Effective Theory for Nuclear Matter With Many-Body Forces

Modeling the EoS of Neutron Stars and Pulsars

César Zen Vasconcellos

Instituto de Física - Universidade Federal do Rio Grande do Sul

La Habana - May 2013

Relativistic Quantum EFT/QHD for Nuclear Matter

- Many excellent EFT descriptions → embody various properties of the nucleus, and nuclear matter at low, medium and high densities.
- QHD: efficient way to parameterize S matrix and other observable → consistent with analyticity, unitarity, causality, cluster decomposition, symmetries (Lorentz invariance, parity conservation, isospin, and spontaneously broken chiral symmetry).
- Renormalizable QHD → difficulties due to large effects from loop integrals (dynamics of the quantum vacuum).
- Modern approach to renormalization: cutoff theories with composite degrees of freedom, provides an alternative.

Relativistic Quantum EFT/QHD for Nuclear Matter

- QHD: Relevant phenomena are confined to a specific length scale:
  1. Not necessary to explicitly include dynamics at significantly shorter length scale.
  2. Integrate out heavier degrees of freedom corresponding to shorter length scales.
  3. Effects of heavier degrees of freedom implicitly contained in various coupling parameters.
  4. Non-renormalizable couplings incorporate the compositeness of low-energy degrees of freedom.

Relativistic Quantum EFT/QHD for Nuclear Matter

- EFT/QHD contains an infinite number of interaction terms, and thus one needs an organizing principle to make sensible calculations.
- Conventional way of classification/organization of interaction terms in EFT:
  1. expand the Lagrangian density in terms of characteristic scales of QCD;
  2. find a suitable expansion parameter (or parameters) that is (are) small in the region of interest;
  3. assumes naturalness, which means that all of the unknown couplings in the theory, when written in appropriate dimensionless form, are of order unity;
  4. estimate contributions from various terms by counting powers of the expansion parameter(s) and then truncate the Lagrangian at the desired level of accuracy.

Relativistic Quantum EFT/QHD for Nuclear Matter

- Take meson fields and nucleons (M) as effective degrees of freedom $\rightarrow$ pion decay constant: $f_\pi = 93 MeV$; chiral parameter: $\Lambda_\chi \sim 1 GeV$; $\Lambda_\chi \leq 4\pi f_\pi$ (low energy chiral parameters of QCD):
- QHD in the framework of the Naive Dimensional Analysis then gives:

$$\mathcal{L} = \left(\frac{\partial \; or \; m_\pi}{M}\right) \left(\frac{\bar{\psi}\Gamma\psi}{f_\pi^2 M}\right)^\ell \sum_{i,\kappa=0}^{\infty} \frac{c_{i,\kappa}}{i!\kappa!} \left(\frac{\sigma}{f_\pi}\right)^i \left(\frac{\omega}{f_\pi}\right)^\kappa f_\pi^2 \Lambda_\chi^2 \quad (1)$$

- Naturalness:

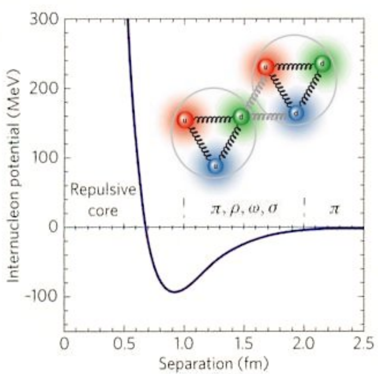
$$c_{i,\kappa} = 1 \rightarrow \mathcal{L} = \left(\frac{\partial \; or \; m_\pi}{M}\right) \left(\frac{\bar{\psi}\Gamma\psi}{f_\pi^2 M}\right)^\ell exp\left(\frac{\sigma}{f_\pi}\right) exp\left(\frac{\omega}{f_\pi}\right) f_\pi^2 \Lambda_\chi^2 \quad (2)$$

Relativistic Quantum EFT/QHD for Nuclear Matter

- Simplest QHD model (Walecka model) + Mean Field Theory (MFT) and meson and baryon effective degrees of freedom:
  - Classical σ and ω meson fields practically exhaust the overwhelming part of the effective *NN* interaction in nuclear medium at ordinary nuclear matter density ($\rho_0 \sim 0.15 fm^{-3}$).
  - At this density domain, hadrons are convenient and efficient degrees of freedom:
    1. Meson exchange models of *NN* interaction accurately describe low-energy properties of the two nucleon system.
    2. Relativistic mean-field theory based on QHD-I and QHD-II provides a realistic description of the bulk and single-particle properties of nuclei.

