Role of Hyperon Interactions in Neutron Stars and Supernova Cores

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Outline

1：Introduction

2：Hyperon mixing in neutron star

3：Hyperon mixing in supernova matter

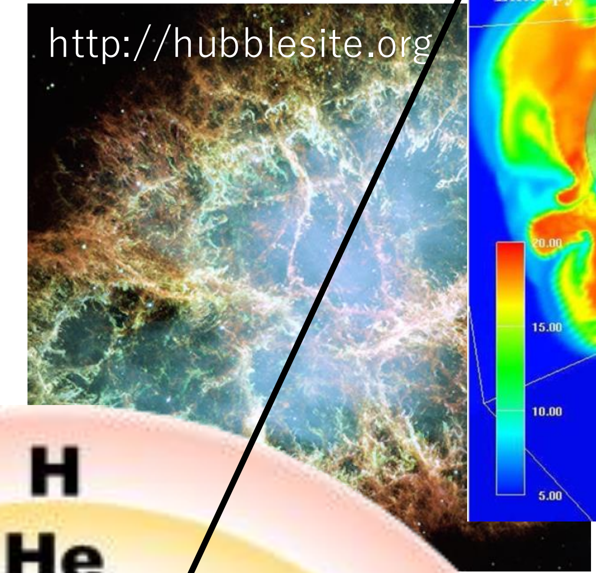
4: Future plan & Summary

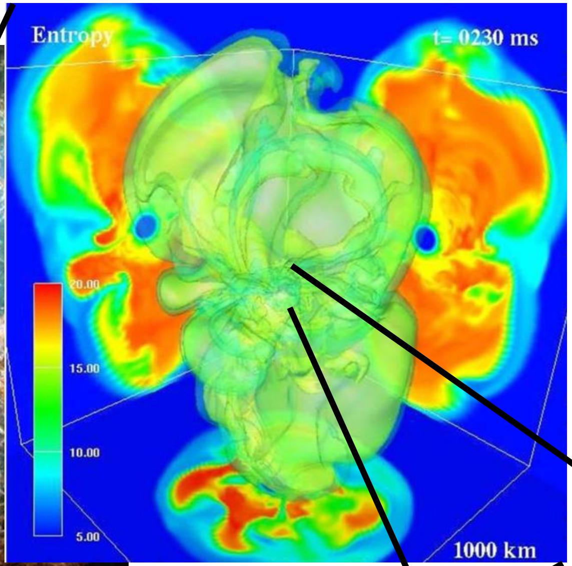
JLab Hypernuclear Collaboration Meeting 2025 @ Jefferson Lab, U.S., May 15, 2025

1. Introduction

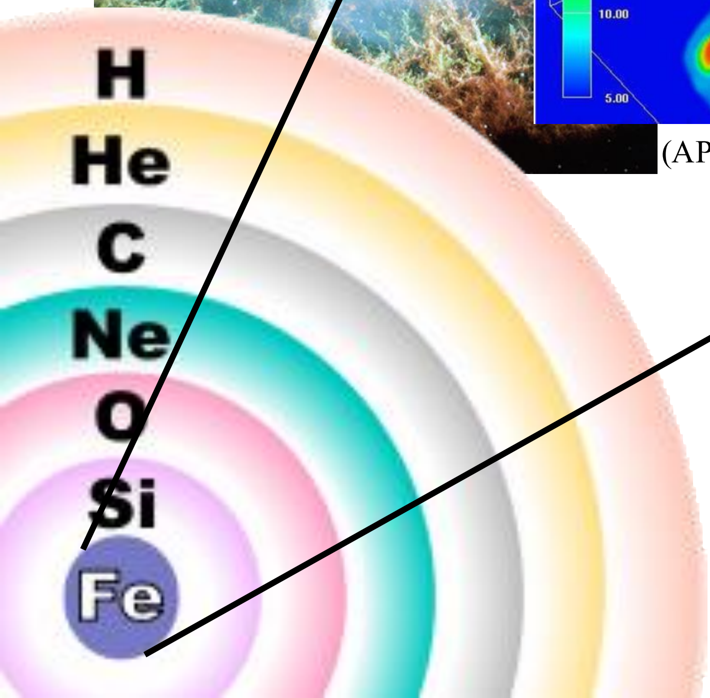
The nuclear equation of state (EOS) plays important roles for astrophysical studies.

Core-Collapse Supernovae

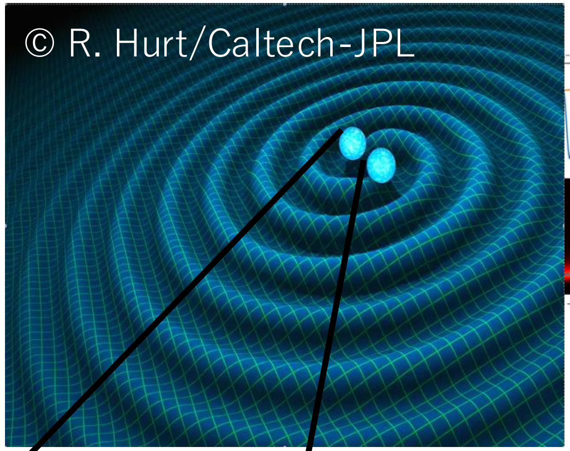


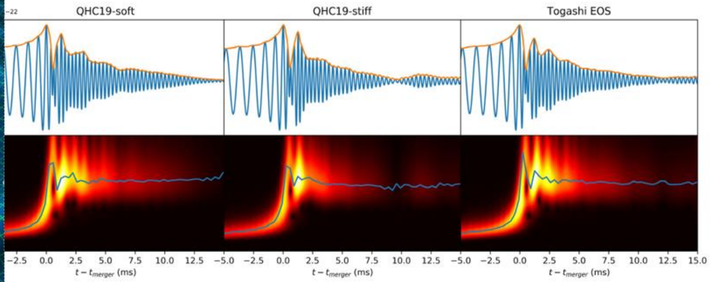


(APJ 786 (2014) 83)

