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中性子星物質におけるハイペロン混合

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1. Neutron-star matter and YN interactions
2. Twin Λ hypernuclei in emulsion and ΞN interaction

中性子星核物質を認識したい！

Σ^- & Ξ^- mixingに関するRHF/DBHF計算との定性的違いは理解できるか？

Our strategy to neutron stars

Neutron-star EOS derived from
Baryon-Baryon interaction model
in relation to **Earth-based experiments**

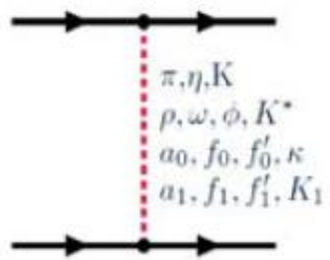
without ad hoc parameter for stiffness of EOS

on the basis of G-matrix theory

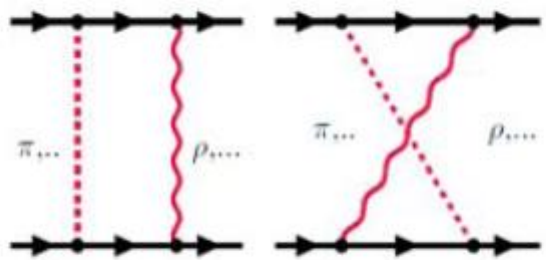
adopted interaction model

Extended Soft-Core Model (ESC)

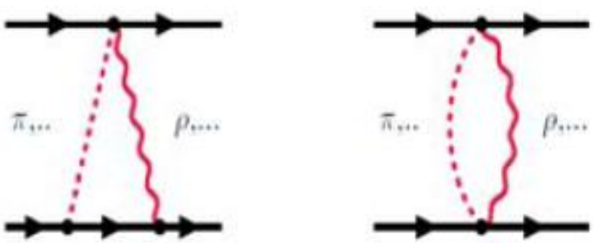
- Two-meson exchange processes are treated explicitly
- Meson-Baryon coupling constants are taken consistently with Quark-Pair Creation model



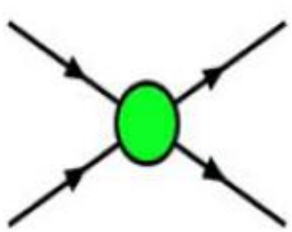
One-Boson-Exchange graphs



Two-Meson-Exchange graphs

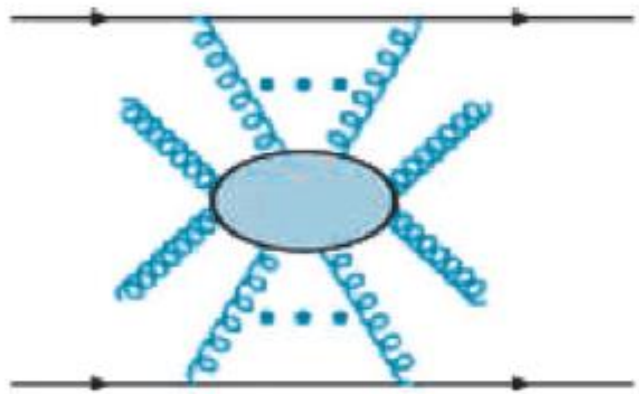


Meson-Pair-Exchange graphs



Pomeron-exchange

repulsive cores

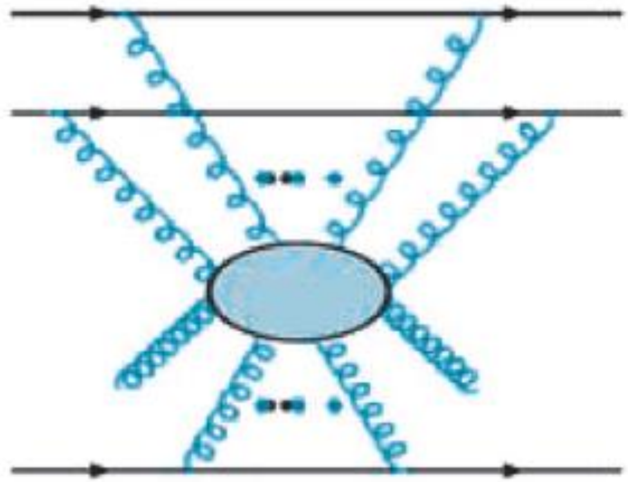


Pomeron-exchange.

g_P

2-body repulsion

Naturally extended



Triple Pomeron-exchange.

g_{3P}

SU_3 scalar universal repulsion

Pomeron is a model for multi-gluon exchange

How to determine coupling constants g_{3P} and g_{4P} ?

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

Y. Yamamoto, T. Furumoto, N. Yasutake and Th. A. Rijken: Phys. Rev. C 88 (2013) 022801(R).

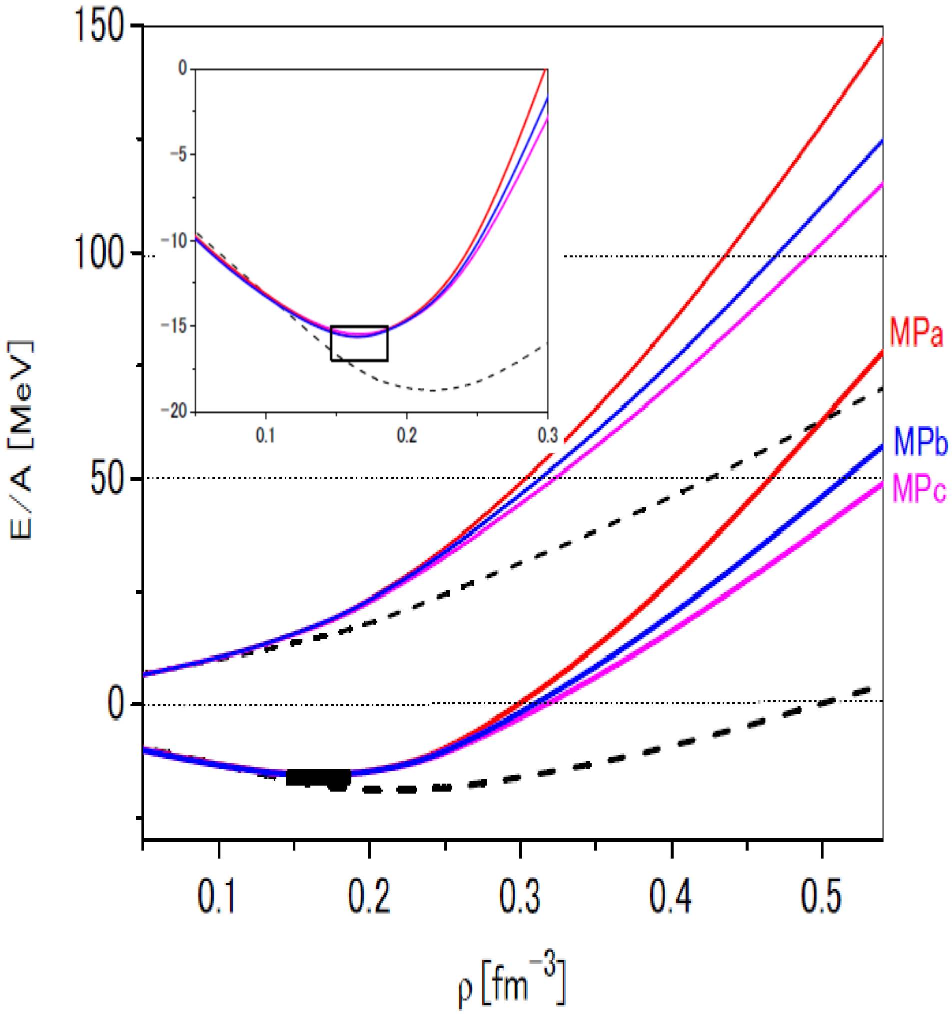
G-matrix interaction (➔ folding potential)

