Charged ρ-meson condensate in neutron stars within RMF models

Konstantin A. Maslov[1,2]
In collaboration with E. E. Kolomeitsev[2,3] and D. N. Voskresensky[1,2]

[1]National Research Nuclear University (MEPhI), Moscow, Russia
[2]Joint Institute for Nuclear Research (JINR), Dubna, Russia
[3] Matej Bel University, Banska Bystrica, Slovakia

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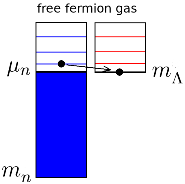
Introduction

- Equation of state (EoS) of strongly interacting hadronic matter for various densities n, temperatures T and isospin asymmetries $\beta = (n_n - n_p)/n$ is needed for describing:
  - finite nuclei ($T = 0$, $n \simeq n_0, \beta \ll 1$)
  - heavy-ion collisions (HICs) ($0 < T < 100 - 200\,\mathrm{MeV}$, $0 < n < 5 - 10\,n_0$, $\beta \ll 1$)
  - neutron star (NS) interiors ($T = 0$, $0 < n \lesssim 10\,n_0$, $0 < \beta < 1$)
  - supernovae and NS mergers ($0 < T \lesssim 100$ MeV, $0 < n \lesssim 10\,n_0$, $0 < \beta < 1$)

  There exists a large amount of experimental constraints to be fulfilled by a viable EoS. For $T = 0$ an EoS should:
  - reproduce bulk properties of nuclear matter
  - allow for existence of NSs with $> M$[PSR J0348+0432] $=$ $2.01 \pm 0.04\,M_\odot$ – maximum precisely measured NS mass.
  - pass the constraint for the pressure at $T = 0$, which follows from analyses of flows and kaon production in HICs.
  - not contradict the existing data on NS cooling

Hyperon/Δ puzzle



Ambartsumyan, V.A. and Saakyan, G.S., AZh 37 (1960),
J. Schaffner-Bielich, NPA 804 (2008) 309.

For realistic in-medium potentials at saturation 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 hadron mass and couplings in-medium modifications
[K. A. M., E. E. Kolomeitsev and D. N. Voskresensky, Phys. Lett. B **748**, 369 (2015), E. E. K., K. A. M. and D. N. V. Nucl.Phys. A961 (2017) 106-141]

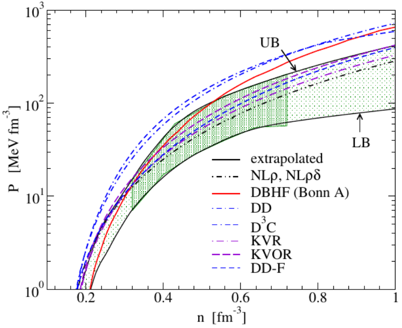
Boson (ρ, π, K) condensation also softens the EoS and lowers the maximum NS mass

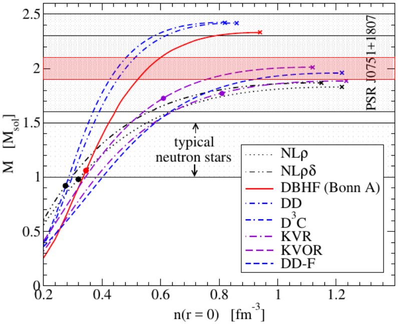
Contradicting constraints

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





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

Additional flexibility is required!

Traditional RMF models

H.-P. Dürr PR103 1956, J. D. Walecka 1974, J. Boguta & A. R. Bodmer 1977

Nonlinear Walecka (NLW) model

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

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:

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

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:

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

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

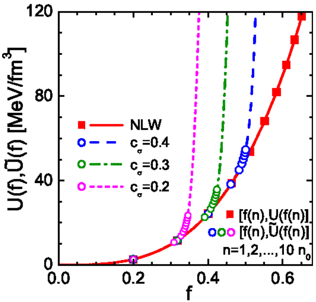
$$n_0 = 0.16 \text{ fm}^{-3}, \quad \mathcal{E}_0 = -16 \text{ MeV}, \quad K = 250 \text{ MeV},$$