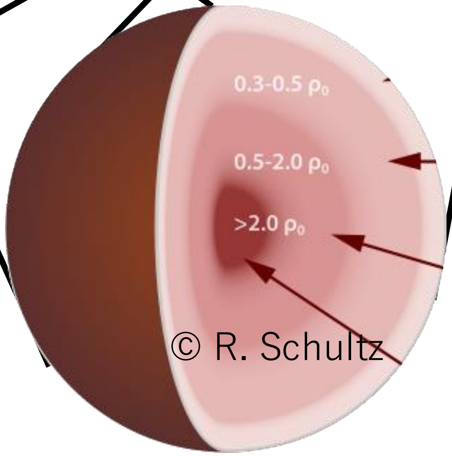


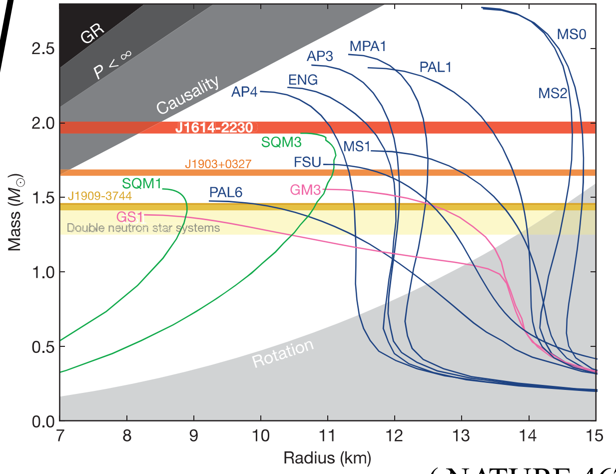
Neutron Star Mergers





(PRL 129 (2022) 181101)





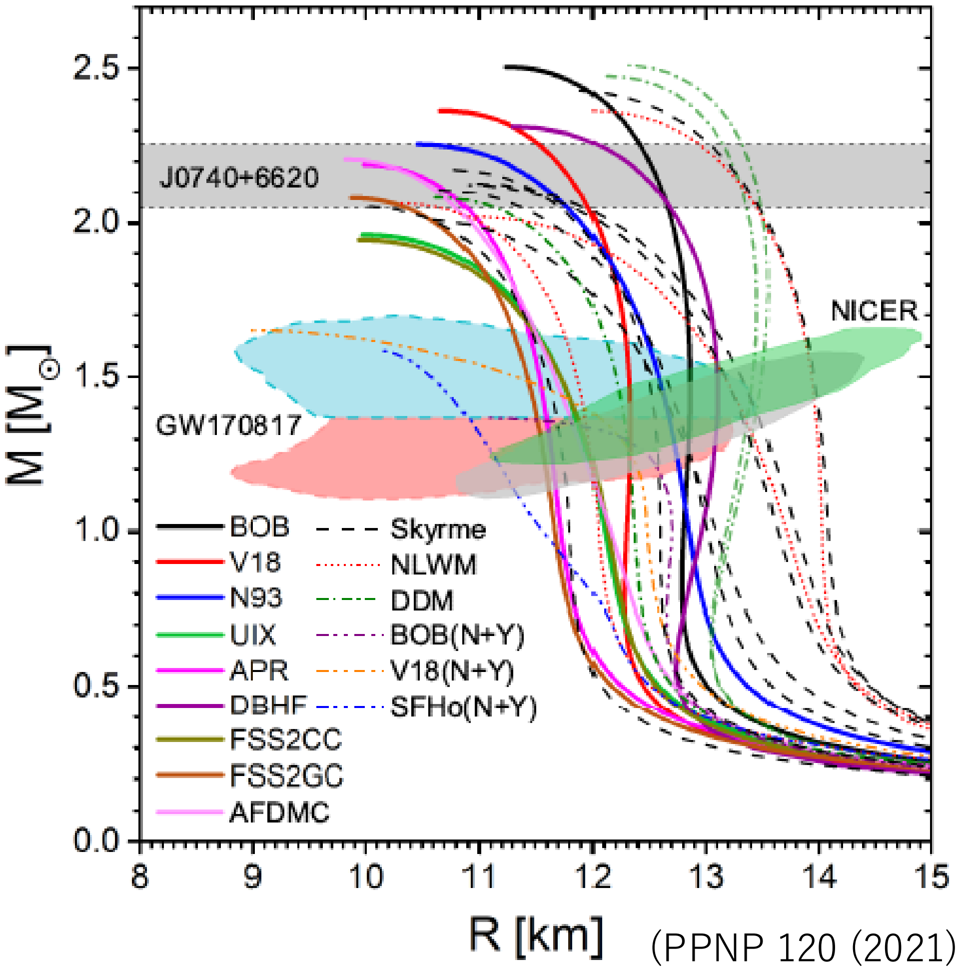
(NATURE 467 (2010) 1081)

Neutron Stars

Neutron Star Matter & Supernova Matter

Neutron Stars (NS)