derived from ESC08c+MPP+TNA

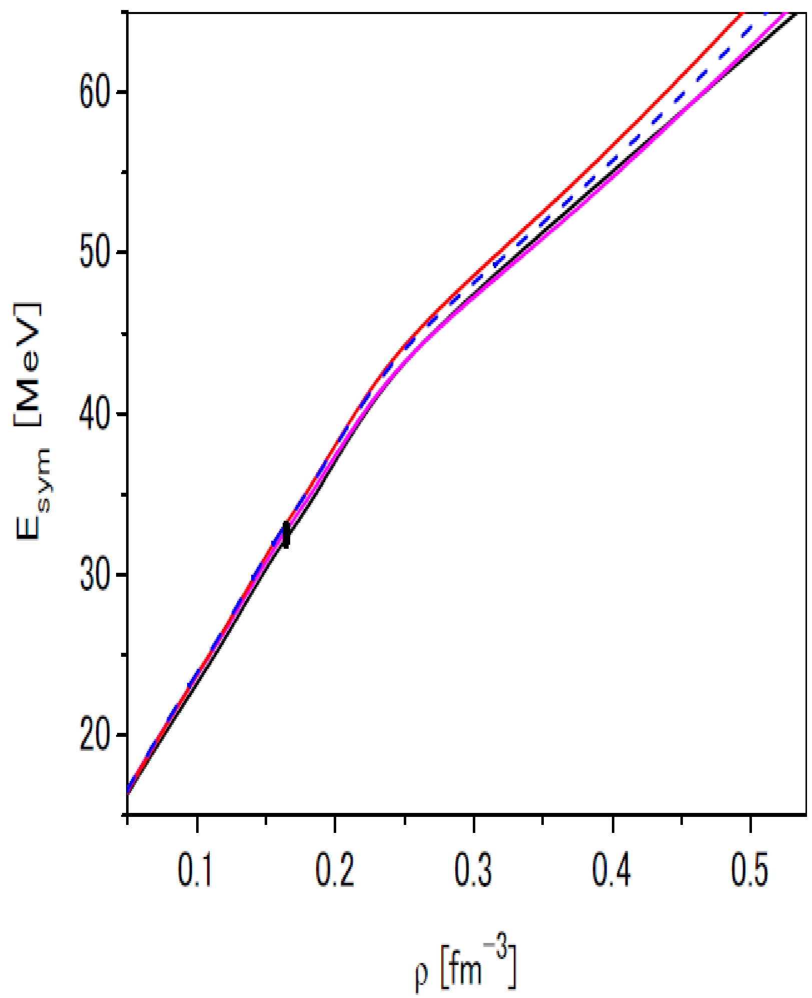
TNA: Three-Nucleon attraction

Both MPP and TNA are needed
to reproduce nuclear saturation property
but, essential is MPP for Nucleus-Nucleus scattering data

