Interplay between Δ particles and hyperons in neutron stars

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arXiv:1907.08583 [astro-ph.HE]

Recent Progress and perspectives in STRANge Exotic atoms studies and related topics

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Neutron stars

Neutron stars are some of the densest manifestations of massive objects in the universe

➔ Ideal laboratories for testing theories of dense matter physics
(establishing connections between nuclear physics, particle physics and astrophysics)

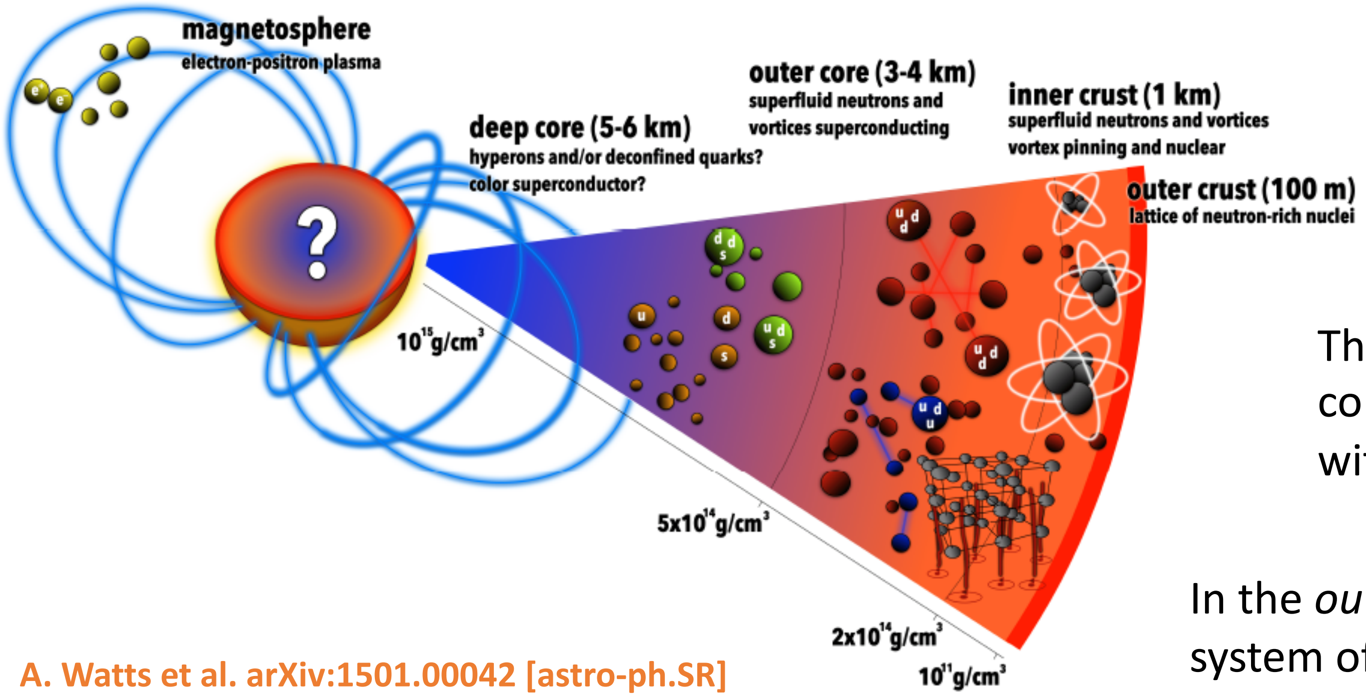
Observations:
studies of binary pulsars
thermal emission from isolated neutron stars
glitches from pulsars
quasi-periodic oscillations from accreting neutron stars
…

$M \sim 1.4\ M_{\odot}$
(most precise measurement $M_{PSR1913+16} = 1.4411 \pm 0.0035\ M_{\odot}$

$R \sim 12$ km

$\rho_c = 10^{14} - 10^{15}$ g/cm^3
(about 5 times the density at the center of nuclei $n_0 \simeq 0.16$ fm^{-3})

Inside a neutron star



A. Watts et al. arXiv:1501.00042 [astro-ph.SR]
PoS AASKA14 (2015) 053

The *outer crust* (10^6 g/cm^3 < ρ < 4×10^{11} g/cm^3) is a solid region where a Coulomb lattice of heavy nuclei co-exist with a relativistic quantum electron gas.

The *inner crust* (4×10^{11} g/cm^3 < ρ < 2×10^{14} g/cm^3) consists of a lattice of neutron–rich nuclei together with a superfluid neutron gas and an electron gas.

In the *outer core* (2×10^{14} g/cm^3 < ρ < 10^{15} g/cm^3) we have a system of deconfined neutrons in β-equilibrium with a smaller concentration of protons and electrons.

At the higher densities of the *inner core* (typically 2-3 times nuclear saturation density, ρ_0=2.8×10^{14} g/cm^3), hyperons may appear, a phase transition to quark matter may take place, kaon condensation may occur, etc… still open to debate!

The knowledge of the EoS of dense matter is essential for calculations of neutron star properties!

β equilibrium conditions

For a given EoS (i.e. $\varepsilon(n_n,n_p,n_e)$) the composition of neutron star matter is found by demanding

$\mu_n = \mu_p + \mu_e$ Equilibrium against weak interaction processes (β-stability) $n \to p\, e^- \, \bar{\nu}_e$

$n_p = n_e$ Charge neutrality

$n = n_n + n_p$ Baryon number conservation

3 equations → n_n,n_p,n_e determined, for a given baryon density n

May other particles appear? Yes! Negative muons...

$$\boxed{\begin{aligned} \mu_n &= \mu_p + \mu_e \\ n_p &= n_e + n_\mu \\ n &= n_n + n_p \\ \mu_\mu &= \mu_e \end{aligned}}$$

4 equations

→ n_n,n_p,n_e,n_μ

EoS:

$\varepsilon(n_n,n_p,n_e,n_\mu)$

Hyperons in neutron stars

Hyperons are also likely to appear in the neutron star core

$$\Lambda \rightarrow p\, e^-\, \bar{\nu}_e \quad \leftrightarrow \quad p\, e^- \rightarrow \Lambda\, \nu_e$$

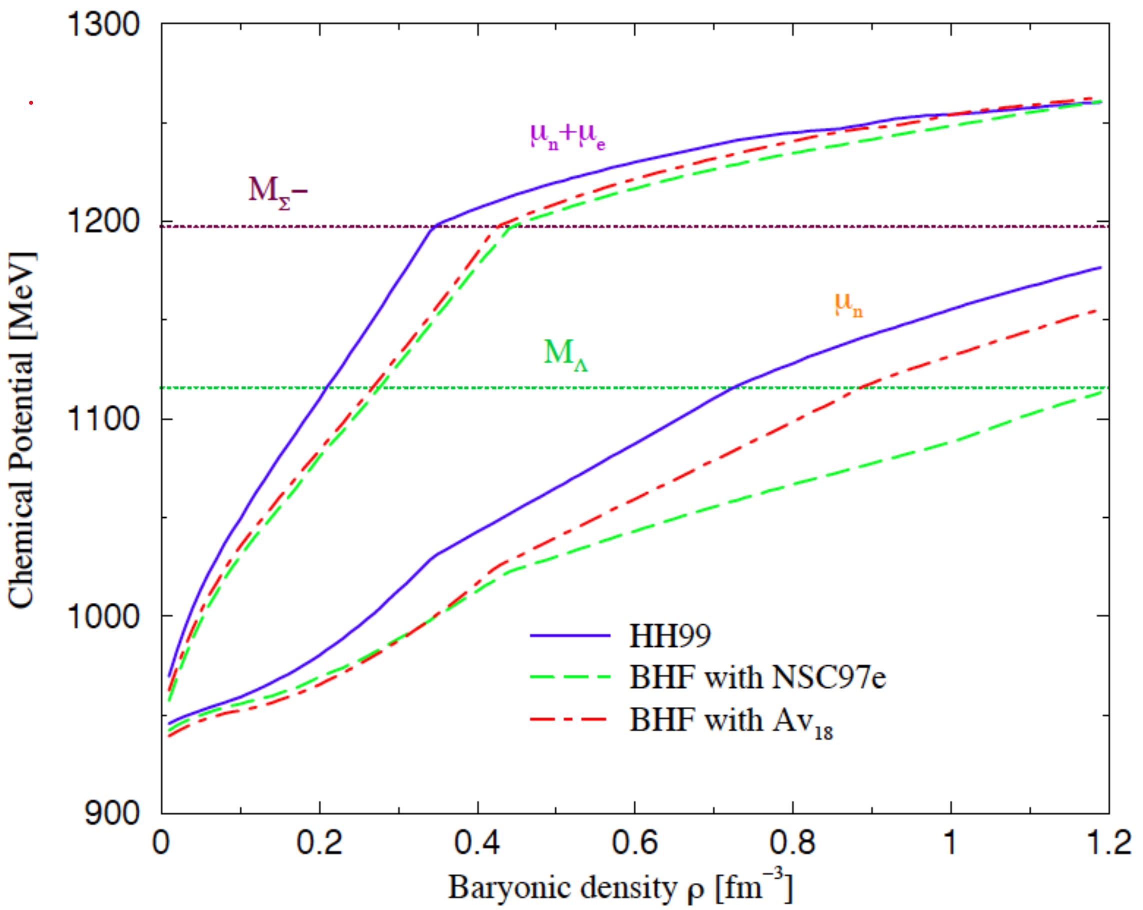
$$\mu_\Lambda = \mu_p + \mu_e \rightarrow \mu_\Lambda = \mu_n$$