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

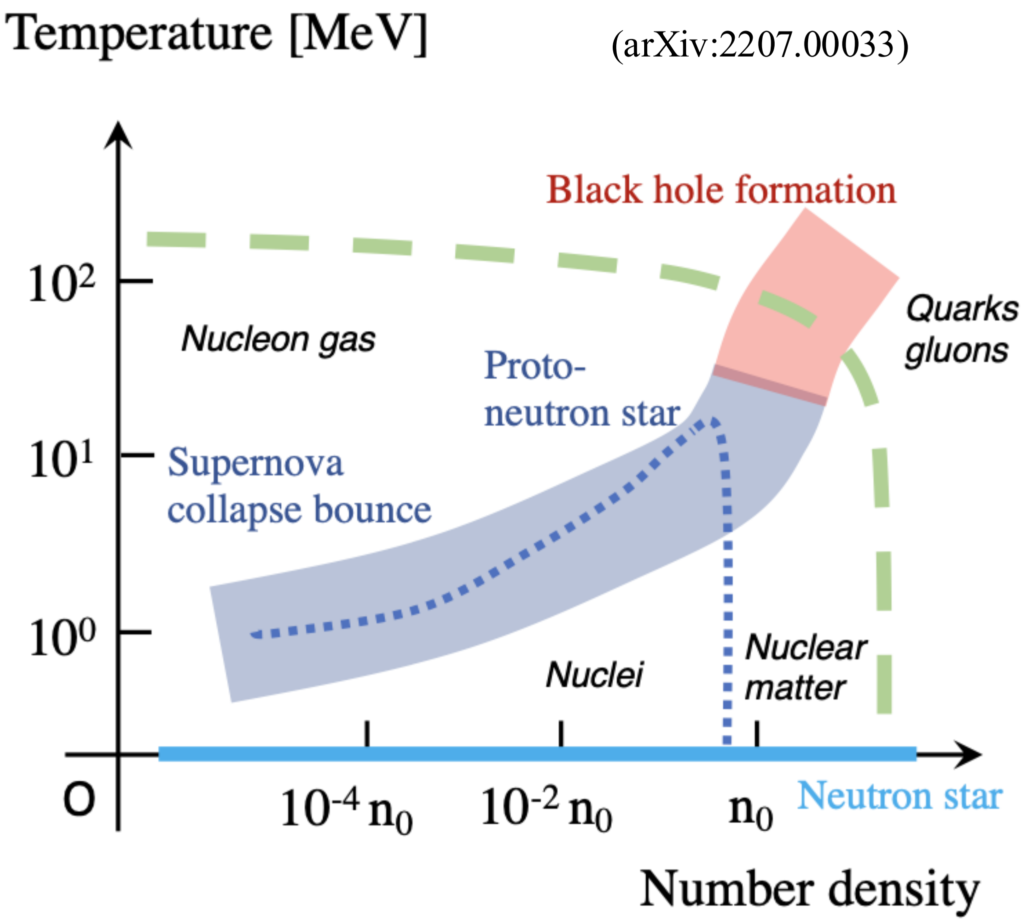


(PPNP 120 (2021) 103879)

Supernovae / NS mergers

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

(arXiv:2207.00033)



Nuclear Matter Theory for Equation of State

1. Analytically expressed function

- *e.g. Expansion around saturation density*

$$\frac{E}{A}(\rho,\beta) = E_0 + \frac{1}{2}K_0 x^2 + \frac{1}{6}Q_0 x^3 + \left(S_0 + Lx + \frac{1}{2}K_{\mathrm{sym}} x^2 + \frac{1}{6}Q_{\mathrm{sym}} x^3\right)\beta^2 + \dots$$

$$x = (\rho - \rho_0)/3\rho_0 \qquad \beta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$$

2. Mean field theory with effective nuclear interaction

- *Effective Hamiltonian & Slater determinant (simple product wave function)*

- Skyrme Hartree-Fock - Relativistic mean field theory

3. Many-body calculation with bare interaction

- *Realistic Hamiltonian & correlated wave function*

- Brueckner-Hartree-Fock - Variational method

- Correlated basis function - Quantum Monte Carlo method

Hyperon Matter Theory for Equation of State

1. Analytically expressed function

- Extend the functional expansion under some assumptions

e.g.) Hyperon symmetry energy S_Y

$$E(\rho, \delta_N, \delta_Y) = E(\rho, 0, 0) + S_N(\rho)\delta_N^2 + S_Y(\rho)\delta_Y^2 + \dots$$

2. Mean field theory with effective nuclear interaction

- Effective interactions in the nuclear medium need to be newly constructed using the experimental data on hypernuclei.

3. Many-body calculation with bare interaction

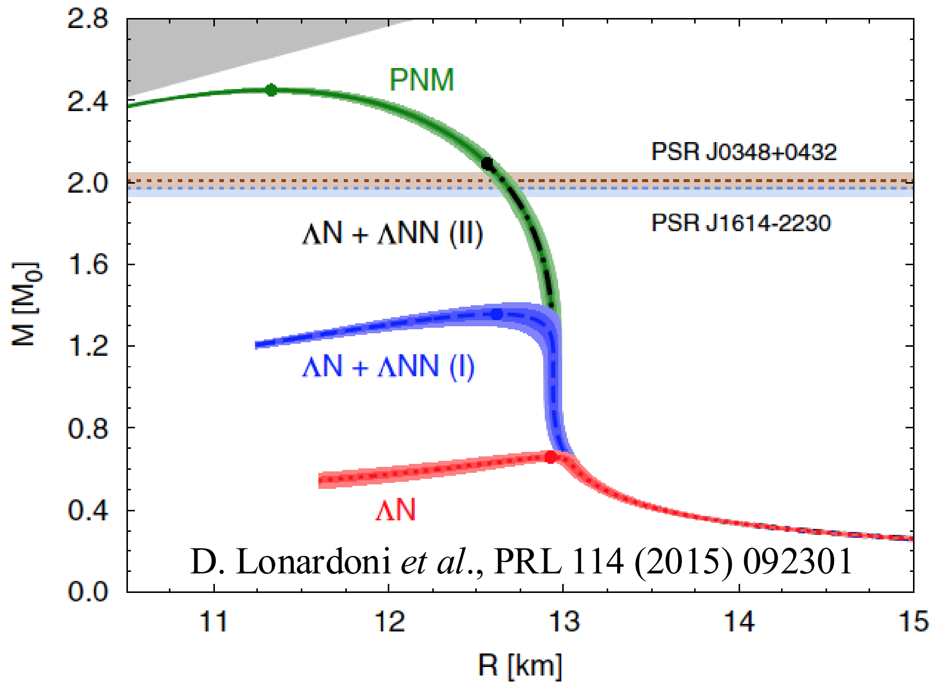
- **Bare interactions (two-body & three-body) are directly connected to the EOS, providing a clear link between baryon forces and matter properties.**

Hyperon Puzzle and Its Possible Solutions

Hyperon Puzzle

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

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



Possible Solutions of the Hyperon Puzzle

- **Hyperon-hyperon two-body repulsion**
- **Hyperonic three-body forces (⊄NN・⊄⊄N・⊄⊄⊄)**
- **Quark phase appearance (at densities below the hyperon threshold)**

