Equation of state for hot hyperonic neutron star matter

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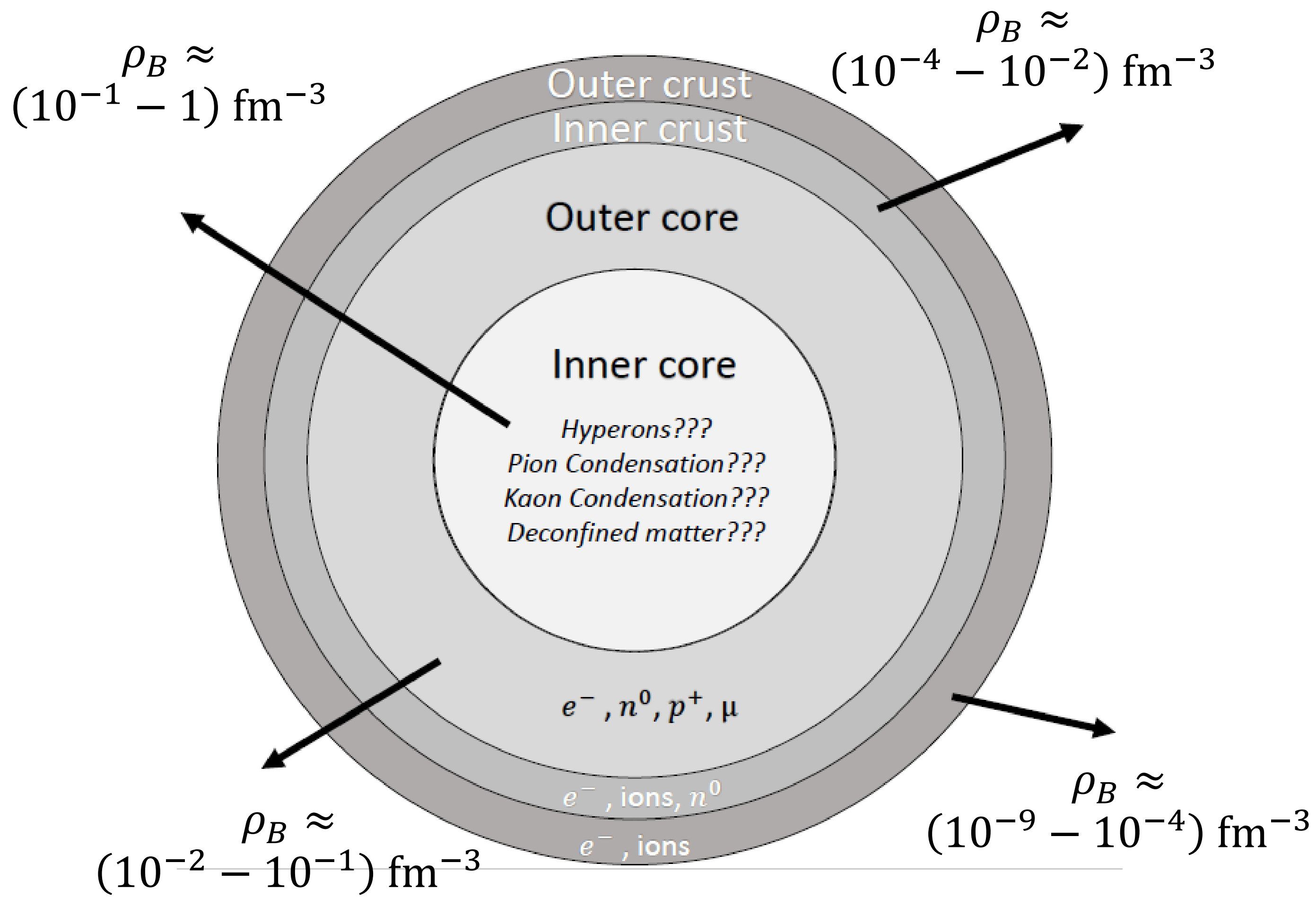
OUTLINE

- ***Motivation. Structure of Neutron Stars (NS)***
- Brief introduction to FSU2H* model
- Equation of State (EoS) and composition of hot neutron star core
- Thermal index of neutron star core
- Summary

Motivation. Structure of NS



- Remnant of supernovae processes: **high density – several times ρ_0**

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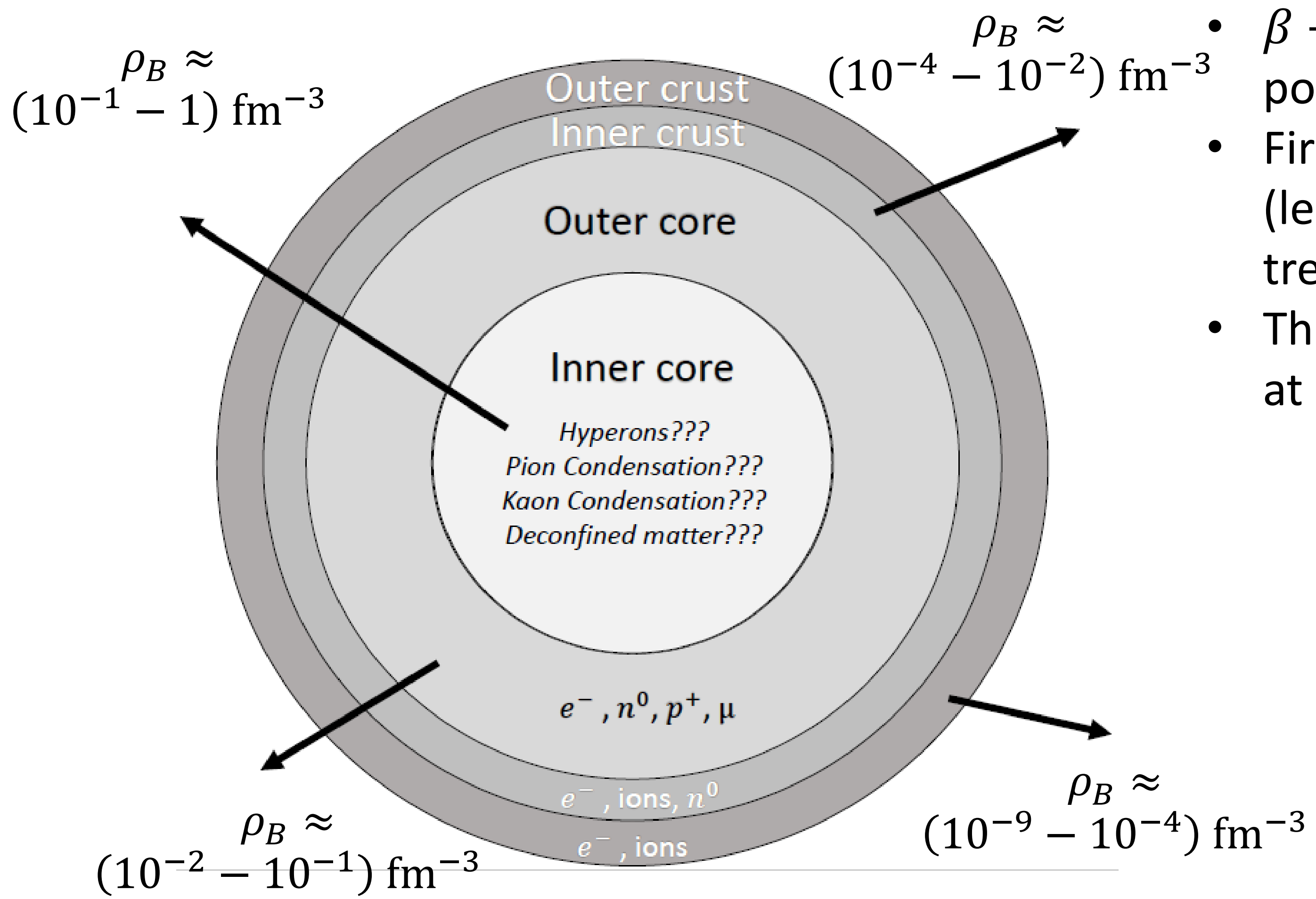

- $\beta -$ stable matter made of nucleons, leptons and possibly exotic particles (**HYPERONS**)
- First stage of the evolution**: proto neutron star** (lepton rich and hot object) – Finite temperature treatement is needed
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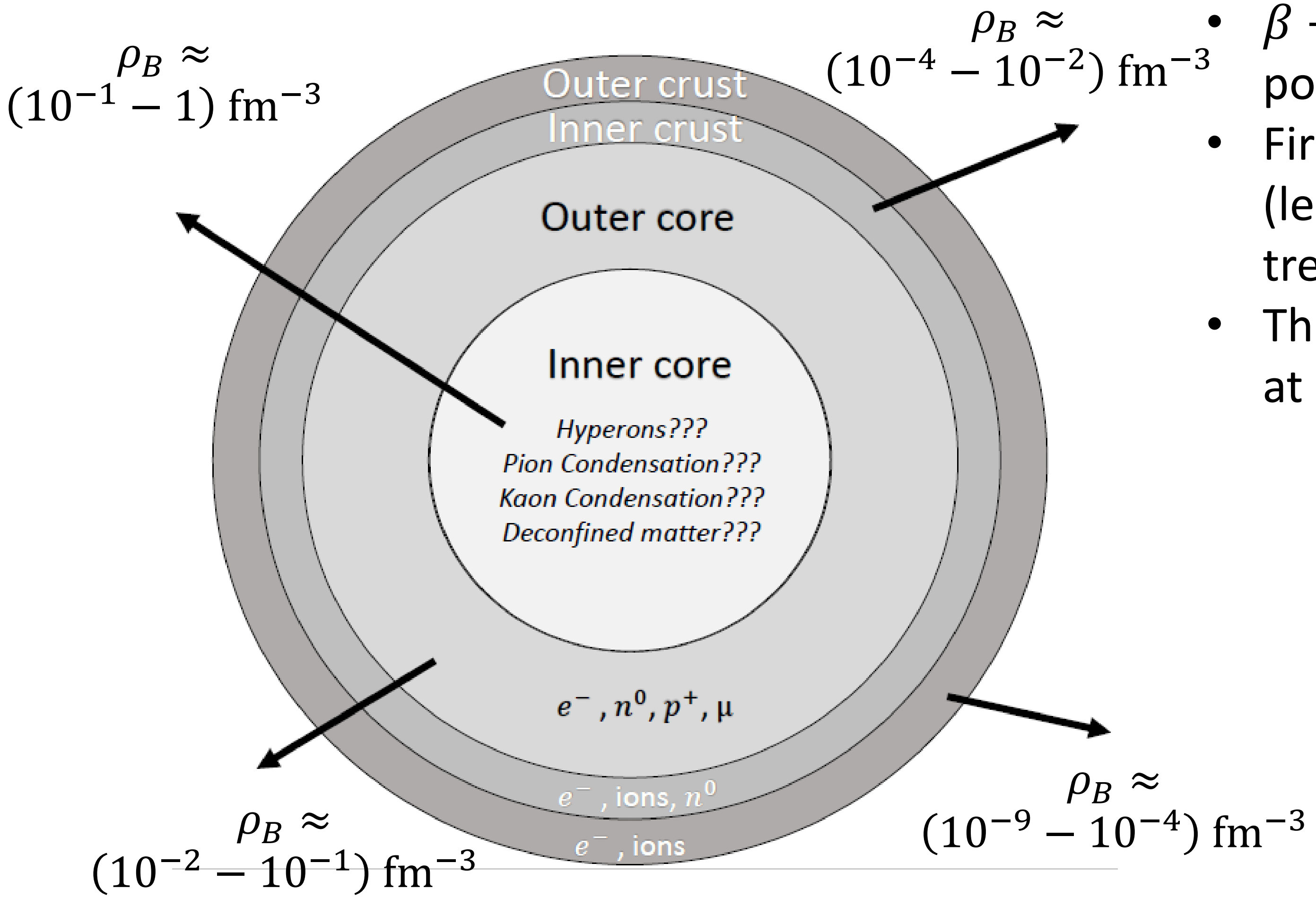

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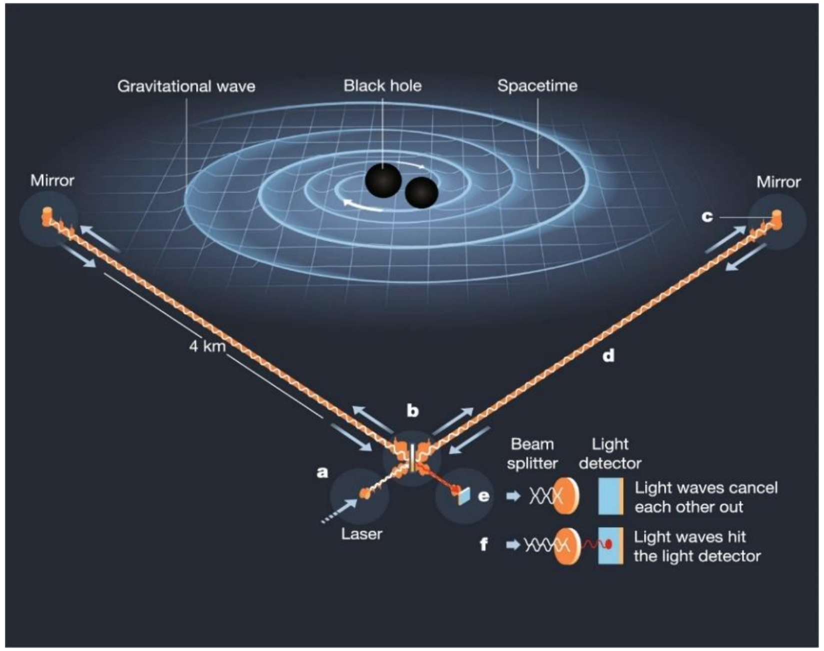

Miller, M.C., Yunes, N. The new frontier of gravitational waves. *Nature*

- Remnant of supernovae processes: **high density – several times ρ_0**
- **But there are new astrophysical measurements!**

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https://arxiv.org/abs/2206.11266

QR code and link of the paper where the results are published

Brief introduction to FSU2H* model

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- **RMF approximation**
- **$\beta -$ equilibrium**
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$$T_{\mu\nu} = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \Phi_\alpha)} \partial_\nu \Phi_\alpha - \eta_{\mu\nu}\mathcal{L}.$$

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$$\epsilon_{tot}, s, P, f$$

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Values of parameters in the model

m_σ (MeV)	m_ω (MeV)	m_ρ (MeV)	m_{σ^*} (MeV)	m_ϕ (MeV)	$g^2_{\sigma N}$	$g^2_{\omega N}$	$g^2_{\rho N}$	κ (MeV)	λ	ζ	Λ_ω
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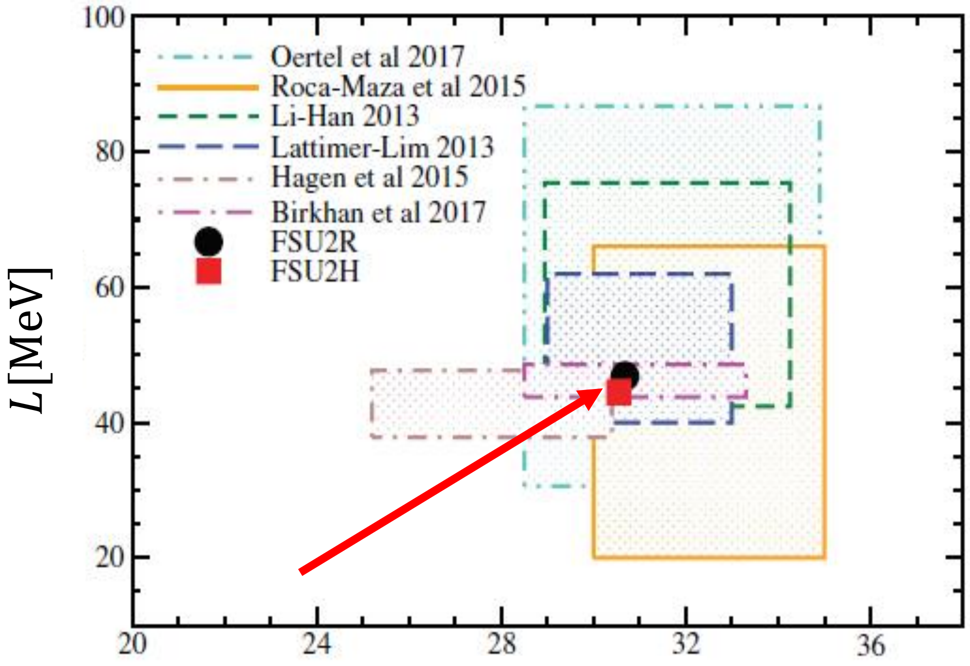
PASA, 34, e065 (2017)



Low density region constrains

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ρ_0 (fm^{-3})	E/A (MeV)	K (MeV)	m^*_N/m_N (ρ_0)	$E_{sym}(\rho_0)$ (MeV)	L (MeV)	K_{sym} (MeV)
0.1505	-16.28	238.0	0.593	30.5	44.5	86.4

Consistent with the majority of the calculations, variety of nuclear data from terrestrial experiments, astrophysical observations…

Why FSU2H* model? II

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Values of the parameters in the model related to hyperons

Y	$R_{\sigma Y}$	$R_{\omega Y}$	$R_{\rho Y}$	$R_{\sigma^* Y}$	$R_{\phi Y}$
Λ	0.6613	2/3	0	0.2812	$-\sqrt{2}/3$
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$$R_{iY} = \frac{g_{iY}}{g_{iN}}; i = (\sigma, \omega, \rho);\ R_{\sigma^* Y} = \frac{g_{\sigma^* Y}}{g_{\sigma Y}}; R_{\phi Y} = \frac{g_{\phi Y}}{g_{\omega N}}$$

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$$U_\Lambda^{(N)}(\rho_0) = -28 \text{ MeV};$$

$$U_\Sigma^{(N)}(\rho_0) = 30 \text{ MeV};$$

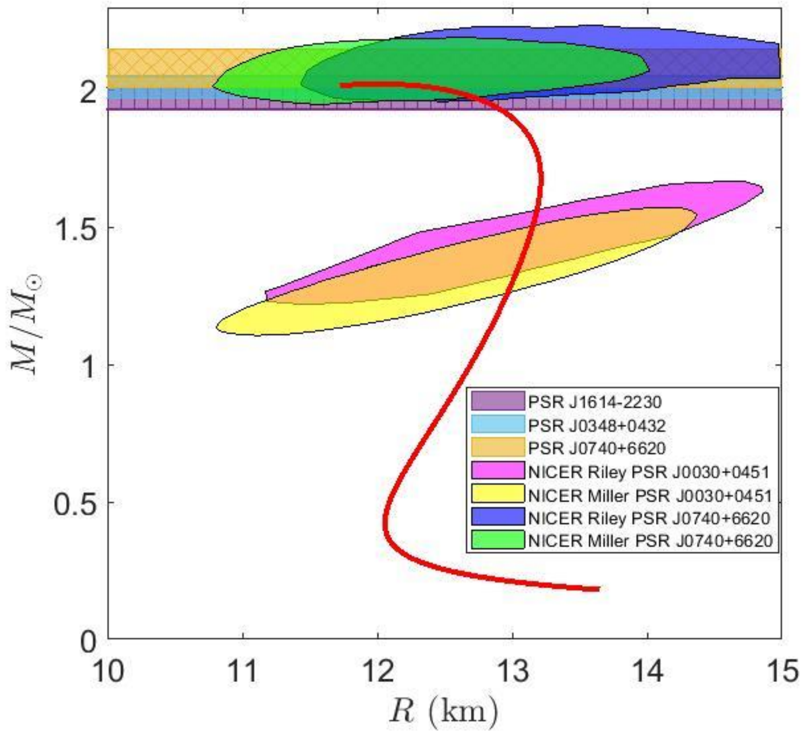
$$U_\Xi^{(N)}(\rho_0) = -24 \text{ MeV};$$

