Hot hybrid neutron star within a statistical baryonic approach and the PNJL quark model

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To model hot hybrid neutron stars:

a statistical model based on Thomas-Fermi approximation for baryonic matter;

the Polyakov-Nambu-Jona-Lasino model for quark matter;

baryon-quark phase transition(PT):

Maxwell construction;

for neutrino-free matter and neutrino-trapped matter;

under the beta equilibrium conditions

Baryonic model

The total nucleon energy:

$$E_{\rm MS} = \sum_{b=n,p} \frac{2}{h^3} \int d^3\mathbf{r}_1 \int d^3\mathbf{p}_1 \left(\frac{p_1^2}{2m_b} + \frac{1}{2} V_b(p_1) + m_b c^2 \right) n_b(p_1)$$

the energy density e of beta-stable nuclear matter can be extracted as follows:

$$e = e_{\rm MS} + e_L + e_\gamma$$

$$e_{\rm MS} = E_{\rm MS}/V$$

$$e_L = \sum_{l=e^-,\mu^-,\nu_e^0,\bar{\nu}_\mu^0} \frac{2}{h^3} \int d^3p \, E_p(p) \, n_l(p)$$

$$e_\gamma = \frac{\pi^2}{15} \frac{T^4}{(\hbar c)^3}$$

Baryonic model

beta equilibrium conditions:

$$\mu_{n^0} - \mu_{p^+} = \mu_{e^-} - \mu_{Le} = \mu_{\mu^-} - \mu_{L\mu}$$

For neutrino-trapped matter $\mu_{Le} = \mu_{\nu_e^0} \quad (\mu_{L\mu} = -\mu_{\bar{\nu}_\mu^0})$

and supernova matter constraints on the electron (muon) lepton number

$$Y_{Le} = \frac{\rho_{e^-} + \rho_{\nu_e^0}}{\rho_B} = 0.3 \qquad Y_{L\mu} = \frac{\rho_{\mu^-} - \rho_{\bar{\nu}_\mu^0}}{\rho_B} = 0$$

For neutrino-trapped matter $\mu_{Le} = 0 \quad (\mu_{L\mu} = 0)$

charge neutrality condition: $X_{p^+} = X_{e^-} + X_{\mu^-}$

Quark model

$$\begin{aligned}\mathcal{L}_{\text{PNJL}} = &\bar{q}(i\gamma_\mu\partial^\mu - m^0)q + G_s\sum_{a=0}^{8}\left[(\bar{q}\lambda_a q)^2 + (\bar{q}\gamma_s\lambda_a q)^2\right] \\ &- K\left\{\det[\bar{q}(1+\gamma_s)q] + \det[\bar{q}(1-\gamma_s)q]\right\} \\ &- G_v\sum_{a=0}^{8}\left[(\bar{q}\gamma_\mu\lambda_a q)^2 + (\bar{q}\gamma_s\gamma_\mu\lambda_a q)^2\right] \\ &- \mathcal{U}(\Phi, \bar{\Phi}, T)\end{aligned}$$

The beta equilibrium conditions for a neutral mixture of quarks

$$\mu_{u^+} = \mu_B - \frac{2}{3}(\mu_e - \mu_{Le}) \qquad \mu_{d^-} = \mu_{s^-} = \mu_B + \frac{1}{3}(\mu_e - \mu_{Le})$$

$$\mu_{e^-} - \mu_{Le} = \mu_{\mu^-} - \mu_{L\mu}$$

$$\mu_B = \frac{2\mu_{d^-} + \mu_{u^+}}{3} \equiv \frac{\mu_n^0}{3} \qquad \frac{2}{3}X_{u^+} - \frac{1}{3}(X_{d^-} + X_{s^-}) - (X_{e^-} + X_{\mu^-}) = 0$$

