2017/3/14 SNP2017

Baryon-Baryon interaction and neutron-star EOS

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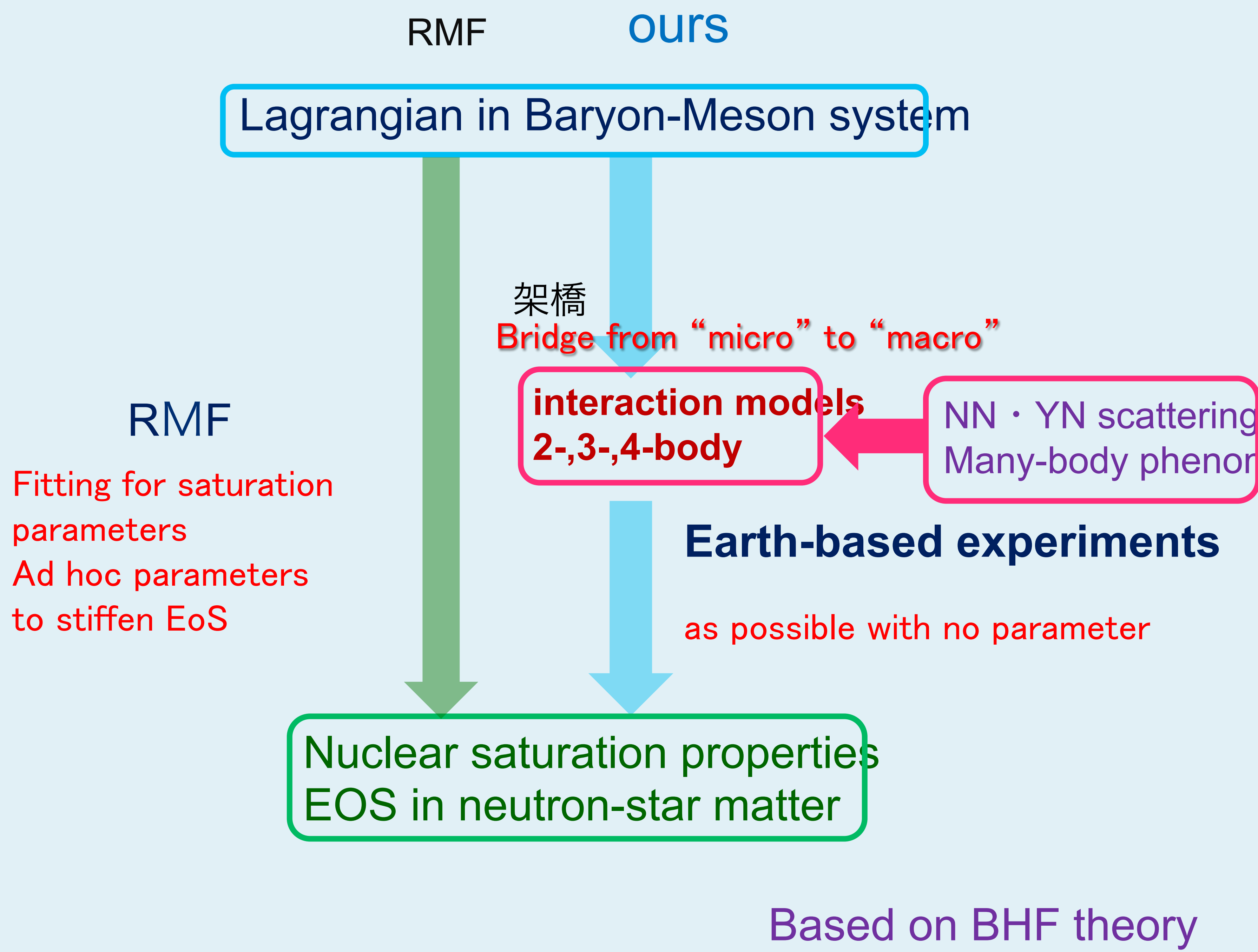

RMF
ours
Lagrangian in Baryon-Meson system
架橋
Bridge from “micro” to “macro”
interaction models
2-,3-,4-body
NN・YN scattering
Many-body pheno
RMF
Fitting for saturation
parameters
Ad hoc parameters
to stiffen EoS
Earth-based experiments
as possible with no parameter
Nuclear saturation properties
EOS in neutron-star matter
Based on BHF theory

Hyperon puzzle !

Massive ($2M_\odot$) neutron stars

2010	**PSR J1614-2230**	$(1.97\pm0.04)M_\odot$
2013	**PSR J0348-0432**	$(2.01\pm0.04)M_\odot$

?

Softening of EOS by hyperon mixing

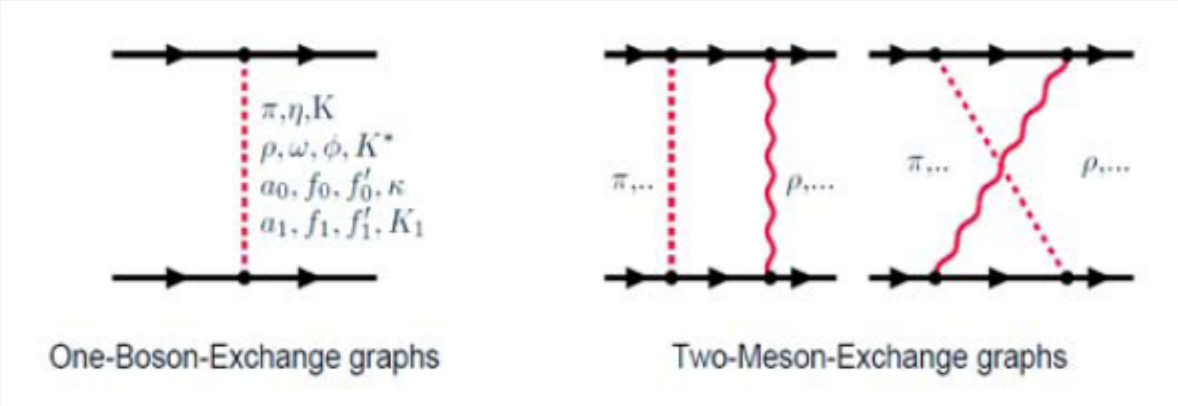
Our approach :
Try to solve the hyperon puzzle by
Universal Multi-Baryon Repulsion
on the basis of terrestrial data

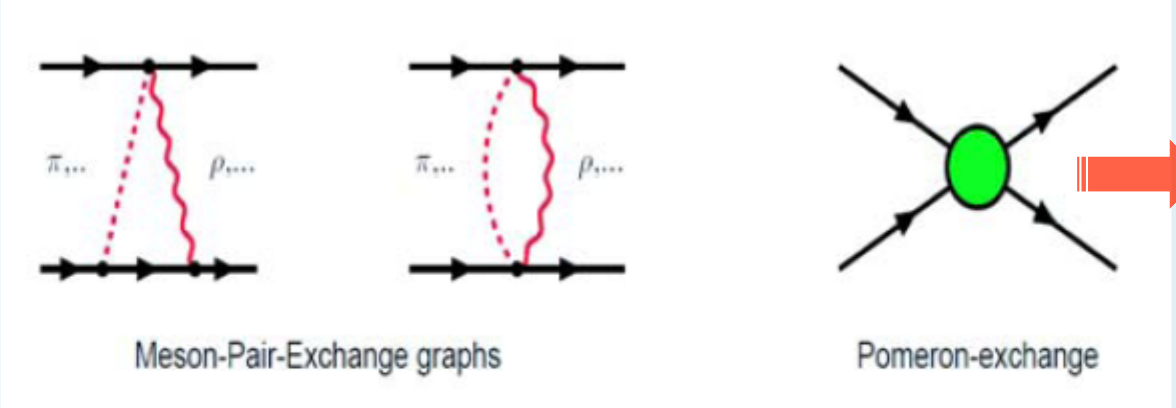
Our approach to neutron-star matter starts from the BB interaction model

Nijmegen Extended Soft-Core Model (ESC)

Proposed by
T. Rijken

SU_3 invariant (NN and YN) interaction





multi-Pomeron
repulsion

universal

repulsive cores

A model of Universal Multi-Baryon Repulsion

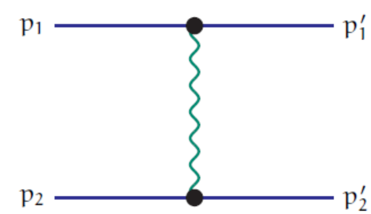
Multi-Pomeron Exchange Potential (MPP)

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

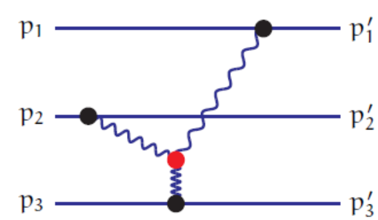
$$\mathcal{L}_{PNN} = g_P \bar{\psi}(x)\psi(x)\,\sigma_P(x)$$

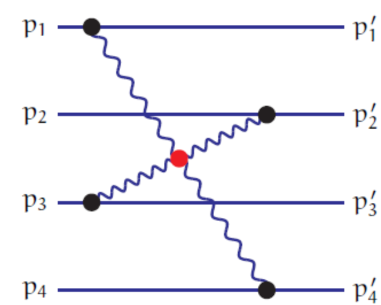
$$\Delta_F^P(k^2) = +\exp(-\mathbf{k}^2/4m_P^2)/\mathcal{M}^2$$

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



Pomeron exchange gives repulsion because of positive propagator





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

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

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

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

Why MPP ?

