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Universal 3-Body Force as a Candidate to Solve the “Hyperon Crisis” Problem

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- □Introduction
- □Importance of universal 3-body force (U)
- □U from String-Junction quark model
- □Hadron-quark crossover (a comment)
- □Summary

Introduction

The hyperon(Y) mixing in neutron stars(NSs) dramatically softens the equation of state (EOS) and the NS maximum mass(M_max) goes down like 1.88M_sun → 1.1M_sun, contradicting even the“minimal mass”1.44M_sun observed for PSR1913+16*)
Recent discoveries of a 2-solar-mass NS make definitive the inconsistency between theory and observation (“Hyperon Puzzle”, “Hyperon Crisis”), strongly suggesting that something is missing in the theory of dense matter relevant to NSs.

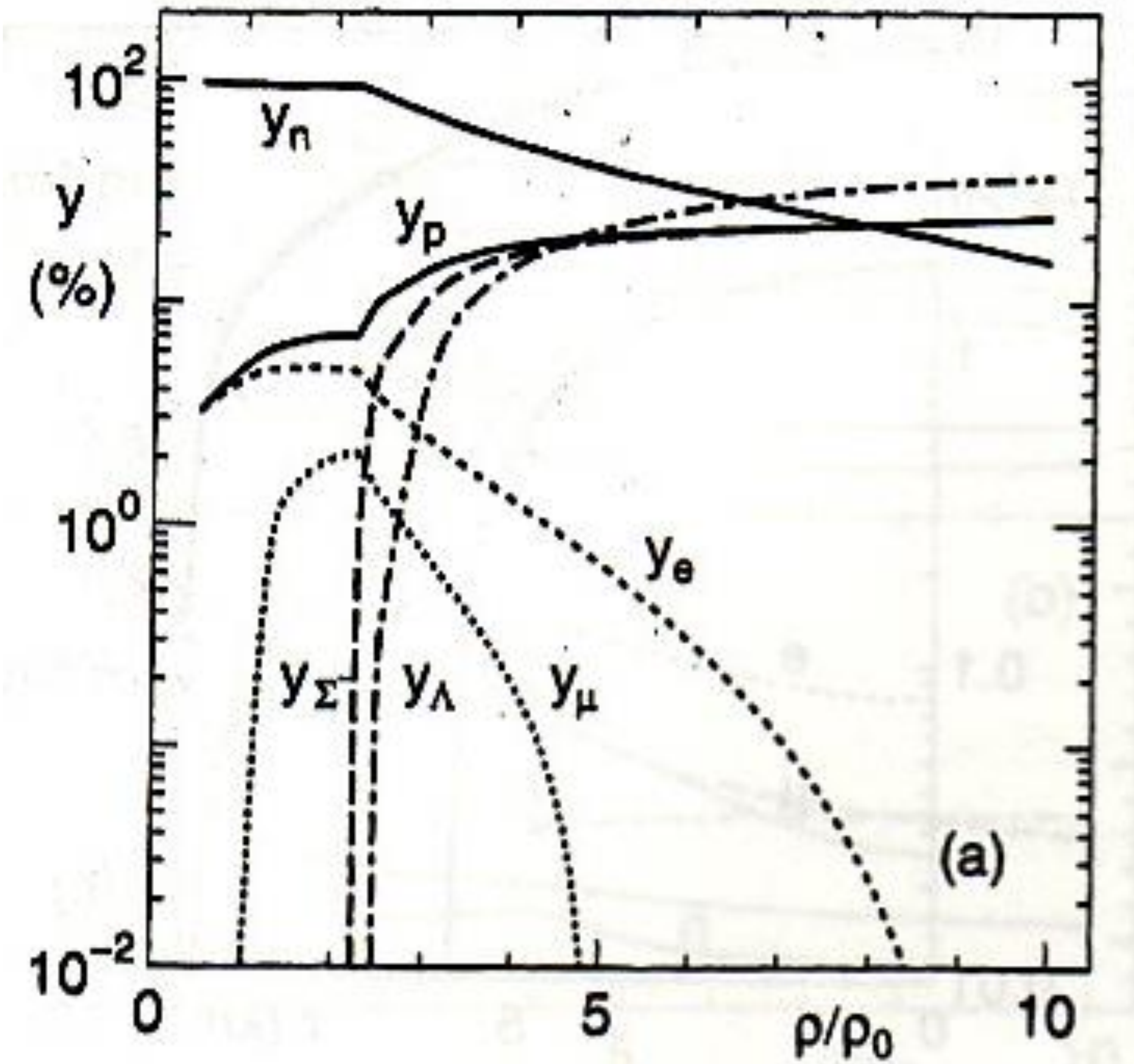
*) [1]S. Nishizaki ,Y. Yamamoto and T. Takatsuka, Prog.Theor.Phys.105(2001)607; 108(2002)703. As a review article, T. Takatsuka,Prog.Theor.Phs.Suppl.No.156 84 (2004).

