Hadron-Quark phase transition in high-mass neutron stars

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PRO SCIENTIA ET PATRIA

IV IWARA 2013

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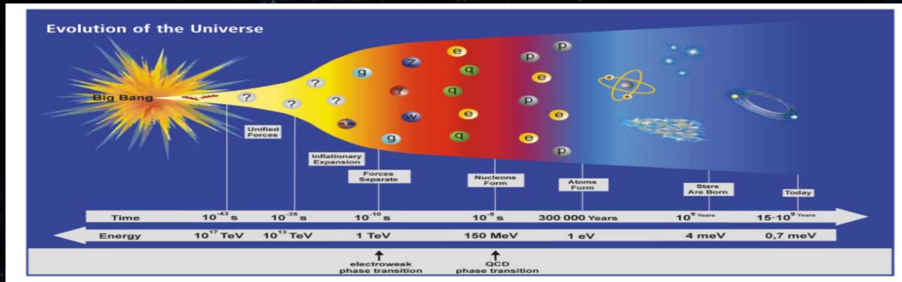
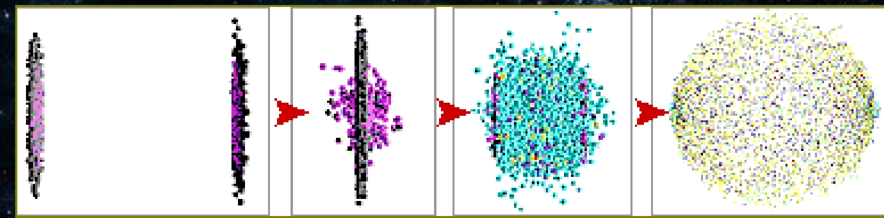
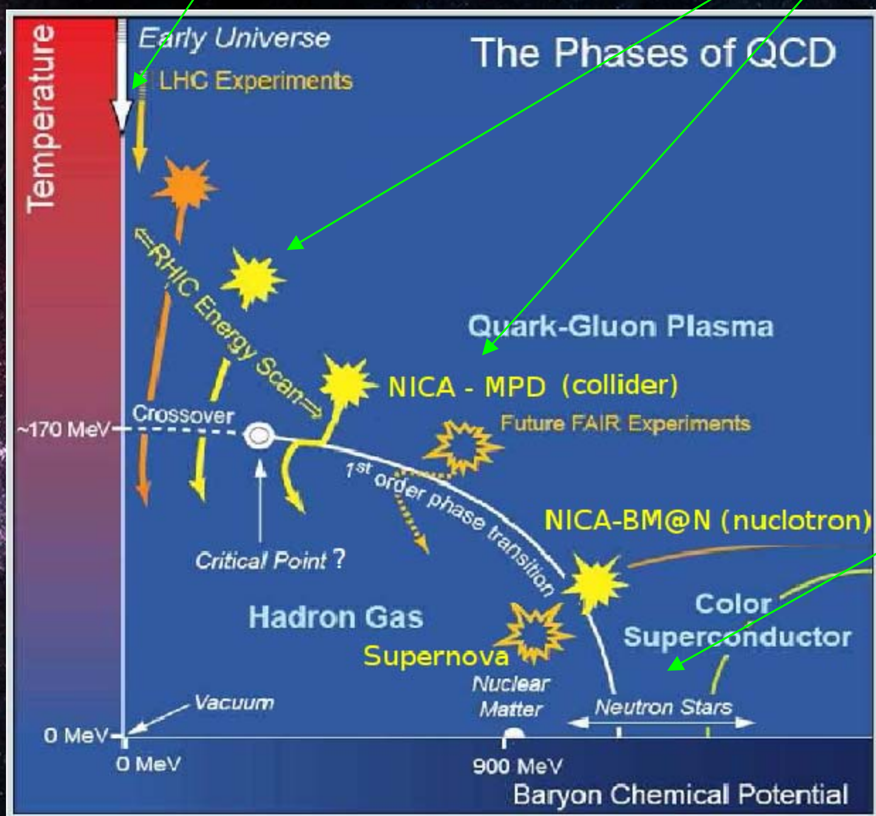
Motivation

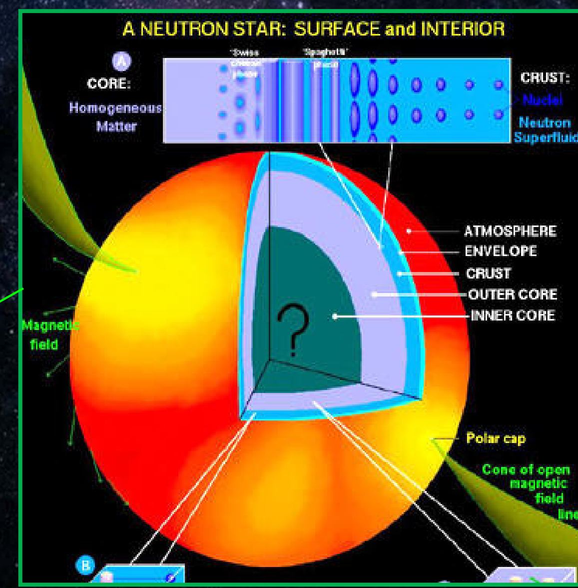
Cosmology





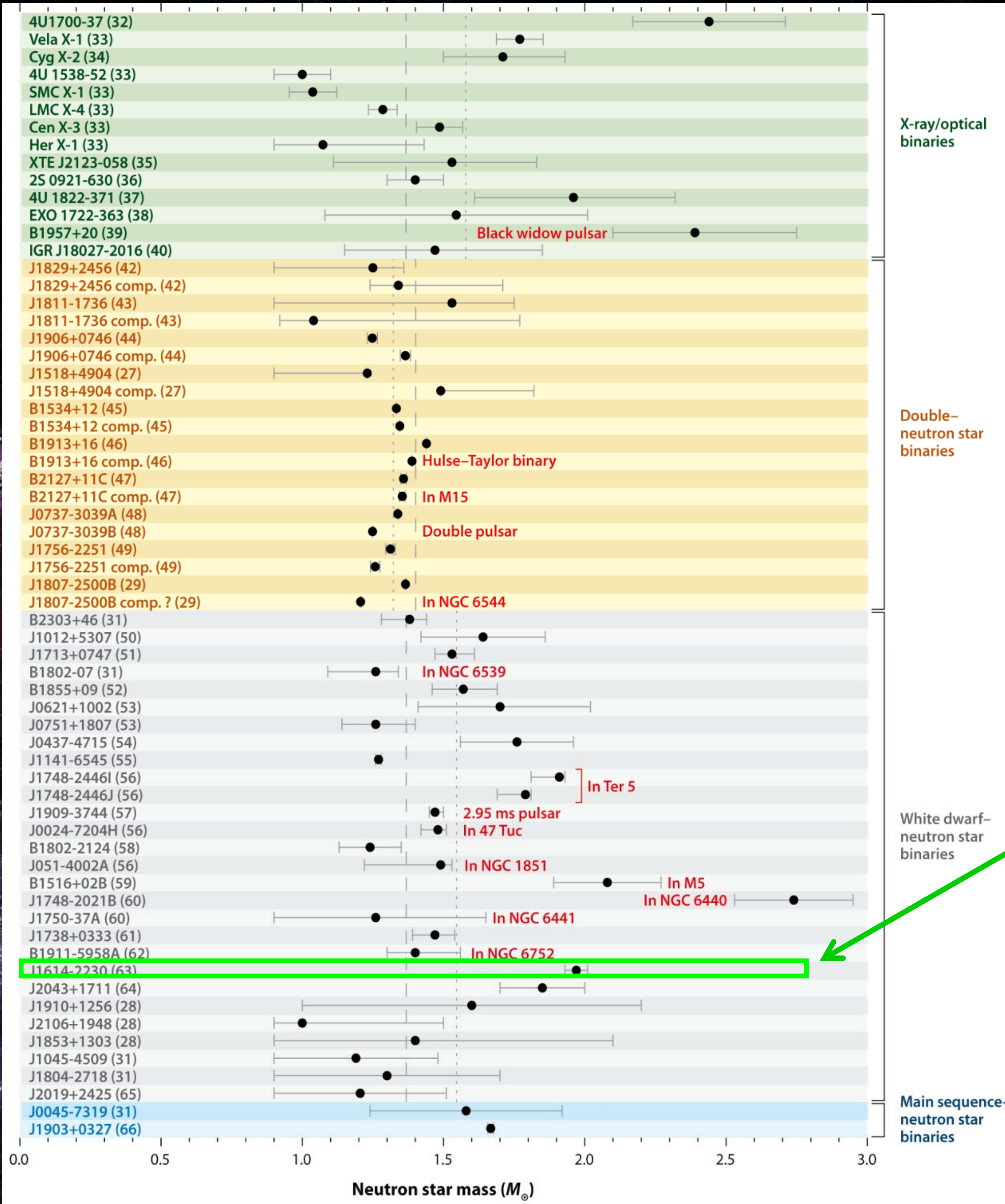
Heavy ion and p^+-p^+ collisions
(RHIC, LHC, FAIR, NICA ...)



