Neutron stars with Quark Core (Hybrid Stars)

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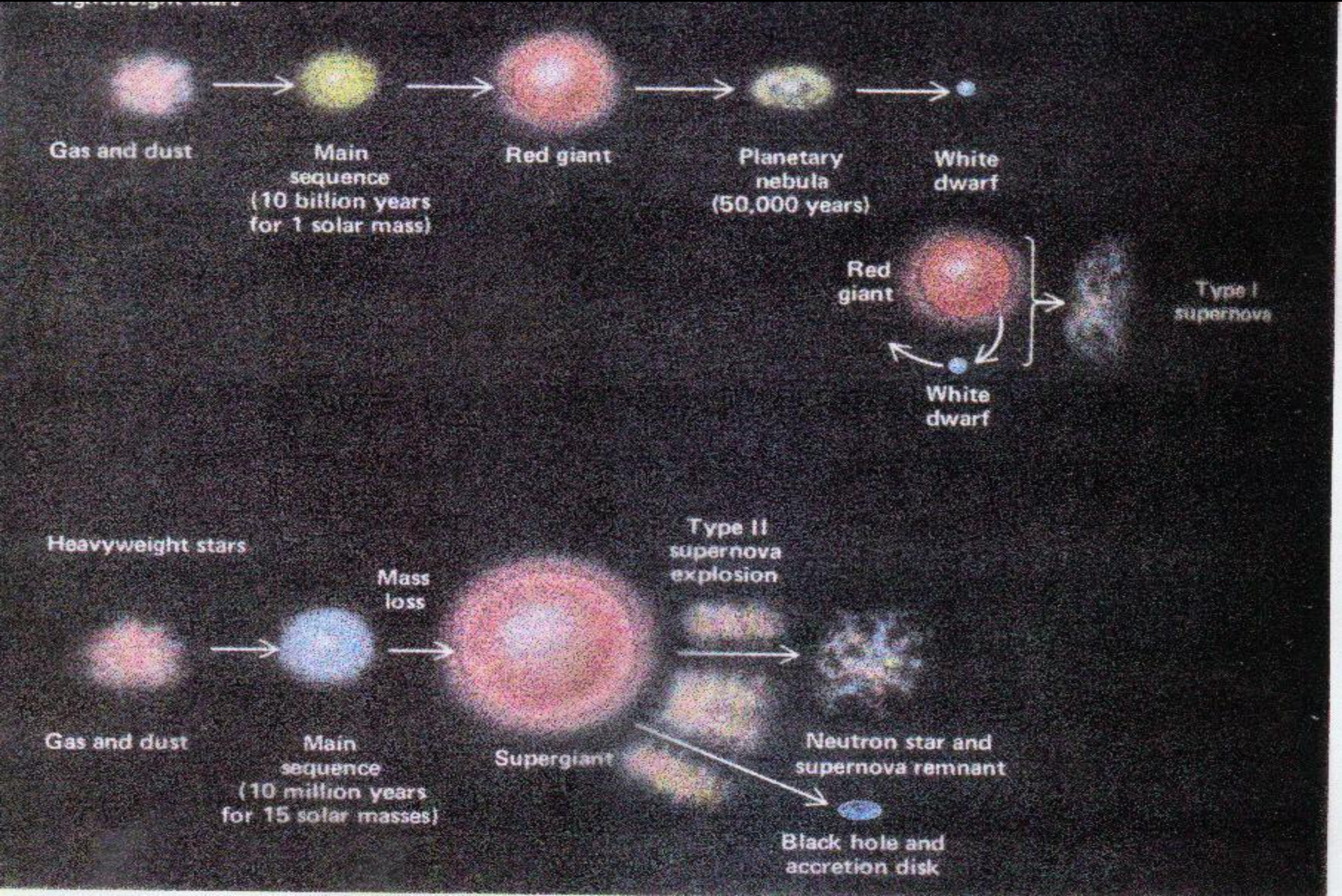
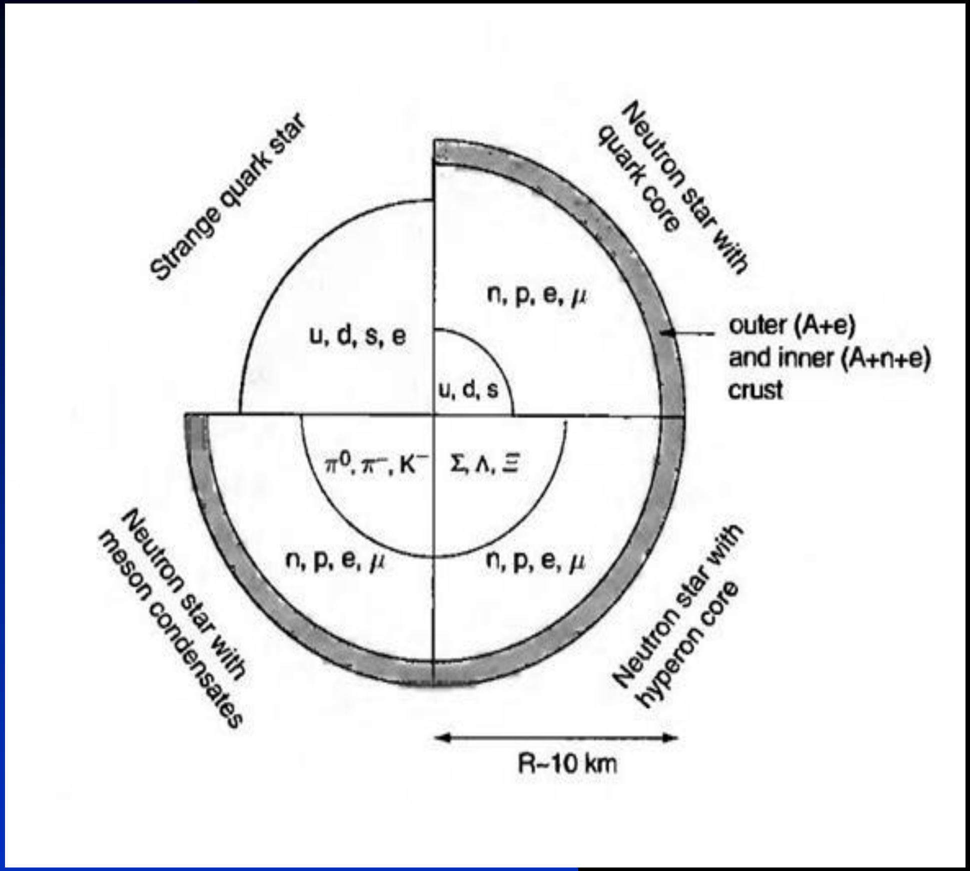
OUTLINE

