Variational approach to neutron star matter with hyperons

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Outline

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3 : Application to neutron stars

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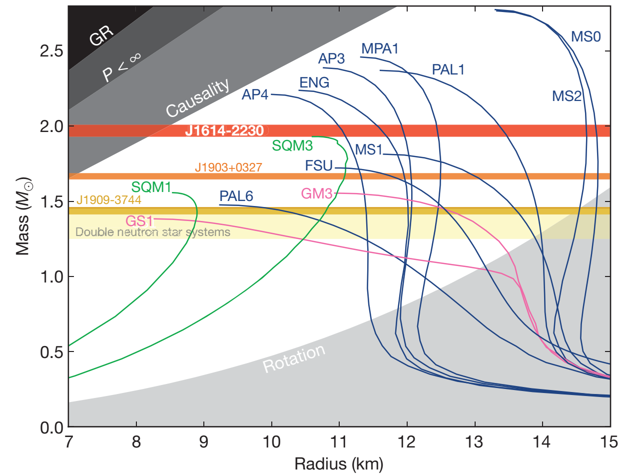
1 : Introduction

Hyperon interactions play important roles in the study of neutron stars.

Hyperons (Λ, Σ, Ξ) are expected to appear in the core of neutron stars.

HYPERON PUZZLE

- Nuclear equation of state (EOS) becomes softer due to the hyperon mixing.
- Maximum mass of neutron star tends to be lower than the observational data.



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

The hyperon mixing in neutron stars has been studied with various nuclear theories.

- **Relativistic mean field theory** (C. Ishizuka et al., J. Phys. G 35 (2008) 085201)
- **Relativistic Hartree-Fock theory** (T. Miyatsu, et al., PRC 88 (2013) 01802)
- **Brueckner-Hatree-Fock theory** (H. Schulze, T. Rijken, PRC 84 (2011) 035801)
- **Variational many-body theory** (D. Lonardoni et al., PRL 114 (2015) 092301)

Our Variational Many-Body Theory

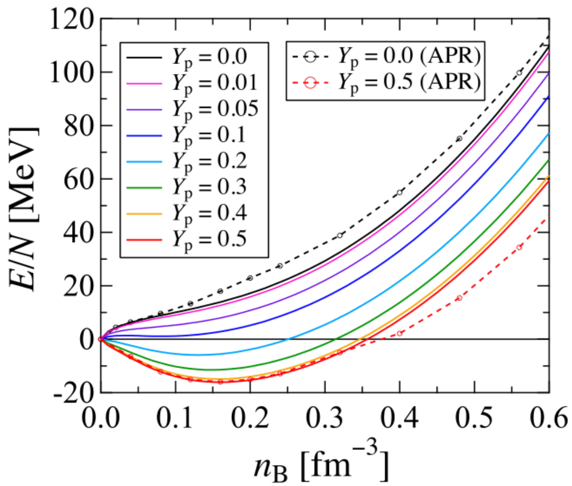
We have constructed the nuclear EOS for core-collapse supernovae with the variational method.

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

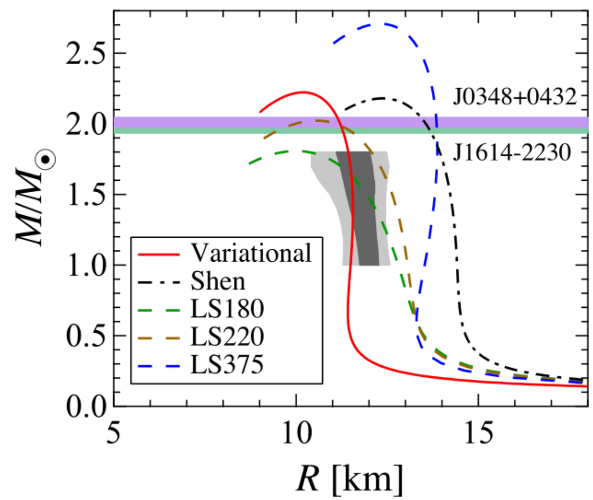
Method : Cluster variational method **Potential : AV18 + UIX**

