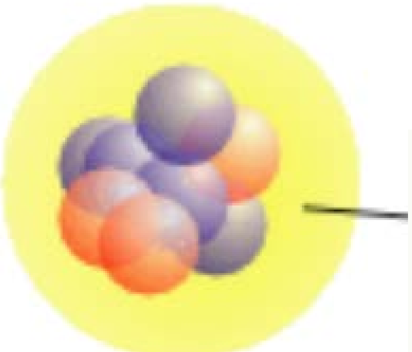
The first University in Korea
Soongsil University

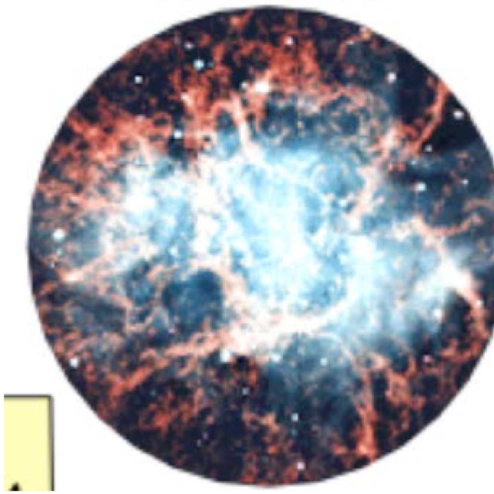
Description of Neutron Star based on various models with Strong Magnetic Field in the f(R) Relativity

Myung-Ki Cheoun,
Sooncheol Choi, T. Miyatsu, Y. Kwon,
T. Maruyama, H. Sagawa ...

Soongsil University, Seoul, Korea
http://ssanp.ssu.ac.kr

Quark Compact Stars (QCS) 2019
Busan, Korea
Sep. 26-29, 2019





RMF, **(C)QMC, (D)BHF, Skyrme, Chiral PT …. QCD**

Results (Dependence on L,K_0, and M*)

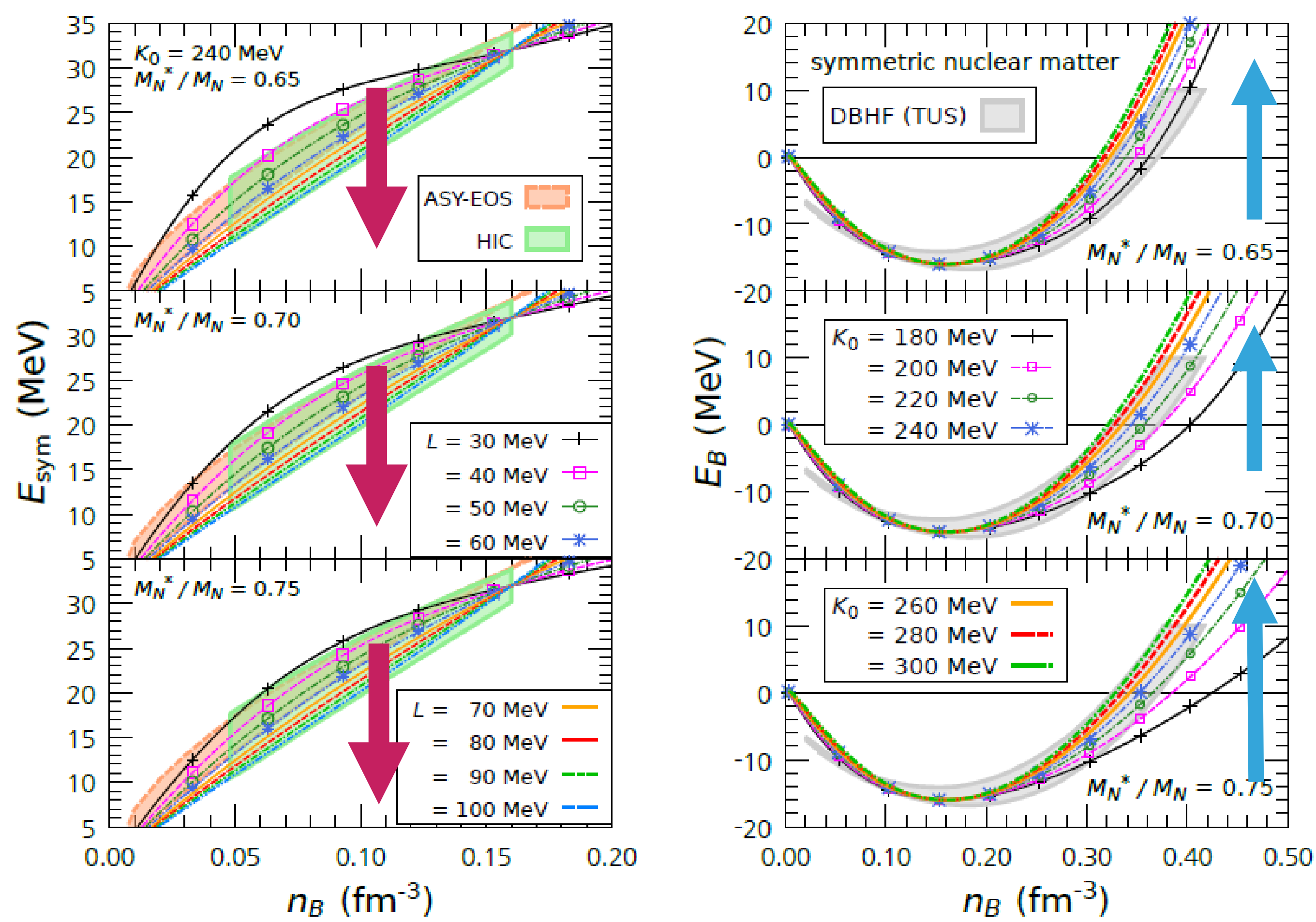


Fig. 1. Density-dependence of E_{sym} (left panel) and E_B (right panel). In the right panel, L is fixed as 70 MeV.

$$\mathcal{L} = \sum_B \bar{\psi}_B \left[i\gamma_\mu \partial^\mu - M_B^*(\sigma_0, \sigma_0^*) - g_{\omega B}\gamma_0\omega_0 - g_{\phi B}\gamma^0\phi_0 - g_{\rho B}\gamma^0\rho_0 I_B^z \right]\psi_B - \frac{1}{2}m_\sigma^2\sigma_0^2 - \frac{1}{2}m_{\sigma^*}\sigma_0^{*2} + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\phi^2\phi_0^2 + \frac{1}{2}m_\rho^2\rho_0^2 - U_{NL}(\sigma_0, \omega_0, \rho_0) + \sum_l \bar{\psi}_l \left(i\gamma_\mu\partial^\mu - m_l \right)\psi_l.$$

$$M_B^*(\sigma_0, \sigma_0^*) = M_B - g_{\sigma B}\sigma_0 - g_{\sigma^* B}\sigma_0^*.$$

Result (dependence on slope parameter L)

- The slope parameter does not affect the maximum mass of neutron star.

