Hyperon stars

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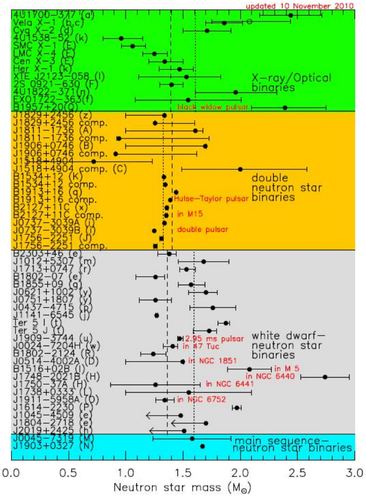
Neutron star masses - results of measurements



Massive neutron stars: neutron star – white dwarf binary systems

P.Demorest et al. Nature (2010)

- PSR J1614-2230
  - $M_{NS} = 1.97 \pm 0.04\ M_{\odot}$
  - $M_{WD} = 0.5 \pm 0.006\ M_{\odot}$

Antoniadis et al. Science (2013)

- PSR J0348+0432
  - $M_{NS} = 2.01 \pm 0.04\ M_{\odot}$
  - $M_{WD} = 0.172 \pm 0.003\ M_{\odot}$

Tolmann-Oppenheimer-Volkoff (TOV) equations of hydrostatic equilibrium

The equilibrium of a spherically symmetric star

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

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

$P(r)$ and $\rho(r)$ - pressure and density at radial coordinate r
Solution of TOV equations requires the knowledge of the equation of state (EoS) of dense asymmetric nuclear matter $\rightarrow P(\rho)$

- gives M-R relation
- enables modeling of the internal structure of a neutron star

Solution of TOV equations provides data on the impact of a given model on the internal structure of a neutron star

Maximum mass of a neutron star

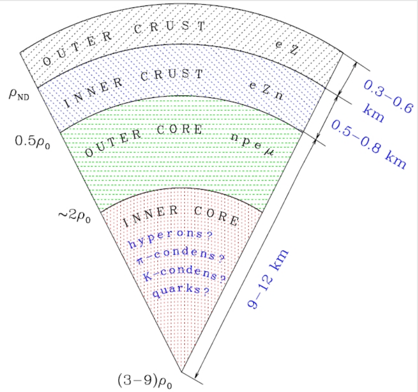
For calculated EoS there exists the maximum achievable neutron star mass M_{max}.
Maximum mass of a neutron star is a decisive factor for observational distinguishing between neutron stars and black holes.
The following condition has to be satisfied:

Measured neutron star masses $\leqslant \mathrm{M}_{max}$:

- limits the value of a neutron star mass
- constrains the EoS of high density nuclear matter
  - lower value of M_{max} - softer EoS - results obtained for binary neutron stars: $\mathrm{M}_{obs} \sim 1.4\mathrm{M}_{\odot} \leqslant \mathrm{M}_{max}$
  - higher value of $\mathrm{M}_{obs} \simeq \mathrm{M}_{max}$ - stiff EoS, massive neutron stars: PSR J1614-2230 and PSR J0348+0432

Neutron star structure

Schematic structure of a neutron star



- atmosphere
- outer crust - lattice of neutron-rich heavy nuclei, degenerate, relativistic electrons - correction to radius
- inner crust - as above plus degenerate non-relativistic neutrons
- outer core - homogeneous nucleonic matter
- inner core - may contain exotic forms of matter

Characteristics of the matter of a neutron star

- β-stable nuclear matter
  - $p + e^- \leftrightarrow n + \nu_e$
  - $n \leftrightarrow p + e^- + \bar{\nu}_e$
- cold, neutrino-free matter $\mu_{\nu_e} = \mu_{\bar{\nu}_e} = 0$
- $\sum_i Q_i n_i = 0$
- $n_B = \sum_i B_i n_i$
- $\mu_i = B_i \mu_i - Q_i \mu_e$
- Constituents of the model:
  - baryons: $N \cup \{\Lambda, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^-\}$
  - leptons: $L \in \{e^-, \mu^-\}$
  - mesons: $M \in \{\sigma, \omega_\mu, \rho^a_\mu\} \cup \{\sigma^*, \varphi_\mu\} \longleftarrow$ introduced to describe YY interaction

