2021/12/10 秋保温泉

EOS softening by hyperon mixing

Neutron Star and Hyperon Puzzle

What is Hyperon Puzzle ?
How related to hypernuclear experiments ?

Y. Yamamoto

Recent information on neutron-star radii

arXiv:2105.06981 14 May 2021

11.52 km < R(1.4Msun) < 13.09 km (PP model)

11.39 km < R(1.4Msun) < 12.74 km (CS model)

arXiv::2105.08688 18 May 2021

11.07 km < R(1.4Msun) < 12.70 km

11～13 km based on NICER

Hyperon-$2M_{sun}$ puzzle !

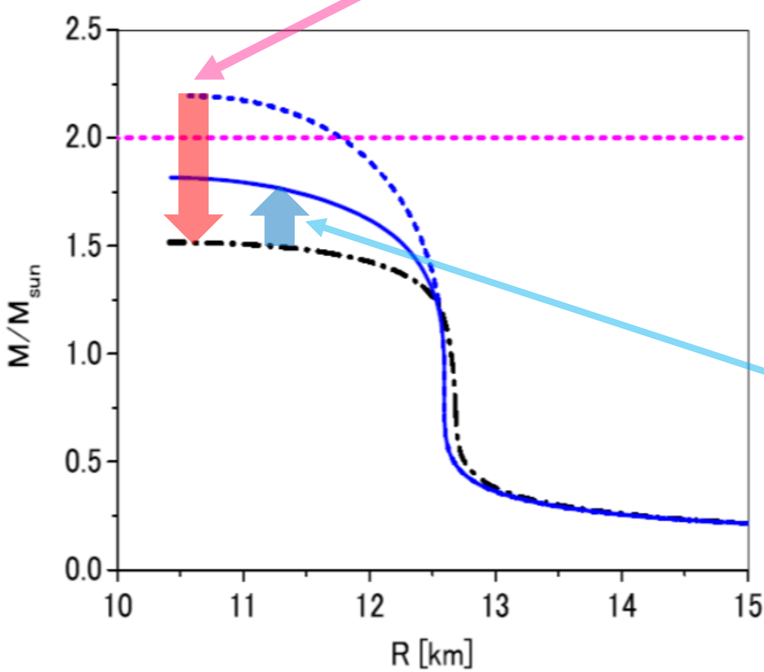
Massive ($2M_\odot$) neutron stars

2010 PSR J1614-2230 $(1.97 \pm 0.04) M_\odot$

2013 PSR J0348-0432 $(2.01 \pm 0.04) M_\odot$

?

Softening of EOS by hyperon mixing



Dropping of pressure by changing of high-momentum neutrons to low-momentum exotic particles (hyperons, Δ, k-mesons, quarks) free from Pauli principle

Universal TBR by Takatsuka

Hadron-phase level

before observation of $2M_{sun}$

Our approach to universal TBR

From experimental data !

Many-body repulsive effect
in high density region (up to $2\rho_0$)

owing to Frozen-Density approximation

➡ Nucleus-Nucleus scattering data
with G-matrix folding potential

__T. Furumoto__, Y. Sakuragi and Y. Yamamoto, (Phys. Rev. C79 (2009) 011601(R))
__T. Furumoto__, Y. Sakuragi and Y. Yamamoto, (Phys. Rev. C.80 (2009) 044614)

A model of Universal Many-Body Repulsion

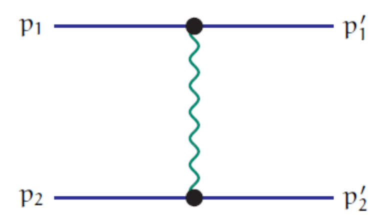
Multi-Pomeron Exchange Potential (MPP)

Same repulsions in all baryonic channels NNN, NNY, NYY, YYY

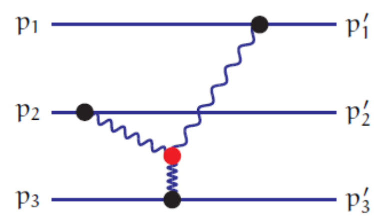
$$\mathcal{L}_{PNN} = g_P \bar{\psi}(x)\psi(x)\,\sigma_P(x)$$

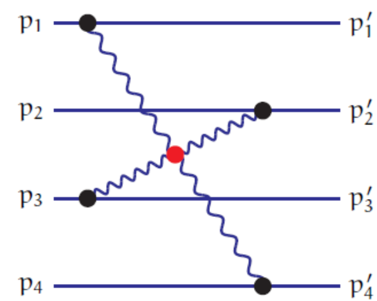
$$\Delta_F^P(k^2) = +\exp(-\mathbf{k}^2/4m_P^2)/\mathcal{M}^2$$

$$V_P(r) = \frac{g_P^2}{4\pi}\frac{4}{\sqrt{\pi}}\frac{m_P^3}{\mathcal{M}^2}\exp\left(-m_P^2 r_{12}^2\right)$$



Pomeron exchange gives repulsion because of positive propagator





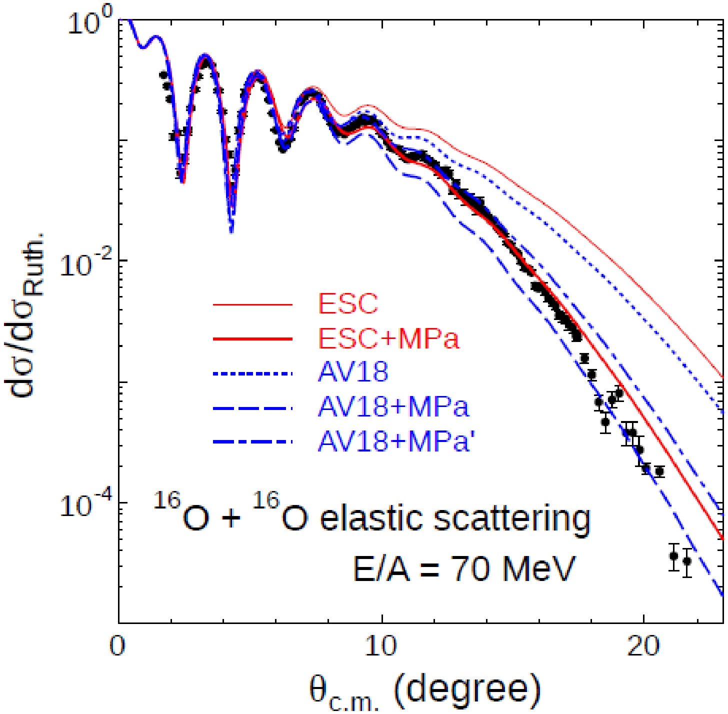
$$V_{\rm eff}^{(3)}(r) = g_P^{(3)}(g_P)^3\frac{\rho}{\mathcal{M}^5}F(r),$$

$$V_{\rm eff}^{(4)}(r) = g_P^{(4)}(g_P)^4\frac{\rho^2}{\mathcal{M}^8}F(r),$$

$$F(r) = \frac{1}{4\pi}\frac{4}{\sqrt{\pi}}\left(\frac{m_P}{\sqrt{2}}\right)^3\exp\left(-\frac{1}{2}m_P^2 r^2\right)$$

Pomeron-exchange repulsion originated from two-gluon exchange

Effective two-body potential from MPP (3- & 4-body potentials)



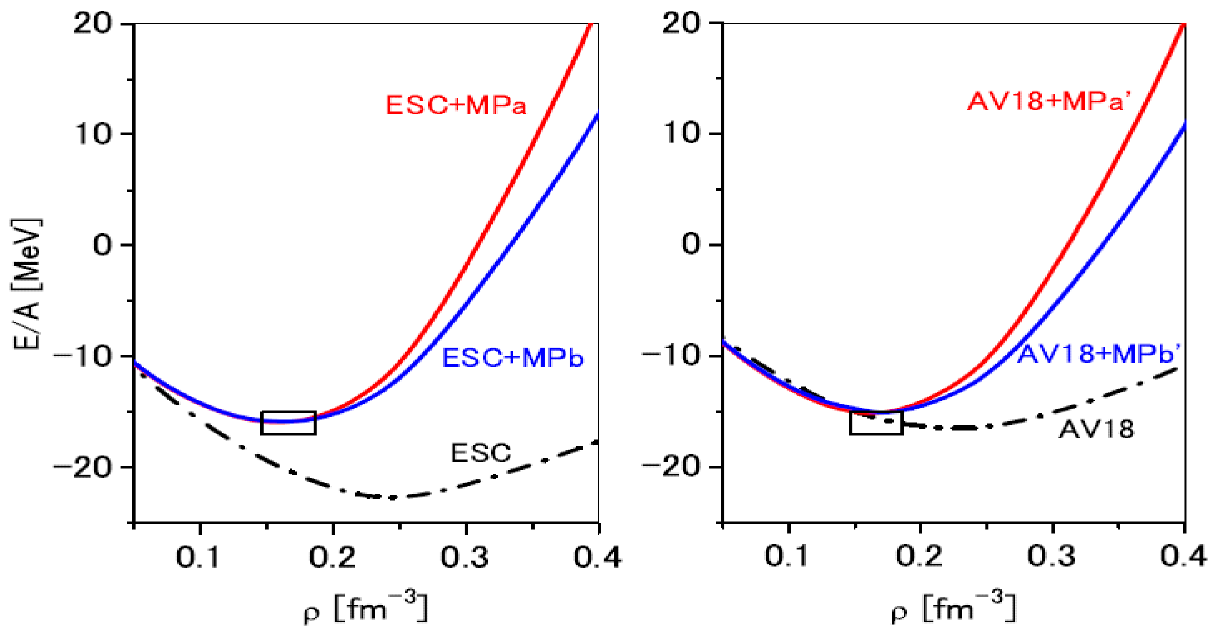
	$g_P^{(3)}$	$g_P^{(4)}$
MPa	2.62	40.0
MPb	3.37	0.0
MPa^+	1.84	80.0

