Hyperon mixing in astrophysical compact objects

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Outline

1：Introduction

2：Hyperon EOS with the variational method

3：Applications to astrophysical compact objects

Workshop PPPY-Λ 2021 @ Sendai, December 10th, 2021

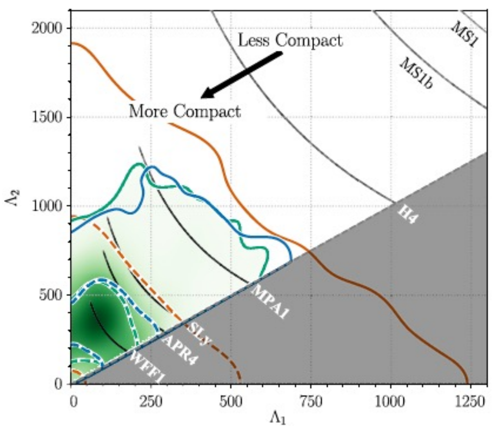
Introduction

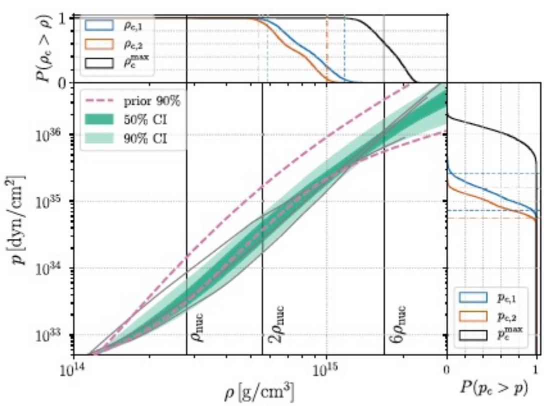
1. Massive Neutron Stars

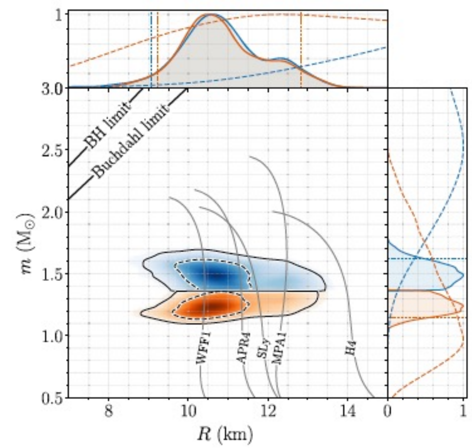
- PSR J1614 – 2230 $(M = 1.928 \pm 0.017\ M_{\odot})$ (Nature 467 (2010) 1081, APJ 832 (2016) 167)
- PSR J0348 + 0432 $(M = 2.01 \pm 0.04\ M_{\odot})$ (Science 340 (2013) 1233232)
- PSR J0740 + 6620 $(M = 2.14\ ^{+0.10}_{-0.09}\ M_{\odot})$ (Nat. Astron. 4 (2020) 72)

2. Gravitational Wave from NS-NS merger

(PRL 119 (2017) 161101,
PRL 121 (2018) 161101))







3. NICER (Neutron star Interior Composition ExploreR)

- PSR J0030 + 0451 $(M = 1.44\ ^{+0.15}_{-0.14}\ M_{\odot},\ R = 13.02\ ^{+1.24}_{-1.06}\ \text{km})$ (Miller et al., APJ 887 (2019) L24)

  $(M = 1.34\ ^{+0.15}_{-0.16}\ M_{\odot},\ R = 12.71\ ^{+1.14}_{-1.19}\ \text{km})$ (Riley et al., APJ 887 (2019) L21)

- PSR J0740 + 6620 $(M = 2.08\ ^{+0.07}_{-0.07}\ M_{\odot},\ R = 13.7\ ^{+2.6}_{-1.5}\ \text{km})$ (Miller et al., APJ 918 (2021) L28)

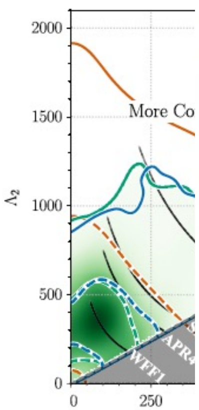
  $(M = 2.072\ ^{+0.067}_{-0.066}\ M_{\odot},\ R = 12.39\ ^{+1.30}_{-0.98}\ \text{km})$ (Riley et al., APJ 918 (2021) L27)

