Constraints on the neutron star equation of state

Constança Providência

Universidade de Coimbra, Portugal

PHAROS WG2 Meeting, 9-11 April, 2018

Universidade de Coimbra

Motivation

- Stellar matter EoS: which NS properties do we get from a constrained EoS?
- How important is it to take a crust-core unified EoS?
- Hyperons in hot dense matter: what do the constraints tell us for equation of state?
- Which quantities are required from consistent EoS by WG2?

Summary

- Constrained EoS
  - Experimental, theoretical and observational constraints
- Constrained EoS: consequences on the NS properties
- Constrained hyperonic EoS
  - Propoerties of hot dense matter with hyperons

Constraints on the EoS

- laboratory measurements of nuclear properties and reactions
  - nuclei, hypernuclei, heavy-ion collisions (HIC)
  - nuclei probe saturation and/or subsaturation densities of symmetric or almost symmetric nuclear matter
  - high density EoS from HIC: depends on transport models
- theoretical ab-initio calculations
  - neutron matter calculation from Quantum Monte Carlo and Chiral effective field theory up to saturation density due to perturbative behavior
- astrophysical observations
  - $2M_\odot$, R (still not well constrained), tidal deformability (pressure and energy density)
  - neutron star cooling and rotation (superfluidity)

Equation of state

- Energy per nucleon

$$e(\rho, \delta) = e(\rho, 0) + S(\rho)\delta^2$$

$\rho = \rho_n + \rho_p$, $\delta = (\rho_n - \rho_p)/\rho$

- EoS for symmetric matter

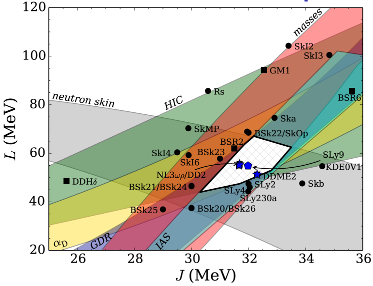
$$e(\rho, 0) = e(\rho_0) + \frac{K}{2}x^2 + \frac{Q}{6}x^3 + \mathcal{O}(4), \quad x = \frac{\rho - \rho_0}{3\rho_0}$$

- Density dependent symmetry energy

$$S(\rho) = J + Lx + \frac{K_{sym}}{2}x^2 + \mathcal{O}(3),$$

- Properties of nuclear matter characterized by expansion coefficients
  - ρ_0, $B = m - e(\rho_0)$, K, Q, $M = Q + 12K$, J, L, K_{sym}

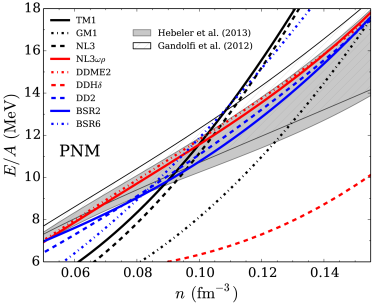
Nuclear constraints : Terrestrial experiments



(Fortin PRC94,035804(2016))

- $B \sim 16$ MeV, $\rho_0 \sim 0.15 - 0.16$ fm^{-3}
  (nuclear masses,density distributions)
- $K = 230 \pm 40$ MeV (from analysis of ISGMR **Khan PRL109**)
  - but $250 < K < 315$ MeV in **Stone 2014**
- constraints in $J - L$ plane:
  - $J = 29.0 - 32.7$ MeV, $L = 44 - 66$ MeV
    (**Lattimer et al 2013,2014**)
  - neutron skin thickness and giant dipole resonance of ^{208}Pb, heavy ion collisions, measured nuclear masses, isobaric analog states, electric dipole polarizability α_D
  - $J = 31.7 \pm 3.2$ MeV, $L = 58.7 \pm 28.1$ MeV (**Oertel et al 2017**)

Nuclear constraints

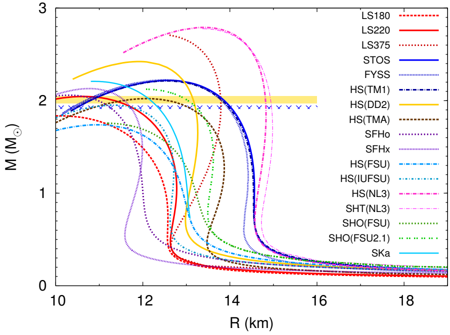


(Fortin PRC94,035804(2016))

