Hybrid stars in the light of the massive pulsar PSR J1614-2230

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Abstract

We perform a systematic study of hybrid star configurations using several parametrizations of a relativistic mean-field hadronic EoS and the NJL model for three-flavor quark matter. For the hadronic phase we use the stiff GM1 and TM1 parametrizations, as well as the very stiff NL3 model. In the NJL Lagrangian we include scalar, vector and 't Hooft interactions. The vector coupling constant g_v is treated as a free parameter. We also consider that there is a split between the deconfinement and the chiral phase transitions which is controlled by changing the conventional value of the vacuum pressure $-\Omega_0$ in the NJL thermodynamic potential by $-(\Omega_0+\delta\Omega_0)$, being $\delta\Omega_0$ a free parameter. We find that, as we increase the value of $\delta\Omega_0$, hybrid stars have a larger maximum mass but are less stable, i.e. hybrid configurations are stable within a smaller range of central densities. For large enough $\delta\Omega_0$, stable hybrid configurations are not possible at all. The effect of increasing the coupling constant g_v is very similar. We show that stable hybrid configurations with a maximum mass larger than the observed mass of the pulsar PSR J1614-2230 are possible for a large region of the parameter space of g_v and $\delta\Omega_0$ provided the hadronic equation of state contains nucleons only. When the baryon octet is included in the hadronic phase, only a very small region of the parameter space allows to explain the mass of PSR J1614-2230. We compare our results with previous calculations of hybrid stars within the NJL model. We show that it is possible to obtain stable hybrid configurations also in the case $\delta\Omega_0=0$ that corresponds to the conventional NJL model for which the pressure and density vanish at zero temperature and chemical potential.

The model

To describe the quark matter phase we use the SU(3) NJL model with scalar-pseudoscalar, isoscalar-vector and 't Hooft six fermion interaction. The Lagrangian density of the model is:

$$\begin{aligned}\mathcal{L}_Q =\; & \bar\psi(i\gamma_\mu\partial^\mu - \hat m)\psi \\ & + g_s\sum_{a=0}^{8}[(\bar\psi\lambda^a\psi)^2+(\bar\psi i\gamma_5\lambda^a\psi)^2] \\ & - g_v\sum_{a=0}^{8}[(\bar\psi\gamma_\mu\lambda^a\psi)^2+(\bar\psi\gamma_5\gamma_\mu\lambda^a\,\psi)^2] \\ & + g_t\{\det[\bar\psi(1+\gamma_5)\psi]+\det[\bar\psi(1-\gamma_5)\psi]\}, \end{aligned} \qquad (1)$$

where $\psi=(u,d,s)$ denotes the quark fields, $\lambda^a(0\le a\le 8)$ are the U(3) flavour matrices, $\hat m = \mathrm{diag}(m_u,m_d,m_s)$ is the quark current mass, and g_s, g_v and g_t are coupling constants. The mean-field thermodynamic potential density Ω for a given baryon chemical potential μ at $T=0$, is given by

$$\begin{aligned}\Omega =& -\eta N_c\sum_i\int_{k_{Fi}}^{\Lambda}\frac{p^2\,dp}{2\pi^2}\sqrt{p^2+M_i^2}+2g_s\sum_i\langle\bar\psi\psi\rangle_i^2 \\ & -2g_v\sum_i\langle\psi^\dagger\psi\rangle_i^2+4g_t\langle\bar u u\rangle\langle\bar d d\rangle\langle\bar s s\rangle \\ & -\eta N_c\sum_i\mu_i\int_0^{k_{Fi}}\frac{p^2\,dp}{2\pi^2}-\Omega_0, \end{aligned}\qquad (2)$$

