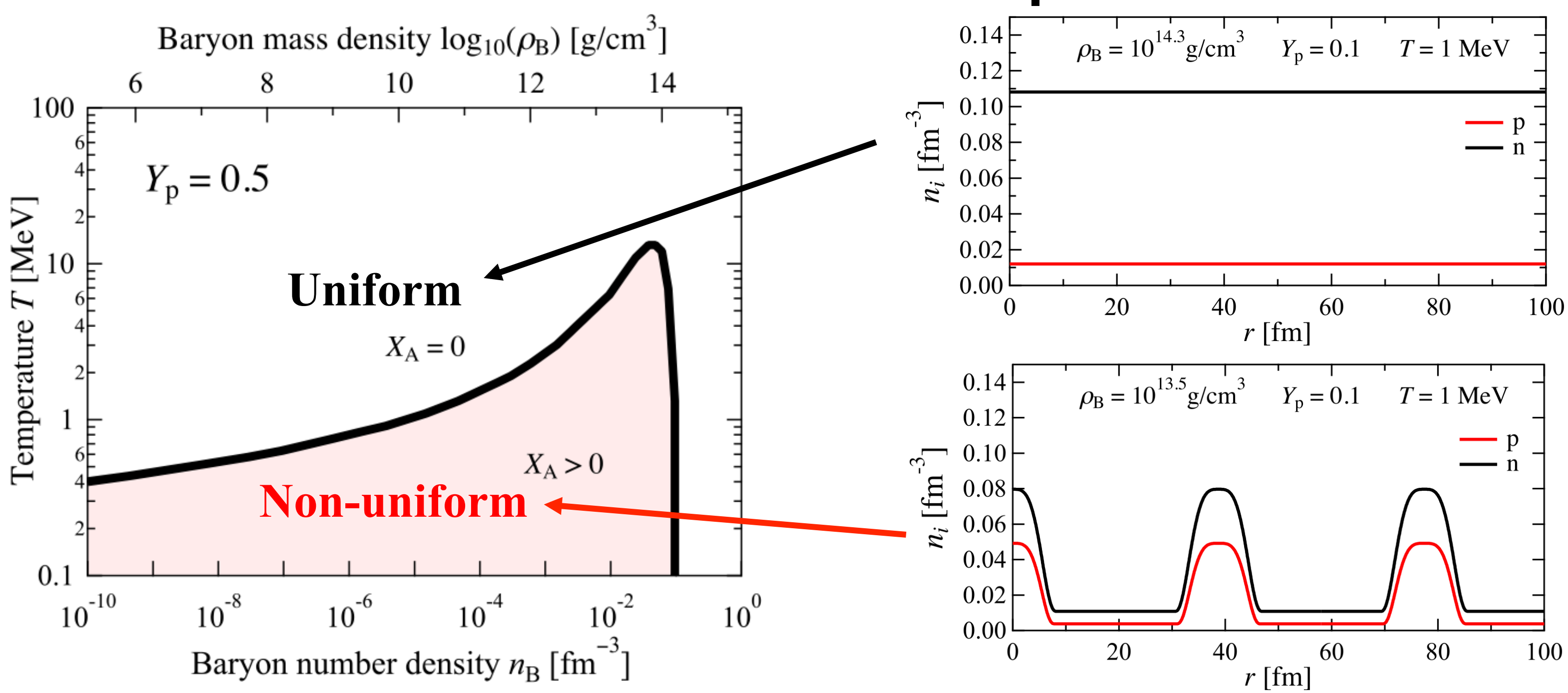


Nuclear EOS for supernova simulations

- 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 SN-EOS with hyperons

SN-EOS list by M. Hempel

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

Hyperon EOS

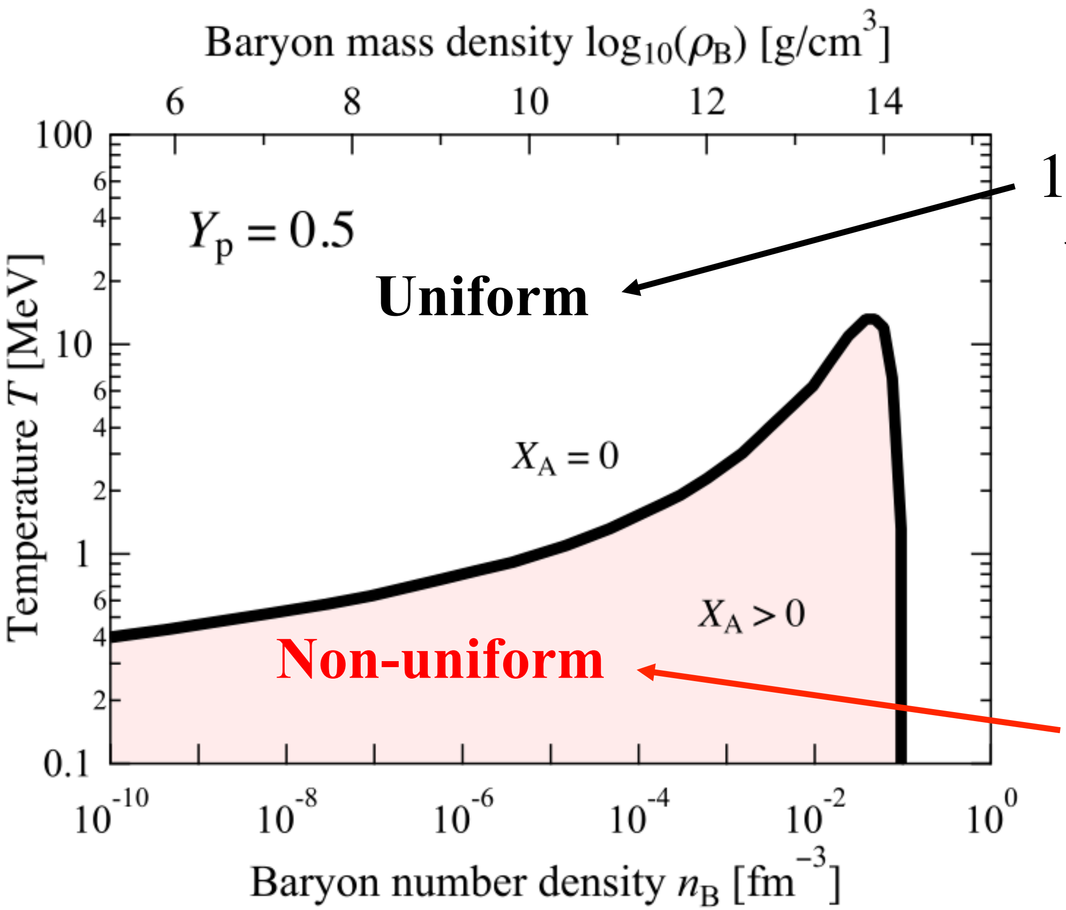
There is no SN-EOSs based on the microscopic many-body theory.

