Neutron and Quark stars

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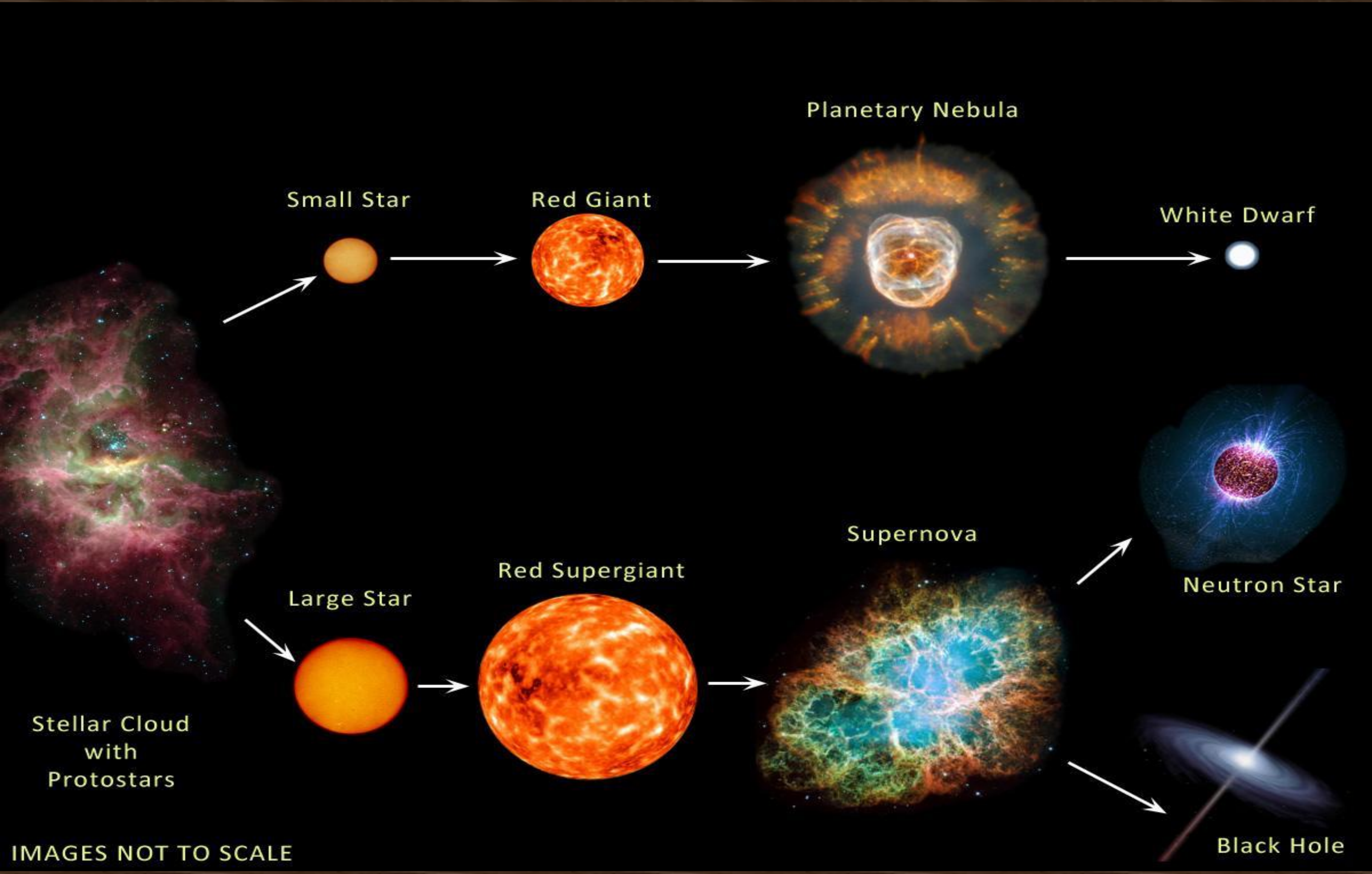
Outline