- **Neutron matter microscopic calculations**
  - chiral effective field theory constrain the properties of neutron matter up to ρ_0 (Hebeler et al 2010, 2013)
  - realistic two- and three-nucleon interactions using quantum Monte Carlo techniques (Gandolfi et al 2012)

Constraining the EOS from neutron star masses

massive neutron stars

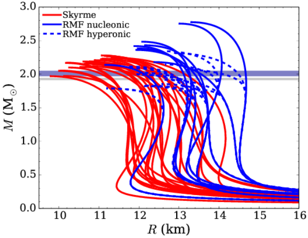


Oertel et al arxiv:1610.03361

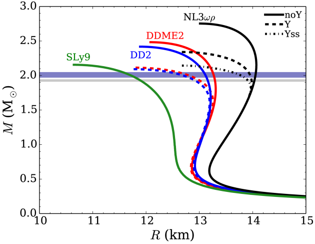
- PSR J0348+0432 (2.01 (4)$M_\odot$, (advance of periastron) (Antoniadis et al, 2013)
- PSR J1614−2230 (1.928(17)$M_\odot$, (Shapiro delay) (Demorest et al 2010, Fonseca et al. 2016)
- PSR J1946+3417 (1.828(22) $M_\odot$, (Shapiro delay and advance of periastron) (Barr et al, MNRAS 2017)

Imposing $2M_\odot$

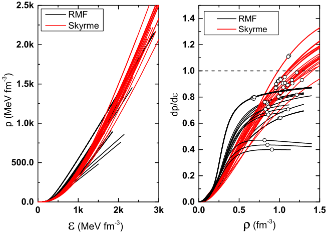
Fortin et al PRC 94,035804



(Fortin et al 2016)



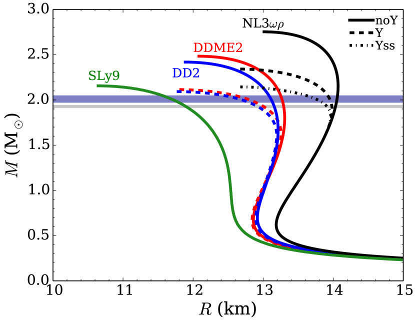
(Fortin et al 2016)

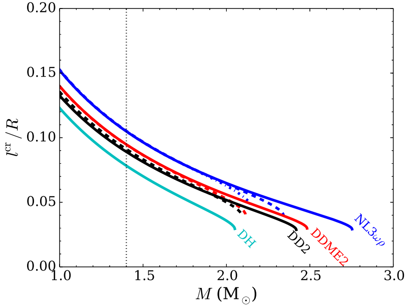


(Malik et al 2018)

- All EoS are causal and predict $M > 2.M_\odot$
  - range of radii spanned:**3km ($1M_\odot$) and 4km ($2M_\odot$)**
- imposing lab and theoretical constraints:**only 4 models remain**
  - range of radii spanned:**1km ($1M_\odot$) and 2km ($2M_\odot$)**
  - large high mass uncertainty: **lack of constraints on high density EoS!**

Nuclear constraints: $\Delta R_{1.4}$ and $\Delta \ell_{cr}$





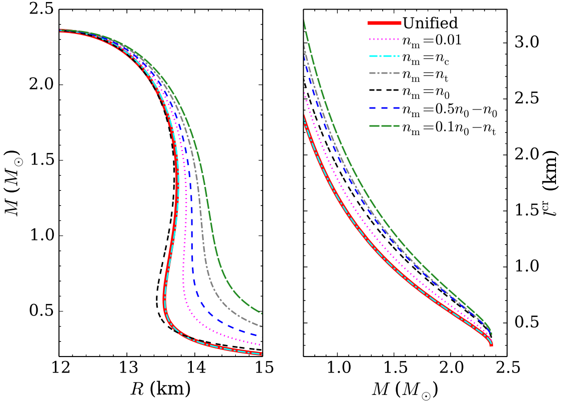
(Fortin PRC94,035804(2016))

Imposing nuclear (experimental, theoretical,observational) constraints:

- $\Delta R_{1.0} = 0.9$ km, $\Delta R_{1.4} = 1.3$ km, $\Delta R_{2.0} = 2.3$ km
- R uncertainties reduced to 30% ($M_{1.0}$) and 50% ($M \geq 1.4 M_{\odot}$)
- $\Delta \ell_{cr,1.4} = 250$ m

Non-unified EOS

Radius and crust thickness

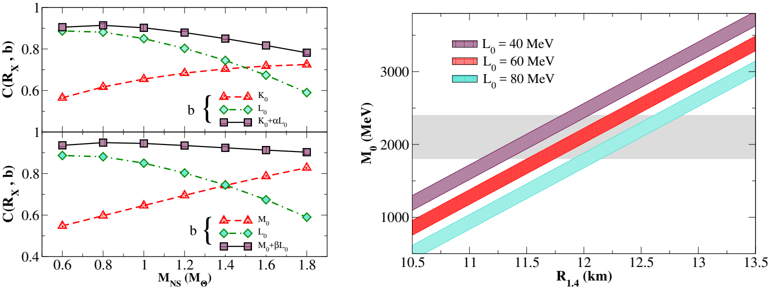


(Fortin PRC94,035804(2016))

- core EOS: GM1, crust EOS: Douchin & Haensel
- different crust-core matching procedures
- 1.4 $M_\odot$ star: ΔR=420 m, $\Delta \ell_{cr}$ = 350 m

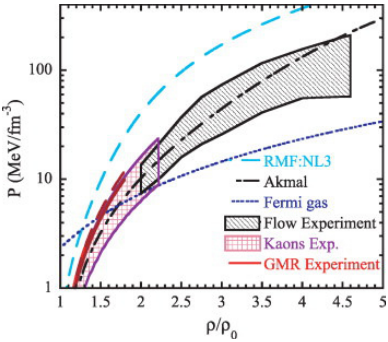
Constraining the EOS from NS

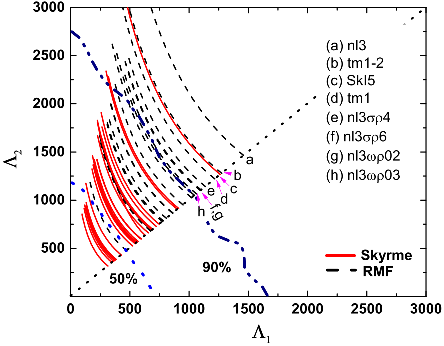
Alam et al PRC 94, 052801



- correlation with **18 RMF EoS+ 24 Skyrme EoS, unified EoS, all describe $2M_\odot$ stars**
- $P = \frac{\rho_0 x^2}{3}\left[K_0(x-1)\left(1-\frac{2x}{3}\right) + \frac{M_0}{18}(x-1)^2 + L_0\delta^2\right]$.,
  $M_0 = Q_0 + 12K_0, \qquad x = \rho/\rho_0$
- $M_0(n_0) = 1800 - 2400$ MeV from energies ISMGR (De 2015)
- Prediction: $R_{1.4} = 11.09 - 12.86$ km

Constraining the EOS at high densities





(Malik et al 2018)

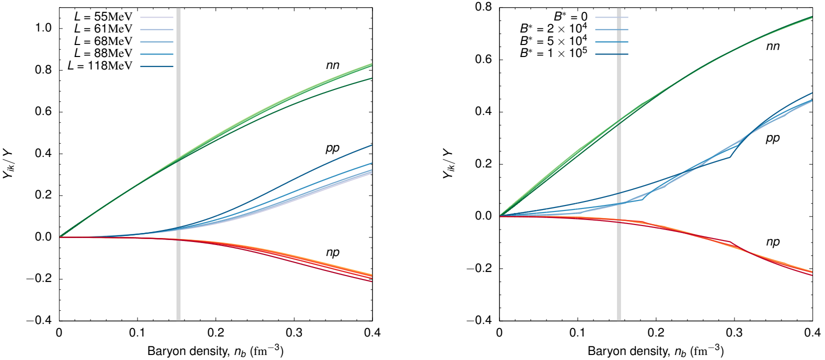
- **HIC**: there are still no consensus in data and transport codes analysis
- **GW170817**: constraints on tidal deformability $\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$
  $\Lambda < 800(500)$ at 90% (50%) confidence
  Λ_1 : high mass M_1 satisfies $1.365 < M_1 < 1.60 M_\odot$
  Λ_2 : low mass M_2 from $M_{\rm chirp} = 1.188 M_\odot$.

