Equation of state for neutron stars in the quark-meson coupling model with the cloudy bag

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8th International Conference on Quarks and Nuclear Physics (QNP 2018)
@ Tsukuba International Congress Center (EPOCHAL TSUKUBA)
November 16, 2018

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Introduction

- The equations of state (EoSs) for neutron stars should be satisfied with the nuclear properties and the astrophysical constrains.
- Since the discovery of massive neutron stars, the discrepancy between the observations and theories becomes a big problem ($2M_\odot$ problem).

PSR J1614-2230 with $1.97 \pm 0.04M_\odot$: P. B. Demorest et al., Nature **467** (2010) 1081, and PSR J0348+0432 with $2.01 \pm 0.04M_\odot$: J. Antoniadis et al., Science **340** (2013) 6131.

- In addition, the gravitational wave from binary neutron star was detected by LIGO and Virgo collaboration.

B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], Phys. Rev. Lett. 119, 161101 (2017).

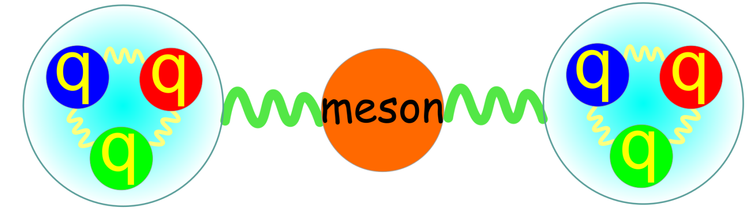
- Exotic degrees of freedom are expected in the core of a neutron star as well as nucleons:
  - hyperons,
  - quark matter,
  - some unusual condensations of boson-like matter,
  - dark matter etc.

Motivation

However · · · in general calculations, baryons are treated as point-like objects as in Quantum Hadrodynamics (QHD).

In the present calculation,

- We try to include the effect of quark degrees of freedom inside a baryon using the quark-meson coupling (QMC) model.
- The extended version of the QMC model based on chiral symmetry is adopted, denoted by the CQMC model.



Baryon description with the cloudy bag model

- Using the volume coupling version of the cloudy bag model (CBM), the hyperfine interaction due to the gluon exchange and the meson clouds is taken into account.

$$\mathcal{L}_{\mathrm{CBM}} = \mathcal{L}_{\mathrm{bag}} + \mathcal{L}_{\pi,K,\eta} + \mathcal{L}_{g} + \mathcal{L}_{\mathrm{int}}.$$

- The interaction Lagrangian density (up to $\mathcal{O}(1/f)$) is

$$\mathcal{L}_{\mathrm{int}} = \bar{\psi}_q \left[i\frac{\hat{m}}{f}\gamma_5 \vec{\lambda}\cdot\vec{\phi} + \frac{1}{2f}\gamma_\mu\gamma_5\vec{\lambda}\cdot\left(\partial^\mu\vec{\phi}\right) + \frac{g}{2}\gamma_\mu\vec{\lambda}\cdot\vec{A}^\mu \right]\psi_q\theta_v,$$

with θ_v the step function for the bag, $\vec{\lambda}$ the Gell-Mann matrices, f (g) the meson octet (gluon) coupling constant $\psi_q = \begin{pmatrix}\psi_u\\ \psi_d\\ \psi_s\end{pmatrix}$, $\hat{m} = \begin{pmatrix} m_u & 0 & 0\\ 0 & m_d & 0\\ 0 & 0 & m_s\end{pmatrix}$, and $\phi =$ $\frac{1}{\sqrt{2}}\left((\pi^+ + \pi^-), \frac{1}{i}(\pi^+ - \pi^-), \sqrt{2}\pi^0, -(K^+ + K^-), \frac{1}{i}(K^+ - K^-), -(K^0 + \bar{K}^0), \frac{1}{i}(K^0 - \bar{K}^0), \sqrt{2}\eta\right)$.

Baryon mass spectra in vacuum

- Baryon (B) mass with OGE and OPE:

$$M_B = \frac{4}{3}\pi B R_B^3 + \frac{1}{R_B}\left(\sum_{q=0,s} n_q \Omega_q - z_B\right) + \Delta E_{OGE} + \Delta E_{OPE},$$

where Ω_0 and Ω_s are calculated under the bag boundary condition, $j_0(x_q) = \beta_q j_1(x_q)$.