- **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)

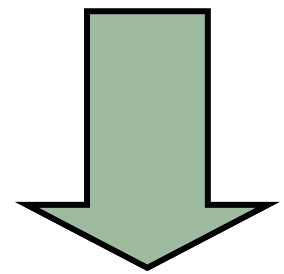
New EOS table for core-collapse simulations

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

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



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



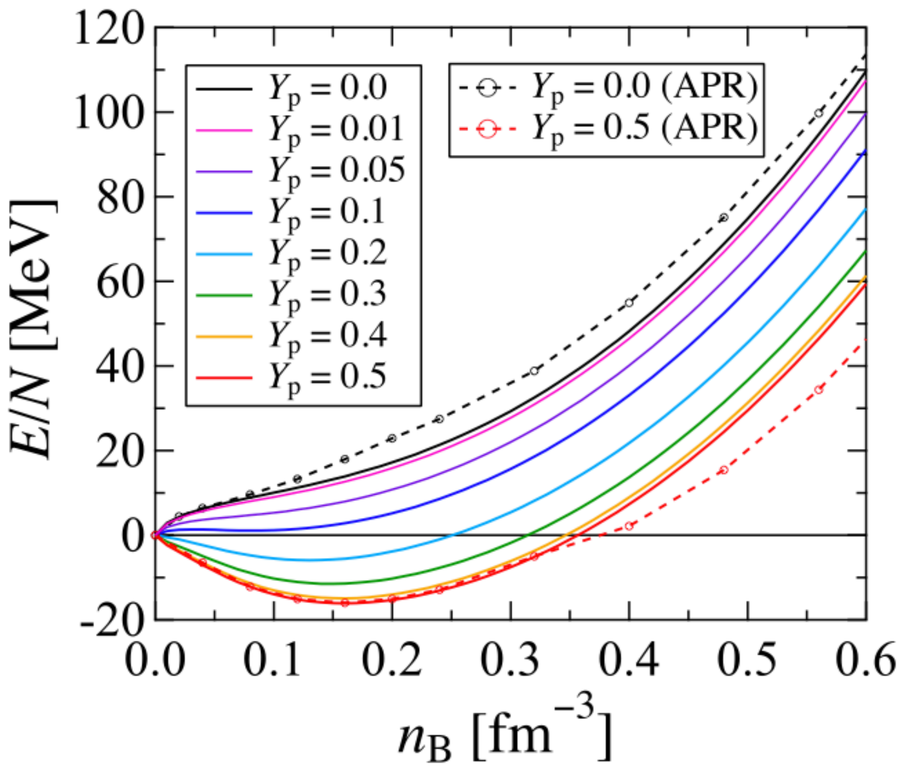
2: **Thomas-Fermi calculation for non-uniform matter**

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

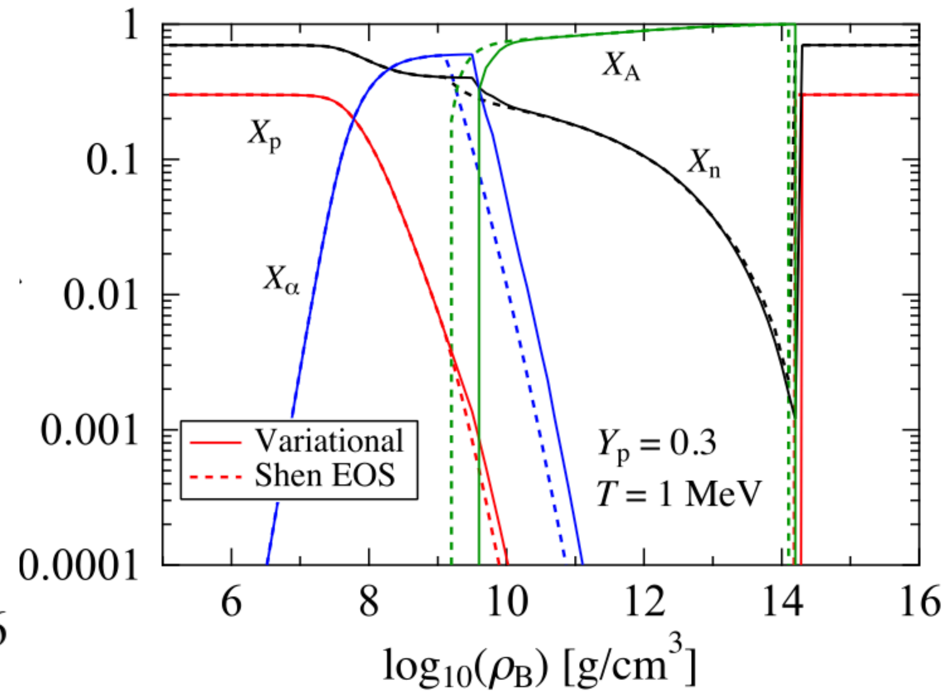
2. Supernova EOS with realistic nuclear forces

