Hadron-Quark Crossover as a Possible Resolution of Hyperon Crisis in Massive Neutron Stars

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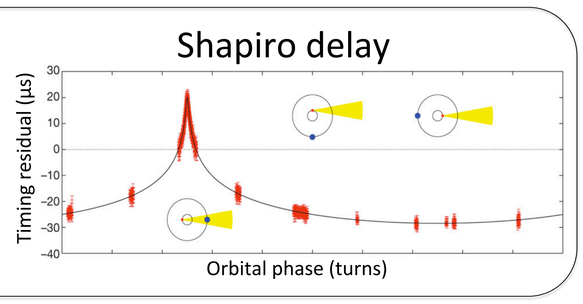
Abstract

We propose a possible resolution of how 2 solar-mass neutron stars are sustained from the point of view of the smooth crossover between the hadronic matter with hyperons and the strongly interacting (2+1)-flavor quark matter at around 3 times the normal nuclear matter density.
This mechanism leads to a stiff EOS and hence to two solar-mass neutron stars with reasonable radius of about 12-13 km. Our idea is in sharp contrast to the conventional approach of the first-order hadron-quark transition where the EOS always becomes soft.
We also try to extend this model to the finite temperature region to treat proto-neutron stars.

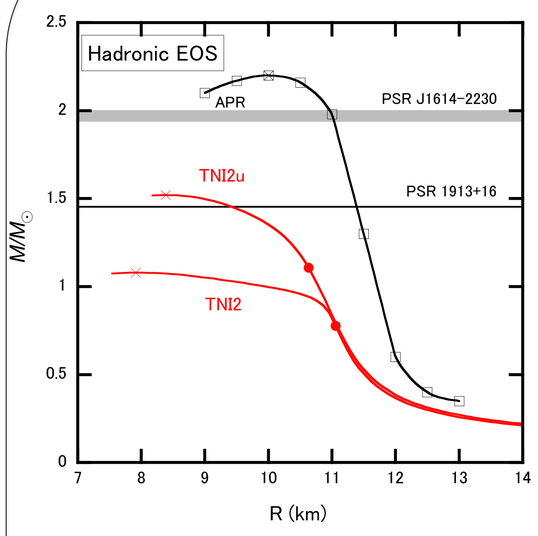
Introduction [1,2,3,4]

•Recent observation [1]

In 2010, NS(PSRJ1614-2230) with (1.97±0.04) $M_\odot$ was found through Shapiro delay .



•Hyperon Crisis [2]



	TNI2(u)	APR
method	G-matrix	Variational
Hyperons	✔	×
3-body force (NNN)	✔	✔
3-body force (YNN,..)	× (✔)	×
Nuclear incomressibility	250	269
Maximum mass	1.08 (1.62)	2.20

A serious conflict between the stiff EOS required from the observations and the soft EOS with hyperons required from theory.

•Key questions

At T=0 MeV [3,4]
- Are there any EOS which can explain $2M_\odot$ NS?
- What is the fate of the quark matter inside a heavy NS ?

At T≠0 MeV
- How do hot NSs impose new constraints on dense matter ?

Quark EOS [5]

We use (2+1)-flavor NJL with β-equilibrium and charge neutrality.

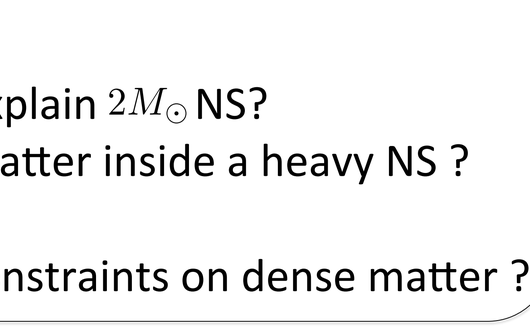
$$L_{NJL} = \bar{q}(i\partial - m)q + \frac{G_s}{2}\sum_{a=0}^{8}[(\bar{q}\lambda^a q)^2 + (\bar{q}i\gamma_5\lambda^a q)^2] - \frac{g_v}{2}[(\bar{q}\gamma_\mu q)^2]$$
$$+G_D[\det\bar{q}(1+\gamma_5)q + \mathrm{h.c}]$$