B	mass (MeV)	z_B (QMC)	z_B (CQMC)
N	939	3.295	2.476
Δ	1232	2.049	2.053
Λ	1116	3.563	2.487
Σ	1193	3.259	2.424
Ξ	1313	3.738	2.529
Ω	1672	3.295	2.476

		QMC	CQMC
	$B^{1/4}$	$= 170.0$ (MeV)	168.8 (MeV)
$m_0 = 5$ (MeV)	m_s	$= 414.1$ (MeV)	275.6 (MeV)

Matter description in the CQMC model

- The Lagrangian density for nuclear matter at the quark-mean field level:

$$\mathcal{L}_{\rm CQMC} = \mathcal{L}_{\rm CBM} + \mathcal{L}_{\sigma\omega\rho},$$

where

$$\mathcal{L}_{\sigma\omega\rho} = \bar{\psi}_q \left[g_\sigma^q \sigma - g_\omega^q \omega - g_\rho^q \rho \right] \psi_q \theta_V - \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{2} m_\omega^2 \omega^2 + \frac{1}{2} m_\rho^2 \rho^2.$$

- The self-consistency condition (SCC) for the σ field:

$$\sigma = -\sum_B \frac{1}{m_\sigma^2} \frac{2}{(2\pi)^3} \int^{k_{F_B}} d\vec{k} \frac{M_B^*}{\sqrt{M_B^{*2} + \vec{k}^2}} \left(\frac{\partial M_B^*}{\partial \sigma} \right)_{R_B}$$

$$= \sum_B \frac{g_{\sigma B}}{m_\sigma^2} \frac{2}{(2\pi)^3} \int^{k_{F_B}} d\vec{k} \frac{M_B^*}{\sqrt{M_B^{*2} + \vec{k}^2}} C_B(\sigma),$$

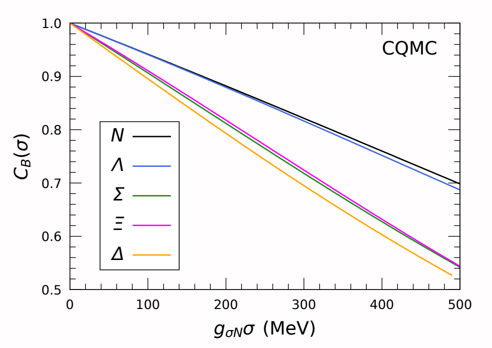
with C_B being the scalar polarizability.

Scalar polarizability

- The scalar polarizabilities can be expressed by the following parameterizations:

$$C_B(\sigma) = b_B \left[1 - a_B (g_{\sigma N}\sigma)\right],$$

where a_B and b_B are parameters.



	QMC		CQMC	
B	a_B (fm)	b_B	a_B (fm)	b_B
N	0.179	1.00	0.118	1.04
Λ	0.172	1.00	0.122	1.09
Σ	0.177	1.00	0.184	1.02
Ξ	0.166	1.00	0.181	1.15
Δ	0.196	1.00	0.197	0.89

gluon
pion

Thus, $M_B^*(\sigma) = M_B - g_{\sigma B}(\sigma)\sigma$,
with $g_{\sigma B}(\sigma) = g_{\sigma B} b_B \left[1 - \frac{a_B}{2}(g_{\sigma N}\sigma)\right]$.

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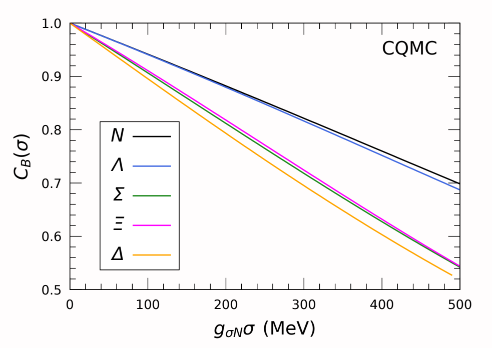

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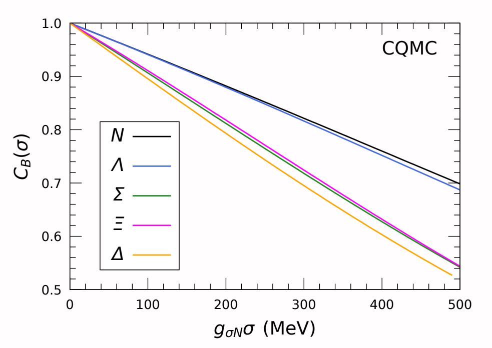

