Effects of hyperon mixing on astrophysical compact objects

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Outline

1 : Introduction

2 : Hyperon mixing in neutron star

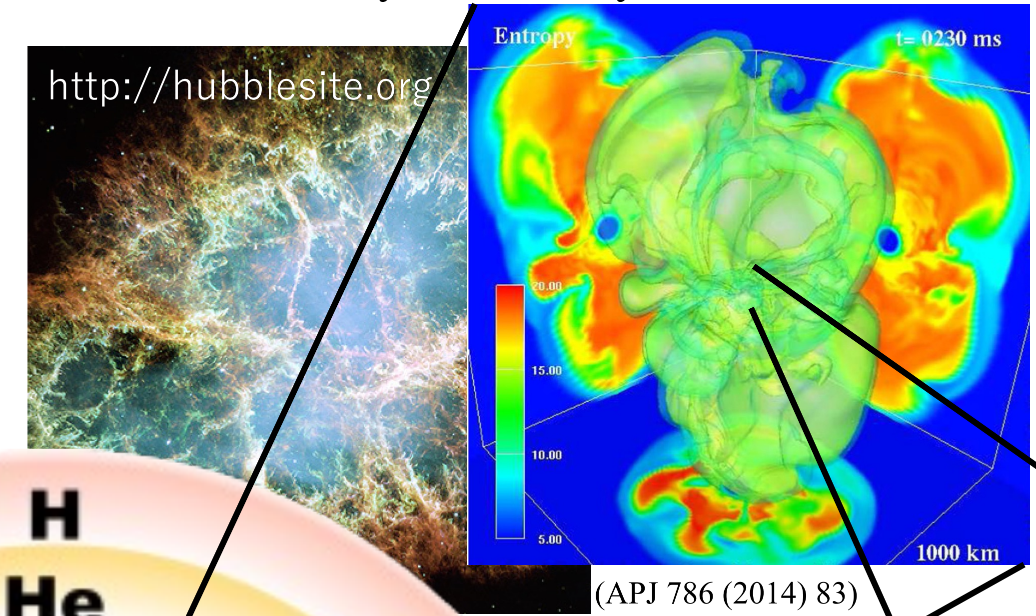
3 : Hyperon micing in supernova matter

Reimei Workshop "Hadron interactions with strangeness and charm" @ Jeju island, Korea, June 28, 2024

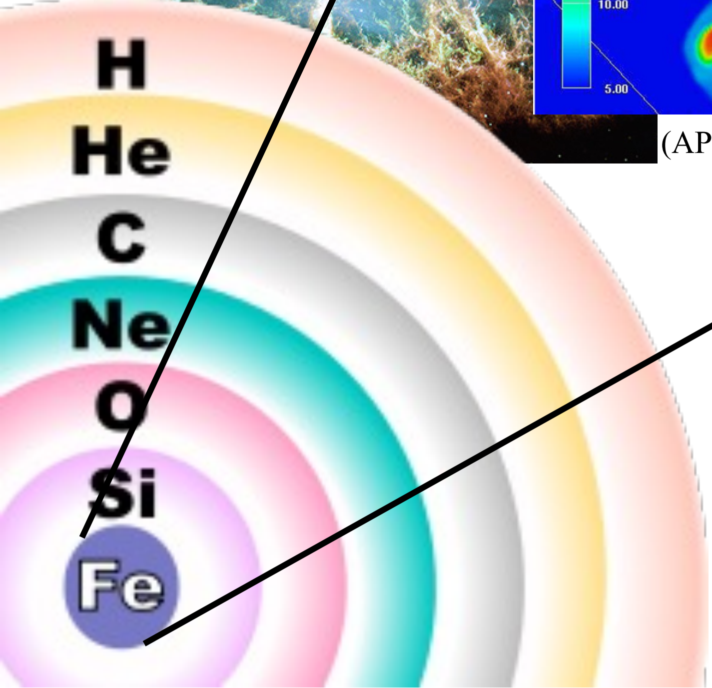
1. Introduction

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

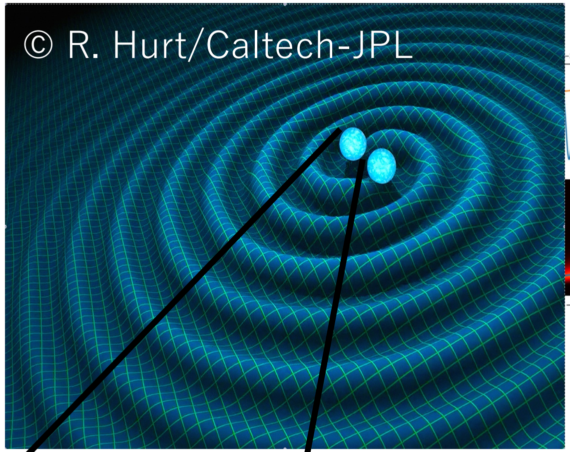
Core-Collapse Supernovae

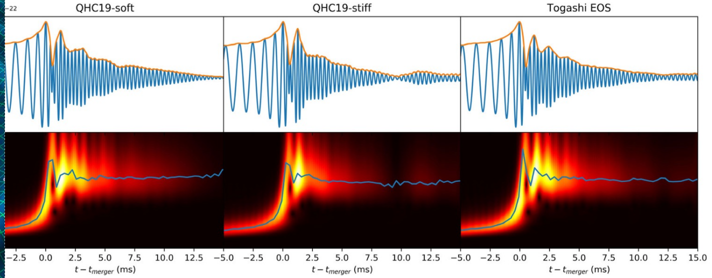


(APJ 786 (2014) 83)

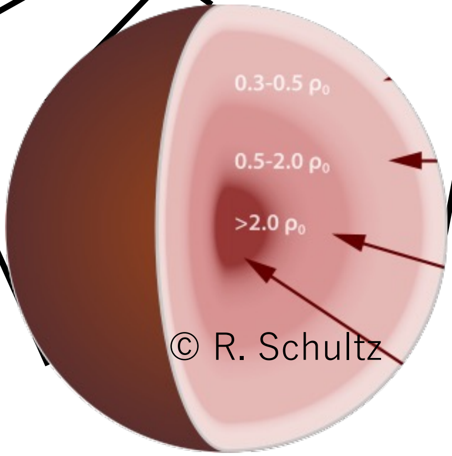


Neutron Star Mergers

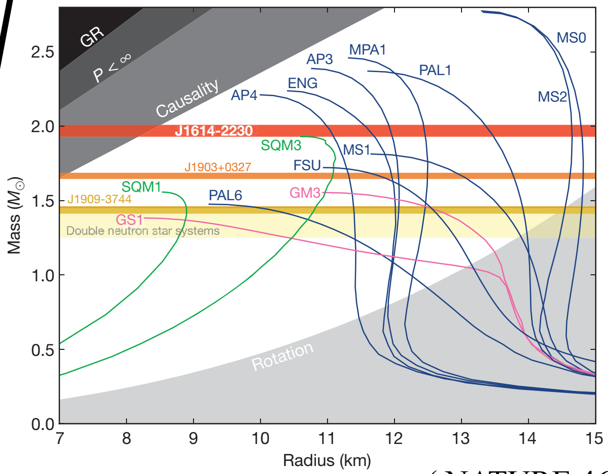




(PRL 129 (2022) 181101)



