Hyperons in neutron star mergers

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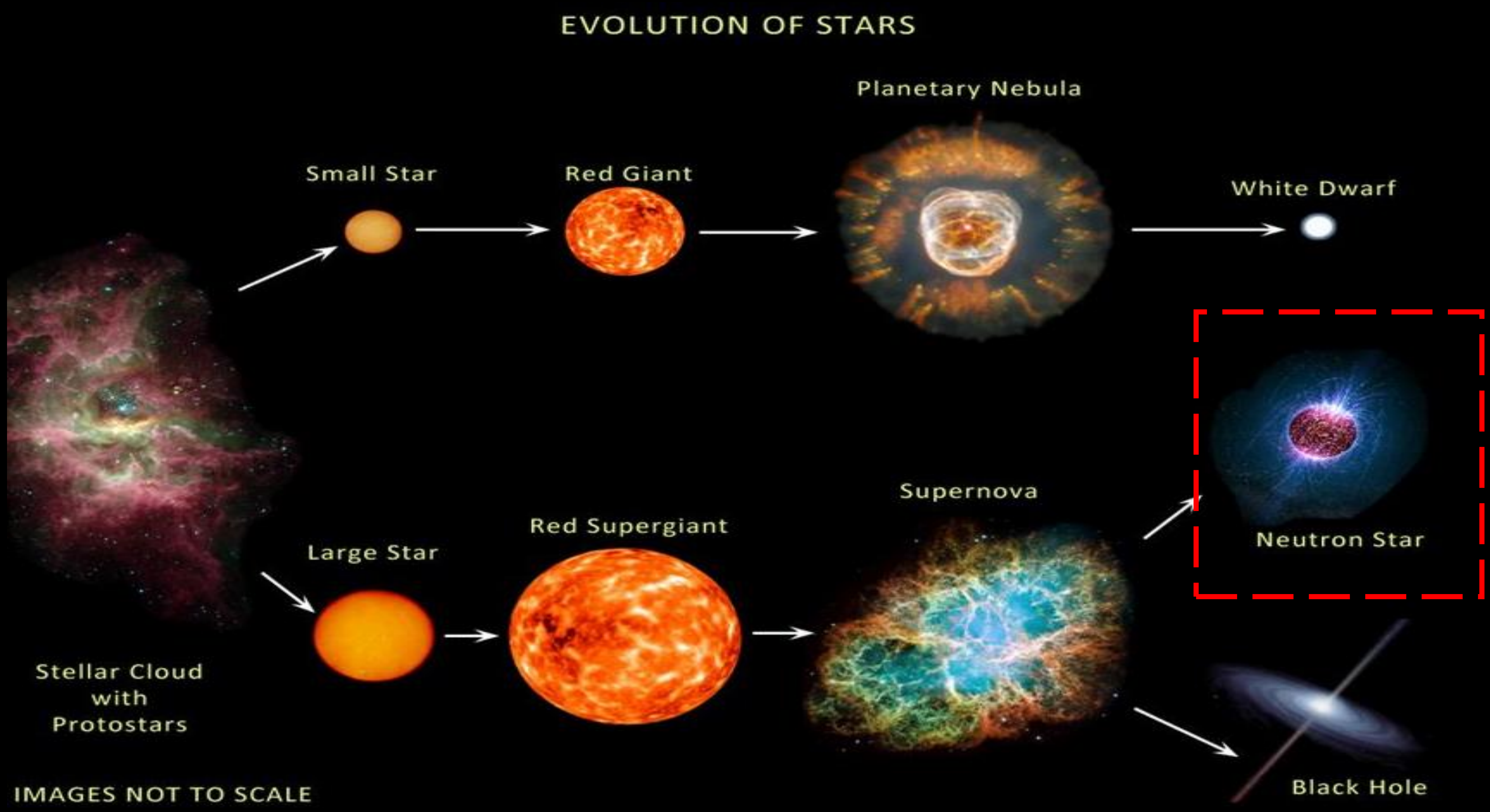
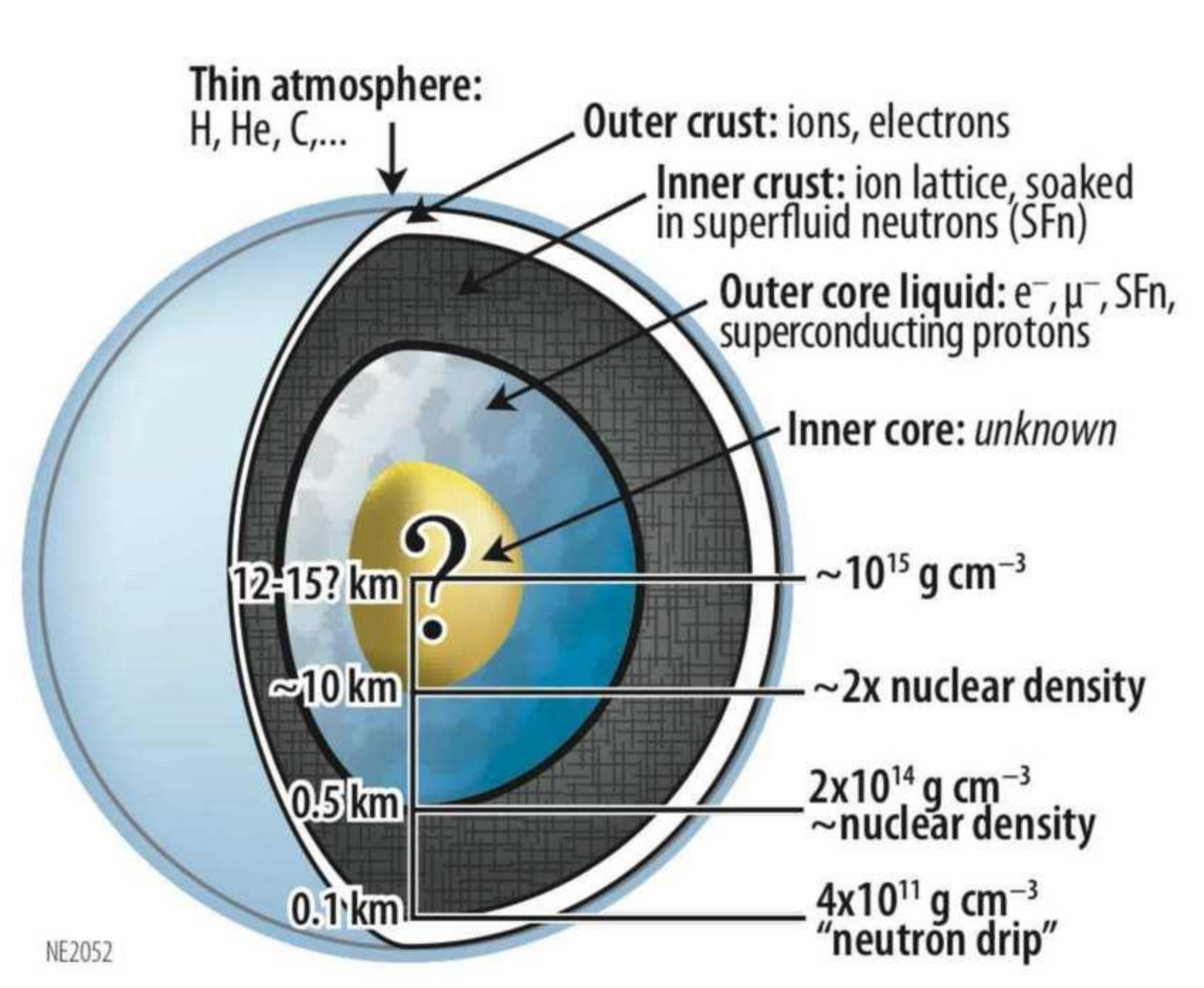
Cross-Collserola PhD Meeting, Barcelona

6 October 2023


EVOLUTION OF STARS
Small Star
Red Giant
Planetary Nebula
White Dwarf
Neutron Star
Supernova
Red Supergiant
Large Star
Stellar Cloud
with
Protostars
Black Hole
IMAGES NOT TO SCALE