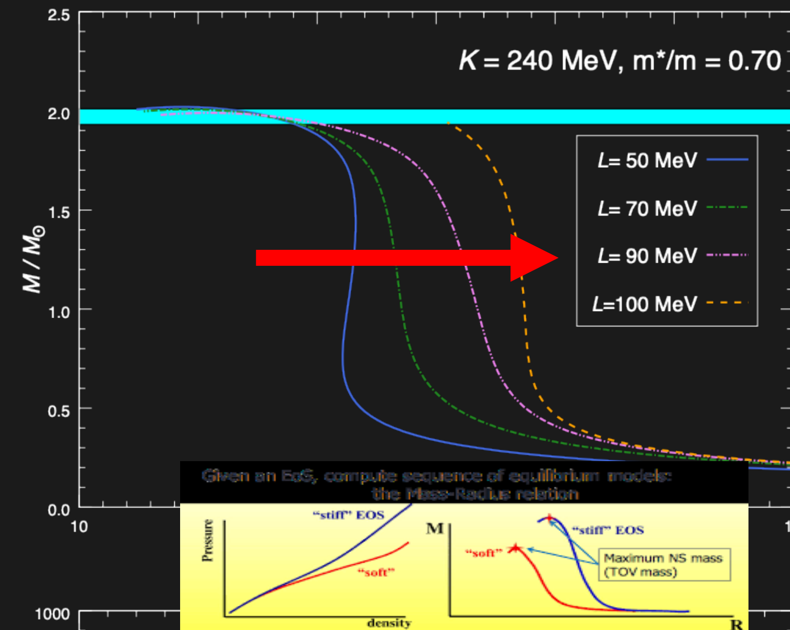
  Large slope parameter

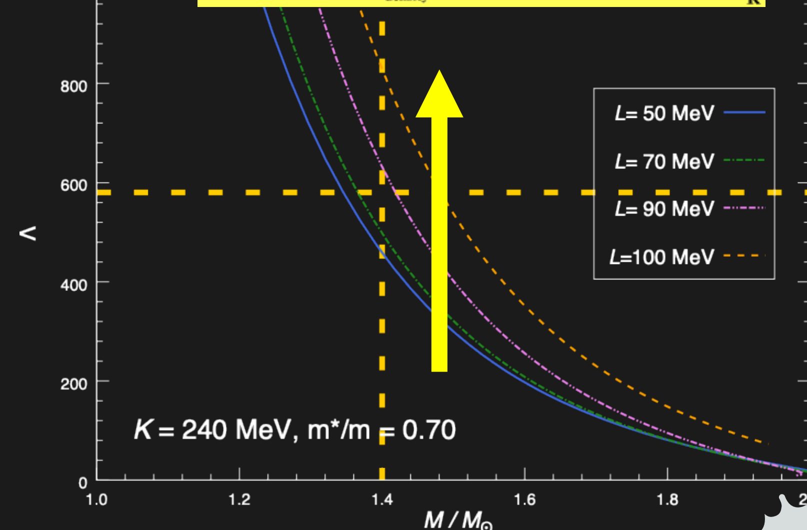
  ⇩

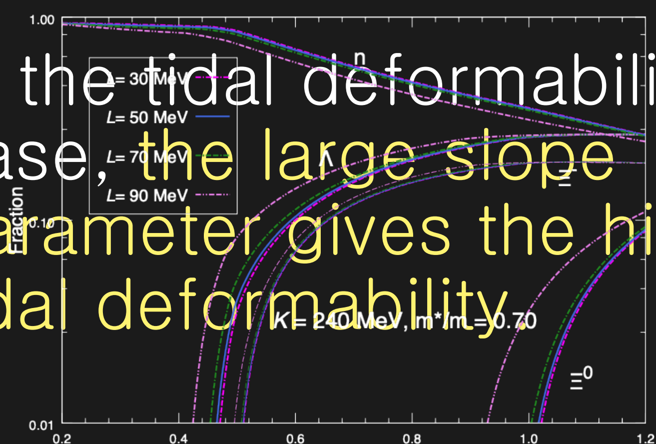
  Large radius of neutron star

- Around the 1.3 solar mass neutron star

- In the tidal deformability case, the large slope parameter gives the high tidal deformability.







Result (dependence on slope parameter)

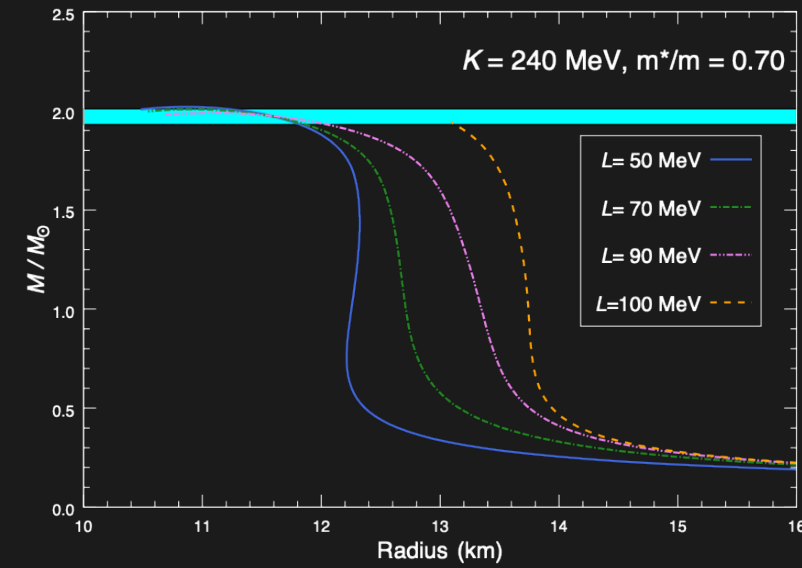
- The slope parameter does not affect the maximum mass of neutron star.

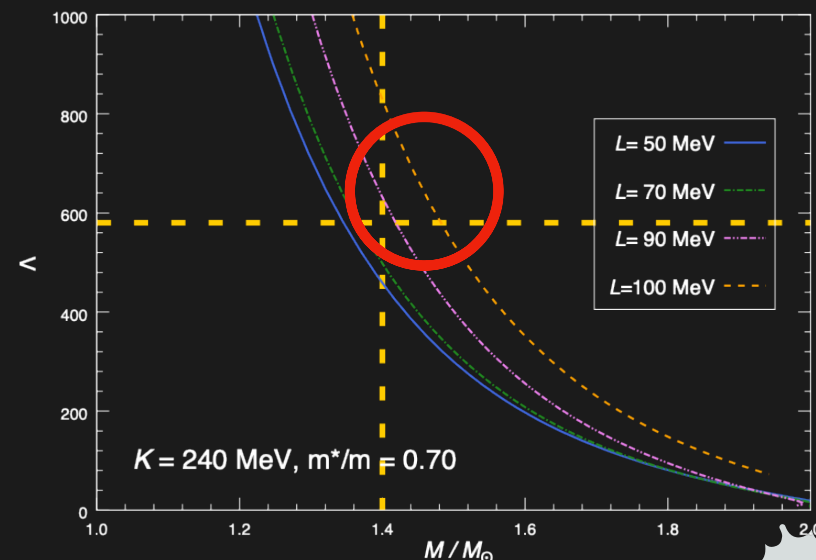
Large slope parameter

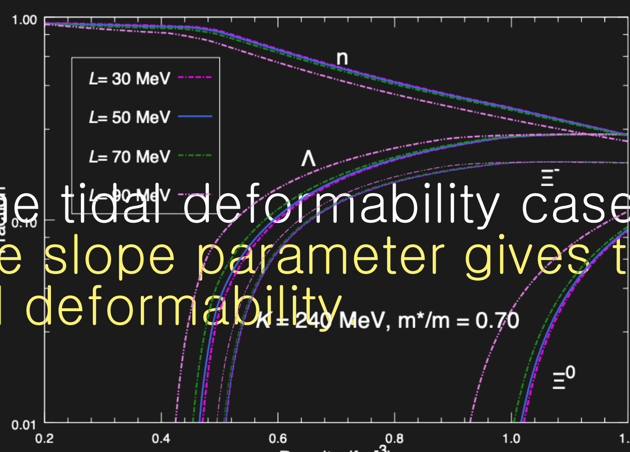
⇓

Large radius of neutron star

- Around the 1.3 solar mass neutron star







- In the tidal deformability case, the large slope parameter gives the high tidal deformability.