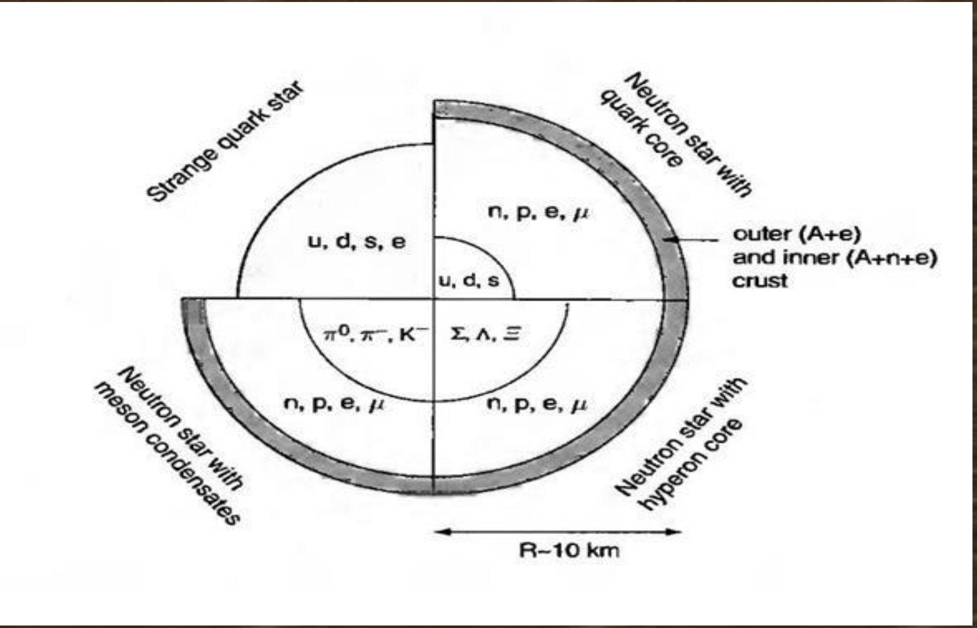
- Introduction
- Strange Quark Stars versus Neutron Stars
- Structure of Hybrid stars & Results

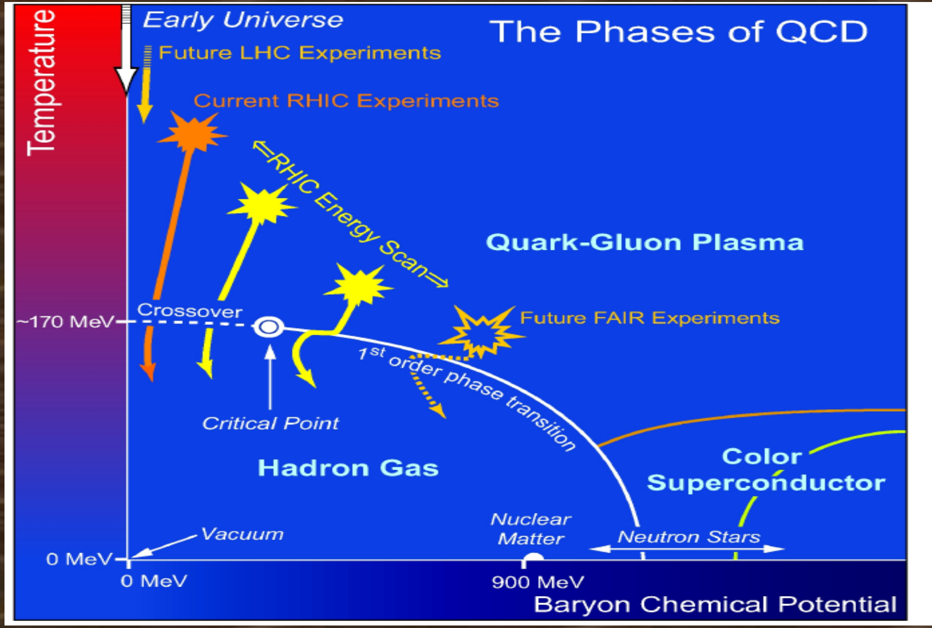
The evolution and fate of stars.



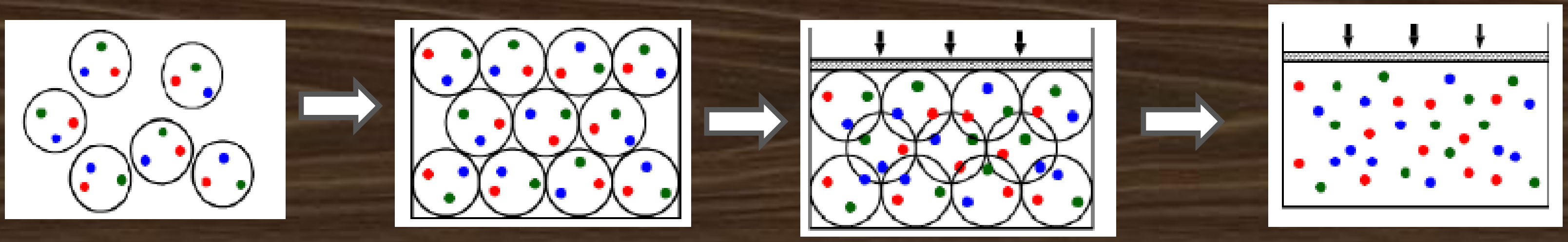
Object	Mass(g)	R(km)	Density(g/cm^{3})
Neutron Star	4×10^{33}	10	5×10^{14}
White Dwarf	2×10^{33}	5400	3×10^{6}
Sun	2×10^{33}	7×10^{5}	1.4 avg, 160 in core
Jupiter	2×10^{30}	7×10^{4}	1.3
Earth	6×10^{27}	6×10^{3}	5.5
Lead nucleus	3.5×10^{-22}	6×10^{-18}	3×10^{14}