Decisive superiority of our approach to universal repulsion

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

MPP prevent softening of EOS from everything

expect

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

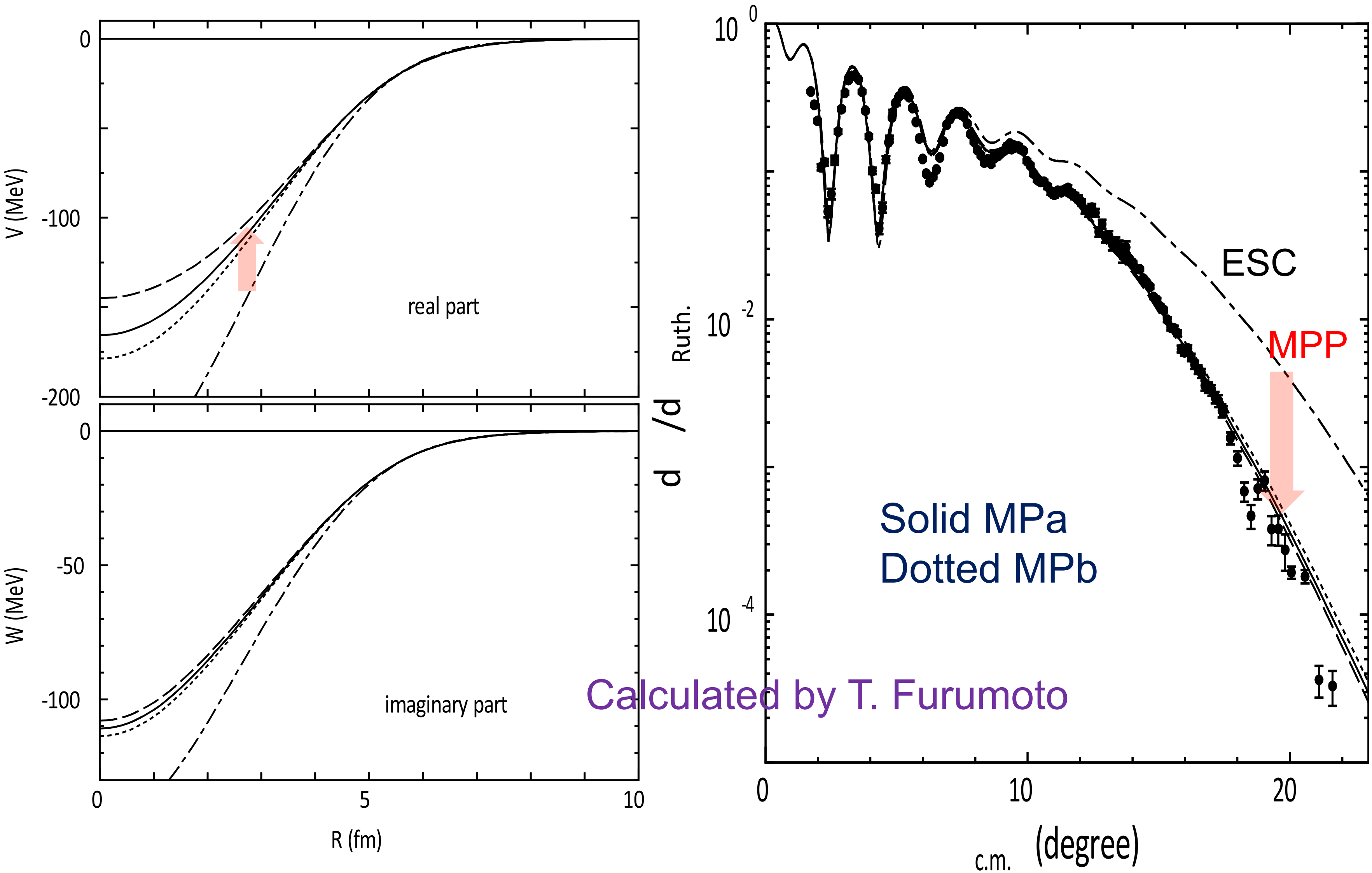
$$V_A(r;\rho) = V_0 \exp[-(r/2.0)^2]\, \rho \exp(-\eta\rho)\,(1+P_r)/2$$

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).

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



Calculated by T. Furumoto

Strength of MPP can be determined !!!

Three parameter sets

Stiffness of EOS

	MPa	MPb	MPb$^+$
K=	270	254	280
L=	61	60	74

	$g_P^{(3)}$	$g_P^{(4)}$	V_0	η	
MPa	2.34	30.0	-54.0	10.0	3- & 4-body MPP
MPb	2.94	0.0	-68.0	11.2	3-body MPP
MPb$^+$	2.94	0.0	-56.0	8.0	Additional T-dependent TBF

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

diffractive production of showers of particles $pp \to pX$

$$g_P^{(3)} = 1.95 \sim 2.6$$

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

Suggesting MPa

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

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

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

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

$$\eta = (KL^2)^{1/3}$$

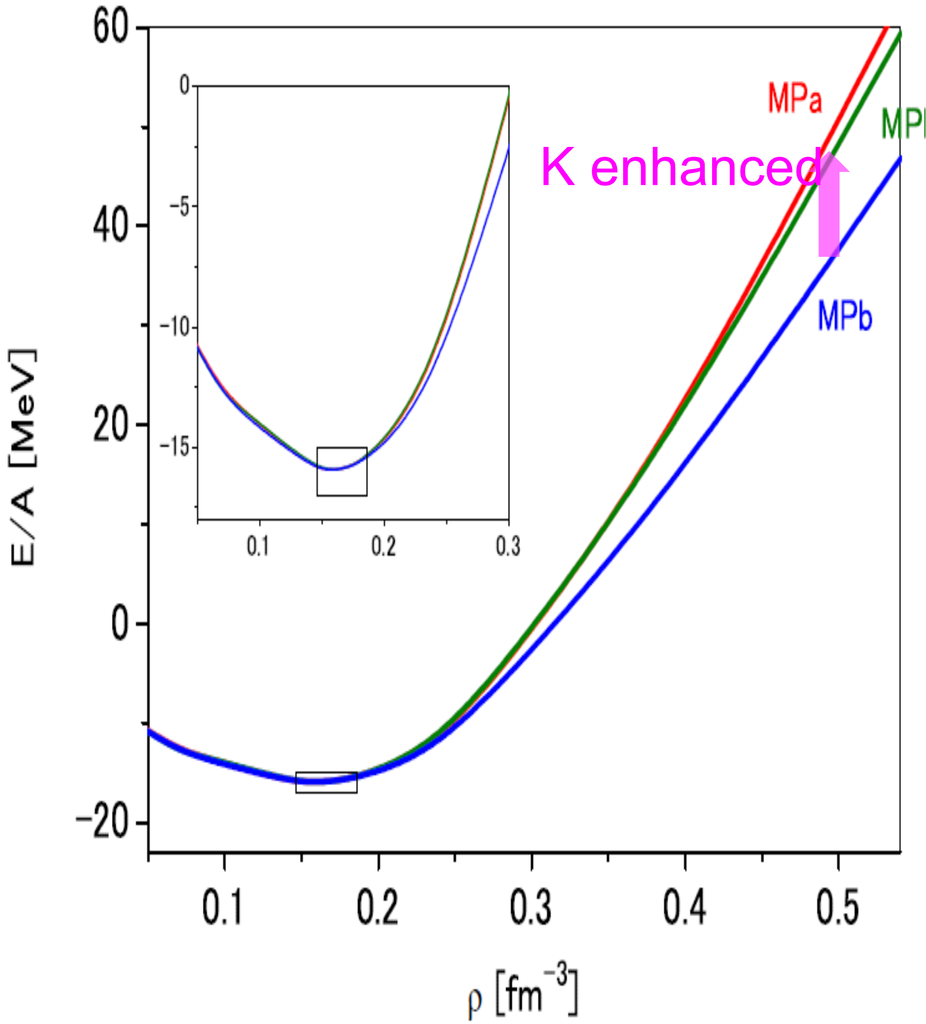
by Sotani

Saturation parameters

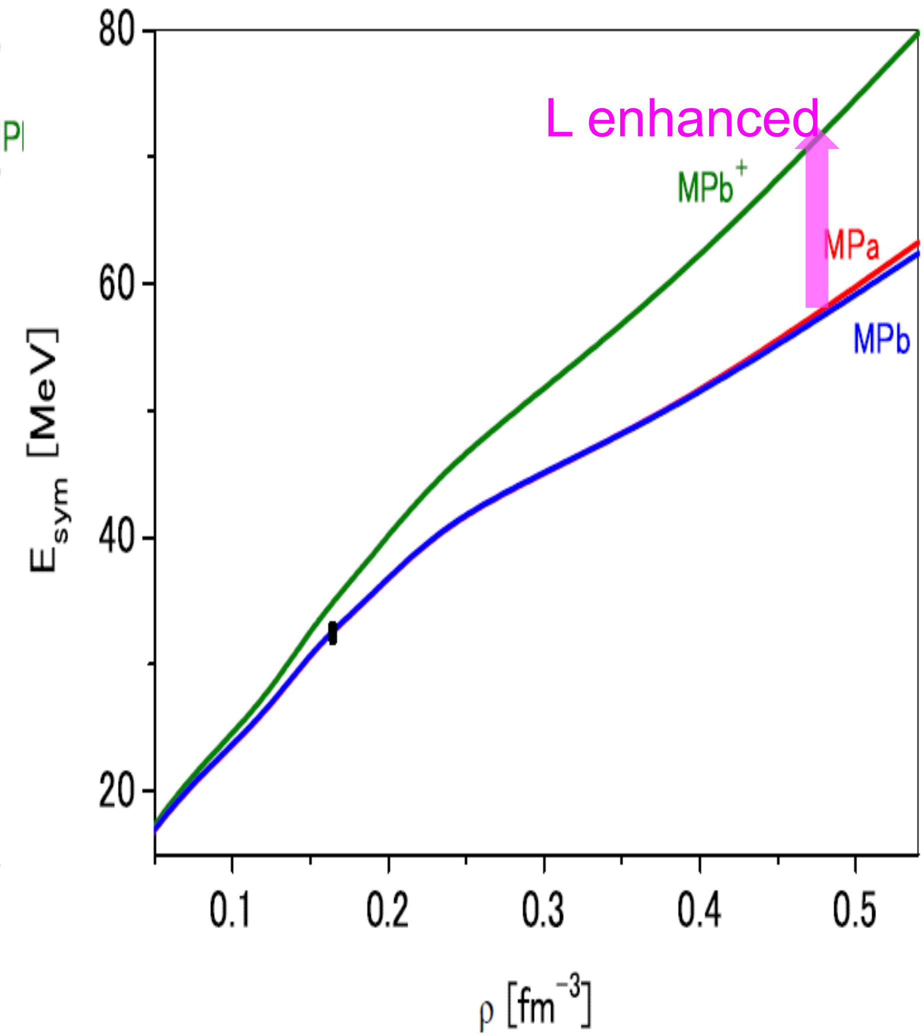
	ρ_0 (fm^{-3})	E/A (MeV)	E_{sym} (MeV)	L (MeV)	K (MeV)	η (MeV)
MPa	0.155	−16.0	31.3	60.7	270	99.8
MPb	0.155	−16.0	31.3	60.2	254	97.3
MPb$^+$	0.155	−16.0	33.3	73.7	280	115