$$\Sigma^- \rightarrow n\, e^-\, \bar{\nu}_e \quad \leftrightarrow \quad n\, e^- \rightarrow \Sigma^-\, \nu_e$$

$$\mu_{\Sigma^-} = \mu_n + \mu_e \rightarrow \mu_{\Sigma^-} = \mu_n + \mu_e$$

The onset density of Λ or Σ^- will depend on the attractive/repulsive nature of their interactions with nucleons.

Typically, hyperons appear at 2-3 ρ_0

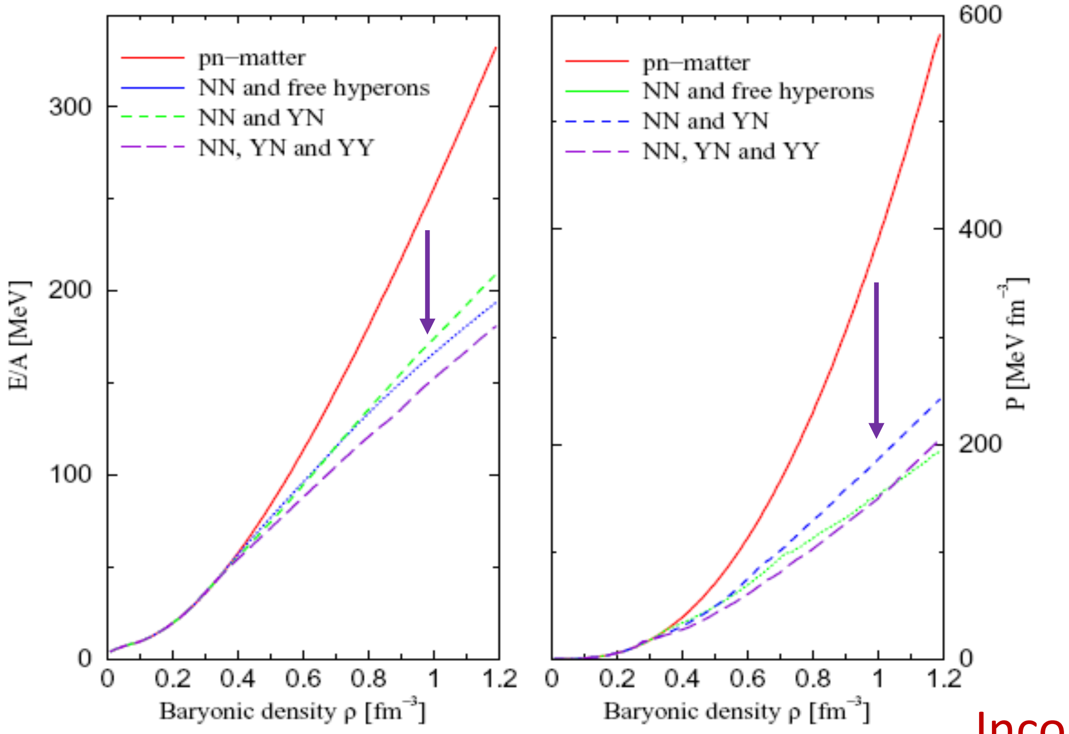


I. Vidaña, 2001

Hyperon “puzzle”

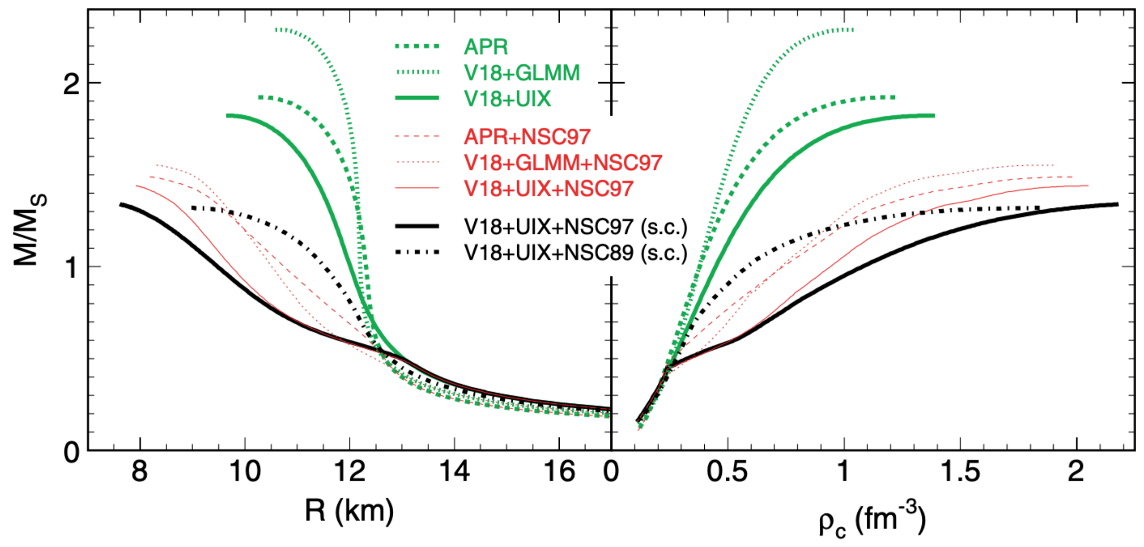
Given an EoS, the Tolman -Oppenheimer-Volkov (TOV) equations determine de Mass-Radius relation.

The appearance of hyperons softens the EoS…



I. Vidaña, 2001

… and reduces the maximum mass of the neutron star



H. J. Schulze, A. Polls, A. Ramos and I. Vidaña, PRC 73, 058801 (2006)

Incompatible with recent observations!

PSR J164-2230 → M= 1.97± 0.04 $M_\odot$ Demorest et al., Nature 467, 1081 (2010)

J0348+0432 → M= 2.01±0.04 $M_\odot$ Antoniadis et al., Science 340, 6131 (2013)

J0740+6620 → M= 2.14±0.10 $M_\odot$ Cromartie et al., Nature Astron. (2019)

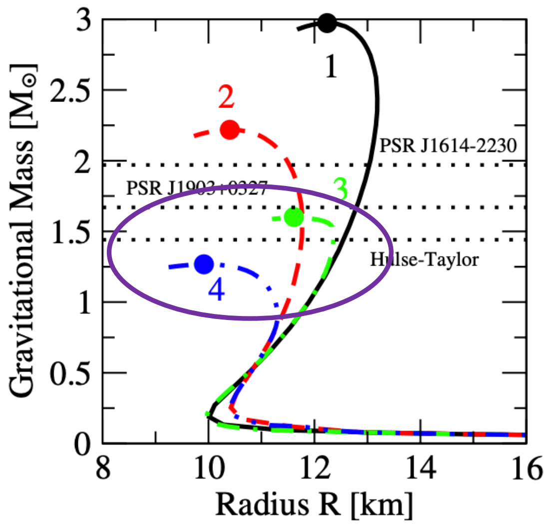
→ need extra pressure at high density

Some solutions have been proposed (see e.g. review **Chatterjee & Vidaña Eur. Phys. J. A52 (2016) no.2, 29**)