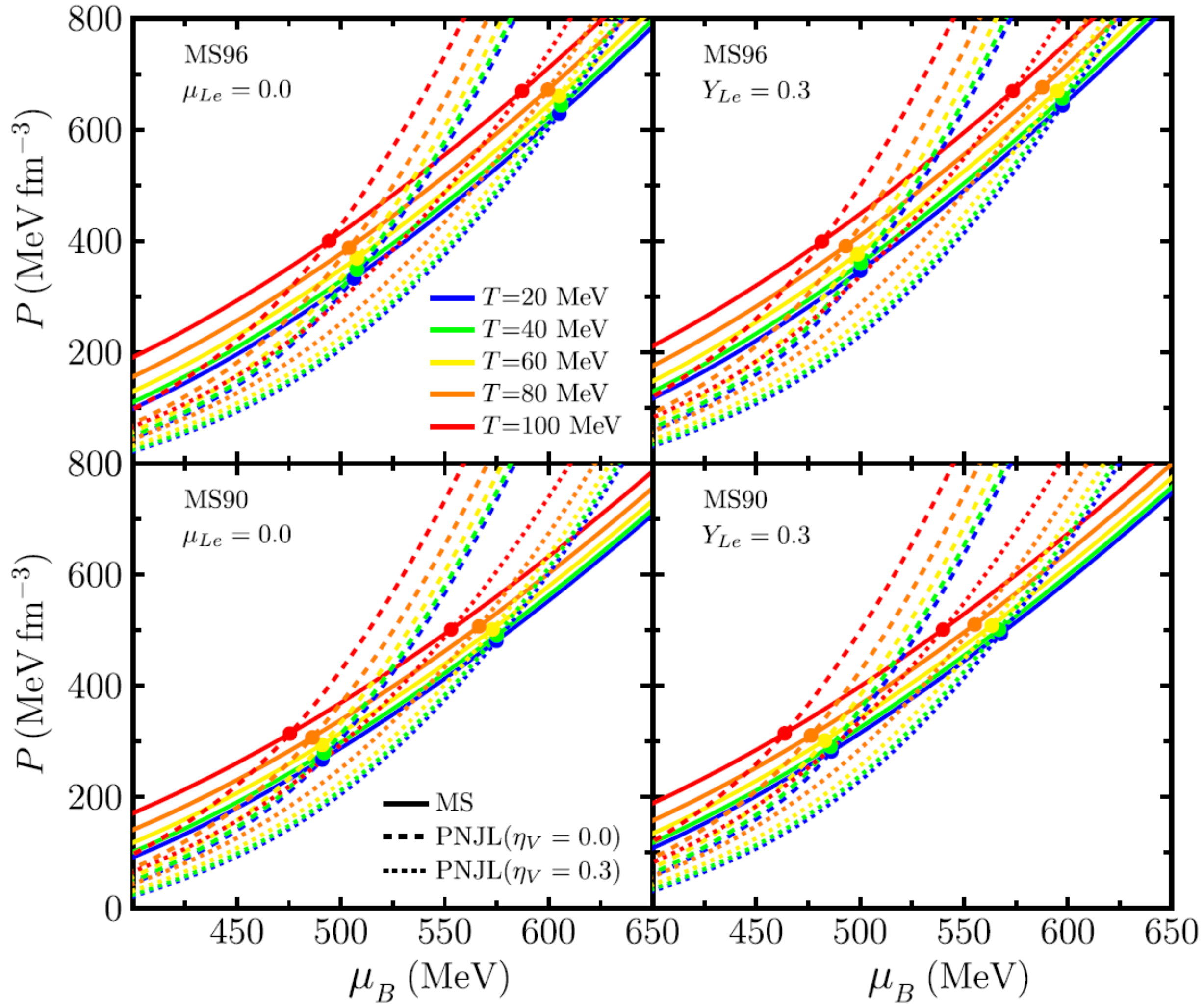
HHNS model

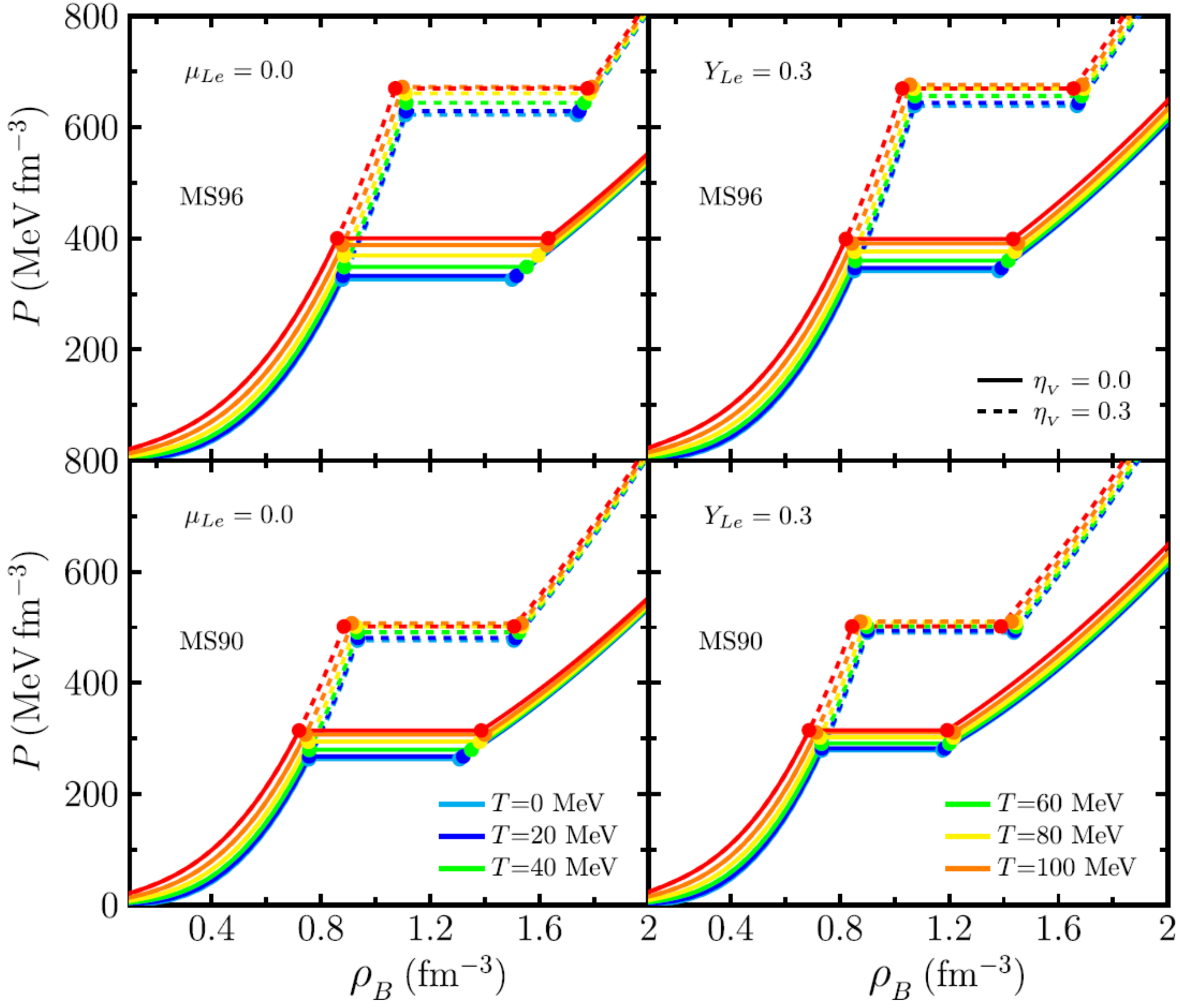
use the Maxwell structure to investigate the baryon-quark PT.