☐ Our approach to NS-matter with Y-mixing

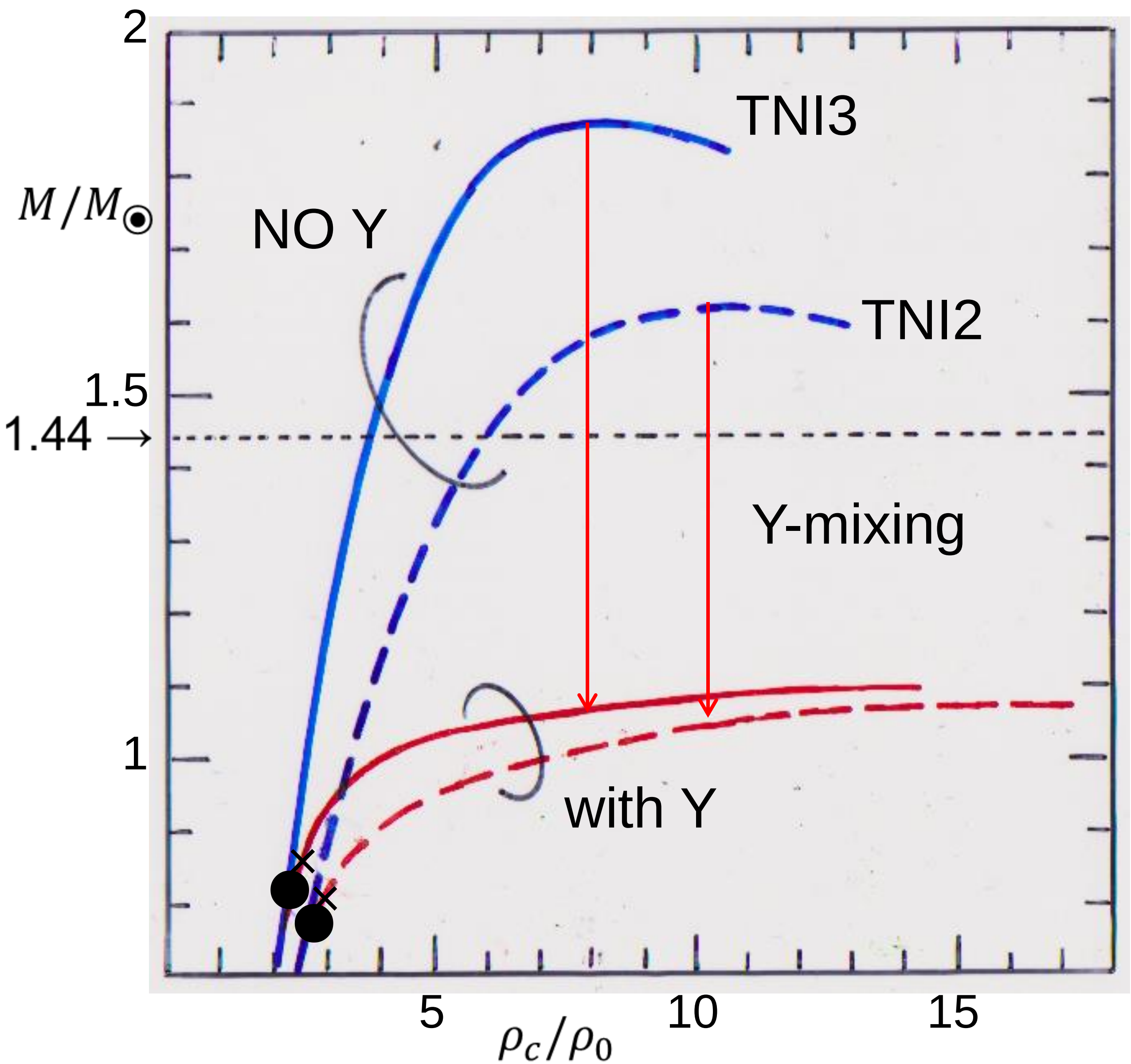
- ○ Matter composed of N (n, p), Y(Λ, Σ^-) and Leptons (e^-, μ^-)
- ○ effective interaction approach based on G-matrix calculations, (effective int. V for NN, NY, YY) Introduction of 3-body force U (TNI, phenomenological Illinoi-type, expressed as effective 2-body force)
- ○ V+U satisfy the saturation property and symmetry energy at nuclear density
- ○ (hard, soft) is classified by the incompressibility κ ; κ=300, 280, 250 MeV for TNI3,TNI6,TNI2

[1] S. Nishizaki, Y. Yamamoto and T. Takatsuka, Prog.Theor. Phys.105 (2001) 607; 108 (2002) 703
[2] T. Takatsuka, Prog. Theor. Phys. Suppl. No. 156 (2004) 84

○ Hyperons appear at $\rho_t \sim (2\text{-}2.5)\rho_0$



$M_{max} < M_{obs}$(Softened EOS by Y)



Strong Softening of the EOS

After 2M_sun observations

Hyperon Crisis
(by T. Hatsuda)

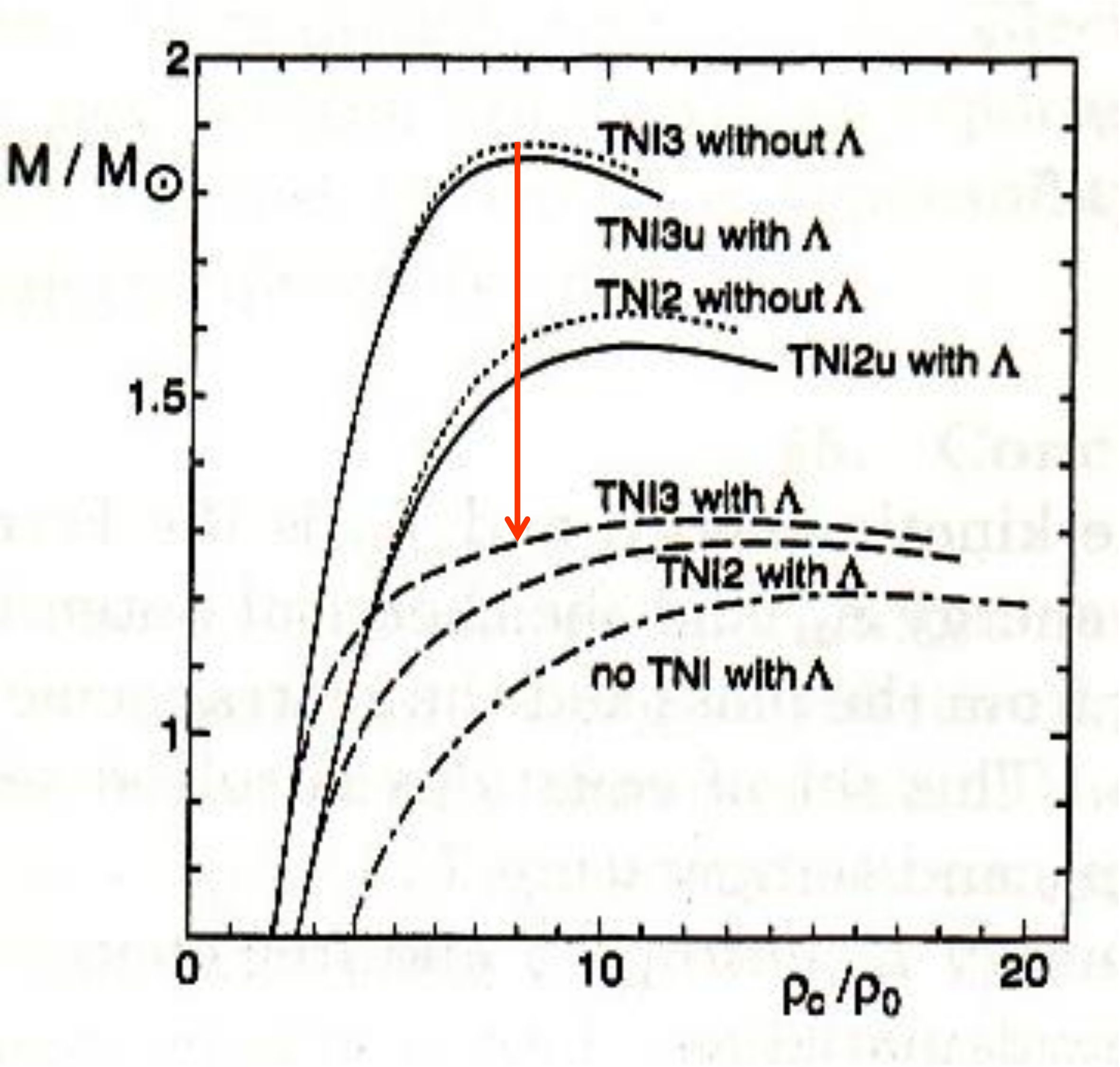
This problem is very serious, because

1) Hyperons are sure to appear in NS cores (Λ , at least)
2) We have a dilemma : enhancing the NN repulsion leads to a more developed Y mixing at lower densities.
3) Even if only Λs are mixed , I.e. assuming no Σ^--mixing. the situation is unaltered.