Entrainment matrix for β equilibrium matter

Effect of the symmetry energy slope L and of the magnetic field B

- Superfluid currents at $T = 0$: $\boldsymbol{Q}_i$ momentum per particle of Cooper pairs i (Gusakov, Kantor, Haensel PRC79)

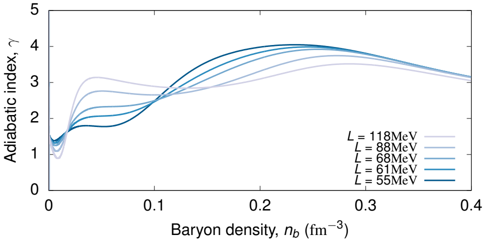
$$\begin{aligned} \boldsymbol{j}_n &= Y_{nn}\boldsymbol{Q}_n + Y_{np}\boldsymbol{Q}_p \\ \boldsymbol{j}_p &= Y_{pn}\boldsymbol{Q}_n + Y_{pp}\boldsymbol{Q}_p. \end{aligned}$$



(Pratapsi, MSc thesis UC 2017)

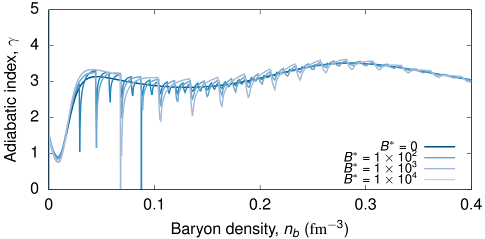
Adiabatic index for β equilibrium matter

Effect of the symmetry energy slope L and of the magnetic field B



Adiabatic index γ: Effect of L.

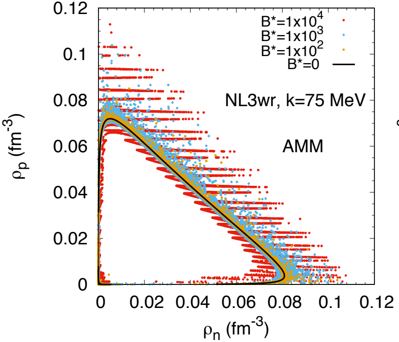
$$\gamma = \frac{p+\varepsilon}{p}\frac{\partial p}{\partial \varepsilon}.$$

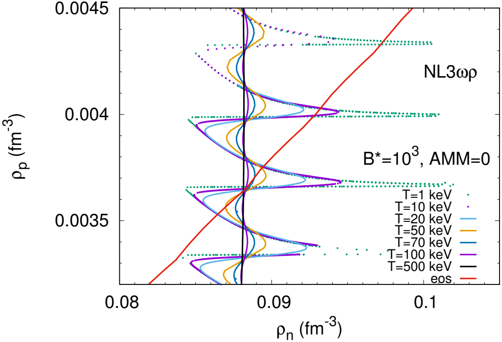


Adiabatic index γ: Effect of the B, $L = 118$MeV.

(Pratapsi, MSc thesis UC 2017)

Effect of the magnetic field B on the crust thickness



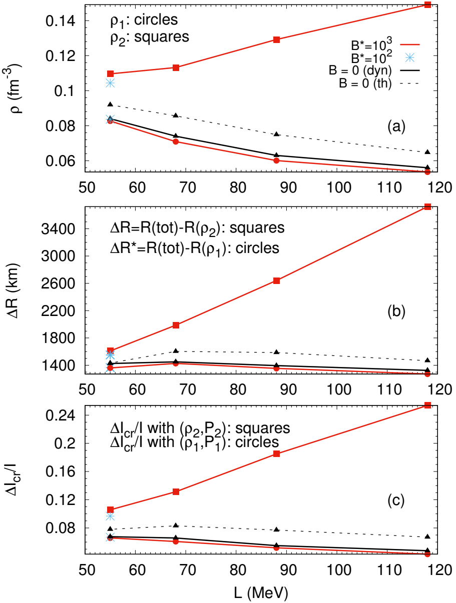


- diffuse separation between homogeneous and clusterized matter
- transition thickness $\Delta\rho > 0.01$ fm^{-3} for $B = 2.2 \times 10^{15}$G

