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Hyperonic many-body effect in hypernuclei and neutron-star matter

Y. Yamamoto

Collaborators:

T. Furumoto	nuclear reaction
N. Yasutake	neutron star
Th.A. Rijken	BB interaction
M. Isaka	Λ hypernuclei/AMD
T. Harada	Σ hypernuclei

Hyperon puzzle !

Massive ($2M_\odot$) neutron stars

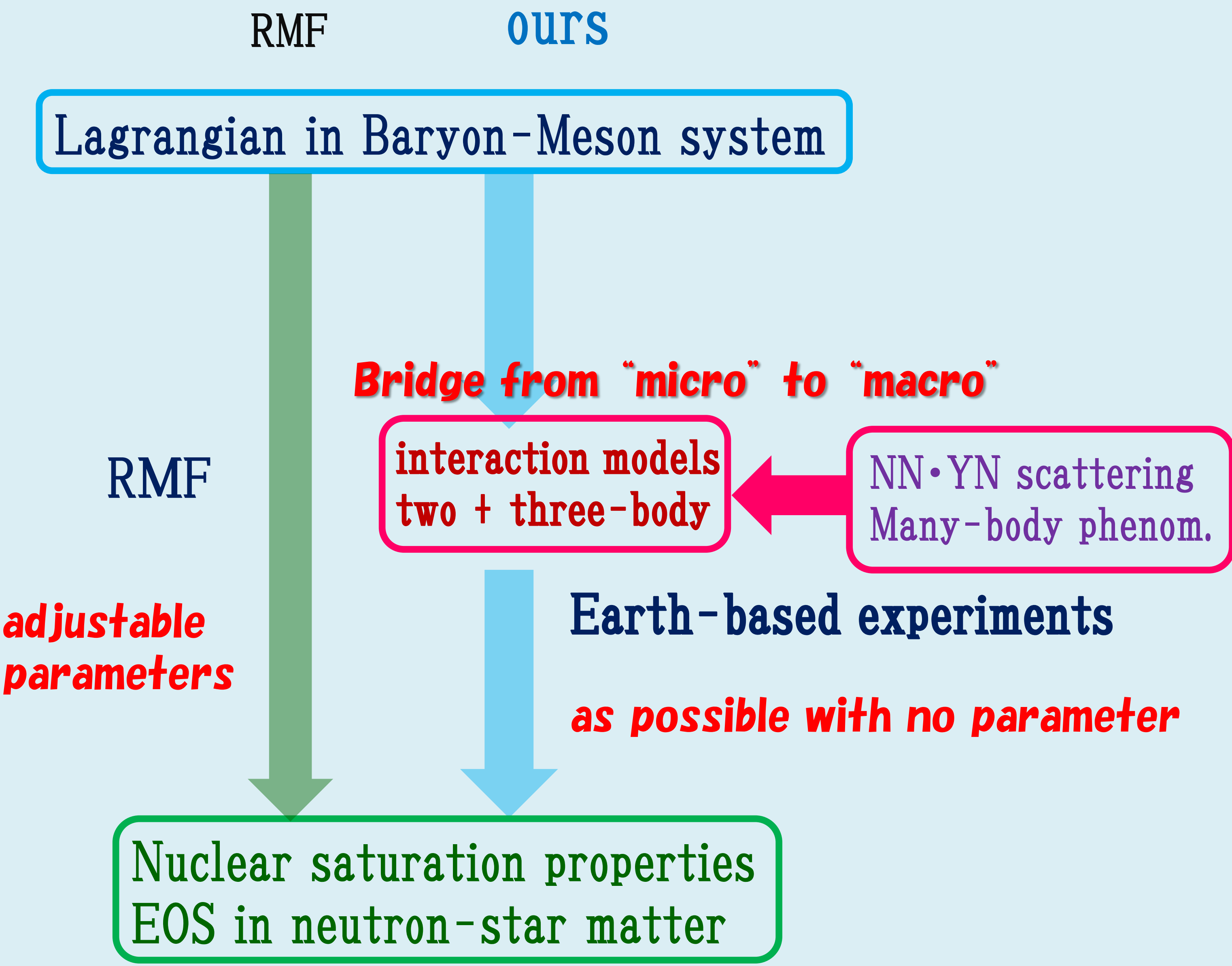
2010 **PSR J1614-2230** $(1.97 \pm 0.04) M_\odot$

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

Softening of EOS by hyperon mixing

Our aim :

Try to solve the hyperon puzzle by
Universal Three-Baryon Repulsion
on the basis of terrestrial data



RMF

ours

Lagrangian in Baryon-Meson system

RMF

adjustable parameters

Bridge from "micro" to "macro"

interaction models
two + three-body

NN・YN scattering
Many-body phenom.

Earth-based experiments

as possible with no parameter

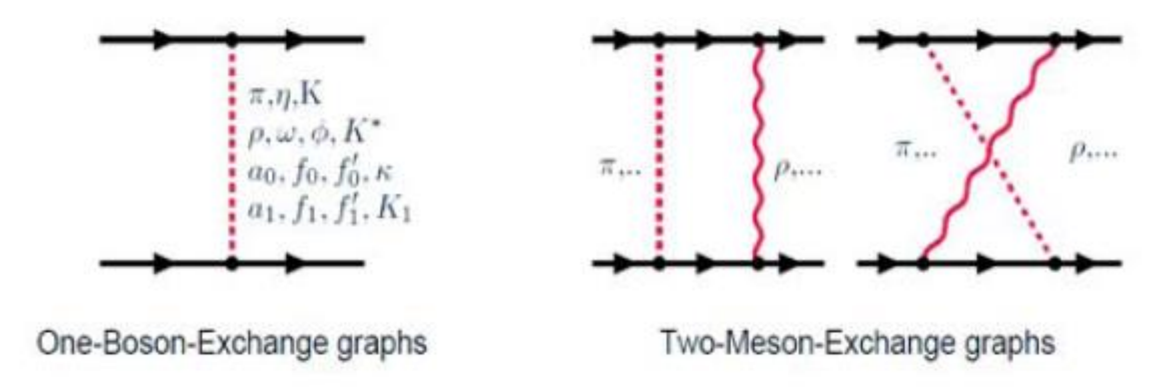
Nuclear saturation properties
EOS in neutron-star matter

Based on BHF theory

Our story to neutron-star matter
starts from the BB interaction model

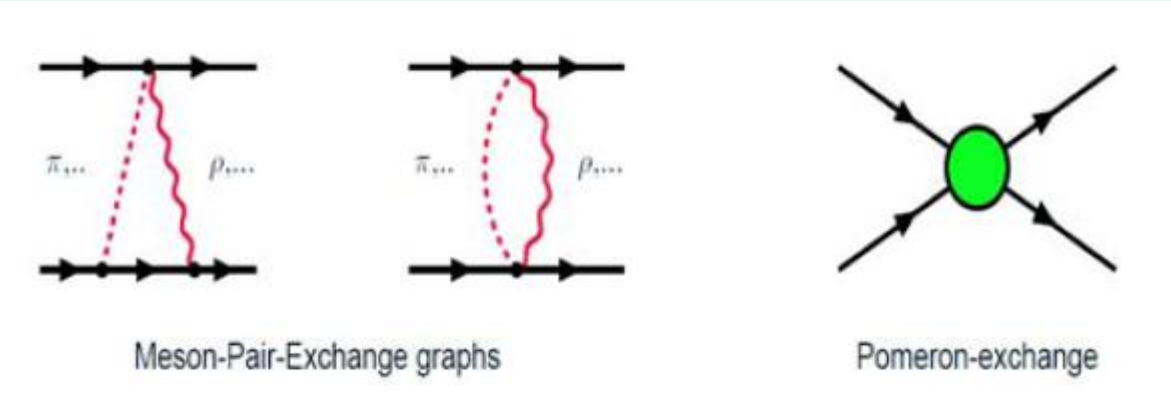
Nijmegen Extended Soft-Core Model (ESC)

SU$_3$ invariant (NN and YN) interaction



One-Boson-Exchange graphs

Two-Meson-Exchange graphs



Meson-Pair-Exchange graphs

Pomeron-exchange

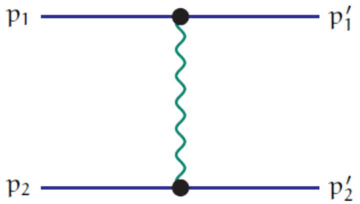
repulsive cores

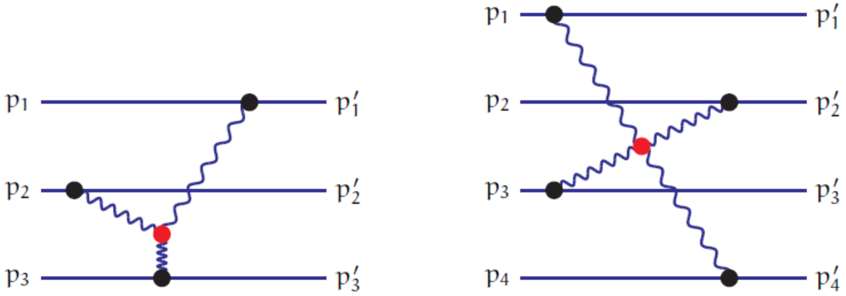
A model of Universal Three-Baryon Repulsion

Multi-Pomeron Exchange Potential (MPP)

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

$$\mathcal{L}_{PNN} = g_P \bar{\psi}(x)\psi(x)\,\sigma_P(x)$$
$$\Delta_F^P(k^2) = +\exp(-\mathbf{k}^2/4m_P^2)/\mathcal{M}^2$$
$$V_P(r) = \frac{g_P^2}{4\pi}\frac{4}{\sqrt{\pi}}\frac{m_P^3}{\mathcal{M}^2}\exp\left(-m_P^2 r_{12}^2\right)$$





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

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

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

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

Three-Nucleon attraction (TNA) phenomenological

Both MPP and TNA are needed
to reproduce nuclear saturation property
and Nucleus-Nucleus scattering data

(MPP is essential for Nucleus-Nucleus scattering data)

density-dependent two-body attraction

$$V_A(r;\rho) = V_0 \exp[-(r/2.0)^2]\,\rho\,\exp(-\eta\rho)\,(1+P_r)/2$$

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

➡ 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).

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

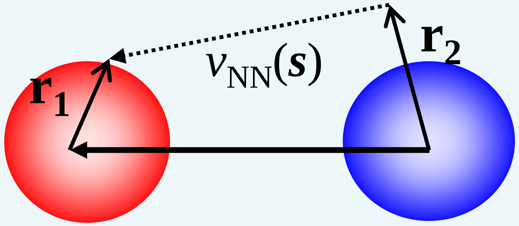
Nucleus-Nucleus scattering data
with G-matrix folding potential

Double Folding

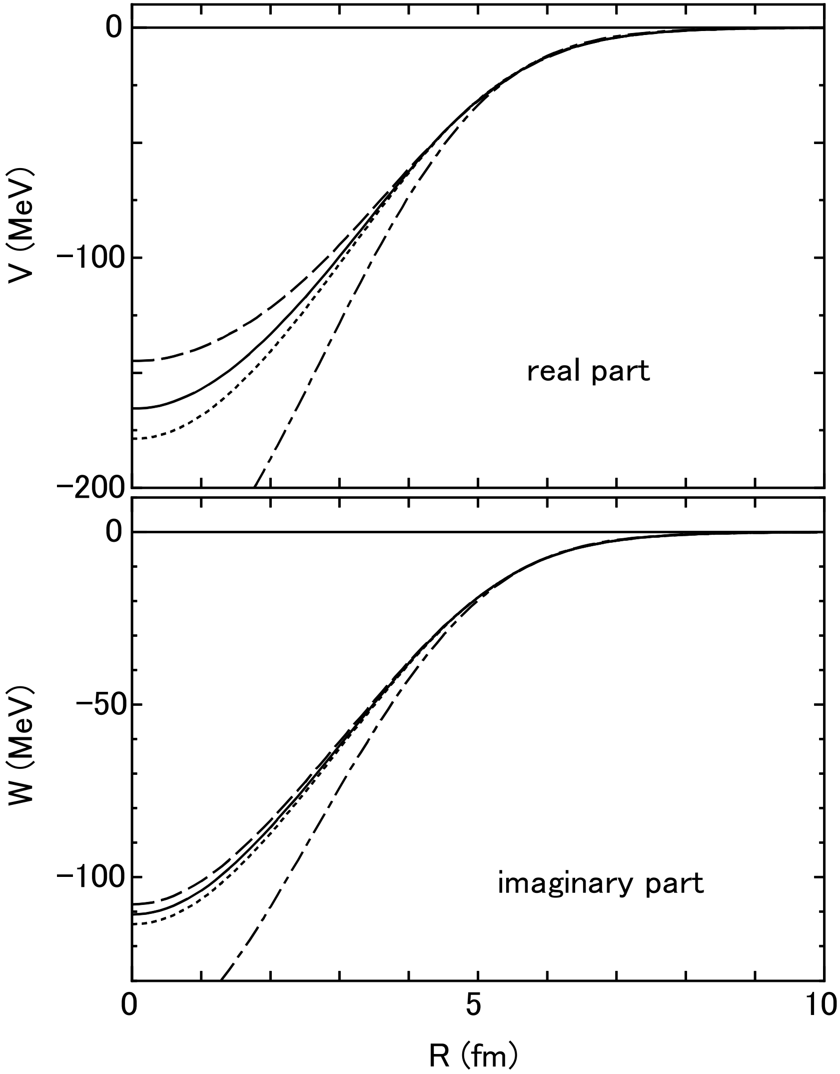
$$
\begin{aligned}
U(\mathbf{R}) &= \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)v_D(\mathbf{s};\rho,E)\,d\mathbf{r}_1 d\mathbf{r}_2 \\
&+ \int \rho_1(\mathbf{r}_1,\mathbf{r}_1-\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2+\mathbf{s})v_{EX}(\mathbf{s};\rho,E)\exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right]d\mathbf{r}_1 d\mathbf{r}_2 \\
&= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R})
\end{aligned}
$$