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

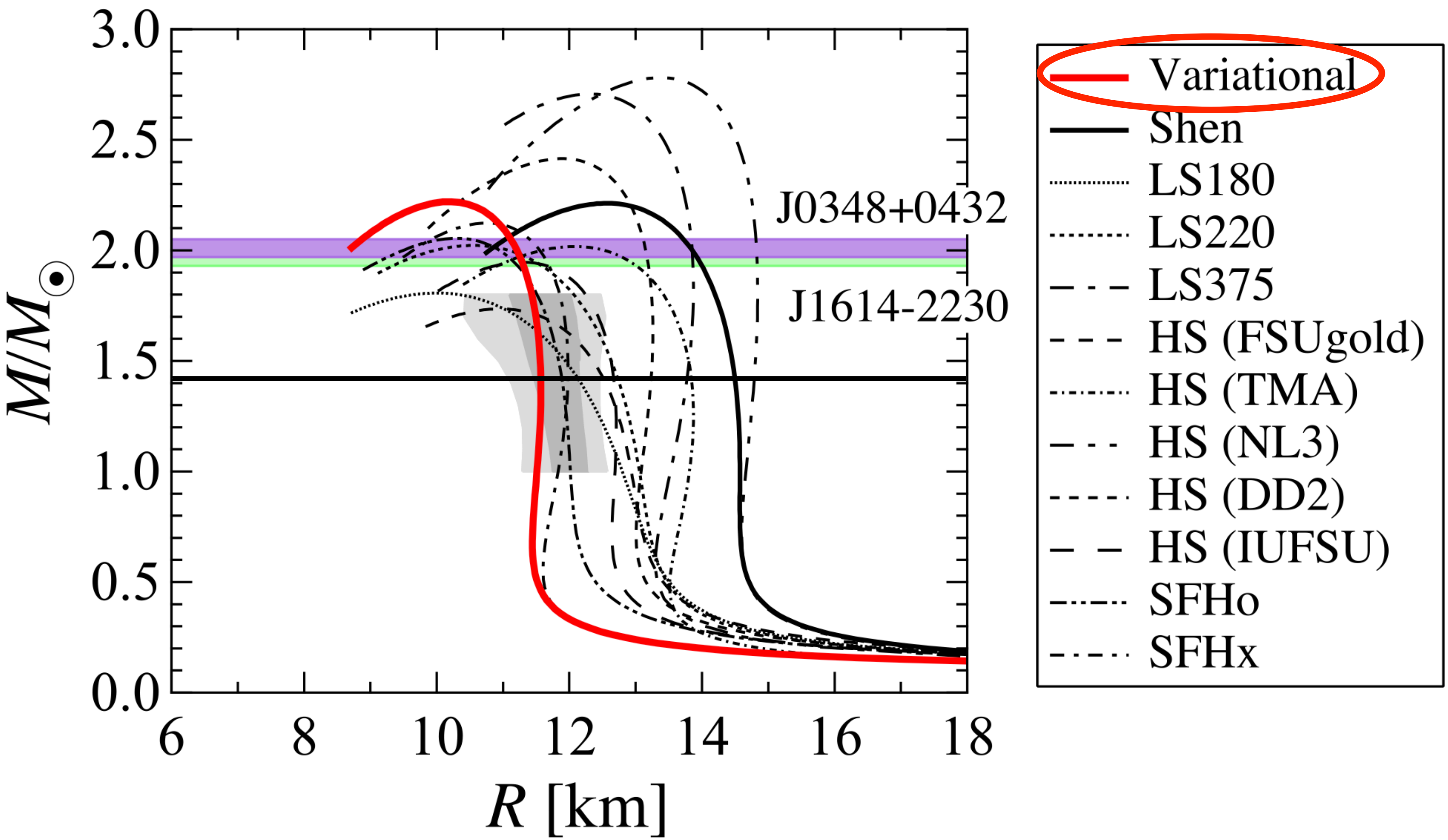
Our EOS : HT and M. Takano, NPA 902 (2013) 53

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)