Neutron Stars

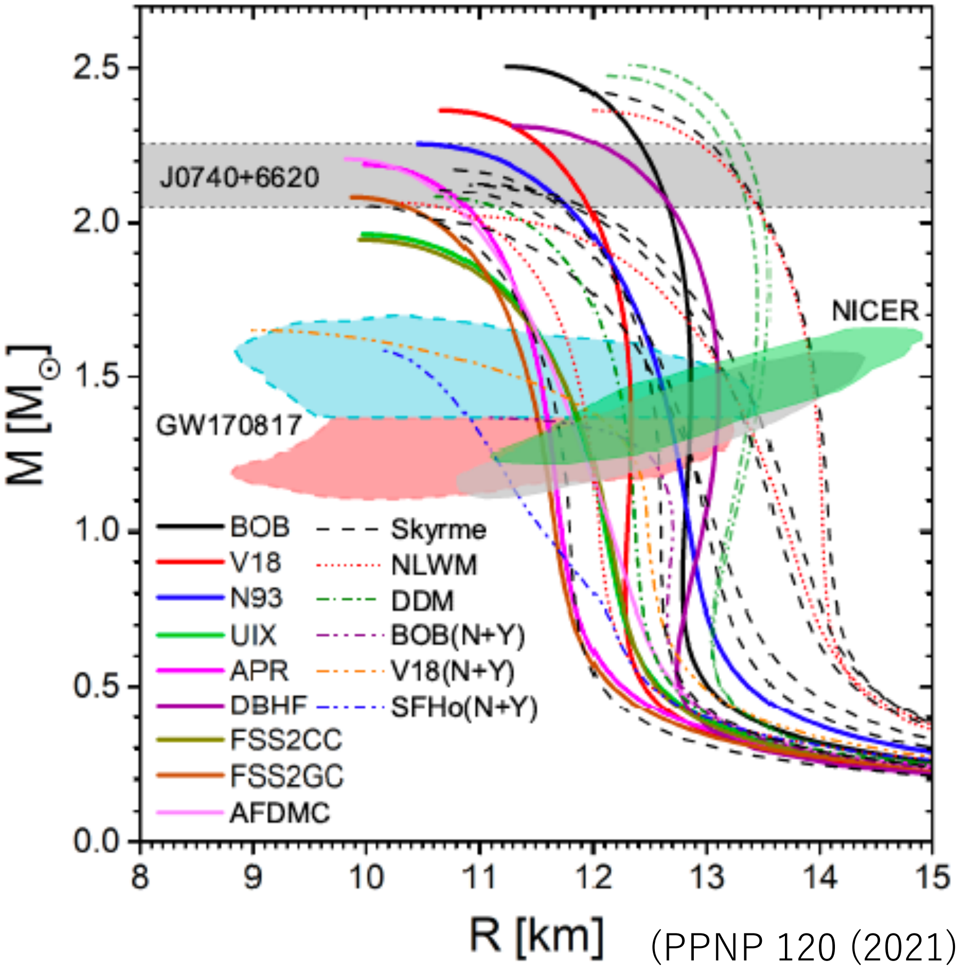


(NATURE 467 (2010) 1081)

Neutron Star Matter & Supernova Matter

Neutron Stars (NS)

- $T = 0$ MeV, $Y_p \sim 0.1$
- Various EOS has been proposed.

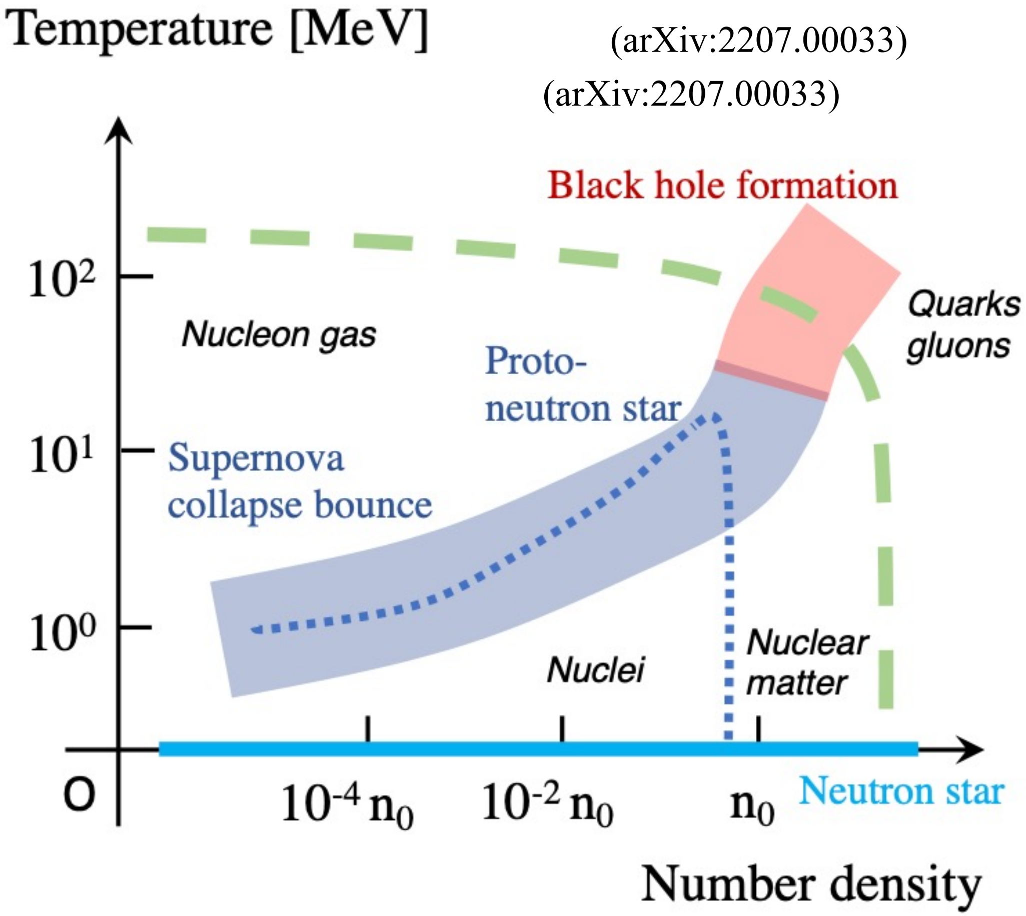


(PPNP 120 (2021) 103879)

Supernovae / NS mergers

- Wide range of T, Y_p, n_B
- Limited number of EOSs are applicable.

(arXiv:2207.00033)



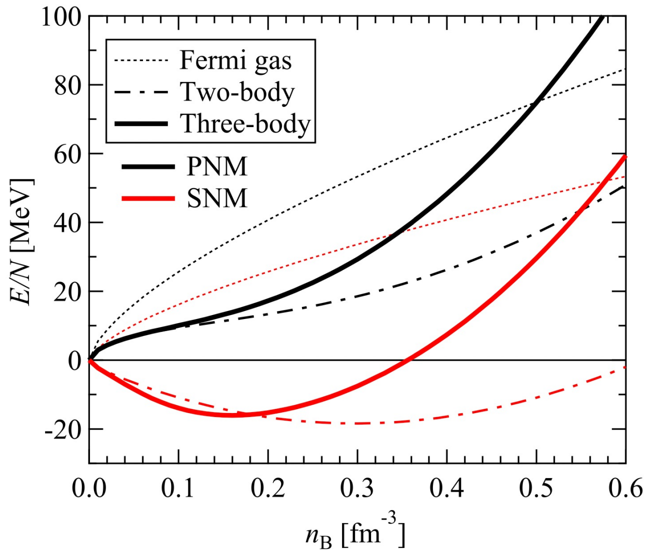
Variational EOS for astrophysical simulations