Result (dependence on incompressibility K)

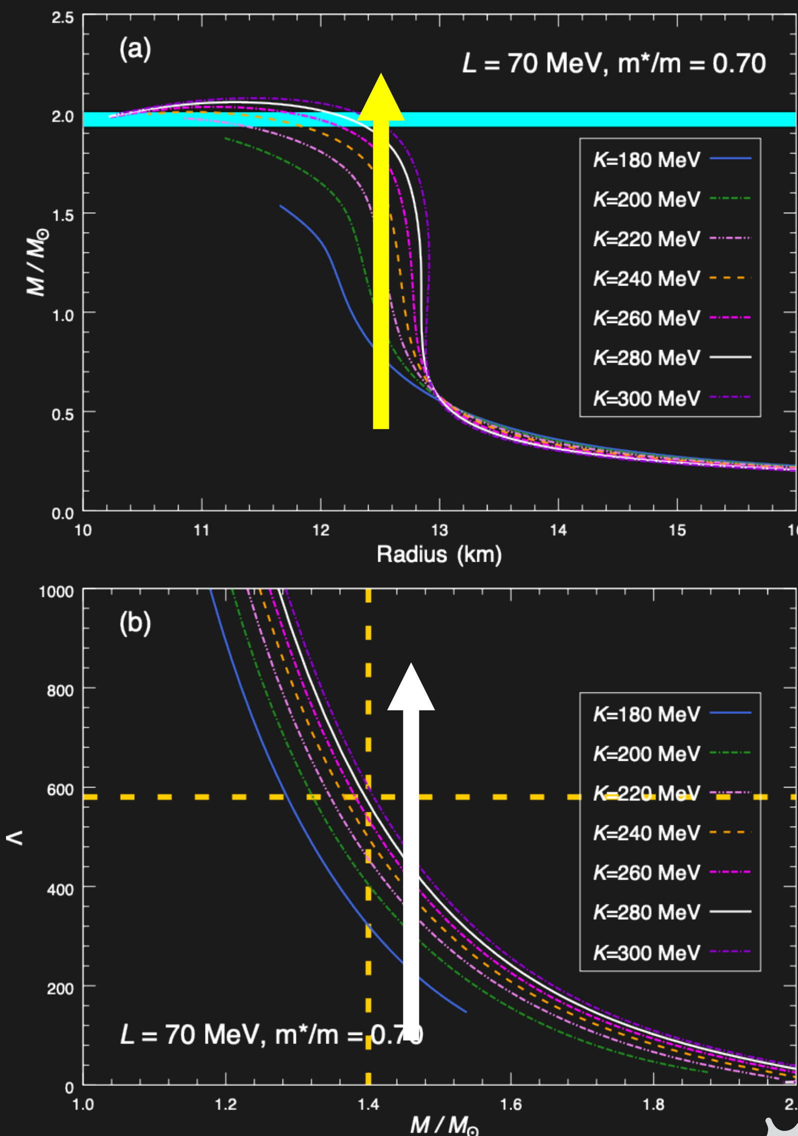
- The incompressibility affect both maximum mass and radius.

Large incompressibility

Large maximum mass

- The effect of incompressibility is around maximum mass of neutron star.

- The two-solar mass neutron star cannot be described in K = 180 and 200 MeV cases.



Result (dependence on incompressibility)

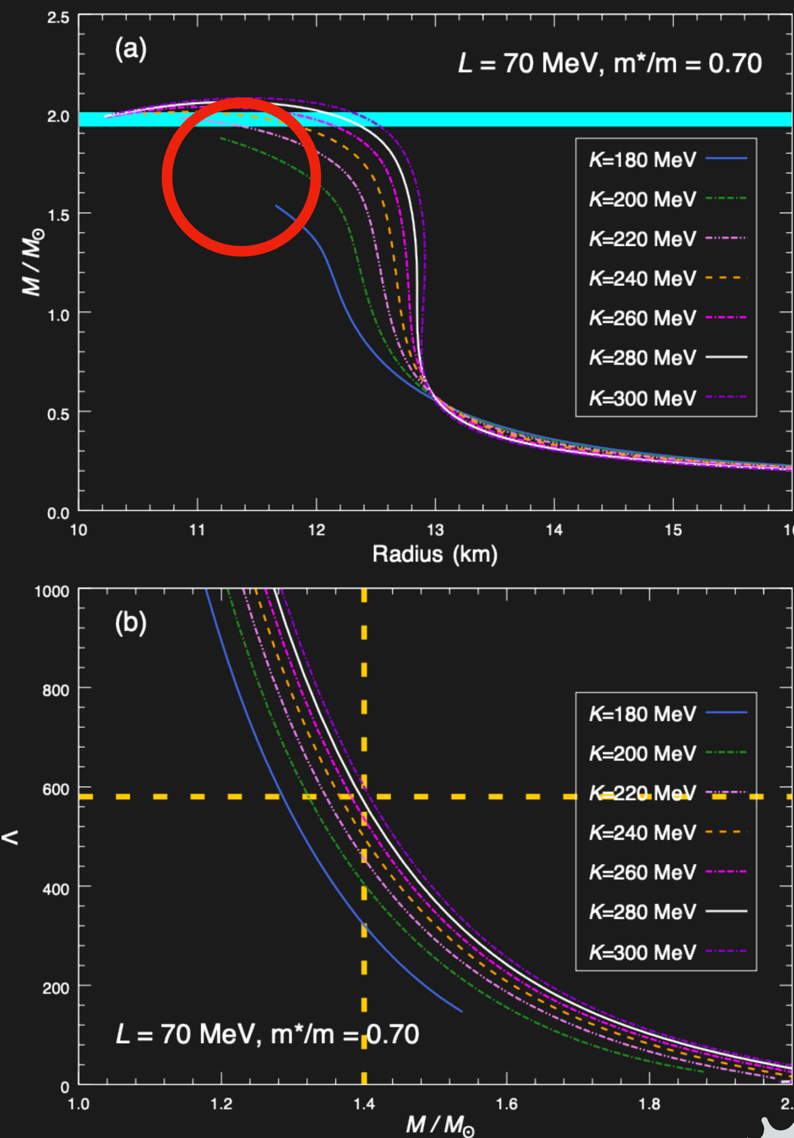
- The incompressibility affect both maximum mass and radius.

Large incompressibility

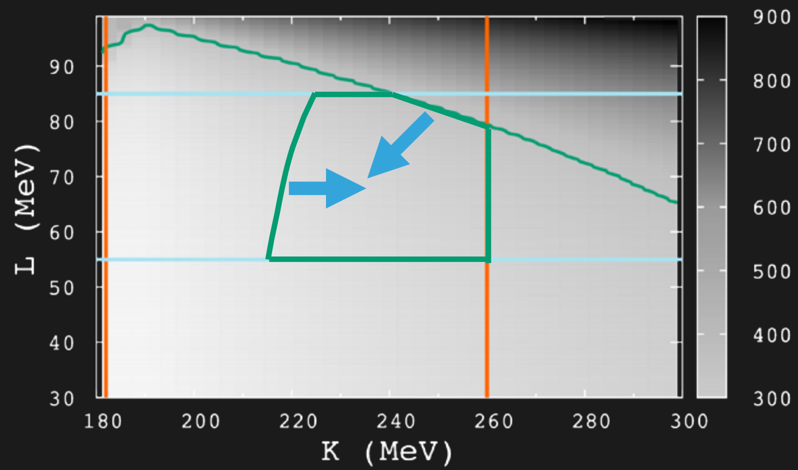
Large maximum mass

- The effect of incompressibility is around maximum mass of neutron star.

- The two-solar mass neutron star cannot be described in K = 180 and 200 MeV cases.



Summary (contour)



- We changed the slope parameter and incompressibility by using RMF model with non-linear potential

- We can constrain on slope parameter and incompressibility
by using astronomical observation data

