Equation of state for the hot hyperonic neutron star core

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Hristijan Kochankovski, Angels Ramos
and **Laura Tolós**

Institute of Space Sciences
CSIC IEEC
FIAS Frankfurt Institute for Advanced Studies

Agència de Gestió d'Ajuts Universitaris i de Recerca AGAUR
Generalitat de Catalunya
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN
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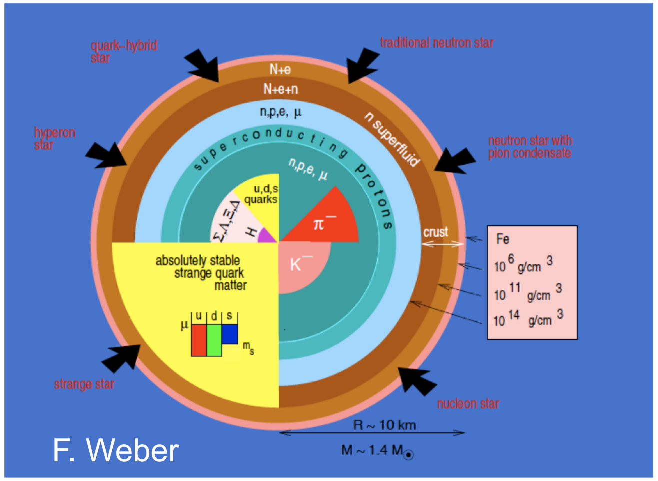
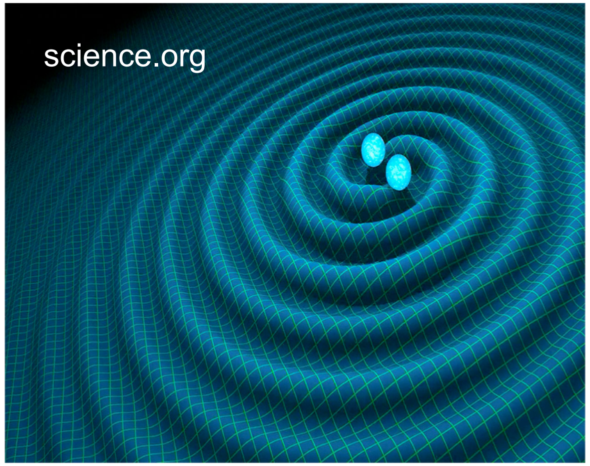
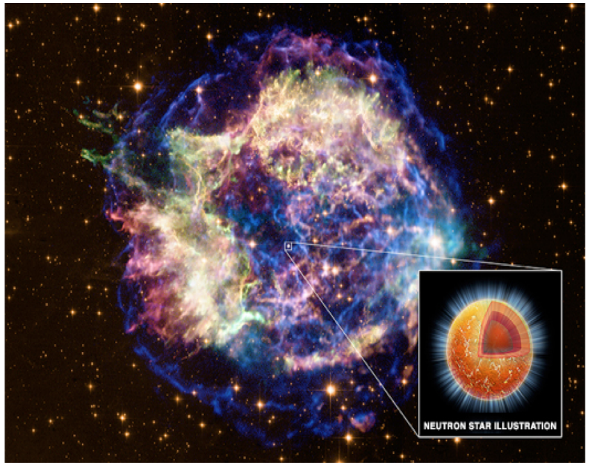
H. Kochankovski, A. Ramos and L. Tolos, 2206.11266 [astro-ph.HE]

presentation based on FAIRNESS2022 talk by H. Kochankovski

Motivation







Neutron stars are one of the most compact objects in the universe. They are a natural laboratory for studying matter under extreme conditions

The core of the neutron star is the most intriguing part as very little is known about its composition, whether only nucleonic degrees of freedom are present or more exotic components can appear.