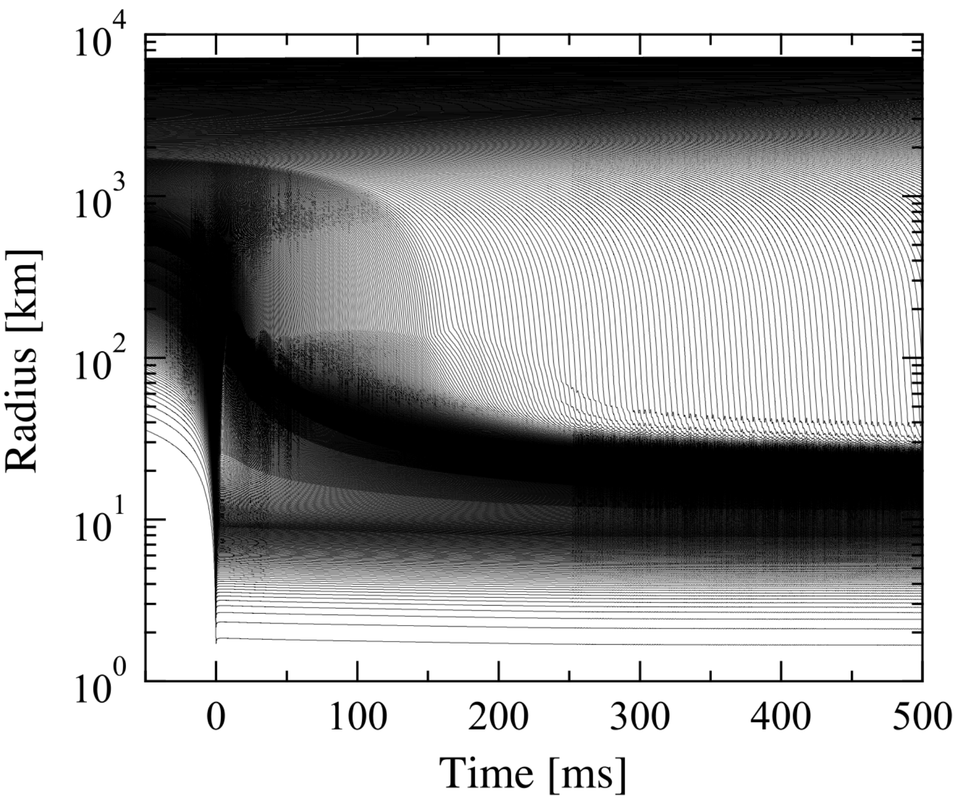
HT *et al.*, NPA 961 (2017) 78

Application to Core-Collapse Supernovae

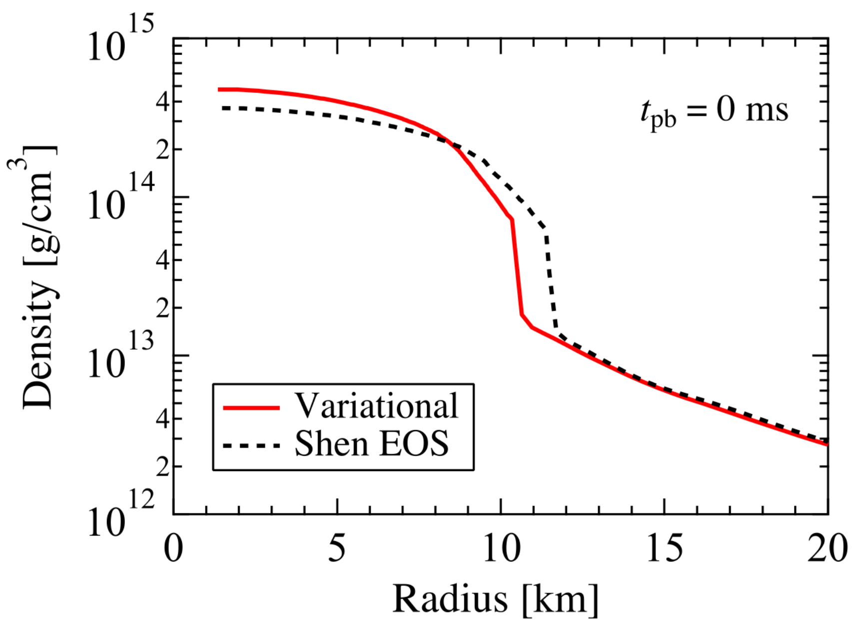
1D neutrino-radiation hydrodynamics simulations

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



Central density: 0.30 fm^{-3}

Temperature: ~10 MeV

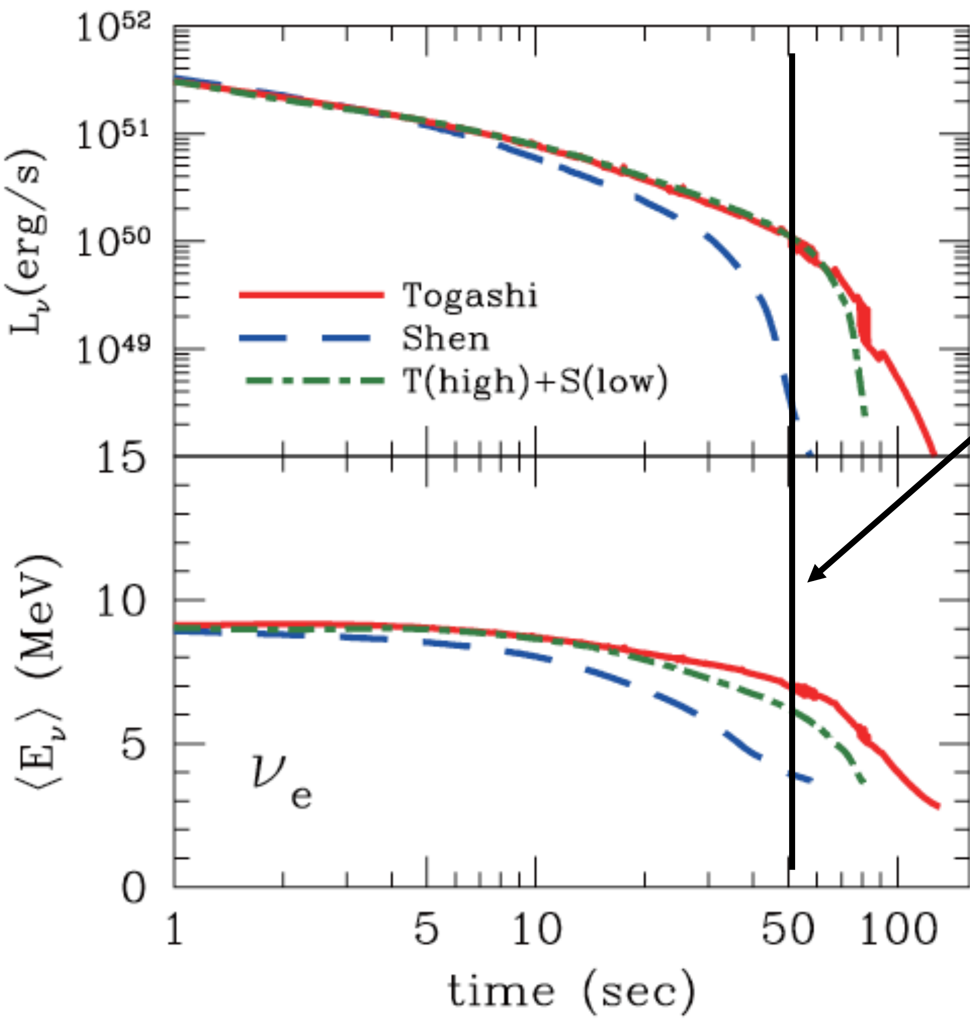
Proton fraction: ~0.3

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

3. Supernova EOS with Λ hyperons

Two-body Hamiltonian

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

V_{ij}^{NN} **: Argonne v18 (AV18) potential**

Hyperon Two-Body Central Potentials

$V_{ij}^{\Lambda\mathrm{N}}$ **: 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 $_{\Lambda\Lambda}^{6}He$ *(NAGARA event)*

E_2: Expectation value of H_2 in ***the two-body cluster approximation***

Expectation value of the Hamiltonian

Jastrow wave function

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

Φ_{F}: The Fermi-gas wave function

Correlation function:

$$f_{ij} = \sum_{\mu,p,s}\left[f^{\mu}_{\mathrm{C}ps}(r_{ij}) + s f^{\mu}_{\mathrm{T}p}(r_{ij}) S_{\mathrm{T}ij} + s f^{\mu}_{\mathrm{SO}p}(r_{ij})(\boldsymbol{L}_{ij}\cdot\boldsymbol{s})\right] P^{\mu}_{psij}$$

p: parity s: two-particle total spin μ: particle pair

Cluster-expansion

$$\frac{\langle H_2\rangle}{N} = \frac{1}{N}\frac{\langle\Psi \mid H_2 \mid \Psi\rangle}{\langle\Psi \mid \Psi\rangle} = \frac{\langle H_2\rangle_2}{N} + \frac{\langle H_2\rangle_3}{N} + \cdots$$

$\boldsymbol{E_2}$ is the expectation value of H_2 in *the two-body cluster approximation* with the Jastrow wave function.