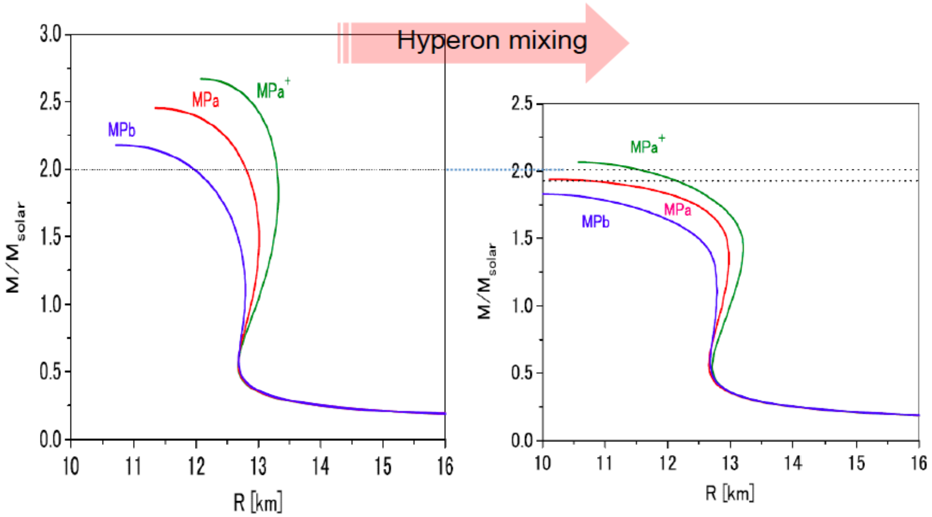
- Improved two-body YN, YY interactions?
  (EFT YN interactions→ strongly repulsive U_Λ at high densities)

  Haidenbauer, Meißner, Kaiser, Weise, Eur.Phys.J. A53 (2017) no.6, 121

- Three-body forces: YNN, YYN, YYY? (no consensus has been reached)

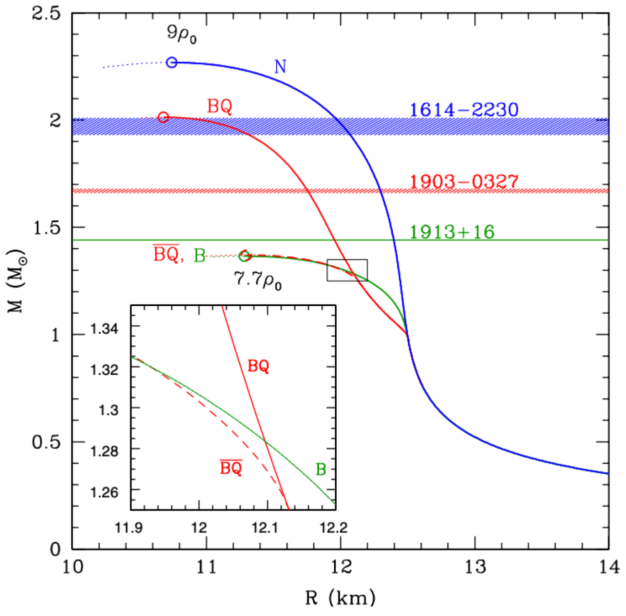


Vidana, Logoteta, Providencia, Polls, Bombaci, Eur. Phys. Lett. 94, 11002 (2011).



Yamamoto et al. PRC 88, 022801 (2013); PRC 90, 045805 (2014)

- Deconfined quark matter phase?



Zdunik, Haensel, Astron. and Astrophys. 551 A61 (2013)

EoS within the RMF model

$$\mathcal{L} = \sum_b \mathcal{L}_b + \cancel{\sum_\Delta \mathcal{L}_\Delta} + \sum_l \mathcal{L}_l + \mathcal{L}_m$$

$$\begin{aligned}
\mathcal{L}_b &= \bar{\Psi}_b(i\gamma_\mu\partial^\mu - m_b + g_{\sigma b}\sigma - g_{\omega b}\gamma_\mu\omega^\mu \\
&\quad - g_{\rho b}\gamma_\mu \boldsymbol{I}_b \cdot \boldsymbol{\rho}^\mu - g_{\phi b}\gamma_\mu\phi^\mu)\Psi_b, \\
&\cancel{\mathcal{L}_\Delta = \bar{\Psi}_\Delta (i\gamma_\mu\partial^\mu - m_\Delta + g_{\sigma\Delta}\sigma - g_{\omega\Delta}\gamma_\mu\omega^\mu} \\
&\quad \cancel{- g_{\rho\Delta}\gamma_\mu \boldsymbol{I}_\Delta \cdot \boldsymbol{\rho}^\mu)\Psi_\Delta,} \\
\mathcal{L}_l &= \bar{\psi}_l(i\gamma_\mu\partial^\mu - m_l)\psi_l, \\
\mathcal{L}_m &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{\kappa}{3!}(g_{\sigma N}\sigma)^3 - \frac{\lambda}{4!}(g_{\sigma N}\sigma)^4 \\
&\quad - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{\zeta}{4!}(g_{\omega N}\omega_\mu\omega^\mu)^4 \\
&\quad - \frac{1}{4}\boldsymbol{R}^{\mu\nu} \cdot \boldsymbol{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu \cdot \boldsymbol{\rho}^\mu \\
&\quad + \Lambda_\omega g_{\rho N}^2 \boldsymbol{\rho}_\mu \cdot \boldsymbol{\rho}^\mu g_{\omega N}^2 \omega_\mu\omega^\mu \\
&\quad - \frac{1}{4}P^{\mu\nu}P_{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu.
\end{aligned}$$

Meson mean fields

$$\bar{\sigma} = \langle\sigma\rangle \quad \bar{\omega} = \langle\omega^0\rangle \quad \bar{\rho} = \langle\rho_3^0\rangle \quad \bar{\phi} = \langle\phi^0\rangle$$

L. Tolos, M. Centelles, A. Ramos Astrophys.J. 834 (2017) no.1, 3

b ={n,p,Λ,Σ^-,Σ^0,Σ^+,Ξ^-,Ξ^0}

$g_{\sigma N}$ and $g_{\omega N}$ → nuclear matter saturation properties

$g_{\rho N}$ → nuclear symmetry energy and properties of neutron rich nuclei and neutron stars

$g_{\omega Y}$, $g_{\rho Y}$, $g_{\phi Y}$ → SU(6) symmetry

$g_{\sigma Y}$ → adjusted to hyperon optical potentials

κ, λ → control de incompressibility

ξ → softens the EoS at high density

Λ_ω → adjusts the desity dependence of the symmetry energy

Energy density:

$$\boxed{\begin{aligned}\epsilon = &\sum_b \epsilon_b + \sum_\Delta \epsilon_\Delta + \sum_l \epsilon_l + \frac{1}{2}m_\sigma^2\bar{\sigma}^2 + \frac{1}{2}m_\omega^2\bar{\omega}^2 \\ &+ \frac{1}{2}m_\rho^2\bar{\rho}^2 + \frac{1}{2}m_\phi^2\bar{\phi}^2 + \frac{\kappa}{3!}(g_{\sigma N}\bar{\sigma})^3 + \frac{\lambda}{4!}(g_{\sigma N}\bar{\sigma})^4 \\ &+ \frac{\zeta}{8}(g_{\omega N}\bar{\omega})^4 + 3\Lambda_\omega(g_{\rho N}g_{\omega N}\bar{\rho}\,\bar{\omega})^2.\end{aligned}}$$

with:

$$\varepsilon_b = \frac{1}{8\pi^2}\left[k_{Fb}E_{\rm Fb}^3 + k_{\rm Fb}^3 E_{\rm Fb} - m_b^{*4}\ln\frac{k_{\rm Fb}+E_{\rm Fb}}{m_b^*}\right]$$

$$\varepsilon_l = \frac{1}{8\pi^2}\left[k_{\rm Fl}E_{\rm Fl}^3 + k_{\rm Fl}^3 E_{\rm Fl} - m_l^4\ln\frac{k_{\rm Fl}+E_{\rm Fl}}{m_l}\right].$$

Pressure:

$$\boxed{P = \sum_i \mu_i n_i - \epsilon}$$

with:

$$\mu_b = (k_{Fb}^2 + m_b^{*2})^{1/2} + g_{\omega b}\bar{\omega} + g_{\rho b}I_{3b}\bar{\rho} + g_{\phi b}\bar{\phi}$$

$$m_b^* = m_b - g_{\sigma b}\bar{\sigma}$$

$$\mu_l = (k_{Fl}^2 + m_l^2)^{1/2}$$

→ We obtain an EoS for the nucleonic and hyperonic inner core of neutron stars that fulfills the 2M$_\odot$ observations as well as the recent determinations of stellar radii below 13 km, as we will see.

