Workshop on anti-matter, hyper-matter and exotica production at the LHC

# Hyperons in neutron star merger matter


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Hristijan Kochankovski
Angels Ramos
Laura Tolos


13-17 February 2023

# OUTLINE

*Motivation*

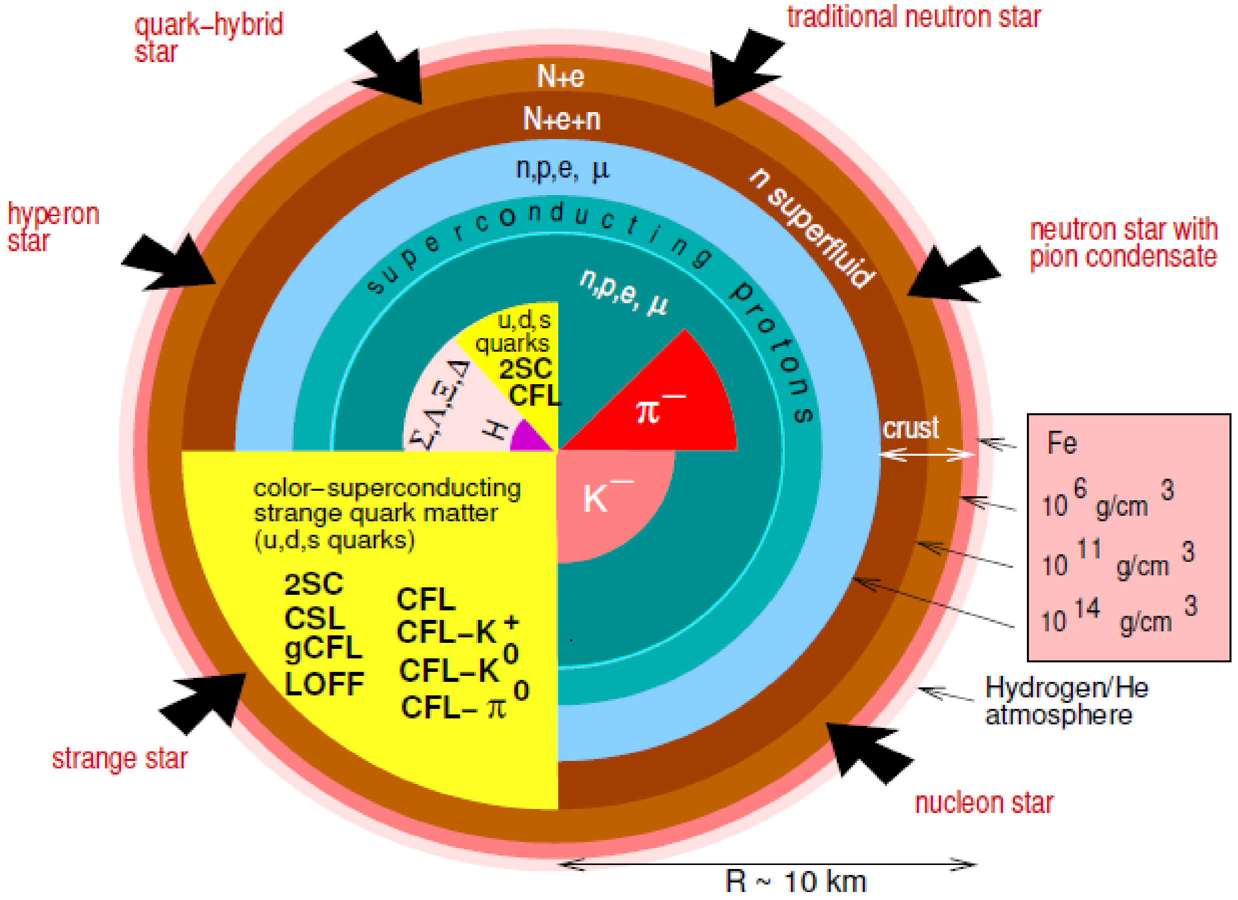
Brief introduction to FSU2H* model

Equation of State (EoS) of hot and cold neutron stars

Summary

# Motivation

F. Weber, Prog.Part.Nucl.Phys.54:193-288,2005




- $\beta -$ **stable** matter made of nucleons, leptons and possibly exotic particles

- Kaon condensation
- Pion condensation
- Quark-gluon plasma
- HYPERONS

- There is no experimental data of the nuclear matter at high densities ($\rho > 2 - 3\rho_0$)

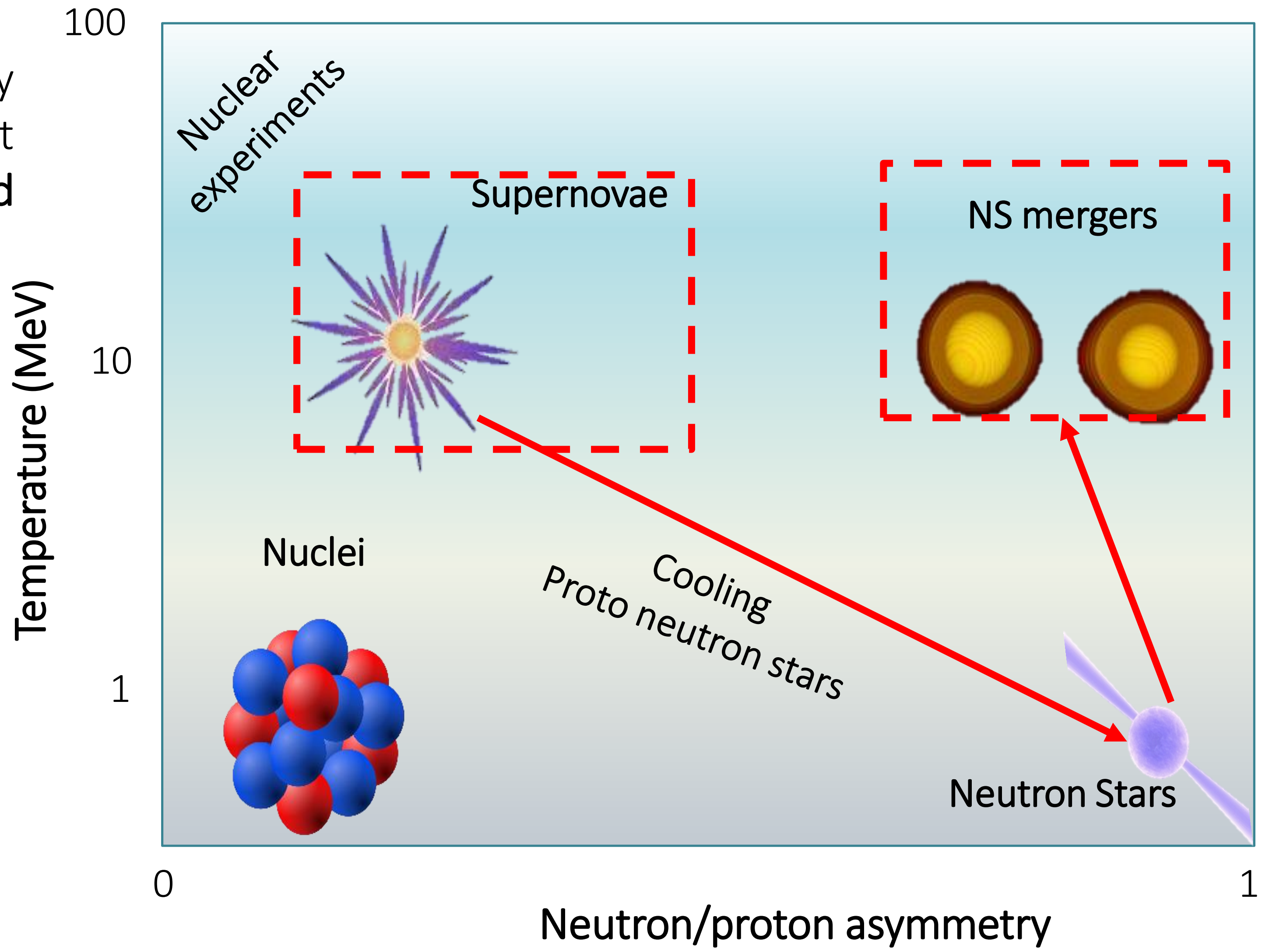
Remanent of supernovae processes: **high density – several times $\rho_0$**

