Properties of neutron stars with hyperons and quarks using relativistic Hartree-Fock approximation and MIT bag model

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Motivation

- Since the discovery of massive neutron stars, the discrepancy between the observations and theories (**hyperon puzzle**) becomes a big problem.

  PSR J1614-2230 with $1.97 \pm 0.04 M_{\odot}$ (P. B. Demorest et al.)
  and PSR J0348+0432 with $2.01 \pm 0.04 M_{\odot}$ (J. Antoniadis et al.)

- Recently, several approaches have been trying to figure out **the hyperon puzzle**.

- However, **other exotic degrees of freedom** are expected in the core of a neutron star:
  - **quark matter**,
  - **some unusual condensations of boson-like matter**,
  - dark matter etc.

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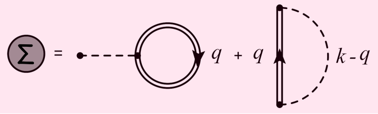
Hadronic EoS

1 Relativistic mean-field (RMF) calculation

- Hartree approximation:
  only direct interaction
- Hartree-Fock approximation:
  direct and exchange interactions

Baryon self-energty



tadpole exchange

2 Hidden strange (σ^* and φ) mesons in SU(3) flavor symmetry

3 The effect of baryon-structure variation in matter using the chiral quark-meson coupling (CQMC) model

Equation of state (EoS) supporting massive neutron stars ($\gtrsim 2M_\odot$)

Lagrangian density

- Lagrangian density for uniform hadronic matter:

$$\mathcal{L}_H = \mathcal{L}_B + \mathcal{L}_M + \mathcal{L}_{int}.$$

We consider the octet baryons (B): proton (p), neutron (n), Λ, Σ^{+0-}, and Ξ^{0-}. In addition, not only the mesons which is composed of light quarks (σ, ω, $\vec{\pi}$, and $\vec{\rho}$) but also the strange quarks (σ^* and φ) are taken into account.

$$\mathcal{L}_{int} = \sum_B \bar{\psi}_B \Big[g_{\sigma B}(\sigma)\sigma + g_{\sigma^* B}(\sigma^*)\sigma^* - g_{\omega B}\gamma_\mu \omega^\mu + \frac{f_{\omega B}}{2\mathcal{M}}\sigma_{\mu\nu}\partial^\nu \omega^\mu - g_{\varphi B}\gamma_\mu \varphi^\mu + \frac{f_{\varphi B}}{2\mathcal{M}}\sigma_{\mu\nu}\partial^\nu \varphi^\mu - g_{\rho B}\gamma_\mu \vec{\rho}^{\,\mu} \cdot \vec{I}_B + \frac{f_{\rho B}}{2\mathcal{M}}\sigma_{\mu\nu}\partial^\nu \vec{\rho}^{\,\mu} \cdot \vec{I}_B - \frac{f_{\pi B}}{m}\gamma_5\gamma_\mu\partial^\mu \vec{\pi} \cdot \vec{I}_B \Big] \psi_B,$$

with $\mathcal{M}$ being the scale mass ($= M_p$).

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field-dependent C.C. using the CQMC model

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Hartree-Fock approximation (tensor couplings)

with $\mathcal{M}$ being the scale mass (= M_p).

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Hartree-Fock approximation (tensor couplings)

pion contribution (pseudovector)

with $\mathcal{M}$ being the scale mass ($= M_p$).

SU(3) flavor symmetry in vector couplings

- SU(6): quark model

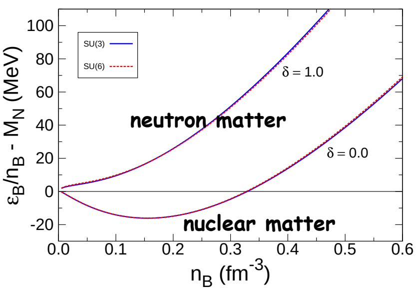
  ideal mixing

  $\theta_v = 35.26^\circ$ and $z = 1/\sqrt{6} \Rightarrow g_{\varphi N} = 0$.
- SU(3): flavor