4-body repulsion

TBA V_0=-8 MeV for ESC

adjusting saturation point

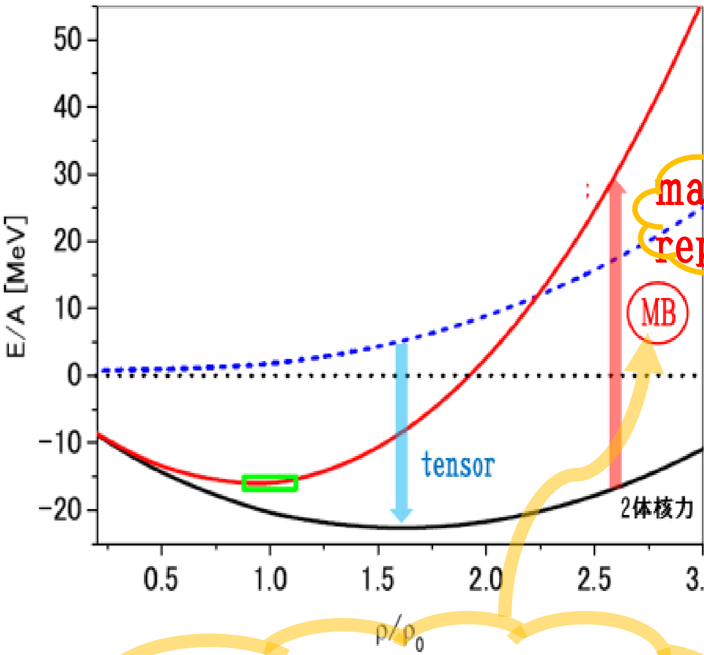
Frozen density app.
up to 2 ρ_0 density



3+4 body repulsions

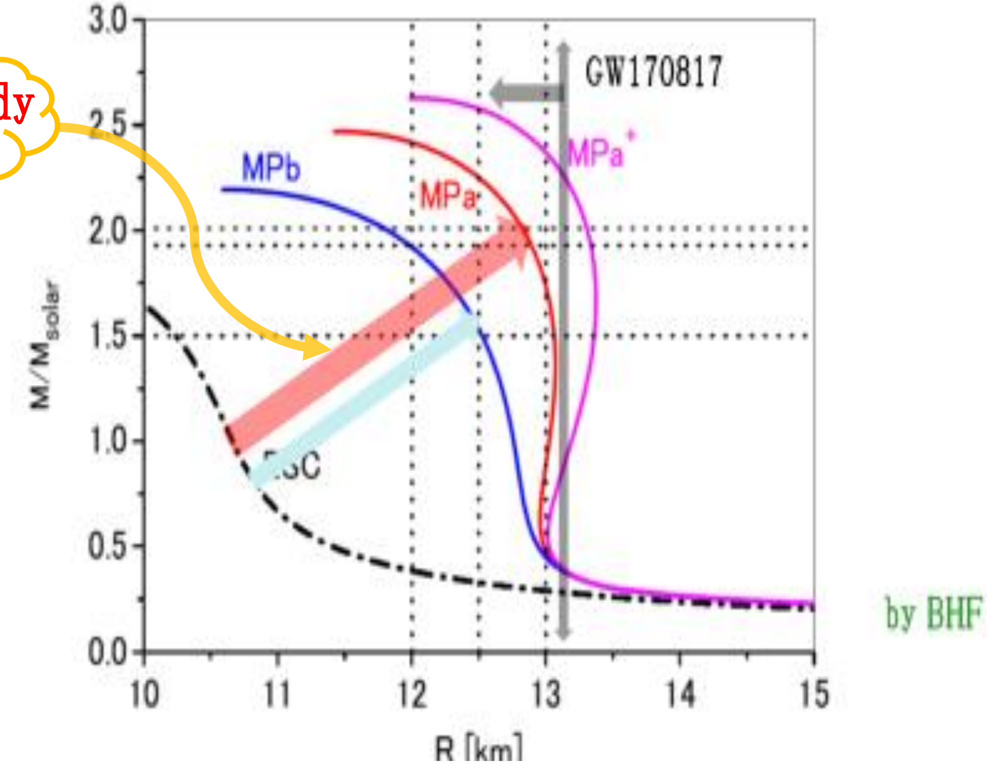
Ratio of 3- and 4-body repulsions cannot be determined !!!

Saturation curve



Saturation cannot be realized only by 2-body repulsive cores

Both of maximum mass and radius are increased simultaneously by many-body repulsion



When observed values of M_{max} and $R(1.4M_{sun})$ are given,
both of them cannot be reproduced simultaneously by adjusting MPP

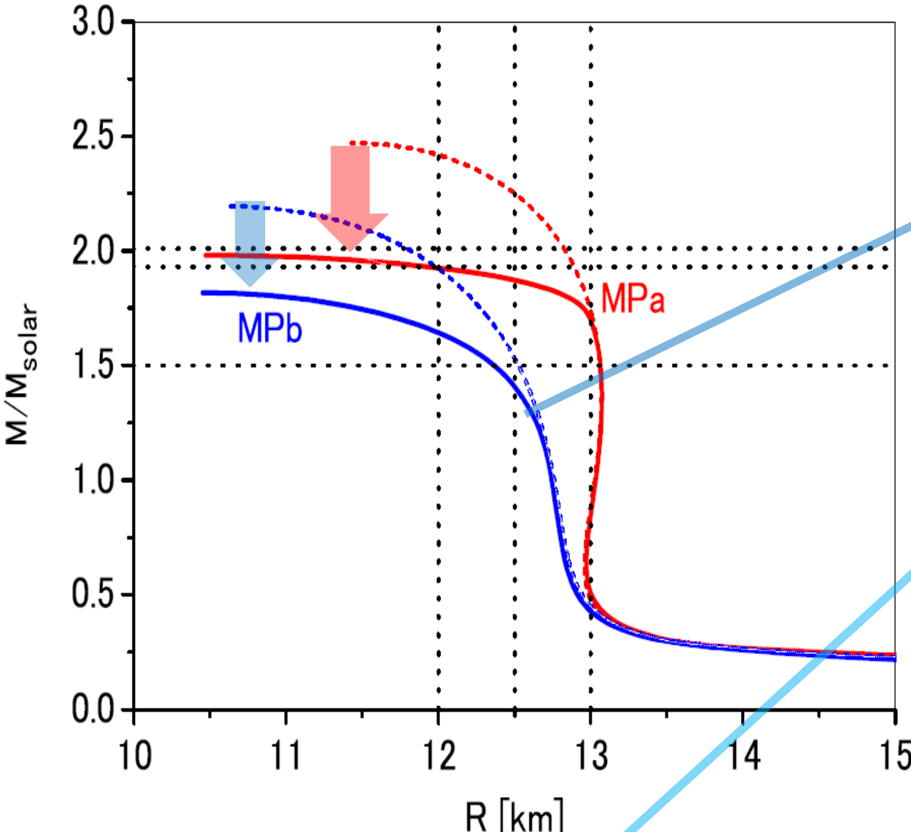
In hadron-quark transition model,
maximum mass (radius) is determined by Q-EOS (H-EOS)

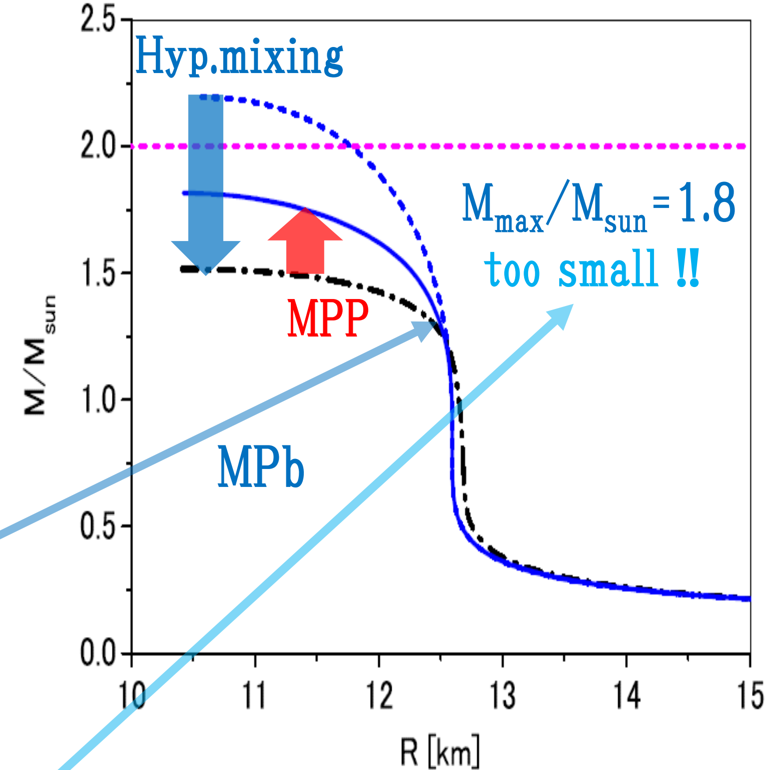
determined independently

Hyperon-mixed Neutron-Star matter with universal TBR (MPP)

EoS of $n+p+\Lambda+\Sigma+e+\mu$ system

ESC(YN) + MPP(YNN) +TBA(YNN)





Softening of EOS by $\Lambda\Sigma^-$ mixing partially recovered by MPP

$R(1.4M_{sun}) \approx$ 12.4km(MPb), 13.3km(MPa)

M_{max}/M_{sun} = 1.82 (MPb), 1.94 (Mpa)

Hyperon mixing is not so related to $R(1.4M_{sun})$ (in our model)

Solutions of the hyperon-$2M_{sun}$ puzzle ?