Relativistic Quantum EFT/QHD for Nuclear Matter

- However, at higher density than ordinary nuclear matter density ($\rho_0 \sim 0.15 fm^{-3}$) Walecka model has to be extended significantly $\rightarrow$ heavier degrees of freedom must be explicitly taken into account. $\rightarrow$ Nuclear repulsive components in the high density regime are predominant (hard core):



Relativistic Quantum EFT/QHD for Nuclear Matter

- Our aim: to develop an EFT/QHD for nuclear matter to shed some light on challenges and open questions facing the high density nuclear many-body problem.

Relativistic Quantum EFT/QHD for Nuclear Matter

- Back to (1):

$$\mathcal{L} = \left(\frac{\partial \text{ or } m_\pi}{M}\right)\left(\frac{\bar{\psi}\Gamma\psi}{f_\pi^2 M}\right)^\ell \sum_{i,\kappa=0}^{\infty} \frac{c_{i,\kappa}}{i!\kappa!}\left(\frac{\sigma}{f_\pi}\right)^i \left(\frac{\omega}{f_\pi}\right)^\kappa f_\pi^2 \Lambda_\chi^2$$

- At least two schemes allow a compact summation of the Lagrangian density (1):

$$c_{i,\kappa} = 1 \rightarrow \mathcal{L} = \left(\frac{\partial \text{ or } m_\pi}{M}\right)\left(\frac{\bar{\psi}\Gamma\psi}{f_\pi^2 M}\right)^\ell exp\left(\frac{\sigma}{f_\pi}\frac{\omega}{f_\pi}\right) f_\pi^2 \Lambda_\chi^2 \quad (3)$$

$$c_{i,\kappa} = i!\kappa! \rightarrow \mathcal{L} = \left(\frac{\partial \text{ or } m_\pi}{M}\right)\left(\frac{\bar{\psi}\Gamma\psi}{f_\pi^2 M}\right)^\ell \left(\frac{1}{1+\frac{\sigma}{f_\pi}}\right)\left(\frac{1}{1+\frac{\omega}{f_\pi}}\right) f_\pi^2 \Lambda_\chi^2 \quad (4)$$

Interaction Lagrangian Density

Our strategy:

1. a phenomenological and more flexible parametrization which combines the two previous limits;
2. an extension of the phase space of baryon and meson fields $\rightarrow$ our QHD interaction Lagrangian includes:
   - the whole fundamental baryon octet (n, p, Σ^-, Σ^0, Σ^+, Λ, Ξ^-, Ξ^0)
   - many-body forces simulated by nonlinear self-couplings and meson-meson interaction terms involving scalar-isoscalar (σ, σ^*), vector-isoscalar (ω, ϕ), vector-isovector (ϱ) and scalar-isovector (δ).

Interaction Lagrangian Density

$$\mathcal{L}_{int} = \prod_{\lambda=\xi,\kappa,\eta} \left(1 + \frac{g_{\sigma B}\sigma + g_{\sigma^* B}\sigma^* + \frac{1}{2} g_{\delta B} \boldsymbol{\tau} \cdot \boldsymbol{\delta}}{\lambda M_B}\right)^{\lambda} \bar{\psi}_B i\gamma_\mu \partial^\mu \psi_B - \bar{\psi}_B \Gamma_{\kappa\eta\xi\varsigma B} \psi_B \quad (5)$$

where the operators $\boldsymbol{\tau} = (\tau_1, \tau_2, \tau_3)$ represent the Pauli isospin matrices.

