Equation of state for hybrid stars with strangeness

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

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

■ The EoS for neutron stars with **hyperons** and **quark matter**

Hadronic EoS for neutron stars

1 The variation in **internal (quark) structure of baryons** in matter using **the chiral quark-meson coupling (CQMC) model**

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

T. M., M. K. Cheoun, and K. Saito, Phys. Rev. C **88** (2013) 015802.

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

- SU(6) symmetry based on quark model: $\theta_v = 35.26^\circ$ and $z = 1/\sqrt{6}$
- SU(3) flavor symmetry: $\theta_v = 37.50^\circ$ and $z = 0.1949$

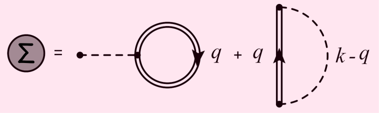
T. A. Rijken, M. M. Nagels, and Y. Yamamoto, Prog. Theor. Phys. Suppl. **185** (2010) 14.

3 Relativistic many-body calculation:

✓ **Hartree** approximation:

✓ **Hartree-Fock** approximation:

Baryon self-energy



tadpole exchange

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.

field-dependent C.C. using the CQMC model

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

Hartree-Fock approximation (tensor couplings)

pion contribution (pseudovector)

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

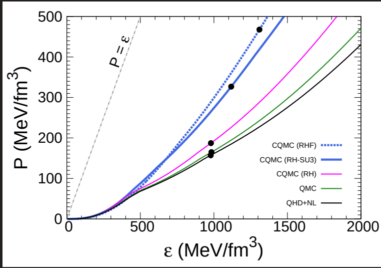
EoS for neutron stars

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

These effects make the EoS stiff and the maximum mass can reach the $2M_\odot$ constraint.



K_0 (MeV)
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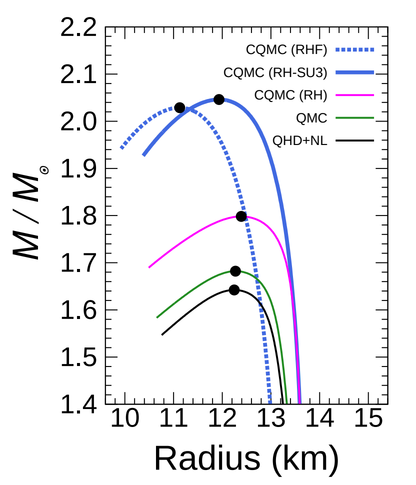

*Hyperons are taken into account.

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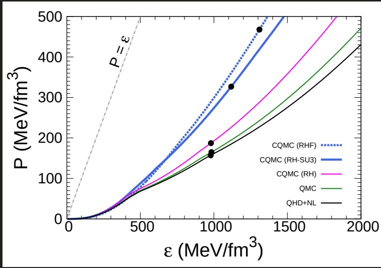

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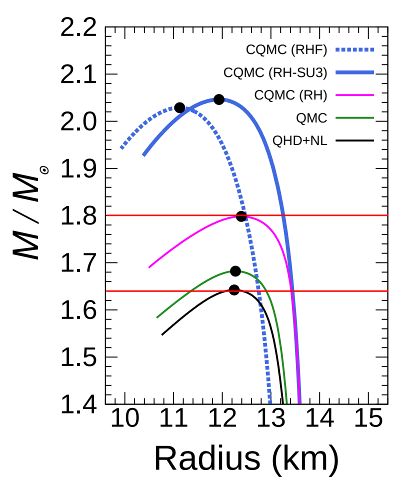

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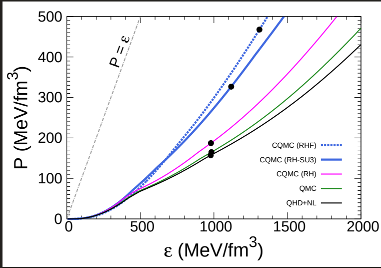

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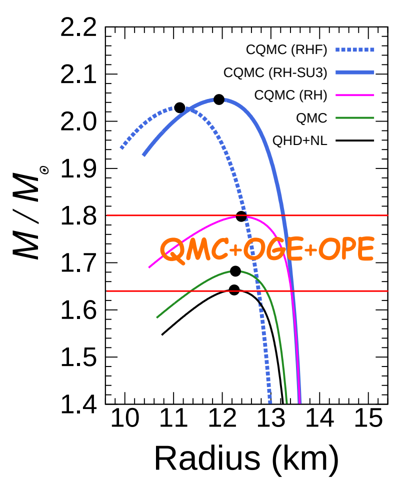