Neutron stars properties

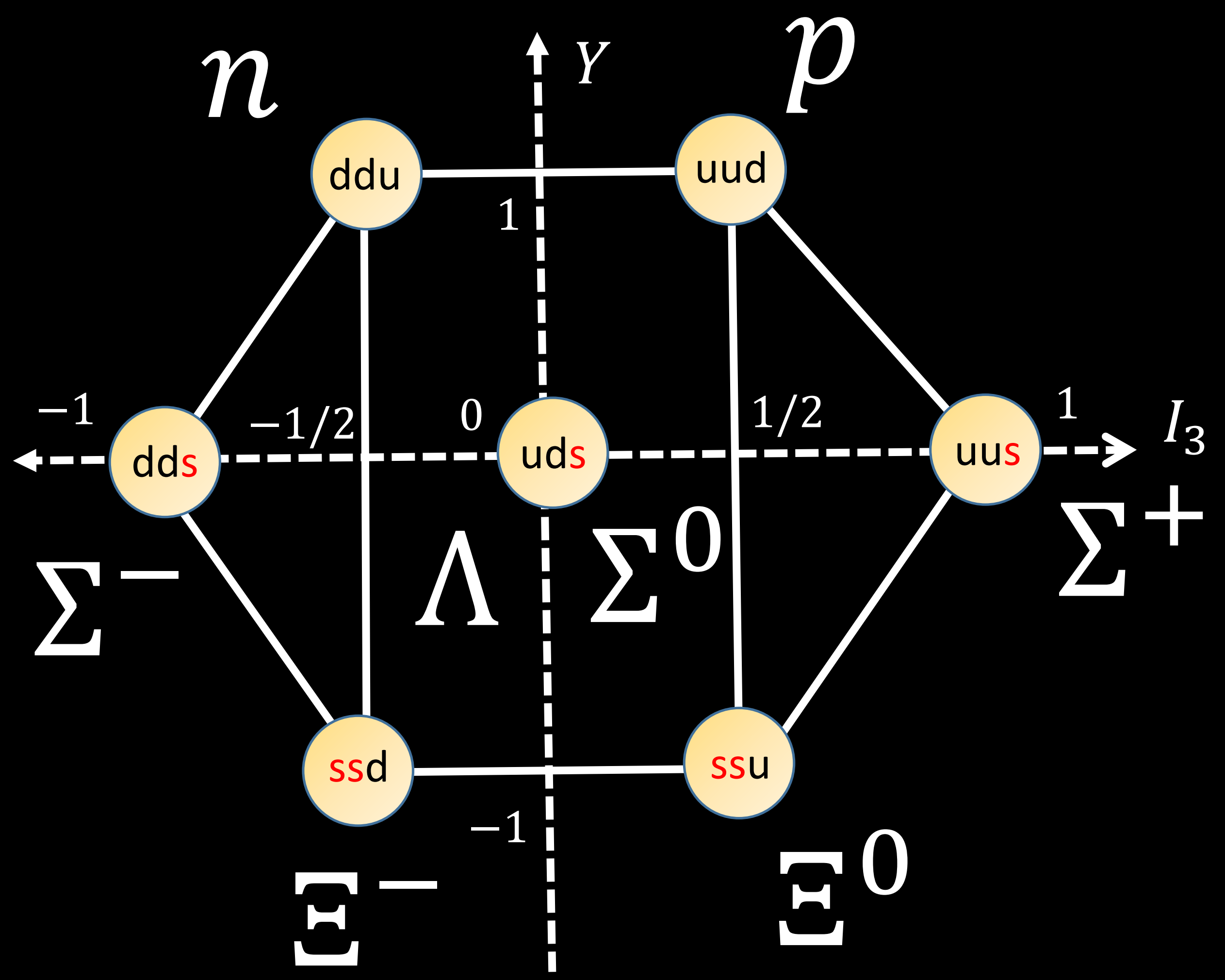


https://heasarc.gsfc.nasa.gov/

Inner core

- Nuclear matter
- Leptons
- ??? Pion condensate ???
- ??? Kaon condensate ???
- **??? Hyperons ???**
- ??? Deconfined quark matter???

Hyperons in the neutron stars?



- Hyperons are baryons made of one or more strange quarks

Electroweak decay

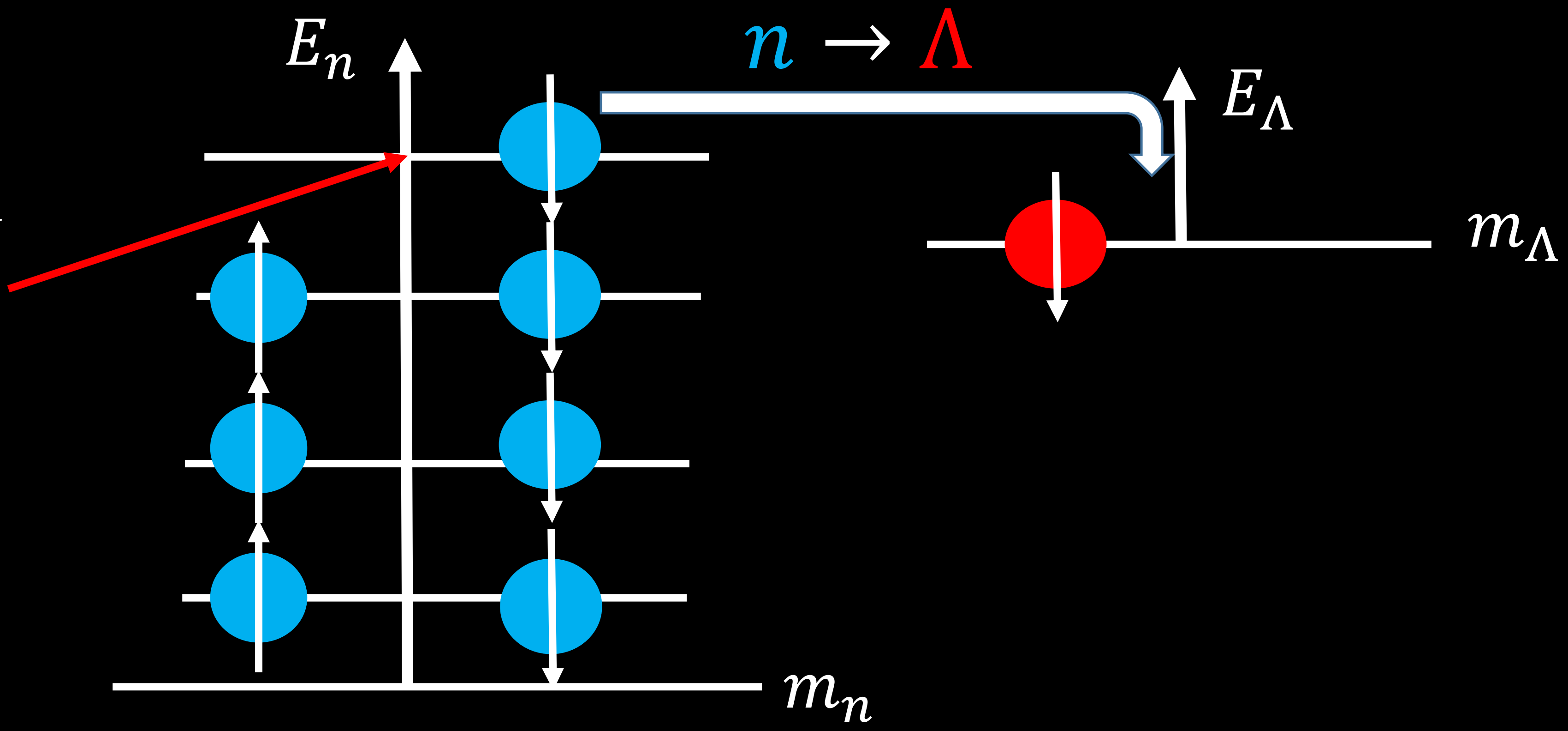
$$\Lambda \to p + \pi^-$$

$$\Lambda \to n + \pi^0$$

CAN THEY BE CREATED INSIDE THE STARS?

Hyperons in the neutron stars?

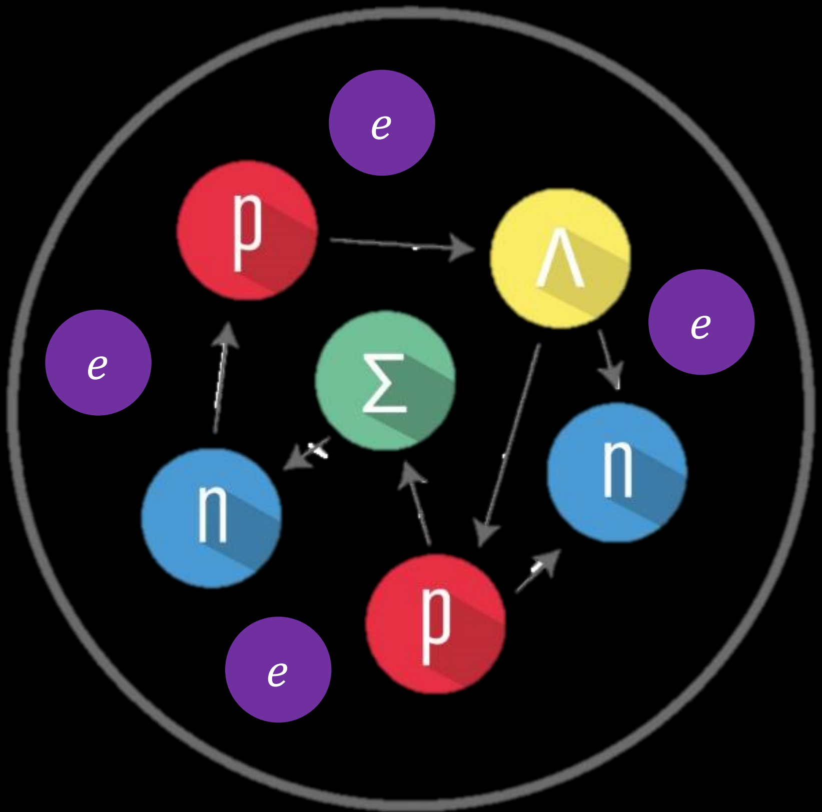
Energetically favorable for Λ hyperon to appear when:
$\mu_n > m_\Lambda$



