

核力・ハドロン相互作用と中性子星物質
--- 2体核力を超えて ---

Y. Yamamoto with Th.A. Rijken

中性子星は巨大な原子核である

---- 核物理の対象としての中性子星物質 ----

基礎的課題

中性子星物質の状態方程式(EOS)より
中性子星の最大質量を導く

原子核・核物質に対する手法

中性子星のMR曲線

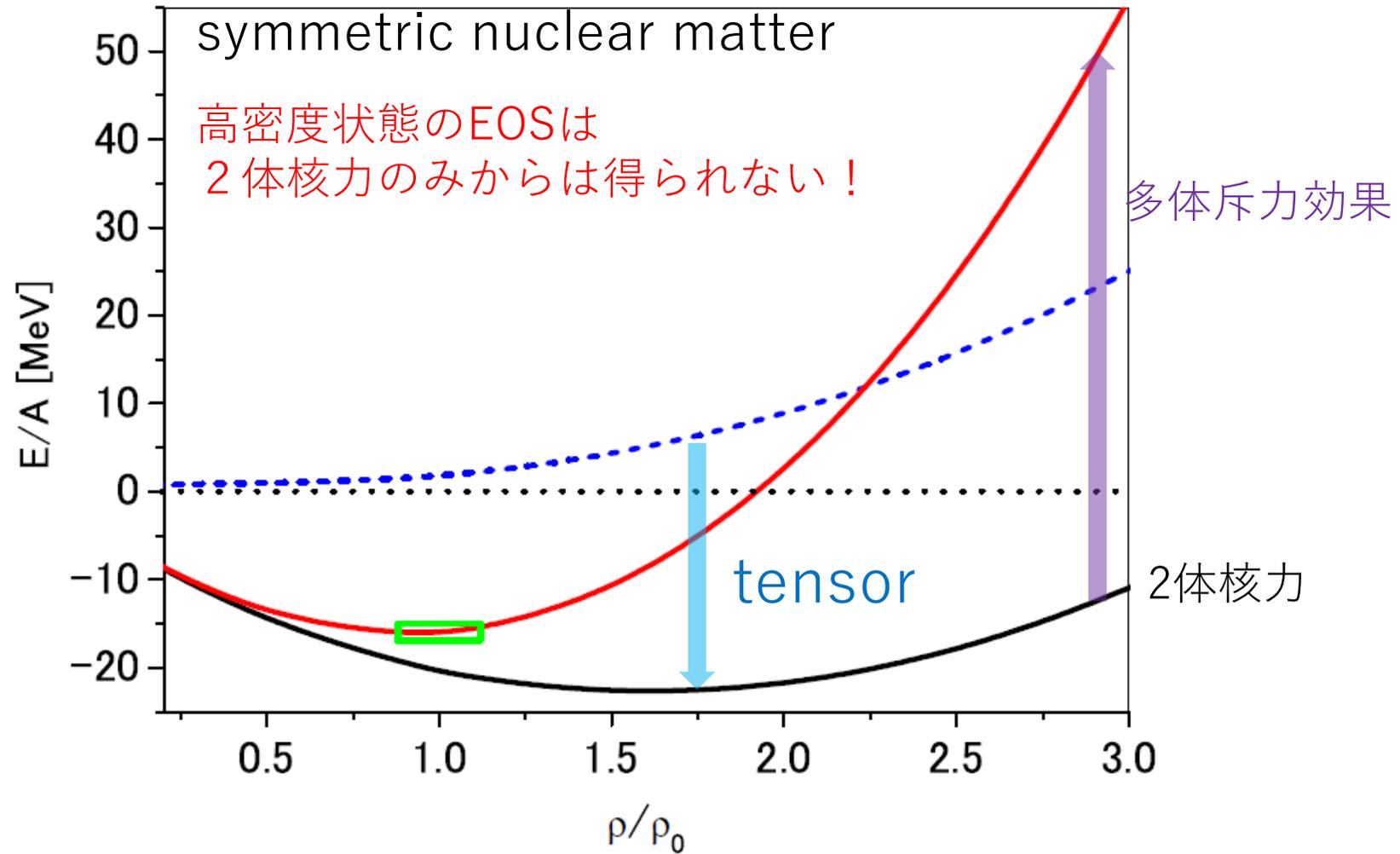


核物質のEOS (E/A曲線)

中性子星は高密度原子核である

2体核力を超える要素が本質的になる

中性子星物質研究の要はEOS stiffening（最大質量）に対応する多体斥力効果にある



パルサー発見 1967年

核物質理論 (Brueckner theory)の進展 ←

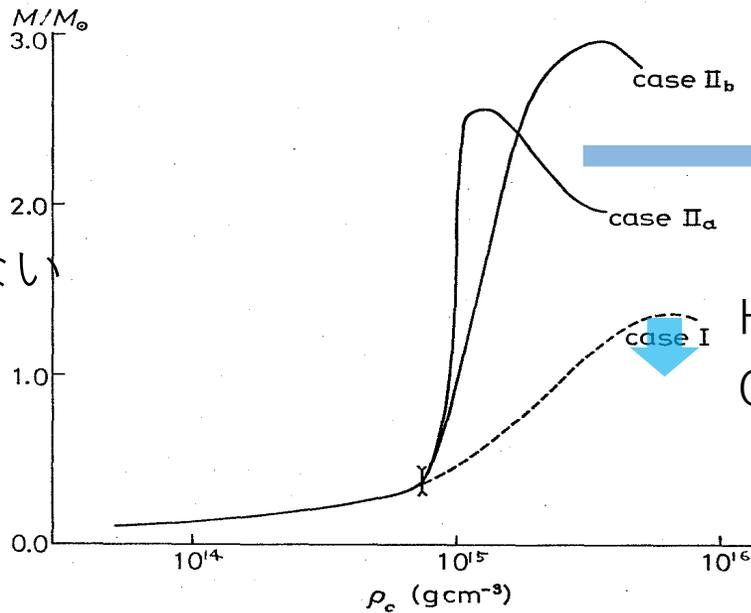
「核力と核構造」研究グループ

Hole Line Expansion method: Y.Akaishi, H.Bando, A.Kuriyama, S.Nagata 1968年 Yamamoto (4年生)

(核力による多体計算スキームの確立)

京大グループ

1971年 S. Ikeuch & S. Nagata et al Bruecner計算



高密度での斥力効果
3体斥力の認識なし

1M_⊙
2体核力のみ

中性子星質量
観測されていない
時代の話

最大質量 1M_⊙ ~ 3M_⊙

核構造
核散乱
ハイパー核
中性子星

現象論的 3 体斥力 TNR の導入 ← 中性子星質量の観測の蓄積

$$V_{\text{TNR}} = \sum U_0 T^2(r_{12}) T^2(r_{13}) \quad T(r) = \text{form of OPEP tensor force}$$

- I.E.Lagaris, V.R.Pandharipande 1981年 : Saturation curve @variational
R.B.Wiringa, V.Fiks, A.Fabrocini 1988年 MR curve @variational
M.Baldo, I.Bombaki, G.F.Burgio 1997年 MR curve @BHF
A.Akmal, V.R.Pandharipande, D.G.Ravenhall 1998年 MR curve @variational