Hot Topic these days

Hyperon Puzzle and Its Possible Solutions

Hyperon Puzzle

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

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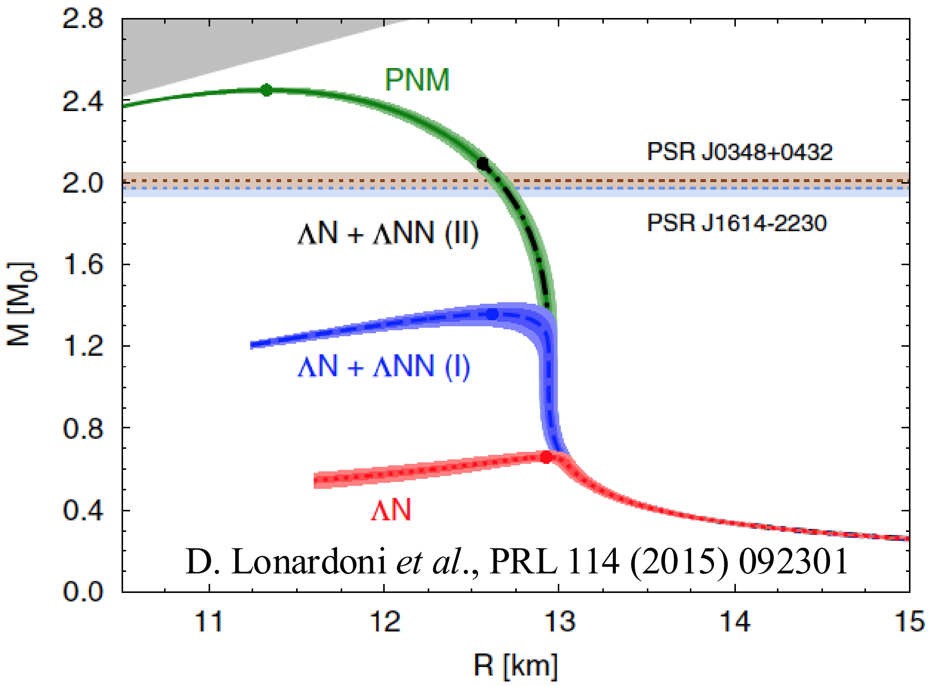


Possible Solutions of the Hyperon Puzzle

Need to clarify why hyperons are absent

- Hyperon-hyperon two-body repulsion
- Hyperonic three-body forces (⊄NN・⊄⊄N・⊄⊄⊄)

Hot Topic these days

- Quark phase appearance at densities below the hyperon threshold

Variational EOS for astrophysical simulations

<u>Variational EOS with realistic nuclear forces</u>

(**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 **<u>neutron stars</u>** and **<u>core-collapse supernovae</u>**.
- This EOS table is available on the web: `http://www.np.phys.waseda.ac.jp/EOS/`

Normal nuclear EOS dependence in core-collapse simulations is gradually being investigated.

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

2. Hyperon mixing in Neutron Star

Hamiltonian of Hyperonic Nuclear Matter

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

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*

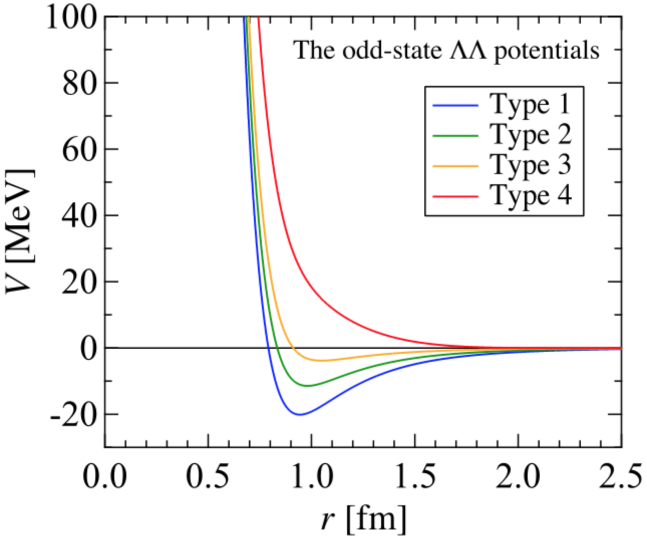
Uncertainty in Hyperon Interactions

I. $\Lambda\Lambda$ two-body interaction in odd-state

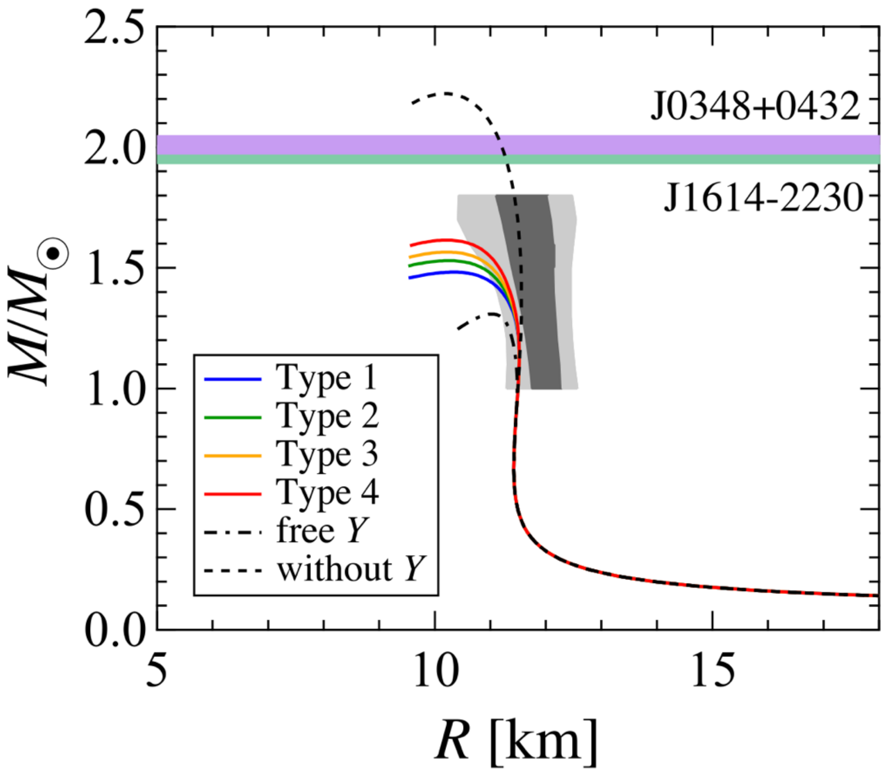
II. Hyperon three-body interactions in ΛNN, $\Lambda\Lambda N$, and $\Lambda\Lambda\Lambda$ (UIX pot. type)

