Scalar–Isovector δ-meson in RMF Theory and the Quark Deconfinement Phase Transition in Neutron Stars

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Introduction

RMF-theory:

$\sigma \omega \rho$ *J.D.Walecka, Ann.Phys. 87, 4951, 1974*
B.D.Serot, J.D.Walecka, Int.J.Mod.Phys. E6, 515, 1997.

Low density asymmetric nuclear matter:

$\sigma \omega \rho \delta$ *S.Kubis, M.Kutschera*, Phys. Lett., B399,191,1997.
B.Liu, V.Greco, V.Baran, M.Colonna, M.Di Toro, Phys. Rev. C65, 045201, 2002.

Heavy ion collisions at intermediate energies:

$\sigma \omega \rho \delta$ *V.Greco, M.Colonna, M.Di Toro, F.Matera*, Phys. Rev. C67, 015203, 2003
V.Greco et al., Phys. Lett. B562, 215, 2003.
T.Gaitanos, M.Colonna, M.Di Toro, H.H.Wolter, Phys.Lett. B595, 209,2004.

Neutron stars without quark deconfinement:

$\sigma \omega \rho \delta$ *B.Liu, H.Guo, M.Di Toro, V.Greco*, arXiv Nucl-th/0409014 v2, 2005

Lagrangian density of many-particle system of p,n.σ,ω,ρ,δ

$$\mathcal{L}=\bar{\psi}_N\left[\gamma^\mu\left(i\partial_\mu-g_\omega\omega_\mu(x)-\frac{1}{2}g_\rho\vec{\tau}_N\cdot\vec{\rho}_\mu(x)\right)-\left(m_N-g_\sigma\sigma(x)-g_\delta\vec{\tau}_N\cdot\vec{\delta}(x)\right)\right]\psi_N+$$

$$+\frac{1}{2}\left(\partial_\mu\sigma(x)\partial^\mu\sigma(x)-m_\sigma^2\,\sigma(x)^2\right)-U(\sigma(x))+\frac{1}{2}m_\omega^2\,\omega^\mu(x)\omega_\mu(x)-\frac{1}{4}\Omega_{\mu\nu}(x)\Omega^{\mu\nu}(x)+$$

$$+\frac{1}{2}\left(\partial_\mu\vec{\delta}(x)\partial^\mu\vec{\delta}(x)-m_\delta^2\,\vec{\delta}(x)^2\right)+\frac{1}{2}m_\rho^2\,\vec{\rho}^\mu(x)\vec{\rho}_\mu(x)-\frac{1}{4}R_{\mu\nu}(x)R^{\mu\nu}(x)\,,$$

$$x=x_\mu=(t,x,y,z)\qquad \sigma(x),\ \omega_\mu(x),\ \vec{\delta}(x),\ \vec{\rho}_\mu(x)\qquad \psi_N=\begin{pmatrix}\psi_p\\ \psi_n\end{pmatrix}$$

$$U(\sigma)=\frac{b}{3}m_N(g_\sigma\sigma)^3+\frac{c}{4}(g_\sigma\sigma)^4,$$

$$\Omega_{\mu\nu}(x)=\partial_\mu\omega_\nu(x)-\partial_\nu\omega_\mu(x),$$

$$\Re_{\mu\nu}(x)=\partial_\mu\rho_\nu(x)-\partial_\nu\rho_\mu(x).$$

	Scalar	Vector
Isoscalar	σ	ω
Isovector	δ	ρ

Relativistic mean-field approach

$$\frac{\partial \mathcal{L}}{\partial \phi(x)} - \partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi(x))} = 0$$

$$e_p(k) = \sqrt{k^2 + m_p^{*\,2}} + g_\omega\, \overline{\omega}_0 + \frac{1}{2} g_\rho\, \overline{\rho}_0^{(3)},$$

$$e_n(k) = \sqrt{k^2 + m_n^{*\,2}} + g_\omega\, \overline{\omega}_0 - \frac{1}{2} g_\rho\, \overline{\rho}_0^{(3)},$$

$$m_\sigma^{\ 2}\, \overline{\sigma} = g_\sigma \left(n_{sp} + n_{sn} - \frac{dU(\overline{\sigma})}{d\overline{\sigma}} \right),$$

$$m_\omega^{\ 2}\, \overline{\omega} = g_\omega \left(n_p + n_n \right) ,$$

$$m_\delta^{\ 2}\, \overline{\delta}^{(3)} = g_\delta \left(n_{sp} - n_{sn} \right),$$

$$m_\rho^{\ 2}\, \overline{\rho}_0^{(3)} = \frac{1}{2} g_\rho \left(n_p - n_n \right),$$

$$m_p^* = m_N - g_\sigma\, \overline{\sigma} - g_\delta\, \overline{\delta}^{(3)},$$

$$m_n^* = m_N - g_\sigma\, \overline{\sigma} + g_\delta\, \overline{\delta}^{(3)}.$$

$$n_p = \frac{k_{Fp}^{\ 3}}{3\pi^2}, \qquad n_n = \frac{k_{Fn}^{\ 3}}{3\pi^2},$$

$$n_{sp} = \frac{1}{\pi^2} \int_0^{k_{Fp}} \frac{m_p^*}{\sqrt{k^2 + m_p^{*\,2}}} k^2 dk\,,$$

$$n_{sn} = \frac{1}{\pi^2} \int_0^{k_{Fn}} \frac{m_n^*}{\sqrt{k^2 + m_n^{*\,2}}} k^2 dk\,.$$

$$\mu_p = e_p(k_{Fp}) = \sqrt{k_{Fp}^{\ 2} + m_p^{*\,2}} + g_\omega\, \overline{\omega}_0 + \frac{1}{2} g_\rho\, \overline{\rho}_0^{(3)},$$

$$\mu_n = e_n(k_{Fn}) = \sqrt{k_{Fn}^{\ 2} + m_n^{*\,2}} + g_\omega\, \overline{\omega}_0 - \frac{1}{2} g_\rho\, \overline{\rho}_0^{(3)}\,.$$

Parametric EOS for nuclear matter

$$g_\sigma \bar{\sigma} \equiv \sigma, \quad g_\omega \bar{\omega}_0 \equiv \omega, \quad g_\delta \bar{\delta}^{(3)} \equiv \delta, \qquad g_\rho \bar{\rho}^{(3)} \equiv \rho,$$

$$\left(\frac{g_\sigma}{m_\sigma}\right)^2 \equiv a_\sigma, \quad \left(\frac{g_\omega}{m_\omega}\right)^2 \equiv a_\omega, \quad \left(\frac{g_\delta}{m_\delta}\right)^2 \equiv a_\delta, \quad \left(\frac{g_\rho}{m_\rho}\right)^2 \equiv a_\rho \qquad \alpha = \frac{n_n - n_p}{n},$$ the asymmetry parameter

$$P(n,\alpha) = \frac{1}{\pi^2} \int_0^{k_F(n)(1-\alpha)^{1/3}} \left(\sqrt{k_F(n)^2(1-\alpha)^{2/3} + (m_N - \sigma - \delta)^2} - \sqrt{k^2 + (m_N - \sigma - \delta)^2} \right) k^2 dk +$$
$$+ \frac{1}{\pi^2} \int_0^{k_F(n)(1+\alpha)^{1/3}} \left(\sqrt{k_F(n)^2(1+\alpha)^{2/3} + (m_N - \sigma + \delta)^2} - \sqrt{k^2 + (m_N - \sigma + \delta)^2} \right) k^2 dk -$$
$$- \tilde{U}(\sigma) + \frac{1}{2}\left(-\frac{\sigma^2}{a_\sigma} + \frac{\omega^2}{a_\omega} - \frac{\delta^2}{a_\delta} + \frac{\rho^2}{a_\rho} \right).$$

$$\varepsilon(n,\alpha) = \frac{1}{\pi^2} \int_0^{k_F(n)(1-\alpha)^{1/3}} \sqrt{k^2 + (m_N - \sigma - \delta)^2}\, k^2 dk +$$
$$+ \frac{1}{\pi^2} \int_0^{k_F(n)(1+\alpha)^{1/3}} \sqrt{k^2 + (m_N - \sigma + \delta)^2}\, k^2 dk + \tilde{U}(\sigma) + \frac{1}{2}\left(\frac{\sigma^2}{a_\sigma} + \frac{\omega^2}{a_\omega} + \frac{\delta^2}{a_\delta} + \frac{\rho^2}{a_\rho} \right),$$

Parameters of RMF theory

$$a_\sigma\,,\ a_\omega\,,\ a_\delta\,,\ a_\rho\,,\ b,\ c$$

Symmetric nuclear matter $(\alpha = 0)$ Saturation density $(n = n_0)$

$$m_N^* = \gamma\, m_N\,, \qquad \sigma_0 = (1-\gamma)\, m_N$$

$$\left.\frac{d\varepsilon(n,\alpha)}{dn}\right|_{\substack{n=n_0\\ \alpha=0}} = \frac{\varepsilon(n_0,0)}{n_0} = m_N + f_0\,, \qquad f_0 = \frac{B}{A},$$ Binding energy per baryon

$$a_\omega = \frac{1}{n_0}\left(m_N + f_0 - \sqrt{k_F(n_0)^2 + (m_N - \sigma_0)^2}\right)$$

$$\omega_0 = a_\omega n_0 = m_N + f_0 - \sqrt{k_F(n_0)^2 + (m_N - \sigma_0)^2}$$

$$\frac{\sigma_0}{a_\sigma} = \frac{2}{\pi^2}\int_0^{k_F(n_0)} \frac{(m_N - \sigma_0)}{\sqrt{k^2 + (m_N - \sigma_0)^2}}\, k^2 dk \ - b m_N \sigma_0^{\,2} - c\sigma_0^{\,3}$$