E/A curve

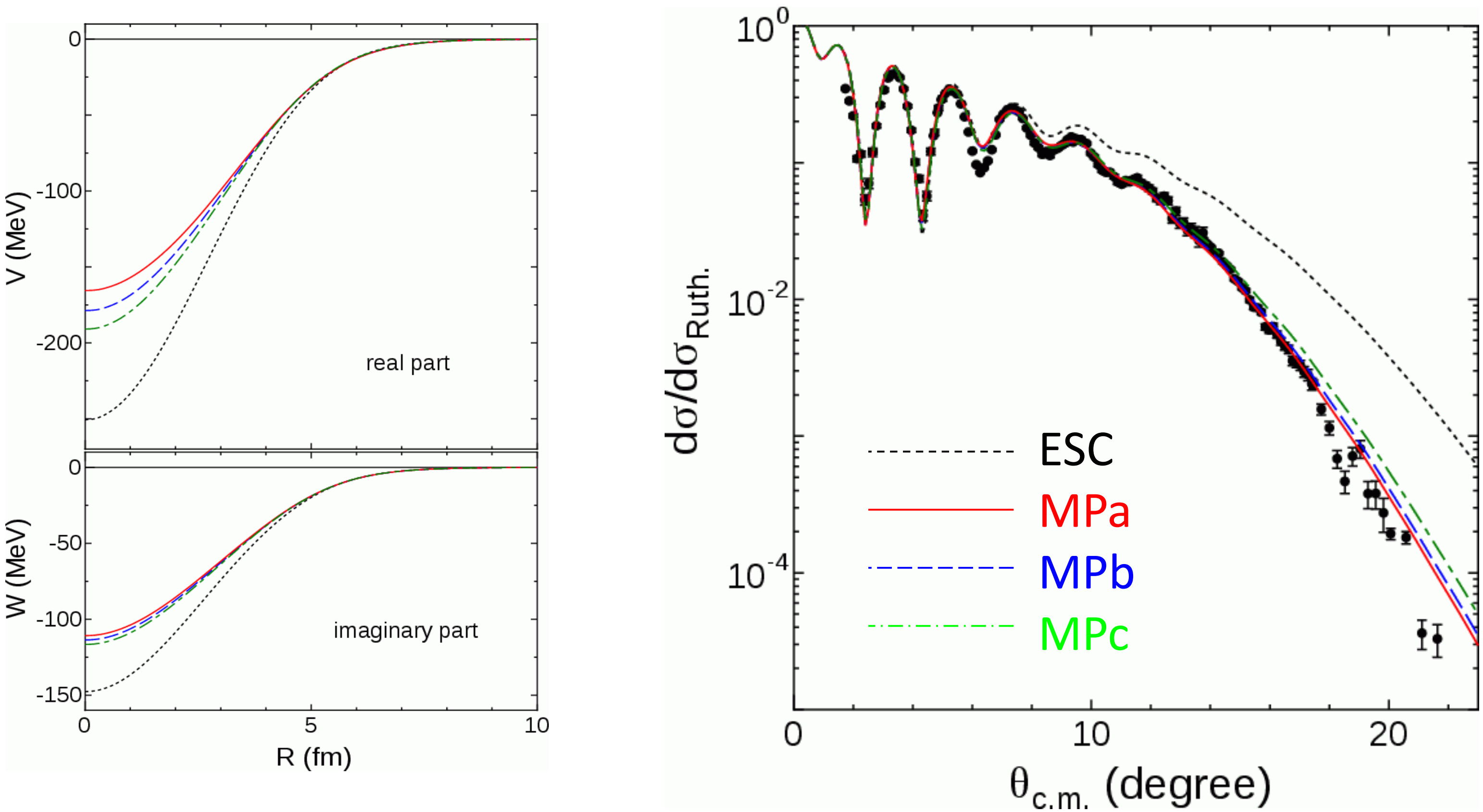


Symmetry energy



Y. Yamamoto, T. Furumoto, N. Yasutake and Th. A. Rijken, submitted to Phys. Rev. C

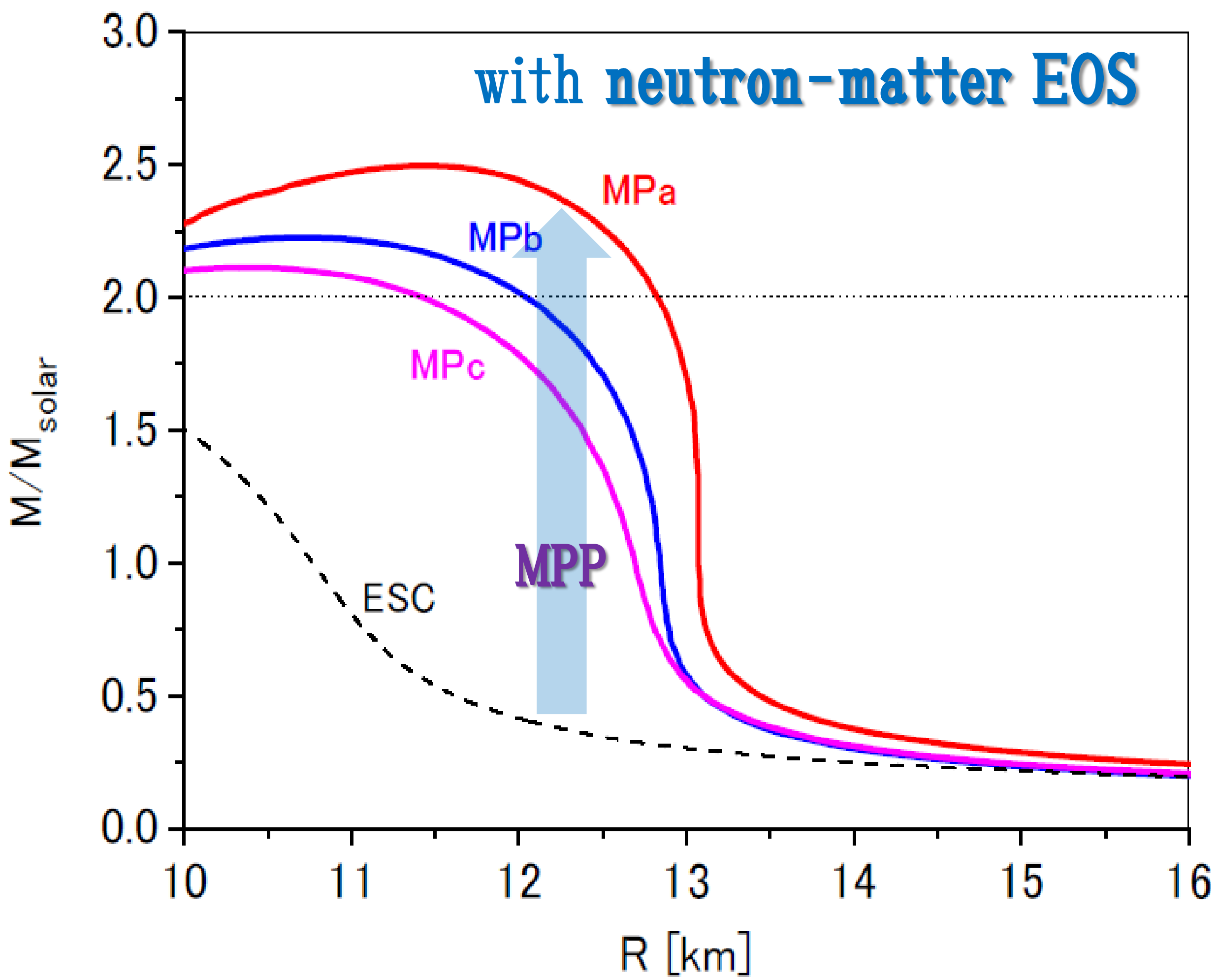
$^{16}O + ^{16}O$ elastic scattering cross section at E/A = 70 MeV



Frozen-Density Approximation is crucial !

MPa: 3-body + 4-body repulsion
MPb/MPc: 3-body repulsion

by solving TOV eq.



No ad hoc parameter to adjust stiffness of EOS !!!

MPa : K=310 MeV
MPb : K=280 MeV
MPc : K=260 MeV

← ^{16}O-^{16}O scattering data

Massive ($2M_\odot$) neutron stars

Softening of EOS by hyperon mixing

Hyperon puzzle !

An idea is Universal Three-Baryon Repulsion (TBR) proposed by Takatsuka

Modeling of TBR in ESC = Multi-Pomeron exchange Potential

Y-nucleus folding potential derived from YN G-matrix interaction $G(r; k_F)$

$$
\begin{aligned}
U_Y(\mathbf{r},\mathbf{r}') &= U_{dr} + U_{ex} \\
U_{dr} &= \delta(\mathbf{r}-\mathbf{r}')\int d\mathbf{r}''\rho(\mathbf{r}'')V_{dr}(|\mathbf{r}-\mathbf{r}''|;\langle k_F\rangle) \\
U_{ex} &= \rho(\mathbf{r},\mathbf{r}')V_{ex}(|\mathbf{r}-\mathbf{r}'|;\langle k_F\rangle) \\
V_{dr} &= \frac{1}{2(2t_Y+1)(2s_Y+1)}\sum_{TS}(2T+1)(2S+1)[G_{TS}^{(+)}+G_{TS}^{(-)}] \\
V_{ex} &= \frac{1}{2(2t_Y+1)(2s_Y+1)}\sum_{TS}(2T+1)(2S+1)[G_{TS}^{(+)}-G_{TS}^{(-)}]
\end{aligned}
$$