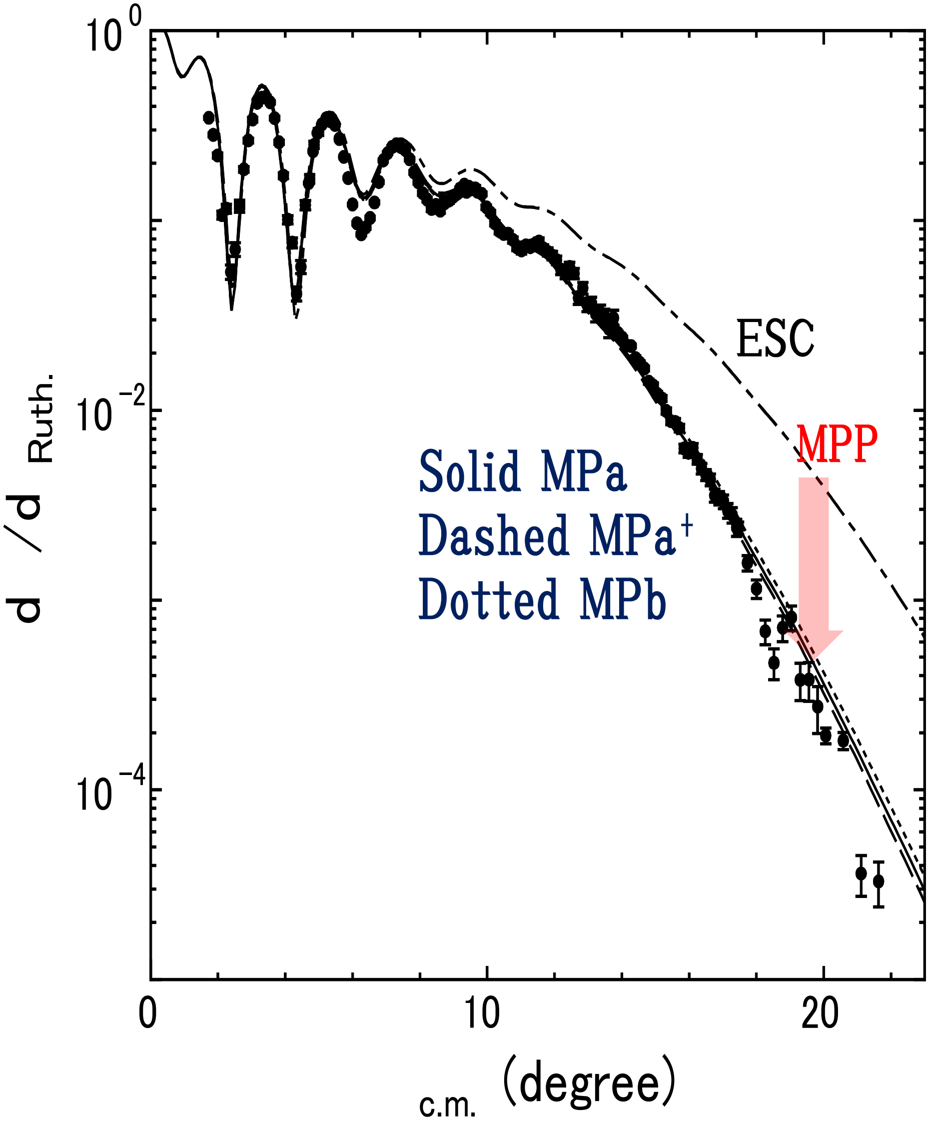
Frozen-Density Approximation $\boxed{\rho = \rho_1 + \rho_2}$

Two Fermi-spheres separated in momentum space
can overlap in coordinate space without
disturbance of Pauli principle

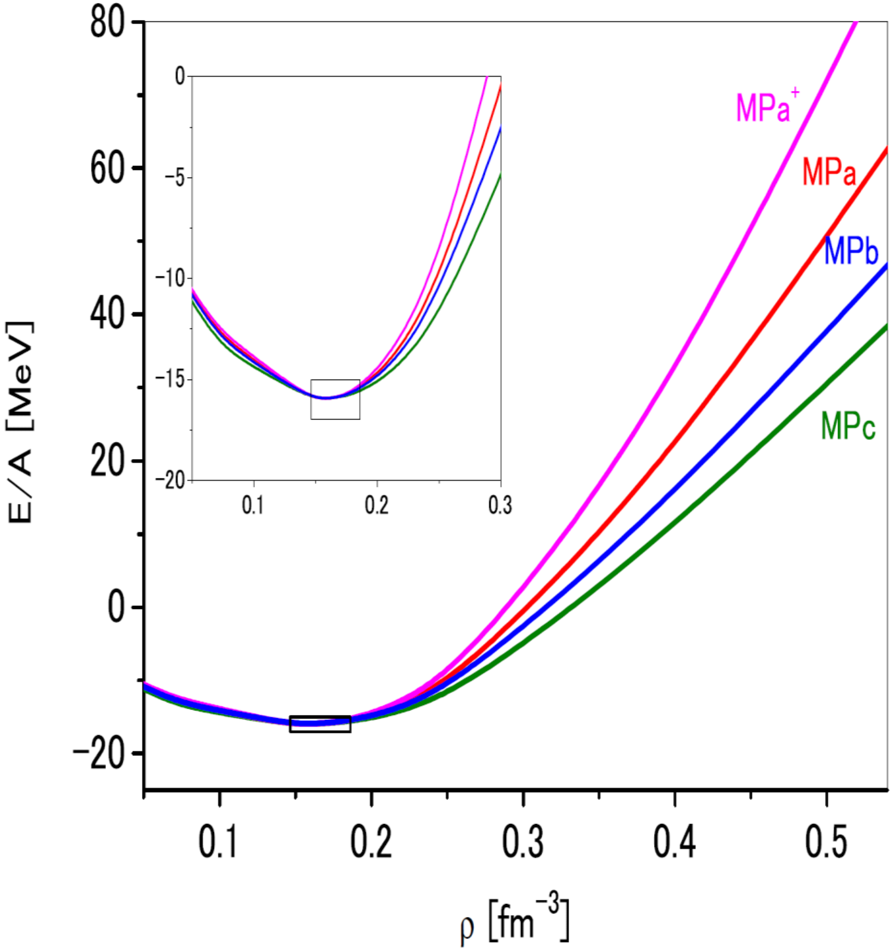


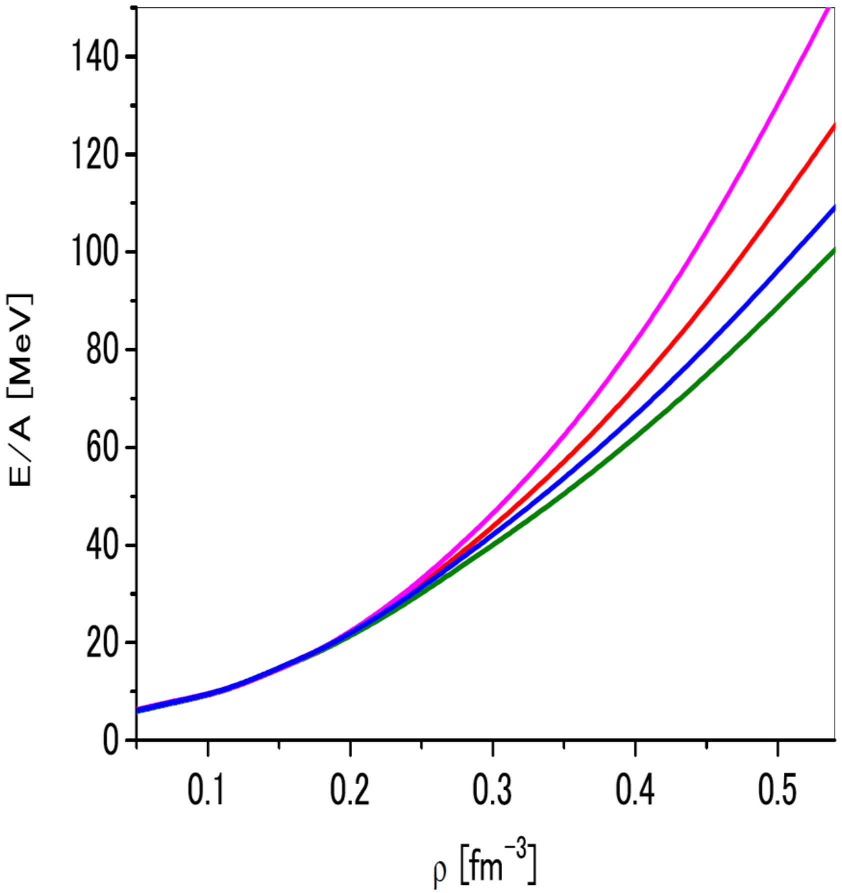
^{16}O + ^{16}O elastic scattering cross section at E/A = 70 MeV





E/A curves





MPa/**MPa$^+$** including 3- and 4-body MPP : **MPb**/**MPc** including 3-body MPP only

$$E_{sym}(\rho) = \frac{E}{A}(\rho, \beta = 1) - \frac{E}{A}(\rho, \beta = 0)$$

$$L = 3\rho_0 \left[\frac{\partial E_{sym}(\rho)}{\partial \rho}\right]_{\rho=\rho_0}$$

$$K = 9\rho_0^2 \left[\frac{d^2}{d\rho^2}\frac{E}{A}(\rho, \beta = 0)\right]_{\rho=\rho_0}$$

$$\beta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

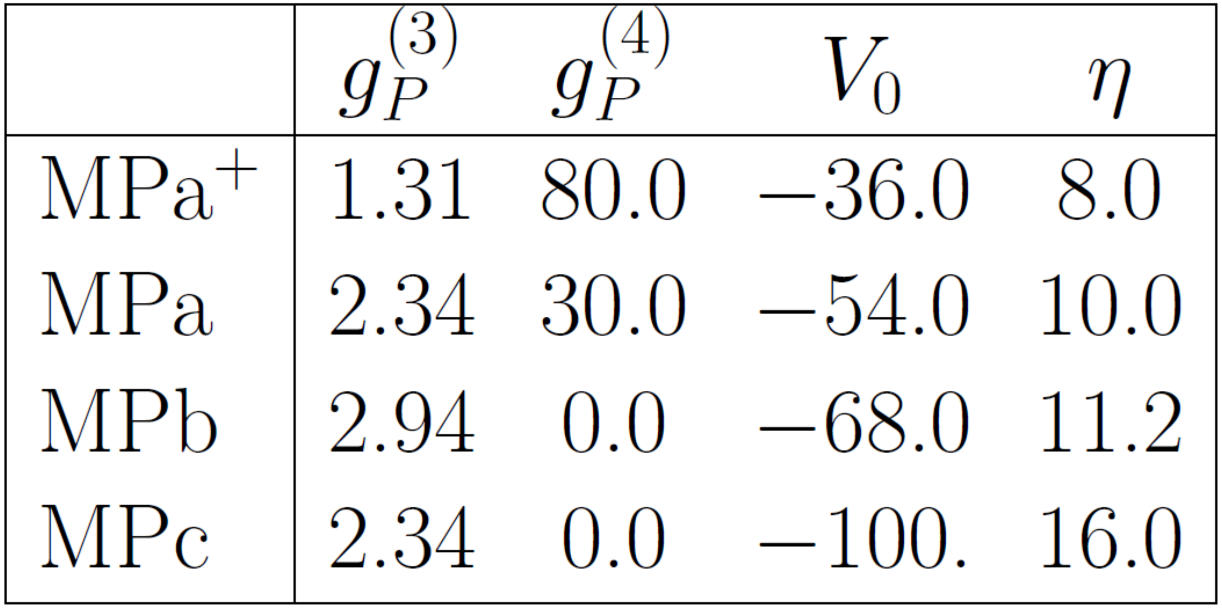
	ρ_0 (fm^{-3})	E/A (MeV)	E_{sym} (MeV)	L (MeV)	K (MeV)
MPa$^+$	0.155	−16.1	31.2	61.2	317
MPa	0.155	−16.0	31.3	60.7	270
MPb	0.155	−16.0	31.3	60.2	254
MPc	0.155	−16.1	31.1	59.9	225

For example, AV8’+UIX : E_{sym}=35.1 MeV L=63.6 MeV (Gandolfi et al.)

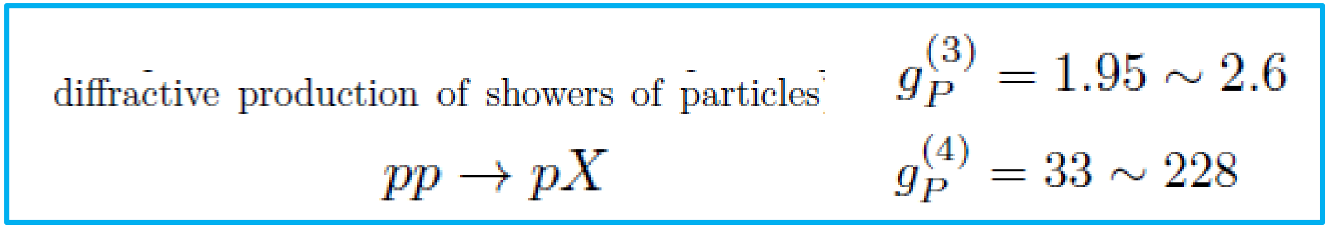
Four parameter sets

Stiffness of EOS : MPa$^+$ > MPa > MPb > MPc

K= 317 270 254 225

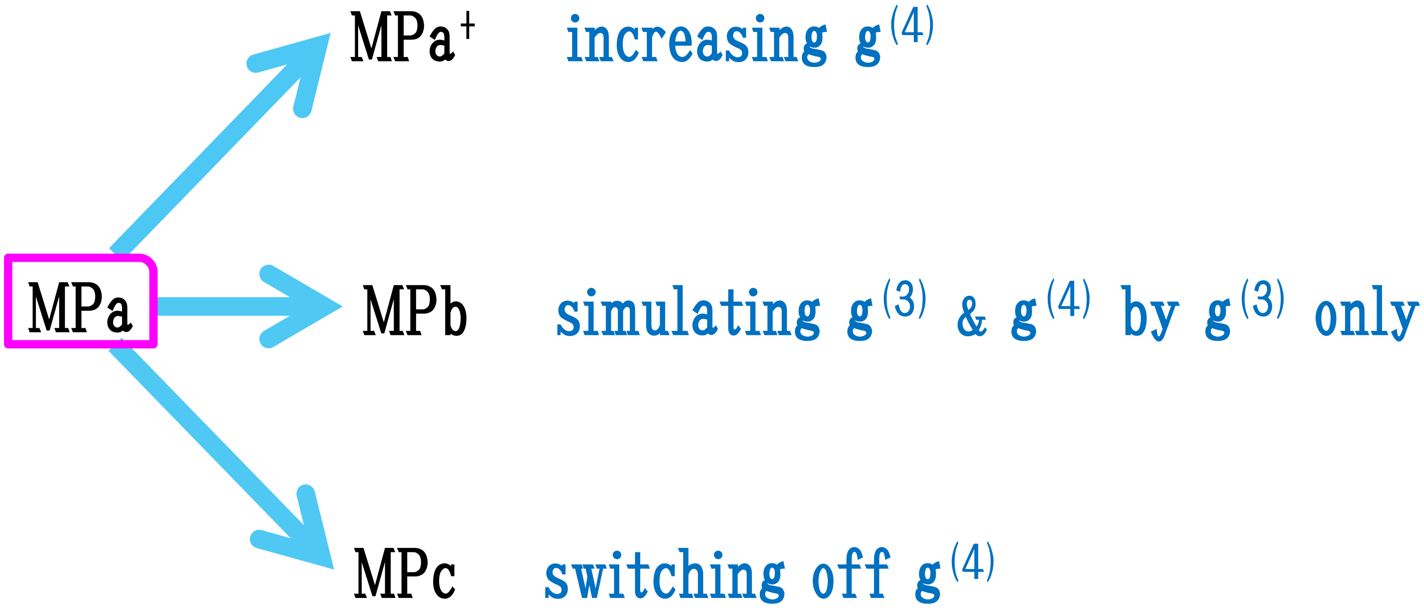


	$g_P^{(3)}$	$g_P^{(4)}$	V_0	η
MPa$^+$	1.31	80.0	−36.0	8.0
MPa	2.34	30.0	−54.0	10.0
MPb	2.94	0.0	−68.0	11.2
MPc	2.34	0.0	−100.	16.0