Interaction Lagrangian Density

In this expression, the Lorentz scalar Γ is defined as

$$\begin{aligned}
\Gamma_{\kappa\eta\xi\varsigma B} &= g_{\omega_B} \prod_{\lambda=\kappa,\eta} \left(1 + \frac{g_{\sigma B}\sigma + g_{\sigma^* B}\sigma^* + \frac{1}{2} g_{\delta B} \boldsymbol{\tau}\cdot\boldsymbol{\delta}}{\lambda M_B}\right)^{\lambda} \gamma_\mu \omega^\mu \\
&+ \frac{1}{2} g_{\varrho B} \prod_{\lambda=\xi,\eta} \left(1 + \frac{g_{\sigma B}\sigma + g_{\sigma^* B}\sigma^* + \frac{1}{2} g_{\delta B} \boldsymbol{\tau}\cdot\boldsymbol{\delta}}{\lambda M_B}\right)^{\lambda} \gamma_\mu \boldsymbol{\tau}\cdot\boldsymbol{\varrho}^\mu \\
&+ g_{\phi_B} \prod_{\lambda=\kappa,\xi} \left(1 + \frac{g_{\sigma B}\sigma + g_{\sigma^* B}\sigma^* + \frac{1}{2} g_{\delta B} \boldsymbol{\tau}\cdot\boldsymbol{\delta}}{\lambda M_B}\right)^{\lambda} \gamma_\mu \phi^\mu \\
&+ M_B \prod_{\lambda=\kappa,\eta,\xi,-\varsigma} \left(1 + \frac{g_{\sigma B}\sigma + g_{\sigma^* B}\sigma^* + \frac{1}{2} g_{\delta_B} \boldsymbol{\tau}\cdot\boldsymbol{\delta}}{\lambda M_B}\right)^{\lambda} . \qquad (6)
\end{aligned}$$

Lagrangian Density

Complete expression of Lagrangian density:

$$\begin{aligned}\mathcal{L} = & \sum_B \bar{\psi}_B \left[\prod_{\lambda=\xi,\kappa,\eta} \left(1 + \frac{g_{\sigma B}\sigma + g_{\sigma^* B}\sigma^* + \frac{1}{2} g_{\delta B} \boldsymbol{\tau} \cdot \boldsymbol{\delta}}{\lambda M_B}\right)^{\lambda} i\gamma_\mu \partial^\mu - \Gamma_{\kappa\eta\xi\varsigma B} \right] \psi_B \\ & + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - {m_\sigma}^2 \sigma^2) + \frac{1}{2}(\partial_\mu \sigma^* \partial^\mu \sigma^* - {m_{\sigma^*}}^2 {\sigma^*}^2) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} \\ & + \frac{1}{2}{m_\omega}^2 \omega_\mu \omega^\mu - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}{m_\phi}^2 \phi_\mu \phi^\mu - \frac{1}{4}\boldsymbol{\varrho}_{\mu\nu} \cdot \boldsymbol{\varrho}^{\mu\nu} + \frac{1}{2} m_\varrho^2 \boldsymbol{\varrho}_\mu \cdot \boldsymbol{\varrho}^\mu \\ & + \frac{1}{2}(\partial_\mu \boldsymbol{\delta} \cdot \partial^\mu \boldsymbol{\delta} - {m_\delta}^2 \boldsymbol{\delta}^2) + \sum_l \bar{\psi}_l \left(i\gamma_\mu \partial^\mu - m_l\right) \psi_l \, , \end{aligned} \quad (7)$$

B and l label respectively the different baryon and lepton (electrons and free muons) species.