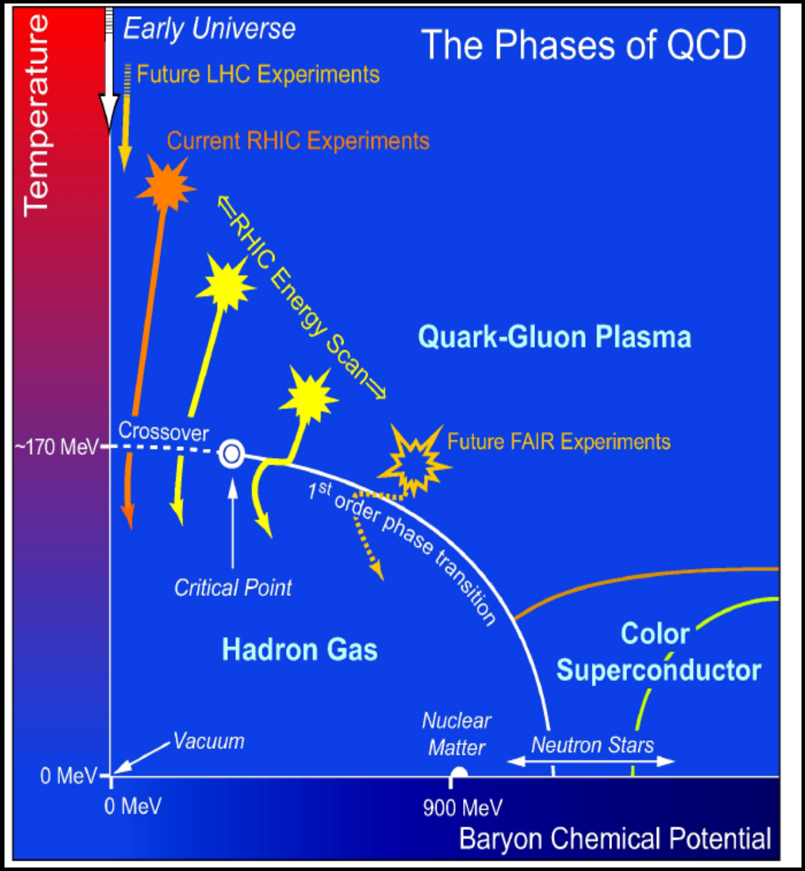
- Introduction
- EOS of Nuclear matter and Neutron Star
- EOS of Quark matter
- Hadron-quark phase transition
- Structure of Hybrid stars
- Summary