diffractive production of showers of particles $g_P^{(3)} = 1.95 \sim 2.6$

$pp \to pX$ $g_P^{(4)} = 33 \sim 228$



MPa

MPa^{+} increasing $g^{(4)}$

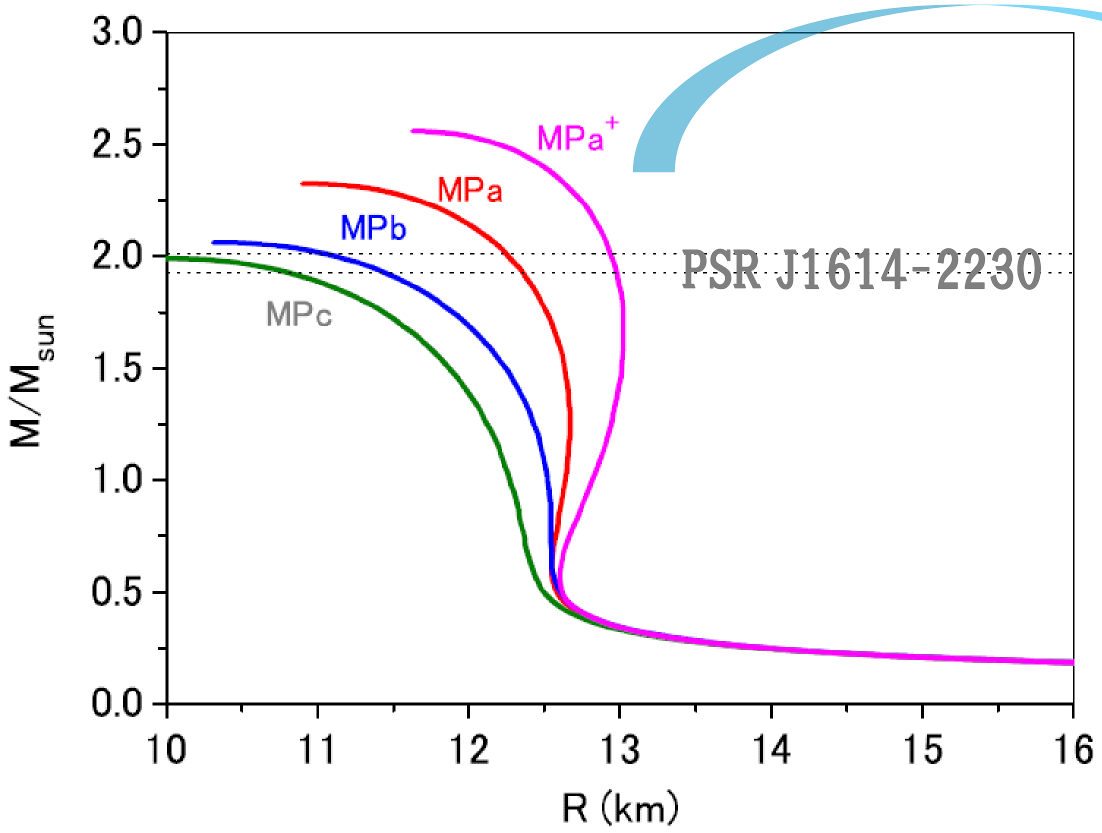
MPb simulating $g^{(3)}$ & $g^{(4)}$ by $g^{(3)}$ only

MPc switching off $g^{(4)}$

All four versions reproduces similarly ^{16}O−^{16}O scattering data

	$g_P^{(3)}$	$g_P^{(4)}$	V_0	η
MPa^{+}	1.31	80.0	−36.0	8.0
MPa	2.34	30.0	−54.0	10.0
MPb	2.94	0.0	−68.0	11.2
MPc	2.34	0.0	−100.	16.0

with n+p β-stable matter   by solving TOV eq.



	K
MPa^{+}	317
MPa	270
MPb	254
MPc	225

2M$_{solar}$ with
no ad hoc parameter

	$M_{max}/M_{\odot}$	$R(M_{max})$ (km)	$R(1.5M_{\odot})$ (km)	$\rho_c(M_{max})/\rho_0$
MPa^{+}	2.56	11.6	13.0	4.9
MPa	2.32	10.9	12.6	5.7
MPb	2.06	10.3	12.2	6.8
MPc	1.99	10.0	11.9	7.2

Hyperon-Mixed Neutron-Star Matter
using YN & YY interaction model

ESC08c consistent with almost all experimental data of hypernuclei (S=-1,-2)

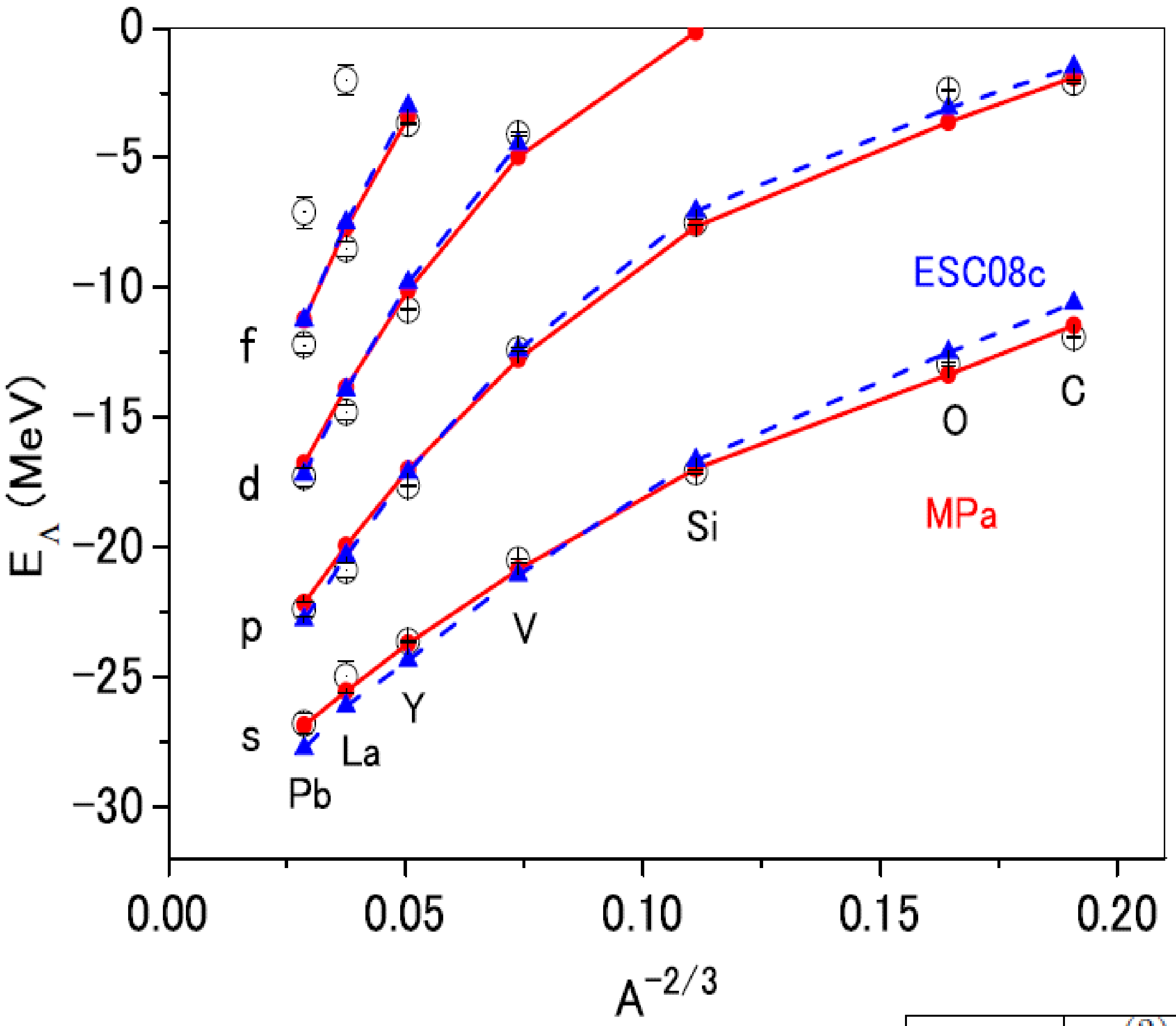
MPP universal in all BB channels

TBA given in S=0 channel ➔ ? in S=-1,-2 channel

(ESC+MPP+TBA) model should be tested in hypernuclei

hyperonic sector

Choosing TBA=TNA ➡ Experimental data of B_Λ reproduced

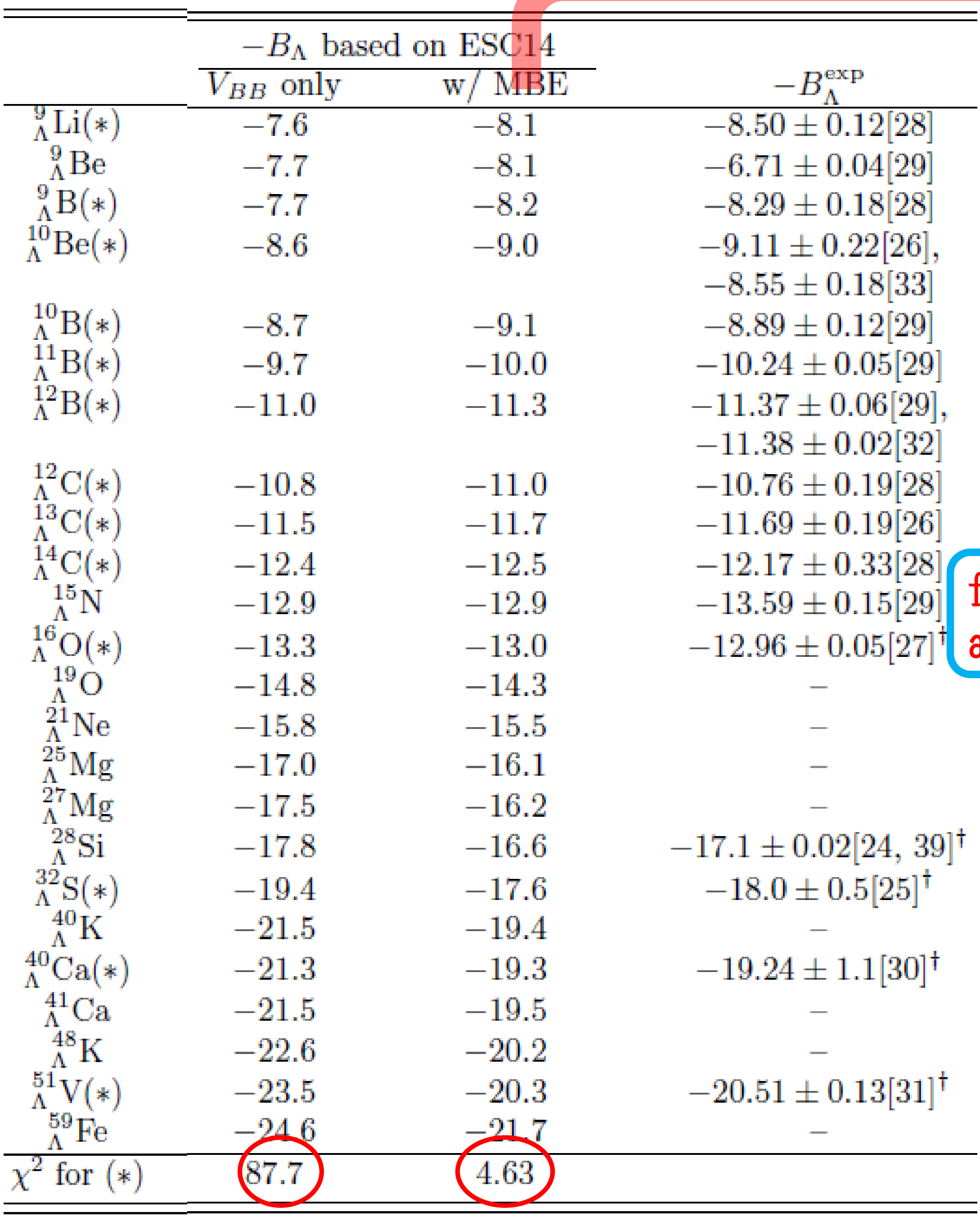


Similarly fitted
for MPb and MPc

G-matrix folding model
with two adjustable parameter :
V_0 and η

	$g_P^{(3)}$	$g_P^{(4)}$	V_0	η
MPa	2.34	30.0	−26.0	5.0
MPb	2.94	0.0	−29.0	5.5
MPc	2.34	0.0	−25.0	6.0