$$P^{(\mathrm{BP})} = P^{(\mathrm{OP})} = P^{(\mathrm{MP})}$$

baryonic model : MS96 and MS90
quark model : $\eta_v = 0$ and $\eta_v = 0.3$

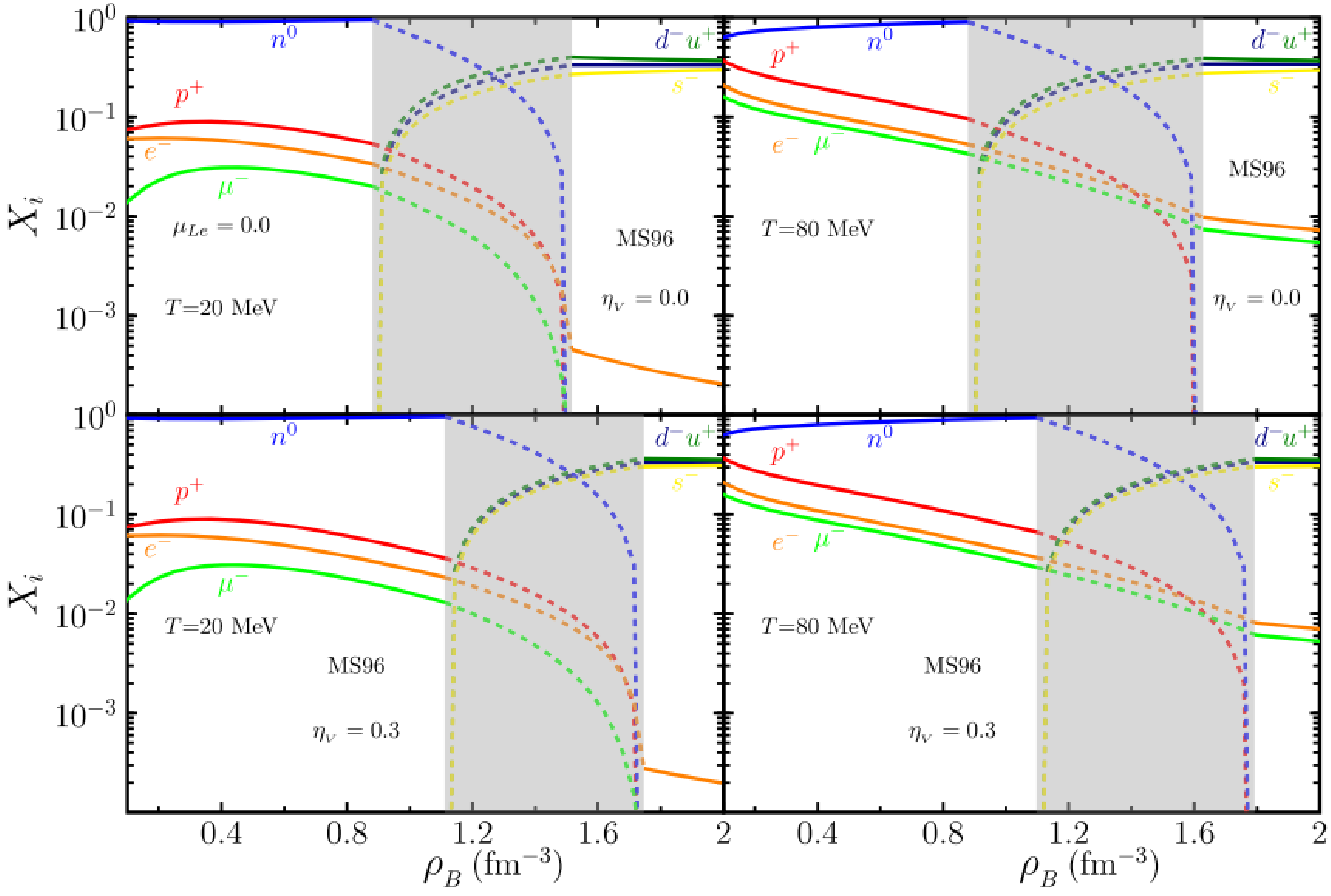
the baryon-quark PT appears in all cases