ΛΛ repulsion effect on neutron star structure

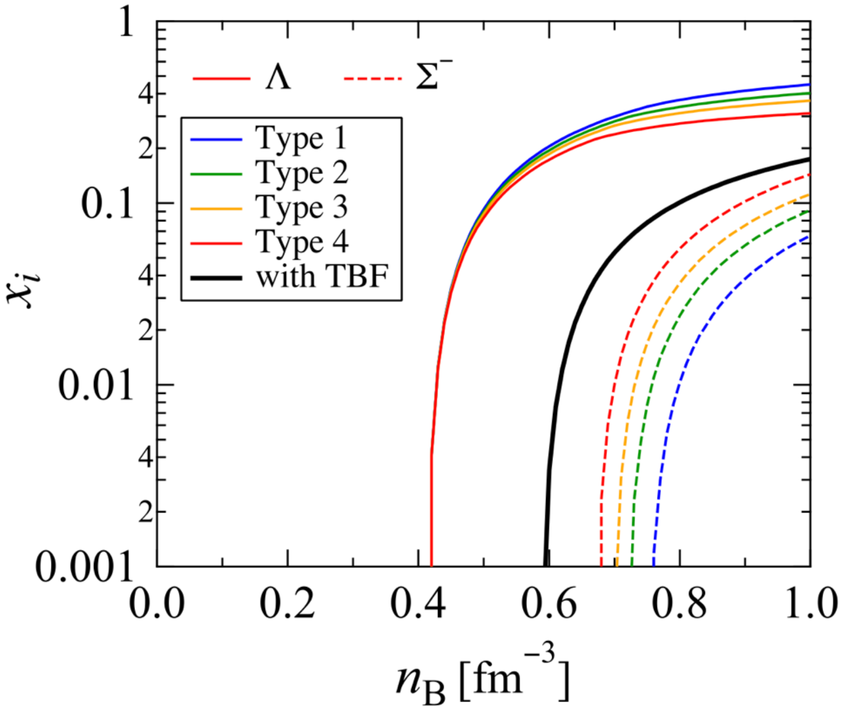
(**HT**, E.Hiyama, Y. Yamamoto, M. Takano, PRC 93 (2016) 035808)



Repulsive effect increases monotonically from Type 1 to 4.



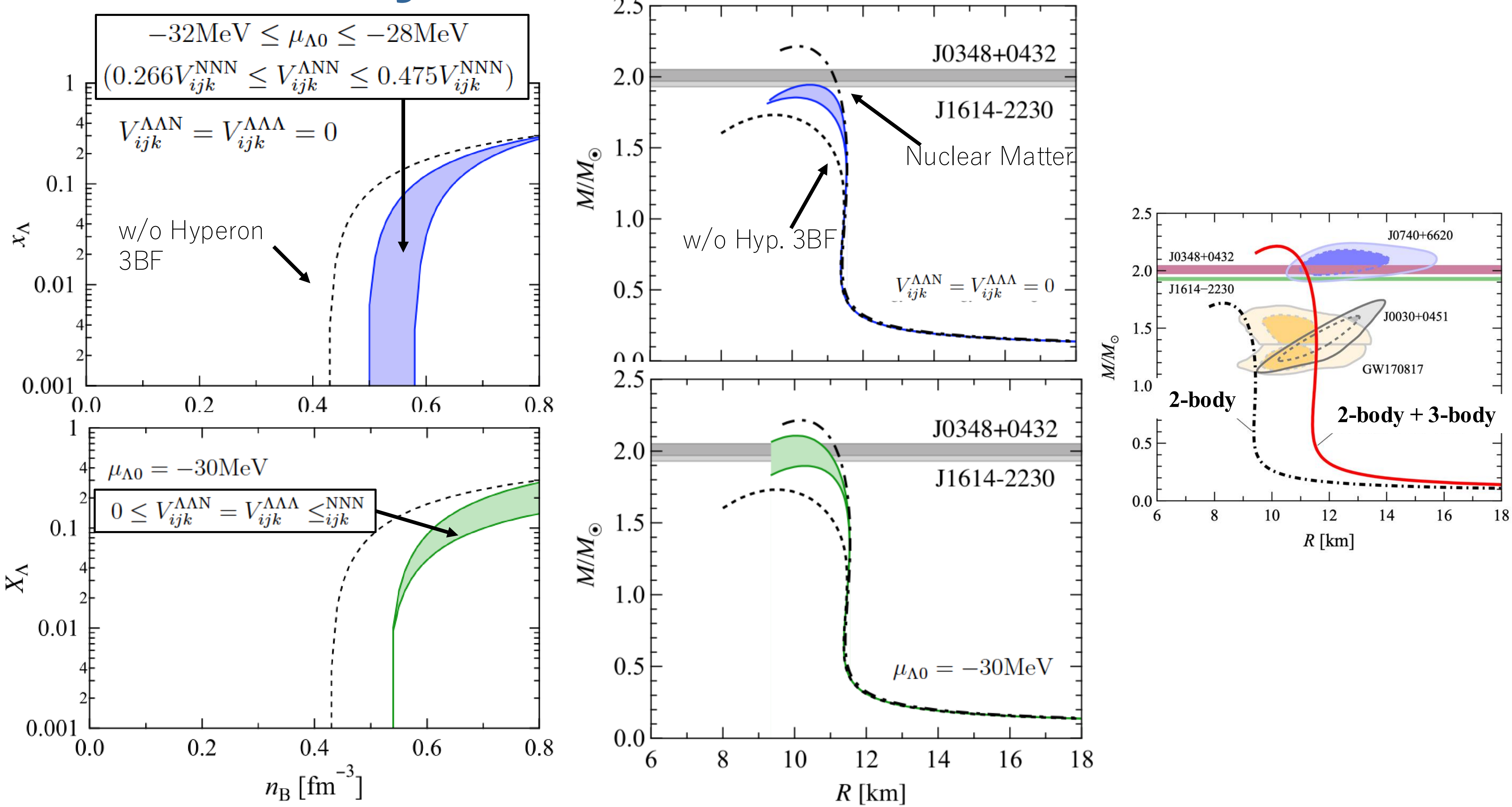
Mass radius relation of cold neutron stars