Cold and Hot Asymmetric Nuclear Matter for arbitrary particle fractions

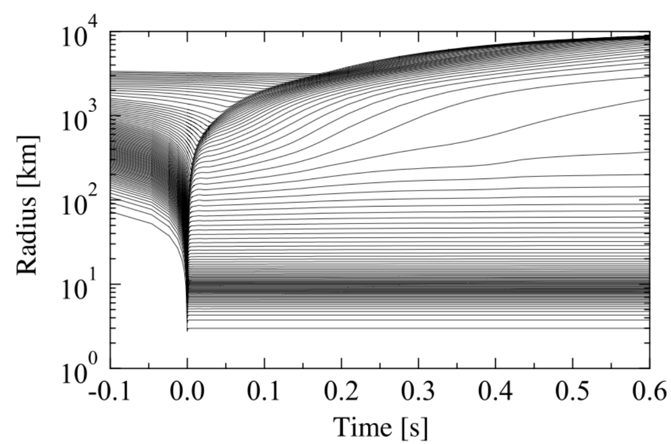
(NPA902 (2013) 53, PTEP 2014 (2014) 023D05)



Energies of uniform matter



Application to Neutron Star



Application to Supernova simulation

It is relatively easy to extend our simple variational method to calculate the EOS of hyperonic nuclear matter.

Our Variational Many-Body Theory

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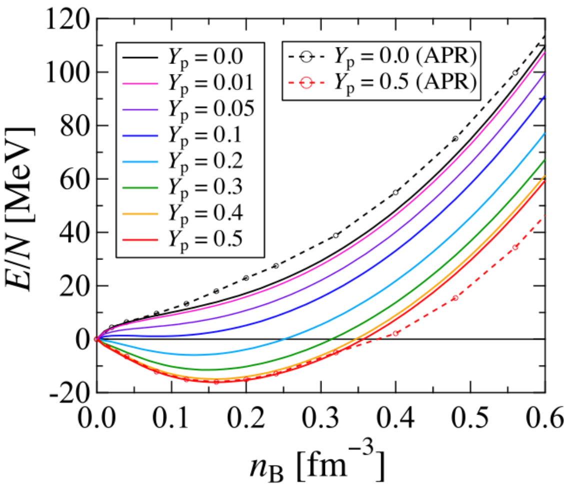
We construct the EOS of nuclear matter