G-matrix interactions

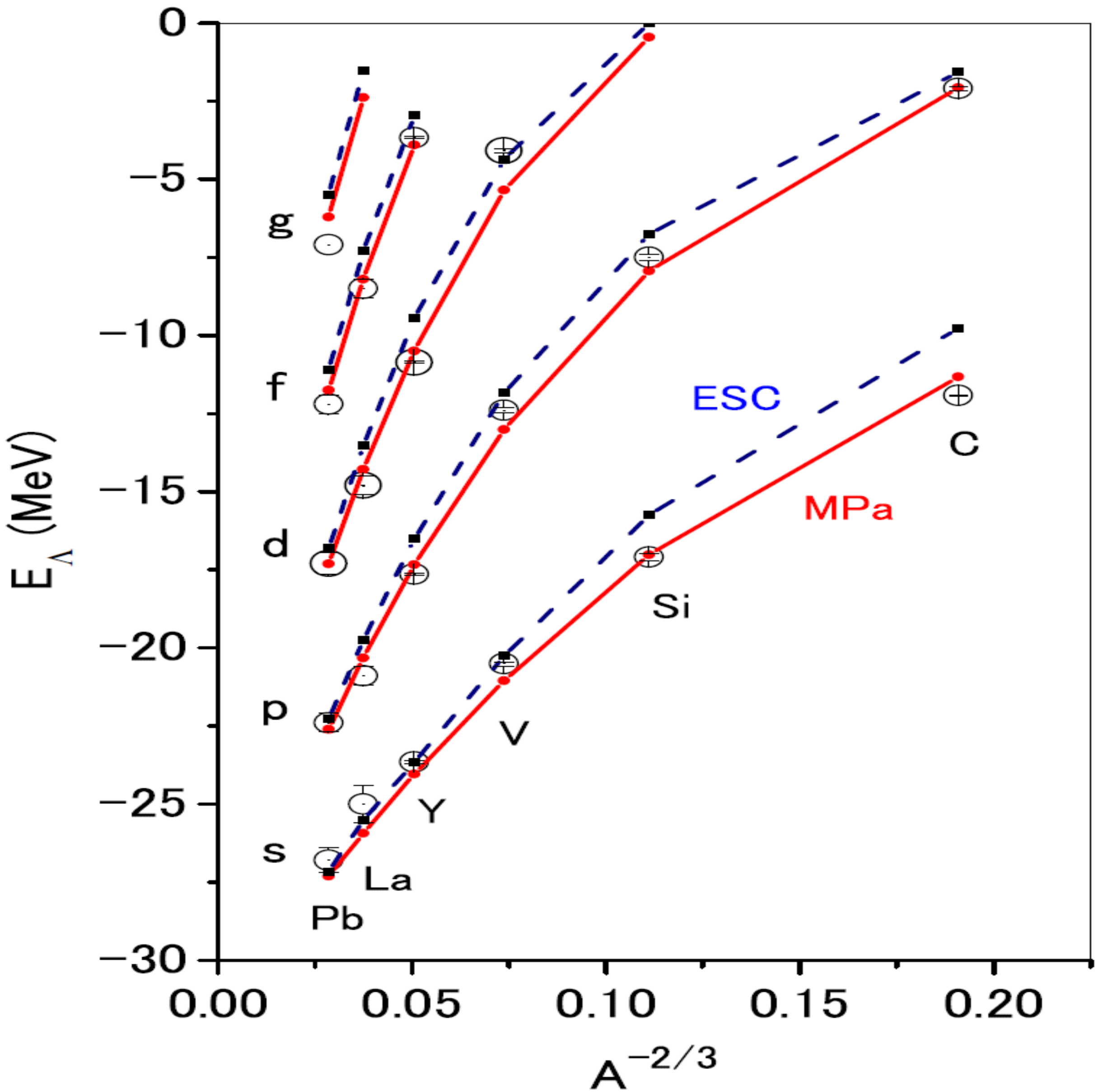
Averaged-k_F Approximation

$$\langle\rho\rangle = \langle\phi_Y(r)|\rho(r)|\phi_Y(r)\rangle$$

$$\langle k_F\rangle = (1.5\pi^2\langle\rho\rangle)^{1/3}$$

calculated self-consistently

Mixed density $\rho(\mathbf{r}_1,\mathbf{r}_2) = \sum_j \varphi_j^*(\mathbf{r}_1)\varphi_j(\mathbf{r}_2)$ obtained from SkHF w.f.



MPa is better than ESC !!!

Quark-Pauli effect in ESC08 models

ESC core = pomeron + ω

Repulsive cores are similar to each other in all channels

Assuming
"equal parts" of ESC and QM are similar to each other

Almost Pauli-forbidden states in [51] are taken into account by changing the pomeron strengths for the corresponding channels phenomenologically

$g_P \Longrightarrow \text{factor} * g_P$

by Oka-Shimizu-Yazaki

Table III. $SU(6)_{fs}$-contents of the various potentials on the isospin, spin basis.

(S,I)	$V = aV_{[51]} + bV_{[33]}$
$(0,1)$	$V_{NN} = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$(1,0)$	$V_{NN} = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$(0,1/2)$	$V_{\Lambda\Lambda} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$(1,1/2)$	$V_{\Lambda\Lambda} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$(0,1/2)$	$V_{\Sigma\Sigma} = \frac{17}{18}V_{[51]} + \frac{1}{18}V_{[33]}$
$(1,1/2)$	$V_{\Sigma\Sigma} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$(0,3/2)$	$V_{\Sigma\Sigma} = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$(1,3/2)$	$V_{\Sigma\Sigma} = \frac{8}{9}V_{[51]} + \frac{1}{9}V_{[33]}$

(S,I)	$V = aV_{[51]} + bV_{[33]}$
$(0,0)$	$V_{\Lambda\Lambda,\Lambda\Lambda} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$(0,0)$	$V_{\Xi N,\Xi N} = \frac{1}{3}V_{[51]} + \frac{2}{3}V_{[33]}$
$(0,0)$	$V_{\Sigma\Sigma,\Sigma\Sigma} = \frac{11}{18}V_{[51]} + \frac{7}{18}V_{[33]}$
$(0,1)$	$V_{\Xi N,\Xi N} = \frac{7}{9}V_{[51]} + \frac{2}{9}V_{[33]}$
$(0,0)$	$V_{\Sigma\Lambda,\Sigma\Lambda} = \frac{2}{3}V_{[51]} + \frac{1}{3}V_{[33]}$
$(0,2)$	$V_{\Sigma\Sigma,\Sigma\Sigma} = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$(1,0)$	$V_{\Xi N,\Xi N} = \frac{5}{9}V_{[51]} + \frac{4}{9}V_{[33]}$
$(1,1)$	$V_{\Xi N,\Xi N} = \frac{17}{27}V_{[51]} + \frac{10}{27}V_{[33]}$
$(1,1)$	$V_{\Sigma\Lambda,\Sigma\Lambda} = \frac{2}{3}V_{[51]} + \frac{1}{3}V_{[33]}$
$(1,1)$	$V_{\Sigma\Sigma,\Sigma\Sigma} = \frac{16}{27}V_{[51]} + \frac{11}{27}V_{[33]}$