Burgio, Schulze, Vidana : arXiv:2105.03747, 2021

Three possible solutions (並列的に羅列しただけ):
(1) Hyperon-hyperon repulsion
(2) Hyperonic three-body forces
(3) Quarks in neutron stars

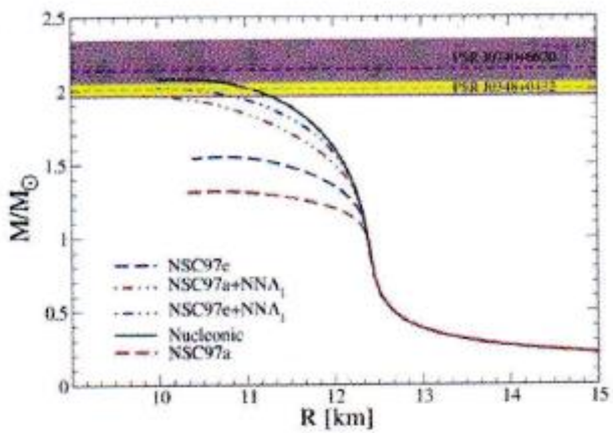
(2)に関して:
"Hyperonic TBFs are not the full solution of the hyperon puzzle"
(Yamamoto, Vidana, Lonardoni, の結果がマチマチである故)
$2M_{sun}$ $1.6M_{sun}$ not conclusive

(3)に関して:
"Whether quarks can provide sufficient repulsion to support $2M_{sun}$ NS"
(色々な論文の紹介をしてるだけ)

いささか浅薄な認識ではある

Bombaki ; Nuclear Physics News, Vol.31/No.3

"It is reasonable to expect that YTBIs can influence dense-matter EOS and represent a likely candidate to solve the hyperon puzzle"



Logotera, Vidana, Bombaki
Eur.Phys.J. A55(2019) 207

{n,p,Λ,e,μ} with NNΛ TBI

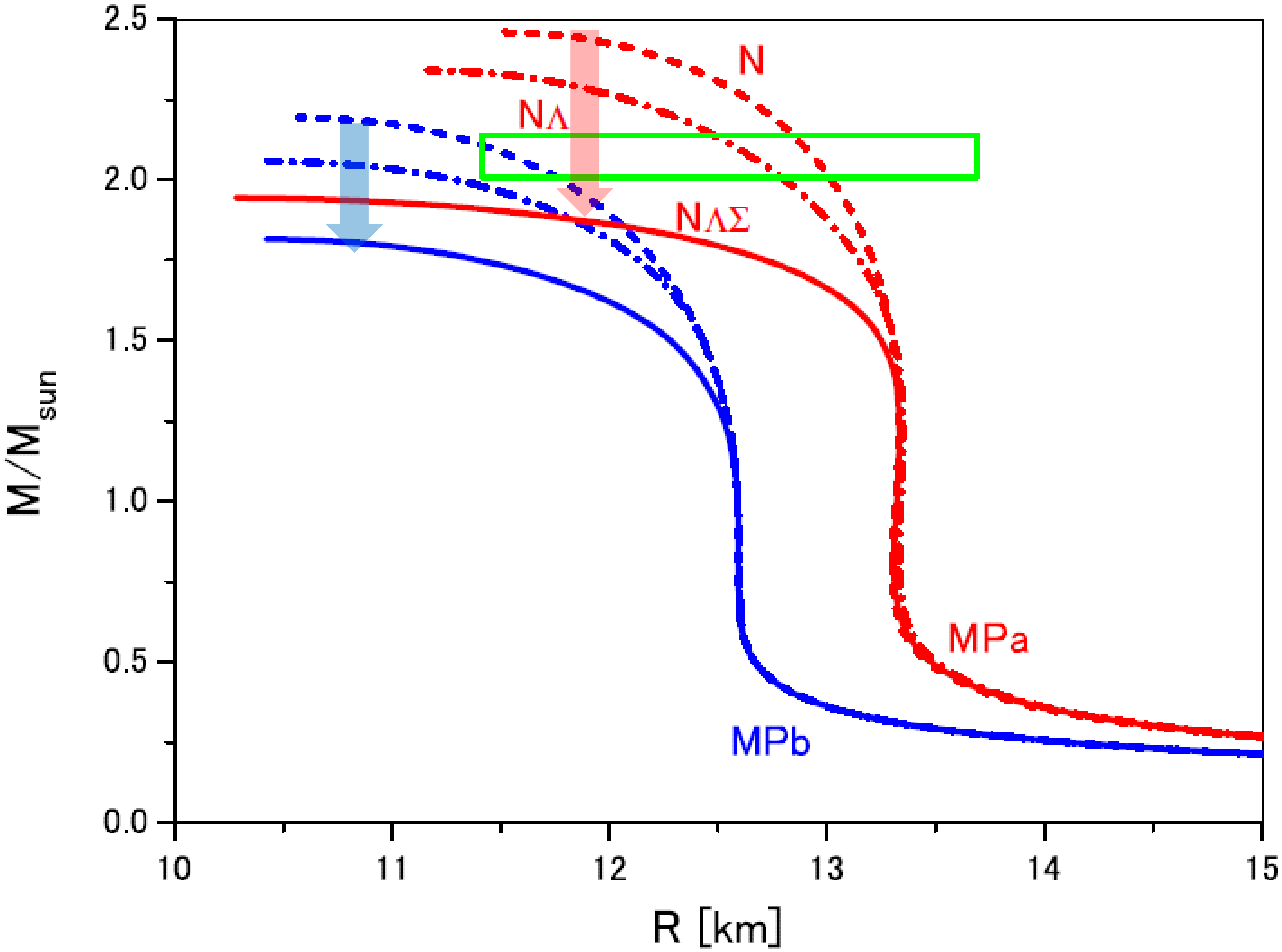
Σ^- が混じると話が違うヨ！

"If YTBIs were repulsive enough, hyperon would never appear at the densities encountered in NS cores"

これは重要な観点であろう！

"We mention a way to <u>circumvent</u> the hyperon puzzle, allowing the presence of strangeness in NSs in the form of strange quark matter"

いささかプラグマティズム！



* Σ^- mixing is important for EOS softening
* Stronger YNN repulsion needed for hyperon-$2M_{sun}$ puzzle ?
  (MPP: universal repulsion)

Remaining problems to solve quantitatively the hyperon-$2M_{sun}$ puzzle in hadron level

* Presence or Absence of Σ^- mixing

ΣN scattering experiment で決められるか??

* Universality of many-body repulsion (V_{YNN} .ne. V_{NNN} ?)

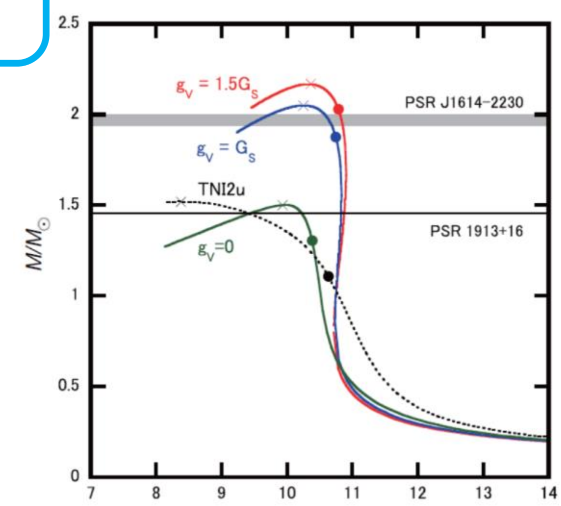
Λ-nuclear spectroscopy で決められるか??