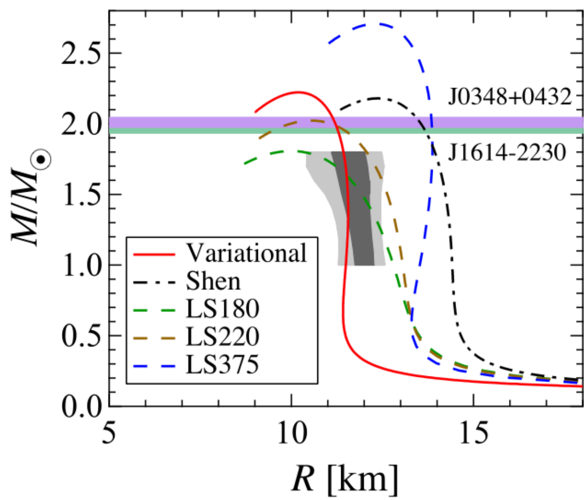
containing Λ and Σ⁻ hyperons

starting from bare baryon interactions

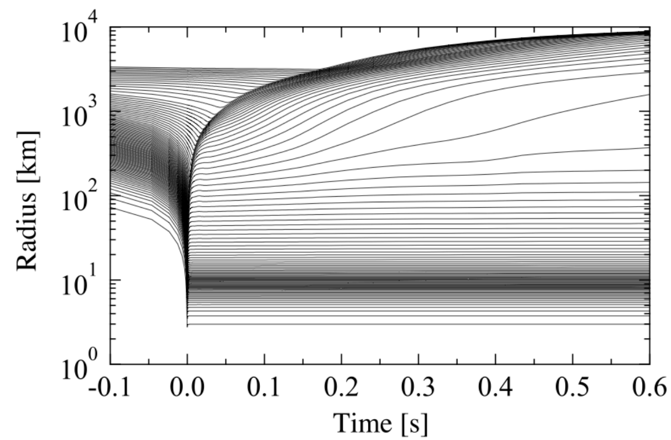
by the cluster variational method



Energies of uniform matter



Application to Neutron Star



Application to Supernova simulation

It is relatively easy to extend our simple variational method to calculate the EOS of hyperonic nuclear matter.

2: Variational method for hyperonic nuclear 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**

Λ*N* interaction (E. Hiyama et al., PRC 74 (2006) 054312)

ΛΛ interaction (E. Hiyama et al., PRC 66 (2002) 024007)

- **The *ab initio* variational calculations for Λ hypernuclei reproduce their experimental eigenvalues.**

Σ^-*N* interaction : Based on the latest version of the **Nijmegen model ESC08**.

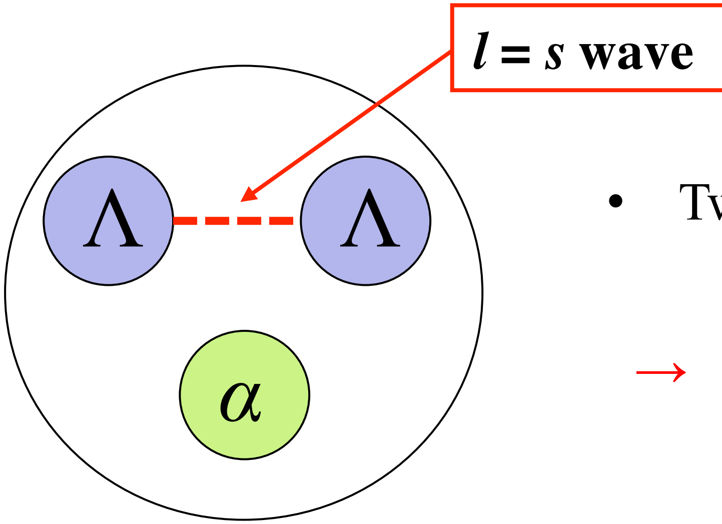
ΛΛ interaction

- ΛΛ interaction is constructed so as to reproduce

the experimental ΛΛ binding energy given by the NAGARA event.

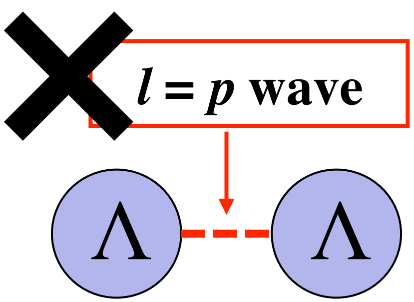
(E. Hiyama et al., PRC 66 (2002) 024007)

${}_{\Lambda\Lambda}^{6}\mathrm{He}$



- Two Λs in the experimentally known double Λ hypernuclei are in the relative *s* orbit.