Stellar evolution



Possible internal structures and compositions of four different types of compact stars





A semi-quantitative phase diagram on T − μ plane

EOS

Equation of states(EOS) of nuclear matter at high density

- Hadron matter
  - Nuclear many body theories: Brueckner-Bethe-Goldstone(BBG),....
  - Relativistic mean field theory
- Quark matter
  - MIT bag model
  - Dyson-Schwinger equations (DSE)
  - Nambu - Jona-Lasino (NJL) model (color superconductivity)
  - ...

Eos of Hadron Matter

We have calculated the equation of state of hadronic matter, we use statistical Thomas-Fermi approach by employing Myers-Swiatecki density dependent potential.

$$H = \sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{1 \le i \le j \le A} V_{ij} \ ,$$

$$H = H_0 + \Delta H \ ,$$

$$H_0 = \sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i=1}^{A} V_i \ ,$$

$$H_0 = H_{0n} + H_{0p}$$

$$V_{12} = -2T_F \rho_0^{-1} f(\frac{r_{12}}{a})\{\frac{1}{2}(1 \mp \xi)\alpha - \frac{1}{2}(1 \mp \zeta) \times [\beta(\frac{p_{12}}{p_F})^2 - \gamma(\frac{p_F}{p_{12}}) + \sigma(\frac{2\bar{\rho}}{\rho_0})^{\frac{2}{3}}]\}.$$

$$f(\frac{r_{12}}{a}) = \frac{1}{4\pi a^3} \frac{exp(-\frac{r_{12}}{a})}{\frac{r_{12}}{a}}$$

Relativistic Star

$$ds^2 = e^{\nu(r)}c^2dt^2 - e^{\lambda(r)}dr^2 - r^2(d\theta^2 + sin^2\theta d\phi^2)$$ → Metric

$$T^{\mu}_{\nu} = (p+\epsilon)u^{\mu}u_{\nu} + p\delta^{\mu}_{\nu}$$ → Energy-Momentum Tensor (EOS)

$$G_{\nu\mu} = 8\pi T_{\nu\mu}$$ → Einstein's Equation

$$\frac{dp}{dr} = -\frac{[p(r)+\epsilon(r)][m(r)+4\pi r^3 p(r)]}{r(r-2m(r))}$$ → TOV equation (General Relativistic Hydrostatic equilibrium)

$$m(r) = 4\pi \int_0^r dr r^2 \epsilon(r)$$ → Stellar mass

$r \to 0$ $\quad m(r) \to 0$ $\quad P \to P_c$ $\quad \epsilon \to \epsilon_c$

can easily be solved numerically for given EoS $\varepsilon(p)$

initial value: $p(r=0) = p_0$

surface of the star: $p(r=R) = 0$

gravitational mass of the star: $M \equiv m(R)$

EOS of Quark Matter (MIT Bag Model)

$$P_q = -B + P_q^{kin} + P_q^{int}$$

$$\varepsilon_q = B + \varepsilon_q^{kin} + \varepsilon_q^{int}$$

$$\Omega = \Omega_u + \Omega_d + \Omega_s + \Omega_e + B$$

$$\Omega_e = -\frac{\mu_e^4}{12\pi^2}$$

$$\begin{aligned}\Omega_q = & -\frac{3m_q^4}{8\pi^2}\left[\frac{\eta_q x_q}{3}(2x_q^2 - 3) + \ln(x_q + \eta_q)\right] \\ & + \frac{3m_q^4\alpha_s}{4\pi^3}\left\{2\left[\eta_q x_q - \ln(x_q + \eta_q)\right]^2 - \frac{4}{3}x_q^4 + 2\ln(\eta_q) \right. \\ & \left. + 4\ln\left(\frac{\sigma_{\mathrm{ren}}}{m_q\eta_q}\right)\left[\eta_q x_q - \ln(x_q + \eta_q)\right]\right\}\end{aligned}$$

