Impact of symmetry energy on heavy baryon formation in neutron stars

Armen Sedrakian
Frankfurt Institute for Advanced Studies
Institute for Theoretical Physics, Wroclaw University

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FIAS Frankfurt Institute for Advanced Studies

Uniwersytet Wrocławski

Talk based on:

- A. Sedrakian and A. Harutyunyan,
  Delta-resonances and hyperons in proto-neutron stars and merger remnants.
  Eur. Phys. J. A **58** (2022) 137
  Universe **7** (2021) 382
- Jia Jie Li, Armen Sedrakian, Fridolin Weber,
  Universal relations for compact stars with heavy baryons.
  Phys. Rev. C **108**, (2023) 025810; arXiv:2306.14190
- Jia Jie Li, Armen Sedrakian,
  Baryonic models of ultra-low-mass compact stars for the central compact object in HESS J1731-347.
  Phys. Lett. B **844**, (2023) 138062; arXiv:2306.14185

For a review:

A. Sedrakian, J.-J. Li and F. Weber
Heavy Baryons in Compact Stars.
Prog. Part. Nucl. Phys. 131 (2023) 104041 [arXiv:2212.01086]

Hyperons and delta-resonances in cold nuclear matter

CDF based equations of states

- Using EoS in the form of density functional: the pressure of dense zero-temperature matter is a functional of energy-density: $P(\varepsilon(r))$.
- The parameters of the functional are adjusted to the available data (astrophysics, laboratory, and ab initio calculations)
- DFT extended to baryon octet and includes hyperons and Delta-resonances
- Fast in implementation to generate quickly families of EoS

- Relativistic models of nuclear matter as DFT:
  (a) relativistic covariance, causality is fulfilled (+)
  (b) The Lorentz structure of interactions is maintained explicitly (+)
  (c) straightforward extension to the strange sector and resonances (+)
  (d) fast implementation (+)
  (e) not a QFT in the QED/QCD sense (-)
- Extended to finite-temperature and iso-entropic case
  The models are studied at $S =$Const. and $Y_e =$Const. (early stages of evolution, no significant entropy gradients in the core)
- Mapping of CDF onto the Taylor expansion of energy of nuclear matter
  A family of models is generated with varying symmetry energy, its slope, etc.

Nuclear matter Lagrangian:

$$
\begin{aligned}
\mathcal{L}_{NM} &= \underbrace{\sum_B \bar\psi_B\Big[\gamma^\mu\Big(i\partial_\mu - g_{\omega BB}\omega_\mu - \frac{1}{2}g_{\rho BB}\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu\Big) - (m_B - g_{\sigma BB}\sigma)\Big]\psi_B}_{\text{baryons}} \\
&+ \underbrace{\frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu}_{\text{mesons}} \\
&- \underbrace{\frac{1}{4}\boldsymbol{\rho}^{\mu\nu}\boldsymbol{\rho}_{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}^\mu\cdot\boldsymbol{\rho}_\mu}_{\text{mesons}} + \underbrace{\sum_\lambda \bar\psi_\lambda(i\gamma^\mu\partial_\mu - m_\lambda)\psi_\lambda}_{\text{leptons}} - \underbrace{\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{electromagnetism}},
\end{aligned}
$$

- B-sum is over the baryonic octet
- Meson fields include σ meson, $\boldsymbol{\rho}_\mu$-meson and ω_μ-meson
- Leptons include electrons, muons and neutrinos for $T \neq 0$

Two types of relativistic density functionals based on relativistic Lagrangians

- linear mesonic fields, density-dependent couplings (DDME2, DD2, etc.)
- non-linear mesonic fields; coupling constants are just numbers (NL3, GM1-3, etc.)
- Extension to include Fock contribution, Fu et al., Phys. Lett. B 834 (2022) 137470

Fixing the couplings: nucleonic sector

$$g_{iN}(\rho_B) = g_{iN}(\rho_0)h_i(x), \qquad h_i(x) = a_i\frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2} \quad i=\sigma,\omega,$$
$$g_{\rho N}(\rho_B) = g_{\rho N}(\rho_0)\exp[-a_\rho(x-1)], \quad i=\rho,(\pi-HF)$$

Meson (i)	m_i (MeV)	a_i	b_i	c_i	d_i	g_{iN}
σ	550.1238	1.3881	1.0943	1.7057	0.4421	10.5396
ω	783	1.3892	0.9240	1.4620	0.4775	13.0189
ρ	763	0.5647				7.3672

$h_i(1)=1$, $h_i''(0)=0$ and $h_\sigma''(1)=h_\omega''(1)$, which reduce the number of free parameters to three in this sector.

