Quark Matter in Neutron Stars in Light of Mass Measurement of PSR J1614-2230

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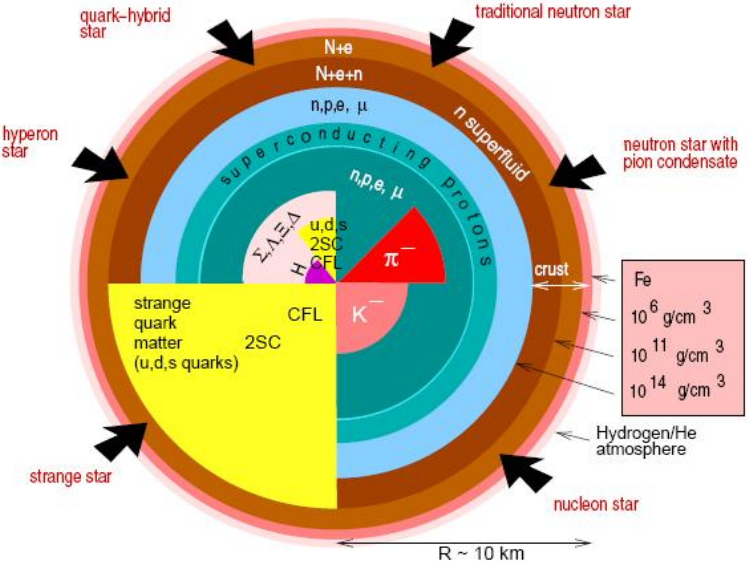
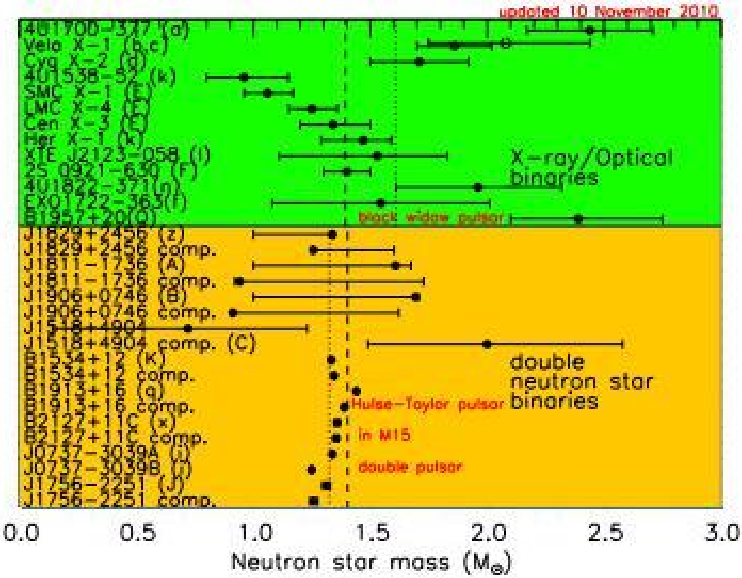
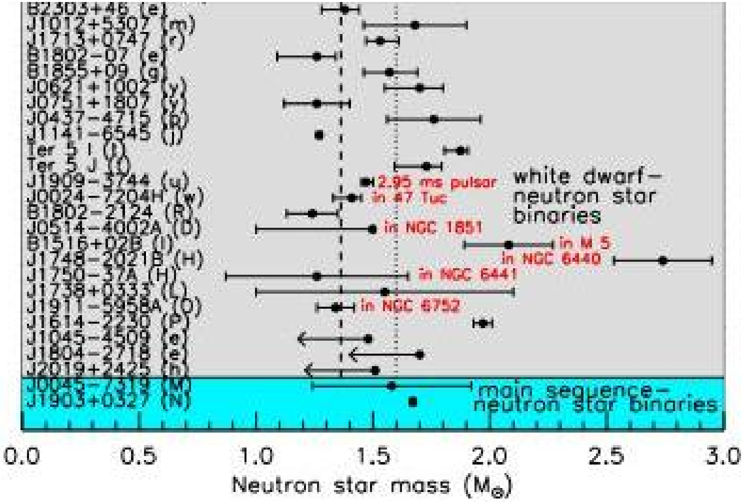
26.05.2012


quark-hybrid star
traditional neutron star
N+e
N+e+n
n,p,e, μ
n superfluid
hyperon star
superconducting protons
n,p,e, μ
neutron star with pion condensate
Σ,Λ,Ξ,Δ
u,d,s
2SC
CFL
H
π⁻
crust
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14 g/cm^3
strange quark matter (u,d,s quarks)
CFL
2SC
K⁻
Hydrogen/He atmosphere
strange star
nucleon star
R ~ 10 km