  $\theta_v = 37.50^\circ$ and $z = 0.1949$ (ESC08).

$$g_{\varphi N} = \frac{\sqrt{3}z - \tan\theta_v}{1 + \sqrt{3}z\tan\theta_v} g_{\omega N},$$

Binding energy



— Results for saturation properties —

Symmetry	w_0 (MeV)	n_0 (fm^{-3})	E_{sym} (MeV)	M_N^*/M_N -	K_0 (MeV)	L (MeV)
SU(6)	−16.1	0.155	32.5	0.742	275	75.3
SU(3)	−16.1	0.155	32.5	0.747	269	78.0

red: input values

Quark matter description

- Quark matter: **MIT bag model** with one-gluon exchange (OGE) interaction

$$\varepsilon^{Q} = \sum_{q=u,d,s} \left[\Omega_q + \mu_q n_q \right] + B(n_B^Q, \beta),$$

where **the density-dependent bag constants** is given by

$$B(n_B^Q, \beta) = B_\infty + (B_0 - B_\infty) \exp\left[-\beta \left(\frac{n_B^Q}{3n_0} \right)^2 \right],$$

with $B_0 = 400$ MeV fm^{-3} and $B_\infty = 50$ MeV fm^{-3}.

- Phase transition: Gibbs criteria

$$P^{HP}(\mu_n, \mu_e) = P^{QP}(\mu_n, \mu_e) = P^{MP}(\mu_n, \mu_e).$$

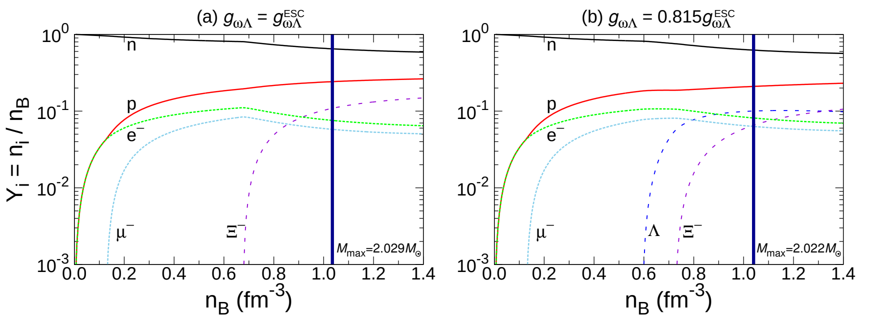
Particle fractions for neutron-star matter

All octet baryons are taken into account.

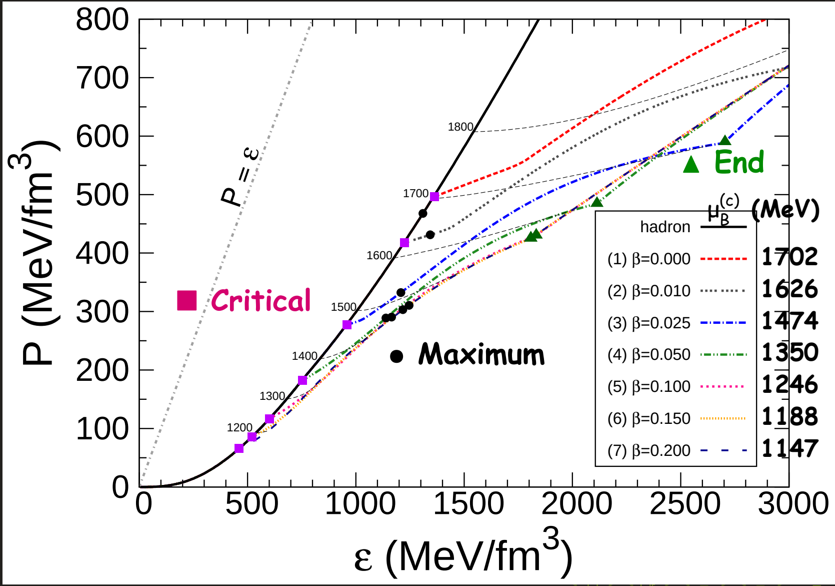
$\Rightarrow$ The coupling constants for hyperons are determined so as to reproduce **the observed, potential depths at** n_0:

$$U_\Lambda^{(N)} = -28 \text{ MeV}, U_\Sigma^{(N)} = +30 \text{ MeV}, U_\Xi^{(N)} = -18 \text{ MeV},$$
$$U_\Xi^{(\Xi)} \simeq U_\Lambda^{(\Xi)} \simeq 2U_\Xi^{(\Lambda)} \simeq 2U_\Lambda^{(\Lambda)} \text{ with } U_\Lambda^{(\Lambda)} \simeq -5 \text{ MeV},$$

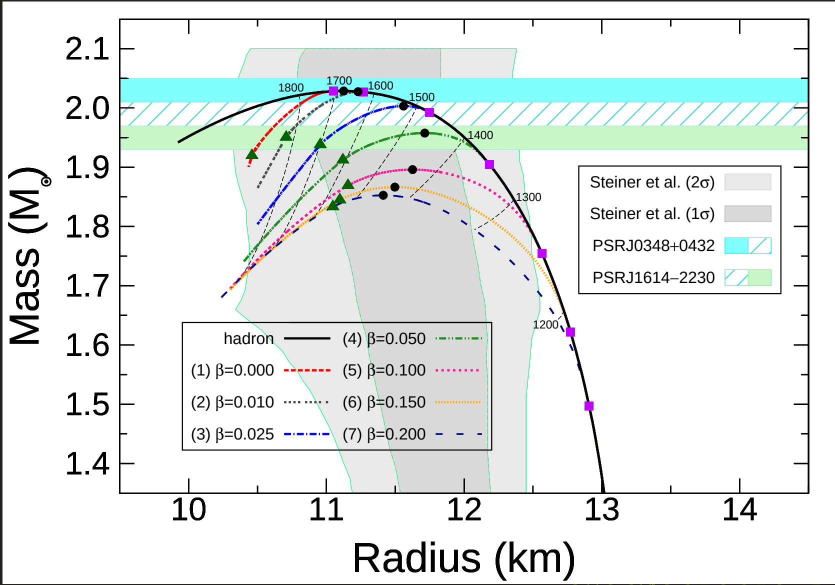
and we refer to the Nijmegen extended-soft-core (ESC) model in vector couplings (**SU(3) flavor symmetry**).