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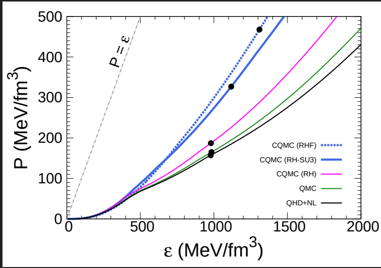

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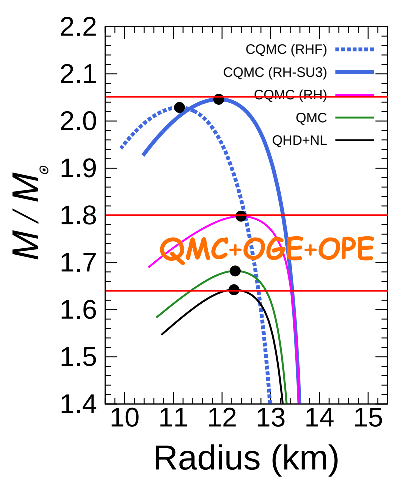

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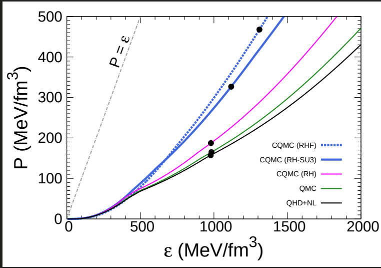

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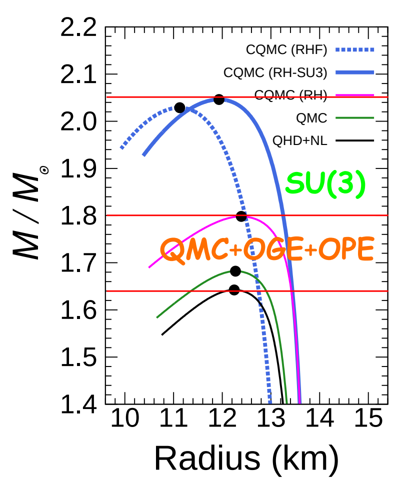

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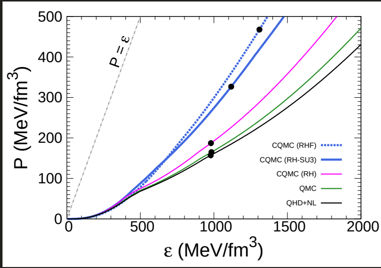

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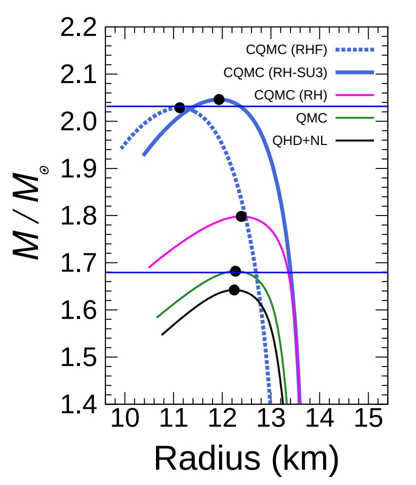

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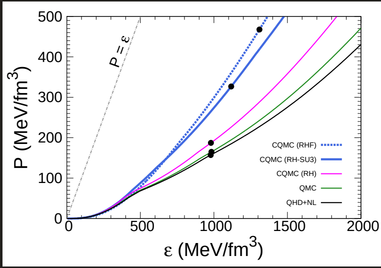

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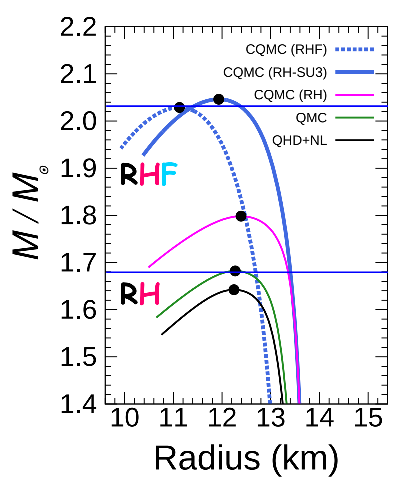

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Quark matter description

— EoS for quark matter —

- **MIT bag model** with the density-dependent bag constant
- **Nambu–Jona–Lasinio (NJL) model**: HK-type parameter set

$$\mathcal{L} = \bar{q}\left(i\gamma_\mu \partial^\mu - \hat{m}\right) q + \frac{1}{2} G_S \sum_{a=0}^{8} \left[(\bar{q}\lambda^a q)^2 + (\bar{q} i \gamma_5 \lambda^a q)^2 \right]$$

$$- G_D \left[\det{}_f \left(\bar{q}(1+\gamma_5)q\right) + \det{}_f \left(\bar{q}(1-\gamma_5)q\right) \right] - \frac{1}{2} g_V \left(\bar{q}\gamma^\mu q\right)^2,$$