Lattimer, James M. et al. . arXiv:1012.3208 [astro-ph.SR]



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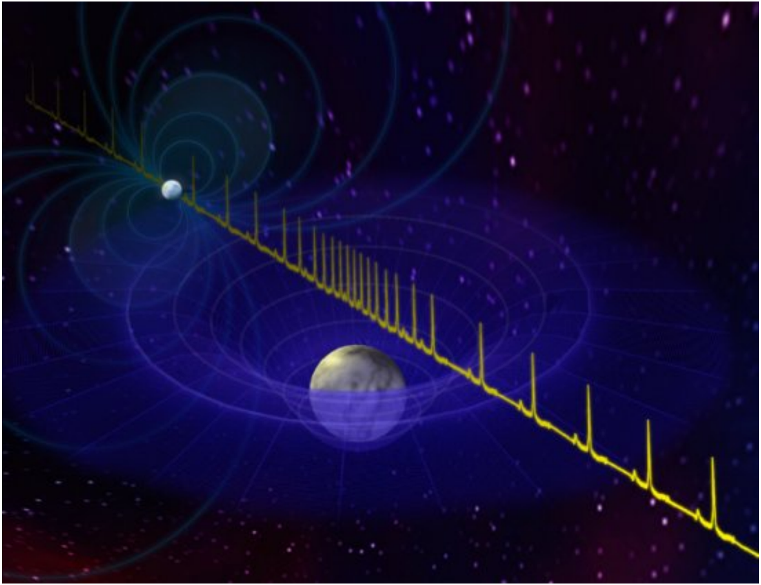


PSR J1614-2230

- Almost edge on system (89.17 inclination angle).
- Companion mass of 0.5 solar masses.
- Companion is a helium-carbon-oxygen white dwarf.
- The neutron star mass:

$$M = 1.97 \pm 0.04 M_{\odot}.$$

- Highest well known mass of NS before:

$$M_{J1903} = 1.66 M_{\odot}.$$

P.Demorest et al., Nature 467, 1081-1083 (2010)

Effective Lagrangian

$$\begin{aligned}\mathcal{L}_{int} &= G_S \eta_D \sum_{a,b=2,5,7} (\bar{q} i\gamma_5 \tau_a \lambda_b C \bar{q}^T)(q^T C i\gamma_5 \tau_a \lambda_a q) \\ &+ G_S \sum_{a=0}^{8} \left[(\bar{q}\tau_a q)^2 + \eta_V (\bar{q} i\gamma_0 q)^2 \right]\end{aligned}$$

Effective Lagrangian

$$\mathcal{L}_{int} = G_S \eta_D \sum_{a,b=2,5,7} (\bar{q} i \gamma_5 \tau_a \lambda_b C \bar{q}^T)(q^T C i \gamma_5 \tau_a \lambda_a q)$$
$$+ \quad G_S \sum_{a=0}^{8} \left[(\bar{q} \tau_a q)^2 + \eta_V (\bar{q} i \gamma_0 q)^2 \right]$$

Thermodynamical potential

$$\Omega(T,\mu) = \frac{\phi_u^2 + \phi_d^2 + \phi_s^2}{8G_S} - \frac{\omega_u^2 + \omega_d^2 + \omega_s^2}{8G_V} + \frac{\Delta_{ud}^2 + \Delta_{us}^2 + \Delta_{ds}^2}{4G_D}$$
$$- \int \frac{d^3p}{(2\pi)^3} \sum_{n=1}^{18} \left[E_n + 2T ln \left(1 + e^{-E_n/T} \right) \right] + \Omega_{lep} - \Omega_0$$

NJL parameters

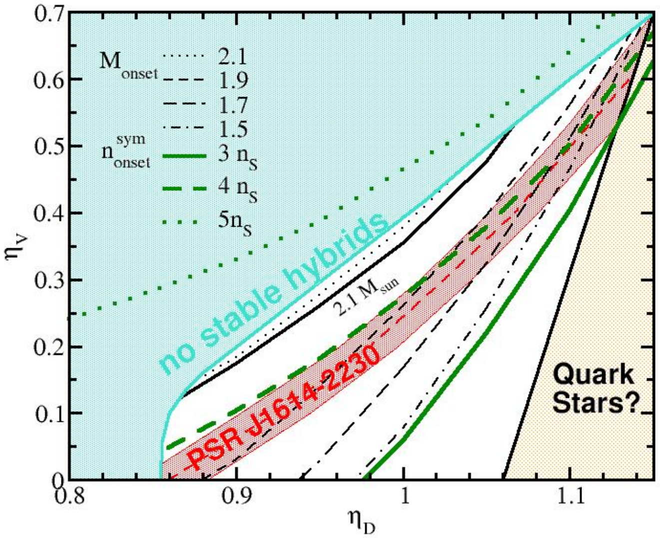
$$\begin{aligned}
\Lambda &= 602.3\,[MeV] \\
G_S &= 6.38427 \\
m_l &= 5.5\,[MeV] \\
\phi_l &= 361.886\,[MeV] \\
m_s &= 138.757\,[MeV] \\
\phi_s &= 447.814\,[MeV]
\end{aligned}$$