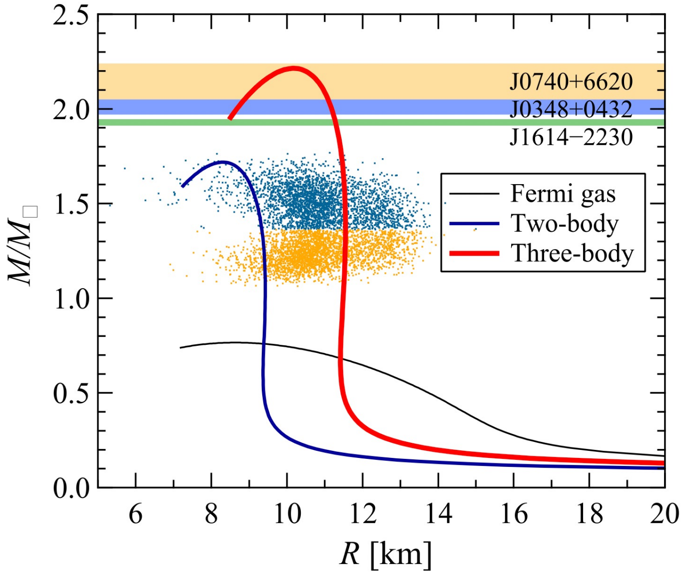
Variational EOS with realistic nuclear forces

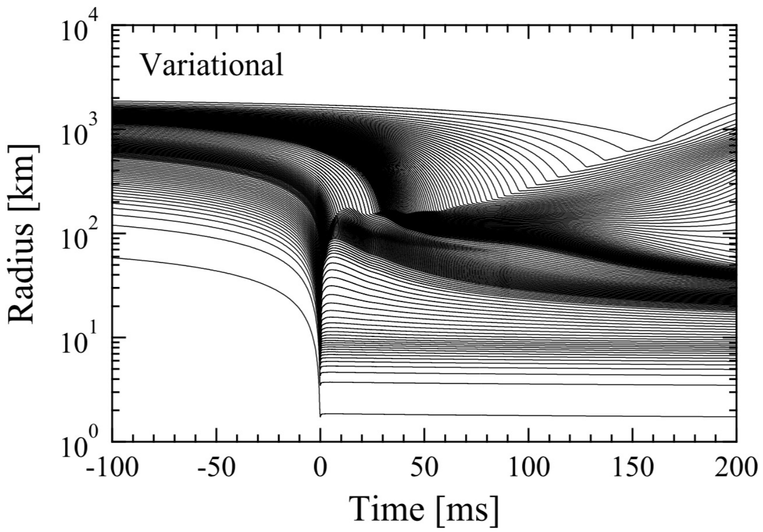
(**HT**, K. Nakazato, Y. Takehara, S. Yamamuro, H. Suzuki, and M. Takano, NPA961 (2017) 78)

Constructed by ***the variational many-body theory*** *with bare nuclear forces (****AV18 +UIX****)*

- This EOS is applicable to the studies for **neutron stars** and **core-collapse supernovae.**
- This EOS table is available on the web: `http://www.np.phys.waseda.ac.jp/EOS/`

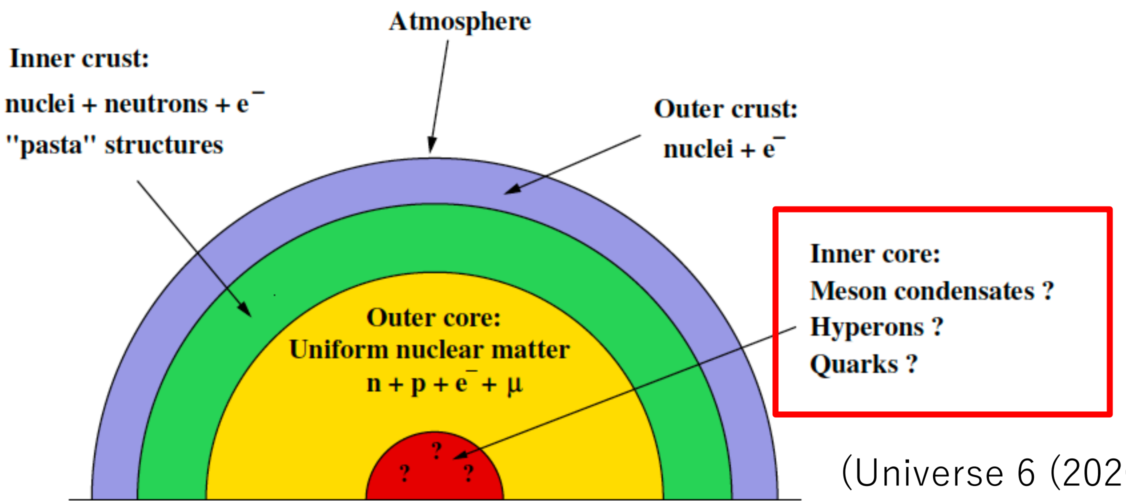






Extend to the EOS for hyperon-mixed nuclear matter
by using the simplified bare baryon forces

2. Hyperon mixing in neutron star



(Universe 6 (2020) 119)

Hyperon Puzzle

- Hyperon must appear in NSs
- EOS with hyperons is too soft

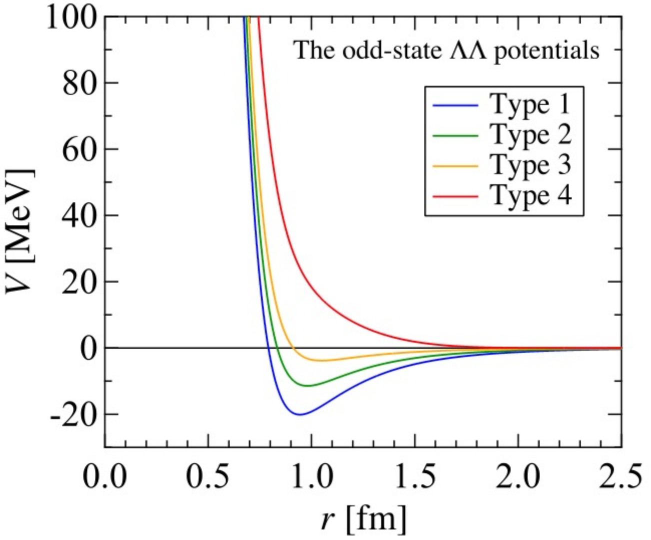
→ cannot support massive NSs ($\sim 2M_\odot$)