Scaling of baryon fields

Change of scale of the baryon fields:

$$\psi_B \to \left(\prod_{\lambda=\xi,\kappa,\eta} \left(1 + \frac{g_{\sigma B}\sigma + g_{\sigma^* B}\sigma^* + \frac{1}{2} g_{\delta B} \boldsymbol{\tau} \cdot \boldsymbol{\delta}}{\lambda M_B} \right)^{-\lambda} \right)^{1/2} \psi_B \,. \tag{8}$$

Lagrangian Density

Complete expression for the Lagrangian density:

$$\mathcal{L}=\sum_B \bar{\psi}_B \left[i\gamma_\mu\partial^\mu - g^*_{\omega B\xi}\gamma_\mu\omega^\mu - \frac{1}{2}g^*_{\varrho B\kappa}\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\varrho}^\mu - g^*_{\phi B\eta}\gamma_\mu\phi^\mu - M^*_{B\varsigma}\right]\psi_B$$
$$+\frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - {m_\sigma}^2\sigma^2) + \frac{1}{2}(\partial_\mu\sigma^*\partial^\mu\sigma^* - {m_{\sigma^*}}^2{\sigma^*}^2) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu}$$
$$-\frac{1}{2}{m_\omega}^2\omega_\mu\omega^\mu + \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}{m_\phi}^2\phi_\mu\phi^\mu - \frac{1}{4}\boldsymbol{\varrho}_{\mu\nu}\cdot\boldsymbol{\varrho}^{\mu\nu} + \frac{1}{2}m^2_\varrho\boldsymbol{\varrho}_\mu\cdot\boldsymbol{\varrho}^\mu$$
$$+\frac{1}{2}(\partial_\mu\boldsymbol{\varrho}\cdot\partial^\mu\boldsymbol{\varrho} - {m_\varrho}^2\boldsymbol{\varrho}^2) + \sum_l \bar{\psi}_l\left(i\gamma_\mu\partial^\mu - m_l\right)\psi_l\,; \tag{9}$$

Parametric couplings: $g^*_{\omega B\xi} \equiv m^*_{B\xi}g_{\omega B}$; $g^*_{\varrho B\kappa} \equiv m^*_{B\kappa}g_{\varrho B}$; $g^*_{\phi B\eta} \equiv m^*_{B\eta}g_{\phi B}$; $i = \xi, \kappa, \eta$;

$$m^*_{Bi} \equiv \left(1 + \frac{g_{\sigma_B}\sigma + g_{\sigma^*_B}\sigma^* + \frac{1}{2}\,g_{\delta_B}\boldsymbol{\tau}\cdot\boldsymbol{\delta}}{iM_B}\right)^{-i}. \tag{10}$$

Extended EFT with Parametric Couplings

The mass term of expression (9) gives rise to the effective baryon masses

$$M^*_{B\varsigma} = \left(1 + \frac{g_{\sigma B}\sigma + g_{\sigma^* B}\sigma^* + \frac{1}{2}g_{\delta B}\boldsymbol{\tau}\cdot\boldsymbol{\delta}}{\varsigma M_B}\right)^{-\varsigma} M_B \equiv m^*_{B\varsigma} M_B\,, \qquad (11)$$

with

$$m^*_{B\varsigma} \equiv \left(1 + \frac{g_{\sigma B}\sigma + g_{\sigma^* B}\sigma^* + \frac{1}{2}g_{\delta B}\boldsymbol{\tau}\cdot\boldsymbol{\delta}}{\varsigma M_B}\right)^{-\varsigma} . \qquad (12)$$

1. The resulting Lagrangian density is physically equivalent to the original formulation.
2. It involves a reorganization of the original interaction Lagrangian density.
3. It allows a more direct comparison with well known QHD models and the use of conventional methods and techniques of field theory.
4. Many-body self-couplings and meson-meson interaction terms $\rightarrow$ parameterized couplings.

Extended EFT with Parametric Couplings

Complete expression for the Lagrangian density in the mean field approximation :

$$\mathcal{L}_{\xi\eta\kappa\varsigma} = \frac{1}{2}m_\sigma^2\sigma_0^2 + \frac{1}{2}m_{\sigma*}^2\sigma_0^{*2} + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\phi^2\phi_0^2 + \frac{1}{2}m_\rho^2\varrho_{03}^2 + \frac{1}{2}m_\delta^2\delta_3^2$$
$$+ \sum_B \bar{\psi}_B \left(i\gamma_\mu\partial^\mu - g_{\omega B} m_{B\xi}^* \gamma^0\omega_0 - \frac{1}{2} g_{\varrho B} m_{B\kappa}^* \gamma^0 \tau^{(3)} \varrho_{03} - g_{\phi B} m_{B\eta}^* \gamma^0 \phi_0 - M_{B\varsigma}^* \right) \psi_B$$
$$+ \sum_l \bar{\psi}_l \left(i\gamma_\mu\partial^\mu - m_l \right) \psi_l. \tag{13}$$

