Exotic Baryons in Hot Neutron Stars

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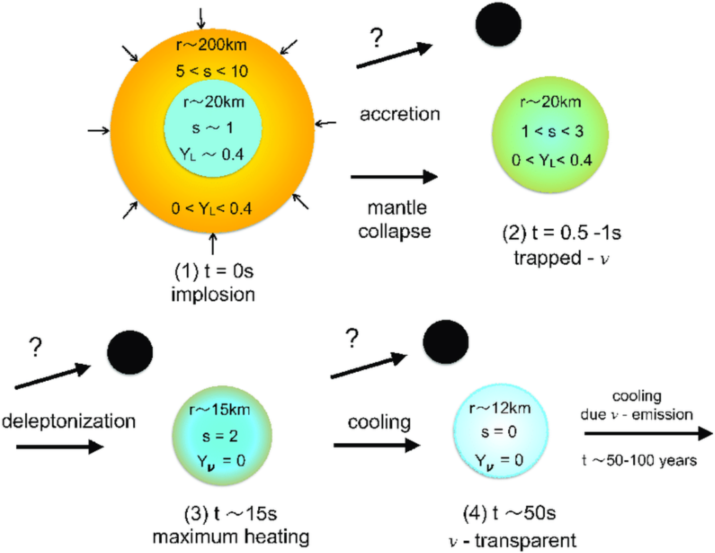
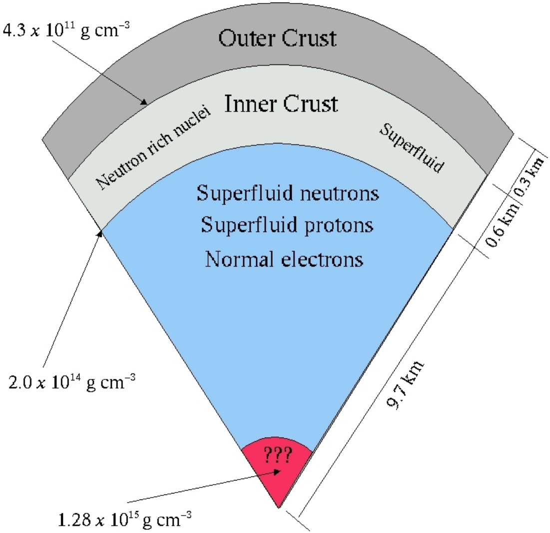
Introduction

- We use a relativistic model within the mean-field approximation with density-dependent coupling to study the evolution of neutron stars
- The model is adjusted by the DDME2 parameterization
- The model is investigated at a fixed entropy to determine:
  - the nuclear EoS
  - particle distribution in the stellar matter
  - temperature profile
  - velocity of sound in the stellar matter
  - and the macroscopic structure of the star

Issifu A., Marquez K. D., Pelicer M. R., Menezes D. P., Mon. Not. Roy. Astron. Soc., 522, 3263 (2023), arXiv:2302.04364 [nucl-th].


r~200km
5 < s < 10
r~20km
s ~ 1
Y_L ~ 0.4
0 < Y_L < 0.4
(1) t = 0s
implosion
?
accretion
mantle
collapse
r~20km
1 < s < 3
0 < Y_L < 0.4
(2) t = 0.5 -1s
trapped - ν
?
deleptonization
r~15km
s = 2
Y_ν = 0
(3) t ~15s
maximum heating
?
cooling
r~12km
s = 0
Y_ν = 0
(4) t ~50s
ν - transparent
cooling
due ν - emission
t ~50-100 years



Neutron Star Pizza

The Model

The model for the study is given by,

$$\mathcal{L}_{\mathrm{RMF}} = \mathcal{L}_{H} + \mathcal{L}_{\Delta} + \mathcal{L}_{\mathrm{mesons}} + \mathcal{L}_{\mathrm{leptons}}. \tag{1}$$