Can be solved the puzzle-$2M_{sun}$ in quark phase？

High-momentum neutrons➔low-momentum particles (no Pauli)
Lowering of pressure ➔ softening of EOS

Dropping of pressure by
exotic particles (hyperons, Δ, mesons, quarks)
free from Pauli principle

If there is no repulsive effect in quark phase
Softening of Q-EOS



Masuda-Hatsuda-Takatsuka

Hadron-Quark transition model
Quark-matter EOS (Q-EOS) → Hybrid Star

Baryon phase by BB interaction
Quark phase by QQ interaction
represented in the same framework (BHF)
Phase transitions between them

Our two-body QQ interaction ⇒ BHF for quark matter

$V_{QQ}=V_{EME}+V_{MPP}+V_{OGE}+V_{INS}$

V_{EME}: extended meson exchange
V_{MPP}: multi-pomeron exchange
} from unfolding of BB interaction

V_{OGE}: one-gluon exchange
V_{INS}: instanton exchange
} from hadron mass spectra

neglecting V_{conf}

no ad hoc parameter

Realistic QQ interaction based on terrestrial data

V_{EME} : extended meson-exchange interaction

ESC model

ESC-QQ interaction with QQM-coupling $m_Q = M_B/3$ —folding→ / ←unfolding— **ESC-BB interaction** with BBM-coupling

Relations between QQM- and BBM-couplings are determined by the condition that BBM vertex is obtained by folding of QQM vertex with SU(6) quark model

$$g^p_{QQ\pi} = g^p_{BB\pi}/3$$

similar relations for the η, K, η'.

$$g^v_{QQ\rho} = \frac{1}{3} g^V_{BB\rho}\ , \quad f^v_{QQ\rho} = \frac{1}{3} f^V_{BB\rho}$$

similar relations for ϕ, K^*, ω.

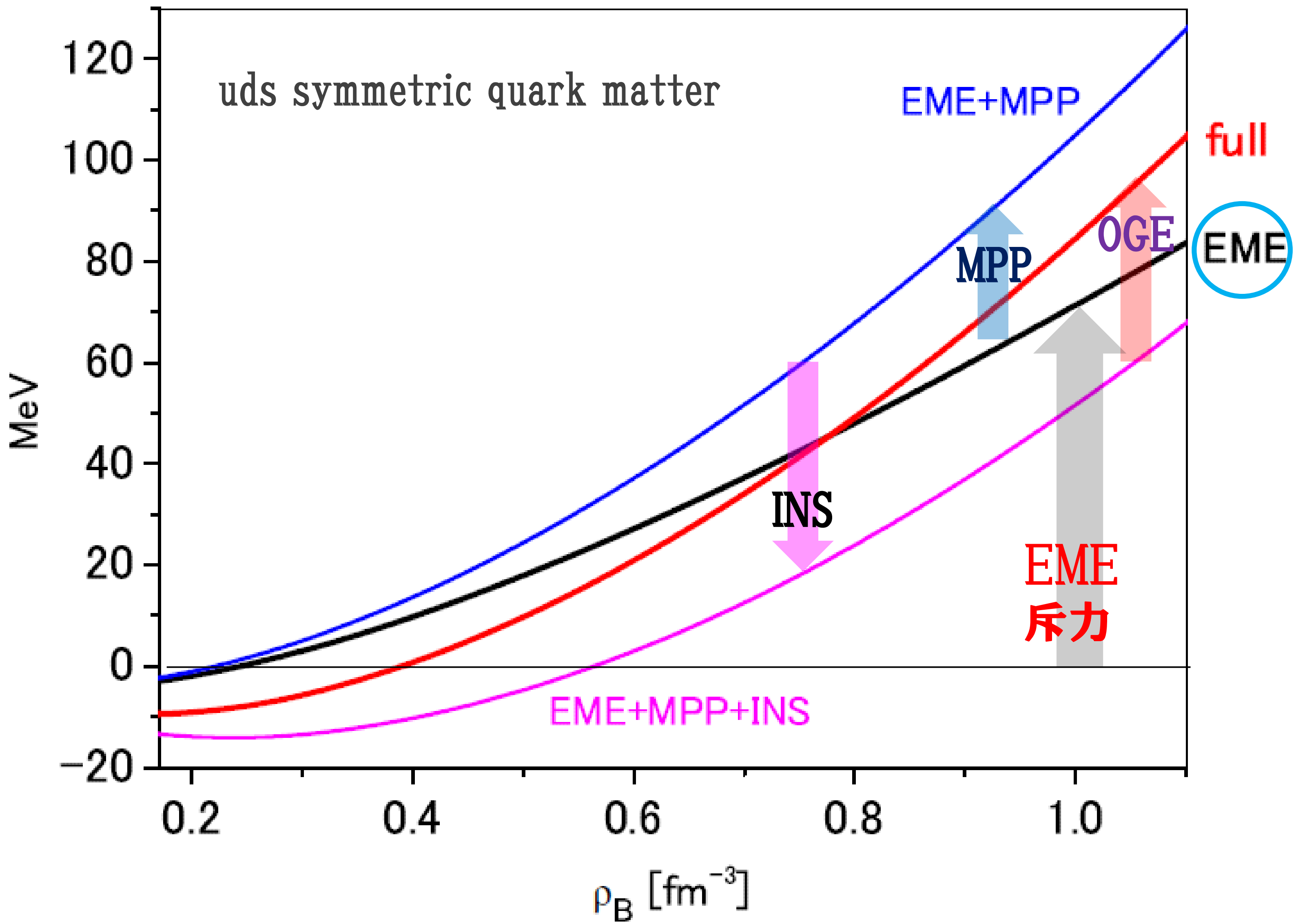
$$g^s_{QQa_0} = \frac{1}{3} g^S_{BBa_0}$$

similar relations for $f_0(993), \kappa, \epsilon = f_0(620)$

$$g^a_{QQA_1} = \frac{1}{3} g^A_{BBA_1}\ , \quad f^a_{QQA_1} = \frac{1}{3} f^A_{BBA_1}$$

similar relations for $D_1(1285)$, $K_A(1336)$, $E_1(1420)$

Averaged potential energy



Same as nuclear repulsive cores

Repulsion EME (vector meson & pomeron exchange) +MPP+OGE ➡ Stiff EOS

Roles of MPP in QQQ and BBB levels

In order to reproduce maximum mass over $2M_{sun}$
MPP_{hyp} (hadron level) is unnecessary (given by Q-EOS)

Origin of QQ repulsion is related to origin of BB repulsion (our model)

* vector-meson & pomeron exchange
* one-gluon exchange (α_s=0.25)

(両者には"double counting"がある。例えば藤原QQ potentialでは
OGE(α_s≒2)に対してvector-meson coupling is zero or small)

MPP repulsion is minor in QQ level (because of $g_{PQQ}=g_{BQQ}/3$)

MPP(QQQ) is folded into MPP(BBB)
Bond number of folding into BBB is larger than that into BB
MPP repulsion becomes strong in BB level, controlling H-EOS

MPP repulsion in BB level is not related to maximum masses,
Making R(>$1.4M_{sun}$) large : in hadron-quark PT model

Density dependent effective QQ interactions
based on G-matrix calculations for quark matter

$$\mathcal{G}_{EME,OGE}(\rho,r) = (a\rho^p + b\rho^q)\cdot\exp(-(r/0.8)^2) + c\cdot\exp(-(r/1.6)^2) ,$$

$$\mathcal{G}_{INS}(\rho,r) = (a\rho^p + b\rho^q)\cdot\exp(-(r/0.6)^2)$$

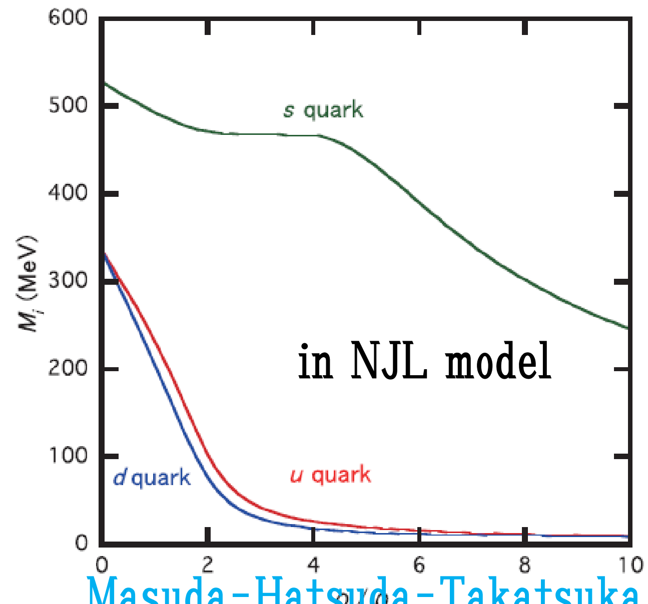
(a,p,b,q,c) → given for each (qq',T, S, P)

It is very easy to calculate Q-EOS by using effective QQ interaction up to high densities

Effective Quark Mass

Constituent quark mass (from chiral symmetry breaking) is larger than (similar to) current quark mass in vacuum (in high-density quark matter)