– DD-ME2 parametrization, G. Lalazissis, et al., Phys. Rev. **C71**, 024312 (2005)
– DD2 parametrizations, S. Typel, Eur. Phys. J. **A52**, 16 (2016)
– MPE parametrizations, S. Typel, Particles **1**, 3 (2018)
– DD-ME2+LQ, J. J. Li, Sedrakian, Phys. Rev. **C100**, 015809 (2019) + arXiv:2308.14457 (ApJ in press)

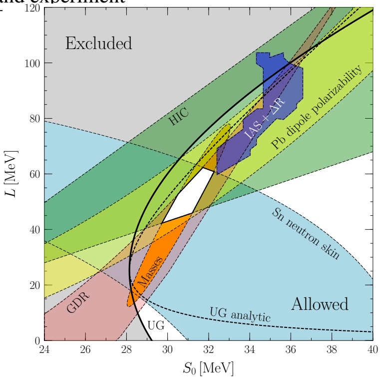
Taylor expansion of nuclear energy

$$E(\chi,\delta) \simeq E_0 + \frac{1}{2!}K_0\chi^2 + \frac{1}{3!}Q_{sym}\chi^3 + E_{sym}\delta^2 + L\delta^2\chi + \mathcal{O}(\chi^4,\chi^2\delta^2), \quad (1)$$

where $\delta = (n_n - n_p)/(n_n + n_p)$ and $\chi = (\rho - \rho_0)/3\rho_0$.

Consistency between the density functional and experiment

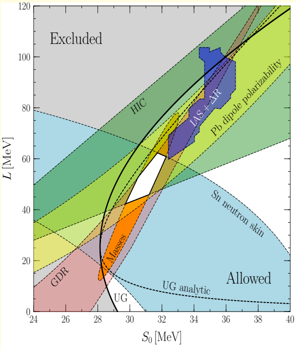
- saturation density $\rho_0 = 0.152\ \mathrm{fm}^{-3}$
- binding energy per nucleon $E/A = -16.14$ MeV,
- incompressibility $K_{sat} = 251.15$ MeV,
- skweness $Q_{sat} = 479$
- symmetry energy $E_{sym} = 32.30$ MeV,
- symmetry energy slope $L_{sym} = 51.27$ MeV,
- symmetry incompressibility $K_{sym} = -87.19$ MeV

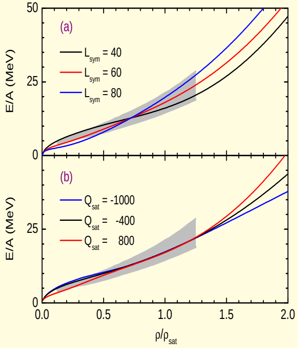


Credit: Tews, et al ApJ, 2017

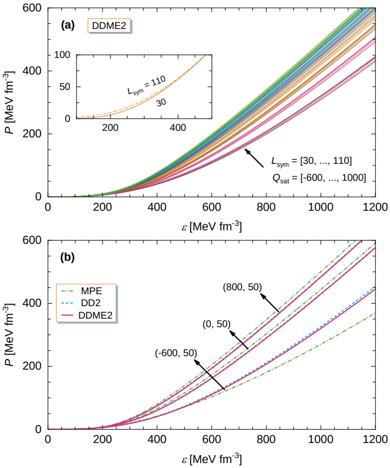
Impact of symmetry energy on heavy baryon formation in neutron stars
A Sedrakian
Introduction and motivation
Hyperons and Delta-resonances
Equation of state of dense matter
Conclusions-I
Results