# Motivation

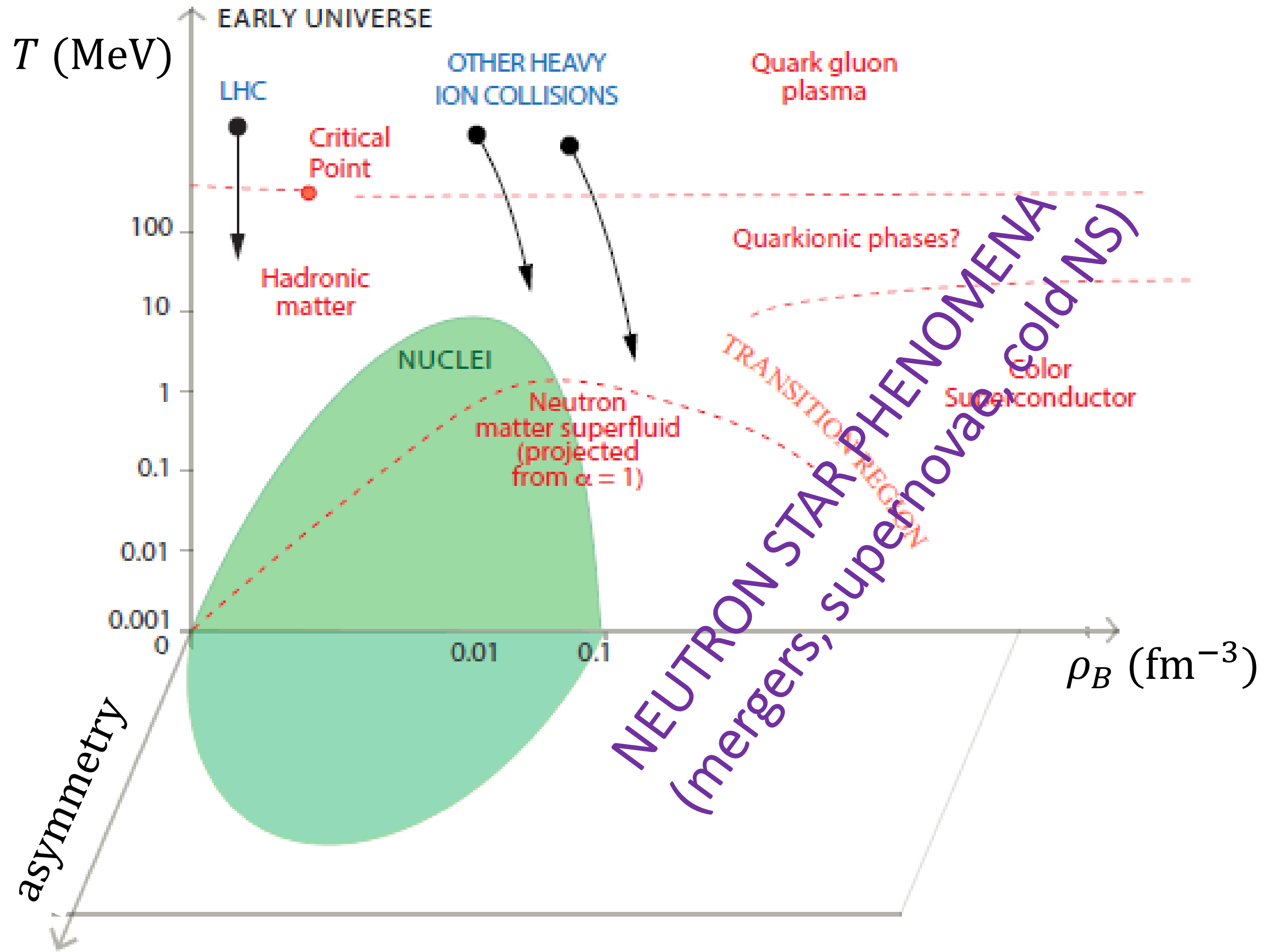
- Contrary to the matter in the already evolved stars, the matter in the violent phenomena **cannot be treated as cold and beta equilibrated**.

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

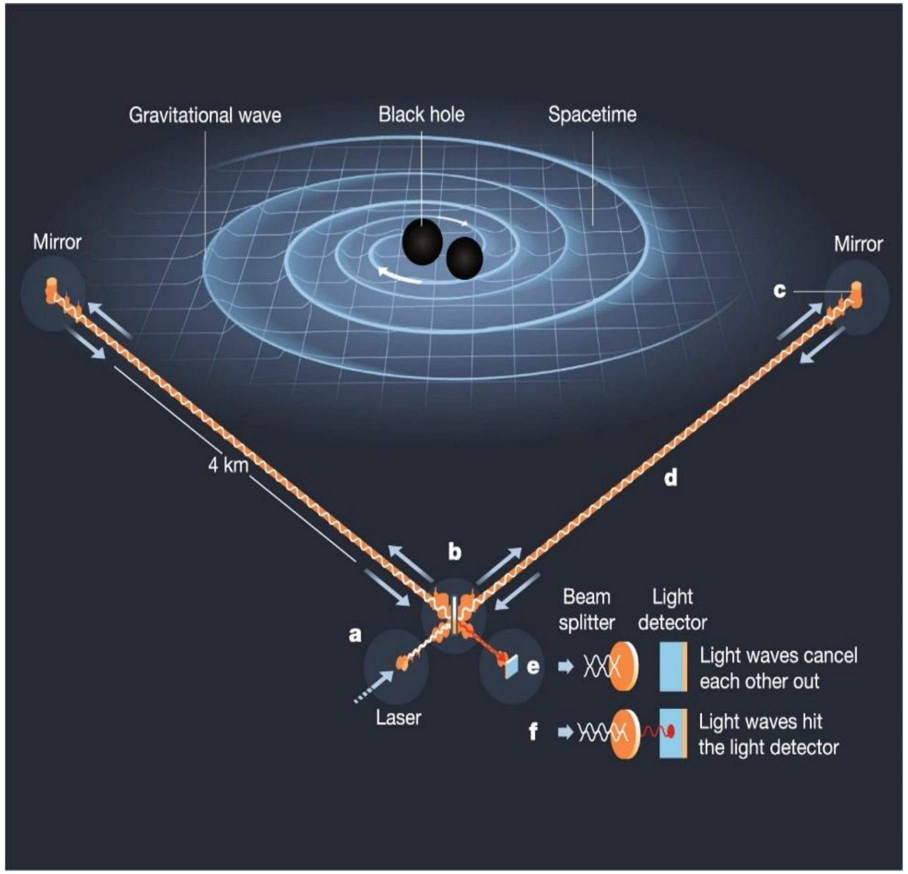
$$T = (0 - 100)\ \mathrm{MeV}$$
$$\rho_B = (0.5 - 10)\rho_0$$
$$Y_Q = (0 - 0.6)$$



# Motivation




A.Watts et al, arXiv:1501.00042v1




- The new astrophysical measurements can be used **to constrain the high density part** of the Equation of State

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

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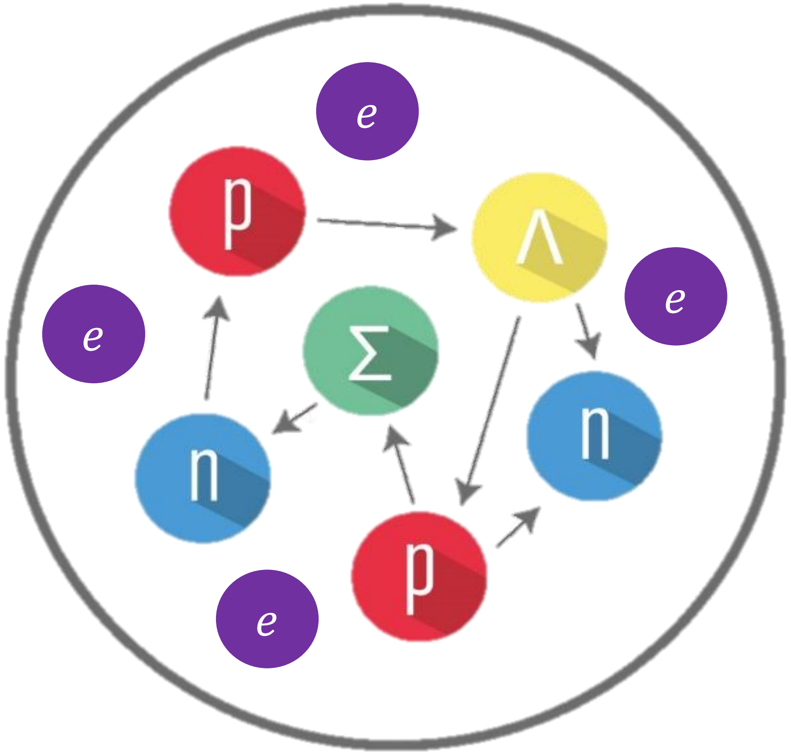
# Theoretical framework

- Homogenous system made of baryons and leptons, where the baryons are **strongly correlated** particles

- Leptons are non-interacting particles




**Phenomenological models**

- **Relativistic mean field (RMF)**
- Skyrme effective interaction
- Chiral mean-field
- …

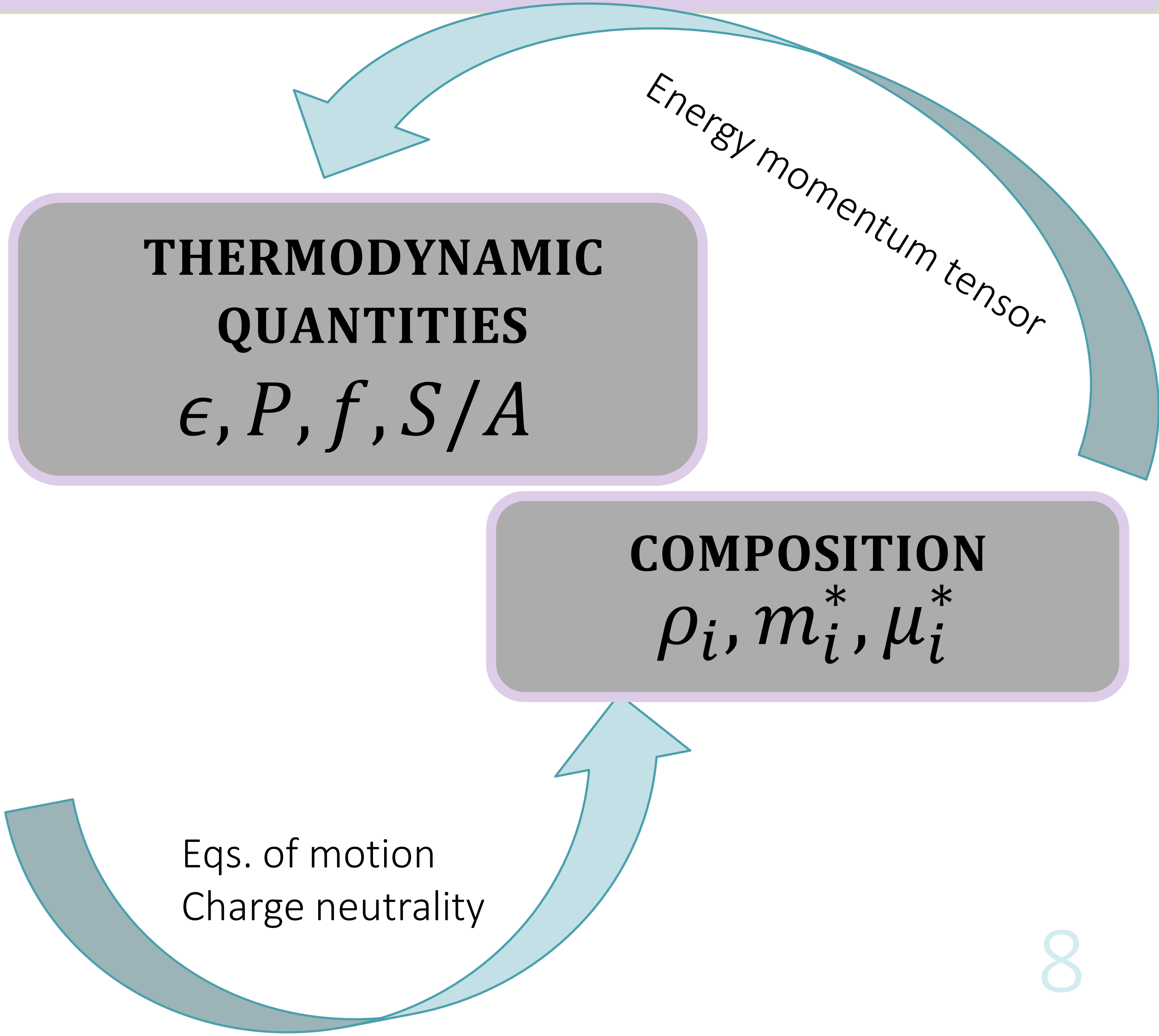
**Microscopical models**

- Brueckner-Hartree-Fock (BHF)
- Relativistic BHF
- Variational method
- …

# FSU2H* model

- Matter at a fixed baryon density ($\rho_B$), temperature ($T$) and charge fraction ($Y_Q$)