→ **We determine only the even-state part of the ΛΛ interaction !**



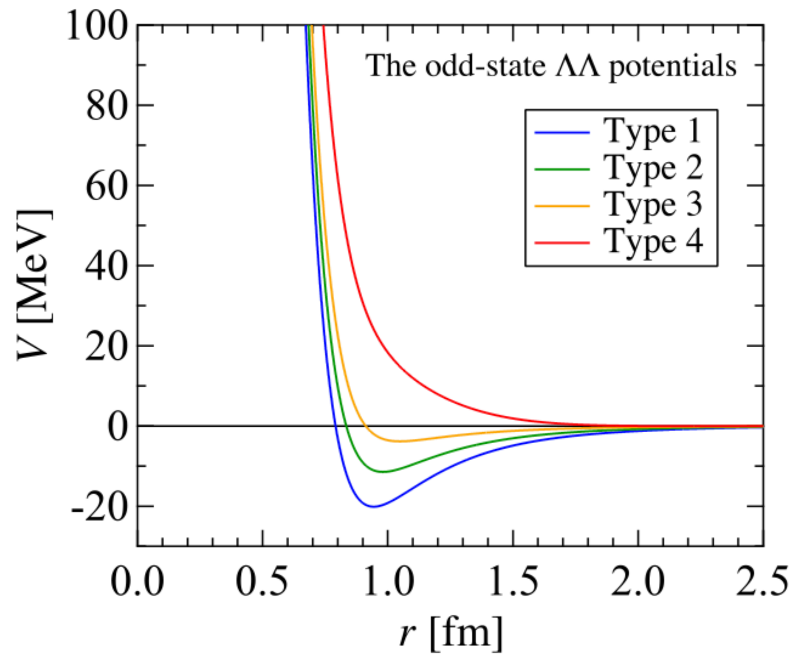
The experimental data on hypernuclei give no information on ***the odd-state part of the ΛΛ interactions****.*

The odd-state part of the ΛΛ interaction

We prepare **four different models** for the odd-state part of the ΛΛ interaction.

Type 1 : *The most attractive*
Type 2 : *Less attractive*
Type 3 : *Slightly repulsive*
Type 4 : *The most repulsive*

The repulsion strength of Type 4 is comparable to that of the odd-state repulsion of Λ*N* interaction.



The repulsive effect increases monotonically from Type 1 to Type 4.

- We investigate the effects of **the odd-state part of bare ΛΛ interactions** on **the structure of neutron stars**.

Expectation Value of H_2

Jastrow wave function

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

Sym [ ]: Symmetrizer

Φ_{F}: The Fermi-gas wave function

f_{ij} : Two-body correlation function

$$f_{ij} = \sum_{p=+}^{-}\sum_{\mu}\sum_{s=0}^{1}\left[f_{\mathrm{C}ps}^{\mu}(r_{ij}) + s f_{\mathrm{T}p}^{\mu}(r_{ij})S_{\mathrm{T}ij} + s f_{\mathrm{SO}p}^{\mu}(r_{ij})(\boldsymbol{L}_{ij}\cdot\boldsymbol{s})\right]P_{psij}^{\mu}$$

Central **Tensor** **Spin-orbit**

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

$$E_2(n_{\mathrm{p}}, n_{\mathrm{n}}, n_{\Lambda}, n_{\Sigma^-}) = \frac{\langle H_2\rangle_2}{A}[f_{\mathrm{C}ps}^{\mu}, f_{\mathrm{T}p}^{\mu}, f_{\mathrm{SO}p}^{\mu}]$$

n_{p} : Proton number density

n_{n} : Neutron number density

n_{Λ} : Λ number density

n_{Σ^-} : Σ^- number density

E_2 is minimized with respect to $f_{Cps}{}^{\mu}(r)$, $f_{Tp}{}^{\mu}(r)$ and $f_{SOp}{}^{\mu}(r)$ by solving the Euler-Lagrange Equations with the appropriate constraints.

