Δ resonances and charged ρ-meson condensation in RMF models with scaled hadron masses and couplings

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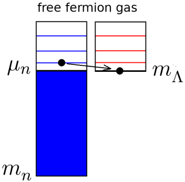
Introduction

- Description of the neutron star (NS) structure requires an equation of state (EoS) of cold ($T = 0$) dense ($n = 1$–$10\, n_0$, where n_0–nuclear saturation density) strongly interacting baryonic matter
- Constraints from the NS observations can be used to select a model parametrization to be used for HIC simulations
  This requires a unified hadronic EoS with strangeness included
- Any EoS is characterized by a maximum mass of a stable NS
  A viable EoS should pass the observed maximum NS mass constraint $M > 2.01 \pm 0.04\, M_\odot$ and many others

Hyperon/Δ puzzle



For realistic hyperon interaction with an increase of the density already at $n \gtrsim 2 \div 3\, n_0$ the conversion $n \to B + Q_B e^-$ becomes energetically favorable. Chemical equilibrium condition:

$$\mu_B = \mu_N - Q_B \mu_e$$

In standard realistic models the maximum NS mass decreases below the observed values.

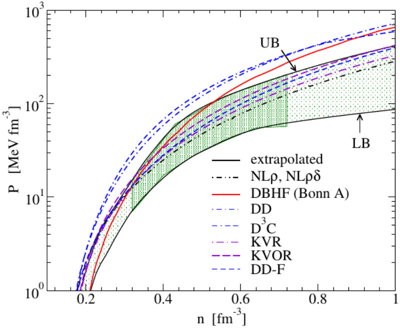
Problem can be resolved in relativistic mean-field (RMF) models by taking into account a hadron mass and couplings in-medium modifications [K. A. Maslov, E. E. Kolomeitsev and D. N. Voskresensky, Phys. Lett. B **748**, 369 (2015)]

Any new degree of freedom softens the EoS and lowers the maximum NS mass

Contradicting constraints

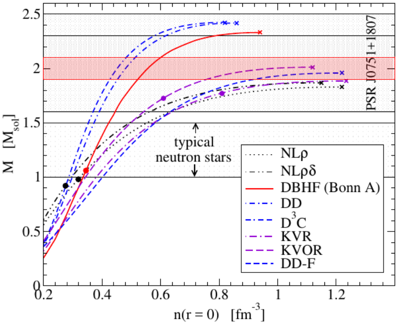
Constraint for the pressure, obtained from analyses of transverse and elliptic flows in heavy-ion collisions
Passed by rather soft EoSs

[P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002)]



The maximum NS mass constraint favors stiff EoS

NS cooling data ⇒ direct URCA (DU) is not operative for most stars ⇒ constraint for the proton fraction



figures from [T. Klahn et al. PRC74 (2006)]

Outline

1. A method of making a EoS stiffer at high densities without altering it at lower densities in RMF models
2. RMF model with scaled masses and couplings
3. Δ-resonances in iso-symmetrical matter (ISM) and beta-equilibrium matter (BEM) of NSs
4. Possibility of charged ρ-meson condensation.

Traditional RMF models

H.-P. Dürr PR103 1956, J. D. Walecka 1974, J. Boguta & A. R. Bodmer 1977
Nonlinear Walecka (NLW) model

$$
\begin{aligned}
\mathcal{L} &= \bar{\Psi}_N\Big[(i\partial_\mu - g_\omega\omega_\mu - g_\rho\vec{t}\vec{\rho}_\mu)\gamma^\mu - m_N + g_\sigma\sigma\Big]\Psi_N \quad \text{nucleons} \\
&+ \frac{1}{2}\Big[(\partial_\mu\sigma)^2 - m_\sigma^2\sigma^2\Big] - \Big(\frac{b}{3}m_N(g_\sigma\sigma)^3 + \frac{c}{4}(g_\sigma\sigma)^4\Big) \quad \text{scalar field} \\
&- \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu^2 - \frac{1}{4}\vec{\rho}_{\mu\nu}\vec{\rho}^{\mu\nu} + \frac{1}{2}m_\rho^2(\vec{\rho}_\mu)^2 \quad \text{vector fields} \\
&+ \sum_{l=e,\mu}\bar{\psi}_l(i\partial_\mu - m_l)\psi_l \quad \text{leptons}
\end{aligned}
$$

Mean-field approximation

Static homogeneous meson fields:

$$\sigma \to \langle\sigma\rangle, \quad \omega^\mu \to \langle\omega^\mu\rangle \equiv (\omega_0, \vec{0}), \quad \rho_i^\mu \to \langle\rho_i^\mu\rangle \equiv \delta_{i3}(\rho_0, \vec{0}).$$

Eqs. of motion for vector fields:

$$
\begin{aligned}
\Big\langle\frac{\partial\mathcal{L}}{\partial\omega^0}\Big\rangle = 0 &\Rightarrow \omega_0 = \frac{g_\omega(n_n + n_p)}{m_\omega^2} \\
\Big\langle\frac{\partial\mathcal{L}}{\partial\rho_3^0}\Big\rangle = 0 &\Rightarrow \rho_0 = \frac{g_\rho(n_n - n_p)}{2m_\rho^2}
\end{aligned}
$$

Energy density

Nucleon effective mass $m_N^* = m_N - g_\sigma \sigma$. In terms of $f \equiv \frac{g_\sigma \sigma}{m_N}$:

$$E = \frac{m_\sigma^4 f^2}{2C_\sigma^2} + U(f) + \frac{C_\omega^2 (n_n + n_p)^2}{2m_N^2} + \frac{C_\rho^2 (n_n - n_p)^2}{8m_N^2}$$
$$+ \sum_{i=n,p} \int_0^{p_{\mathrm{F},i}} \frac{p^2\, dp}{\pi^2} \sqrt{p^2 + m_N^{*2}} + \sum_{l=e,\mu} \int_0^{p_{\mathrm{F},l}} \frac{p^2 dp}{\pi^2} \sqrt{p^2 + m_l^2},$$

Free parameters: $C_i = \frac{g_{iN} m_N}{m_i}, \quad i = \sigma, \omega, \rho +$ parameters of $U(\sigma)$:

$U(f) \equiv m_N^4 (\frac{b}{3} f^3 + \frac{c}{4} f^4)$

- Equation of motion for the scalar field:

$$\frac{\partial E}{\partial f} = 0 \Rightarrow \frac{m_N^4 f}{C_\sigma^2} + U'(f) = g_\sigma (n_{S,n} + n_{S,p}),$$

$$n_{S,i} = \int_0^{p_{\mathrm{F,i}}} \frac{p^2 dp}{\pi^2} \frac{m_N^*}{2\sqrt{p^2 + m_N^{*2}}}$$

- Electrical neutrality condition: $n_p = n_e + n_\mu$
- Beta-equilibrium conditions: $\mu_e = \mu_n - \mu_p, \quad \mu_i = \frac{\partial E}{\partial n_i}$

Input parameters

Energy per particle expansion:

$$\mathcal{E} = \mathcal{E}_0 + \frac{K}{18}\epsilon^2 - \frac{K^{'}}{162}\epsilon^3 + ... + \beta^2 \left(\mathcal{E}_{\rm sym} + \frac{L}{3}\epsilon + \frac{K_{\rm sym}}{18}\epsilon^2 ... \right),$$

$$\epsilon = (n - n_0)/n_0, \quad \beta = [(n_n - n_p)/n_0]_{n_0}$$

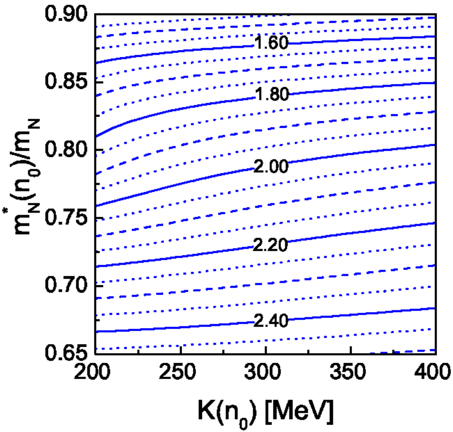
$$n_0 = 0.16 \text{ fm}^{-3}, \quad \mathcal{E}_0 = -16 \text{ MeV}, \quad K = 250 \text{ MeV},$$

$$\mathcal{E}_{\rm sym} = 30 \text{ MeV}, \quad m_N^*(n_0)/m_N = 0.8$$

NLW model with these parameters gives $M_{\rm max} = 1.92\ M_\odot$

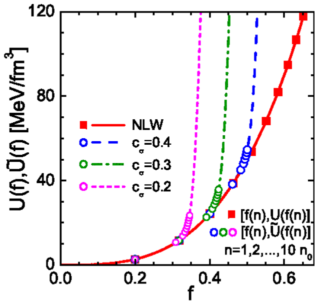
Maximum mass for NLW model

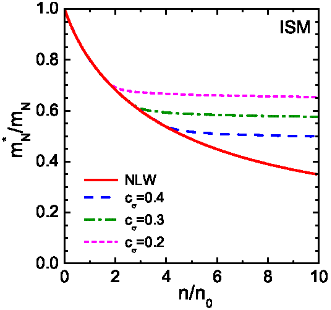
$M_{\max}$ contours for NLW model:



Can we stiffen the EoS by playing with the scalar field potential?

Scalar potential modification





$$\frac{df}{dn} = \frac{2(\partial n_S/\partial n)}{m_N^3 C_\sigma^{-2} + \widetilde{U}''(f)/m_N - 2(\partial n_S/\partial f)}$$

$$\frac{\partial n_S}{\partial n} = \frac{m_N^*}{2\sqrt{p_{\rm F}^2 + m_N^{*2}}}, \quad -\frac{\partial n_S}{\partial f} = \int_0^{p_{\rm F}} \frac{m_N p^4 dp/\pi^2}{(p^2 + m_N^{*2})^{3/2}}$$

Rapid growth
of the potential results in saturation of $f(n)$

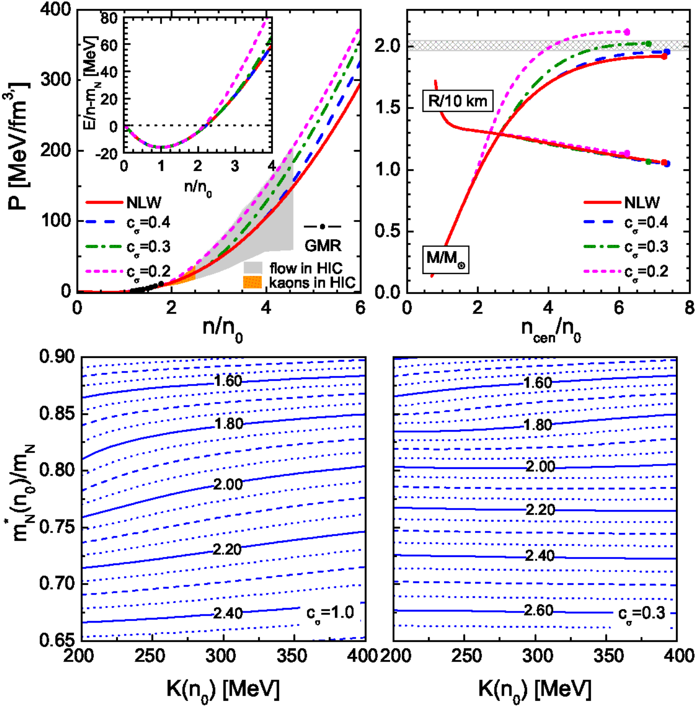
NLWcut models
[K.A.M., E.E.K. & D.N.V. PRD92 (2015)]

$$U(f) \to \widetilde{U}(f) = U(f) + \Delta U(f)$$

soft core: $\Delta U(f) = \alpha \ln[1 + \exp(\beta(f - f_{\rm s.core}))]$,

hard core: $\Delta U(f) = \alpha[\delta f/(f_{h.core} - f)]^{2\beta}$

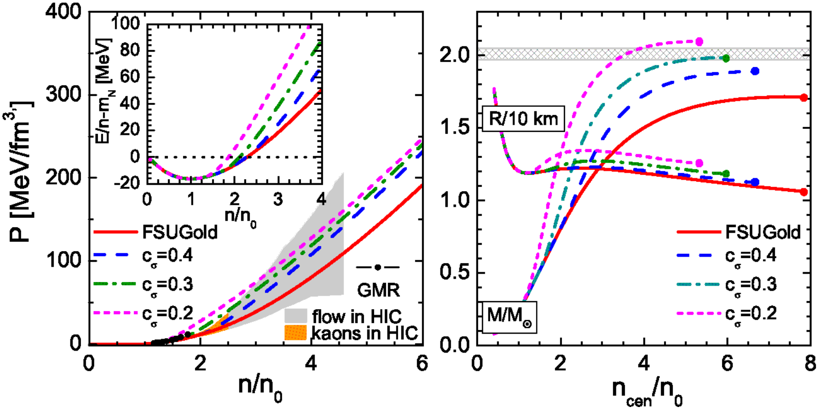
$f_{\rm s.core} = f_0 + c_\sigma(1 - f_0)$
$m_N^*(f) = m_N(1 - f)$