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

E/A curves



E_{sym}

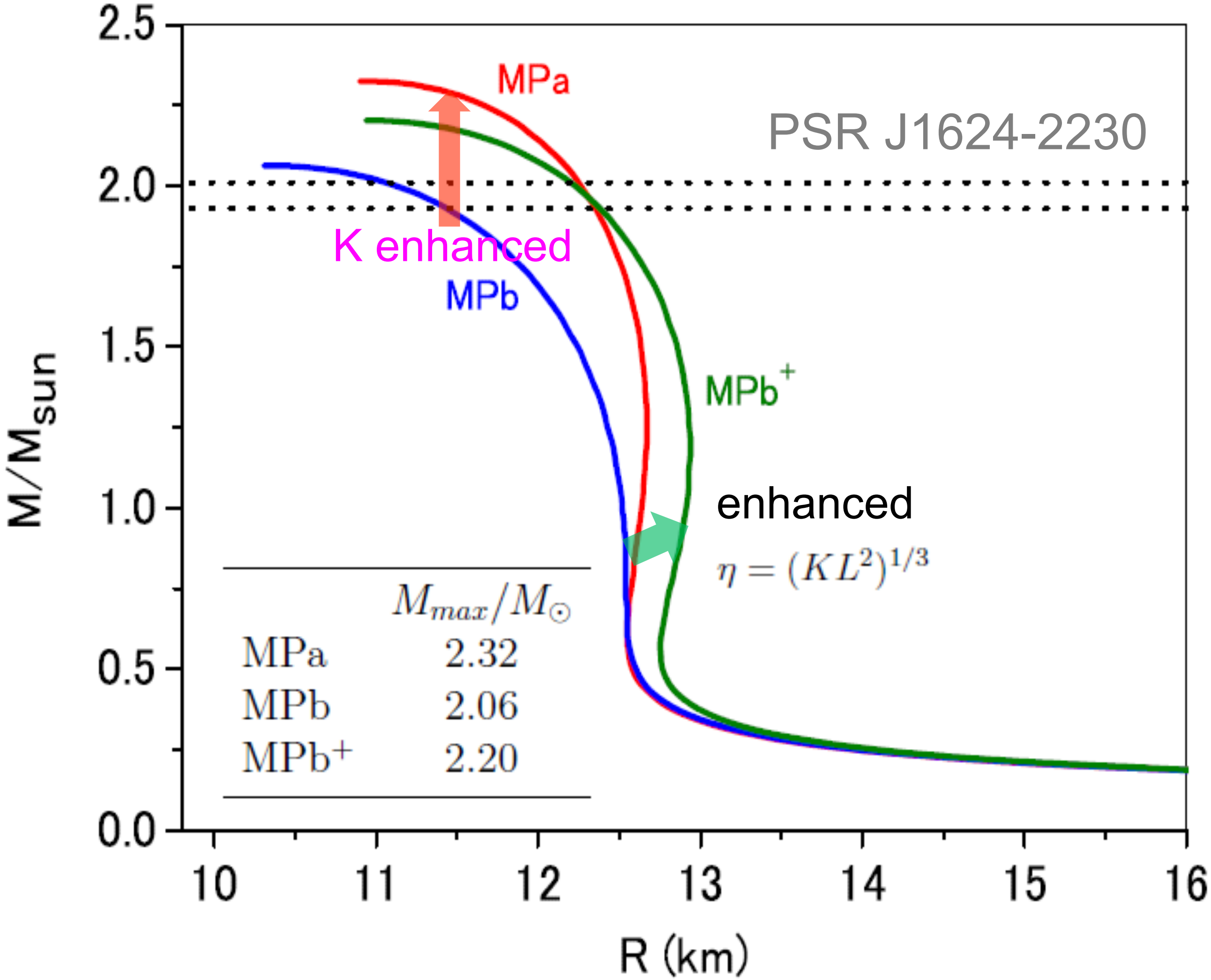


MPa including 3- and 4-body MPP **:** **MPb** including 3-body MPP only

MPb^+ MPb+ T-dependent MPP

by solving TOV eq.

with n+p β-stable matter



$2M_{solar}$ with
no ad hoc parameter

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

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

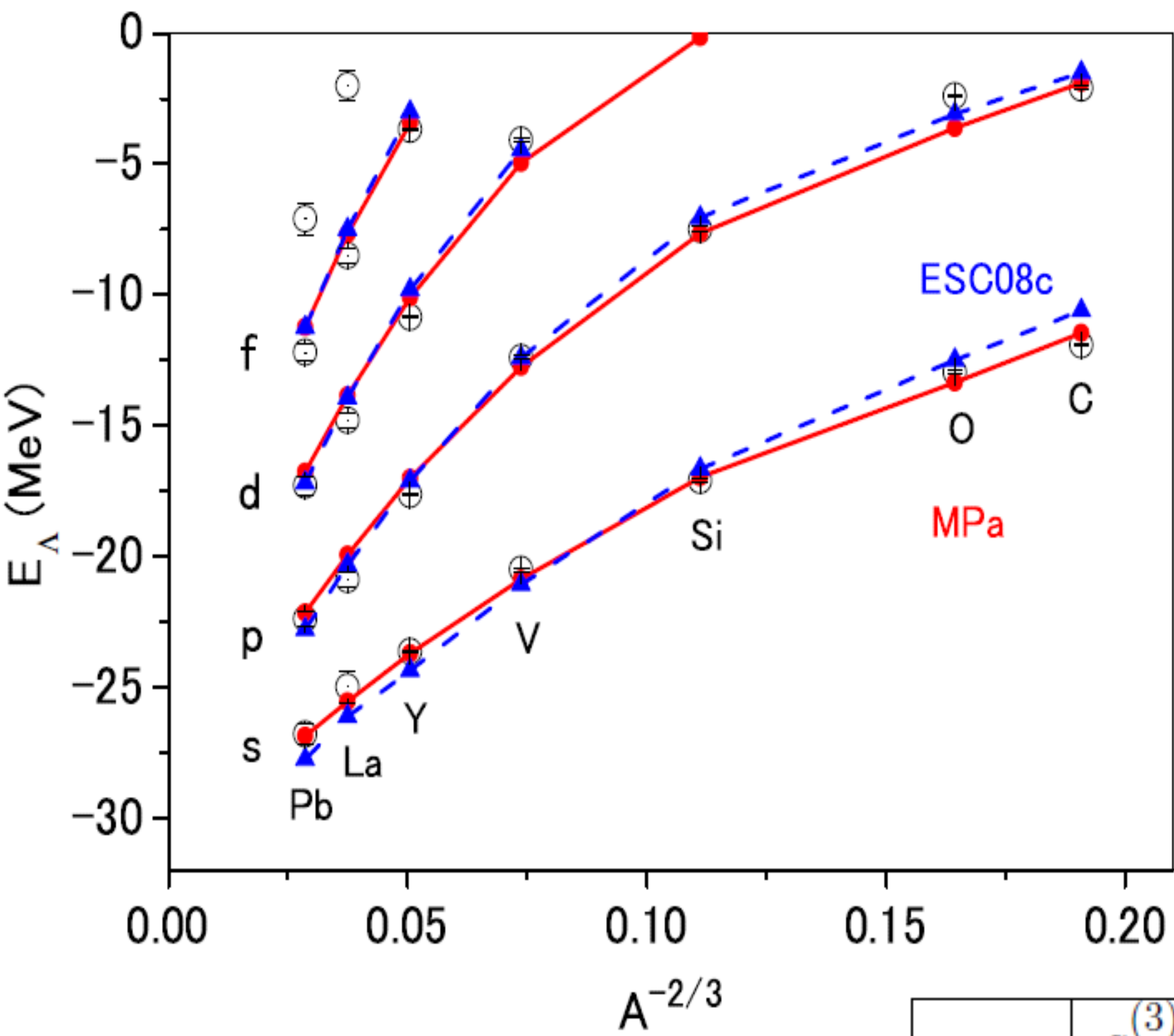
Averaged-k_F Approximation

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

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

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.