Density dependent quark mass



Masuda-Hatsuda-Takatsuka

phenomenological

Density-dependent quark mass

Controlling phase transitions

$$M_Q^*(\rho_Q) = M_Q/[1 + \exp\{\gamma(\rho_Q - \rho_c\}] + m_0 + C$$

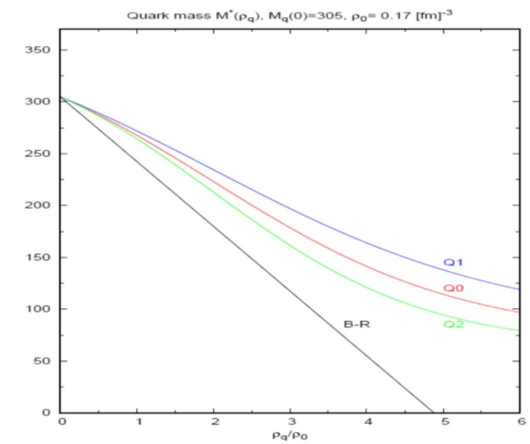
$$C = M_Q - M_Q/[1 + \exp(-\gamma\rho_c)] \qquad M_Q^*(0) = M_Q$$

$$B(\rho_Q) = M_Q^*(0) - M_Q^*(\rho_Q)$$

vacuum energy

$\rho_c = 6\rho_0$ fixed

γ is taken so that phase transitions occur at $(2\text{-}3)\rho_0$



Sets of QQ interactions

Q0 : V_{EME} with γ=1.2

Q1 : $V_{EME} + V_{INS} + V_{OGE}$ with γ=1.0

Q2 : $V_{EME} + V_{MPP} + V_{INS} + V_{OGE}$ with γ=1.4

with relativistic kinetic energy

BB interactions

H1 : ESC+MPb

H2 : ESC+MPa

H3 : ESC+MPa$^+$

f quark potential in quark matter composed of f' quarks

$$\begin{aligned} U_f(k) &= \sum_{f'} U_f^{(f')}(k) \qquad\qquad f, f' = u, d, s \\ &= \sum_{f'} \sum_{k' < k_F^{f'}} \langle kk' | \mathcal{G}_{ff',ff'} | kk' \rangle \end{aligned}$$

$$\begin{aligned} \varepsilon_f &= 2N_c \sum_f \int_0^{k_F^f} \frac{d^3k}{(2\pi)^3} \left\{ \sqrt{\hbar^2 k^2 + M_f^2} + \frac{1}{2} U_f(k) \right\} \\ &+ B(\rho_Q) \end{aligned}$$

$$\mu_f = \frac{\partial \varepsilon_Q}{\partial \rho_f} \ ,$$

$$P_Q = \rho_Q^2 \frac{\partial(\varepsilon_Q/\rho_Q)}{\partial \rho_Q} = \sum_f \mu_f \rho_f - \varepsilon_Q$$

