Are hyperonic degrees of freedom present in neutron stars?

Constança Providência

Universidade de Coimbra, Portugal

HADES Mini-simposium, 23 September, 2022

UNIVERSIDADE DE COIMBRA

CFisUC

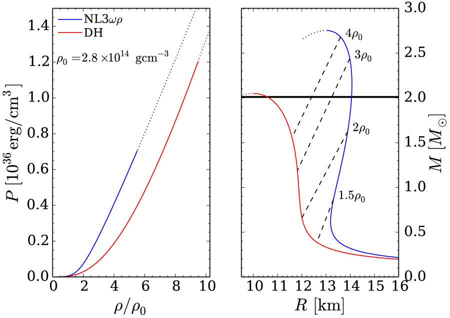
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

Motivation

- What do hypernuclei tell us about the neutron star EoS?
- Which are possible signatures of the presence of hyperons inside neutron stars?
- What do the constraints tell us about hyperons in hot dense matter?

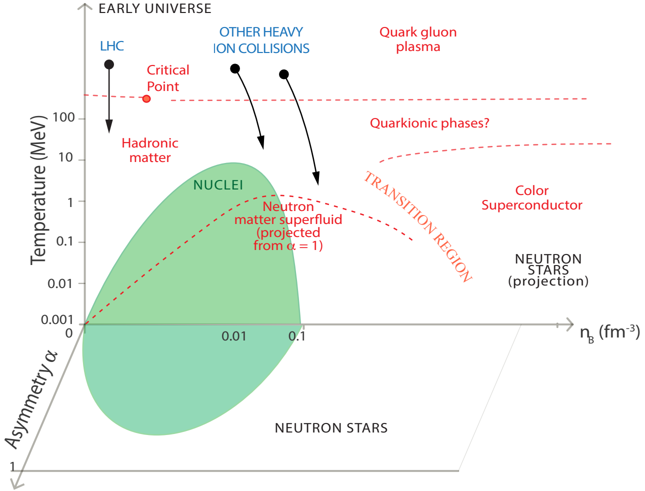
Probing the interior of Neutron Stars

- Neutrons stars provide a laboratory for testing
  - nuclear physics: high density, highly asymmetric matter
  - QCD: deconfinement, quark matter, superconducting phases
  - nuclear superfluidity: critical temperature, properties
- microscopic model → equation of state → mass-radius



- equation of state → maximum mass and spin frequency, moment of inertia

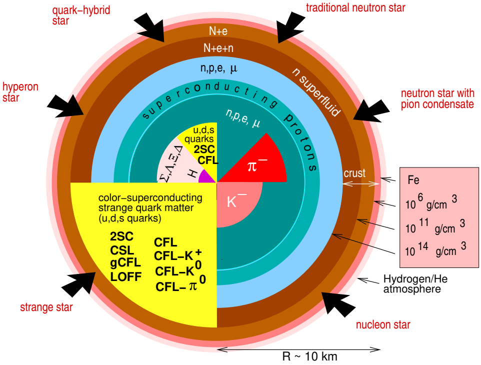
QCD phase diagram

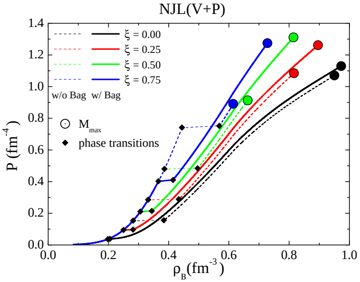


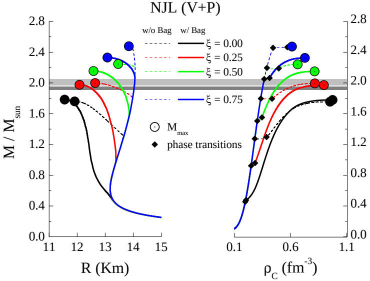
A.Watts et al, arXiv:1501.00042v1

Neutron star interior

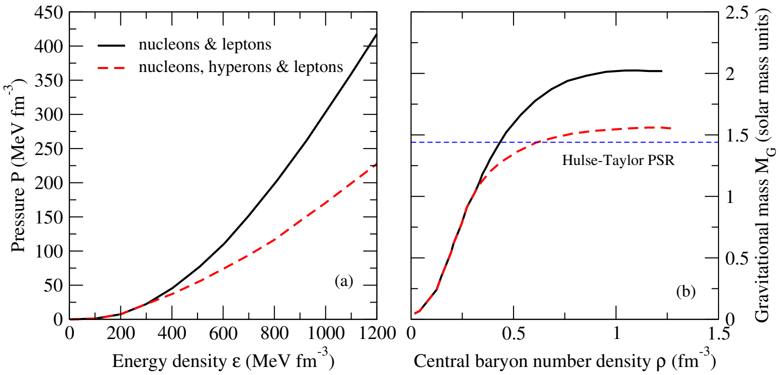
Hybrid stars :







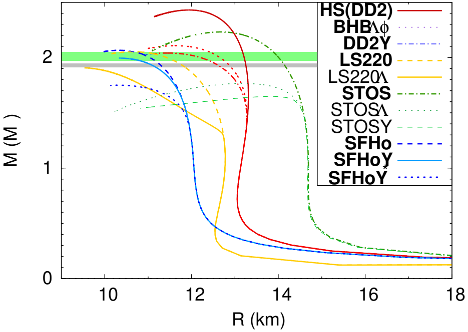
What is the effect of hyperons in NS?