Similarly fitted by MPb

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

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

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

HyperAMD
by M. Isaka

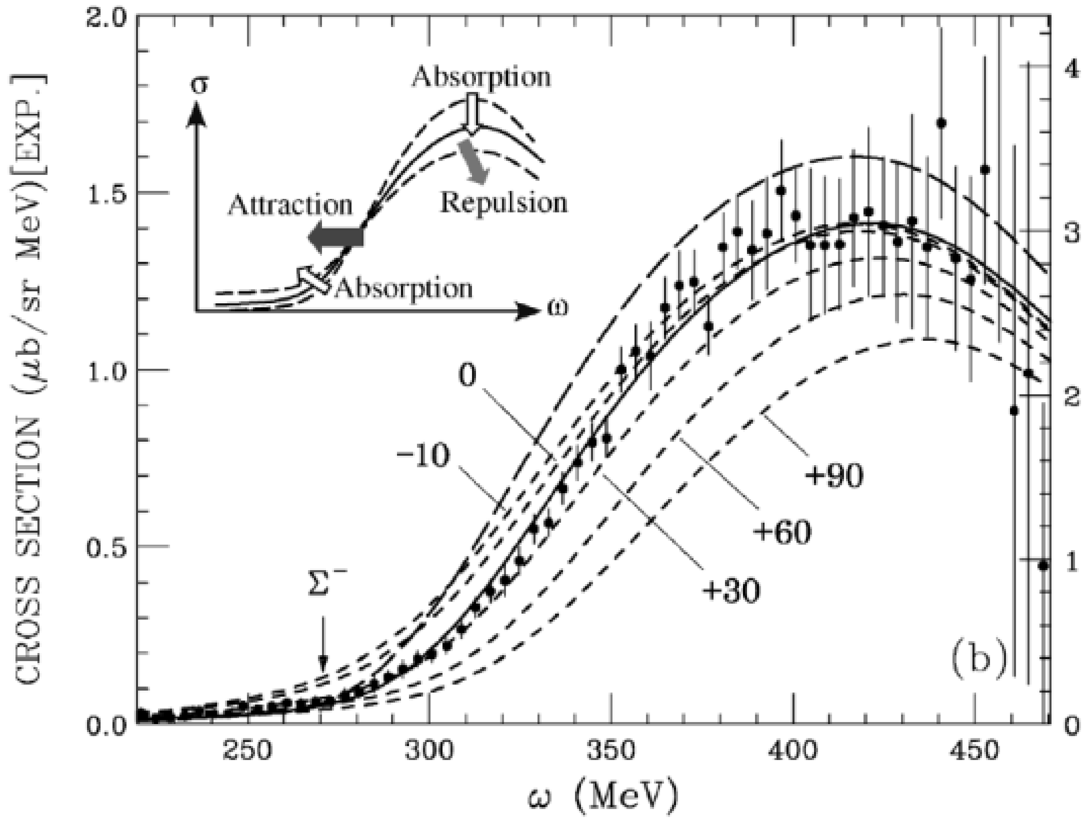
	$-B_\Lambda$ based on ESC14		
	V_{BB} only	w/ MBE	$-B_\Lambda^{\rm exp}$
${}^{9}_{\Lambda}$Li(∗)	−7.6	−8.1	-8.50 ± 0.12[28]
${}^{9}_{\Lambda}$Be	−7.7	−8.1	-6.71 ± 0.04[29]
${}^{9}_{\Lambda}$B(∗)	−7.7	−8.2	-8.29 ± 0.18[28]
${}^{10}_{\Lambda}$Be(∗)	−8.6	−9.0	-9.11 ± 0.22[26], -8.55 ± 0.18[33]
${}^{10}_{\Lambda}$B(∗)	−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-



by T. Harada

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

$\boxed{U_\Sigma = +20\sim 30 \text{ MeV}}$

$$(V_0^\Sigma, W_0^\Sigma) = (+20 \text{ MeV}, \ -20 \text{ MeV})$$
$$(+30 \text{ MeV}, \ -40 \text{ MeV})$$

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

Pauli-fo r bidden 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 ?

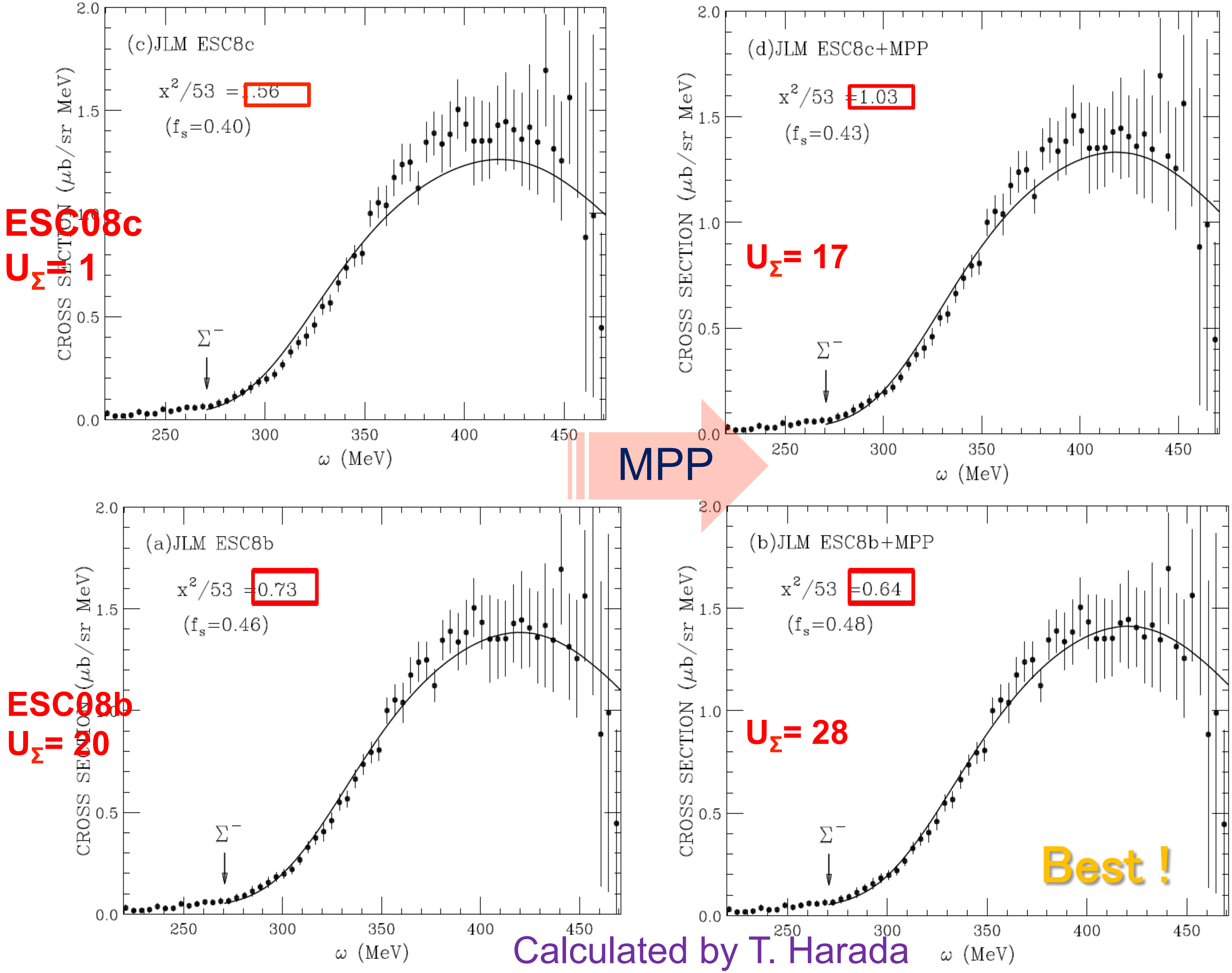
U_Σ(ESC08c)=+0.8 MeV ➔ too weak repulsion ?

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

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

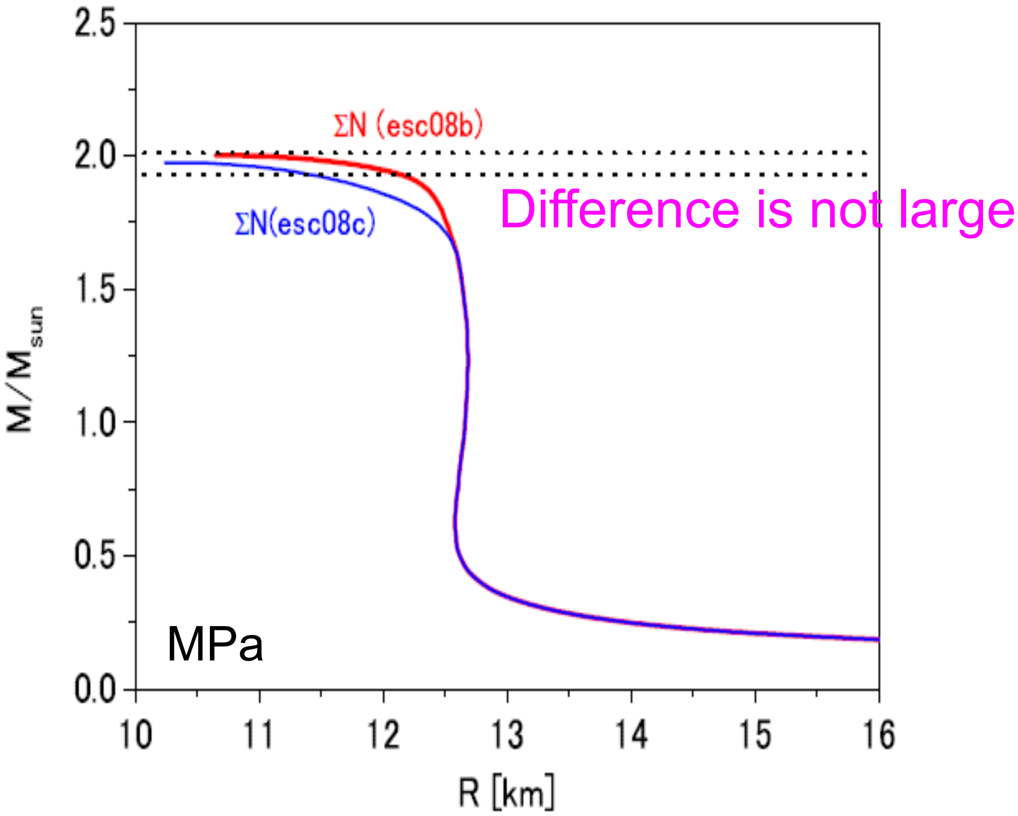
4 cases	ESC08c	ESC08c+MPP
	ESC08b	ESC08b+MPP

MPP=MPa without TNA



(c)JLM ESC8c
x²/53 =1.56
(fs=0.40)
ESC08c
UΣ= 1
(d)JLM ESC8c+MPP
x²/53 =1.03
(fs=0.43)
UΣ= 17
MPP
(a)JLM ESC8b
x²/53 =0.73
(fs=0.46)
ESC08b
UΣ= 20
(b)JLM ESC8b+MPP
x²/53 =0.64
(fs=0.48)
UΣ= 28
Best !
CROSS SECTION (μb/sr MeV)
ω (MeV)
Σ⁻
Calculated by T. Harada

We use **ESC08b** for ΣN parts in MPa/b (TBA=0)



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

EoS of n+p+Λ+Σ+e+μ 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

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

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

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

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

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

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 components are highly model-dependent
Results from special modeling should not be generalized