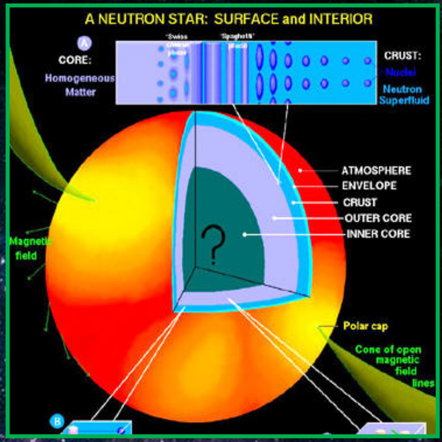


Compact stars astrophysics

QCD Phase Diagram?



Lattimer JM. 2012.
Annu. Rev. Nucl. Part. Sci. 62:485–515



PSR J1614 – 2230
(M = 1.97 ± 0.04 M_{sun})

Demorest et al.

Nature 467, 1081 (2010).

Motivation

- Recent high precision determination of two high mass Neutron Stars (NS) J1614-2230 ($1.97\pm0.04\ M_{Sun}$) [1] and J0348+0432 ($2.01\pm0.04\ M_{Sun}$) [2].

[1] P. B. Demorest et al, Nature 467, 1081 (2010).
[2] L. Antoniadis et al, Science 340, 6131 (2013).

- What are the fundamental building blocks in the core of such stars?
- Does quark deconfinement occur?

How could we modelate matter under such conditions?

- We have analyzed the global structure and composition of massive NSs in the framework of a non-local 3-flavor NJL model (n3NJL) for quark matter and a non-linear relativistic model for hadronic matter [3,4].

[3] M. Orsaria, H. Rodrigues, F. Weber, G. A. Contrera, Phys. Rev. D 87, 023001 (2013).
[4] M. Orsaria, H. Rodrigues, F. Weber, G. A. Contrera, arXiv:1308.1657 [nucl-th].

Quark Phase: Local vs. Non-local NJL models

Local NJL	Non-local NJL model
• Lack of confinement	• Confinement with a proper choice of the non-local regulator and model parameters [1]
• Quark-quark scalar-isoscalar and pseudoscalar-isovectorial local interaction	• Quark-quark interaction through phenomenologically effective quark propagator
• Non-renormalizable. Ultra-violet (UV) cutoff Λ is needed	• UV divergences are fixed [2] Model dependent form factor $g(p)$
• Dynamical quark masses are momentum independent	• Dynamical quark masses are momentum dependent as also found in lattice calculations of QCD [3]
• Divergences in the meson loop integrals. Extra cutoffs are needed.	• The momentum dependent regulator makes the theory finite to all orders in the $1/N_c$ expansion [4]
• The cutoff Λ is turned off at high momenta, limiting the applicability of the model at high densities	• The form factor provides a natural cutoff that falls off at high momenta

[1] Bowler & Birse, Nucl. Phys. A 582, 655 (1995); Plant & Birse, Nucl. Phys. A 628, 607 (1998);
[2] G. Ripka, Quarks bound by chiral fields (Oxford University Press, Oxford, 1997);
[3] Parappilly et al., Phys. Rev. D 73, 054504 (2006);
[4] D. Blaschke et al., Phys. Rev. C 53, 2394 (1996).

Quark Phase: n3NJL

Euclidean effective action including vector interaction

$$S_E = \int d^4x \left\{ \bar{\psi}(x)\left[-i\partial\!\!\!/ + \hat{m}\right]\psi(x) - \frac{G_S}{2}\left[j_a^S(x)\, j_a^S(x) + j_a^P(x)\, j_a^P(x)\right] - \frac{H}{4}\, T_{abc}\left[j_a^S(x) j_b^S(x) j_c^S(x) - 3\, j_a^S(x) j_b^P(x) j_c^P(x)\right] - \frac{G_V}{2} j_V^\mu(x) j_V^\mu(x) \right\}$$

$$j_a^S(x) = \int d^4z\, \widetilde{g}(z)\, \bar{\psi}\left(x + \frac{z}{2}\right)\ \lambda_a\ \psi\left(x - \frac{z}{2}\right)\ ,$$

$$j_a^P(x) = \int d^4z\, \widetilde{g}(z)\, \bar{\psi}\left(x + \frac{z}{2}\right)\ i\,\gamma_5\lambda_a\ \psi\left(x - \frac{z}{2}\right)$$

$$j_V^\mu(x) = \int d^4z\, \widetilde{g}(z)\, \bar{\psi}\left(x + \frac{z}{2}\right)\ \gamma^\mu\ \psi\left(x - \frac{z}{2}\right),$$

Form factor responsible for the non-local interaction

After the standard bosonization of the Euclidean action…

$$\Omega^{NL}(M_f,0,\mu_f) = -\frac{N_c}{\pi^3}\sum_{f=u,d,s}\int_0^\infty dp_0\int_0^\infty dp\,\ln\left\{\left[\widehat{\omega}_f^2 + M_f^2(\omega_f^2)\right]\frac{1}{\omega_f^2+m_f^2}\right\}$$
$$-\frac{N_c}{\pi^2}\sum_{f=u,d,s}\int_0^{\sqrt{\mu_f^2-m_f^2}} dp\,p^2\,\left[(\mu_f-E_f)\theta(\mu_f-m_f)\right] - \frac{1}{2}\left[\sum_{f=u,d,s}\left(\bar{\sigma}_f\,\bar{S}_f + \frac{G_S}{2}\,\bar{S}_f^2\right) + \frac{H}{2}\bar{S}_u\,\bar{S}_d\,\bar{S}_s\right] - \sum_{f=u,d,s}\frac{\varpi_f^2}{4G_V}$$

$$N_c = 3,\; E_f = \sqrt{p^2+m_f^2},\text{ and } \omega_f^2 = (\,p_0 + i\,\mu_f\,)^2 + \;p^2$$

$$M_f(\omega_f^2) \;=\; m_f + \bar{\sigma}_f\, g(\omega_f^2)$$

$$\mu_f \;\rightarrow \widehat{\mu}_f = \mu_f - g(\omega_f^2)\varpi_f$$

$$g(\omega_f^2) = \exp\left(-\omega_f^2/\Lambda^2\right)$$

$$\omega_f^2 \;\rightarrow \widehat{\omega}_f^2 = (\,p_0 \;+\; i\,\widehat{\mu}_f\,)^2 \;+\; p^2$$

$$\bar{S}_f = -\,16\,N_c\int_0^\infty dp_0\int_0^\infty \frac{dp}{(2\pi)^3}\, g(\omega_f^2)\,\frac{M_f(\omega_f^2)}{\widehat{\omega}^2 + M_f^2(\omega_f^2)}$$

$$\frac{\partial\Omega^{NL}}{\partial\bar{\sigma}_f} = 0\,, \qquad \frac{\partial\Omega^{\mathrm{NL}}}{\partial\varpi_f} = 0$$