The model

- Lagrangian of the model: $\mathcal{L} = \mathcal{L}_0 + \mathcal{L}^M_{nonl}$
- $\mathcal{L}_0$ includes contributions from baryons and mesons
- $\mathcal{L}^M_{nonl}$ the part describing meson interactions

$$\begin{aligned} \mathcal{L}^M_{nonl} &= U_{scalar}(\sigma) + U_{vec}(\omega,\rho,\varphi) \\ U_{scalar}(\sigma) &= 1/3 g_3 \sigma^3 + 1/4 g_4 \sigma^4 \\ U_{vec}(\omega,\rho,\phi) &= U^{S=0}_{vec}(\omega,\rho) + U^{S}_{vec}(\omega,\rho,\phi) \end{aligned}$$

When the matter of the neutron star includes only nucleons the vector meson potential reduces to the part

$$\begin{aligned} U^{S=0}_{vec}(\omega,\rho) &= \frac{1}{4}c_3(\omega^\mu\omega_\mu)^2 + \frac{1}{4}c_3(\rho^{\mu a}\rho^a_\mu)^2 + \\ &+ \Lambda_V(g_{N\omega}g_{N\rho})^2(\omega^\mu\omega_\mu)(\rho^{\mu a}\rho^a_\mu). \end{aligned}$$

The case of non-strange matter

Extended isovector sector

$$E_{sym}(n_B) = \frac{k_F^2}{\sqrt{(k_F^2 + M_{eff}^2)}} + \frac{\rho}{8(m_\rho^2/g_{N\rho}^2 + 2\Lambda_V(g_{N\omega}\omega)^2)}$$

- $\omega - \rho$ meson coupling $\rightarrow$ modification of the high density limit of the symmetry energy
- the parameter $g_{N\rho}$ is adjusted to reproduce the symmetry energy $E_{sym} = 25.68$ MeV at $k_F = 1.15\mathrm{fm}^{-1}$
- the density slope of the symmetry energy L - current experimental results: $40.5 - 61.9$ MeV

Coupling constants

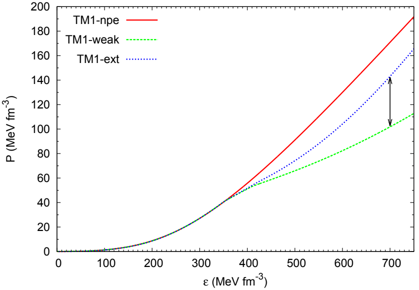
Baryon–vector meson coupling constants are estimated on the basis of SU(6) symmetry.
Scalar and vector coupling constants are strongly correlated - fixed by the potential depth of the corresponding hyperons:

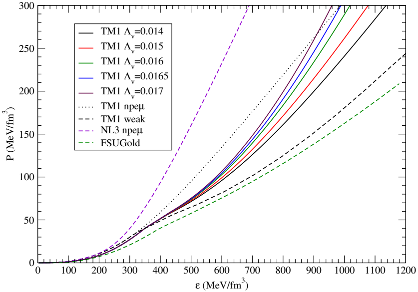
$$U_{\Lambda}^{(N)} = -28\text{MeV},\ \ U_{\Sigma}^{(N)} + 30\text{MeV},\ \ U_{\Xi}^{(N)} = -18\text{MeV}.$$

The coupling constants of hyperons to the meson σ^* were calculated from relations:

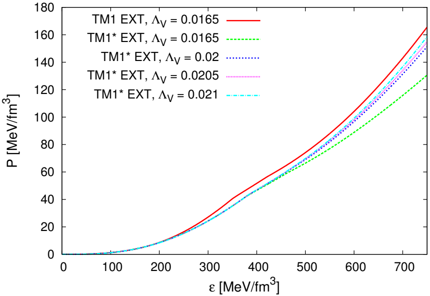
$$U_{\Xi}^{(\Xi)} \simeq U_{\Lambda}^{(\Xi)} \simeq 2U_{\Xi}^{(\Lambda)} \simeq 2U_{\Lambda}^{(\Lambda)}.$$