Equilibrium conditions:

$$\mu_\Lambda = \mu_{\Sigma^0} = \mu_n$$
$$\mu_{\Sigma^+} = \mu_p$$
$$\mu_{\Sigma^-} = \mu_{\Xi^-} = 2\mu_n - \mu_p$$

Equation of state (EoS) of inner core



Difficult task – to model the interaction between the strongly interacting particles

THE JOB OF THE NUCLEAR PHYSICS

$$P = P(\rho_B, T, Y_Q)$$

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

Relativistic mean-field framework

Hyperons thermal signatures on the EoS

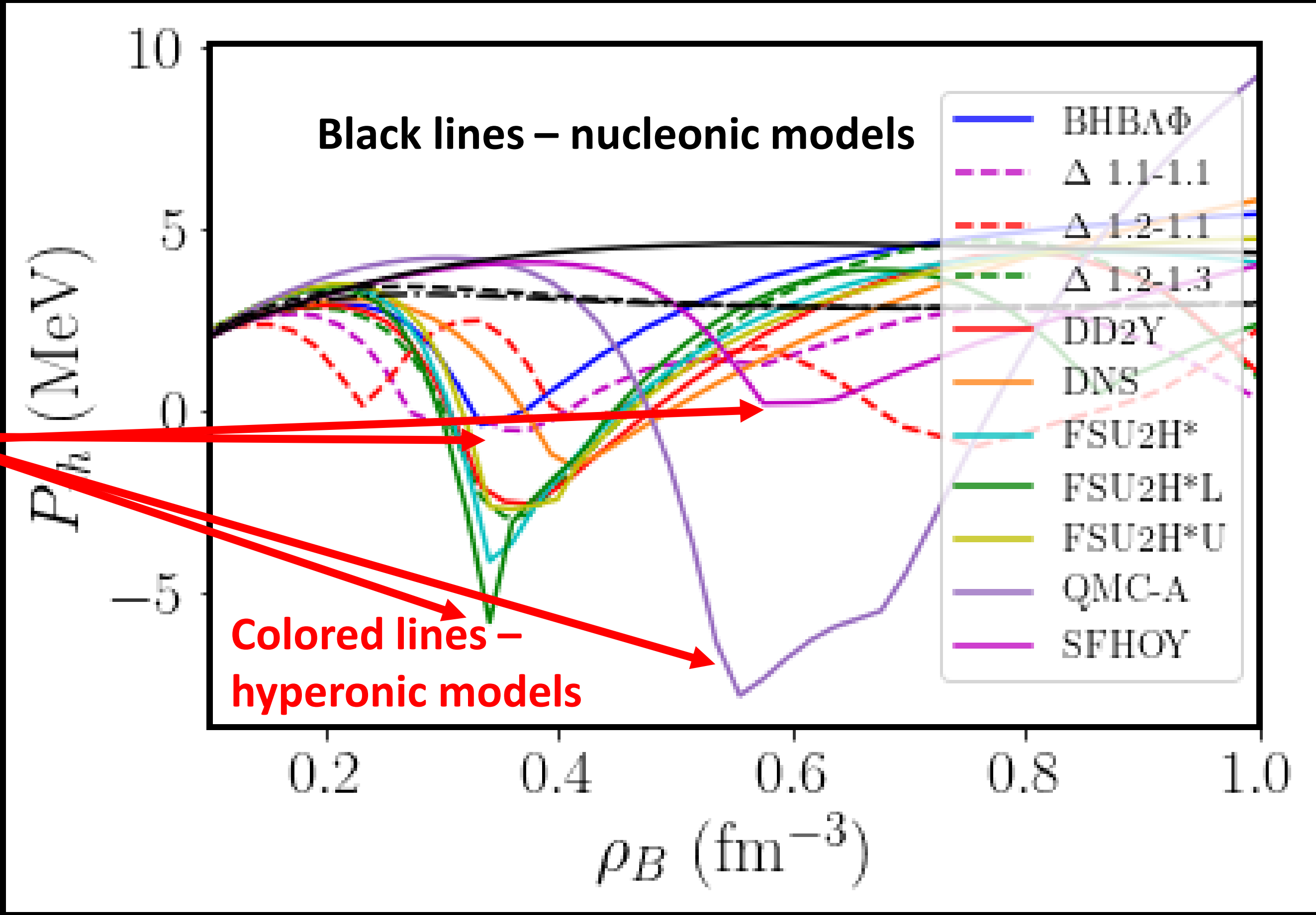
Homogenous matter at
Charge fraction $Y_Q = 0.1$ *and Temperature* $T = 25$ *MeV*

Thermal pressure P_{th}

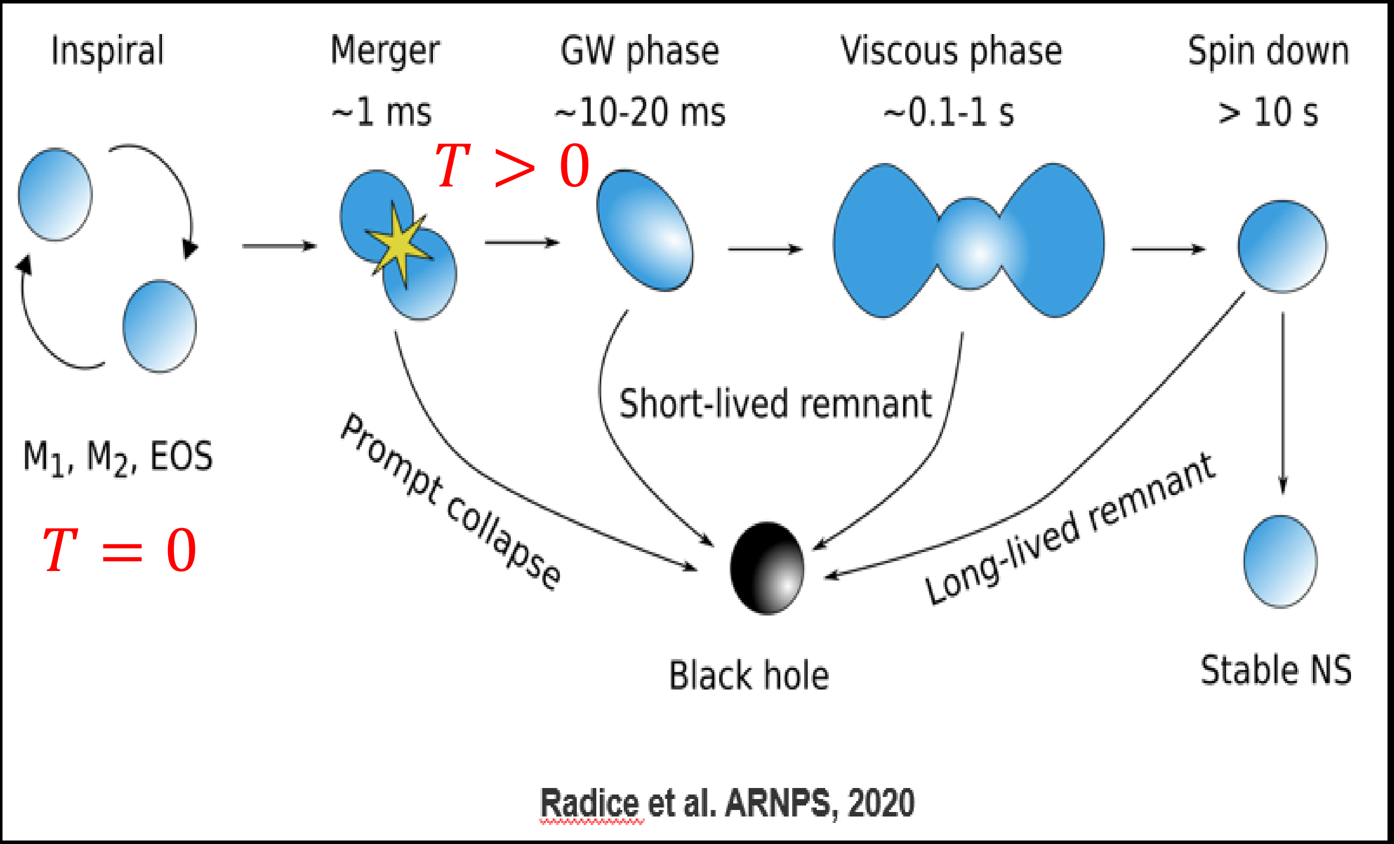
$$P_{th} = P(T, \rho_B, Y_Q) - P(0, \rho_B, Y_Q)$$