Three-Body Energy

Nuclear EOS (previous study)

$$\frac{E_3}{N} = \underbrace{\frac{1}{N}\langle \sum_{i<j<k}^{N} [\alpha V_{ijk}^{\mathrm{R}} + \beta V_{ijk}^{2\pi}] \rangle_{\mathrm{F}}}_{\text{Modified expectation value of } H_3 \text{ with } \Phi_{\mathrm{F}}} + \underbrace{\gamma n_{\mathrm{B}}^2 e^{-\delta n_{\mathrm{B}}} [1-(1-2Y_{\mathrm{p}})^2]}_{\textbf{Correction term}}$$

Repulsive part of UIX pot. is extended to the potential for Hyperon TBF

$$V_{ijk}^{\mathrm{R}} = \sum_{\mu} \alpha^{\mu} V_{ijk}^{\mathrm{R}} P_{ijk}^{\mu} \quad (\mu = \mathrm{NNN}, \Lambda\mathrm{NN}, \Lambda\Lambda\mathrm{N}, \Lambda\Lambda\Lambda)$$

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

α^{NNN}: we use the value in the nuclear EOS
(Saturation properties＋ Thomas-Fermi calculation for atomic nuclei)

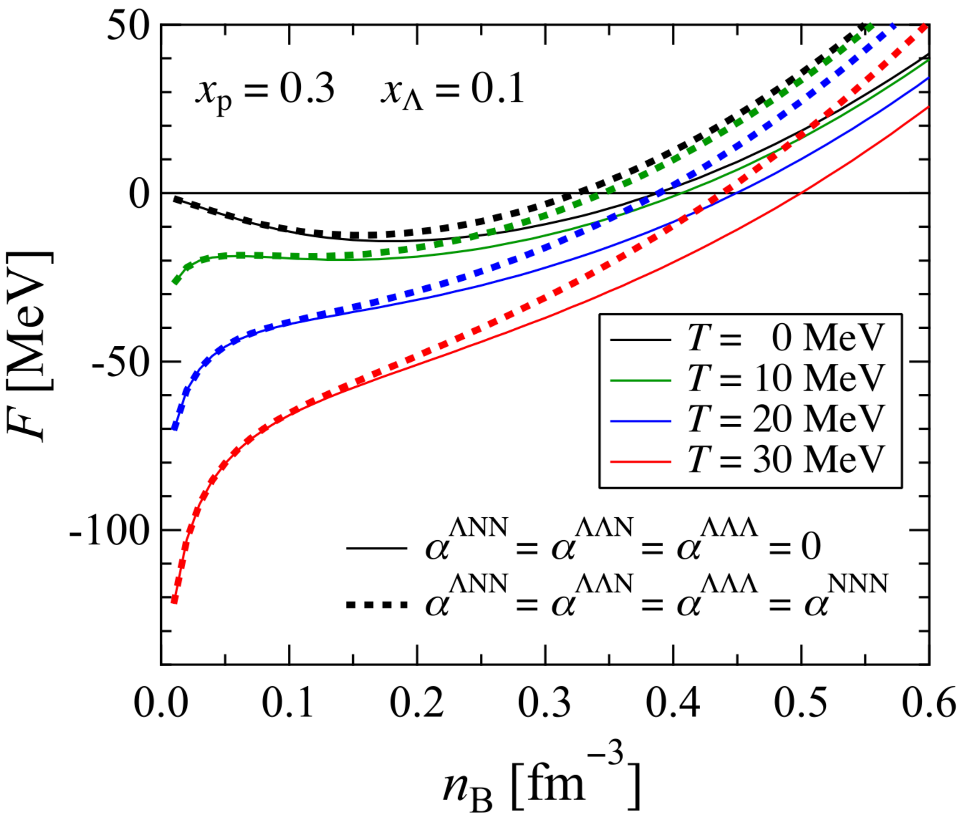
$\alpha^{\Lambda\mathrm{NN}}$. $\alpha^{\Lambda\Lambda\mathrm{N}}$, $\alpha^{\Lambda\Lambda\Lambda}$: Free parameters ($0 \leq \alpha^{\mu} \leq \alpha^{\mathrm{NNN}}$)

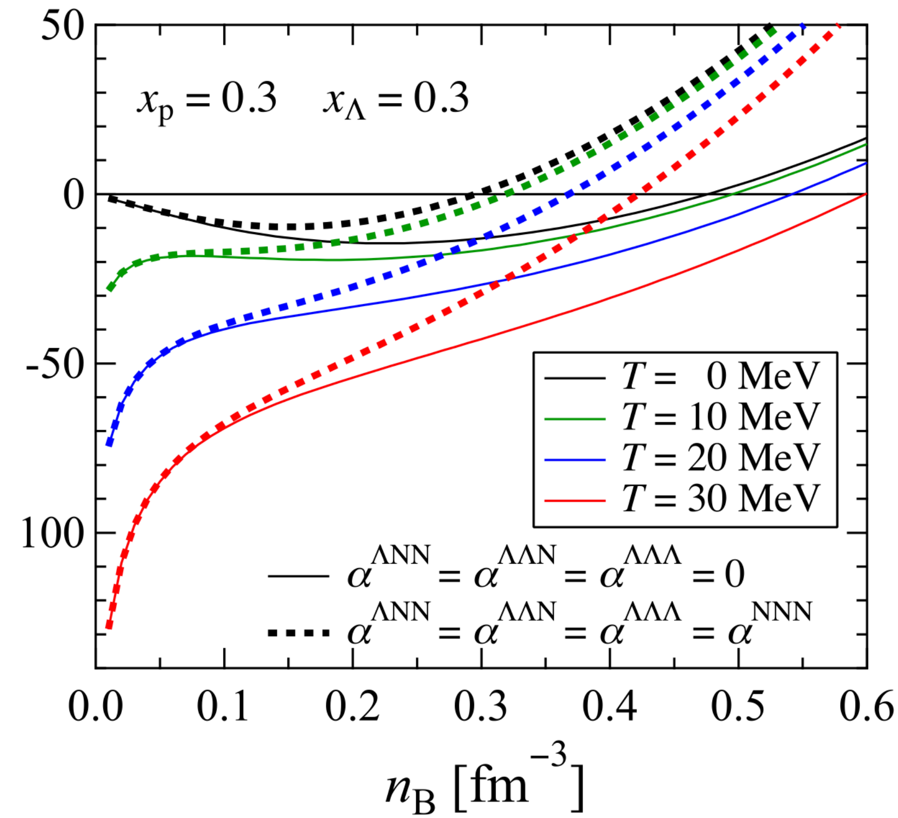
Free energy for Λ hyperon matter

Total energy per baryon: $E\,(n_B, x_p, x_\Lambda) = E_2 + E_3$

Baryon number density : $n_B = n_p + n_n + n_\Lambda$ Particle fraction: $x_i = n_i / n_B \quad (i = \mathrm{p}, \Lambda)$

The prescription by Schmidt and Pandharipande is employed to obtain the free energy ***at finite temperature***.