P [MeV/fm^3]
n/n_0
E/n-m_N [MeV]
NLW
c_σ=0.4
c_σ=0.3
c_σ=0.2
GMR
flow in HIC
kaons in HIC
R/10 km
M/M_⊙
n_cen/n_0
m*_N(n_0)/m_N
K(n_0) [MeV]
1.60
1.80
2.00
2.20
2.40
2.60
c_σ=1.0
c_σ=0.3

Application to the FSUgold model

There exist realistic phenomenological EoSs well tuned to describe finite nuclei and low-density nuclear matter properties, but yielding a low maximum NS mass [FSUgold Todd-Rutel, Piekariewicz 2005]



This simple method:

- Can make the EoS stiffer at high density leaving it unchanged at lower densities
- Can be applied to all RMF models

Generalized RMF model

E. E. Kolomeitsev and D. N. Voskresensky NPA 759 (2005) 373

- Model with the in-medium change of masses and coupling constants of all hadrons.
- Common decrease of hadron masses [Brown, Rho Phys. Rev. Lett. 66 (1991) 2720; Phys. Rept. 363 (2002) 85]:

$$\frac{m_N^*}{m_N} \simeq \frac{m_\sigma^*}{m_\sigma} \simeq \frac{m_\omega^*}{m_\omega} \simeq \frac{m_\rho^*}{m_\rho}$$

- Hadron masses and coupling constants depend on the scalar field σ

Model labelled KVOR was succesfully tested in Klaehn at al., PRC74 (2006) 035802.
We constructed a better parametrization (MKVOR) which satisfies new constraints on the nuclear EoS and incorporate more baryon species

Generalized relativistic mean-field model

E. E. Kolomeitsev, D.N. Voskresensky, NPA 759 (2005)
K. A. M, E. E. K. and D. N. V., Phys. Lett. B 748 (2015),
E. E. K., K. A. M. and D. N. V., NPA 961 (2017)

$$\mathcal{L} = \mathcal{L}_{\rm bar} + \mathcal{L}_{\rm mes} + \mathcal{L}_l,$$

$$\mathcal{L}_{\rm bar} = \sum_{i=b\cup r} (\bar{\Psi}_i \left(iD_\mu^{(i)}\gamma^\mu - m_i \Phi_i(\sigma)\right) \Psi_i,$$

$$D_\mu^{(i)} = \partial_\mu + ig_{\omega i}\chi_{\omega i}(\sigma)\omega_\mu + ig_{\rho i}\chi_{\rho i}(\sigma)\vec{t}\vec{\rho}_\mu + ig_{\phi i}\chi_{\phi i}(\sigma)\phi_\mu,$$

$$\{b\} = (N, \Lambda, \Sigma^{\pm,0}, \Xi^{-,0}, \Delta^-, \Delta^0, \Delta^+, \Delta^{++})$$

$$\mathcal{L}_{\rm mes} = \frac{\partial_\mu\sigma\partial^\mu\sigma}{2} - \frac{m_\sigma^2\Phi_\sigma^2(\sigma)\sigma^2}{2} - U(\sigma) +$$

$$+\frac{m_\omega^2\Phi_\omega^2(\sigma)\omega_\mu\omega^\mu}{2} - \frac{\omega_{\mu\nu}\omega^{\mu\nu}}{4} + \frac{m_\rho^2\Phi_\rho^2(\sigma)\vec{\rho}_\mu\vec{\rho}^\mu}{2} - \frac{\rho_{\mu\nu}\rho^{\mu\nu}}{4} +$$

$$+\frac{m_\phi^2\Phi_\phi^2(\sigma)\phi_\mu\phi^\mu}{2} - \frac{\phi_{\mu\nu}\phi^{\mu\nu}}{4},$$

$$\omega_{\mu\nu} = \partial_\nu\omega_\mu - \partial_\mu\omega_\nu, \quad \vec{\rho}_{\mu\nu} = \partial_\nu\vec{\rho}_\mu - \partial_\mu\vec{\rho}_\nu + g_\rho\chi'_\rho[\vec{\rho}_\mu \times \vec{\rho}_\nu],$$

$$\phi_{\mu\nu} = \partial_\nu\phi_\mu - \partial_\mu\phi_\nu,$$

$$\mathcal{L}_l = \sum_l \bar{\psi}_l(i\partial_\mu\gamma^\mu - m_l)\psi_l, \quad \{l\} = (e,\, \mu).$$

Energy density functional

$$E = \frac{m_N^4 f^2}{2C_\sigma^2}\eta_\sigma(f) + U(f) + \frac{C_\omega^2}{2m_N^2\eta_\omega(f)}\Big(\sum_b x_{\omega b} n_b\Big)^2 +$$
$$+\frac{C_\rho^2}{2m_N^2\eta_\rho(f)}\Big(\sum_b x_{\rho b} t_{3b} n_b\Big)^2 + \frac{C_\omega^2}{2m_N^2\eta_\phi(f)}\frac{m_\omega^2}{m_\phi^2}\Big(\sum_H x_{\phi H} n_H\Big)^2 +$$
$$+\sum_b \int_0^{p_{\mathrm{F},b}} \frac{p^2\,dp}{\pi^2}\sqrt{p^2 + m_b^2\Phi_b^2(f)} + E_l,$$

$$E_l = \sum_{l=e,\mu}\int_0^{p_{\mathrm{F},l}} \frac{p^2 dp}{\pi^2}\sqrt{p^2+m_l^2}\,, \quad C_i = \frac{g_{iN} m_N}{m_i}, \quad i = \sigma, \omega, \rho.$$