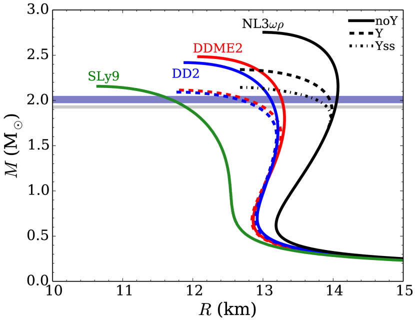
(Vidana & Chatterjee (2015))

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

What is the effect of 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?

How to attain $2M_\odot$?

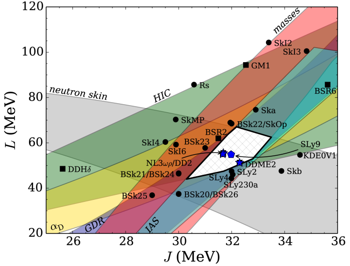
Additional repulsion is needed!

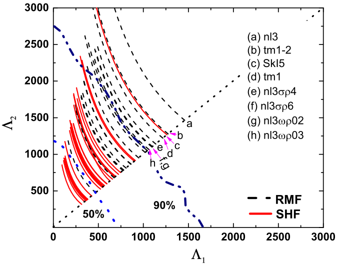
- inclusion of a repulsive YY interaction (through the exchange of vector mesons, higher order couplings or density dependent couplings)
- inclusion of repulsive hyperonic three-body forces
- possible a phase transition to deconfined quark matter at densities below the hyperon threshold

However, the high density nucleonic EoS is not constrained!

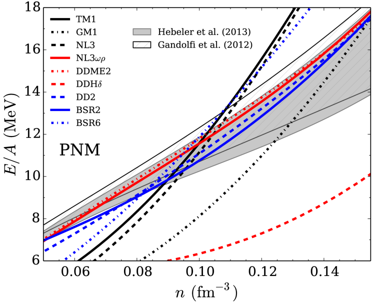
Constraints on the EoS

- $B \sim 16$ 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**)
  - $J = 31.7 \pm 3.2$ MeV, $L = 58.7 \pm 28.1$ MeV (**Oertel et al 2017**)
- theoretical ab-initio calculations for neutron matter
- astrophysical observations: $2M_\odot$, R, tidal deformability





Nuclear constraints

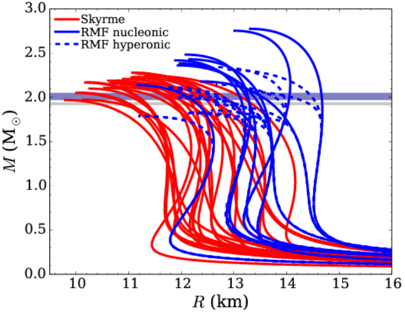


(Fortin PRC94,035804(2016))

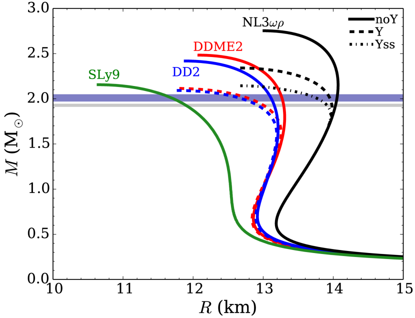
- **Neutron matter microscopic calculations**
  - chiral effective field theory constrain the properties of neutron matter up to ρ_0 (Hebeler et al 2010, 2013)
  - realistic two- and three-nucleon interactions using quantum Monte Carlo techniques (Gandolfi et al 2012)

Imposing $2M_\odot$

Fortin et al PRC 94,035804



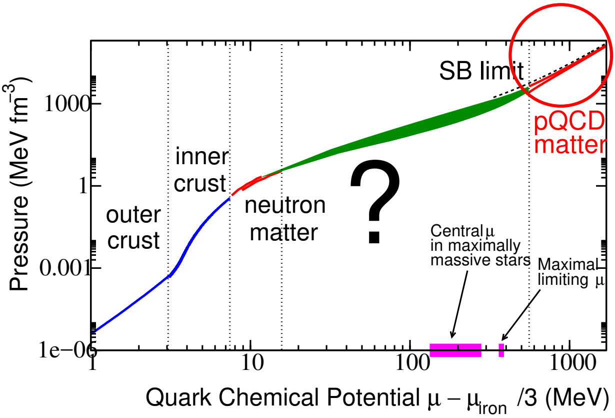
(Fortin et al 2016)



(Fortin et al 2016)

- 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!**

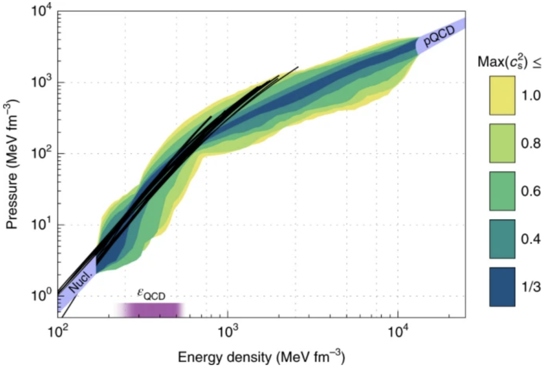
High density constraints



(Kurkela ApJ 789, 2014)