Consistency between the density functional with experiment and ab initio theory

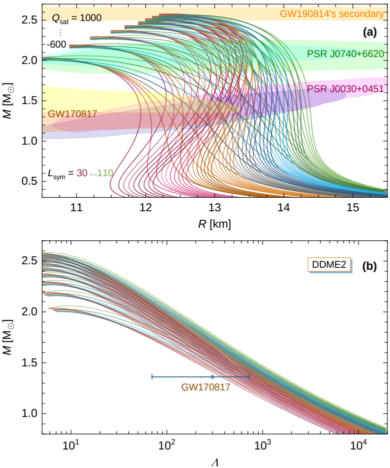




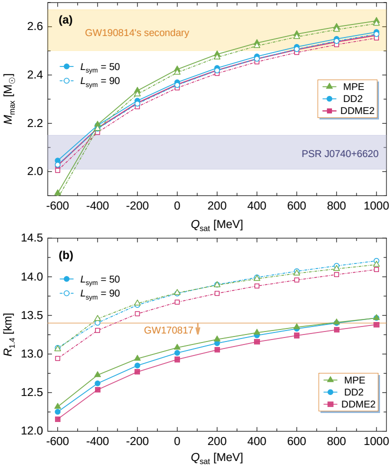
– Uncertainties will be quantified in terms of variation of higher-order characteristics around the central fit values.
– Low density physics depends strongly on the value of $L_{\rm sym}$ with a strong correlation to the radius of the star and tidal deformability
– High-density physics strongly depends on the value of $Q_{\rm sym}$ with strong correlations to the mass of the star.



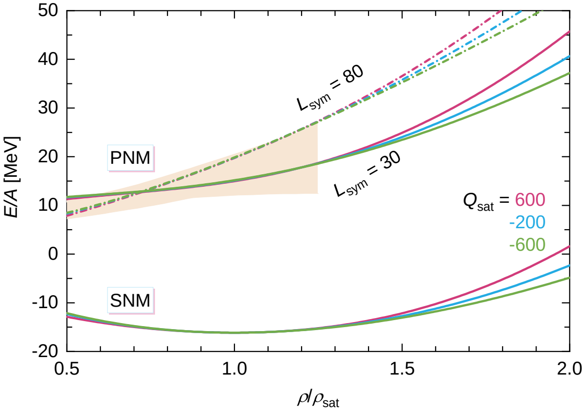
EoS for purely nucleonic stellar matter. In panel (a) the models are generated with DDME2 family of CDF models by varying the parameters $Q_{\rm sat} \in [-600,\ 1000]$ MeV and $L_{\rm sym} \in [30,\ 110]$ MeV. The effects of parameter $L_{\rm sym}$ on the low-density region of EoS are shown in the inset for illustration. In panel (b) the same is shown for three families of CDF models with fixed values of pairs $(Q_{\rm sat},\ L_{\rm sym})$ (in MeV) as indicated in the plot.



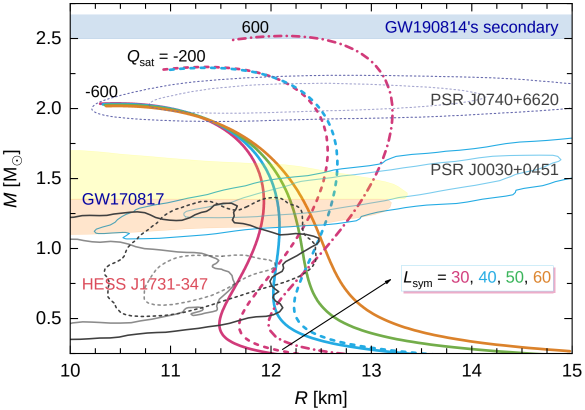
Mass-radius [panel (a)] and mass-tidal deformability [panel (b)] relations for nucleonic EoS modes with different pairs of values of $Q_{\rm sat}$ and $L_{\rm sym}$ (in MeV). In panel (a) the color regions show the 90% CI ellipses from each of the two NICER modeling groups for PSR J0030+0451 and J0740+6620, the 90% CI regions for each of the two compact stars that merged in the gravitational wave event GW170817, and finally the 90% CI for the mass of the secondary component of GW190814. In panel (b) the constraint for a $1.36\,M_\odot$ star deduced from the analysis of GW170817 event is shown too