$$\mu_s = \mu_d \equiv \mu, \quad \mu_u = \mu - \mu_e,$$

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0$$

m_q , μ_q : q quark mass and chemical potential.
$x_q = \sqrt{\mu_q^2 - m_q^2}/m_q$
$\eta_q = \sqrt{1 + x_q^2} = \mu_q/m_q$
α_s : QCD fine structure constant

$$\rho_q = -\frac{\partial\Omega_q}{\partial\mu_q}$$

$$\begin{aligned}\epsilon_Q &= \sum_q(\Omega_q + \mu_q\rho_q) + B \\ P_Q &= -\sum_q \Omega_q - B\end{aligned}$$

$$B(\rho) = B_\infty + (B_0 - B_\infty)\exp\left[-\beta\left(\frac{\rho}{\rho_0}\right)^2\right]$$

with $B_\infty = 60$ MeV fm^{-3}, $B_0 = 400$ MeV fm^{-3}, and $\beta = 0.17$.

Hadron-quark phase transition

Gibbs condition at zero temperature between hadron phase and quark phase

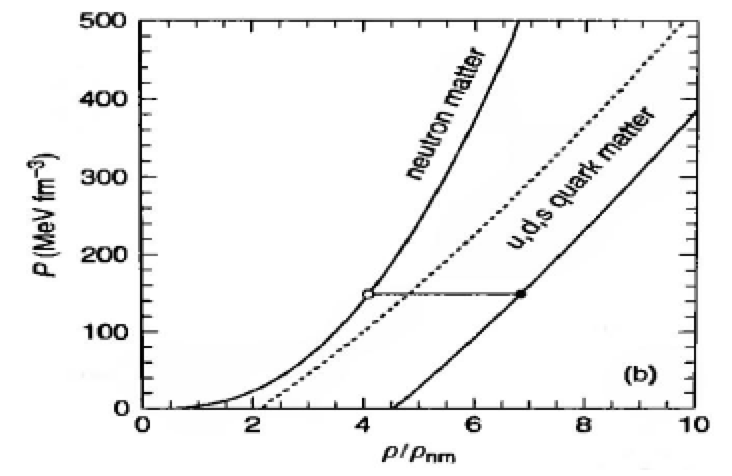
$$p_{HP}(\mu_n, \mu_e) = p_{QP}(\mu_n, \mu_e).$$