Scaling functions

In the homogeneous medium $\eta_M = \Phi_M^2(f)/\chi_{Mb}^2(f)\,,$

$\Phi_N(f) = \Phi_m(f) = 1 - f,$ universal scaling of hadron masses

$\Phi_H(f) = \Phi_N(g_{\sigma H}\chi_{\sigma H}(\sigma)\sigma/m_H) \equiv \Phi_N(x_{\sigma H}\xi_{\sigma H}(f) f m_N/m_H)\,,$

$\xi_{\sigma H}(f) = \chi_{\sigma H}(f)/\chi_{\sigma N}(f).$

Energy density functional

$$E = \frac{m_N^4 f^2}{2C_\sigma^2}\eta_\sigma(f) + U(f) + \frac{C_\omega^2}{2m_N^2 \eta_\omega(f)}\Big(\sum_b x_{\omega b} n_b\Big)^2 +$$

$$+\frac{C_\rho^2}{2m_N^2\eta_\rho(f)}\Big(\sum_b x_{\rho b} t_{3b} n_b\Big)^2 + \frac{C_\omega^2}{2m_N^2\eta_\phi(f)}\frac{m_\omega^2}{m_\phi^2}\Big(\sum_H x_{\phi H} n_H\Big)^2 +$$

$$+\sum_b \int\limits_0^{p_{\mathrm{F},b}} \frac{p^2\,dp}{\pi^2}\sqrt{p^2 + m_b^2 \Phi_b^2(f)} + E_l,$$

$$E_l = \sum_{l=e,\mu} \int\limits_0^{p_{\mathrm{F},l}} \frac{p^2 dp}{\pi^2}\sqrt{p^2+m_l^2}\,, \quad C_i = \frac{g_{iN} m_N}{m_i}, \quad i = \sigma, \omega, \rho.$$

⊕ Equation of motion: $\dfrac{\partial E}{\partial f} = 0 \Rightarrow f(\{n_B\})$.

Energy density functional

$$E = \frac{m_N^4 f^2}{2C_\sigma^2}\eta_\sigma(f) + U(f) + \frac{C_\omega^2}{2m_N^2\eta_\omega(f)}\Big(\sum_b x_{\omega b} n_b\Big)^2 +$$
$$+\frac{C_\rho^2}{2m_N^2\eta_\rho(f)}\Big(\sum_b x_{\rho b} t_{3b} n_b\Big)^2 + \frac{C_\omega^2}{2m_N^2\eta_\phi(f)}\frac{m_\omega^2}{m_\phi^2}\Big(\sum_H x_{\phi H} n_H\Big)^2 +$$
$$+\sum_b \int_0^{p_{\mathrm{F},b}} \frac{p^2\,dp}{\pi^2}\sqrt{p^2 + m_b^2\Phi_b^2(f)} + E_l,$$

$$E_l = \sum_{l=e,\mu}\int_0^{p_{\mathrm{F},l}} \frac{p^2 dp}{\pi^2}\sqrt{p^2+m_l^2}\,, \quad C_i = \frac{g_{iN} m_N}{m_i}, \quad i = \sigma, \omega, \rho.$$

- Equation of motion: $\dfrac{\partial E}{\partial f} = 0 \Rightarrow f(\{n_B\})$.
- Beta-equilibrium condition: $\mu_n = \mu_B - q_B\mu_e \Rightarrow \{n_B(n)\}$.

Energy density functional

$$E = \frac{m_N^4 f^2}{2C_\sigma^2}\eta_\sigma(f) + U(f) + \frac{C_\omega^2}{2m_N^2\eta_\omega(f)}\Big(\sum_b x_{\omega b} n_b\Big)^2 +$$

$$+\frac{C_\rho^2}{2m_N^2\eta_\rho(f)}\Big(\sum_b x_{\rho b} t_{3b} n_b\Big)^2 + \frac{C_\omega^2}{2m_N^2\eta_\phi(f)}\frac{m_\omega^2}{m_\phi^2}\Big(\sum_H x_{\phi H} n_H\Big)^2 +$$

$$+\sum_b \int_0^{p_{\mathrm{F},b}} \frac{p^2\,dp}{\pi^2}\sqrt{p^2 + m_b^2\Phi_b^2(f)} + E_l,$$

$$E_l = \sum_{l=e,\mu}\int_0^{p_{\mathrm{F},l}} \frac{p^2 dp}{\pi^2}\sqrt{p^2+m_l^2}\,, \quad C_i = \frac{g_{iN} m_N}{m_i}, \quad i = \sigma, \omega, \rho.$$

⊕ Equation of motion: $\dfrac{\partial E}{\partial f} = 0 \Rightarrow f(\{n_B\})$.

⊕ Beta-equilibrium condition: $\mu_n = \mu_B - q_B\mu_e \Rightarrow \{n_B(n)\}$.

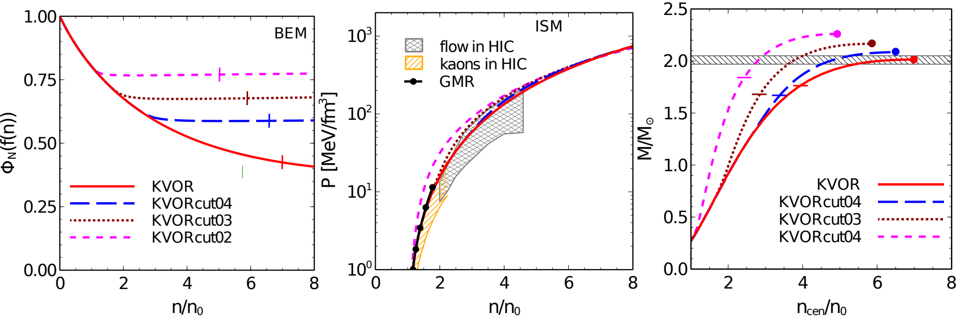
Choice $\eta_i = 1,\ \Phi_N(f) = 1 - f$ reproduces the standard Walecka model

Generalization to finite temperatures: [Khvorostukhin, Toneev, Voskresensky Nucl.Phys. A791 (2007) 180-221, Nucl.Phys. A813 (2008) 313-346]