The description of the cold neutron star core is given by one-parameter equation of state that relates the pressure to (energy)density

A finite temperature treatment is necessary in order to understand the evolution of a young neutron star, the collapse of supernovae or the merger of a binary system of neutron stars

Brief introduction to FSU2H* model

$$
\begin{aligned}
\mathcal{L} &= \sum_b \mathcal{L}_b + \mathcal{L}_m + \sum_l \mathcal{L}_l, \\
\mathcal{L}_b &= \bar{\Psi}_b(i\gamma_\mu\partial^\mu - q_b\gamma_\mu A^\mu - m_b \\
&+ g_{\sigma b}\sigma \boxed{+ g_{\sigma^* b}\sigma^*} - g_{\omega b}\gamma_\mu\omega^\mu \\
&- g_{\phi b}\gamma_\mu\phi^\mu - g_{\rho,b}\gamma_\mu\vec{I}_b\vec{\rho}^{\,\mu})\Psi_b, \\
\mathcal{L}_m &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{\kappa}{3!}(g_{\sigma b}\sigma)^3 - \frac{\lambda}{4!}(g_{\sigma b})^4 \\
&+ \boxed{\frac{1}{2}\partial_\mu\sigma^*\partial^\mu\sigma^* - \frac{1}{2}m_{\sigma^*}^2\sigma^{*2}} \\
&- \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{\zeta}{4!}g_{\omega b}^4(\omega_\mu\omega^\mu)^2 \\
&- \frac{1}{4}\vec{R}^{\mu\nu}\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^{\,\mu} + \Lambda_\omega g_{\rho b}^2\vec{\rho}_\mu\vec{\rho}^{\,\mu}g_{\omega b}^2\omega_\mu\omega^\mu \\
&- \frac{1}{4}P^{\mu\nu}P_{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}, \\
\mathcal{L}_l &= \bar{\Psi}_l\left(i\gamma_\mu\partial^\mu - q_l\gamma_\mu A^\mu - m_l\right)\Psi_l,
\end{aligned}
$$

Need of an equation of state (EoS) that depends on temperature (T), baryon density (ρ_B) and lepton fraction (Y_l)

→ construct a relativistic mean-field model (RMF): **FSU2H* model**

from the **energy-momentum tensor** we extract **thermodynamic properties**

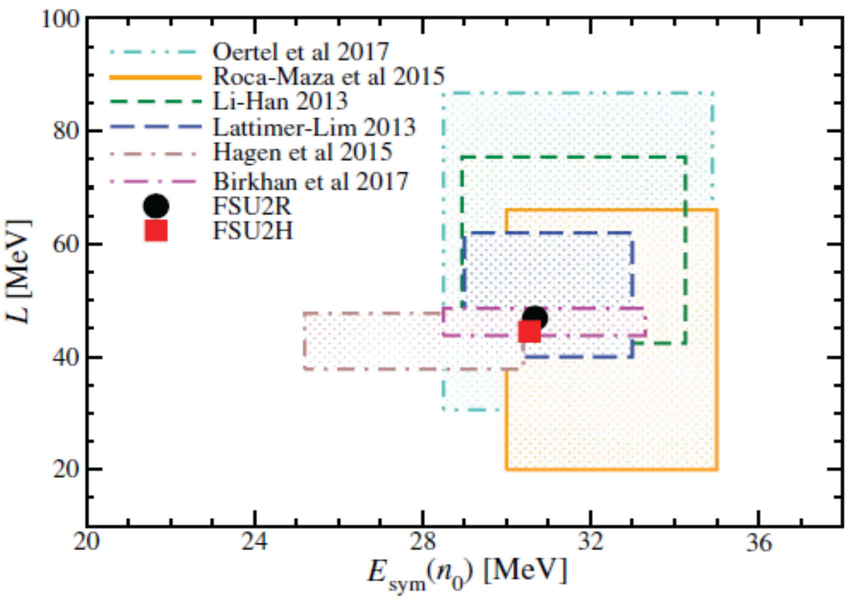
$\epsilon_{tot}, \mathbf{P}, \mathbf{s}, \mathbf{f}$

Euler eqs. of motion
RMF approximation
β − equilibrium and charge neutrality
conservation of baryon and lepton numbers

FSU2H* model: nuclear properties

Parameters of the FSU2H*model (nucleon mass m_N=939 MeV)

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
497.479	782.500	763.000	980.000	1020.000	102.72	169.53	197.27	4.00014	-0.0133	0.008	0.045



Tolos, Centelles and Ramos '17

Nuclear properties at T = 0

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	86.7

EoS fulfills saturation properties of nuclear matter and finite nuclei together with constraints on high-density coming from HiCs