- $T = 0$ high density perturbative QCD (pQCD)
  - **state-of-that-art** (Kurkela et al PRD81 2010): perturbative calculation
  - EOS converges reasonably well for $\mu_B > 2.6\text{GeV}$

High density constraints



(Annala et al Nature 2021)

- $T = 0$ high density perturbative QCD (pQCD)
- low density: CET *ab-initio* calculations of neutron matter(Hebeler et al 2013)
- Interpolation: large numbers of individual EoSs generated with the speed-of-sound interpolation method.
- Agnostic approach: no information on composition

EOS: relativistic mean field description

RMF Lagrangian for stellar matter

- Lagrangian density
  - Lorentz-covariant Lagrangian with baryon densities and meson fields
  - causal by construction

$$\mathcal{L}_{NLWM} = \sum_{B=baryons} \mathcal{L}_B + \mathcal{L}_{mesons} + \mathcal{L}_l,$$

  - Baryonic contribution: $\mathcal{L}_B = \bar{\psi}_B \left[\gamma_\mu D_B^\mu - M_B^*\right] \psi_B,$
    $D_B^\mu = i\partial^\mu - g_{\omega B}\omega^\mu - \frac{g_{\rho B}}{2}\boldsymbol{\tau} \cdot \mathbf{b}^\mu - g_{\phi B}\phi^\mu$
    $M_B^* = M_B - g_{\sigma B}\sigma - g_{\sigma^* B}\sigma^*$
  - Meson contribution

$$\mathcal{L}_{mesons} = \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_{\sigma^*} + \mathcal{L}_\phi + \mathcal{L}_{non-linear}$$

  - Lepton contribution: $\mathcal{L}_l = \sum_l \bar{\psi}_l \left[\gamma_\mu i\partial^\mu - m_l\right] \psi_l$

Constraining the density functional with hypernuclei

- Self-consistent calculation of Λ-hypernuclei
- single Λ-hypernuclei binding energies:
  fix the σ-hyperon coupling
- double Λ-hypernuclei: fix the σ^*-hyperon coupling
- a weak Λ-nuclear spin-orbit interaction: tensor term (Noble 1980, Shen 2006)

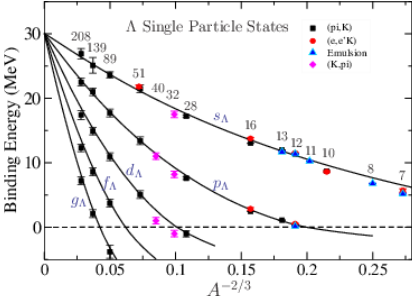
$$\mathcal{L}_{T\Lambda} = \bar{\psi}_\Lambda \frac{f_{\omega\Lambda}}{2M_\Lambda} \sigma^{\mu\nu} \partial_\nu \omega_\mu \, \psi_\Lambda \ ,$$

- vector meson ω and ϕ -hyperon: SU(6) symmetry

$$R_\omega = 2/3, \qquad R_\phi = -\sqrt{2}/3, \qquad R_i = g_{Yi}/g_{Ni}$$

- ρ-meson does not couple to Λ but couples to Σ and Ξ

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

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

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

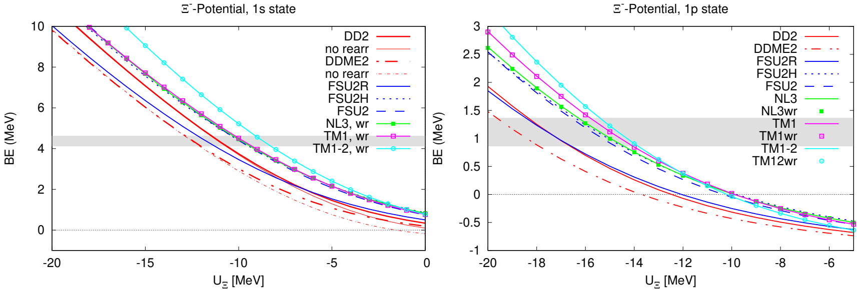
- Unambiguous measurement ${}^{6}_{\Lambda\Lambda}$He by KEK (2001)

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

Hypernuclei

Ξ and Σ

- $^{12}C(K^-, K^+)^{12}_{\Xi}Be$ (E885 Col.)
  - attractive Ξ-nucleus interactions, $U_{\Xi}^{N} \sim -14$ MeV.
- recently bound state of $\Xi - ^{14} N$ (Nakazawa et al 2015): Ξ^- removable energy
  - $E_B = 4.38 \pm 0.25$MeV (1s) or 1.11 ± 0.25 MeV (1p)
  - Sun et al (PRC94, 064319) suggest $^{14}N + \Xi^-(1p)$



- no unambiguous Σ-hypernucleus: most probably Σ-nucleus potential repulsive

  Phenomenology: $+30 \pm 20$ MeV (Gal et al 2015)