Hyperon fraction in neutron star

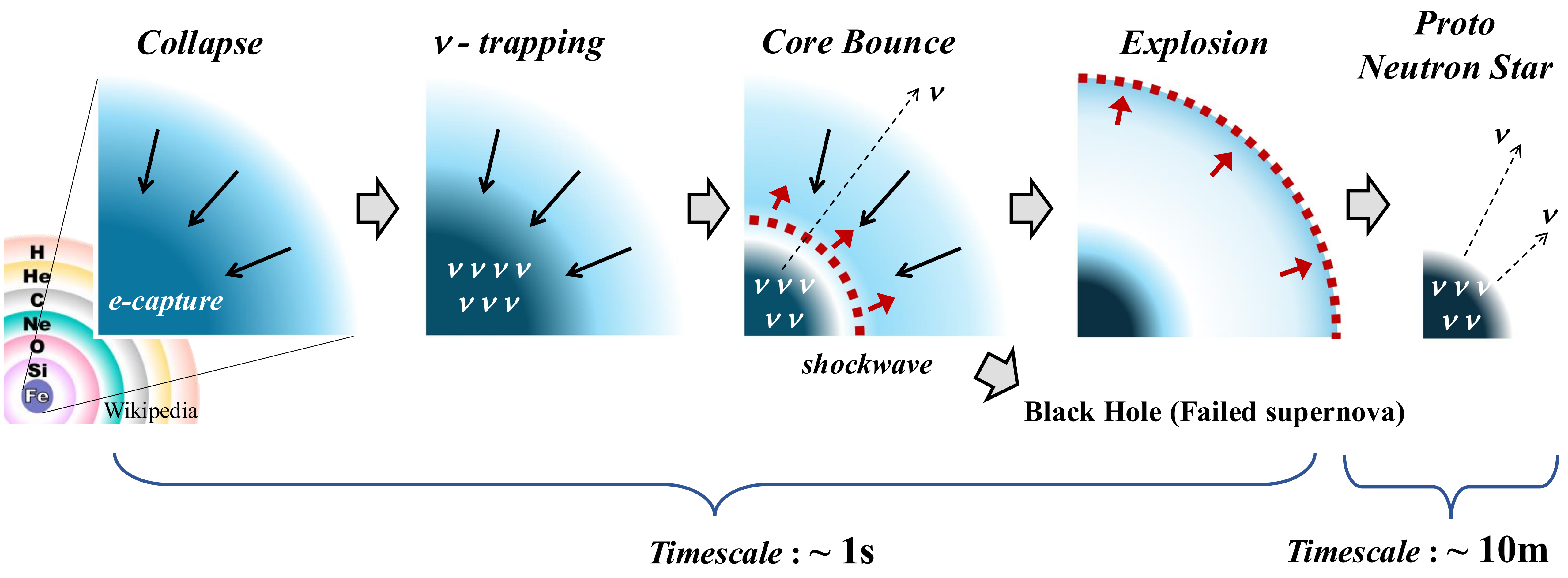
Repulsion strength is not enough to support the massive neutron stars.

Three-body effects on neutron star structure



3. Hyperon mixing in supernova matter

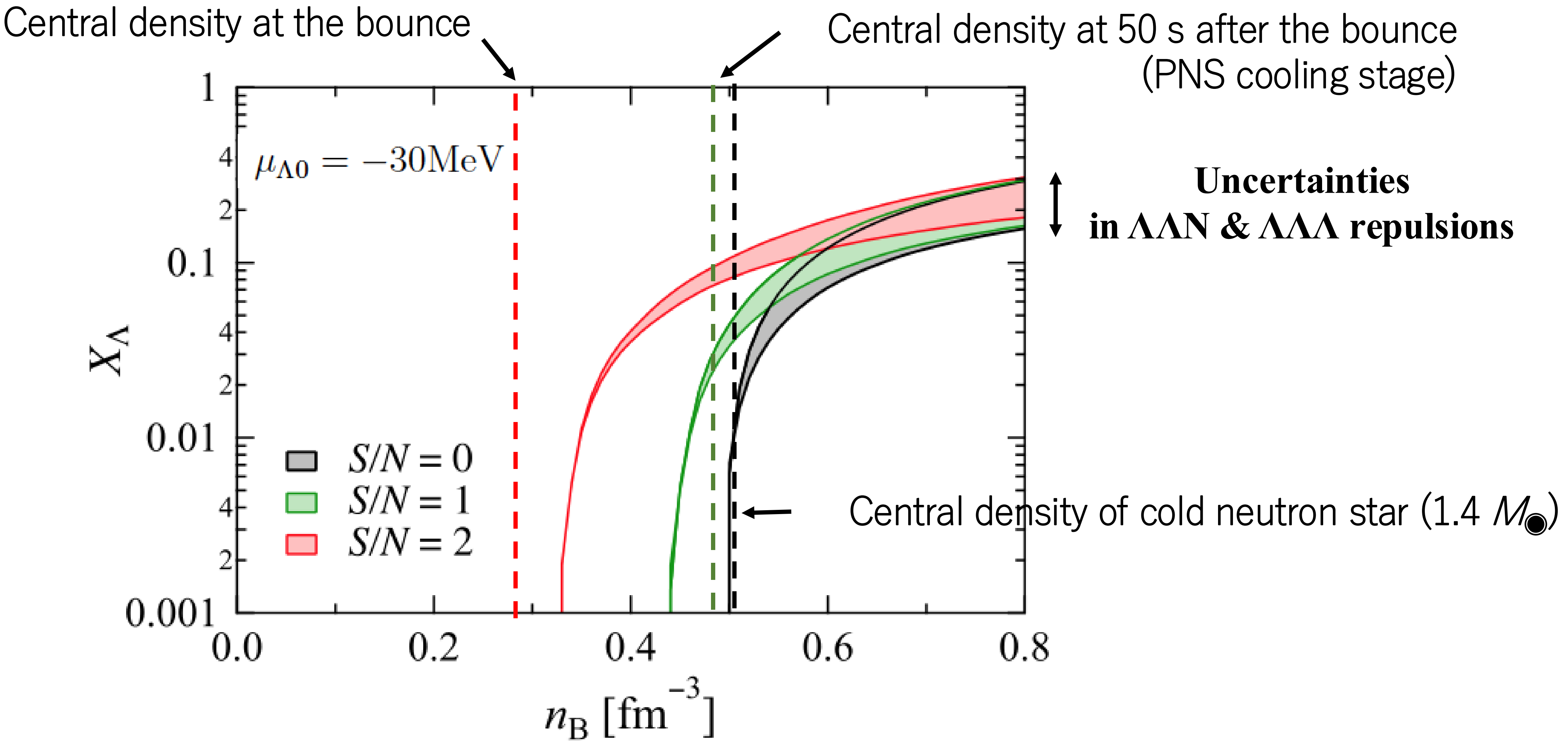
Core-collapse mechanism of massive stars