The maximum mass M_{max} [panel (a)] and the radius $R_{1.4}$ of a canonical 1.4 $M_\odot$ mas star [panel (b)] that are predicted by three families of EoS generated from each CDFs used for various values of L_{sym} as a function of Q_{sat} (in MeV). In panel (a) the shadings show the masses of PSR J0470+6620 and the secondary component of GW190814, while in panel (b) the vertical line indicates the upper limit on the radius set by the analysis of GW170817.



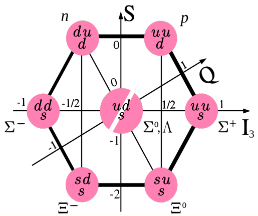
Energy per particle of symmetric nucleonic matter (SNM) and pure neutron matter (PNM) as a function of density ρ/ρ_{sat}, obtained from six representative $(Q_{sat},\ L_{sym})$ pairs (in MeV). The band corresponds to the combined χEFT results from Huth et al. (2021).

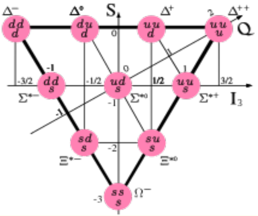


$M - R$ relation for nucleonic EoS models with different pairs of values of Q_{sat} and L_{sym}. We show three branches of $M - R$ curves, for $Q_{sat} = -600$ (solid lines), -200 (dashed lines) and 600 MeV (dash-doted lines). For each of these, L_{sym} is varied from 30 MeV to larger values that are still compatible with the ellipse of HESS J1731-347 at 95.4% CI. The shaded regions show the constraints from analysis of GW events the ellipses indicate the regions compatible with the inferences from NICER observations, the contours show the $M - R$ constraints for the CCO in HESS J1731-347 Doroshenko (2022).

Beyond nucleons: Baryon octet $J^p = 1/2^+$ and baryon decuplet $J^p = 3/2^+$

Strangeness carrying baryons + resonances (nucleon excitations)





$R_{\alpha Y} = g_{\alpha Y}/g_{\alpha N}$ and $\kappa_{\alpha Y} = f_{\alpha Y}/g_{\alpha Y}$ for hyperons in SU(6) spin-flavor model

$R\backslash Y$	Λ	Σ	Ξ
$R_{\sigma Y}$	2/3	2/3	1/3
$R_{\sigma^* Y}$	-$\sqrt{2}/3$	-$\sqrt{2}/3$	-2$\sqrt{2}/3$
$R_{\omega Y}$	2/3	2/3	1/3
$\kappa_{\omega Y}$	-1	$1 + 2\kappa_{\omega N}$	$-2 - \kappa_{\omega N}$
$R_{\phi Y}$	-$\sqrt{2}/3$	-$\sqrt{2}/3$	-2$\sqrt{2}/3$
$\kappa_{\phi Y}$	$2 + 3\kappa_{\omega N}$	$-2 - \kappa_{\omega N}$	$1 + 2\kappa_{\omega N}$
$R_{\rho Y}$	0	2	1
$\kappa_{\rho Y}$	0	$-3/5 + (2/5)\kappa_{\rho N}$	$-6/5 - (1/5)\kappa_{\rho N}$
$f_{\pi Y}$	0	$2\alpha_{ps}$	-$(1/2)\alpha_{ps}$

$\alpha_{ps} = 0.40$. κ is the ratio of the tensor to vector couplings of the vector mesons.