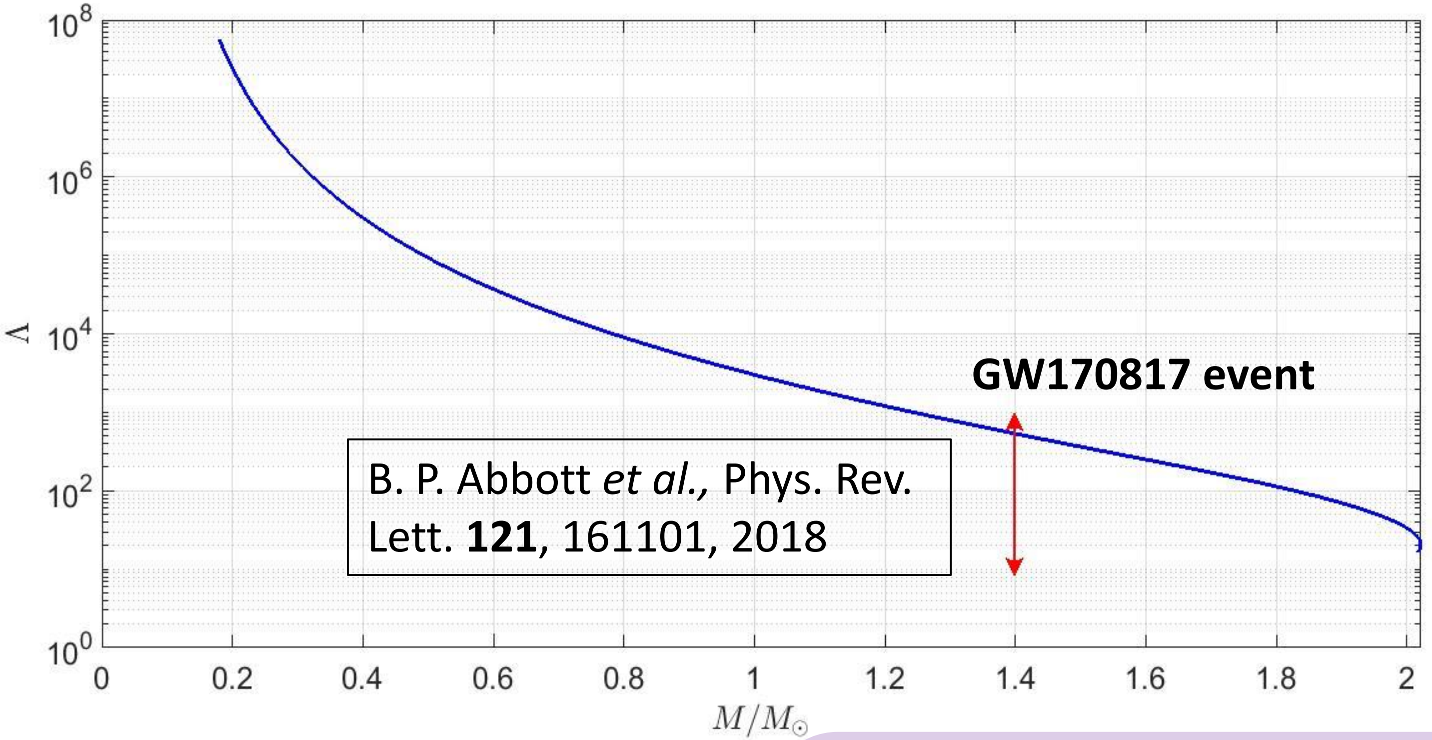
Hyperon potentials in SNM

$$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\text{He}) = 0.67 \text{ MeV}$$

$\Lambda\Lambda$ interaction energy

Why FSU2H* model? III





Intermediate and high density regions constrains

$M_{\mathbf{max}}$ ($M_\odot$)	$R(M_{\mathbf{max}})$ (km)	$R(1.4M_\odot)$ (km)	$\mathbf{\Lambda}(1.4M_\odot)$
2.03	12.02	13.08	526.3

In agreement with:

- $M_{\max} > 2M_\odot$
- **70 < $\Lambda(1.4M_\odot)$ < 580**
- **10.5 km < $R(1.4M_\odot)$ < 13.3 km**

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Composition and EoS of hot neutron star core I

- The finite temperature EoS depends on three parameters (ρ_B, T, Y_e)

Wide range of values to **account for conditions in PNS and NS mergers:**

T = (0 – 100) MeV

$\rho_B = (0.5 - 10)\rho_0$

$Y_e = (0 - 0.4); \nu$ free case

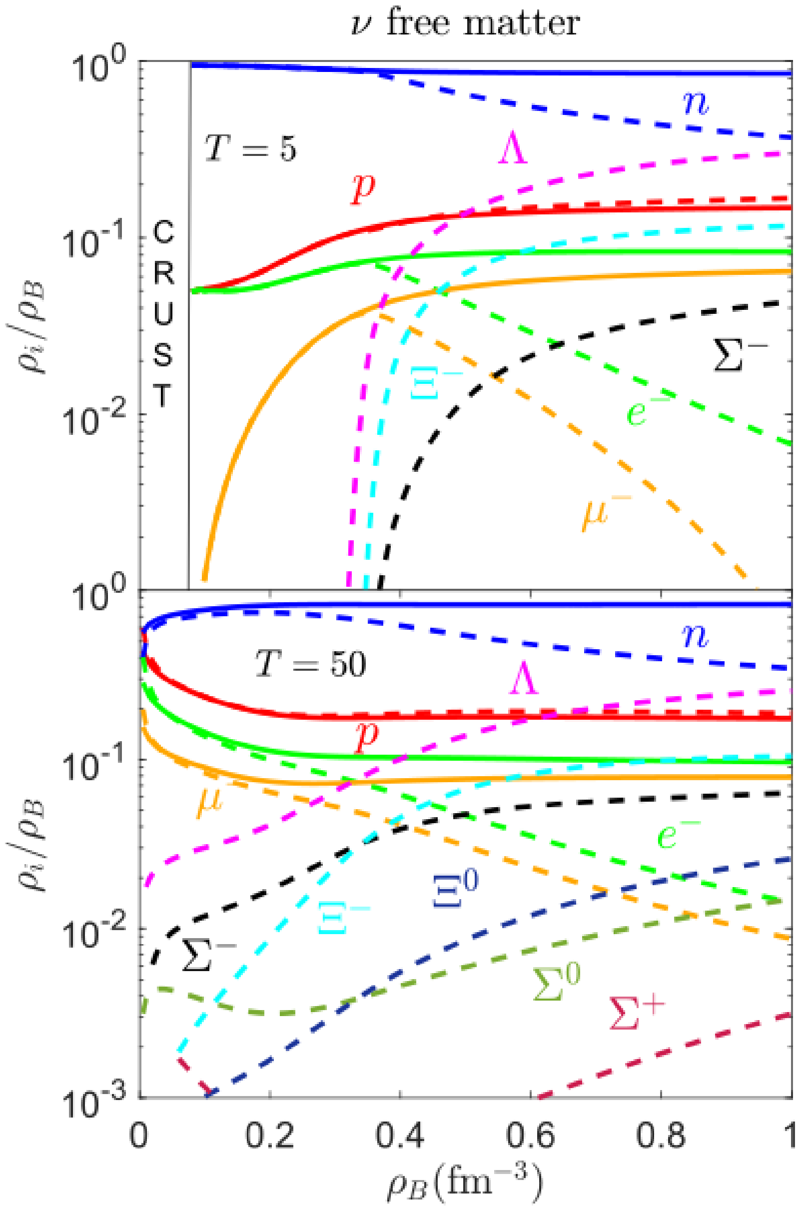
- We focus on:

$T = 5$ MeV and $T = 50$ MeV

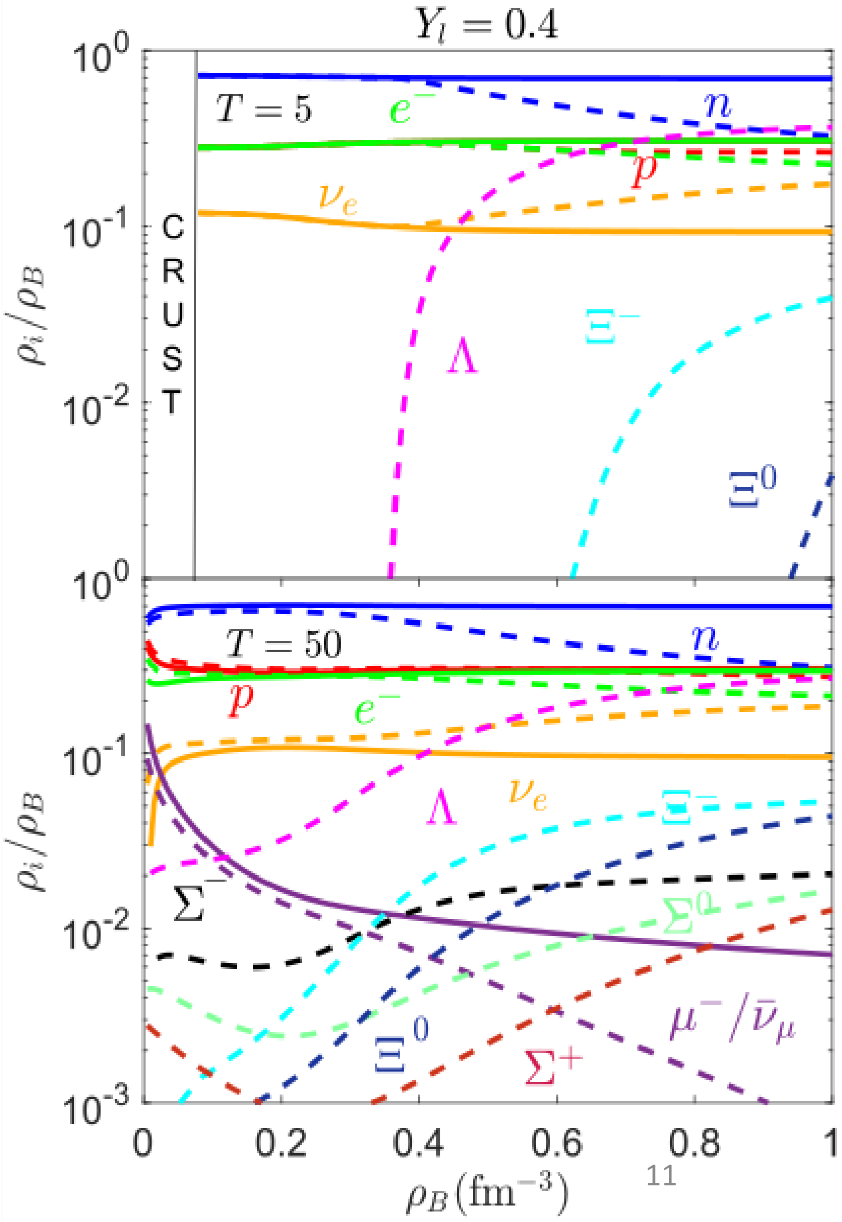
and two different lepton situations:

$Y_e = 0.4$ and ν free matter

Composition and EoS of hot neutron star core II



Solid lines – core without hyperons
Dashed lines – core with hyperons



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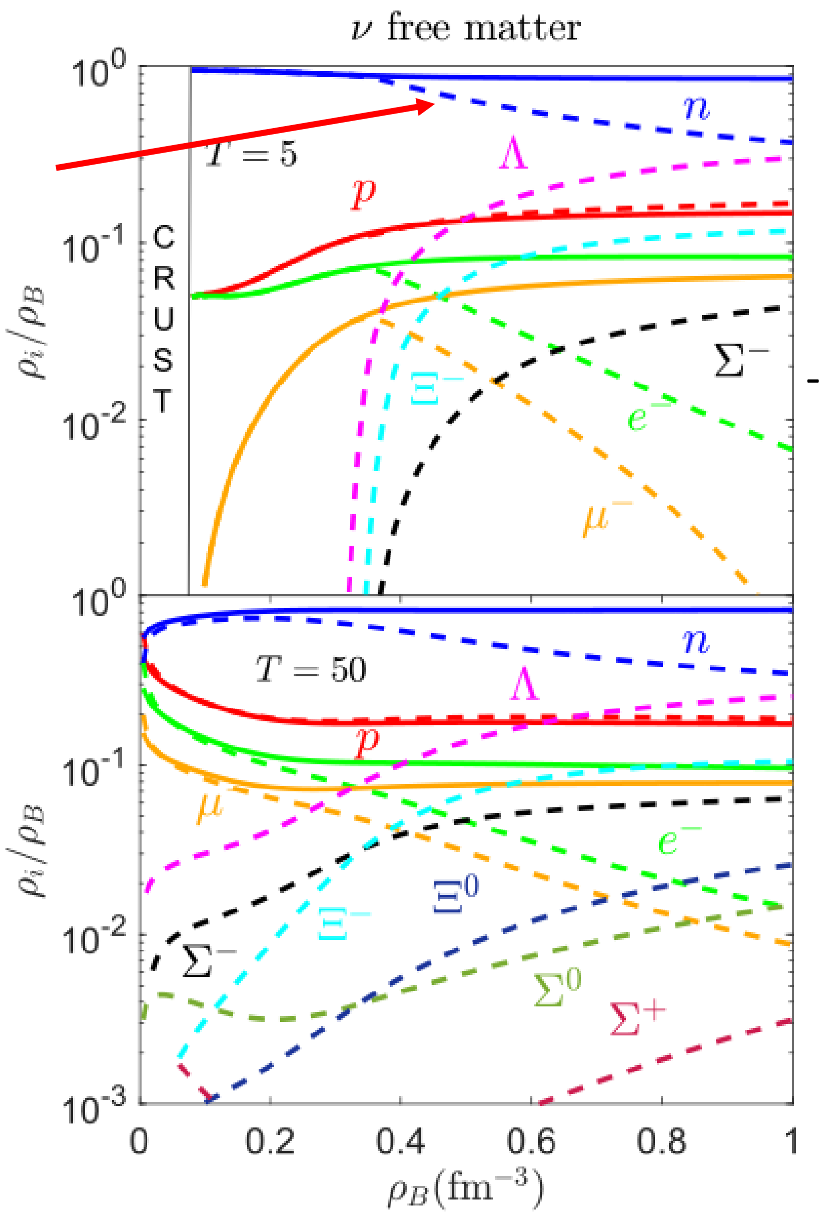

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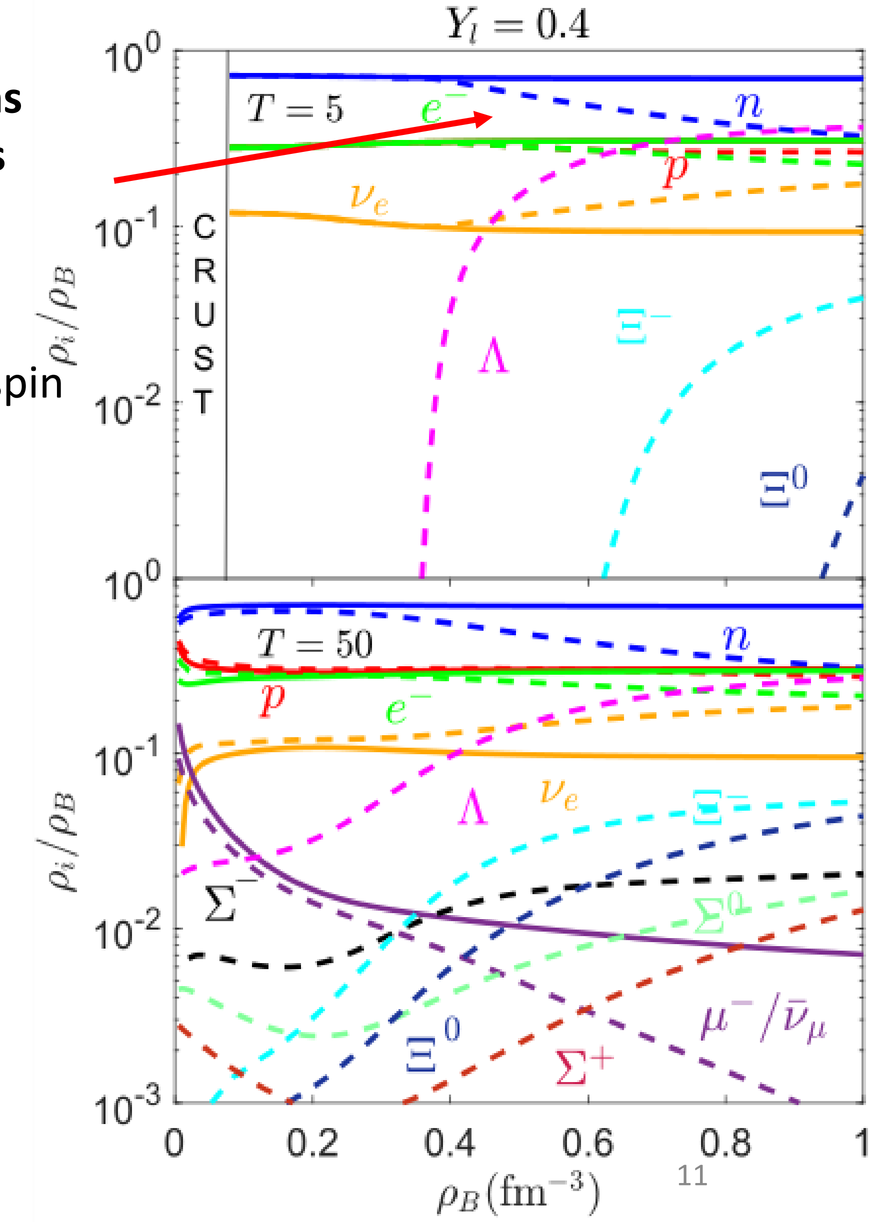
Main effects:

- Hyperons make the matter more isospin symmetric



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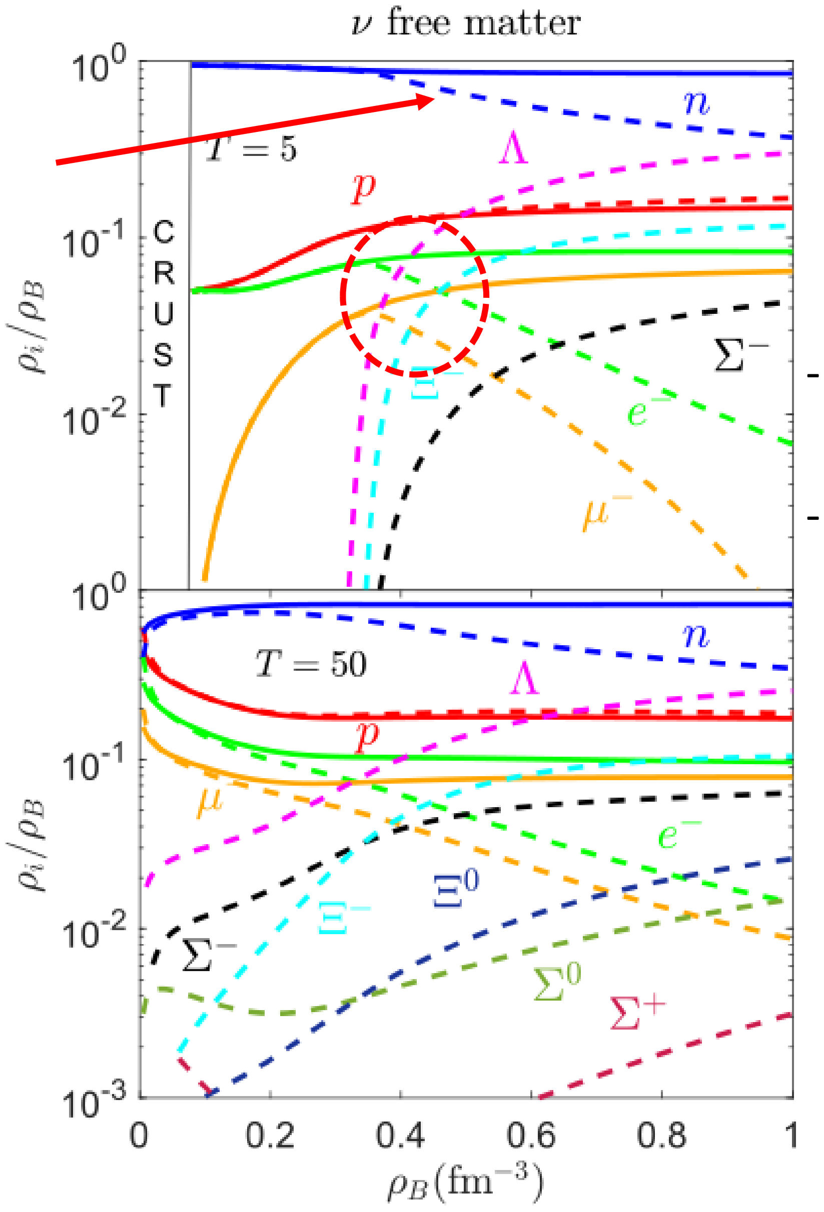

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Main effects:

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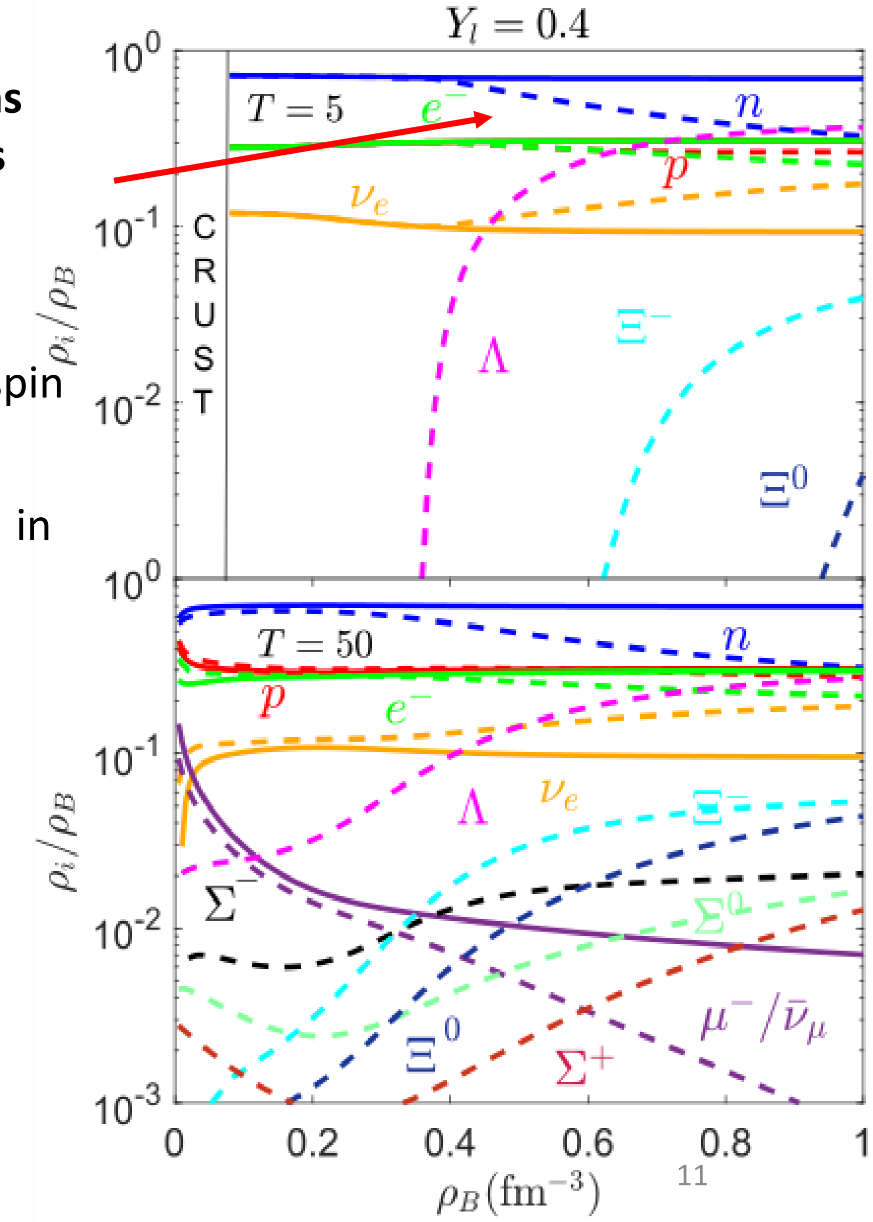
- Hyperons replace the negative leptons in order charge neutrality to be fulfilled.



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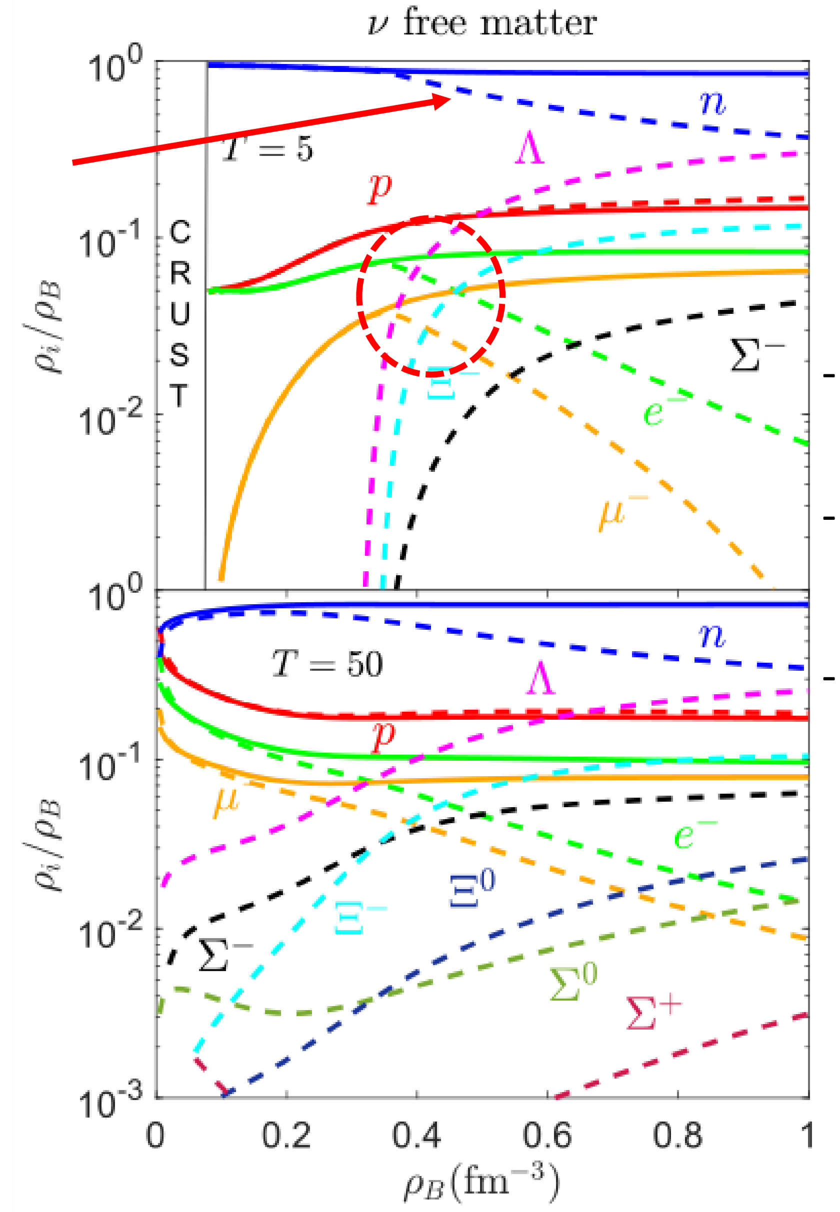

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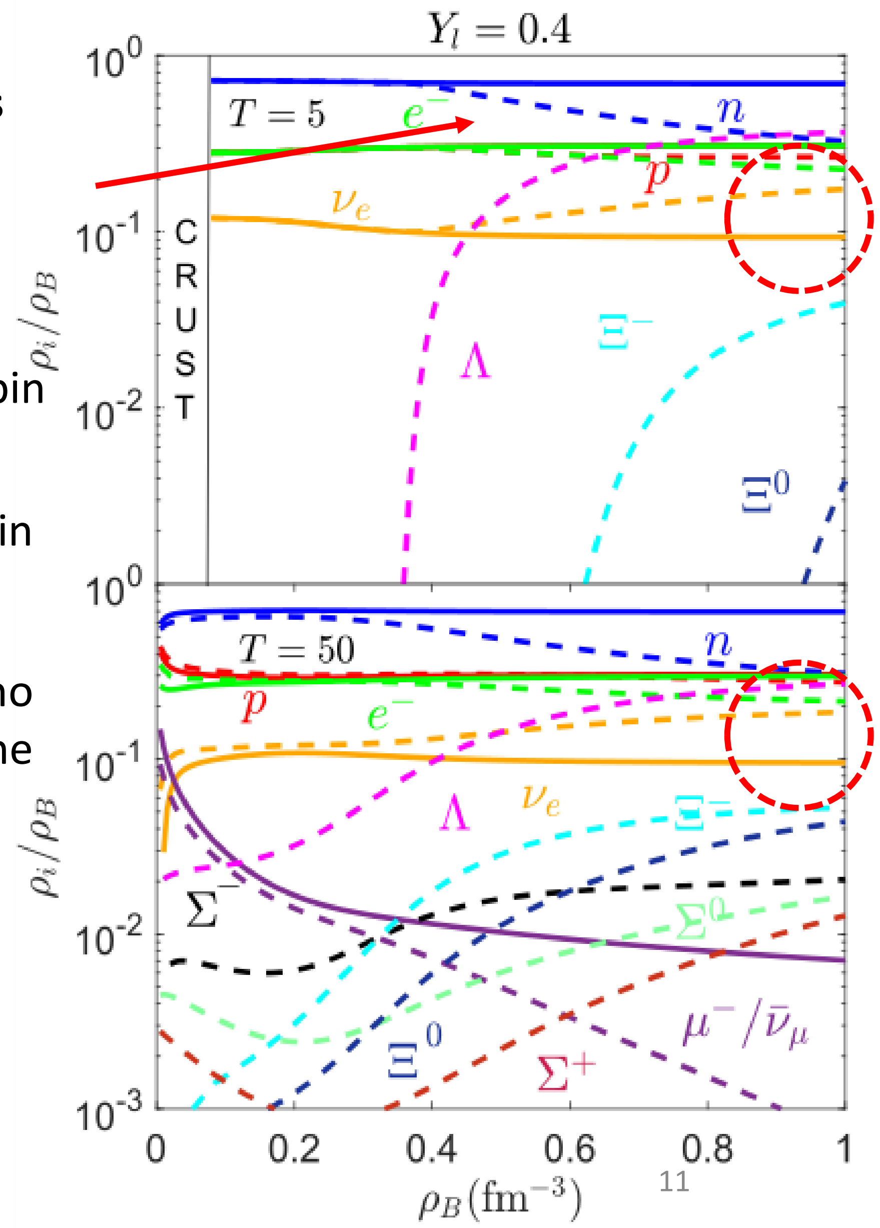

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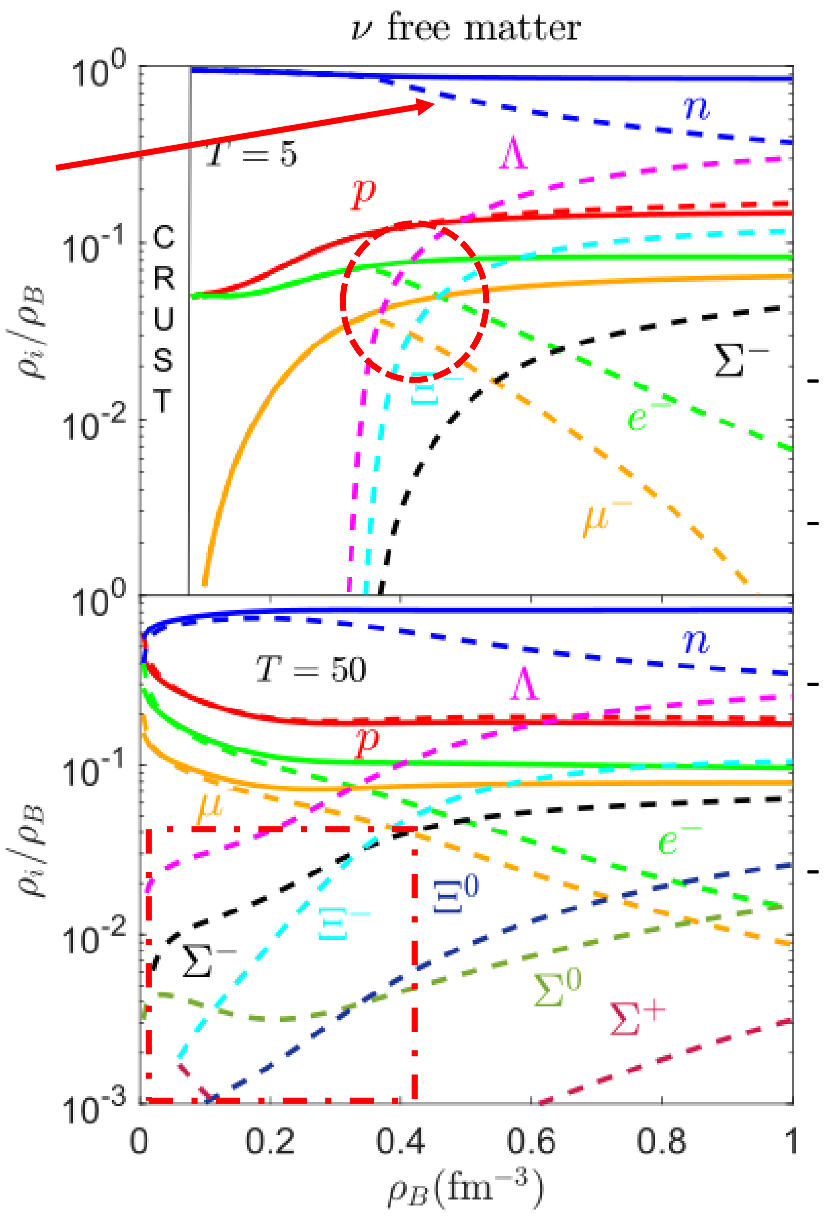

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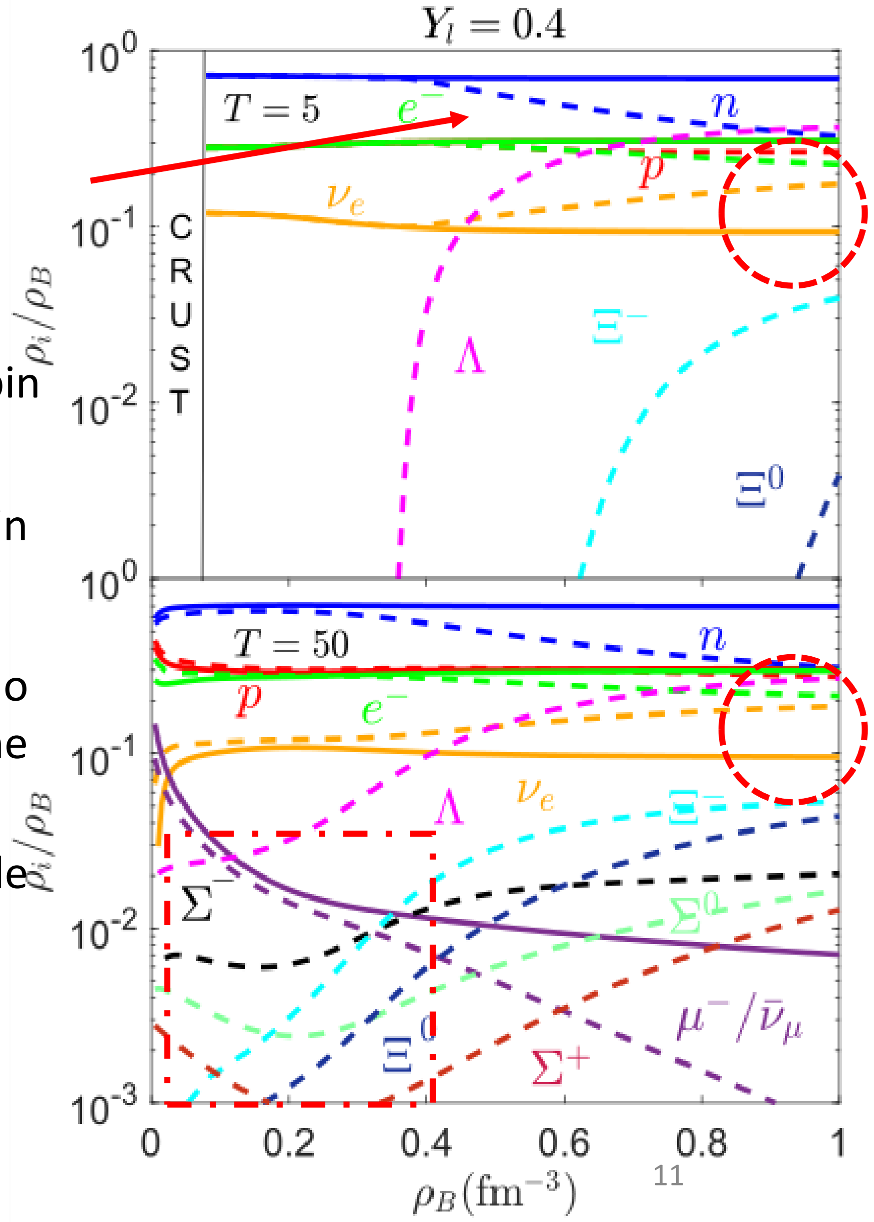
- At high temperature hyperons are inside the core at any density