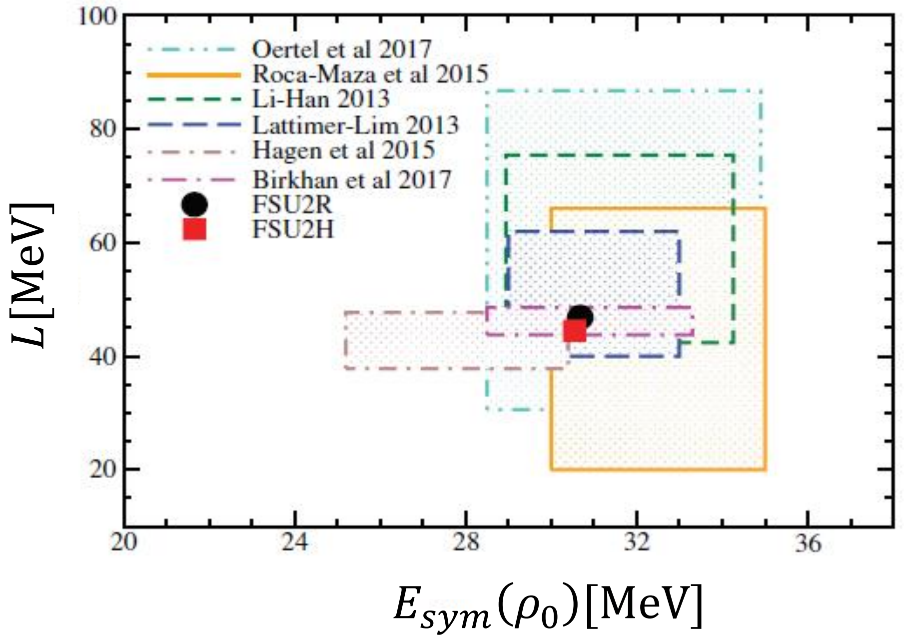
$$
\begin{aligned}
\mathcal{L} &= \sum_b \mathcal{L}_b + \mathcal{L}_m + \sum_l \mathcal{L}_l, \\
\mathcal{L}_b &= \bar{\Psi}_b(i\gamma_\mu\partial^\mu - q_b\gamma_\mu A^\mu - m_b \\
&\quad + g_{\sigma b}\sigma + g_{\sigma^* b}\sigma^* - g_{\omega b}\gamma_\mu\omega^\mu - g_{\rho,b}\gamma_\mu\vec{I}_b\vec{\rho}^\mu)\Psi_b,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



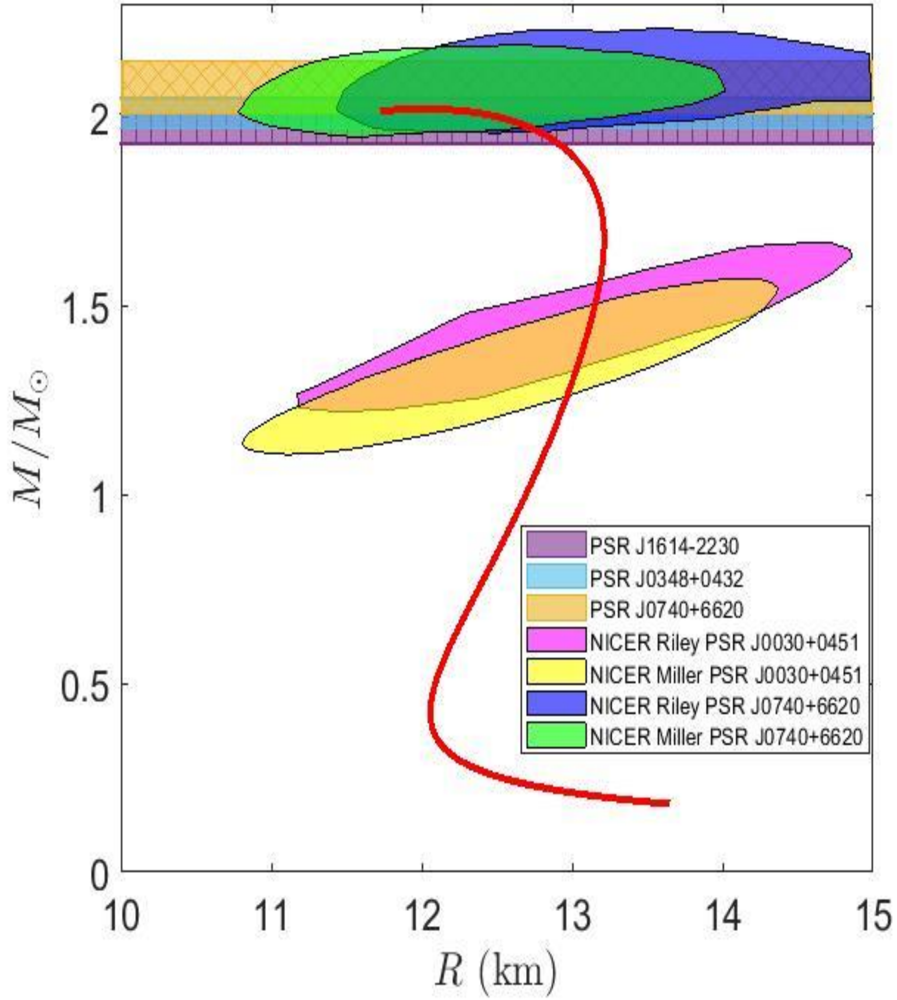
# FSU2H* model characteristics

## Low density region constraints

PASA, 34, e065 (2017)