KVORcut models

The same procedure can be applied to the scaling functions $\eta_\omega(f)$:

$$\eta_\omega(f)^{\mathrm{KVOR}}(f) \to \eta_\omega^{\mathrm{KVOR}}(f) + \frac{a_\omega}{2}[1 + \tanh(b_\omega(f - f_{\mathrm{cut},\omega}))]$$

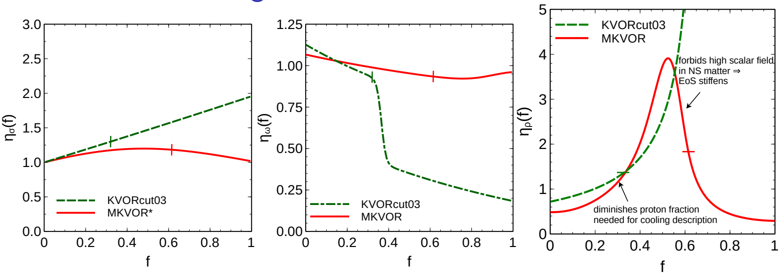


- KVOR model can be stiffened enough to have a high maximum NS mass
- KVORcut03 is the most realistic (flow constraint)

MKVOR model

The procedure can be applied to the isospin-asymmetric part ($\eta_\rho(f)$)
Does not change symmetric matter EoS, but stiffens the asymmetric part

Choice of the scaling functions



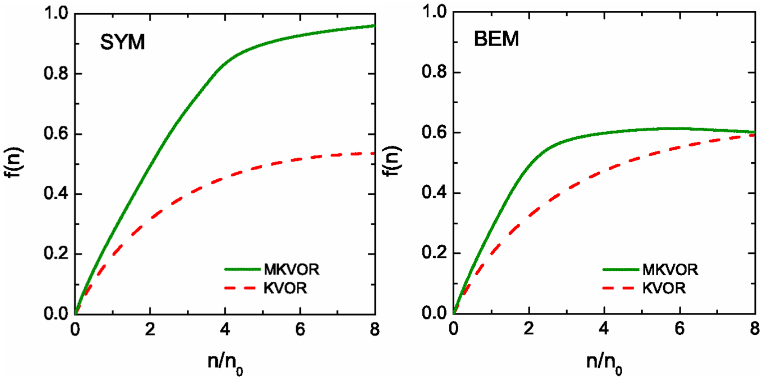
$\eta_\sigma(f)$: governs low density ($n \lesssim 2.5\, n_0$) behavior – needed for passing flow constraint

$\eta_\omega(f)$: needed to pass flow constraint at higher n

$\eta_\rho(f)$: sharp increase at low f lowers proton fraction – needed for DU constraint

sharp decrease at $f \gtrsim 0.6$ – "cut"-mechanism for stiffening the EoS of NS matter

Density dependence of the mean scalar field



$$\Phi_N(f) = 1 - f \Rightarrow$$

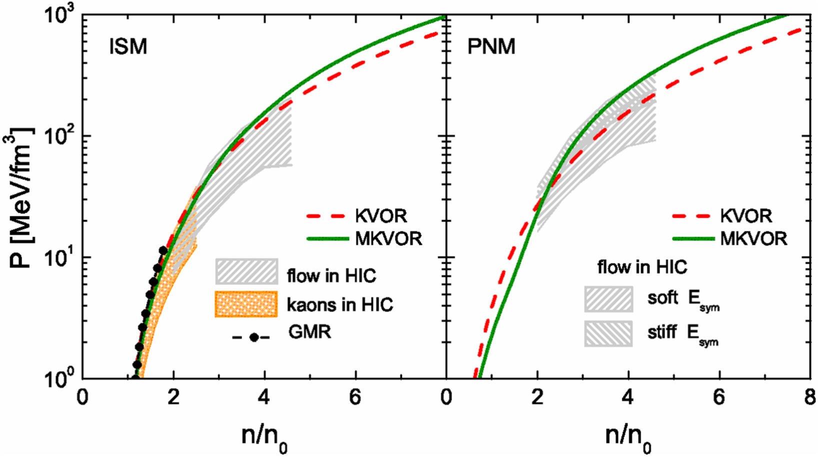
- Effective mass in ISM monotonously decreases to low values
- Effective mass in NS matter decreases, then saturates at a constant value

Constraints from HIC

Constraint on the pressure in the ISM

- from the analyses of transverse and elliptic flows
- from the analyses of kaon production

  [W. G. Lynch et al. Prog. Part. Nucl. Phys. 62 (2009)]
- Cannot be passed by a typical EoS which yields a large maximum NS mass



Inclusion of hyperons

Hyperons are included with the vector coupling constants from SU(6) symmetry:

$$g_{\omega\Lambda} = g_{\omega\Sigma} = 2g_{\omega\Xi} = \frac{2}{3} g_{\omega N}, \;\; g_{\rho\Sigma} = 2g_{\rho\Xi} = 2g_{\rho N},$$

$$2g_{\phi\Lambda} = 2g_{\phi\Sigma} = g_{\phi\Xi} = \frac{2\sqrt{2}}{\sqrt{3}} g_{\omega N}.$$

Scalar coupling constants are deduced from hyperon binding energies at $n = n_0$:

$$\mathcal{E}^{H}_{\rm bind}(n_0) = \frac{C_\omega^2}{m_N^2} x_{\omega H} n_0 - x_{\sigma H}\, \xi_{\sigma H}(\bar{f}_0)\, [m_N - m_N^*(n_0)]\,,$$

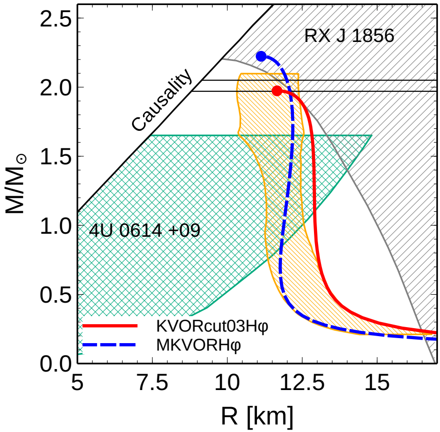
$$\mathcal{E}^{\Lambda}_{\rm bind} = -28 \text{ MeV}, \quad \mathcal{E}^{\Sigma}_{\rm bind} = +30 \text{ MeV}, \quad \mathcal{E}^{\Xi}_{\rm bind} = -18 \text{ MeV}$$