The depth of hyperonic potentials in the symmetric nuclear matter are used as a guide the range of hyperonic couplings:

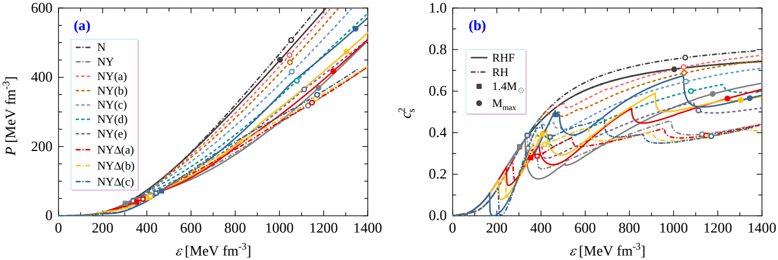
- Λ particle: $V_{\Lambda}^{(N)}(\rho_0) \simeq -30$ MeV
- Ξ particle: $V_{\Xi}^{(N)}(\rho_0) \simeq -14$ MeV
- Σ particle: $V_{\Xi}^{(N)}(\rho_0) \simeq +30$ MeV

These ranges capture the most interesting regions of the parameter space of masses and radii.

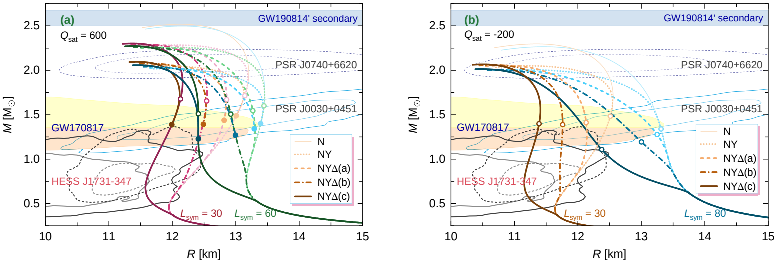
The depth of Δ-potentials in the symmetric nuclear matter is used as a guide for the range of the couplings:

- Electron and pion scattering: $-30 \text{ MeV} + V_{\Delta}^{(N)}(\rho_0) \leq V_{\Delta}(\rho_0) \leq V_N(\rho_0)$
- Use instead $R_{m\Delta} = g_{m\Delta}/g_{mN}$ for which the the typical range used is

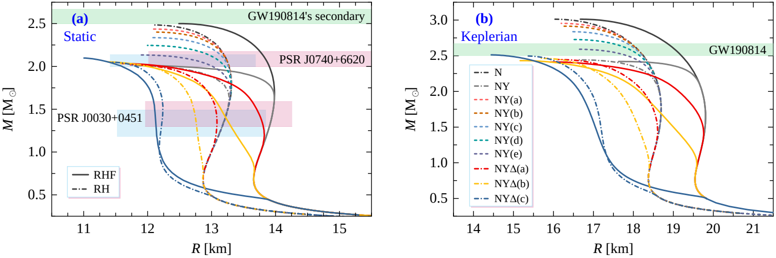
$$R_{\rho\Delta} = 1, \quad 0.8 \leq R_{\omega\Delta} \leq 1.6, \quad R_{\sigma\Delta} = R_{\omega\Delta} \pm 0.2.$$



EoSs for stellar matter featuring different compositions, i.e., nucleonic (N), hyperonic (NY), and hyperon-Δ admixed (NYΔ) one (panel a), and the associated speed of sound squared c_s^2 (panel b). The results are obtained using both the RHF and RH approaches. The positions for canonical-mass and maximum-mass configurations are marked by squares and circles.



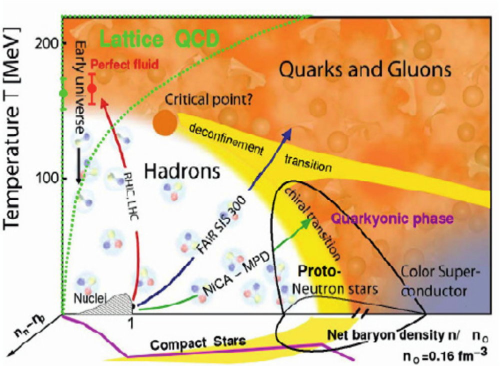
$M - R$ relation for hyperon-Δ admixed EoS models for different Δ potential depths at nuclear saturation density $U_\Delta/U_N = 1,\ 4/3,\ 5/3$, which are labeled as "NYΔ(a)-(c)", respectively. The results for purely nucleonic and hyperonic EoS models are also shown. In panel (a) the EoS models are constructed from the nucleonic model with pairs of $(Q_{sat}, L_{sym}) = (600,\ 30)$ and $(600,\ 60)$ MeV, combined with either SU(6) or a SU(3) symmetric model for the hyperonic sector. In panel (b) the EoS models are constructed from the nucleonic model with pairs of $(Q_{sat}, L_{sym}) = (-200,\ 30)$ and $(-200,\ 80)$ MeV and a SU(3) symmetric parametrization of the hyperonic sector. The onset mass of hyperons for each EoS model is marked by circles.