HyperAMD by Isaka



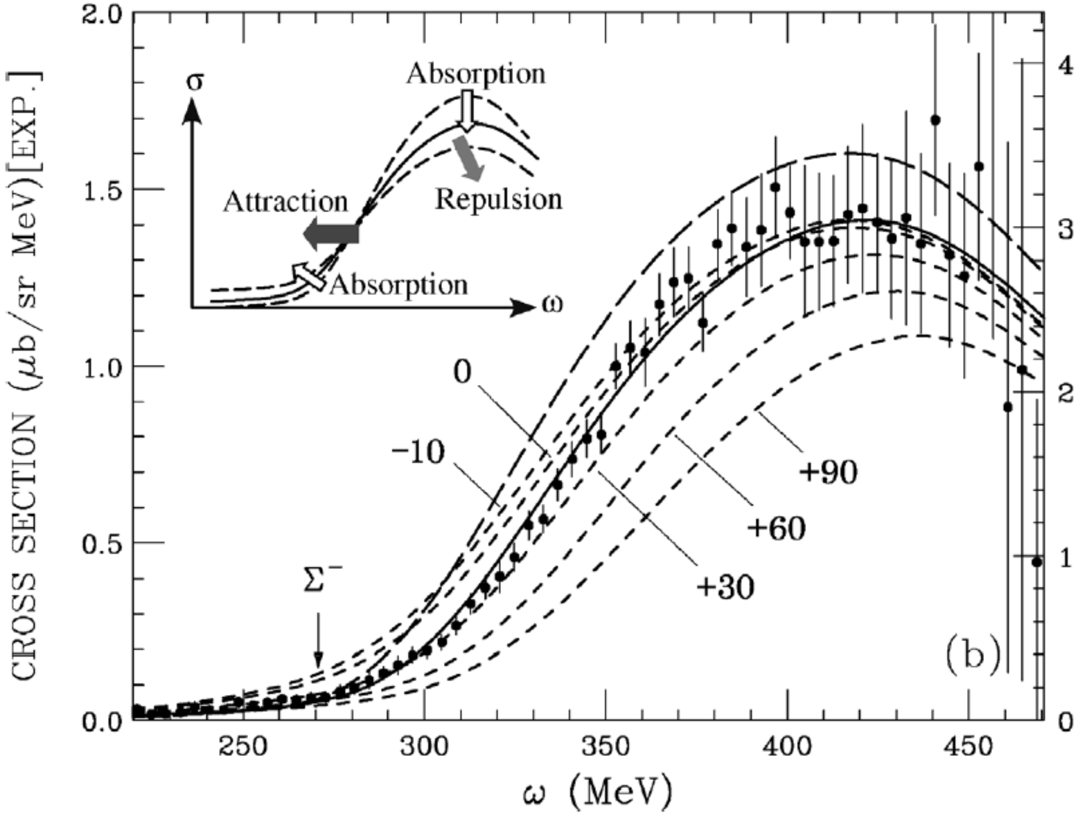
	$-B_\Lambda$ based on ESC14		
	V_{BB} only	w/ MBE	$-B_\Lambda^{\rm exp}$
${}^{9}_{\Lambda}$Li(∗)	−7.6	−8.1	-8.50 ± 0.12[28]
${}^{9}_{\Lambda}$Be	−7.7	−8.1	-6.71 ± 0.04[29]
${}^{9}_{\Lambda}$B(∗)	−7.7	−8.2	-8.29 ± 0.18[28]
${}^{10}_{\Lambda}$Be(∗)	−8.6	−9.0	-9.11 ± 0.22[26], -8.55 ± 0.18[33]
${}^{10}_{\Lambda}$B(∗)	−8.7	−9.1	-8.89 ± 0.12[29]
${}^{11}_{\Lambda}$B(∗)	−9.7	−10.0	-10.24 ± 0.05[29]
${}^{12}_{\Lambda}$B(∗)	−11.0	−11.3	-11.37 ± 0.06[29], -11.38 ± 0.02[32]
${}^{12}_{\Lambda}$C(∗)	−10.8	−11.0	-10.76 ± 0.19[28]
${}^{13}_{\Lambda}$C(∗)	−11.5	−11.7	-11.69 ± 0.19[26]
${}^{14}_{\Lambda}$C(∗)	−12.4	−12.5	-12.17 ± 0.33[28]
${}^{15}_{\Lambda}$N	−12.9	−12.9	-13.59 ± 0.15[29]
${}^{16}_{\Lambda}$O(∗)	−13.3	−13.0	-12.96 ± 0.05[27]†
${}^{19}_{\Lambda}$O	−14.8	−14.3	–
${}^{21}_{\Lambda}$Ne	−15.8	−15.5	–
${}^{25}_{\Lambda}$Mg	−17.0	−16.1	–
${}^{27}_{\Lambda}$Mg	−17.5	−16.2	–
${}^{28}_{\Lambda}$Si	−17.8	−16.6	-17.1 ± 0.02[24, 39]†
${}^{32}_{\Lambda}$S(∗)	−19.4	−17.6	-18.0 ± 0.5[25]†
${}^{40}_{\Lambda}$K	−21.5	−19.4	–
${}^{40}_{\Lambda}$Ca(∗)	−21.3	−19.3	-19.24 ± 1.1[30]†
${}^{41}_{\Lambda}$Ca	−21.5	−19.5	–
${}^{48}_{\Lambda}$K	−22.6	−20.2	–
${}^{51}_{\Lambda}$V(∗)	−23.5	−20.3	-20.51 ± 0.13[31]†
${}^{59}_{\Lambda}$Fe	−24.6	−21.7	–
χ^2 for (∗)	87.7	4.63	

including MPP+TBA

fitted within a few hundred keV

Σ-nucleus interaction is strongly repulsive !!!

T. Harada, Y. Hirabayashi / Nuclear Physics A 759 (2005) 143-



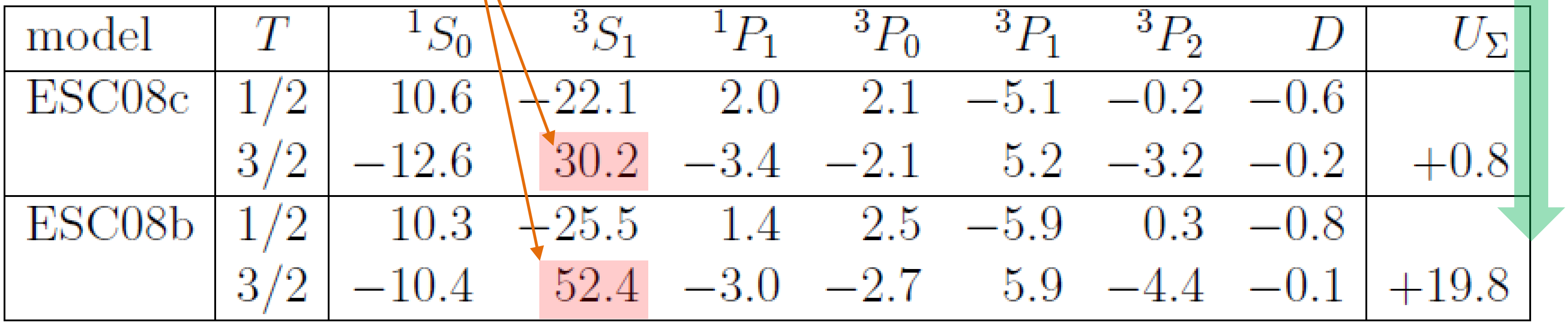
^{28}Si(π^-, K^+) reaction at $p_\pi = 1.20$ GeV/c (6°).

$$(V_0^{\Sigma}, W_0^{\Sigma}) = (+20\ \text{MeV},\ -20\ \text{MeV})$$

$$(+30\ \text{MeV},\ -40\ \text{MeV})$$

In various RMF models
with U_Σ=20-30 MeV
Σ^- mixing does not occur

Pauli-forbidden state



model	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	D	U_Σ
ESC08c	1/2	10.6	−22.1	2.0	2.1	−5.1	−0.2	−0.6	
	3/2	−12.6	30.2	−3.4	−2.1	5.2	−3.2	−0.2	+0.8
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

?

U_{WS} ≈ 20-30 MeV

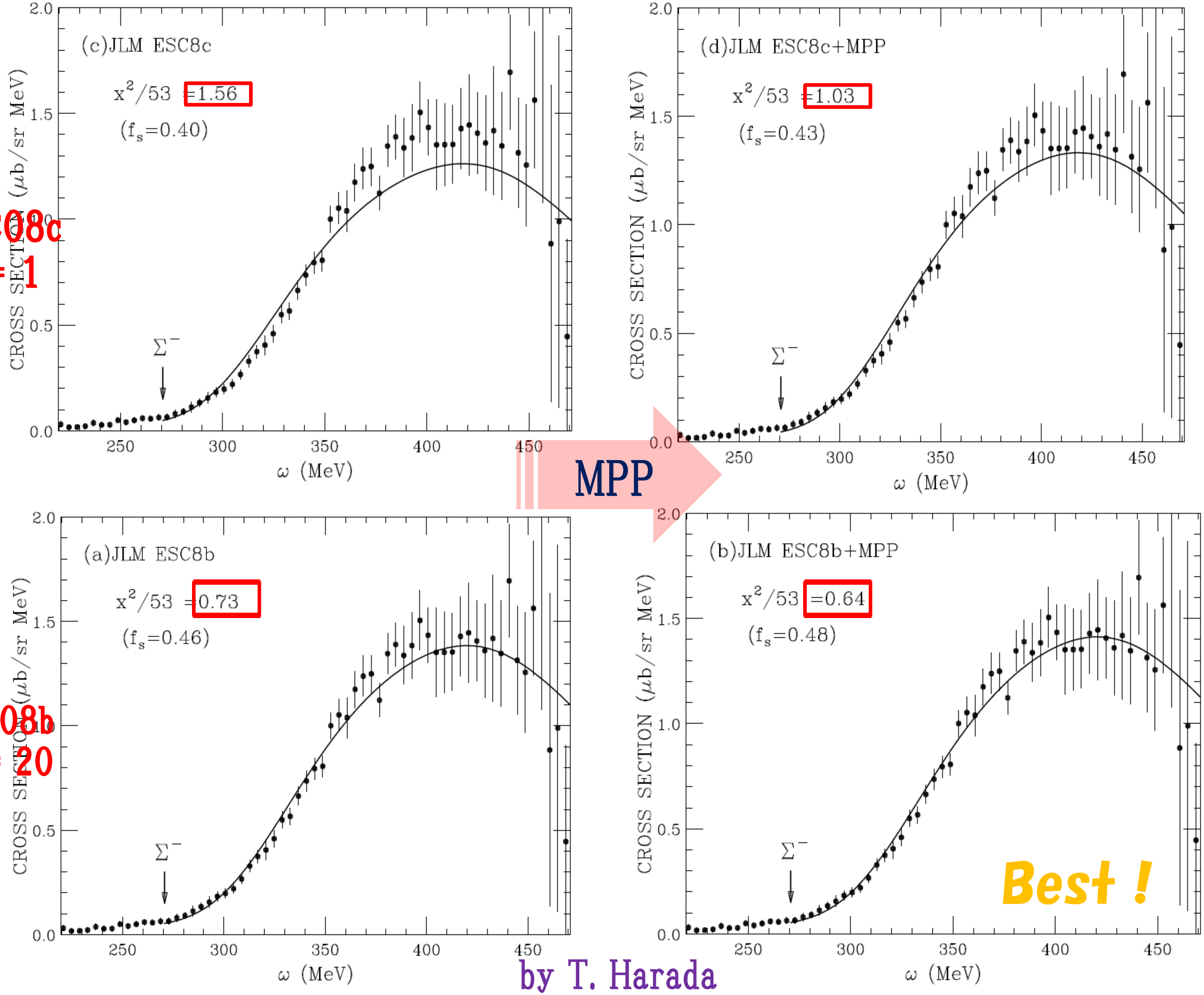
How different two interactions in ^{28}S(K^-,K^+) spectrum ?

$^{28}\mathrm{Si}(\pi^-, K^+)$ reaction at $p_\pi = 1.20\ \mathrm{GeV}/c\ (6°)$,

Calculation with Σ-nucleus LDA potential
given by ΣN G-matrices

4 cases	ESC08c	ESC08c+MPP
	ESC08b	ESC08b+MPP

MPP=MPa without TNA



ESC08c
$U_\Sigma = 1$

MPP

ESC08b
$U_\Sigma = 20$

Best !

by T. Harada

We use **ESC08b** with MPa/b/c (TBA=0) for ΣN

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

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

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

Hyperon-mixed neutron matter

Starting from single particle potentials calculated with the G-matrix theory:

$$U_B(k) = \sum_{B'} U_B^{(B')}(k) \quad \text{with} \quad B, B' = n, p, \Lambda, \Sigma^-$$

$U_B^{(B')}$ means a single particle potential of B particle in B' matter

Energy density

$$\begin{aligned}
\varepsilon &= \varepsilon_{mass} + \varepsilon_{kin} + \varepsilon_{pot} \\
&= 2\sum_B \int_0^{k_F^B} \frac{d^3k}{(2\pi)^3} \left[M_B - M_n + \frac{\hbar^2 k^2}{2M_B} + \frac{1}{2} U_B(k) \right]
\end{aligned}$$

$$\varepsilon_{mass} = \sum_B (M_B - M_n)\rho_B$$

$$\varepsilon_{kin} = \sum_B \frac{3}{5} \frac{\hbar^2 (k_F^B)^2}{2M_B} \rho_B = \sum_B \frac{3}{5} \frac{\hbar^2}{2M_B} (3\pi^2)^{2/3} (\rho_B)^{5/3}$$

$$\varepsilon_{pot} = 2\sum_B \int_0^{k_F^B} \frac{d^3k}{(2\pi)^3} \frac{1}{2} U_B(k) = \frac{1}{2} \sum_B \int_0^{k_F^B} \frac{k^2 dk}{\pi^2} U_B(k)$$

Chemical potential : $\mu_B = \frac{\partial \varepsilon}{\partial \rho_B}$

Chemical potential : $\mu_B = \frac{\partial \varepsilon}{\partial \rho_B}$

Chemical equilibrium conditions:

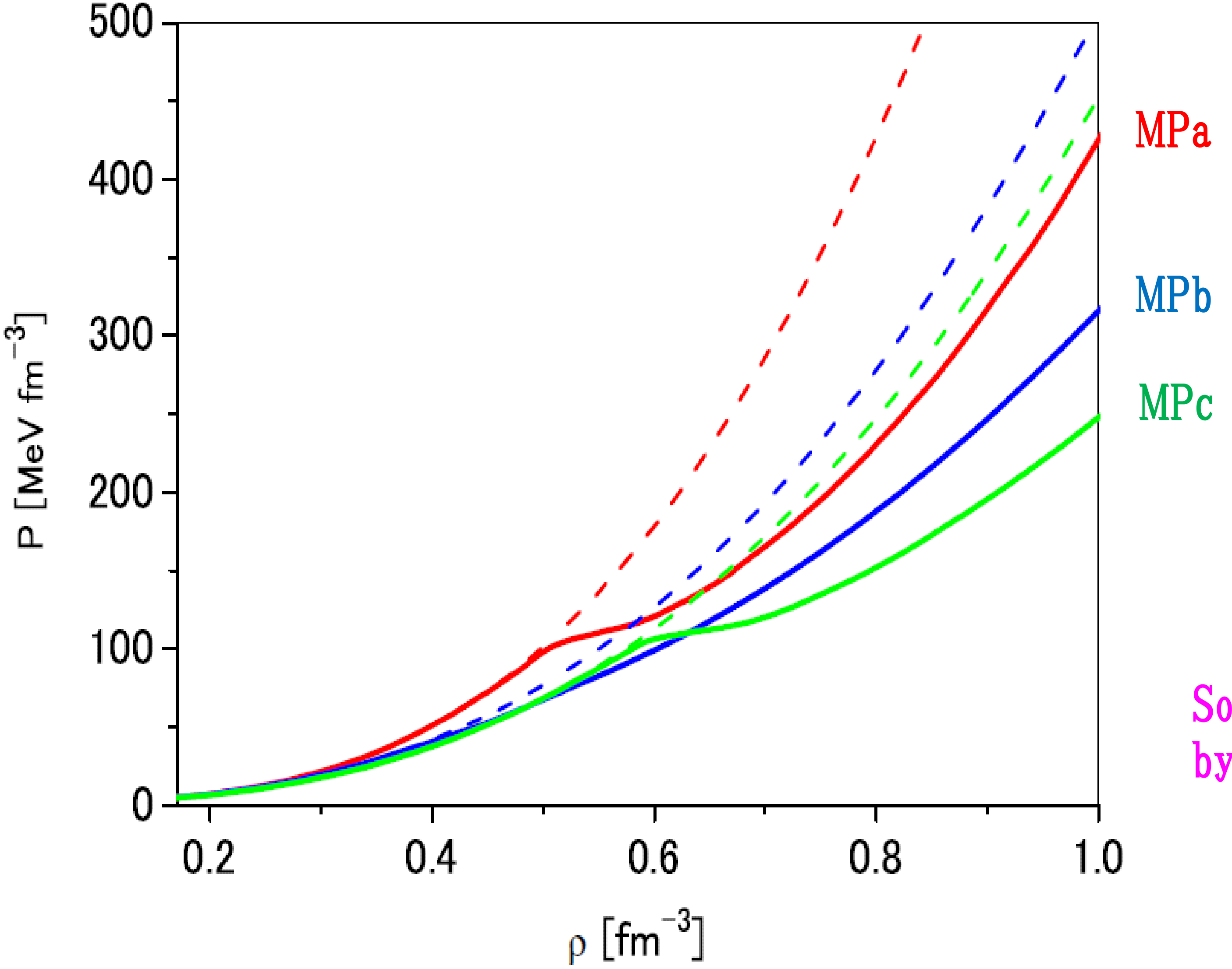
$$\begin{aligned} \mu_n &= \mu_p + \mu_e \\ \mu_e &= \mu_\mu \\ \mu_{\Sigma^-} &= \mu_n + \mu_e \\ \mu_\Lambda &= \mu_n \end{aligned}$$

Baryon-number conservation : $y_n + y_p + y_\Lambda + y_{\Sigma^-} = 1$

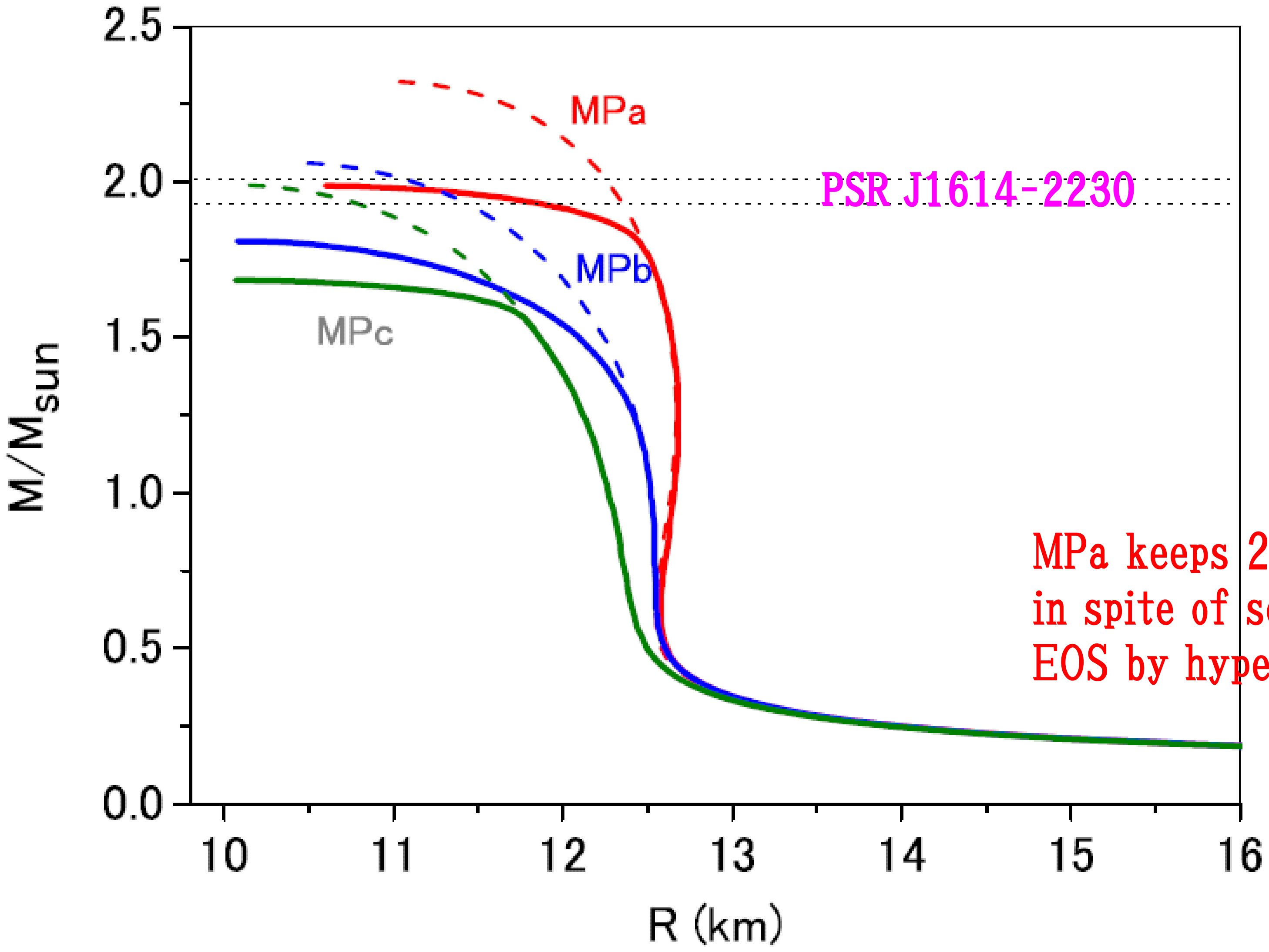
Charge neutrality : $y_p = y_{\Sigma^-} + y_e + y_\mu$

Hyperon-mixed neutron-star matter

Λ Σ^-



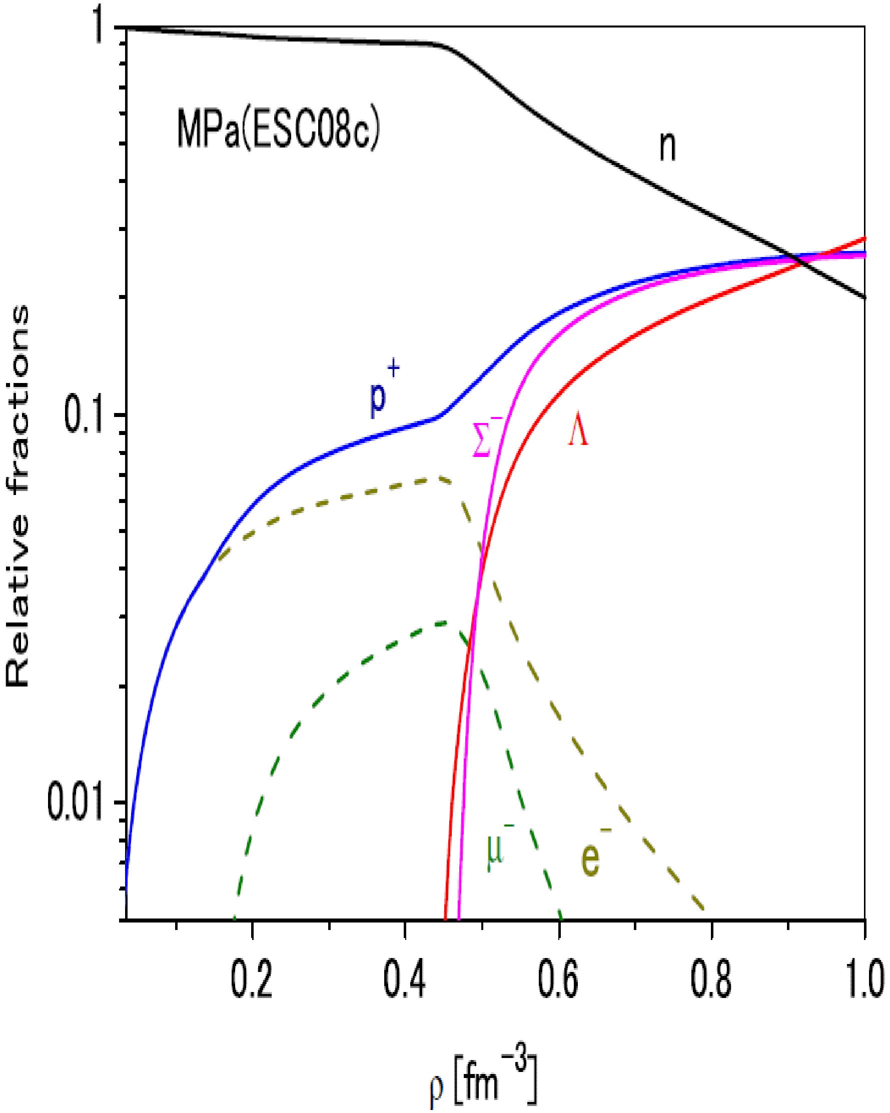
Softening of EOS
by hyperon mixing



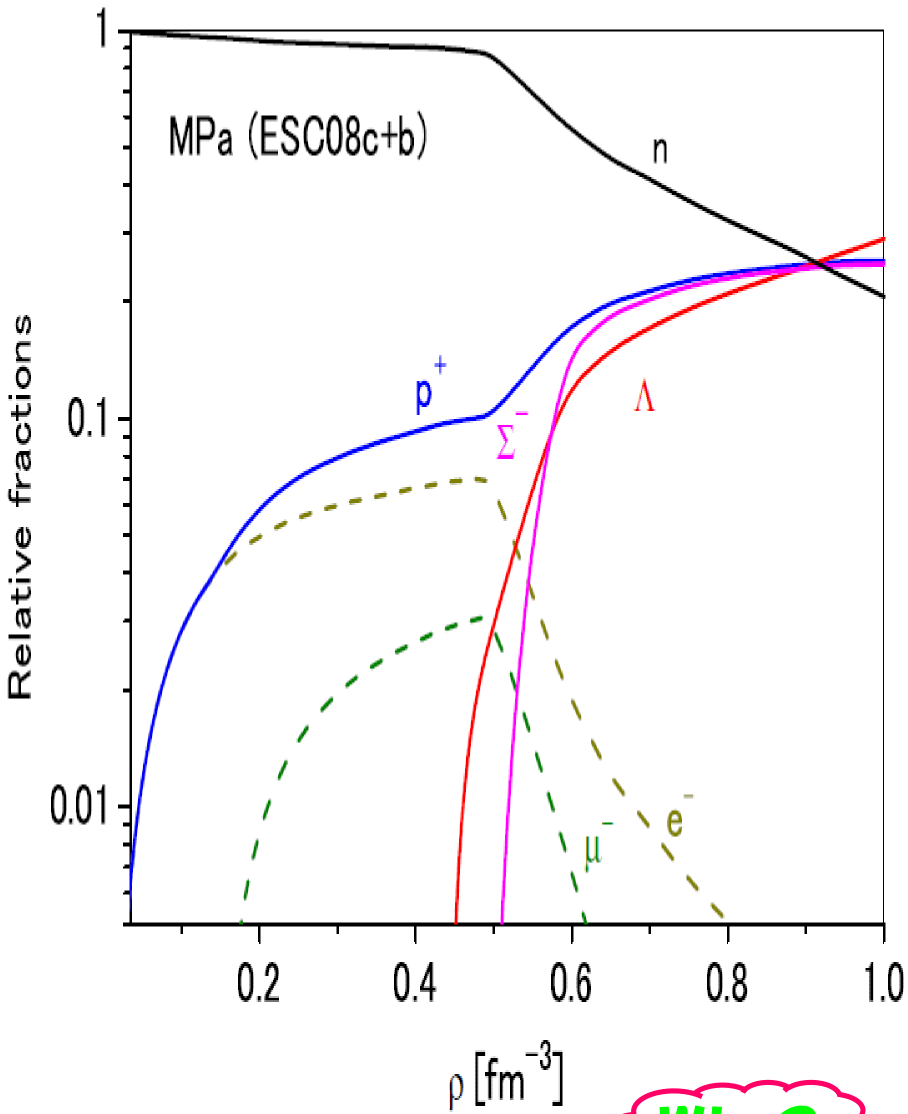
MPa keeps $2M_\odot$ in spite of softening of EOS by hyperon mixing