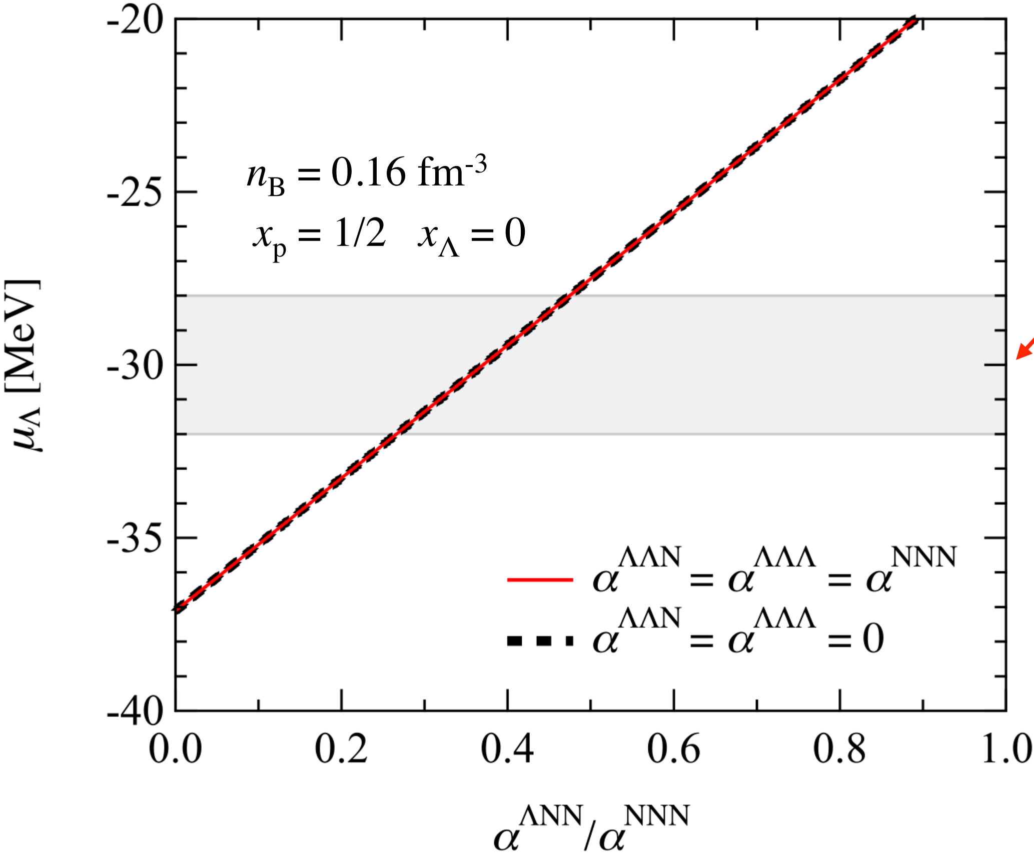
Single particle potential for Λ particle

Total energy per baryon: $E\,(n_B, x_p, x_\Lambda) = E_2 + E_3$

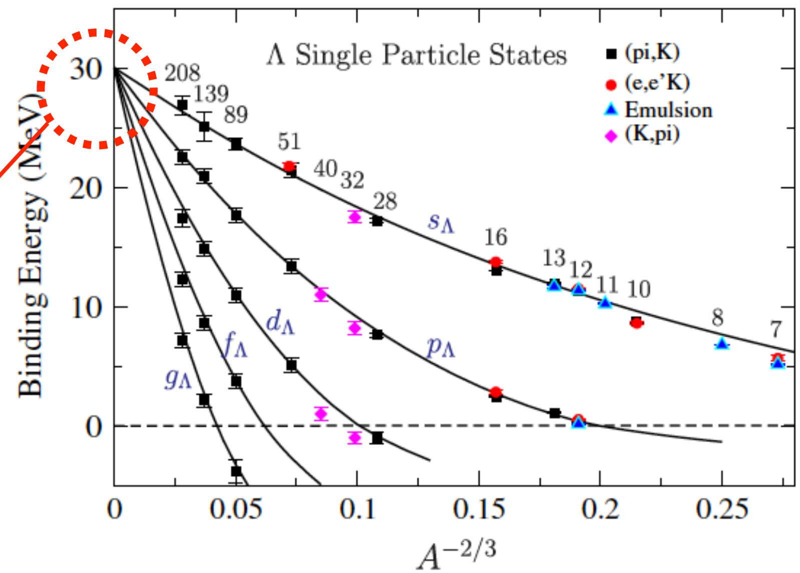
$$\mu_\Lambda(n_B, x_p, x_\Lambda) = [\partial(n_B E)/\partial n_\Lambda]_{n_n, n_p}$$

