Hadron-Quark Crossover and Massive Hybrid Stars

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Abstract

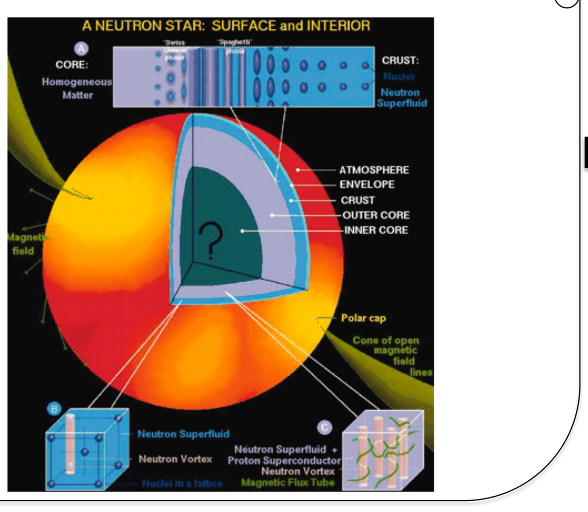
Using the idea of smooth crossover from hadronic matter with hyperons to quark matter with strangeness, we show the maximum mass of neutron stars with quark matter core can be larger than $2M_\odot$. It is in contrast to conventional softening of EOS due to exotic components in the case of 1_{st} order transition.

Essential conditions: (I) the crossover takes place at relatively low densities, around 3 times the normal nuclear density.
(II) the quark matter is strongly interacting in the crossover region.

Introduction

•Observation

Typical observed mass for double NS binaries: $1.4M_\odot$



•Theory

TOV equation

$$\begin{cases} \frac{dP}{dr} = -(M+4\pi Pr^3)(\varepsilon+P)\left(\frac{r^2}{G}-2Mr\right)^{-1} \\ M = \int 4\pi r^2 \varepsilon(x)dx \end{cases}$$

EOS = Equation of State: $P = f(\varepsilon)$

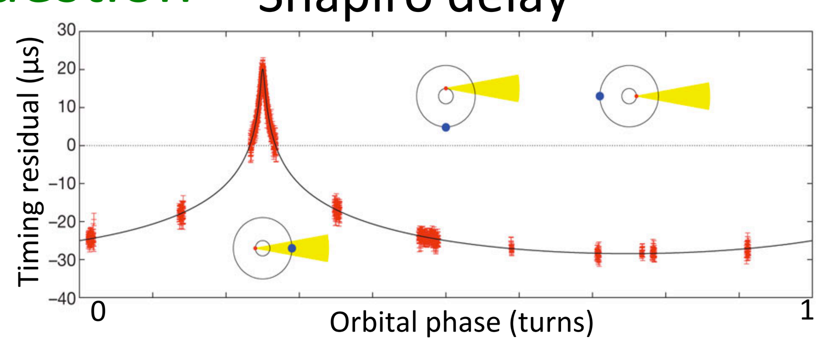
↕ one-to-one correspondence

Mass-Radius(M-R) relation for NS

•Recent discovery [1] and Key question

In 2010, NS(PSRJ1614-2230) with $(1.97\pm0.04)M_\odot$ was found

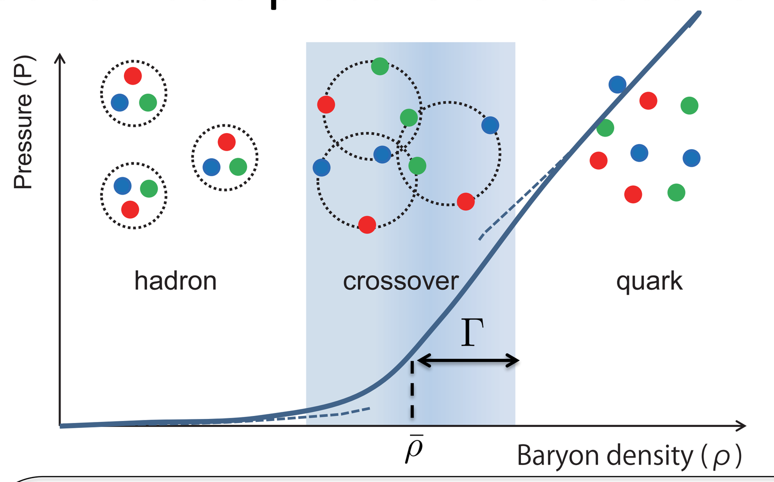
Shapiro delay



- Are there any EOS which can explain $2M_\odot$ NS?
- Is there Hadron-Quark transition inside the NS?