At the same time, we reproduce the properties of nuclear matter and finite nuclei, while fulfilling the restrictions on high-density matter deduced from heavy-ion collisions.

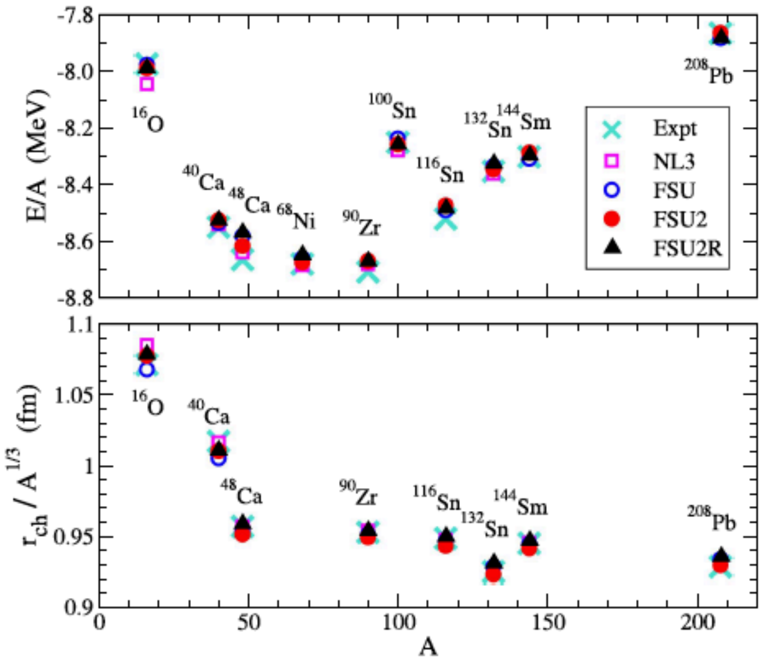


Figure 3. Energy per nucleon E/A and charge radius r_{ch} over $A^{1/3}$, where A is the mass number, of several nuclei with magic proton and/or neutron numbers. The values calculated with the models discussed in the text are compared with experiment. The experimental data are from Wang et al. (2012) for the energies and from Angeli & Marinova (2013) for the charge radii.

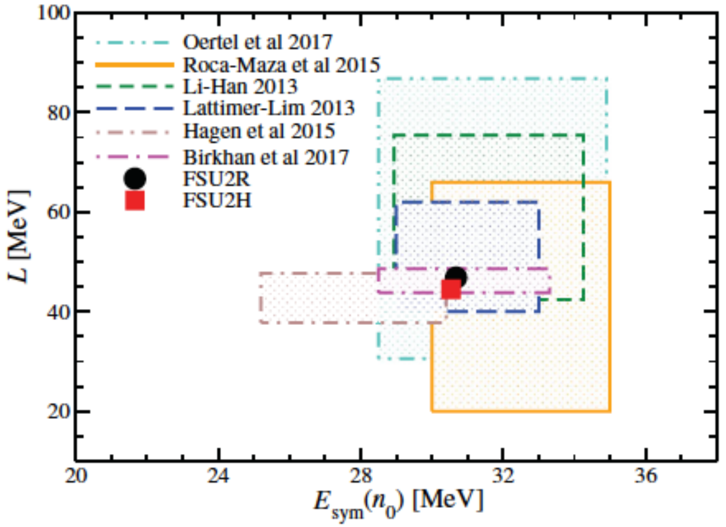


Figure 1. Slope of the symmetry energy (L) versus symmetry energy [$E_{sym}(n_0)$] at the nuclear matter saturation density for the models FSU2R and FSU2H discussed in text. The shaded regions depict the determinations from Li & Han (2013), Lattimer & Lim (2013), Roca-Maza et al. (2015), Hagen et al. (2015), Oertel et al. (2017), and Birkhan et al. (2017).

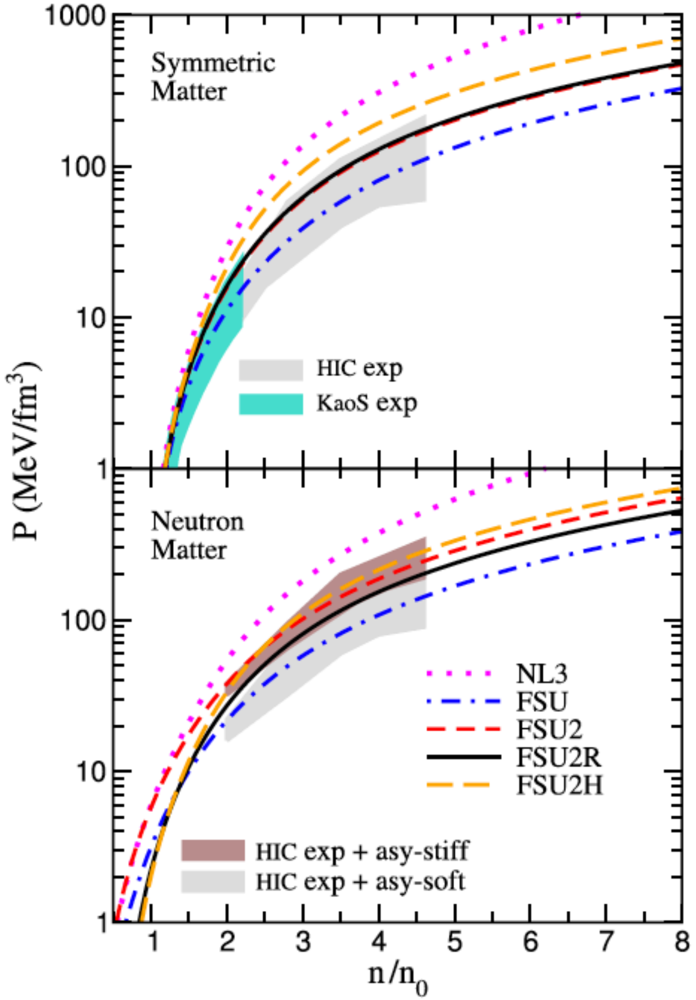
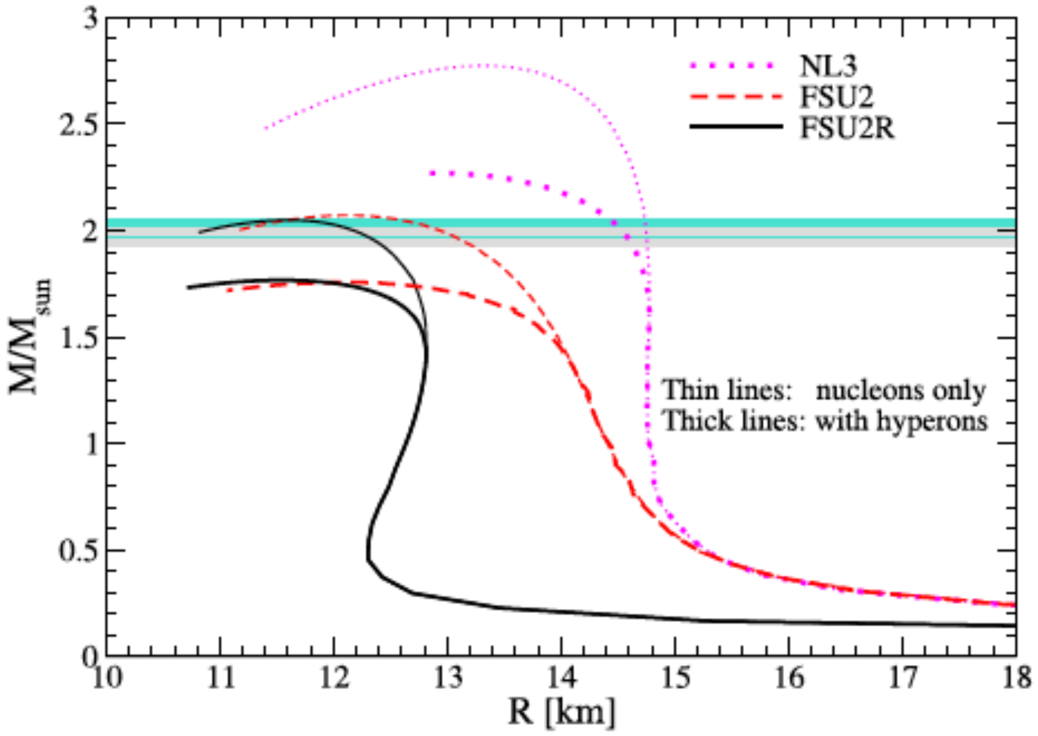