Maximum mass for MPb/MPc (no 4-body repulsion) is less than $2M_{solar}$

	$M_{max}/M_\odot$	$R(M_{max})$ (km)	$R(1.5M_\odot)$ (km)	$\rho_c(M_{max})/\rho_0$
MPa	1.99	10.6	12.6	6.6
MPb	1.81	10.1	12.1	7.6
MPc	1.68	10.1	11.9	7.8



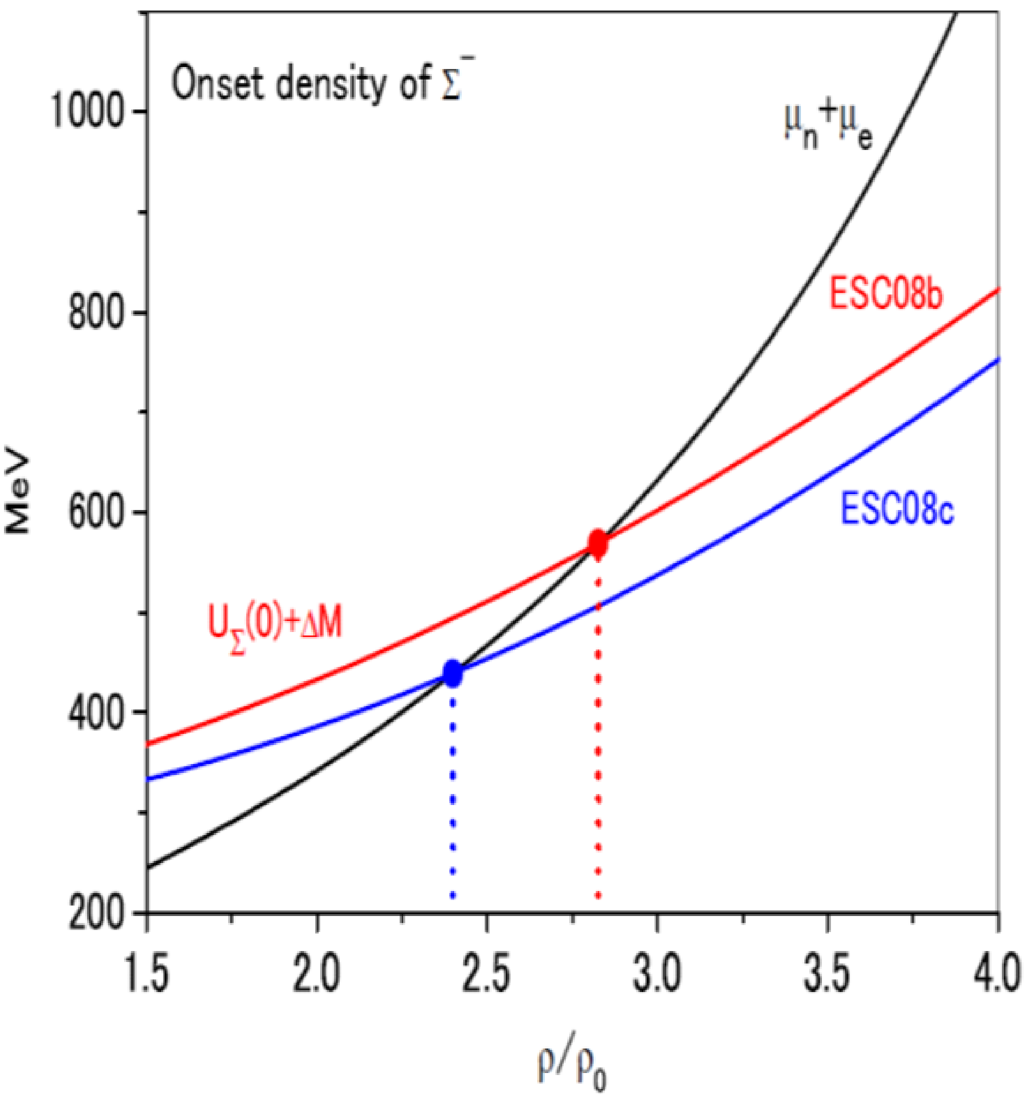
$U_{\Sigma}(\rho_0) \approx 1$ MeV

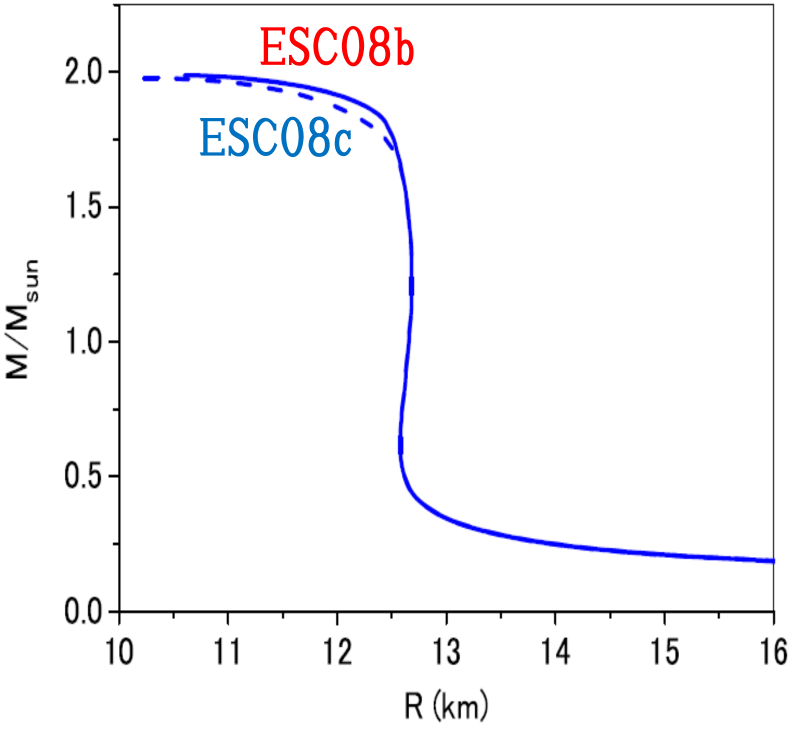


$U_{\Sigma}(\rho_0) \approx 20$ MeV

Why?

Σ^- does not disappear !

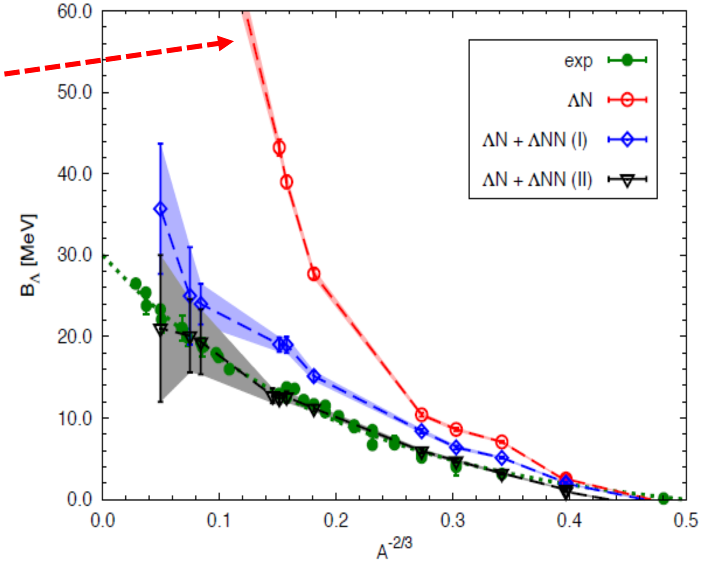

Onset density of Σ^-
$\mu_n + \mu_e$
ESC08b
ESC08c
$U_\Sigma(0)+\Delta M$
MeV
1000
800
600
400
200
1.5
2.0
2.5
3.0
3.5
4.0
ρ/ρ_0


ESC08b
ESC08c
M/M_{sun}
2.0
1.5
1.0
0.5
0.0
10
11
12
13
14
15
16
R (km)

In what situation do hyperons disappear ?

In various RMF models
with U_Σ=20-30 MeV
Σ^- mixing does not occur

ΛN interaction overbinding



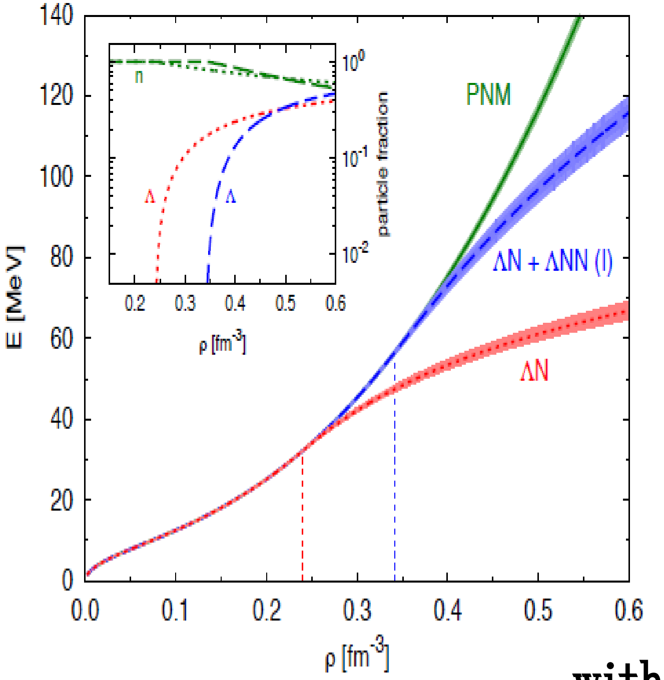
(I) $\left\{\begin{array}{lcll} C_P & = & 0.60 & \text{MeV} \\ C_S & = & 0.00 & \text{MeV} \\ W_D & = & 0.015 & \text{MeV} \end{array}\right.$

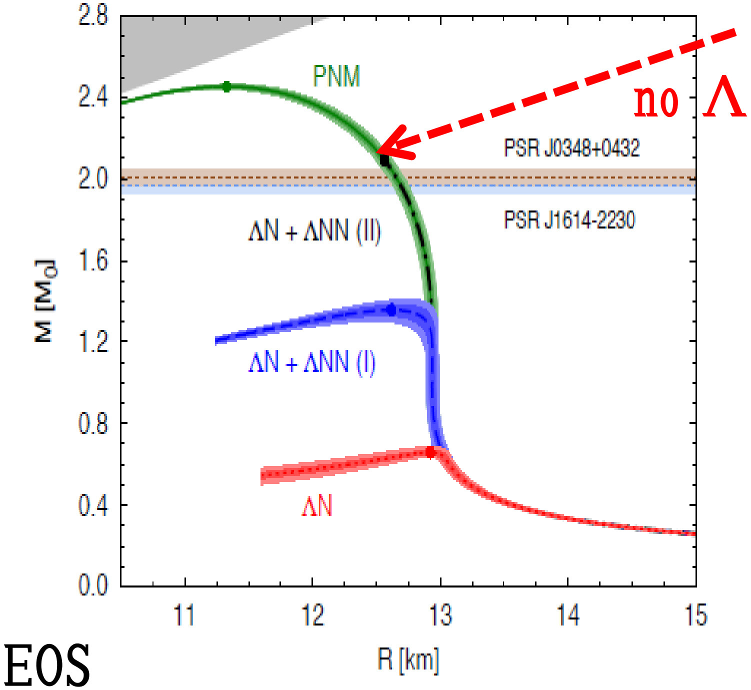
(II) $\left\{\begin{array}{lcll} C_P & = & 1.00 & \text{MeV} \\ C_S & = & 1.50 & \text{MeV} \\ W_D & = & 0.035 & \text{MeV} \end{array}\right.$

UIX: U0=0.0048 MeV

D. Lonardoni

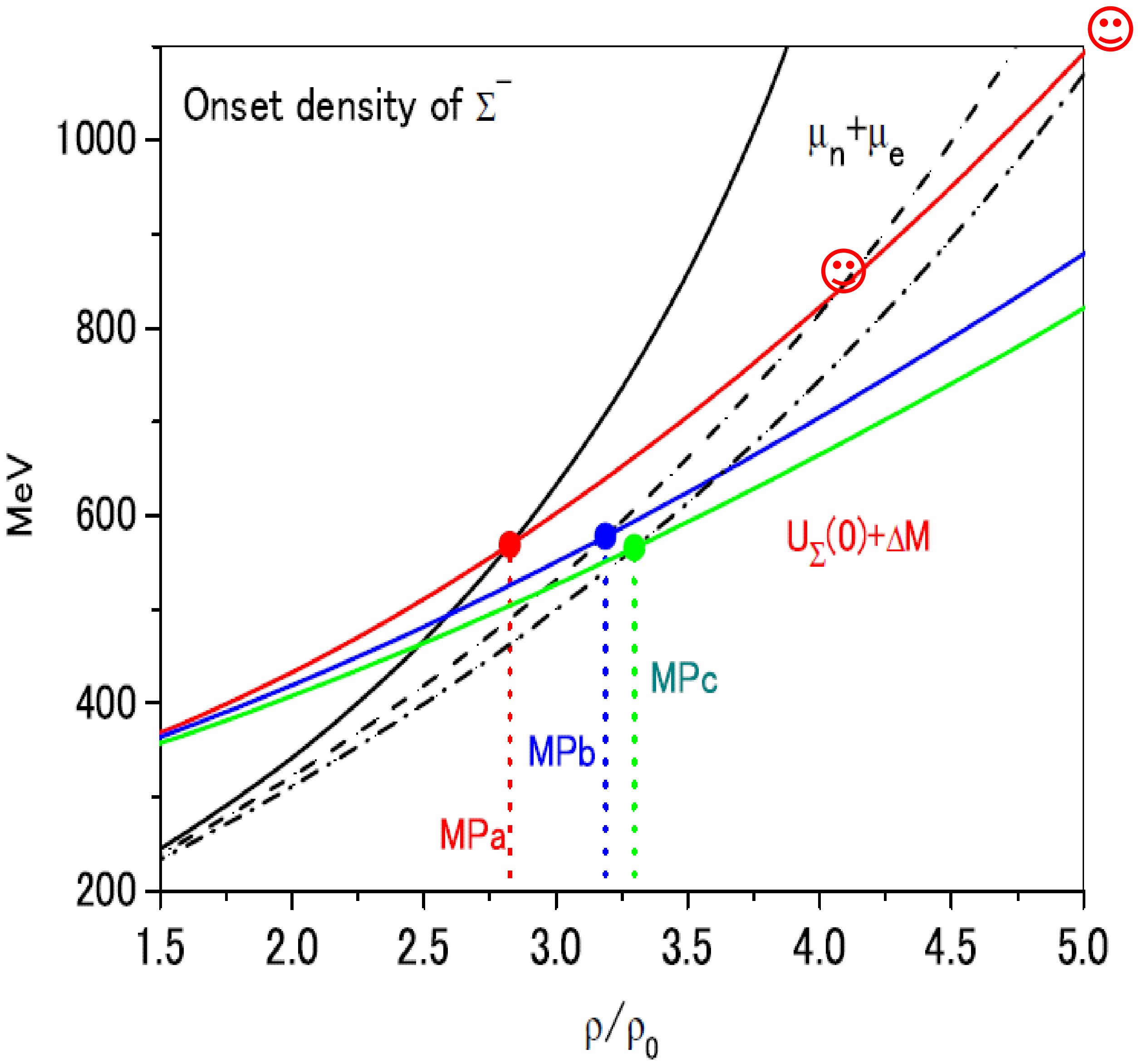
Calculations of $_{\Lambda}He^{5}$ & $_{\Lambda}O^{17}$ Simulation up to $_{\Lambda}Zr^{91}$