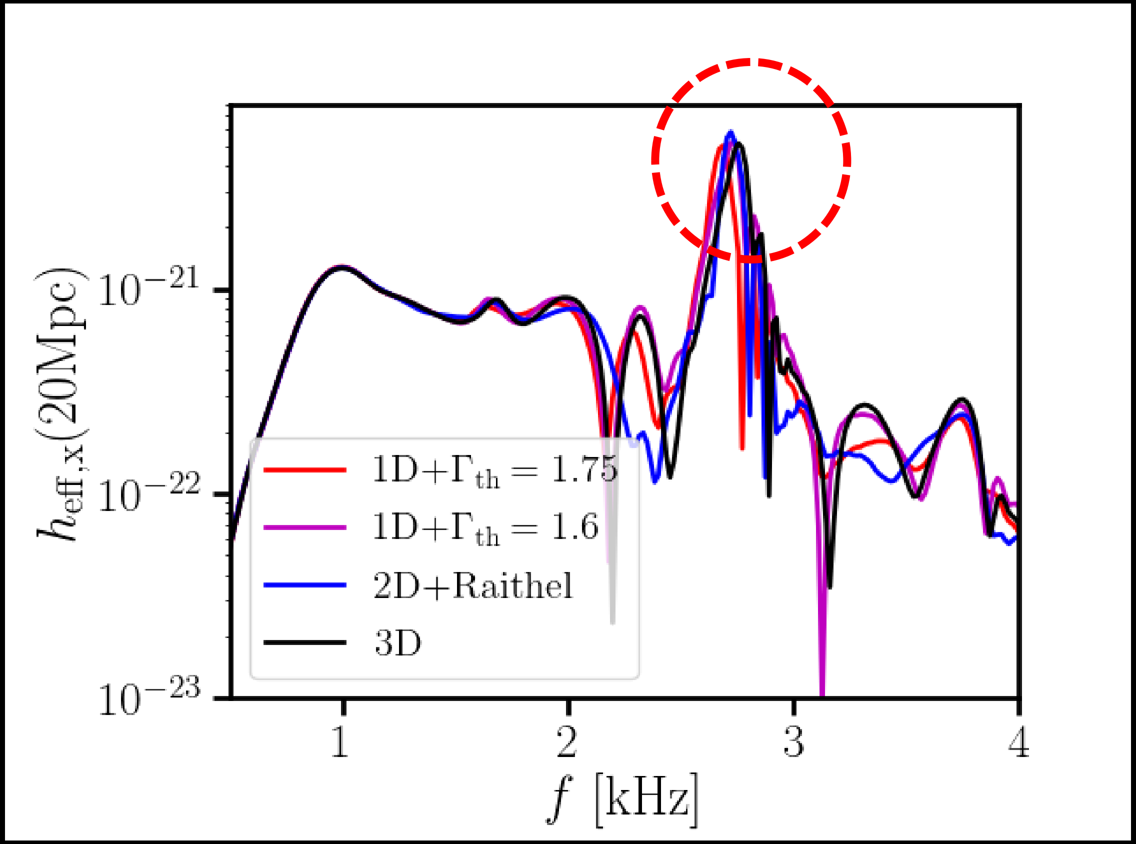
The introduction of the hyperons induces a drop in the thermal index

MODEL INDEPENDENT FEATURE



Binary NS merger simulations and observables





WE CAN LEARN SOMETHING ABOUT THE COMPOSITION FROM THE GRAVITATIONAL WAVE OBSERVABLES

Summary

- Neutron stars are natural laboratories for studying matter at extreme conditions.
- In their deepest layers, exotic components, such as hyperons can 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 leave a characteristic hyperon signature on the astrophysical observables obtained from neutron star mergers.

THANK YOU FOR YOUR ATTENTION

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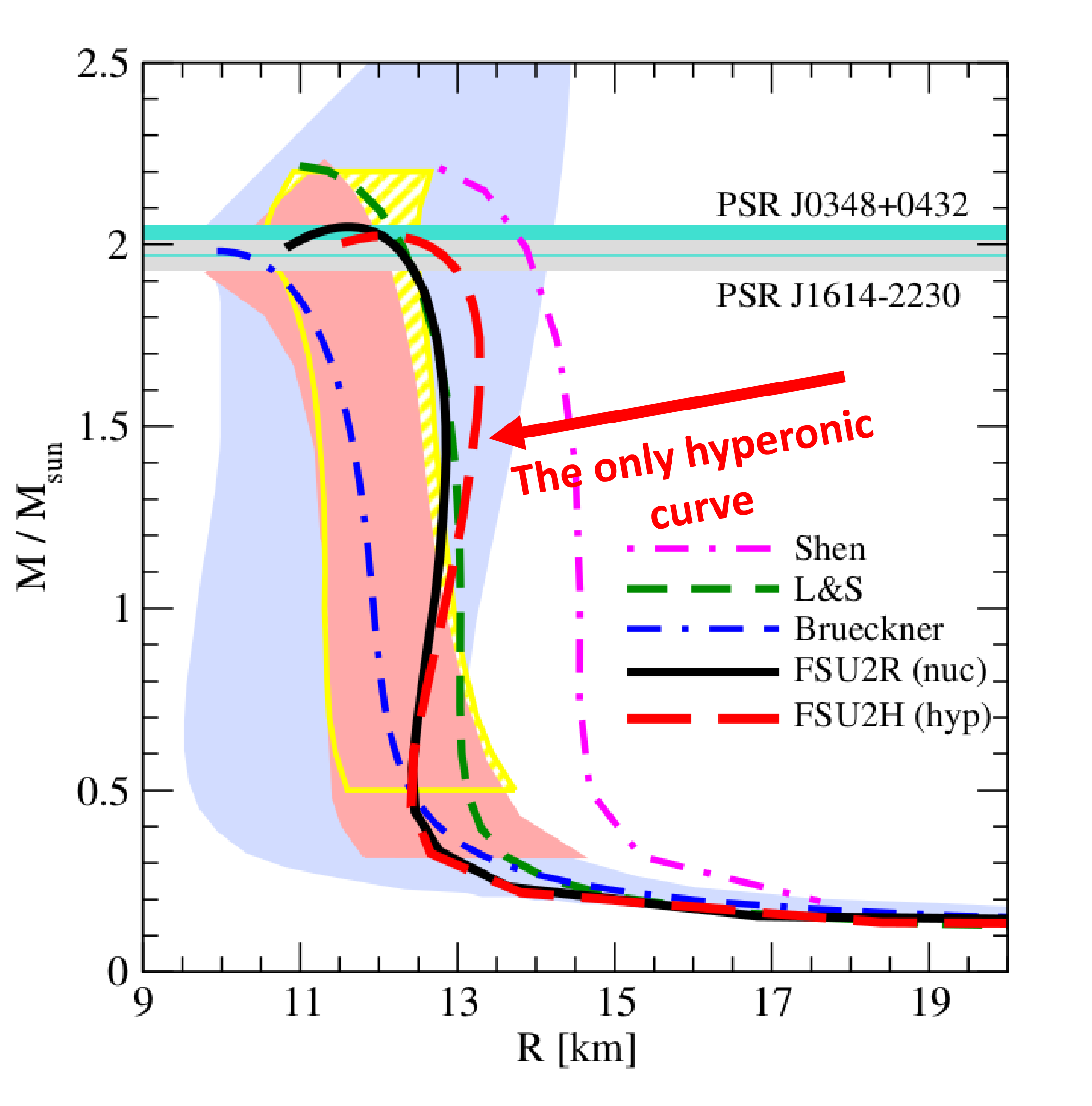
Hyperons signatures on the EoS

- Although the difference between a hyperonic and non-hyperonic EoS within a given model is big, it is difficult to distinguish them from other nucleonic models

(Large uncertainties in the properties of dense matter)



PASA, 34, e065 (2017)