Hyperon Fraction in Supernova Matter

Supernova matter

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

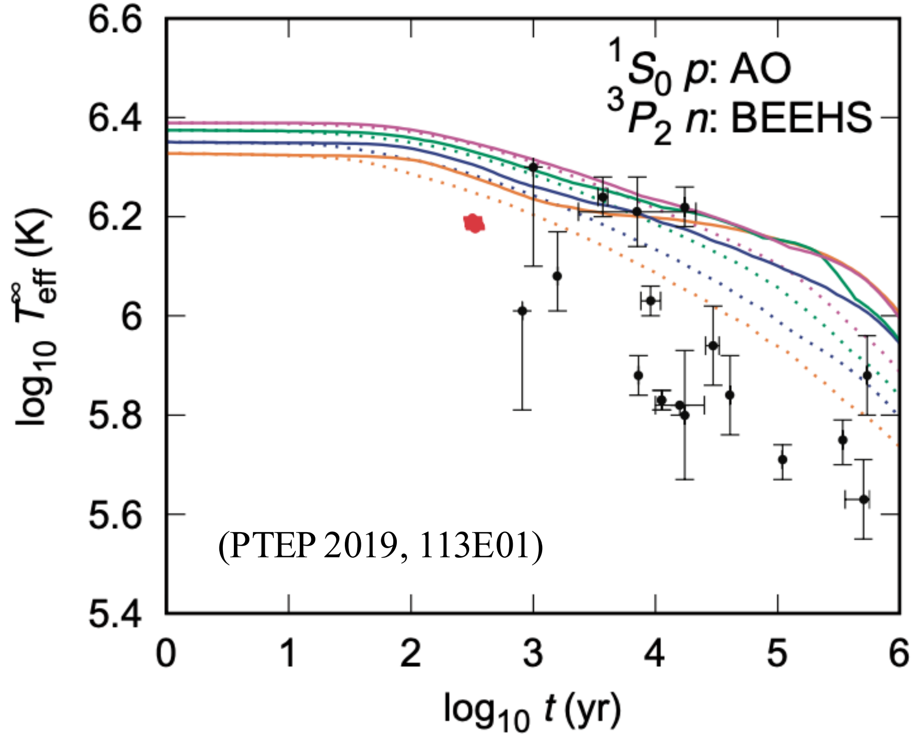


4. Next Steps in Hyperon Matter Study

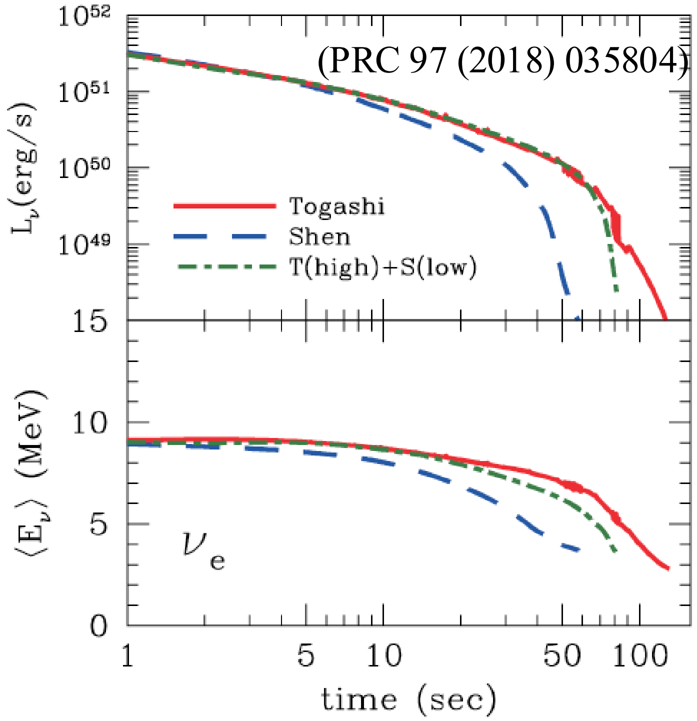
Weak Reaction Rates in nuclear medium should also be provided by nuclear physics.