Composition and EoS of hot neutron star core III

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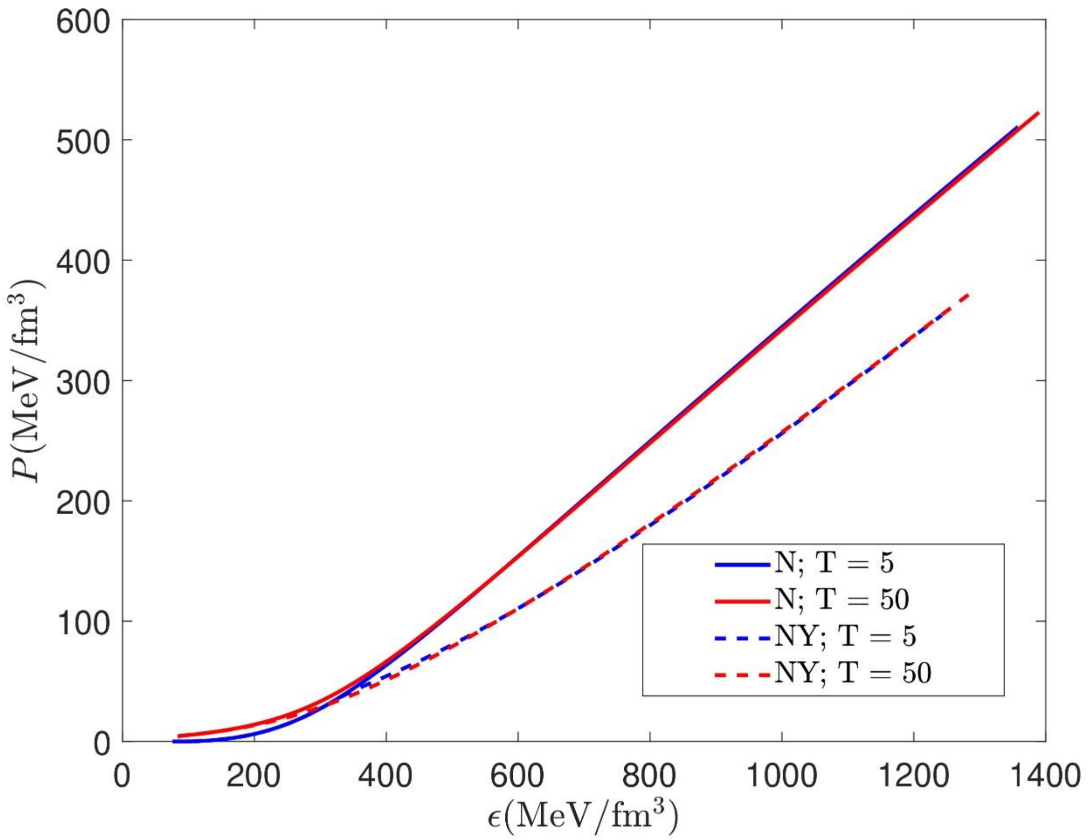
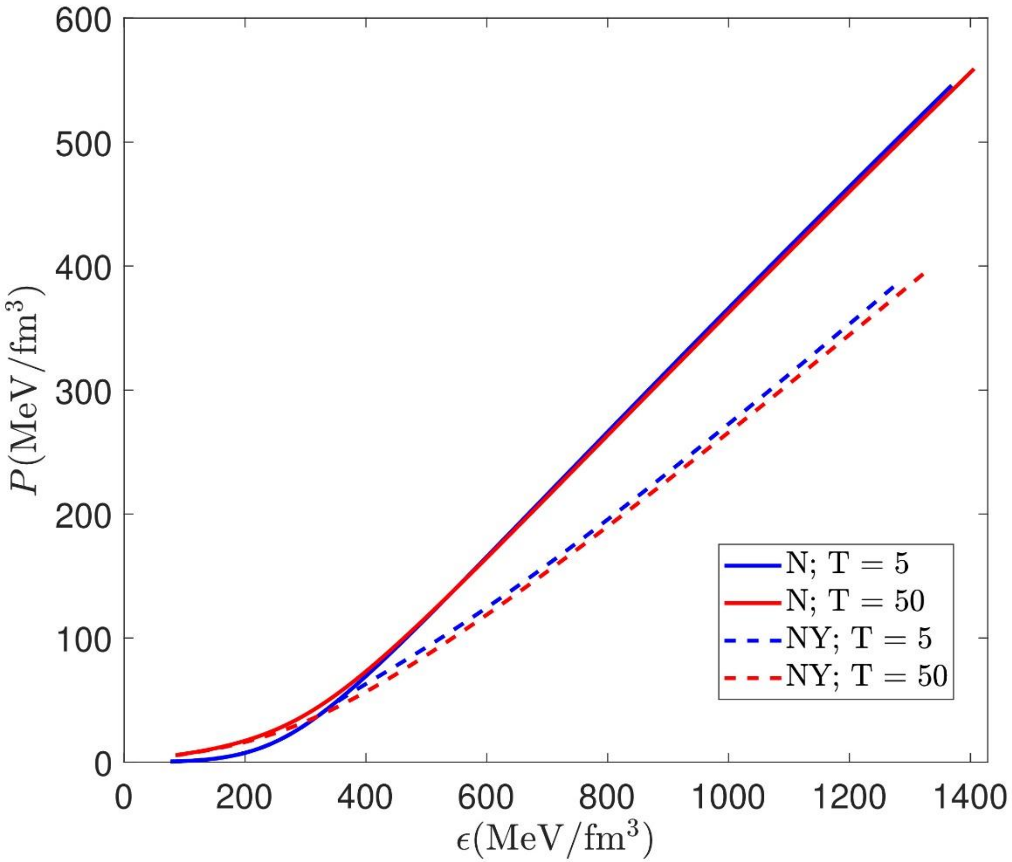
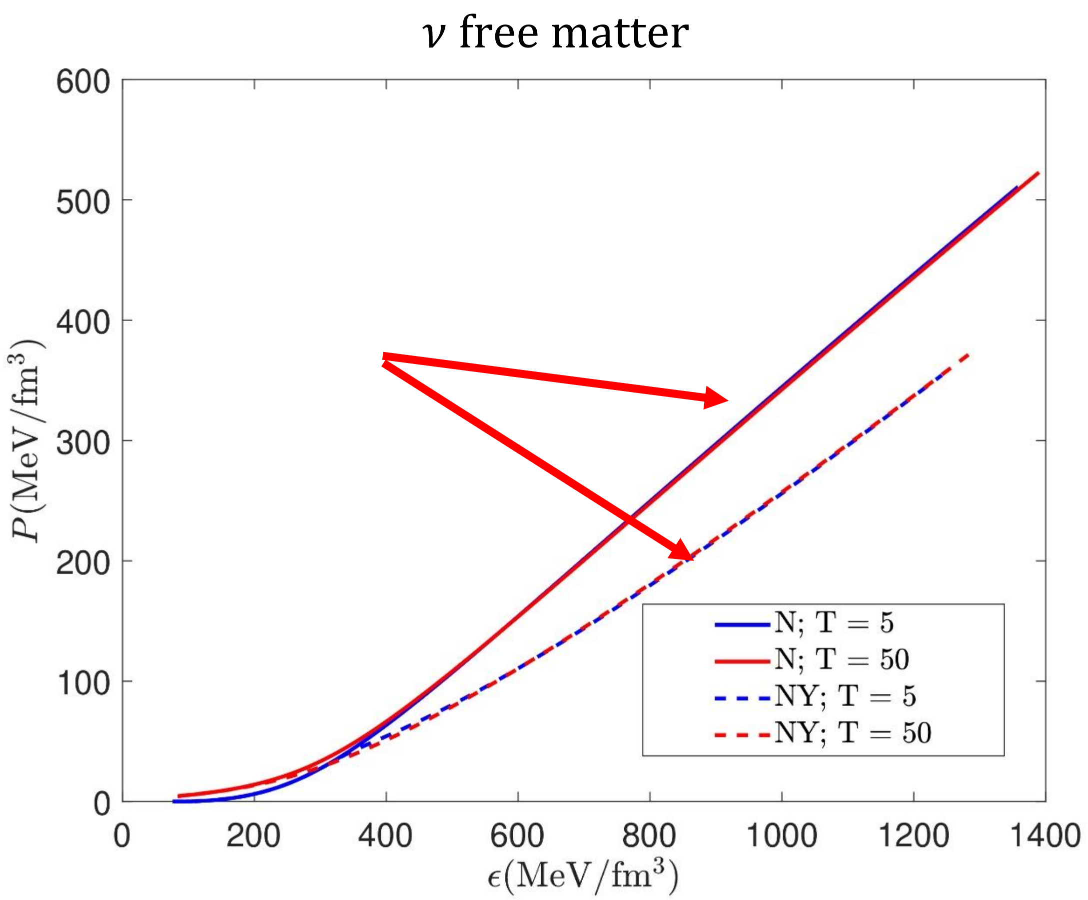
ν free matter

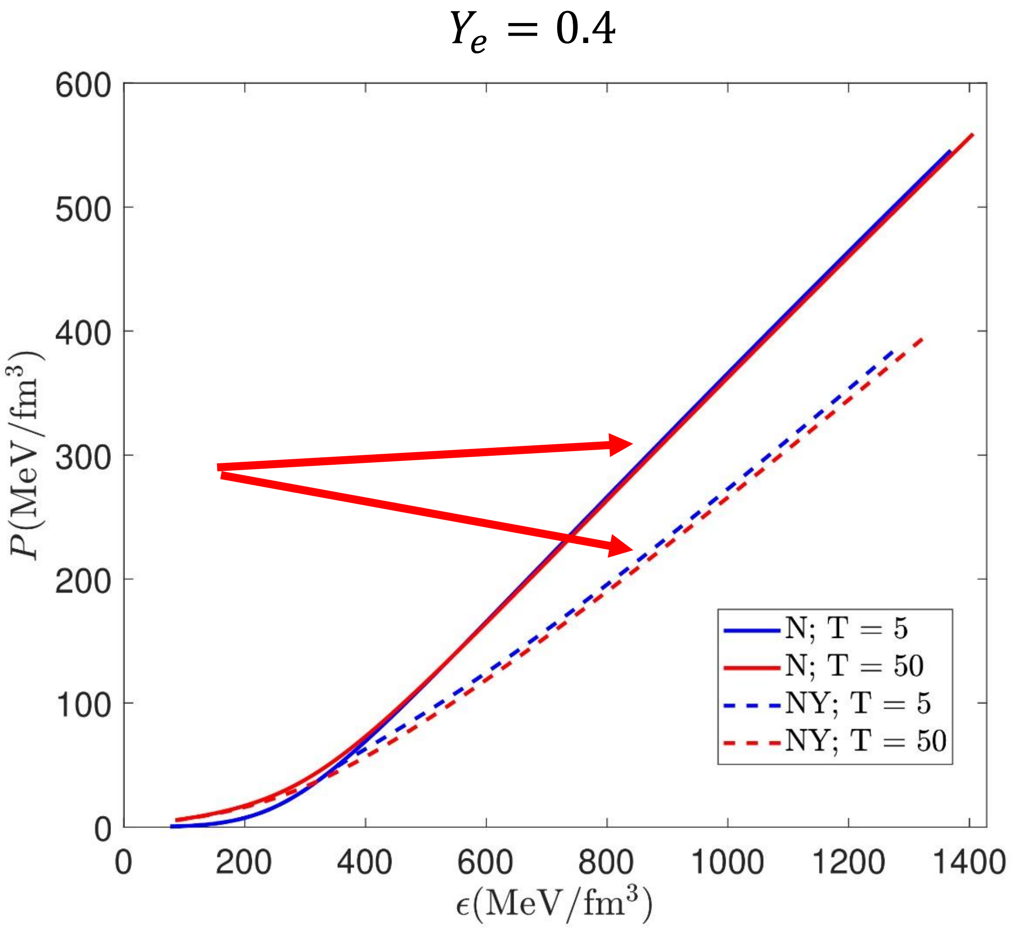


$Y_e = 0.4$



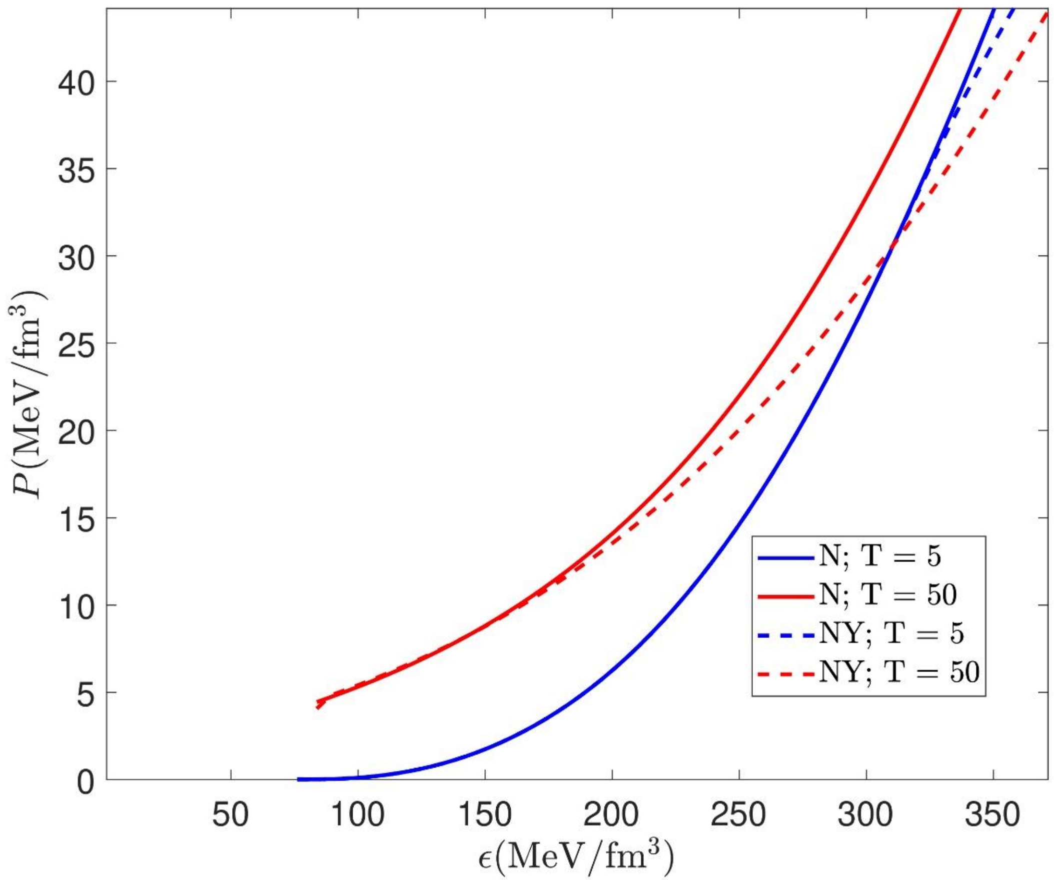
Composition and EoS of hot neutron star core III

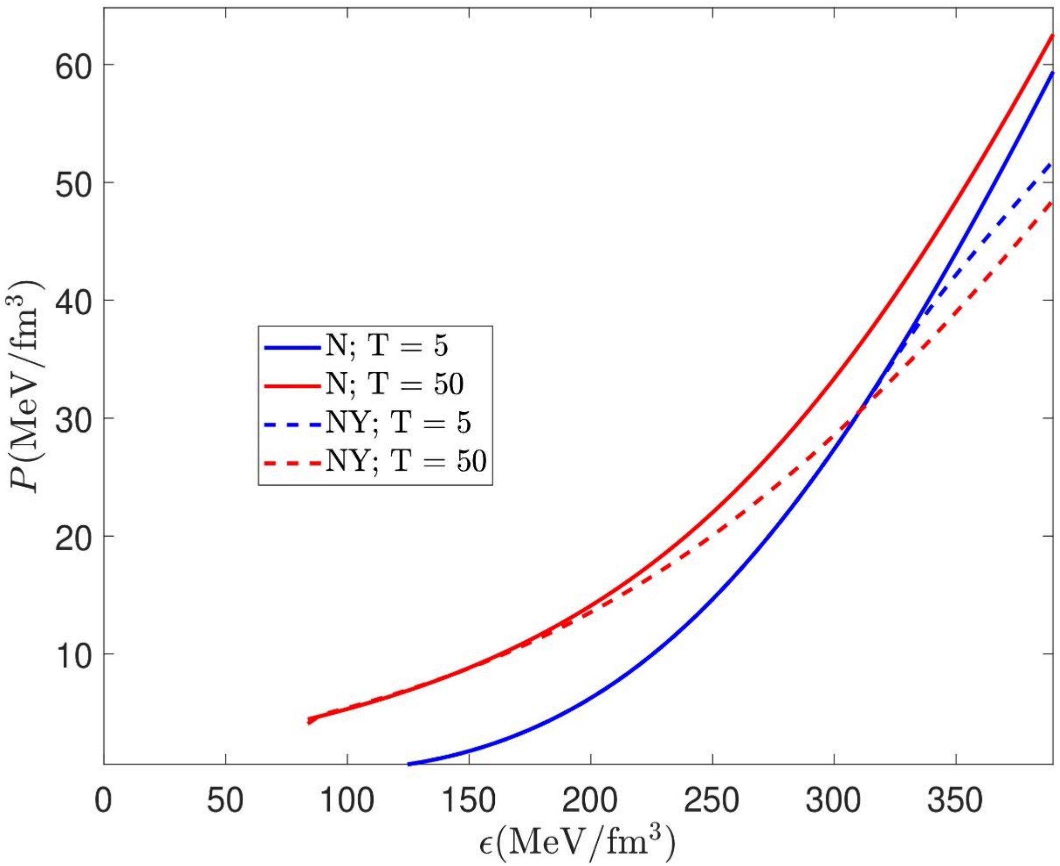




- Hyperons induce significant softening of the EoS
- When neutrinos are trapped, the EoS becomes stiffer

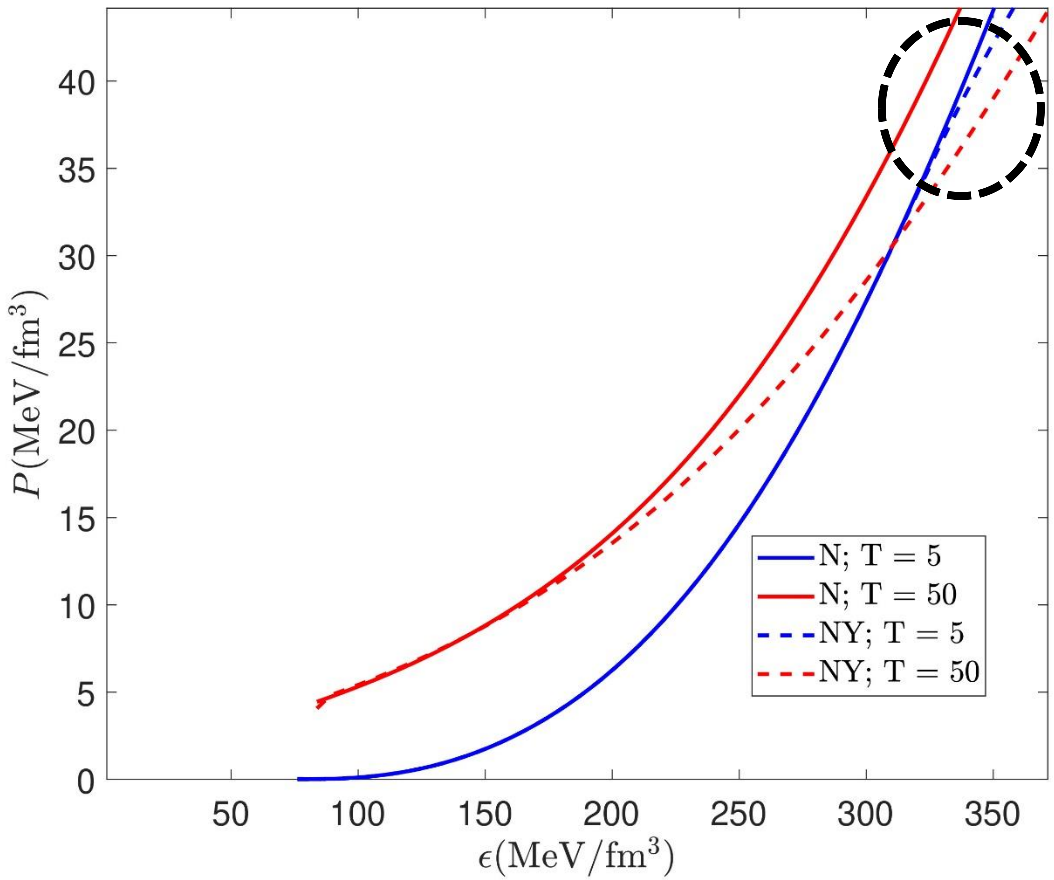
Composition and EoS of hot neutron star core III