↓

Indeed , so to say, "Hyperon Crisis"

Even Λ-only mixing, situation is the same!



In our earlier works ,we have found that possible **candidate to solve the problem**

Universal 3-body force

: an extended use of the phenomenological 3-body force U of Illinoi's type(Friedman-Pandharipande*) : NNN $\longrightarrow$ BBB

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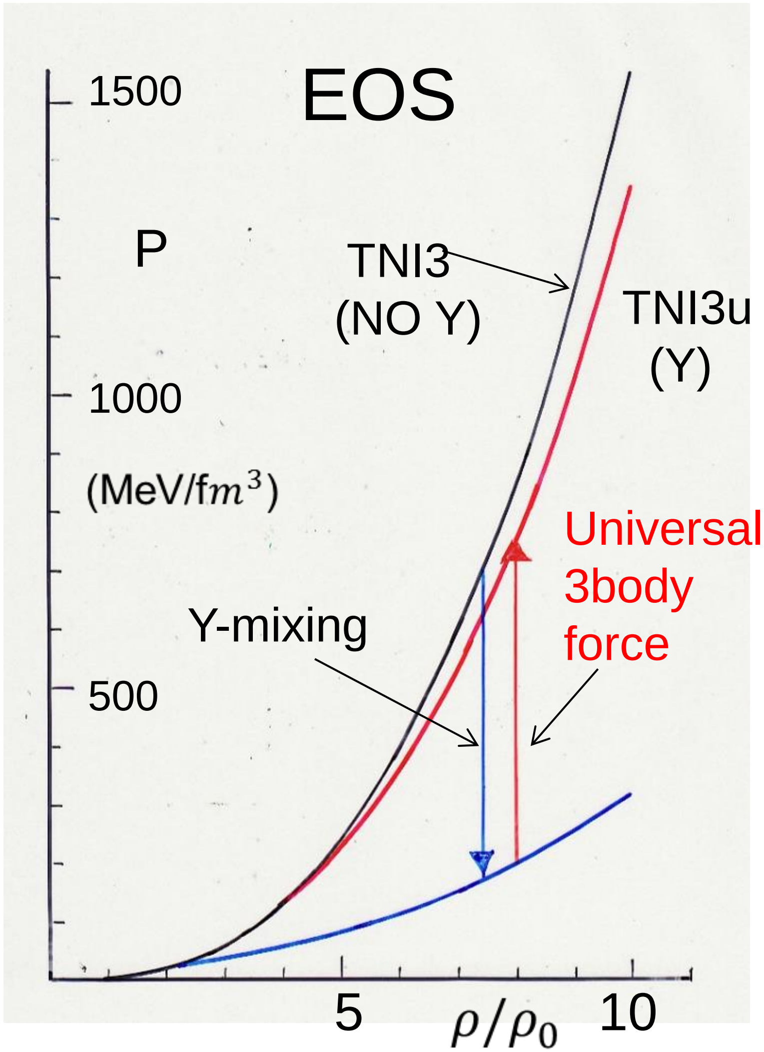
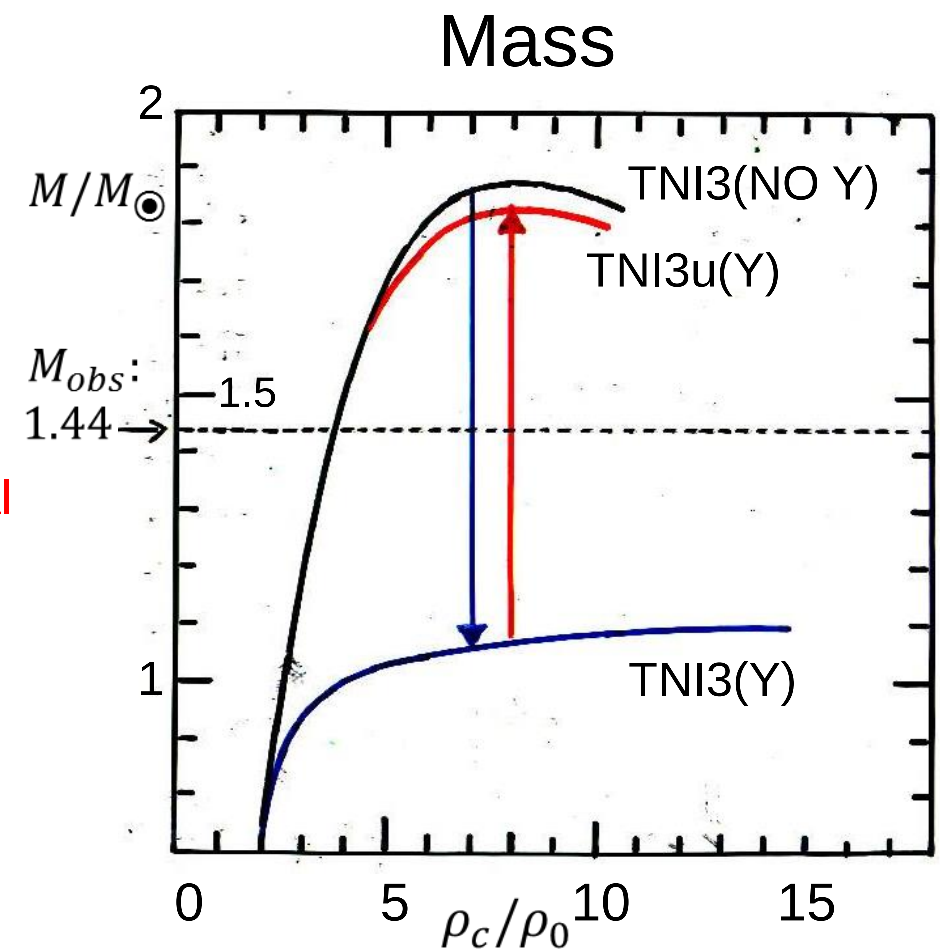
*) B. Friedmann and V. R. Pandharipande, Nucl.Phys. A361,502 (1981)

Dramatic softening of EOS ⟶ Necessity of "Extra Repulsion"





As a review ⟶ T.Takatsuka, Prog.Theor.Phys.Suppl.No.156 (2004) 84.