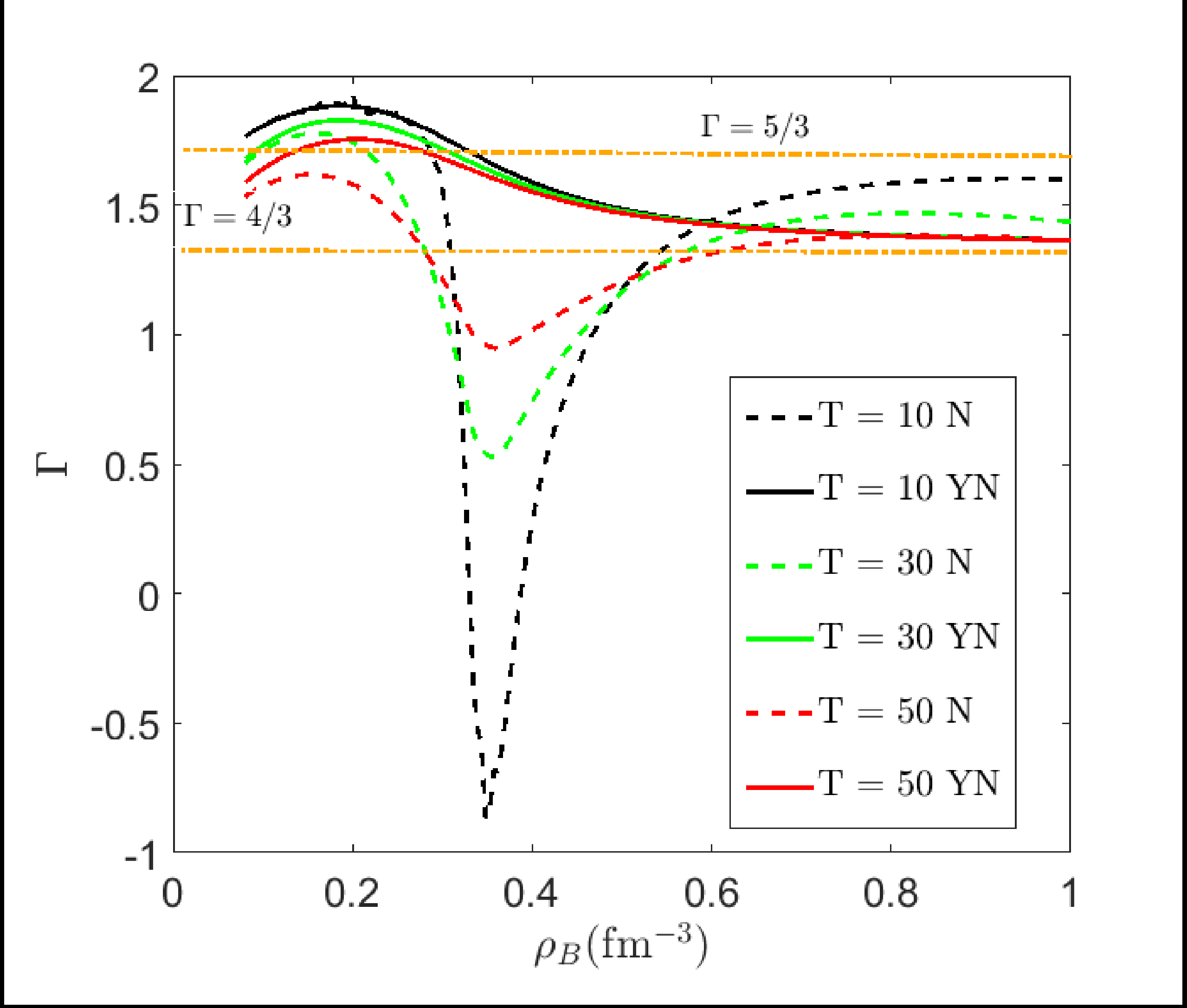
Hyperons signatures on the EoS

- Different thermal behavior between the hyperonic and the nucleonic EoSs

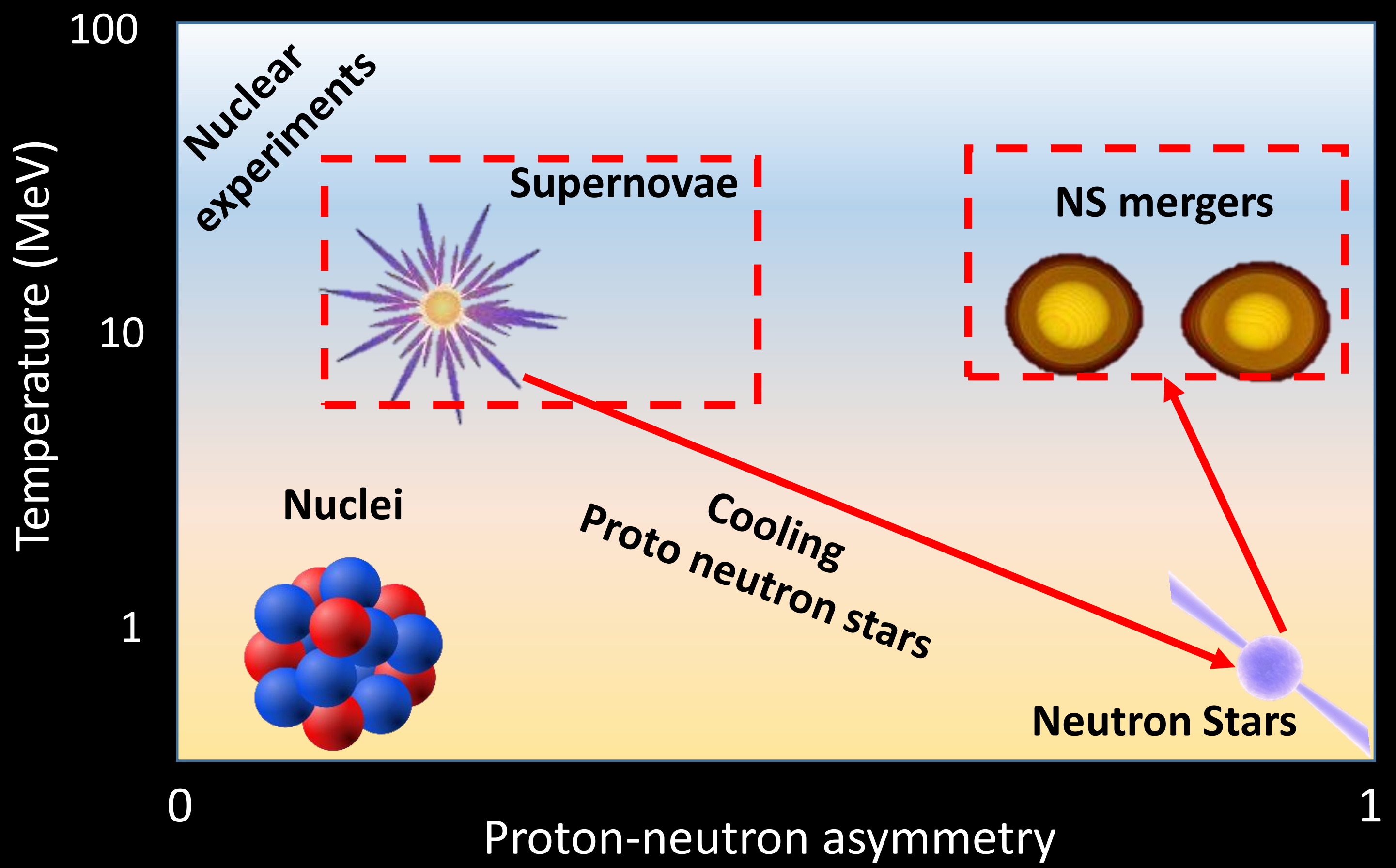
- We define a quantity that is known as thermal index:

$$\Gamma(T,\rho_B,\beta) = 1 + \frac{P(T,\rho_B,\beta) - P(0,\rho_B,\beta)}{\epsilon(T,\rho_B,\beta) - \epsilon(0,\rho_B,\beta)}$$

- The introduction of the hyperons induces a drop in the thermal index – **MODEL INDEPENDENT FEATURE**