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The Lagrangian for the $J^P = 1/2^+$ baryon octet

$$\mathcal{L}_H = \sum_{b \in H} \bar{\psi}_b \Big[i\gamma^\mu \partial_\mu - \gamma^0 \left(g_{\omega b}\omega_0 + g_{\phi b}\phi_0 + g_{\rho b} I_{3b}\rho_{03} \right) - \Big(m_b - g_{\sigma b}\sigma_0 \Big) \Big] \psi_b, \quad (2)$$

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and the Rarita-Schwinger–type Lagrangian for the $J^P = 3/2^+$ baryons

$$\mathcal{L}_\Delta = \sum_{d\in\Delta} \bar{\psi}_{d\nu} \Big[\gamma^\mu i\partial_\mu - \gamma^0 \left(g_{\omega d}\omega_0 + g_{\rho d} I_{3d}\rho_{03} \right) - (m_d - g_{\sigma d}\sigma_0) \Big] \psi_{d\nu}. \tag{3}$$

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The mesonic part is given by

$$\mathcal{L}_{\mathrm{mesons}} = -\frac{1}{2} m_\sigma^2 \sigma_0^2 + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{1}{2} m_\phi^2 \phi_0^2 + \frac{1}{2} m_\rho^2 \rho_{03}^2. \tag{4}$$

UFSC

Finally, the free leptons are described by

$$\mathcal{L}_{\text{leptons}} = \sum_{L} \bar{\psi}_L \left(i\gamma^{\mu}\partial_{\mu} - m_L \right) \psi_L . \tag{5}$$

UFSC

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$$g_{ib}(n_B) = g_{ib}(n_0) a_i \frac{1 + b_i(\eta + d_i)^2}{1 + c_i(\eta + d_i)^2}, \tag{6}$$

where $i = (\sigma, \phi, \text{and}\, \omega)$, with $\eta = n_B/n_0$ and

$$g_{\rho b}(n_B) = g_{ib}(n_0) \exp\left[-a_\rho (\eta - 1)\right], \tag{7}$$

here, $n_0 = 0.152\,\text{fm}^{-3}$.

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$$\mu_b^* = \mu_b - g_{\omega b}\omega_0 - g_{\rho b} I_{3b} \rho_{03} - g_{\phi b}\phi_0 - \Sigma^r \tag{8}$$

$$\mu_d^* = \mu_d - g_{\omega b}\omega_0 - g_{\rho d} \rho_{03} I_{3d} - \Sigma^r, \tag{9}$$

where Σ^r is the rearrangement term

$$\Sigma^r = \sum_b \left[\frac{\partial g_{\omega b}}{\partial n_b} \omega_0 n_b + \frac{\partial g_{\rho b}}{\partial n_b} \rho_{03} I_{3b} n_b + \frac{\partial g_{\phi b}}{\partial n_b} \phi_0 n_b - \frac{\partial g_{\sigma b}}{\partial n_b} \sigma_0 n_b^s + b \leftrightarrow d \right]. \tag{10}$$

UFSC

Also,

$$P_b = \gamma_b \int \frac{d^3k}{(2\pi)^3} \frac{k}{E_b} \left[f_{b+} + f_{b-}\right], \qquad \varepsilon_b = \gamma_b \int \frac{d^3k}{(2\pi)^3} E_b \left[f_{b+} + f_{b-}\right], \tag{11}$$

where $\gamma_b = 2$ and

$$f_{b\pm}(k) = \frac{1}{1 + \exp[(E_b \mp \mu_b^*)/T]}. \tag{12}$$

This expression also holds for Δ-resonances and leptons by $b \leftrightarrow (d, L)$, with degeneracies of $\gamma_d = 4$ and $\gamma_L = 2$ or $\gamma_L = 1$ for neutrinos respectively.