Chemical equilibrium

Prakash et al PhysRep (1997)

- Hyperon content is determined by equilibrium conditions

$$B_1 \to B_2 + \ell + \bar{\nu}_\ell, \qquad B_1 + \ell \to B_2 + \nu_\ell$$

- Chemical equilibrium (neutrino free matter)

$$\mu_B = \mu_n - q_B \mu_e$$

- Chemical equilibrium (neutrino trapped matter)

$$\mu_B = \mu_n - q_B(\mu_e - \mu_{\nu_e})$$

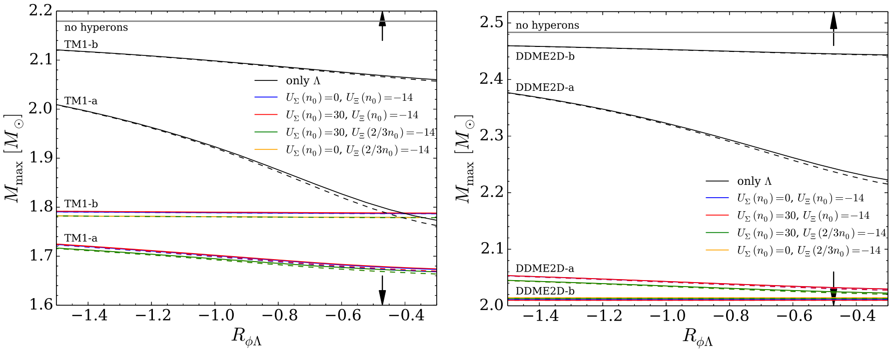
- Charge neutrality

$$\sum_B q_B x_b + \sum_l q_l x_l = 0$$

$x_i = \rho_i / \rho$

Hyperonic stars

Fortin et al PRC 95



- Vector meson couplings

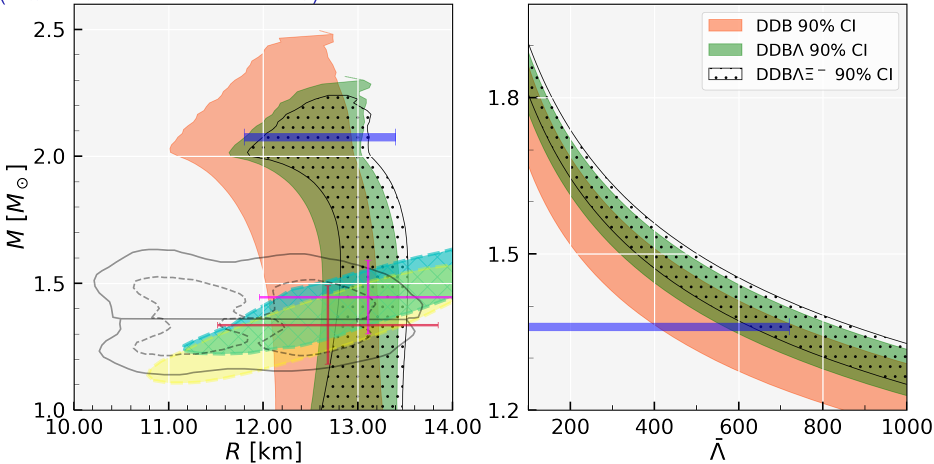
  choice a: SU(6) symmetry for ω, varying ϕ -hyperon

  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: $U_\Sigma^N(n_0) = 0, +30$ MeV
- Ξ-σ coupling: $U_\Xi^N(n_0) = -14$ MeV

Nucleonic versus hyperonic EoS: Bayesian Approach

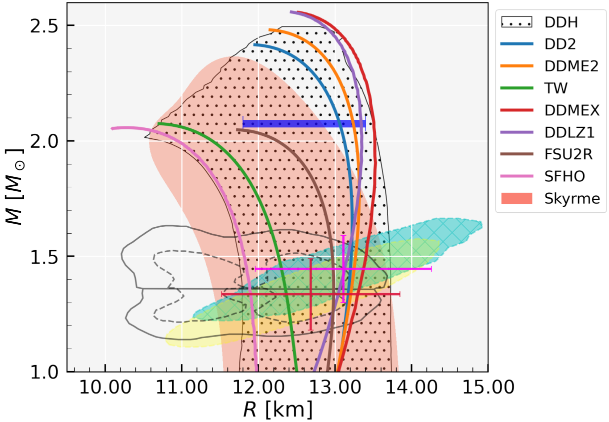
(Malik 2022 arxiv:2205.15843)



- Hyperons couplings in DDBΛ snd DDB$\Lambda\Xi$: SU(6) for vector mesons, constrained by hypernuclei for σ-meson
- No hyperons: maximum mass $\approx 2.5M_\odot$, $R_{1.4} \gtrsim 12$km
- Hyperons: maximum mass $\approx 2.2M_\odot$, $R_{1.4} > 12.5$km

Nucleonic RMF EoS (Bayesian Approach): how limitative is the method?