Hadronic Phase

- Non-linear Relativistic Mean Field approximation

$$\mathcal{L} = \mathcal{L}_H + \mathcal{L}_\ell$$

$$\mathcal{L}_\ell = \sum_{\lambda = e^-, \mu^-} \bar{\psi}_\lambda (i\gamma_\mu \partial^\mu - m_\lambda)\psi_\lambda$$

$$\begin{aligned}\mathcal{L}_H = & \sum_{B=n,p,\Lambda,\Sigma,\Xi} \bar{\psi}_B \left[\gamma_\mu (i\partial^\mu - g_\omega \omega^\mu - g_\rho \vec{\rho}_\mu) - (m_N - g_\sigma \sigma)\right]\psi_B \\ & + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - \frac{1}{3} b_\sigma m_N (g_\sigma \sigma)^3 - \frac{1}{4} c_\sigma (g_\sigma \sigma)^4 \\ & - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu - \frac{1}{4}\vec{\rho}_{\mu\nu}\vec{\rho}^{\mu\nu}\end{aligned}$$

- Full baryon octet: p, n, Λ, Σ^+, Σ^+, Σ^0, Ξ^-, Ξ^0
- Mesons: σ, ω, ρ
- Leptons: e^-, μ^-

Hadronic Phase

Coupling constants	Parametrizations		
	GM1	GM3	NL3
g_σ	8.910	8.175	10.217
g_ω	10.610	8.172	12.868
g_ρ	8.196	8.259	8.948
b_σ	0.002947	0.008659	0.002055
c_σ	-0.001070	-0.002421	-0.002651

	Parametrizations		
Properties	GM1	GM3	NL3
ρ_0 (fm^{-3})	0.153	0.153	0.148
E/N (MeV)	-16.3	-16.3	-16.3
K (MeV)	300	240	272
m^*/m_N	0.78	0.70	0.60
a_{sy} (MeV)	32.5	32.5	37.4

[1] N. K. Glendenning, S. A. Moszkowski, Phys. Rev. Lett, 67, 2414 (1991).
[2] G. A. Lalazissis, J. Konig, P. Ring, Phys. Rev. C 55, 540 (1997).