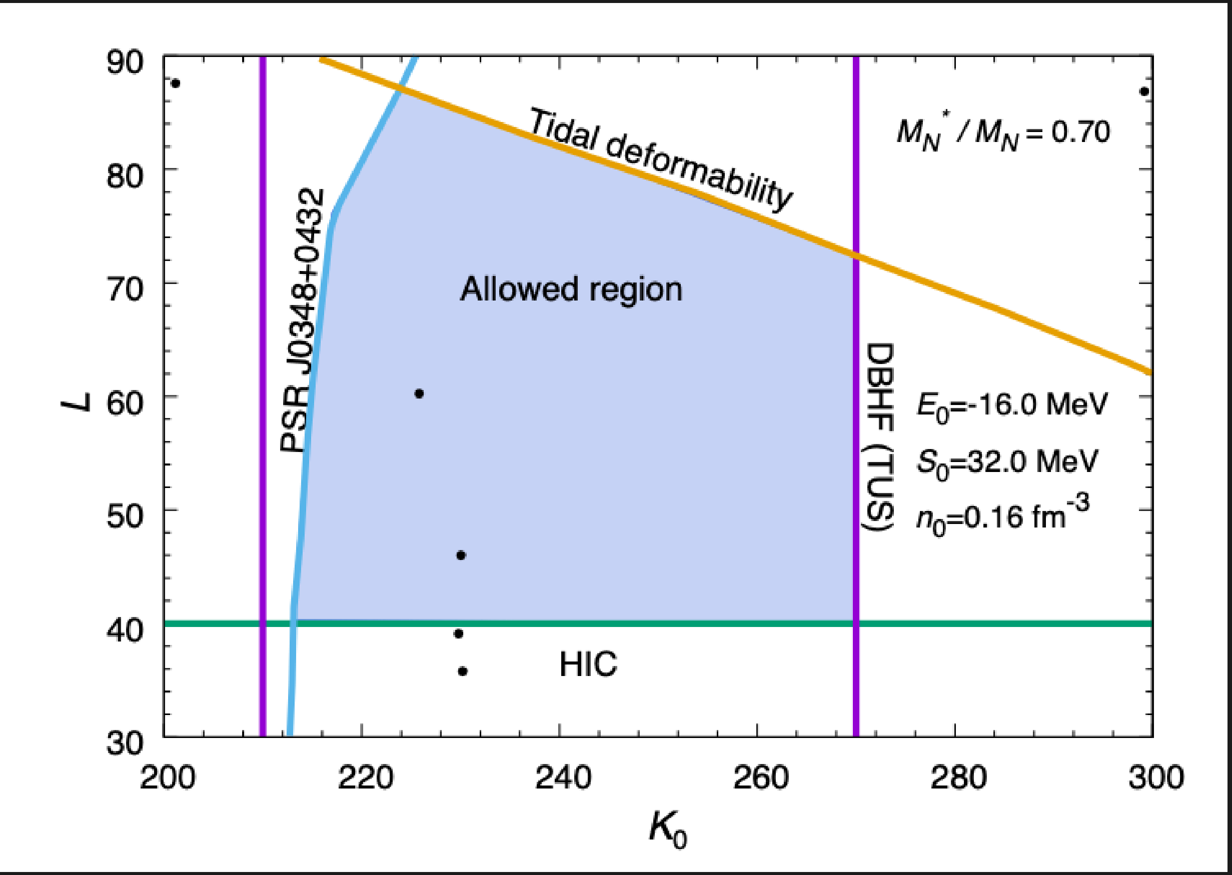
- In the ongoing process, we are studying the constraint on these values by using finite-nuclei data.

PRL 121 161101 (2018)

$70 \leq \Lambda(1.4M_{\odot}) \leq 580$ Nature 467 1081-1083 (2010)

$1.94M_{\odot} \leq M_{\rm NS} \leq 2.33M_{\odot}$ APJL 852 L25 (2018)

[2]PLB 778 207212 (2018) [1]PRL 108 052501 (2012)



90
80
70
60
50
40
30
L
200
220
240
260
280
300
K0
PSR J0348+0432
Tidal deformability
MN* / MN = 0.70
Allowed region
DBHF (TUS)
E0=-16.0 MeV
S0=32.0 MeV
n0=0.16 fm-3
HIC

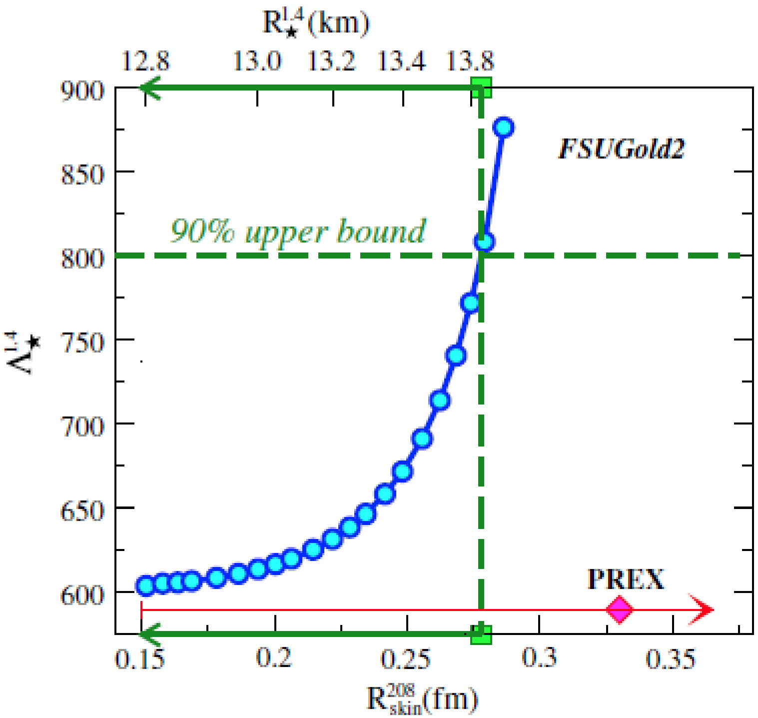


FIG. 1. The dimensionless tidal polarizability $\Lambda_\star^{1.4}$ of a $1.4M_\odot$ neutron star as a function of the neutron-skin thickness of ^{208}Pb (lower abscissa) and the radius of a $1.4M_\odot$ neutron star (upper abscissa) as predicted by the FSUGold2 family of relativistic interactions. Constraints on R_{skin}^{208} and $R_\star^{1.4}$ are inferred from adopting the $\Lambda_\star^{1.4} \leq 800$ limit deduced from GW170817 [2].

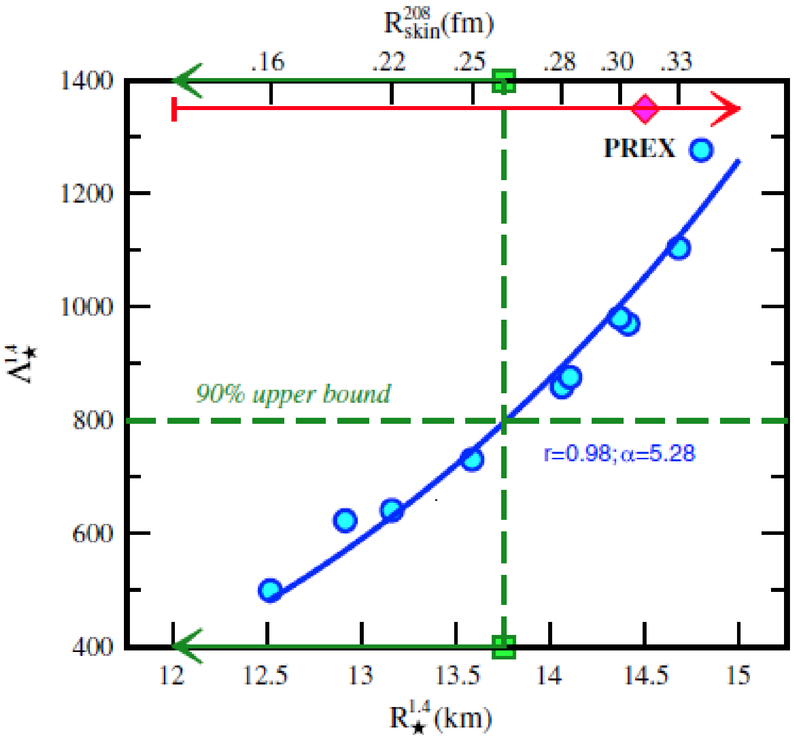


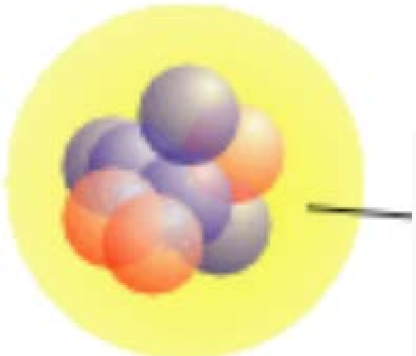
FIG. 3. As in Fig. 1, predictions are shown for $\Lambda_\star^{1.4}$ as a function of the radius of a $1.4\ M_\odot$ neutron star and the neutron-skin thickness of ^{208}Pb, but now for the ten RMF models discussed in the text.