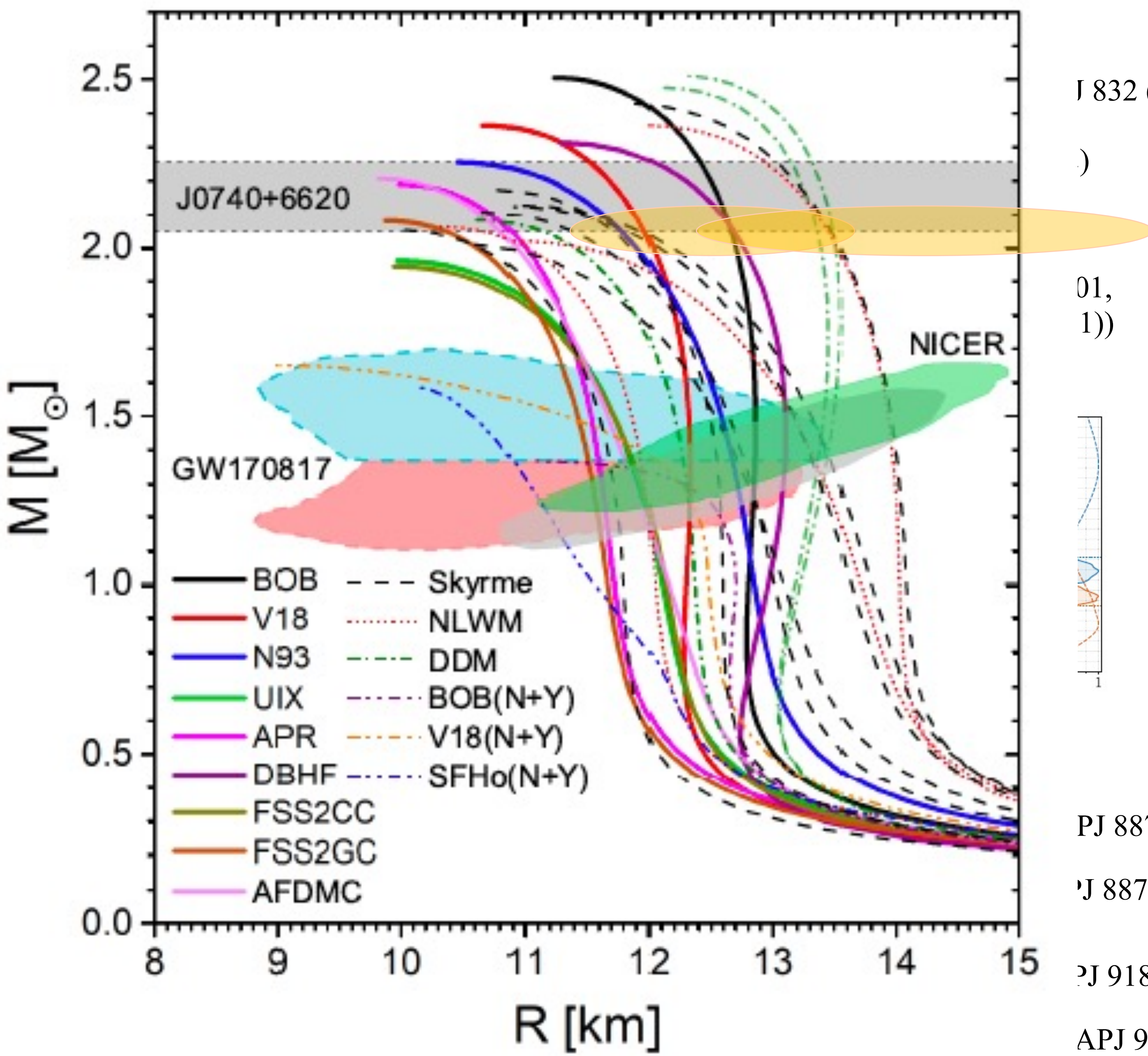
Introduction

1. Massi

- PSR J 832 (2016) 167)
- PSR)
- PSR

2. Gravi 01, 1))

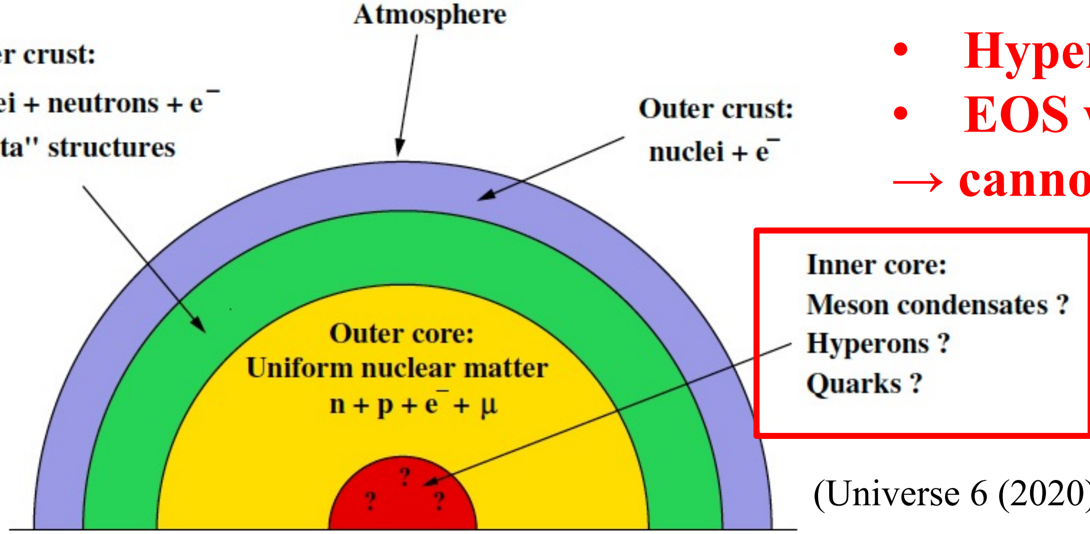




3. NICE

- PSR JC PJ 887 (2019) L24)
  PJ 887 (2019) L21)
- PSR JC PJ 918 (2021) L28)
  APJ 918 (2021) L27)

Hyperon Puzzle



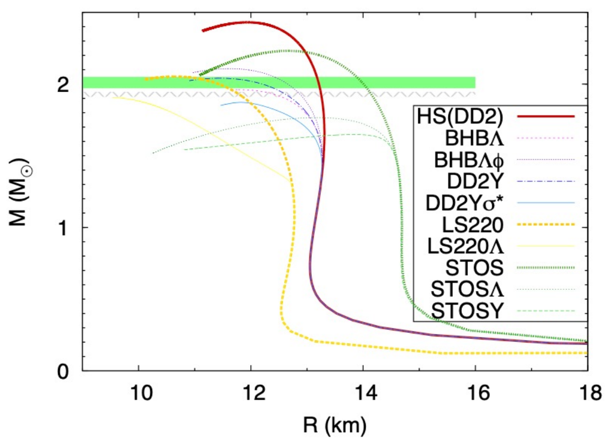
(Universe 6 (2020) 119)