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$$\varepsilon_m = \frac{m_\sigma^2}{2}\sigma_0^2 + \frac{m_\omega^2}{2}\omega_0^2 + \frac{m_\phi^2}{2}\phi_0^2 + \frac{m_\rho^2}{2}\rho_{03}^2, \qquad P_m = -\frac{m_\sigma^2}{2}\sigma_0^2 + \frac{m_\omega^2}{2}\omega_0^2 + \frac{m_\phi^2}{2}\phi_0^2 + \frac{m_\rho^2}{2}\rho_{03}^2. \tag{13}$$

UFSC

The associated equations of motion are:[1]

$$m_\sigma^2 \sigma_0 = \sum_b g_{\sigma b} n_b^s + \sum_d g_{\sigma d} n_d^s, \tag{14}$$

$$m_\omega^2 \omega_0 = \sum_b g_{\omega b} n_b + \sum_d g_{\omega d} n_d, \tag{15}$$

$$m_\phi^2 \phi_0 = \sum_b g_{\phi b} n_b, \tag{16}$$

$$m_\rho^2 \rho_{03} = \sum_b g_{\rho b} n_b I_{3b} + \sum_d g_{\rho d} n_d I_{3d}. \tag{17}$$

The baryon density is given by

$$n_b = \gamma_b \int \frac{d^3k}{(2\pi)^3} \left[f_{b\,+} - f_{b\,-} \right] \tag{18}$$

and the scalar density

$$n_b^s = \gamma_b \int \frac{d^3k}{(2\pi)^3} \frac{m_b^*}{E_b} \left[f_{b\,+} + f_{b\,-} \right]. \tag{19}$$

[1] Dutra M., et al., 2014, Phys. Rev. C, 90, 055203

[2]

meson(i)	m_i(MeV)	a_i	b_i	c_i	d_i	$g_{iN}(n_0)$
σ	550.1238	1.3881	1.0943	1.7057	0.4421	10.5396
ω	783	1.3892	0.9240	1.4620	0.4775	13.0189
ρ	763	0.5647	—	—	—	7.3672

Table: DDME2 parameters.

[3]

b	$\chi_{\omega b}$	$\chi_{\sigma b}$	$\chi_{\rho b}$	$\chi_{\phi b}$
Λ	0.714	0.650	0	-0.808
Σ^0	1	0.735	0	-0.404
Σ^-, Σ^+	1	0.735	0.5	-0.404
Ξ^-, Ξ^0	0.571	0.476	0	-0.606
Δ^-, Δ^0, Δ^+, Δ^{++}	1.285	1.283	1	0

Table: The ratio of the baryon coupling to the corresponding nucleon coupling for hyperons and Δs ($\chi_{ib} = g_{ib}/g_{iN}$).

[2] Lalazissis G. A., et al., 2005, Phys. Rev. C, 71, 024312
[3] Lopes L. L., et al., 2022

UFSC

The effective masses are

$$m^*_{b,d} = m_{b,d} - g_{\sigma b,d}\sigma_0. \tag{20}$$

[4] Typel S., et al., 2022, Eur. Phys. J. A, 58, 221

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Total energy and pressure are;

$$\varepsilon_B = \varepsilon_b + \varepsilon_m + \varepsilon_d + \varepsilon_L, \qquad P_B = P_b + P_m + P_d + P_L + P_r. \tag{21}$$

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For thermodynamic consistency and energy-momentum conservation

$$P_r = n_B \Sigma^r. \tag{22}$$

The free-energy density $\mathcal{F}_B = \varepsilon_B - Ts_B$, and the entropy density[4]

$$s_B = \frac{\varepsilon_B + P_B - \sum_b \mu_b n_b - \sum_d \mu_d n_d}{T}. \tag{23}$$

UFSC

[4] Typel S., et al., 2022, Eur. Phys. J. A, 58, 221

The relevant conditions are; [5]

- β-equilibrium;

  $\mu_b = \mu_B - q_B(\mu_l - \mu_{\nu l})$.
- charge neutrality;

  $n_p + n_{\Sigma^+} + 2n_{\Delta^{++}} + n_{\Delta^+} - (n_{\Sigma^-} + n_{\Xi^-} + n_{\Delta^-}) = n_e + n_\mu$.
- lepton number conservation;

  $Y_L = Y_l + Y_{l\nu}$ with $Y_L = (n_l + n_{\nu l})/n_B$.
- baryon conservation;

  $n_B = \sum_{i=b,\Delta} n_i$.