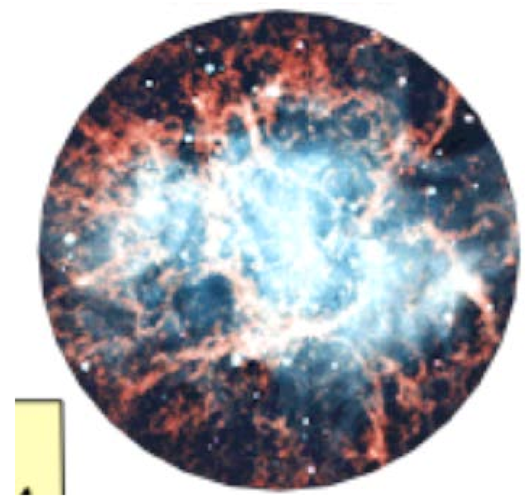
PHYSICAL REVIEW LETTERS **120**, 172702 (2018)

Editors' Suggestion Featured in Physics

Neutron Skins and Neutron Stars in the Multimessenger Era

F. J. Fattoyev,[1,*] J. Piekarewicz,[2,†] and C. J. Horowitz[1,‡]





RMF, (C)QMC, (D)BHF, Skyrme, Chiral PT .... QCD

Eq. of State   Results by the Hybrid Model (SHF+TB)

M. Dutra, O. Lourenco, J. S. Sa Martins, A. Delfino, J. R. Stone, P. D. Stevenson, Phys. Rev. C **85**, 035201 (2012).

	Group A			Group B			
	SLy4 [49]	SkI4 [50]	SG1 [51]	KDE0v1[57]	LNS[56]	NRAPR[46]	SKRA[58]
t_0	–2488.91	–1855.8	–1603.0	–2553.0843	–2484.97	–2719.7	–2895.4
t_1	486.82	473.8	515.9	411.6963	266.735	417.64	405.5
t_2	–546.39	1006.9	84.5	–419.8712	–337.135	–66.687	–89.1
t_3	13777.0	9703.0	8000.0	14603.6069	14588.2	15042	16660
x_0	0.834	0.41	–0.02	0.6483	0.06277	0.16154	0.08
x_1	–0.344	–2.89	–0.5	–0.3472	0.65845	–0.047986	0
x_2	–1.000	–1.33	–1.731	–0.9268	–0.95382	0.027170	0.2
x_3	1.354	1.15	0.1381	0.9475	-0.03413	0.13611	0
σ	1/6	1/4	1/3	0.1673	0.16667	0.14416	0.1422

Table 2 Parameter sets for Skyr
are in the unit of MeV · fm^5. t_3 is in
are commonly used Skyrme paramet
new sets and deduced from the mac
[48].

Table 4 Saturation properties for various Skyrme model parameter sets and BHF model by Y. Yamamoto *et al.* [40]. ρ_0 and B/A are the saturation density and the saturation energy, respectively, and $E_{\rm sym}$ and L are the volume and the slope parameters of symmetry energy, respectively. The last column shows the value of incompressibility defined by $K_\infty = 9\rho_0^2 \frac{\partial^2(\rho,0)}{\partial \rho^2}|_{\rho=\rho_0}$.

Type	$\rho_0(\rm fm^{-3})$	B/A(MeV)	$E_{\rm sym}$(MeV)	L(MeV)	K_∞(MeV)
SG1	0.155	-15.9	29	69	263
SkI4	0.160	-16.1	29	59	246
SLy4	0.160	-16	32	47	230
SLy4′	0.160	-16	39	72	230
KDE0v1	0.161	-16.1	33	45	229
LNS	0.175	-15.3	33.4	61	211
NRAPR	0.161	-15.8	32.8	59	226
SKRA	0.159	-15.8	31.3	53	217
BHF [40]	0.154	-15.8	31.7	67	283

Results by the Hybrid Model (SHF+TB)

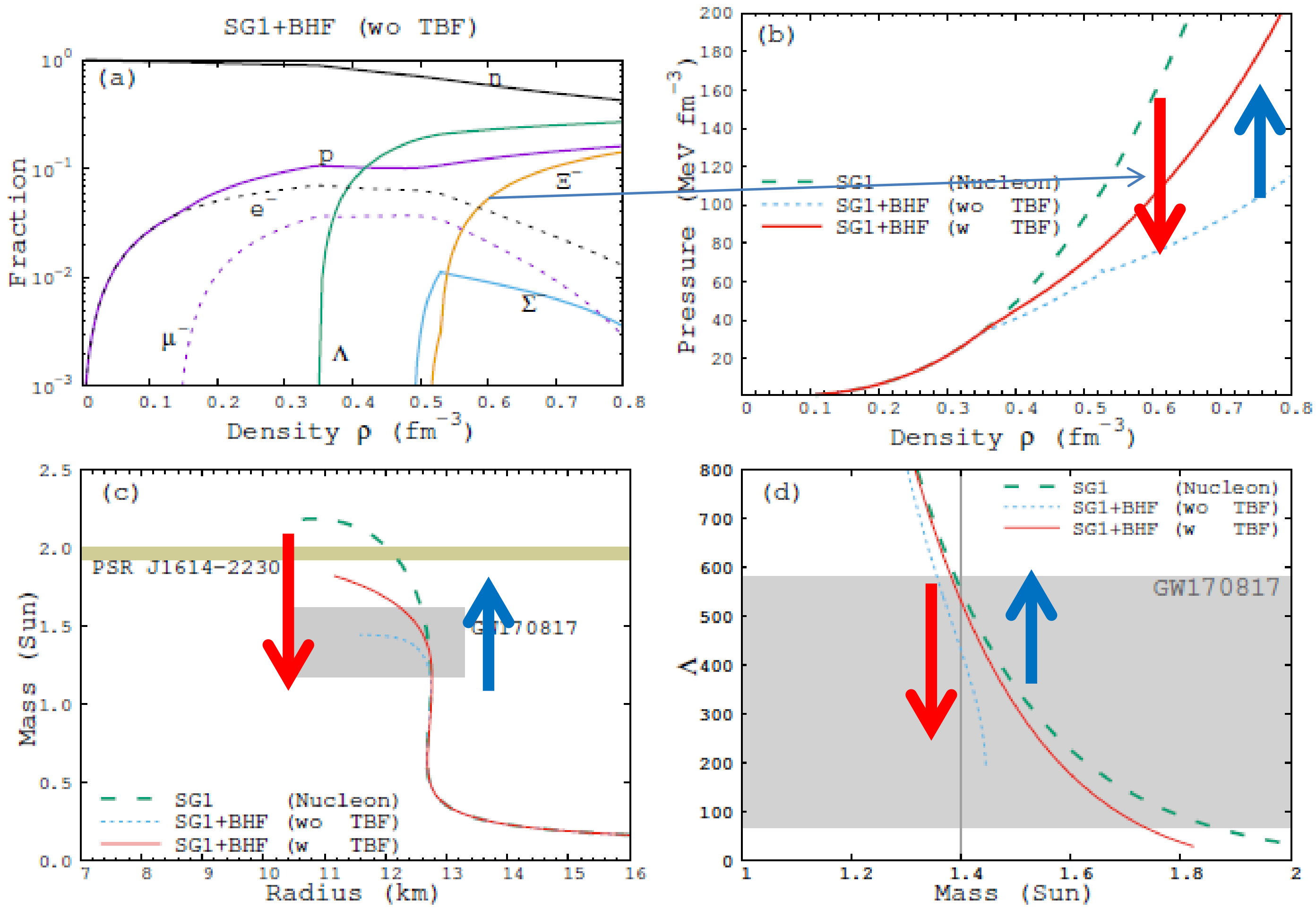


Fig. 6 (Color online) Roles of the TBF in the SG1 hybrid model: Particle profile function without TBF (a), EoS (b), mass-radius relation (c) and the tidal deformability (d) with (red solid) and without (blue dotted) the TBF contribution. Particle profile functions with TBF are presented in Fig.2.