Mass-radius relations of CSs in the static and maximally rotating (Keplerian) limits for various EoS models. The masses and radii for PSR J0030+0451. and PSR J0740+6620(68.3% credible interval) are inferred from NICER data, and the mass range extracted for the secondary of the GW190814 event is shown as well.

Hot compact stars and BNS mergers

Exploration of the strong sector of the Standard Model



The big picture of QCD phase diagram:

1. High-temperature and low-density HIC and lattice QCD simulations
2. High-temperature and high-density - CCSN and BNS mergers
3. Low-temperature and high-density - compact stars
4. Low-temperature and low density - HIC, nuclear structure, compact stars

The equation of state (EoS) and composition of dense and hot Δ-resonance admixed hypernuclear matter is studied under conditions that are characteristic of neutron star binary merger remnants and supernovas.

- Baryon and lepton charges:

$$Y_Q = n_Q/n_B, \quad Y_{e,\mu} = (n_{e,\mu} - n_{e^+,\mu^+})/n_B$$
$$n_Q = n_p + n_{\Sigma^+} + 2n_{\Delta^{++}} + n_{\Delta^+} - (n_{\Sigma^-} + n_{\Xi^-} + n_{\Delta^-}).$$

- Trapped regime - fixed lepton numbers

$$Y_{L,e} = Y_e + Y_{\nu_e} \quad Y_{L,\mu} = Y_\mu + Y_{\nu_\mu},$$
$$\text{BNS}: Y_{L,e} = Y_{L,\mu} = 0.1 \quad \text{Supernova}: Y_{L,e} = 0.4 \quad Y_{L,\mu} = 0.$$

- Transparent regime (neutrino chemical potentials vanish) - equilibrium with respect to the weak processes imply

$$\mu_\Lambda = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_{\Delta^0} = \mu_n = \mu_B, \quad \mu_{\Sigma^-} = \mu_{\Xi^-} = \mu_{\Delta^-} = \mu_B - \mu_Q,$$
$$\mu_{\Sigma^+} = \mu_{\Delta^+} = \mu_B + \mu_Q, \quad \mu_{\Delta^{++}} = \mu_B + 2\mu_Q,$$

where the baryon μ_B and charge $\mu_Q = \mu_p - \mu_n$ chemical potentials are associated with conservations of these quantities.

- Thus the conditions are

$$\mu_e = \mu_\mu = -\mu_Q = \mu_n - \mu_p, \quad \text{(free streaming)}$$
$$\mu_e = \mu_{L,e} - \mu_Q, \quad \mu_\mu = \mu_{L,\mu} - \mu_Q. \quad \text{(trapped)}$$

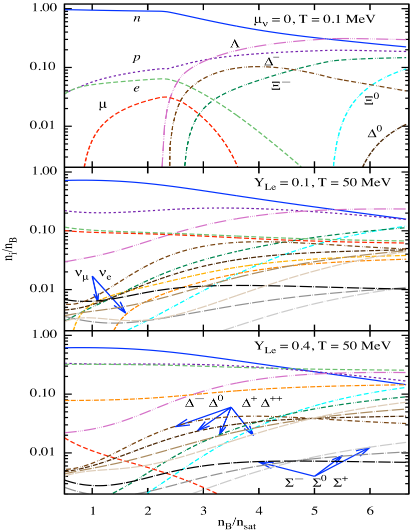
- BNS mergers, the initial conditions correspond to two cold neutron stars,