FSU2H* model: the role of hyperons

Parameters of the FSU2H* 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	$-\sqrt{2}/3$
Σ	0.4673	2/3	2	0.2812	$-\sqrt{2}/3$
Ξ	0.3305	1/3	1	0.5624	$-2\sqrt{2}/3$

$$R_{iY} = \frac{g_{iY}}{g_{iN}}; i = (\sigma, \omega, \rho);\ R_{\sigma^* Y} = \frac{g_{\sigma^* Y}}{g_{\sigma Y}};\ R_{\phi Y} = \frac{g_{\phi Y}}{g_{\omega N}}$$

Obtained assuming flavour SU(3) symmetry, the vector dominance model, and ideal mixing for the physical ω and ϕ field

Potential felt by a hyperon *i* in *j*-particle matter is given by

$$U_i^{(j)}(\rho_j) = $$
$$= -g_{\sigma i}\bar{\sigma}^{(j)} - g_{\sigma i}^{*}\bar{\sigma}^{*(j)} + g_{\omega i}\bar{\omega}^{(j)} + g_{\rho i} I_{3i}\bar{\rho}^{(j)} + g_{\phi i}\bar{\phi}^{(j)}$$

Hyperon potentials

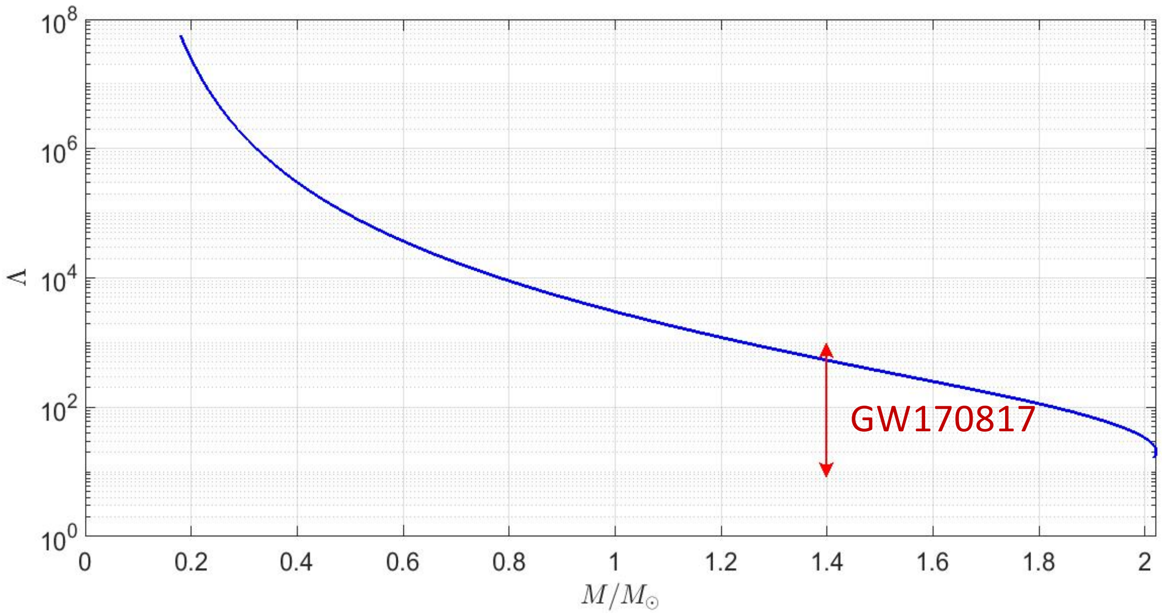
$$U_\Lambda^{(N)}(\rho_0) = -28 \text{ MeV}$$