Possible Solutions of the Hyperon Puzzle

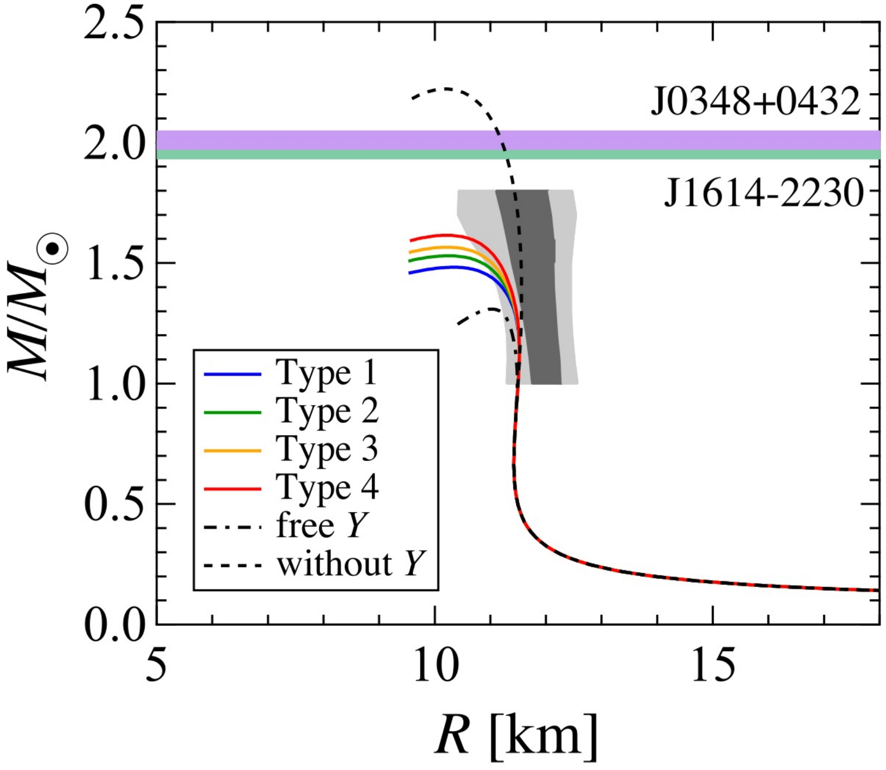
- Hyperon-hyperon two-body repulsion
- Hyperonic three-body forces (ΛNN・ΛΛN・ΛΛΛ)
- Quark phase appearance at densities below the hyperon threshold

ΛΛ repulsion with the variational method

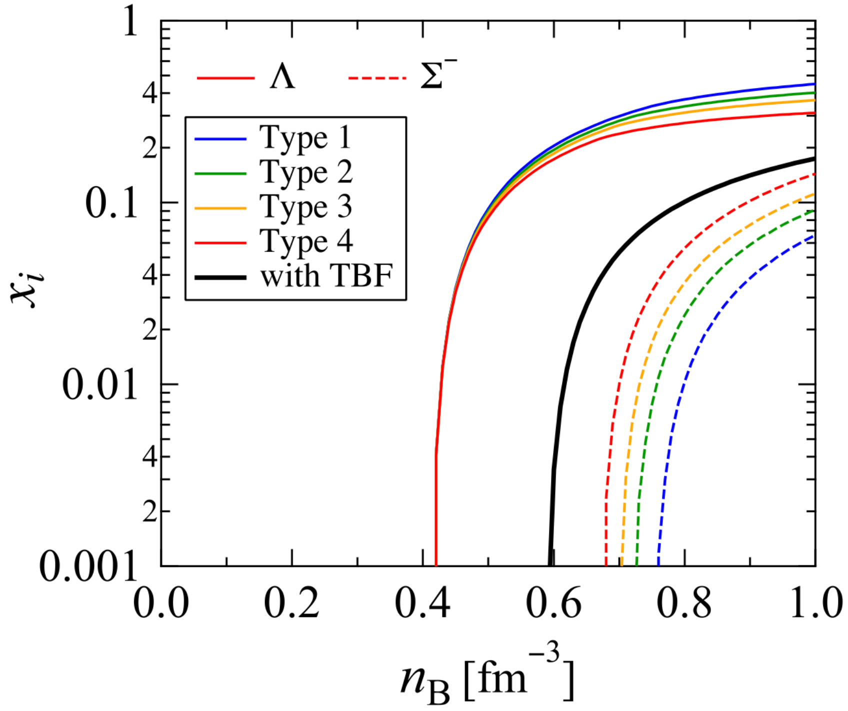
(**HT**, E.Hiyama, Y. Yamamoto, M. Takano, PRC 93 (2016) 035808)



Repulsive effect increases monotonically from Type 1 to 4.



Mass radius relation of cold neutron stars



Hyperon fraction in neutron star

Repulsion strength is not enough to support the massive neutron stars.

Three-baryon forces including hyperons

Hamiltonian of Hyperonic Nuclear Matter

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

Interactions for nuclear sector

- Argonne v18 (AV18) two-body potential
- Urbana IX (UIX) three-body potential

Interactions for hyperonic sector

- two-body **central** potential (E. Hiyama et al., PRC 74 (2006) 054312) (E. Hiyama et al., PRC 66 (2002) 024007)

- *Constructed so as to reproduce the experimental binding energies of light hypernuclei*

Hyperon three-body forces

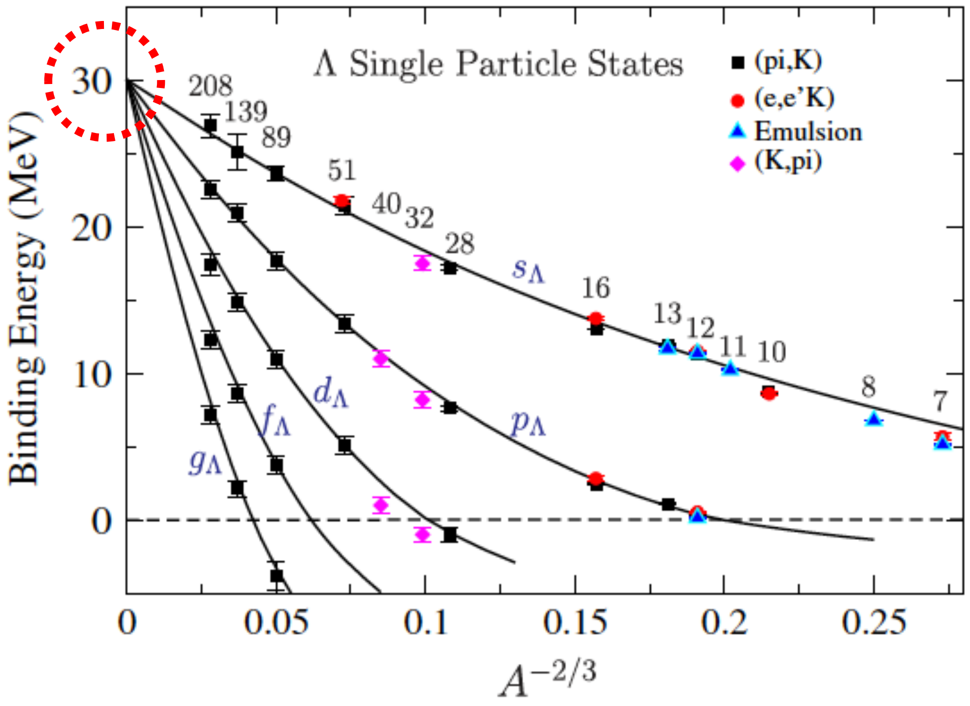
$V_{ijk}^{\Lambda NN}$, $V_{ijk}^{\Lambda\Lambda N}$, $V_{ijk}^{\Lambda\Lambda\Lambda}$: phenomenological three-body potential