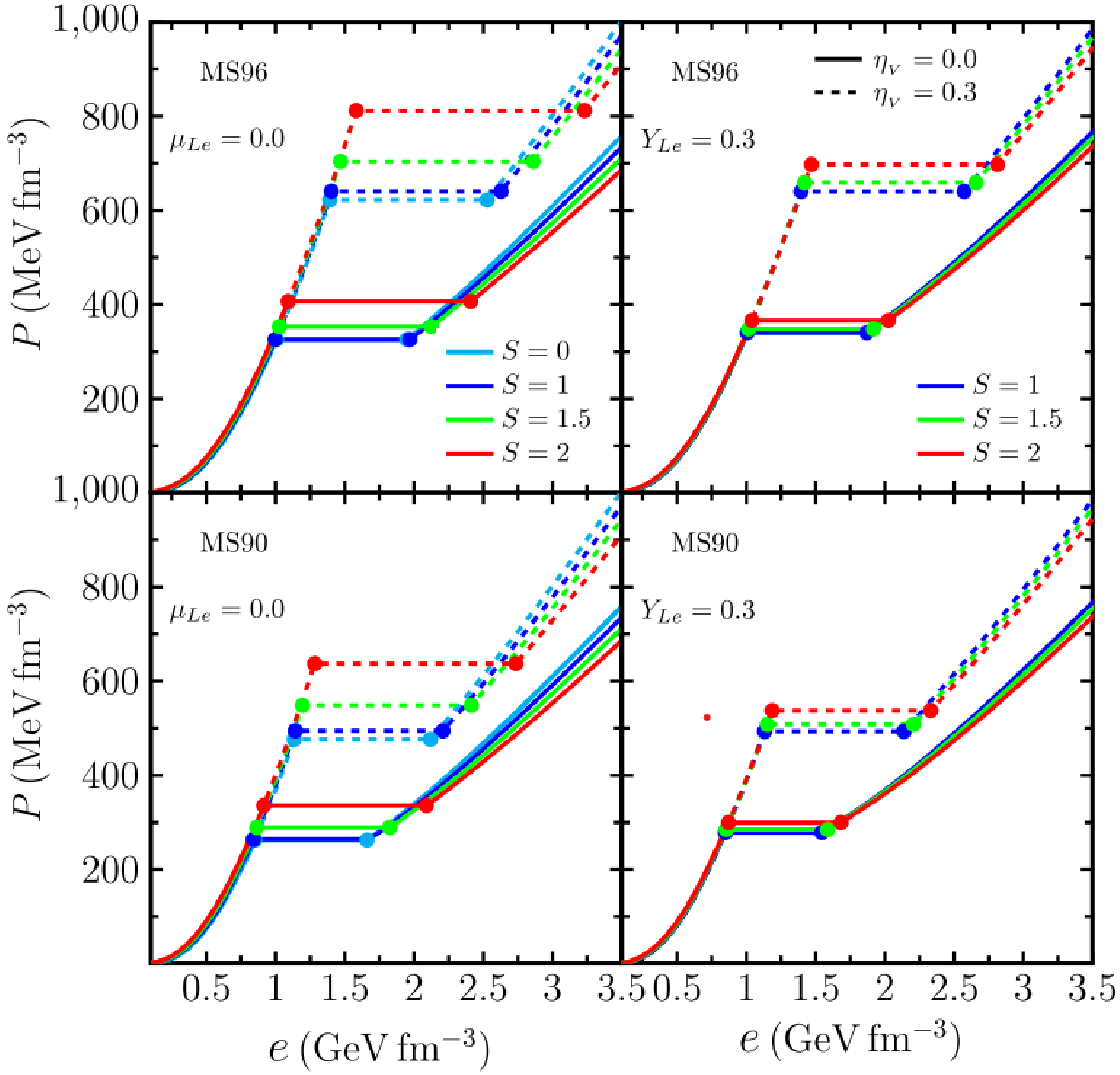


The mixed-phase(MP) data are given by the interpolation approach based on the volume factor $\chi(0 \leq \chi \leq 1)$