Eq. of State | Results by the Hybrid Model (SHF+TB)

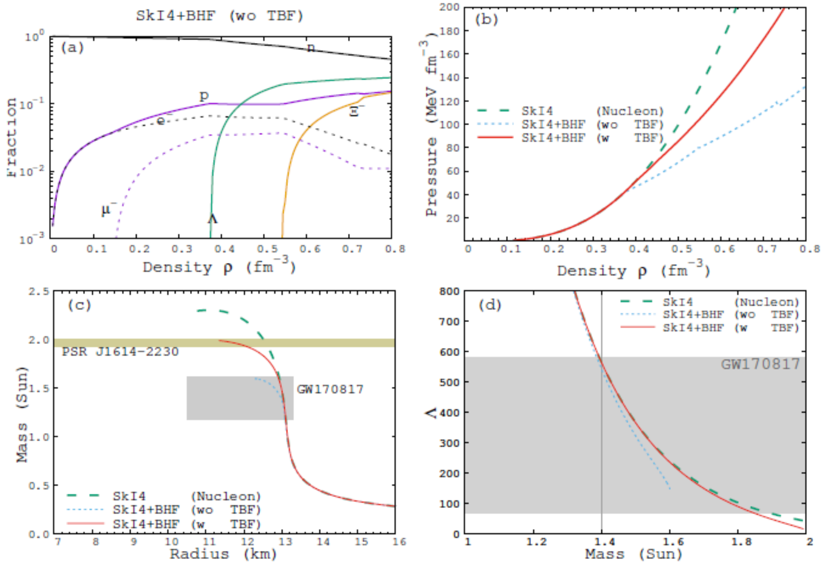


Fig. 7 (Color online) Same as Fig. 6, but for SkI4 hybrid model (SkI4 + BHF).

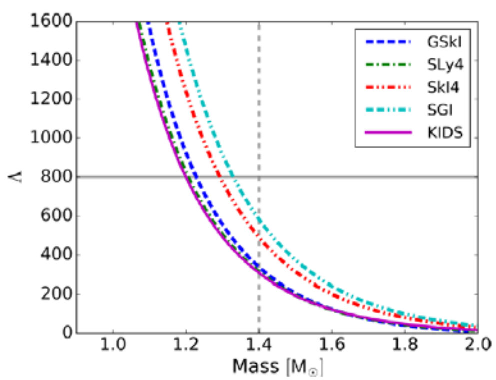


FIG. 2. Dimensionless tidal deformability (Λ) of a single neu-

PHYSICAL REVIEW C **98**, 065805 (2018)

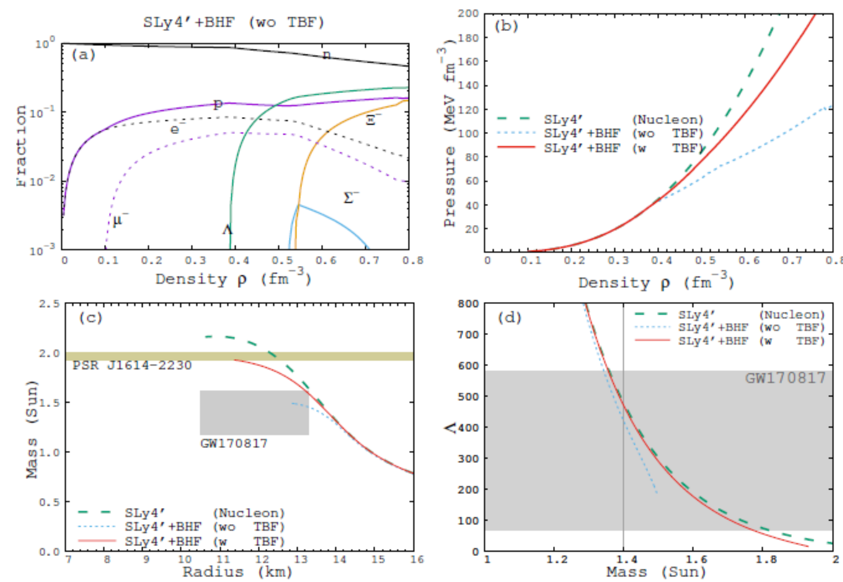


Fig. 8 (Color online) Same as Fig. 6, but for SLy4′ hybrid model (SLy4’ + BHF).

Tidal deformability of neutron stars with realistic nuclear energy density functionals

Young-Min Kim,[1] Yeunhwan Lim,[2] Kyujin Kwak,[1] Chang Ho Hyun,[3] and Chang-Hwan Lee[4]

Results by the Hybrid Model (SHF+TB)

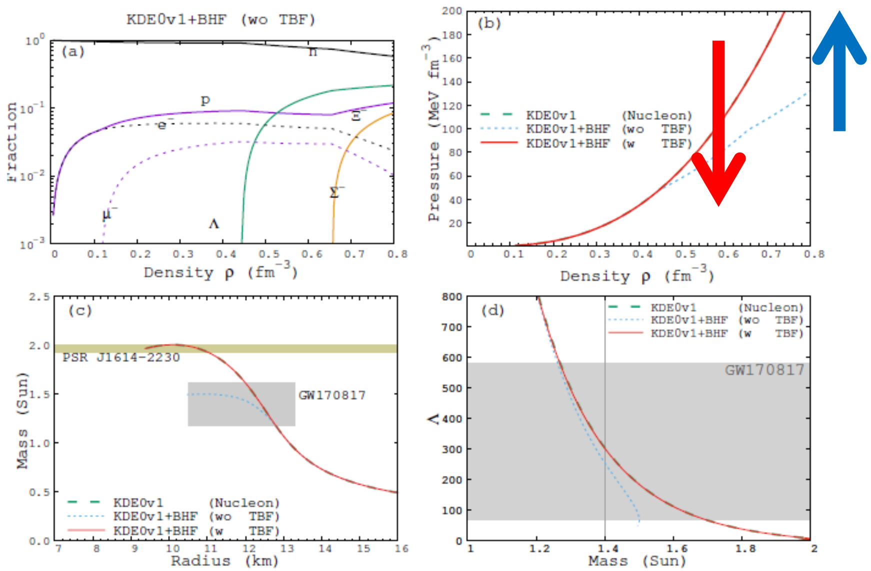


Fig. 9 (Color online) Same as Fig. 6, but for KDE0v1 hybrid model (KDE0v1 + BH

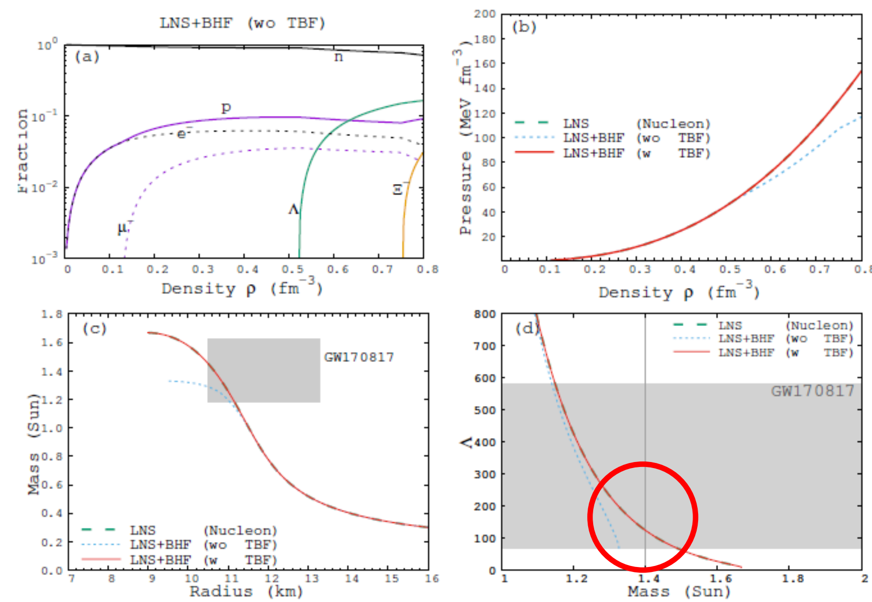


Fig. 10 (Color online) Same as Fig. 6, but for LNS hybrid model (LNS + BHF).