Fang PRC95.045802

Effect of the magnetic field B on the crust thickness

Crust thickness and symmetry energy

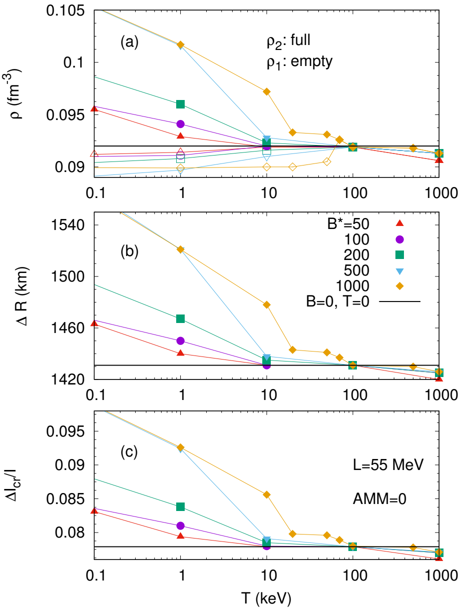


$T = 0$, $B = 5 \times 10^{16}$G

- Transition densities
- crust thickness ΔR
- crust fractional I
- $B = 0$ (black)

Fang PRC95,062801

Magnetized Crust thickness versus Temperature

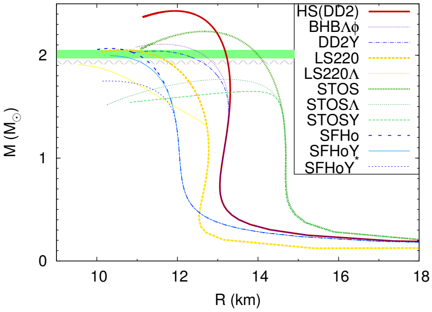


NL3$\omega\rho$, L = 55 MeV

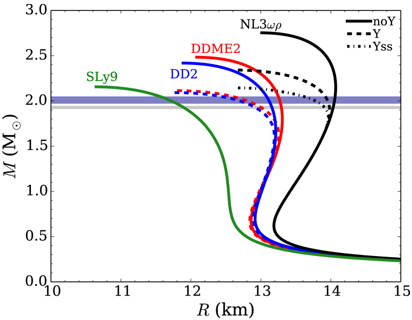
- Transition densities
- crust thickness ΔR
- crust fractional I

Fang PRC95,062801

How important are hyperons in NS?



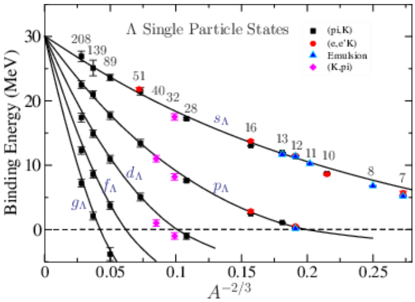
(Fortin et al (2018))



(Fortin et al 2016)

- Is it possible to satisfy hypernuclei properties and have $2M_\odot$ NS?
- What do experimentally constrained hyperonic EoS tell us?

Hypernuclei



(Gal et al (2016))

- scattering events: $\rightarrow$ not enough to constrain interactions
- hypernuclei
  - $\gtrsim$ 40 single Λ-hypernuclei
  - a few double Λ and single-Ξ
  - no unambiguous Σ-hypernucleus:most probably Σ-nucleus potential repulsive
  - $^{12}C(K^-, K^+)^{12}_{\Xi}Be$ (E885 Col.)
  - attractive Ξ-nucleus interactions, $U^N_\Xi \sim -14$ MeV.