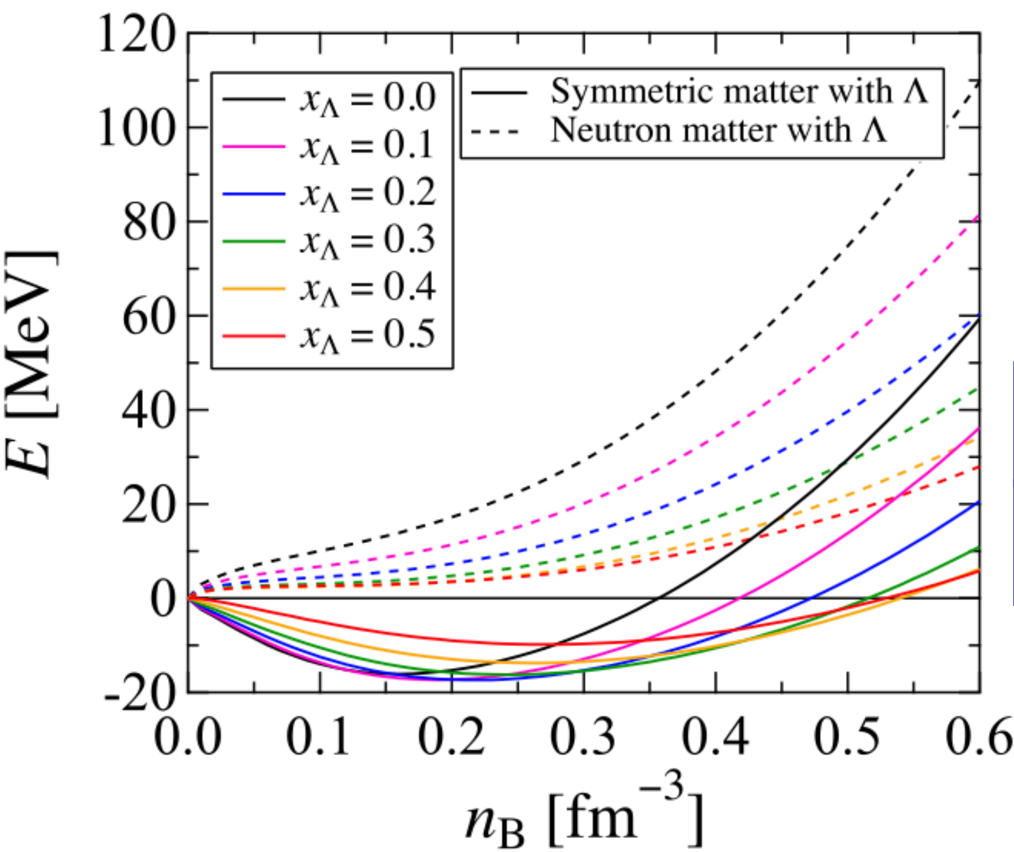
Energy of Hyperonic Nuclear Matter

Energy per baryon $E(n_p, n_n, n_\Lambda, n_{\Sigma^-}) = E_2(n_p, n_n, n_\Lambda, n_{\Sigma^-}) + E_3^N$