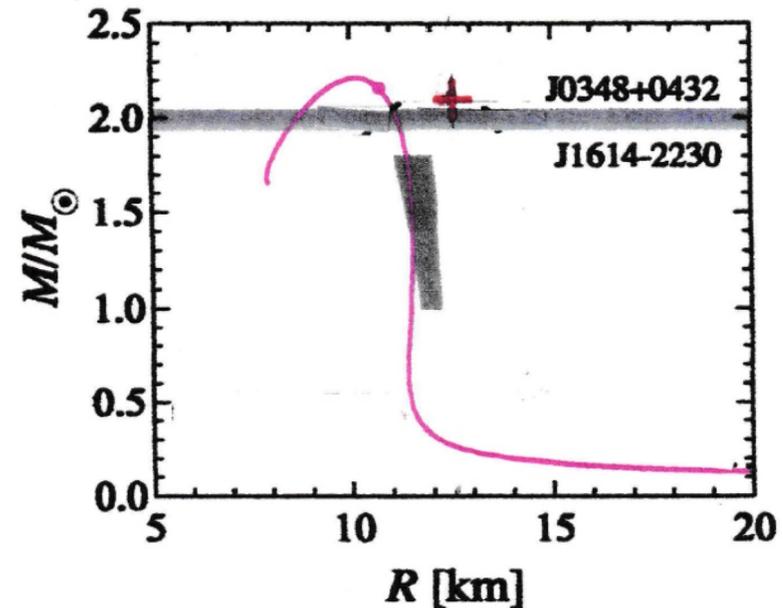
最大質量の
現実的理解へ

AV18 + UIX



1980年～2000年

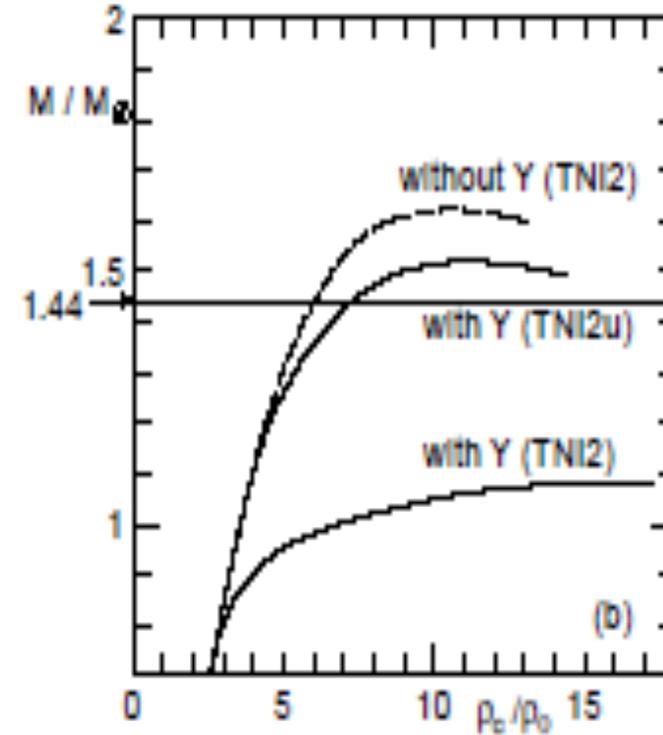
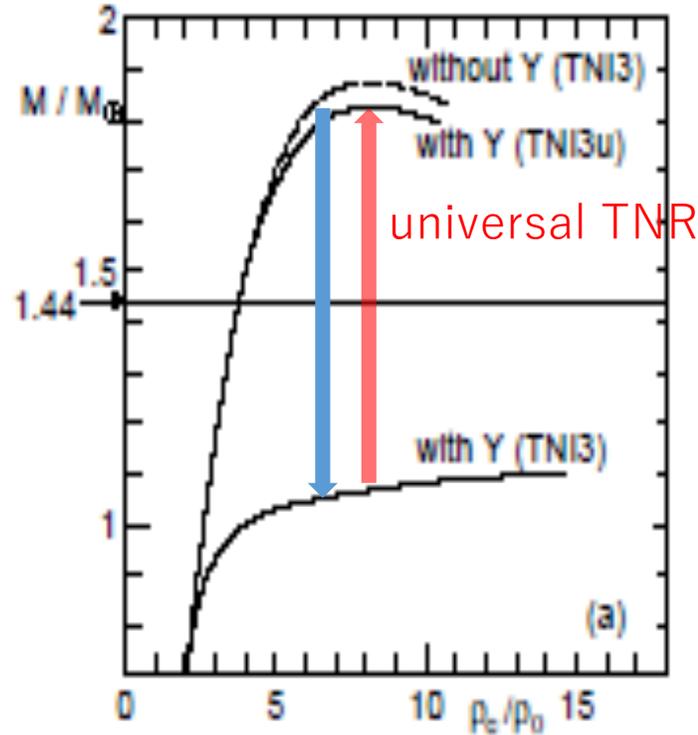
Togashi EOS (AV18+UIX)



ハイペロン混合によるEOSのソフト化(後にHyperon Puzzleと命名された)

シンプルな物理 *S. Nishizaki, Y. Yamamoto and T. Takatsuka* 2002年

2 M_{sun} NS
未発見の時代



TNR効果が
台無し

Fig. 9. The mass of a neutron star in units of the solar mass M_{\odot} as functions of the central baryon density ρ_c with use of (a) TNI3 and (b) TNI2. The notation here is the same as in Fig. 8.



A model of universal TNR (TBR) : Multi-Pomeron exchange Potential (MPP) by Rijken-Ya

MPP repulsionの決め方

Universal TBR ($V_{NNN}=V_{\Lambda NN}=V_{\Lambda \Lambda N}$)

Added by phenomenological TBA

^{16}O - ^{16}O 散乱角度分布を用いてMPPの強さ

$E/A(\rho_0)$ や E_{Λ} を合わすようにTBA

要するに現象論

ただし、2Msolar を出すためのパラメータは含まない

Observations of $2M_{\odot}$ neutron stars restrict EOSs strongly

Massive ($2M_{\odot}$) neutron stars

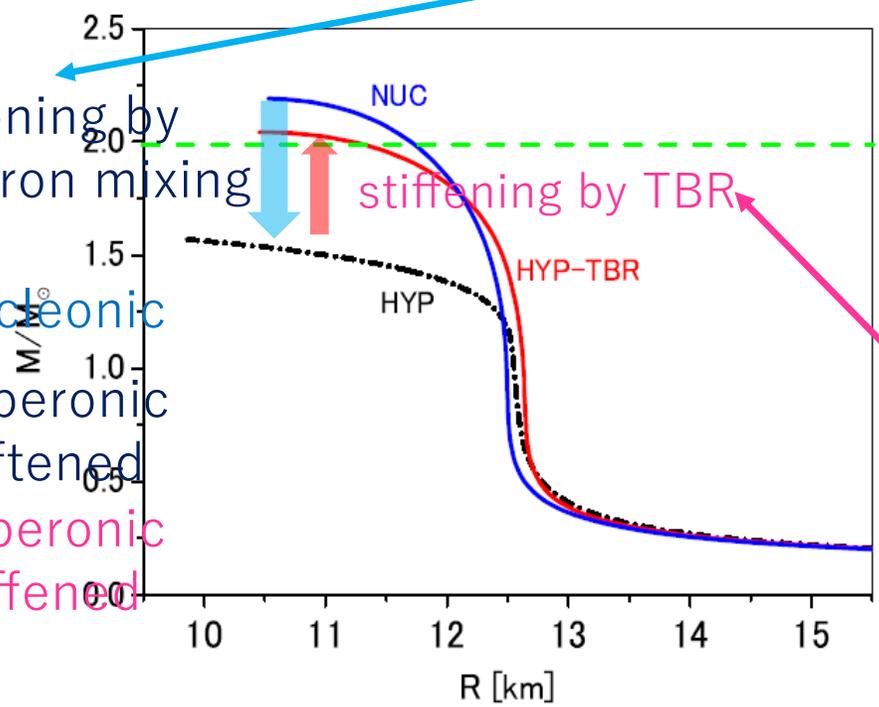
2010 PSR J1614-2230 (1.97 ± 0.04) M_{\odot}

2013 PSR J0348-0432 (2.01 ± 0.04) M_{\odot}

ハイペロンパズル 顕在化

Dropping of pressure by changing of high-momentum neutrons to low-momentum hyperons free from Pauli principle

MR curves for Baryonic Matter EOS



EOS softening by Hyperon mixing (Hyperon Puzzle)

MR curve for nucleonic EOS goes down by hyperon mixing (EOS softening)

EOS softening by hyperon mixing should be recovered by some EOS stiffening, TBR

Three-Baryon Repulsions (MPP)

TBR is one of models for EOS stiffening

Recent observations

Mass and Radius of massive NS

further restriction for EOS

NICER measurement for **PSR J0740+6620**

Medium values of M and R

$$M = (2.08 \pm 0.07) M_{\odot}$$
$$R = 12.49^{+1.28}_{-0.88} \text{ km}$$

$$\text{MR point : } (M = 2.1 M_{\odot} \quad R_{2.1 M_{\odot}} = 12.5 \text{ km})$$