- $\Lambda\Lambda$ binding from double and single Λ-hypernuclei

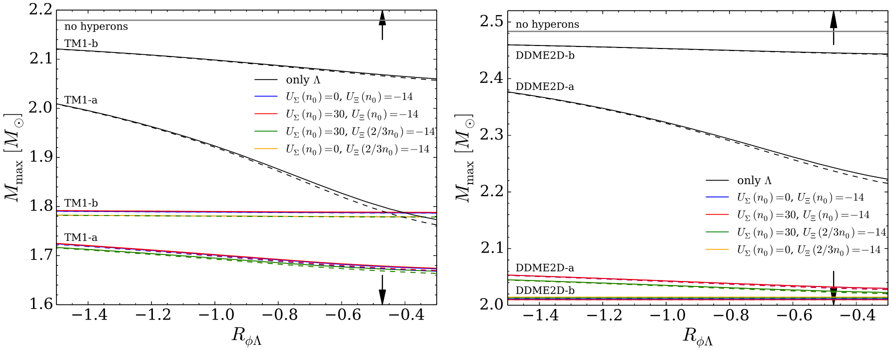
$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_\Lambda({}^{A-1}_{\Lambda}Z)$$

- Unambiguous measurement ${}^{6}_{\Lambda\Lambda}He$ by KEK (2001)

$$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17 \text{MeV}$$

Hyperonic stars

Fortin et al PRC 95



- Vector meson couplings
  - **choice a**: SU(6) symmetry for ω, varying ϕ -hyperon
  - **choice b**: $g_{Y\omega} = g_{N\omega}$, varying ϕ -hyperon
  - **ρ-meson**: $g_{\rho\Xi} = \frac{1}{2} g_{\rho\Sigma} = g_{\rho N}$
- Σ-σ coupling: $U^N_\Sigma(n_0) = 0, +30$ MeV
- Ξ-σ coupling: $U^N_\Xi(n_0) = -14$ MeV and $U^N_\Xi(2n_0/3) = -14$ MeV

ΛN-potential

Fortin et al PRC 95

Model	$R_{\omega\Lambda}$	$R_{\sigma\Lambda}$	$U_{\Lambda}^{N}(n_0)$
TM1-a	2/3	0.621	-30
TM1-b	1	0.892	-31
DDME2D-a	2/3	0.621	-32
DDME2D-b	1	0.896	-35

- YN potential

$$U_Y^N(n_0) = -\left(g_{\sigma Y} + g'_{\sigma Y}\rho_s\right)\sigma_0 + \left(g_{\omega Y} + g'_{\omega Y}n_0\right)\omega_0,$$

- $U_{\Lambda}^{N}(n_0) \simeq -30$ **MeV in agreement with the binding energy of single Λ-hypernuclei in the s- and p-shells**
- $R_{\sigma\Lambda} \sim 0.62$ **for SU(6) value for $g_{\omega\Lambda}$, independent of the model considered.**

$\Lambda\Lambda$-potential

Fortin et al PRC 95

Model			$\Delta B_{\Lambda\Lambda}$ = 0.50		$\Delta B_{\Lambda\Lambda}$ = 0.84	
		$R_{\phi\Lambda}$	$R_{\sigma^*\Lambda}$	$U_\Lambda^\Lambda(n_0)$	$R_{\sigma^*\Lambda}$	$U_\Lambda^\Lambda(n_0)$
TM1-a	SU(6)	$-\sqrt{2}/3$	0.533	-11.2	0.557	-14.2
TM1-b		$-\sqrt{2}/2$	0.843	2.7	0.864	-1.2
NL3-a	SU(6)	$-\sqrt{2}/3$	0.534	-9.9	0.559	-13.2
NL3-b		$-\sqrt{2}/2$	0.846	9.0	0.868	4.8
DDME2D-a	SU(6)	$-\sqrt{2}/3$	0.535	-11.9	0.555	-11.7
DDME2D-b		$-\sqrt{2}/2$	0.846	-3.4	0.862	-3.4

Λ potential in pure Λ matter :$-14 < U_\Lambda^\Lambda(n_0) < +9$ MeV

in literature taken between -1 or -5 MeV

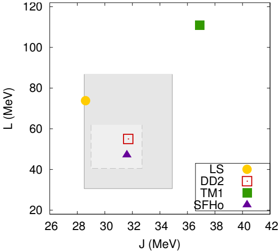
Protoneutron stars/Binary neutron star mergers

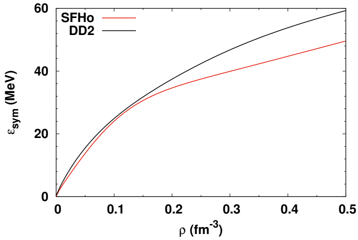
- PNS and binary NS mergers:
  - High densities and high temperatures are attained inside
  - $T = 10 - 100$ MeV affect the NS composition, favor the production of non-nucleonic degrees of freedom
  - Which is the role of non-nucleonic degrees of freedom?
- How will constraints on the EoS affect the evolution of PNS and NS mergers in the evolution of these systems?
- Information on the EoS is expected from
  - the tidal deformability during late inspiral
  - post merger oscillations
  - observation of GW correlated with an electromagnetic signal

Hyperons in hot dense matter

What do the constraints tell us for the EoS?