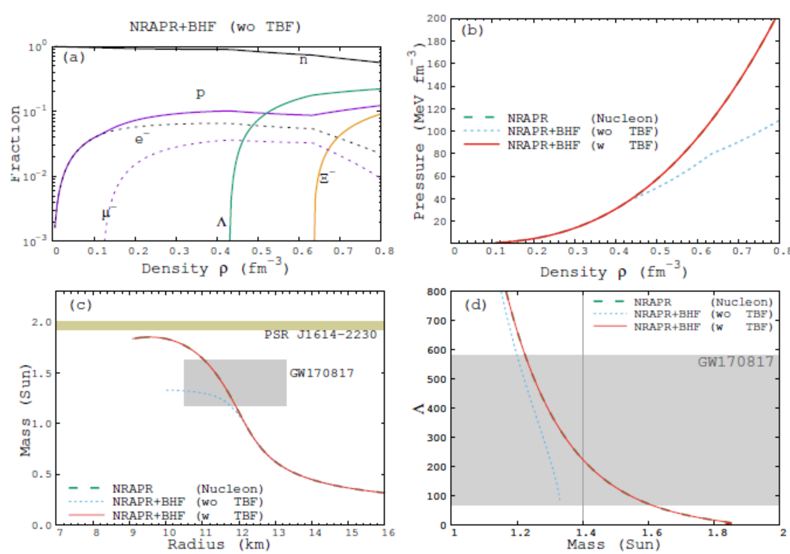


Fig. 11 (Color online) Same as Fig. 6, but for NRAPR hybrid model (NRAPR + BHF).

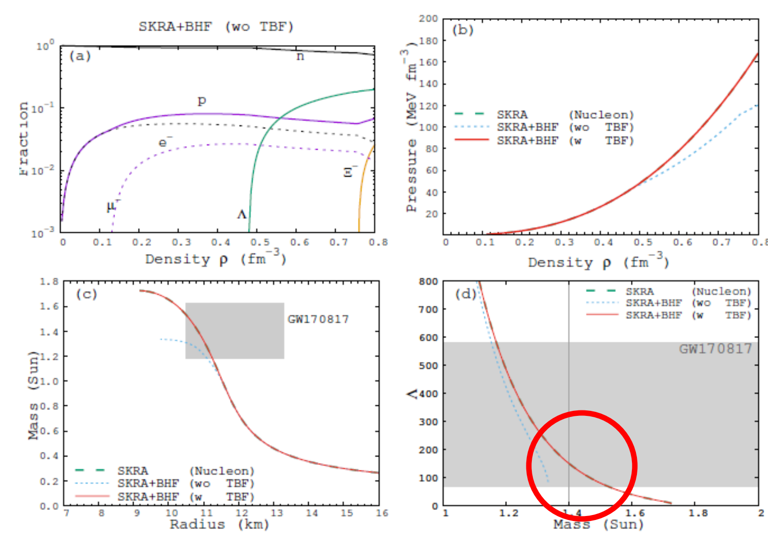
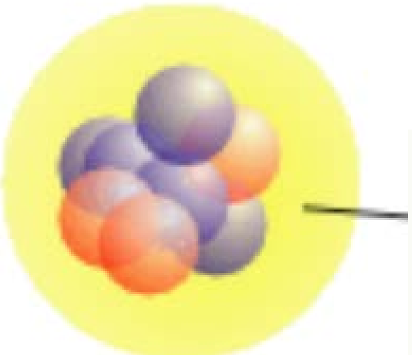
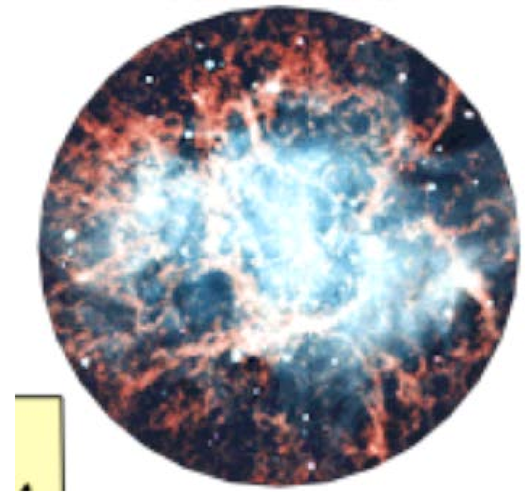


Fig. 12 (Color online) Same as Fig. 6, but for SKRA hybrid model (SKRA + BHF).

The gravitational field at a neutron star's surface is about 2×10^{11} times stronger than on Earth,.





RMF, (C)QMC, (D)BHF, Skyrme, Chiral PT .... QCD

Motivation 2: Modified Gravity

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

JCAP07(2011)020

Constraints on perturbative $f(R)$ gravity via neutron stars

Savaş Arapoğlu,[a] Cemsinan Deliduman[b] and K. Yavuz Ekşi[a]

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The current accelerated expansion of the universe

Although the cosmological constant is arguably the simplest explanation and the best fit to all observational data, its theoretical value predicted by quantum field theory is many orders of magnitude greater than the value to explain the current acceleration of the universe. This

categories, both of them introducing new degrees of freedom [9]: The first approach is to add some unknown energy-momentum component to the right hand side of Einstein's equations with an equation of state $p/\rho \approx -1$, dubbed *dark energy*. In the more radical second

approach, the idea is to modify the left hand side of Einstein's equations, so-called *modified gravity*. Trying to explain such perplexing observations by modifying gravity rather than postulating an unknown dark energy has been an active research area in the last few years and in this paper we adopt this path.

Modified TOV equations of $f(R)$ gravity

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} f(R) + S_{\text{matter}}$$

$$\alpha \lesssim 5 \times 10^{15}\ \text{cm}^2$$

$$f(R) = R + \alpha h(R) + \mathcal{O}(\alpha^2)$$

How will be the modified gravity effect in the stellar scale ???

Theoretical Frameworks 2: Modified TOV by M. Gravity

Modified Action

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}f(R) + S_{\text{matter}} \qquad f(R) = R + \alpha h(R) + \mathcal{O}(\alpha^2)$$

Modified E. Equation

$$(1+\alpha h_R)G_{\mu\nu} - \frac{1}{2}\alpha(h - h_R R)g_{\mu\nu} - \alpha(\nabla_\mu\nabla_\nu - g_{\mu\nu}\Box)h_R = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} \qquad h_R = \tfrac{dh}{dR}$$

$$ds^2 = -e^{2\phi_\alpha}dt^2 + e^{2\lambda_\alpha}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$\phi_\alpha = \phi + \alpha\phi_1 + \ldots \quad \lambda_\alpha = \lambda + \alpha\lambda_1 + \ldots \quad M_\alpha = M + \alpha M_1 + \ldots$$

$$\rho_\alpha = \rho + \alpha\rho_1 + \ldots \quad P_\alpha = P + \alpha P_1 + \ldots$$

If alpha dep. terms go to 0, Standard Gravity

Modified TOV

$$\frac{dP_\alpha}{dr} = -(\rho_\alpha + P_\alpha)\frac{d\phi_\alpha}{dr}.$$

$$2(r - M_\alpha)\frac{d\phi_\alpha}{dr} = 8\pi r^2 P_\alpha + \frac{M_\alpha}{r} - \alpha h_R\left[\begin{array}{l} 8\pi r^2 P + \frac{r^2}{2}\left(\frac{h}{h_R} - R\right) \\ +\left(2r - \frac{3}{2}M + 4\pi P r^3\right)\frac{h_R'}{h_R} \end{array}\right]$$

Results by the MTOV from Modified Gravity

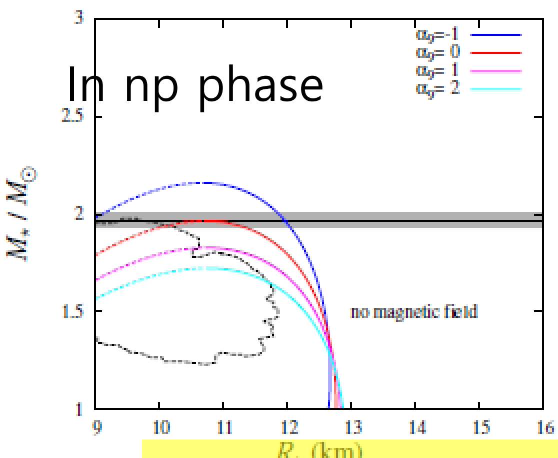
$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}f(R) + S_{\text{matter}} \qquad f(R) = R + \alpha h(R) + \mathcal{O}(\alpha^2)$$