↳ mean field approximation

parameter [5]	$\Lambda(\mathrm{MeV})$	$G_s\Lambda^2$	$G_D\Lambda^5$	$m_{u,d}(\mathrm{MeV})$	$m_s(\mathrm{MeV})$
	631.4	3.67	9.29	5.5	135.7

Hadron-quark crossover

Hot NSs are composed of ``supernova matter'' characterized by constant entropy per baryon S and lepton fraction Y.



•Definition of EOS for supernova matter

we hypothesis $\bar{\rho}$ and Γ do not depend on T.

Helmholtz free energy F(ρ,T) = E(ρ,T) - TS(ρ,T)

$$F(\rho,T) = F_H(\rho,T)\times\frac{1-\tanh\left(\frac{\rho-\bar{\rho}}{\Gamma}\right)}{2} + F_Q(\rho,T)\times\frac{1+\tanh\left(\frac{\rho-\bar{\rho}}{\Gamma}\right)}{2}$$

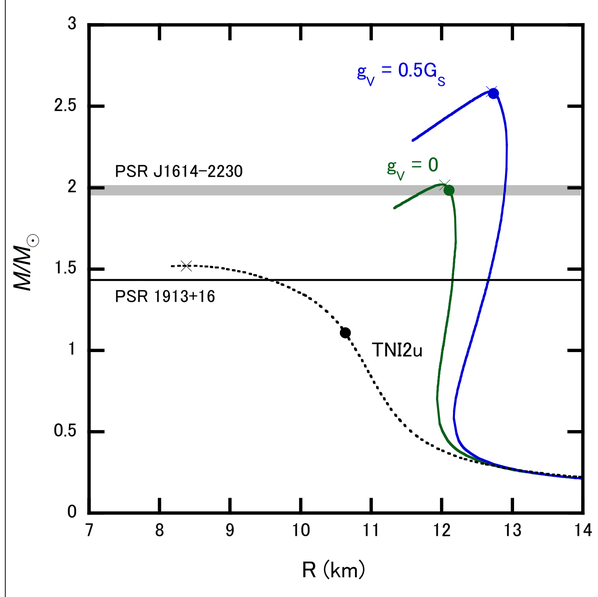
thermodynamic relation ↕

$$s(\rho,T) = s_H(\rho,T)\times\frac{1-\tanh\left(\frac{\rho-\bar{\rho}}{\Gamma}\right)}{2} + s_Q(\rho,T)\times\frac{1+\tanh\left(\frac{\rho-\bar{\rho}}{\Gamma}\right)}{2}$$