Measurements for $1.4 M_{\odot}$ NS

$$R_{1.4 M_{\odot}} \approx 12.4 \text{ km}$$

How to obtain EOS consistent with these two constraints

It is difficult that a hadronic-matter EOS meets both constraints

Promising idea is to focus on possible repulsive effects of quark phases

quark-hadron crossover model
quarkyonic matter

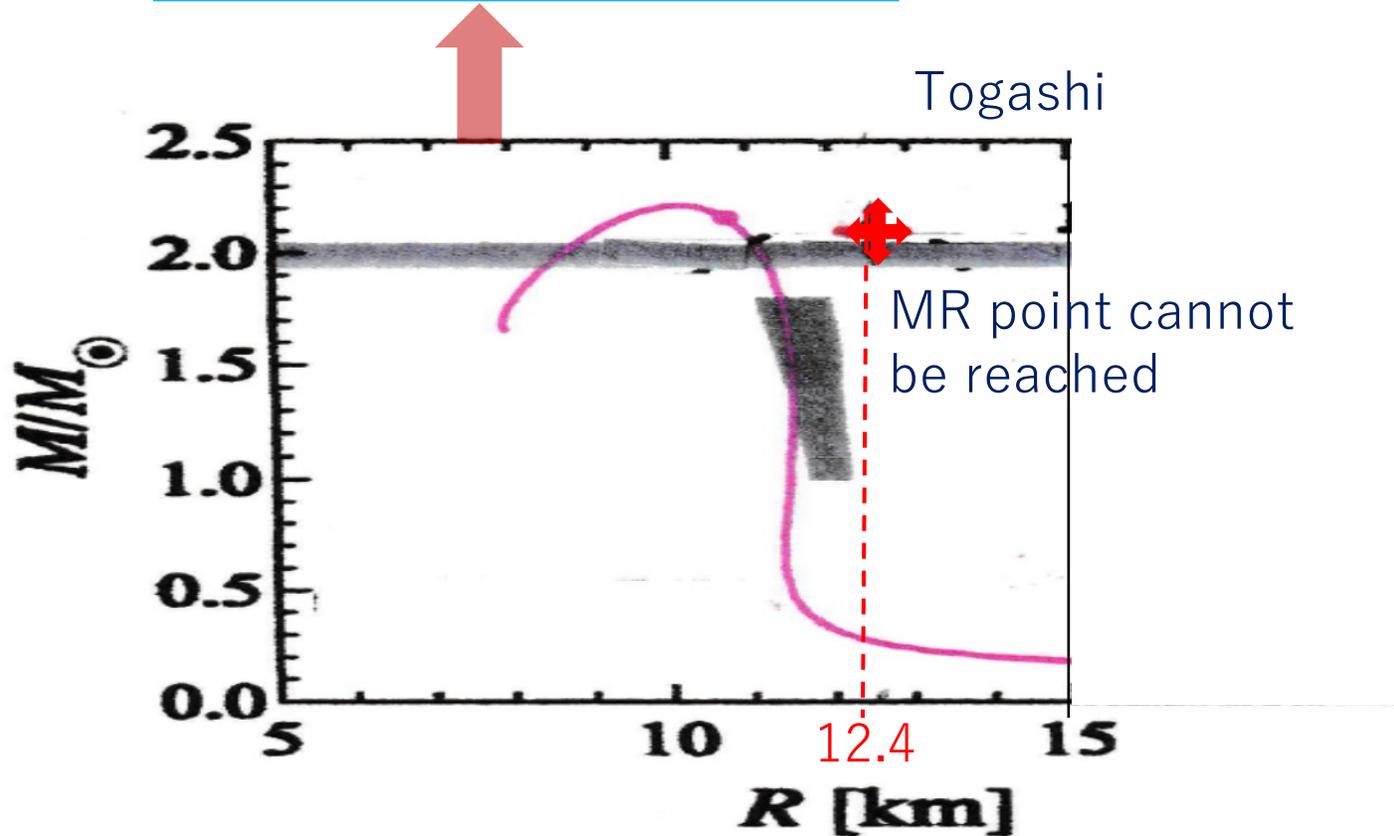
Baryon-Quark mixed matter
our model

Example

Togashi EOS

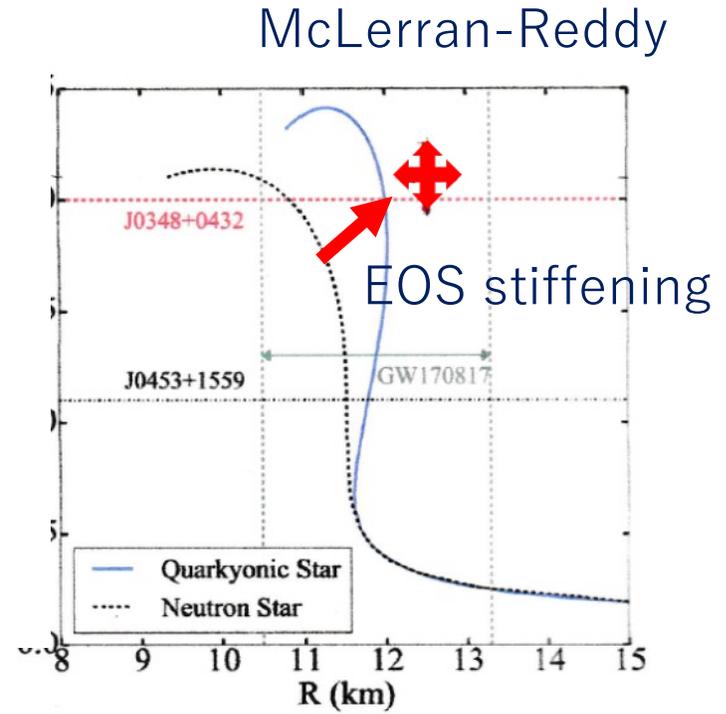
MR curve for nucleonic matter EOS (AV18+UIX) does not reach MR point

⊕ (M=2.1M_⊙ R_{2.1M_⊙}=12.5 km)
R_{1.4M_⊙} ≈ 12.4 km

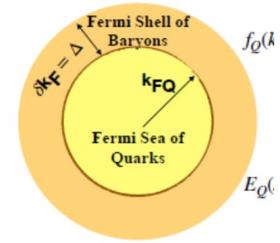


EOS with realistic nuclear force (AV18+UIX)

MR curve for **quarkyonic matter EOS** is accessible easily



Quarkyonic matter EOS



Our approach to EOS stiffening

Baryon-Quark mixed matter in BHF formalism

with two-body BB & BQ & QQ effective interactions

$$G_{BB} \quad G_{BQ} \quad G_{QQ}$$

Mixed matter

n	p	Λ
u	d	s
e		

Potential energy densities of B and Q

$$U_{BB}(k) = \sum_{B'=n,p,\Lambda} U_B^{(B')}(k) = \sum_{B'=n,p,\Lambda} \sum_{k' < k_F^{(B')}} \langle kk' | \mathcal{G}_{BB'} | kk' \rangle$$

$$U_{BQ}(k) = \sum_{Q'=u,d,s} U_B^{(Q')}(k) = \sum_{Q'=u,d,s} \sum_{k' < k_F^{(Q')}} \langle kk' | \mathcal{G}_{BQ'} | kk' \rangle$$

$$U_{QQ}(k) = \sum_{Q'=u,d,s} U_Q^{(Q')}(k) = \sum_{Q'=u,d,s} \sum_{k' < k_F^{(Q')}} \langle kk' | \mathcal{G}_{QQ'} | kk' \rangle$$

$$U_{QB}(k) = \sum_{B'=n,p,\Lambda} U_q^{(B')}(k) = \sum_{B'=n,p,\Lambda} \sum_{k' < k_F^{(B')}} \langle kk' | \mathcal{G}_{QB'} | kk' \rangle$$

Energy Densities

EOS stiffeningの要
Baryon-Quark repulsion

$$\varepsilon_B = m_B \rho_B + \tau_B + v_B = m_B \rho_B + g_s \int_0^{k_F^B} \frac{d^3k}{(2\pi)^3} \left\{ \sqrt{\hbar^2 k^2 + m_B^2} + \frac{1}{2} U_{BB}(k) + \frac{1}{2} U_{BQ}(k) \right\} \quad B = n, p, \Lambda$$

$$\varepsilon_Q = m_Q \rho_Q + g_s N_c \int_0^{k_F^Q} \frac{d^3k}{(2\pi)^3} \left\{ \sqrt{\hbar^2 k^2 + m_Q^2} + \frac{1}{2} U_{QQ}(k) + \frac{1}{2} U_{QB}(k) \right\} \quad Q = u, d, s$$

$$g_s = 2 \text{ and } N_c = 3$$

omitted for simplicity
(small contributions)

Chemical potential $\mu_i = \frac{\partial \varepsilon_i}{\partial \rho_i}, \quad (i = n, p, \Lambda, u, d, s, e)$

Pressure $P = \sum_{i=n,p,\Lambda,u,d,s,e} \mu_i \rho_i - \varepsilon$

Constituent quark mass m_Q
treated as a parameter to
adjust onset density of
BQ-mixed state
taken as 312 MeV or 330 MeV

$$\varepsilon = \varepsilon_n + \varepsilon_p + \varepsilon_\Lambda + \varepsilon_u + \varepsilon_d + \varepsilon_s + \varepsilon_e$$

BB interactions G_{BB} are chosen so as to give reasonable Baryonic matter EOS for n , p , Λ