Extended EFT with Parametric Couplings

Model	ς	ξ	κ	η
S-model	$\neq 0$	0	0	0
SV model	$= \xi \neq 0$	$= \varsigma \neq 0$	0	0
SVI model	$= \xi = \kappa \neq 0$	$= \varsigma = \kappa \neq 0$	$= \varsigma = \xi \neq 0$	0
SVIV model	$= \xi = \kappa$ $= \eta \neq 0$	$= \eta = \kappa$ $= \varsigma \neq 0$	$= \xi = \eta$ $= \varsigma \neq 0$	$= \xi = \kappa$ $= \varsigma \neq 0$

Table: Examples of parameterizations of our model: systematic variations of varsigma, xi, kappa and eta.

- S-model: scalar model;
- SV model: scalar-vector model;
- SVI model: scalar-vector-iso-scalar model;
- SVIV model: scalar-vector-iso-vector model

Extended EFT with Parametric Couplings

Explore new model possibilities:

- S-model: scalar model $\rightarrow$ in the scalar-isoscalar and scalar-isovector meson sectors;
- SV model: scalar-vector model $\rightarrow$ in the scalar-isoscalar, scalar-isovector and the vector-isoscalar meson sectors;
- SVI model: scalar-vector-iso-scalar model $\rightarrow$ scalar-isoscalar, scalar-isovector, the vector-isoscalar and the heavy vector-isoscalar meson sectors;
- SVIV model: scalar-vector-iso-vector model $\rightarrow$ all meson sectors.

Extended EFT with Parametric Couplings

As an example, take $\xi = 1 \rightarrow m^*_{B\xi}$ reduces to

$$m^*_{B1} = \left(1 + \frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2} g_{\delta B}\tau_3\delta_{30}}{M_B}\right)^{-1}$$

$$\sim 1 - \left(\frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2} g_{\delta B}\tau_3\delta_{30}}{M_B}\right) + \frac{1}{2}\left(\frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2} g_{\delta B}\tau_3\delta_{30}}{M_B}\right)^2$$

$$-\frac{1}{3!}\left(\frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2} g_{\delta B}\tau_3\delta_{30}}{M_B}\right)^3 + \frac{1}{4!}\left(\frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2} g_{\delta B}\tau_3\delta_{30}}{M_B}\right)^4 - \ldots \quad (14)$$

Extended EFT with Parametric Couplings

For $-g_{\omega B} m^*_{B\xi}\gamma^0\omega_0$ for $\xi = 1$, we get:

$$-g_{\omega B} m^*_{B1}\gamma^0\omega_0 = -g_{\omega B}\left(1 + \frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2}g_{\delta B}\tau_3\delta_{30}}{M_B}\right)^{-1}\gamma^0\omega_0$$
$$\sim -\left[g_{\omega B} - g_{\omega B}\left(\frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2}g_{\delta B}\tau_3\delta_{30}}{M_B}\right)\right]\gamma^0\omega_0$$
$$-\left[\frac{1}{2}g_{\omega B}\left(\frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2}g_{\delta B}\tau_3\delta_{30}}{M_B}\right)^2 - \frac{1}{3!}g_{\omega B}\left(\frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2}g_{\delta B}\tau_3\delta_{30}}{M_B}\right)^3\right]\gamma^0\omega_0$$
$$-\frac{1}{4!}g_{\omega B}\left(\frac{g_{\sigma B}\sigma_0 + g_{\sigma^* B}\sigma^*_0 + \frac{1}{2}g_{\delta B}\tau_3\delta_{30}}{M_B}\right)^4\gamma^0\omega_0 \ldots \qquad (15)$$

→ additional repulsive and attractive contributions to the Lagrangian density due to many body self-couplings and meson-meson interaction terms (many-body forces).