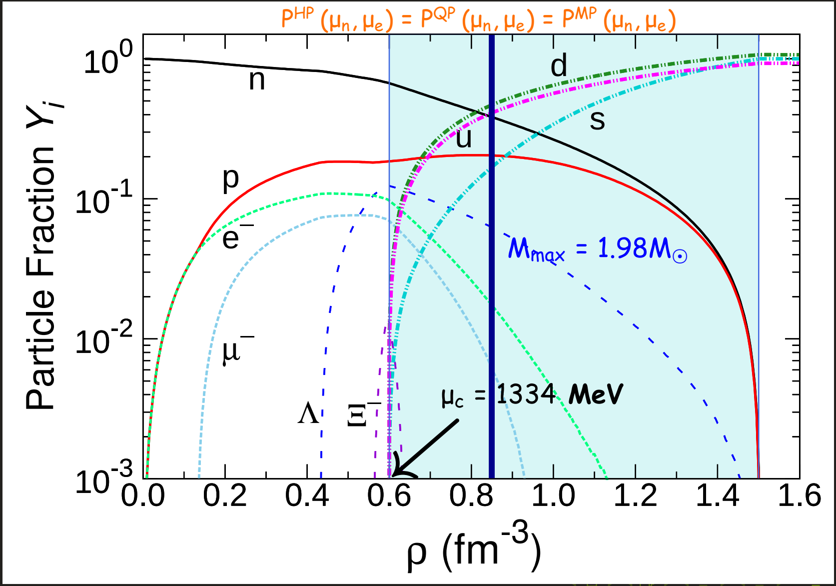
with a universal repulsion among different flavors, $0 \leq g_V \leq 1.5 G_S$.

K. Masuda, T. Hatsuda, and T. Takatsuka, PTEP **2013** (2013) no.7, 073D01.

— Hadron-quark phase transition —

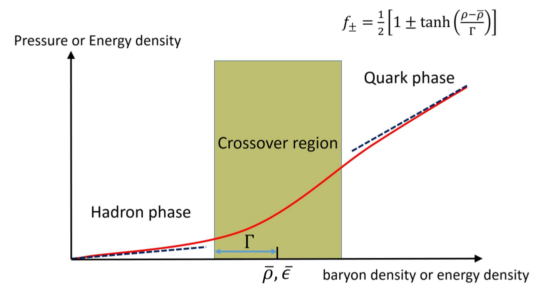
- **First-order phase transition** under Gibbs criterion
- **Hadron-quark crossover**

First-order phase transition (Gibbs)

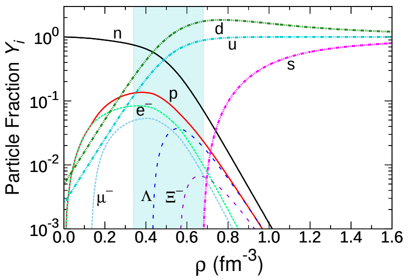


Hadron-quark crossover

- Energy density - baryon density interpolation
- Pressure - baryon density interpolation
- Pressure - energy density interpolation



P-ρ interpolation



e.g. $P(\epsilon) = P_{HP}(\epsilon)f_{-}(\epsilon) + P_{QP}(\epsilon)f_{+}(\epsilon),$

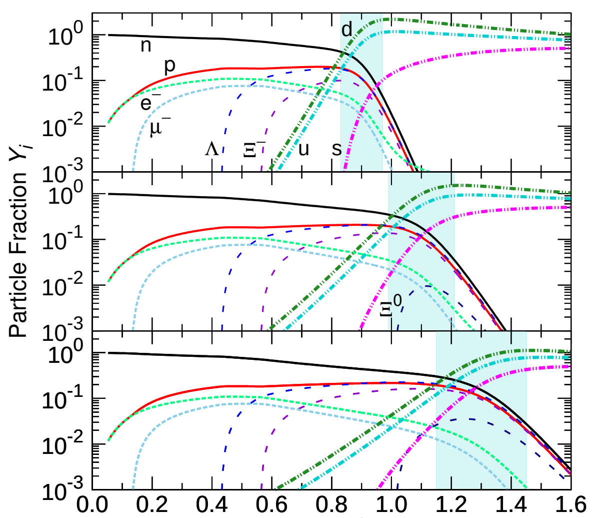
$$\frac{d\rho}{\rho} = \frac{d\epsilon}{P(\epsilon)+\epsilon}.$$

T. Hell and W. Weise, Phys. Rev. C **90** (2014) 045801.

— Nuclear physics —
Crossover region moves to higher densities.