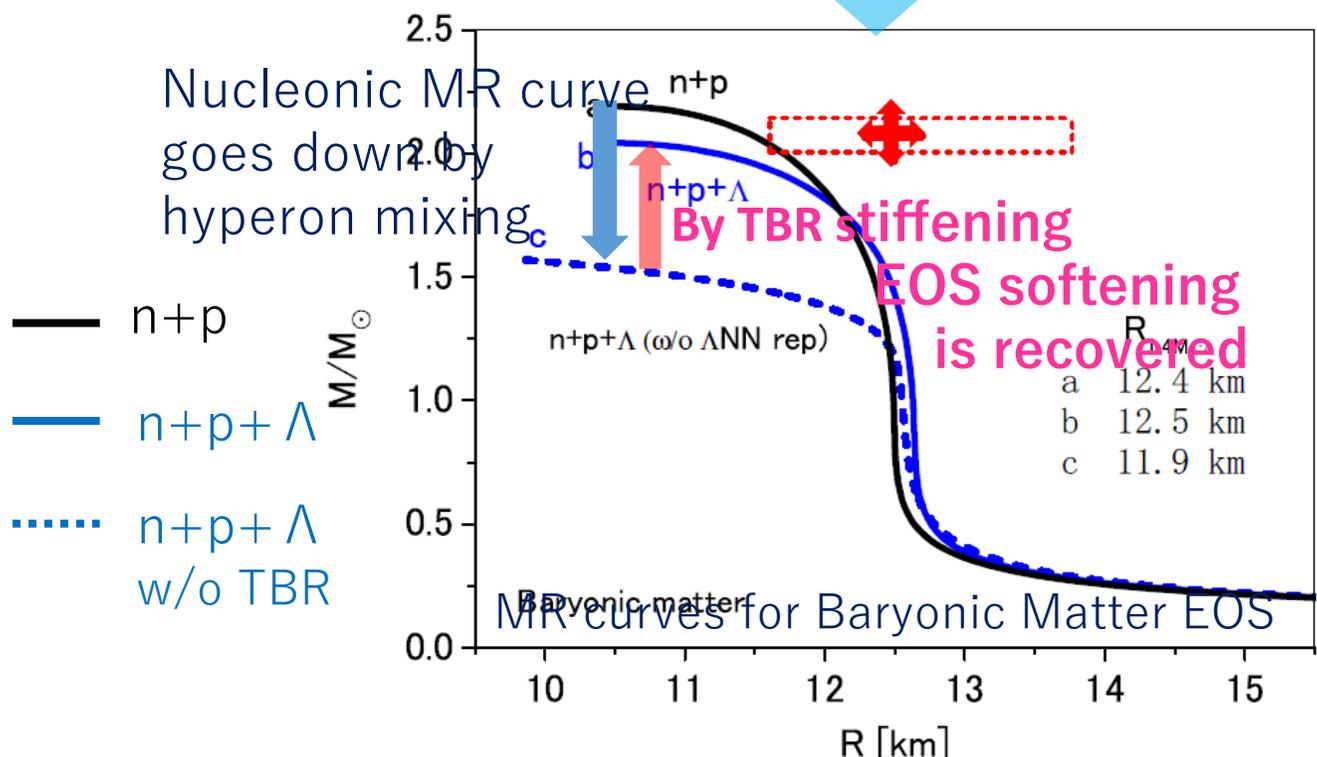
BB interaction = $V_{BB} + V_{BBB}$ \rightarrow G_{BB} derived from $V_{BB} + V_{BBB}$

V_{BB} SU₃-invariant BB interaction (Extended Soft-Core model)

V_{BBB} Three-Baryon Repulsion (Multi-Pomeron exchange Potential)

same repulsions in NNN, NNY, NYY, YYY channels

our previous works



MR curves for nucleonic and baryonic matter EOSs do not reach MR point ($M=2.1M_\odot$ $R_{2.1M_\odot}=12.5$ km)

$R_{1.4M_\odot} \approx 12.5$ km

(V_{BBB} is more repulsive than UIX in APR)

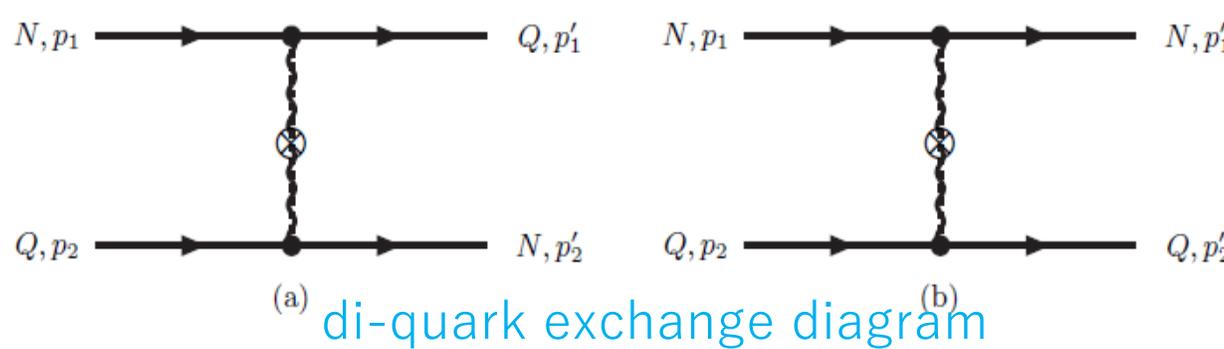
EOS stiffening by TBR is not enough to reach the MR point !

Further stiffening needed Baryon-Quark mixing !!

Baryon-Quark interaction derived by Th.A. Rijken EOS stiffeningの要

$V_{NQ} = V_{DQE}$: di-quark exchange interaction (repulsive)

($V_{\Lambda Q}$ is obtained from V_{NQ} by using SU_3 relation)



: Diquark-exchange (a) $NQ \rightarrow QN$ and (b) $NQ \rightarrow NQ$ transitions.

$$\mathcal{L}_{int}^{(2)} = \lambda_3^2 (\bar{\psi} \gamma_5 \gamma_\mu \tau Q) \cdot \bar{Q} \gamma_5 \gamma^\mu \tau \psi) / M^2$$

Parameter sets of λ_3 and m_Q

EOS	$\lambda_3/\sqrt{4\pi}$	m_Q	onset density
D1.5	0.37	312	$1.5\rho_0$
D2.0	0.46	312	$2.0\rho_0$
D2.0'	0.27	330	$2.0\rho_0$
D2.5	0.55	312	$2.5\rho_0$

λ_3 and m_Q are basic parameters to give onset densities of BQ-mixed states

$$V_{DQE}^{(qN)}(r) = -\lambda_3^2 \frac{\Lambda}{4\pi\sqrt{\pi}} \frac{\Lambda^2}{M^2} (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \mathcal{P}_x$$

$$\times \left[1 - \frac{3\Lambda^2}{4m_N m_q} \left(1 - \frac{\Lambda^2 r^2}{6} \right) \right] \exp \left[-\frac{\Lambda^2 r^2}{4} \right]$$

$\Lambda = 700 \text{ MeV}$

nucleon-triquark coupling

$$\lambda_3 \approx \sqrt{e/2} (2\pi)^{-2} [M_N/(\hbar c)]^3 \text{ giving } \lambda_3/\sqrt{4\pi} \approx 1.0$$

using QCD-sum-rules

➡ treated as an parameter to control EOS

chemical equilibrium conditions

In Baryons $\mu_n = \mu_p + \mu_e$, $\mu_n = \mu_\Lambda$

Mixing ratio of p, Λ , u, d, s, e in neutrons are determined by chemical equilibrium conditions

Solved in baryonic matter $y_p = \rho_p / \rho_n$ $y_\Lambda = \rho_\Lambda / \rho_n$
 → used in baryon-quark mixed matter

Baryon-Quark $\mu_n = \mu_u + 2\mu_d$, $\mu_p = 2\mu_u + \mu_d$, $\mu_\Lambda = \mu_u + \mu_d + \mu_s$