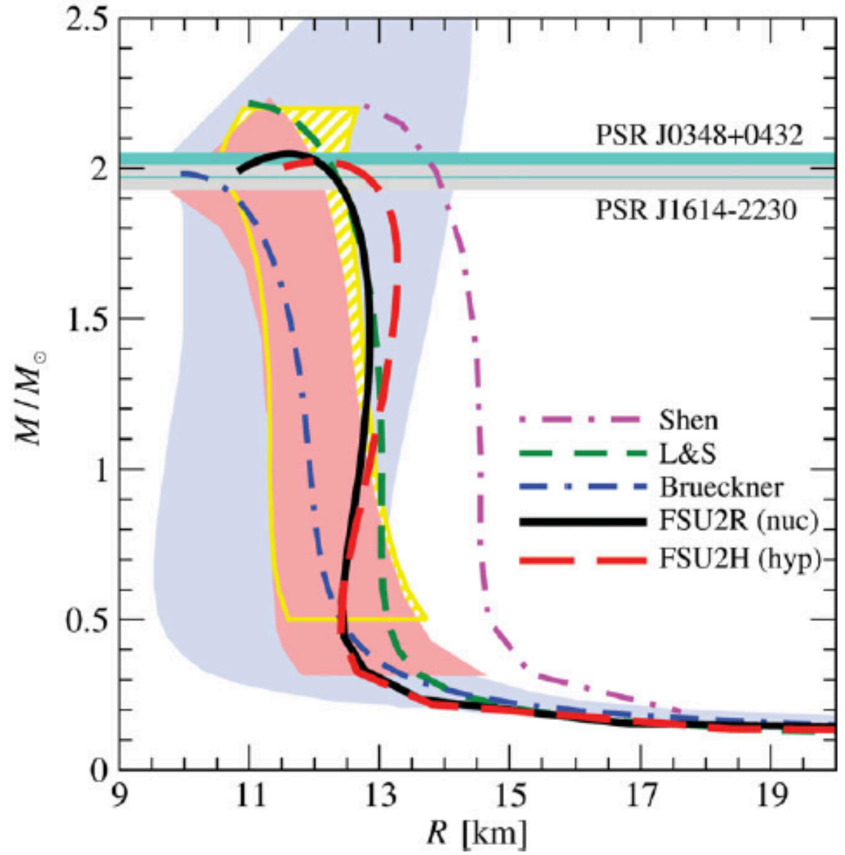
Figure 1. Pressure vs. baryon density for SNM (upper panel) and PNM (lower panel) for the different models presented in the text: NL3 (Lalazissis et al. 1997), FSU (Todd-Rutel & Piekarewicz 2005), FSU2 (Chen & Piekarewicz 2014), FSU2R (this work), and FSU2H (this work, Section 4). The regions compatible with the experimental data on collective flow (Danielewicz et al. 2002) and on kaon production (Fuchs et al. 2001; Lynch et al. 2009) in HICs are depicted in gray and turquoise, respectively, in the upper panel. The shaded areas in the panel of PNM correspond to the constraints from the flow data supplemented by a soft (gray area) and a stiff (brown area) symmetry energy (Danielewicz et al. 2002).

FSU2**R**: parameters fitted to reproduce low neutron star **radii** (< 13 km)

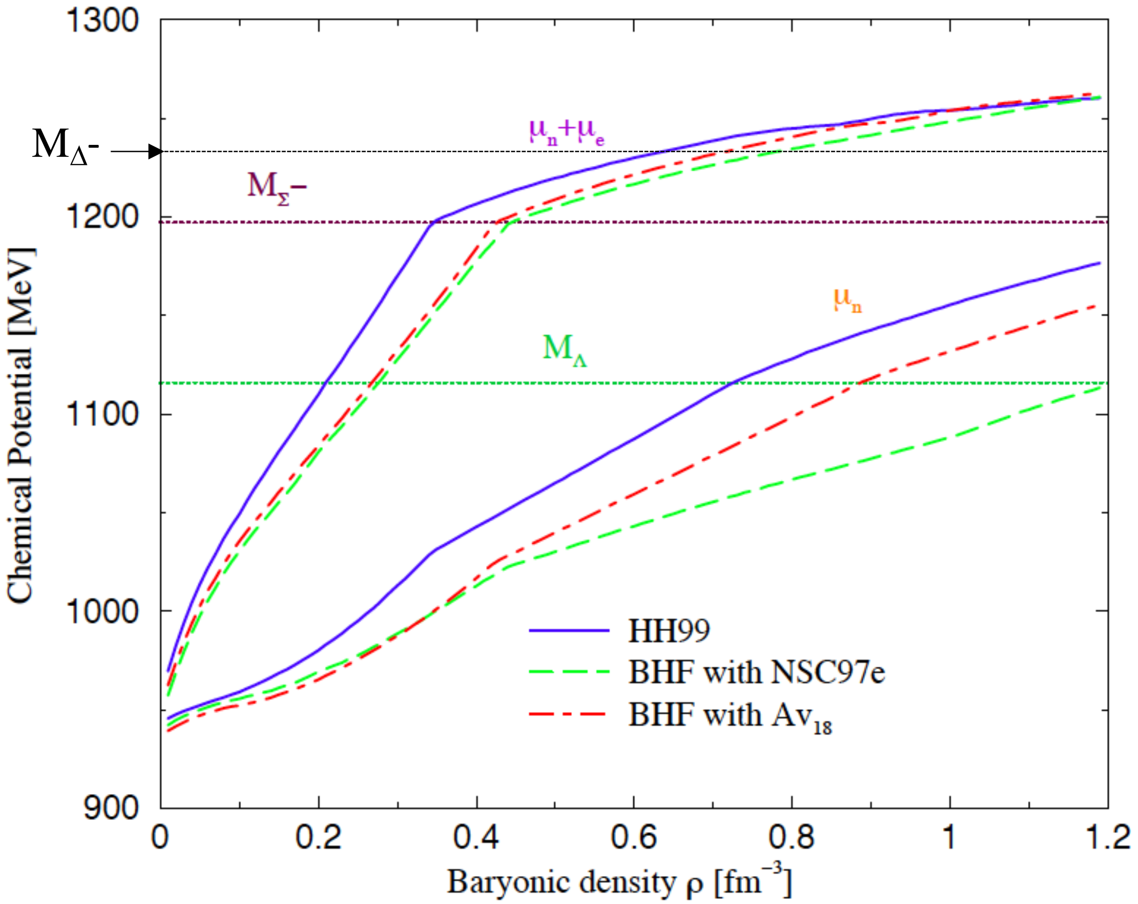
But, when hyperons are considered, the maximum mass is too low



FSU2**H**: higher density behavior of the EoS slightly modified to reproduce maximum mass when **hyperons** are present



Δ's in neutron stars



Ribes, Ramos, Tolós, González, Centelles; Astrophys.J. 883 (2019) 168

$$\mu_n + \mu_e = \mu_{\Delta^-}$$

Onset density:

$$g_{\rho\Delta}\bar{\rho} + \sqrt{k_{Fn}^2 + m_n^{*2}} + \mu_e = m_{\Delta^-}^*$$

$\bar{\rho}<0$

Larger values of symmetry energy slope L:

larger μ_e

smaller $g_{\rho\Delta}$ → Δ^- appears at lower densities

and vicevesa

Typically, onset density: 1.5-2.5 ρ_0!