The β-equilibrium follows the direct Urca processes

$$B_1 \rightarrow B_2 + l + \bar{\nu}_e \quad \text{and} \quad B_2 + l \rightarrow B_1 + \nu_e. \tag{24}$$

[5] Baym G., et al., 2018, Rept. Prog. Phys., 81, 056902

Results

Particle abundances for neutrino trapped matter

The particle fraction is given by,

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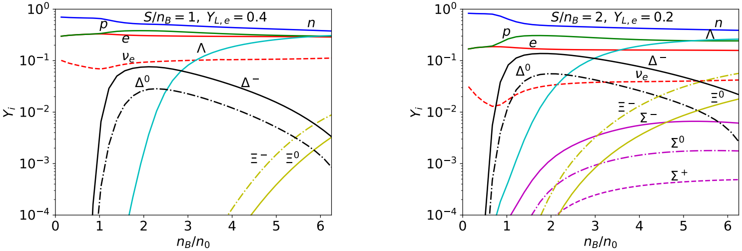

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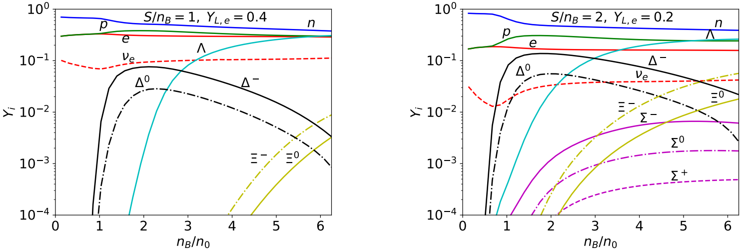
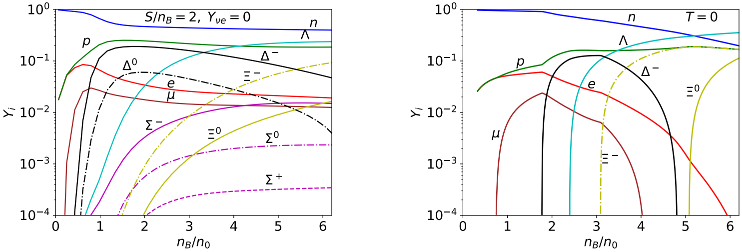


Baryon asymmetry in the system

$$\delta = \frac{n_n - n_p}{n}, \qquad n = n_n + n_p. \tag{26}$$

Neutrino transparent matter



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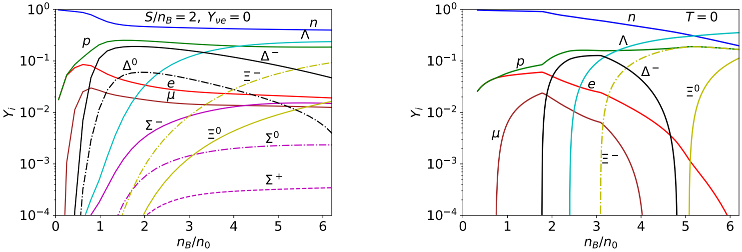

- The Y_p/Y_n decreases across the panels
- The presence of neutrinos affects the particle distribution inside the star

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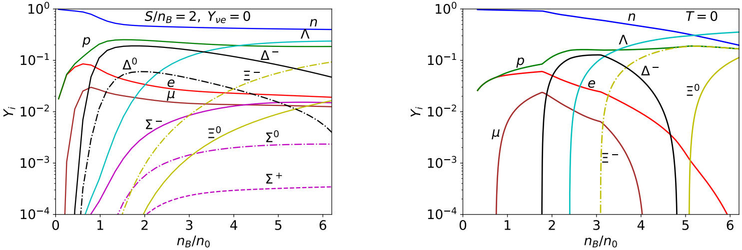