(Malik 2022 arxiv:2205.15843)



- 99% CI $pne\mu$, no-hyperons
- Constraints: $M \geq 2M_\odot$, χEFT, nuclear properties

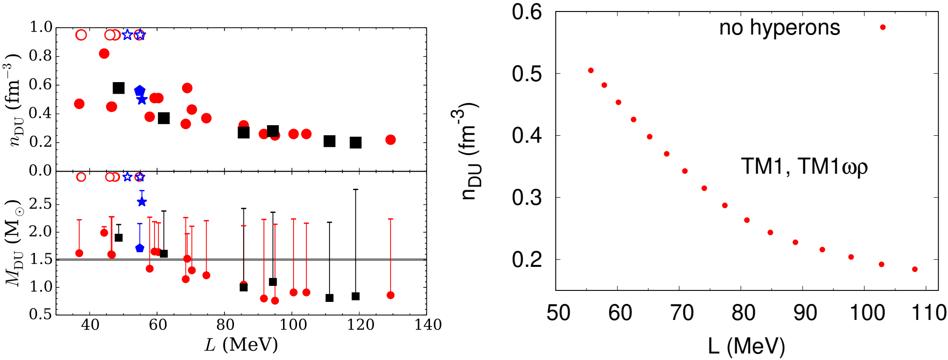
Direct Urca process: nucleonic stars

The most efficient NS cooling mechanism

$$n \to p + e^- + \bar{\nu}_e, \qquad p + e^- \to n + \nu_e.$$

Momentum conservation implies

$$p_{\mathrm{F}n} \leq p_{\mathrm{F}p} + p_{\mathrm{F}e}, \to Y_p^{\mathrm{min}} = 1/\left(1 + \left(1 + x_e^{1/3}\right)^3\right), \; x_e = \frac{n_e}{n_e + n_\mu}$$



(Fortin 2016

Direct Urca process: hyperonic stars

In the presence of hyperons, other channels are opened for neutrino emission (Prakash 92)

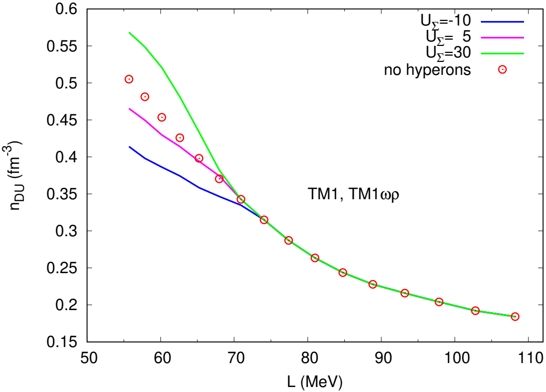
$$
\begin{array}{llll}
\Sigma^- \to \Sigma^0 \ell^- \bar{\nu}_\ell, & R = 0.61 & \Xi^- \to \Xi^0 \ell^- \bar{\nu}_\ell, & R = 0.22 \\
\Sigma^- \to \Lambda \ell^- \bar{\nu}_\ell, & R = 0.21 & \Xi^0 \to \Sigma^+ \ell^- \bar{\nu}_\ell, & R = 0.06 \\
\Lambda \to p \ell^- \bar{\nu}_\ell, & R = 0.04 & \Xi^- \to \Sigma^0 \ell^- \bar{\nu}_\ell, & R = 0.03 \\
\Xi^- \to \Lambda \ell^- \bar{\nu}_\ell, & R = 0.02 & \Sigma^- \to n \ell^- \bar{\nu}_\ell, & R = 0.01
\end{array}
$$

Amount of Σ-hyperons affects strongly cooling!

Nucleon - electron DUrca defined by

$$
\left(\frac{n_p}{n_p + n_n}\right) = \frac{1}{1 + \left(1 + {x_e^Y}^{1/3}\right)^3}, \quad x_e^Y = \frac{n_e}{n_e + n_\mu - n_Y^{ch}},
$$

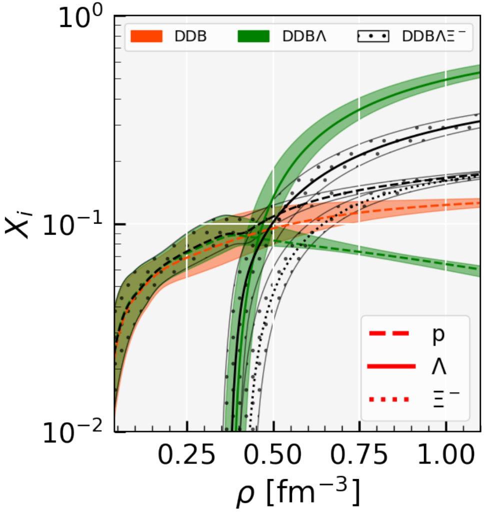
Direct Urca process: hyperonic stars



- **Effect of L**:
  - small $L \to$ larger n_{DU} because Y_P becomes smaller
  - presence of hyperons $\to$
    - affects n_{DU} if $L \lesssim 70$ MeV
    - reduces M_{DU}
  - attractive $U_{\Sigma^-} \to$ decreases n_{DU}