Baryon number density : $n_B = n_p + n_n + n_\Lambda$

Particle fraction: $x_i = n_i / n_B \quad (i = p, \Lambda)$



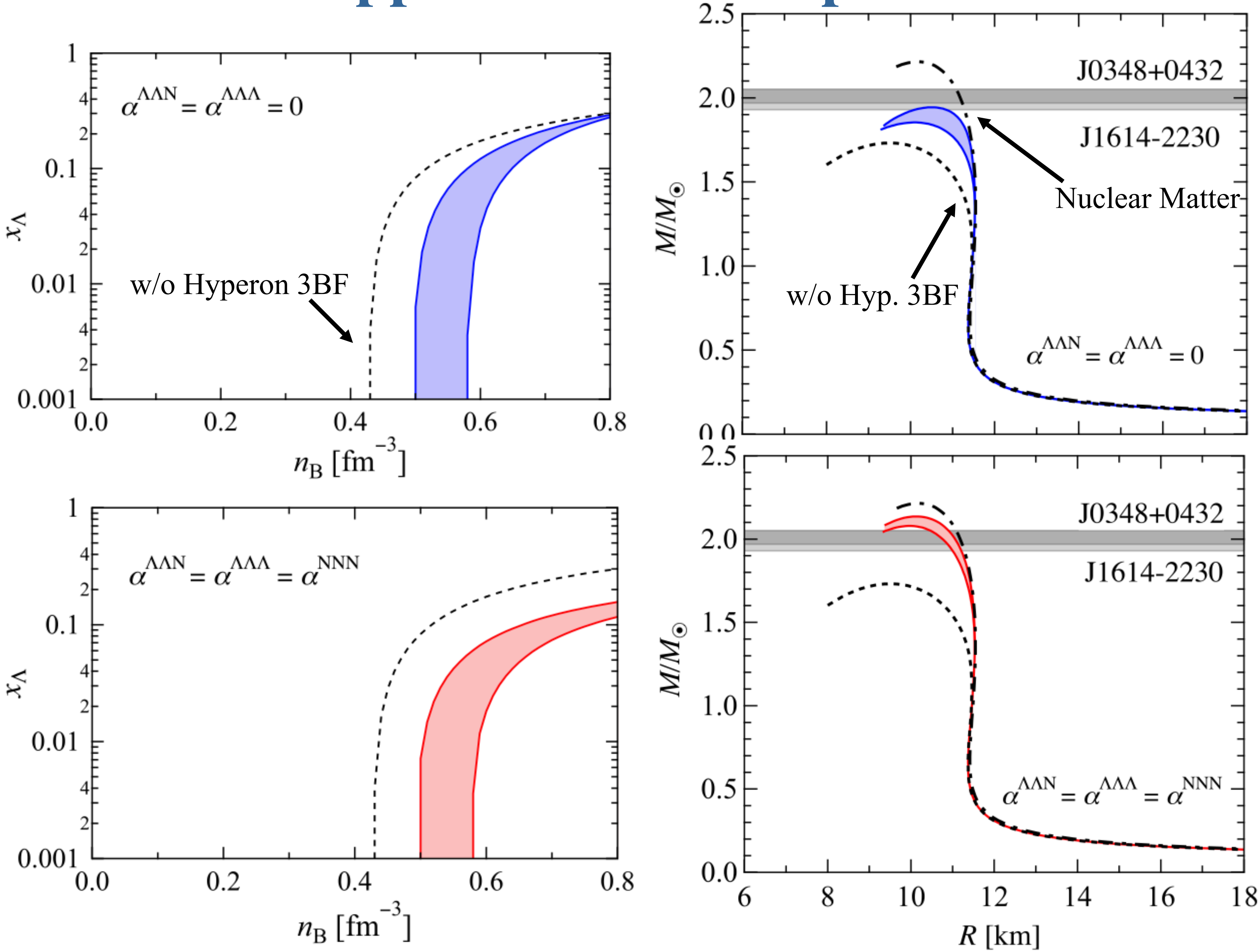
Chemical potential of Λ: μ_Λ



Energy levels of the Λ single-particle major shells (Rev. Mod. Phys. 88 (2016) 035004)

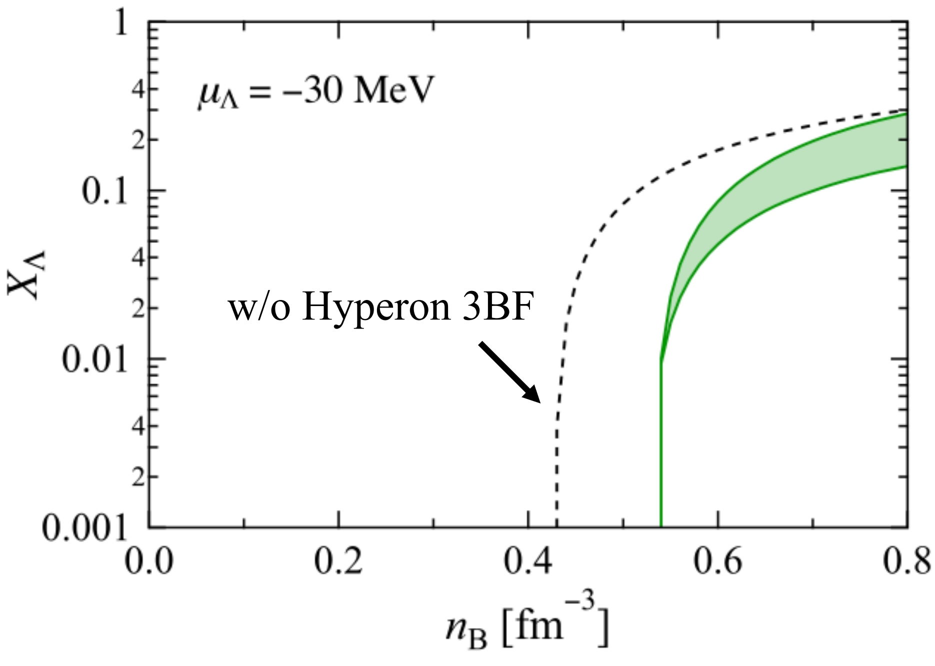
$$-32\ \text{MeV} \le \mu_\Lambda \le -28\ \text{MeV} \quad \rightarrow \quad 0.266 \le \alpha^{\Lambda NN}/\alpha^{NNN} \le 0.475$$