New EOS with hadron-quark crossover [2,3]

Schematic picture of crossover



• key point

Hypothesis of the hadron-quark crossover specified by free parameters: $\bar{\rho}$, Γ

• Condition

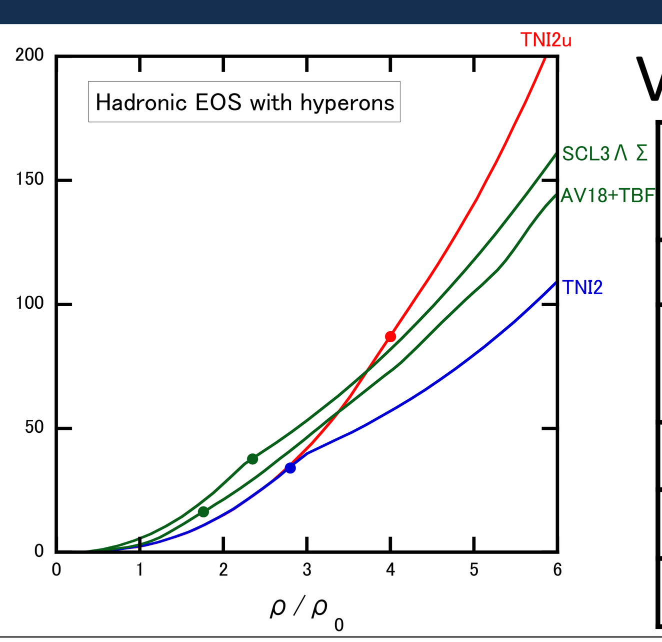
At ρ_0 , hadron picture must be correct $\longrightarrow \bar{\rho}-2\Gamma \geq \rho_0$

• Definition of pressure P and energy density ε

$$P = P_H \times \frac{1-\tanh\left(\frac{\rho-\bar{\rho}}{\Gamma}\right)}{2} + P_Q \times \frac{1+\tanh\left(\frac{\rho-\bar{\rho}}{\Gamma}\right)}{2}, \quad P = \rho^2 \frac{\partial(\varepsilon/\rho)}{\partial\rho}$$

P_H: pressure in a hadron phase; P_Q: pressure in a quark phase; $\bar{\rho}$: crossover density; Γ: width of the crossover region

Hadronic phase: TNI2u EOS [4]



Various EOS with hyperons

	TNI2u	TNI2	AV18 + TBF	SCL3ΛΣ
method	G-matrix	G-matrix	G-matrix	RMF
universal 3-body force	○	×	×	×
κ (MeV)	250	250	192	211
maximum mass($M_\odot$)	1.52	1.08	1.22	1.36
central density(ρ_0)	11.06	16.10	7.35	5.89

Quark phase: NJL EOS

(2+1)-flavor NJL with β-equilibrium and charge neutrality ($+e^-, \mu^-$)

$$L_{NJL} = \bar{q}(i\partial\!\!\!/ - m)q + \frac{G_s}{2}\sum_{a=0}^{8}[(\bar{q}\lambda^a q)^2 + (\bar{q}i\gamma_5\lambda^a q)^2] - \frac{g_v}{2}[(\bar{q}\gamma_\mu q)^2]$$
$$+G_D[\det\bar{q}(1+\gamma_5)q + \mathrm{h.c}]$$

[5],[6]