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

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

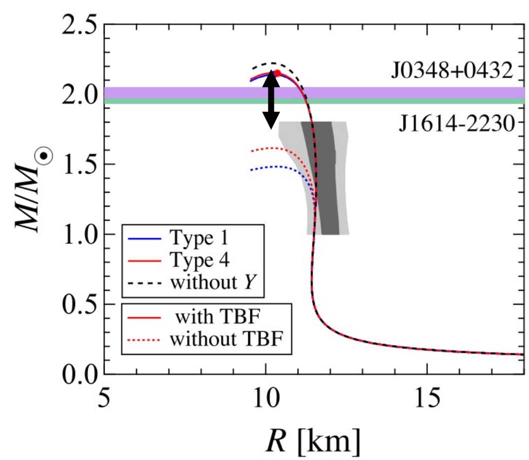
Possible Solutions of the Hyperon Puzzle

(1) Hyperon-hyperon repulsion (RMF theory)



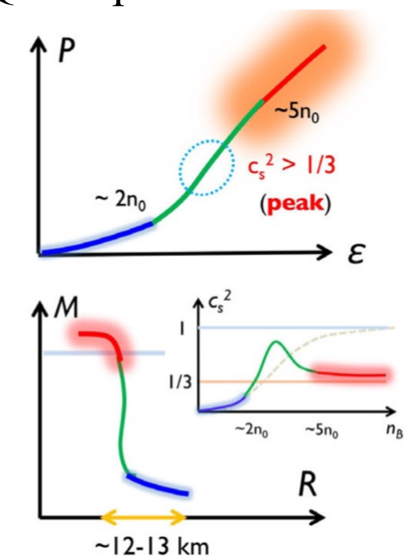
(PRC 96 (2017) 045806)

(2) Hyperonic three-body forces (Microscopic theory)



(PRC 93 (2016) 035808)

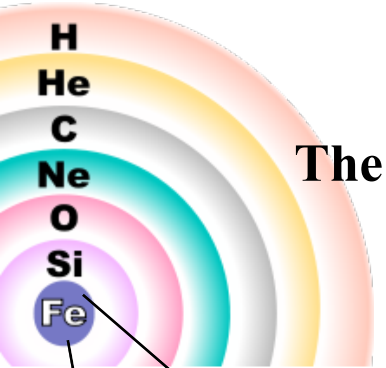
(3) Quark phase transition



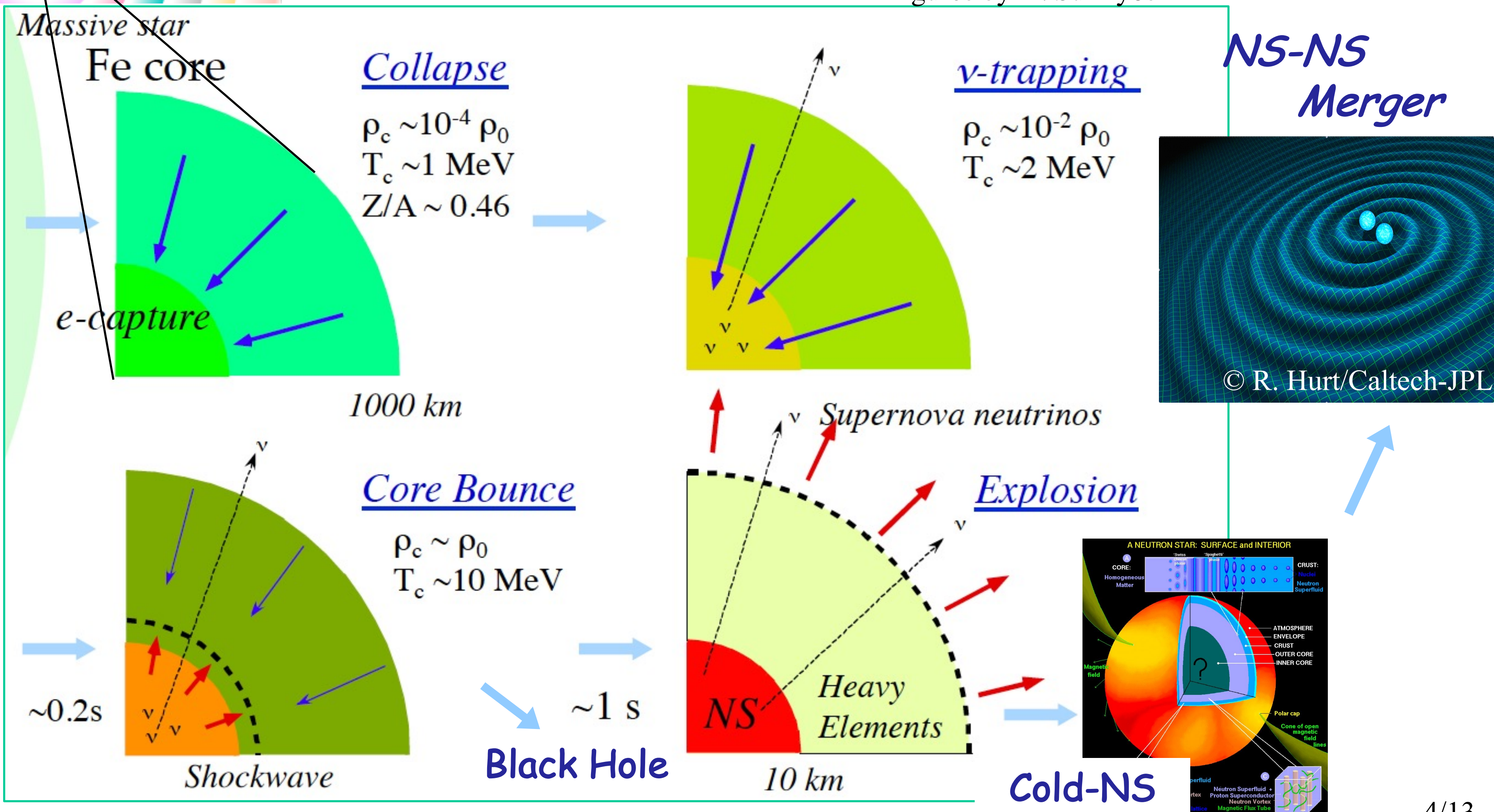
(PRD 104 (2021) 063036)

Core-collapse mechanism

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



Figures by K. Sumiyoshi



General purpose EOS for astrophysical simulations

- EOS should provide thermodynamic quantities in the wide ranges.