Our universal 3-body force, however, is introduced quite phenomenologically , following the one (TNI) from Friedman-Pandharipande type*).

In this talk, we aim to discuss the problem by using the 3-body force (U(3B)) based on the microscopic descriptions. We use U(3B) consisting of two parts (U(2πΔ) and U(SJM)). Here U(2πΔ) is the extended version of 2π-exchange via isobar Δ excitation(so-called Fujita-Miyazawa type) to be applied to (N+Y) system which mainly works in the long and intermediate distances. U(SJM) is that from a string-junction quark model (SJM) of baryons proposed recently by R.Tamagaki **) and predominantly works in the short distance. It should be noted that U(SJM) is independent of quark flavor and hence satisfies the required universal nature of 3-body force. We have shown that the Y-mixed NS-EOS with this U(3B) can generate NSs with the mass greater than 2M_sun, compatible with recent observations of so massive NSs***). TNA is the attractive part of TNI to assure the empirical saturation properties .

$$U(3B) = U(SJM) + U(2\pi\Delta) + U(TNA)$$

.*) B.Friedmann and V.R.Pandharipande,Nucl.Phys.A361,502(1981).

**) R.Tamagaki,Prog.Theor. Phys.119,963(2008).

***) T.Takatsuka,S.Nishizaki and R.Tamagaki, AIP Conf.Proc. 1011, 209 (2008).

Extended 2πΔ-Type 3-body Force
; not universal

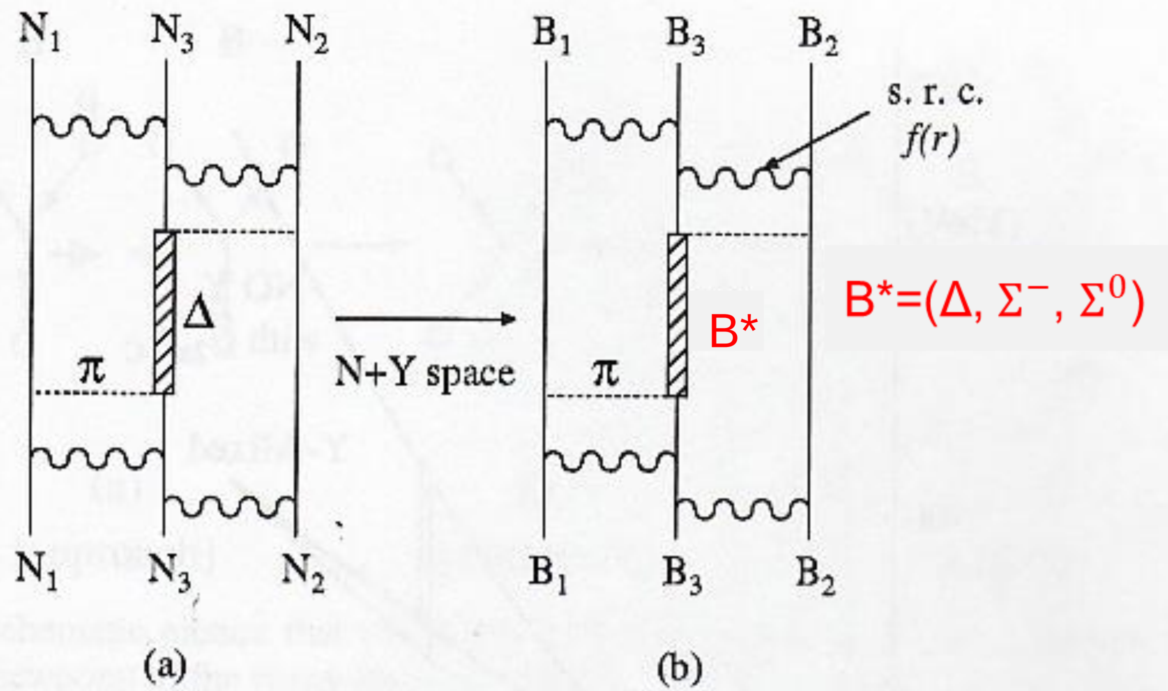
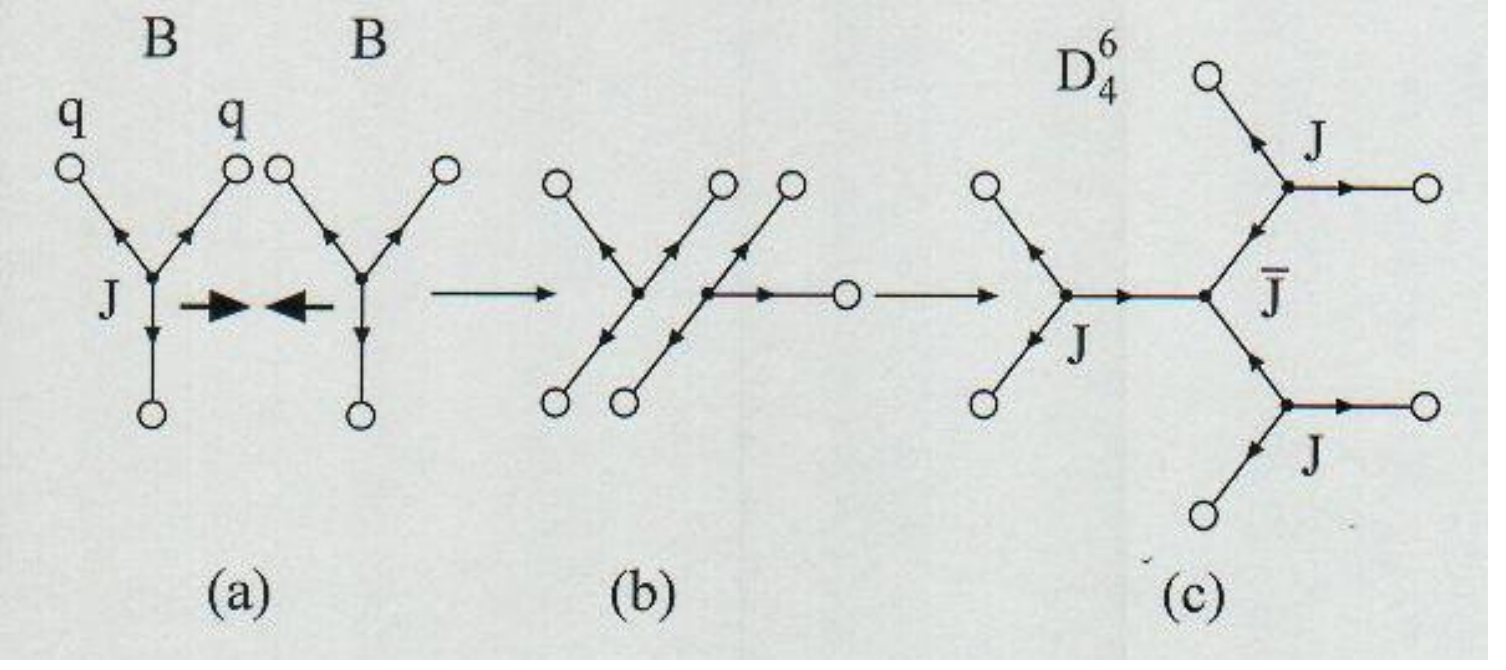