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

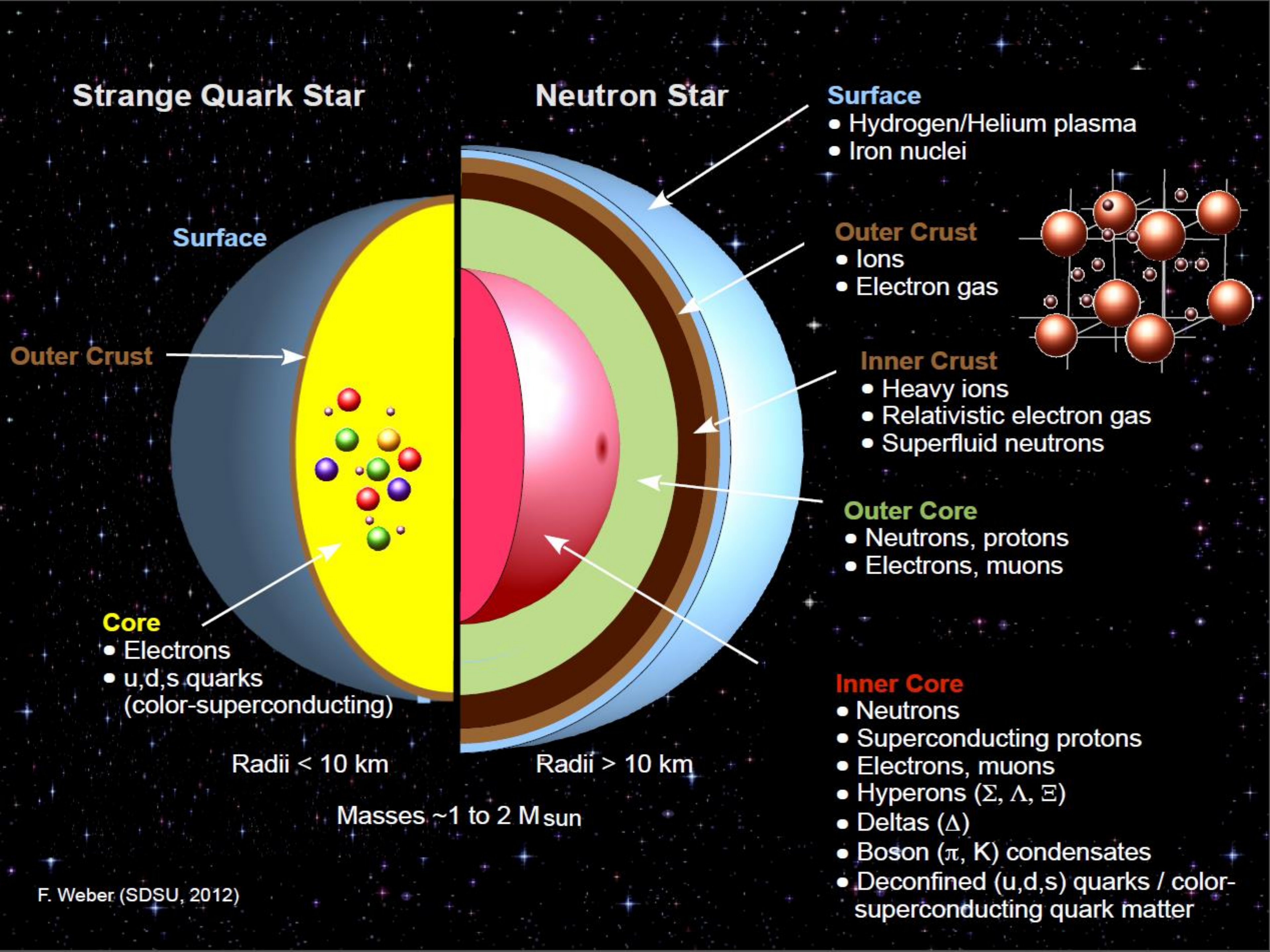




A semi-quantitative phase diagram on T − μ plane



quark deconfined phase transition


Strange Quark Star
Neutron Star
Surface
• Hydrogen/Helium plasma
• Iron nuclei
Surface
Outer Crust
• Ions
• Electron gas
Outer Crust
Inner Crust
• Heavy ions
• Relativistic electron gas
• Superfluid neutrons
Outer Core
• Neutrons, protons
• Electrons, muons
Core
• Electrons
• u,d,s quarks
(color-superconducting)
Inner Core
• Neutrons
• Superconducting protons
• Electrons, muons
• Hyperons (Σ, Λ, Ξ)
• Deltas (Δ)
• Boson (π, K) condensates
• Deconfined (u,d,s) quarks / color-superconducting quark matter
Radii < 10 km
Radii > 10 km
Masses ~1 to 2 Msun
F. Weber (SDSU, 2012)