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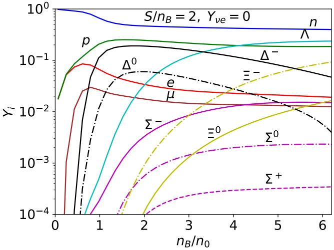
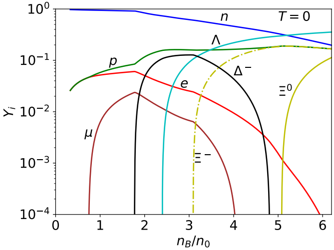
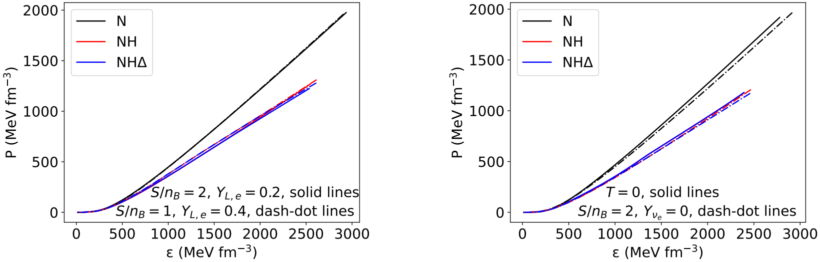




- The Y_p/Y_n decreases across the panels
- The presence of neutrinos affects the particle distribution inside the star
- High $Y_{\nu e}$ delays the appearance of strange matter particles
- The most abundant particle in the stellar matter at all stages of star evolution is the Λ

The EoSs



N
NH
NHΔ
P (MeV fm^{-3})
ε (MeV fm^{-3})
$S/n_B = 2$, $Y_{L,e} = 0.2$, solid lines
$S/n_B = 1$, $Y_{L,e} = 0.4$, dash-dot lines
$T = 0$, solid lines
$S/n_B = 2$, $Y_{\nu_e} = 0$, dash-dot lines

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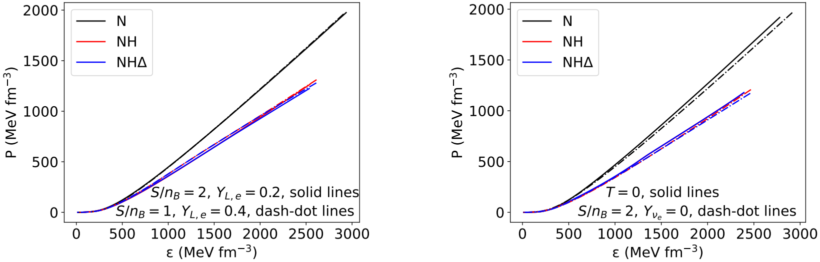
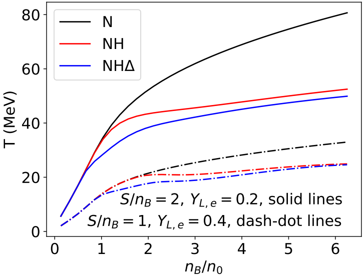


- Increasing entropy density softens the EoS
- Adding new degrees of freedom to the stellar matter softens the EoS significantly
- At $T = 0$ the star catalyzes, reduces in size, pressure in its core increases, and the EoS becomes stiff

Temperature Profile



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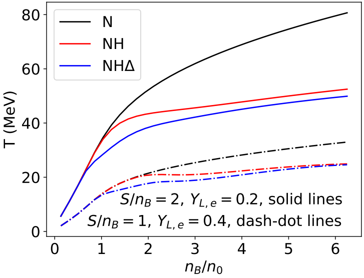