where the sum is over the quark flavor $(i=u,d,s)$, the constants $\eta=2$ and $N_c=3$ are the spin and color degeneracies, and Λ is a regularization ultraviolet cutoff to avoid divergences in the medium integrals. The Fermi momentum of the particle i is given by $k_{Fi}=\theta(\mu_i^*-M_i)\sqrt{(\mu_i^{*2}-M_i^2)}$, where μ_i^* is the quark chemical potential modified by the vectorial interaction, i.e. $\mu^*_{u,d,s}=\mu_{u,d,s}-4g_v\langle\psi^\dagger\psi\rangle_{u,d,s}$.
The conventional procedure for fixing the Ω_0 term in Eq. (2) is to assume that the grand thermodynamic potential Ω must vanish at zero μ and T. Nevertheless, this prescription is no more than an arbitrary way to uniquely determine the EoS of the NJL model without any further assumptions [1]. In view of this, [2] adopt a different strategy. They fix a bag constant for the hadron-quark deconfinement to occur at the same chemical potential as the chiral phase transition. This method leads to a significant change in the EoS with respect to the conventional procedure. Differently, we may explore the above possibility of having chiral restoration and deconfinement occurring at different densities. To this end, we shall substitute Ω_0 in Eq. (2) by the new value $\Omega_0+\delta\Omega_0$, where $\delta\Omega_0$ is a free parameter:

$$\Omega_0 \longrightarrow \Omega_0+\delta\Omega_0 \quad \text{in Eq. (2)}. \qquad (3)$$

With this change, the thermodynamic potential Ω can be non-vanishing at zero μ and T, and the μ of the deconfinement transition can be tuned. In order to illustrate the dependence of the EoS on the new parameter $\delta\Omega_0$ we depict in Fig. 1 the pressure as a function of the chemical potential for different values of $\delta\Omega_0$ and the pressure of the deconfinement transition P_{pht} as a function of $\delta\Omega_0$. Notice that a small change in the value of $\delta\Omega_0$ may result in a significant modification of the phase transition density, and consequently, in a very different hybrid EoS.