EoS of β-stable quark matter composed of u, d, s, e^-

(1) chemical equilibrium conditions,

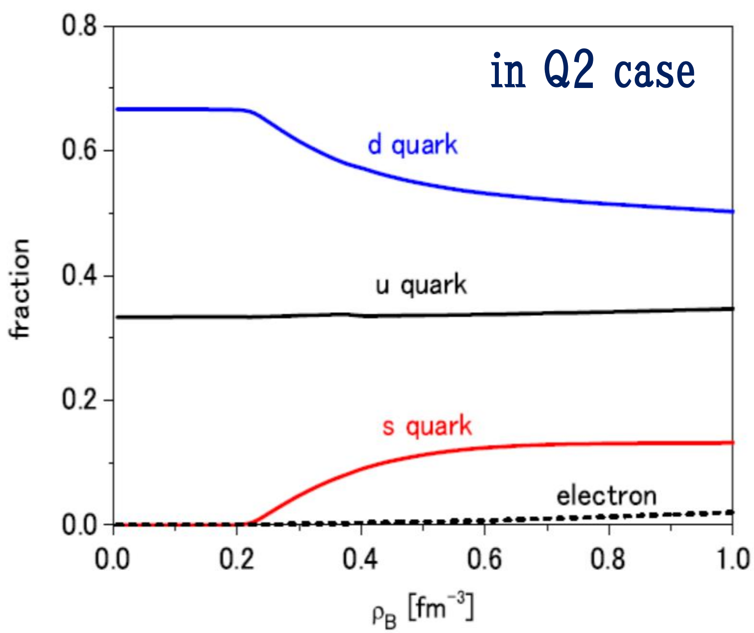
$$\mu_d = \mu_s = \mu_u + \mu_e$$

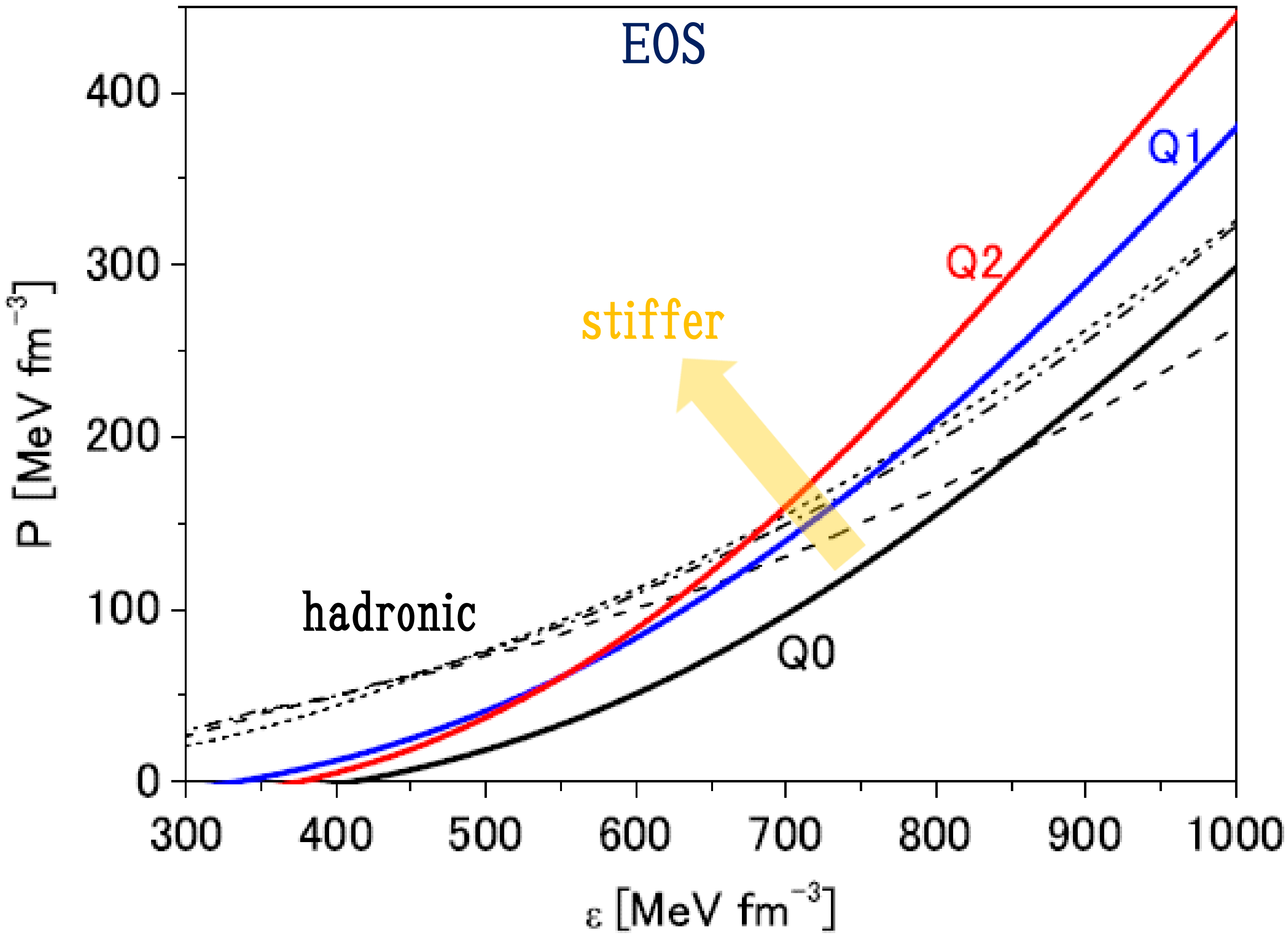
(2) charge neutrality,

$$0 = \frac{1}{3}(2\rho_u - \rho_d - \rho_s) - \rho_e$$

(3) baryon number conservation,

$$\rho_B = \frac{1}{3}(\rho_u + \rho_d + \rho_s) = \frac{1}{3}\rho_Q$$

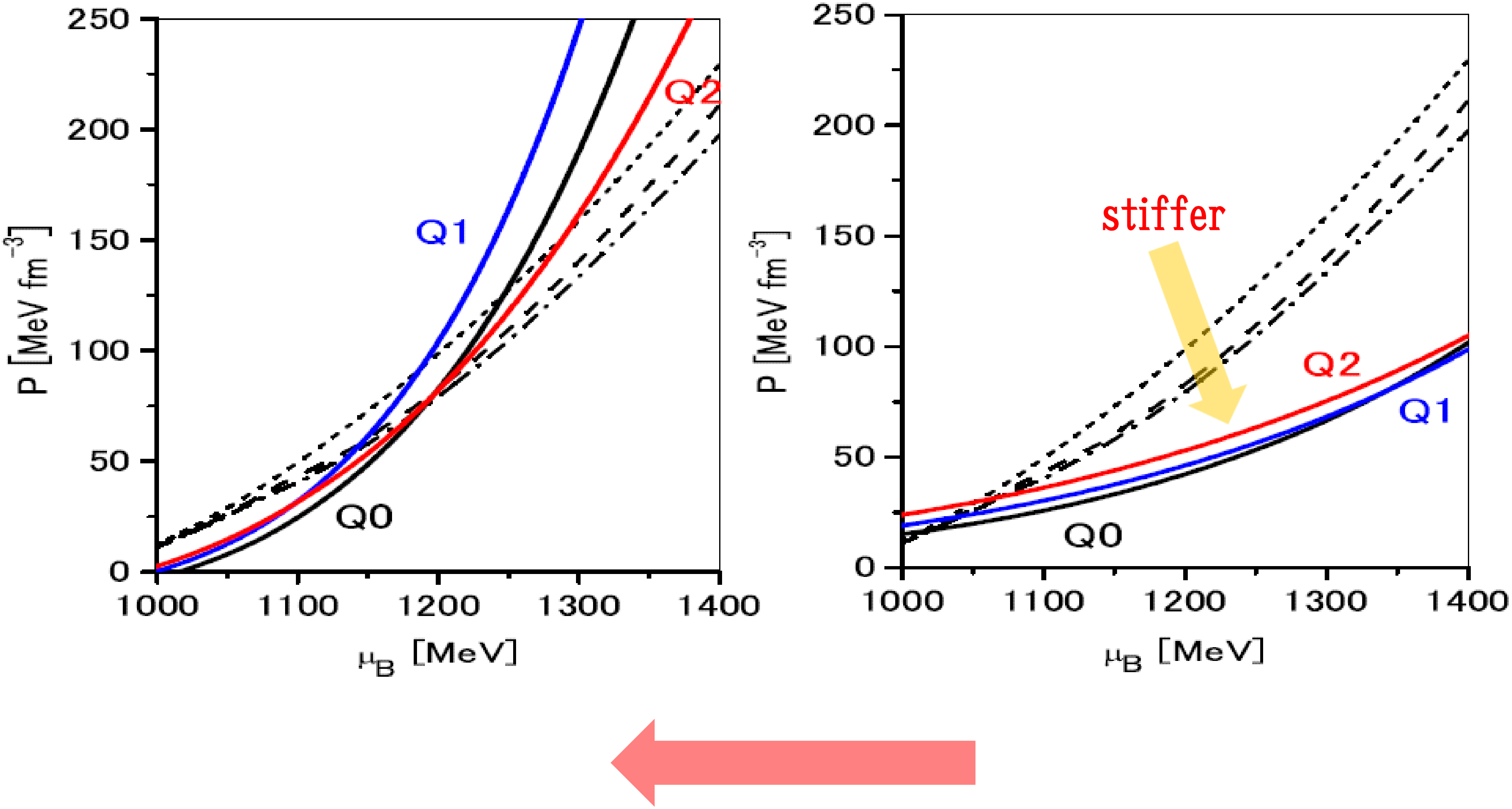




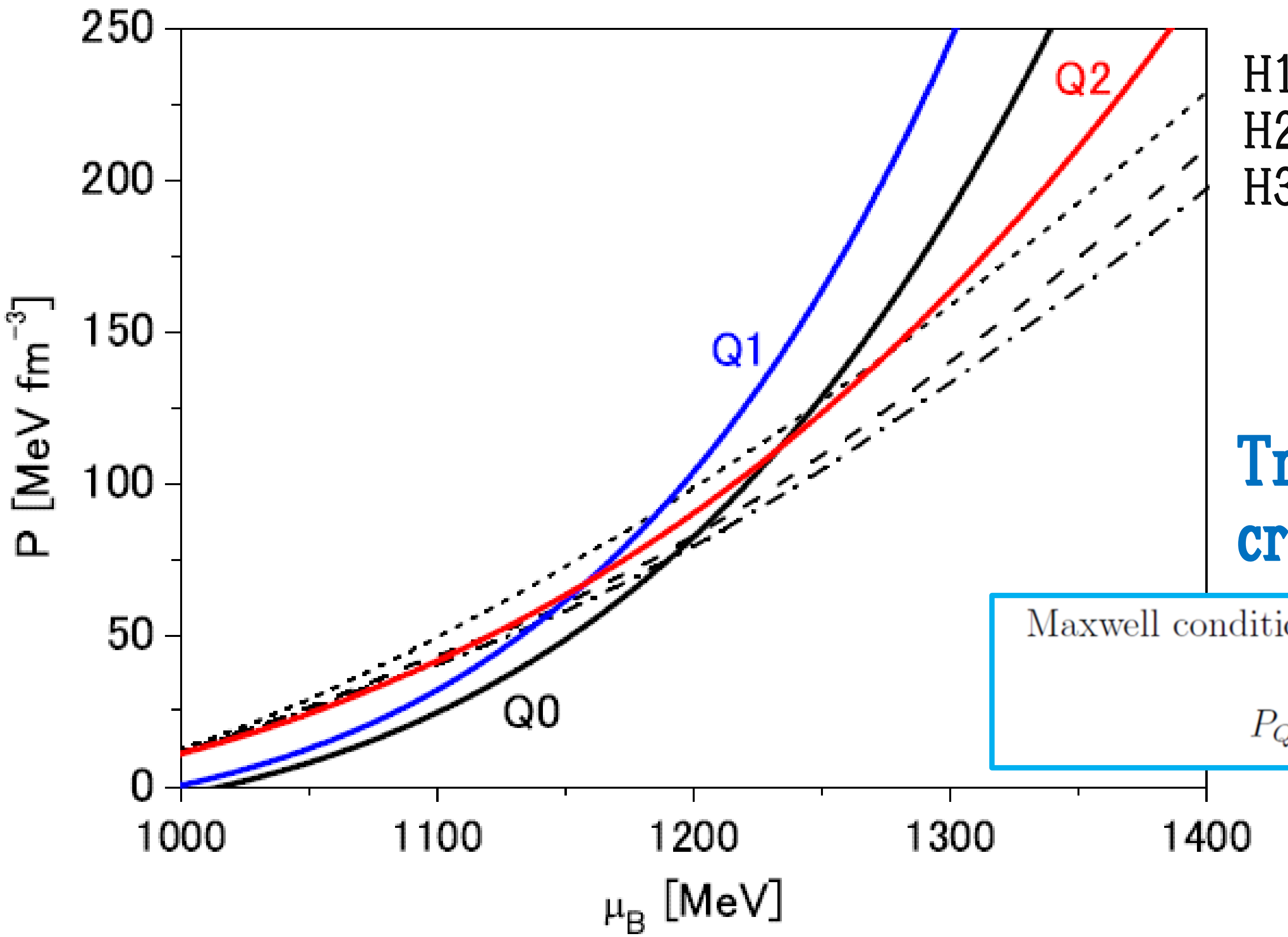
EOS (pressure P as a function of energy density ε)