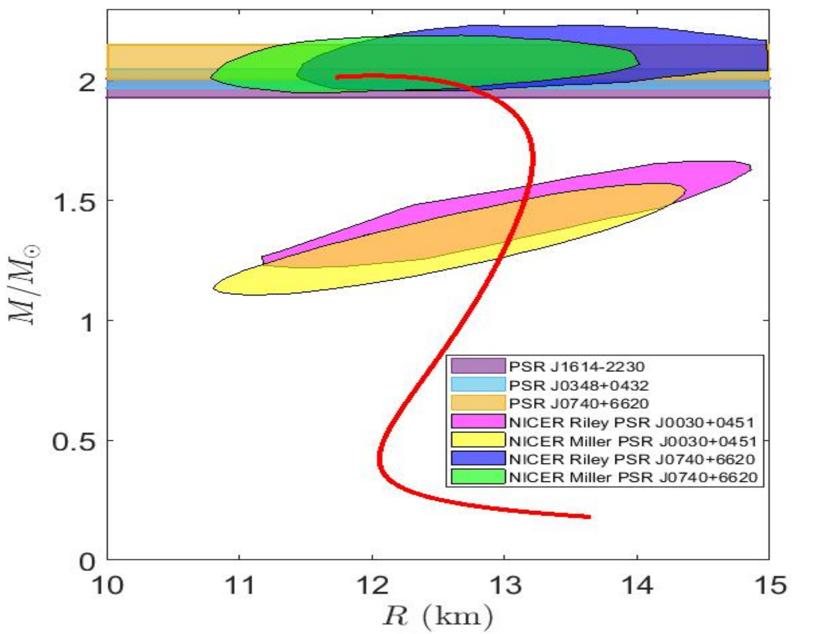
$$U_\Sigma^{(N)}(\rho_0) = 30 \text{ MeV}$$

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

$$U_\Lambda^{(\Lambda)}(\rho_0/5) = -0.67 \text{ MeV}$$

FSU2H* model: masses, radii and tidal deformability (T=0)





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

in agreement with 2 $M_\odot$ observations, with NICER measurements on radii and constraints from GW170817 on tidal deformability

EoS and composition of the hot neutron star core

finite temperature EoS depends on three parameters (ρ_B, T, Y_l)

wide range of values to account for the conditions in protoneutron stars and neutron star mergers

$$\mathrm{T} = (0 - 100)\ \mathrm{MeV}$$

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

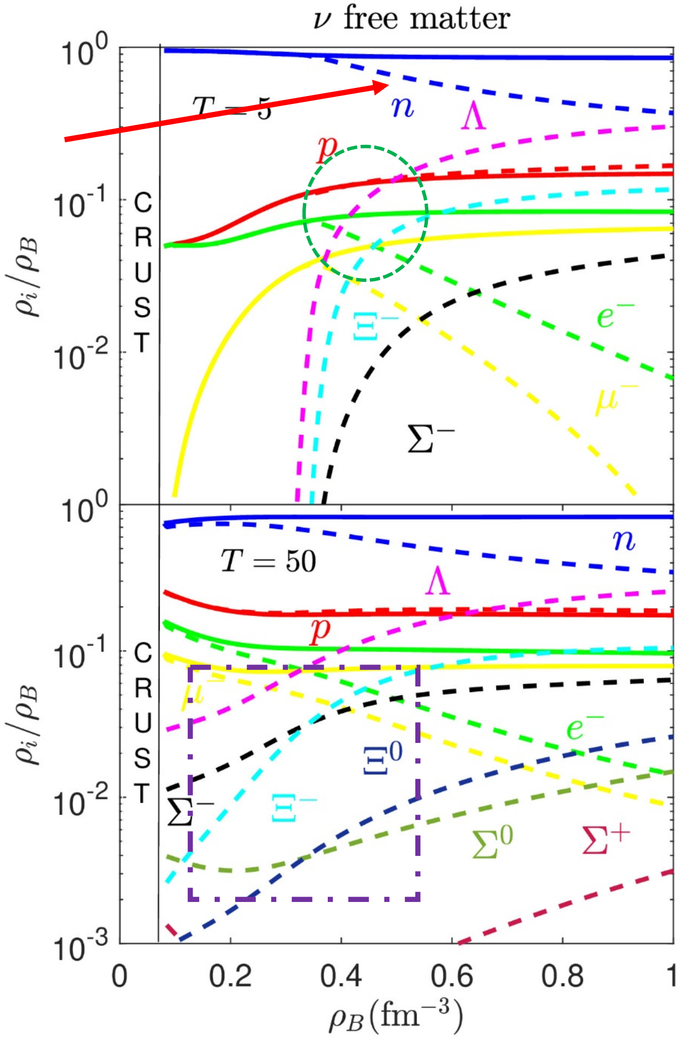
$$Y_l = (0 - 0.4);\ \nu \text{ free case}$$