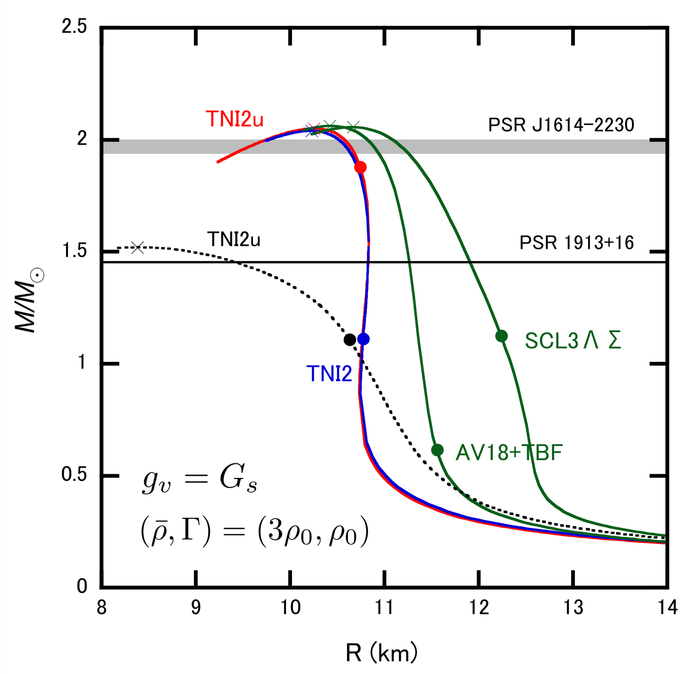
parameter	HK	RKH	LKW
Λ(MeV)	631.4	602.3	750
$G_s\Lambda^2$	3.67	3.67	3.64
$G_D\Lambda^5$	9.29	12.36	8.9
$m_{u,d}$(MeV)	5.5	5.5	3.6
m_s(MeV)	135.7	140.7	87

↳ mean field approximation

In this poster, we choose HK and change g_v in the range $0 \leq \frac{g_v}{G_s} \leq 1.5$

Results

1. Maximum mass [2],[3]

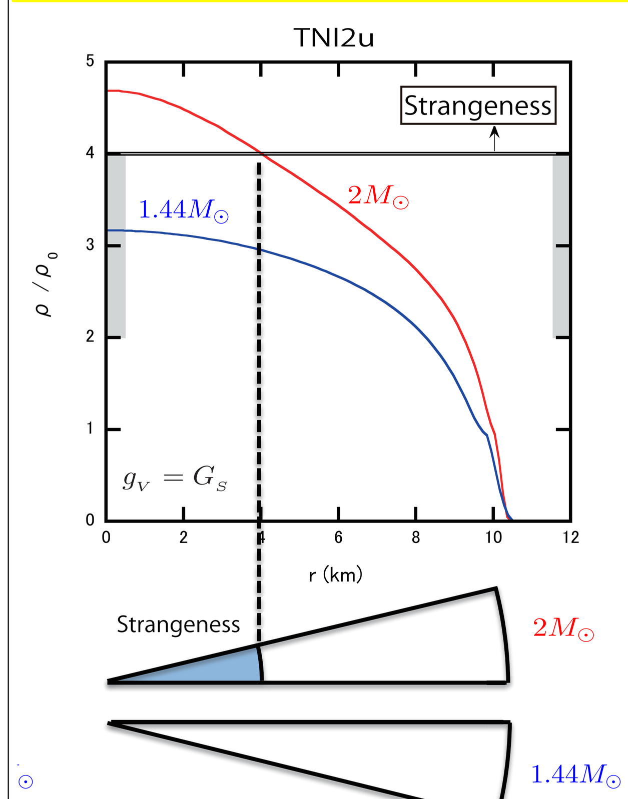


Maximum mass $\frac{M_{\max}}{M_\odot}$ with TNI2u H-EOS

$\bar{\rho}$ / ρ_0	$\Gamma/\rho_0 = 1$		$\Gamma/\rho_0 = 2$	
	$g_v = G_s$	$g_v = 1.5G_s$	$g_v = G_s$	$g_v = 1.5G_s$
3	2.05	2.17	-	-
4	1.89	1.98	-	-
5	1.73	1.80	1.74	1.80
6	1.60	1.65	1.62	1.66

- $M_{\max}$ does not depend on H-EOS
- strongly interacting quark phase at relatively low densities $\rightarrow 2M_\odot$