basic relation

It is difficult to solve simultaneous equations

$\mu_n(\rho_n, y_u, y_d, y_s) = \mu_u(y_u) + 2\mu_d(y_d)$

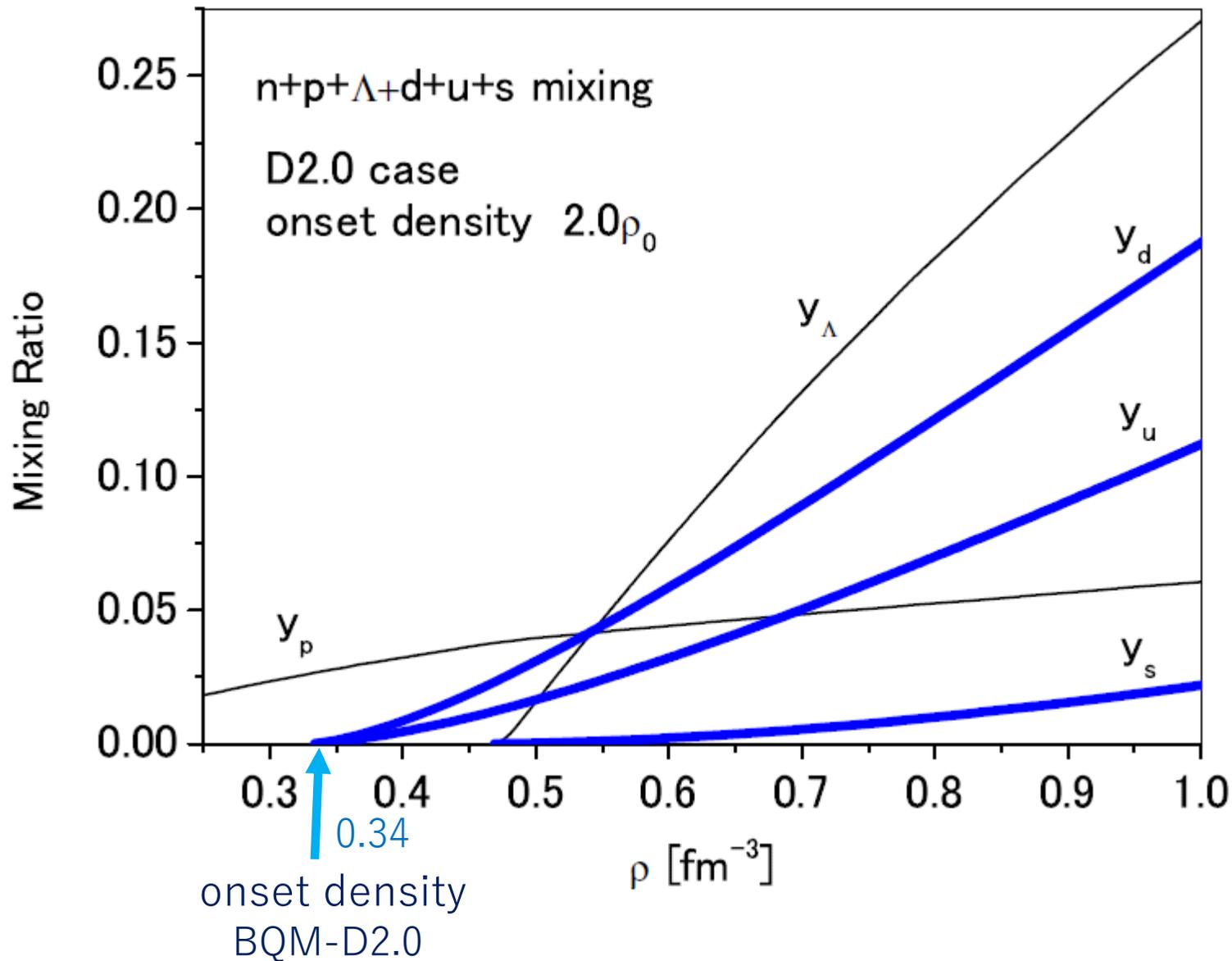
approximation

Equation for y_d can be solved

Assuming that y_u/y_d and y_s/y_d for free quarks are the same as those for quarks confined in baryons

Note ! Hyperon mixing and Quark mixing are treated in common framework

Mixing ratio of p, Λ , u, d, s /neutron



$$y_\Lambda = \rho_\Lambda / \rho_n$$

$$y_d = \rho_d / \rho_n$$

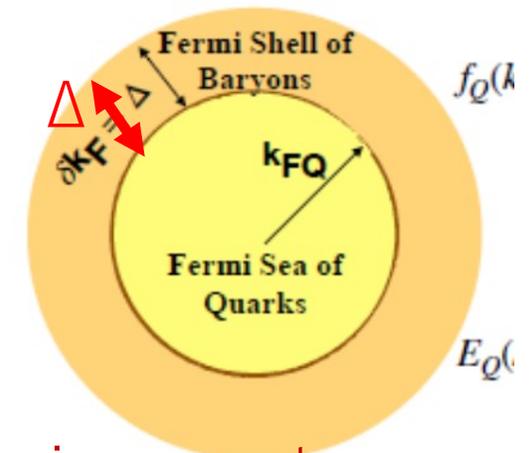
$$y_u = \rho_u / \rho_n$$

$$y_p = \rho_p / \rho_n$$

$$y_s = \rho_s / \rho_n$$

Comparison with Quarkyonic Matter

McLerran-Reddy



In both cases of **Quarkyonic matter** and **NQ-mixed matter**, nucleons and quarks are uniformly mixed spatially

in momentum space
Thickness Δ of neutron Fermi shell is a basic parameter

In **Quarkyonic matter**, neutrons are pushed up to high-momentum states by repulsion from quark Fermi sea in momentum space

In **NQ-mixed matter**, NQ relative states are in high momenta by NQ repulsions,

definition

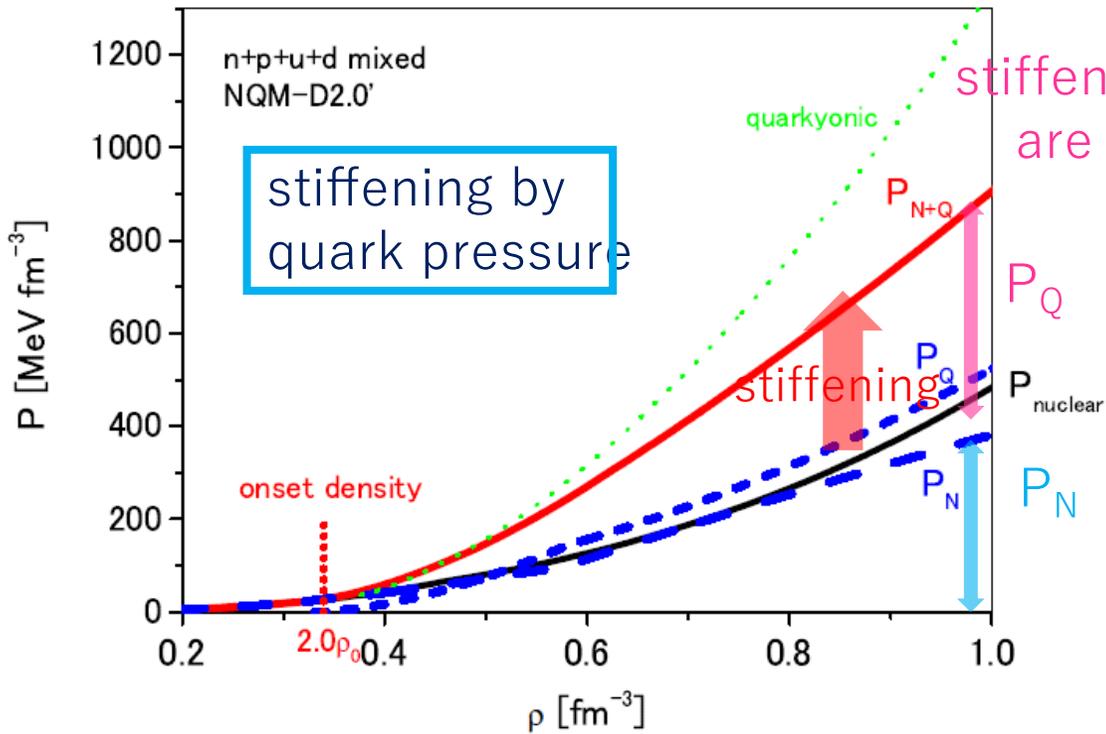
NQ-mixed matter : $n+p+u+d+e$

BQ-mixed matter : $n+p+\Lambda+u+d+s+e$

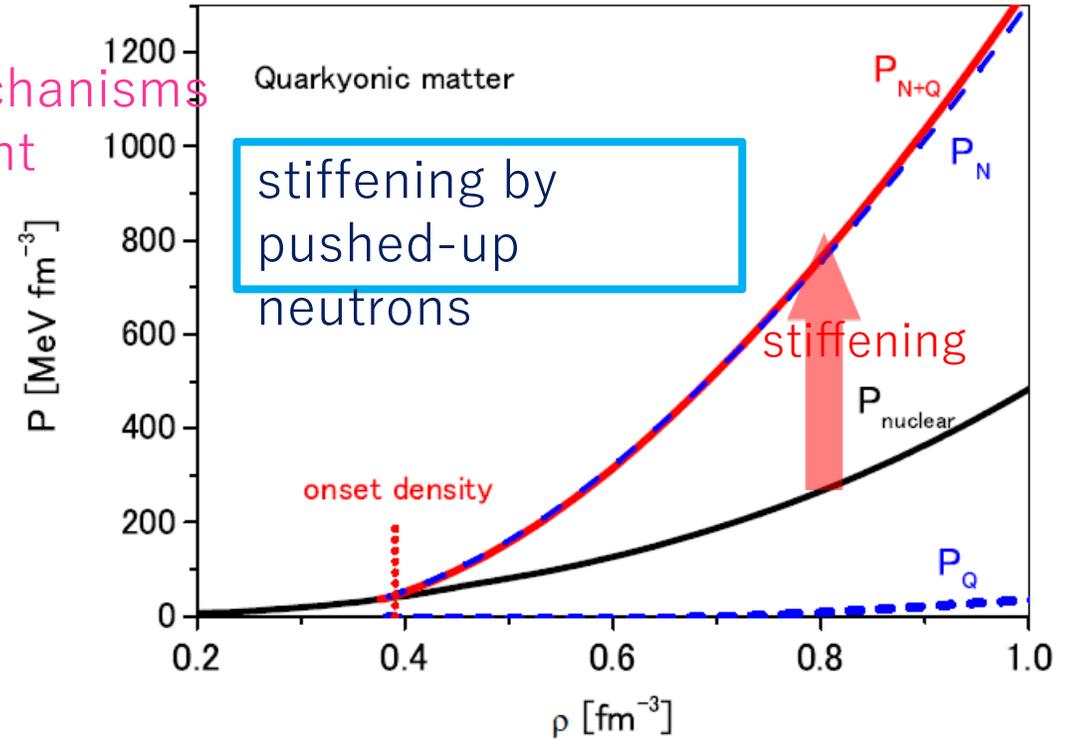
Pressure P as a function of density ρ

Partial pressures $P_N(\rho)$ and $P_Q(\rho)$: $P_{N+Q}(\rho) = P_N(\rho) + P_Q(\rho)$
 Total pressure