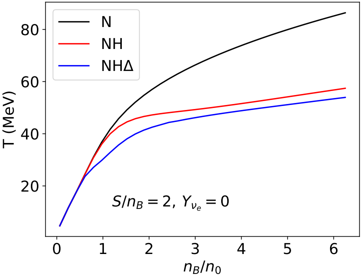

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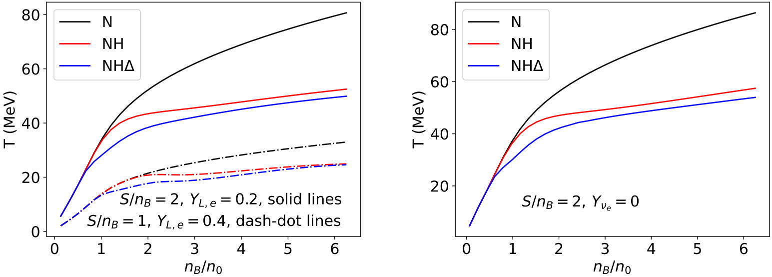

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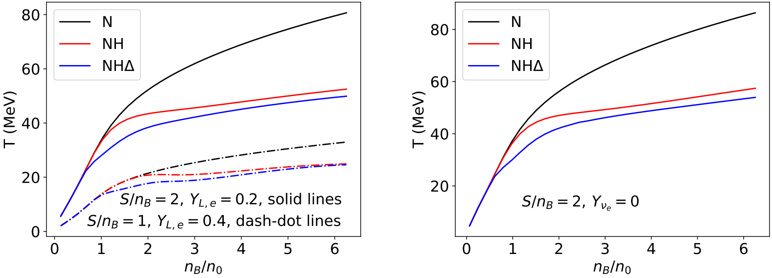

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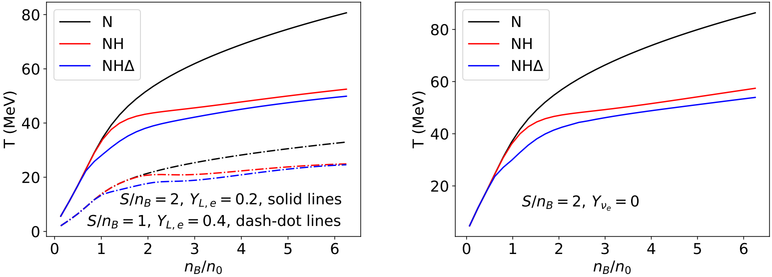

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- Second stage: $S/n_B = 2$, $\mathrm{Y}_{L,e} = 0.2$, deleptonization stage, the star gets heated and expands due to neutrino diffusion
- Third Stage: $S/n_B = 2$, $\mathrm{Y}_{\nu e} = 0$, the star is maximally heated, neutrino-transparent

The Mass–Radius Diagram

We assume spherically symmetric fluid and solve the standard TOV equations,[6]

$$\frac{dP(r)}{dr} = -[\varepsilon(r) + P(r)]\frac{M(r) + 4\pi r^3 P(r)}{r^2 - 2M(r)r} \tag{27}$$

$$\frac{dM(r)}{dr} = 4\pi r^2 \varepsilon(r), \tag{28}$$

imposing all the necessary equilibrium conditions.