Conclusion

1. From this expression we can identify repulsive and attractive many-body couplings involving products of "classical number" $\sigma_0\omega_0$, $\sigma_0^2\omega_0$, $\sigma_0^{*2}\omega_0$, $\delta_{30}\omega_0$, $\delta_{30}^2\omega_0$, $\sigma_0\sigma_0^*$, $\delta_{30}\omega_0$ and many others.
2. Remaining interaction terms of $\mathcal{L}$ will also exhibit additional many-body attractive and/or repulsive terms $\rightarrow$ which decrease (the first) or increase (the latter) the internal pressure.
3. An EoS is more rigid than another if the internal pressure associated with the first, at any density, is higher than the internal pressure of the latter. Endowed with a higher internal pressure, the first (more rigid) can withstand greater compression and shall have a gravitational mass higher than the second one (softer) $\rightarrow$ for a stiffer EoS, the role of repulsive contributions to the nuclear force are crucial!

Conclusion

- Nuclear repulsive components in the high density regime are predominant (hard core). Role of many-body forces? Key: binomial theorem
  $(a+b)^{-\lambda} \sim a^{-\lambda} - \lambda a^{-\lambda-1} b/\lambda + \frac{\lambda(\lambda+1)}{2} a^{-\lambda-2}(b/\lambda)^2 + \ldots + (b/\lambda)^{-\lambda}$
  - first and dominant corrections have different/equal signals of the original terms (as for instance in Walecka model) $\rightarrow$ it decrease/increase the intensity of the attractive or repulsive original contributions;
  - in particular, the original Walecka's attractive/repulsive contributions becomes less/more intense for lower/larger values of λ (attraction and repulsion can be shielded by many-body forces) at very high densities.
- For $c_{i,j,k,l,m,n} \rightarrow 1$ the interaction terms of our EFT reduces to an exponential form

$$L_{eff} = \sum_B \left(\frac{\partial \text{ or } m_\pi}{M_B}\right)\left(\frac{\bar{\psi}_B \Gamma \psi_B}{f_\pi^2 M_B}\right) f_\pi^2 \Lambda^2 \, e^{\left(\frac{g_\sigma \sigma}{f_\pi} + \frac{g_{\sigma^*} \sigma^*}{f_\pi} + \frac{g_\omega \omega}{f_\pi} + \frac{g_\phi \phi}{f_\pi} + \frac{g_\varrho \varrho}{f_\pi} + \frac{g_\delta \delta}{f_\pi}\right)}$$

Example: Scalar Version of the Model

- Lagrangian density (hyperon couplings: based on experimental analysis of hyper-nucleus data.):

$$\mathcal{L} = \sum_B \bar{\psi}_B(i\gamma_\mu\partial^\mu - m_b)\psi_b + \sum_l \bar{\psi}_l(i\gamma_\mu\partial^\mu - m_l)\psi_l$$
$$+ \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) + \Big(-\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu\Big)$$
$$+ \Big(-\frac{1}{4}\boldsymbol{\varrho}_{\mu\nu}\cdot\boldsymbol{\varrho}^{\mu\nu} + \frac{1}{2}m_\varrho^2\boldsymbol{\varrho}_\mu\cdot\boldsymbol{\varrho}^\mu\Big)$$
$$+ \big(g^*_{\sigma B}\bar{\psi}_B\psi_B\sigma - g_{\omega B}\bar{\psi}_B\gamma_\mu\psi_B\omega^\mu - \frac{1}{2}g_{\varrho B}\bar{\psi}_B\gamma_\mu\psi_B\boldsymbol{\tau}\cdot\boldsymbol{\varrho}^\mu\big)$$

- Parametric coefficient $g^*_{\sigma B} = g_{\sigma B} m^*_{\lambda B}$; $m^*_{\lambda B} \equiv \left(1 + \frac{g_\sigma \sigma}{\lambda M_B}\right)^{-\lambda}$.
- Scalar-meson coupling generates the baryon effective mass:

$$M_B^* = M_B - \frac{g_{\sigma B}\sigma_0}{\left(1 + \frac{g_\sigma\sigma_0}{\lambda M_B}\right)^\lambda}.$$