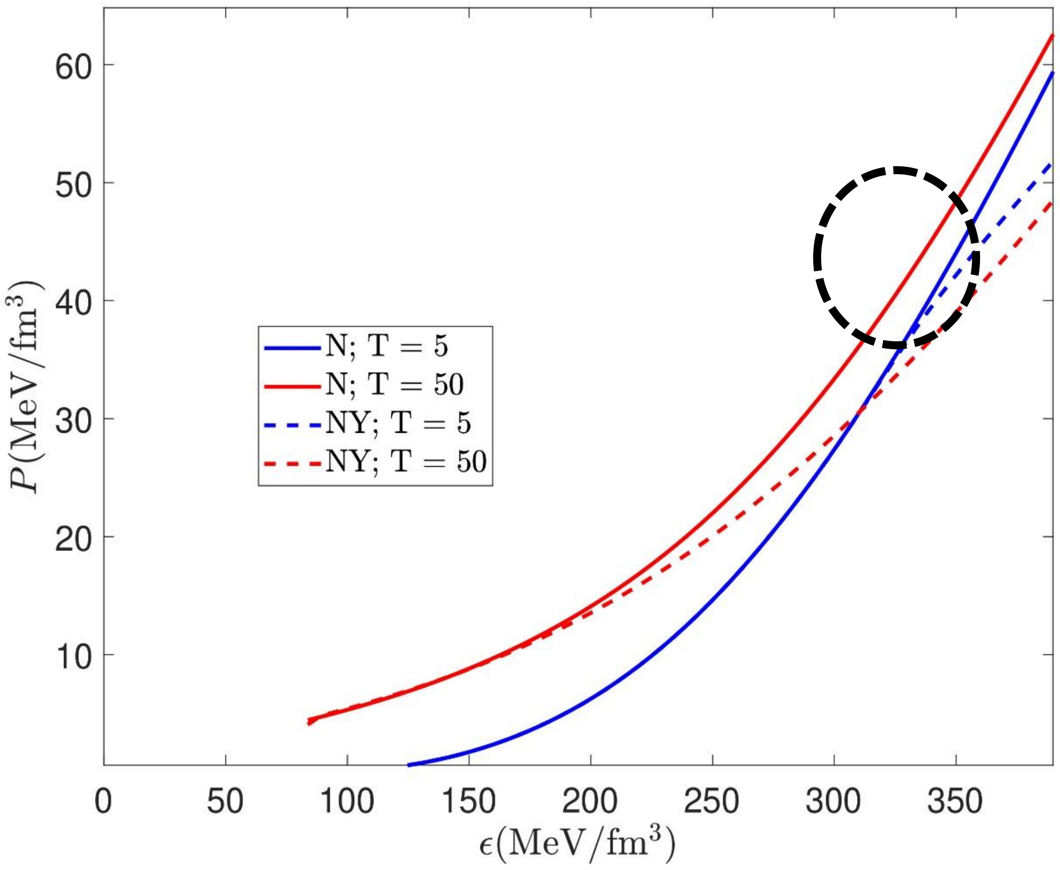




- Hyperons induce significant softening of the EoS
- When neutrinos are trapped, the EoS becomes stiffer
- At low temperatures their production changes the slope of the curve

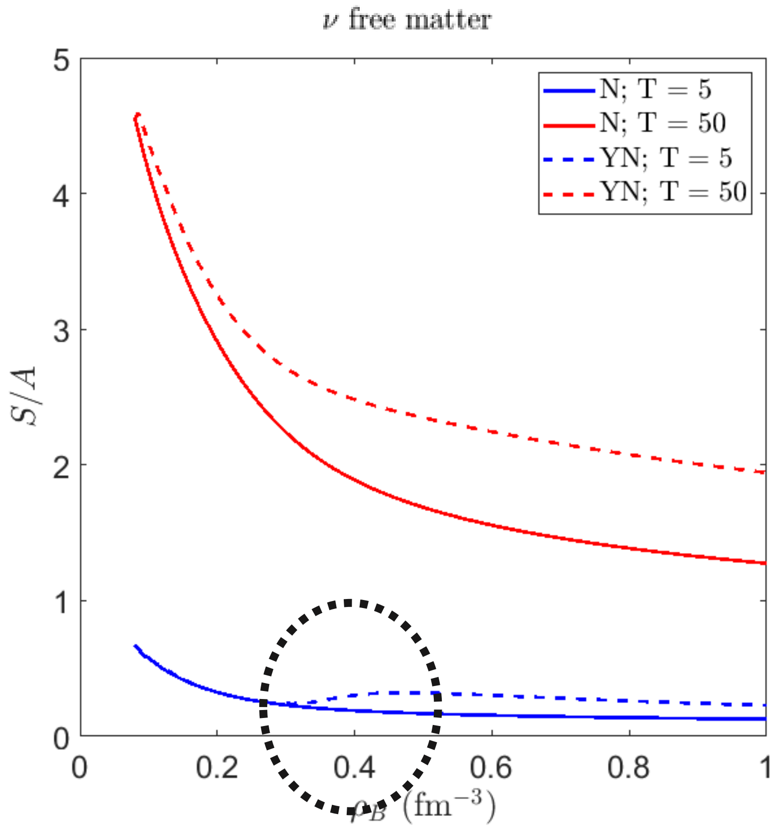
Composition and EoS of hot neutron star core III

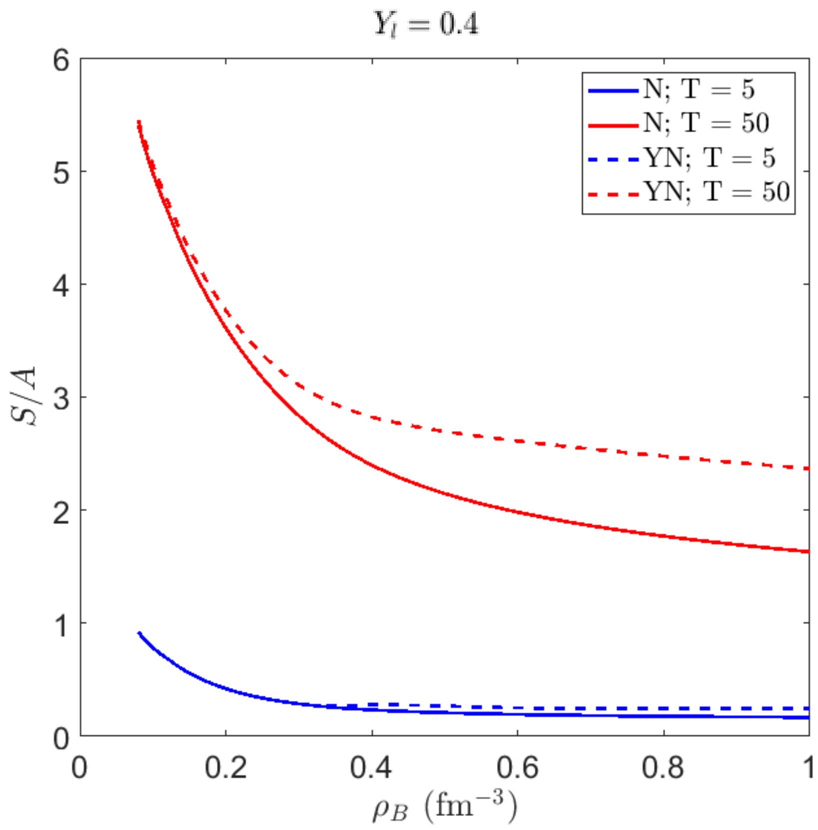




- Hyperons induce significant softening of the EoS
- When neutrinos are trapped, the EoS becomes stiffer
- At low temperatures their production changes the slope of the curve

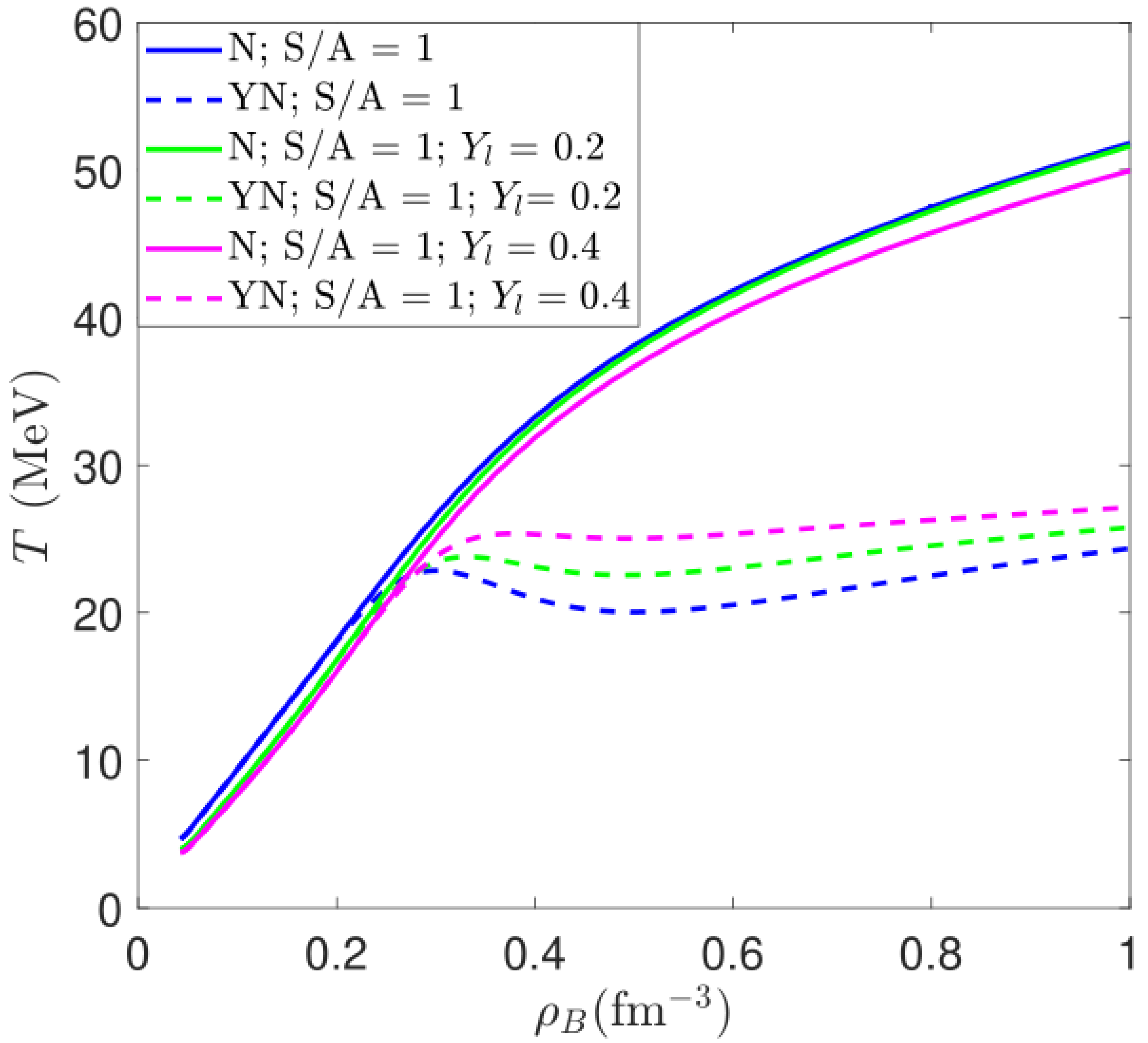
Composition and EoS of hot neutron star core IV





- Hyperons have strong influence on the entropy per particle
- The effect is more important in ν free matter
- At low temperatures can even break the monotonous behavior of the curve

Composition and EoS of hot neutron star core IV



- Important for stars with isentropic profile
- Flattening the temperature profile in wide range of the core

OUTLINE

- Motivation. Structure of Neutron Stars (NS)
- Brief introduction to FSU2H* model
- Equation of State (EoS) and Composition of hot neutron star core
- ***Thermal index of neutron star core***
- Summary

Thermal index - introduction

- Useful in complicated simulations in order to reproduce thermal effects on the EoS

$$\Gamma(\rho_B, T) \equiv 1 + \frac{P_{\rm th}}{\epsilon_{\rm th}} \qquad P_{\rm th} = P(\rho_B, T) - P(\rho_B, T=0)$$
$$\epsilon_{\rm th} = \epsilon(\rho_B, T) - \epsilon(\rho_B, T=0)$$

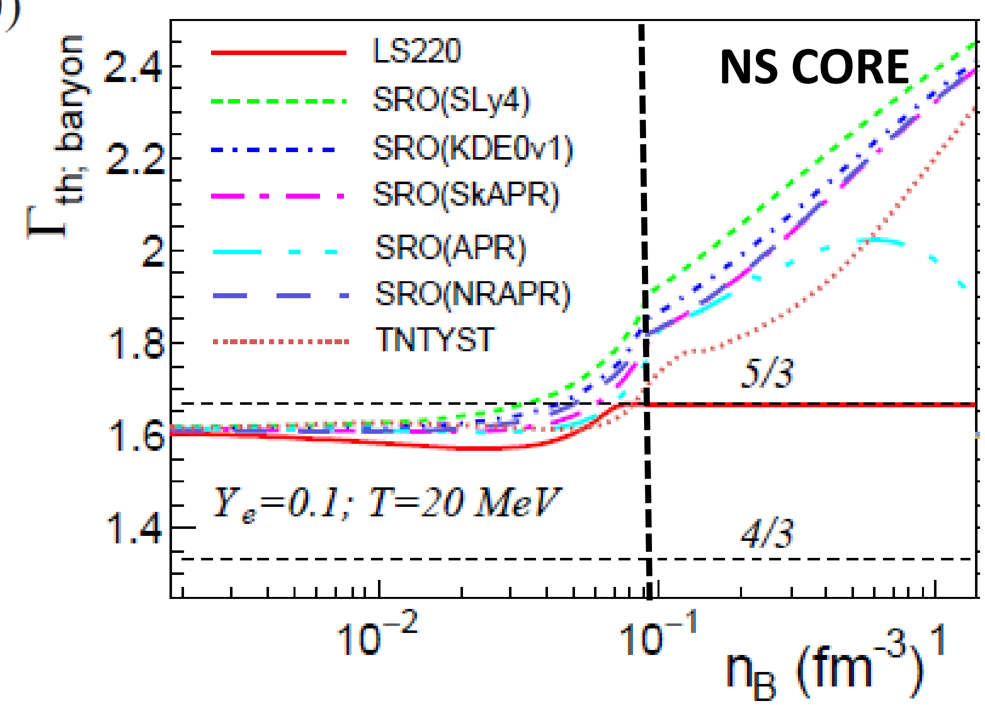
- One decomposes the energy density and the pressure to a zero-temperature contribution and a thermal correction

- Simulation uses Γ that is constant, so $P(\epsilon)$ relation can be found only knowing $T=0$ EoS:

$$\boldsymbol{P} = P(T=0) + (\Gamma - 1)(\boldsymbol{\epsilon} - \epsilon(T=0))$$

- The parameter that is evolving with the time in simulations is the energy density, so the equation above is from a special interest

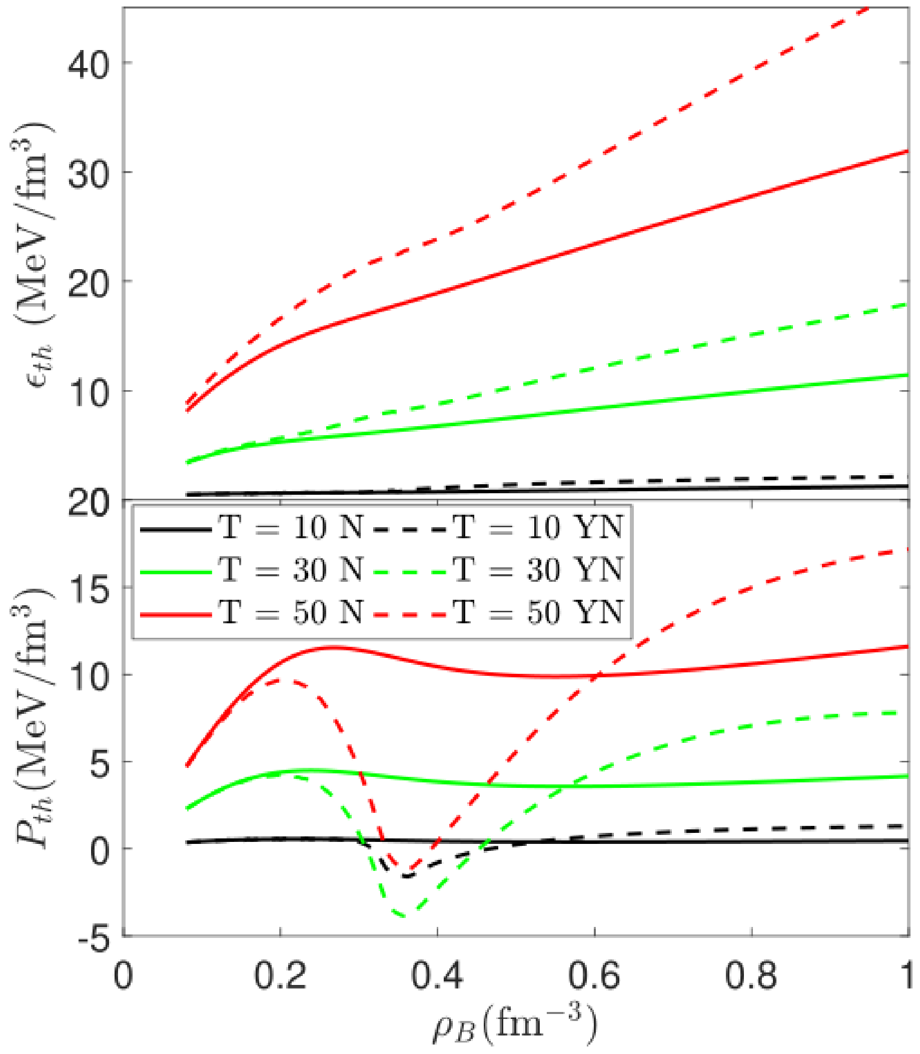
However, this approach can be inaccurate!