Parameters of RMF theory

$$\varepsilon_0 = n_0(m_N + f_0) = \frac{2}{\pi^2}\int_0^{k_F(n_0)} \sqrt{k^2 + (m_N - \sigma_0)^2}\, k^2 dk + \frac{b}{3} m_N \sigma_0^3 + \frac{c}{4}\sigma_0^4 + \frac{1}{2}\left(\frac{\sigma_0^2}{a_\sigma} + n_0^2 a_\omega\right)$$

$$K = 9\, n_0^2 \frac{d^2}{dn^2}\left(\frac{\varepsilon(n,\alpha)}{n}\right)\Bigg|_{\substack{n=n_0\\ \alpha=0}}$$

compressibility module

$$\frac{\varepsilon_{sym}}{n} = E_{sym}(n)\,\alpha^2 \quad \Longrightarrow \quad E_{sym}(n) = \frac{1}{2n}\frac{d^2\varepsilon(n,\alpha)}{d\alpha^2}\Bigg|_{\alpha=0}$$

Symmetry energy

$m_N = 938{,}93\ MeV$

$n_0 = 0{,}153\ fm^{-3}$

$\gamma = \frac{m_N^*}{m_N} = 0{,}78$

$K = 300\ MeV$

$f_0 = -16{,}3\ MeV$

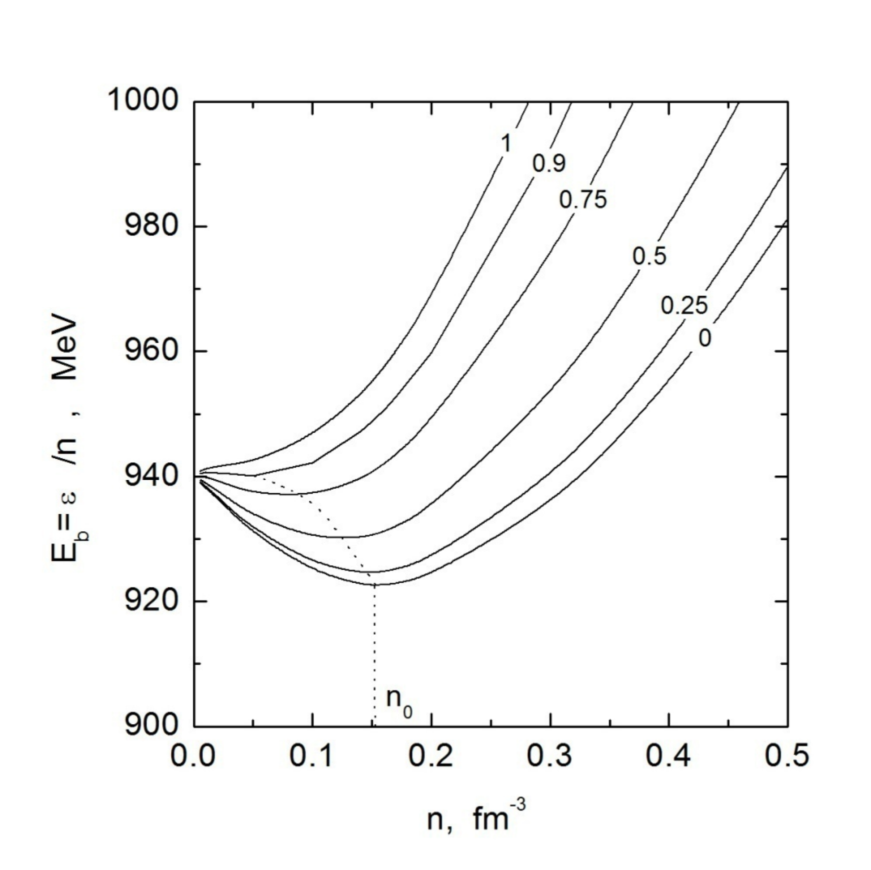
$E_{sym}^{(0)} = 32{,}5\ MeV$

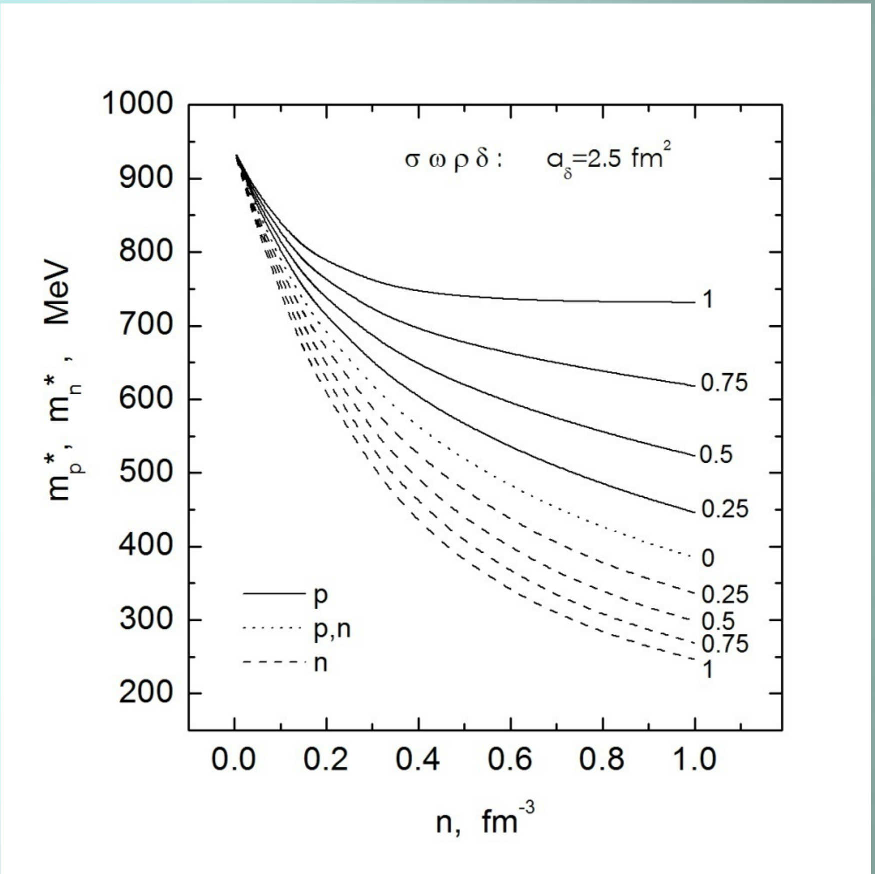
$a_\delta\ fm^2$	0	0,5	1	1,5	2	2.5	3
$a_\rho\ fm^2$	4,794	6,569	8,340	10,104	11,865	13,621	15,372

Parameters of RMF theory

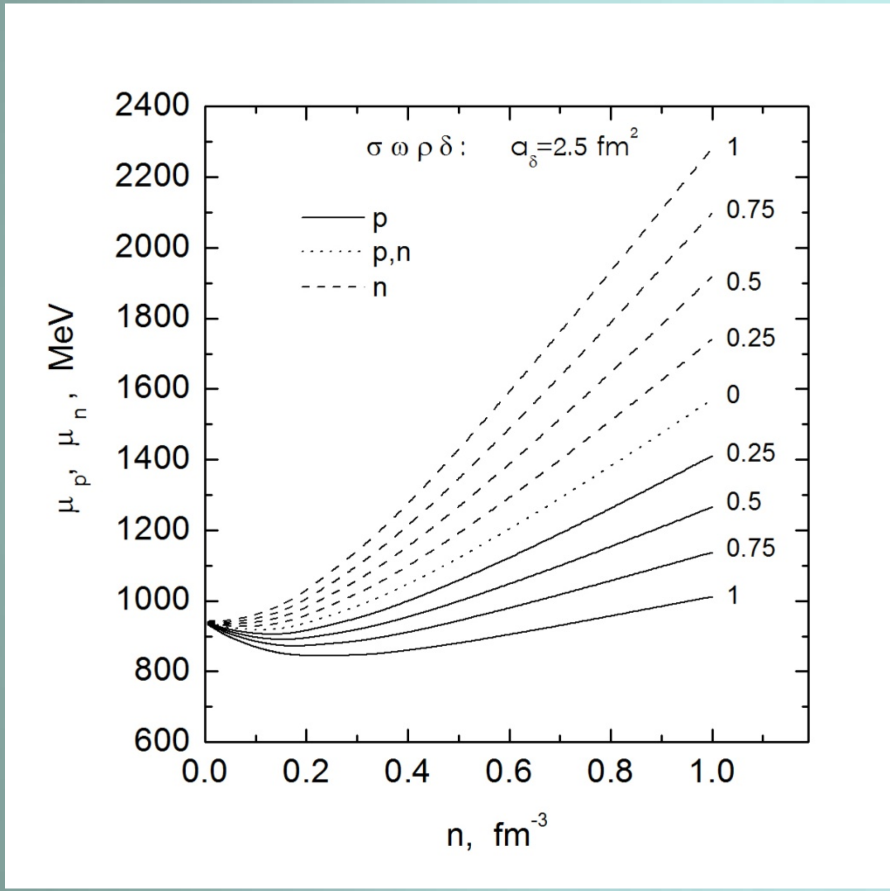
Parameters	$\sigma\omega\rho$	$\sigma\omega\rho\delta$
a_σ , fm^2	9.154	9.154
a_ω , fm^2	4.828	4.828
a_δ , fm^2	0	2.5
a_ρ, fm^2	4.794	13.621
b , fm^{-1}	$1.654\ 10^{-2}$	$1.654\ 10^{-2}$
c	$1.319\ 10^{-2}$	$1.319\ 10^{-2}$