Example: Scalar Version of the Model

TOV Equations for Hydrostatic Equilibrium:

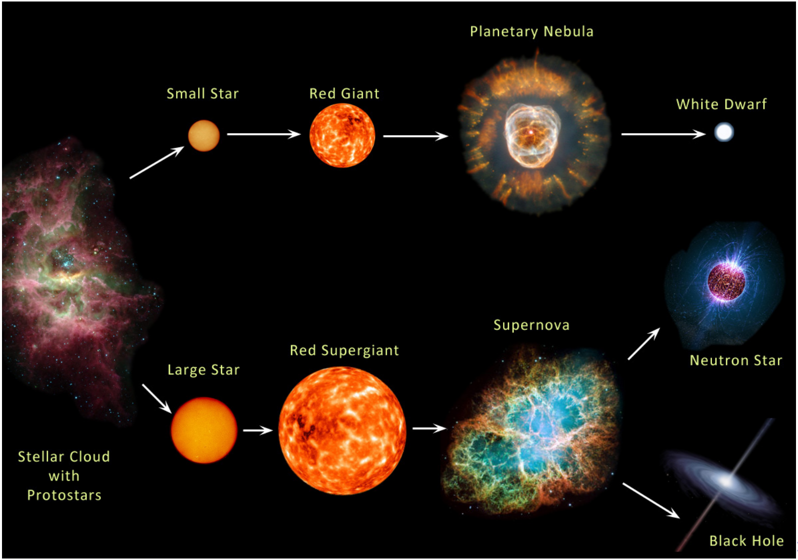
$$\frac{dp(r)}{dr} = -\frac{\varepsilon(r)M(r)}{r^2}\left[1+\frac{p(r)}{\varepsilon(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{M(r)}\right]\left[1-\frac{2M(r)}{r}\right]^{-1}$$

$$M(r) = \int_0^r 4\pi \left(r'\right)^2 \varepsilon(r')dr'$$

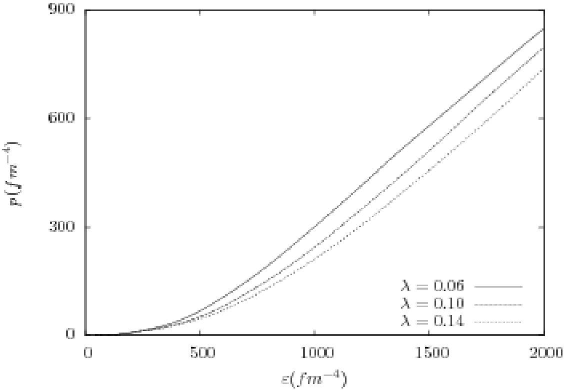
1. Ideal fluid: spherically symmetric, homogeneous, isotropic, static and relativistic;
2. M : gravitational mass;
3. Pressure: source of gravity;

Moreover: Charge neutrality and beta equilibrium.