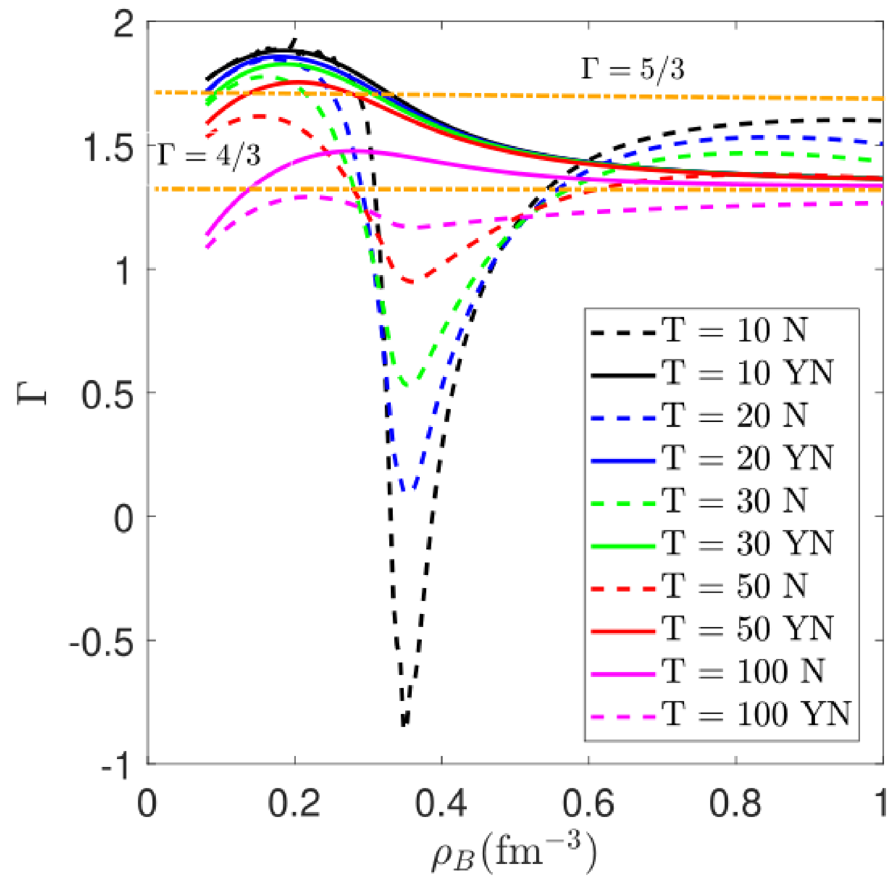


arXiv:2109.00251v1

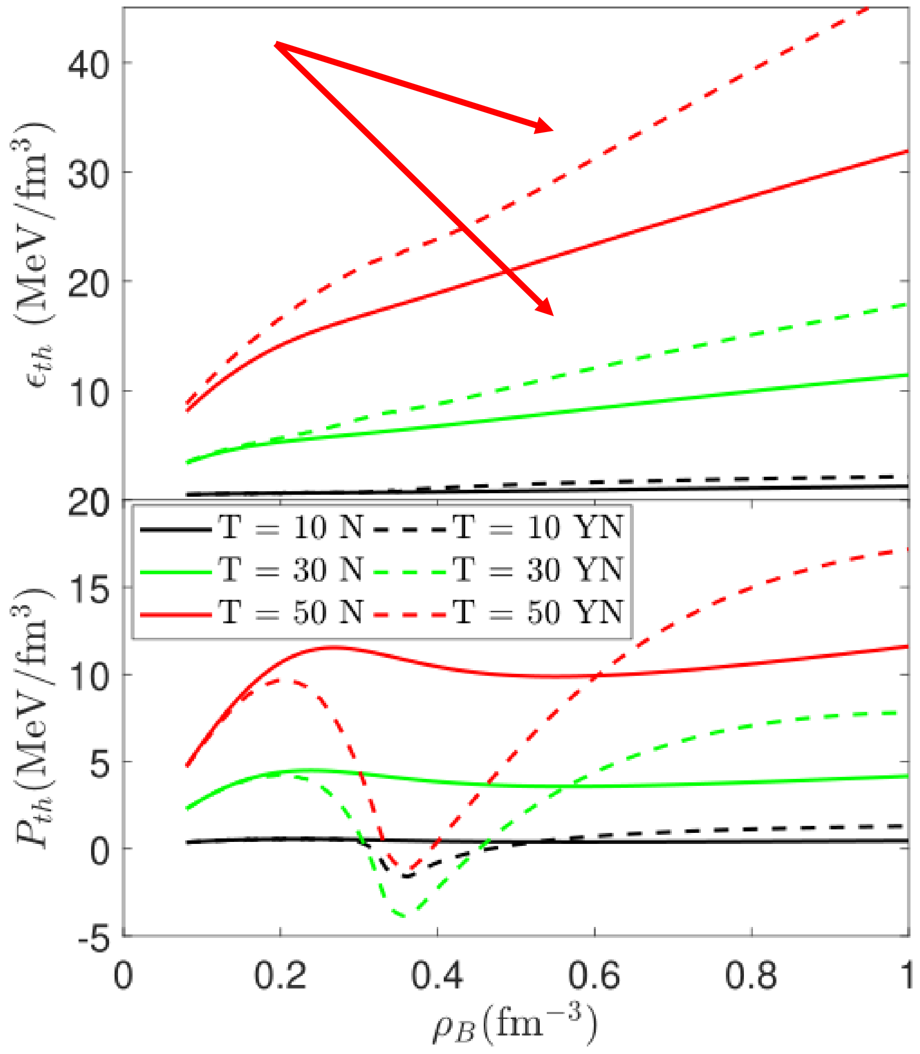
In all models on the graph, nucleons are the only baryons considered

Thermal index – β- stable ν free matter in FSU2H* I

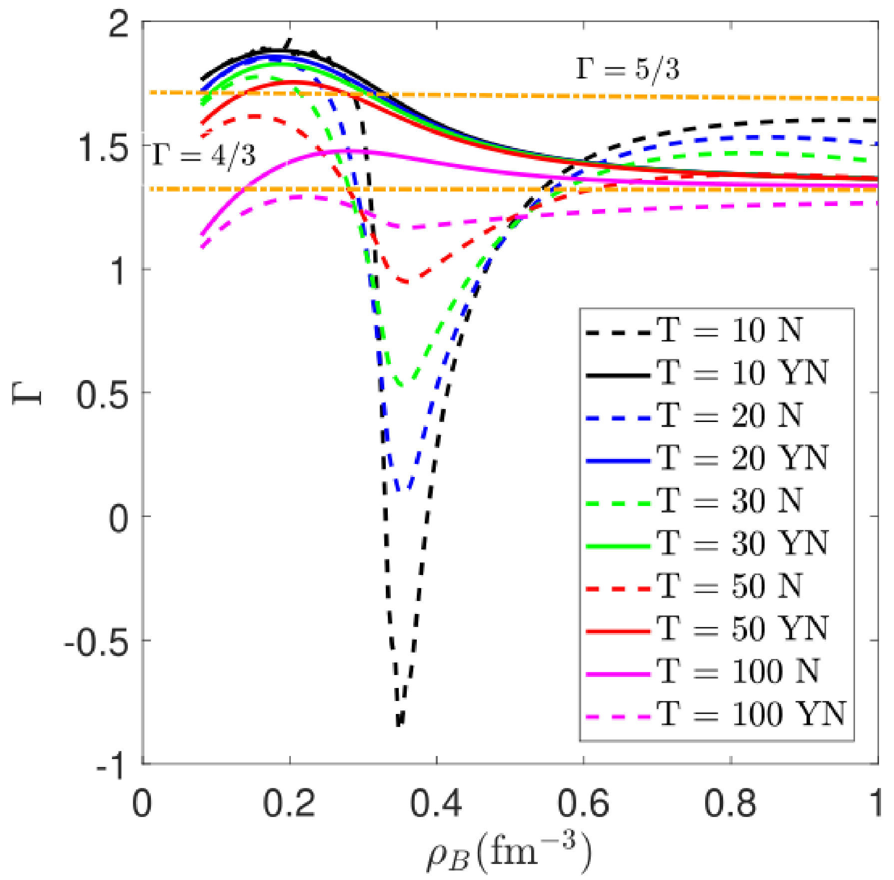




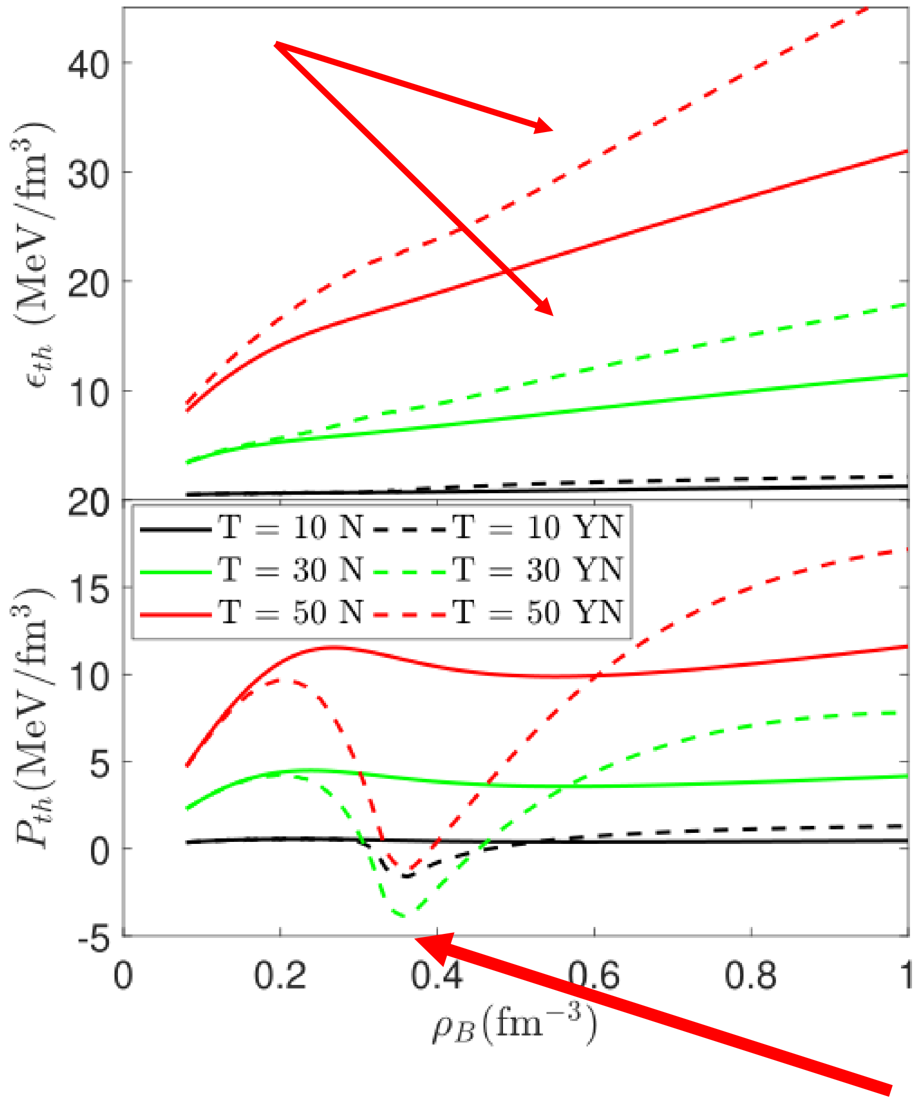
Thermal index – β- stable ν free matter in FSU2H* I



- Thermal effects are more emphasized when hyperons are included

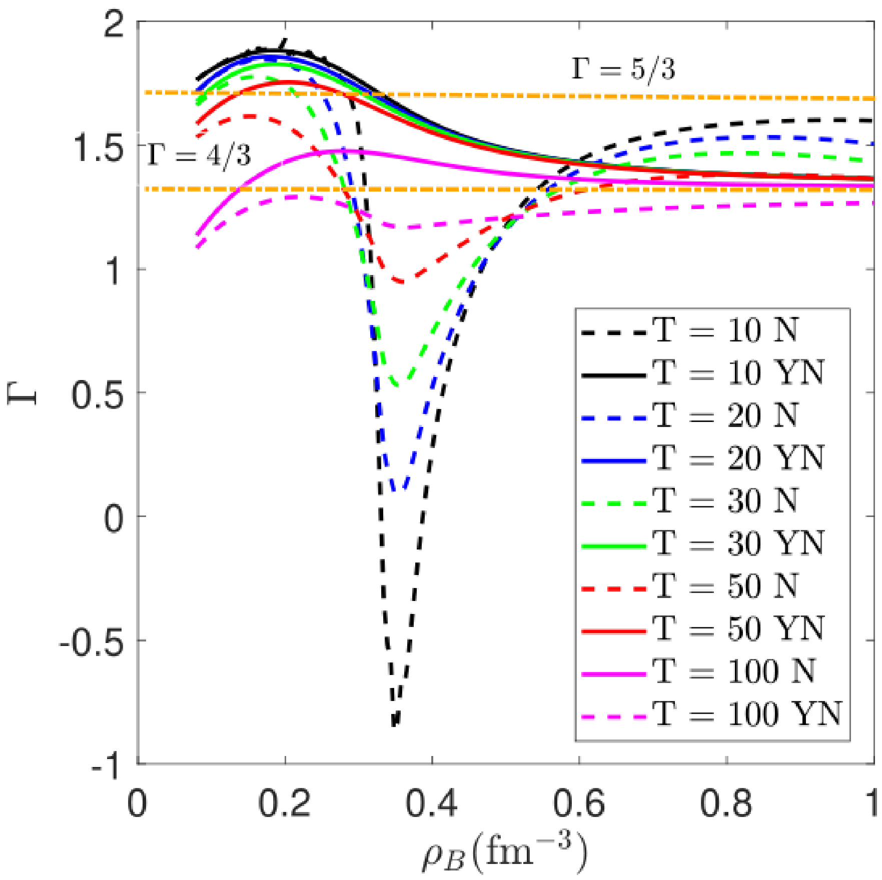


Thermal index – β- stable ν free matter in FSU2H* I

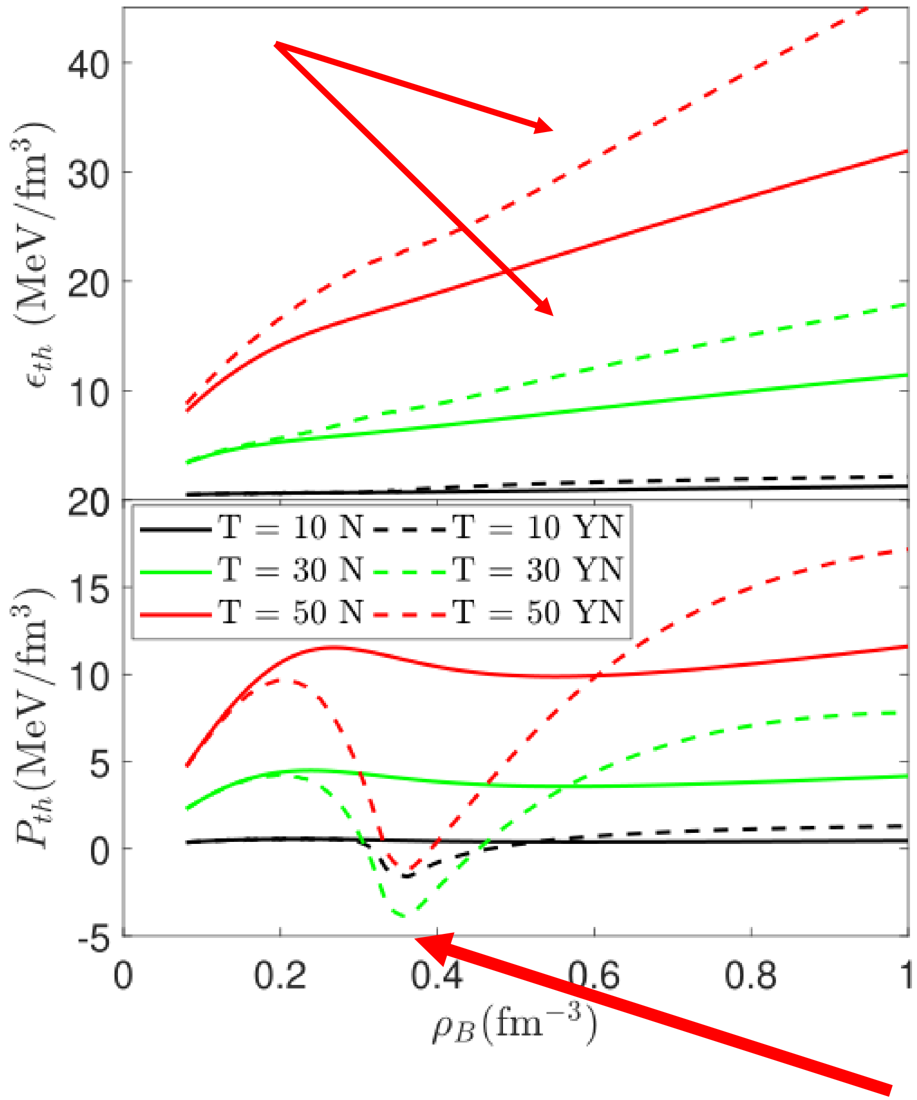


- Thermal effects are more emphasized when hyperons are included

- Significant effect on the thermal pressure – **can be lower than 0!**



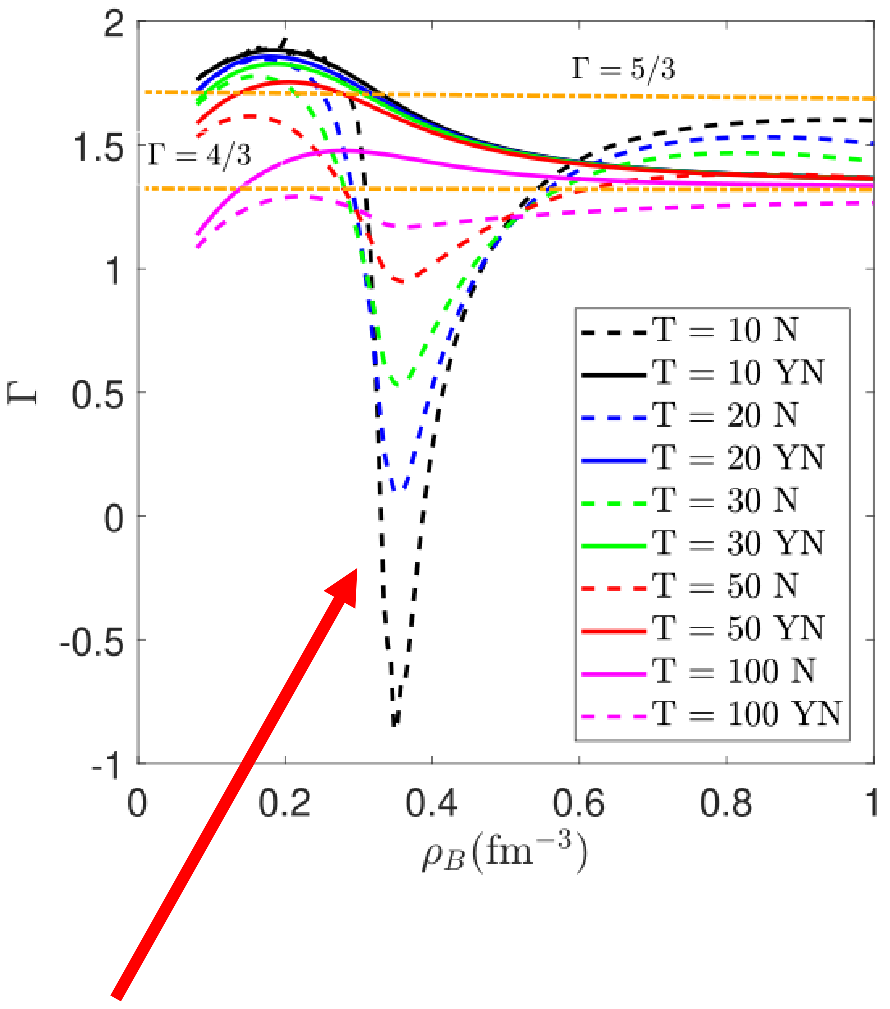
Thermal index – β- stable ν free matter in FSU2H* I