- Repulsive part of the UIX pot. is employed

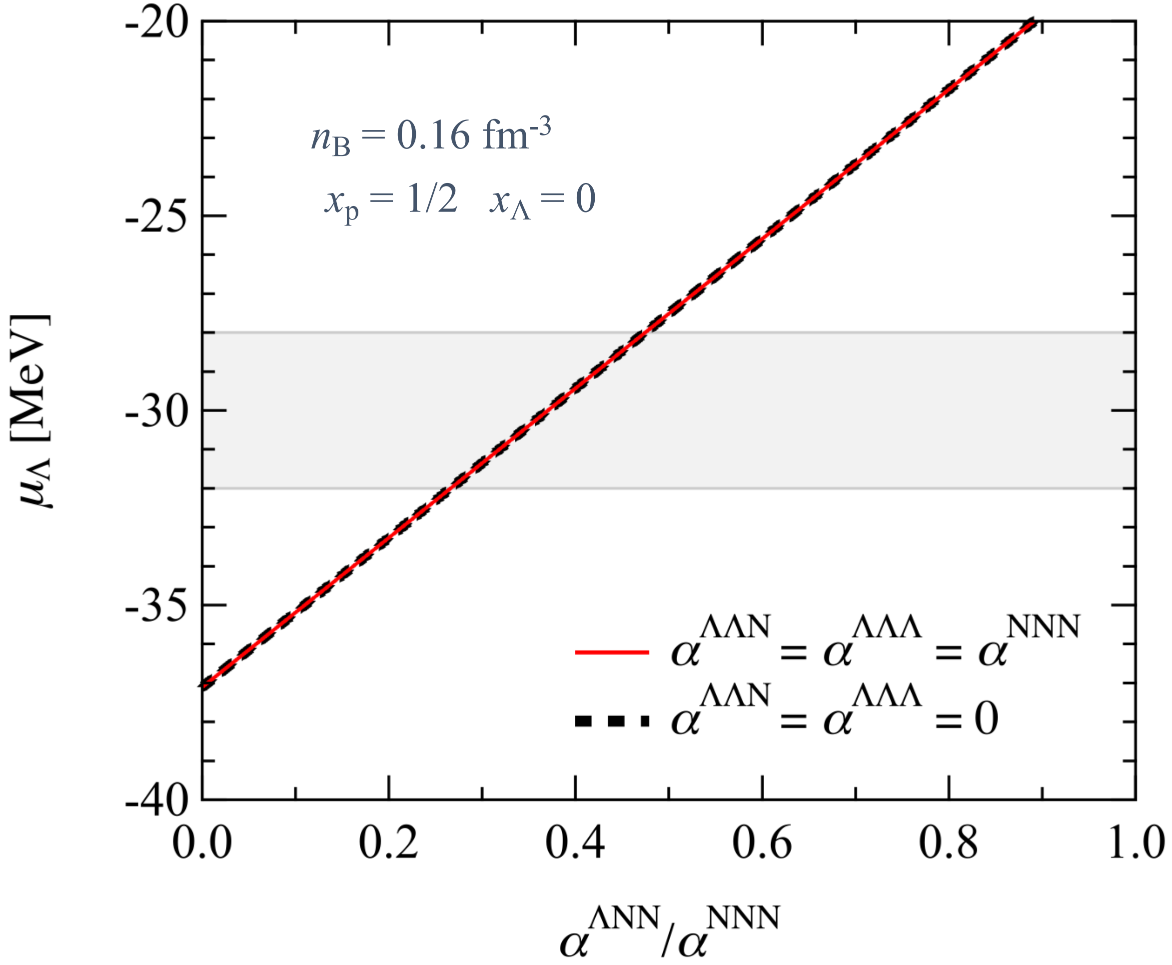
– Strength parameters are taken to be free parameters.

Single particle potential for Λ hyperons

Empirical value of single particle potential for Λ in symmetric nuclear matter ~ –30 MeV

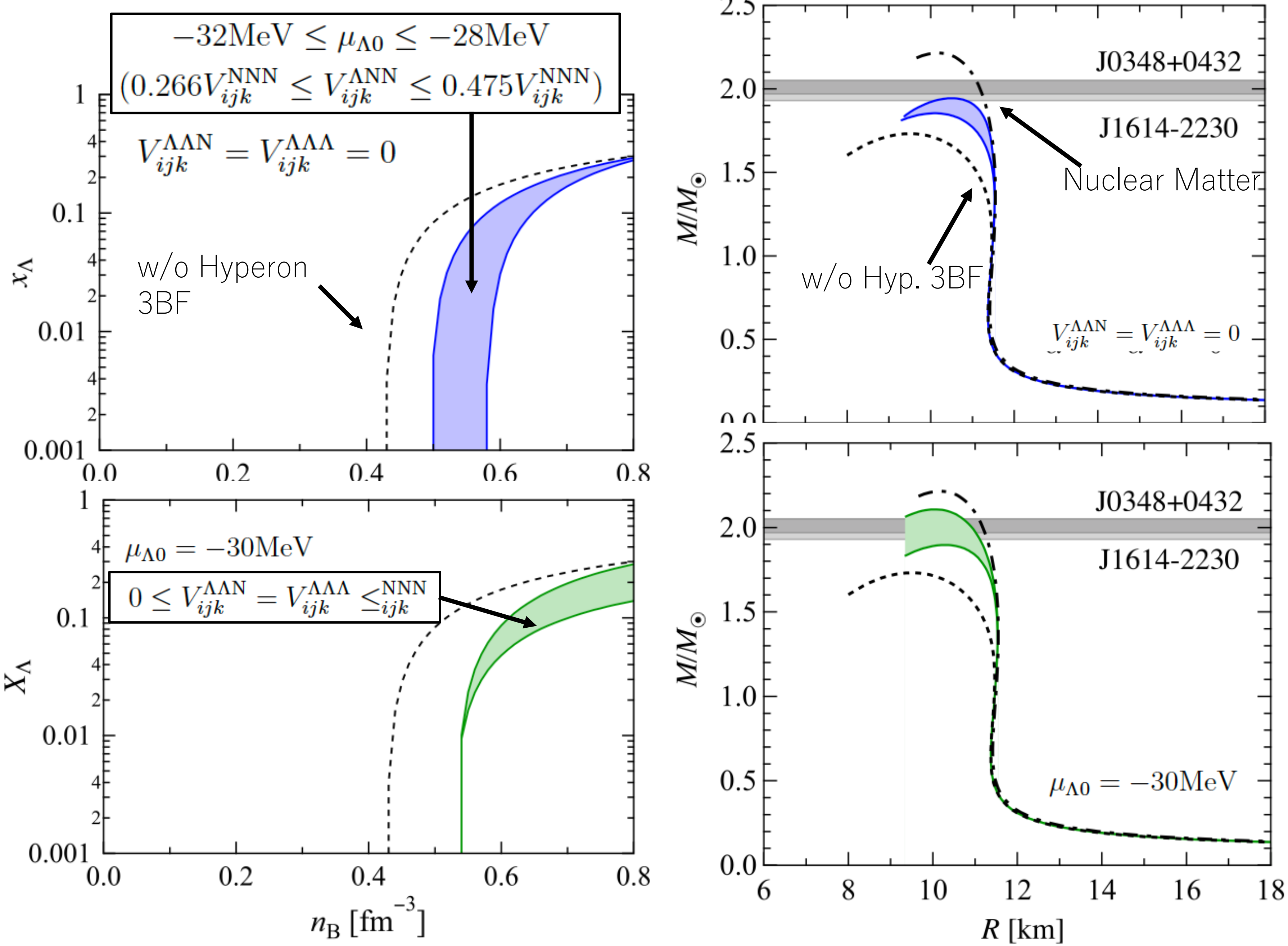


Energy levels of the Λ single-particle major shells (Rev. Mod. Phys. 88 (2016) 035004)



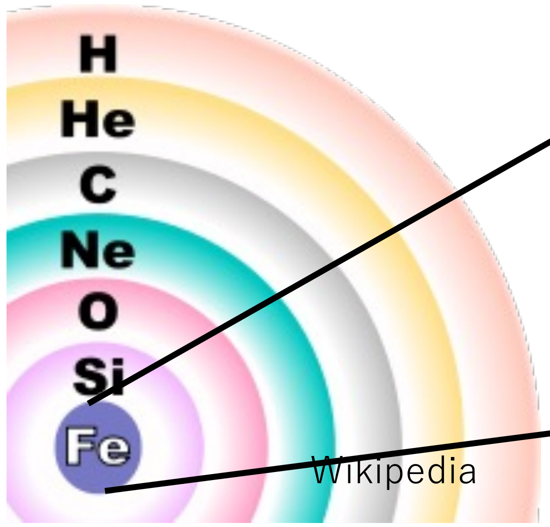
Single particle potential μ_Λ as a function of strength ratio