We assume the ϕ-meson universal *mass scaling*, but with *vacuum* coupling constants $(H\phi)$:

$\Phi_\phi(f) = 1 - f, \; \chi_\phi(f) = 1, \; \eta_\phi(f) = (1-f)^2.$

Maximum mass constraint

- The largest precisely measured NS mass $M[PSR J0348+0432] = 2.01 \pm 0.04 M_\odot$ (Antoniadis et al., 2012).
- 4U 0614+091: QPO; RX J1856: isolated NS thermal radiation



MKVORHϕ passes the constraint, KVORcut03Hϕ passes marginally
Dashed region – constraint from [Lattimer, Steiner, Astrophys. J. 784 (2014) 123]

Inclusion of Δ-isobars

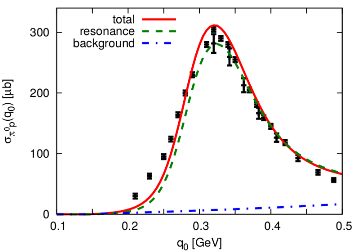
Coupling constants

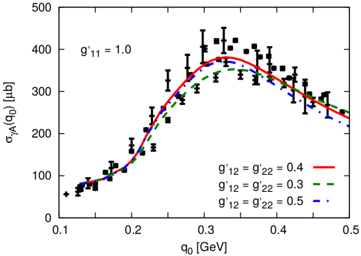
Vector mesons – quark counting: $g_{\omega\Delta} = g_{\omega N}\,, \quad g_{\rho\Delta} = g_{\rho N}\,, \quad g_{\phi\Delta} = 0$

Scalar meson – from the potential

$$U_\Delta(n_0) = -x_{\sigma\Delta} m_N\, f_0 + x_{\omega\Delta} C_\omega^2 (n_0/m_N^2).$$

Photoabsorption off nuclei with self-consistent vertex corrections:
$U_\Delta \simeq -50\,\mathrm{MeV}$ [Riek,Lutz and Korpa, PRC 80, 024902 (2009)]

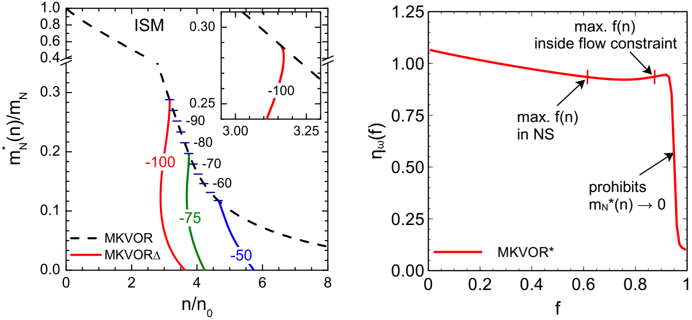




In this work we explore $-50\,\mathrm{MeV} > U_\Delta > -100\,\mathrm{MeV}$

ISM: MKVOR* model

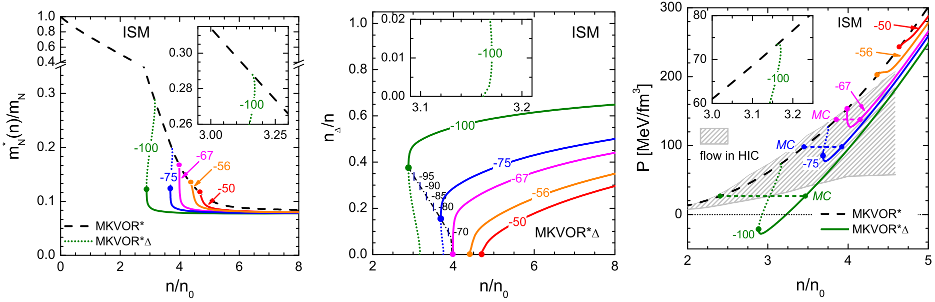
The fast decrease of the nucleon effective mass in MKVOR model in the ISM leads to early Δ appearance and at some point $m_N^* \to 0$.
Can be cured by introducing a sharp decrease into $\eta_\omega(f)$ at $f = f^*$. All the results for BEM and for ISM (for $n \leq 5\, n_0$) remain unchanged.



For $U_\Delta < -67$ MeV – multiple solutions for equilibrium n_Δ

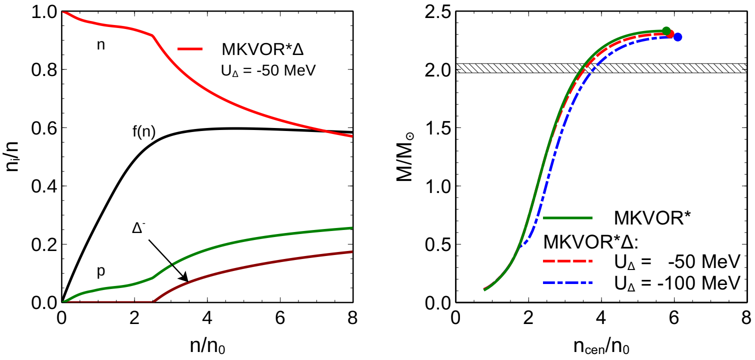
$\Rightarrow$ $1^{\rm st}$ order phase transition!

ISM: Δ concentrations and the pressure



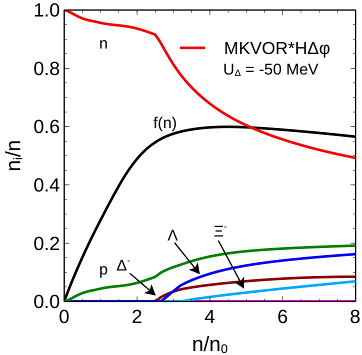
- 1^{st} order phase transition for $U_\Delta < -56\,\mathrm{MeV}$.
- Could manifest itself as an increase of the pion yield at typical energies and momenta corresponding to the $\Delta \to \pi N$ decays
- For $U_\Delta < -65$ MeV the pressure curve lies within the constraint.