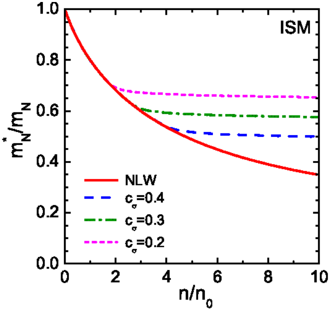
$$\mathcal{E}_{\rm sym} = 30 \text{ MeV}, \quad m_N^*(n_0)/m_N = 0.8$$

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

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

Scalar potential modification («cut» mechanism)





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

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

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

NLWcut models

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

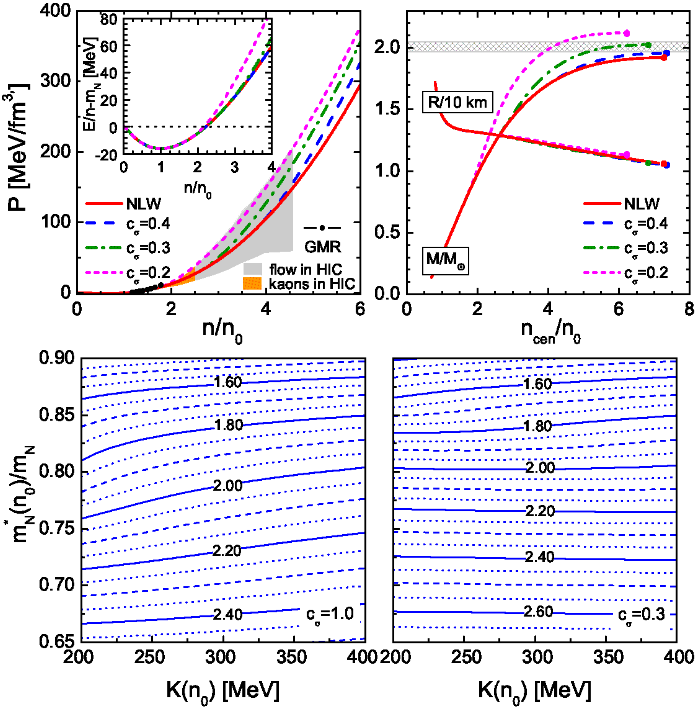
$$U(f) \to \widetilde{U}(f) = U(f) + \Delta U(f)$$

«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$_\sigma$=0.4
c$_\sigma$=0.3
c$_\sigma$=0.2
GMR
flow in HIC
kaons in HIC
R/10 km
M/M$_\odot$
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$_\sigma$=1.0
c$_\sigma$=0.3

Generalized RMF model

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

- 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).

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

We constructed a better parametrization (MKVOR*) which satisfies new constraints on the nuclear EoS with hyperons and Δs

Generalized RMF model

E. E. Kolomeitsev, D.N. Voskresensky, NPA 759 (2005) (KVOR model)
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)

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

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

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

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

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

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

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

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

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

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

Energy density functional

$$E = \frac{m_N^4 f^2}{2C_\sigma^2}\eta_\sigma(f) + U(f) + \frac{C_\omega^2}{2m_N^2\eta_\omega(f)}\Big(\sum_b x_{\omega b} n_b\Big)^2 +$$
$$+\frac{C_\rho^2}{2m_N^2\eta_\rho(f)}\Big(\sum_b x_{\rho b} t_{3b} n_b\Big)^2 + \frac{C_\omega^2}{2m_N^2\eta_\phi(f)}\frac{m_\omega^2}{m_\phi^2}\Big(\sum_H x_{\phi H} n_H\Big)^2 +$$
$$+\sum_b \int\limits_0^{p_{\mathrm{F},b}} \frac{p^2\,dp}{\pi^2}\sqrt{p^2 + m_b^2\Phi_b^2(f)} + E_l,$$