Earlier (contemporary) works:

Drago, Lavagno, Pagliara, Pigato, PRC 90, 65809 (2014)

Cai, Fattoyev, Li, Newton, PRC 92, 015802 (2015)

Li, Sedrakian, Weber, PLB783, 234 (2018)

Zhu, Li, Hu, Sagawa, PRC94, 045803 (2016)

Now, the Lagrangian must include the contribution of the Δ:

$$\mathcal{L}_\Delta = \bar{\Psi}_\Delta \left(i\gamma_\mu\partial^\mu - m_\Delta + g_{\sigma\Delta}\sigma - g_{\omega\Delta}\gamma_\mu\omega^\mu - g_{\rho\Delta}\gamma_\mu \boldsymbol{I}_\Delta \cdot \boldsymbol{\rho}^\mu\right)\Psi_\Delta,$$

The couplings $g_{\sigma\Delta}$, $g_{\omega\Delta}$, $g_{\rho\Delta}$ of the Δ's are poorly constrained.

$$x_{\sigma\Delta} = \frac{g_{\sigma\Delta}}{g_{\sigma N}} \qquad x_{\omega\Delta} = \frac{g_{\omega\Delta}}{g_{\omega N}} \qquad x_{\rho\Delta} = \frac{g_{\rho\Delta}}{g_{\rho N}}$$

There is consensus on the fact that the Δ feels attraction in the medium, but the strength varies from a few tenths of MeV to 30% larger than that of the nucleon

→ $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ will be varied within [0.8-1.3]

No information for the coupling of the Δ to the ρ meson

→ $x_{\rho\Delta} = 1$, but we will explore other values (0 and 2)

Onset density: Δ^- and Λ

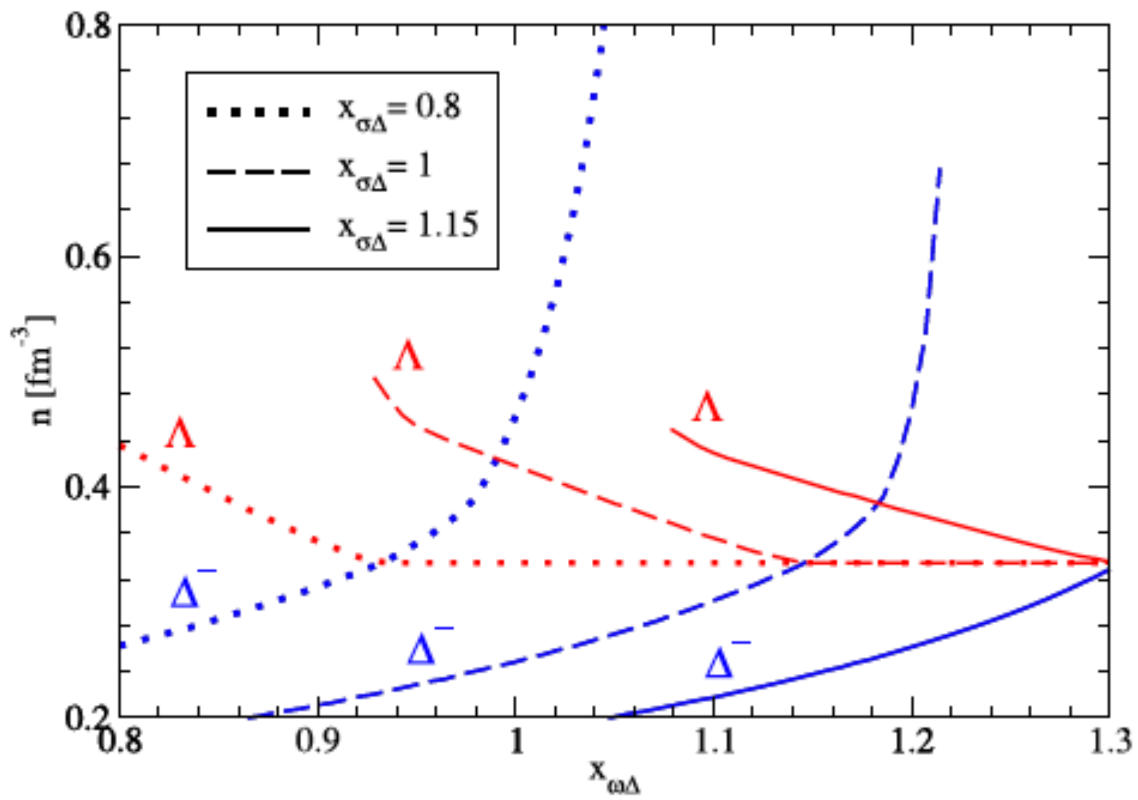


Figure 1. Threshold densities of the Λ hyperon and the Δ^- particle as function of $x_{\omega\Delta}$ for three different values of $x_{\sigma\Delta}$, fixing $x_{\rho\Delta} = 1$.

For a given value of $x_{\sigma\Delta}$, the Δ^- appears before the Λ for the lower values of $x_{\omega\Delta}$.

Increasing $x_{\omega\Delta}$ makes the Δ^- more repulsive, permitting the Λ to appear first.

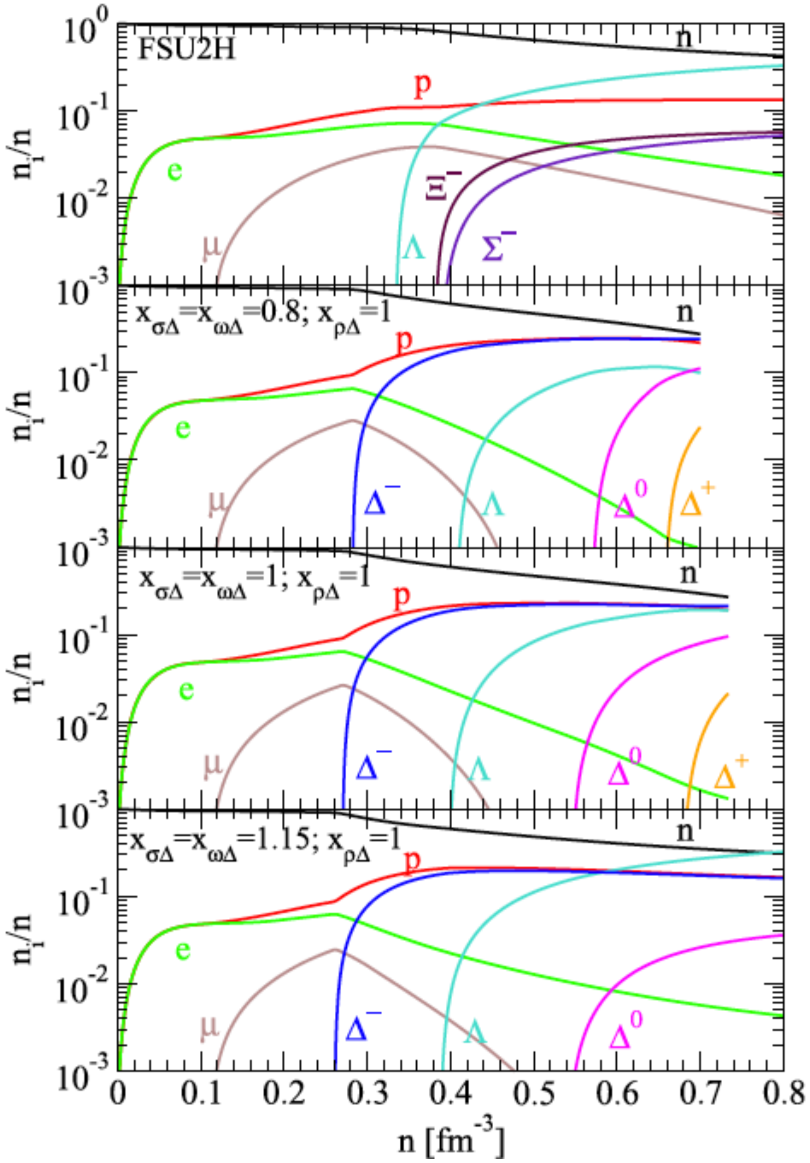
Analysis of electron scattering experiments in nuclei in the region of the Δ suggest:

$$0 \lesssim x_{\sigma\Delta} - x_{\omega\Delta} \lesssim 0.2$$

Wehrberger et al. 1989

But we have found that moving away of $x_{\sigma\Delta} \gtrsim x_{\omega\Delta}$ produces inestabilities in the EoS.

Neutron star composition



The presence of the Δ^- delays the appearence of the hyperons.
(→ only the Λ hyperons appear!)

