Hybrid stars with the Field correlator method

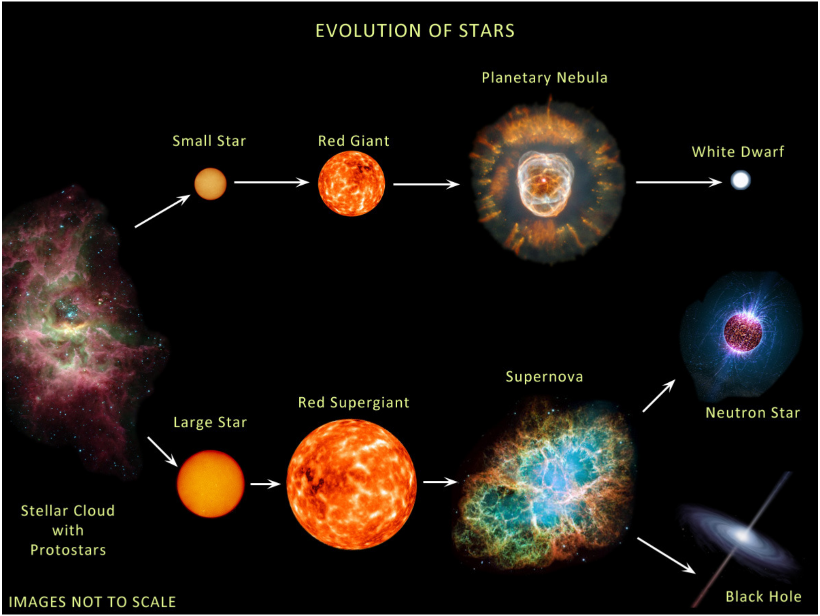
Domenico Logoteta

In collaboration with: Prof. I. Bombaci

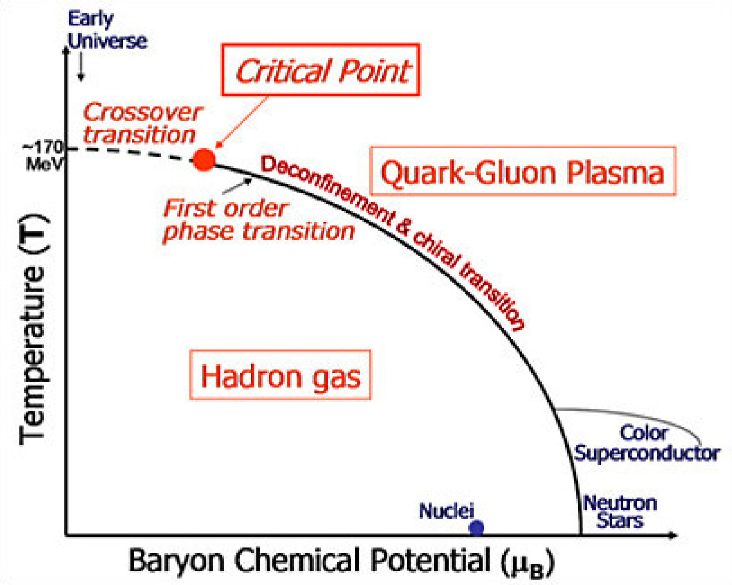
30 ottobre 2013

- Neutron stars
- The neutron star core: Nucleons, hyperons ?... quarks ?
- EoS of hadronic and quark matter
- Hybrid neutron stars with the FCM
- Connection with lattice QCD calculations

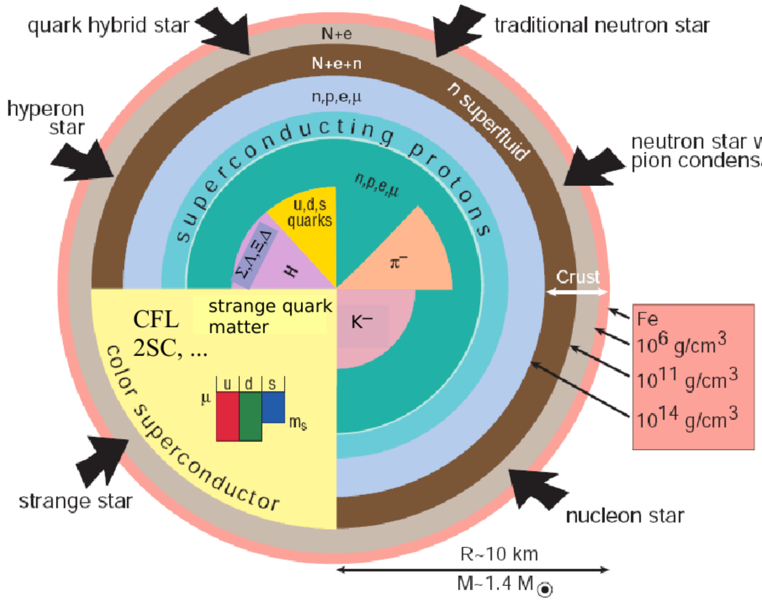
Stellar evolution



QCD phase diagram



Neutron star structure



- Walecka model:

$$\mathscr{L} = \sum_B \bar{\psi}_B[i\gamma_\mu(\partial^\mu - g_{\omega B}\gamma_\mu\omega^\mu) - m_B + g_{\sigma B}\sigma) - \frac{1}{2}g_{\sigma B}\gamma_\mu\tau\cdot\rho^\mu]\psi$$
$$+ \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\rho_{\mu\nu}\rho^{\mu\nu}$$
$$+ \frac{1}{2}m_\rho^2\rho_\mu\rho^\mu - \frac{1}{3}bm(g_\sigma\omega)^2 - \frac{1}{4}c(g_\sigma\omega)^4 \,.$$

- Nucleon coupling constants are related to the hyperon ones by:

$$g_{\sigma B} = x_\sigma g_{\sigma N}, \quad g_{\omega B} = x_\omega g_{\omega N}, \quad g_{\rho B} = x_\rho g_{\rho N}.$$

- $x_\sigma = 0.6$–0.8, $x_\omega = x_\rho \Rightarrow$ from hypernuclear calculations.
- Stellar matter requires in addition:

$$\mu_B = q_B\mu_n - q_e\mu_e \qquad \mu_e = \mu_\mu \,,$$
$$n_p + n_{\Sigma^+} - n_{\Sigma^-} - n_{\Xi^-} - n_\mu - n_e = 0 \,.$$

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- Dynamics of confinement $\Rightarrow D^E(x),\ D_1^E(x),\ D^H(x),\ D_1^H(x)$

$$P_q/T^4 = \frac{1}{\pi^2}[\phi_\nu(\frac{\mu_q - V_1/2}{T}) + \phi_\nu(-\frac{\mu_q + V_1/2}{T})]$$

$$\phi_\nu(a) = \int_0^\infty du \frac{u^4}{\sqrt{u^2+\nu^2}} \frac{1}{\exp[\sqrt{u^2+\nu^2} - a] + 1}, \quad \nu = m_q/T$$

$$V_1(T) = \int_0^{1/T} d\tau (1 - \tau T) \int_0^\infty d\chi\, \chi\, D_1^E(\sqrt{\chi^2 + \tau^2}).$$

$$D_1^E(x) = D_1^E(0)\exp(-|x|/\lambda), \quad \lambda = 0.34\ fm.$$

$$P_{qg} = P_g + \sum_{u,d,s} P_q - \frac{9}{64} G_2 .$$

$G_2 = (0.012 \pm 0.006)\ \mathrm{GeV}^4 \Rightarrow$ From lattice QCD calculations

$V_1(0) = 10 - 100\ \mathrm{MeV} \Rightarrow$ Parameter (M. Baldo et al. Phys. Rev. D **78**, 063009 (2008))

Mixed phase: Gibbs VS Maxwell

- Gibbs conditions for phase coexistence:

$$\mu_H(P_H, T_H) = \mu_Q(P_Q, T_Q), \quad T_H = T_Q, \quad P_H(\mu_H, T) = P_Q(\mu_Q, T) = P_T.$$

- Gibbs construction: Charge neutrality is not imposed locally but globally.

$$\chi \rho_c^Q + (1 - \chi)\rho_c^H + \rho_c^l = 0\,.$$

- Energy density and baryonic density in the mixed phase read:

$$< \epsilon >= (1 - \chi)\, \epsilon_H - \chi\, \epsilon_Q\,,$$
$$< n >= (1 - \chi)\, n_H - \chi\, n_Q\,.$$

- Maxwell construction: Charge neutrality is imposed locally!.