## High density region constraints




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

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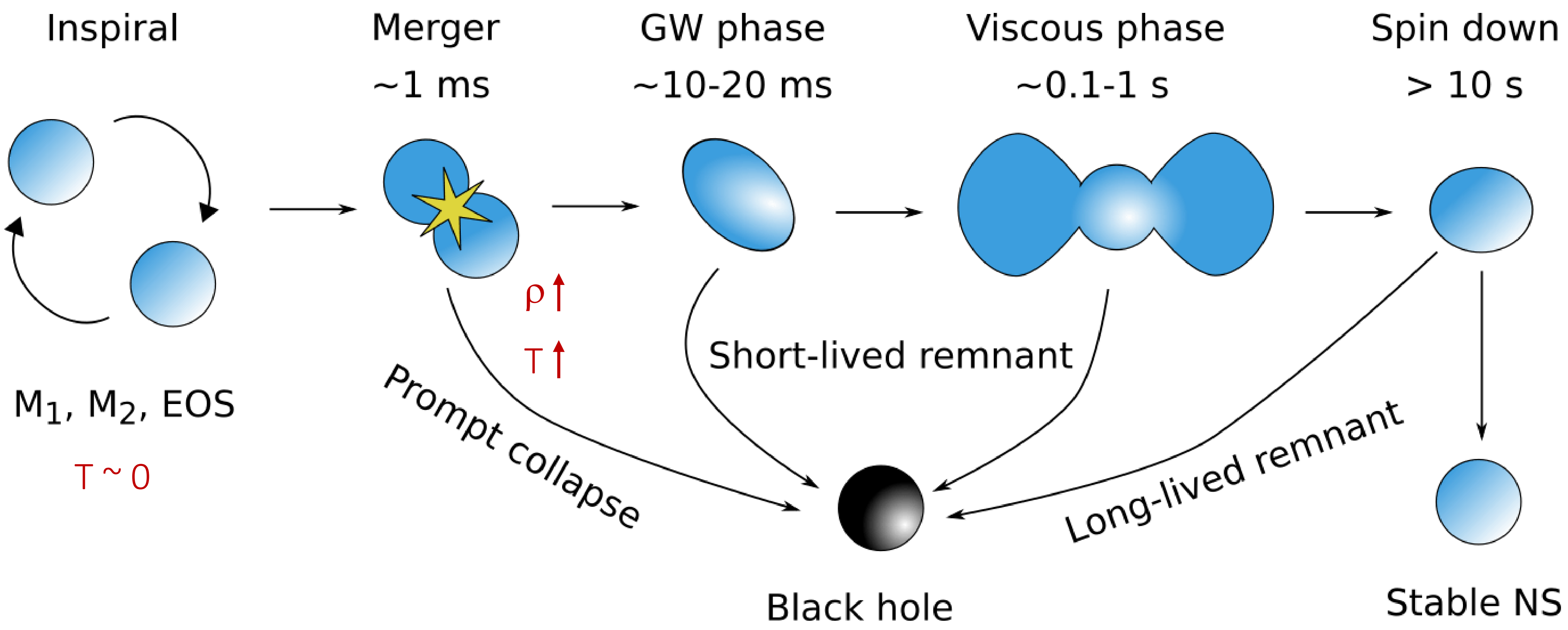
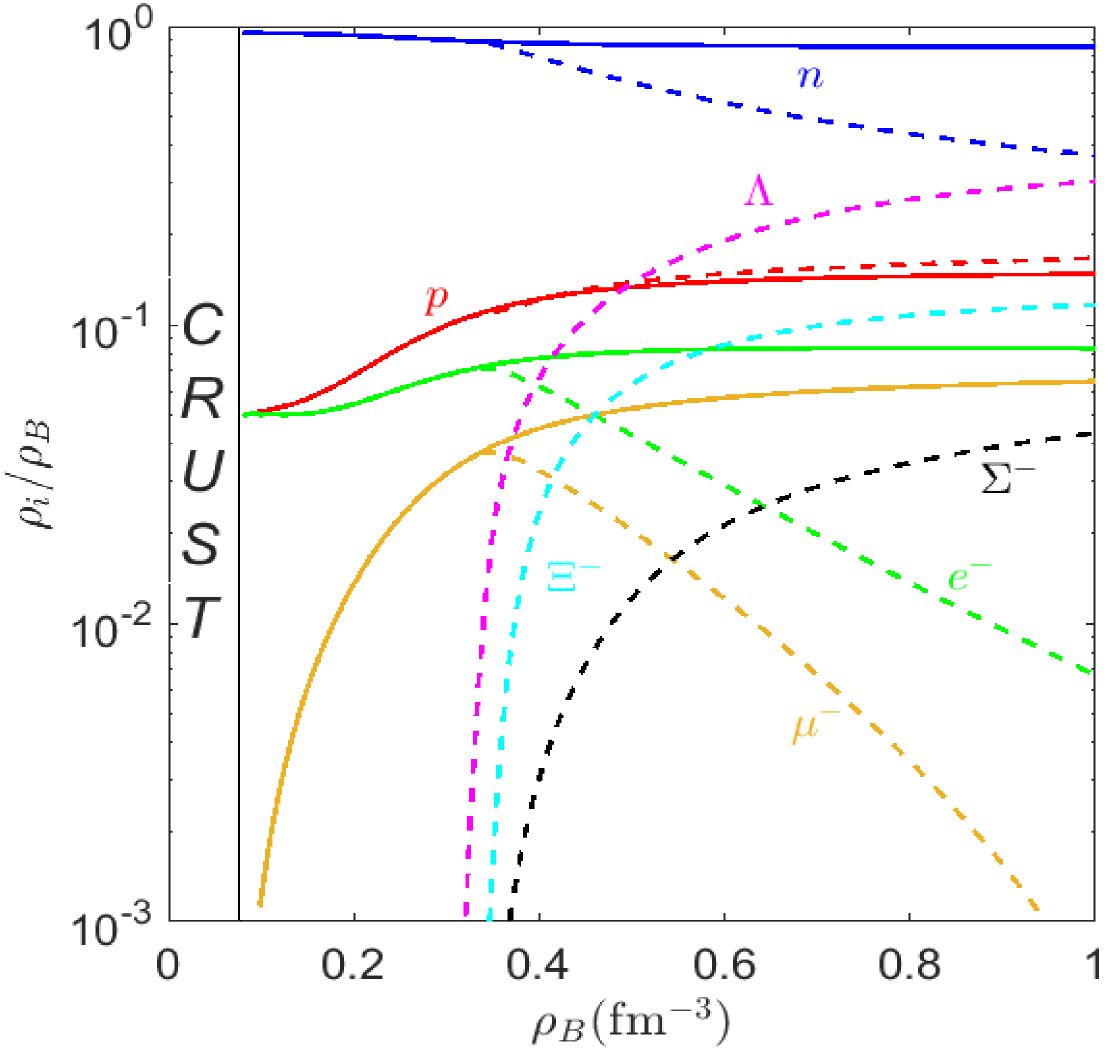
# Phases of merging