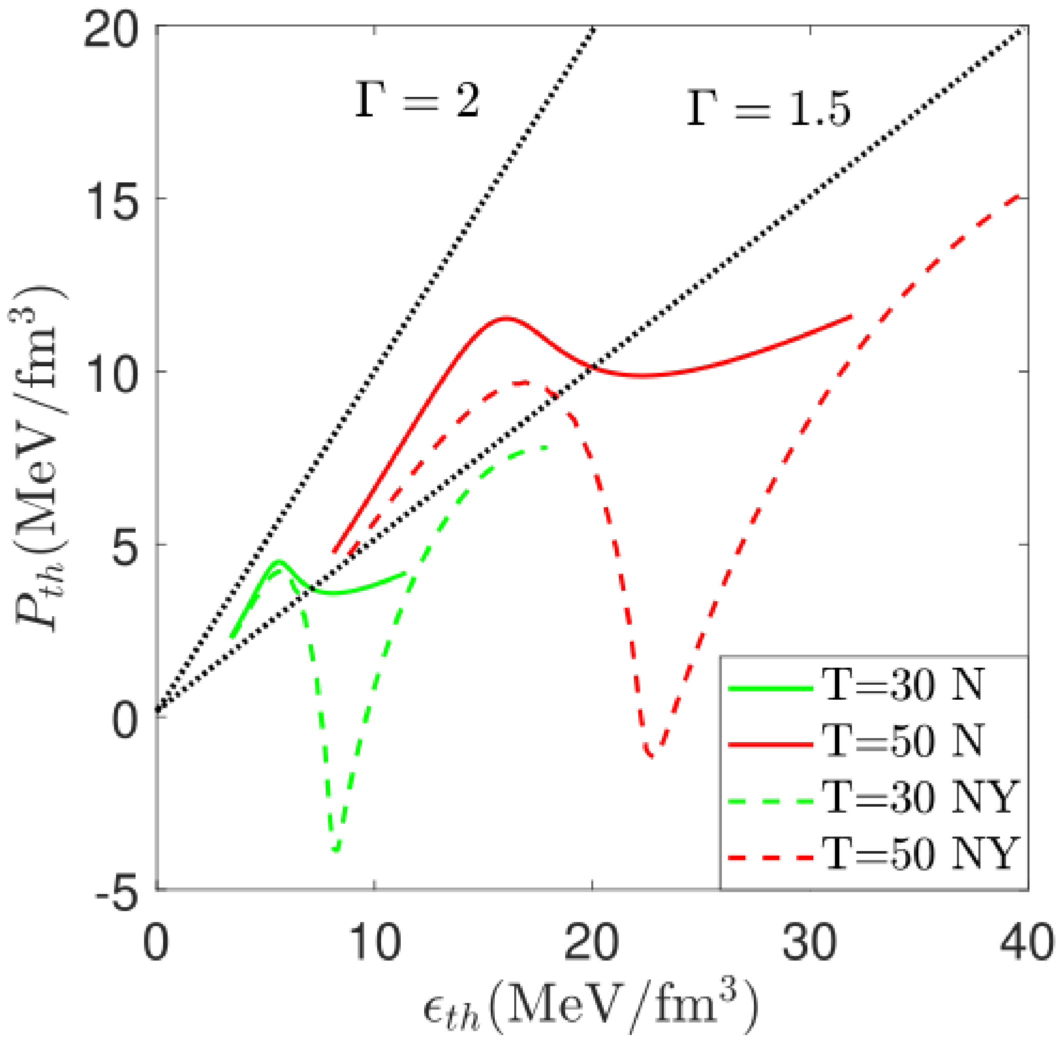
- Thermal effects are more emphasized when hyperons are included

- Significant effect on the thermal pressure – **can be lower than 0!**

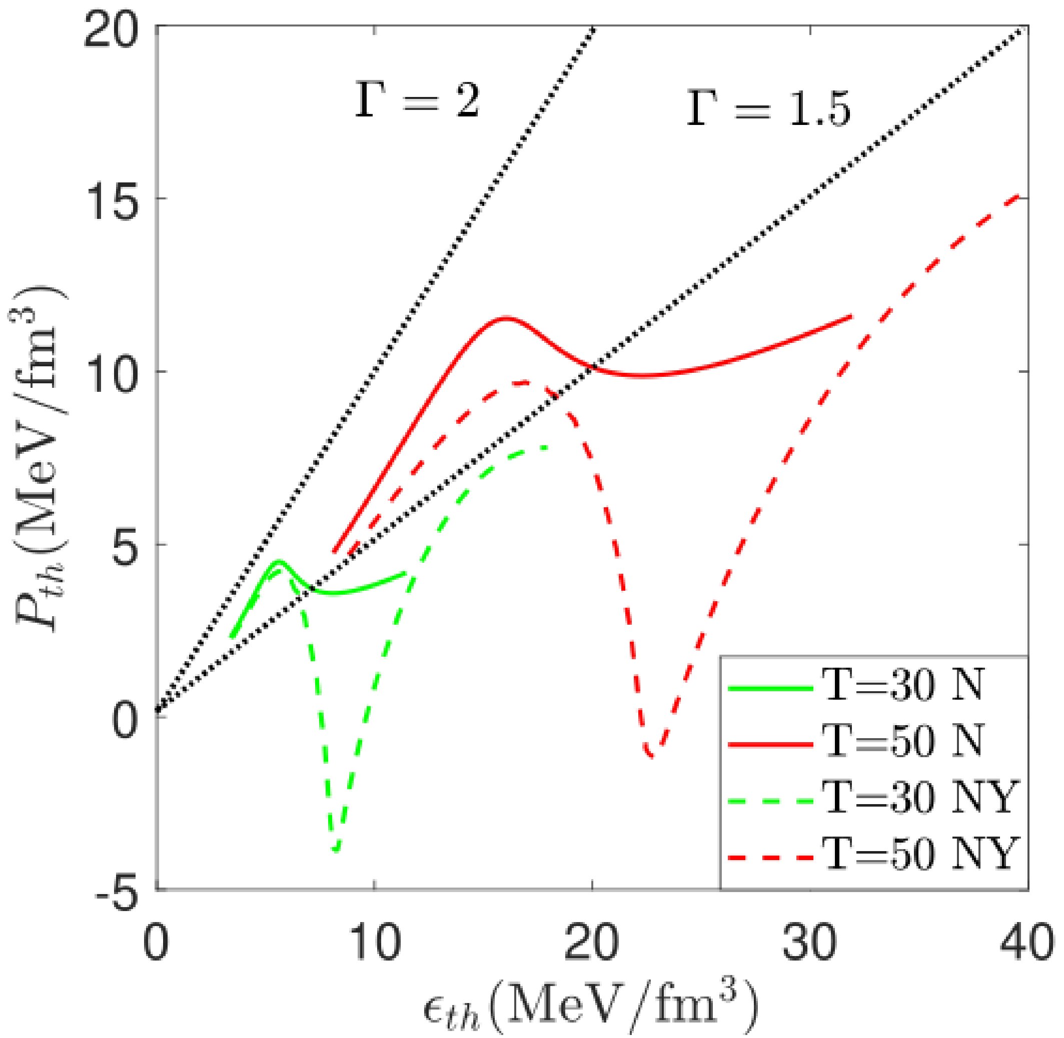
- Thermal index is directly affected by the behavior of p_{th}



Thermal index – β- stable ν free matter in FSU2H* II

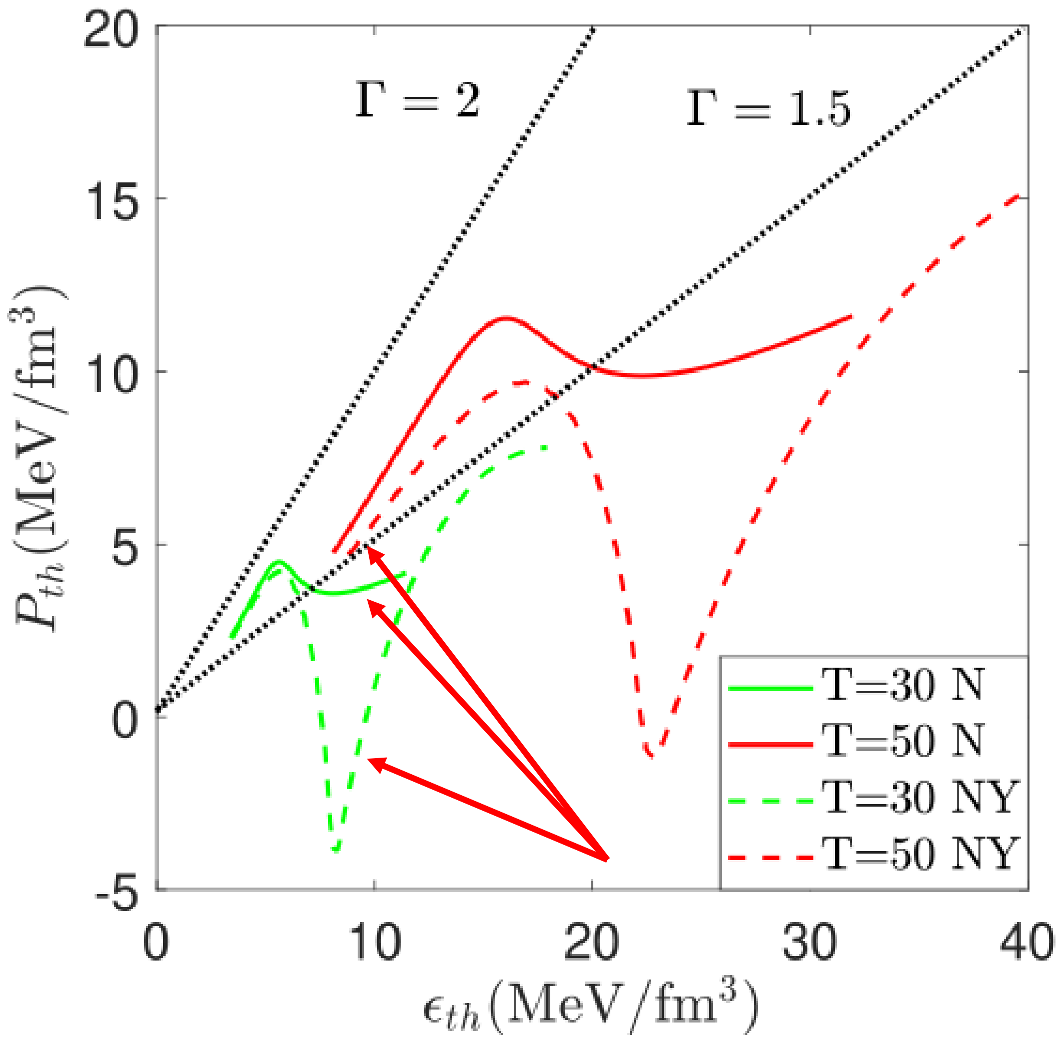


Thermal index – β- stable ν free matter in FSU2H* II



$$P_{th} = (\Gamma - 1)\epsilon_{th}$$

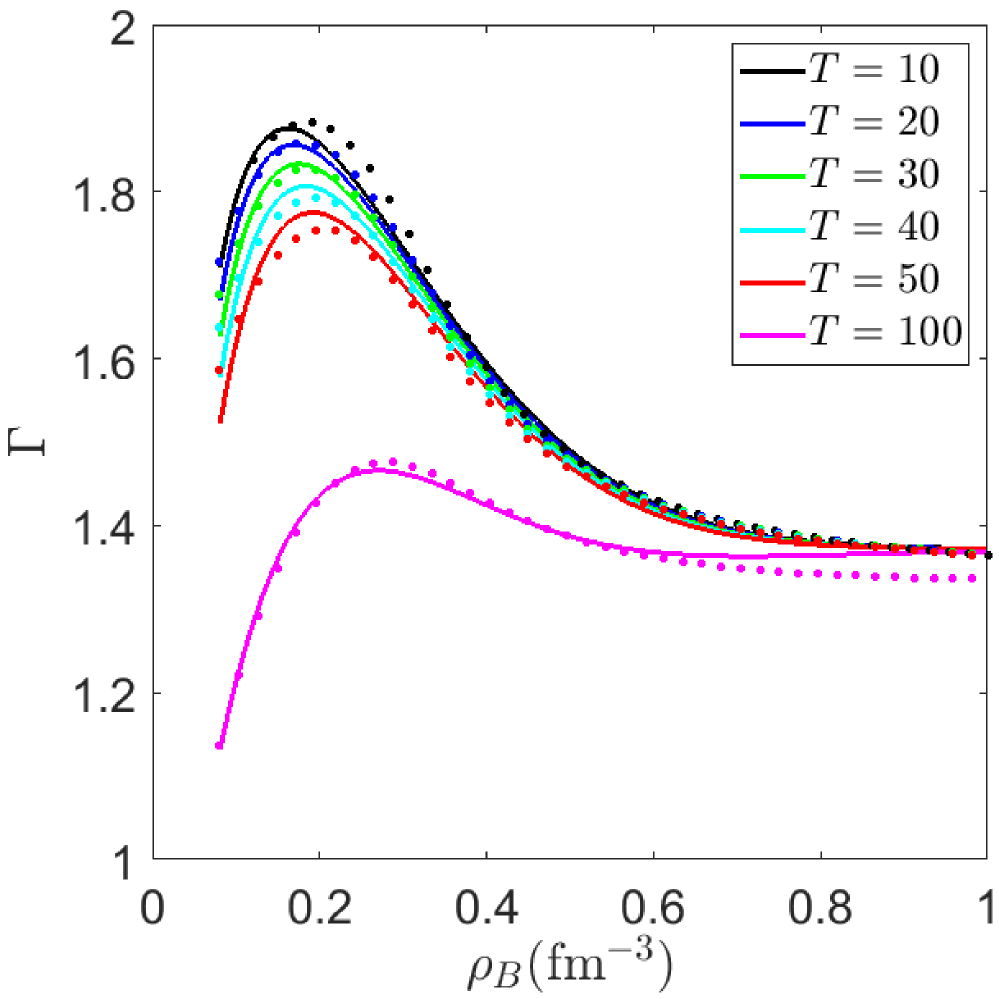
Thermal index – β- stable ν free matter in FSU2H* II



$$P_{th} = (\Gamma - 1)\epsilon_{th}$$

Thermal effects calculated with constant Γ index are not accurate!

Thermal index – parametrization of the thermal index I



NEUTRINOLESS NUCLEONS ONLY CASE

- We assume that the thermal index has the following functional dependence:

$$\Gamma(\rho_B, T) = a_1 + b_1\,\mathrm{e}^{-c(T)\rho_B^2} + d_1\,\mathrm{e}^{-e(T)\rho_B}$$

$$c(T) = c_1 T + c_2$$

$$e(T) = e_1 T + e_2$$

- The values of the parameters:

i	a_i	b_i	c_i	d_i	e_i
1	1.37	6.89×10^{-1}	1.69×10^{-3}	1.47	-1.41×10^{-1}
2	/	/	6.59	/	20.29

Thermal index – parametrization of the thermal index I

NEUTRINOLESS HYPERONIC CASE

- We assume that the thermal index has the following functional dependence:

$$\Gamma(\rho_B, T) = \frac{a(T)\rho_B + b(T)}{(\rho_B - \rho_{B_c})^2 + c(T)\rho_B + d(T) + e(T)\rho_B + f(T)\sqrt{\rho_B} + g(T)}$$

$$a(T) = a_1 T + a_2$$

$$b(T) = b_1 T + b_2$$

$$c(T) = c_1 T^2 + c_2 T + c_3$$

$$d(T) = d_1 T^2 + d_2 T + d_3$$

$$e(T) = e_1 T^2 + e_2 T + e_3$$

$$f(T) = f_1 T + f_2$$

$$g(T) = g_1 T^2 + g_2 T + g_3$$

$$\rho_{Bc} = 0.3715 \ \text{fm}^{-3}$$

Thermal index – parametrization of the thermal index I

NEUTRINOLESS HYPERONIC CASE

- We assume that the thermal index has the following functional dependence:

$$\Gamma(\rho_B, T) = \frac{a(T)\rho_B + b(T)}{(\rho_B - \rho_{B_c})^2 + c(T)\rho_B + d(T) + e(T)\rho_B + f(T)\sqrt{\rho_B} + g(T)}$$

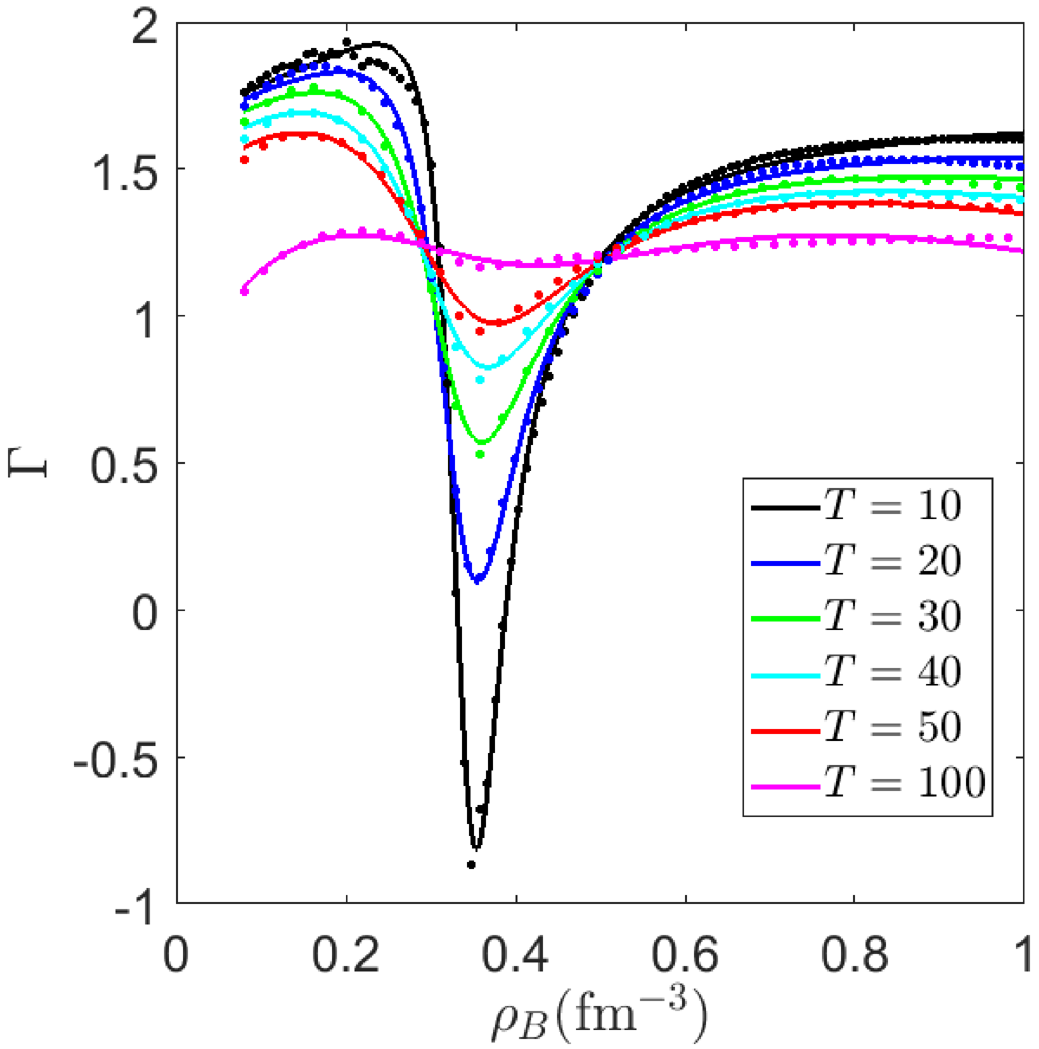
$$a(T) = a_1 T + a_2$$

$$b(T) = b_1 T + b_2$$

$$c(T) = c_1 T^2 + c_2 T + c_3$$

i	a_i	b_i	c_i	d_i	e_i	f_i	g_i
1	-2.02×10^{-4}	1.98×10^{-2}	-1.71×10^{-5}	1.24×10^{-5}	1.11×10^{-4}	3.21×10^{-2}	-6.64×10^{-5}
2	-6.14×10^{-2}	-1.26×10^{-4}	1.83×10^{-3}	-6.22×10^{-4}	-3.63×10^{-2}	2.60×10^{-1}	-5.13×10^{-3}
3	/	/	1.56×10^{-2}	-4.83×10^{-3}	7.15×10^{-2}	/	1.48

Thermal index – parametrization of the thermal index I



NEUTRINOLESS HYPERONIC CASE

- We assume that the thermal index has the following functional dependence:

$$\Gamma(\rho_B, T) = \frac{a(T)\rho_B + b(T)}{(\rho_B - \rho_{B_c})^2 + c(T)\rho_B + d(T) + e(T)\rho_B + f(T)\sqrt{\rho_B} + g(T)}$$

$$a(T) = a_1 T + a_2$$

$$b(T) = b_1 T + b_2$$

$$c(T) = c_1 T^2 + c_2 T + c_3$$

	d_i	e_i	f_i	g_i
−5	1.24×10^{-5}	1.11×10^{-4}	3.21×10^{-2}	-6.64×10^{-5}
3	-6.22×10^{-4}	-3.63×10^{-2}	2.60×10^{-1}	-5.13×10^{-3}
2	-4.83×10^{-3}	7.15×10^{-2}	/	1.48

Summary

- We extended the **FSU2H** hyper-nucleonic model to **finite temperature**, constructing the new so-called **FSU2H*** model, in order to be used in early stages of NS evolution and in NS mergers.