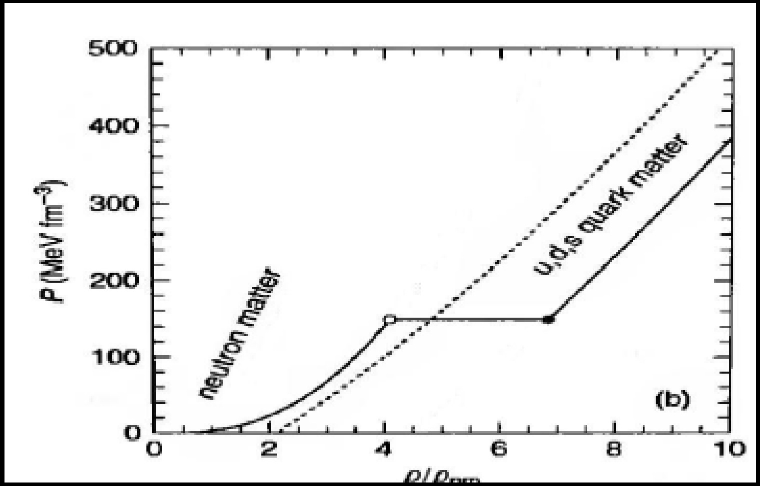
the total electrical charge is

$$0 = \frac{Q}{V} = \chi q_{QP} + (1 - \chi) q_{HP}$$

and the total energy density is

$$\epsilon = \frac{E}{V} = \chi \epsilon_{QP} + (1 - \chi) \epsilon_{HP}$$