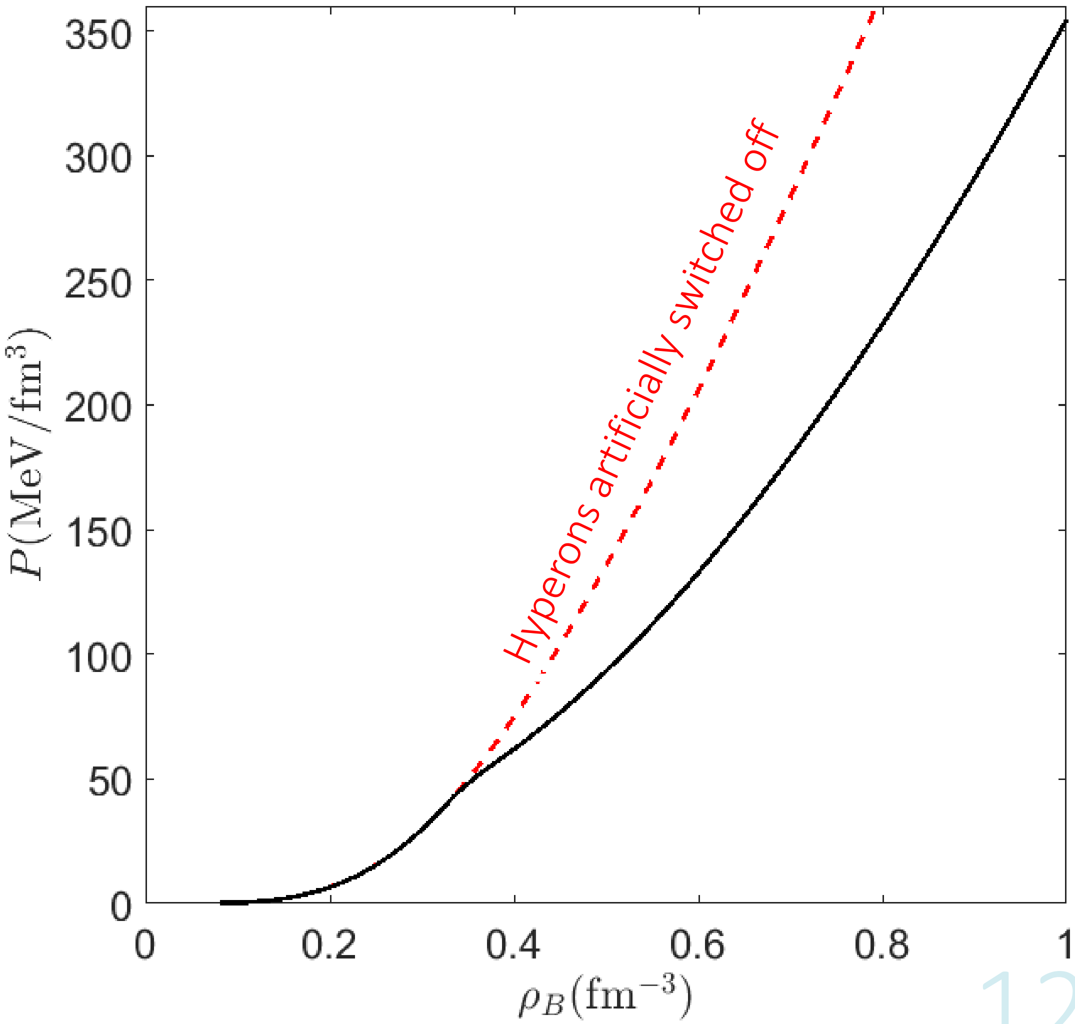



**Radice et al. ARNPS, 2020**

# Initial conditions – cold stars

**$T = 0$ $\beta^-$ equilibrated matter**



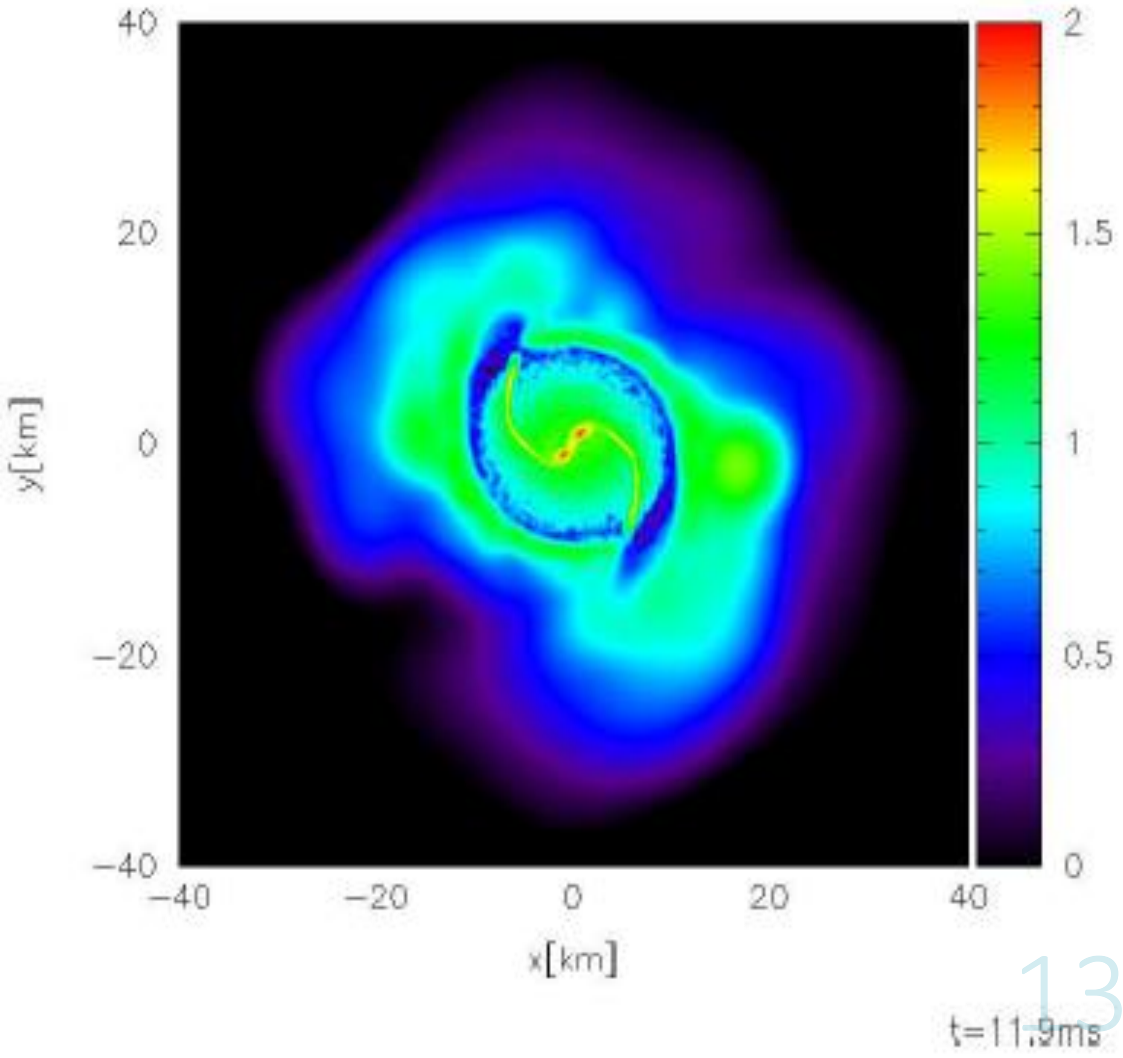
# Merging phase – warm stars

- The matter can get heat up significantly during the merging phases

- Many EoSs do not have finite temperature extension

- Approximate treatments have been adopted such as the use of constant thermal index

Bauswein et al. 2010, PRD



# Thermal index - introduction

- It is useful to reproduce thermal effects on the EoS in complicated simulations

$$\Gamma(\rho_B, Y_Q, T) = 1 + \frac{P_{ther}}{\epsilon_{ther}} = 1 + \frac{P(T) - P_0}{\epsilon(T) - \epsilon_0}$$

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

$$\epsilon(T) = \epsilon_{ther} + \epsilon_0;$$
$$P(T) = P_{ther} + P_0$$

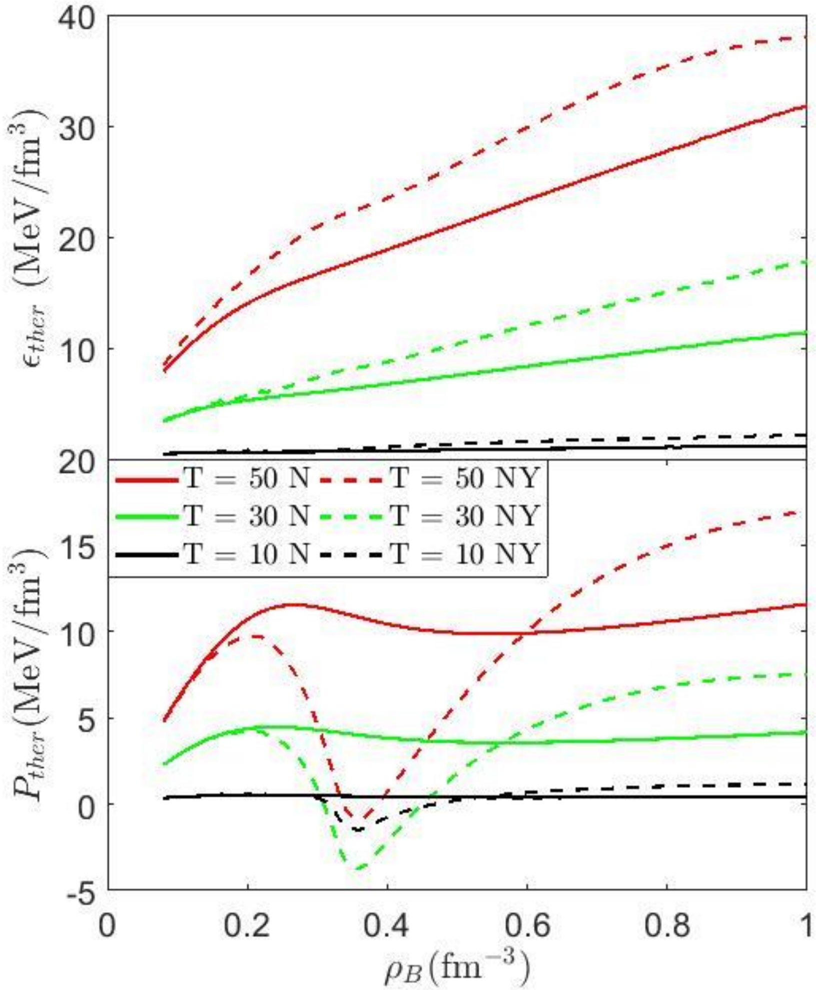
- If one assumes $\Gamma$ to be constant and not to depend on the temperature, a $P(\epsilon)$ relation can be found only knowing the zero temperature EoS.

- In the simulations a thermal index in the range of $\Gamma =$ (1.5–2.0) is used, being $\boldsymbol{\Gamma = 1.75}$ the most common value.

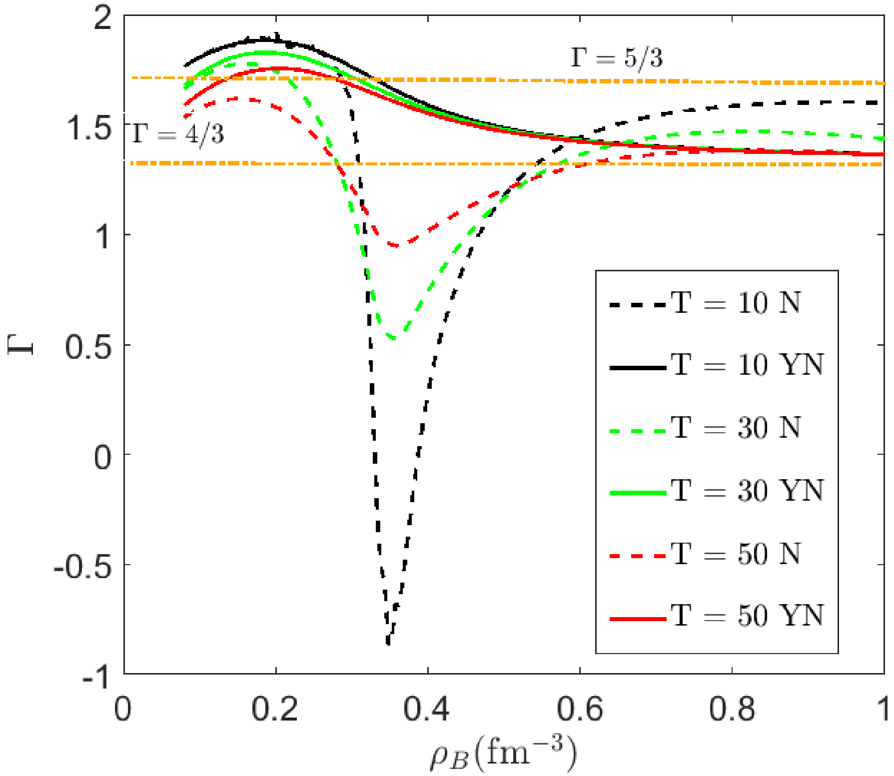
We will use the thermal index in two ways:

- To quantify the thermal effects in different matter conditions
- To show that the use of constant thermal index can be inaccurate and widely overestimate the temperature effects

# Thermal index – $\beta$- stable $\nu$ free matter in FSU2H*




- Thermal effect are more emphasized when hyperons are included.
- Significant effect on the thermal pressure – **can be lower than 0!**
- Induces a drop in the thermal index