Effects of hyperon three-body forces on neutron star structure



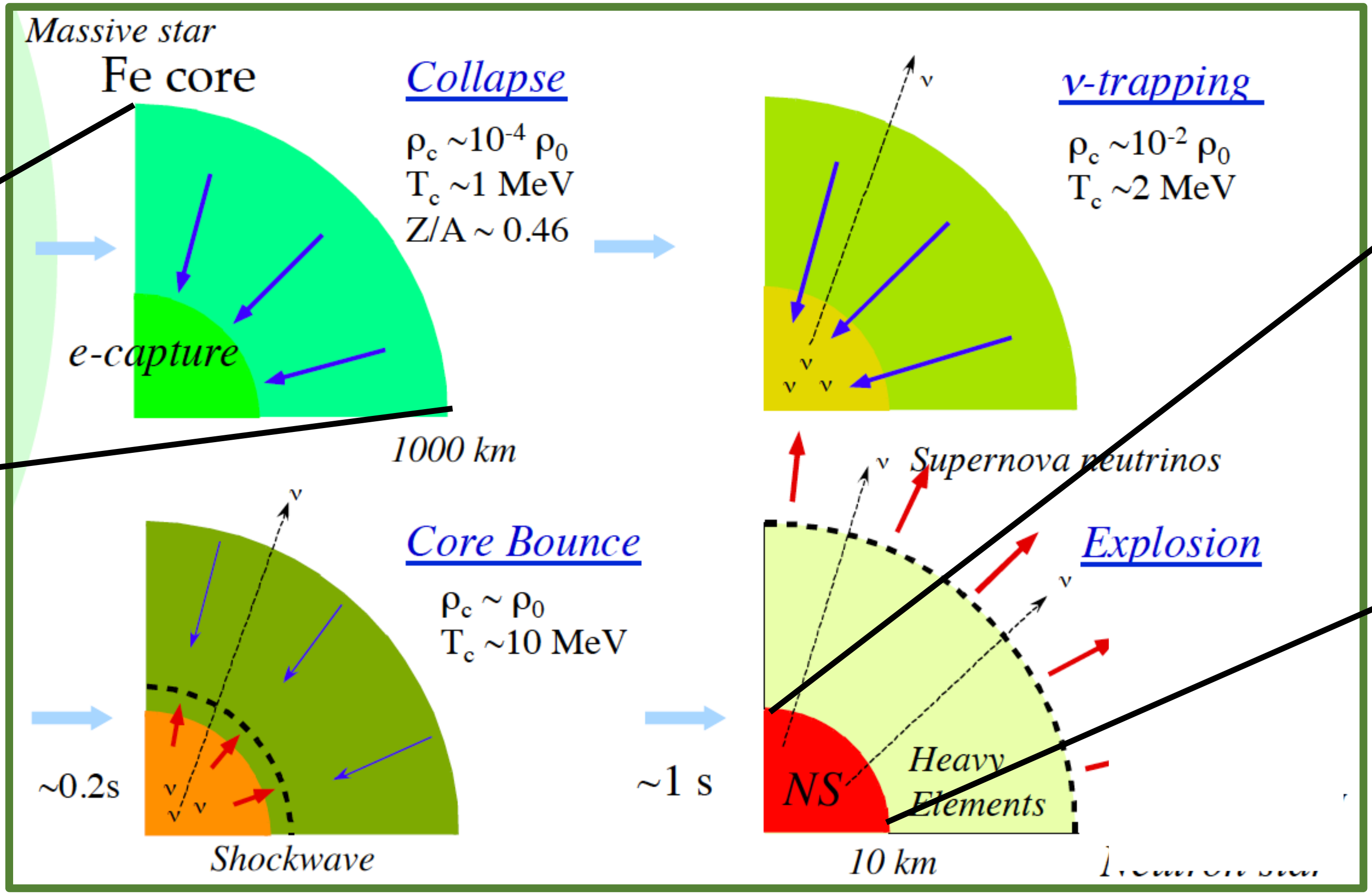
3. Hyperon mixing in supernova matter

Phase I:
Stellar Evolution



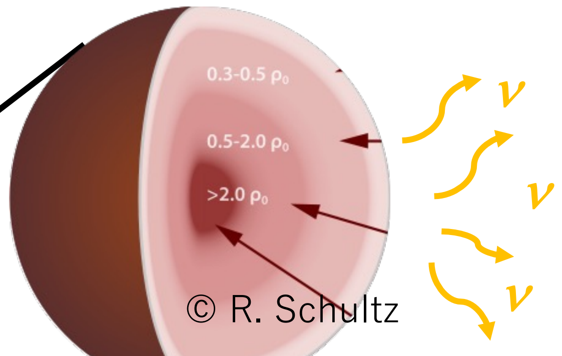
***Timescale* : ~10^7 y**

Phase II:
Core-collapse, bounce, shock propagation



***Timescale* : ~ 1s**

Phase III:
Proto-neutron star
cooling



***Timescale* : ~ 1m**

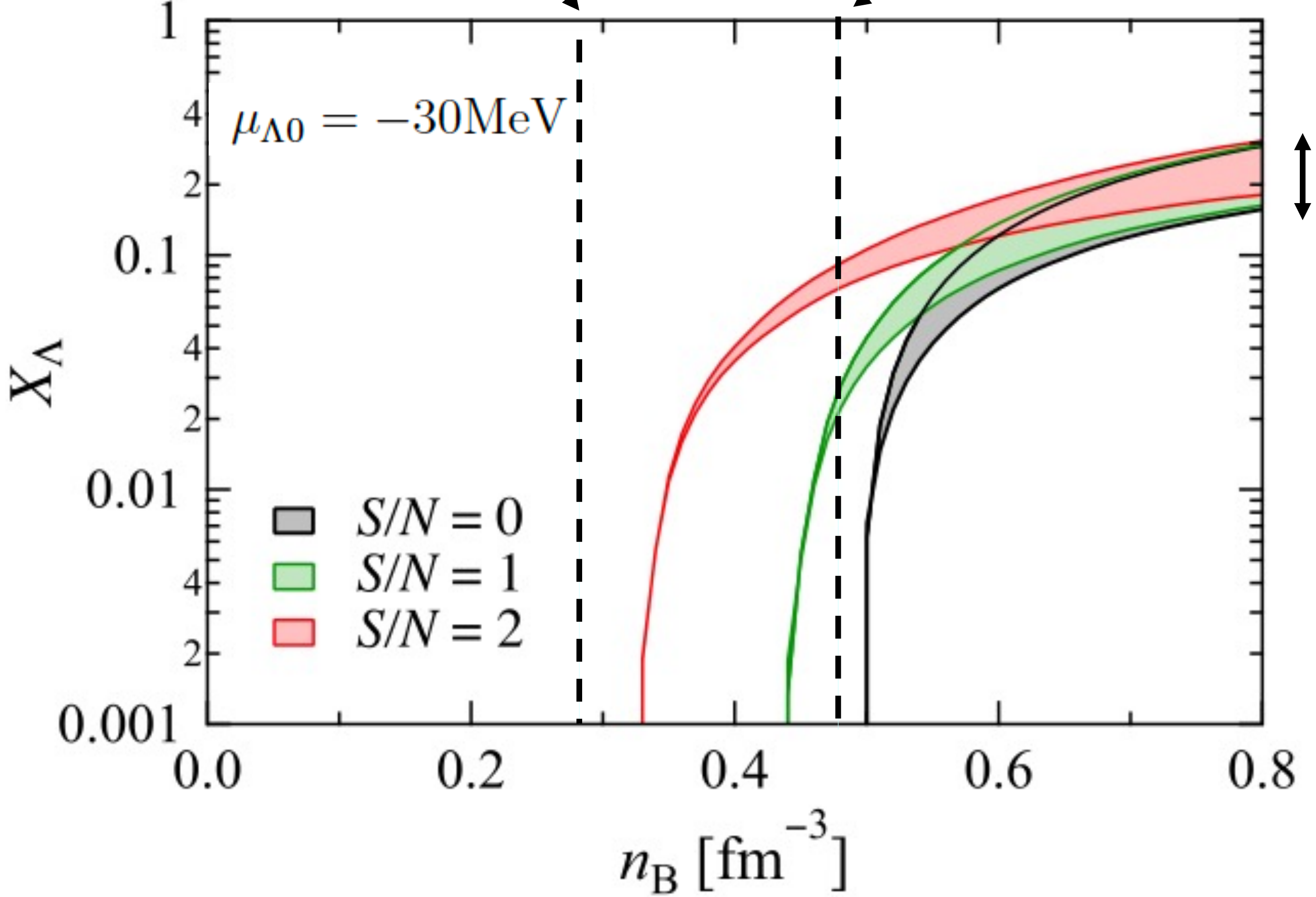
Hyperon Fraction in Supernova Matter

Supernova matter