Particle fractions

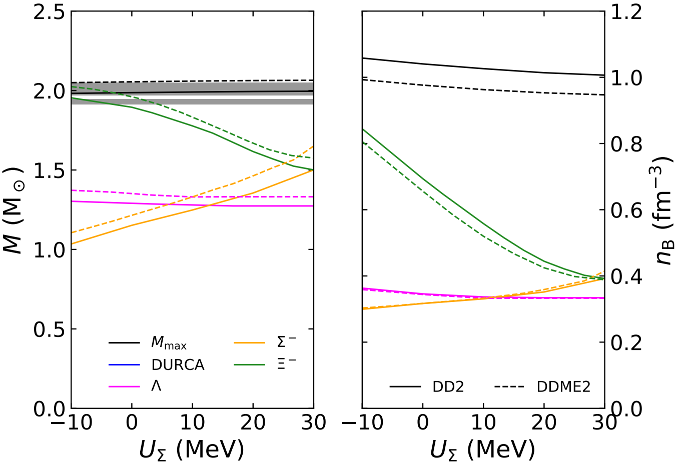
(Malik 2022 arxiv:2205.15843)



- The median and 90% CI for the particle fractions X_i
- Presence of hyperons affects fraction of protons!

Hyperon species inside NS

Effect of U_Σ

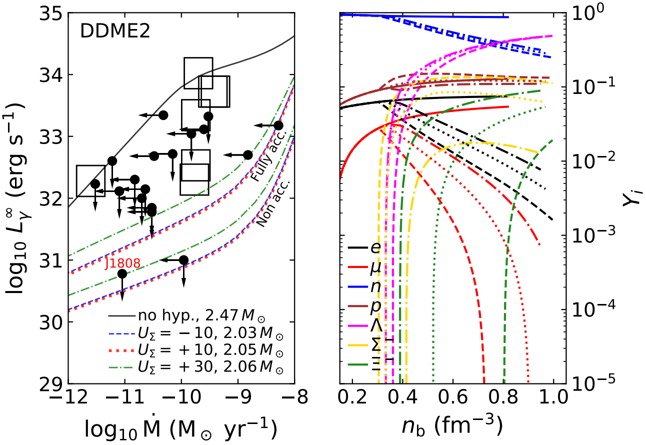


(Providencia 2018)

- **DDME2, DD2**: RMF with density dependent couplings
  - no nucleonic eletron DU
  - Ξ^- does not set in for $-10 < U_\Sigma < +30$ MeV
  - $\Sigma^- \to \Lambda$ ($R = 0.21$): opens in stars with $1.1 M_\odot$

Is SAX J1808-3658 an hyperonic star?

DDME2 (Lalazissis 05)



$\Sigma^- \to \Lambda \, (R = 0.21)$

$\Lambda \to p \, (R = 0.04)$

$\Xi^- \to \Lambda \, (R = 0.02)$

(Providencia 2018)

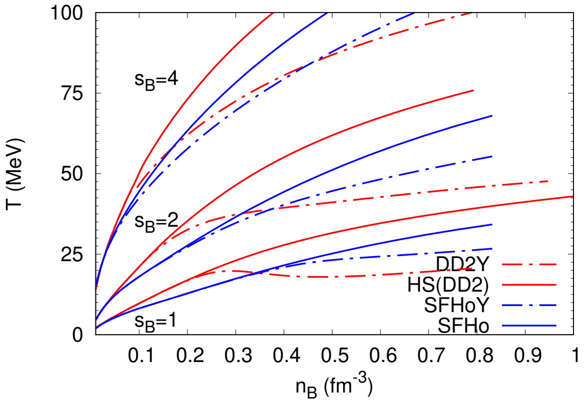
- **DDME2 EoS: SAX J1808.4-3658 is compatible with a NS**
  - with no/small amount of accreted matter in the envelope
  - EoS with hyperons

Direct Urca and hyperons

- Direct Urca process is sensitive
  - the slope L: DU is affected by hyperons if $L \lesssim 70$ MeV
  - the value of U_Σ: n_{DU} larger for more repulsive U_Σ
- Density dependent RMF models: DD2 and DDME2
  - only hyperonic direct Urca processes
  - when hyperonic channels open cooling is faster
  - SAX J1808.4-3658:
    is an hiperonic star with $M \gtrsim 1.3 M_\odot$

Temperature for fixed entropy per baryon

s_B = 1, 2, 4, β-equilibrium (Fortin PASA 2018)



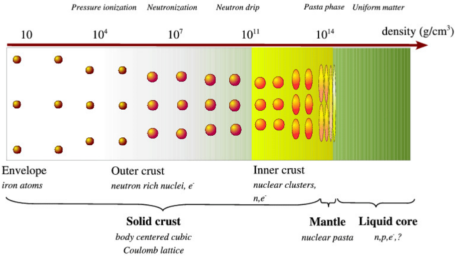
- As soon as hyperons set in the temperature drops
  - DD2Y: larger hyperon fraction $\rightarrow$ T drops more strongly
  - at large ρ, $T_{DD2Y} < T_{SFHOY}$

Hyperonic EoS at finite T

- Model dependence: SFHo softer EoS than DD2
  - SFHoY has smaller hyperon fractions, smaller effect on temperature
- Possible consequences
  - different proto-neutron star evolution
  - different impact of hyperonic degrees of freedom on neutron star merger dynamics