→ Key ingredient for emitted neutrino light curves

Neutron Star Cooling



Core-Collapse Supernovae



In our simulations

EOS: Hyperon effects included

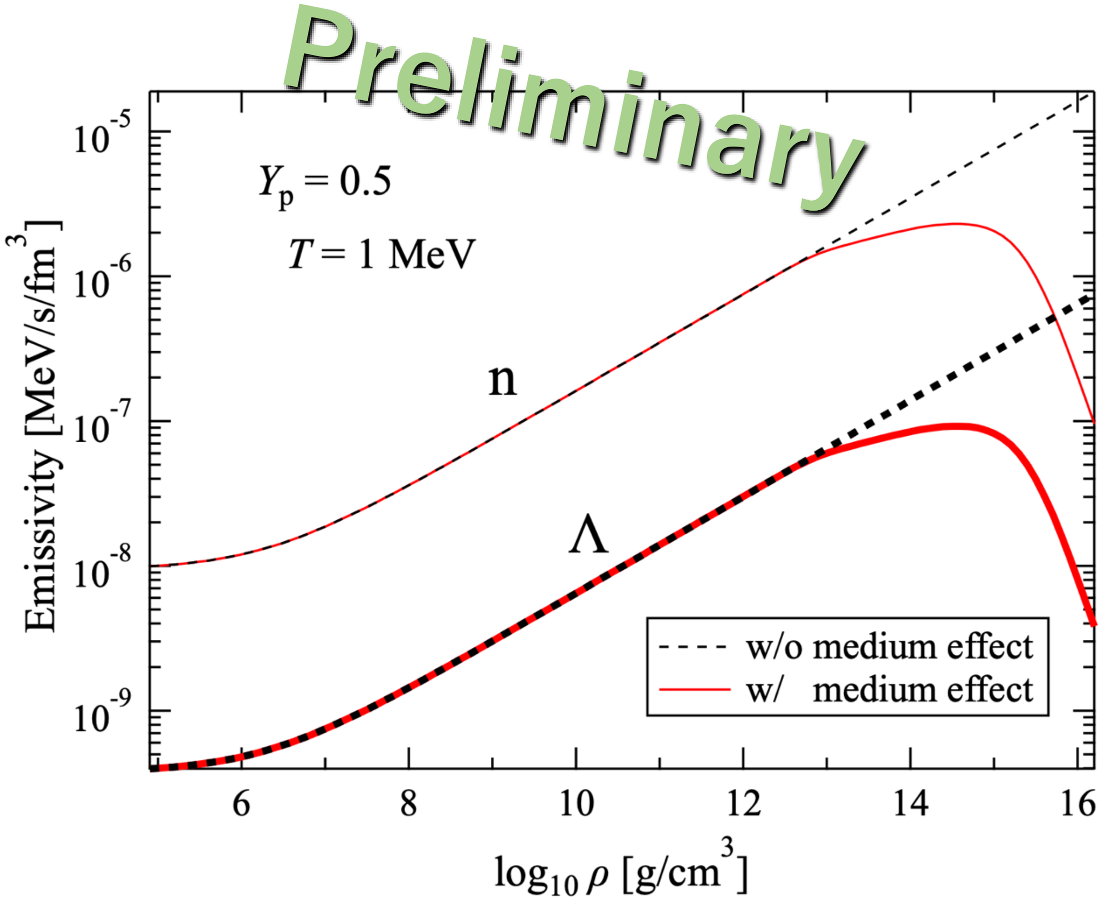
Weak reaction rate: Hyperon effects neglected

Reaction rates for core-collapse simulations

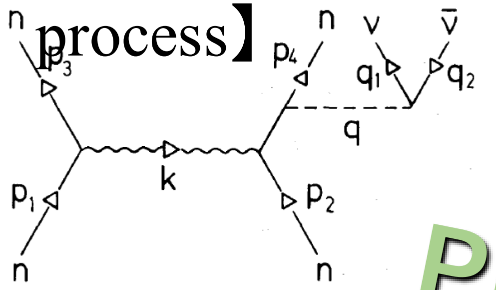
【Charged current reaction on baryons】

$$\Lambda \rightarrow p + e^- + \bar{\nu}_e$$

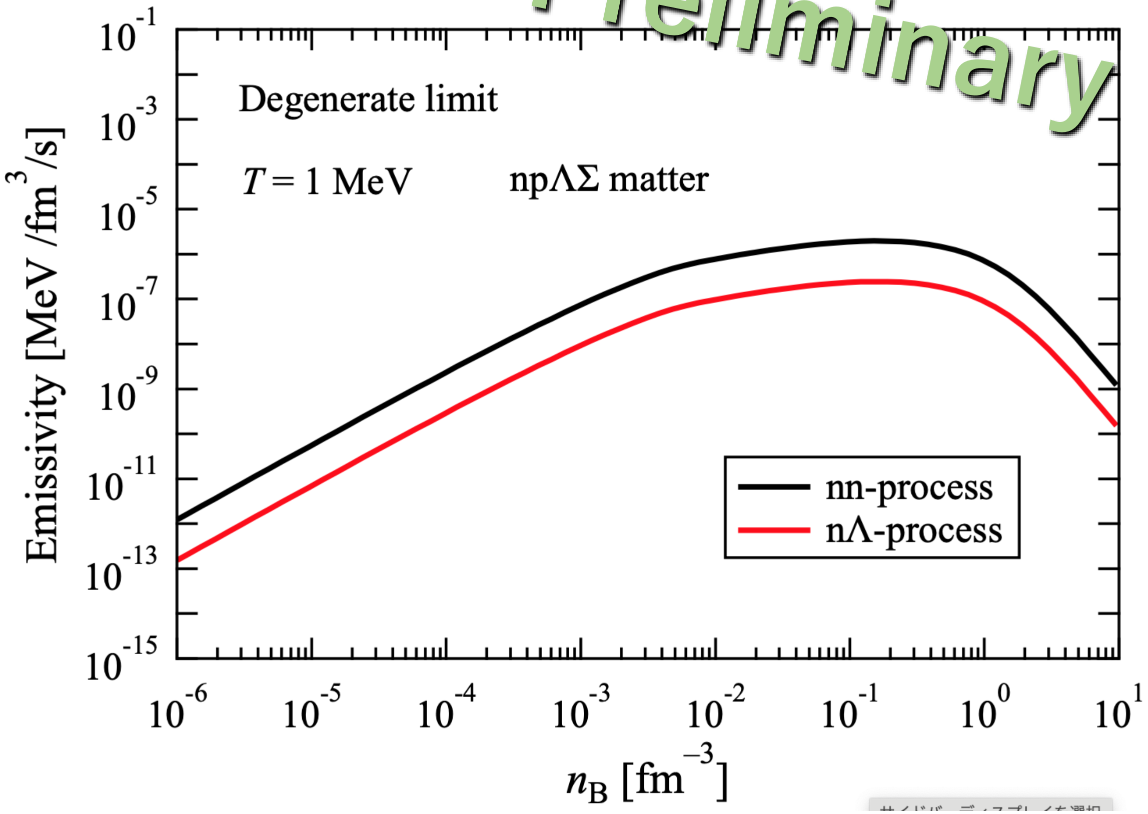
$$p + e^- \rightarrow \Lambda + \nu_e$$



【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

- ΛNN three-body force is affect on the onset density of hyperon in NS & supernova core.
- ΛΛN and ΛΛΛ three-body forces affect on the maximum mass of neutron stars.

Hypernuclear experiments are essential to improve our understanding of dense astrophysical phenomena!