Three-nucleon energy E_3^N

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

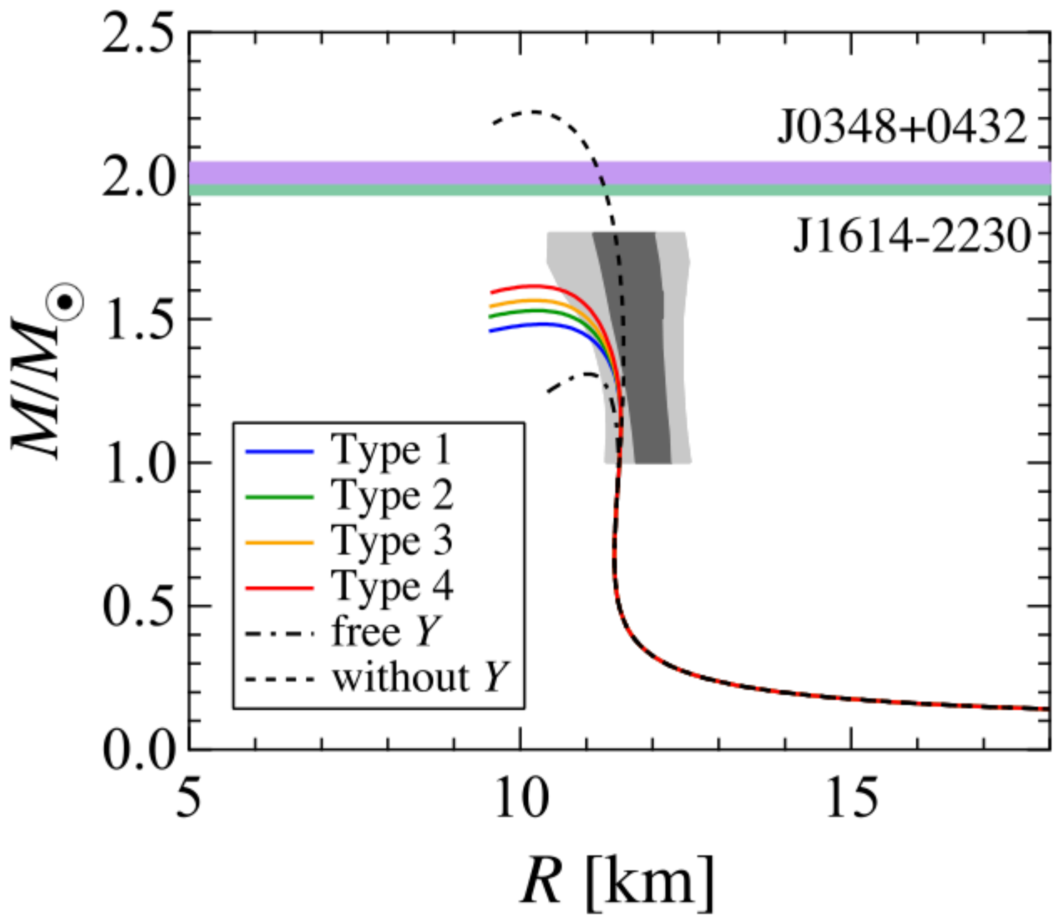
(NPA902 (2013) 53)



Energy of hyperonic nuclear matter (Type 1)