Mixed Quark-Hadron Phase: Gibbs conditions

$$P^H(\mu_b^H, \mu_e^H, \{\phi\}) = P^q(\mu_b^q, \mu_e^q, \{\psi\})$$

$$\mu_b^H = \mu_b^q$$

$$\mu_e^H = \mu_e^q$$

$$n_b = (1-\chi)n_b^H + \chi n_b^q$$

$$\mu_b = 1/3 \sum_f \mu_f$$

$$\varepsilon = (1-\chi)\varepsilon^H + \chi\varepsilon^q$$

$$\mu_f = \mu_b - Q\mu_e$$

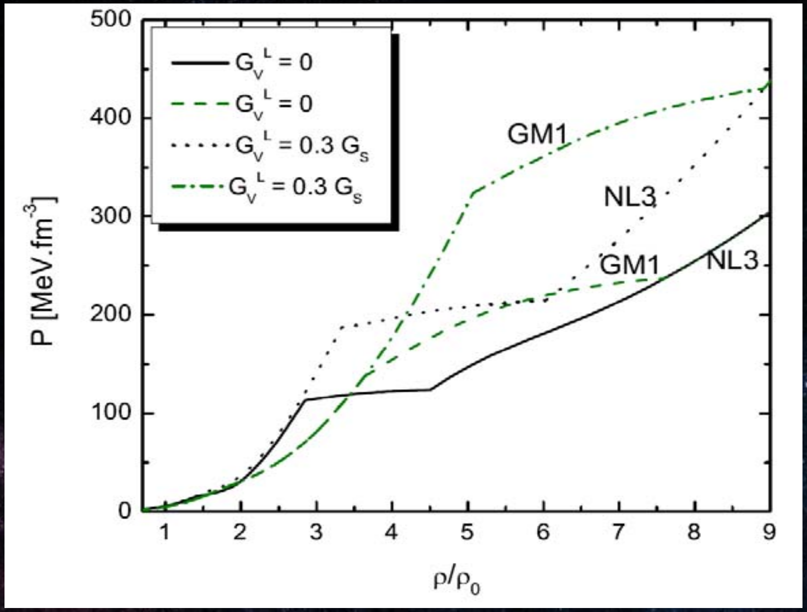
$$\chi = \frac{n^q}{(n^q + n^H)}$$

$$Q = \mathrm{diag}(2/3, -1/3, -1/3)$$

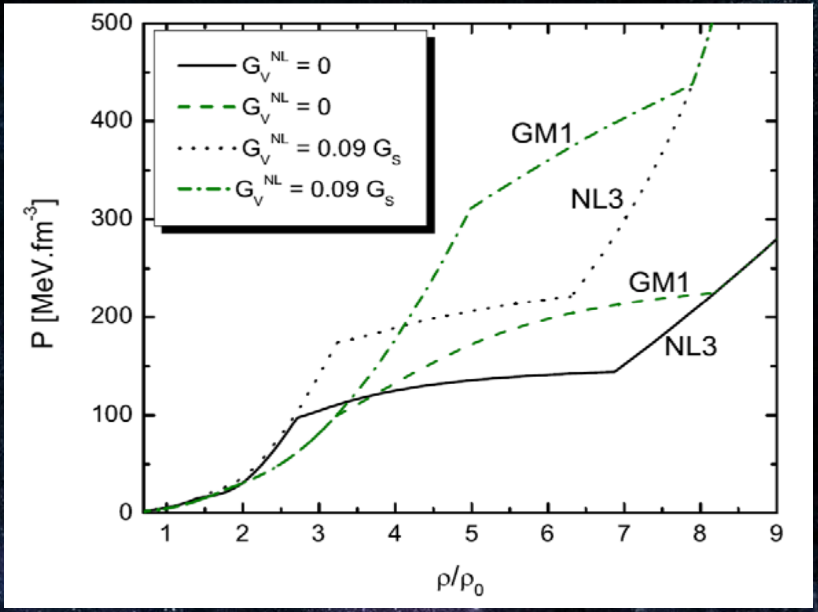
Global electric charge neutrality

$$(1-\chi) \sum_{i=B,l} q_i^H \, n_i^H + \chi \sum_{i=q,l} q_i^q \, n_i^q = 0$$

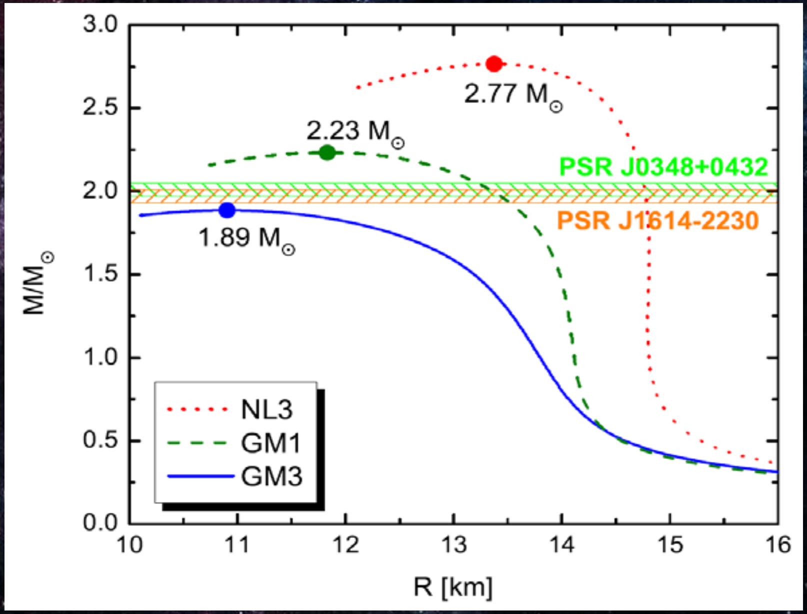
EoS for Local NJL model



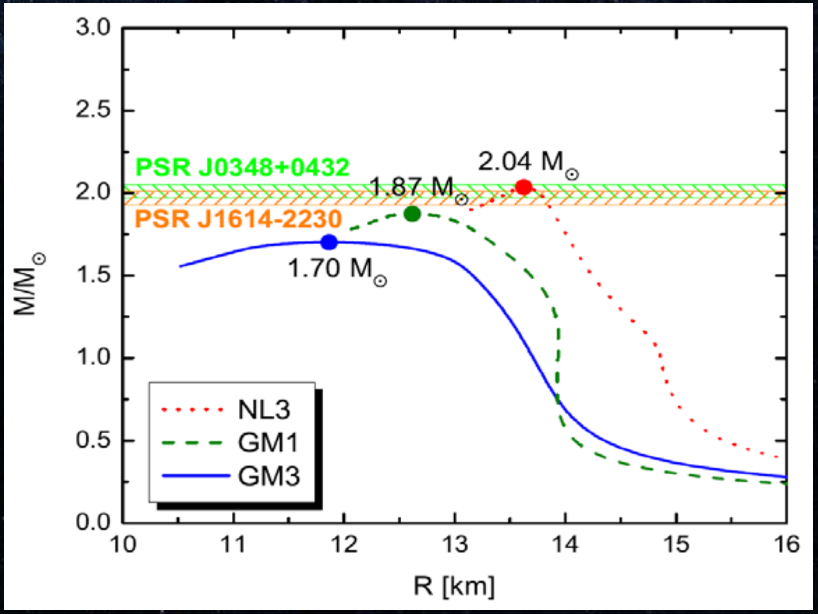
EoS for non-local NJL model



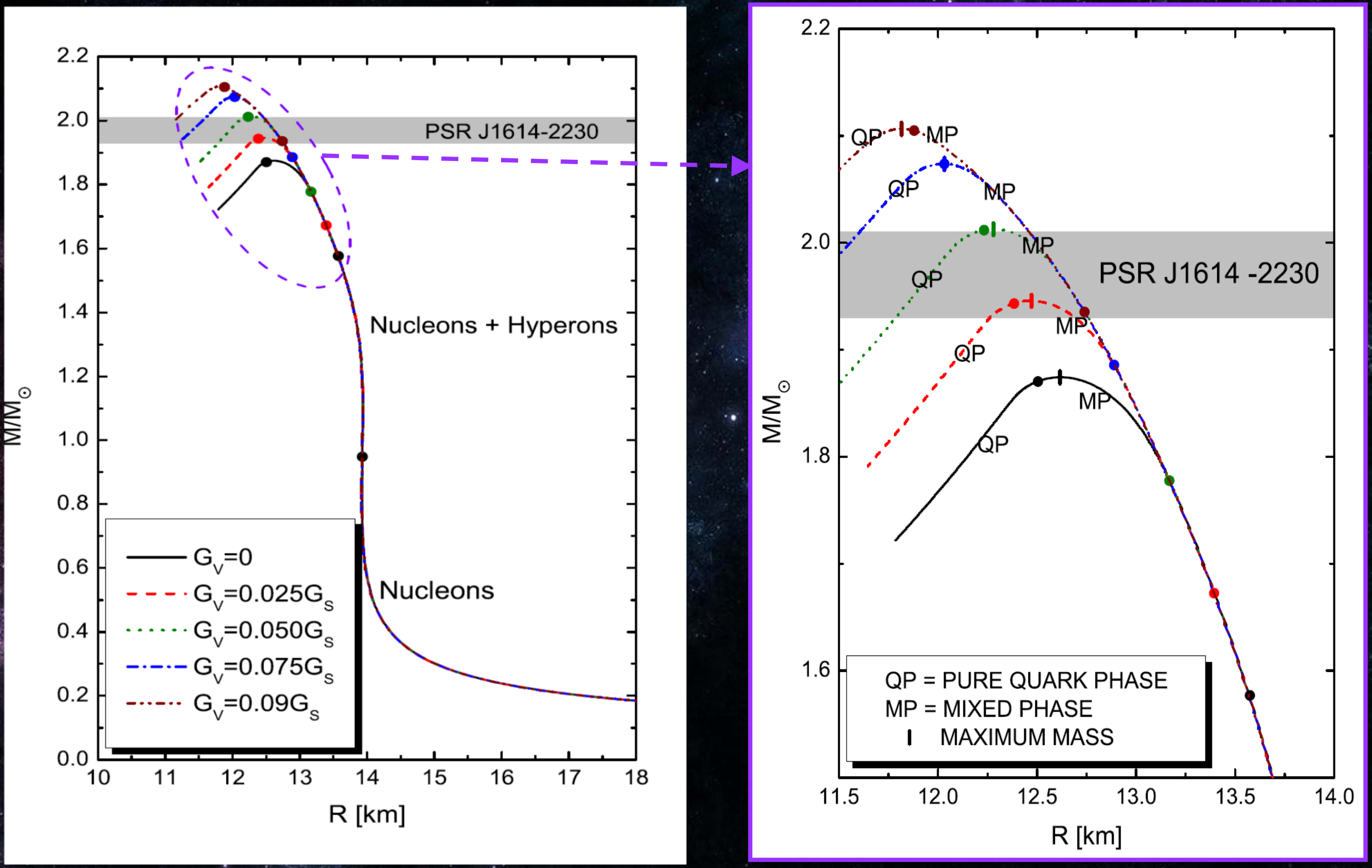
pure Hadronic stars



stars with a mixed phase (hadrons+quarks)