FIGURE 2. Extension of 3-body force from 2π-exchange via Δ excitation type $(2\pi\Delta)$ in N-space (a) into $\{N+Y\}$ space (b), where B^* stands for Δ, Σ^{*-}, Σ^{*0} and $f(r)$ is the short-range correlation function.

○ Short-range correlations among N_1, N_2 and N_3 are duly Kaken into account ;T.Kasahara,Y.Akaishi and H.Tanaka,PTP Suppl.No.56(1974)96

Repulsion from SJM-----flavor independent



(a) 2B come in short distance
(b) Deformation (resistance)
(c) Fusion into 6-quark state

(by R. Tamagaki)
Prog. Theor. Phys. 119 (2008) 965.

○ Energy barrier (∼2GeV) corresponds to repulsive core of BB interactions

Univesal BBB Pot.
from SJM
,
Given by an effective
2-body BB Pot.

*U(0)=2GeV given by SJM
**Parameter λ=4.5,4.0,3.5 fm^-2
for SJM1, SJM2, SJM3

R.Tamagaki,Prog.Theor.Phys.
119, 965 (2008).

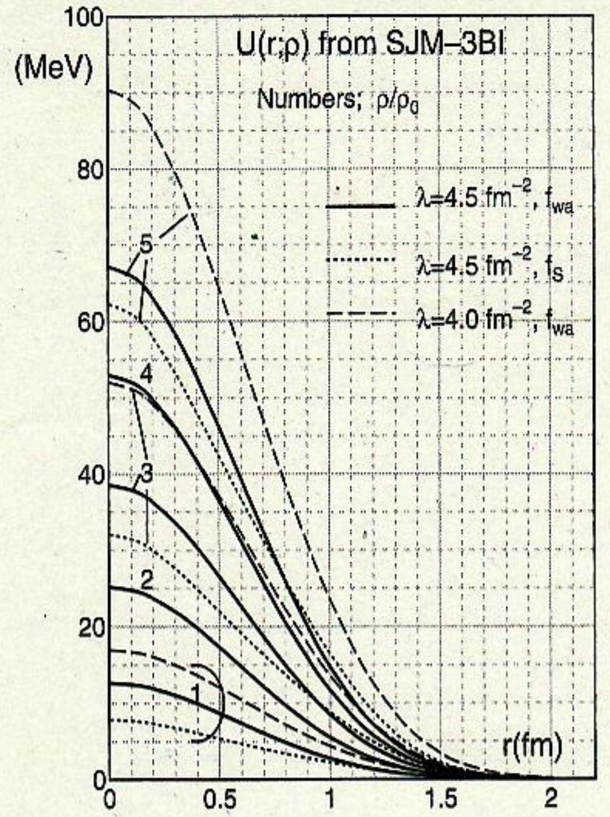
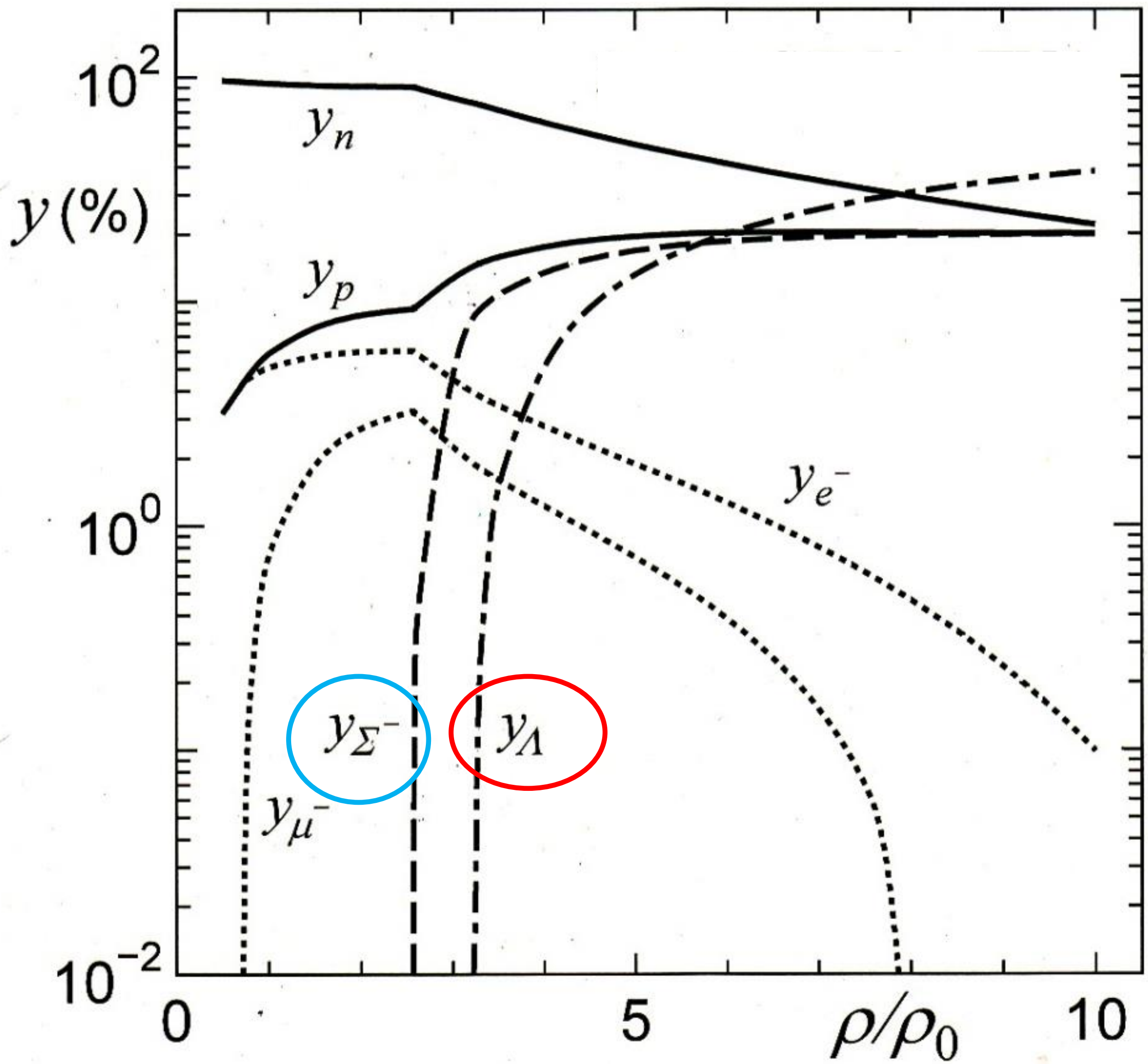