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

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

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

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

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

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

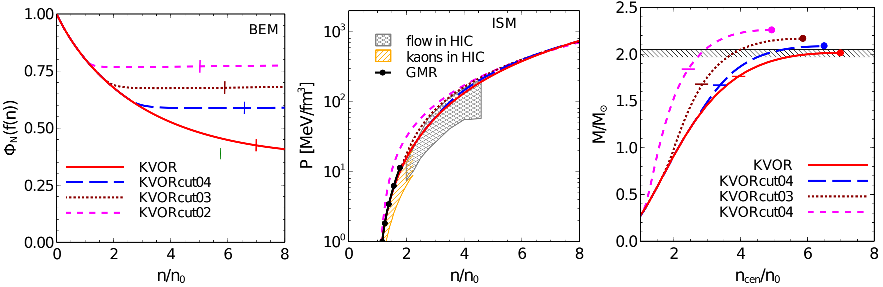
Choice $\eta_i = 1$, $\Phi_N(f) = 1 - f$ reproduces the standard Walecka model

Vector mesons coupled to $\sigma \Rightarrow$ naturally generated effective potential for σ, dependent on density (from $\eta_\omega(f)$) and isospin density (from $\eta_\rho(f)$)

KVORcut models

The stiffening procedure is applied to the scaling function $\eta_\omega(f)$:

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

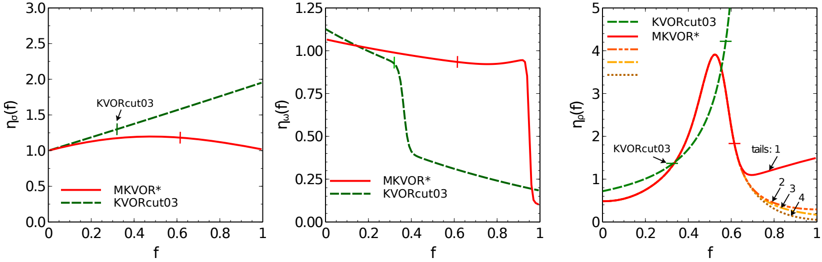


- KVOR model can be stiffened enough to have a high maximum NS mass
- KVORcut03 is the most realistic (flow constraint)

MKVOR* model

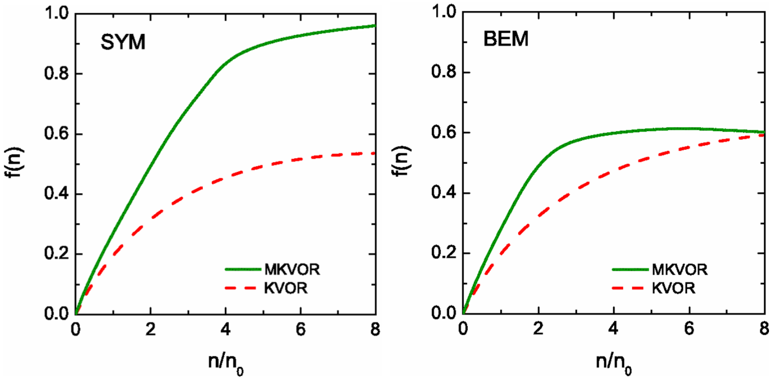
The stiffening procedure is applied to the isospin-asymmetric part ($\eta_\rho(f)$)
Does not change symmetric matter EoS, but stiffens the asymmetric part

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 L – needed for reducing the proton fraction (DU constraint)
sharp decrease at $f \gtrsim 0.6$ – stiffens the EoS of β-equilibrium matter
Choice of scaling functions for $f > f_{\max}$ (dashes) doesn't affect the EoS, if no second solutions are present (MKVOR*: curves 2, 3, 4)

Density dependence of the mean scalar field



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

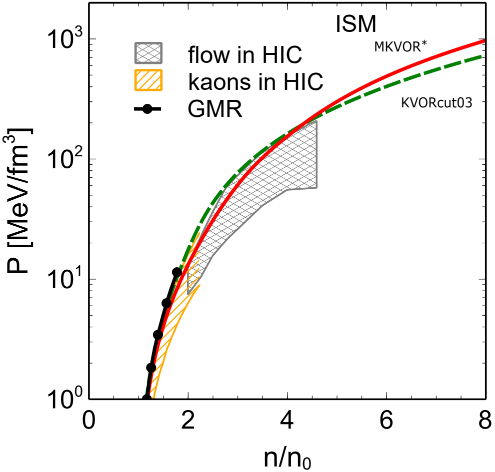
- Effective mass in ISM monotonously decreases to low values
- Effective mass in NS matter decreases, then saturates at a constant value