Vector interactions and Mass - Radius relation



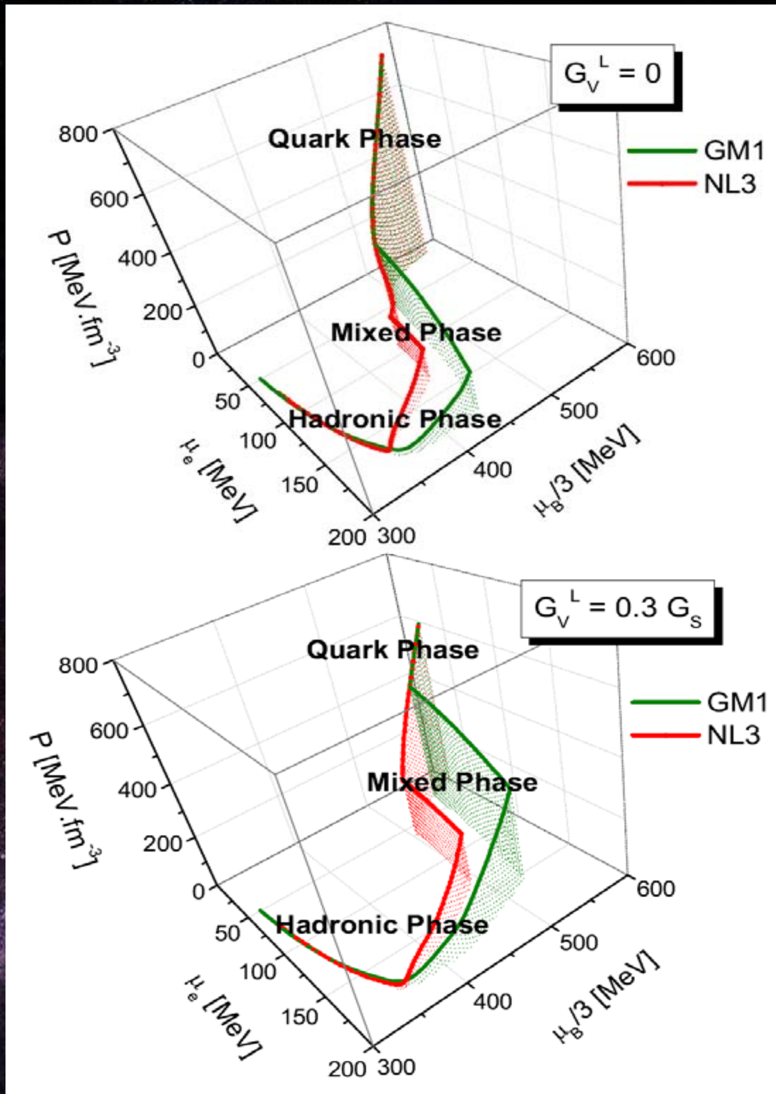


Figure 3. (Color online) Pressure as a function of neutron ($\mu^n = \mu_B/3$) and electron (μ^e) chemical potential for the local NJL model, l3NJL, hadronic parametrizations GM1 and NL3, and vector repulsions $G_V^L/G_s = 0$ and $G_V^L/G_s = 0.3$.

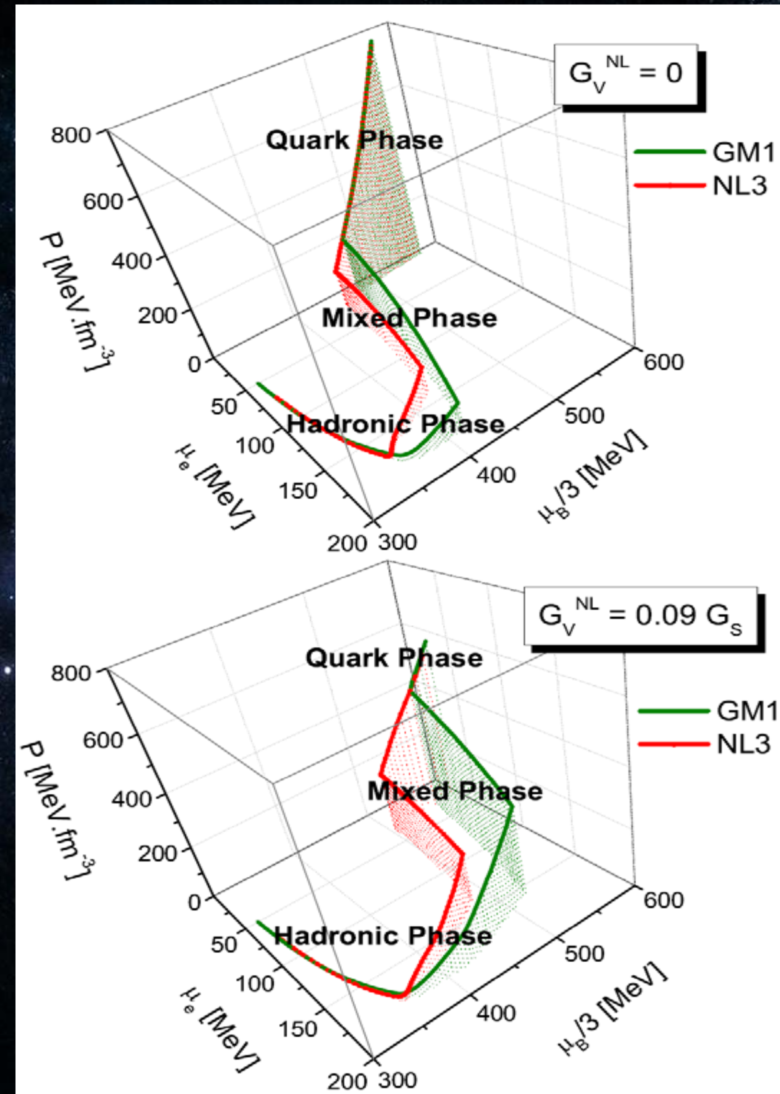
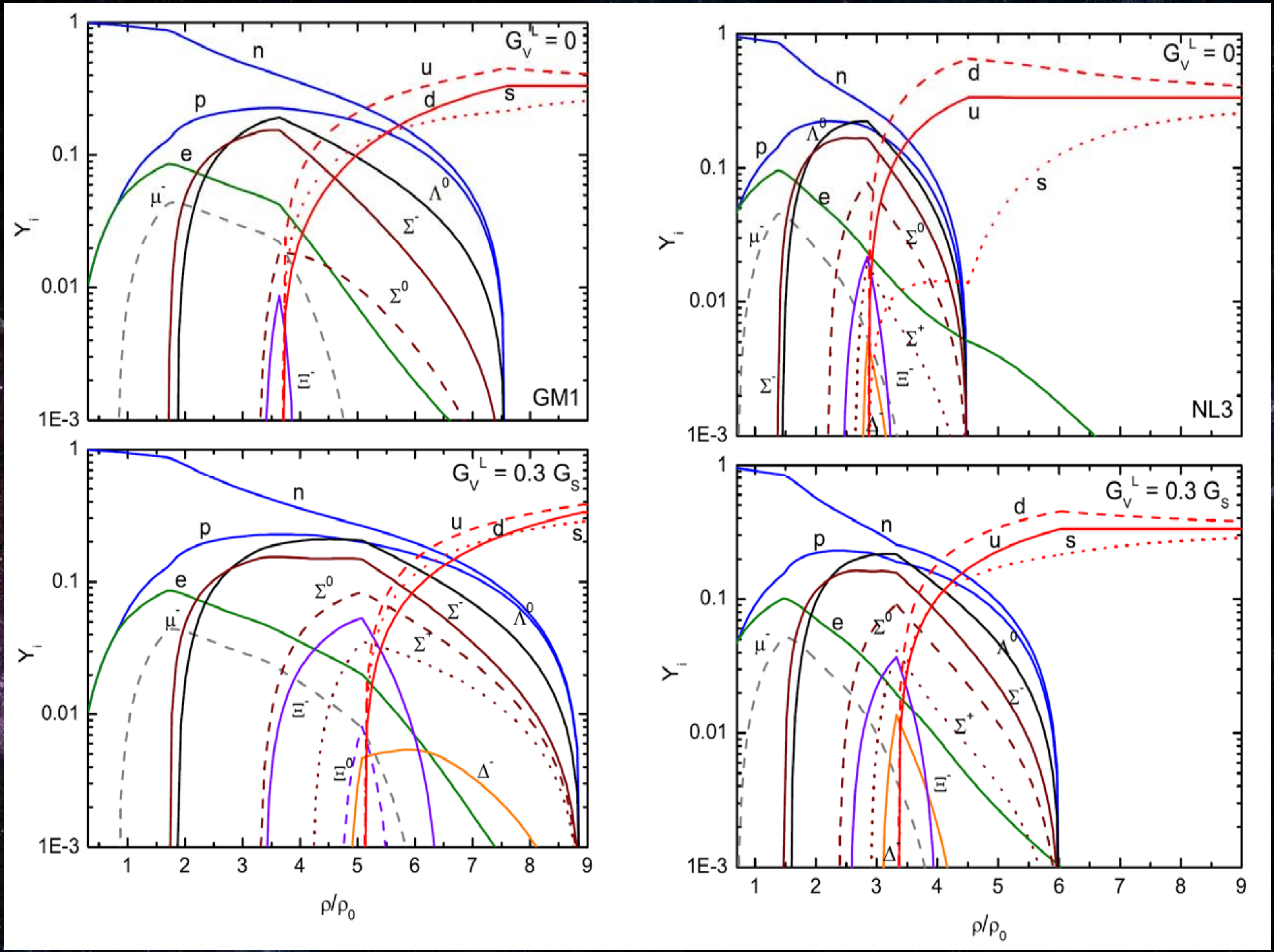
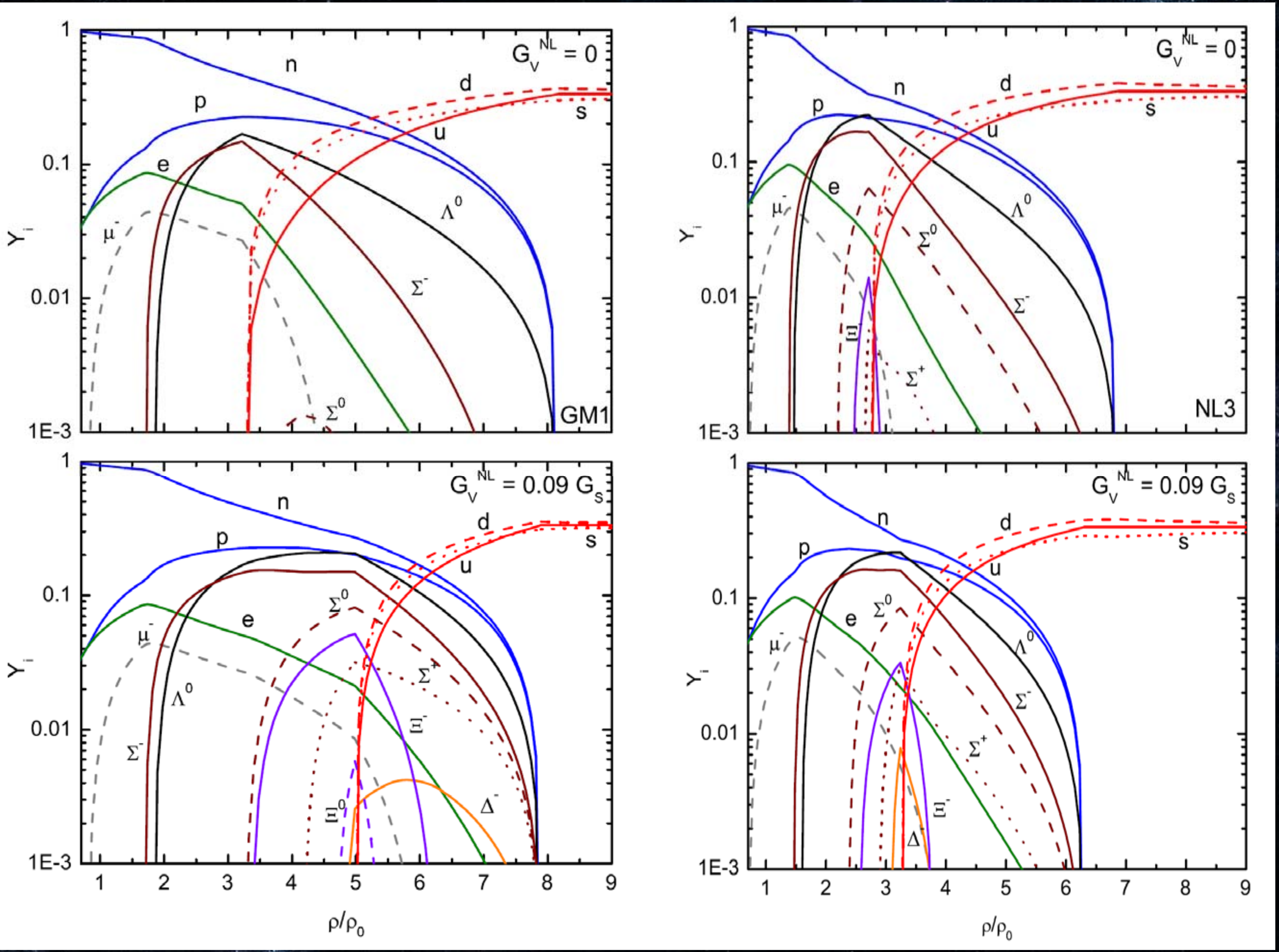