- Temperature T : $0 \le T \le 400$ MeV
- Density ρ : $10^{5.1} \le \rho_B \le 10^{16.0}$g/cm^3
- Proton fraction Y_p : $0 \le Y_p \le 0.65$

Currently existing general purpose EOSs with hyperons

- **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)
- **SFH EOS with Λ, Σ, Ξ [M_{max} = 1.98 $M_\odot$]** (M. Fortin et al., PASA 35 (2018) e044)

There exist only phenomenological hyperon EOSs applicable to the dynamical simulations of the astrophysical phenomena.

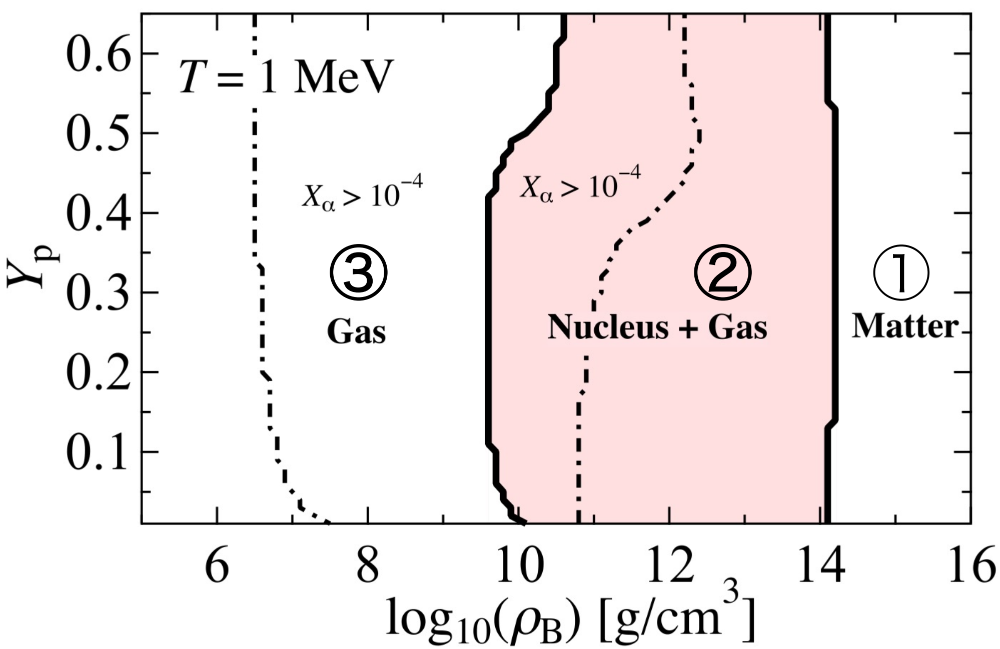
Extension of the Variational EOS Table

Nuclear EOS with realistic nuclear forces

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

- This is **the ONLY microscopic nuclear EOS** for astrophysical simulations based on realistic nuclear forces (AV18 + UIX).

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



Phase diagram of hot dense natter

① Uniform liquid phase (n, p, Λ)
- Variational method with hyperon

② Non-uniform phase (n, p, A, α)
- Thomas-Fermi calculation

③ Uniform gas phase (n, p, Λ, α)
- Variational method with hyperon

2. Hyperon EOS with the variational method

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

$V_{ij}^{\Lambda N}$, $V_{ij}^{\Lambda\Lambda}$: 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*

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

- *Repulsive part of the UIX pot. is employed*

– ΛNN: Strength parameter is determined so that $\mu_{\Lambda 0} = -30\text{MeV}$
– ΛΛN and ΛΛΛ: Strength parameters are taken to be free parameters.

Expectation value of the Hamiltonian

Jastrow wave function

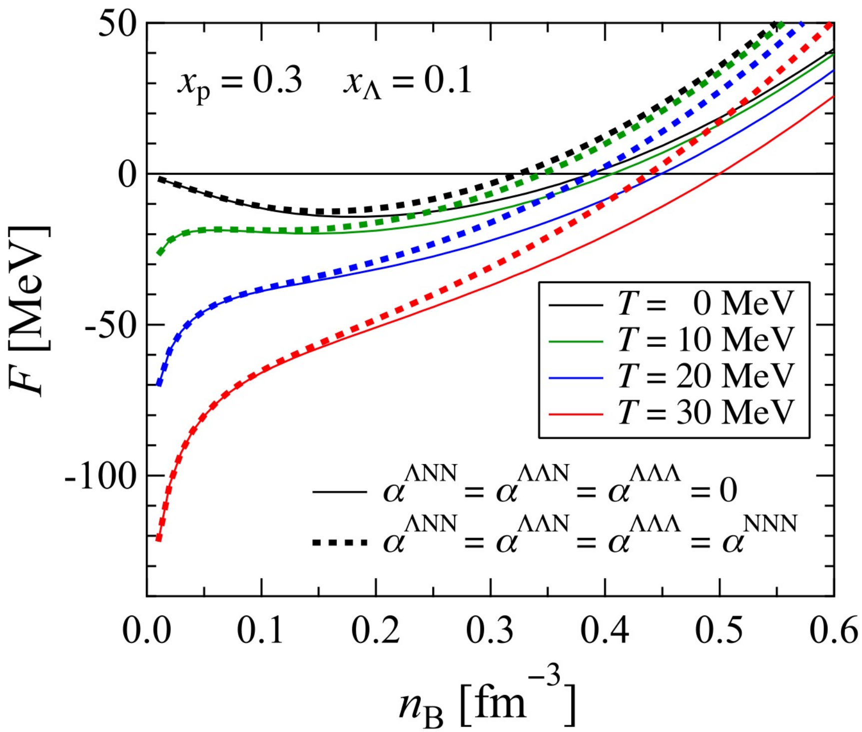
$$\Psi = \mathrm{Sym}\left[\prod_{i<j} f_{ij}\right]\Phi_{\mathrm{F}}$$