Parameter set taken from Table III. ($M(p = 0) = 367.5[MeV]$) of:
H. Grigorian, Phys.Part.Nucl.Lett. 4 (2007) 223-231
With corrected current strange quark mass:
http://3fcs.pendicular.net/psolver

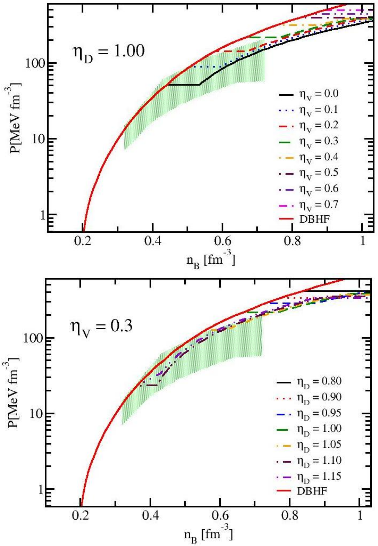
Phase transition

- Hadrons not yet described by NJL model
- Two phase system:
    - quark-gluon plasma described by NJL
    - nuclear matter described by DBHF
- Phase transition construction:
    - Maxwell construction - "sharp" phase transition
    - Gibbs construction - "smooth" phase transition
    - "pasta" phases - surface tension is unknown!
- Additional freedom in modelling

PSR J1614-2230 constraint

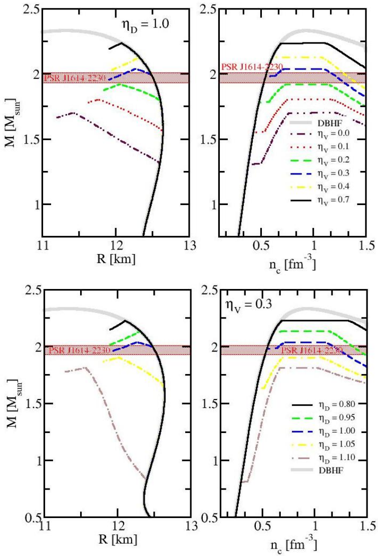


Symmetric EoS systematics



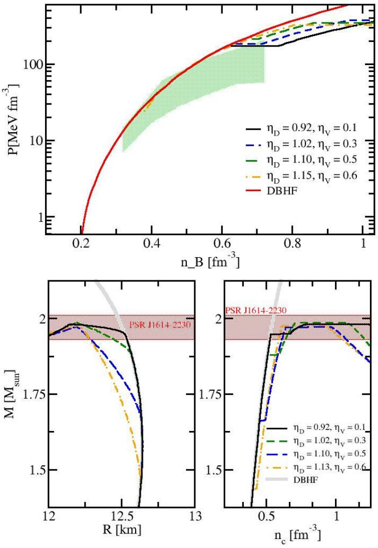
- Increase in η_D leads to earlier onset of quark matter and as an effect better fit with flow constraint
- Increase in η_V leads to later onset of quark matter and as an effect to high transition density in symmetric matter and conflict with flow constraint

Compact stars configurations



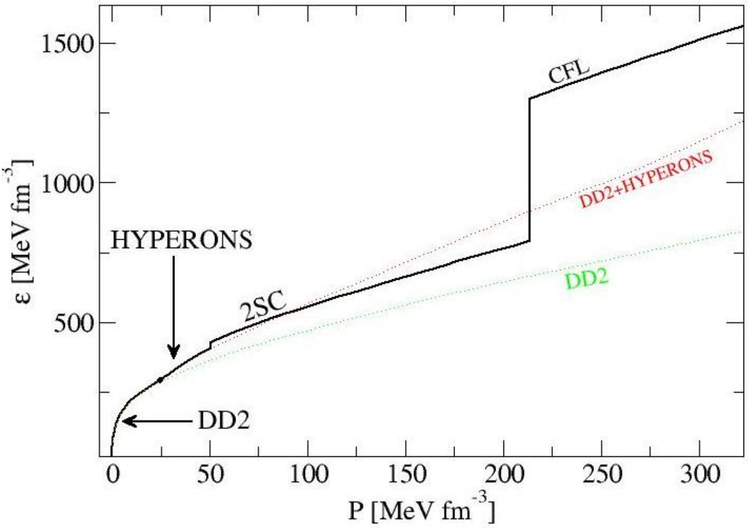
- Increase in η_D leads to earlier onset of quark matter and lower maximum mases of compact stars
- Increase in η_V leads to later onset of quark matter and higher maximum mases of compact stars