focus on

$$T = 5\ \mathrm{MeV} \text{ and } T = 50\ \mathrm{MeV}$$

$$Y_l = 0.4 \text{ and } \nu \text{ free matter}$$

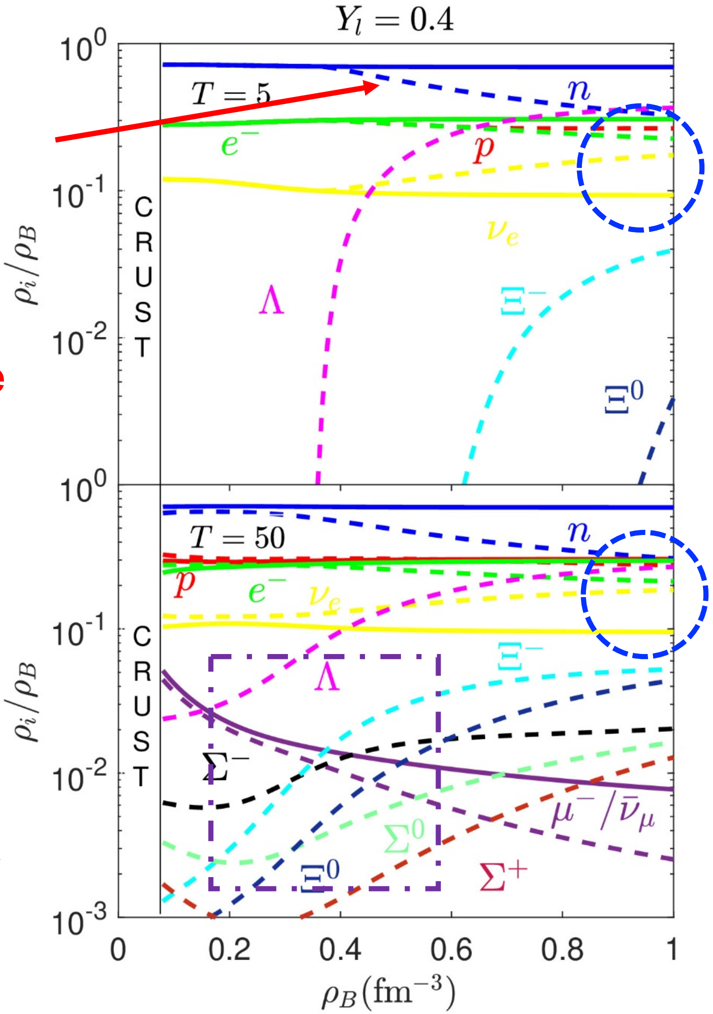
EoS and composition: composition at finite temperature