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 additional baryons

Vector meson couplings – from SU(6) symmetry:

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

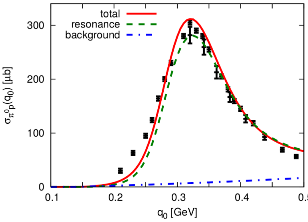
$$2g_{\phi\Lambda} = 2g_{\phi\Sigma} = g_{\phi\Xi} = \frac{2\sqrt{2}}{\sqrt{3}}g_{\omega N}\,, \quad g_{\omega\Delta} = g_{\omega N}$$

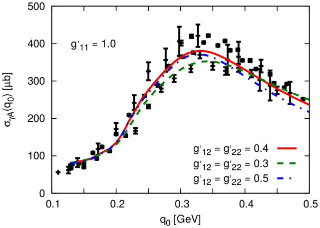
Scalar meson couplings – from baryon potentials at $n = n_0$:

$$U_B(n_0) = \frac{C_\omega^2}{m_N^2} x_{\omega B} n_0 - x_{\sigma B}\,\xi_{\sigma B}(\bar{f}_0)\,[m_N - m_N^*(n_0)]\,,$$

$$U_\Lambda = -28 \text{ MeV}, \quad U_\Sigma = +30 \text{ MeV}, \quad U_\Xi = -18 \text{ MeV}, \quad U_\Delta \to -50\text{MeV}$$

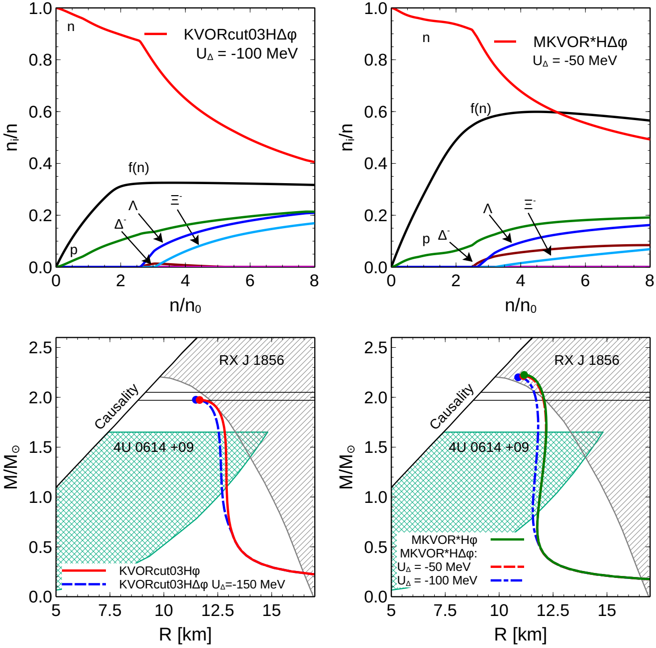
Photoabsorption off nuclei with self-consistent vertex corrections: $U_\Delta \simeq -50\,\text{MeV}$
[Riek,Lutz and Korpa, PRC 80, 024902 (2009)]



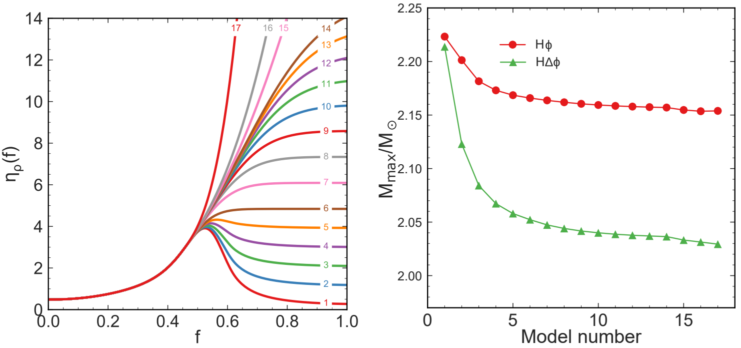


In our works we explored $-50\,\text{MeV} > U_\Delta > -100\,\text{MeV}$

Baryon species and maximum NS mass



Effect of the isospin-dependent σ quenching



Scaling function 1 maximizes the NS mass and minimizes the effect of Δs

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:

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

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

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

Solutions for the condensate

Equation of motions are:

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

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

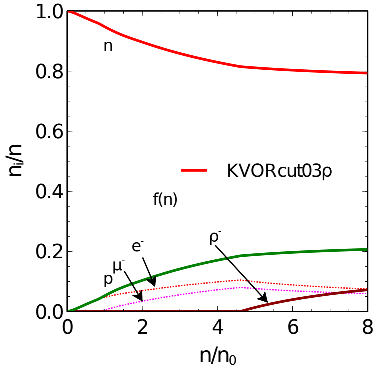
Standard solution	Charged condensate if $\lvert n_I\rvert - n_\rho > 0$
$\rho_0^{(3)} = \frac{g_\rho}{m_\rho^2}\,\frac{\chi_\rho}{\Phi_\rho^2}\,n_I$	$\rho_0^{(3)} = \frac{\mu_{\mathrm{ch},\rho} - m_\rho\Phi_\rho}{g_\rho\chi'_\rho}$
$\rho_c = 0$	$\lvert\rho_c\rvert^2 = \frac{\lvert n_I\rvert - n_\rho}{2\,m_\rho\,\eta_\rho^{1/2}\,\chi'_\rho}$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

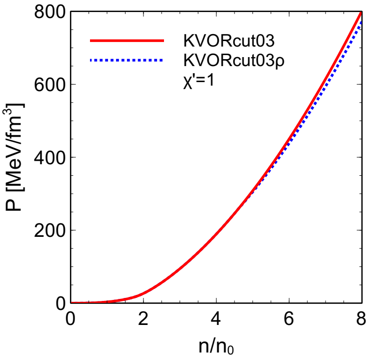
$$n_\rho = a\,(m_\rho\,\Phi_\rho - \mu_{\mathrm{ch},\rho}),\;\; a = \frac{m_N^2\,\eta_\rho^{1/2}\,\Phi_\rho}{C_\rho^2\chi'_\rho} > 0$$

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

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

KVORcut03 model



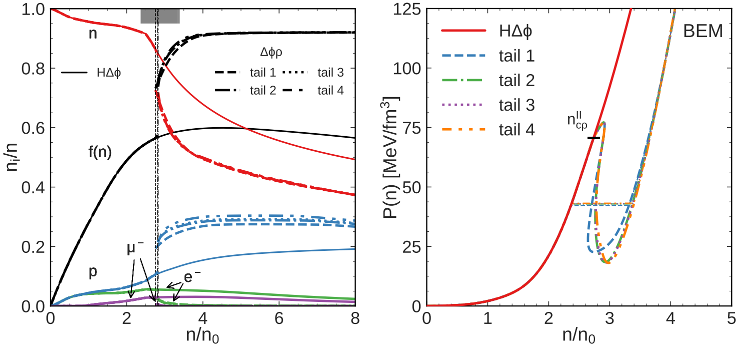


The effect of ρ^- condensate is tiny, maximum NS mass lowers from $2.17\, M_\odot$ to $2.16\, M_\odot$

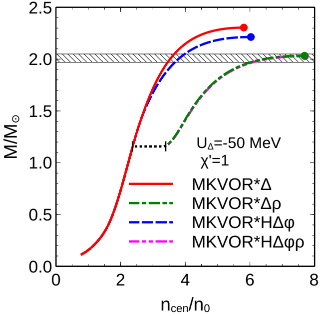
No condensate in models with hyperons and Δs

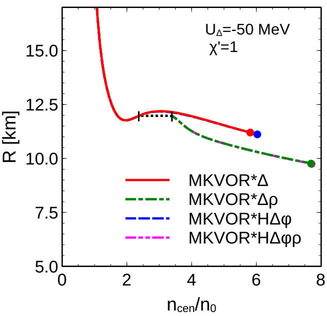
Phase transition of the 2$^{\rm nd}$ order