Quark Stars* vs “Neutron” Stars

Quark Stars*	“Neutron” Stars
Made entirely of deconfined quarks and leptons	May contain deconfined quark matter only in stellar core
Self-bound ($M \sim R^3$)	Bound by gravity
Baryon number $\mathcal{O}(1) < B < 10^{57}$	10^{56} to 10^{57}
Electron sea at surface (super-high electric fields)	Absent
May posses outer crusts	Outer crusts
No inner crusts	Inner crusts
Two-parameter stellar sequences	One-parameter stellar sequence

*E. Witten, Phys. Rev. D 30 (1984) 272; Alcock, Farhi, Olinto, ApJ 310 (1986) 261; Alcock & Olinto, Ann. Rev. Nucl. Part. Sci. 38 (1988) 161; Madsen, Lecture Notes Phys. 516 (1999) 162.

TOV equation of hydrostatic equilibrium

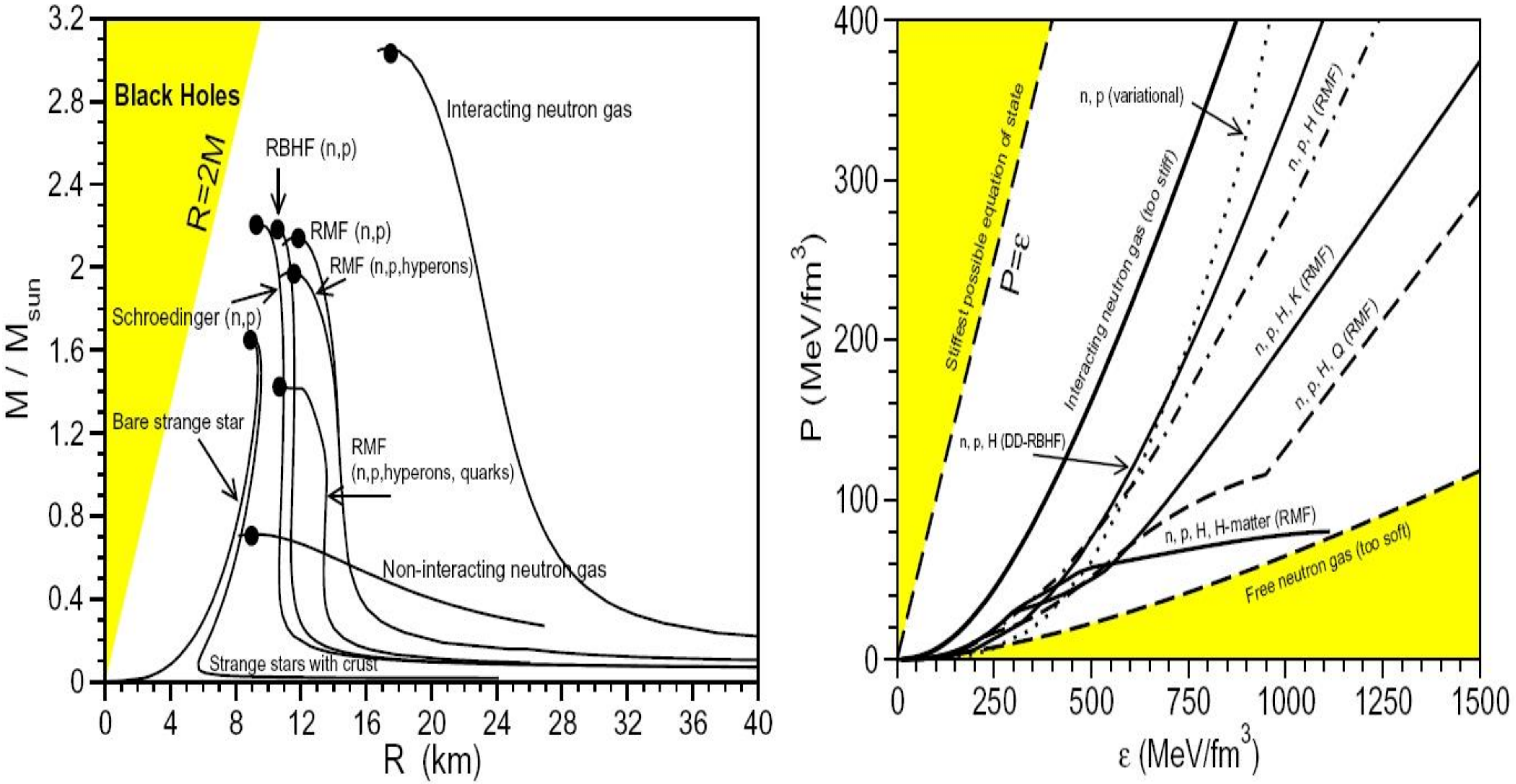
$$\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2}\frac{(1+P/\rho c^2)[1+4\pi r^3 P/m(r)c^2]}{1-2G\,m(r)/rc^2}$$