Pauli-forbidden state in $V_{[51]}$ → strengthen pomeron coupling

$\Sigma^+ p(^3S_1, T = 3/2), \Sigma N(^1S_0, T = 1/2)$, and $\Xi N(^1S_0, T = 1)$

→ ESC08a/b 全部考慮： ESC08c

Table 1: Values of U_Σ at normal density and partial wave contributions with Continuous Choice.

model	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	D	U_Σ
ESC08c	1/2	11.1	−22.0	2.4	2.1	−6.1	−1.0	−0.7	
	3/2	−12.8	30.7	−4.8	−1.8	6.0	−1.4	−0.2	+1.4
ESC08b	1/2	10.3	−25.5	1.4	2.5	−5.9	0.3	−0.8	
	3/2	−10.4	52.4	−3.0	−2.7	5.9	−4.4	−0.1	+19.8

Pauli-forbidden state in QCM ➔ strong repulsion in **T=3/2 $^3S_1$** state

older versions

ESC04a	1/2	11.6	−26.9	2.4	2.7	−6.4	−2.0	−0.8	
	3/2	−11.3	2.6	−6.8	−2.3	5.9	−5.1	−0.2	−36.5
NSC97f	1/2	14.9	−8.3	2.1	2.5	−4.6	0.5	−0.5	
	3/2	−12.4	−4.1	−4.1	−2.1	6.0	−2.8	−0.1	−12.9

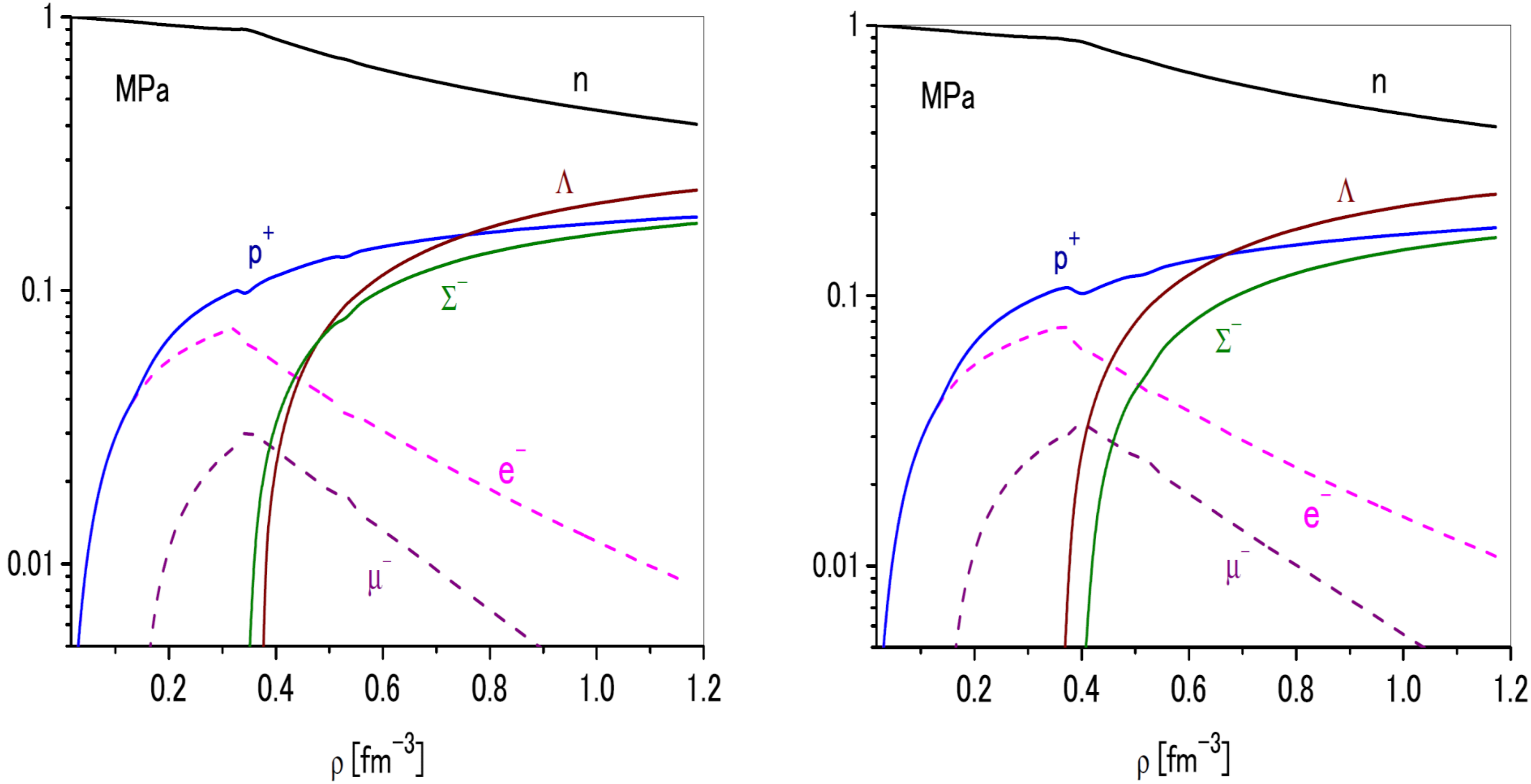
Hyperon-mixed Neutron-Star matter with universal TBR (MPP)