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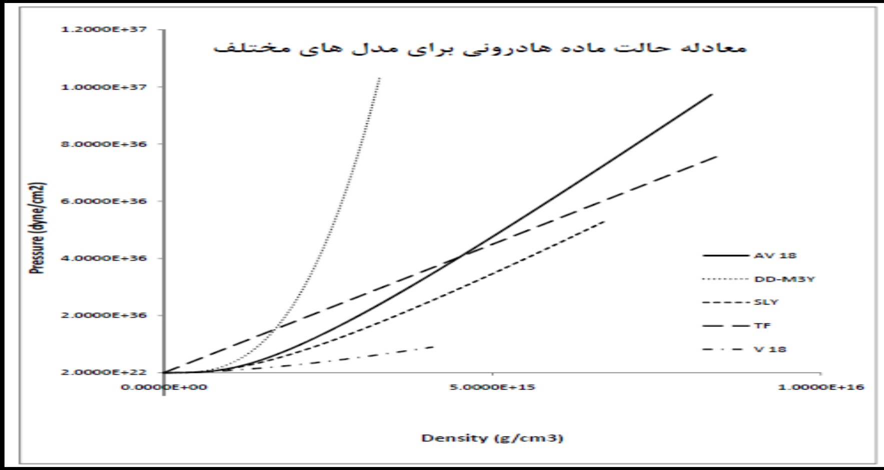
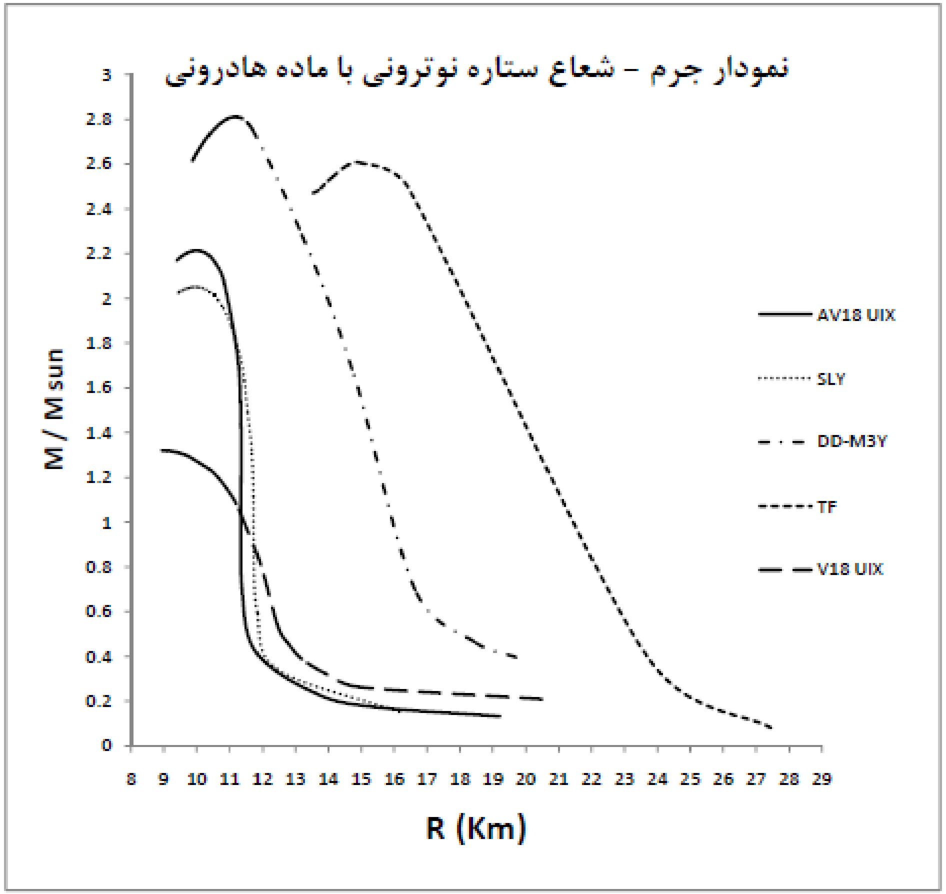
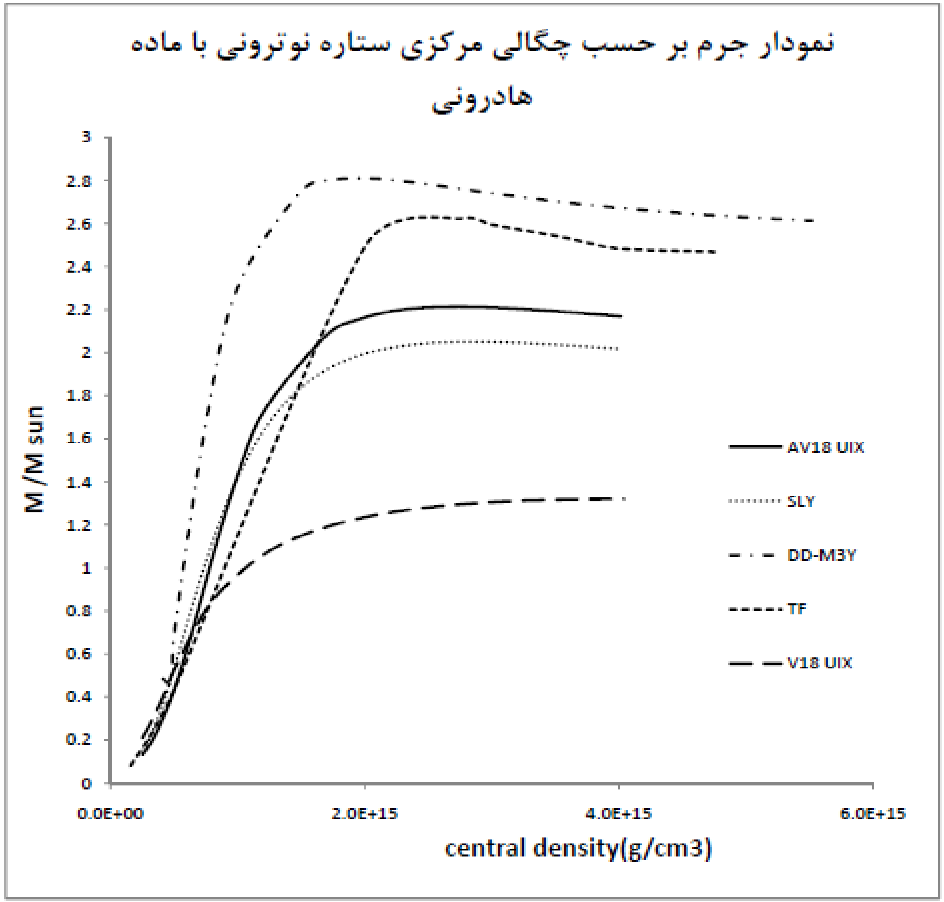
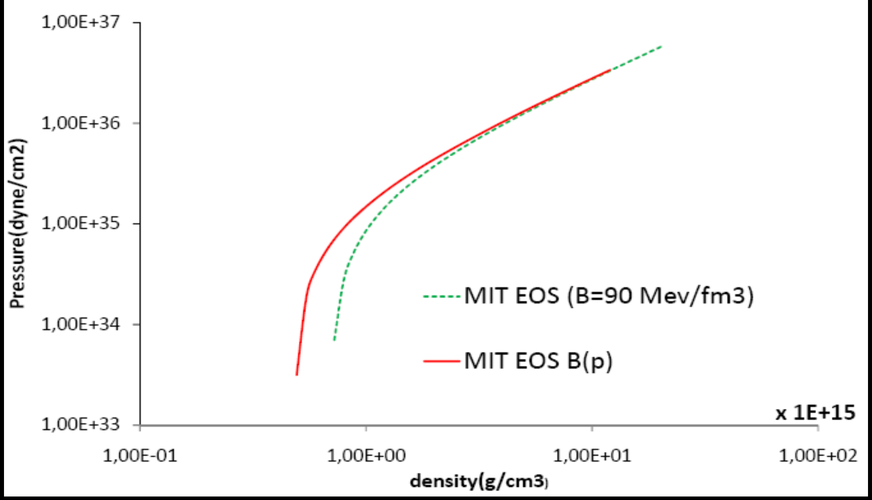
Results of hadron matter