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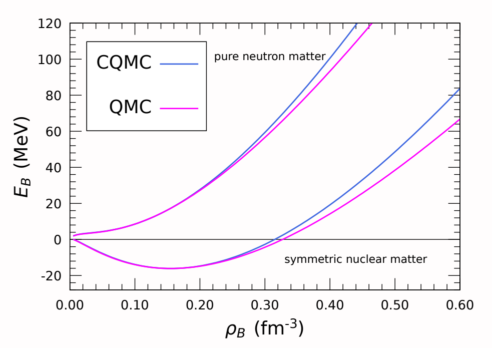
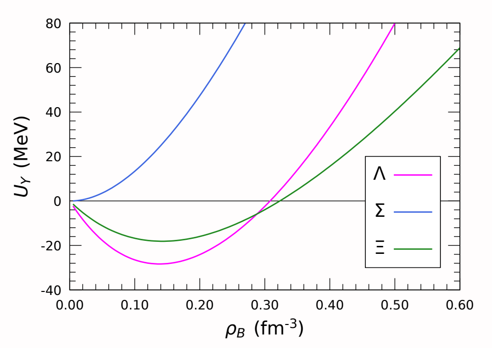
Properties of nuclear matter and hyperons

- Nuclear properties are calculated as in the same manner of the relativistic mean-field models based on Quantum Hadrodynamics (QHD).

$E_{\rm sym} = 32.5$ MeV (fixed)



$U_{\Lambda(\Sigma)[\Xi]} = -28(+30)[-18]$ MeV at ρ_0 (fixed)



$K_0^{\rm QMC(CQMC)} = 286(309)$ MeV, $L^{\rm QMC(CQMC)} = 88(91)$ MeV

Neutron-star matter in the CQMC model

- The Lagrangian density for neutron-star matter: $B = N, \Lambda, \Sigma^{+,0,-}, \Xi^{0,-}, \ell = e^-, \mu^-$

$$\begin{aligned}
\mathcal{L}_{\mathrm{NS}} &= \sum_B \bar{\psi}_B \left[i\gamma_\mu \partial^\mu - M_B^*(\sigma, \boldsymbol{\sigma^*}) - g_{\omega B}\gamma_\mu \omega^\mu - g_{\phi B}\gamma_\mu \boldsymbol{\phi^\mu} - g_{\rho B}\gamma_\mu \vec{\rho}^\mu \cdot \vec{I}_B \right] \psi_B \\
&+ \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) + \frac{1}{2}\left(\partial_\mu\sigma^*\partial^\mu\sigma^* - m_{\sigma^*}^2\sigma^{*2}\right) + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} \\
&+ \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu - \frac{1}{4}P_{\mu\nu}P^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu \cdot \vec{\rho}^\mu - \frac{1}{4}\vec{R}_{\mu\nu} \cdot \vec{R}^{\mu\nu} + \sum_\ell \bar{\psi}_\ell \left[i\gamma_\mu\partial^\mu - m_\ell \right] \psi_\ell .
\end{aligned}$$

Introducing strange mesons, σ^* and ϕ.

- In addition, the charge neutrality and β equilibrium under weak processes are imposed in solving the TOV equation.

$$g_{\sigma B}(\sigma) = g_{\sigma B} b_B \left[1 - \frac{a_B}{2}\left(g_{\sigma N}\sigma\right) \right], \quad g_{\sigma^* B}(\sigma^*) = g_{\sigma^* B} b'_B \left[1 - \frac{a'_B}{2}\left(g_{\sigma^* \Lambda}\sigma^*\right) \right].$$

SU(3) flavor symmetry in the vector couplings

Hyperon puzzle:

- Since the discovery of massive neutron stars, the discrepancy between the observations and theories becomes a big problem ($2M_\odot$ problem).