$$Y_{L,e} = Y_{L,\mu} = 0.1,$$

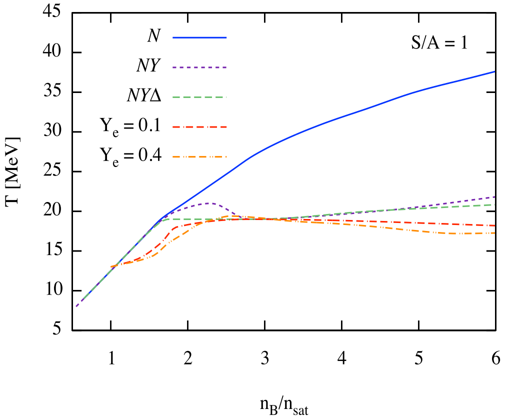
- For supernova matter the predicted electron and μ-on lepton numbers are typically

$$Y_{L,e} = 0.4, \quad Y_{L,\mu} = 0.$$

Dependence of composition on baryon density for fixed T.

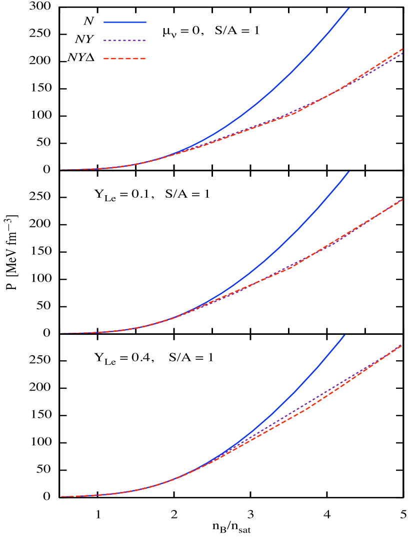


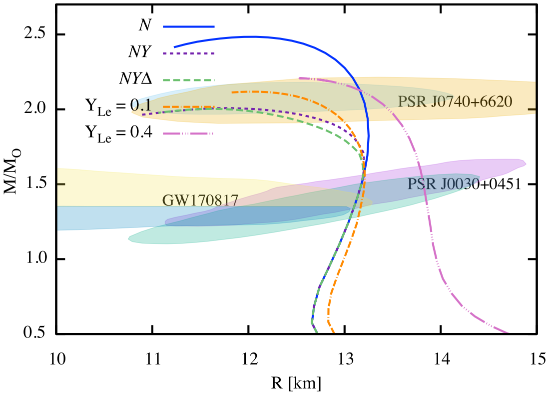
Dependence of temperature on density for fixed $S/A = 1$.



No significant changes in the composition compared to fixed T.

Dependence of pressure on baryon density for $S/A = 1$.





Gravitational mass versus radius for non-rotating spherically-symmetric stars. Three sequences are shown for β-equilibrated, neutrino-transparent stars with nucleonic (N), hypernuclear (NY) and Δ-admixed hypernuclear ($NY\Delta$) composition for $T = 0.1$ MeV. In addition, we show sequences of fixed $S/A = 1$ neutrino-trapped, isentropic stars composed of $NY\Delta$ matter in two cases of constant lepton fractions $Y_{Le} = Y_{L\mu} = 0.1$ and $Y_{Le} = 0.4,\ Y_{L\mu} = 0$. The ellipses show 90% CI regions for PSR J0030+0451, PSR J0740+6620 and gravitational wave event GW170817.

Physics output and conclusions:

- Large number of stellar models for injection studies of the Einstein Telescope (mass, radius, tidal deformabilities, variation of characteristics L and Q of the EoS).
- 3D tables for numerical simulations (in progress)
- More on properties of hot compact stars: rotation, universal relation, arXiv:2306.14190, arXiv:2102.00988, arXiv:2008.00213
- At a more fundamental level - improved DFs and, in particular, CDFs...
- 2D EoS tables can be downloaded from `https://github.com/asedrakian/DD_CDFs/` repository.