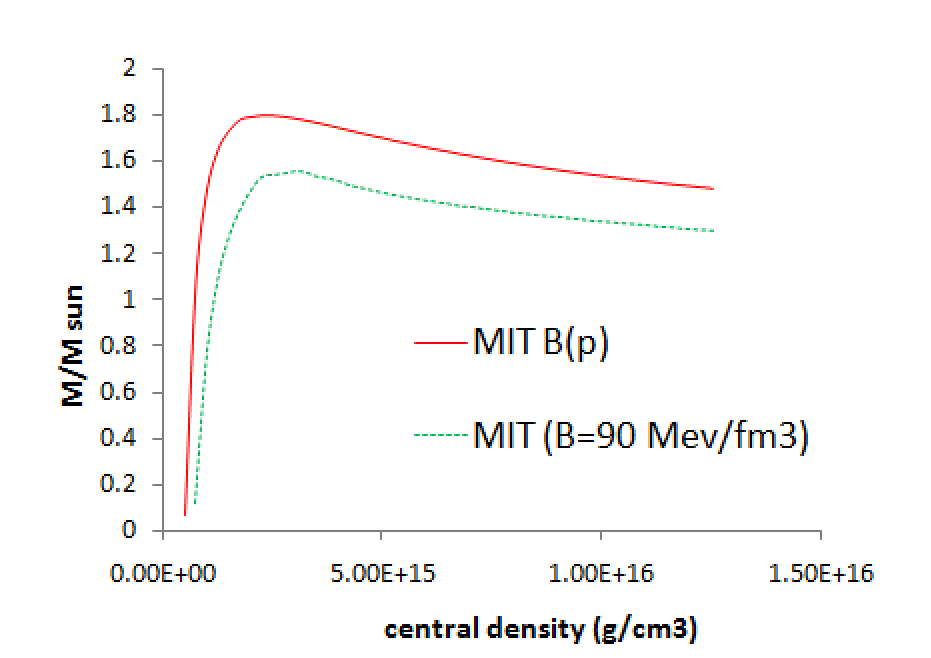


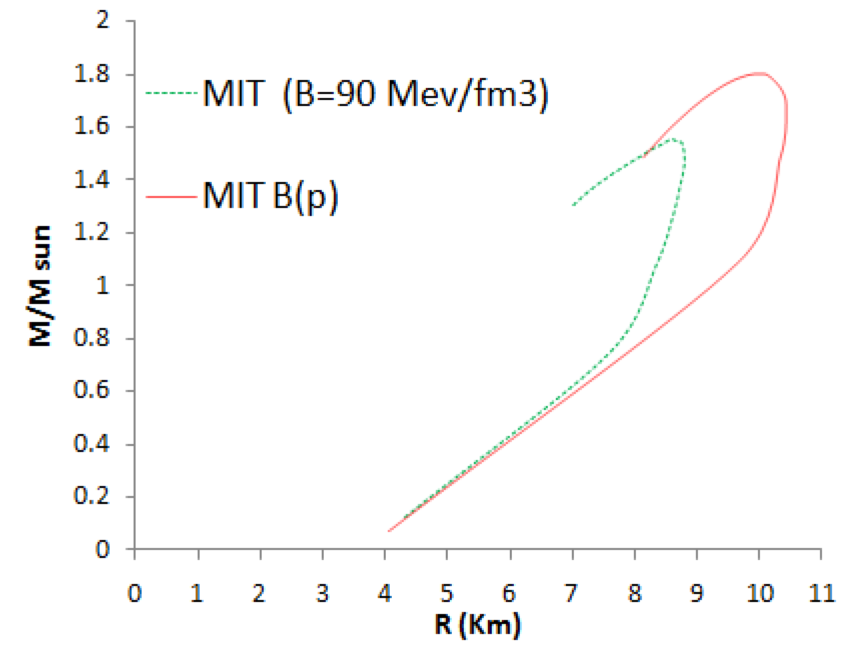




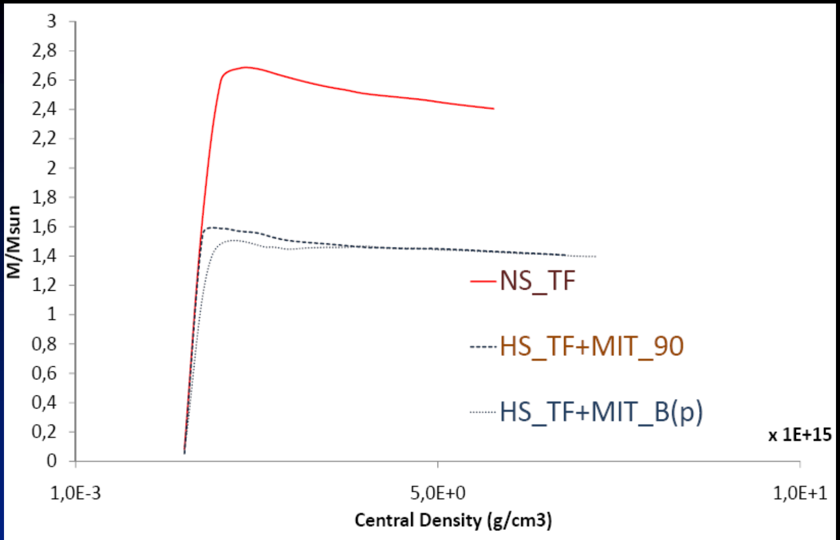
Results of quark matter