Hyperon Onset Density in neutron matter estimated by

$$U_\Lambda(0) + (M_\Lambda - M_n) = \mu_n$$

176 MeV

$$U_{\Sigma^-}(0) + (M_{\Sigma^-} - M_n) = \mu_n + \mu_e$$

258 MeV

~190 MeV @2.5ρ_0

$$U_{\Xi^-}(0) + (M_{\Xi^-} - M_n) = \mu_n + \mu_e$$

382 MeV

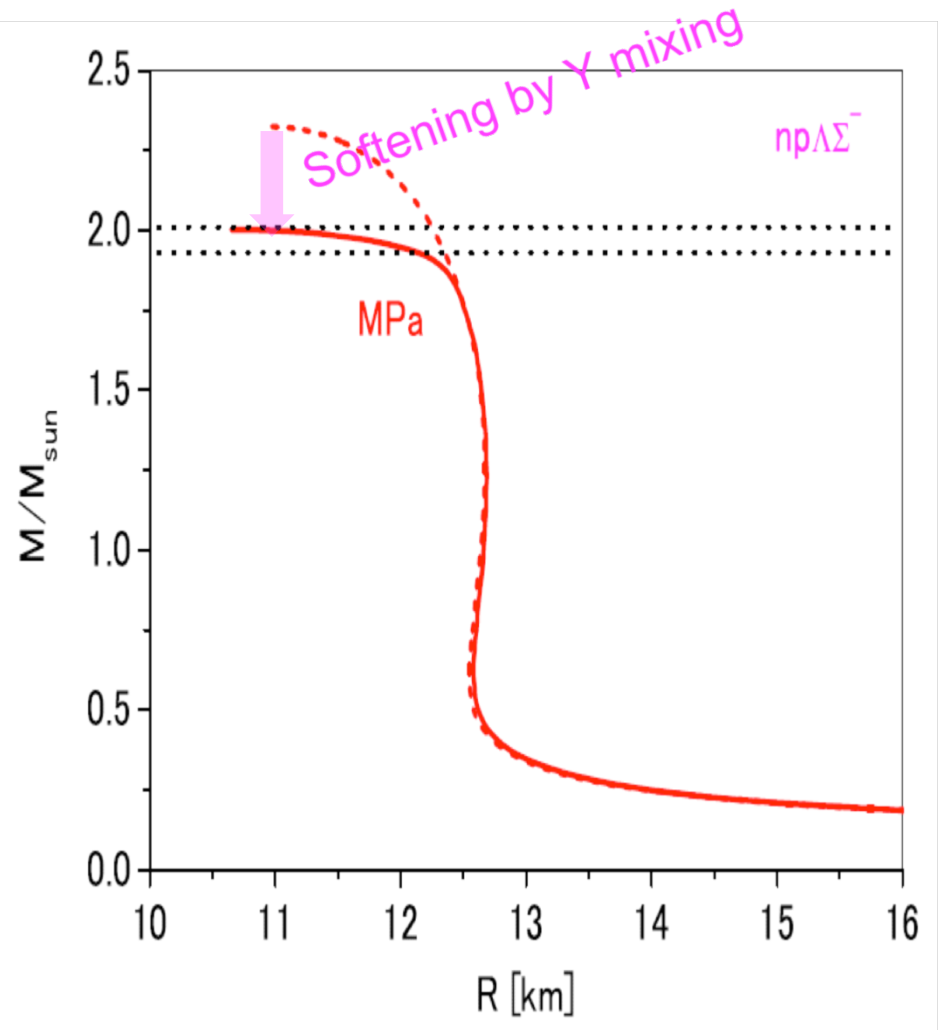
μ_e makes Σ^- mixing easier than Λ mixing
This merit is partially canceled by positive $U_\Sigma(0)$

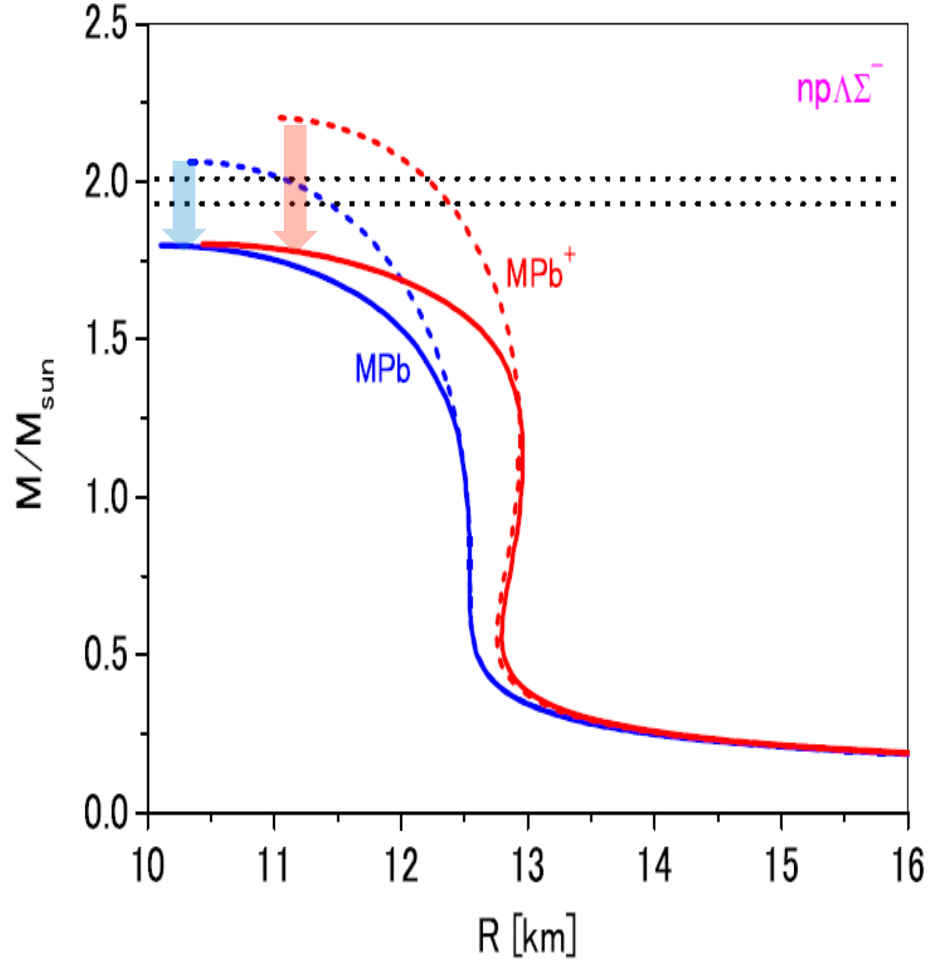
Large M_Ξ-M_n is disadvantageous for Ξ^- mixing
in spite of merits by μ_e and negative $U_\Xi(0)$

RMF models insufficient

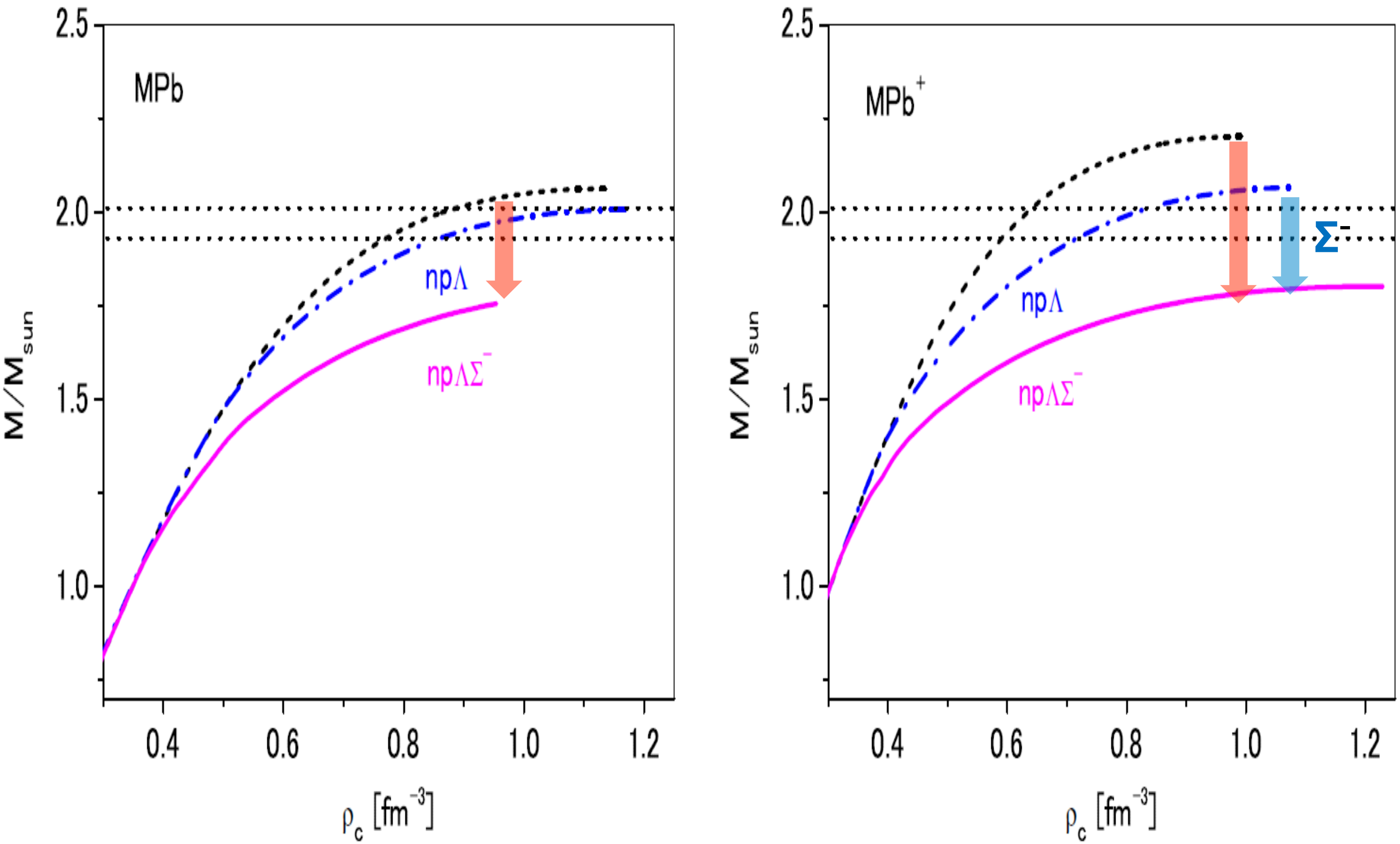
In our model

U_Σ>0 does not lead to no Σ^- mixing automatically
nnn repulsion in μ_n works favorably to Σ mixing, even if U_Σ>0