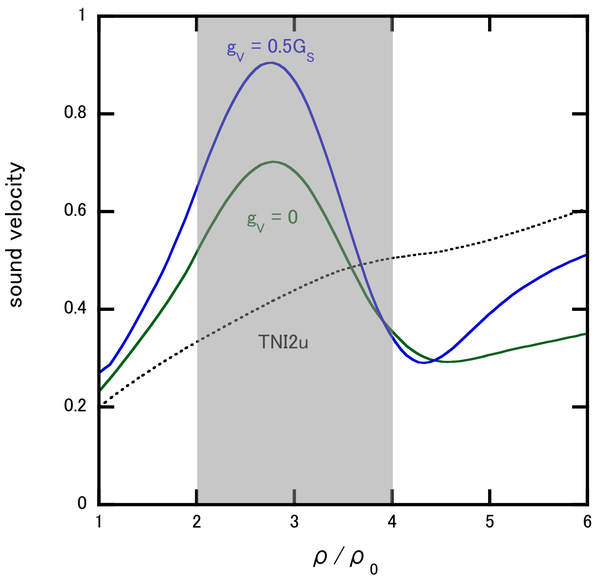
Results

1. Effects of crossover H-EOS: TNI2u $(\bar{\rho},\Gamma) = (3\rho_0,\rho_0)$

M-R relation



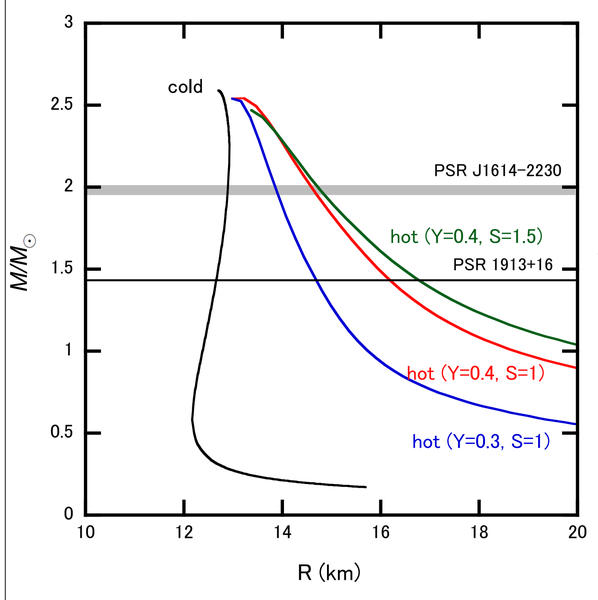
Sound velocity



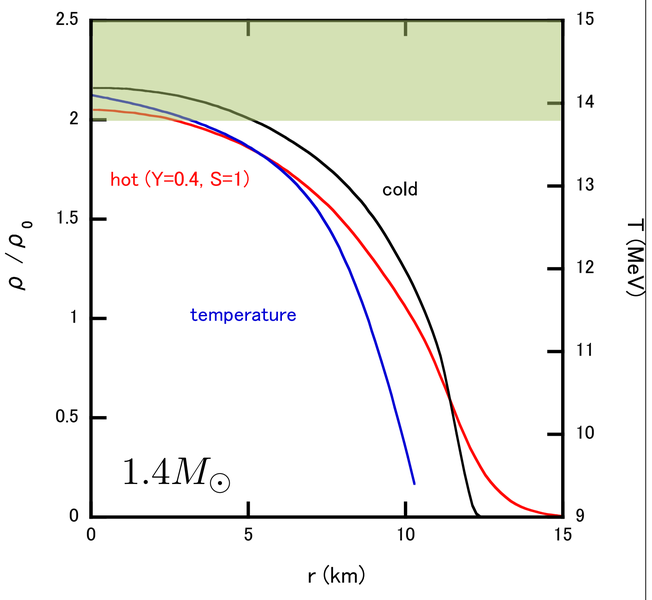
The sound velocity is found to increase in the crossover region, which leads to a stiff EOS.

2. Finite temperature extension $g_V = 0.5G_S$ $(\bar{\rho},\Gamma) = (3\rho_0,\rho_0)$

M-R relation



ρ-r, T-r relation



- For typical neutron stars, quarks appear in the very central region and strange quarks do not emerge.
- Due to the color degree of freedom of quarks, the internal temperature becomes lower.

Summary

- By using crossover picture, EOS can become hard due to strongly interacting quark matter.
- The three-body forces acting among nucleons and hyperons play essential role for the cooling of neutron stars.
- Due to the color degree of freedom of quarks, temperature becomes lower .

Future works
1. Cooling from our crossover model.
2. Constraints on EOS from other observables. (Radius etc.)

References

[1]P. B. Demorest et al., Nature **467** (2004), 1081-1083
[2]T. Takatsuka, S. Nishizaki and J. Hiura, Prog. Theor. Phys. **92** (1994), 4.
[3]K. Masuda, T. Hatsuda and T. Takatsuka, ApJ **764**, 12 (2013)
[4]K. Masuda, T. Hatsuda and T. Takatsuka, PTEP 073D01 (2013)
[5]T. Hatsuda and T. Kunihiro, Physics Reports , **247** (1994), 221-367