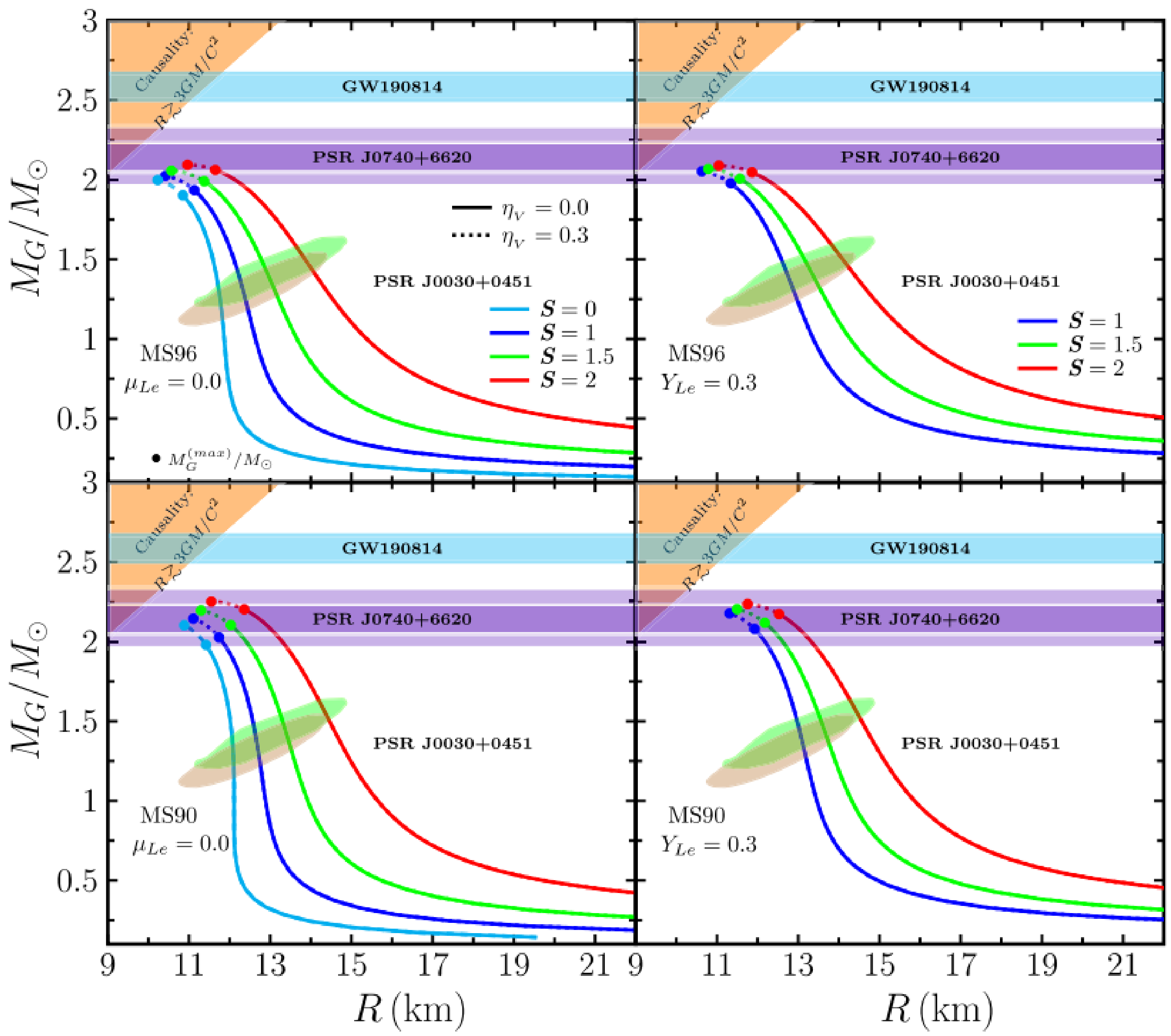
$$\rho_B^{(MP)} = (1 - \chi)\rho^{(BP)} + \chi\rho^{(QP)}$$



The relative fraction of each particle



EoS at entropies per baryon S=0, 1, 1.5, 2



The gravitational mass meets a maximum.