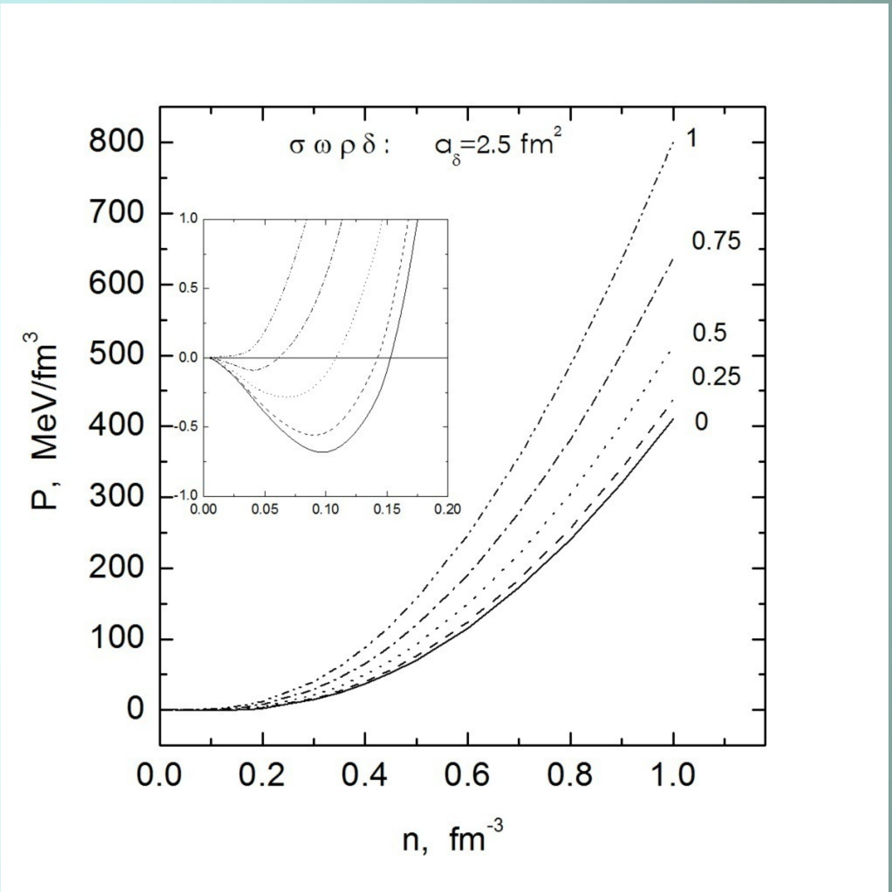
Properties of asymmetric nuclear matter





Properties of asymmetric nuclear matter

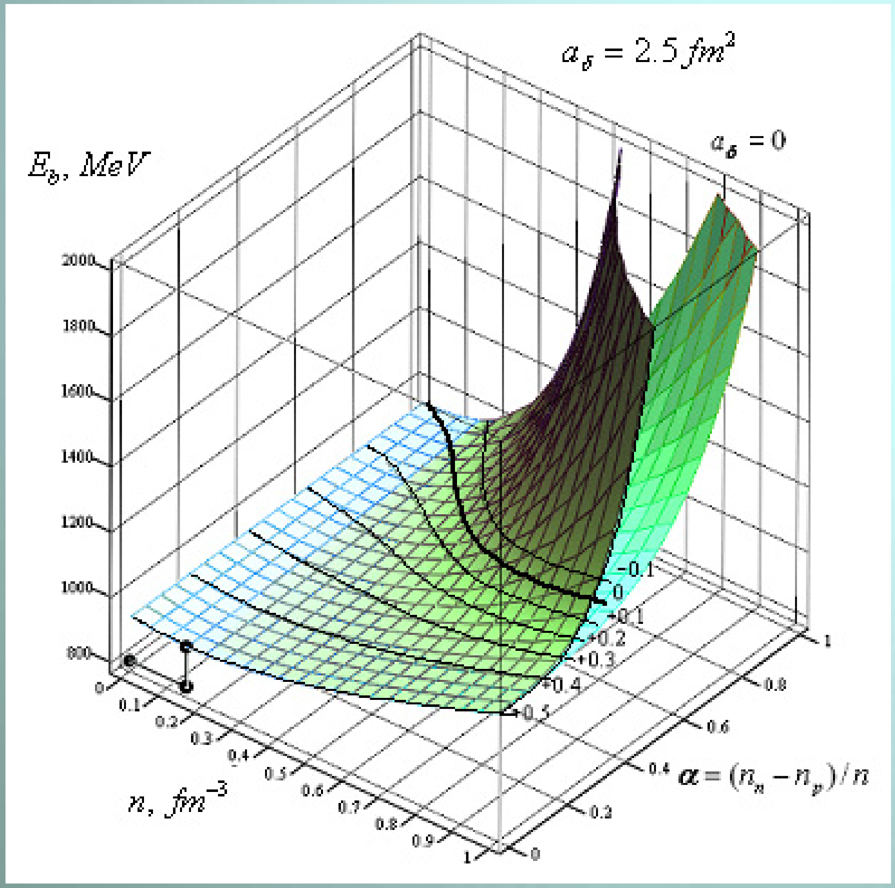




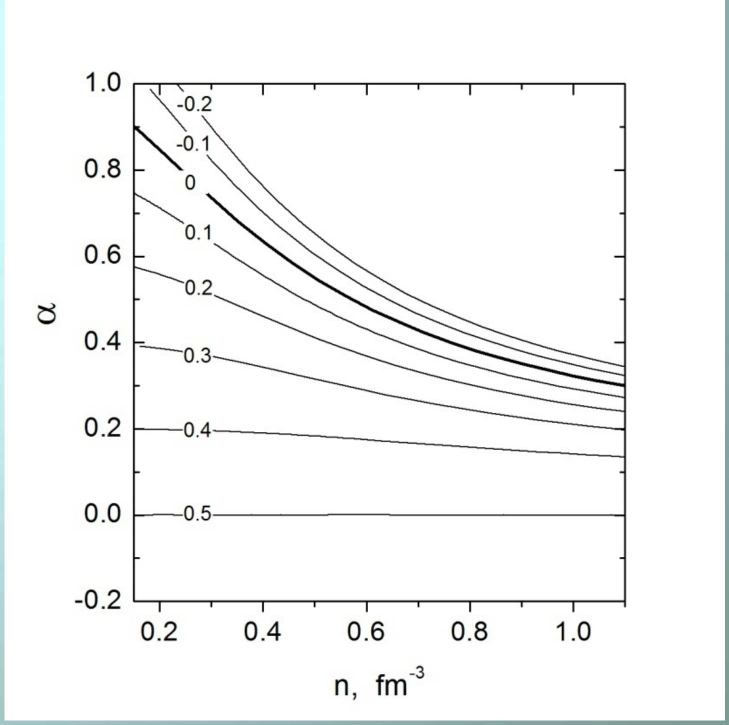
Characteristics of β-equilibrium npe- plasma

$$\varepsilon_{NM}(n,\alpha,\mu_e) = \varepsilon(n,\alpha) + \varepsilon_e(\mu_e),$$