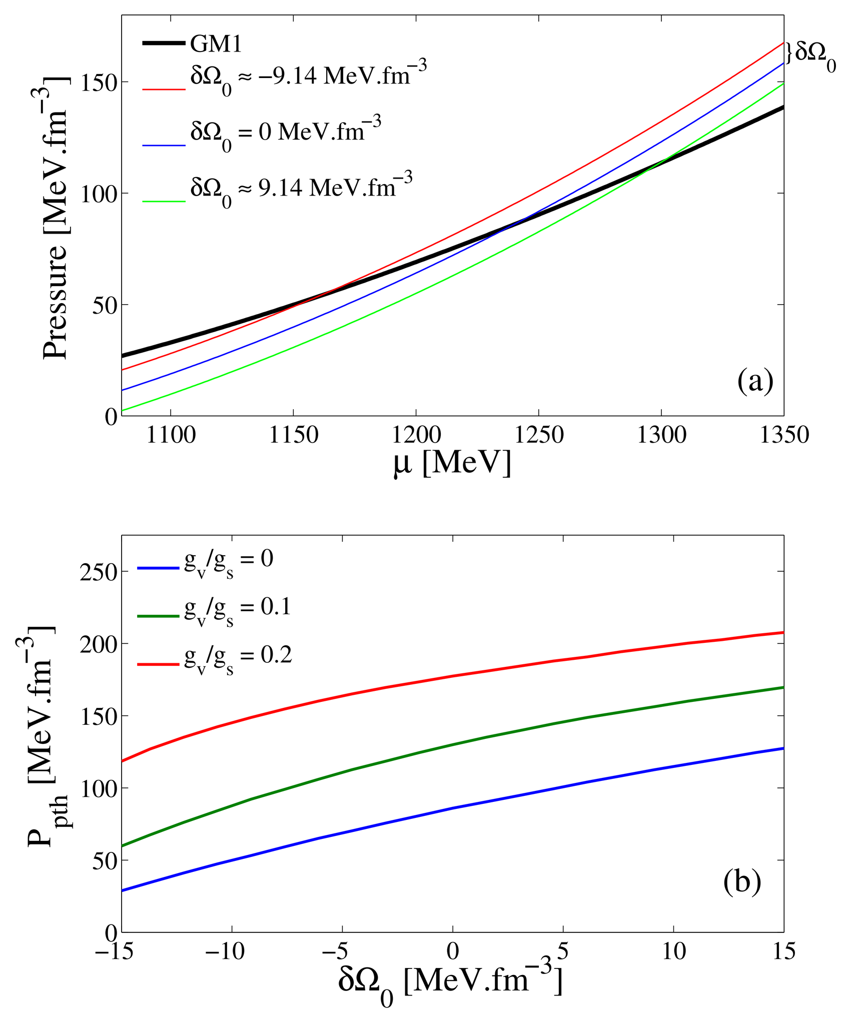

Fig. 1: (a) Pressure as a function of the chemical potential for different values of the parameter $\delta\Omega_0$. (b) Pressure of the deconfinement phase transition as a function of $\delta\Omega_0$ for different values of the coupling constant g_v. Notice that a small change in $\delta\Omega_0$ can produce a significant change in the pressure of the phase transition.

Results

We have solved the Tolman-Oppenheimer-Volkoff equations for spherically symmetric and static stars in order to investigate the influence of g_v and $\delta\Omega_0$ on the maximum mass of hybrid stars. In Figs. 2 and 3 we show the EoS for some specific parametrizations and the corresponding stellar configurations in a diagram of mass M versus central energy density ϵ_c. The plateaus represent the hadron-quark phase transition as a consequence of a first order Maxwell construction.

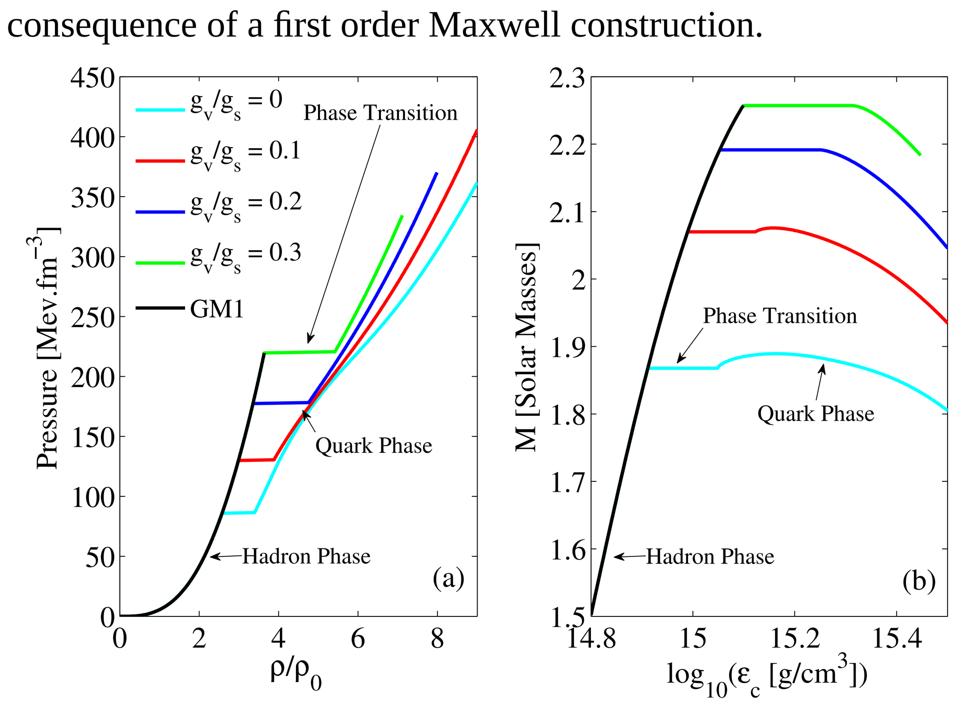

Fig. 2: (a) Pressure as a function of the baryon number density in units of the nuclear saturation density ρ_0 (we assumed $\rho_0=0.17\ \mathrm{fm}^{-3}$). (b) Mass of hybrid stars as a function of the central mass-energy density ϵ_c. We use $\delta\Omega_0=0$ and different values of g_v.