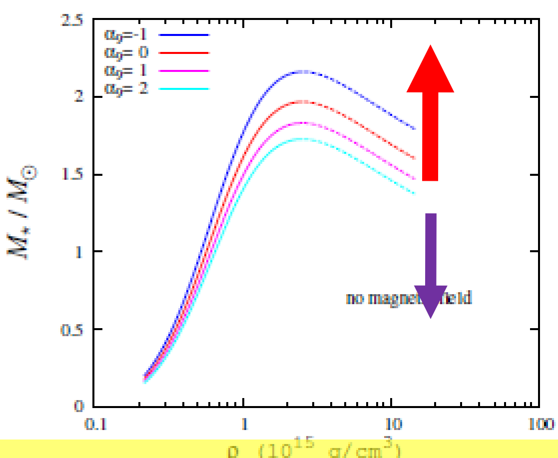
Modified TOV

$$\frac{dP_\alpha}{dr} = -(\rho_\alpha + P_\alpha)\frac{d\phi_\alpha}{dr}.$$

$$2(r - M_\alpha)\frac{d\phi_\alpha}{dr} = 8\pi r^2 P_\alpha + \frac{M_\alpha}{r} - \alpha h_R\left[\begin{array}{l} 8\pi r^2 P + \frac{r^2}{2}\left(\frac{h}{h_R} - R\right) \\ +\left(2r - \frac{3}{2}M + 4\pi P r^3\right)\frac{h'_R}{h_R}\end{array}\right]$$

★ the parameter α depend heavily on the length scale considered.
related to the Yukawa correction to the Newtonian potential, $\frac{G}{3}\exp(-r/\lambda)$ $\quad \lambda = \sqrt{6\alpha}$





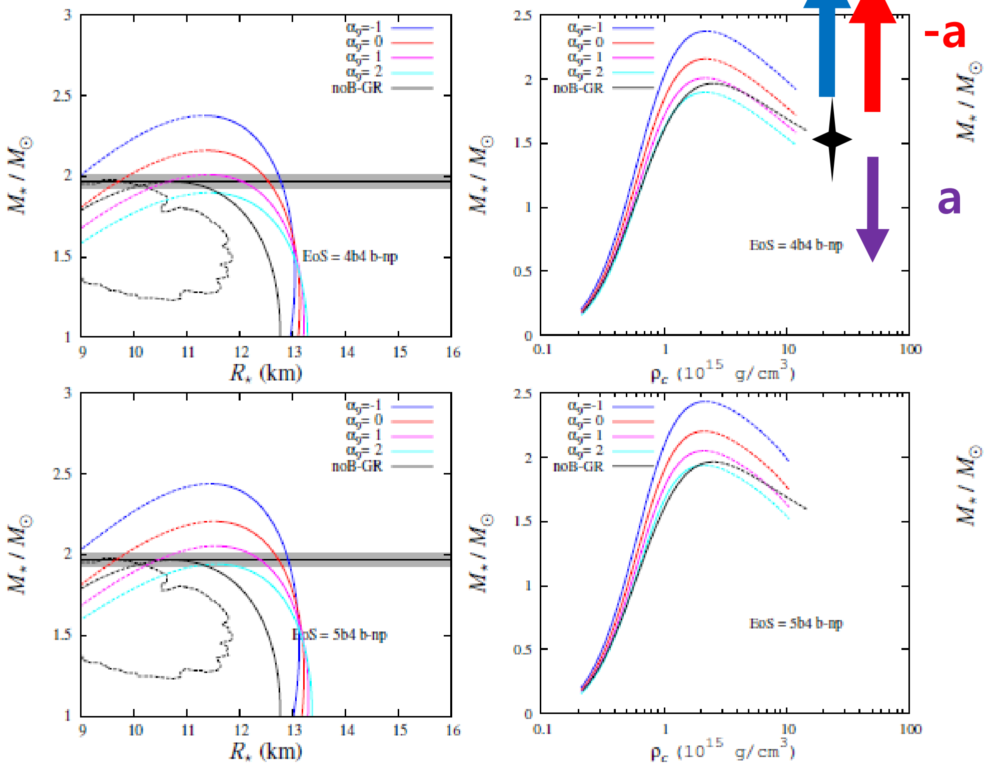
For alpha = **-1(+1)**, more steeper (softer) EOS and more massive (light) Masses !!

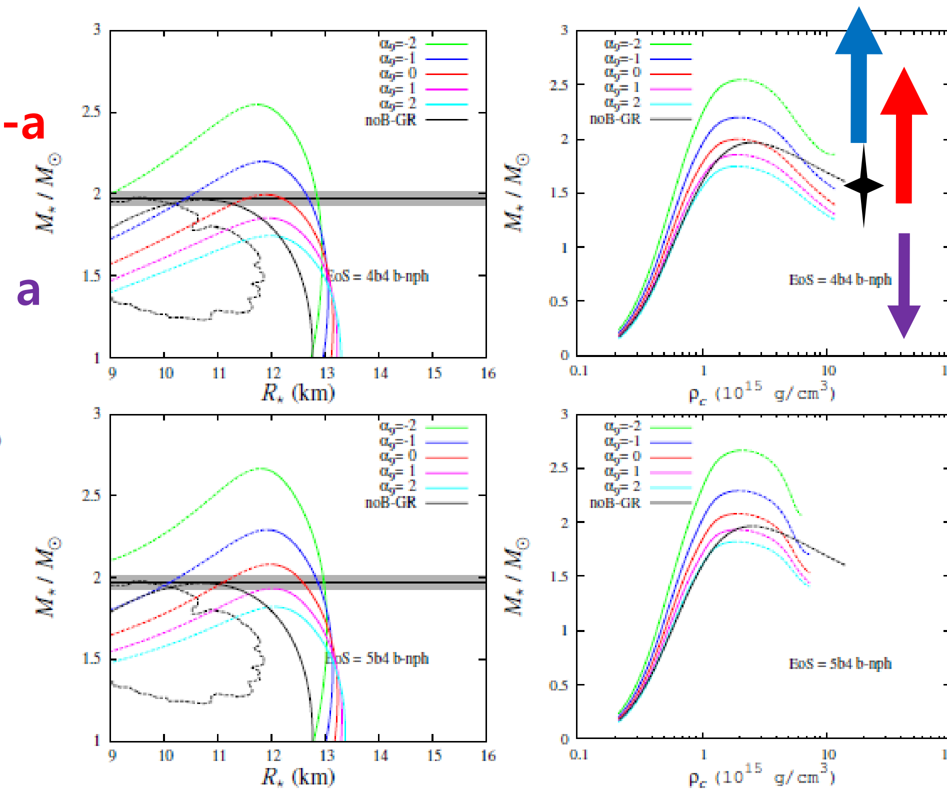
Hyperonic NS may go to 2.0 solar mass by the modified gravity with reasonable magnetic field **without any modification in RMF** !!

Results by MTOV and Magnetic fields

MKC et.al, PRC 82, 025804, (2010); PRC 83, 018802 (2011); JCAP 10, 21 (2013)

In np and nph phase with stronger magnetic field





$\alpha_9 \equiv \alpha/10^9\,\mathrm{cm}^2 = -2, -1, 0, 1, 2$ in the $f(R) = R + \alpha R^2$ gravity.

$$B(\rho/\rho_0) = B^{surf} + B_0\left[1 - \exp\{-\alpha(\rho/\rho_0)^\beta\}\right]$$

the Kaluza–Klein action expands into:

$$\mathcal{R} \to f(R) = R - \alpha|F|^2 \;\; ,$$

For stronger m. field, we obtain more stiffer EOS and more massive Masses !! May **compensate modified gravity (alpha >0).**

Summary and Conclusion

1. Quark production the EoS softer and suppresses the hyperons in high density region. Hybrid star can explain the 2.0 solar massive neuron star.
2. SU(3) extension of RMF models may give rise to roles of sigma* and phi* meson, which suppress the appearance of hyperons in profile functions on the neutrons star. EoS becomes stiffer even with hyperons. With TBF, it becomes more steeper again !
3. Modified f(R) gravity is developed to consider the dark energy (or cosmological constant) and extended to modified TOV equation for neutrons stars.
4. Magnetic fields are also included to the Modified gravity and applied to the EOS of neutron star.
5. Negative alpha can make NS, in particular, supersoft EOS, stiffer. Positive alpha may compensate the stiffness by strong magnetic fields.

Thanks for your Attention !!