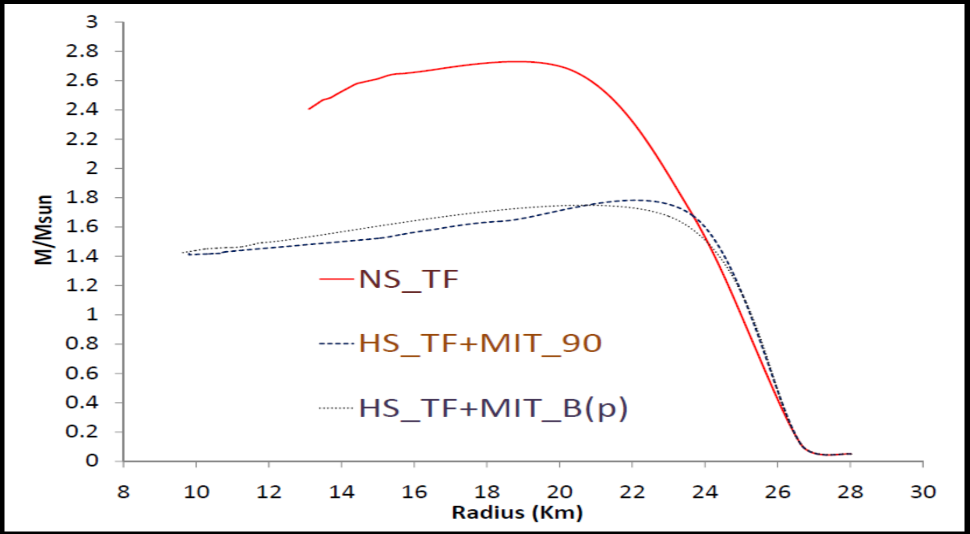


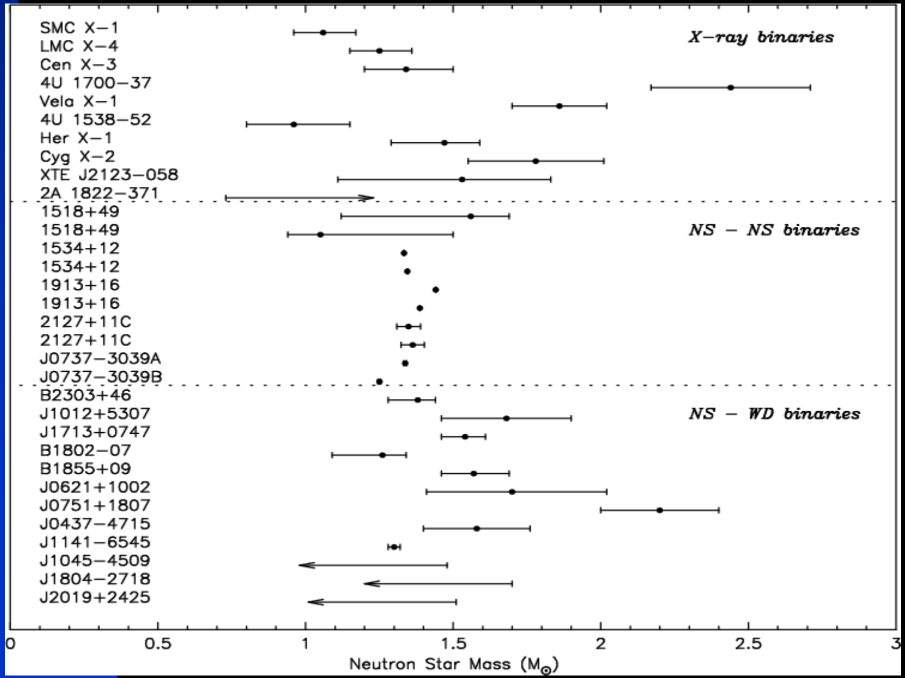




Conclusions







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Thank you for your attention.