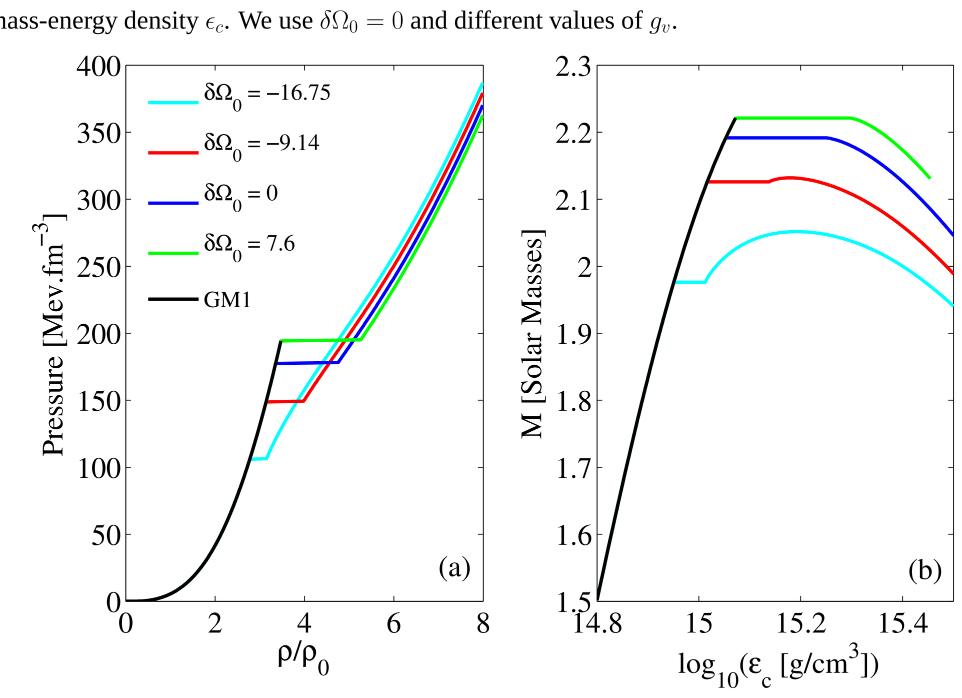

Fig. 3: Same as Fig. 2 but adopting $g_v/g_s=0.2$ and different values of $\delta\Omega_0$ (labels for $\delta\Omega_0$ are in $\mathrm{MeV\ fm}^{-3}$).

In Fig. 4 we have represented the maximum mass of hybrid stars for different parametrizations of the NJL model (more deals see the label of Figure). An interesting feature of Fig. 4, is that large masses are situated on the right-upper corner but stable configurations are located on the left-lower corner of the figure (or left side of the figure in the case of NL3). This clearly illustrates the difficulty of obtaining stable hybrid stars with arbitrarily large masses. Concerning the effect of the hadronic model we see that stable hybrid stars have higher values of the maximum mass for the stiffer hadronic EoS.
The observed mass of PSR J1614-2230 can be explained by parameters within the large region located between the red dashed line and the solid black line in each panel of Fig. 4. However, a hypothetical future observation of a neutron star with a mass a $\sim 10\%$ larger than the mass of PSR J1614-2230 will be hard to explain within hybrid star models using the GM1 and TM1 EoS (see panels (a) and (b) of Fig. 4) and will require a very stiff hadronic model such as NL3.