Hyperons in clusterized matter

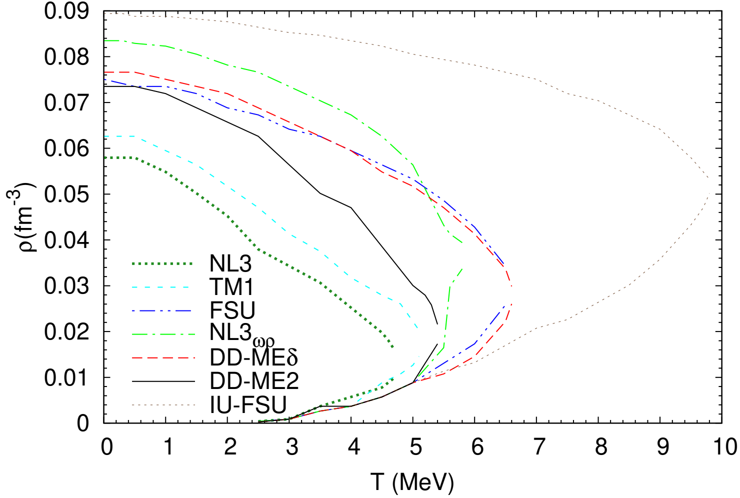
Crust



- Cold catalyzed matter
  (Chamel and Haensel, Living Reviews 2008)
  - Surface on NS: $p = 0$; ^{56}Fe
  - a bit deeper: nuclei embedded in a electron sea
  - $\rho > \rho_{drip}$: pasta phases in a background gas of neutrons and electrons
- Above cristalization temperature: the crust melts and light clusters contribute to the equilibrium
- Light clusters play a role: supernova matter properties, neutron star cooling, accreting systems, and binary mergers. (Arcones et al PRC78 (2008), Heckel et al PRC80 2009, Lalit et al EPJA 55:10 2019

Effect of T on pasta/crust extension

β-equilibrium matter, no light clusters



- The critical temperature for heavy clusters: T_{crit} is model, dependent but below 10 MeV

Light clusters in neutron stars

- Supernova EoS with clusters:
  - quantum statistical approach (QS): quantum correlations with the medium, takes into account the excited states and temperature effect. But, the mass shifts available only for a few nuclear species and a limited density domain. Can be implemented only with approximations (Typel et al 2010)
  - RMF approach with light clusters
    - considered as new degrees of freedom.
    - characterized by a density, and possibly temperature, dependent effective mass,
    - interact with the medium via meson couplings.
    - In-medium effects are incorporated via the meson couplings, the effective mass shift, or both.
  - Constraints are needed to fix the couplings!

Constraining light clusters

- Cluster formation has been measured in heavy ion collisions (Qin et al PRL 108 (2012), Hagel et al PRL108,062702): equilibrium constants, Mott points and medium cluster binding energies
- Cluster formation in Supernova EOS constrained with equilibrium constants from HIC was studied in (Hempel et al PRC91, 045805 (2015))
  - the SN EoS should incorporate: mean-field interactions of nucleons, inclusion of all relevant light clusters, and a suppression mechanism of clusters at high densities

EOS

RMF Lagrangian for stellar matter

- Lagrangian density: $\mathcal{L} = \mathcal{L}_N + \mathcal{L}_c + \mathcal{L}_m + L_e$
  - nucleons, tritium, helion

$$\mathcal{L}_j = \bar{\psi}_j \left[\gamma_\mu i D_j^\mu - M_j^*\right] \psi_j \qquad i = p,\ n,\ t,\ 3he$$

  - alphas, deuterons

$$\begin{aligned}
\mathcal{L}_\alpha &= \frac{1}{2}(iD_\alpha^\mu \phi_\alpha)^*(iD_{\mu\alpha}\phi_\alpha) - \frac{1}{2}\phi_\alpha^* M_\alpha^2 \phi_\alpha, \\
\mathcal{L}_d &= \frac{1}{4}(iD_d^\mu \phi_d^\nu - iD_d^\nu \phi_d^\mu)^*(iD_{d\mu}\phi_{d\nu} - iD_{d\nu}\phi_{d\mu}) - \frac{1}{2}\phi_d^{\mu *} M_d^2 \phi_{d\mu},
\end{aligned}$$

$$\begin{aligned}
iD_j^\mu &= i\partial^\mu - g_{vj}\omega^\mu - \frac{g_{\rho j}}{2}\boldsymbol{\tau}\cdot\mathbf{b}^\mu, \\
M_j^* &= m_* = m - g_s\phi_0, \quad j = p, n \\
M_j^* &= M_j - g_{sj}\phi_0 - \mathbf{B}_j, \quad j = t, h, d, \alpha
\end{aligned}$$

- couplings: constrained by HIC data ou first principle calculations

Mass shift in clusters - g_{sj}

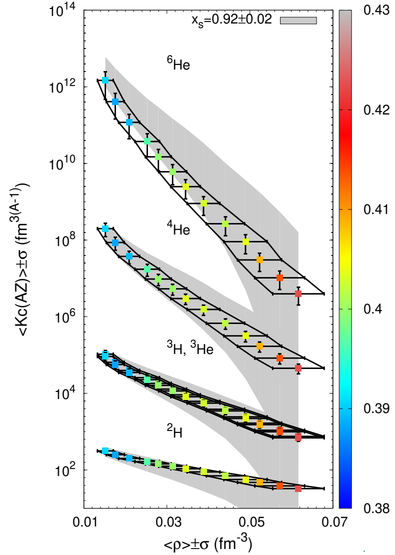
- Binding energy for each cluster: $B_j = A_j m^* - M_j^*$
- $m^* = m - g_s \phi_0$, nucleon effective mass
- $M_j^* = A_j m - g_{sj} \phi_0 - (B_j^0 + \delta B_j)$, cluster effective mass
- $g_{sj} = x_{sj} A_j g_s$, the cluster- scalar meson coupling
  - needs to be determined from experiments
- δB_j: the energy states occupied by the gas are excluded (double counting avoided!)