NQ-mixed Matter (D2.0') \rightarrow similar MR curves \leftarrow Quarkyonic Matter (onset $2.3 \rho_0$)



$P_N(\rho)$ is similar to $P_{\text{nuclear}}(\rho)$
 $P_{N+Q}(\rho)$ is larger than $P_{\text{nuclear}}(\rho)$ by $P_Q(\rho)$
 stiffening is given by quark pressures

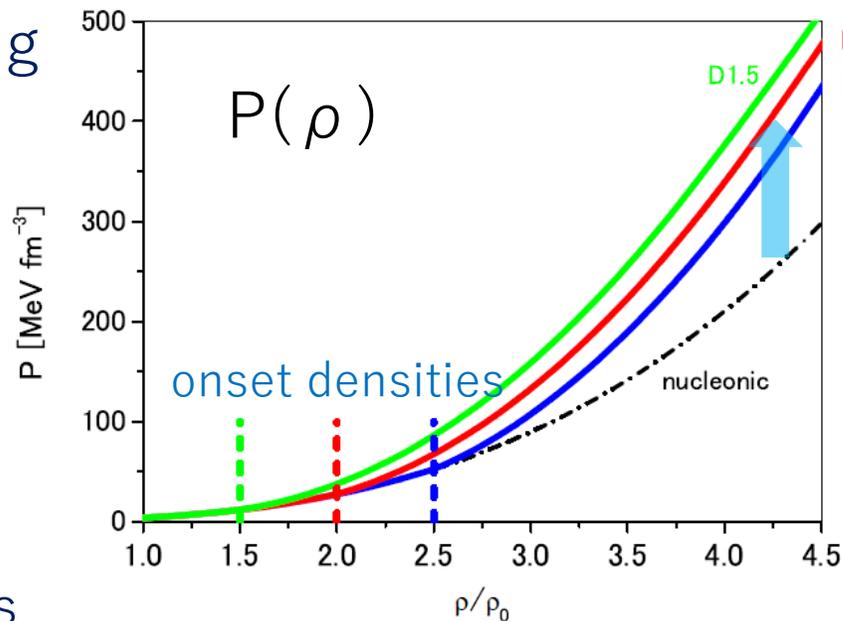


Thickness Δ is taken to give onset density $2.3\rho_0$ giving MR curve similar to the one for NQM-D2.0'.
 Quark pressures are negligible

EOS stiffening by NQ-mixing n+p+u+d+e model

- onset density
- D2.5 — $2.5 \rho_0$
- D2.0 — $2.0 \rho_0$
- D1.5 — $1.5 \rho_0$

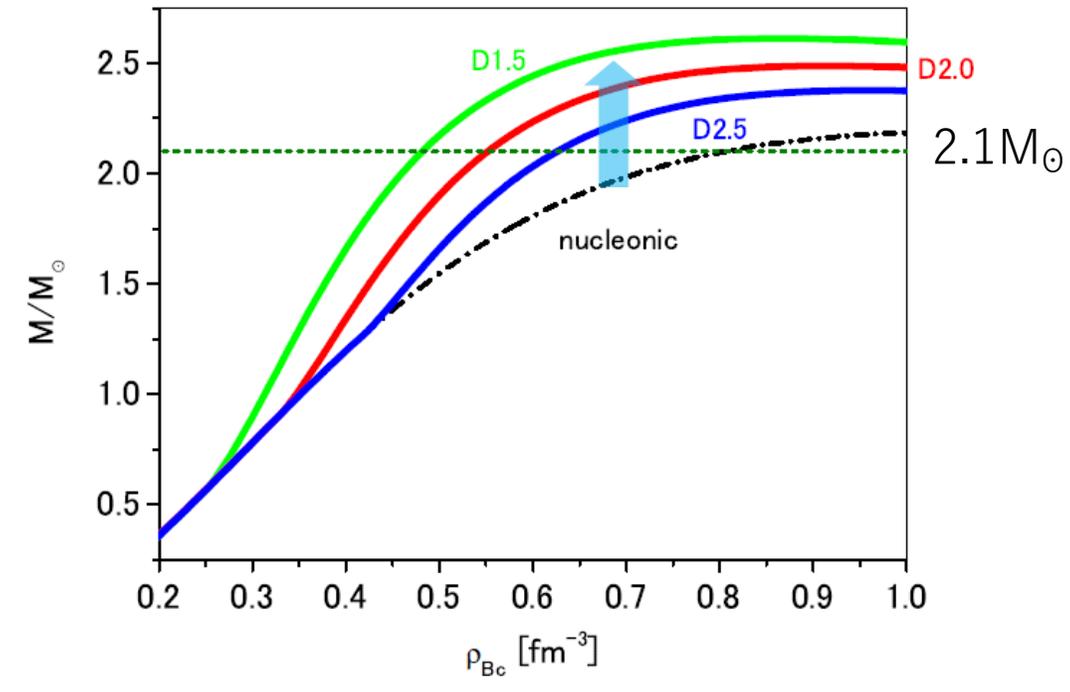
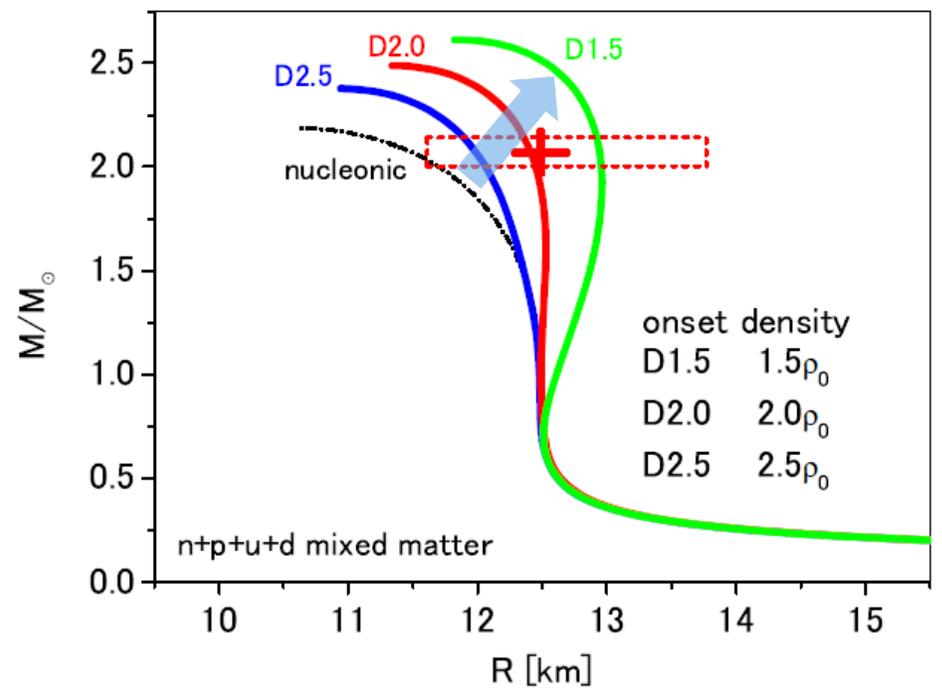
$m_Q = 312 \text{ MeV}$