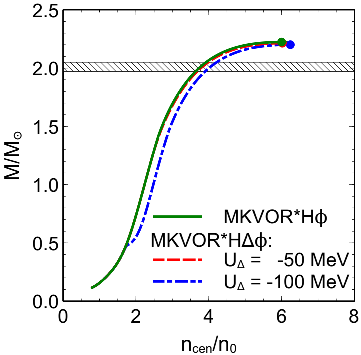
BEM: Δ and nucleons



Δ appear at $1.7 - 2.5\, n_0$, but the maximum mass decrease is less than $0.06\, M_\odot$

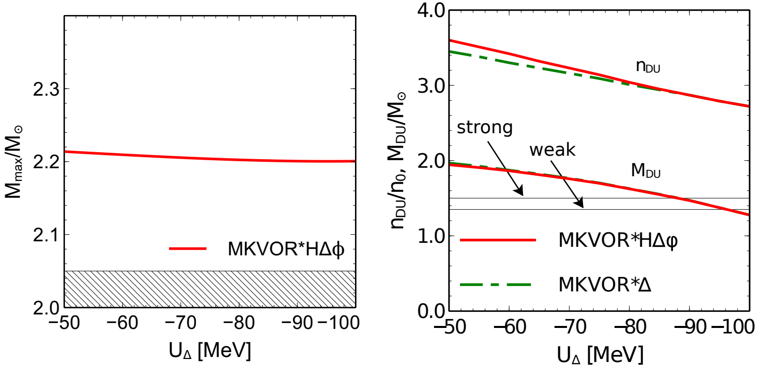
BEM: HΔϕ





Hyperons suppress Δ concentrations

BEM: U_Δ dependence



The DU constraint is passed for:

$U \gtrsim -88$ MeV – "strong" constraint $M_{DU} > 1.5\, M_\odot$

$U \gtrsim -96$ MeV – "weak" constraint $M_{DU} > 1.35\, M_\odot$

Condensation of charged ρ mesons

With taking into account the non-Abelian term: [D.N. Voskresensky, Phys. Lett. B **392** (1997), E.E. Kolomeitsev and D.N. Voskresensky, Nucl. Phys. A **759** (2005)]

$$\begin{aligned}\mathcal{L}_\rho &= -\frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\Phi_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu - g_\rho\chi_\rho\vec{\rho}_\mu\vec{j}_I^\mu\,, \quad (\vec{j}_{\mu,I})^a = \delta^{a3}\delta_{\mu 0}n_I\,,\\ \vec{R}_{\mu\nu} &= \partial_\mu\vec{\rho}_\nu - \partial_\nu\vec{\rho}_\mu + g'_\rho\chi'_\rho[\vec{\rho}_\mu\times\vec{\rho}_\nu] + \mu_{\mathrm{ch},\rho}\delta_{\nu 0}[\vec{n}_3\times\vec{\rho}_\mu] - \mu_{\mathrm{ch},\rho}\delta_{\mu 0}[\vec{n}_3\times\vec{\rho}_\nu].\end{aligned}$$

If the ρ effective mass decreases, the energy can be minimized by a non-standard ansatz:

$$\rho_0^{(3)} \neq 0, \quad \rho_i^{\pm} = (\rho_i^{(1)} \pm i\rho_i^{(2)}) \neq 0, \quad i = 1,2,3,$$

together with the conditions:

$$\rho_i^{(3)} = \rho_0^{(i)} = 0, \quad \rho_i^{+}\rho_j^{-} = \rho_i^{-}\rho_j^{+} \Rightarrow \rho_i^{(+)}/\rho_i^{(-)} = \mathrm{const}$$

$$\rho_i^{(-)} = a_i\,\rho_c,\;\; \rho_i^{(+)} = a_i\,\rho_c^\dagger, \quad (a_i)^2 = 1$$

$$\begin{aligned}P_\rho[\{n_b\}; f, \rho_0^{(3)}, \rho_c; \mu_{\mathrm{ch},\rho}] = &-g_\rho\,\chi_\rho n_I\,\rho_0^{(3)} + \frac{1}{2}(\rho_0^{(3)})^2\, m_\rho^2\,\Phi_\rho^2\\ &+ \left[\left(g_\rho\chi'_\rho\,\rho_0^{(3)} - \mu_{\mathrm{ch},\rho}\right)^2 - m_\rho^2\,\Phi_\rho^2\right]\,|\rho_c|^2.\end{aligned}$$

Solutions for the condensate

Equation of motions are:

$$\left[\left(g_\rho\,\chi_\rho^{'}\,\rho_0^{(3)}-\mu_{\mathrm{ch},\rho}\right)^2-m_\rho^2\,\Phi_\rho^2\right]\rho_c=0\,,$$

$$m_\rho^2\,\Phi_\rho^2\,\rho_0^{(3)}+2\,g_\rho\,\chi_\rho^{'}\left(g_\rho\chi'_\rho\,\rho_0^{(3)}-\mu_{\mathrm{ch},\rho}\right)|\rho_c|^2=g_\rho\,\chi_\rho\,n_I\,.$$

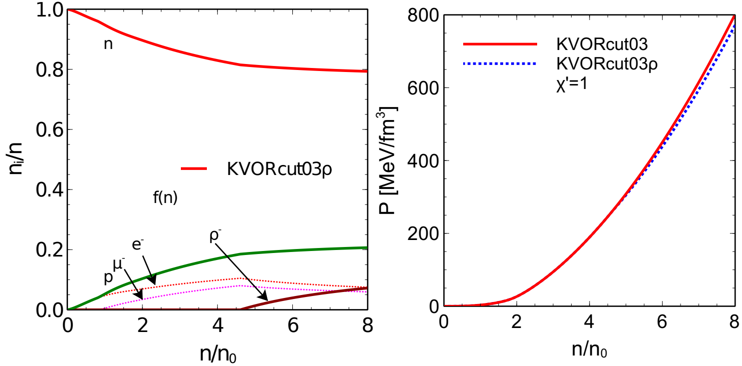
Standard solution	Charged condensate if $\lvert n_I\rvert-n_\rho>0$
$\rho_0^{(3)}=\frac{g_\rho}{m_\rho^2}\,\frac{\chi_\rho}{\Phi_\rho^2}\,n_I$	$\rho_0^{(3)}=\frac{\mu_{\mathrm{ch},\rho}-m_\rho\Phi_\rho}{g_\rho\chi'_\rho}$
$\rho_c=0$	$\lvert\rho_c\rvert^2=\frac{\lvert n_I\rvert-n_\rho}{2\,m_\rho\,\eta_\rho^{1/2}\,\chi'_\rho}$
$P_\rho^{(1)}=-\frac{C_\rho^2n_I^2}{2\,m_N^2\,\eta_\rho(f)}$	$P_\rho^{(2)}=P_\rho^{(1)}+\frac{C_\rho^2}{2\,m_N^2\,\eta_\rho}\left(\lvert n_I\rvert-n_\rho\right)^2\theta(\lvert n_I\rvert-n_\rho)$