$2M_{\odot}$ is (not) obtained by MPa (MPb and MPb^{+})



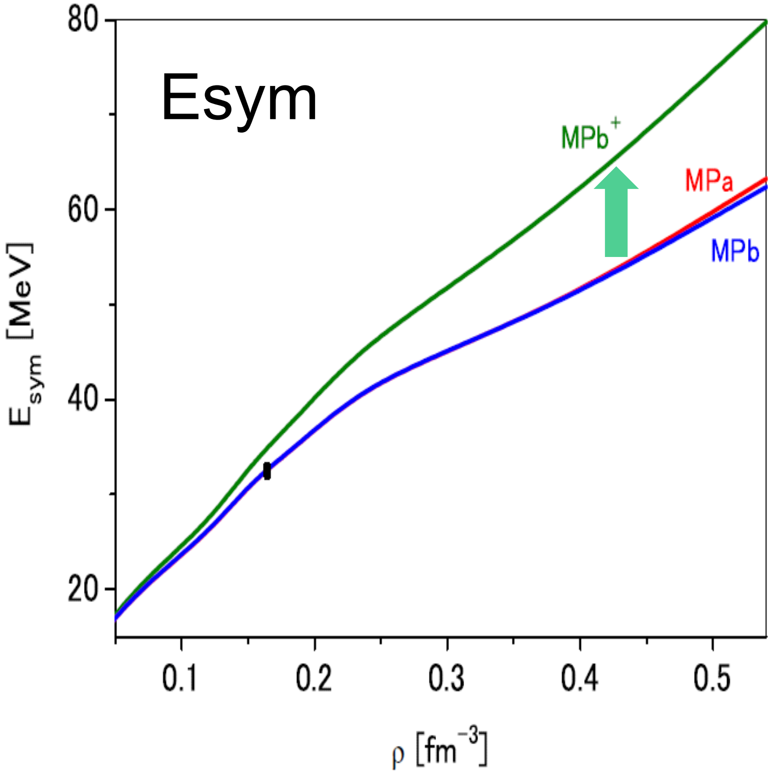
Softening of EOS by hyperon mixing is more remarkable in MPb^{+} case

Differently from RMF models, there still appears Σ^{-} mixing in our model even if ΣN interaction (ESC08b) giving U_{Σ}～+28 MeV is used

Effect of Σ^- mixing is more remarkable than that of Λ mixing

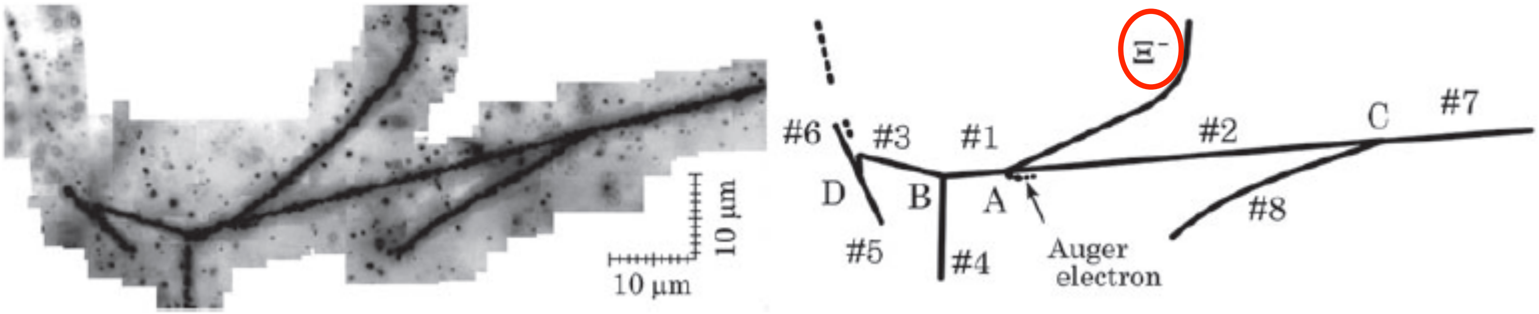
sensitive to symmetry energy in nuclear part

slope parameter L



Ξ^- mixing in neutron-star matter based on ESC+MPP+TBA model

KISO event



KISO event is uniquely identified as

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

with $B_\Lambda({}^{10}_{\Lambda}\mathrm{Be})$=8.60±0.07 MeV @ $(e, e'K^+)$ exp. JLab E05-115

$B_{\Xi^-} = 3.87 \pm 0.13$ MeV

assuming ${}^{10}_{\Lambda}$Be in first excited state, $B_{\Xi^-} = 1.11 \pm 0.25$ MeV

such a value of B_{Ξ^-} is only by the Ξ^- capture from $\boxed{2P \text{ state}}$

1.03±0.18 MeV by Nakazawa

ESC modeling

BB interactions in all baryon channels (NN, ΛN, ΣN, ΞN, ---)
are given by single parameter set simultaneously

Almost all features of hypernuclear data are reproduced well

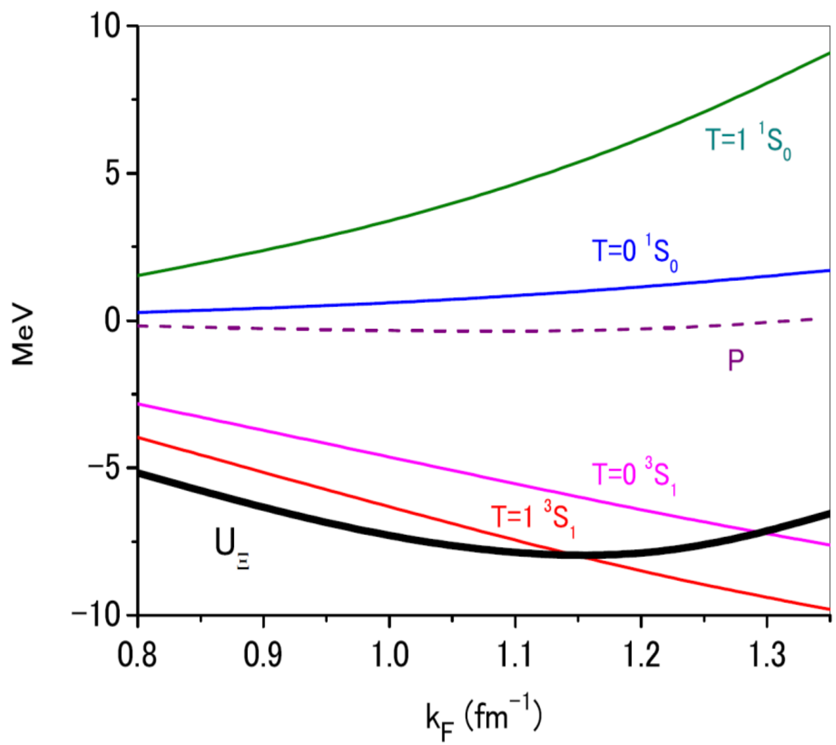
No ad hoc parameter for ΞN sector

U_Ξ

$U_\Xi(\rho_0)$ and partial wave contributions for ESC2016

	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ^c_Ξ
ESC2016	0	1.7	−7.6	−0.2	0.5	1.5	−1.9		
	1	9.1	−9.8	1.2	0.8	−2.2	0.3	−6.6	6.7

k_F=1.35



More attractive at k_F=1.0〜1.2 fm^{-1}

Important in light Ξ systems

$^3S_1$ attractions (T=0,1) are owing to tensor forces !!!

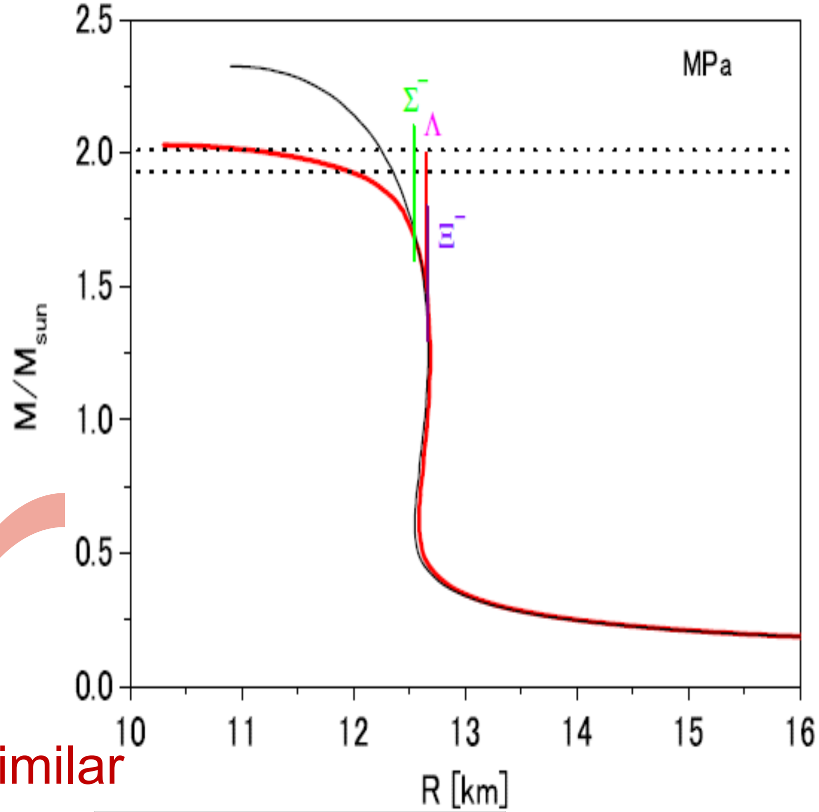
Table 1: Calculated quantities in Ξ^-+^{12}C and Ξ^-+^{14}N systems for ESC2016 and ESC2016+MPP. Binding energies B_{Ξ^-} and conversion width $\Gamma^c_{\Xi^-}$ are in MeV. R.m.s. radius $\sqrt{\langle r^2 \rangle}$ is in fm.