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- The extension of SU(6) spin-flavor symmetry to SU(3) flavor symmetry is examined in determining the couplings of the vector mesons to the octet baryons, introducing the strange vector mesons:

SU(6) symmetry		*the extended – soft core (ESC) model by the Nijmegen group*
$\alpha_v = F/(F+D) = 1$	$\Longrightarrow$	$\alpha_v = 1$
$\theta_v^{ideal} = 35.26^\circ$		$\theta_v = 37.50^\circ$
$z \simeq 0.4082$		$z = 0.1949$

Breaking about 50 %

T. A. Rijken, et.al., Prog. Theor. Phys. Suppl. **185** (2010) 14.

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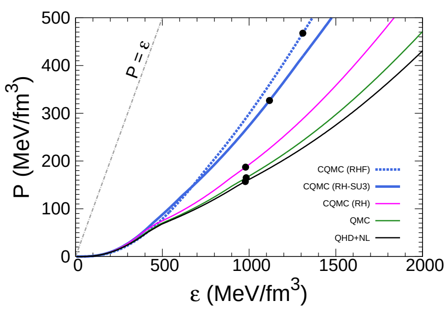
Neutron-star properties

1. Baryon-structure variation in matter using the CQMC model
2. SU(3) flavor symmetry
3. Relativistic many-body calculation

   Hartree approximation
   Hartree-Fock approximation



K_0 (MeV)
269
309
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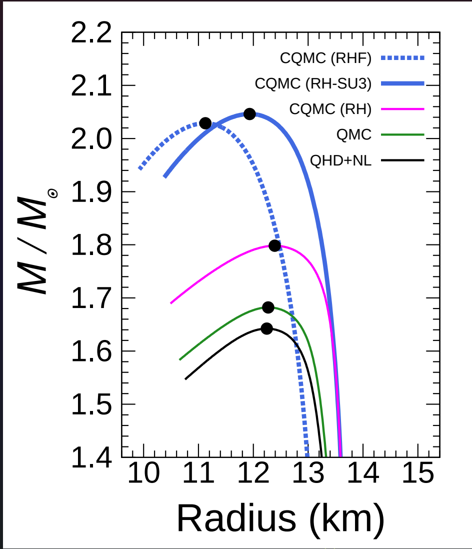

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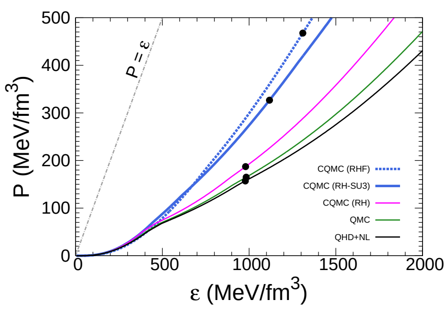

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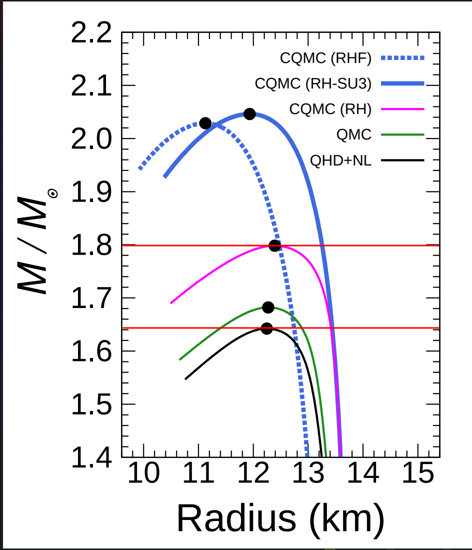

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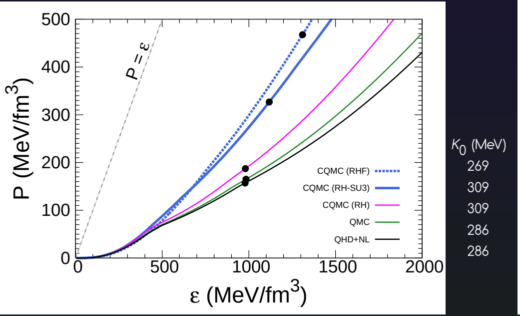