- The model satisfies the major constraints that come from nuclear experiments and astrophysical measurements.

- In order to get the properties of the matter computed within the framework of our model, we performed calculations for β - stable matter at different temperatures and different lepton fractions.

- The composition patterns and the EoS are strongly affected by the introduction of hyperons.

- Thermal effects in the star cannot be reproduced with high accuracy with the so-called Γ-law, and that is especially important when hyperons are considered in the core.

- A simple parametrization is constructed to account for the strong dependence of the thermal index in ν-less beta stable matter.

Thank you for your attention

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Laura Tolos
Angels Ramos

EXOTICO workshop 2022
Trento, Italy

17-21 October 2022

EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

FONDAZIONE BRUNO KESSLER

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AGENCIA ESTATAL DE INVESTIGACIÓN

ICCUB

Backup slides

RMF model extended I

$$(i\gamma_\mu \partial^\mu - m_b^* - g_{\omega b}\gamma_0\omega^0 - g_{\phi b}\gamma_0\phi^0 - g_{\rho b} I_{3b}\gamma_0\rho_3^0)\Psi_b = 0,$$
$$(i\gamma_\mu\, \partial^\mu - q_l\, \gamma_\mu\, A^\mu - m_l)\, \psi_l = 0,$$

Baryon’s and lepton’s equations of motions

$$\rho_b = <\bar{\Psi}_b\gamma^0\Psi_b> = \frac{\gamma_b}{2\pi^2}\int_0^\infty dk\, k^2\, f_b(k,T),$$
$$\rho_b^s = <\bar{\Psi}_b\Psi_b> = \frac{\gamma_b}{2\pi^2}\int_0^\infty dk\, k^2\, \frac{m_b^*}{\sqrt{k^2 + m_b{}^{*2}}} f_b(T,k)$$

Scalar and baryonic density

$$m_\sigma^2\bar{\sigma} + \frac{\kappa}{2}g_{\sigma b}^3\bar{\sigma}^2 + \frac{\lambda}{3!}g_{\sigma b}^4\bar{\sigma}^3 = \sum_b g_{\sigma b}\rho_b^s,$$
$$m_{\sigma^*}^2\bar{\sigma}^* = \sum_{b^*} g_{\sigma b^*}\rho_b^s$$
$$m_\omega^2\bar{\omega} + \frac{\zeta}{3!}g_{\omega b}^4\bar{\omega}^3 + 2\Lambda_\omega g_{\rho,b}^2 g_{\omega,b}^2\bar{\omega}\bar{\rho}^2 = \sum_b g_{\omega b}\rho_b,$$
$$m_\rho^2\bar{\rho} + 2\Lambda_\omega g_{\rho,b}^2 g_{\omega,b}^2\bar{\omega}^2\bar{\rho} = \sum_b g_{\rho b} I_{3b}\rho_b,$$
$$m_\phi^2\bar{\phi} = \sum_b g_{\phi b}\rho_b,$$

Meson’s equation of motion in RMF approximation

$$f_b(k,T) = \left[1 + exp\left(\frac{\sqrt{k^2 + m_b^{*2}} - \mu_b^*}{T}\right)\right]^{-1}$$

Fermi – dirac distribution

$$\mu_b^* = \mu_b - g_{b\omega}\bar{\omega} - g_{b\rho}\bar{\rho} - g_{b\phi}\bar{\phi}.$$
$$m_b^* = m_b - g_{\sigma b}\sigma - g_{\sigma^* b}\sigma^*,$$

Effective chemical potential and charge neutrality

RMF model extended II

$$\mu_{b^0} = \mu_n,$$
$$\mu_{b^-} = 2\mu_n - \mu_p,$$
$$\mu_{b^+} = \mu_p,$$
$$\mu_n - \mu_p = \mu_e - \mu_{\nu_e},$$
$$\mu_e = \mu_\mu + \mu_{\nu_e} - \mu_{\bar{\nu}_\mu},$$

β equilibrium

$$\rho_B = \sum_b \rho_b,$$
$$Y_l \cdot \rho_B = \rho_l + \rho_{\nu_l}$$

Conservation of baryon and lepton numbers

$$T_{\mu\nu} = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \Phi_\alpha)} \partial^\mu \Phi_\alpha - \eta_{\mu\nu} \mathcal{L};$$

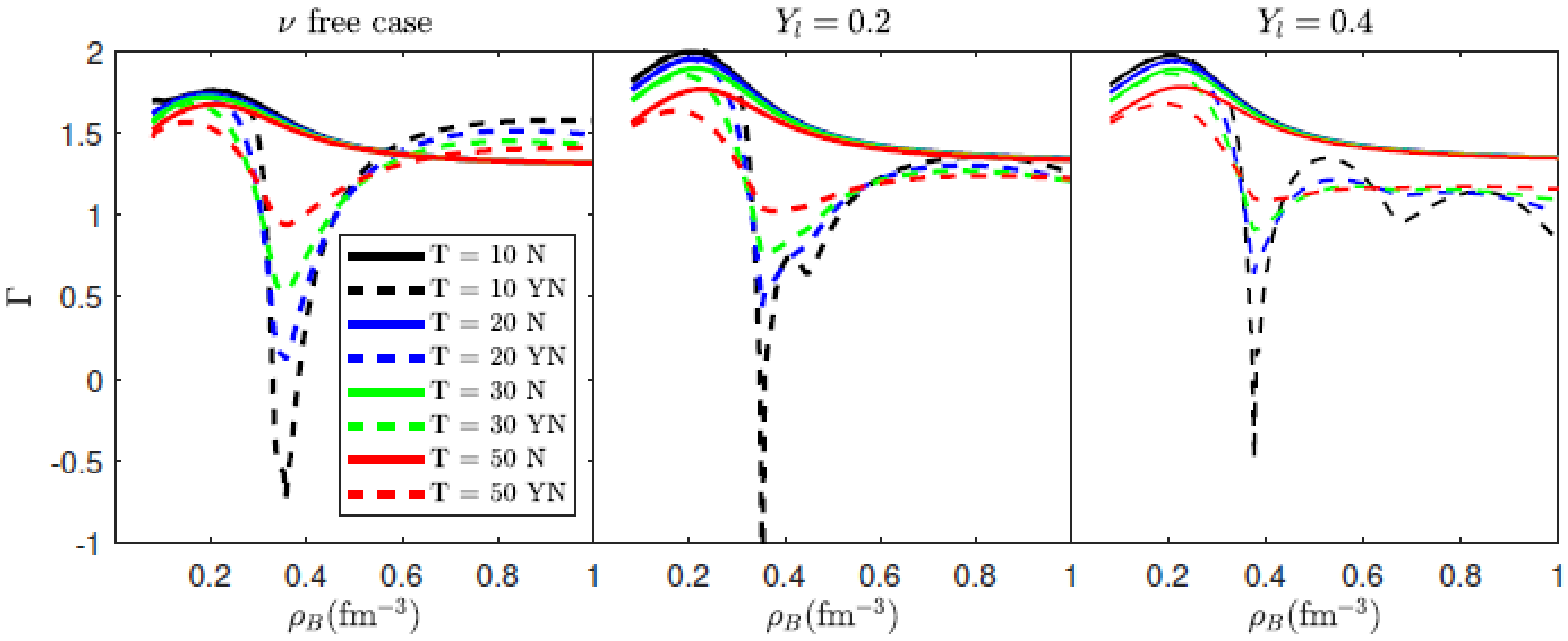
Energy-momentum tensor

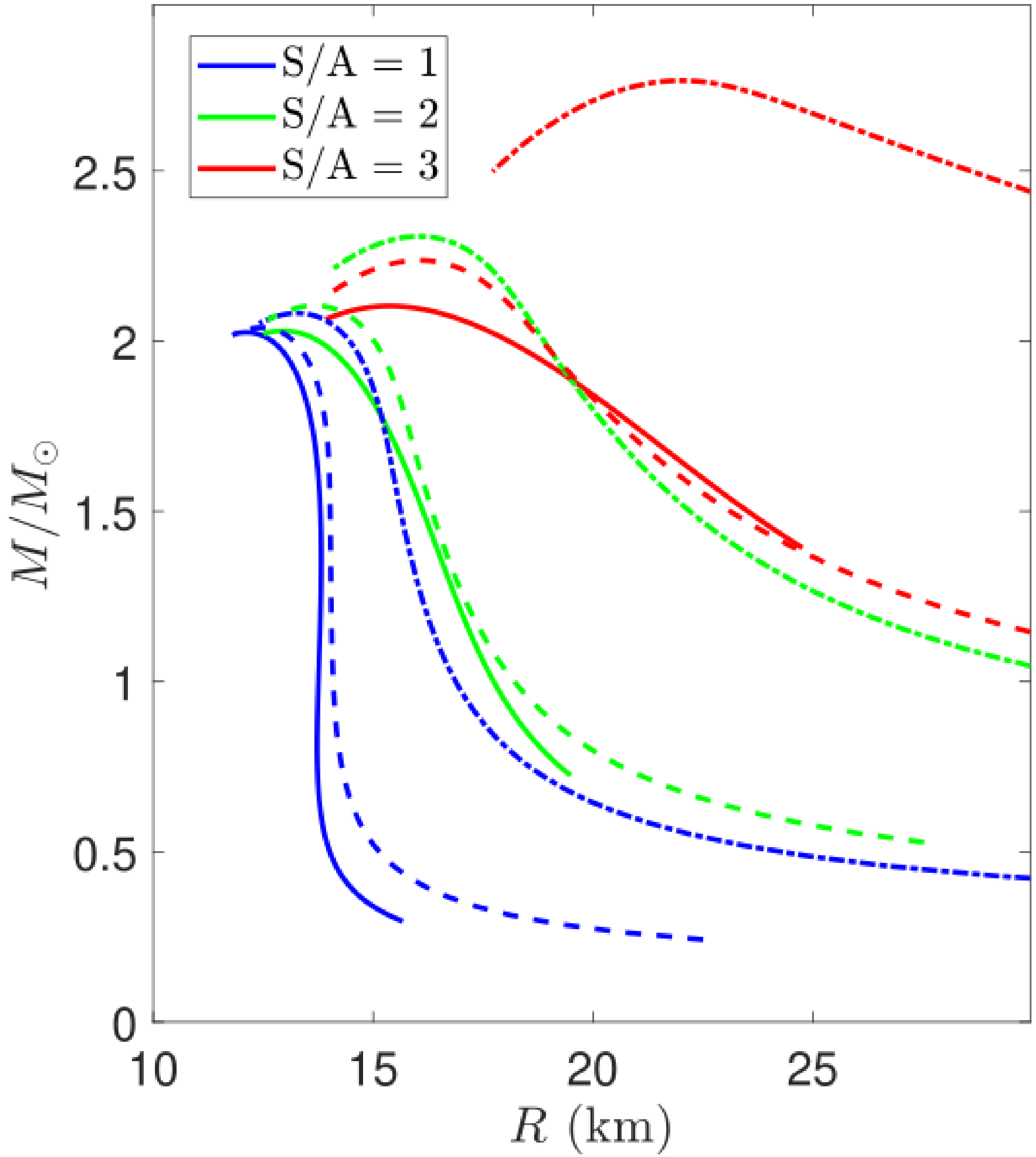
$$\begin{aligned}
\epsilon = &< T_{00} > \\
&= \frac{1}{2\pi^2} \sum_b \gamma_b \int_0^\infty dk k^2 \sqrt{k^2 + m_b^{*2}} f_b(k,T) \\
&+ \frac{1}{2\pi^2} \sum_l \gamma_l \int_0^\infty dk k^2 \sqrt{k^2 + m_l^2} f_l(k,T) \\
&+ \frac{1}{2}(m_\omega^2 \bar{\omega}^2 + m_\rho^2 \bar{\rho}^2 + m_\phi^2 \bar{\phi}^2 + m_\sigma^2 \bar{\sigma}^2 + m_{\sigma^*}^2 \bar{\sigma}^{*^2}) \\
&+ \frac{\kappa}{3!}(g_\sigma \bar{\sigma})^3 + \frac{\lambda}{4!}(g_\sigma \bar{\sigma})^4 + \frac{\zeta}{8}(g_\omega \bar{\omega})^4 + 3\Lambda_\omega (g_\rho g_\omega \bar{\rho} \bar{\omega})^2, \\
P = &\frac{1}{3} < T_{jj} > \\
&= \frac{1}{6\pi^2} \sum_b \gamma_b \int_0^\infty dk \frac{k^4}{\sqrt{k^2 + m_b^{*2}}} f_b(k,T) \\
&+ \frac{1}{6\pi^2} \sum_l \gamma_l \int_0^\infty dk \frac{k^4}{\sqrt{k^2 + m_l^2}} f_l(k,T) \\
&+ \frac{1}{2}(m_\omega^2 \bar{\omega}^2 + m_\rho^2 \bar{\rho}^2 + m_\phi^2 \bar{\phi}^2 - m_\sigma^2 \bar{\sigma}^2 - m_{\sigma^*}^2 \bar{\sigma}^{*^2}) \\
&- \frac{\kappa}{3!}(g_\sigma \bar{\sigma})^3 - \frac{\lambda}{4!}(g_\sigma \bar{\sigma})^4 + \frac{1}{24}\zeta(g_\omega \bar{\omega})^4 + \Lambda_\omega (g_\rho g_\omega \bar{\rho} \bar{\omega})^2,
\end{aligned}$$

$$s = \frac{1}{T}\left(\epsilon + P - \sum_i \mu_i \rho_i\right)$$
$$f = \sum_i \mu_i \rho_i - P.$$

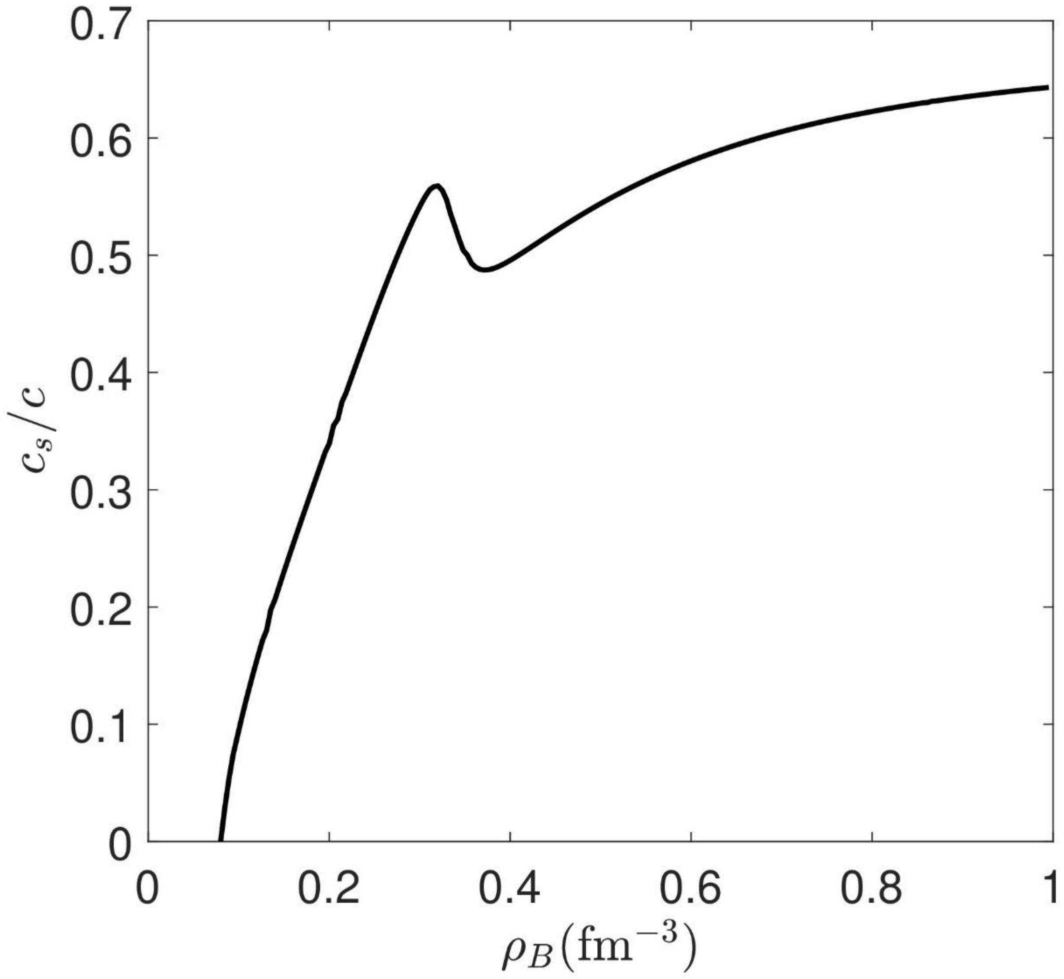
Thermodynamic quantities

Thermal index for different lepton fractions




S/A = 1
S/A = 2
S/A = 3
2.5
2
1.5
1
0.5
0
10
15
20
25
$M/M_\odot$
R (km)

Speed of sound (T = 0)



$$\frac{c_s}{c} = \sqrt{\frac{dp}{d\epsilon}}$$