Figure 4. (Color online) Same as Fig. 3, but for the non-local NJL model, n3NJL, hadronic parametrizations GM1 and NL3, and vector repulsions $G_V^{NL}/G_s = 0$ and $G_V^{NL}/G_s = 0.09$.

Particle Population for local NJL model



Particle Population for non-local NJL model



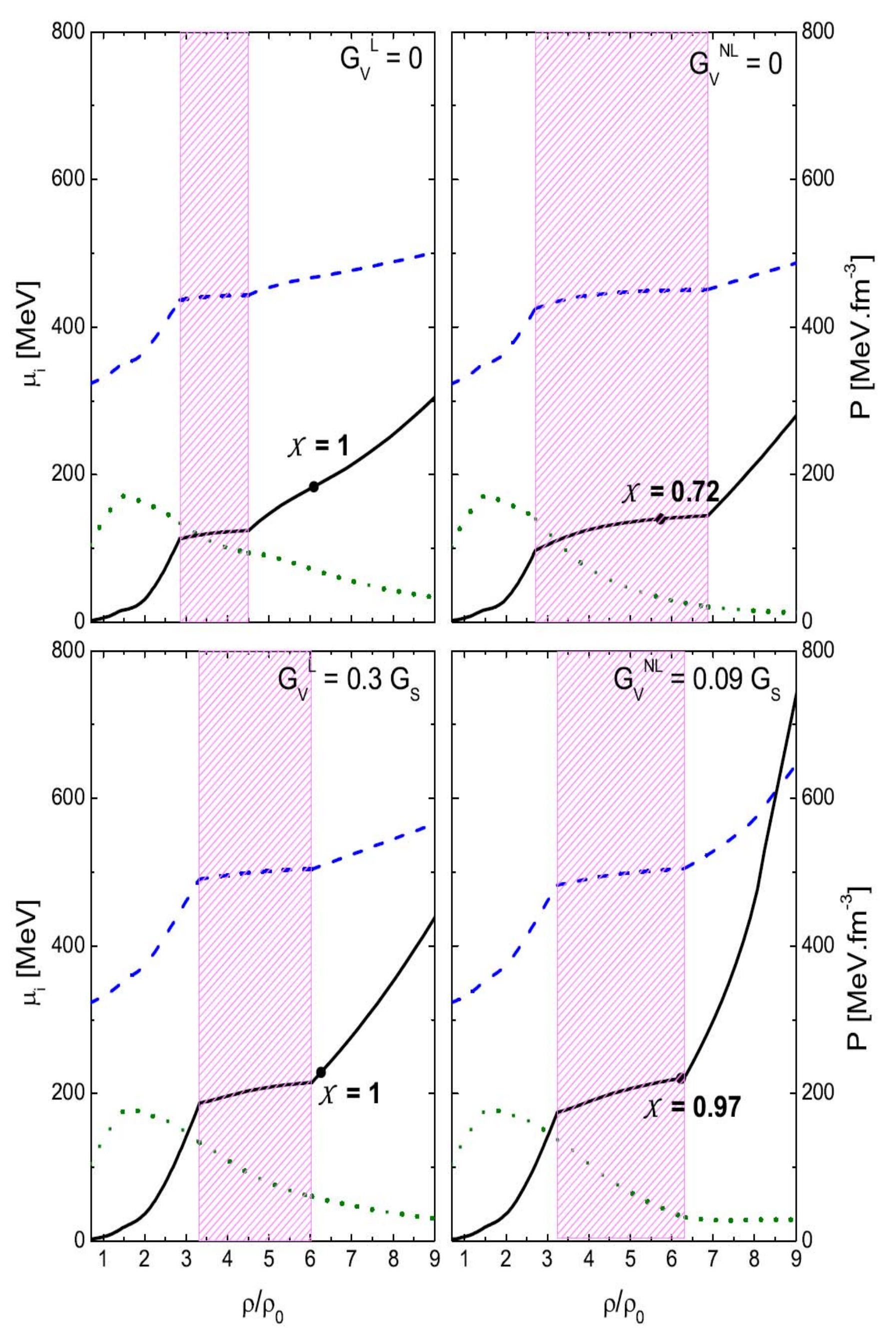
Pressure P (solid lines), baryonic chemical potential μ_B (dashed lines), and electron chemical potential μ_e (dotted lines) as a function of baryon number density in units of normal nuclear matter density, ρ_0 =0.16 fm^{-3} for parametrization NL3.