Q-EOS is stiffer than H-EOS

phase transition



Density-dependent quark mass



Transition at crossing point

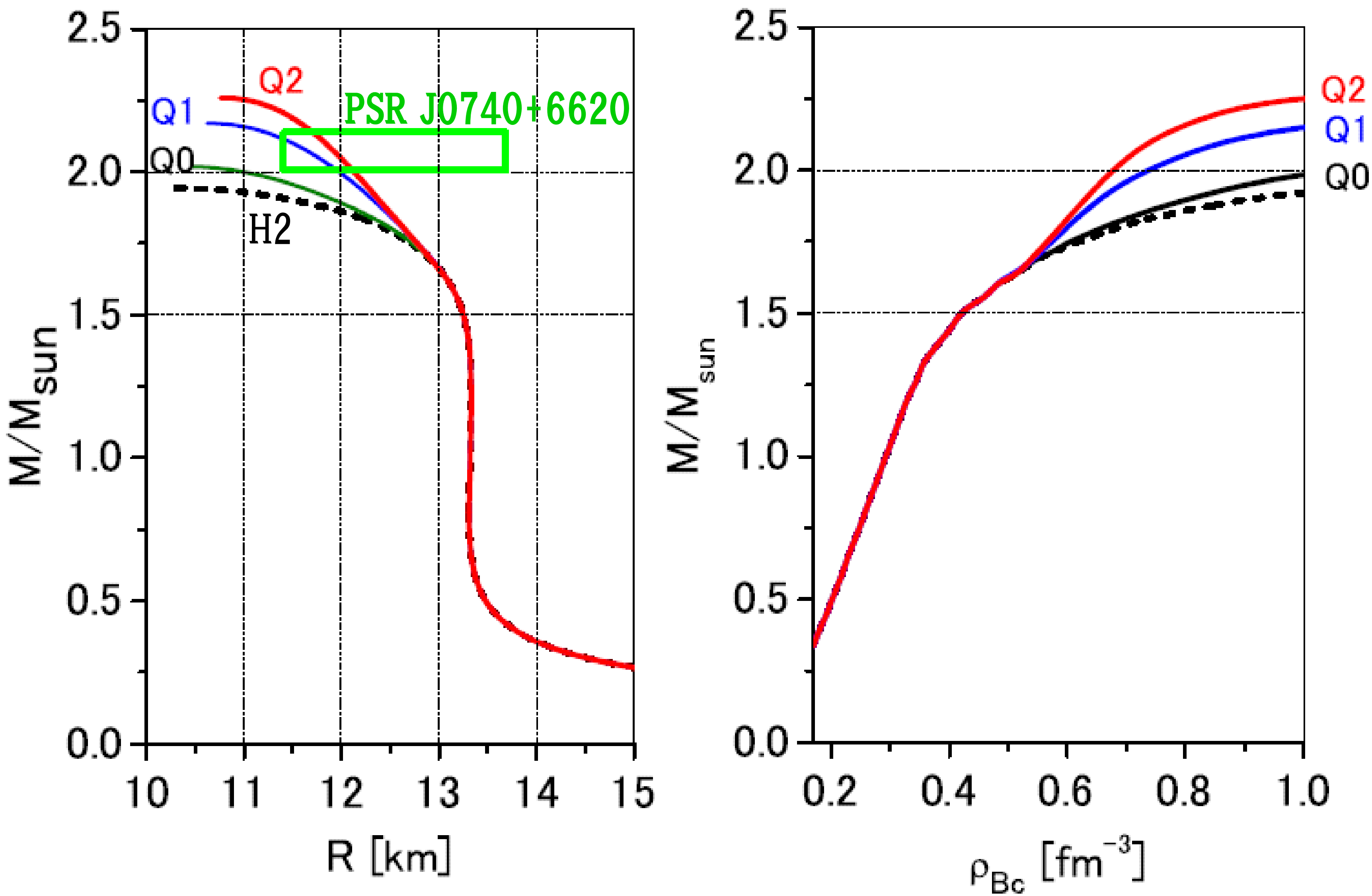
Maxwell condition

$$P_Q(\mu_c) = P_H(\mu_c) = P_c$$

Replacement Interpolation Method

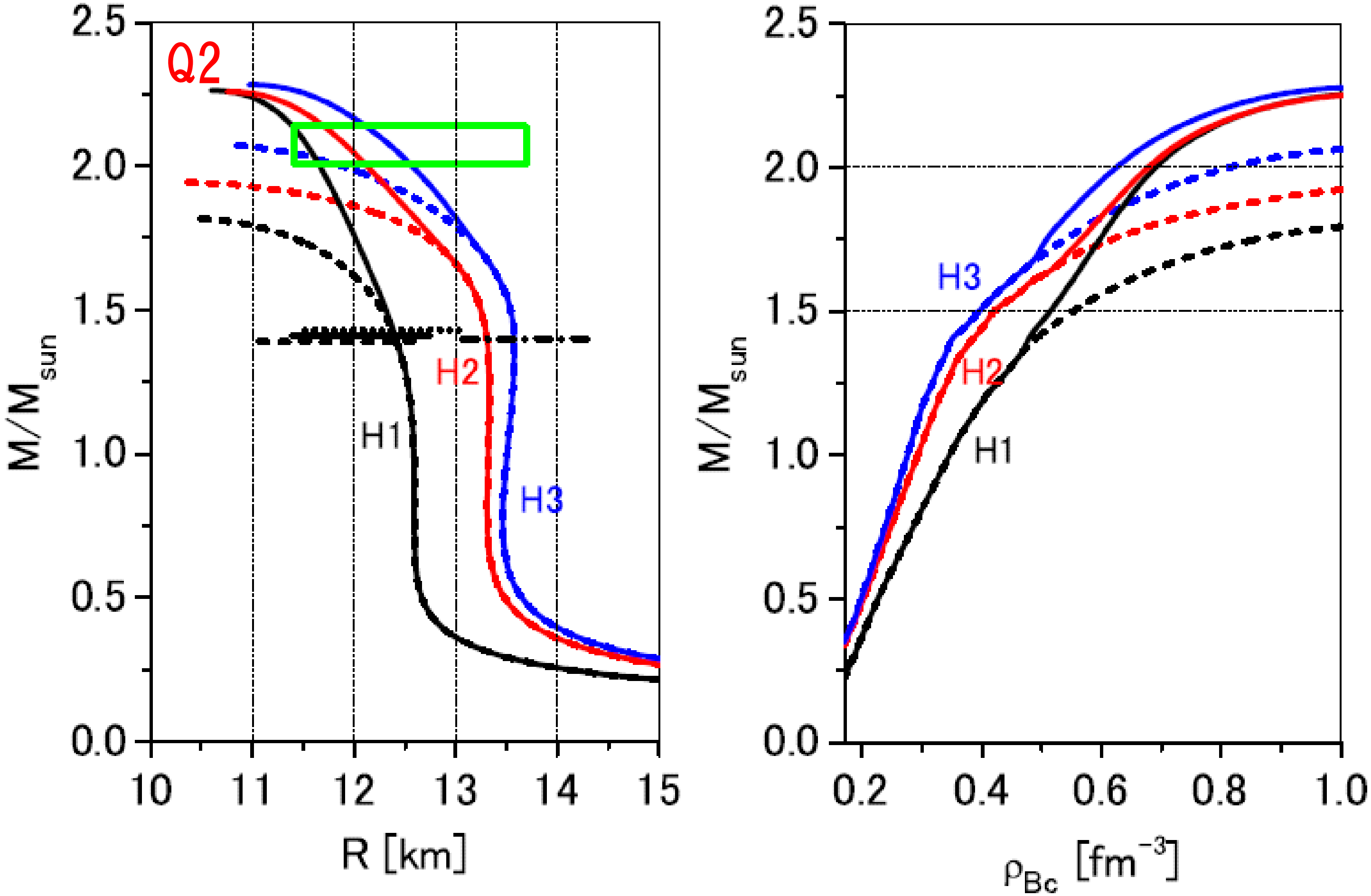
Q-curves are connected smoothly from H-curves at crossing points

simple treatment for the Gibbs construction



M_{max} is determined by Q-EOS: Q1 & Q2 give reasonable values of M_{max}

PSR J0740+6620 : Both of mass and radius are observed

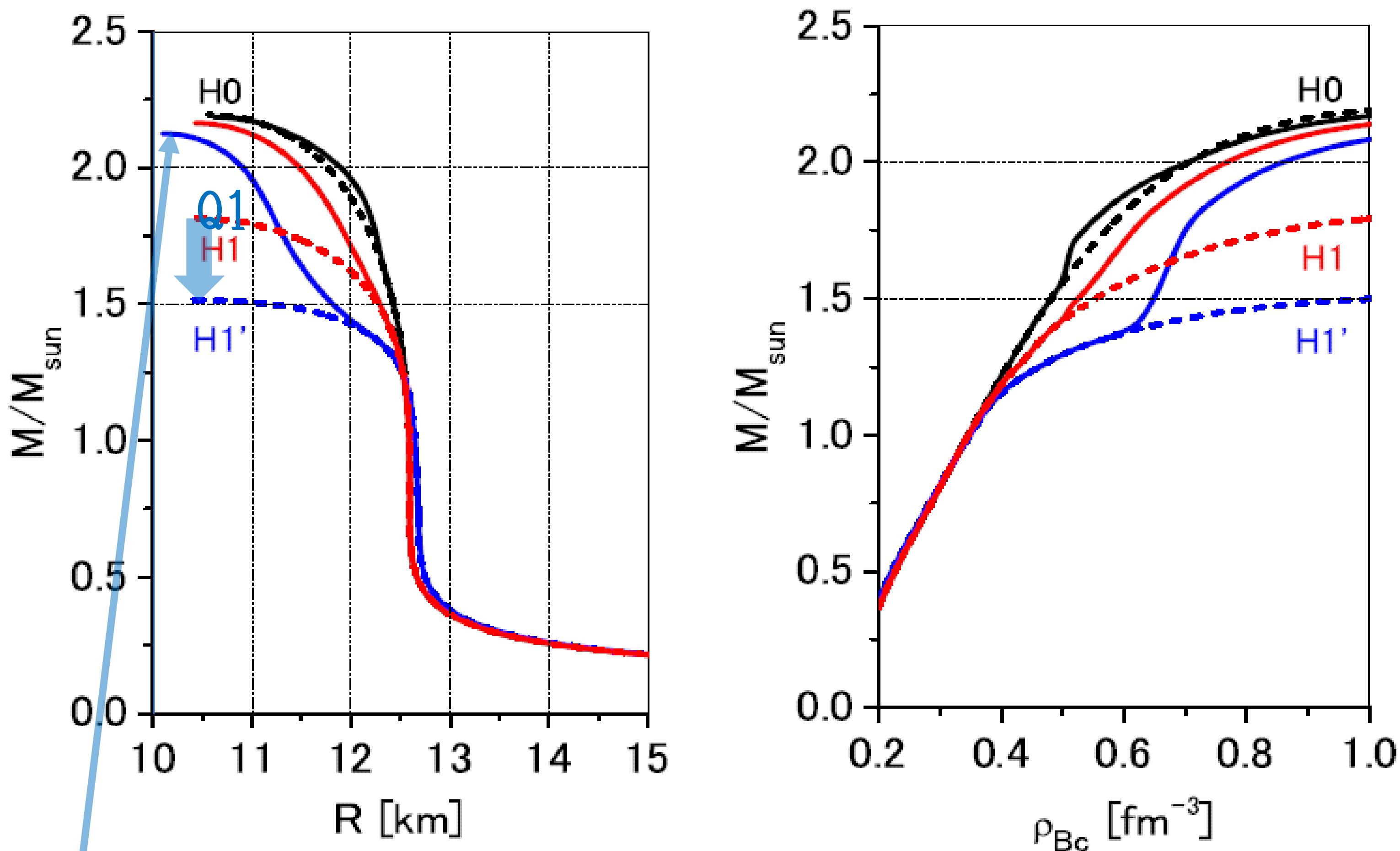


R($1.4M_{sun}$) is determined by H-EOS

H1
- Dotted : $R_{1.4M_\odot} = 12.33^{+0.76}_{-0.81}$ km (arXiv:2105.06981)
- Solid : $R_{1.4M_\odot} = 12.18^{+0.56}_{-0.79}$ km
- Dashed : $R_{1.4M_\odot} = 11.94^{+0.76}_{-0.87}$ km (arXiv:2105.08688)