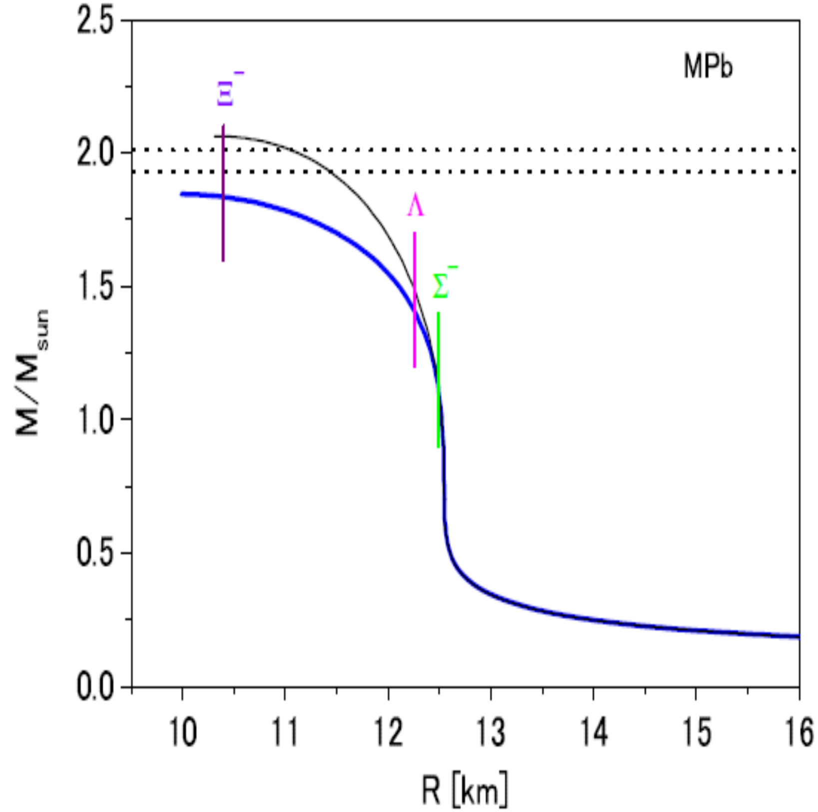
Ξ^-+^{12}C		ESC2016	+MPP	exp
$1S$	B_{Ξ^-}	5.11	4.02	
	$\Gamma^c_{\Xi^-}$	3.02	2.65	
	$\sqrt{\langle r^2 \rangle}$	2.87	3.16	
$2P$	B_{Ξ^-}	0.83	0.76	0.82 ± 0.14
	$\Gamma^c_{\Xi^-}$	0.92	0.87	
	$\sqrt{\langle r^2 \rangle}$	6.42	6.84	
Ξ^-+^{14}N		ESC2016	+MPP	exp
$1S$	B_{Ξ^-}	6.23	5.05	
	$\Gamma^c_{\Xi^-}$	3.65	3.24	
	$\sqrt{\langle r^2 \rangle}$	2.78	3.02	
$2P$	B_{Ξ^-}	1.55	1.38	1.03 ± 0.18
	$\Gamma^c_{\Xi^-}$	1.60	1.48	
	$\sqrt{\langle r^2 \rangle}$	4.85	5.17	

with G-matrix folding model

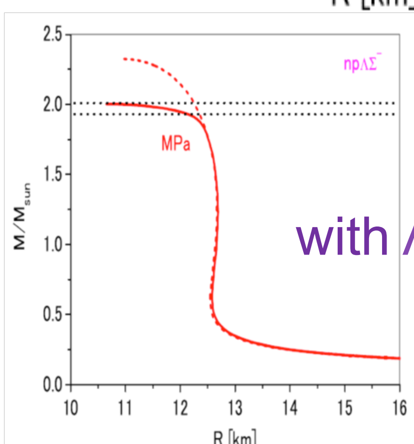
with ΛΣ⁻Ξ⁻ mixing

$2M_{\odot}$ is (not) obtained by MPa (MPb)