Example: Scalar Version of the Model

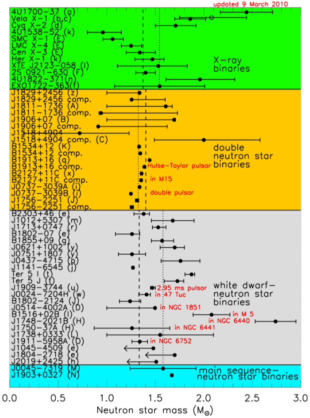


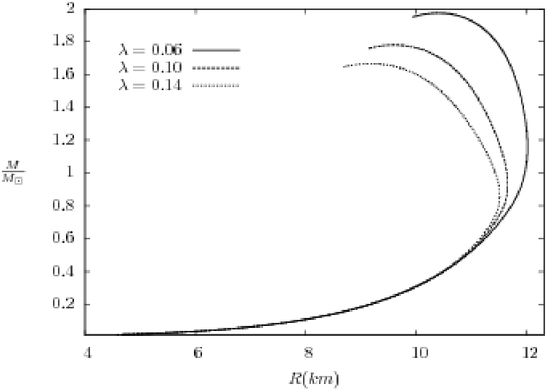
Example: Scalar Version of the Model



Equation of State - Stiffer EOS (more rigid) → higher values of internal pressure → more intense contributions from repulsive components of nuclear force → Many body forces: lower values of λ → lower intensity of attractive interaction (relative increase of repulsion due to higher shielding effect of attractive interaction) → higher values of the compressibility modulus of nuclear matter. (Rosana Gomes and Rodrigo Negreiros)

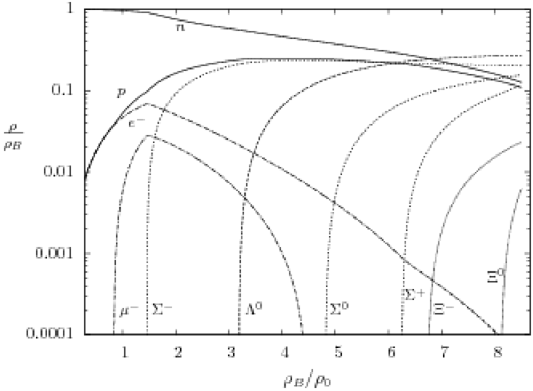
Example: Scalar Version of the Model





Neutron star mass-radius relationship. Many-body hyperon-meson interaction model with parametric couplings → neutron star masses in agreement with the observed mass of J1614-2230 (Demorest 2011). (Rosana Gomes and Rodrigo Negreiros)

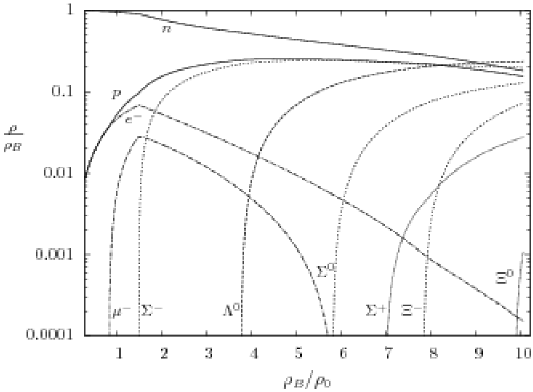
Example: Scalar Version of the Model



Particle population for $\lambda = 0.06$ - each value of λ generates a sequence of stars, where each star will have a different particle population and a different central density.

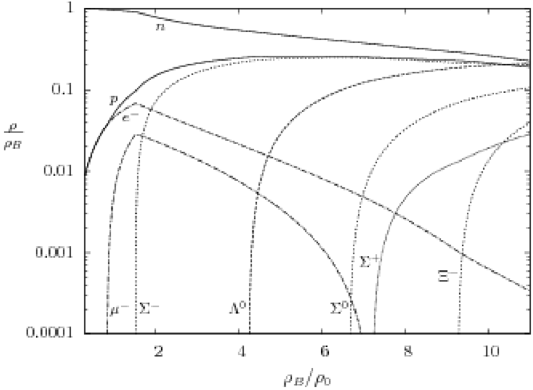
(Rosana Gomes and Rodrigo Negreiros)

Example: Scalar Version of the Model



Particle population for $\lambda = 0.10$. (Rosana Gomes and Rodrigo Negreiros)

Example: Scalar Version of the Model



Particle population for $\lambda = 0.14$. (Rosana Gomes and Rodrigo Negreiros)

...Ésta, oh misterio que de mí naciste

Cual la cumbre nació de la montaña

Ésta, que alumbra y mata, es una estrella:

Como que riega luz, los pecadores

Huyen de quien la lleva, y en la vida,

Cual un monstruo de crímenes cargado,

Todo el que lleva luz se queda solo.

Pero el hombre que al buey sin pena imita,

Buey vuelve a ser, y en apagado bruto,

La escala universal de nuevo empieza.

El que la estrella sin temor se ciñe,

Como que crea, crece...

José Martí (Yugo y Estrella)