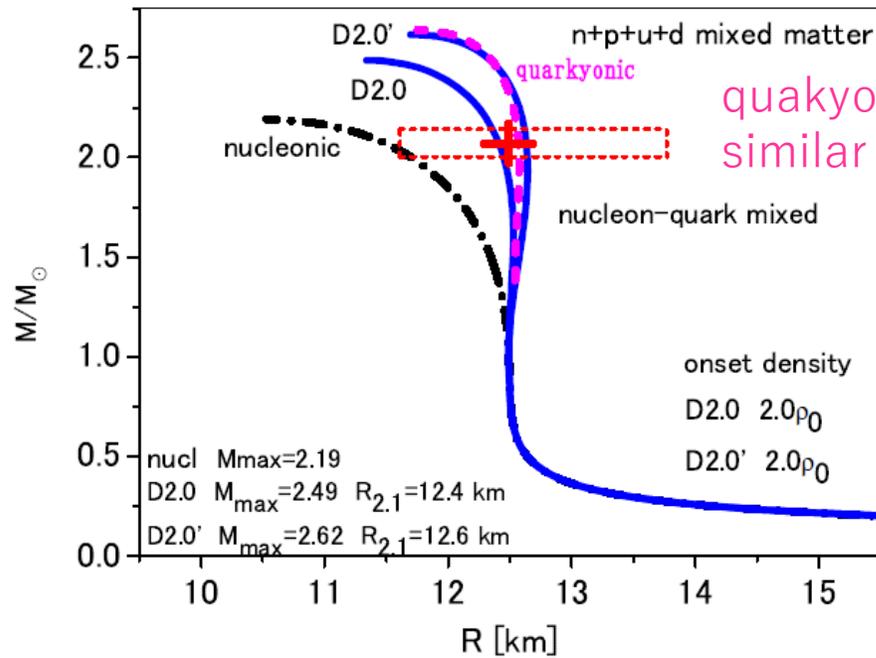
EOS stiffening
by quark pressure

MR curves

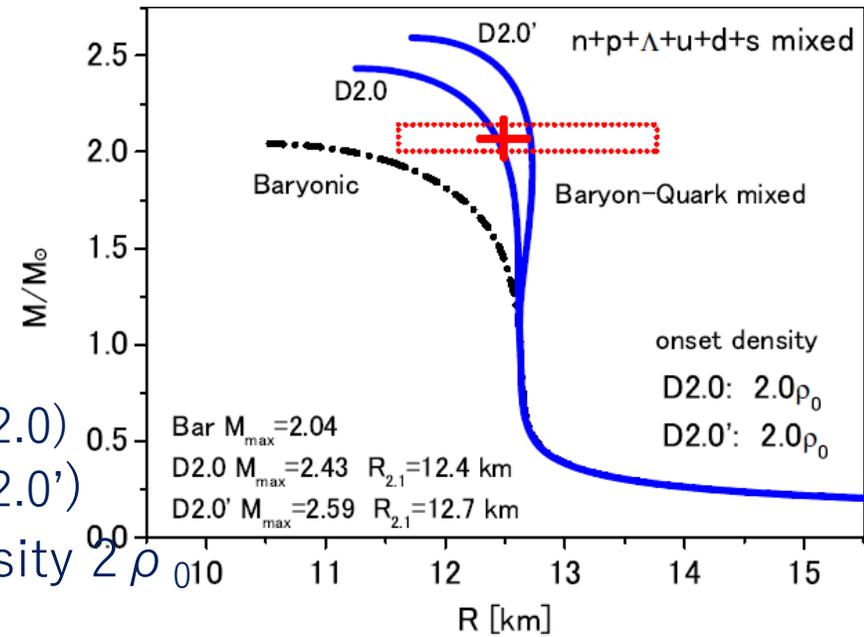
$M\rho$ curves



NQ-mixed matter



BQ-mixed matter



quarkyonic curve similar to D2.0' curve

$m_Q=312$ (D2.0)
 $m_Q=330$ (D2.0')

Onset Density $2\rho_0$

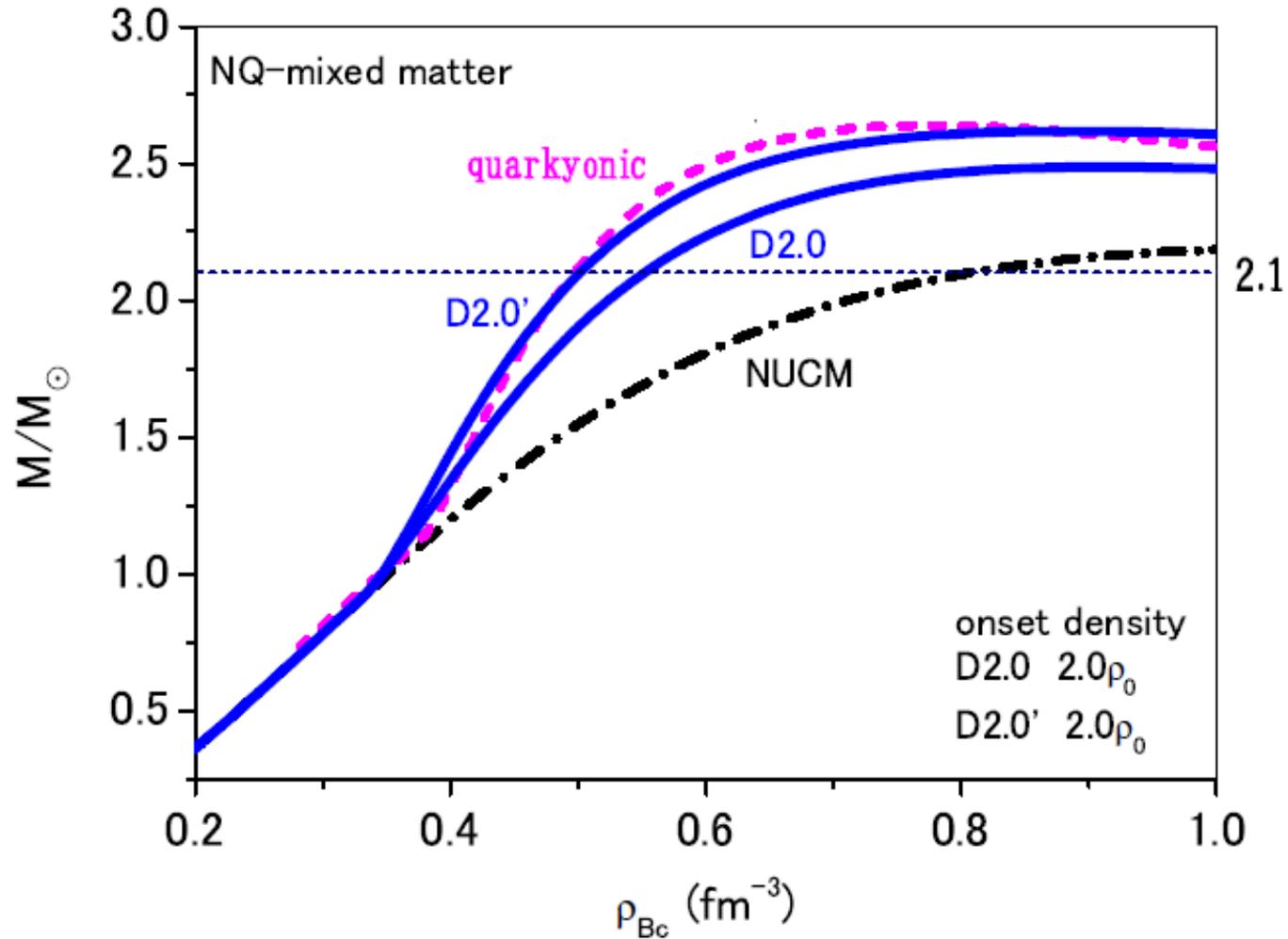
MR curves reach MR point
 $(M = 2.1M_\odot, R_{2.1M_\odot} = 12.5 \text{ km})$
 by EOS stiffening

NQM and BQM lead to similar MR curves to each other
 Basic reason is that MR curves for Nucleonic and Baryonic matter EOSs are similar to each other owing to TBR stiffening in Baryonic matter

	M_{\max}/M_\odot	$R_{2.1M_\odot}$ (km)
NQM-D2.0	2.49	12.4
NQM-D2.0'	2.62	12.6
BQM-D2.0	2.43	12.4
BQM-D2.0'	2.59	12.7
NUCM	2.19	11.4
BRYM	2.04	
BRYM0	1.57	
Observations	> 2.1	~ 12.5

Star mass as a function of central density for NQM-D2.0 and NQM-D2.0'

Onset density $2\rho_0$ $m_Q=312(\text{D2.0}), 330(\text{D2.0}')$



NQM-D2.0'

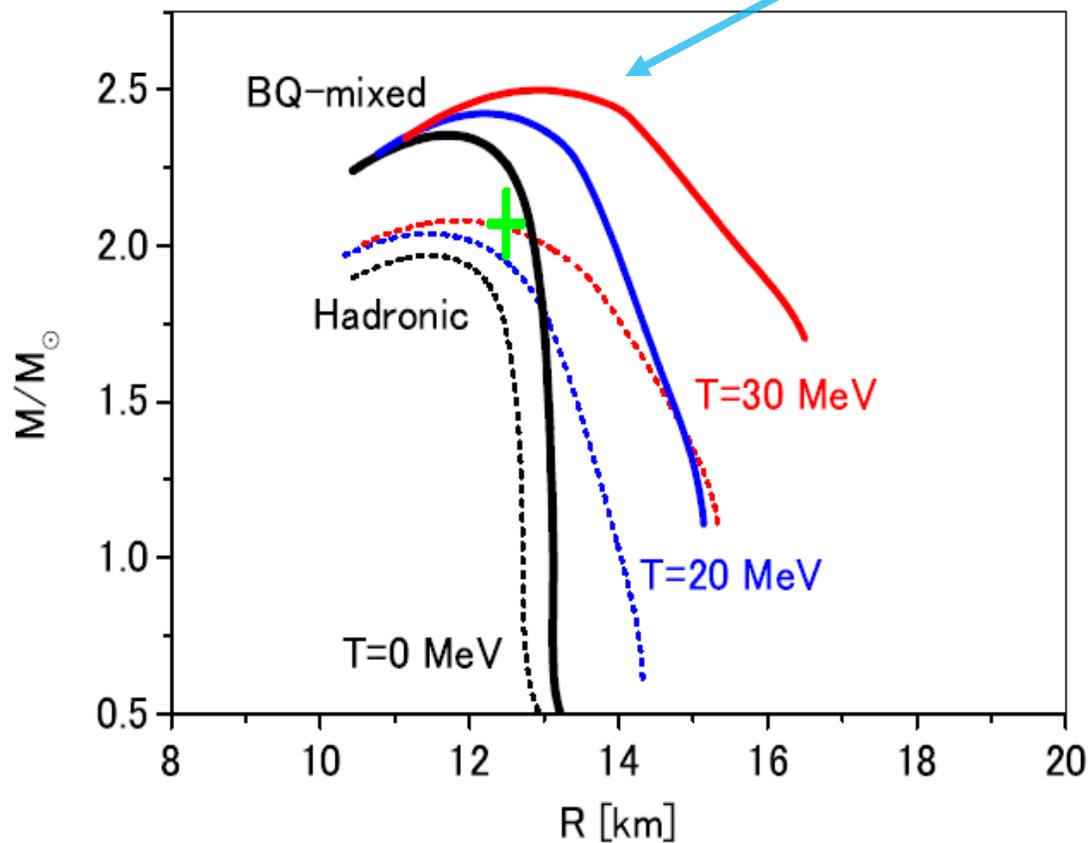
EOS stiffening in NQ-mixed matter adjusted so as to give $M-\rho$ curve similar to quarkyonic matter EOS ($2.3\rho_0$)