EoS GM1(N)+FCM ($V_1 = 0.01$ GeV)

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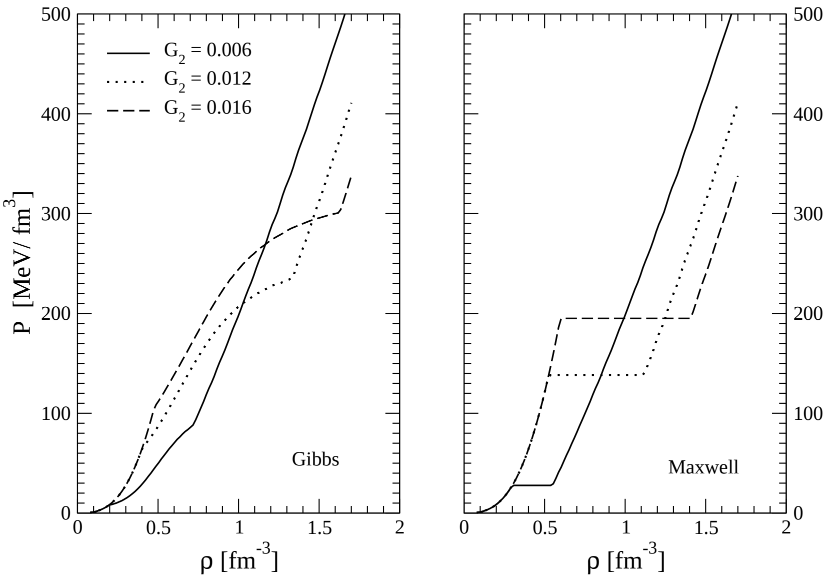

Hydrostatic equilibrium

- Neutron stars have a very strong gravitational field $\Rightarrow$ their structure is described by General theory of relativity.

- Equations of hydrostatic equilibrium in general relativity of Tolman-Oppenheimer-Volkoff (TOV):

$$\frac{dP}{dr} = -\frac{G\rho m}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1},$$

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho\,.$$

- Fixed an EOS and a value of the central pressure value P_c TOV equations are solved numerically.

- Output $\Longrightarrow$ $M_G(R)$, $M_G(P_c)$ (or $M_G(M_B)$)

- $M_B = m_u \int n_B(r)dV$, $\qquad m_u = (m_n + m_p)/2$

Mass-Radius relation GM1(N)+FCM ($V_1 = 0.01$ GeV)

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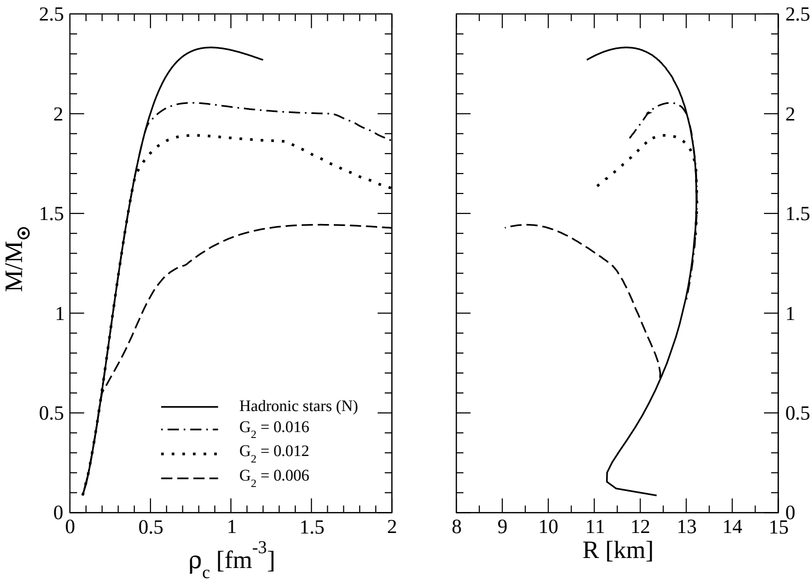
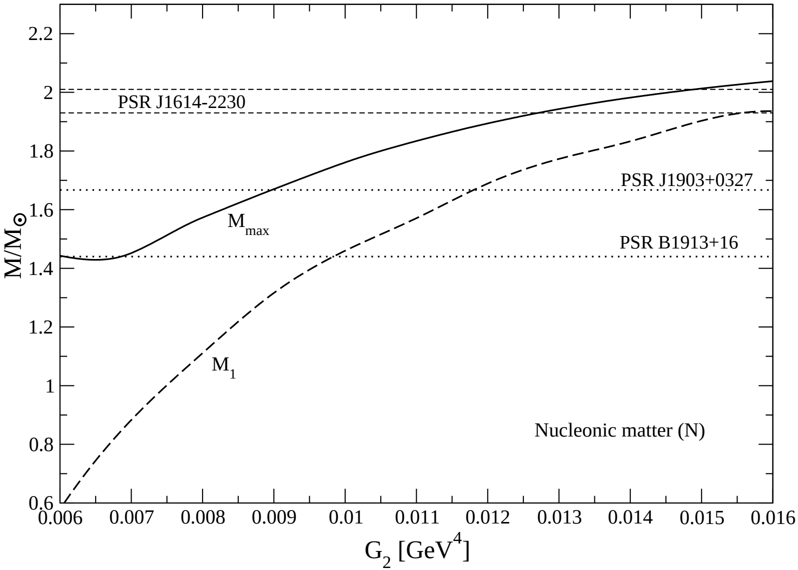
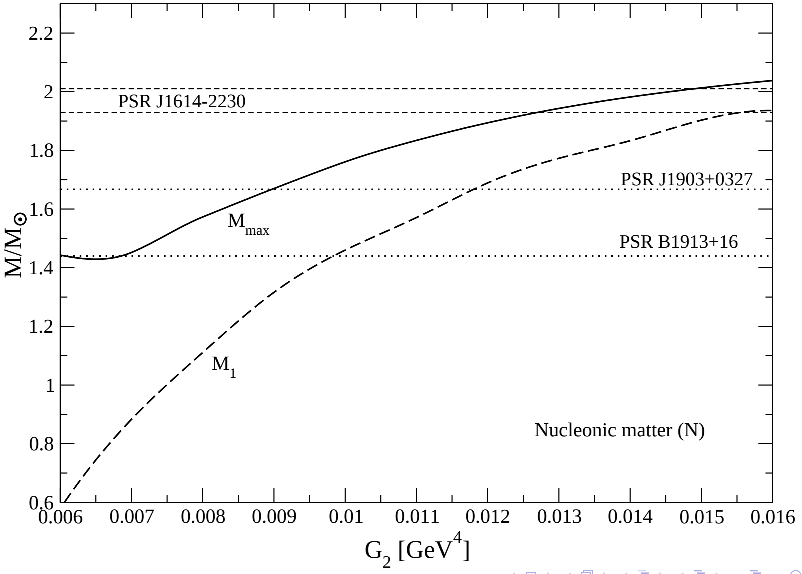