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

3: Application to neutron stars



Mass-radius relations of neutron stars

Maximum mass of neutron stars

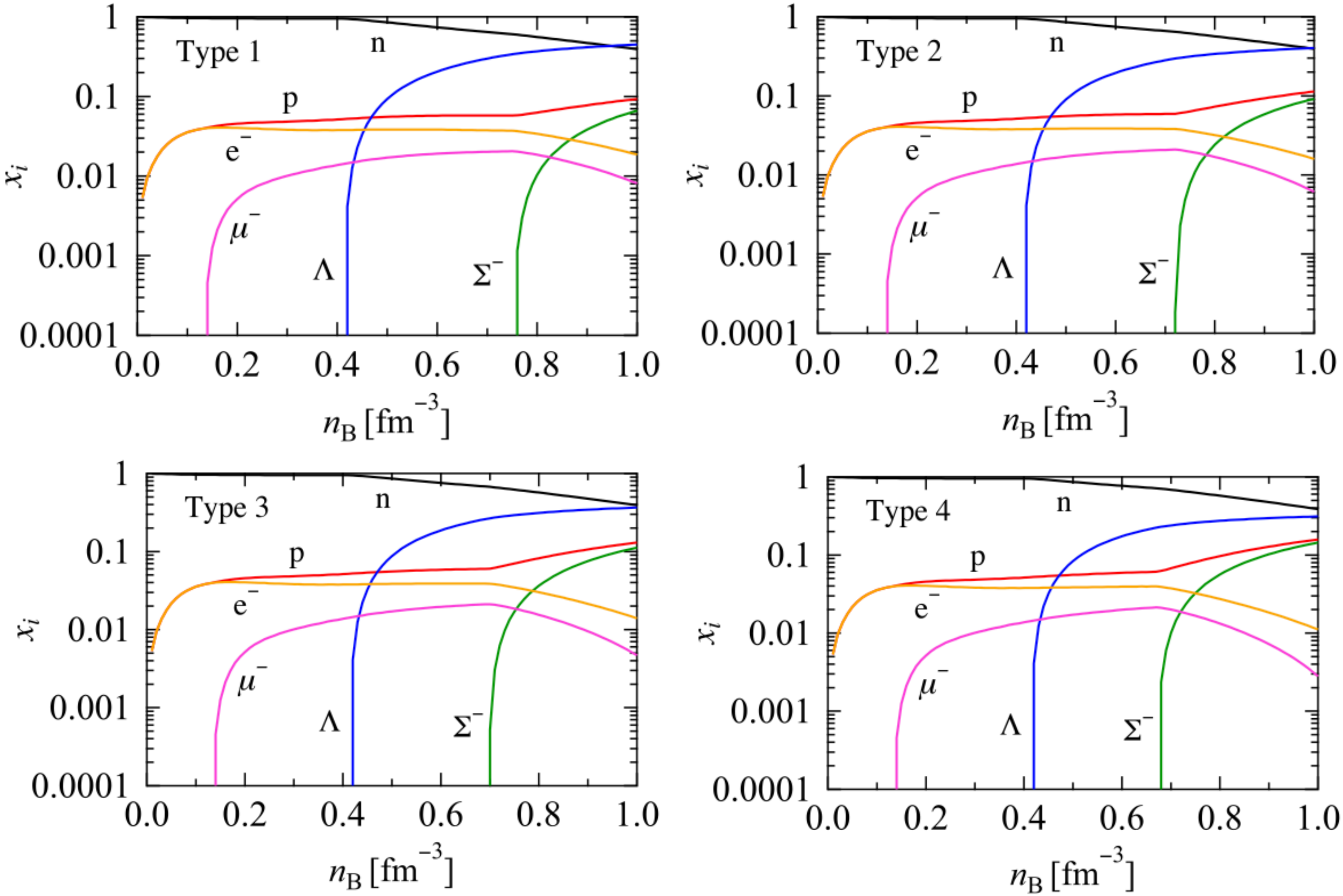
Type 1	1.48 $M_\odot$
Type 2	1.53 $M_\odot$
Type 3	1.57 $M_\odot$
Type 4	1.62 $M_\odot$
free Y	1.31 $M_\odot$
without Y	2.22 $M_\odot$

The maximum mass increases.
(1.48 $M_\odot$ → 1.62 $M_\odot$)

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)