hot neutron stars

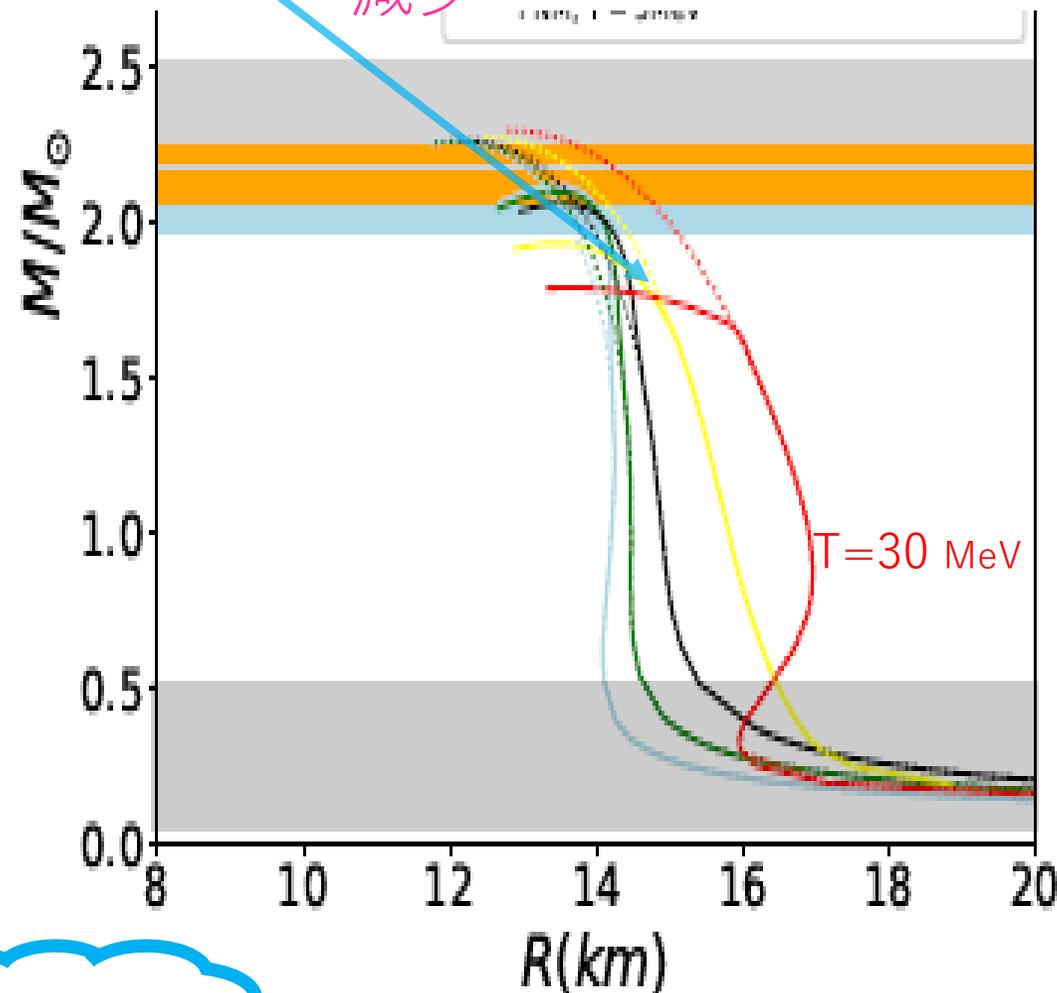
$M_{\max}(T)$

増加

減少



Thermal Baryon-Quark mixed matter



Thermal Quarkyonic matter
arXiv: 12669 (2025)

顕著な差!?

まとめ

2体核力のみから導かれるNSの最大質量は $1M_{\odot}$ 程度であり、 $2M_{\odot}$ に達する最大質量に対してはTNRの寄与が本質的である

ハイペロン混合によるEOSソフト化は最大質量に対するTNRの寄与を打ち消してしまう(Hyperon Puzzle)。これを逃れるシンプルな方法がUniversal TBRの導入である。

NICERによる高質量中性子星の半径観測から得られた条件

$$(M = 2.1M_{\odot}, R_{2.1M_{\odot}} = 12.5 \text{ km}).$$

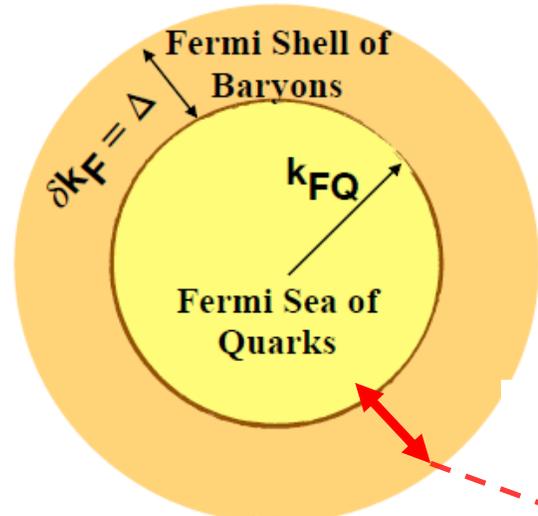
を満たすことは

Hadronic matter EOSでは困難であり、クォーク相の存在が更なるEOS stiffeningをもたらすと考えられる

ひとつの具体的モデルとしてBQ-mixed matter EOSが提案される。Baryon-Quark repulsionがEOS stiffeningをもたらす効果により条件を満たすMR曲線が得られる

quarkyonic-matter EoS

MeLerran-Reddy model



“フェルミ殻”

$$n_B = n_n + \frac{N_c}{3}(n_u + n_d)$$

$$= \frac{g_s}{6\pi^2} \left[k_{Fn}^3 - k_{0n}^3 + \frac{N_c}{3}(k_{Fu}^3 + k_{Fd}^3) \right]$$

$$\epsilon_n(k_{0n}) = N_c \epsilon_q(k_{Fq})$$

$$k_{Fd} = \frac{1}{N_c} k_{0n}$$

$$k_{Fu} = 2^{-1/3} k_{Fd}$$

$$k_{0n} = k_{Fn} - \Delta_{qyc}$$

$$\Delta_{qyc} = \frac{\Lambda^3}{\hbar c^3 k_{Fn}^2} + \kappa \frac{\Lambda}{N_c^2 \hbar c}$$

$\Delta_{qyc} \sim \Lambda_{QCD}$

Λ is most important parameter

$$U_n(k) = \sum_{k_{0n} < k' < k_{Fn}} \langle kk' | \mathcal{G}_{nn,nn} | kk' \rangle$$

$$\epsilon_n = g_s \int_{k_{0n}}^{k_{Fn}} \frac{d^3k}{(2\pi)^3} \left\{ \sqrt{\hbar^2 k^2 + M_n^2} + \frac{1}{2} U_n(k) \right\}$$

フェルミ殻で積分

$$U_f(k) = \sum_{f, f' = u, d} U_f^{(f')} (k) = \sum_{f'} \sum_{k' < k_{Ff}^{f'}} \langle kk' | \mathcal{G}_{ff',ff'} | kk' \rangle$$

$$\epsilon_q = g_s N_c \sum_{f=u,d} \int_0^{k_{Ff}} \frac{d^3k}{(2\pi)^3}$$

フェルミ球で積分

$$U_{fn}(k) = \sum_{k_{0n} < k' < k_{Fn}} \langle kk' | \mathcal{G}_{fn,fn} | kk' \rangle$$

$$\left\{ \sqrt{\hbar^2 k^2 + M_f^2} + \frac{1}{2} U_f(k) + U_{fn}(k) \right\}$$