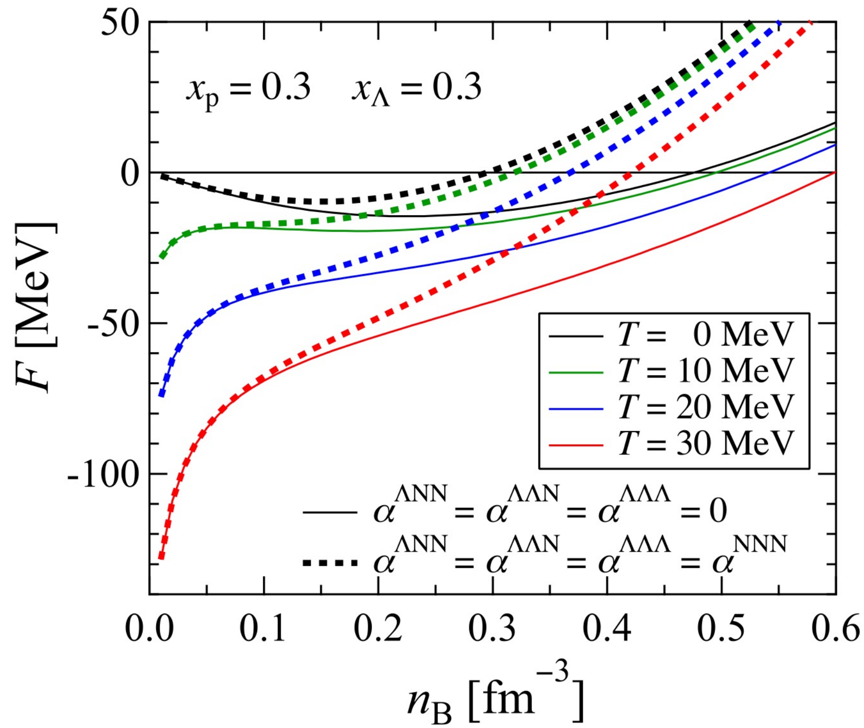
Φ_{F}: The Fermi-gas wave function

Correlation function

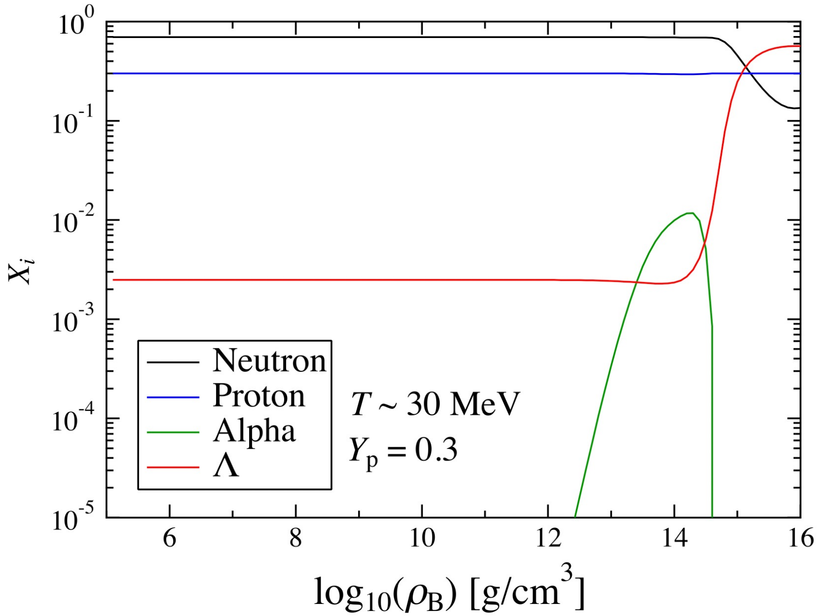
$$f_{ij} = \sum_{\mu,p,s}\left[f^{\mu}_{\mathrm{C}ps}(r_{ij}) + s f^{\mu}_{\mathrm{T}p}(r_{ij}) S_{\mathrm{T}ij} + s f^{\mu}_{\mathrm{SO}p}(r_{ij})(\boldsymbol{L}_{ij}\cdot\boldsymbol{s})\right] P^{\mu}_{psij}$$

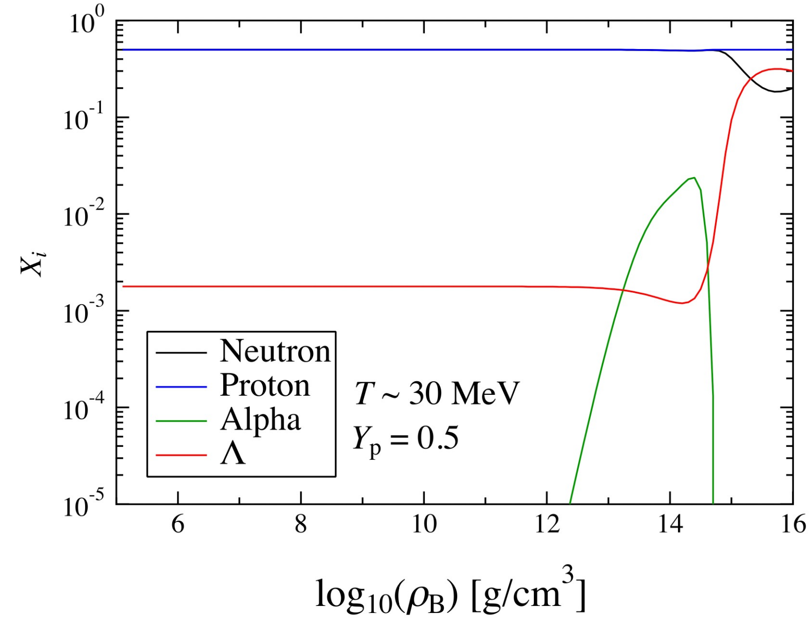
p: parity s: two-particle total spin μ: particle pair