EoS of n+p+Λ+Σ+e+μ system

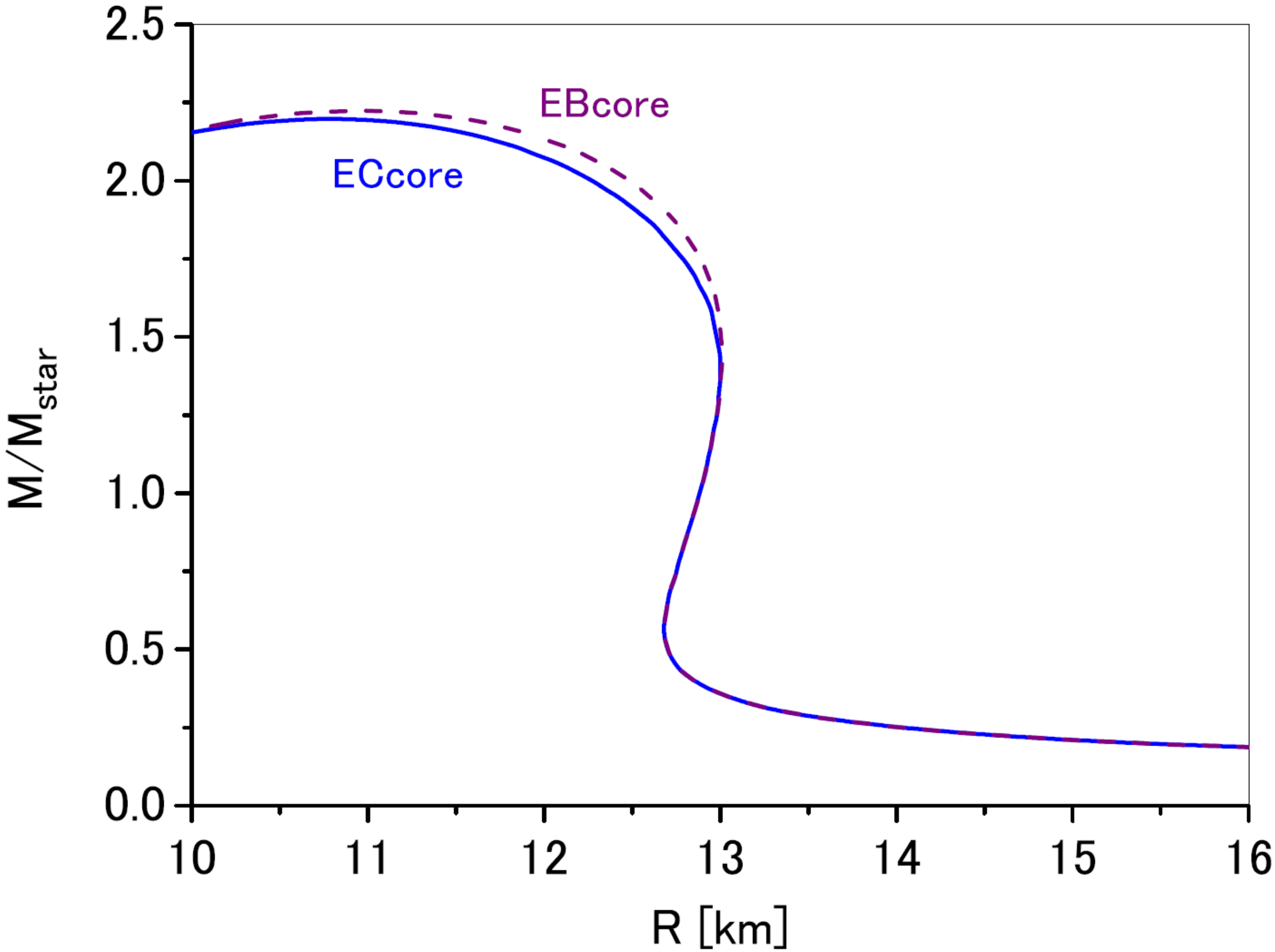
ESC08c(YN) + MPP(YNN) +TBA(YNN)

ESC08b(ΣN)

β-stable n+p+Λ+Σ⁻ matter



stronger Σ^-n repulsion ➡ 極端なことは起こらない



EBcore
ECcore
2.5
2.0
1.5
1.0
0.5
0.0
M/M_{star}
10
11
12
13
14
15
16
R [km]

Events of twin-Λ hypernuclei in emulsion and ΞN interactions

Importance of precise data of B_Λ obtained from (e,e'K) reactions

E176 events

Event I (most probable mode) [1]

$$(A) \quad \Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{4}_{\Lambda}\mathrm{H} \quad (B_{\Xi^-} = 0.82 \pm 0.17\ \mathrm{MeV}) ,$$

$$(B) \quad \Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{4}_{\Lambda}\mathrm{H}^* \quad (B_{\Xi^-} = -0.23 \pm 0.17\ \mathrm{MeV}) ,$$

Event II (three possibilities) [2]

$$(A) \quad \Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{4}_{\Lambda}\mathrm{H} \quad (B_{\Xi^-} = 3.89 \pm 0.14\ \mathrm{MeV}) ,$$

$$(B) \quad \Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{9}_{\Lambda}\mathrm{Be}^* + {}^{4}_{\Lambda}\mathrm{H} \quad (B_{\Xi^-} = 0.82 \pm 0.14\ \mathrm{MeV}) ,$$

$$(C) \quad \Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{4}_{\Lambda}\mathrm{H}^* \quad (B_{\Xi^-} = 2.84 \pm 0.15\ \mathrm{MeV}) ,$$

$$(D) \quad \Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{9}_{\Lambda}\mathrm{Be}^* + {}^{4}_{\Lambda}\mathrm{H}^* \quad (B_{\Xi^-} = -0.19 \pm 0.15\ \mathrm{MeV}) ,$$

Assuming Ξ^- absorption from 2P orbits leads to consistent interpretations

KISO event

$$\Xi^- + {}^{14}\text{N} \rightarrow {}^{10}_{\Lambda}\text{Be} + {}^{5}_{\Lambda}\text{He}$$

(A) ${}^{10}_{\Lambda}\text{Be}$ in ground state $(B_{\Xi^-} = 3.82 \pm 0.18\text{MeV})$,

(B) ${}^{10}_{\Lambda}\text{Be}$ in excitation of 2.68MeV $(B_{\Xi^-} = 1.14 \pm 0.18\text{MeV})$

JLAB E05-115

Predicted by Ehime+Yamamoto

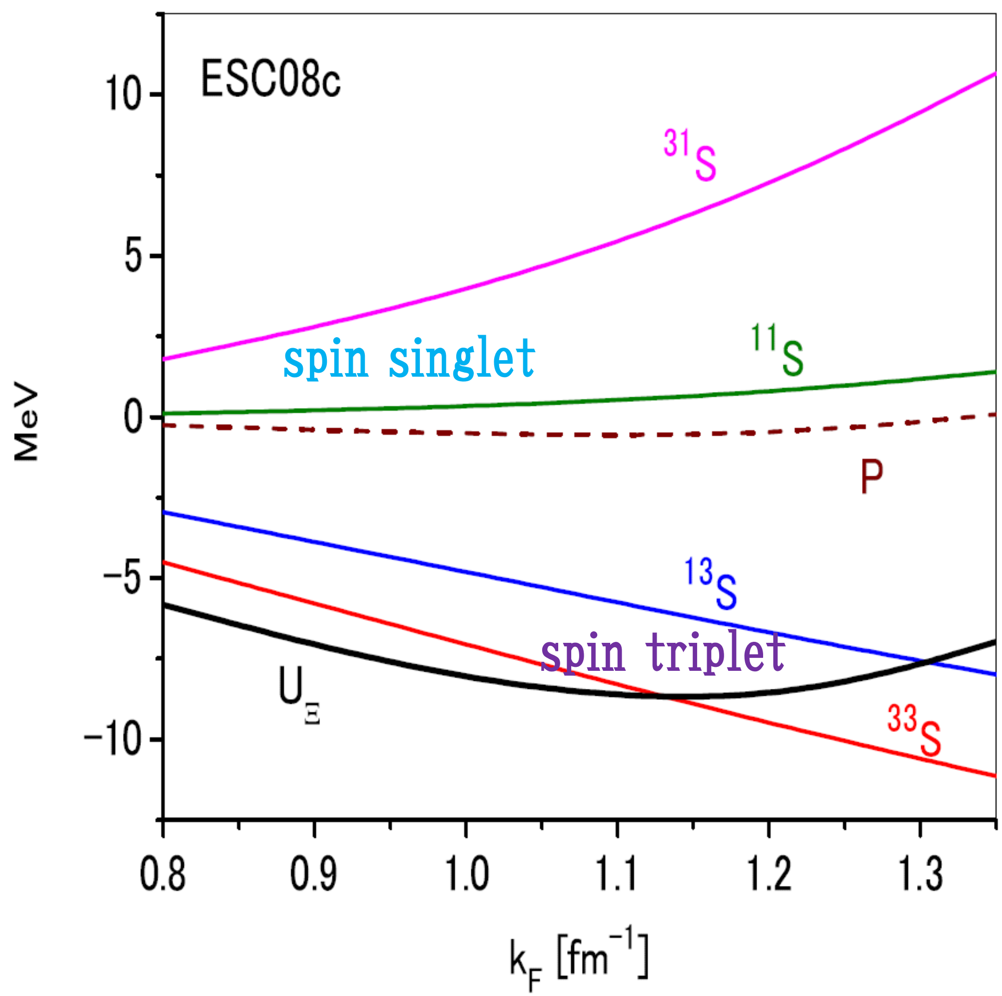
Progress of Theoretical Physics, Vol. 105, No. 4, April 2001