where

$$m(r) = \int_0^r 4\pi r^2 \rho dr$$

Equation of State (EOS) : P(ε(r),T)

Tolman-Oppenhiemer-Valkoff Equation



← quarks → ← hadrons →

(Weber et al. ArXiv: 0705.2708)

Baryonic Matter EOS

Interaction in strange baryonic matter

$$H = \sum_{i=1}^{A} T_i + \sum_{i<j}^{A} v_{ij} ,$$

The baryon-baryon interaction :

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

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

H R Moshfegh, M Ghazanfari Mojarrad. (2011) Thermal properties of baryonic matter. Journal of Physics G: Nuclear and Particle Physics 38:8, 085102.

EOS of Quark Matter (MIT Bag Model)

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

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

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

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

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

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

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

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

$$\begin{cases} d \rightarrow u + e + \overline{\nu_e} \\ u + e \rightarrow d + \nu_e \\ s \rightarrow u + e + \overline{\nu_e} \\ u + e \rightarrow s + \nu_e \\ s + u \leftrightarrow d + u \end{cases}$$

$B = 90$ Mev fm^{-3}

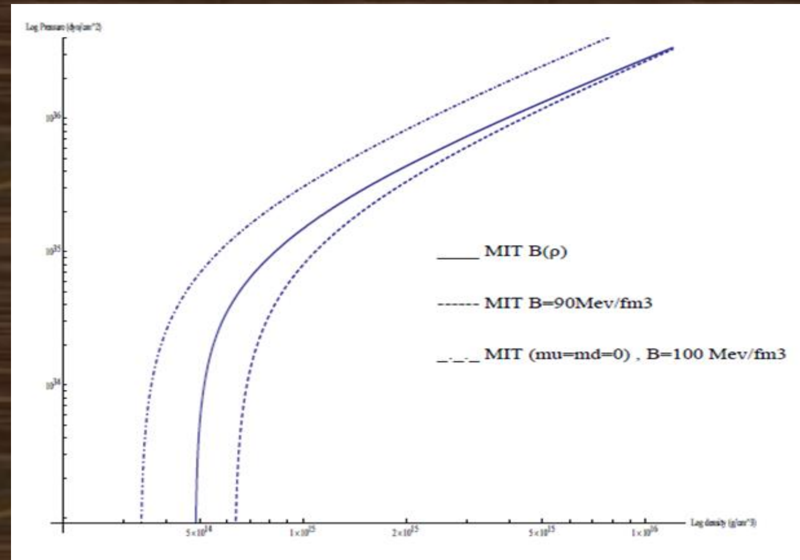
56 Mev fm^{-3} $< B <$ 250 Mev fm^{-3}

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

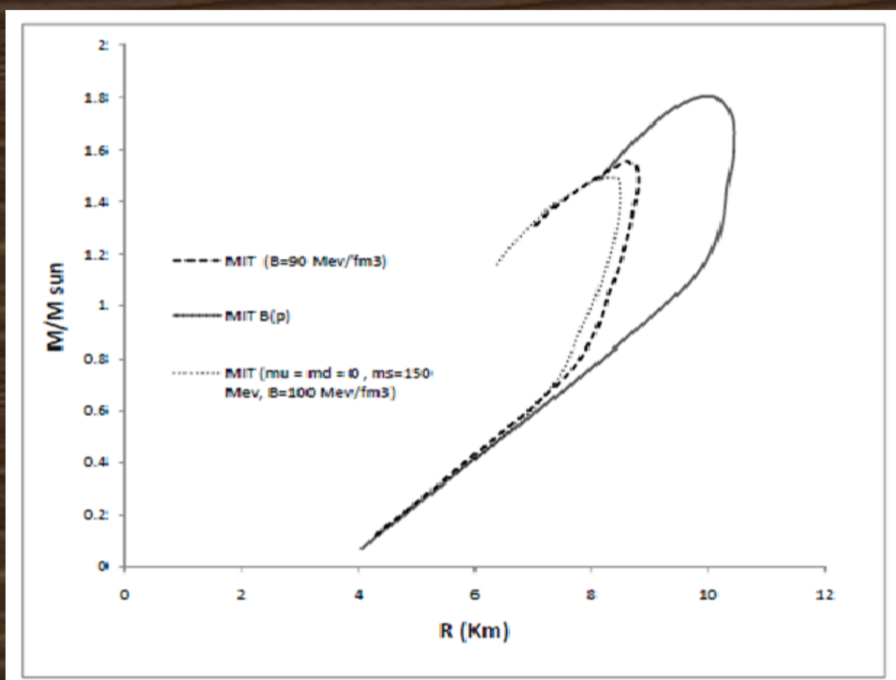
B_∞ = 60 Mev fm^{-3}

B_0 = 400 Mev fm^{-3}

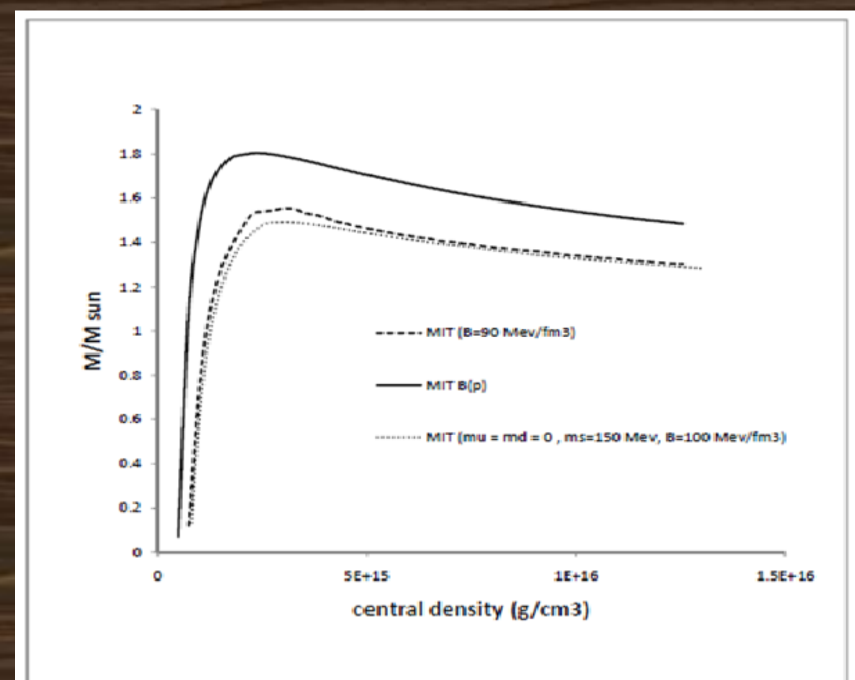
Quark Stars



MIT B(ρ)
MIT B=90Mev/fm3
MIT (mu=md=0) , B=100 Mev/fm3



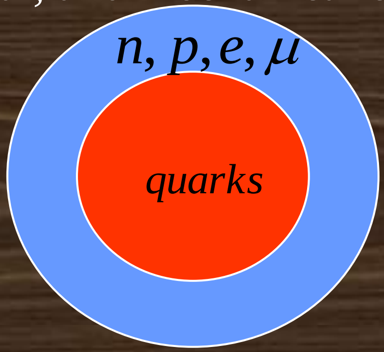
M/M sun
R (Km)
0
2
4
6
8
10
12
MIT (B=90 Mev/fm3)
MIT B(p)
MIT (mu = md = 0 , ms=150
Mev, B=100 Mev/fm3)



M/M sun
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
5E+15
1E+16
1.5E+16
central density (g/cm3)
MIT (B=90 Mev/fm3)
MIT B(p)
MIT (mu = md = 0 , ms=150 Mev, B=100 Mev/fm3)