Fig. 8. Effective two-body potential $U(r;\rho)$ from universal repulsion of SJM-3BI. Numbers attached to the curves show ρ/ρ_0. Parameters of the force range λ and the SRC function f are indicated in the figure.

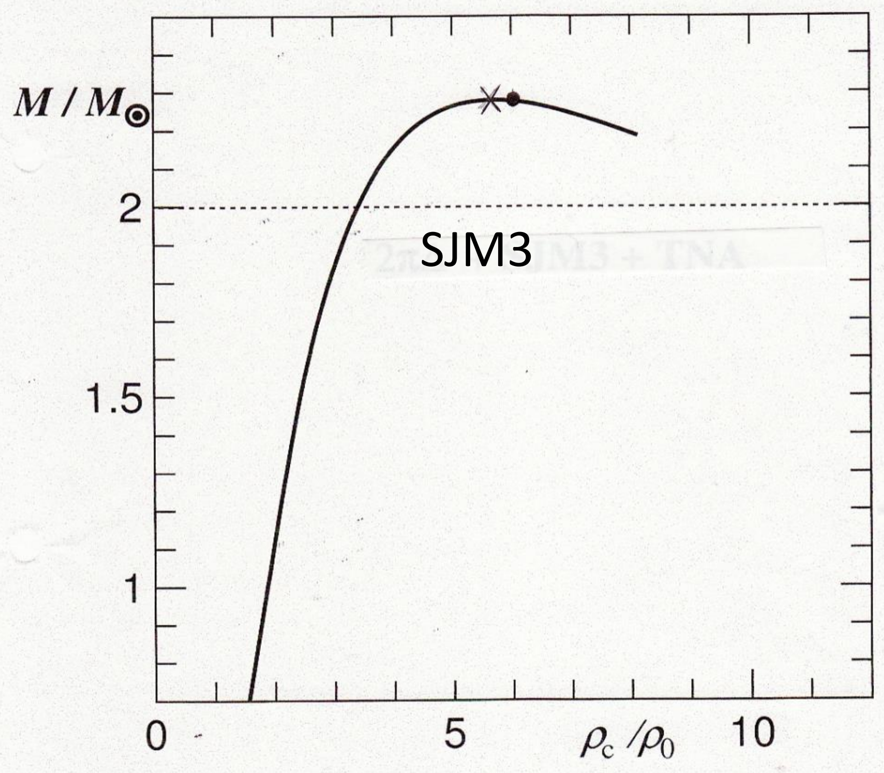
SJM2 + 2πΔ + TNA

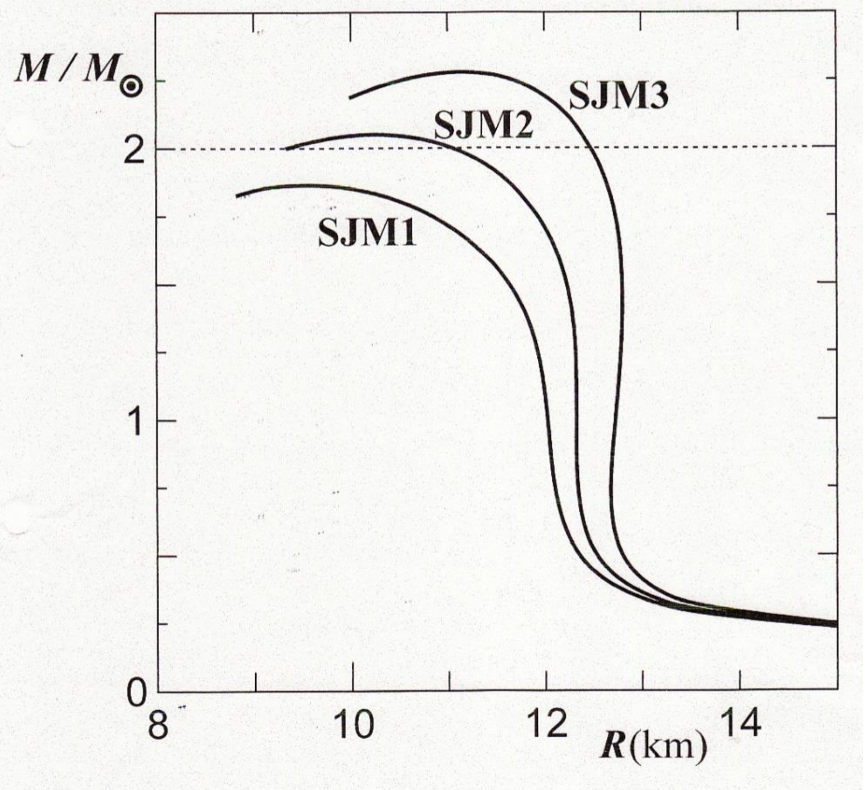


M-ρ_c

(SJM+2πΔ+TNA)