Composition of Neutron Star Matter



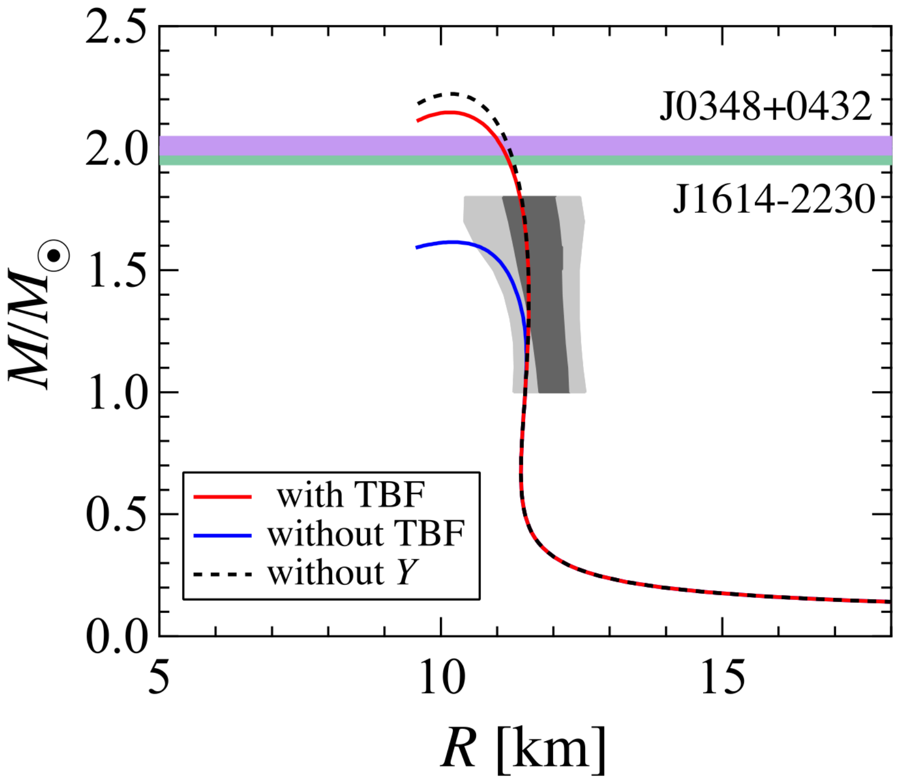
Onset density of Λ : 0.42 fm^{-3}

Onset density of Σ^- : 0.76 fm^{-3} → 0.72 fm^{-3} → 0.70 fm^{-3} → 0.68 fm^{-3}

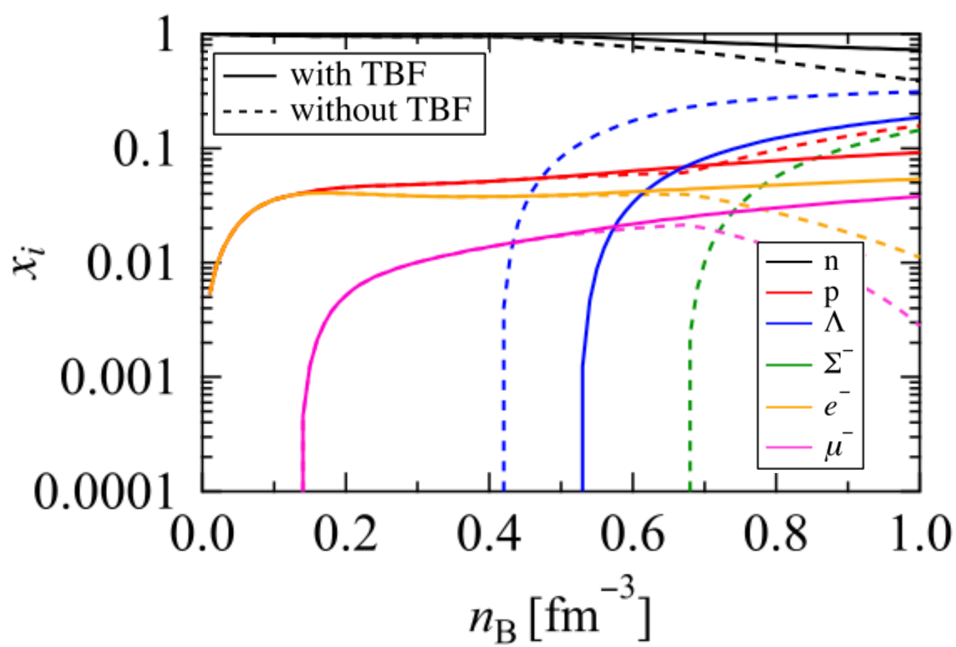
Neutron Star Matter with Three-Baryon Force

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



Mass-radius relations of neutron stars (Type 4)



Composition of neutron star matter (Type 4)

4: Summary

We construct the EOS of nuclear matter containing Λ and Σ⁻ hyperons by the cluster variational method.

We investigate the effects of the odd-state ΛΛ interactions on the structure of neutron stars.

- The repulsion in the odd-state ΛΛ interaction raises the maximum mass of neutron star. ($1.48\ M_\odot \rightarrow 1.62\ M_\odot$)
- The onset density of Σ^- strongly depends on the odd-state ΛΛ interaction.
- Maximum mass of neutron stars with TBF is consistent with the observational data.

Future Plans

- Taking into account mixing of other hyperons (Σ^0, Σ^+, Ξ^0, Ξ^-)
- Hyperon EOS at finite temperatures
- Employing more sophisticated baryon interactions (e.g. Nijmegen)