ΞN and $\Xi\Xi$ OBEP and Ξ^--Nucleus Bound States

Masahiro YAMAGUCHI,[1] Kouji TOMINAGA,[1,*)] Yasuo YAMAMOTO[2]
and Tamotsu UEDA[1]

Twin dataを用いた
唯一の理論！
NPでrejected!

T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ^c_Ξ
0	1.4	−8.0	−0.3	1.8	1.4	−2.1		
1	10.7	−11.1	1.1	0.7	−2.6	−0.0	−7.0	4.5



Ξ -nucleus folding model

$$
\begin{aligned}
U_\Xi(\mathbf{r},\mathbf{r}') &= U_{dr} + U_{ex}\ , \\
U_{dr} &= \delta(\mathbf{r}-\mathbf{r}')\int d\mathbf{r}''\rho(\mathbf{r}'')\,V_{dr}(|\mathbf{r}-\mathbf{r}''|;k_F) \\
U_{ex} &= \rho(\mathbf{r},\mathbf{r}')V_{ex}(|\mathbf{r}-\mathbf{r}'|;k_F)\ ,
\end{aligned}
$$

$$
\begin{pmatrix} V_{dr} \\ V_{ex} \end{pmatrix} = \frac{1}{2(2t_Y+1)(2s_Y+1)}\sum_{TS}(2T+1)(2S+1)[\mathcal{G}^{TS}_{(\pm)} \pm \mathcal{G}^{TS}_{(\mp)}]
$$

$$
\breve{\bar{k}}_F = (1+\alpha)\,(1.5\pi^2\bar{\rho})^{1/3}
$$

$$
\bar{\rho} = \langle\phi_\Xi(r)|\rho(r)|\phi_\Xi(r)\rangle
$$

Table 3: Calculated quantities in $\Xi^- + {}^{12}$C and $\Xi^- + {}^{14}$N systems for α=0.10 and 0.02. Binding energies B_{Ξ^-} and conversion width $\Gamma^c_{\Xi^-}$ are in MeV. R.m.s. radius $\sqrt{\langle r^2 \rangle}$ is in fm.

$\Xi^- + {}^{12}$C		$\alpha = 0.10$	$\alpha = 0.02$
$1S$	B_{Ξ^-}	3.83	4.88
	$\Gamma^c_{\Xi^-}$	1.49	1.71
	$\sqrt{\langle r^2 \rangle}$	3.34	3.00
$2P$	B_{Ξ^-}	0.68	1.00
	$\Gamma^c_{\Xi^-}$	0.44	0.69
	$\sqrt{\langle r^2 \rangle}$	7.54	5.70
$\Xi^- + {}^{14}$N		$\alpha = 0.1$	$\alpha = 0.02$
$1S$	B_{Ξ^-}	4.82	5.98
	$\Gamma^c_{\Xi^-}$	1.87	2.10
	$\sqrt{\langle r^2 \rangle}$	3.18	2.91
$2P$	B_{Ξ^-}	1.22	1.70
	$\Gamma^c_{\Xi^-}$	0.77	1.04
	$\sqrt{\langle r^2 \rangle}$	5.66	4.69

EXP

$B_{\Xi^-} = 0.82 \pm 0.17$ MeV

$B_{\Xi^-} = 1.14 \pm 0.25$ MeV

${}^{10}_{\Lambda}$Be (Jlab E05-115)