M-R





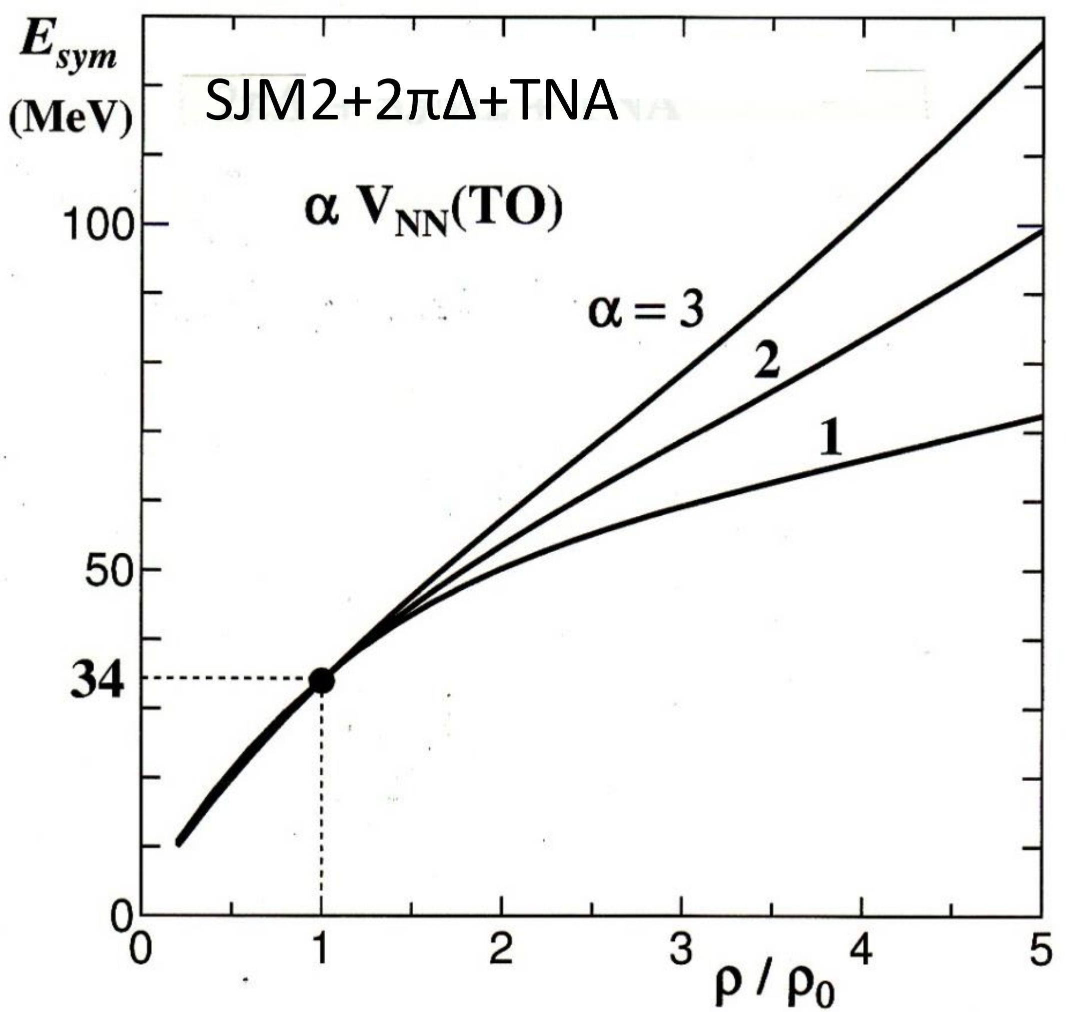
× : maximum – mass point

▪ : critical point for causality

λ=4.5, 4.0,3 .5 fm^-2 for SJM1, SJM2,SJM3 , respectively.

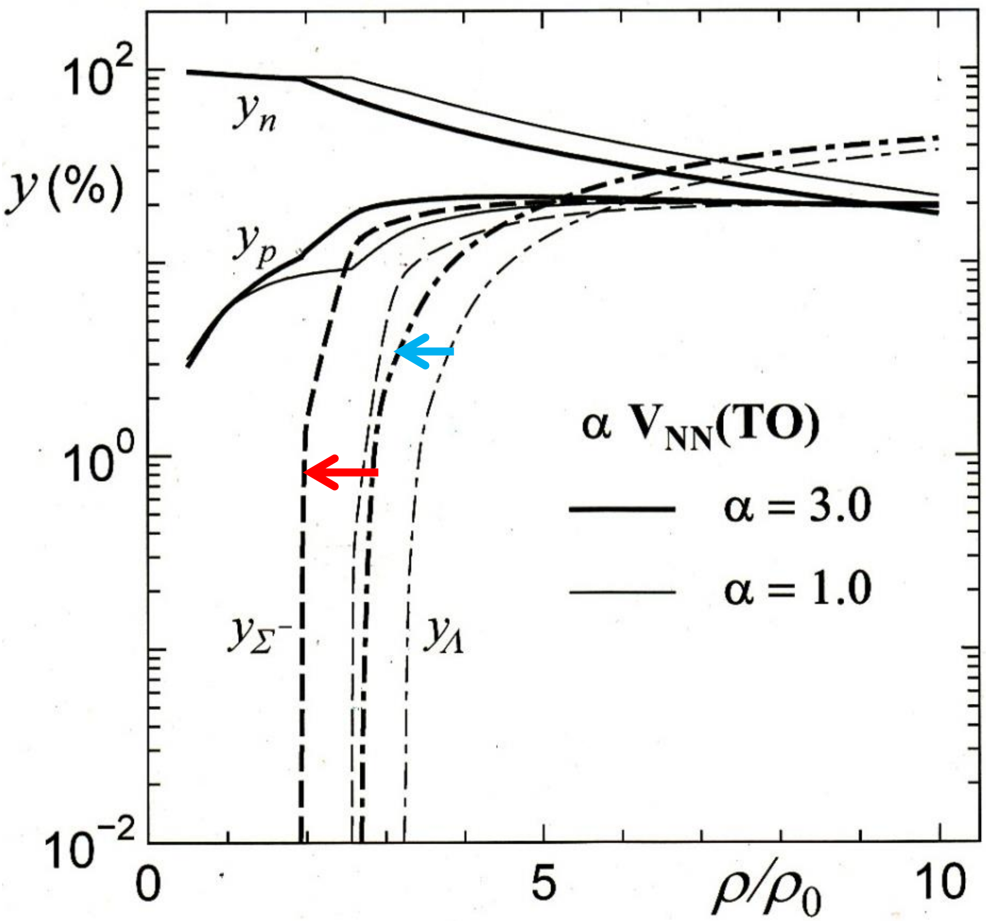
Symmetry energy controlled;