Table VI. Width of the mixed phase, central densities of the associated maximum-mass star of the QHS in the Local NJL model case.

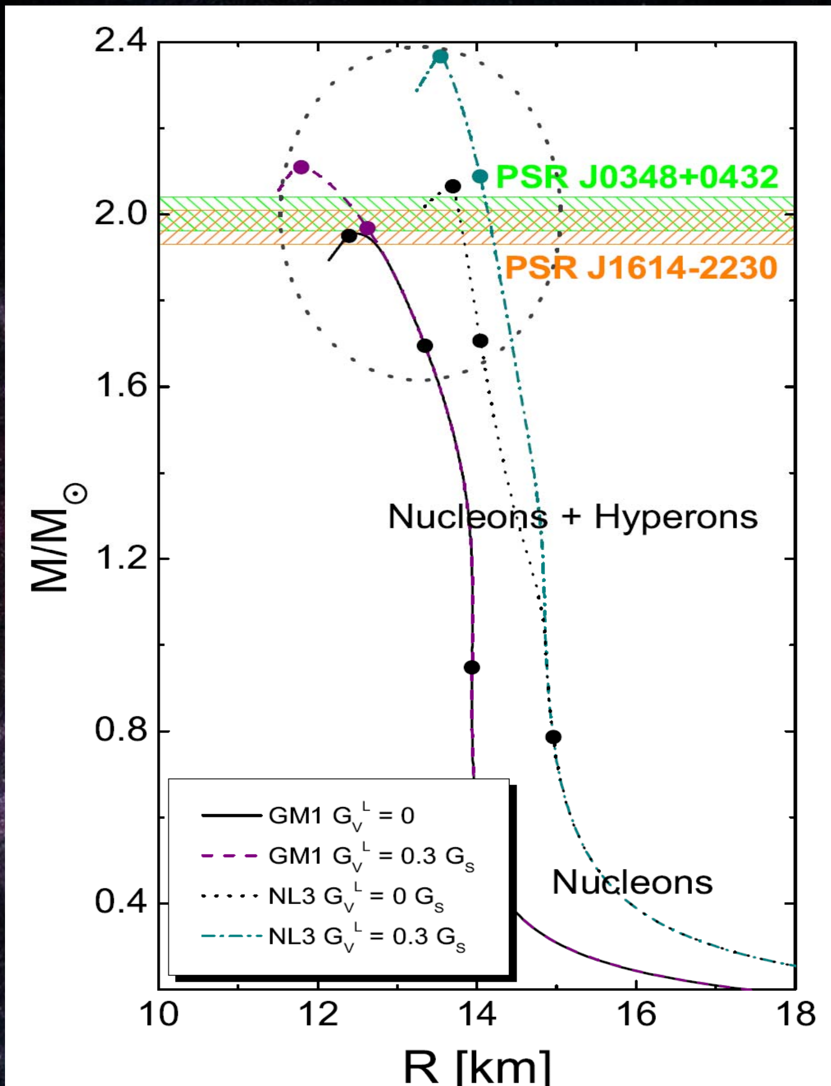
G_V^L	Mixed phase (ρ_0)	Central density of M_{max} (ρ_0)
0 (GM1)	3.64 – 7.60	7.21
0.30 (GM1)	5.07 – 8.92	8.81
0 (NL3)	2.85 – 4.51	5.96
0.30 (NL3)	3.33 – 6.03	6.52

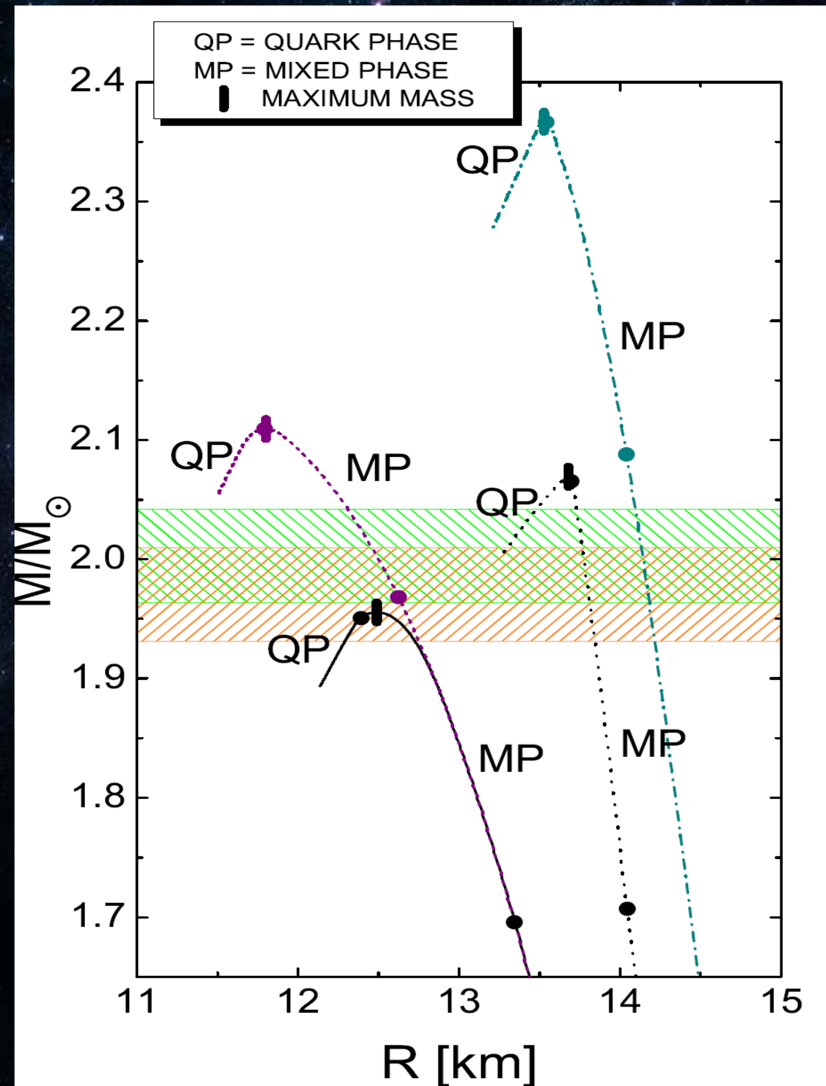
Table VII. Widths of the mixed phases and central densities of the associated maximum-mass stars for the non-local NJL model.