Equilibrium constants: model versus experimental data

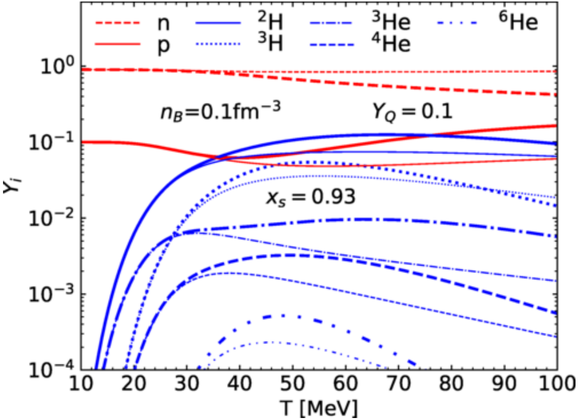
System $^{136}Xe+^{124}Sn$ (INDRA - GANIL, Bougault *et al* JPG 47 (2020) 025103

Chemical equilibrium constants :

- $K_c[i] = \rho_i/(\rho_p^{Z_i}\rho_n^{N_i})$
- chemical equilibrium constants for homogeneous matter with five light clusters
- calculated at the average value of (T, $\rho_{\rm exp}$, $y_{pg,\rm exp}$)
- cluster-meson scalar coupling constants $g_{s_i} = x_{s_i} A_i g_s$, with $x_{s_i} = 0.92 \pm 0.02$
- global proton fraction: color code

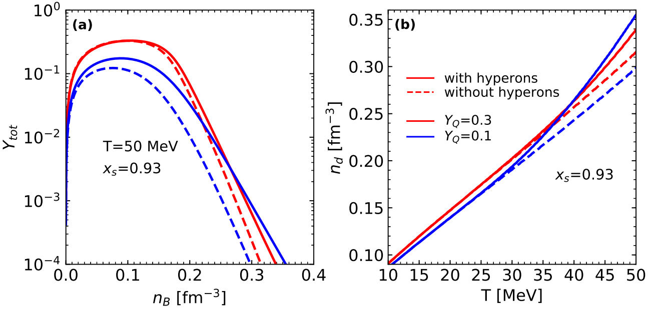


Hyperon effect of light cluster and unbound nucleons abundances



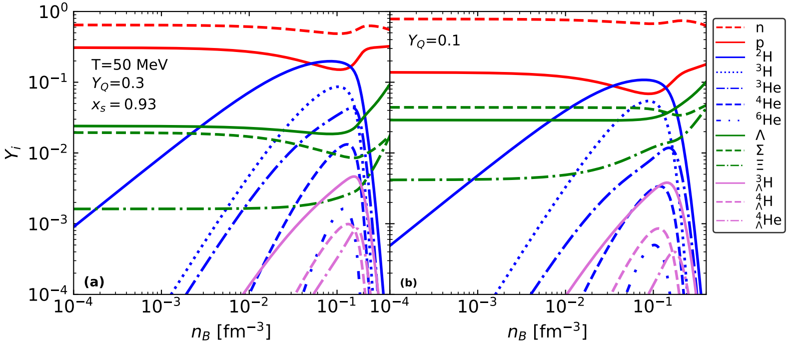
- Unbound nucleon and light cluster fractions with hyperons (thick lines) and without hyperons (thin lines)
- Hyperons: smaller fraction of unbound nucleons and larger fraction of light clusters
- Hyperons: larger dissolution density

Hyperon effect of light cluster abundances



- Total mass fraction of the light clusters versus density (T = 50 MeV)
- dissolution density of the clusters versus temperature

Light hyperclusters



- Mass fractions of the unbound protons and neutrons Λ, Σ and Ξ, light clusters and light hypernuclei

- Hypernuclei may be more abundant than α-particles or other heavier clusters, for small Y_Q

Hyperons and hypernuclei in NS

The presence of hyperons

- shifts the dissolution of clusters to larger densities
- increases the amount of clusters
- smaller charge fractions $\rightarrow$ larger effects
- the dissolution of the less-abundant clusters occurs at larger densities due to smaller Pauli-blocking effects.

Hyperons in neutron stars: conclusions

- Presence in the core:
  - more information on hypernuclei: with Ξ, Σ, with double hyperons ...
  - more information on phase shifts including hyperons
  - for microscopic calculations: information on YY, YYY, NYY
- Presence of light clusters in hot matter
  - in medium mass shifts
  - Mott densities

Thank you !