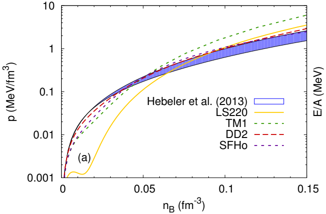
- Symmetry enegy

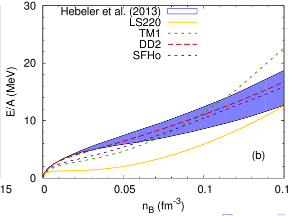




(Oertel et al 2017)

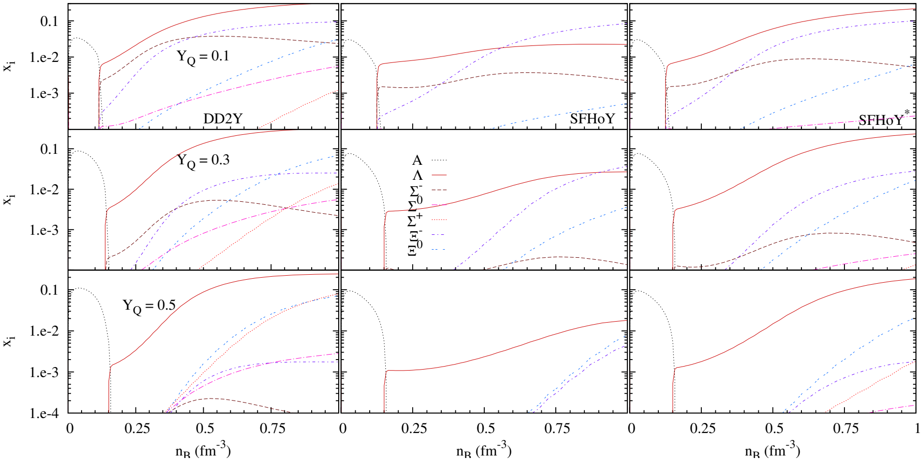
- contraint: ab-initio calculations of pure neutron matter





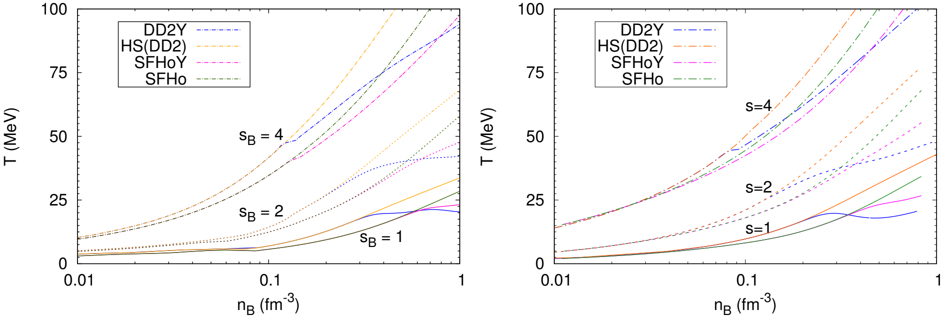
Hyperon fractions

T = 30 MeV, Y_Q = 0.1, 0.3, 0.5



Temperature for fixed entropy per baryon

$s_B = 1, 2, 4$



$Y_L = 0.4$ β-equilibrium

Hyperons in hot stellar matter: conclusions

- DD2Y EoS (Marques2017) and SFHoY: only general purpose EoS models with the entire baryon octet and compatible with the relevant constraints on the EoS
- SFHo:softer symmetry energy than DD2, additional repulsion
  - SFHoY has smaller hyperon fractions
  - the effects on thermodynamic properties are much less pronounced
- Possible consequences
  - different proto-neutron star evolution
  - different impact of hyperonic degrees of freedom on neutron star merger dynamics
- SFHoY and SFHoY*: available in COMPOSE database

Thank you !