Maximum mass vs G_2 for GM1(N)+FCM ($V_1 = 0.01$ GeV)

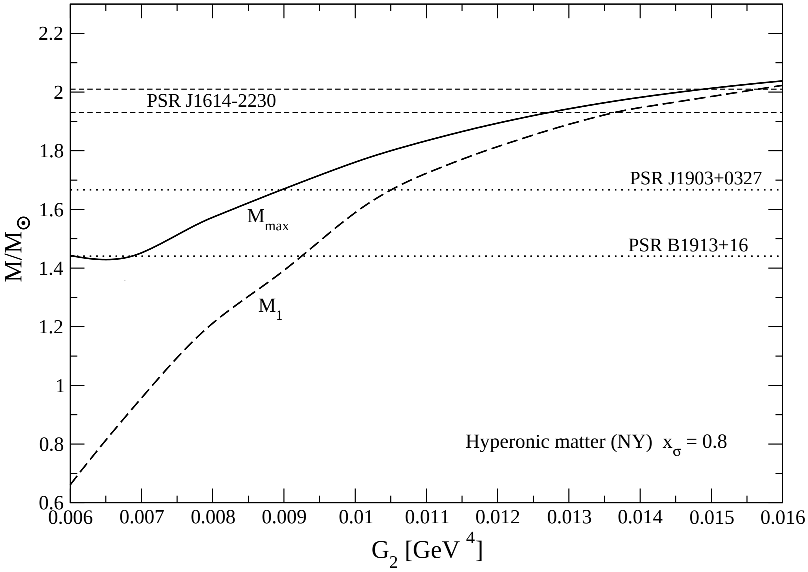


Maximum mass vs G_2 for GM1(N)+FCM ($V_1 = 0.01$ GeV)