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

Central density at the bounce

Central density at 50 s after the bounce
(PNS cooling stage)

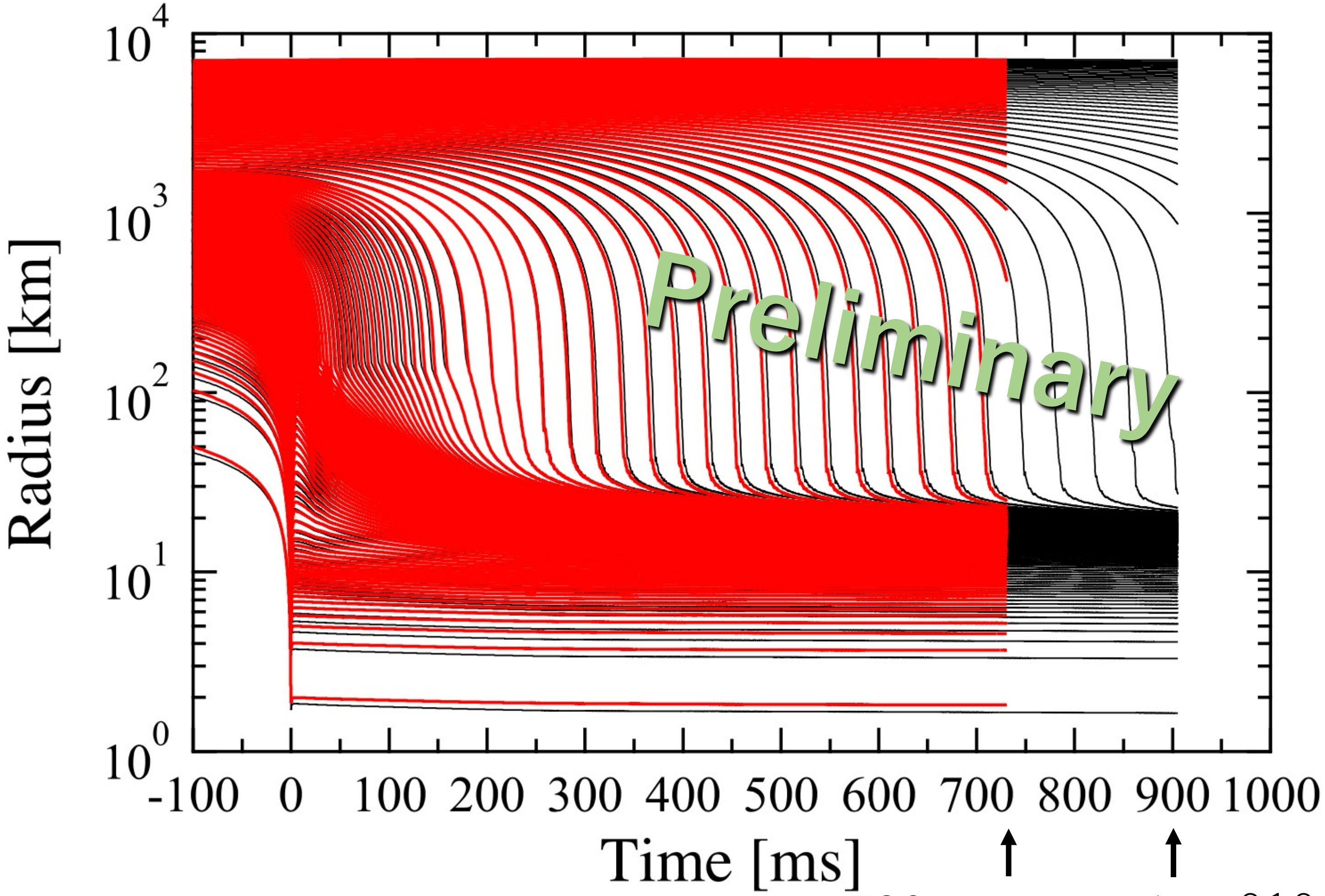


Uncertainties
in ΛΛN & ΛΛΛ repulsions

Hyperon mixing in black hole formation

1D hydrodynamics simulations without neutrinos

Progenitor: Woosley Weaver 1995, $40M_\odot$ (K. Sumiyoshi, et al., NPA 730 (2004) 227) (Astrophys. J. Suppl. 101 (1995) 181)



t_{pb} =730 ms (with Λ hyperon)

t_{pb} =910 ms (without Λ hyperon)