EoS of dense matter and relativistic simulations I

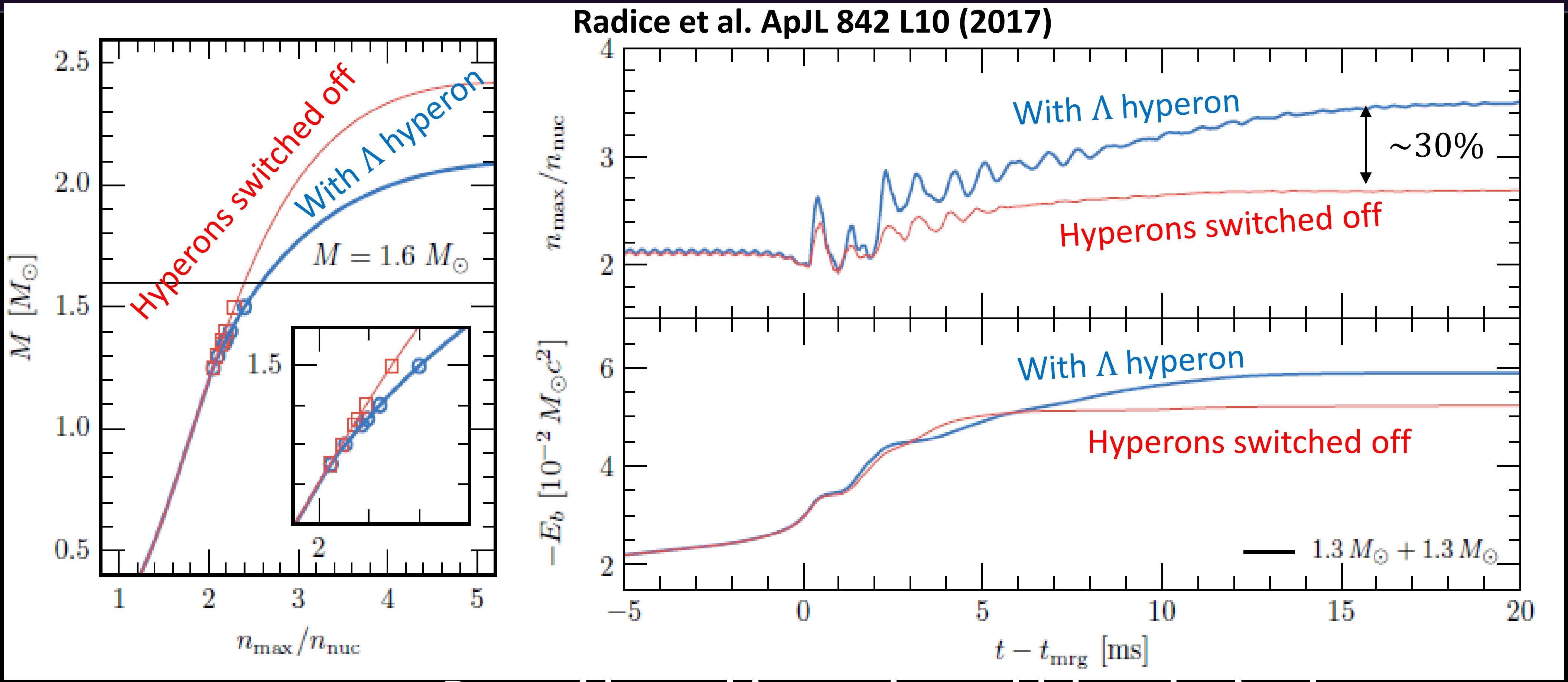


- The EoS represents the main input needed for simulating the violent phenomena such as core-collapse supernovae or binary stars mergers.

- The EoS is needed for a wide range of the parameter values:

- Density
- Temperature
- Charge fraction

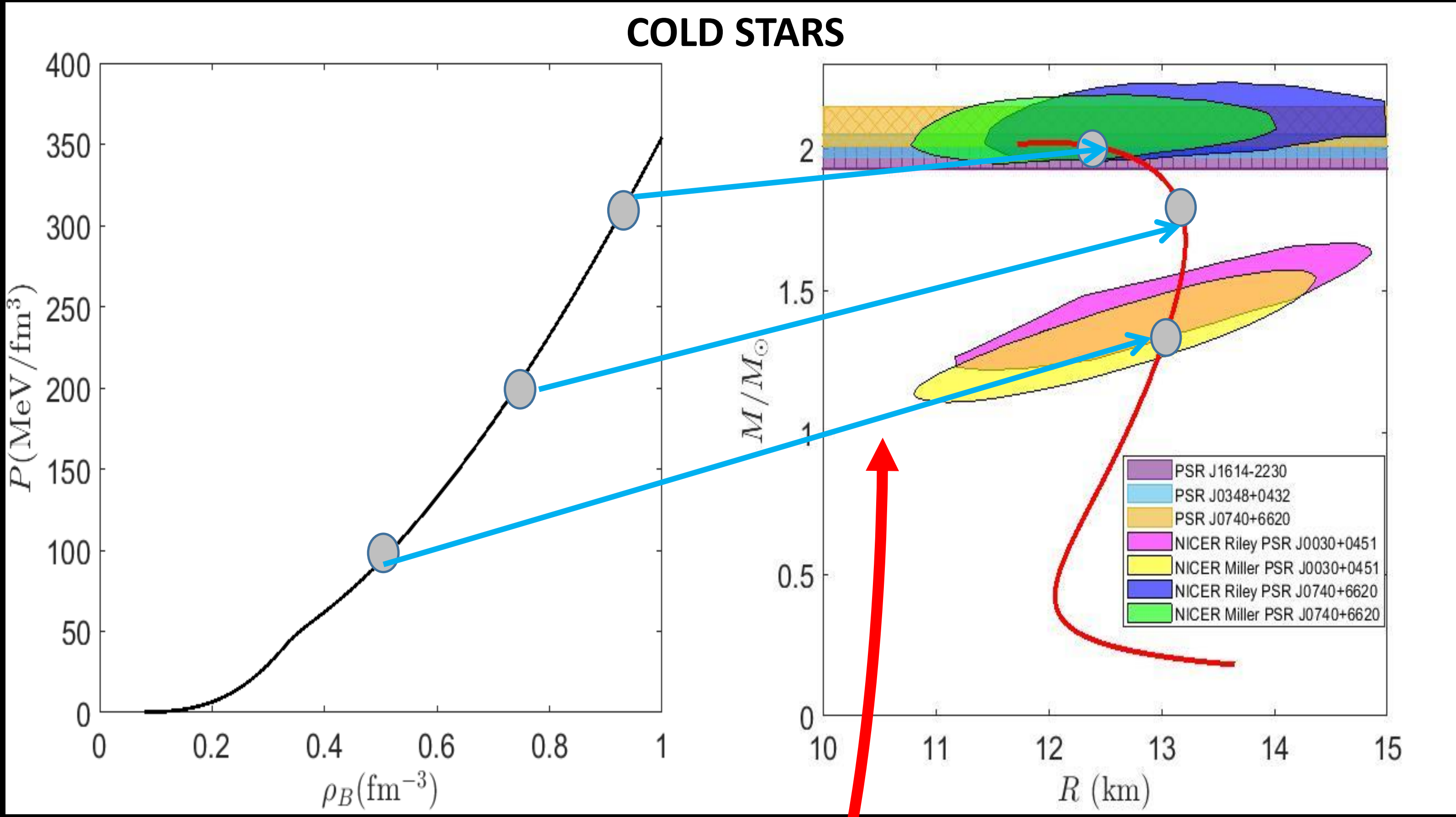
Signal of hyperons in the GW observables?



- Downside – this result could be obtained from other purely nucleonic EoS model.
  (it would not be signaling the presence of hyperons)

GW simulations and observables

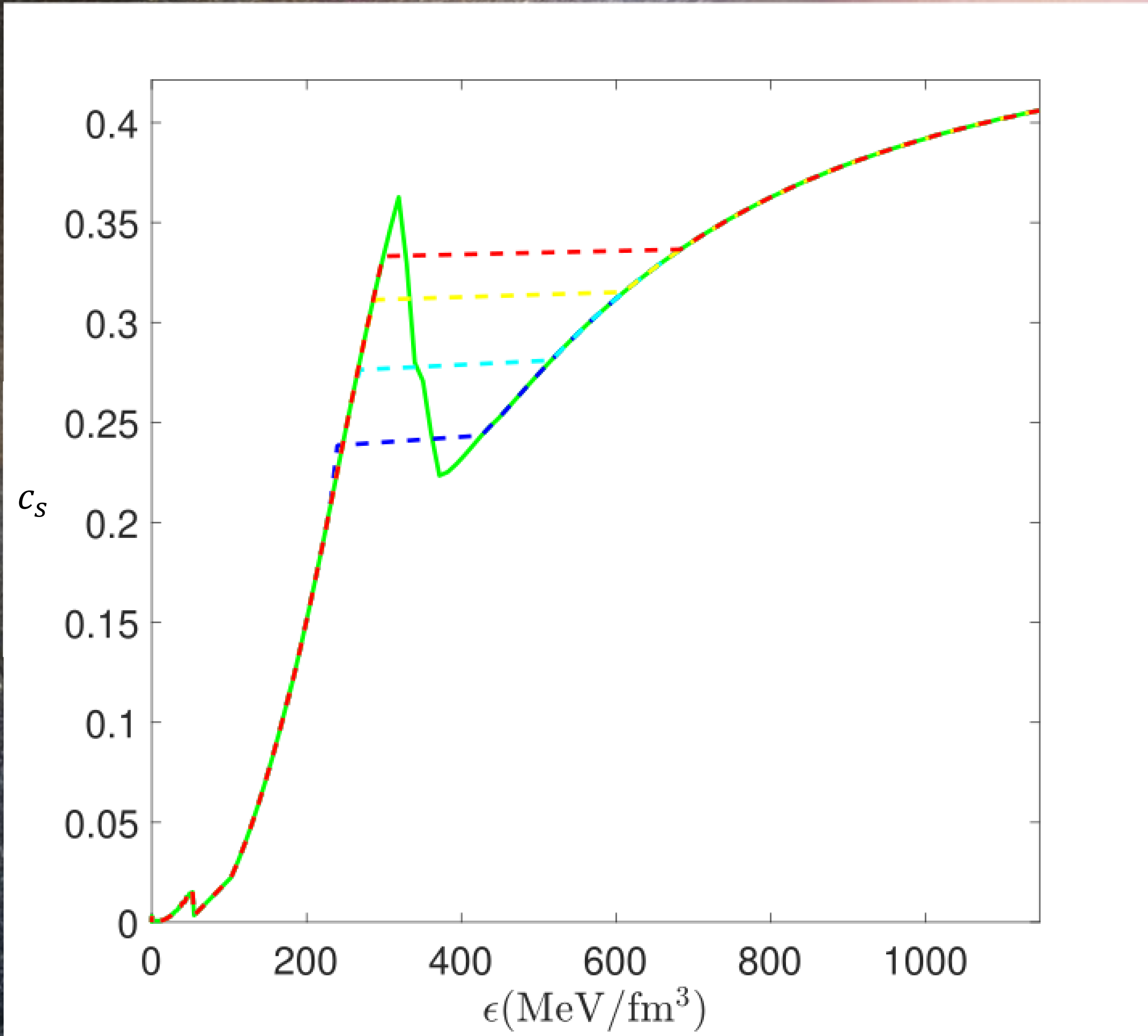
- The EoS uniquely determine global properties of the stars
- The model also satisfies the constraints from astrophysical observables



