Extending the quark-meson-coupling model of neutron star interiors to include hidden strangeness interactions

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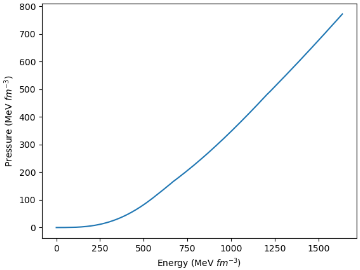
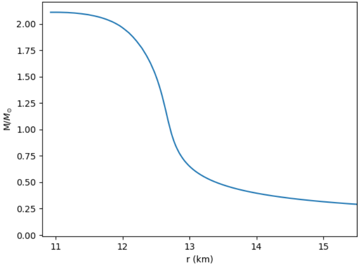
Neutron Stars

- Dense remnants of Type II supernovae
- Interior nuclear matter considered to contain nucleons, hyperons, electrons and muons (H dibaryon also included)
- Aiming to determine the equation of state (EoS) of the nuclear matter in neutron stars
- In this research, we focus on cold, slowly rotating neutron stars
- The nuclear matter inside the stars must satisfy β-equilibrium (total energy density minimised, charge and baryon number conserved, overall neutral charge)

Equation of State (EoS)

- Pressure as a function of energy density $p = p(\epsilon)$
- Provides a full characterization of the matter within the star
- Bulk properties of the star can be derived from the EoS via the Tolman-Oppenheimer-Volkoff (TOV) equations
- Maximum stellar mass and the corresponding radius are useful in comparing the model to observations
- Can observe this maximum mass on an MR (mass-radius) curve (see lower figure)





Observations

- Maximum mass measured $\sim 2.1 M_\odot$
  - e.g. PSR J0740+6620: $M \approx 2.072 M_\odot$, $R \approx 12.39$km
- Typical radius < 13.5km for a $1.4 M_\odot$ star
- In previous models, the inclusion of hyperons has reduced the maximum mass (appearance of hyperons instead of further neutrons limits the neutron Fermi pressure)
- The "hyperon puzzle": conditions in the star are sufficient to produce hyperons, but their presence in the model lowers the maximum mass below what has been observed

The quark-meson-coupling (QMC) model

- Interactions considered at the quark level, whereas in relativistic mean field (RMF) models, the internal structure of baryons is not considered

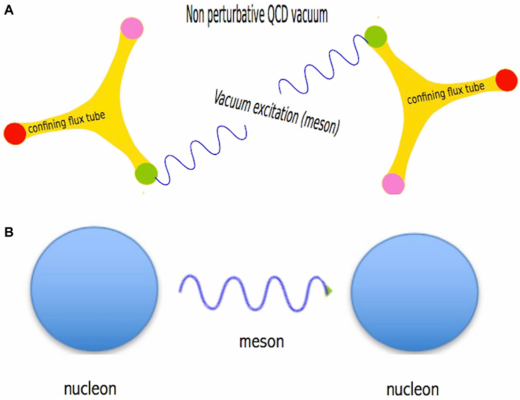
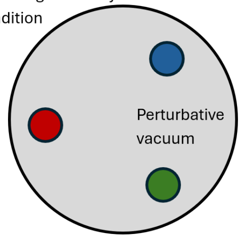


Image credit: Stone et al., 2022.

The quark-meson-coupling (QMC) model (continued)

- The baryons are modelled using the MIT bag model
- Quark interactions occur via exchange of both scalar and vector mesons



- The meson interactions are treated in a relativistic mean field approximation - the nucleons are Dirac particles interacting through effective meson fields
- This research includes scalar (σ), vector (ω) and isovector (ρ) mesons which couple to the light u and d quarks
- Scalar (σ^*) and vector (ϕ) mesons coupling to the s quark are being added to the model

The quark-meson-coupling (QMC) model (continued)

- Advantage of QMC: meson coupling constants are calculable directly from the theory, whereas other relativistic mean field (RMF) models have these as free parameters
- Effective baryon mass (with the effect of the σ field):

$$M_B^*(\sigma, R_B(\sigma)) = \frac{N_u\Omega_u + N_d\Omega_d + N_s\Omega_s}{R_B} - \frac{z_0}{R_B} + BV + \Delta E_M$$

- Effective quark mass (dependent on σ, where q is either u or d):

$$m_q^* = m_q - g_\sigma \sigma$$

- In the above, the quantities Ω can be calculated from the model
- Our model also includes a phenomenological short-distance repulsive force (Leong et al., 2023)

Hidden Strangeness Interactions

- Both scalar (σ^*) and vector (ϕ) hidden strangeness mesons have been added to our model
- These mesons couple to the strange (s) quark, present in the Λ (uds), Ξ^0 (uss), Ξ^- (dss) and H dibaryon (uuddss)
- Analogous to the σ and ω mesons, it was expected that σ^* would be a source of attraction, while ϕ would contribute additional repulsion
- Additional repulsion enables a larger star to be supported, therefore favouring a higher maximum mass

Hidden Strangeness Interactions (continued)