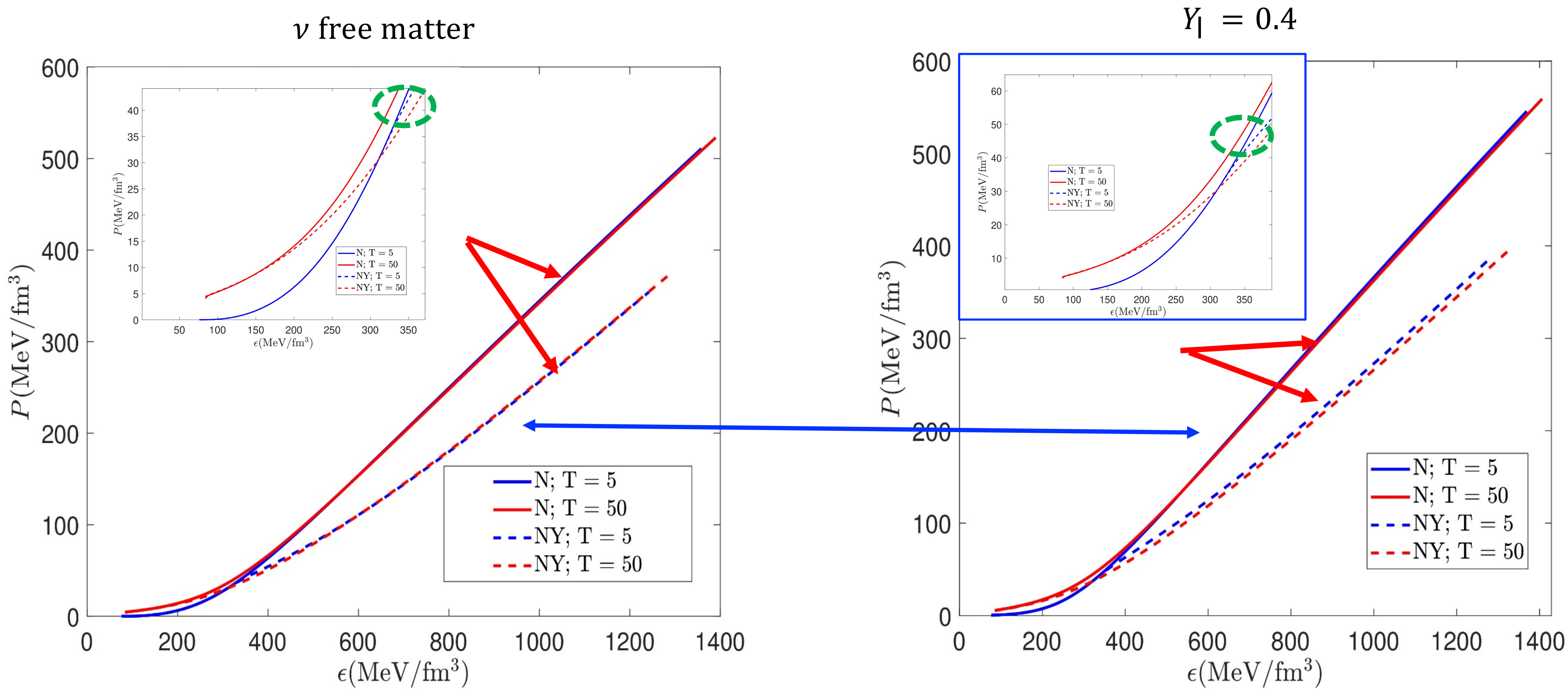
Solid lines – core without hyperons
Dashed lines – core with hyperons

Main conclusions:

- Hyperons make matter more isospin symmetric
- Hyperons induce a deleptonization
- Hyperons increase the neutrino abundance when they are trapped in the core
- At high temperatures hyperons are found inside the core at any density



EoS and composition: EoS at finite temperature



- Hyperons produce a significant softening of the EoS
- At low T hyperons induce a more drastic change of the EoS slope than at high T
- EoS becomes stiffer when neutrinos are trapped