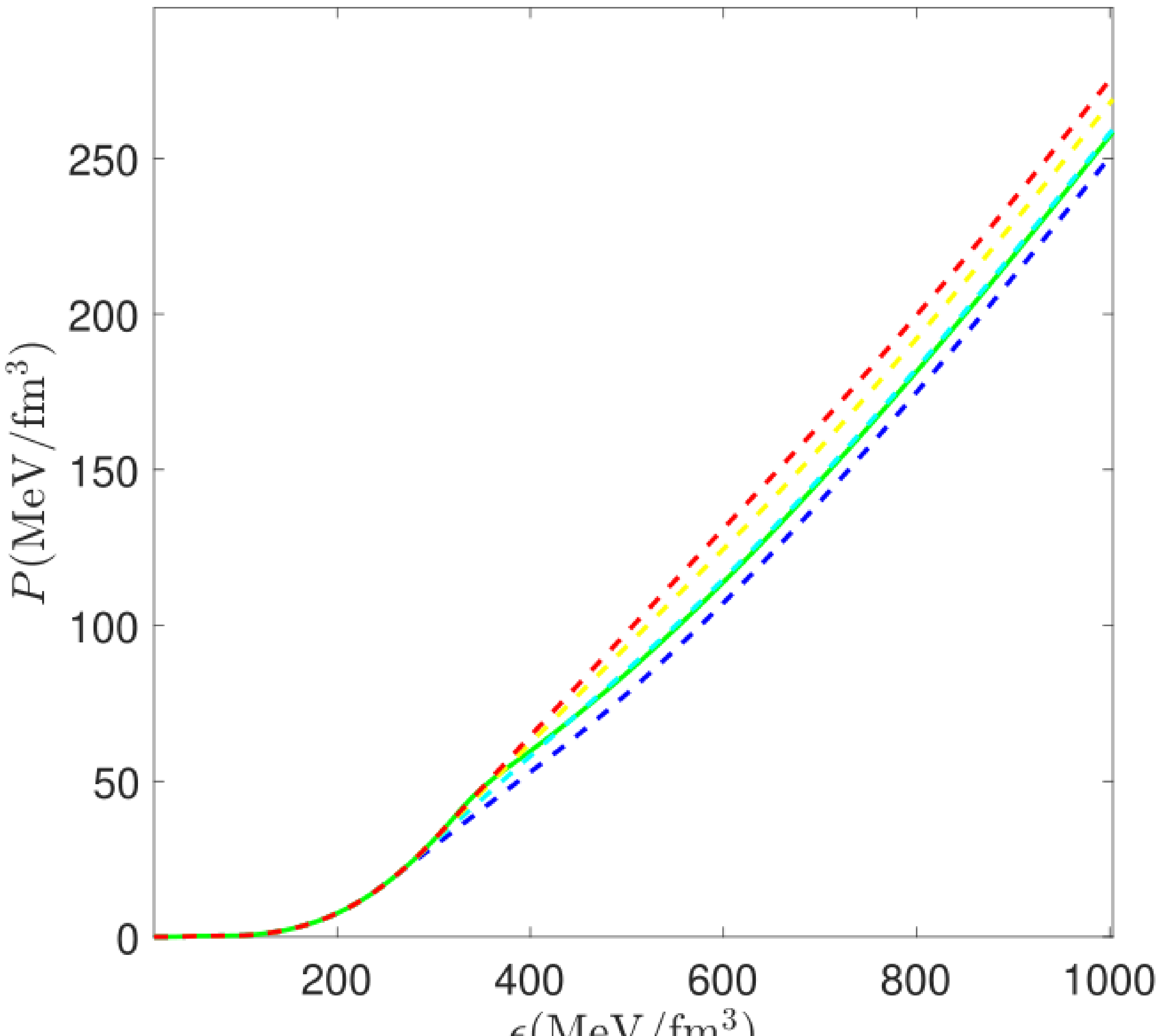
$$\frac{dP}{dr} = -\frac{G\rho m}{r^2}\left(1+\frac{P}{\rho_B c^2}\right)\left(1+4\pi P\frac{r^3}{mc^2}\right)\left(1-\frac{2Gm}{c^2 r}\right)^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

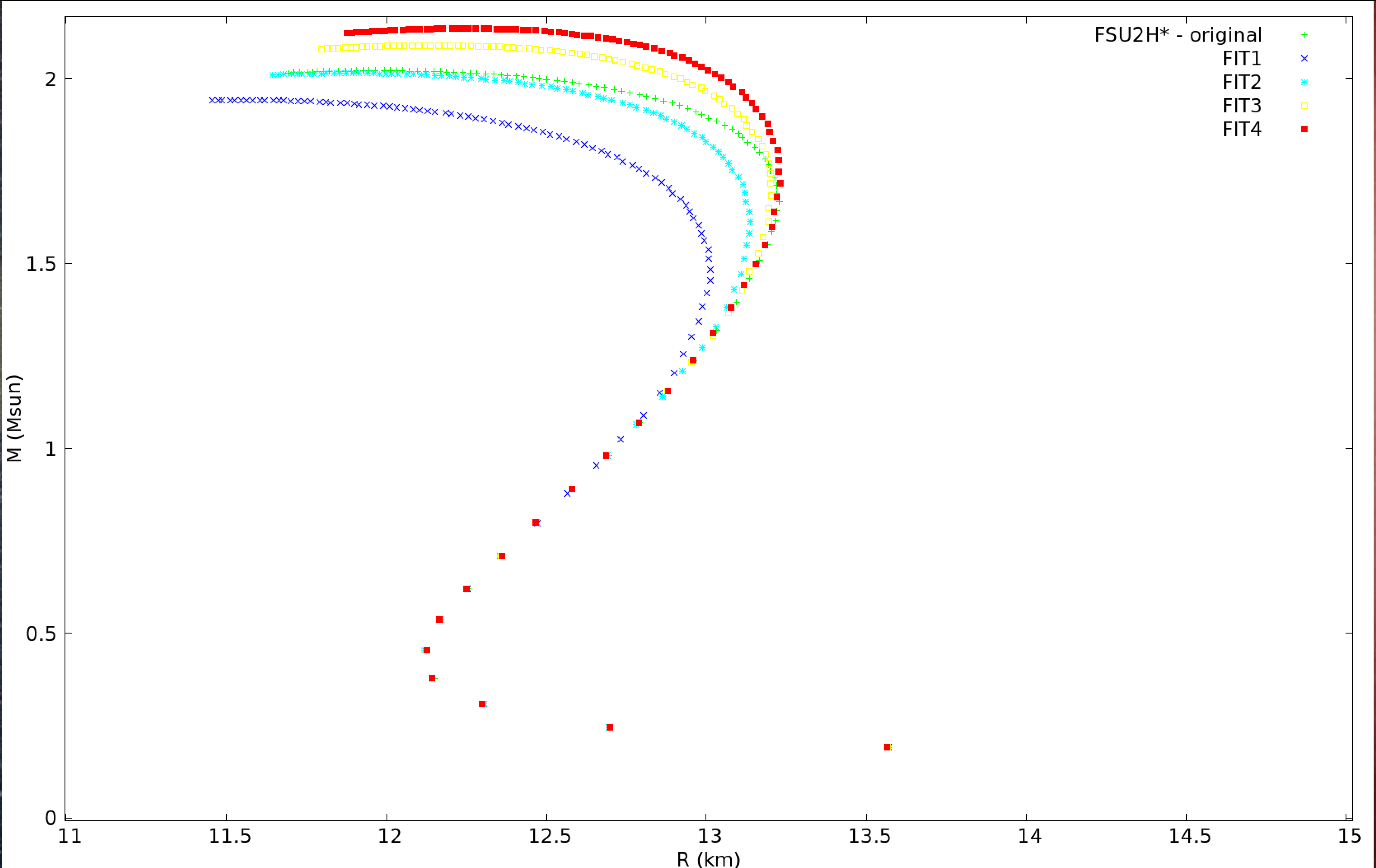
Structure equations (TOV equations)