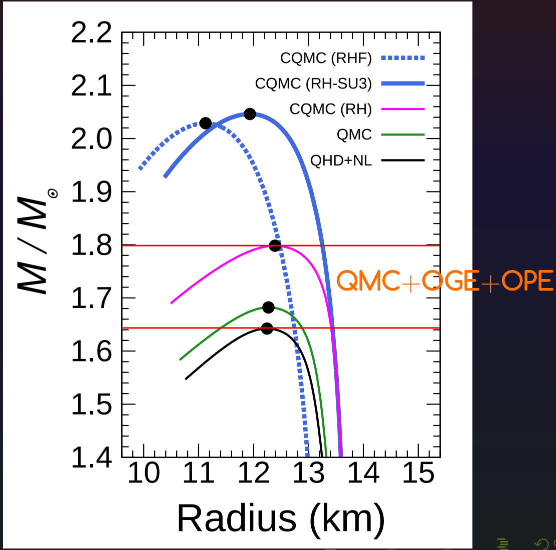

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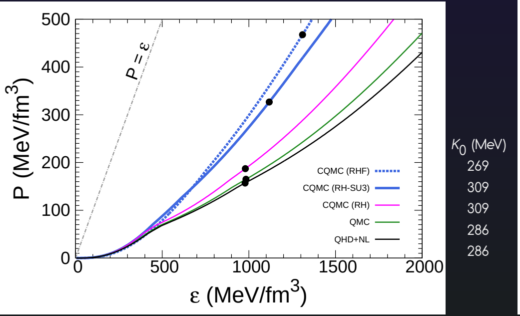

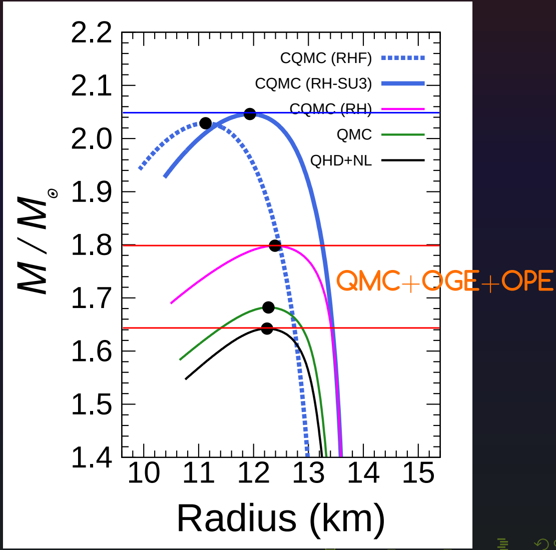

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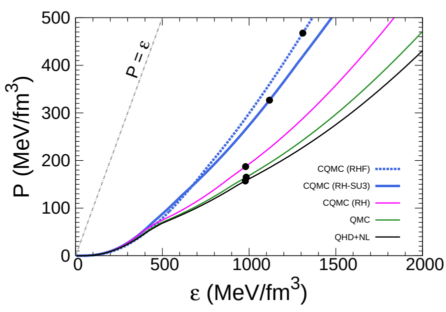

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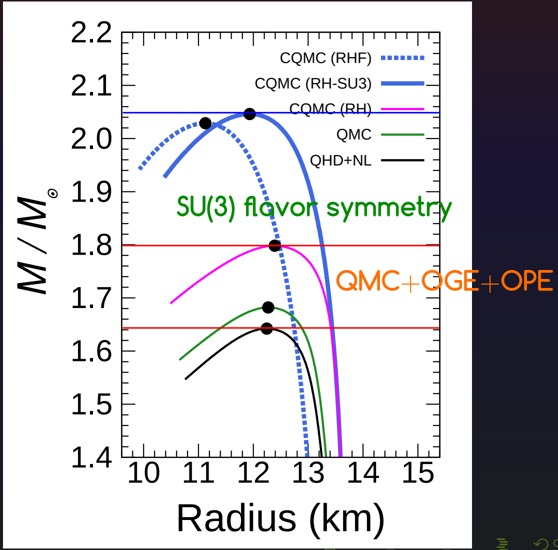

Summary

Motivation:

- We try to include the effect of quark degrees of freedom inside a baryon using the quark-meson coupling (QMC) model.

Results:

- We construct the chiral quark-meson coupling model which can be applied to hadron physics, nuclear Physics, and astrophysics.
- The hyperfine interaction due to the gluon exchange as well as that due to the pion cloud is taken into account.
- The extension of SU(6) spin-flavor symmetry to SU(3) flavor symmetry is examined in determining the couplings of the vector mesons to the octet baryons (hyperon puzzle).

Thank You for Your Attention.