$$n_\rho=a\,(m_\rho\,\Phi_\rho-\mu_{\mathrm{ch},\rho}),\;\; a=\frac{m_N^2\,\eta_\rho^{1/2}\,\Phi_\rho}{C_\rho^2\chi'_\rho}>0$$

$$n_{\mathrm{ch},\rho}=-\frac{\partial P_\rho}{\partial\mu_{\mathrm{ch},\rho}}=-2m_\rho\Phi_\rho|\rho_c|^2$$

Charge neutrality: $\sum_b Q_b n_b+n_{\mathrm{ch},\rho}-n_e-n_\mu=0$

KVORcut03 model

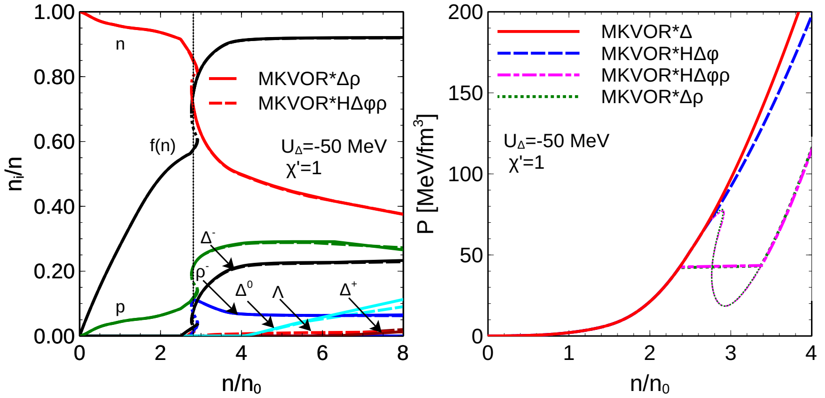


The effect of ρ^- condensate is tiny, maximum NS mass lowers from $2.17\,M_\odot$ to $2.16\,M_\odot$

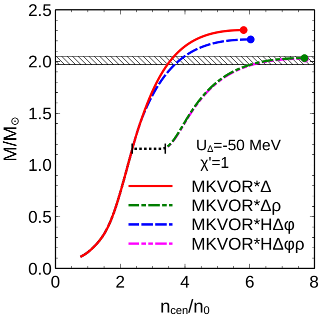
No condensate in models with hyperons and Δs

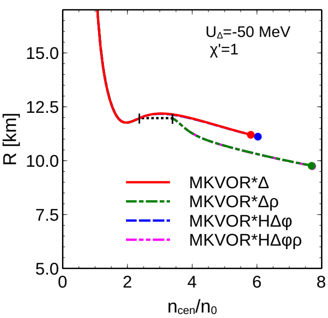
Phase transition of the $2^{\rm nd}$ order

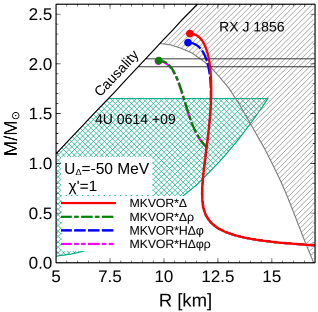
MKVOR* model



Multiple solutions for the equilibrium concentrations for a given $n \Rightarrow 1^{\mathrm{st}}$ order phase transition







- Maximum NS mass decreases strongly to $M_{\max} \simeq 2.03\, M_\odot$
- Still passes the constraint
- Energy jump not enough to have twins

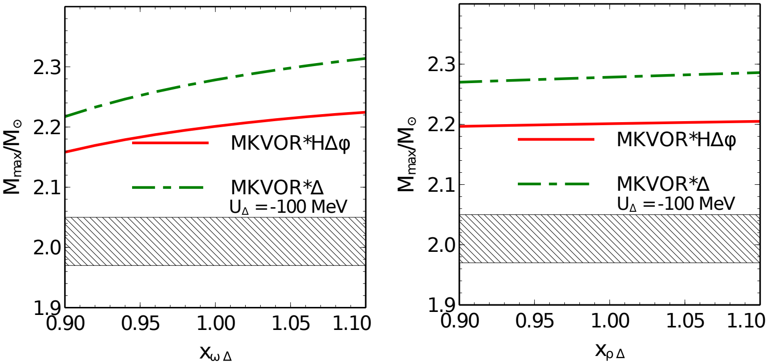
Conclusions

- We have developed a simple procedure of stiffening an arbitrary RMF EoS, which can be applied in scalar (NLWcut), vector (KVORcut) and isovector (MKVOR) sectors
- The RMF model with scaled hadron masses and couplings is flexible enough to satisfy many astrophysical constraints, constraints from HIC and miscroscopic calculations and resolve the hyperon puzzle
- In the ISM Δs can appear by a I$^{\rm st}$ order phase transition, if U_Δ is sufficiently attractive. Δ isobars do not spoil the description of 2 $M_\odot$ neutron star
- Condensation of ρ^- mesons is possible in realistic models. Results are strongly model dependent. In MKVOR* model it can lead to 1$^{\rm st}$ order phase transition a dramatic decrease of the maximum NS mass, but it still passes the constraint

Further development

- Meson $(\pi,\, K)$ condensation with taking into account in-medium modification of their properties
- Calculation of the NS cooling
- Extension of new models to the finite temperatures

BEM: Additional parameters variation



Almost insensitive to $x_{\rho\Delta}$

Possible microscopic origin of effective mass saturation

Paeng, Lee, Rho, Sasaki Phys. Rev. D88 (2013) 105019
Observed the nucleon mass saturation interplay with renormalization group-evolved ωN interaction