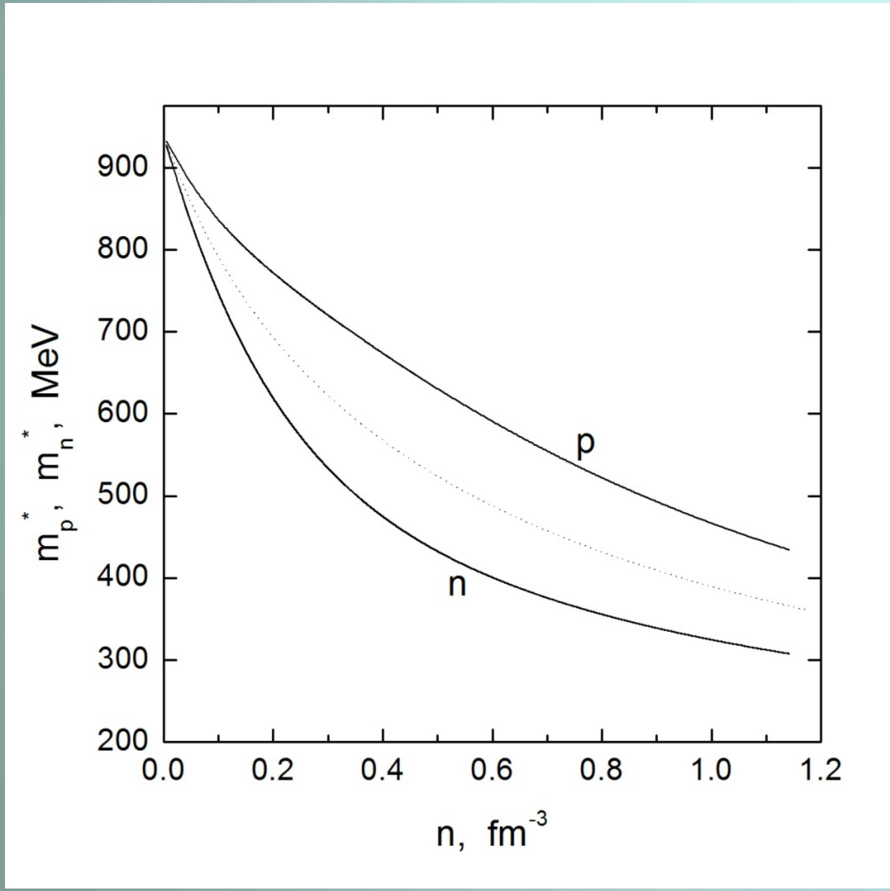
$$P_{NM}(n,\alpha,\mu_e) = P(n,\alpha) + \frac{1}{3\pi^2}\mu_e(\mu_e{}^2 - m_e{}^2)^{3/2} - \varepsilon_e(\mu_e)$$