Neutrino reactions in supernova simulations

1. electron-type neutrino absorption on neutrons and its inverse,

$$\nu_e + n \longleftrightarrow e^- + p,$$

2. electron-type antineutrino absorption on protons and its inverse,

$$\bar{\nu}_e + p \longleftrightarrow e^+ + n,$$

3. neutrino scattering on nucleons,

$$\nu + N \longleftrightarrow \nu + N,$$

4. neutrino scattering on electrons,

$$\nu + e^- \longleftrightarrow \nu + e^-,$$

5. electron-type neutrino absorption on nuclei,

$$\nu_e + A \longleftrightarrow A + e^-,$$

6. neutrino coherent scattering on nuclei,

$$\nu + A \longleftrightarrow \nu + A,$$

7. electron-positron pair annihilation and creation,

$$e^- + e^+ \longleftrightarrow \nu + \bar{\nu},$$

8. plasmon decay and creation,

$$\gamma^* \longleftrightarrow \nu + \bar{\nu},$$

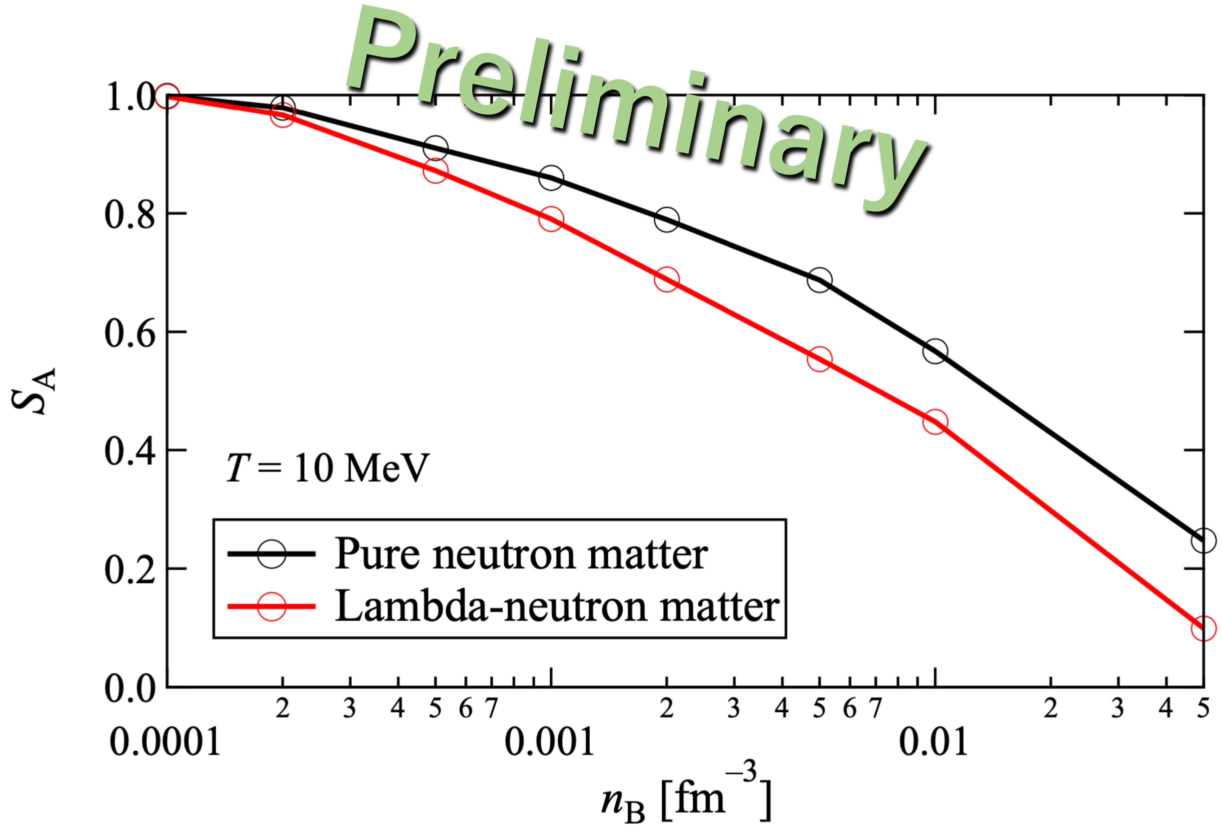
9. neutrino bremsstrahlung,

$$N + N' \longleftrightarrow N + N' + \nu + \bar{\nu}.$$

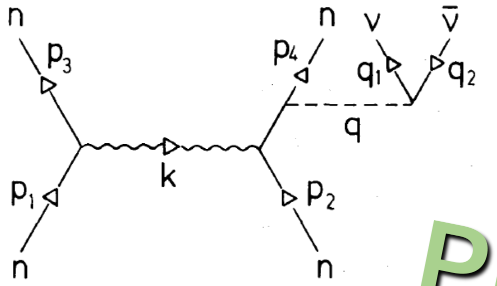
Reaction kernel for core-collapse simulations

【Neutrino scattering on baryons】

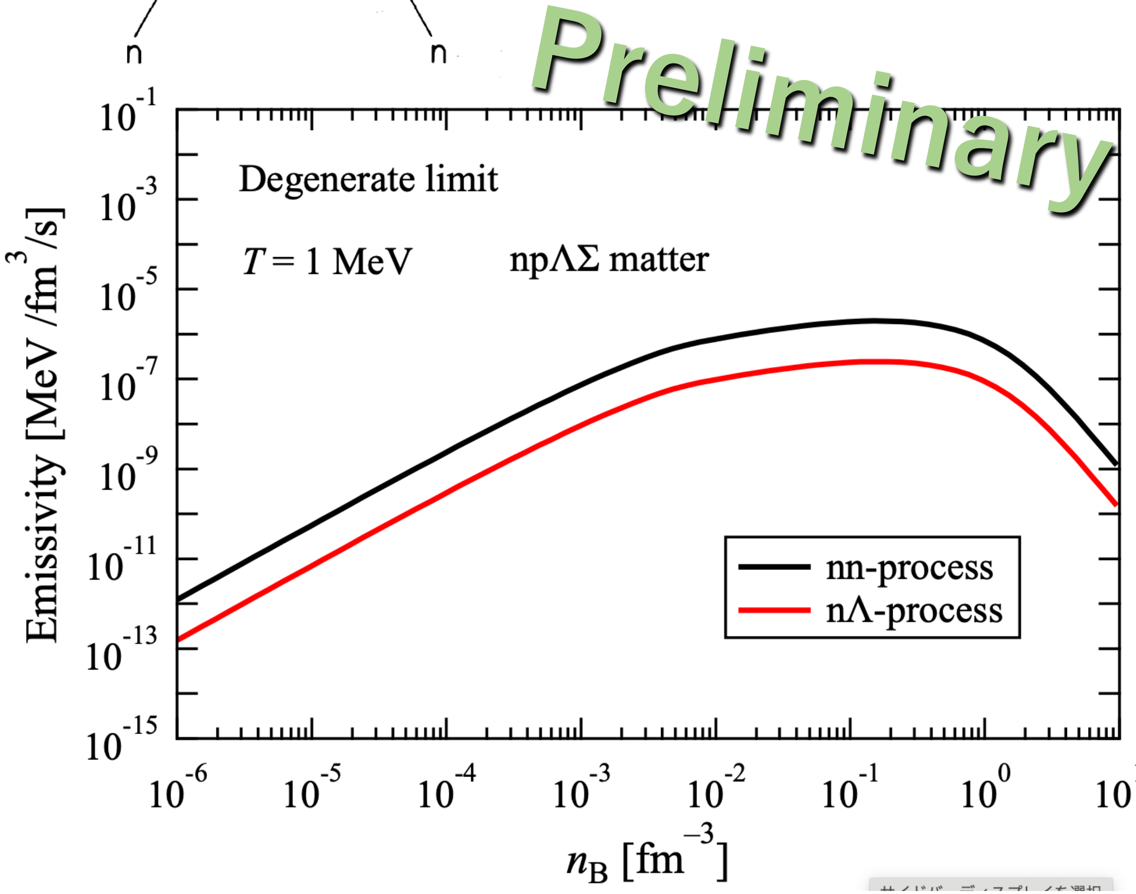
$$\frac{1}{N}\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2}\left(g_a^2(3-\cos\theta)S_a(q) + (1+\cos\theta)S_v(q)\right)$$



【Neutrino Bremsstrahlung process】



Astrophys. J. 316 (1987) 691.



Summary

We investigate the hyperon mixing effect using the EOS based on bare hyperon interactions with the variational method.

ΛΛ two-body Repulsion

- Repulsion strength is not enough to support the massive neutron stars.

Three-Baryon Repulsion

- ΛΛN and ΛΛΛ three-body forces affect on the maximum mass of neutron stars.

In hot dense matter

- Hyperons are expected to appear at the center of proto-neutron star during the cooling process.

Future Plans

- Taking into account mixing of other hyperons (Σ^0, Σ^+, Ξ^0, Ξ^-)
- Taking into account Neutrino-hyperon reaction in simulations