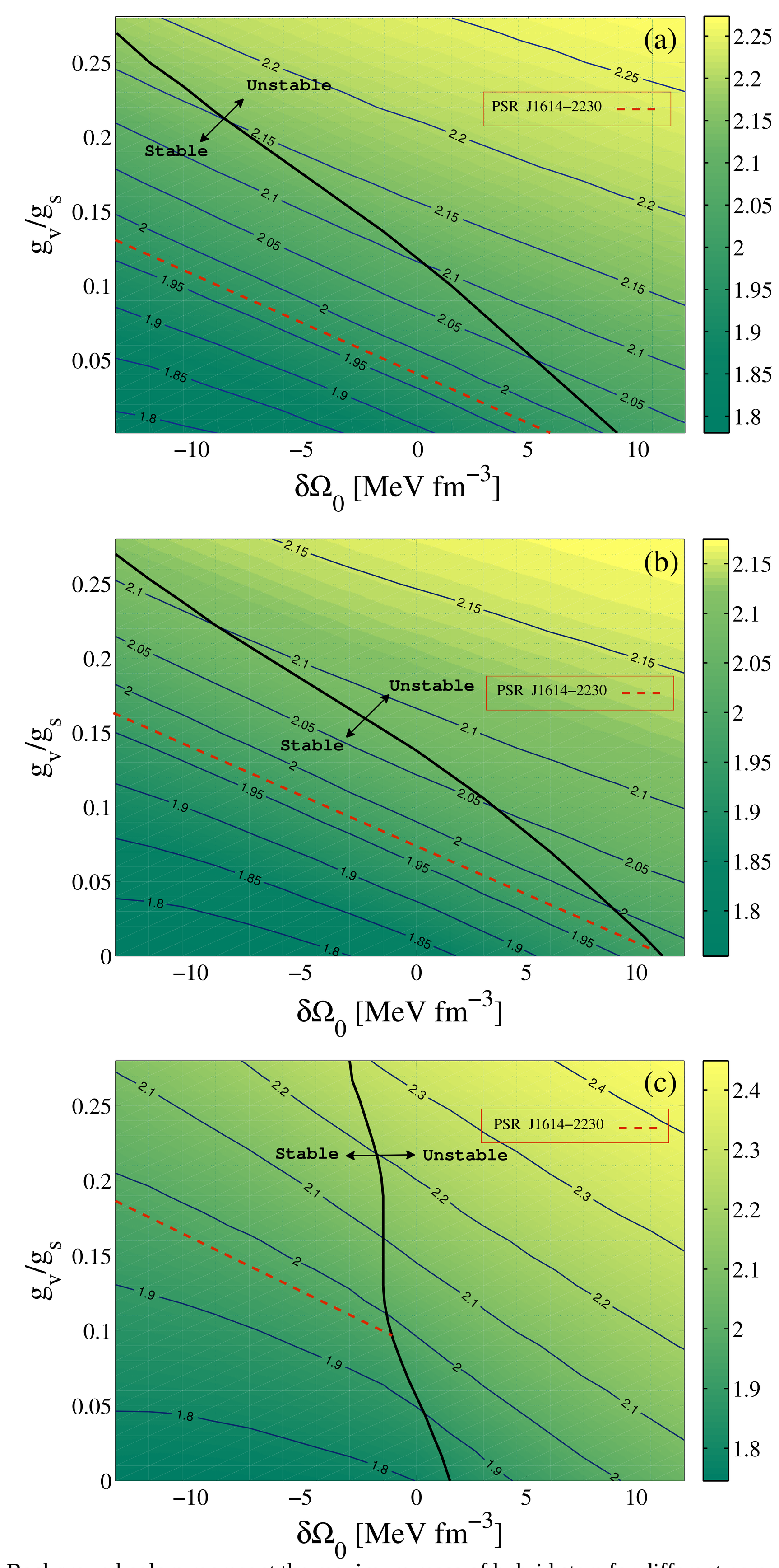

Fig. 4: Background colors represent the maximum mass of hybrid stars for different parametrizations of the NJL model (i.e. different values of g_v and $\delta\Omega_0$). In each panel we use a different hadronic EoS (without hyperons): (a) GM1, (b) TM1 and (c) NL3. Notice that the color scale is different for each panel. The solid contour lines indicate specific values of the maximum mass. The black solid line represents the boundary between parametrizations that allow for stable hybrid stars and parametrizations that do not. The red dashed line indicates the value $1.97M_\odot$ corresponding to the observed mass of PSR J1614-2230 [3]. The region between the red dashed line and the solid black line allows to explain the mass of PSR J1614-2230.

The effect of hyperons is shown in Fig. 5 where we consider the NL3 parametrization with the inclusion of the baryon octet. Compared with the case without hyperons, the maximum mass values are altered by a few percent.