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

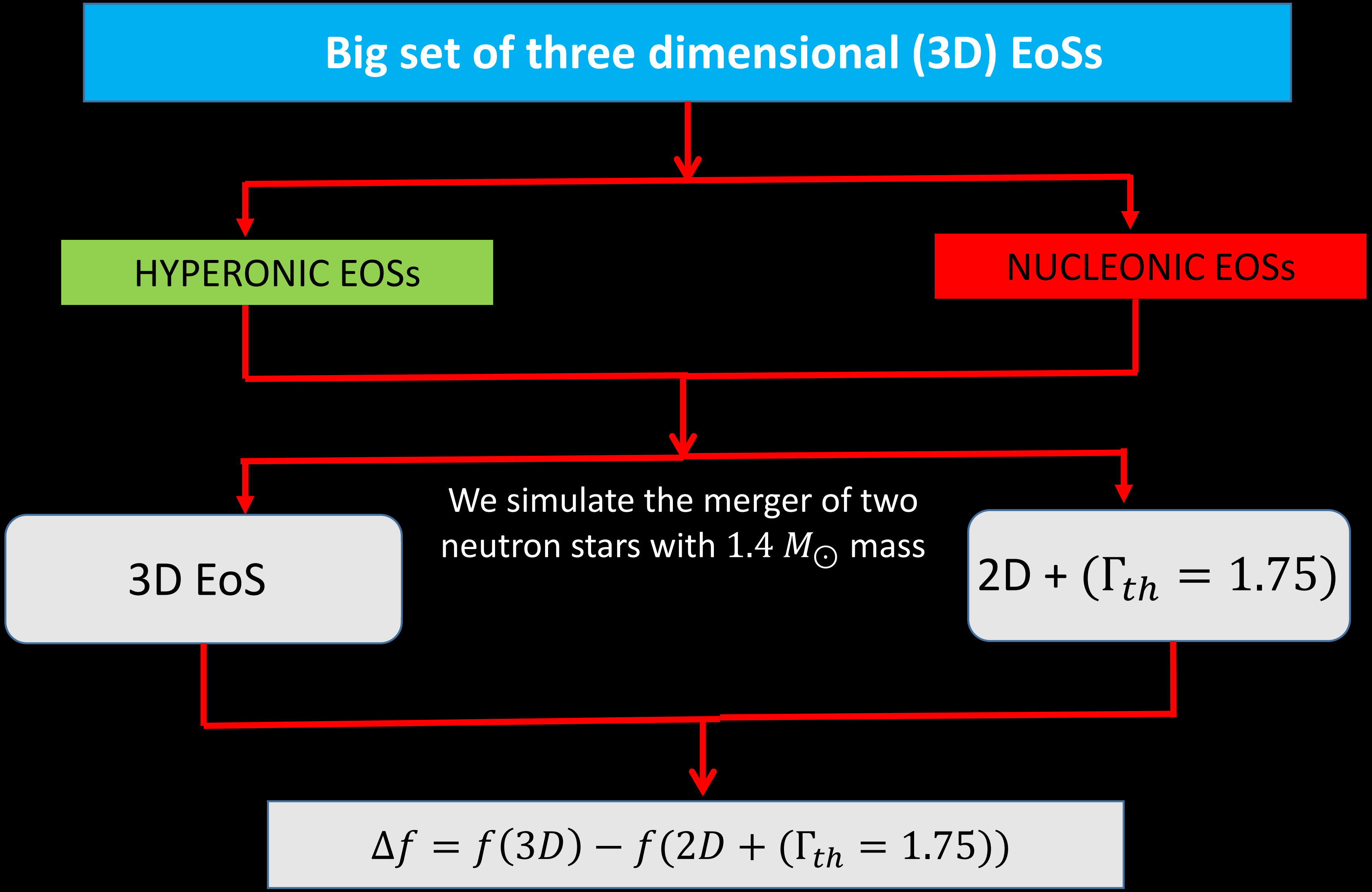


$P(\mathrm{MeV/fm^3})$
0
50
100
150
200
250
200
400
600
800
1000



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

Identifying the hyperonic signature



Signal of hyperons in the GW observables? I

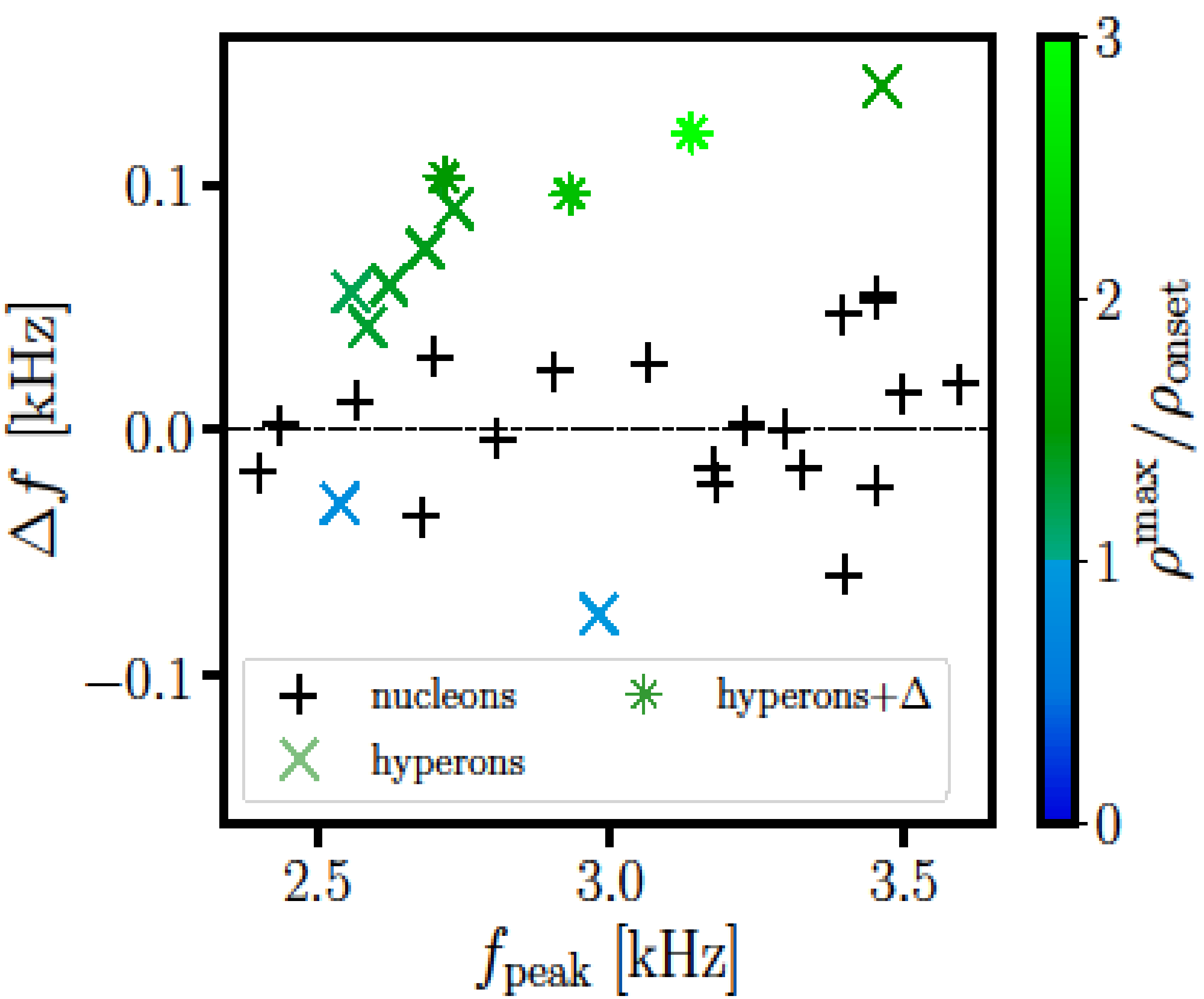
- The difference in the frequencies is defined as:
  $\Delta f = f(3D) - f(2D + \Gamma_{th} = 1.75)$

- All hyperonic models that reach the onset density (density at which the hyperons appear in cold matter) have a positive shift.

- Nucleonic models are grouped around $\Delta f \approx 0$.

- Hyperonic models that do not reach high enough densities are behaving like nucleonic models.

arXiv:2307.03710



Signal of hyperons in the GW observables? II

- Another useful way to illustrate the hyperonic imprint is to show the following relation

$$f_{peak} = f_{peak}(\Lambda(1.75M_{\odot}))$$

- All hyperonic models that have densities above the onset ones predict frequency that lies above the second order polynomial fit of the nucleonic models.

- Most of the hyperonic models also lie above the maximum deviation of the nucleonic models.

arXiv:2307.03710