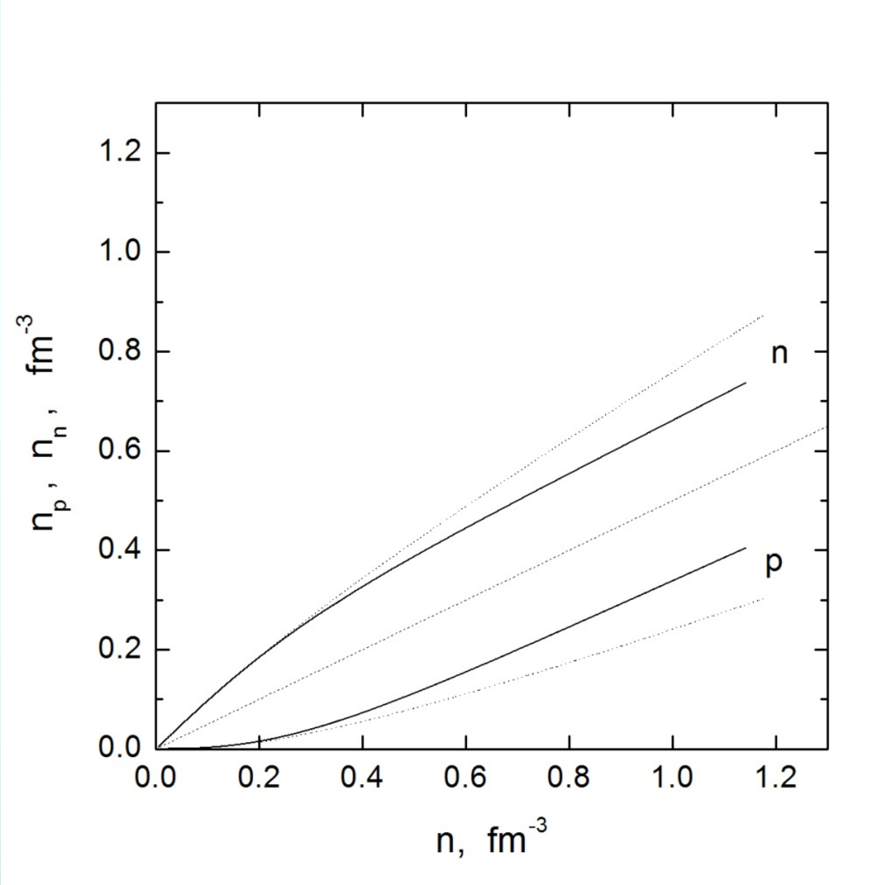


$$q = \frac{n_p - n_e}{n} = \frac{1}{2}(1-\alpha) - \frac{n_e}{n}$$

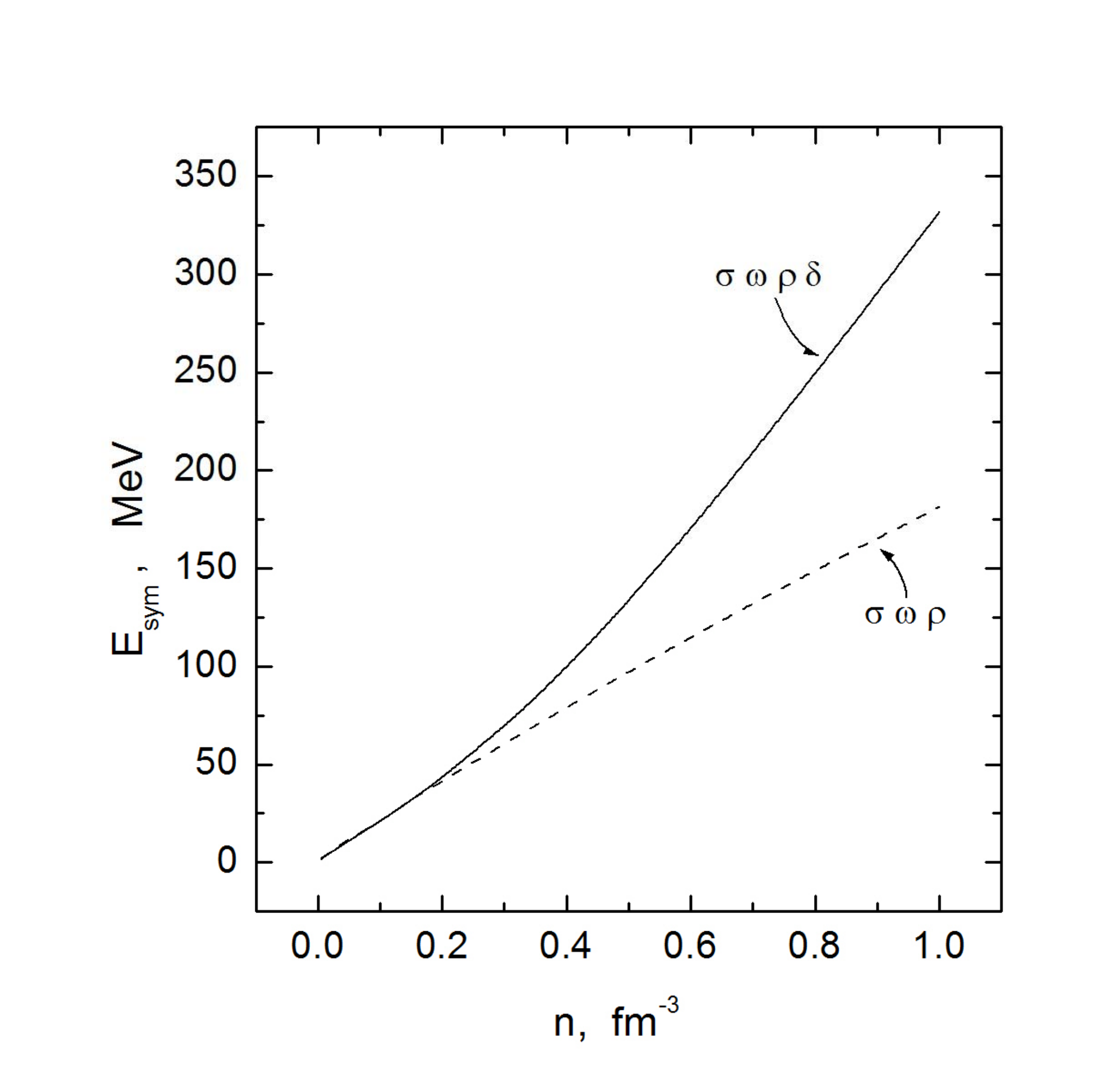


Characteristics of charge neutral and β-stable npe- plasma

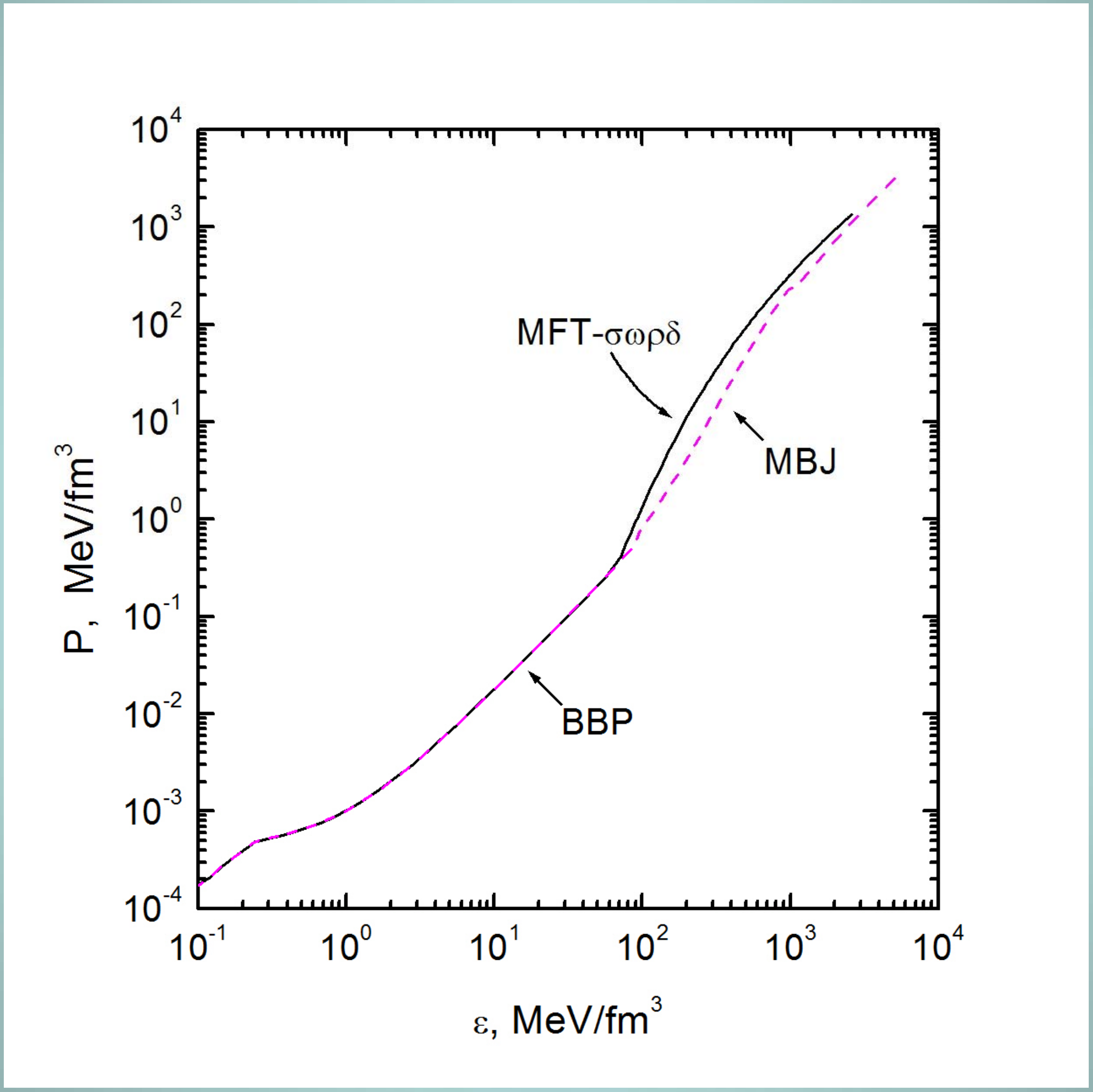




Symmetry energy



EOS of neutron star matter in nucleonic phase



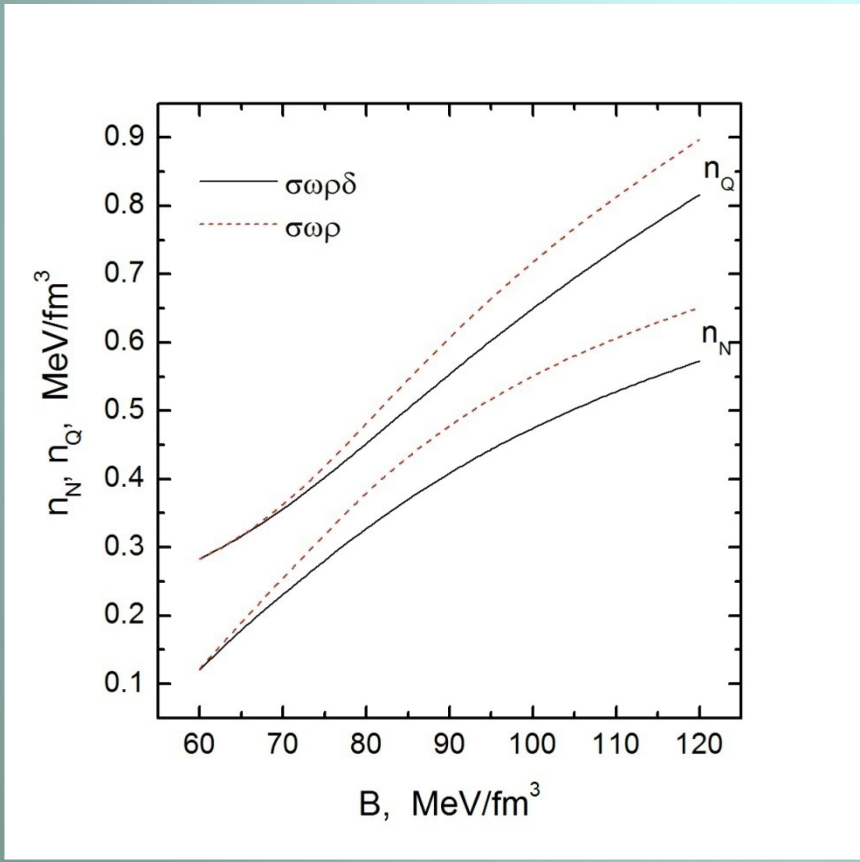
Parameters of deconfinement phase transition

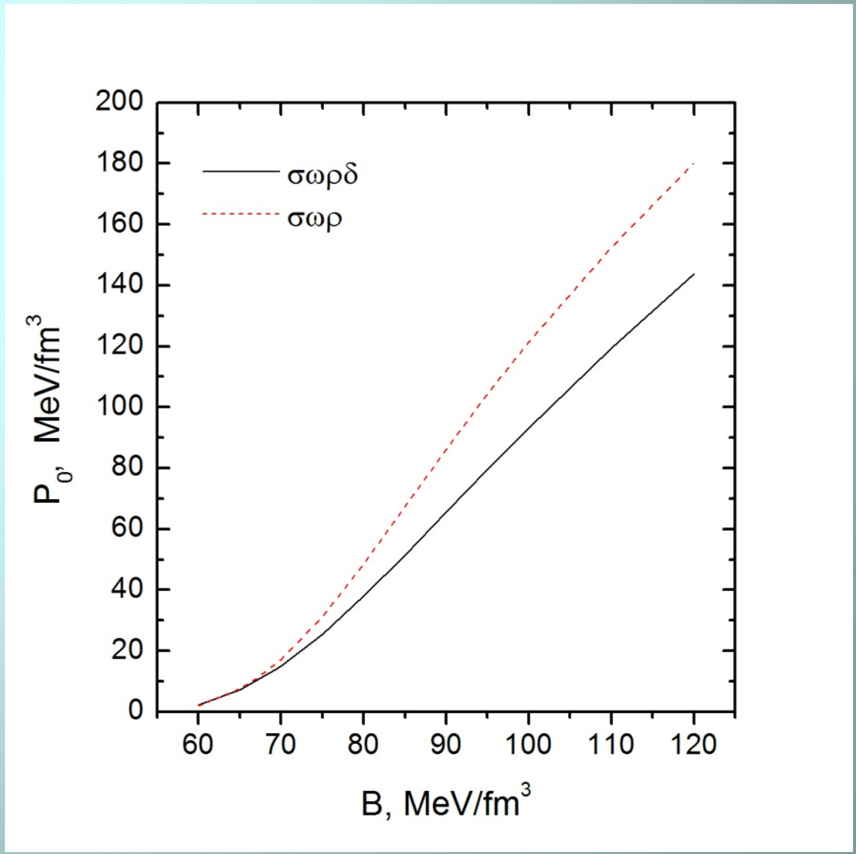
MFTσωρδ + MIT-bag $\alpha_s = 0.5\,,\ m_u = 5\ MeV\,,\quad m_d = 7\ MeV\,,\quad m_d = \ 150\ MeV$