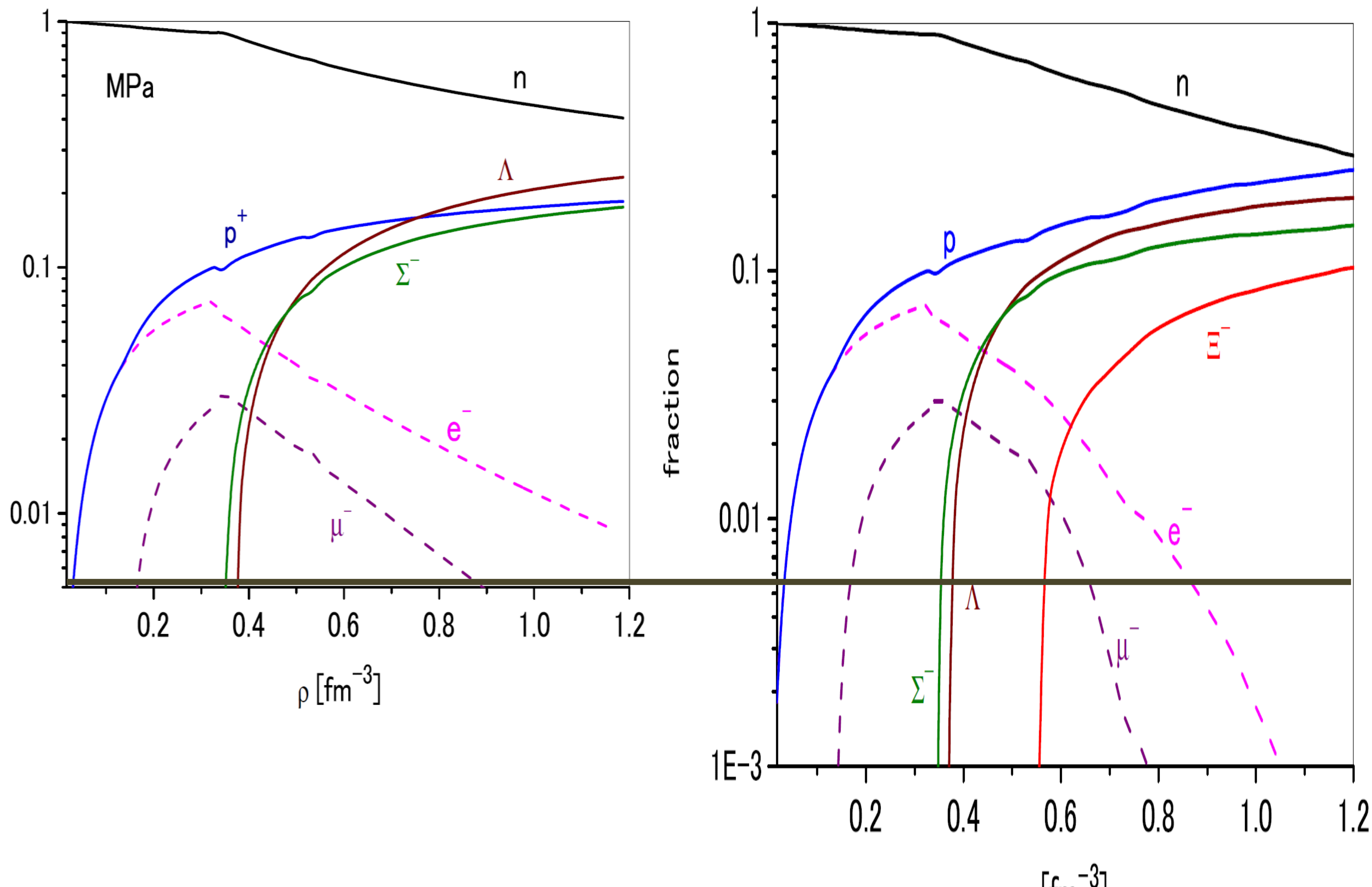
$0.9 \sim 1.5$ MeV $1.6 \sim 2.2$ MeV

second   first   excited state of ${}^{10}_{\Lambda}$Be

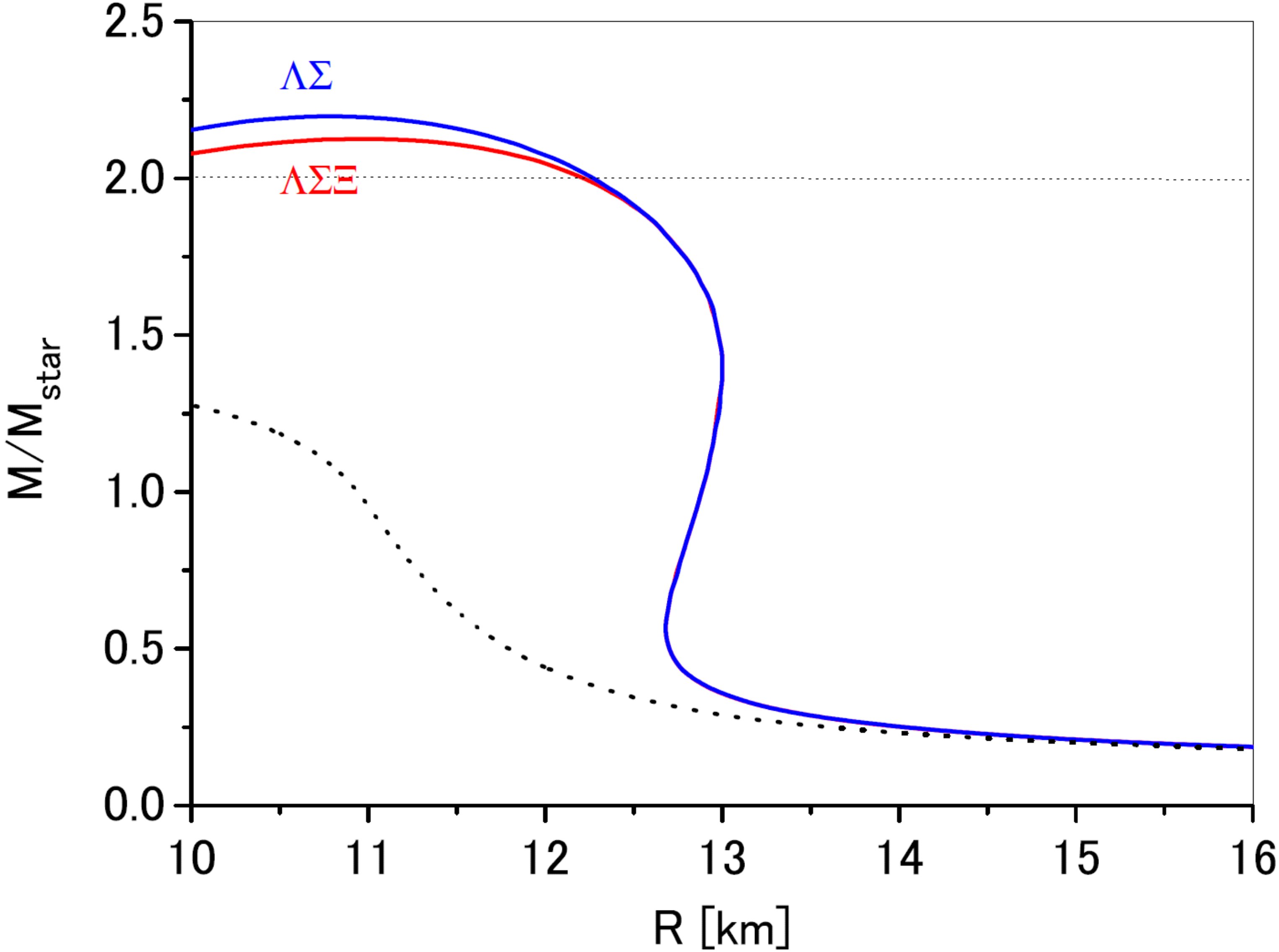
Strength of ΞN interaction in ESC08c is consistent with B_{Ξ} data from twin Λ-hypernuclei in emulsion

↓

To study Ξ mixing in neutron-star matter



MPa
n
Λ
p^+
Σ^-
e^-
μ^-
1
0.1
0.01
0.2
0.4
0.6
0.8
1.0
1.2
ρ [fm^-3]
fraction
n
p
Ξ^-
e^-
Λ
μ^-
Σ^-
1E-3



ΛΣ
ΛΣΞ
M/M_star
R [km]
0.0
0.5
1.0
1.5
2.0
2.5
10
11
12
13
14
15
16

Conclusions

ESC08c+MPP+TBA model

* MPP strength determined by analysis for $^{16}O+^{16}O$ scattering
* TNA adjusted phenomenologically to reproduce
  $E/A(\rho_0) = -15.8$ MeV with $\rho_0 = 0.16\ fm^{-3}$
* Consistent with hypernuclear data
* No ad hoc parameter to stiffen EOS

BB interactions based on on-Earth experiments

MPa set including 3- and 4-body repulsions leads to massive neutron stars with $2M_\odot$ in spite of significant softening of EOS by hyperon mixing

Ξ^- mixing does not change the conclusion qualitatively