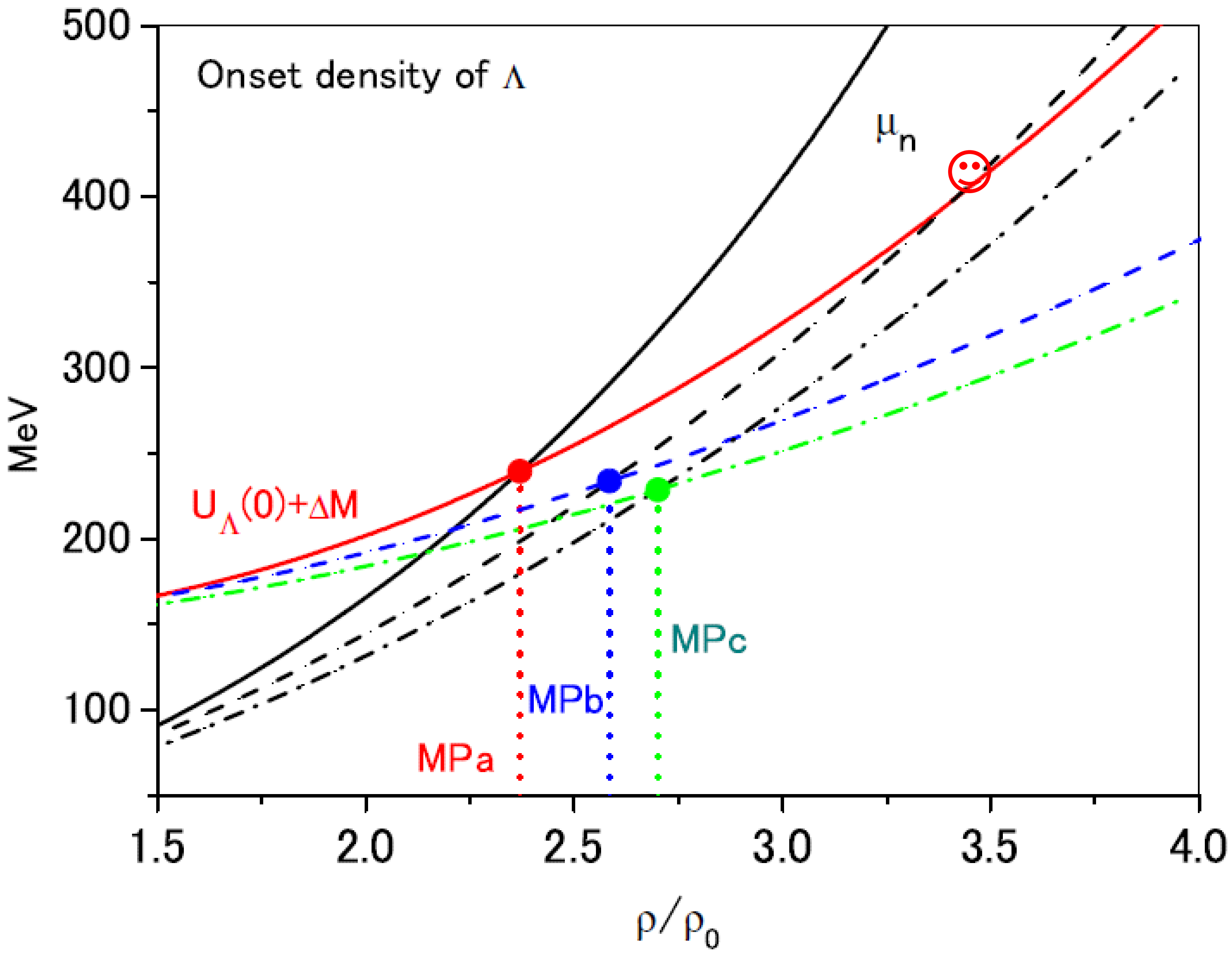


no Λ mixing

with n+Λ EOS

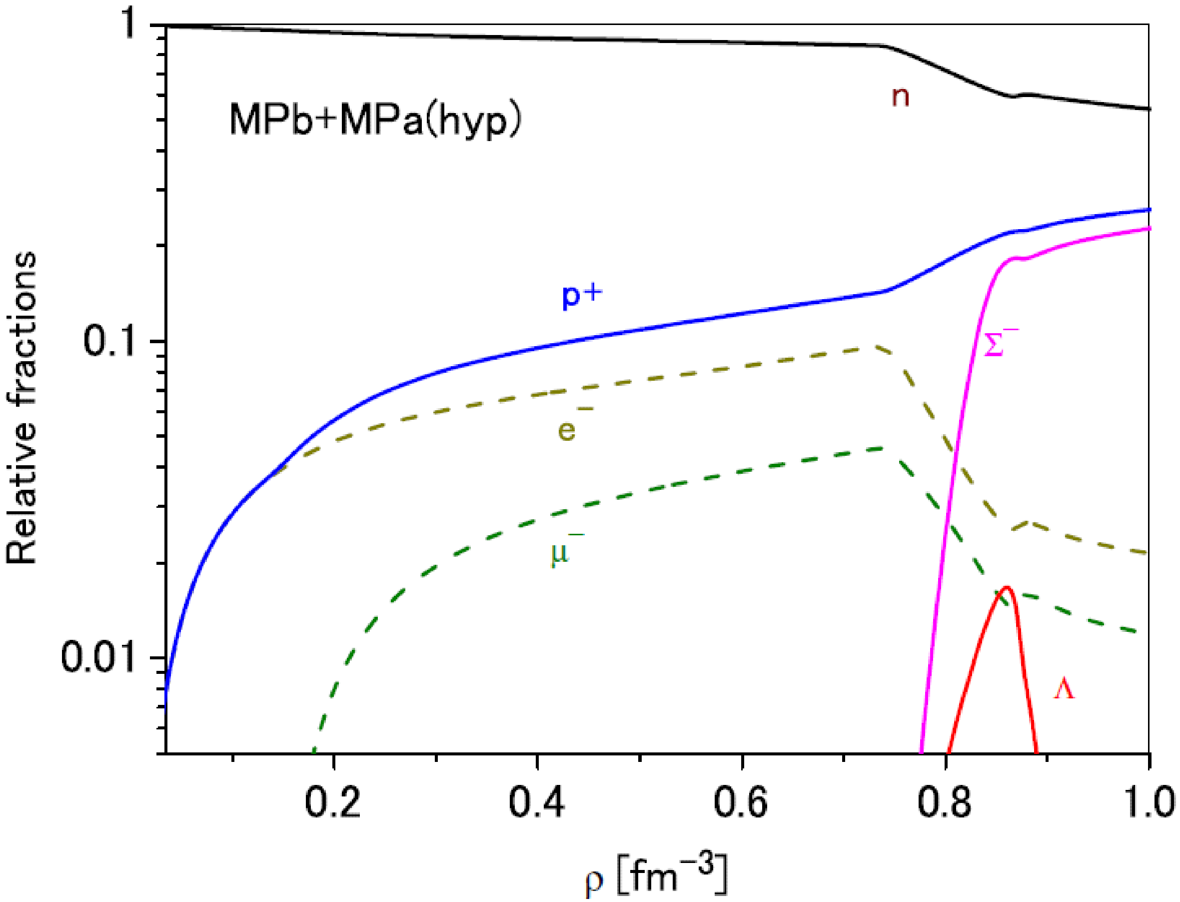


Red curve does not cross with dot-dashed curve !
no onset



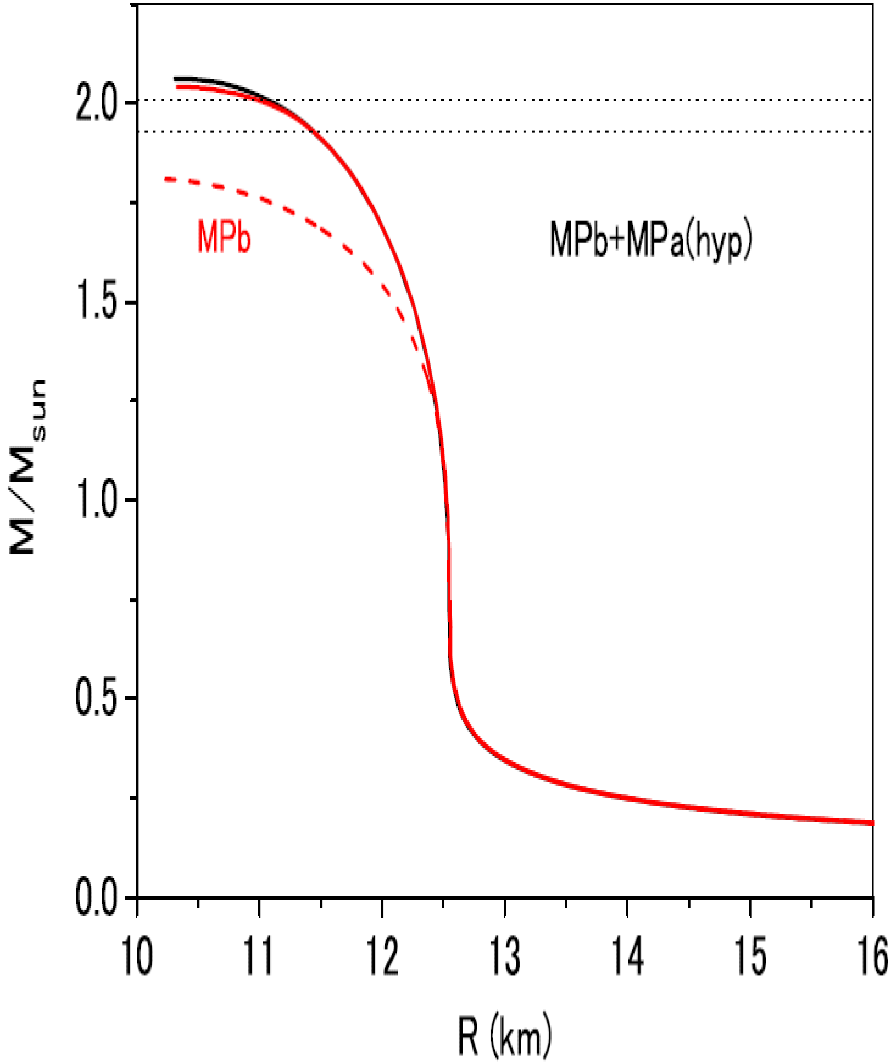
Red curve does not cross with dot-dashed curve !
no onset

Try MPb/c(NN) + MPa(YN)

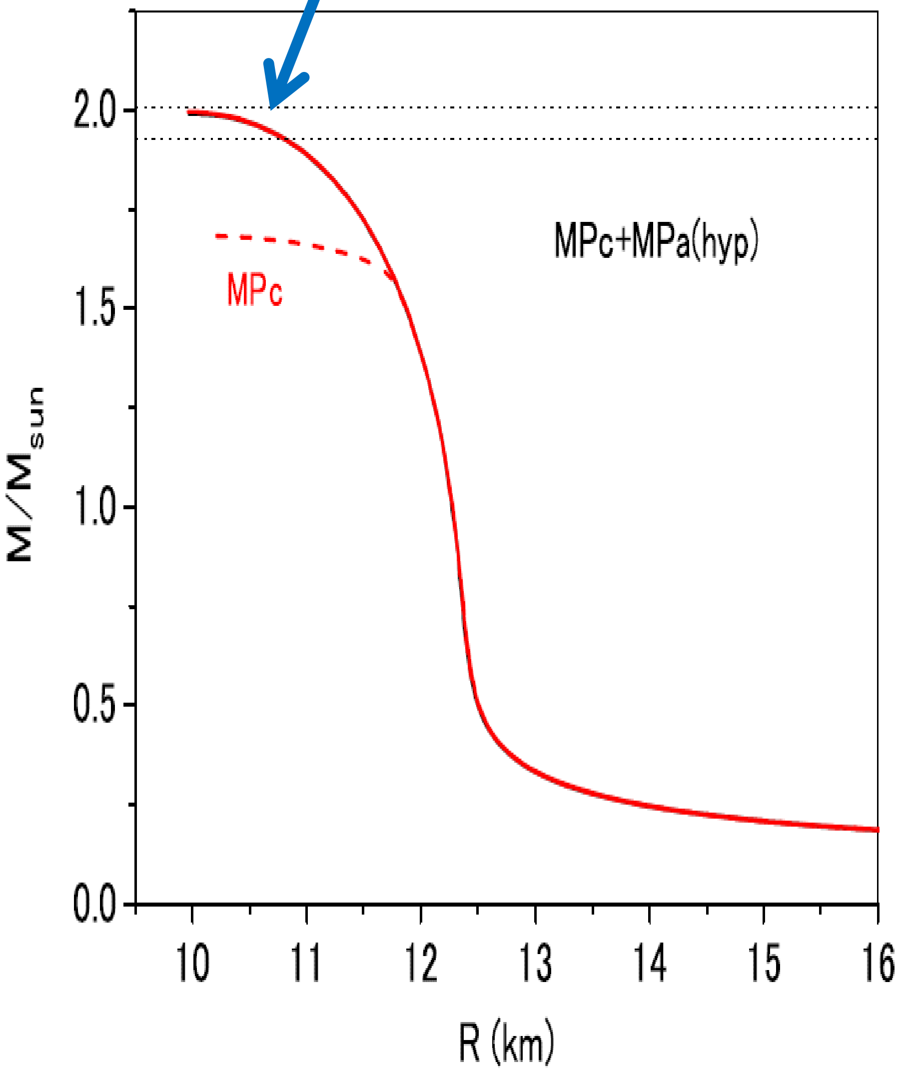


MPa(hyp) is more repulsive than MPb(nuc)