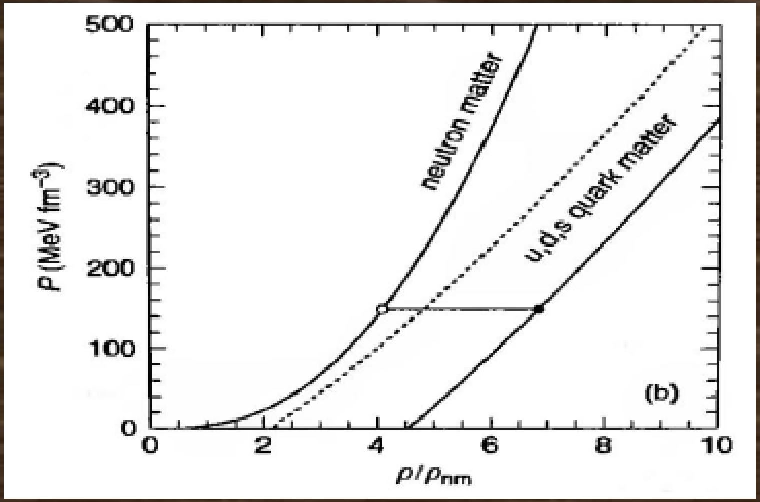
Hyperon-Quark Phase transition

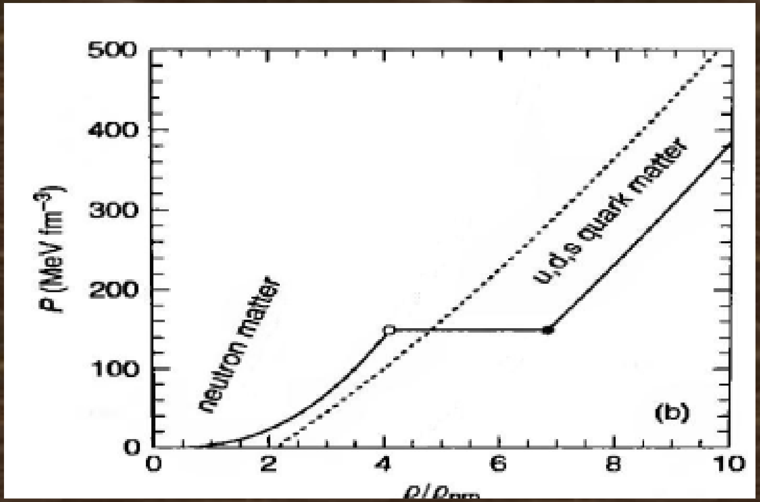
In the language of Gibbs, the two phases are in equilibrium when their (baryon) chemical potentials, temperatures, and pressures are equal, corresponding respectively to chemical, thermal, and mechanical equilibrium :



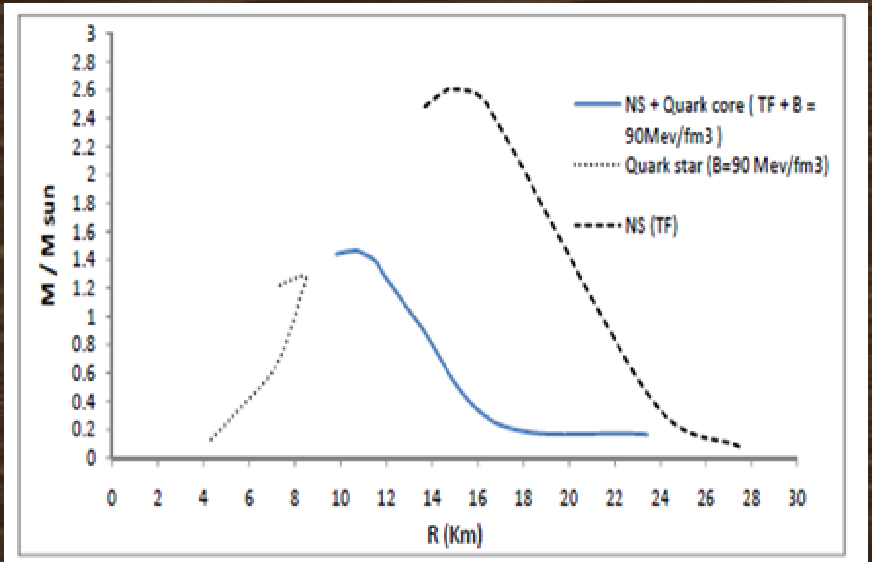
$$\mu_H = \mu_Q = \mu \,,$$
$$T_H = T_Q = T \,,$$
$$P_H(\mu_n, \mu_e, T) = P_Q(\mu_n, \mu_e, T) = P \,.$$