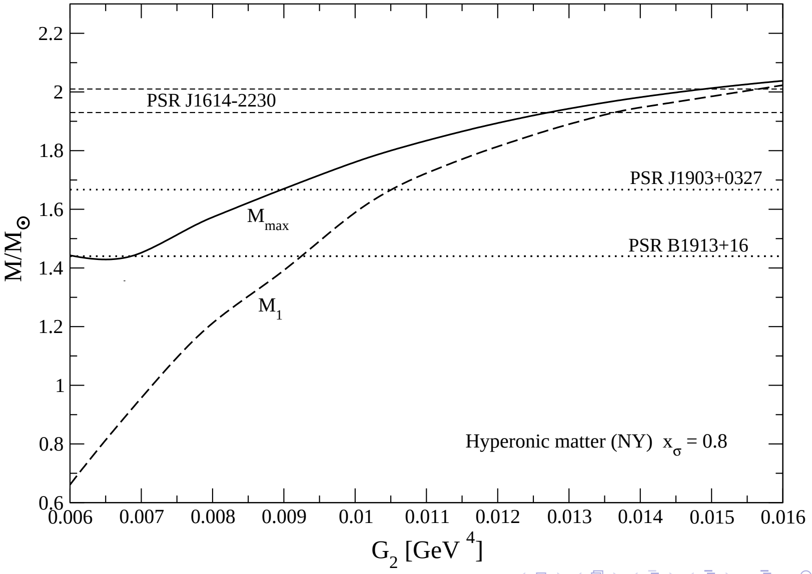
$G_2 = 0.013$–$0.018\,\mathrm{GeV}^4$



Maximum mass vs G_2 for GM1(NY)+FCM ($V_1 = 0.01$ GeV)



$G_2 = 0.0127–0.018\,\mathrm{GeV}^4$



HotQCD collaboration $\Rightarrow$ $T_c = (154 \pm 9)\,\mathrm{MeV}$

Wuppertal–Budapest collaboration $\Rightarrow$ $T_c = (147 \pm 5)\,\mathrm{MeV}$

$$T_c = \frac{a_0}{2} G_2^{1/4} \left(1 + \sqrt{1 + \frac{V_1(T_c)}{2 a_0 G_2^{1/4}}} \right), \qquad a_0 = (3\pi^2/768)^{1/4}$$

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$$V_1(T) = V_1(0) \left\{ 1 - \frac{3}{2} \frac{\lambda T}{\hbar c} + \frac{1}{2} \left(1 + 3 \frac{\lambda T}{\hbar c} \right) e^{-\frac{\hbar c}{\lambda T}} \right\}.$$

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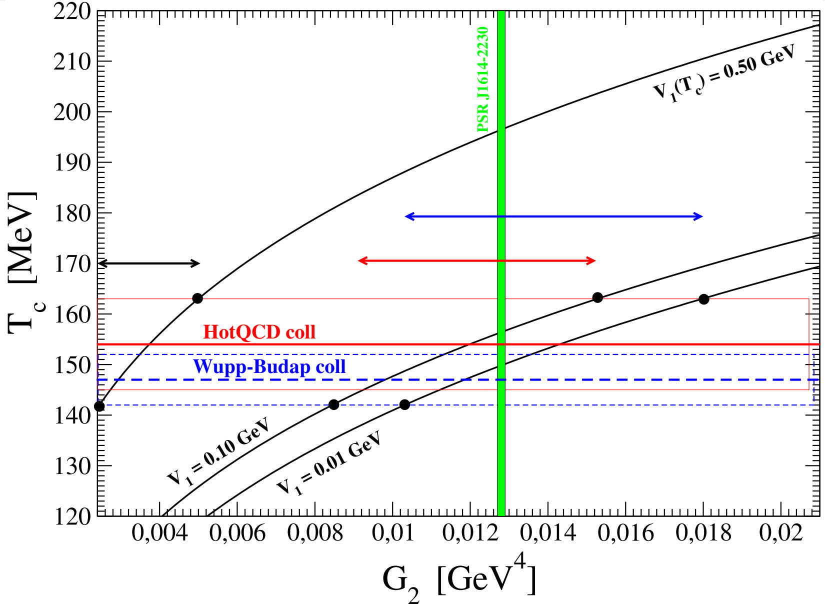
- $V_1(T_c) = 0.5\,\mathrm{GeV} \Rightarrow V_1(0) = 0.85\,\mathrm{GeV}$ ($G_2 = 0.0025$–$0.005\,\mathrm{GeV}^4$)
- $V_1(0) = 0.01\,\mathrm{GeV} \Rightarrow G_2 = 0.0103$–$0.0180\,\mathrm{GeV}^4$
- $V_1(0) = 0.1\,\mathrm{GeV} \Rightarrow G_2 = 0.0085$–$0.0153\,\mathrm{GeV}^4$

Lattice QCD calculations VS Neutron star masses



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Conclusions and future perspectives

- We built hybrid neutron stars using GM1+FCM.
- Maximum mass obtained are able to reproduce the spectrum of observed neutron stars.
- Constraints imposed by neutron star mass mesurements on G_2 are compatible with lattice QCD calculations.
- Results confirmed also using hadronic microscopic approaches: BHF+TBF(N) and DBHF(N)
- In future: BHF calculation with NN+NNN+NY+NNY +FCM
- FCM is a powefull approach to link astrophysical and lattice QCD calculations.

Thank you !

Obrigadinho !

Gibbs VS Maxwell for GM1(N)+FCM ($V_1 = 0.01$ GeV)