Increasing $x_{\sigma\Delta}$ and $x_{\omega\Delta}$ makes the Δ^- appear at lower density

EoS with Δ's

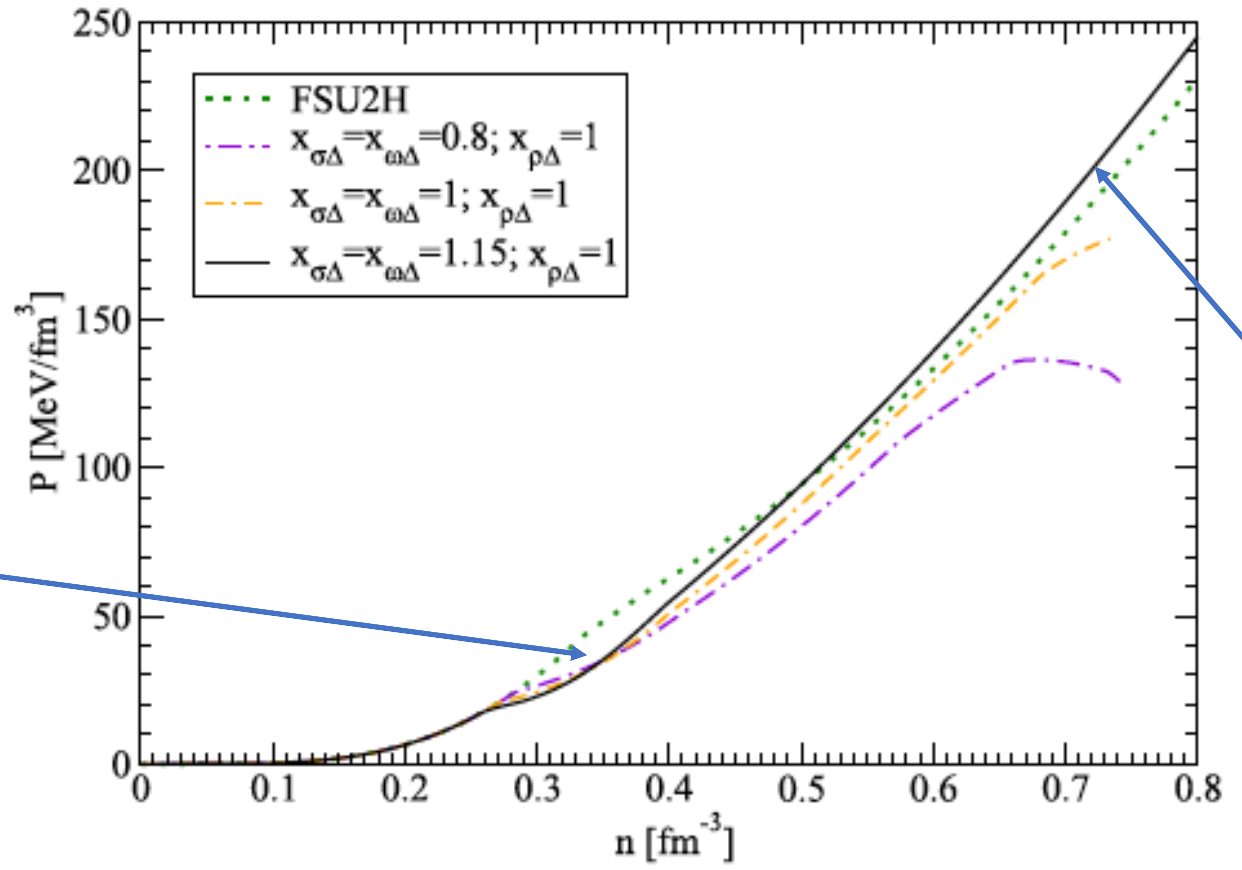
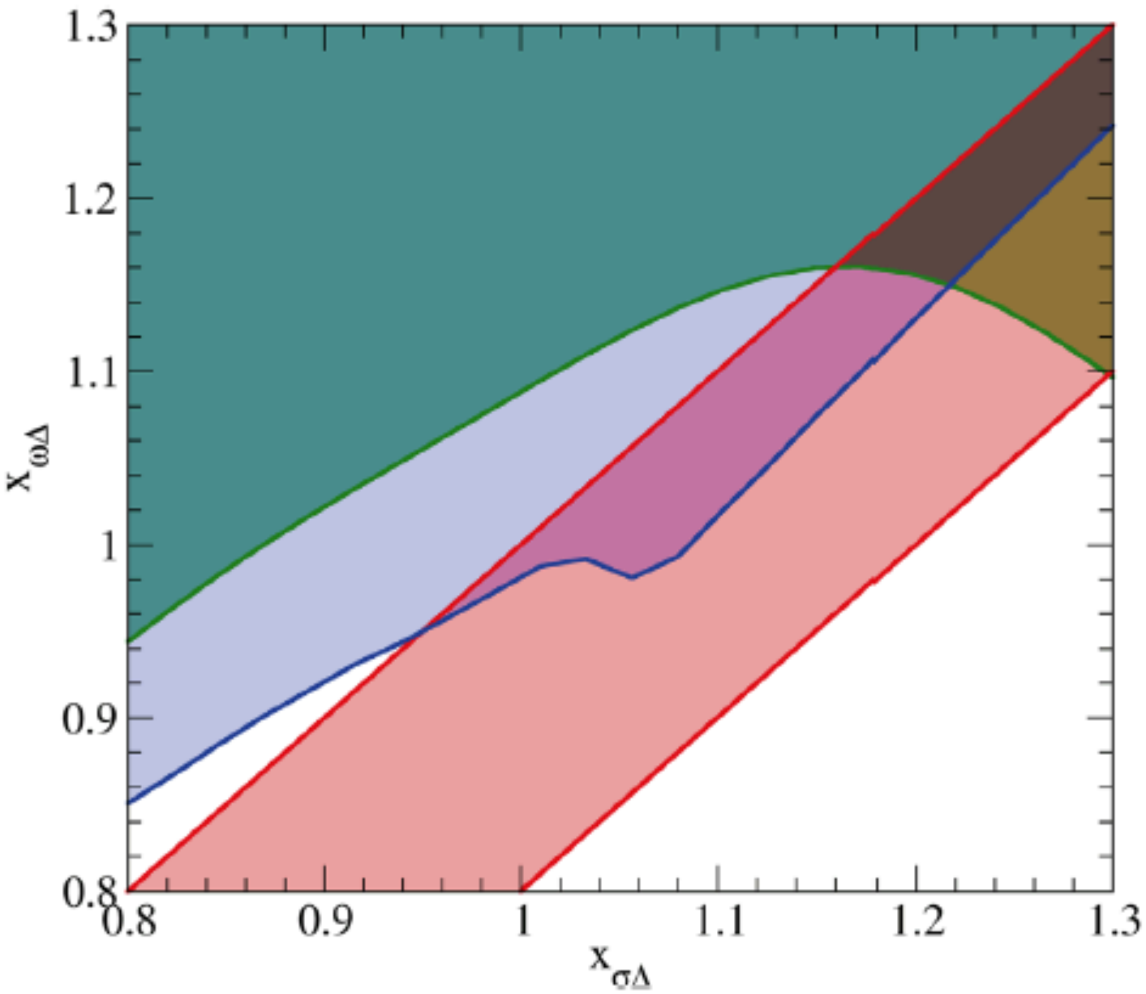


Figure 4. Pressure vs. baryon density of β-stable NS matter for the FSU2H model and various strengths of the Δ-meson couplings.