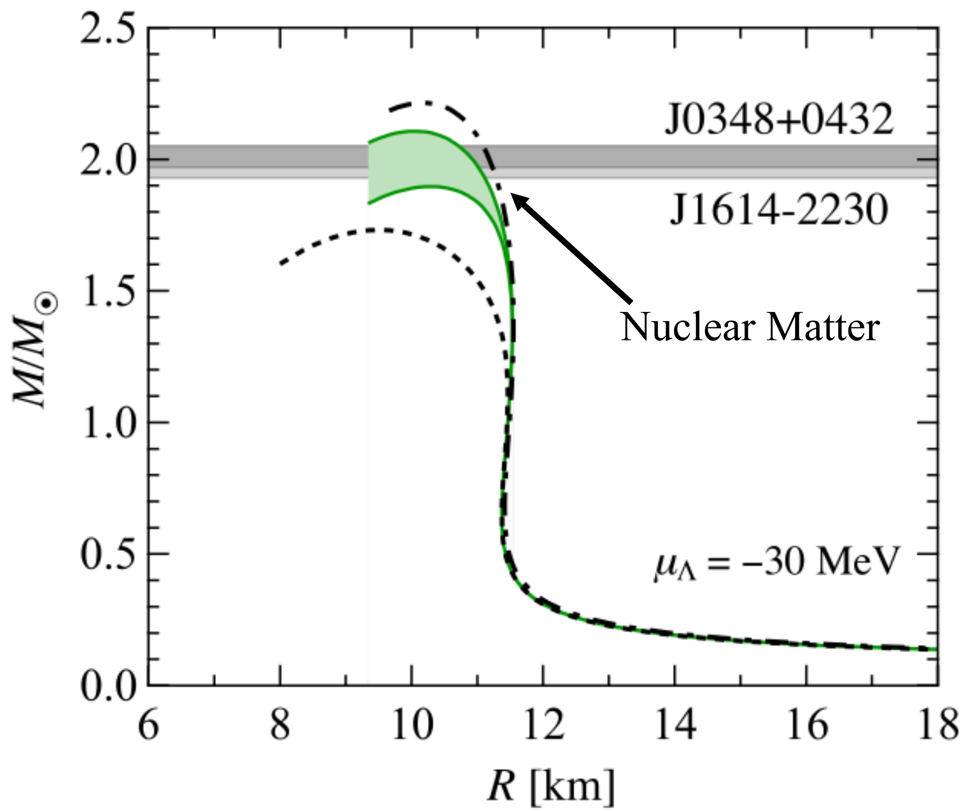
4. Application to Compact Stars



ΛΛN and ΛΛΛ three-body forces

- $\mu_\Lambda = -30$ MeV   ($\alpha^{\Lambda NN} = 0.370\ \alpha^{NNN}$)
- $0 \leq \alpha^{\Lambda\Lambda N} = \alpha^{\Lambda\Lambda\Lambda} \leq \alpha^{NNN}$





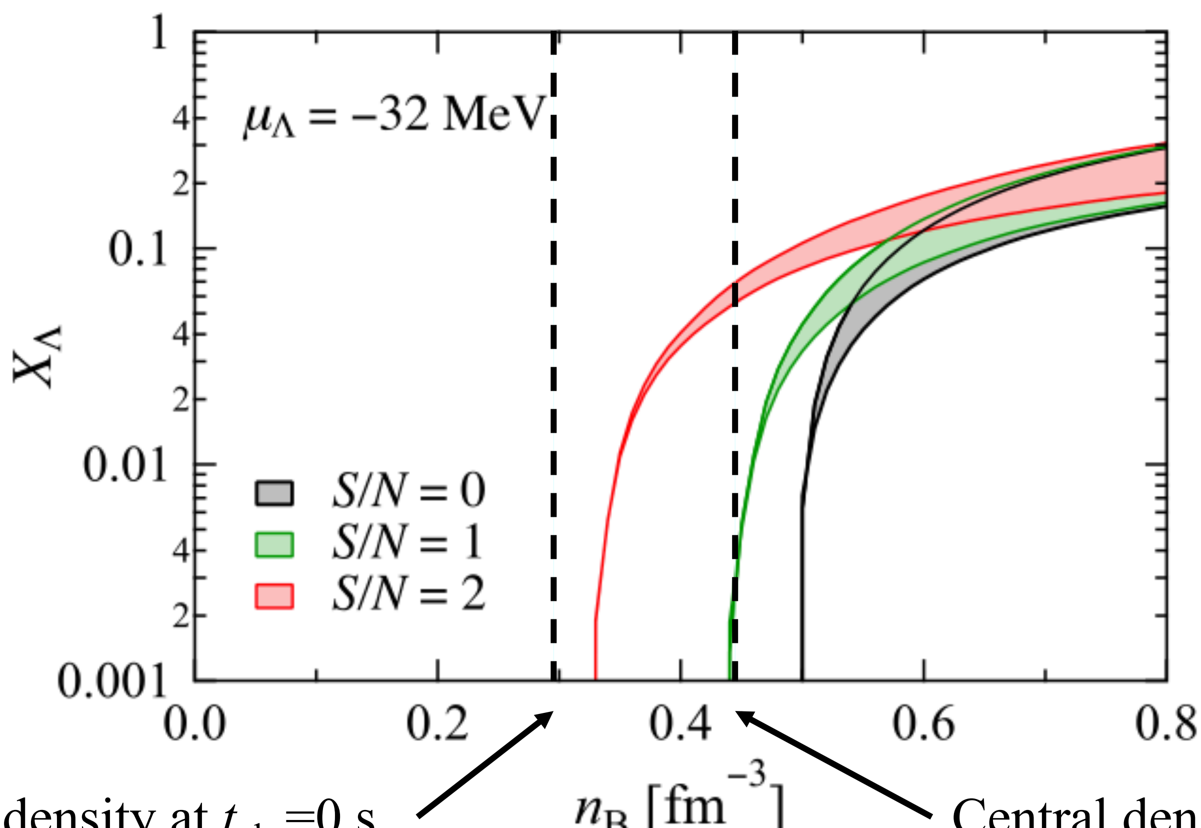
ΛΛN and ΛΛΛ three-body force:
affect on the maximum mass of neutron stars (Important for HYPERON PUZZLE!?)

Hyperon mixing in supernova matter

Supernova matter

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

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



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

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

Summary

We construct the EOS for nuclear matter including Λ hyperons at zero and finite temperatures by the variational method.

Application of the EOS to compact stars

- ΛNN three-body force:
affects on the single-particle potential and the onset density of Λ hyperon mixing
- ΛΛN and ΛΛΛ three-body forces:
affect on the maximum mass of neutron stars (Important for HYPERON PUZZLE!?)
- Λ hyperon fraction in supernova matter becomes larger at higher entropies.

Future Plans

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

→ we extend the cluster variational method to take into account coupled channels.
(Poster presentation in QNP 2018)