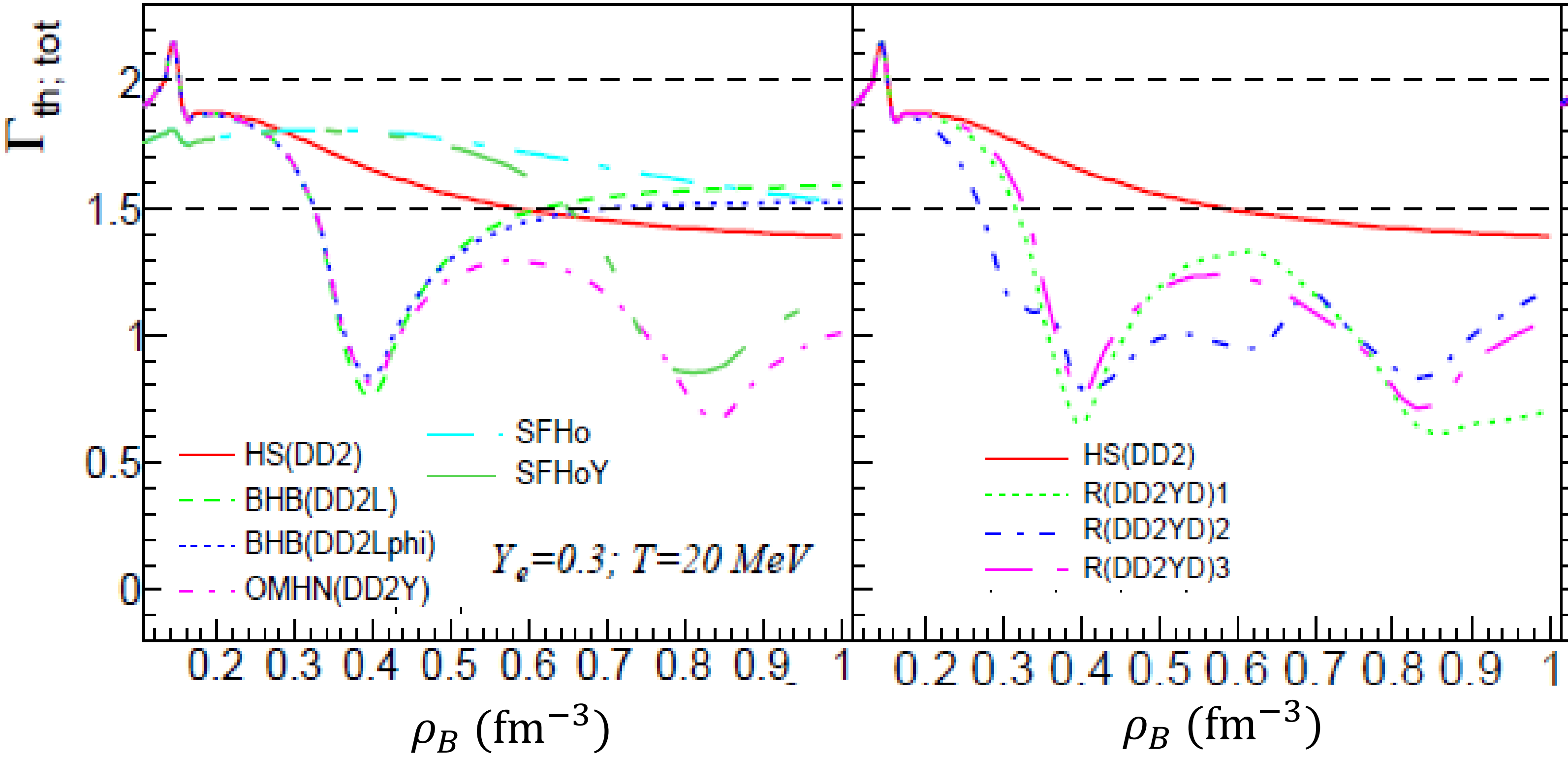



Kochankovski et al, 2022, MNRAS

# Thermal index – other hyperonic models

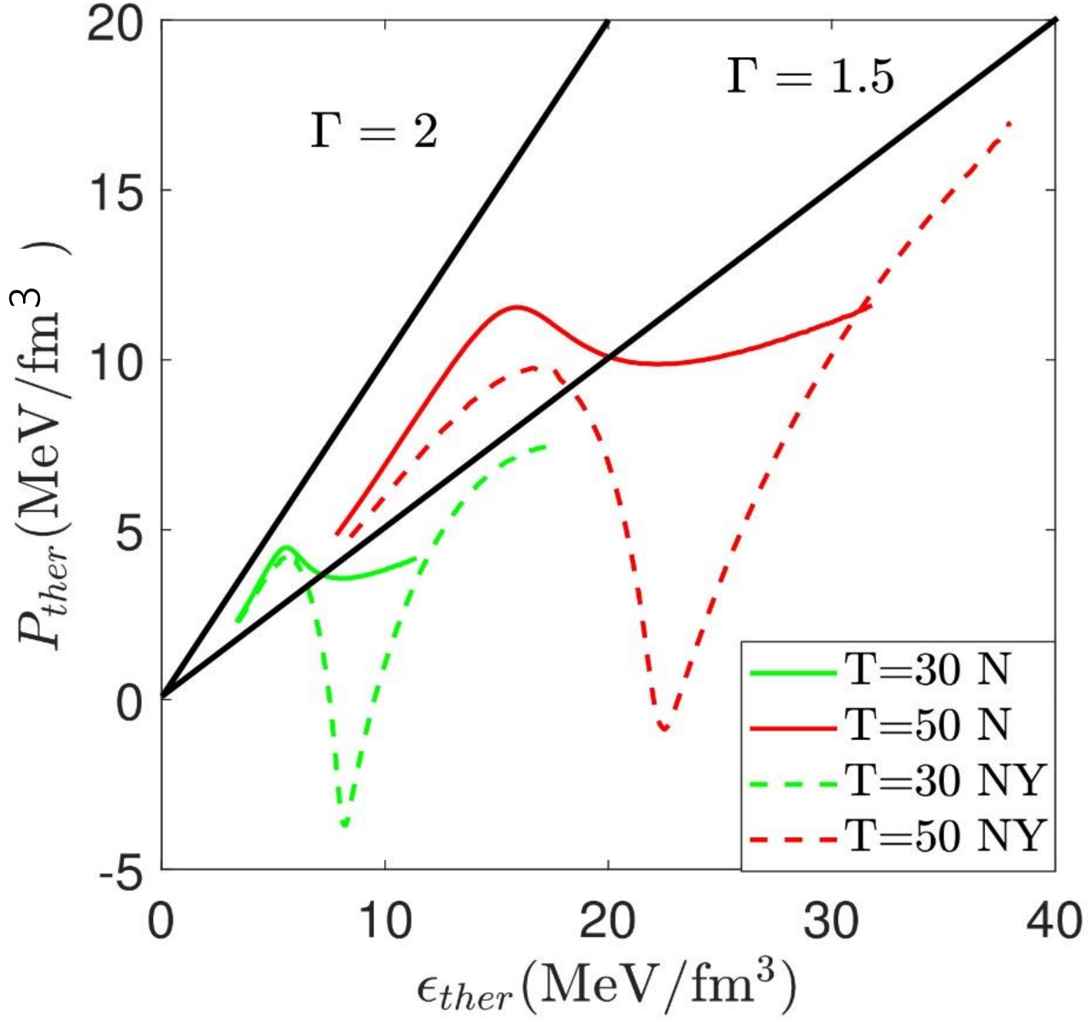
- The drop of the thermal index is a feature that all hyperonic models have

- For a wide range of densities the thermal index is lower than $\Gamma = 1.5$




Raduta et al, 2022, EPJA

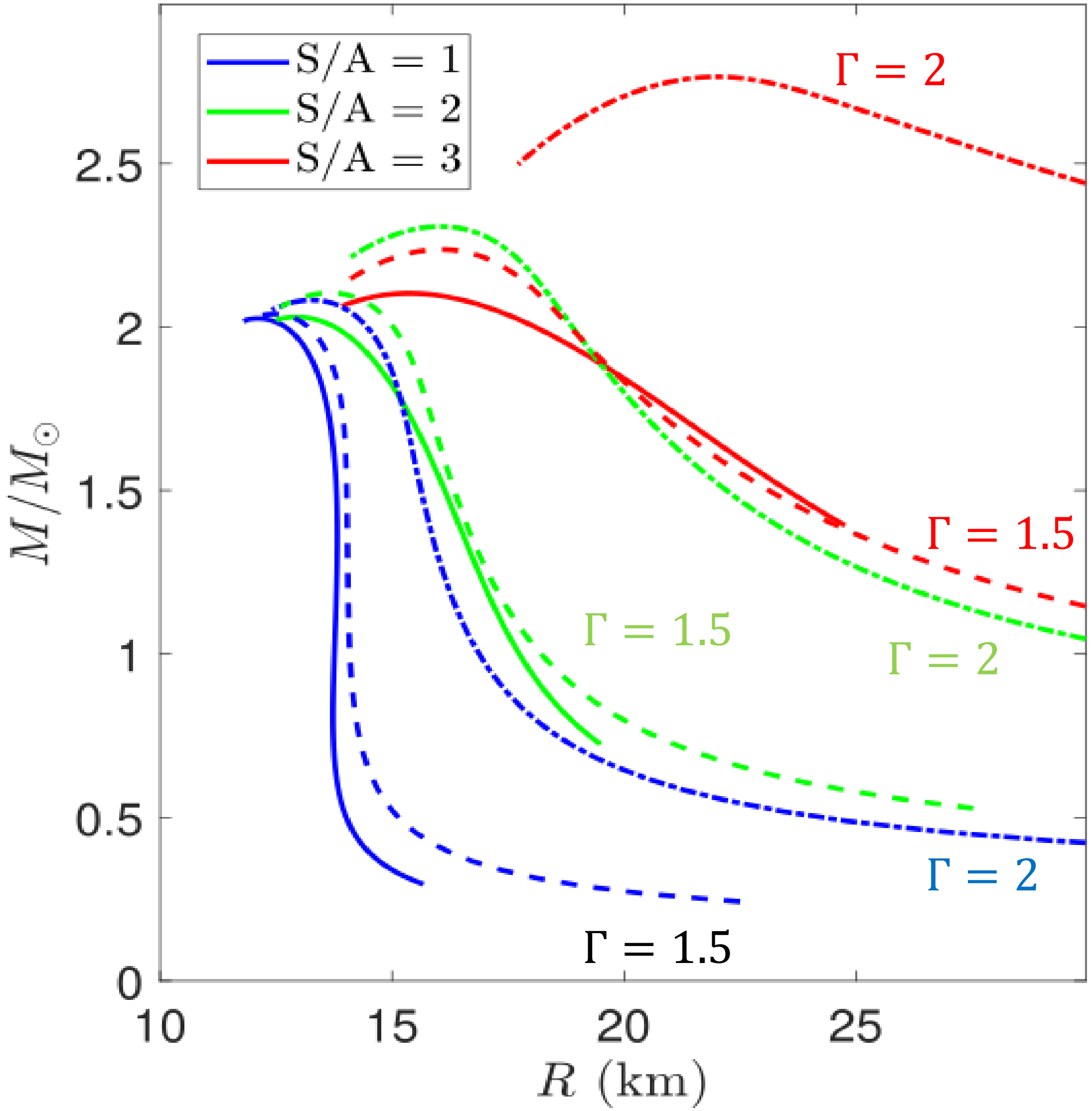
# Thermal index – $\boldsymbol{\beta}$- stable $\boldsymbol{\nu}$ free matter in FSU2H*




- For temperatures found during the mergers this can induce a big error

- The relation between the thermal energy and thermal pressure is not linear!

# Simple example– TOV solutions at constant S/A with hyperons




- To test how this can influence the relativistic simulations, we do calculations of the mass-radius relations for stars at constant entropy per baryon

- These cases are relevant for later stages of evolution in proto-neutron stars

- The approximate approach can be inaccurate at high temperatures

# Summary

- Due to the high densities in the events, neutron star mergers are excellent “laboratories” to test different models of matter

- Exotic particles, such as hyperons, are likely to appear

- The appearance of the hyperons has a strong impact on both **cold** and **finite-temperature** EoSs.

- The differences in the thermal contributions are especially important because they may have an influence on the observables measured from the events.