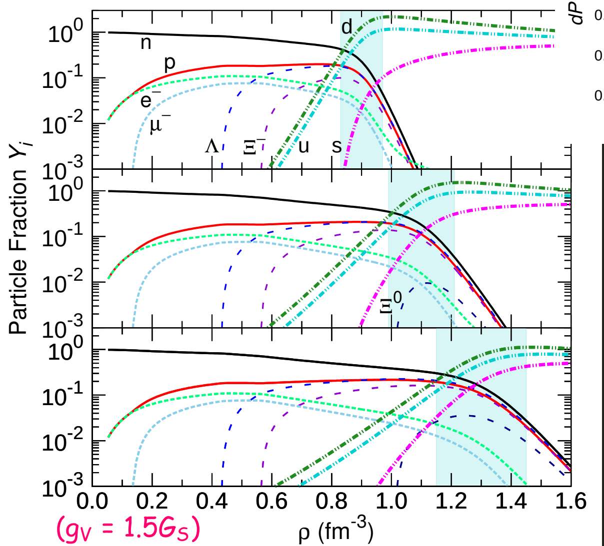
— Astrophysics —
The $2M_{\odot}$ constant

Pressure-energy density interpolation



$(g_V = 1.5G_S)$

Pressure-energy density i



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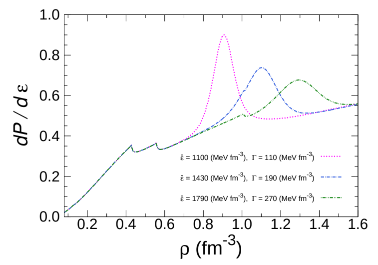

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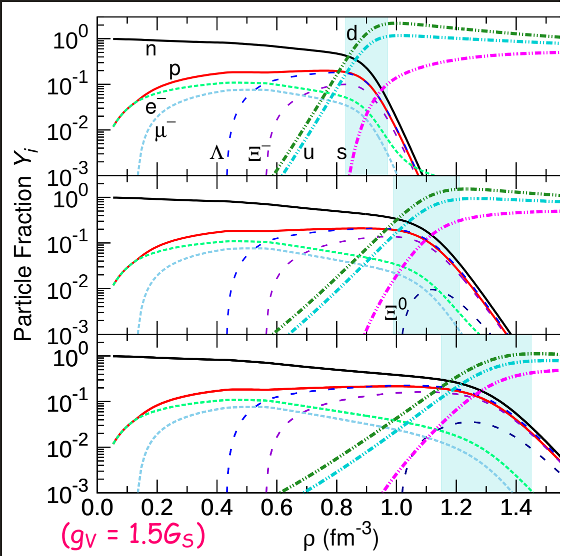

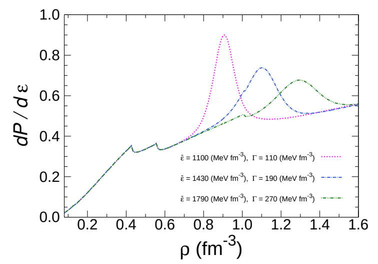

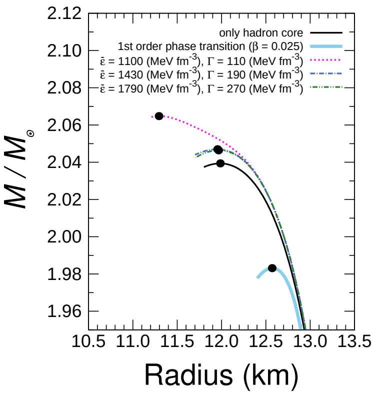

Summary

Hadronic EoS:

1. The variation in **internal (quark) structure of baryons** in matter using **the chiral quark-meson coupling (CQMC) model**
2. **Hidden strange (σ^* and φ) mesons** in SU(3) flavor symmetry
3. Relativistic **Hartree**-**Fock** approximation

$\Rightarrow$ The EoS with hyperons can support $2M_\odot$ neutron stars.

Hybrid stars:

- ✓ Hadron-quark phase transition: **first-order phase transition** under Gibbs criterion and **hadron-quark crossover**
- ✓ In order to suppress the amount of quarks at low densities, the center of crossover moves to higher densities.
- ✓ If the stiff Hadronic and quark EoSs are taken into account, the pressure-energy density interpolation can satisfy the constrains from nuclear physics and astrophysics.

Thank You for Your Attention.