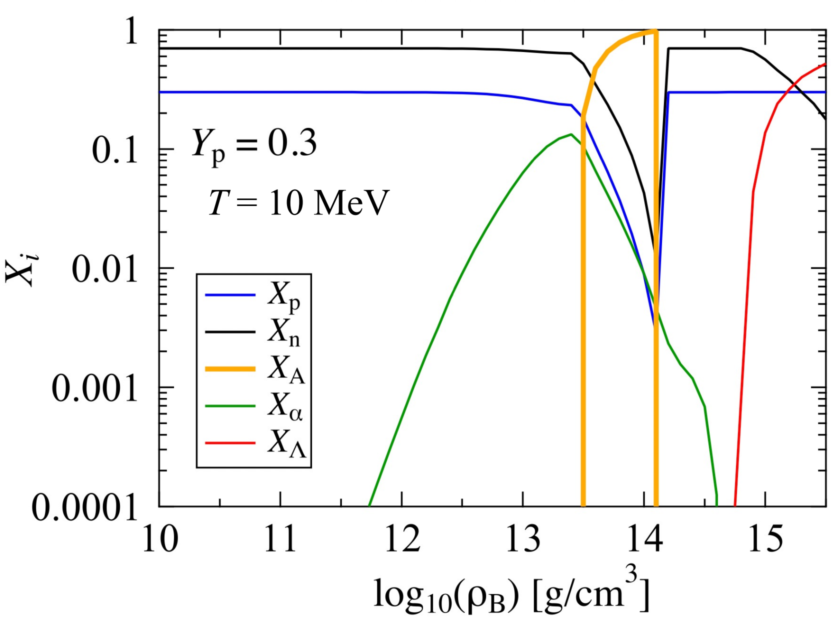


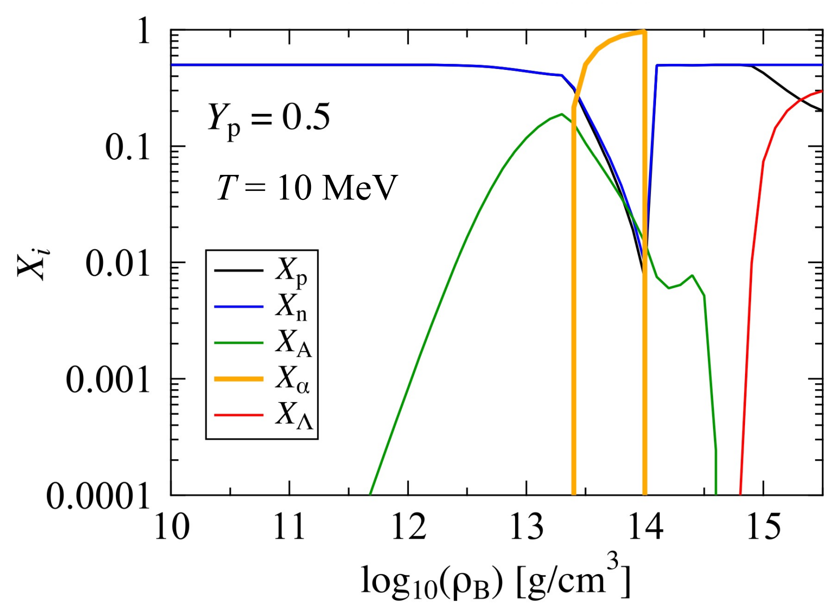


Particle Composition in Hot Dense Matter