MPc+MPa(hyp) → no hyperon mixing



MPa (hyp) > MPb (nuc)



No hyperon mixing

MPa (hyp) > MPc (nuc)

MPa (3BR+4BR)
K=270

switching off 4BR
same 3BR

MPc (3BR only)
K=225

$M_{max}=2.3\ M_\odot$

no hyperon mixing

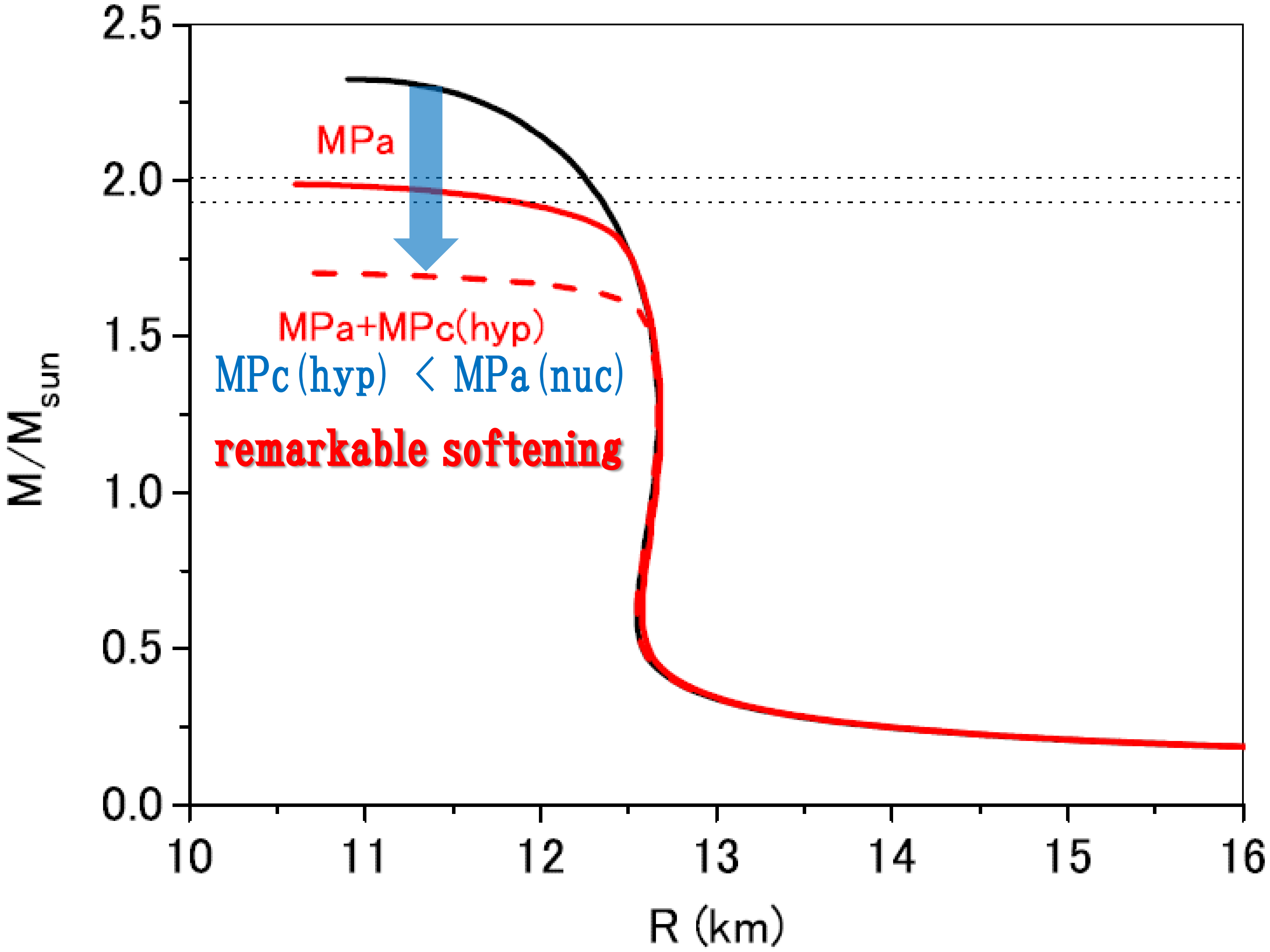
$M_{max}=2.0\ M_\odot$

MPa and MPc reproduce ^{16}O-^{16}O data well

Adopting MPc (nuc) and MPa (hyp), 4BR in hyperon channel only

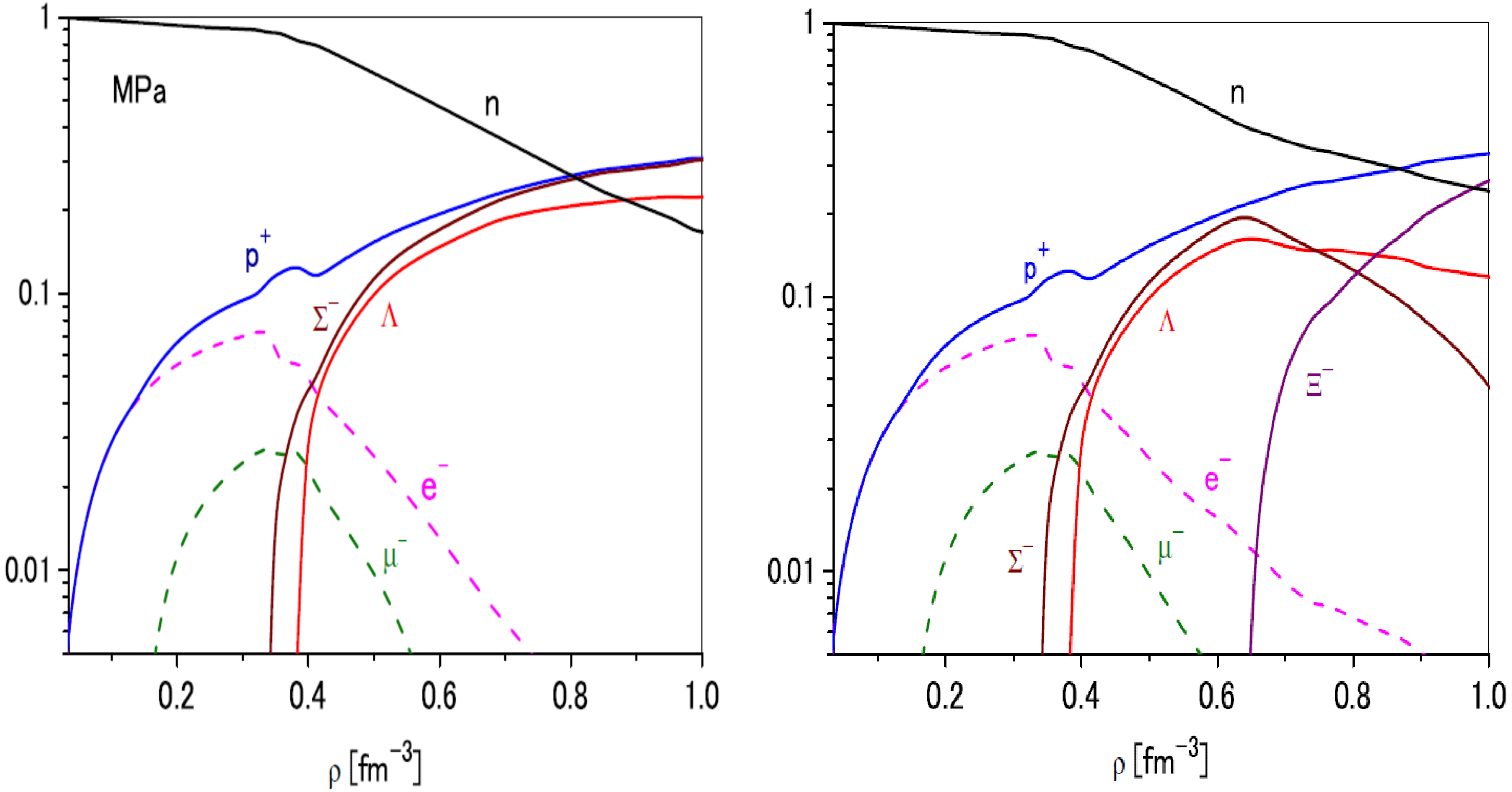
$2M_\odot$ star with no hyperon mixing

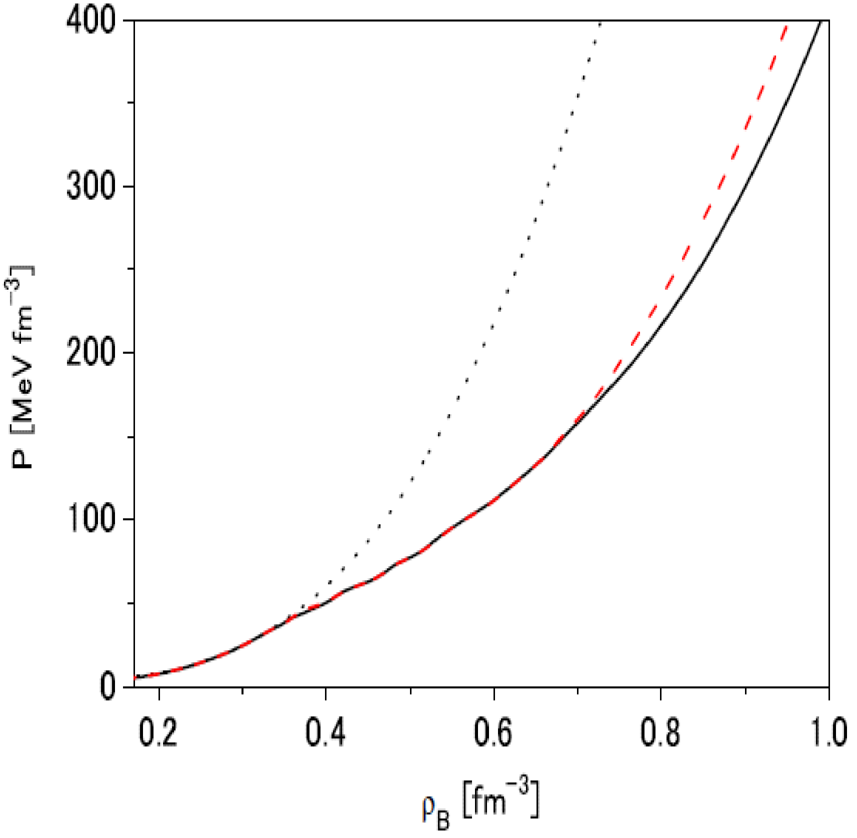
Case:　MPc(hyp) ＜ MPa(nuc)

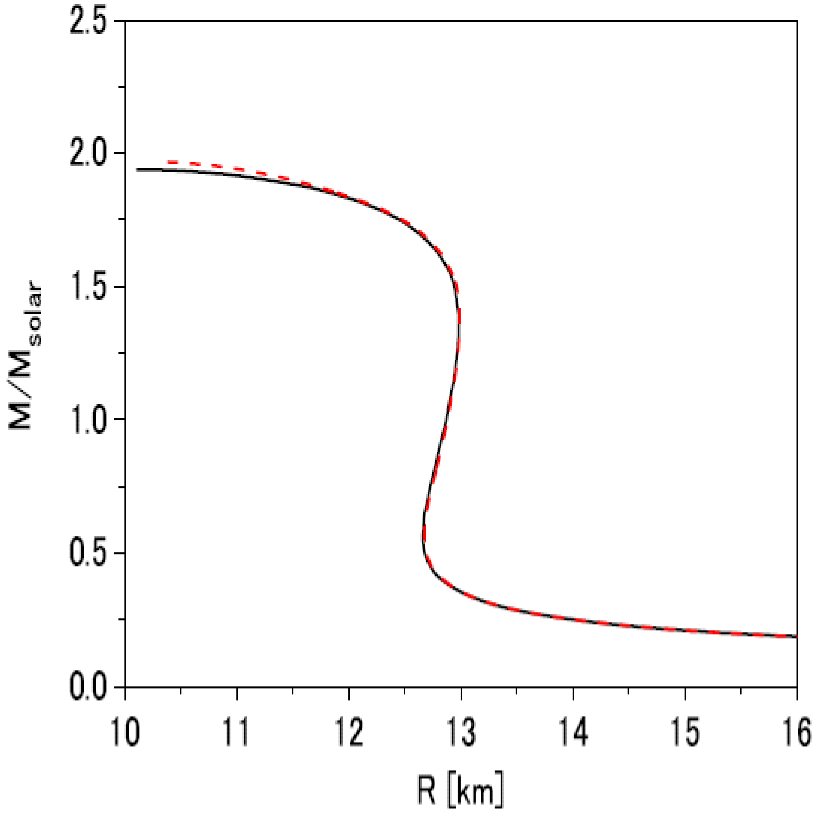


2M_{solar} cannot be obtained in this case！

Ξ^- mixing


MPa
1
0.1
0.01
n
p+
Σ−
Λ
e−
μ−
0.2
0.4
0.6
0.8
1.0
ρ [fm−3]
1
0.1
0.01
n
p+
Λ
Ξ−
e−
Σ−
μ−
0.2
0.4
0.6
0.8
1.0
ρ [fm−3]





Maximum mass is not changed by Ξ^- mixing

Conclusion

ESC+MPP+TBA model

- MPP strength determined by analysis for $^{16}O+^{16}O$ scattering
- TNA adjusted phenomenologically to reproduce saturation properties
- Consistent with hypernuclear data
- No ad hoc parameter to stiffen EOS

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

MPb/c including 3-body repulsion only lead to
slightly smaller values than $2M_\odot$ quantitatively
MPP(hyp) > MPP(nuc) and MPP(hyp) < MPP(nuc) lead to
large reduction and enhancement of softening
by hyperon mixing, respectively

Final comment:

Decisive superiority of our approach to universal repulsion

MPP works among everything (not only N,Y, but also Δ, K^-, q, etc)

MPP prevent softening of EOS from everything