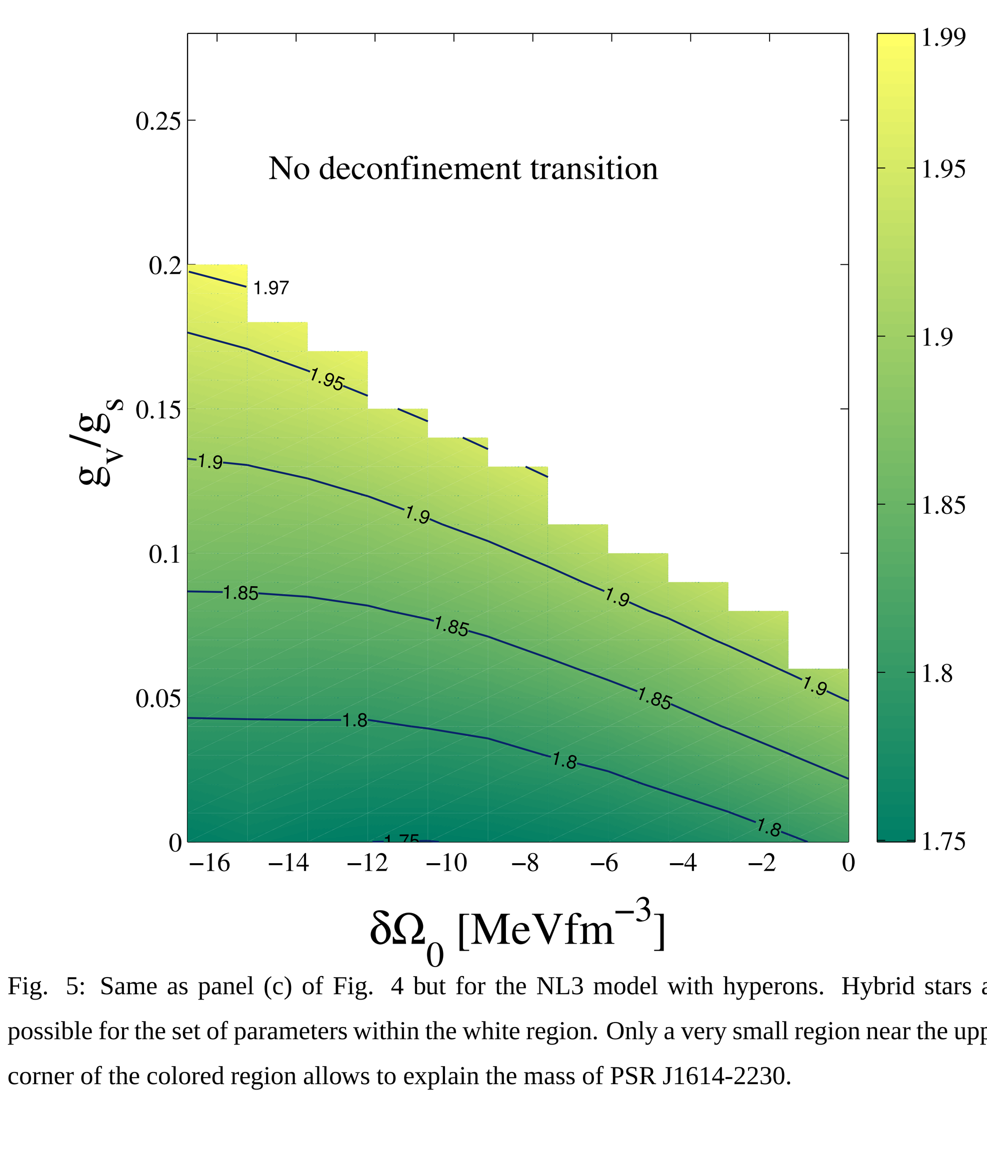

Fig. 5: Same as panel (c) of Fig. 4 but for the NL3 model with hyperons. Hybrid stars are not possible for the set of parameters within the white region. Only a very small region near the upper-left corner of the colored region allows to explain the mass of PSR J1614-2230.

References

[1] Schertler K., Leupold S., & Schaffner-Bielich, J., 1999, Phys. Rev. C, 60, 025801

[2] Pagliara, G. & Schaffner-Bielich, J., 2008, Phys. Rev. D, 77, 063004

[3] Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T. 2010, Nature, 467, 1081

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