$$\mu_{NM}(P_0) = \mu_{QM}(P_0)$$

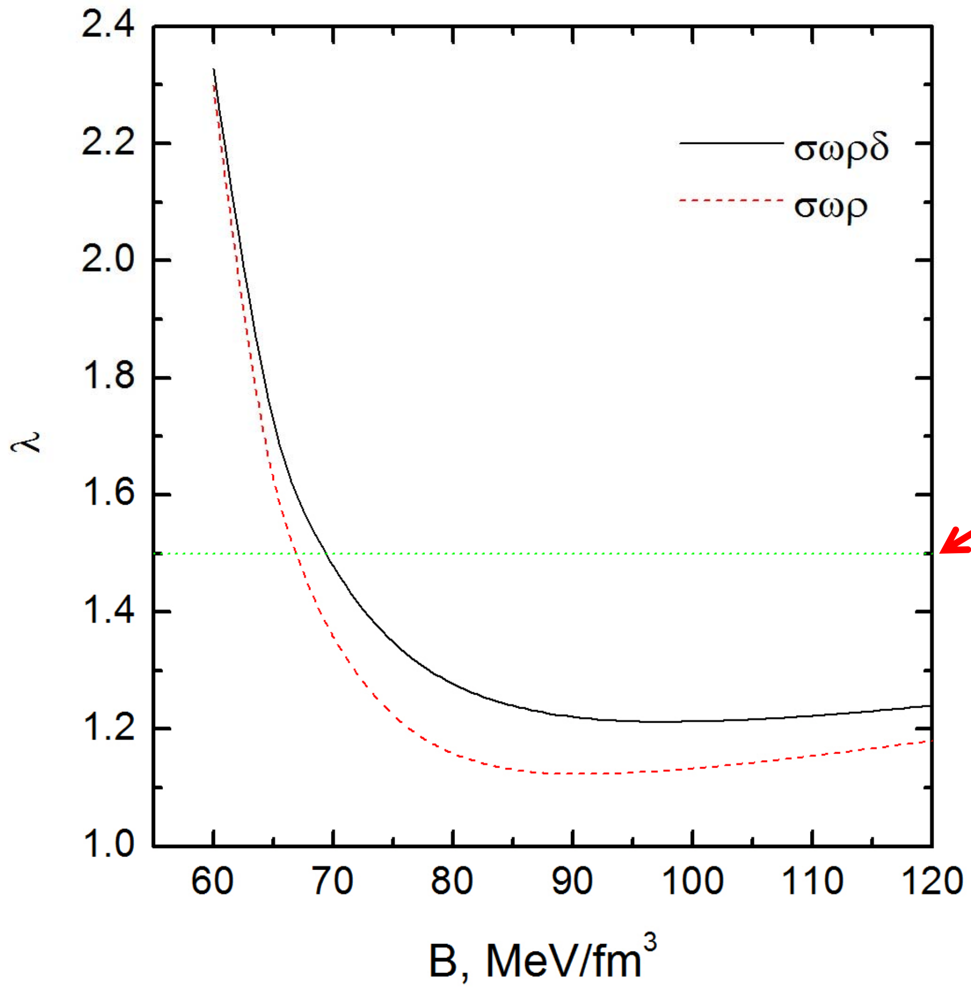
Maxwell's construction

B - bag parameter





Parameters of deconfinement phase transition



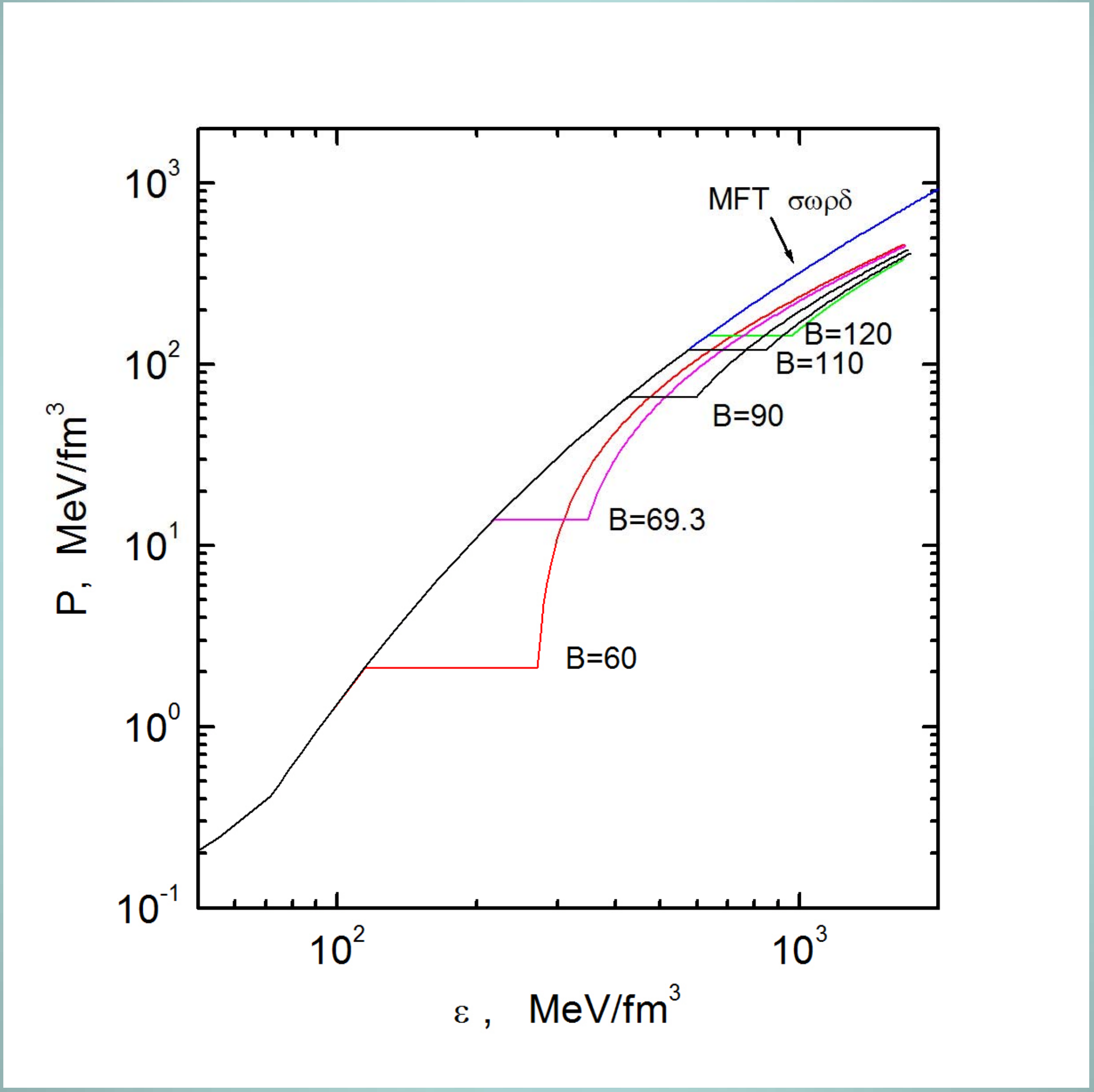
$$\lambda = \frac{\varepsilon_Q}{\varepsilon_N + P_0}$$