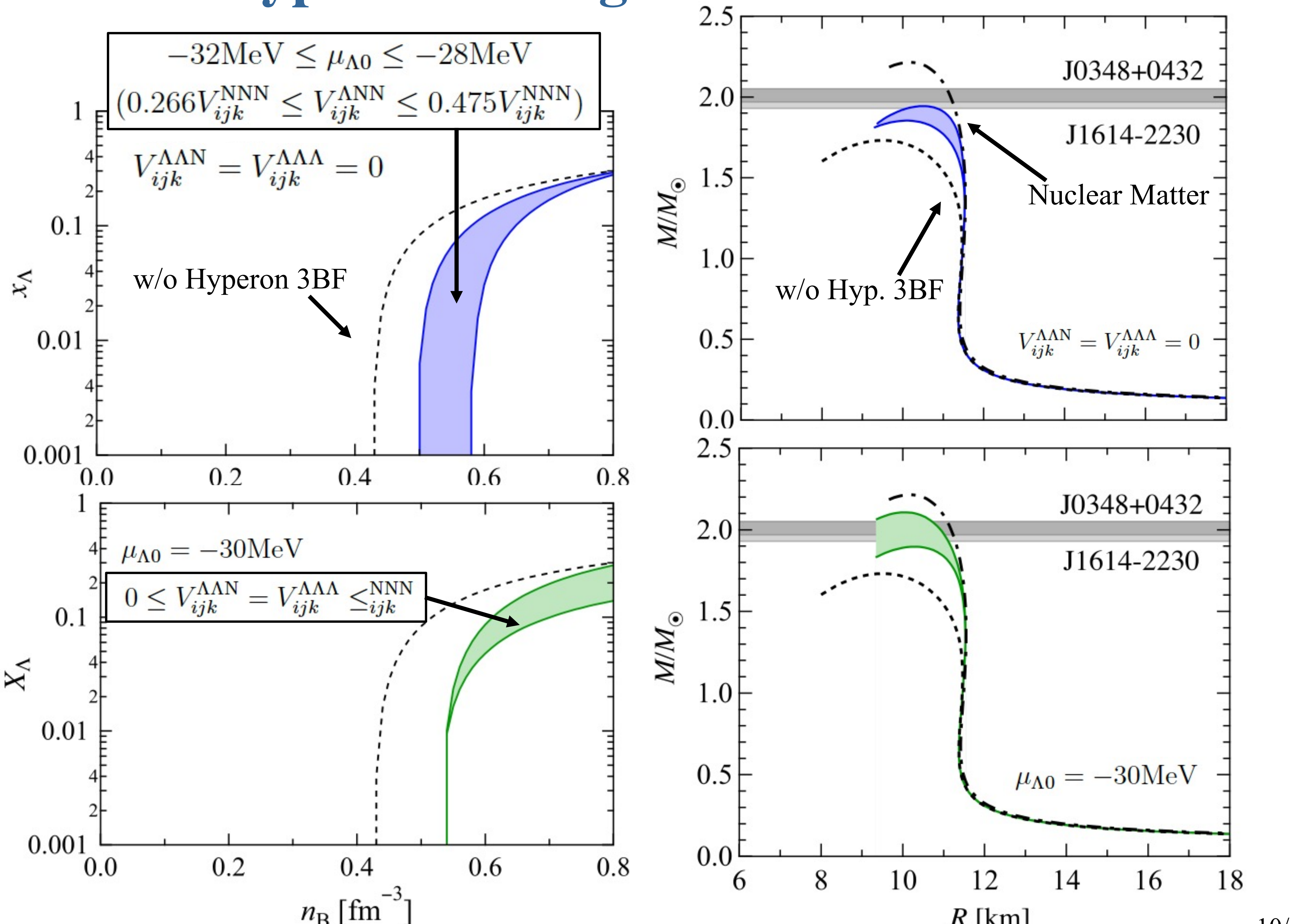








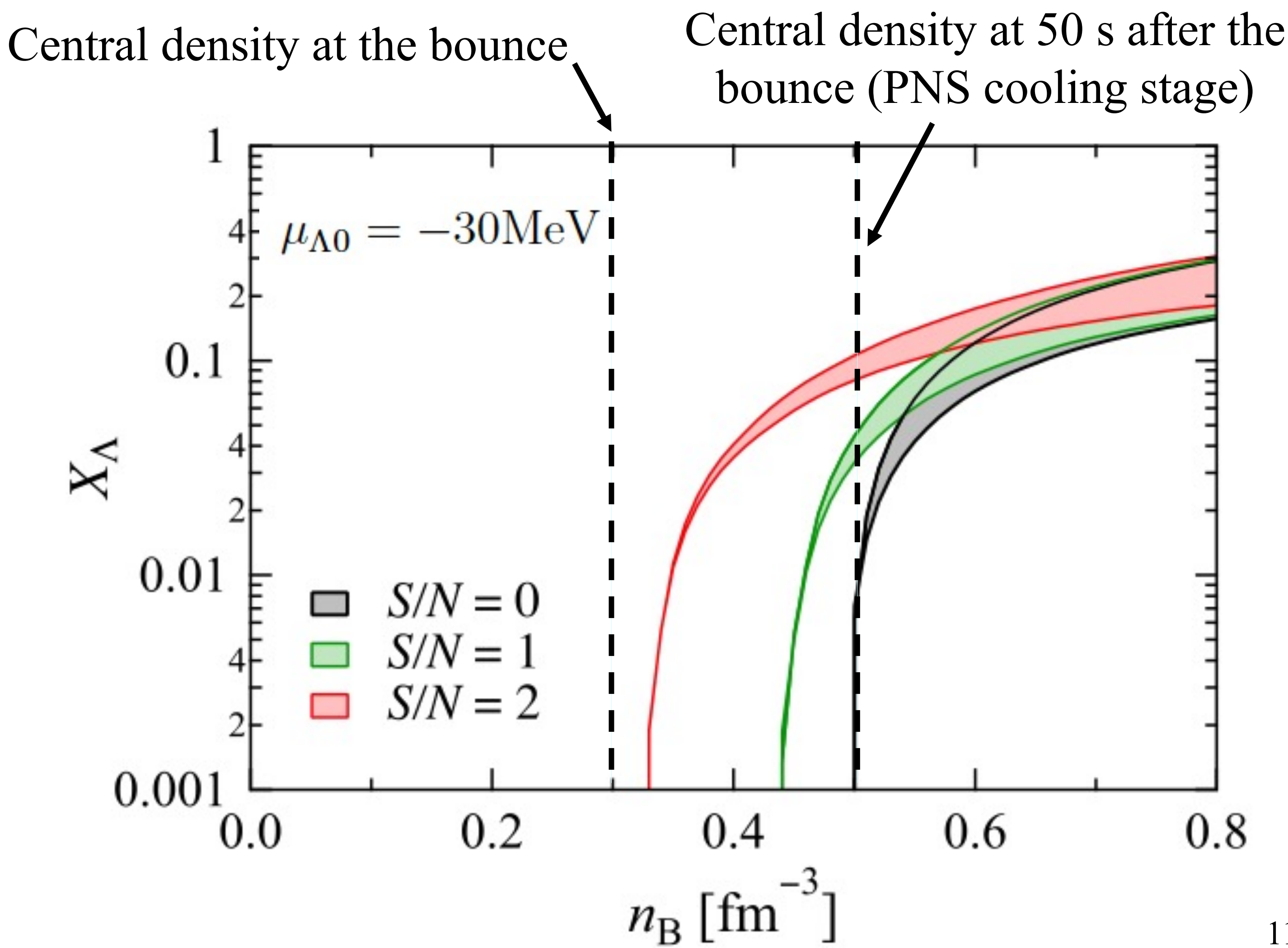
3-1. Hyperon mixing in neutron-star matter