H2/H3
- Dot-dashed : $R_{1.4M_\odot} = 13.80 \pm 0.47$ km (arXiv:2101.03193)

For soft H-EOS



Black: H0 without hyperons

Red : H1 with hyperons including universal repulsions

Blue : H1' with hyperons including only NNN repulsions

Result of H1'+Q1 shows that $2M_{sun}$ is reproduced without MPP_{hyp} : Effect of MPP_{hyp} appears in R(>$1.4M_{sun}$)

arXiv:2105.06981 14 May 2021

$11.52\ \mathrm{km} < R(1.4M_{sun}) < 13.09\ \mathrm{km}$ (PP model)

$11.39\ \mathrm{km} < R(1.4M_{sun}) < 12.74\ \mathrm{km}$ (CS model)

arXiv:2105.08688 18 May 2021

$11.07\ \mathrm{km} < R(1.4M_{sun}) < 12.70\ \mathrm{km}$

arXiv:2101.03193 ; taking into account of PREX-II

$13.80\ \mathrm{km} < R(1.4\mathrm{Msun}) < 14.26\ \mathrm{km}$

model	$R(1.4M_{sun})$	
H1	12.4 km	$M_{max} = 1.8M_{sun}$
H1+Q0	12.4 km	$M_{max} = 2.0M_{sun}$
H1+Q1	12.4 km	$M_{max} = 2.2M_{sun}$
H1+Q2	12.4 km	$M_{max} = 2.3M_{sun}$
H2	13.3 km	
H3	13.6 km	

	$M_{max}/M_\odot$	$R_{M_{max}}$ (km)	$R_{1.4M_\odot}$ (km)	$\Lambda_{1.4M_\odot}$
H1	1.82	10.4	12.4	422.
H1+Q0	1.99	10.0	12.4	422.
H1+Q1	2.16	10.4	12.4	422.
H1+Q2	2.26	10.6	12.4	422.
H1'	1.52	10.4	12.1	334.
H1'+Q1	2.13	10.1	12.2	337.

w/o MPP_{hyp}

H2	1.94	10.3	13.3	671.
H2+Q0	2.02	10.5	13.3	671.
H2+Q1	2.17	10.6	13.3	671.
H2+Q2	2.26	10.8	13.3	671.

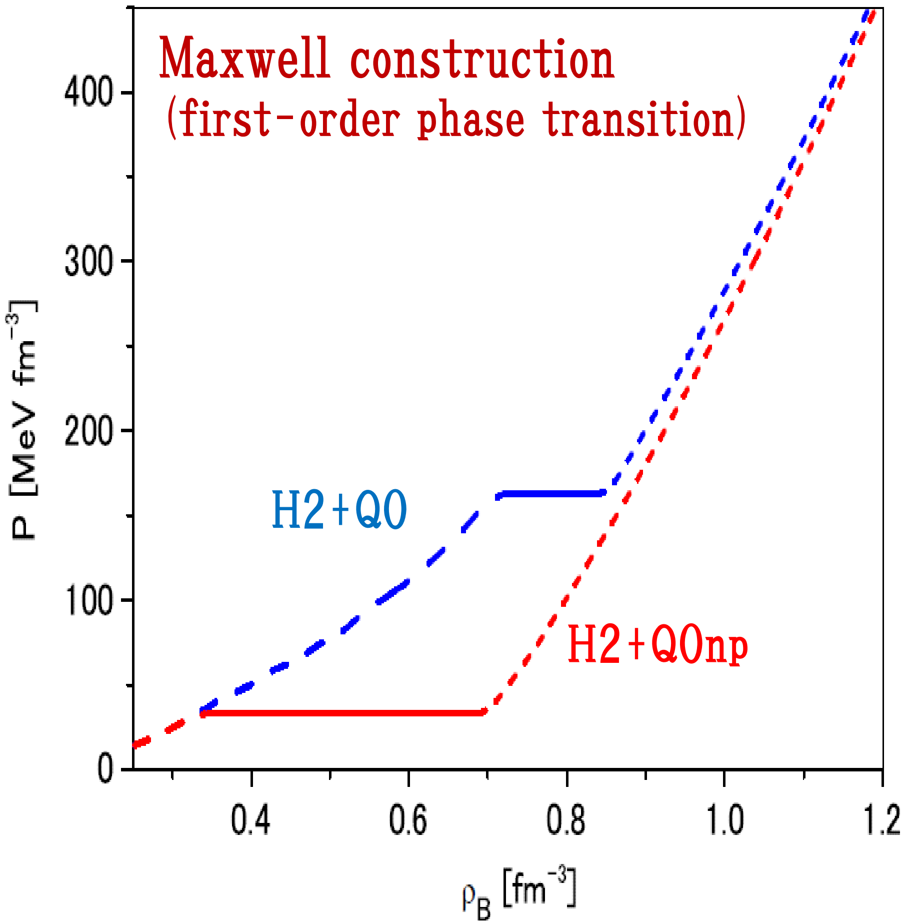
In the case of H-EOS only, M_{max} depends on $R(1.4M_{sun})$
It is difficult to be over $2M_{sun}$
In the case of H-EOS+Q-EOS, M_{max} can be over $2M_{sun}$ independently of $R(1.4M_{sun})$

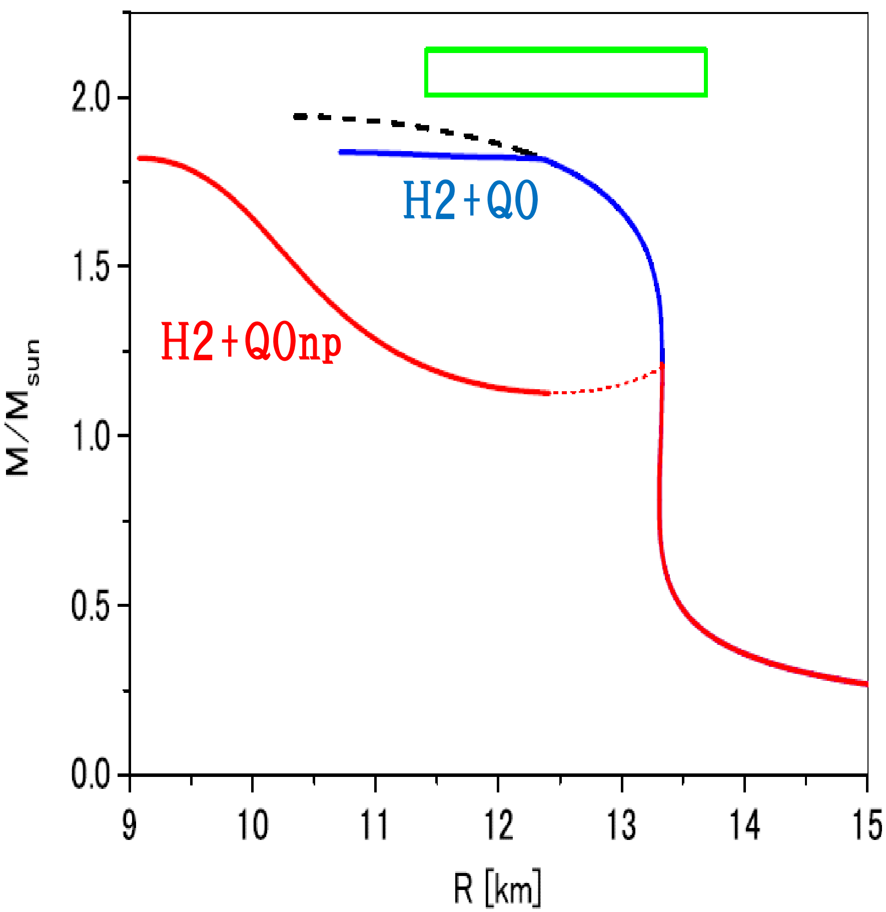
QQ repulsion in our approach

Repulsions in BB interaction
(ω meson + pomeron in ESC)

Followed in QQ interaction

Q1: $V_{EME} + V_{INS} + V_{OGE}$
Q1np: V_{EME} (no pomeron) $+ V_{INS} + V_{OGE}$





Q0np : no pomeron-exchange

conclusion

In order to avoid EOS softening by mixing of
exotic phase (hyperon, quark, etc)
high-density repulsions are needed in respective phases

EOS softening in baryonic phase by hyperon mixing
can be avoided by universal repulsion (MPP)

In our QQ interaction model, stiff Q-EOS can be
realized mainly by exchange repulsions of vector-meson
& pomeron related to the origin of BB repulsion.

By using H-EOS and Q-EOS for hybrid stars based on
our QQ/BB interaction model, both observed values of
M_{max} and $R(1.4M_{sun})$ can be reproduced
without ad hoc parameters

蛇足

実験でΛNN-TBRの強さを決める意義

In Isaka calculations:
* ESC14+MPP(needed for NS)
* ESC12+weak MPP
Small difference of Λ-nuclear spectra → MPPの上限を決める程度でも意義あり!!

クォーク相まで考慮する時には、ΛNN-TBRの強さは
Hyperon-2M_{sun} puzzle を解くためと云うより
NSにおけるΛ-mixingのonset densityを
与えるものと位置付けられるのではないか

例えばLonardoniの非常に強いΛNN repulsionの
下ではΛ-mixingは(故にEOSソフト化も)起こらない

まずはそのような可能性を実験的に排除することが
できれば、それだけでも非常に意味がある