Equation of State





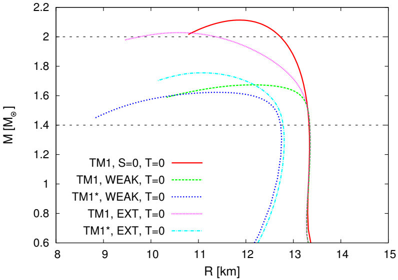
Equation of State

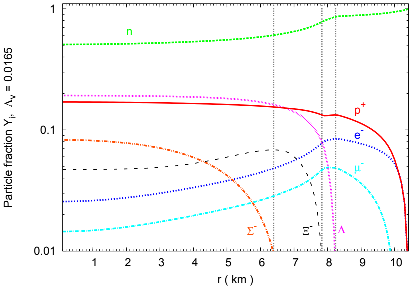


TM1* parameter set

- modification of TM1 parameter set
- inclusion of scalar-vector meson coupling constant
- improvement of density slope of symmetry energy

M-R relations and the structure of a neutron star

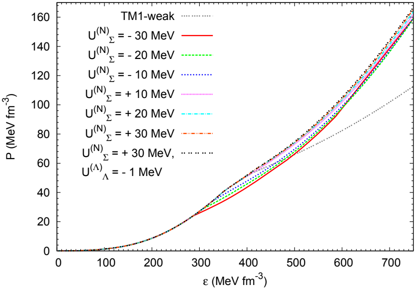


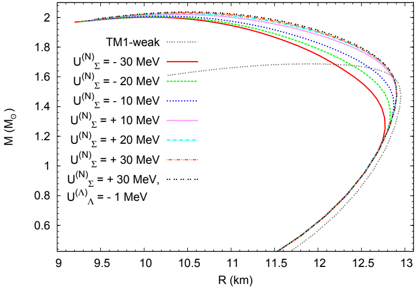


The effect of the $U_Y^{(N)}$ potential

Implications for neutron stars

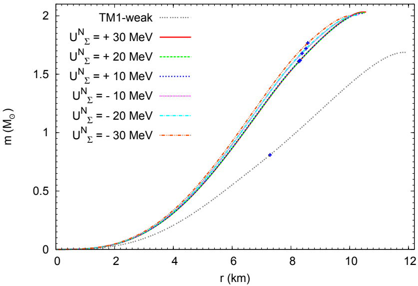
- bulk properties of a neutron star
- structure and composition of a neutron star

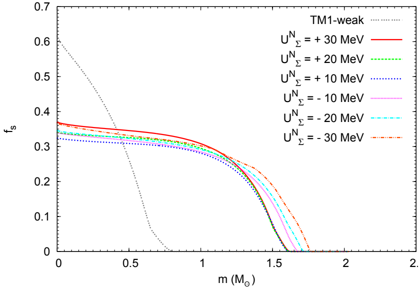




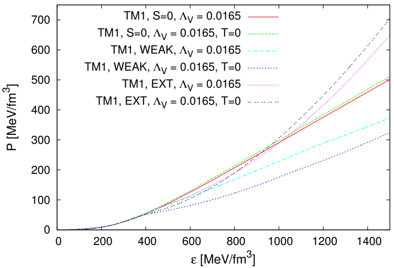
Results obtained for different values of the $U_\Lambda^{(N)}$ potential.

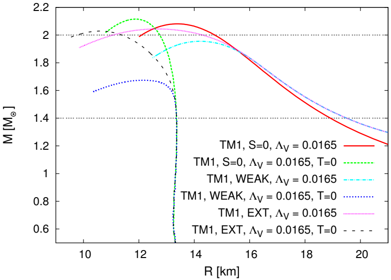
Internal structure of the maximum mass configurations



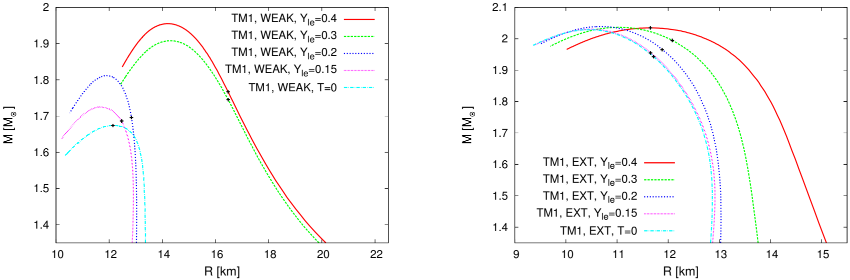


Neutron star evolution





Neutron star evolution



Conclusions

- Neutron stars with hyperons - reduction of masses
- Solution - extra repulse is needed
- Alternative solution - strange quark matter

Thank you for your attention!