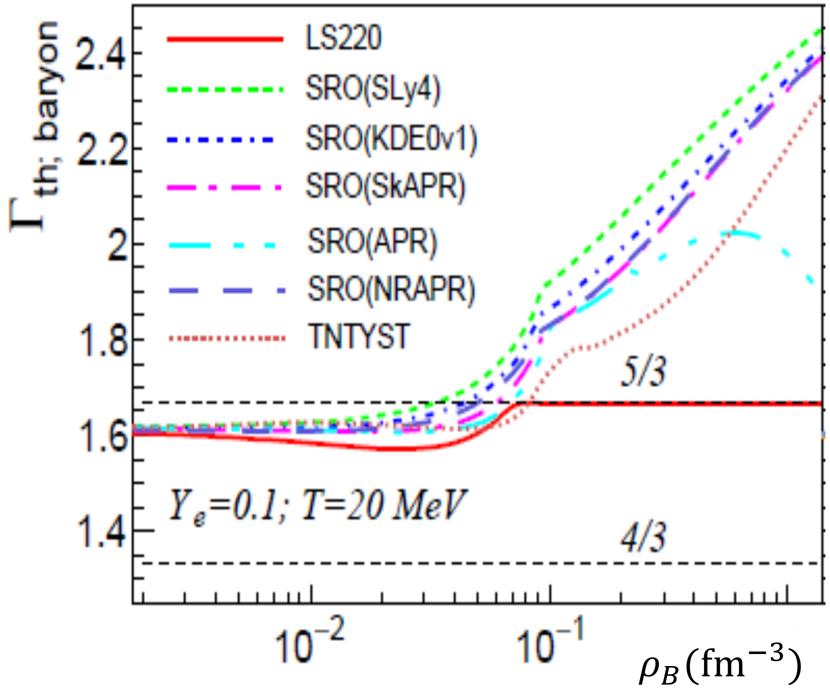
Thermal index of the neutron star core

Raduta, Nacu and Oertel ‘21

Thermal index

$$\Gamma(\rho_B, T) \equiv 1 + \frac{P_{\rm th}}{\epsilon_{\rm th}}$$

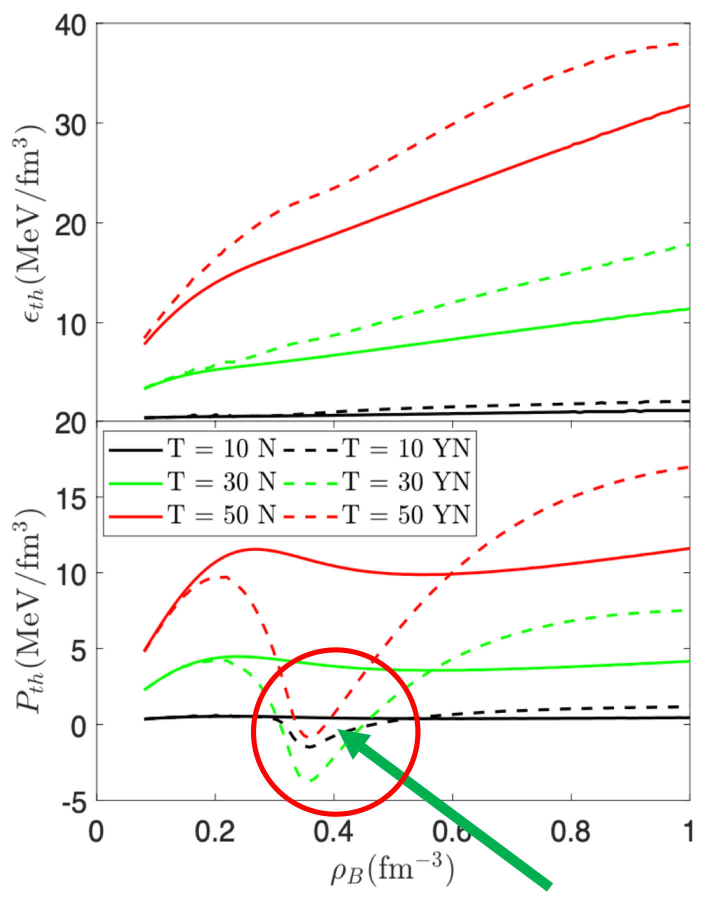
$$\begin{aligned} P_{\rm th} &= P(\rho_B, T) - P(\rho_B, T=0) \\ \epsilon_{\rm th} &= \epsilon(\rho_B, T) - \epsilon(\rho_B, T=0) \end{aligned}$$



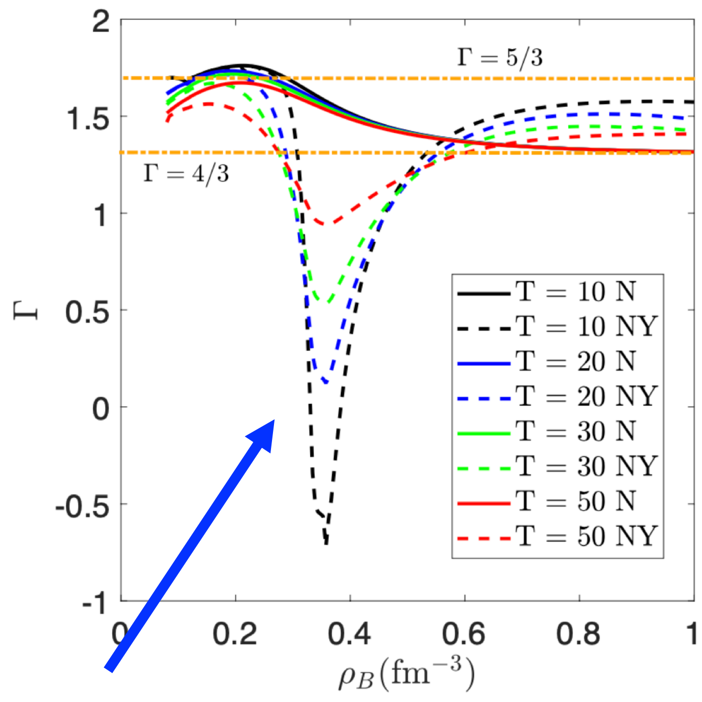
Merger simulations usually use a Γ that is constant. However, this procedure can be inaccurate