Systematics along the constraint line

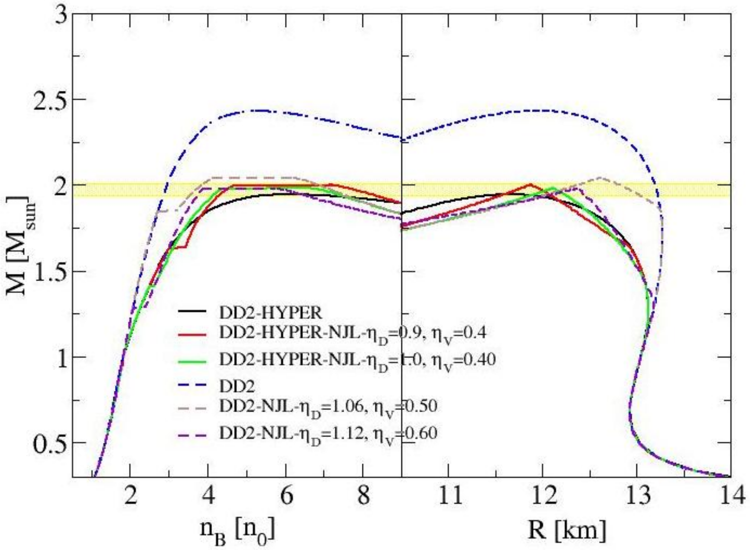


- Parameters chosen such that maximum mass is equal to that of "Demorest pulsar"
- The onset of quark matter can be tuned to values as low as $1.5 M_{sun}$
- Flow constraint is violated by this configurations

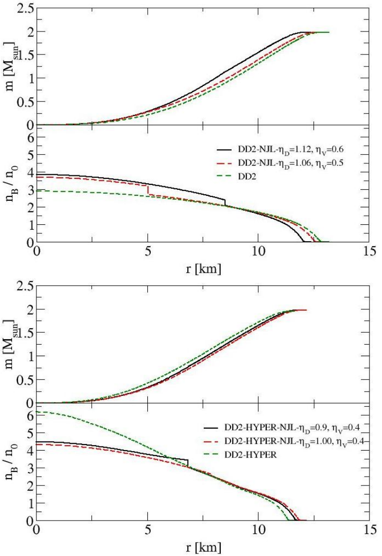
Equation of state



M-R relations



Inner structure of hybrid stars



- Small differences between profiles of hadronic(DD2) and hybrid configurations
- Step change in density at phase transition point
- Significant difference in central density between hyperonic configuration and hybrid configuration
- Similar radiuses for all configurations regardless of composition
- Significant volume of the star in quark phase

Formulas

Effective Lagrangian

$$\begin{aligned}\mathcal{L}_{int} &= G_S \eta_D \sum_{a,b=2,5,7} (\bar{q} i \gamma_5 \tau_a \lambda_b C \bar{q}^T)(q^T C i \gamma_5 \tau_a \lambda_a q) \\ &+ G_S \sum_{a=0}^{8} \left[(\bar{q} \tau_a q)^2 + \eta_V (\bar{q} i \gamma_0 q)^2 \right] \\ &- \mathbf{K[\det_f(\bar{q}(1+\gamma_5)q) + \det_f(\bar{q}(1-\gamma_5)q)]}\end{aligned}$$

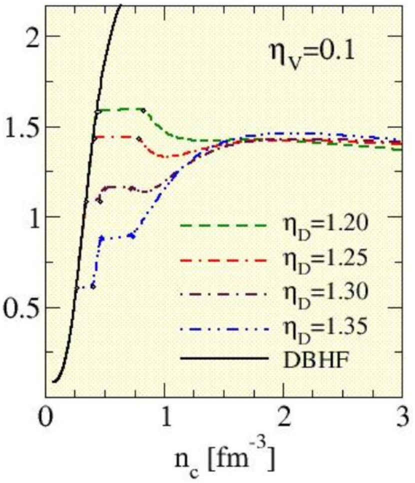
Formulas

Thermodynamical potential

$$\begin{aligned}\Omega(T,\mu) &= \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S}+\frac{\Delta_{ud}^2+\Delta_{us}^2+\Delta_{ds}^2}{4G_D}\\ &- \frac{\omega_u^2+\omega_d^2+\omega_s^2}{8G_V}+\frac{\mathbf{K\phi_u\phi_d\phi_s}}{\mathbf{16G_S^3}}\\ &- \int\frac{d^3p}{(2\pi)^3}\sum_{n=1}^{18}\left[E_n+2Tln\left(1+e^{-E_n/T}\right)\right]+\Omega_{lep}-\Omega_0\end{aligned}$$