Equation of state for hybrid stars



Mass-radius relation



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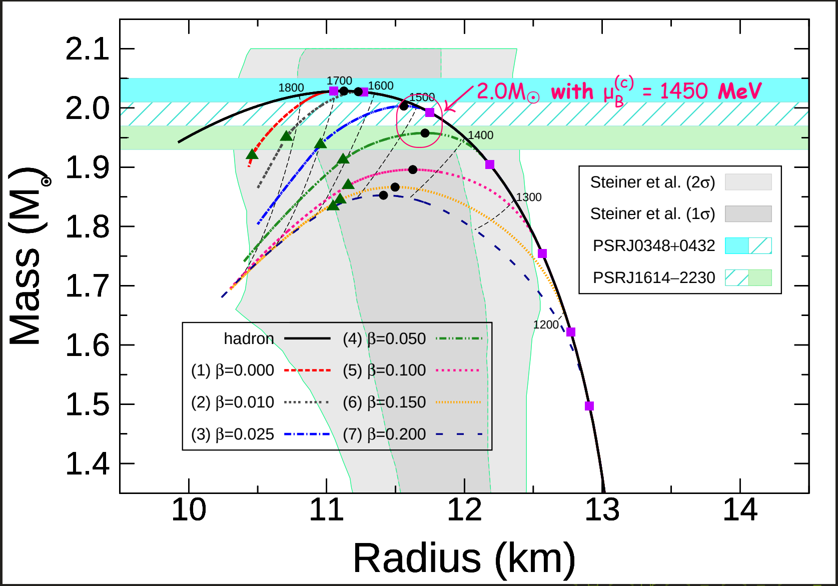
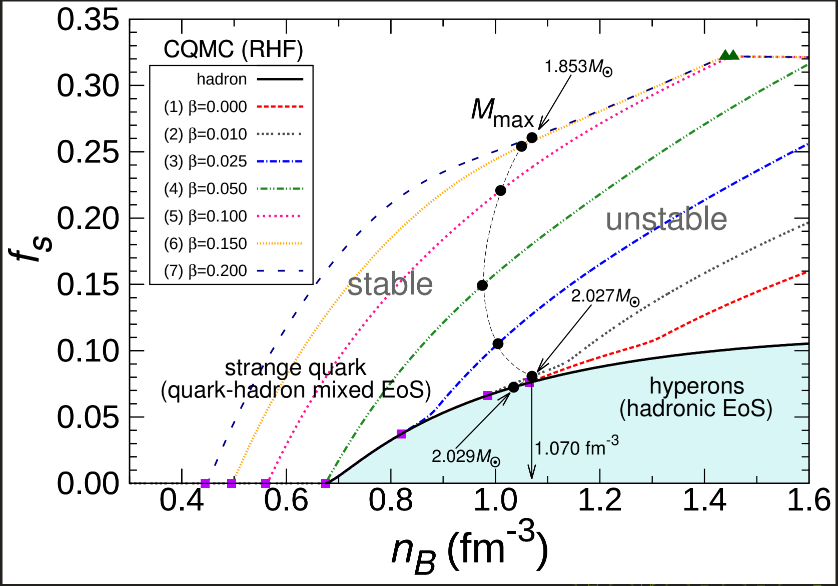


Strangeness fraction, $f_s = \left(\sum_Y n_Y |s_Y| + n_s\right) / 3n_B$



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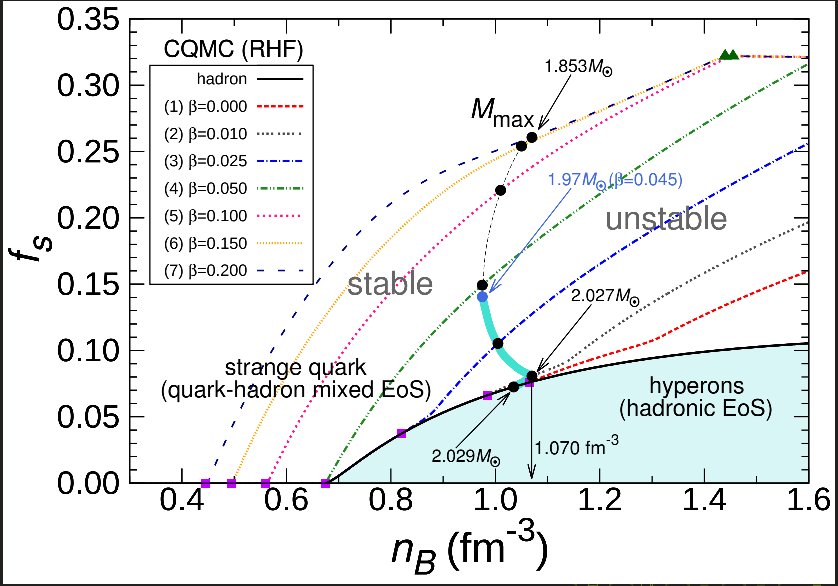

Summary

Hyperon stars:

- Relativistic Hartree-Fock approximation.
- SU(3) flavor symmetry in vector couplings with strange mesons.
- Baryon-structure variation in matter using the CQMC model.
- The maximum mass of a neutron star: $2.03M_{\odot}$ (Λ and Ξ^-).

Hybrid stars:

- Quark matter can be seen in mixed (coexistence) phase.
- The maximum mass of a hybrid star: $2.0M_{\odot}$ with $\mu_B^{(c)} = 1450$ MeV.
- The maximum fraction of strangeness: 14% ($1.97M_{\odot}$).

Outlook:

- Coexistence of baryons, quarks, and meson condensates.

Thank You for Your Attention.