G_V^{NL}	Mixed phase (ρ_0)	Central density of M_{max} (ρ_0)
0 (GM1)	3.22 – 8.18	6.87
0.09 (GM1)	4.83 – 7.89	8.69
0 (NL3)	2.71 – 6.87	5.68
0.09 (NL3)	3.24 – 6.31	6.28

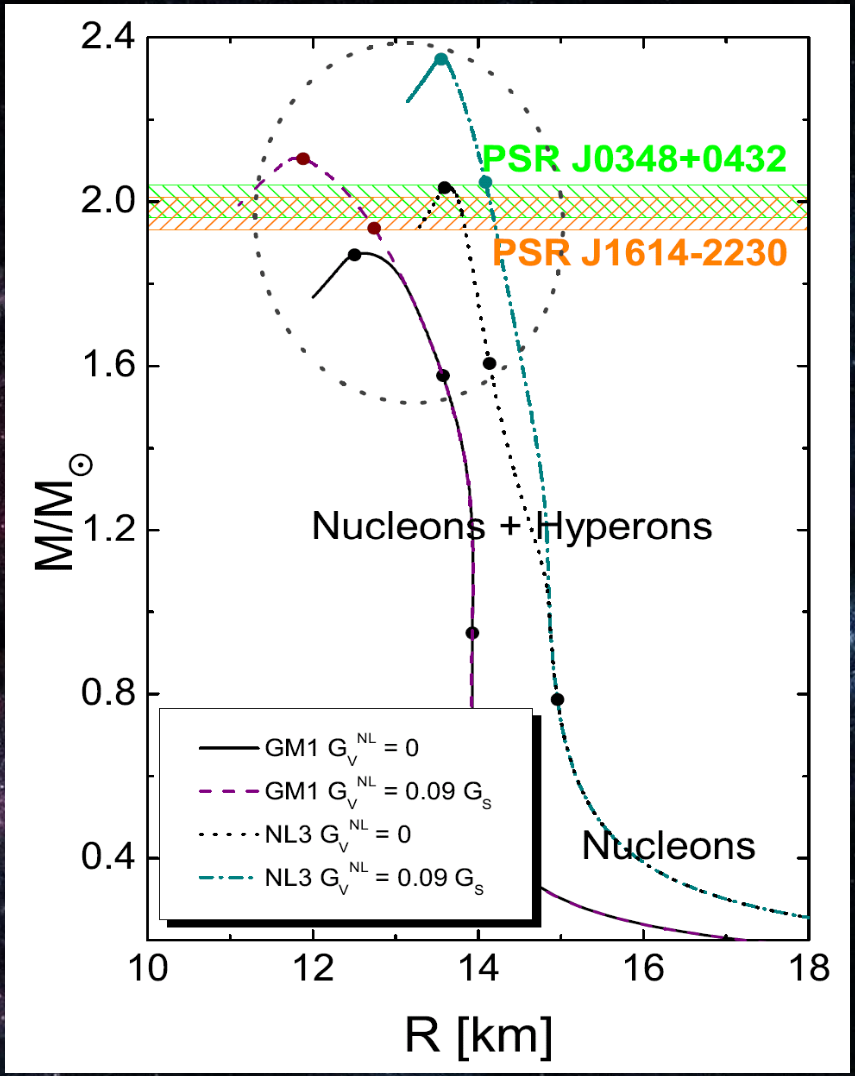


Mass – Radius for local NJL model





Mass – Radius relation for non-local NJL model



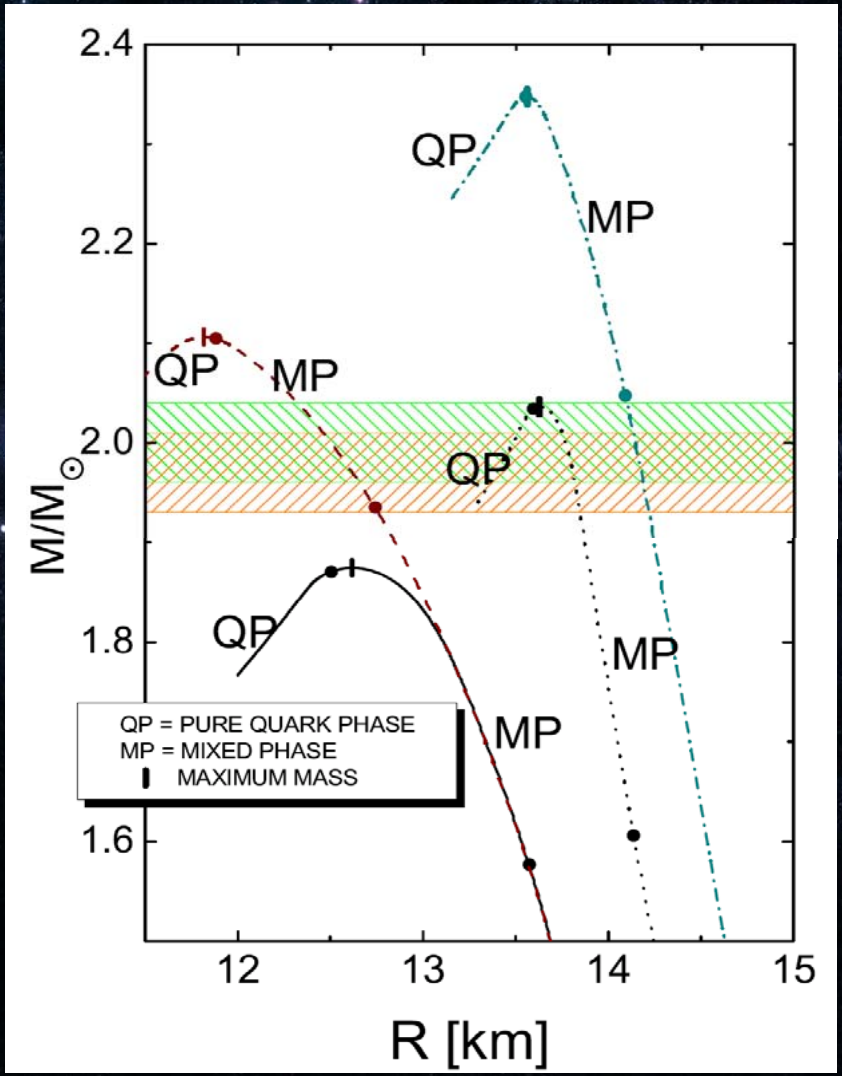


Table VIII. Maximum masses and radii of neutron stars made of quark-hybrid matter for different vector repulsion (G_V/G_S).

NJL Model	G_V/G_S	$R_{\max}$ (km)	$M_{\max}/M_{\odot}$
Local	0	12.49	1.96
GM1	0.30	11.80	2.11
Local	0	13.68	2.07
NL3	0.30	13.53	2.37
Non-local	0	12.62	1.87
GM1	0.09	11.81	2.11
Non-local	0	13.62	2.04
NL3	0.09	13.56	2.35

Summary

• **We have used a non-local 3-flavor NJL model to modelate the quark matter and a non-linear Walecka model for the hadronic phase.**

• **The inclusion of the vector interaction is crucial for the stiffens of the EoS and the consequent increase of then M-R relationship.**

• **According to our results, high-mass Neutron Stars such as PSR J1614-2230 and J0348+0432 may contain a mixed phase of quarks and hadrons in their cores.**

Outlook

• **Extension to finite temperature : protoneutron stars.**

• **Color Superconductivity**

Thank you very much for your attention!

Gustavo A. Contrera