M-R relations

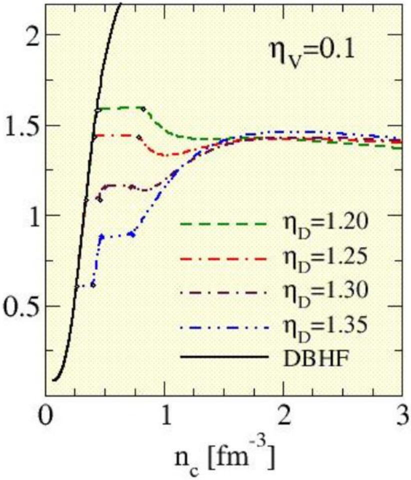
- White dwarfs → "normal" neutron star → CFL hybrid star



$$\frac{dP(r)}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[M(r) + 4\pi r^3 \frac{P(r)}{c^2}\right]\left[1 - \frac{2GM(r)}{c^2 r}\right]^{-1}$$

M-R relations

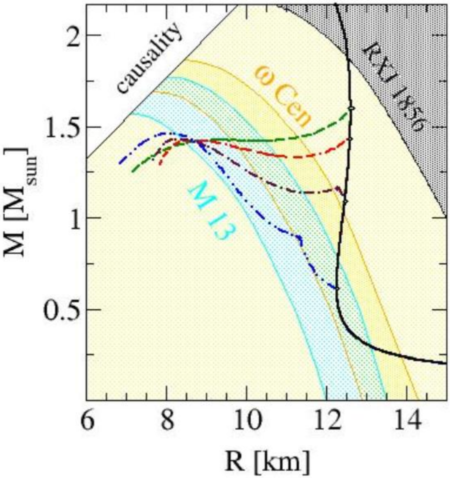
- White dwarfs → "normal" neutron star → CFL hybrid star
- On the right: solutions of TOV equation (non-rotating configurations)



$$\frac{dP(r)}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[M(r) + 4\pi r^3 \frac{P(r)}{c^2}\right]\left[1 - \frac{2GM(r)}{c^2 r}\right]^{-1}$$

M-R relations

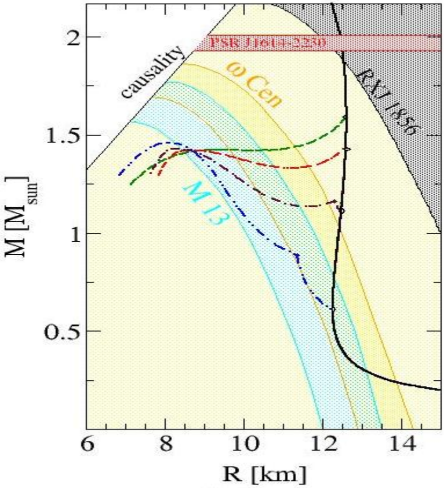
- White dwarfs → "normal" neutron star → CFL hybrid star
- On the right: solutions of TOV equation (non-rotating configurations)
- PSR J1614-2230 constraint



$$\frac{dP(r)}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[M(r) + 4\pi r^3 \frac{P(r)}{c^2}\right]\left[1 - \frac{2GM(r)}{c^2 r}\right]^{-1}$$

M-R relations

- White dwarfs → "normal" neutron star → CFL hybrid star
- On the right: solutions of TOV equation (non-rotating configurations)
- PSR J1614-2230 constraint
- Model excluded!



$$\frac{dP(r)}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[M(r) + 4\pi r^3 \frac{P(r)}{c^2}\right]\left[1 - \frac{2GM(r)}{c^2 r}\right]^{-1}$$

Conclusions

- Mass measurements of neutron star can provide constraints on equation of state of cold, dense matter
- The measurements of the mass of PSR J1614-2230 does not exclude possibility of deconfined quark matter in neutron stars
- More precise and more extreme measurements can be very useful
- Connection can be made between physics of heavy-ion collisions and physics of neutron stars, double constraining the EoS
- Future colliders, in particular NICA and FAIR, can probe regions of phase diagram which is relevant for physics of Super-Nova explosions and neutron stars