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# Thank you for your attention

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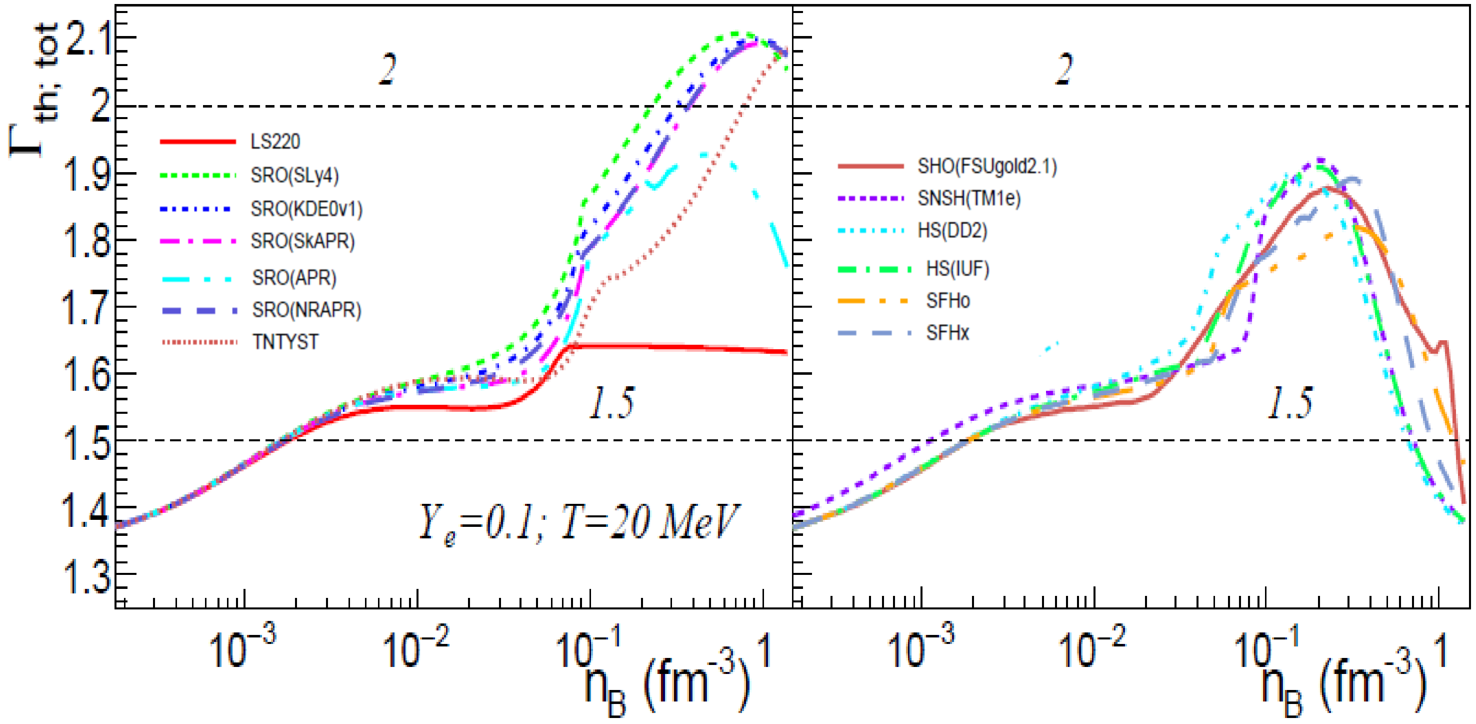
# Thermal index – other nucleonic models

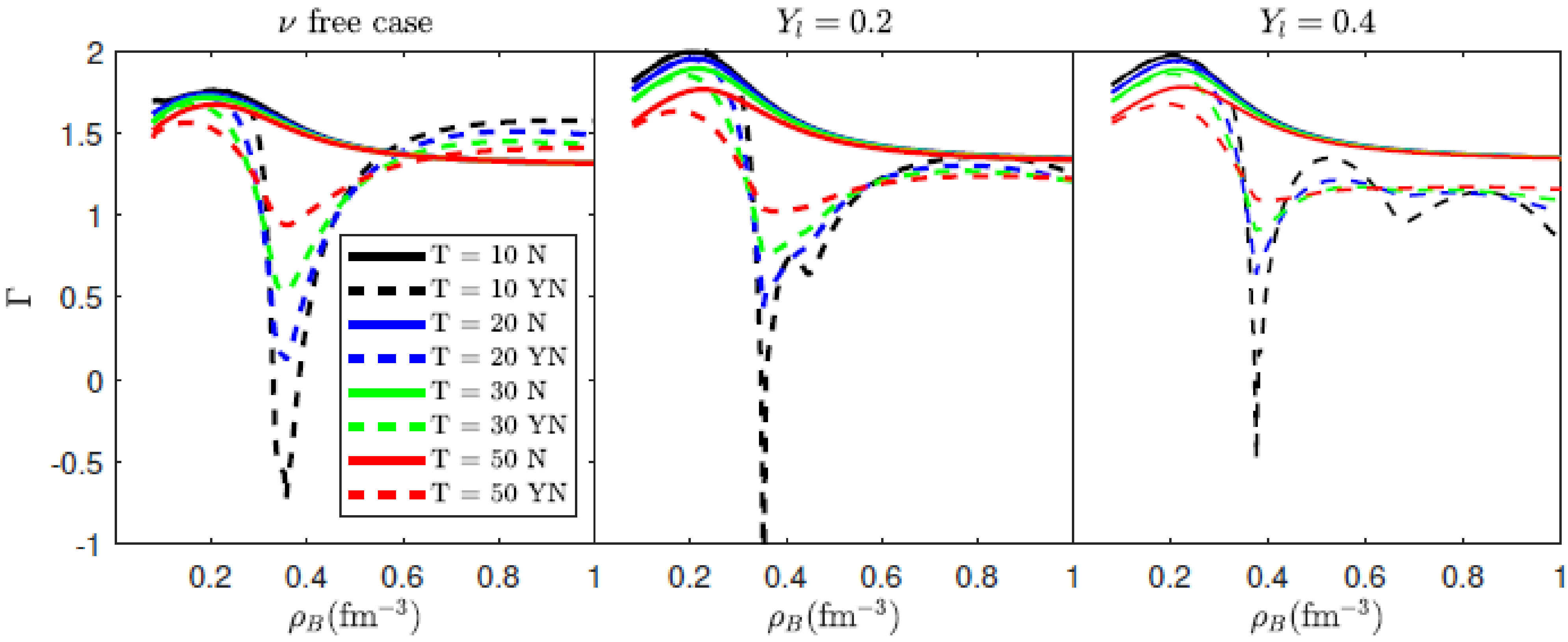
- Both microscopical and phenomenological nucleonic models show non constant behavior of the thermal index

- All relativistic mean-field models, at high densities have $\Gamma < 1.5$ due to the small effective mass of the nucleons




Raduta et al, 2021, EPJA

# Thermal index for different lepton fractions



# 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

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

$\beta$ equilibrium

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

Conservation of baryon and lepton numbers

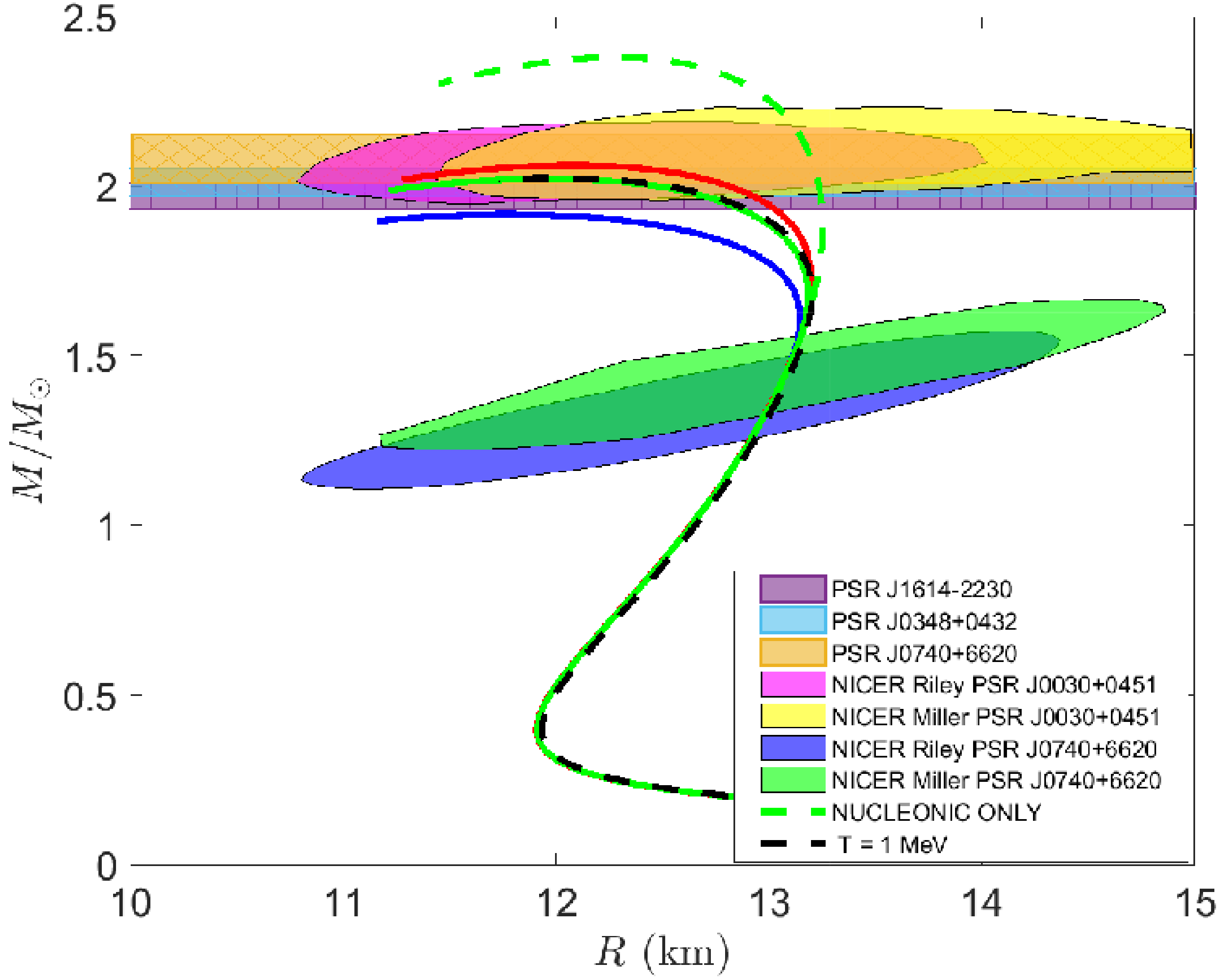
$$T_{\mu\nu} = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \Phi_\alpha)} \partial^\mu \Phi_\alpha - \eta_{\mu\nu}\mathcal{L},$$