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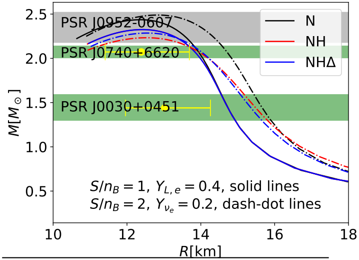

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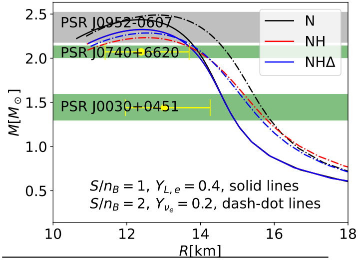

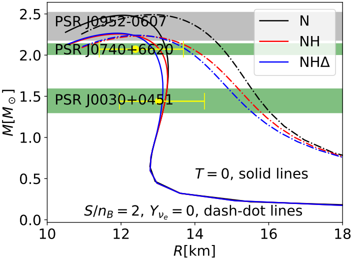

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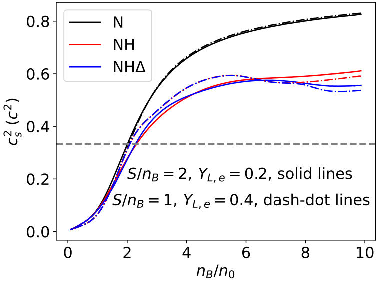

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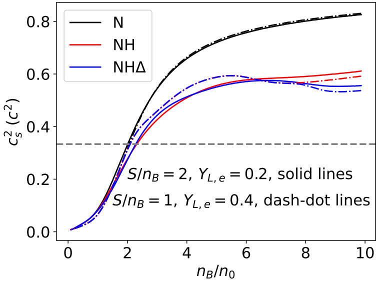

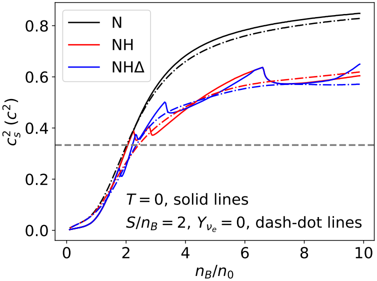

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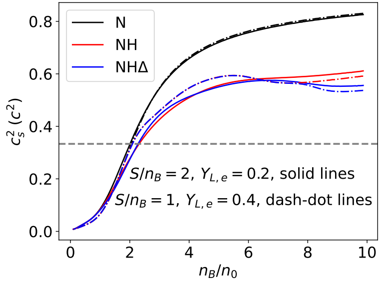

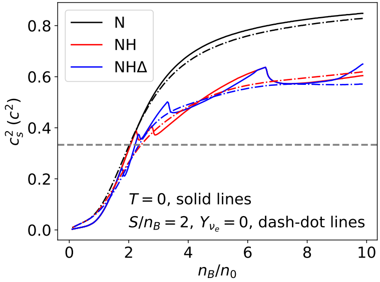

- For exactly conformal matter $c_s^2 = 1/3$
- Causality requires that $c_s^2 \leq 1$

Sound velocity

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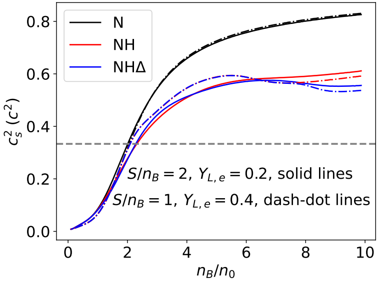

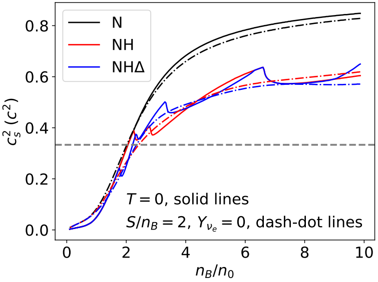

- For exactly conformal matter $c_s^2 = 1/3$
- Causality requires that $c_s^2 \leq 1$
- For hadronic matter $c_s^2 > 1/3$
- For thermodynamic stability $c_s^2 > 0$

Summary

- The particle population depends sensitively on S/n_B
- Adding new particles to the stellar matter softens the EoS, reduces T profile and c_s^2
- Increasing S/n_B leads to an increase in R, T and c_s^2
- In the neutrino-transparent region, the stellar radii decrease from $S = 2$ to $T = 0$

Acknowledgements

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Thank You!