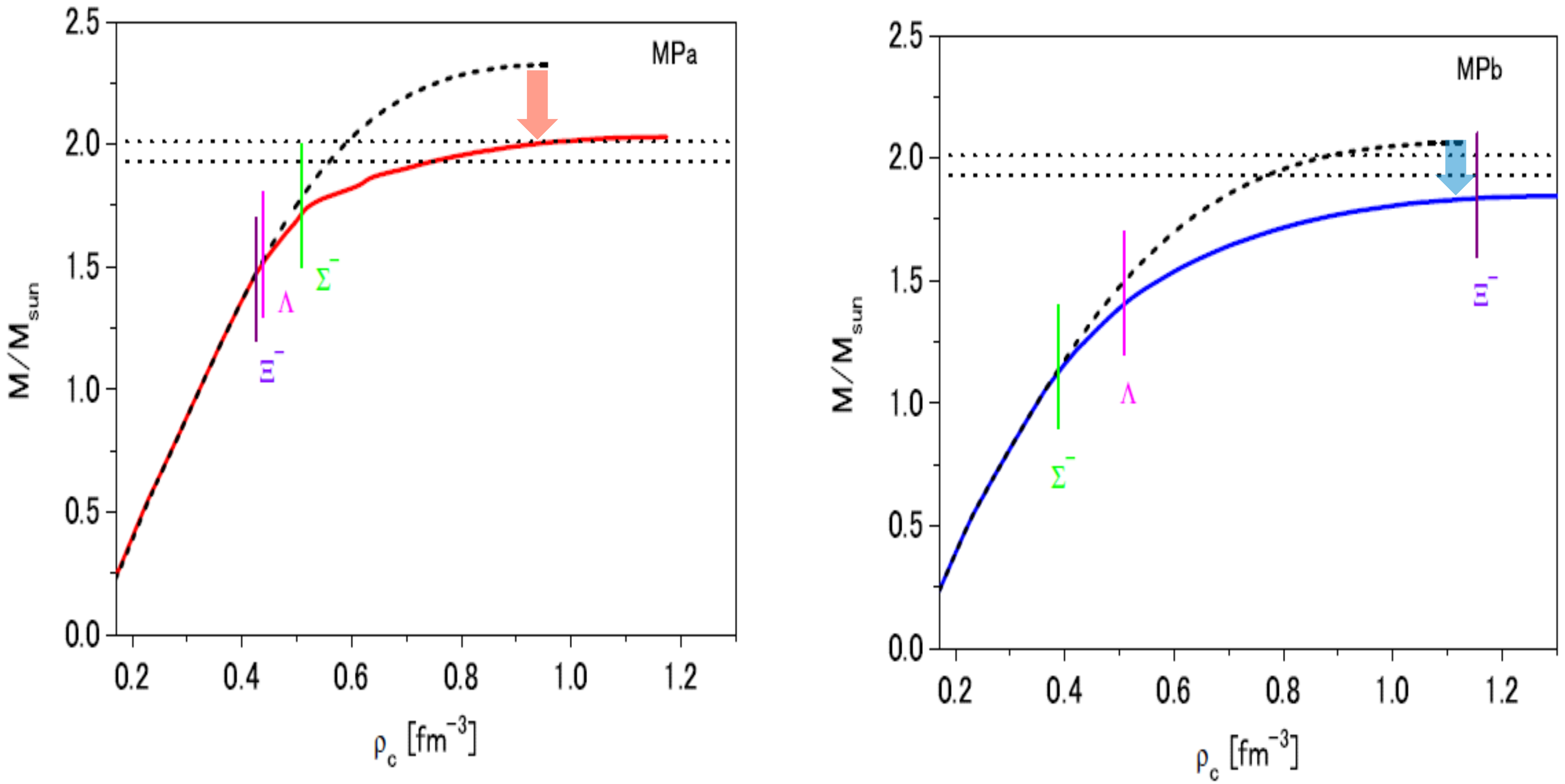


similar

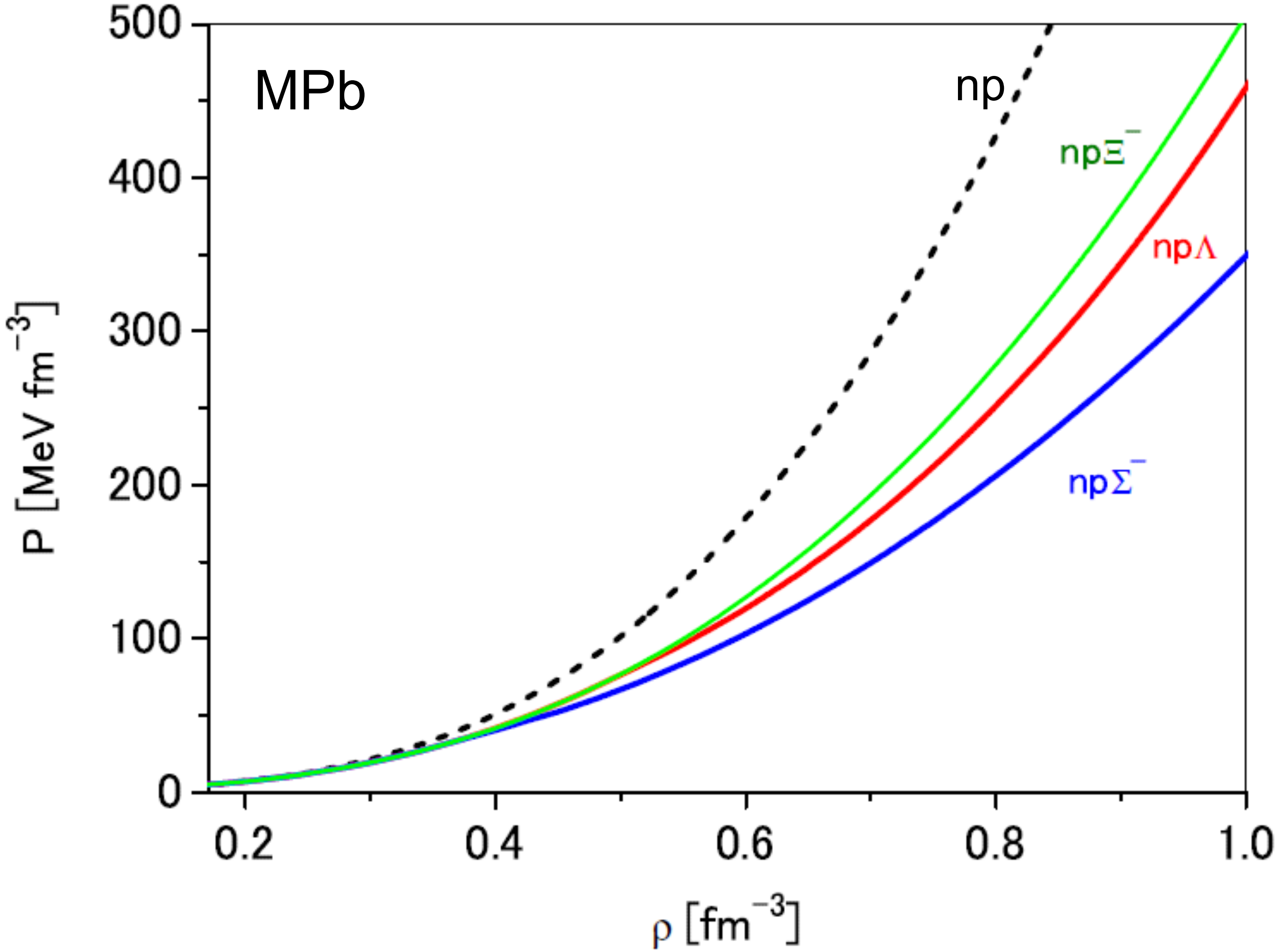


with ΛΣ⁻ mixing

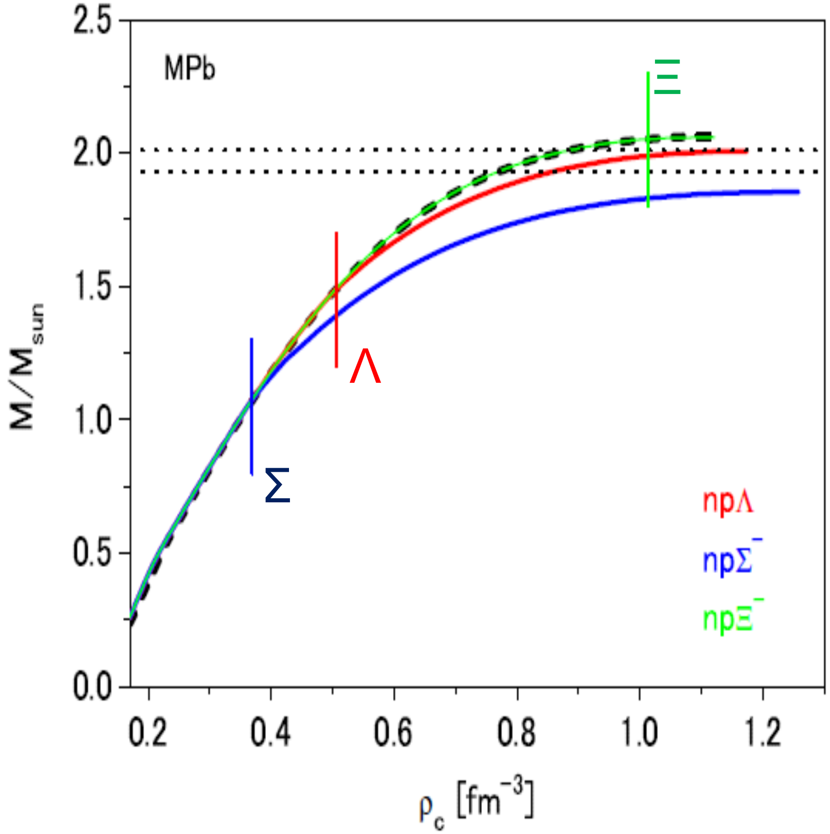
with ΛΣ⁻Ξ⁻ mixing



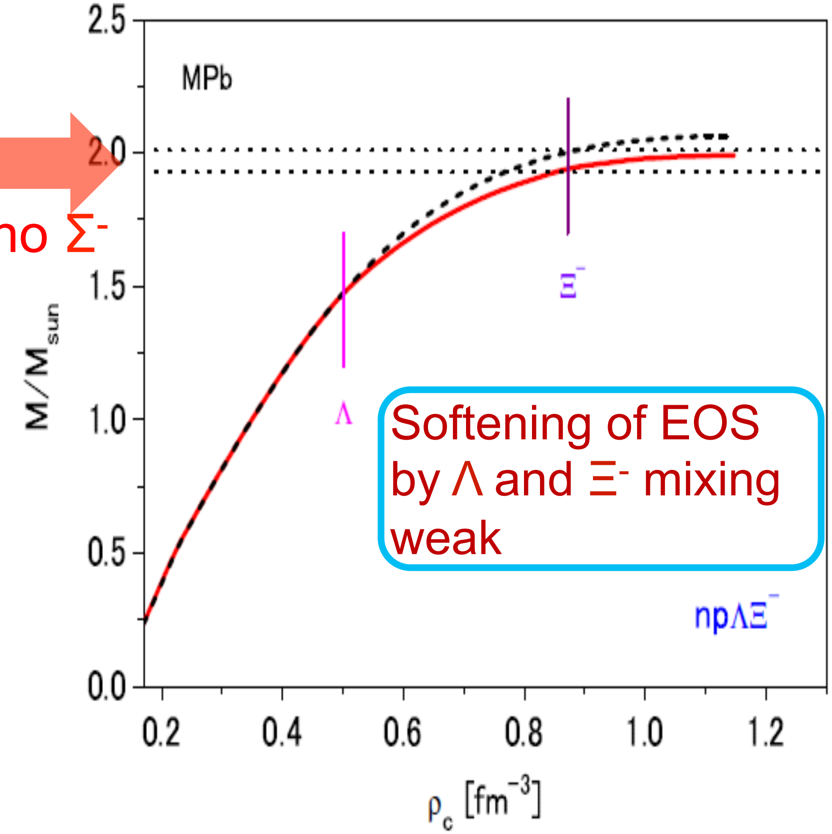
Neutron-star mass as a function of central density



Softening by Σ^- mixing is stronger than those by Λ and Ξ^- mixing



no Σ^-



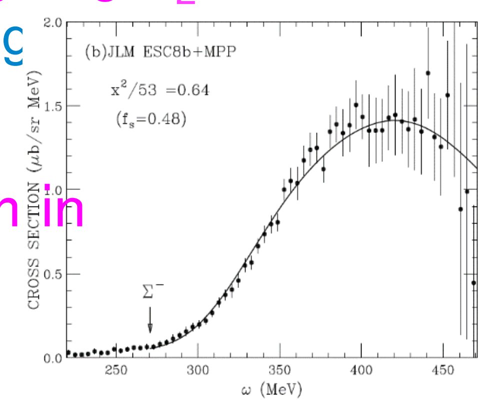
In MPb case

If Σ^- mixing is hindered by some additional Σnn repulsion giving U_Σ > +30MeV

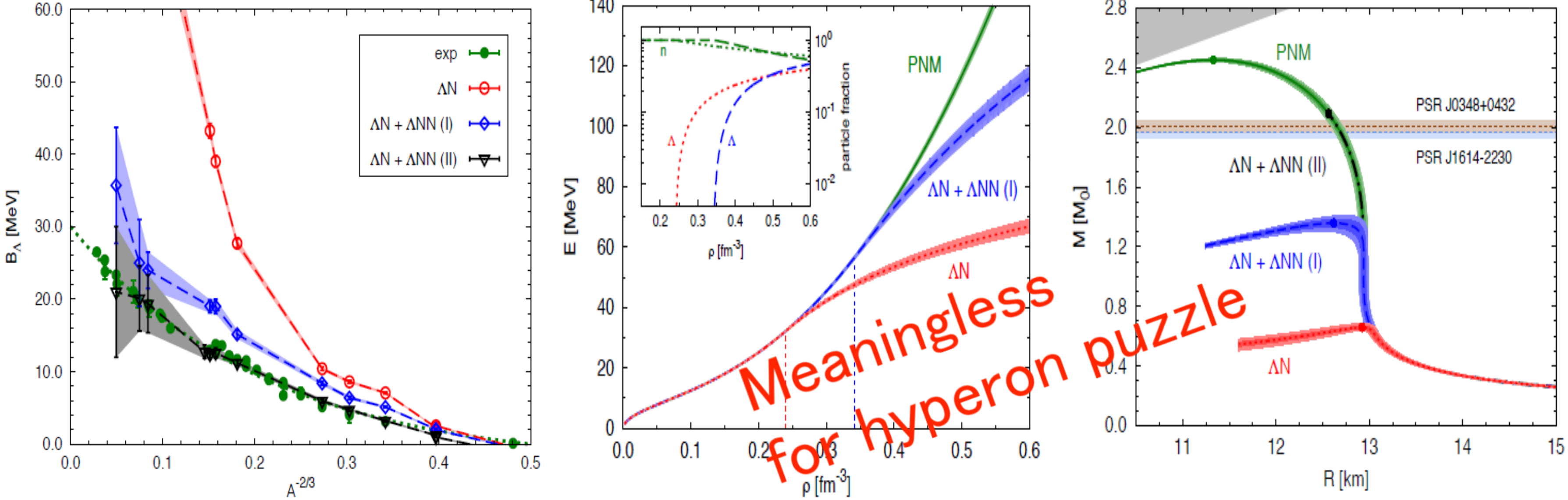
$2M_\odot$ is reproduced by MPb modeling under Λ and Ξ^- mixing

Non mixing of Σ^- is
a possible solution
for hyperon puzzle

still remain a room in



D. Lonardoni



Assuming of no Σmixing

Σ^- mixing exist in neutron star

unless U_Σ～+30MeV with extra Σnn repulsion (MPb case)

or if universal 4-body repulsions (MPa case)

Also, many RMF models w/o Σ^- mixing are problematic

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 set including 3-body repulsion only lead to slightly smaller values than $2M_\odot$ quantitatively

Softening of EOS by Σ^-mixing is stronger than those by Λ or Ξ^-mixing

Softening of EOS by Ξ^-mixing is weak