2. Internal structure [3] $(\bar{\rho},\Gamma) = (3\rho_0, \rho_0)$



Universal 3-body force delays hyperon mixture
$2.5\rho_0$ (TNI2) $\rightarrow 4\rho_0$ (TNI2u)

↓

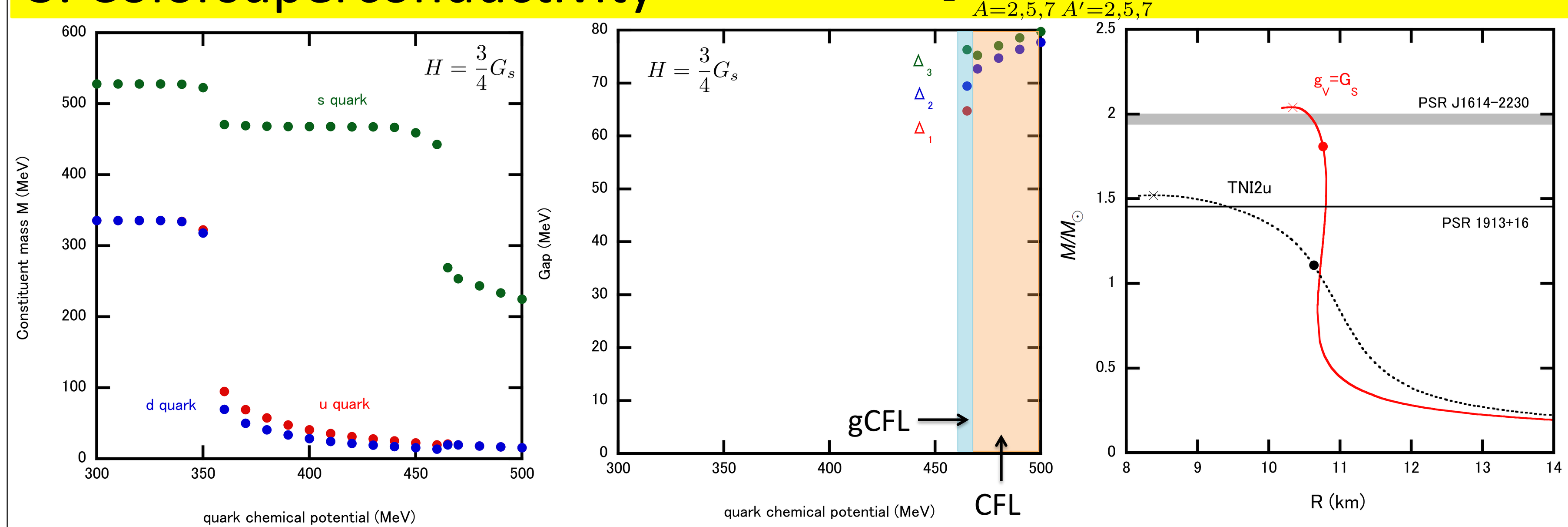
Only the massive neutron stars would have strangeness core in a form of quark matter.

↓

This may solve the well-known problem of rapid cooling of neutron stars with hyperon core.

3. Colorsuperconductivity

$$L = L_{NJL} + \frac{H}{2}\sum_{A=2,5,7}\sum_{A'=2,5,7}(\bar{q}i\gamma_5\tau_A\lambda_{A'}C\bar{q}^T)(q^T C i\gamma_5\tau_A\lambda_{A'}q)$$



- At very high density, colorsuperconducting (CSC) phase appears.
- CSC softens EOS, but its effect on the maximum mass is very small.

Summary

New EOS with Crossover

Hadron phase: TNI2u (hyperons and universal 3-body force)
Quark phase : (2+1)-flavor NJL with β-equilibrium and charge neutrality

↳ strongly interacting quark matter can sustain $2M_\odot$ NS.
It is in contrast to the case of 1_{st} order transition.

Future Works

- Finite temperature extension to treat proto-neutron star
- Constraints on EOS from other observables (cooling, ...) ...

References

[1]P. B. Demorest et al., Nature **467** (2004), 1081-1083
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