In this case, nucleons are the only baryons considered

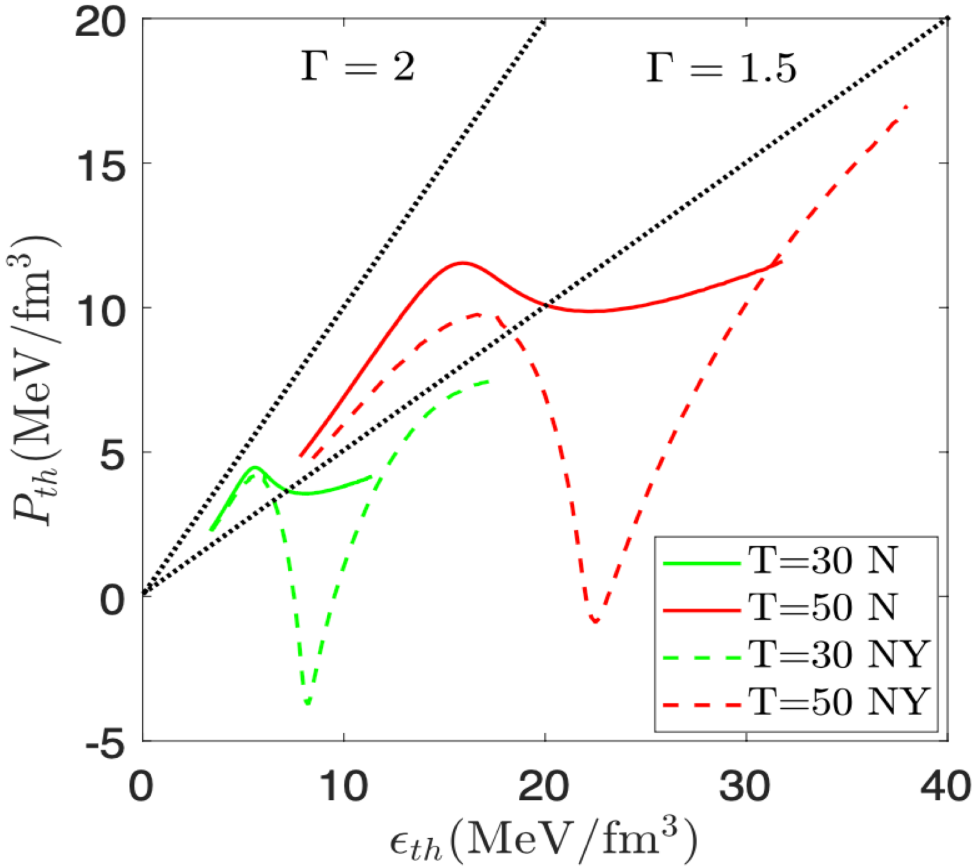
Thermal index : β- stable ν free matter with FSU2H*



- The appearance of hyperons has a strong effect on the thermal pressure
- The thermal pressure experiences a sizable drop when hyperon abundance starts being significant
- The complex behavior of the thermal pressure heavily influences the thermal index



Thermal index : β- stable ν free matter with FSU2H*



Thermal effects with Γ constant are not accurate, specially when hyperons are present

Be aware when using Γ constant in merger simulations!

Summary

- We have constructed a model for the core of neutron stars, named **FSU2H* model**, by improving the hyperonic FSU2H scheme, and extended it to include finite temperature effects to be used in early stages of neutron star evolution and in neutron star mergers

- **FSU2H* model at T=0** satisfies most important constraints that come from nuclear experiments and astrophysical observations

- We have investigated the **EoS and composition of neutron star matter at finite temperature** with and without hyperons. We have observed the thermal corrections to have a strong influence on the composition of the inner core, being clearly manifest when hyperons are considered

- The temperature effects have been analyzed in terms of the **thermal index** Γ, which depends non-negligibly on temperature and density, specially when hyperons are present. Thus, thermal effects with Γ constant are inaccurate and should be taken with caution in merger simulations

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