$$\lambda_{cr} = 3/2$$

Seidov criterium

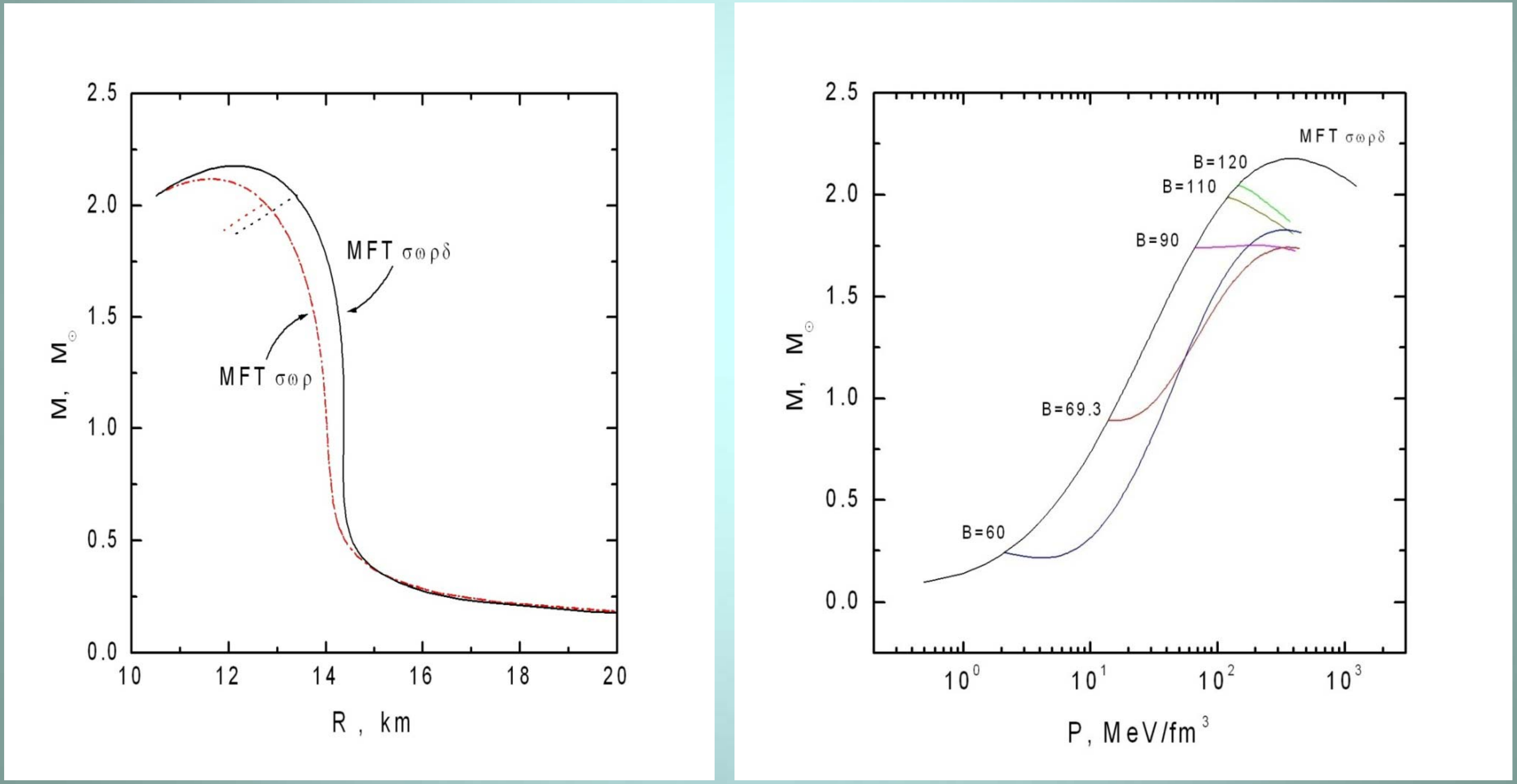
Z Seidov, Ast.Zh., 48, 443,1971

EOS with quark deconfined phase transition

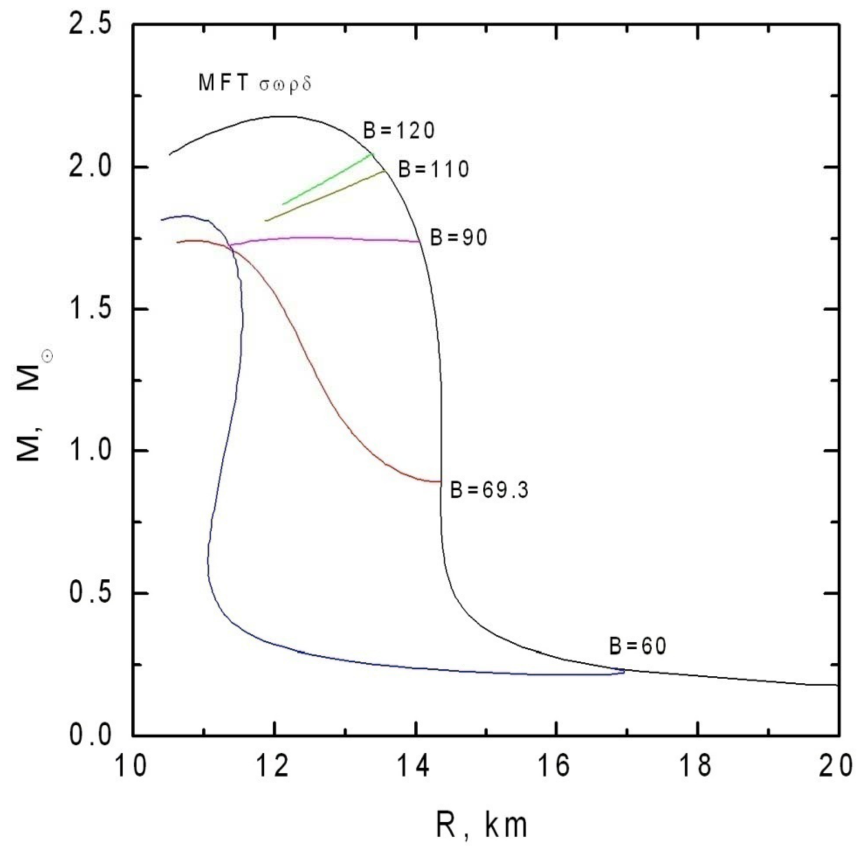


Neutron stars with quark core

TOV equations



Neutron stars with quark core



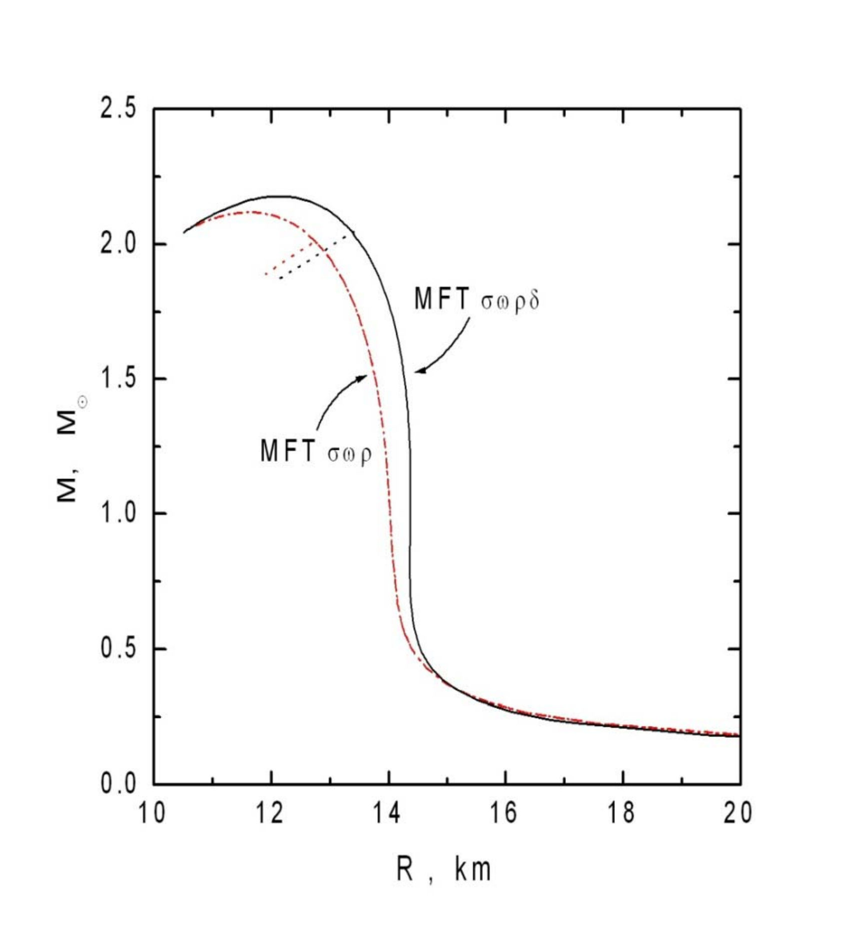
$\lambda > 3/2 \longrightarrow B < 69,3$ MeV/fm^3

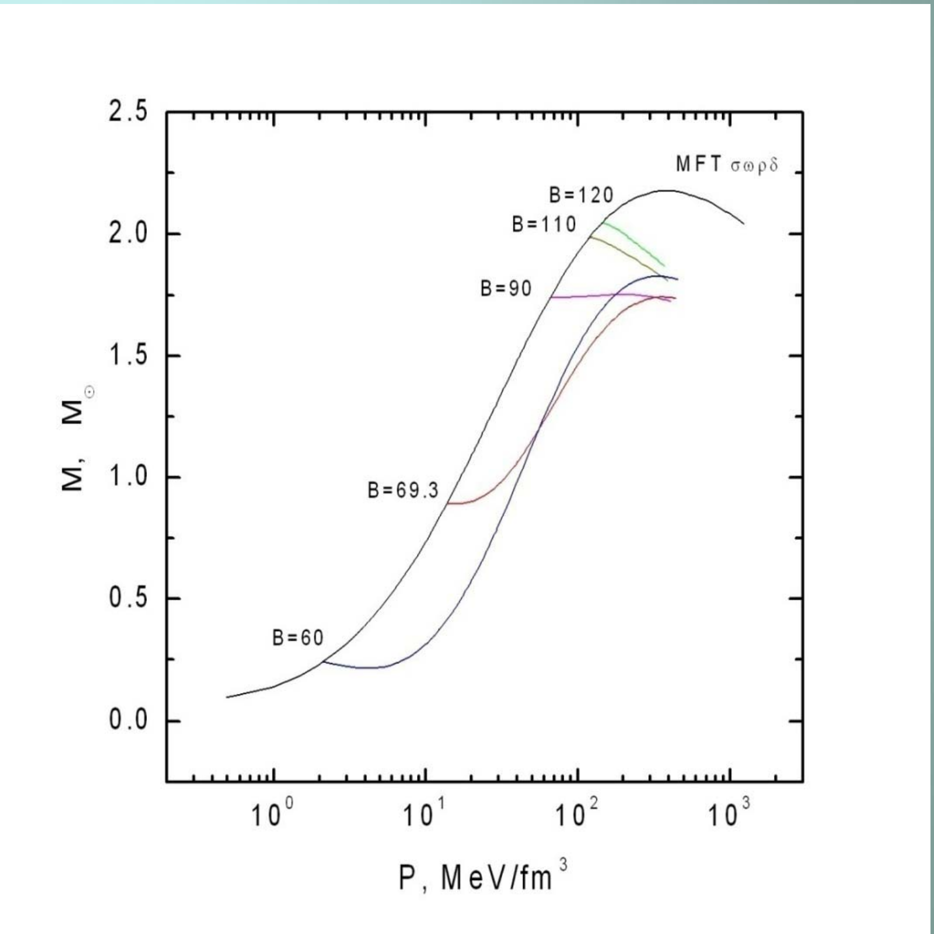
$\lambda_{cr} = 3/2 \longrightarrow B \approx 69,3$ MeV/fm^3