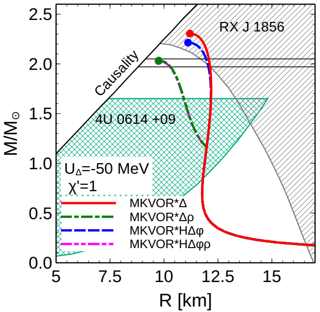
MKVOR* model



Multiple solutions for the equilibrium concentrations for a given $n \Rightarrow$
$1^{\rm st}$ order phase transition
Large f involved - results depend on the $\eta_\rho(f)$ tails



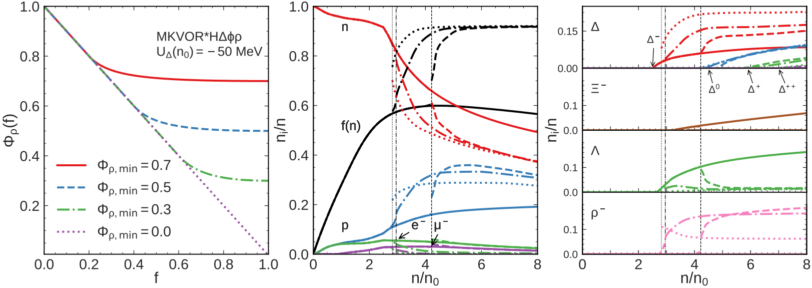




- Maximum NS mass decreases strongly to $M_{\max} \simeq 2.03\, M_\odot$
- Still passes the constraint
- Energy jump not enough to have twins

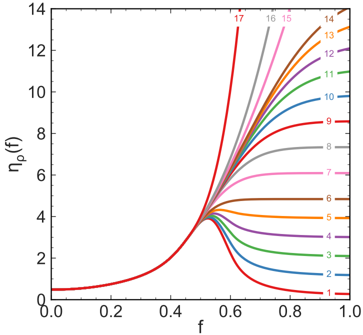
Variation of $m_\rho^*(f)$

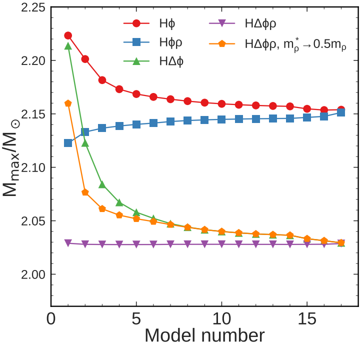
The critical density of the $1^{\rm st}$ order PT depends on the decrease rate of the effective boson mass



The ρ-condensation becomes weaker as we limit the decrease of $m_\rho^*(f)$, and for $\Phi_{\rho,\min} \simeq 0.7$ the condensate disappears

Variation of $\eta_\rho(f)$





Scaling function 1 minimizes the effect of Δs, but maximizes the NS mass loss due to ρ^- condensation $\Rightarrow M_{\rm max}$ almost independent on $\eta_\rho(f)$ (for a particular $\Phi_\rho(f) = \Phi_N(f)$)

Can be changed by assuming slower decrease for m^*_ρ at high densities (e.g. $\Phi_{{\rm min},\rho} = 0.5$)

Conclusions

- In our realistic models the condensation of ρ^- mesons is possible. Results are strongly model dependent:
  - In the KVORcut03 model the condensate appears by a $2^{\rm nd}$ order phase transition, and leads to a minor decrease of the NS mass. No condensate appears with hyperons/Δs included
  - In MKVOR* model it can lead to $1^{\rm st}$ order phase transition with a dramatic decrease of the maximum NS mass. Nevertheless, the constraint is still passed
  - If the common hadron mass scaling holds up to high densities, we face the alternative: either many Δs or strong ρ^--condensation. Limiting the decrease of ρ-meson mass reduces the condensation effect.

Further developments

- Other relevant meson (π, K) condensation with taking into account in-medium modification of their properties
- Extension of the models to finite temperatures
- Quark-hadron phase transition in NSs