Softer EoS at intermediate densities

Stiffer EoS at high densities

Constraining the Δ couplings



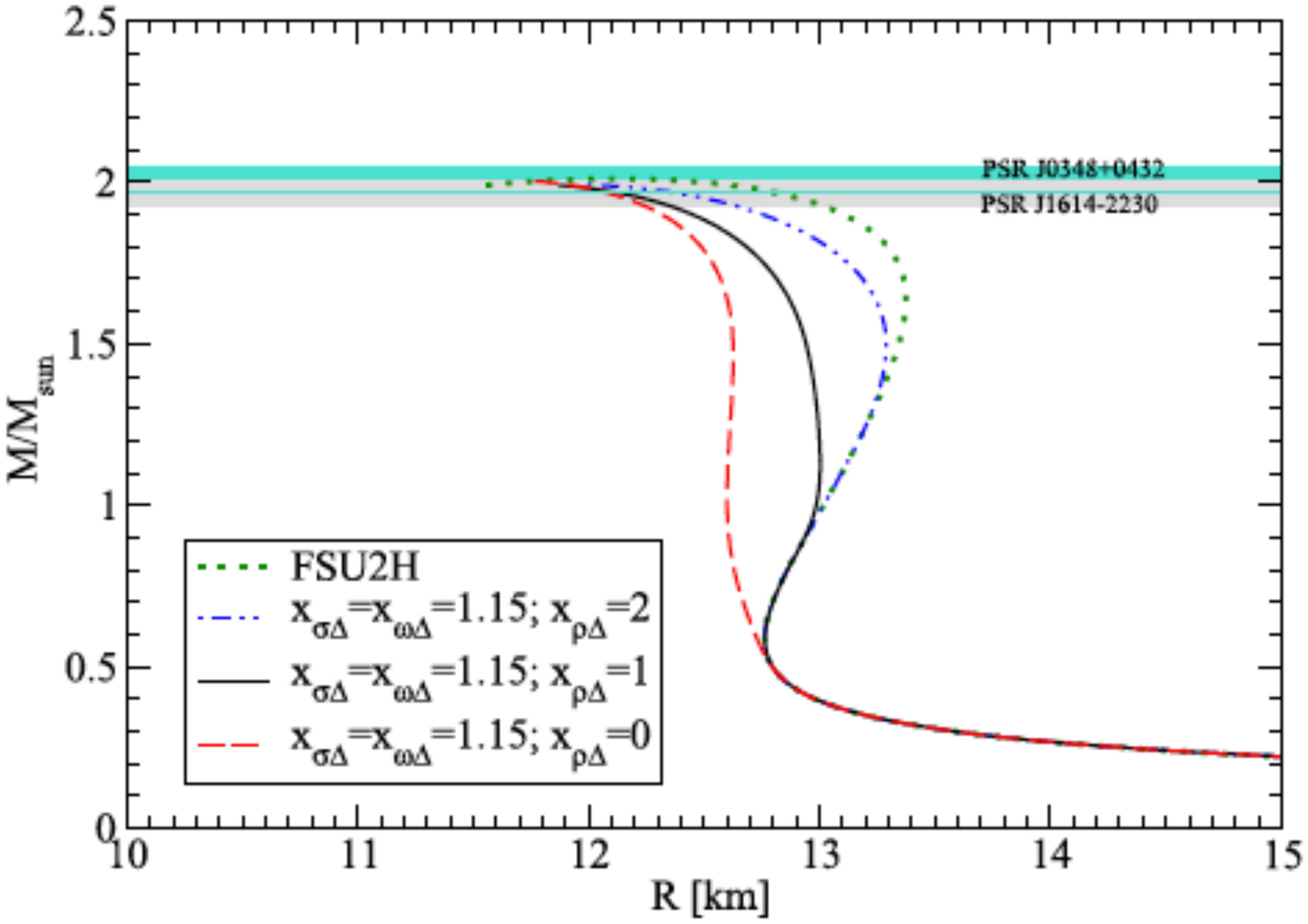
Blue → stability region

Red → electron scattering constraints

Green → 2 $M_{\odot}$ solar mass constraint

→ In order to fulfill all the constraints (dark brown region) the interaction between Δ isobars and the σ and ω meson fields must be 10%–30% larger than in the case of nucleons.

M-R relation



The presence of Δ's produces neutron stars with smaller radii (black line)

If we decrease $x_{\rho\Delta}$ one can even produce smaller radii (red line)

BNS merger GW170817

On August 17, 2017, the LIGO-Virgo detector network observed a gravitational-wave signal from the inspiral of two low-mass compact objects consistent with a binary neutron star (BNS) merger

B. P. Abbott et al. PRL 119, 161101 (2017); PRL121, 161101 (2018); PRX, 9, 011001 (2019).

This observation can be used to explore the equation of state of matter at supernuclear densities:

➔ the analysis of the gravitational waves permits deriving the so-called “tidal effects” that depend on the mass of the two stars, M_1 and M_2, as well as on the “deformability” (octupole deformation) encoded in the parameter k_2 (Love number) that depends on the EoS

Tidal deformability

Tidal deformability: $\lambda = \frac{2}{3}\frac{R^5}{G}k_2$

Love number

Chirp mass: $\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$

$M_1 \in (1.36\ 1.60)\ M_\odot$

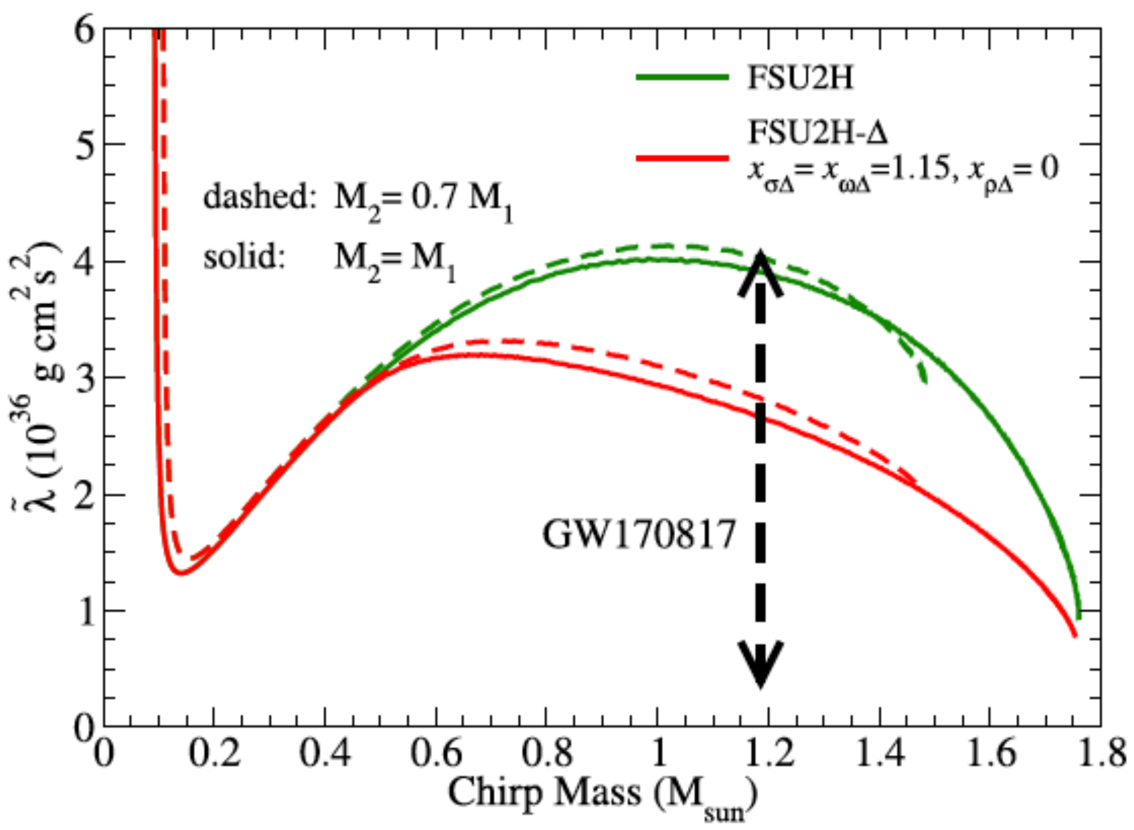
$M_2 \in (1.16\ 1.36)\ M_\odot$

"Mass-weighted" tidal deformability:

$$\tilde{\lambda} = \frac{1}{26}\left(\frac{M_1 + 12M_2}{M_1}\lambda_1 + \frac{M_2 + 12M_1}{M_2}\lambda_2\right)$$

or, in dimensionless form: $\tilde{\Lambda} = \frac{32}{G^4(M_1 + M_2)^5}\tilde{\lambda}$

During the early stages of an inspiral, the phase of the gravitational-wave signal is determined to leading order by $\tilde{\Lambda}$



The inclusion of Δ's reduces the mass-weighted tidal deformability.

→ makes it compatible with the GW170817 value measured at a chirp mass of $\mathcal{M} = 1.186\ M_\odot$

Conclusions

We have studied the implications of the appearance of Δ's in the interior of neutron stars within the newly developed RMF model FSU2H which also incorporates hyperons

- ✓ The presence of the Δ^- in the composition of the star postpones the emergence of the Λ to higher densities.
- ✓ In order to fulfill the observations of massive NSs and the phenomenological analyses on electron-nucleus reactions, while having a stable solution for the EoS, the interaction between the Δ baryon and the σ and ω fields must be 10%–30% larger than for nucleons
- ✓ The EoS with Δ degrees of freedom is softer at intermediate densities and stiffer at higher densities. As a consequence, NSs with smaller radii are obtained while still reproducing the 2 $M_\odot$ observations.
- ✓ These small values for radii favor smaller tidal deformabilities, more consistent with the value derived from the recent LIGO-Virgo gravitational-wave detection GW170817 from a BNS merger