Energy-momentum tensor

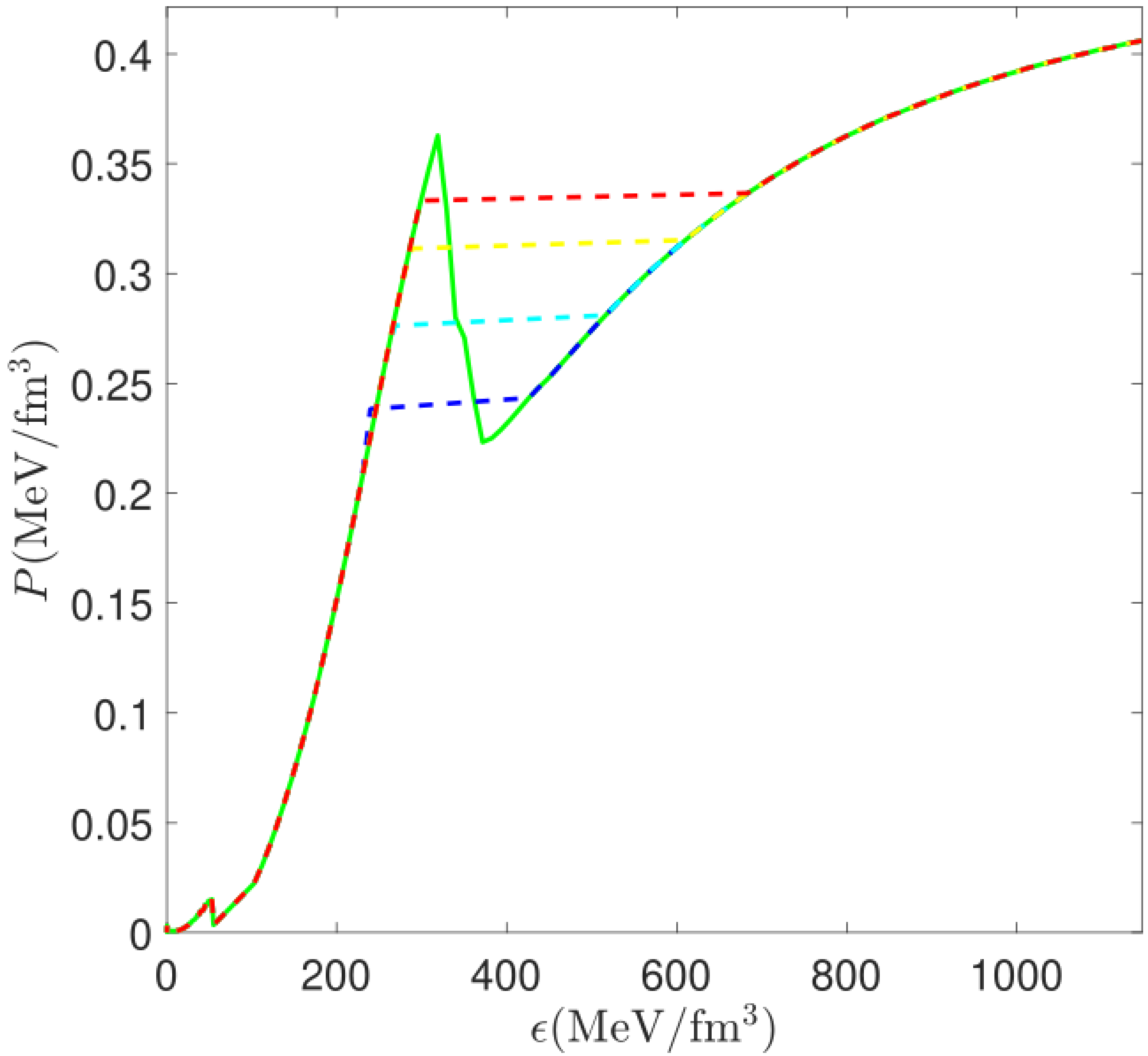
$$\begin{aligned}
\epsilon &= < T_{00} > \\
&= \frac{1}{2\pi^2}\sum_b \gamma_b \int_0^\infty dk k^2 \sqrt{k^2 + m_b^{*2}} f_b(k,T) \\
&+ \frac{1}{2\pi^2}\sum_l \gamma_l \int_0^\infty dk k^2 \sqrt{k^2 + m_l^2} f_l(k,T) \\
&+ \frac{1}{2}(m_\omega^2 \bar{\omega}^2 + m_\rho^2 \bar{\rho}^2 + m_\phi^2 \bar{\phi}^2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

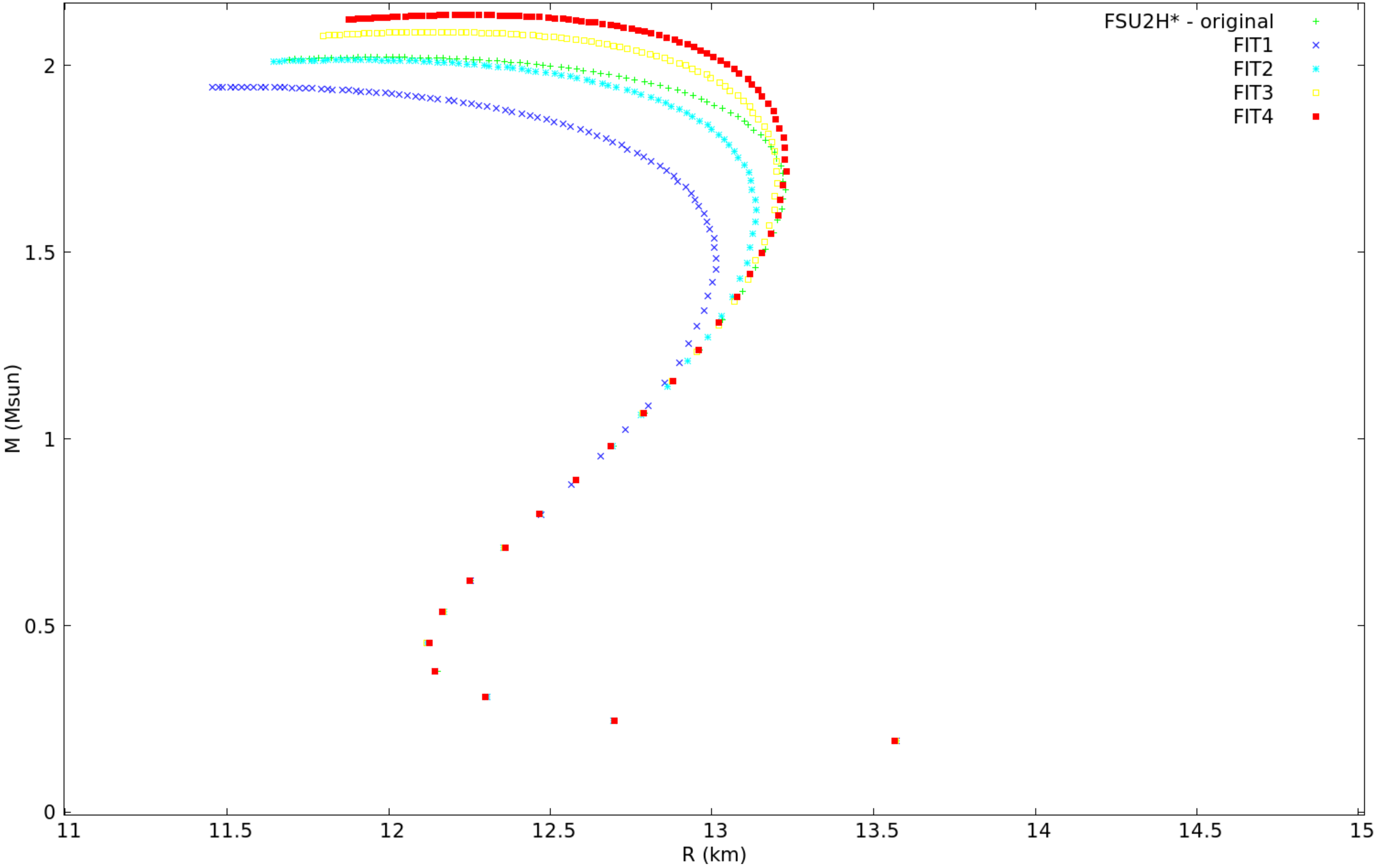
$$s = \frac{1}{T}\left(\epsilon + P - \sum_i \mu_i \rho_i\right)$$
$$f = \sum_i \mu_i \rho_i - P.$$

Thermodynamic quantities



2.5
2
1.5
1
0.5
0
10
11
12
13
14
15
$M/M_{\odot}$
$R$ (km)
PSR J1614-2230
PSR J0348+0432
PSR J0740+6620
NICER Riley PSR J0030+0451
NICER Miller PSR J0030+0451
NICER Riley PSR J0740+6620
NICER Miller PSR J0740+6620
NUCLEONIC ONLY
T = 1 MeV


0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
$P(\mathrm{MeV/fm^3})$
0
200
400
600
800
1000
$\epsilon(\mathrm{MeV/fm^3})$



FSU2H* - original
FIT1
FIT2
FIT3
FIT4
M (Msun)
R (km)
0
0.5
1
1.5
2
11
11.5
12
12.5
13
13.5
14
14.5
15