3-2. Hyperon mixing in supernova matter

Supernova matter

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



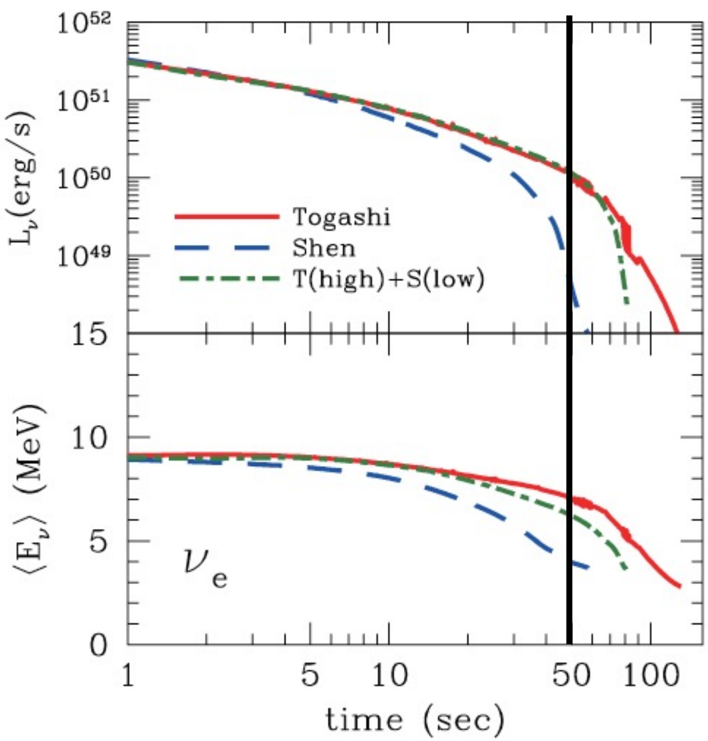
3-2. Hyperon mixing in supernova matter

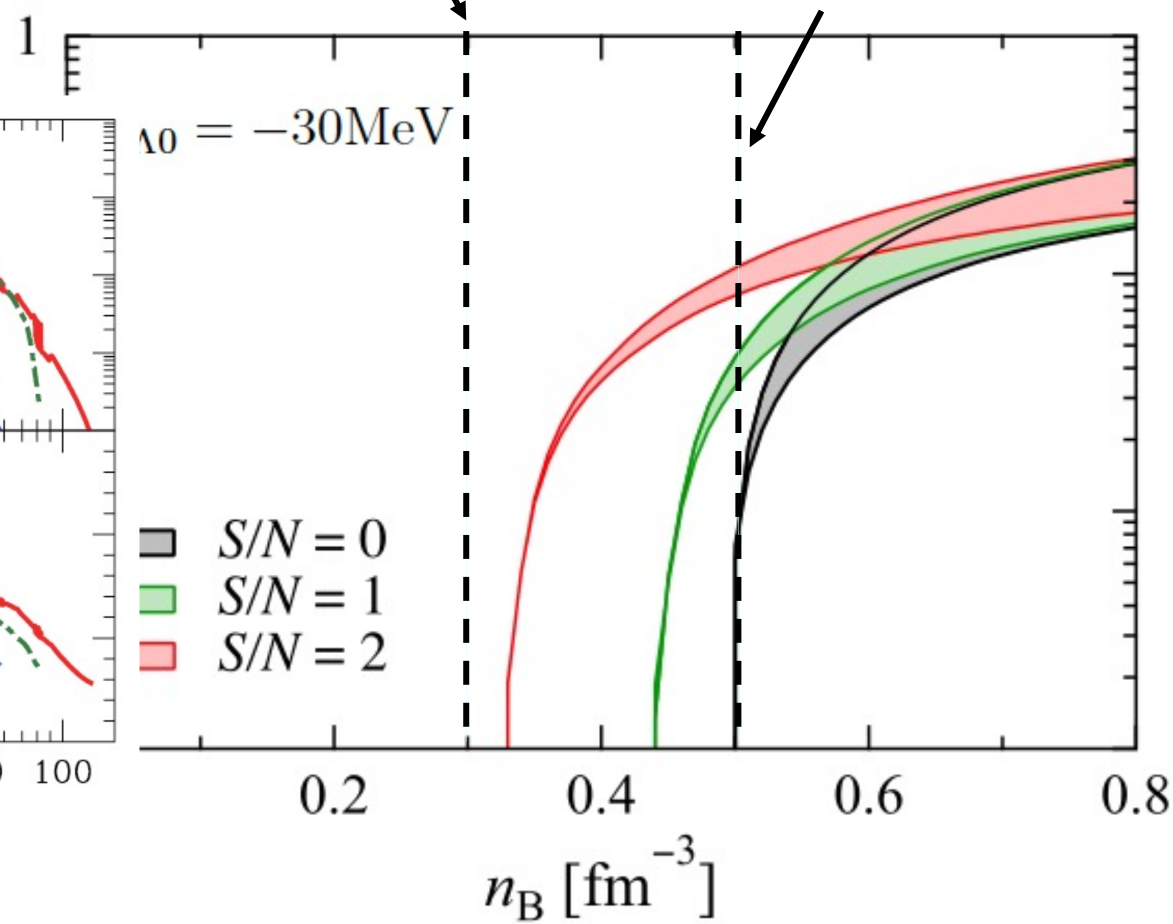
Supernova matter

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

Central density at the bounce

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





(PRC 97 (2018) 035804)

Summary

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

Cold neutron stars

- ΛΛN and ΛΛΛ three-body forces:

affect on the maximum mass of neutron stars (Important for HYPERON PUZZLE!?)

Core-Collapse supernovae

- Λ hyperon does not appear in the stellar core at the bounce stage.
- Λ hyperon fraction is 0.04 in the stellar core at the proto-neutron star cooling stage.

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)