$\lambda \leq 3/2 \longrightarrow 69,3 \leq B \leq 90$ MeV/fm^3

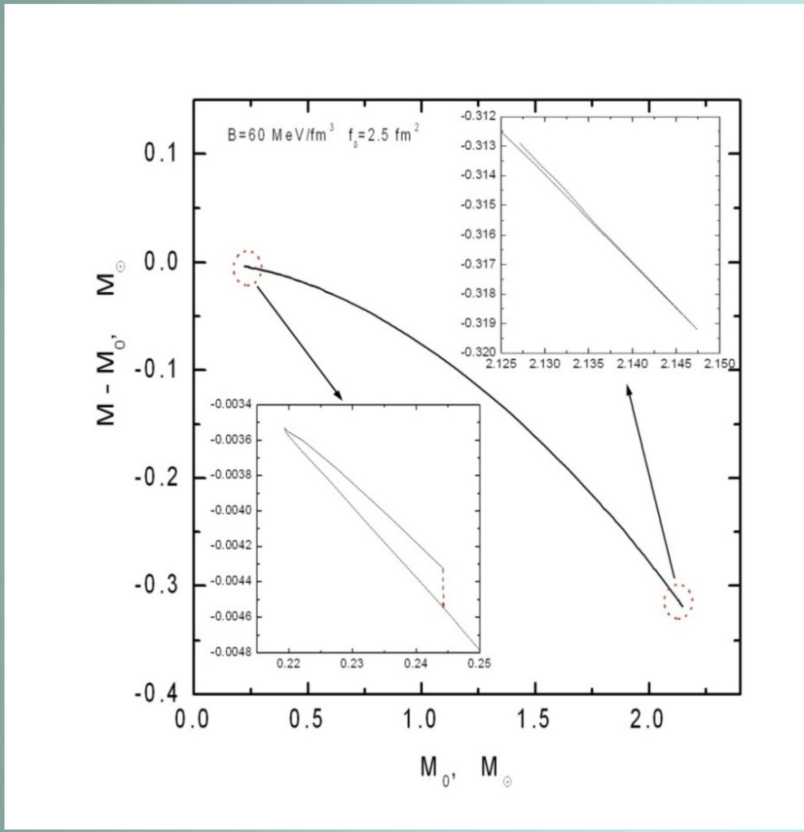
$B > 90$ MeV/fm^3 Unstable QP

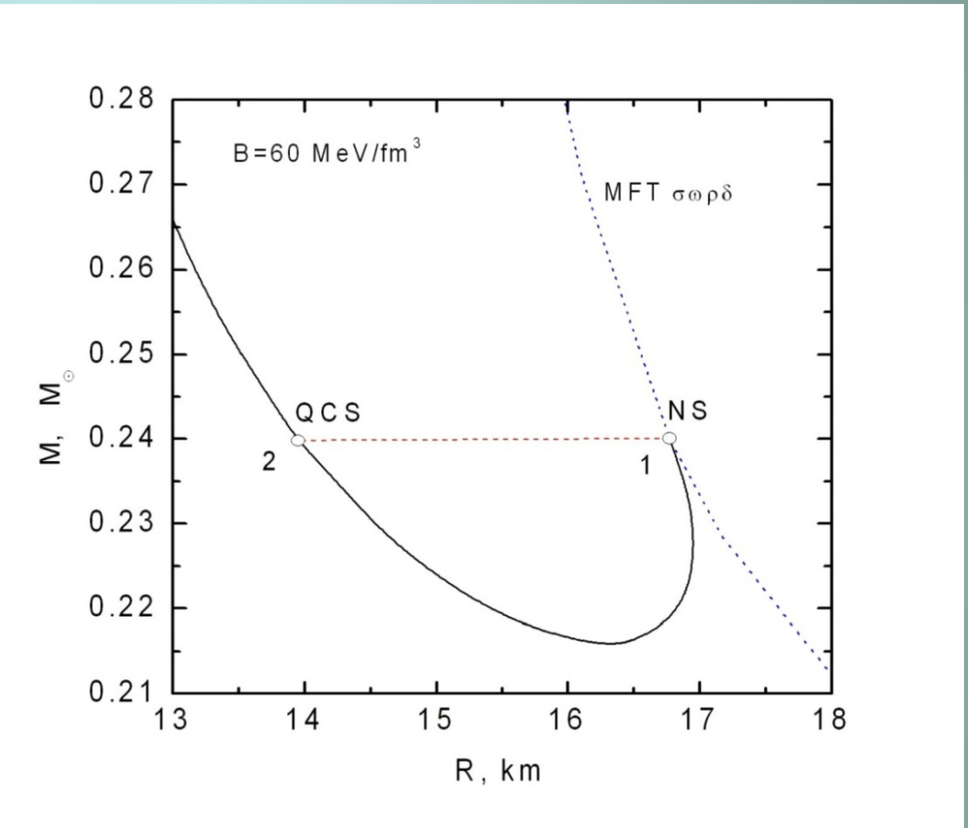
Neutron stars with quark core





Catastrophic conversion due to deconfined phase transition





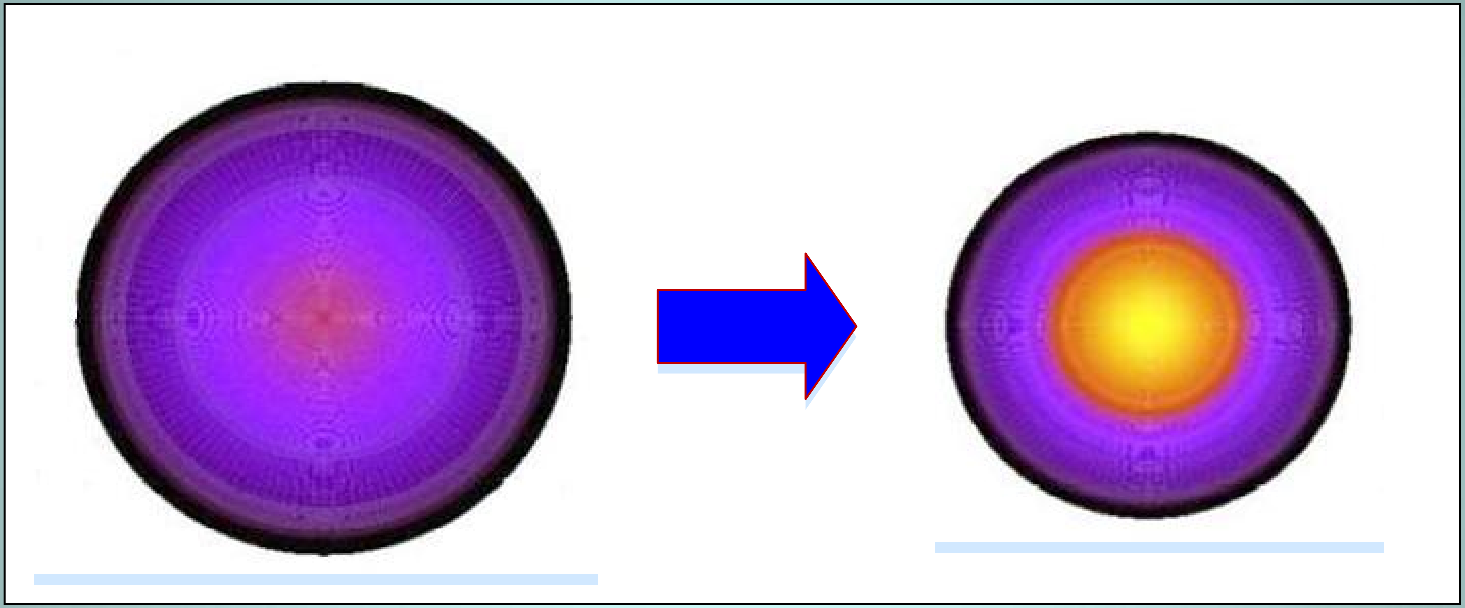
$$M \approx 0.24\, M_\odot$$
$$R \approx 16,77 \text{ km}$$

$$M_{core} \approx 0.087\, M_\odot$$
$$R_{core} \approx 4,38 \text{ km}$$
$$R \approx 13,95 \text{ km}$$

$$E_{conv} \approx 4 \cdot 10^{50}\, erg$$

Catastrophic conversion due to deconfined phase transition

$$M \approx 0.24\, M_{\odot}$$



$$R \approx 16.75\ km$$

$$M_{core} \approx 0.087\, M_{\odot}$$

$$R_{core} \approx 4.38\ km$$

$$R \approx 13.95\ km$$

Summary

- The account of δ-meson field results in reduction of phase transition parameters, P_0, n_N, n_Q
- The density jamp parameter λ, that has important significance from the point of view of infinitisimal quark core stability in neutron star, is increased.
- In case of bag parameter values $B < 69.3\ MeV/fm^3$ the condition $\lambda > 3/2$ is satisfied, and infinitisimal quark core is unstable.
- For $B > 90\ MeV/fm^3$ the quark phase is unstable.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THANK YOU