$$T \to 0 \qquad P_H(\mu_n, \mu_e) = P_Q(\mu_n, \mu_e) = P$$

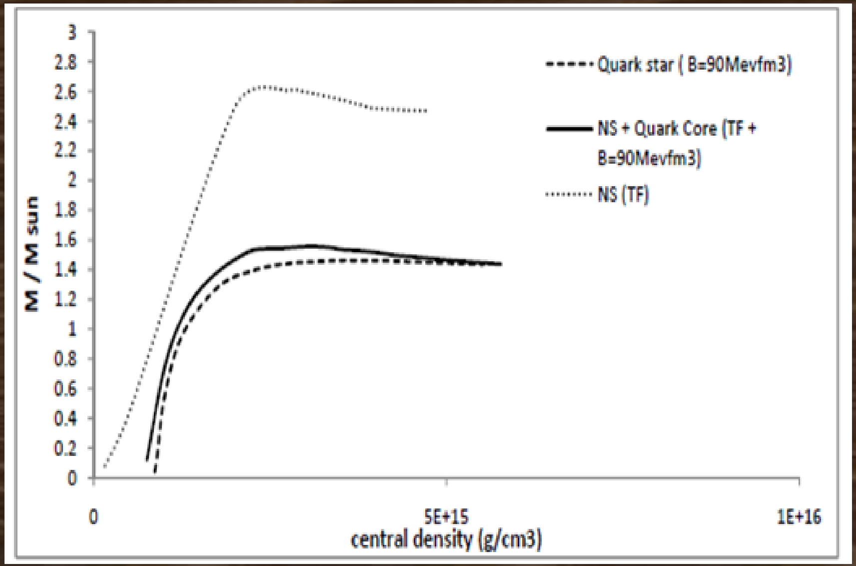




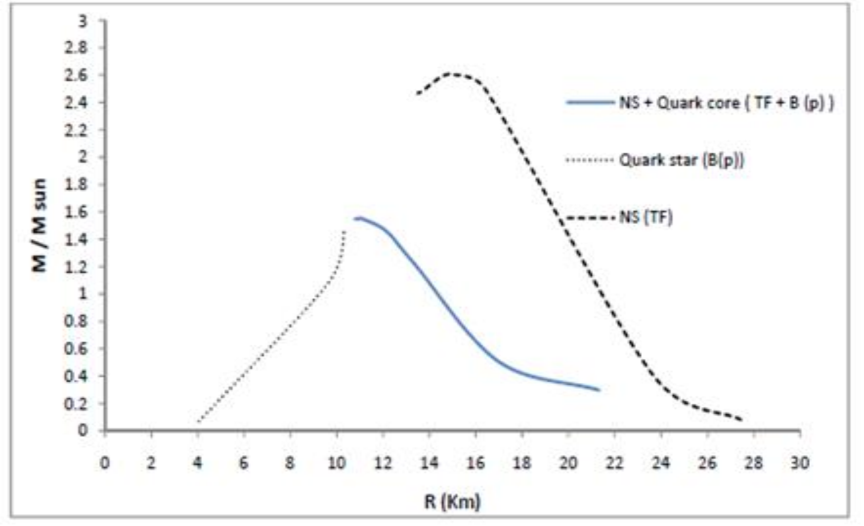
Results



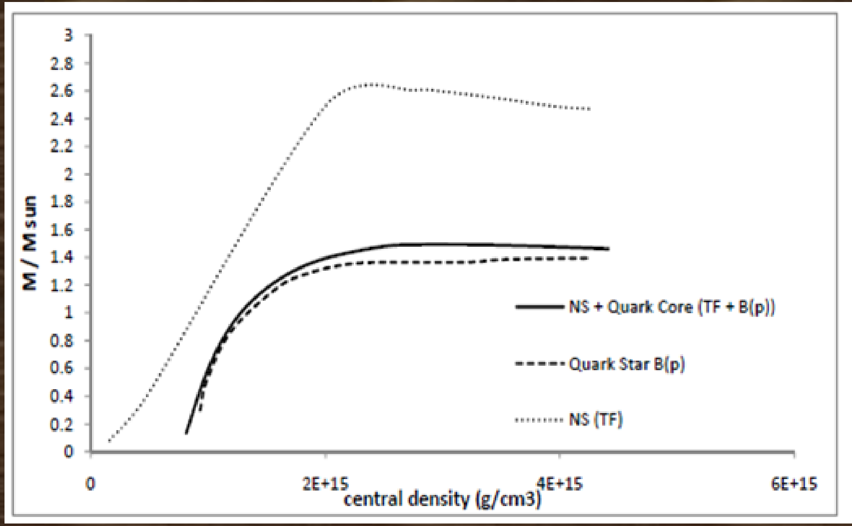
M / M sun
R (Km)
NS + Quark core (TF + B = 90Mev/fm3)
Quark star (B=90 Mev/fm3)
NS (TF)



M / M sun
central density (g/cm3)
Quark star (B=90Mevfm3)
NS + Quark Core (TF + B=90Mevfm3)
NS (TF)



M / M sun
R (Km)
NS + Quark core (TF + B (p))
Quark star (B(p))
NS (TF)



M / M sun
central density (g/cm3)
NS + Quark Core (TF + B(p))
Quark Star B(p)
NS (TF)

References:

•N.K. Glendenning COMPACT STARS, Nuclear Physics, Particle Physics and General Relativity, Springer, 2000.

• Weber et al. ArXiv: 0705.2708

•H.R. Moshfegh et al. J.Phys.G38:085102, 2011.


Thank you for your attention