- The σ^* meson couples to the strange quark, shifting its effective mass by an amount dependent on the σ^* field strength (in the same way that σ influences the effective mass of the light quarks):

$$m_s^* = m_s - g_{\sigma^*}\sigma^*$$

- This effective quark mass makes the subsequent effective baryon mass M_B^* nonlinear in σ^*
- M_B^* is then parameterized as quadratic in σ^* (Taylor expansion):

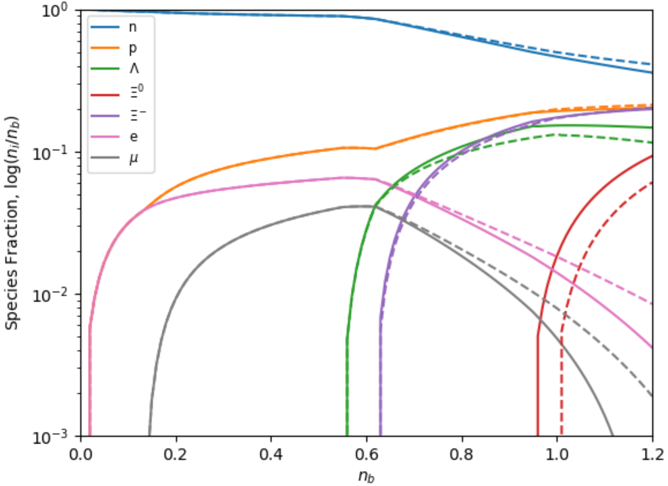
$$M_B^*(\sigma^*) = M_B - g_{\sigma^*}^B\sigma^* + \frac{d_B}{2}(g_{\sigma^*}\sigma^*)^2$$

- Similarly for σ:

$$M_B^*(\sigma) = M_B - g_{\sigma}^B\sigma + \frac{D_B}{2}(g_{\sigma}\sigma)^2$$

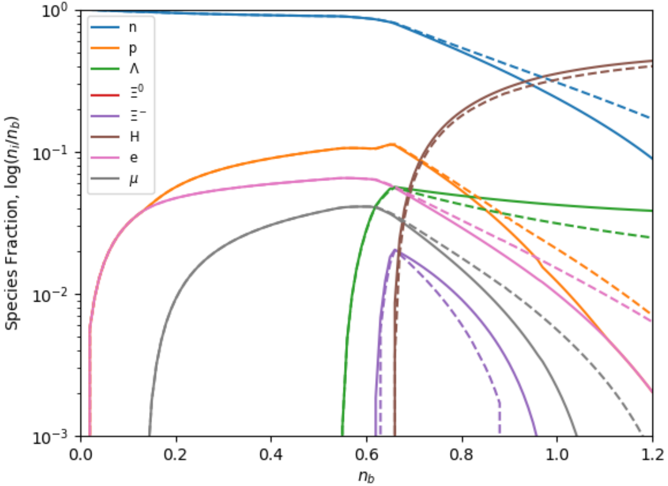
Preliminary Results

- Baryon species included in the model: n, p, Λ, Ξ^0, Ξ^-
- Also included: e^-, μ^-



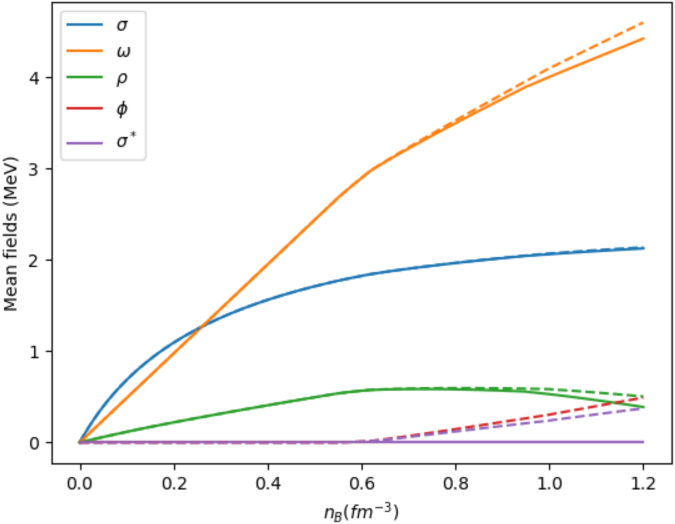
Species Fractions (continued)

- Including the H dibaryon:



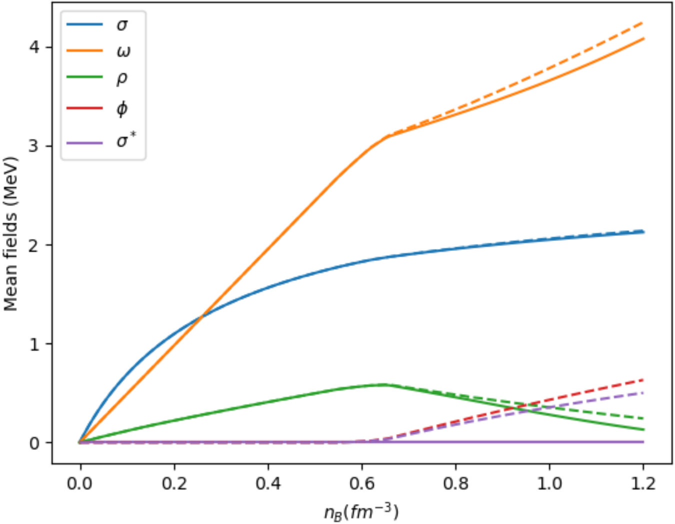
Meson Field Strengths

Without H dibaryon:



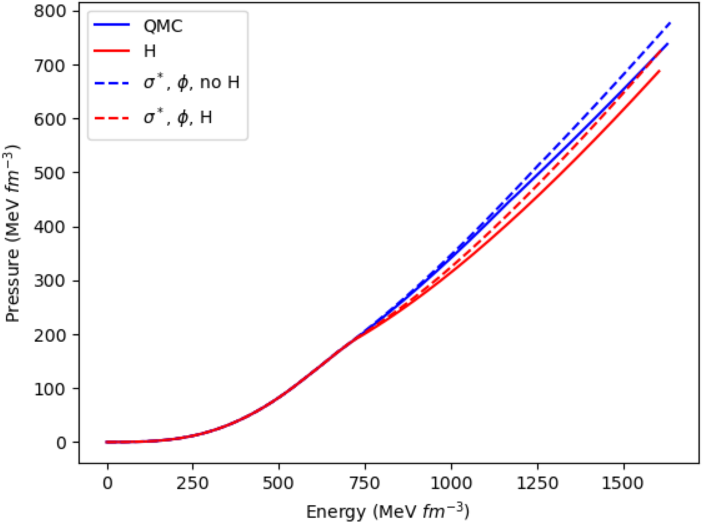
Meson Field Strengths (continued)

With H dibaryon:



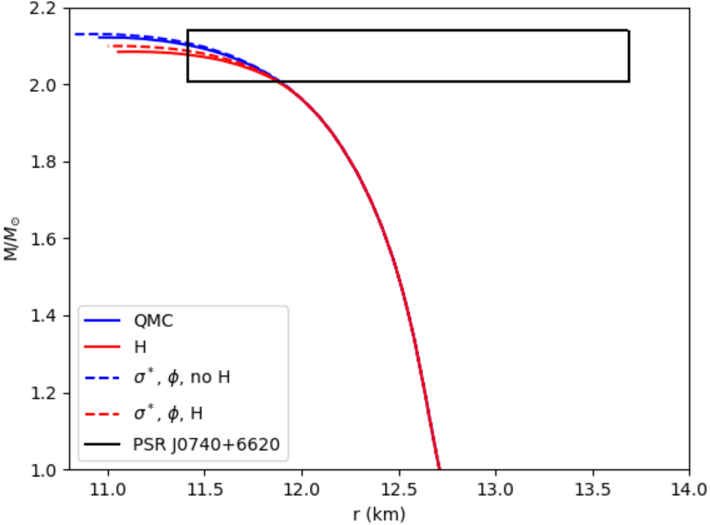
Equation of State (EoS)

Comparing the baseline model to models with the addition of the σ^*, ϕ and/or the H dibaryon:

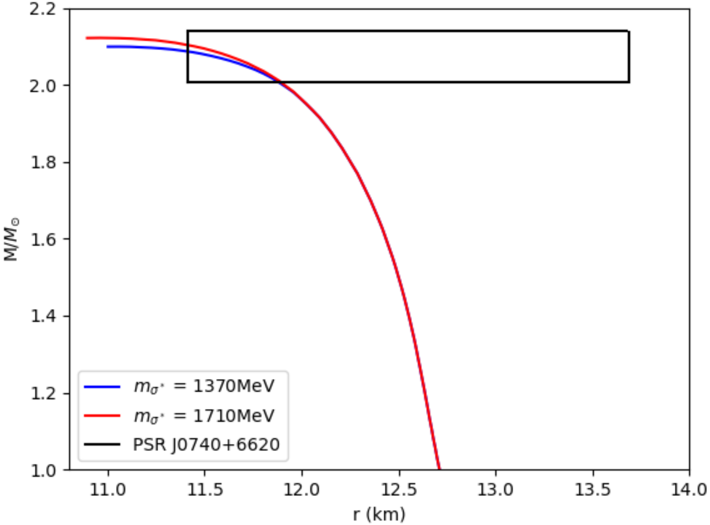


MR Curve

Comparing the baseline model to models with the addition of the σ^*, ϕ and/or the H dibaryon (also including additional high-density repulsion):



MR Curve (varied σ^* mass)



Summary

- Hidden strangeness interactions have been added to a QMC model of neutron star matter through both scalar (σ^*) and vector (ϕ) mesons
- The introduction of the strangeness mesons stiffens the EoS, leading to a higher maximum mass
- The maximum mass is reduced by the dominating H dibaryon, however with the additional overlap repulsion maximum masses comparable with observations are reached ($\sim 2.15 M_\odot$)
- A higher mass of the σ^* meson leads to a higher maximum mass, also in good agreement with observed stellar masses