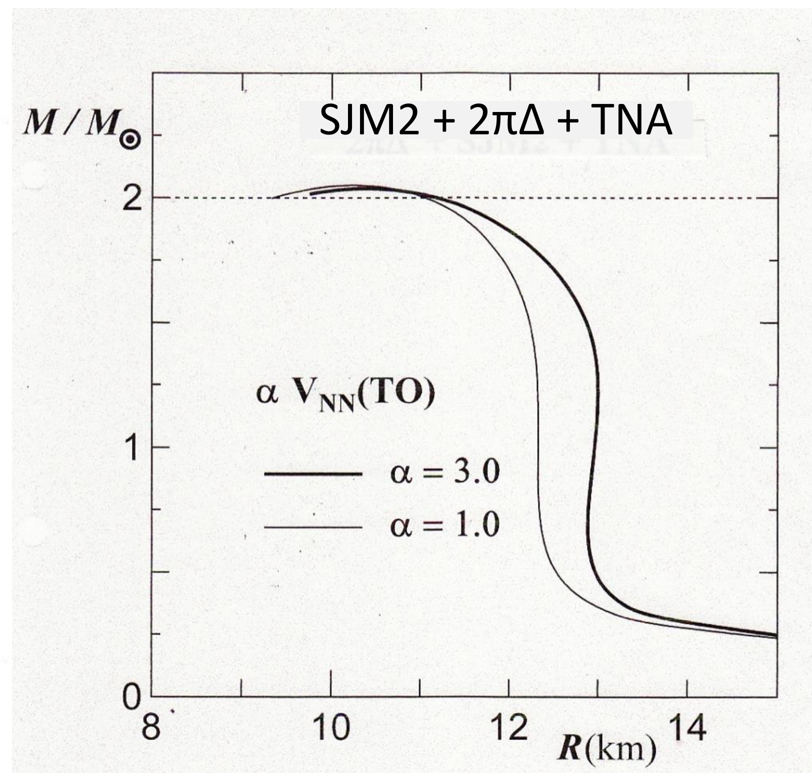
3O NN-Pot. multiplied by a factor α



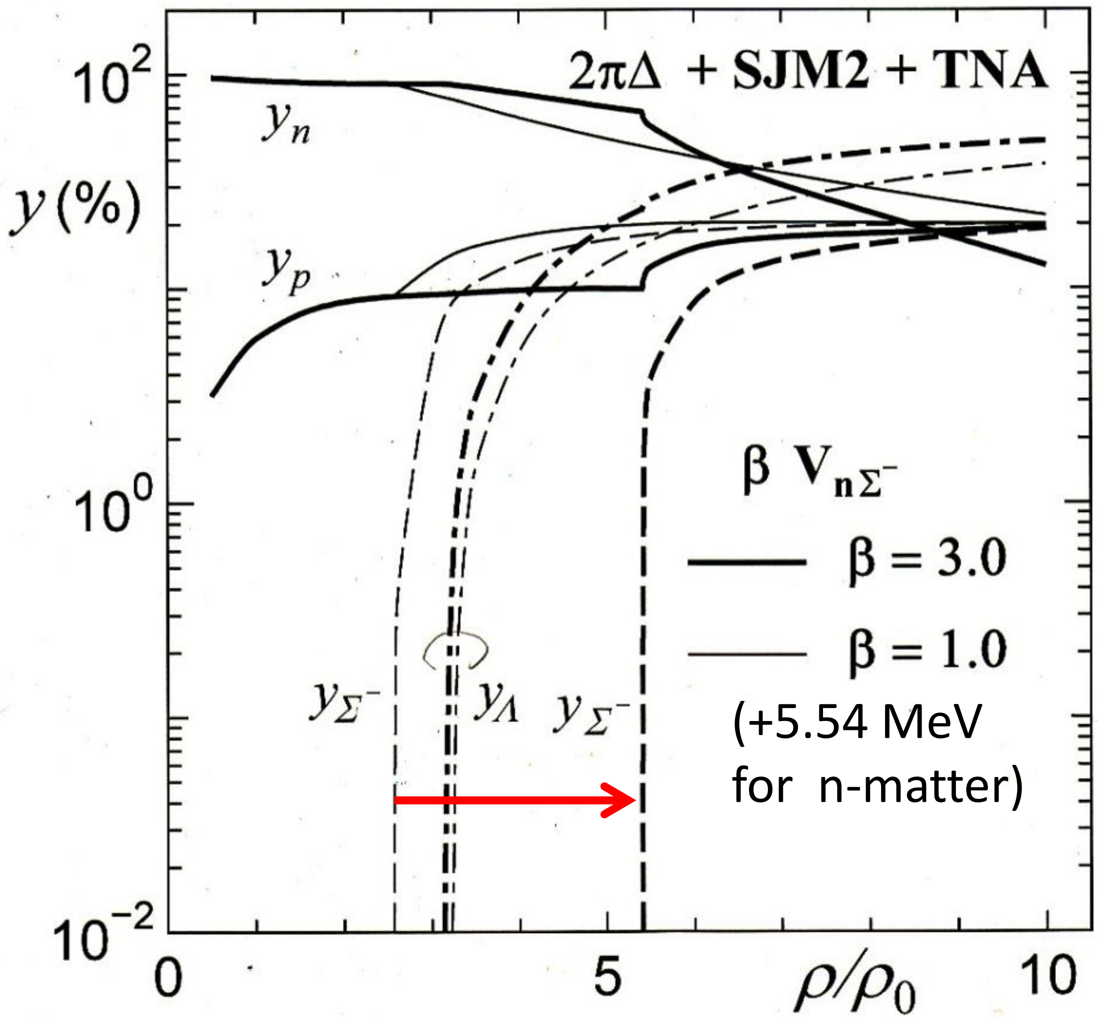
Efects of symmetry energy

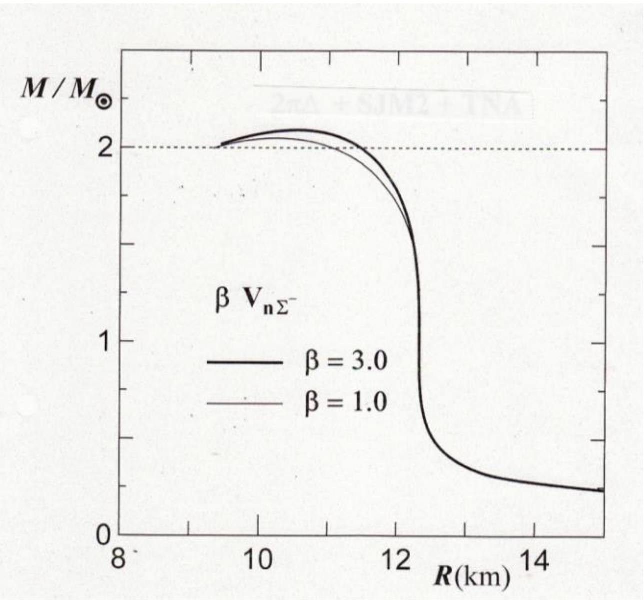
(SJM2+2πΔ+TNA)





Effects of Σ⁻n repulsion





Comment: Hadron-Quark Crossover Model

In the BB (BBB) approach ,however, there is a basic problem wether baryons keep their identities and a point-like particle description is allowed ,when they overlap at high densities. So it is of great interest to study the 2-solar-mass problem, introducing explicitly a quark degrees of freedom.

From a viewpoint of quark percolation through hadrons, we construct a phenomenological EOS by assuming a smooth crossover transition from hadron matter to quark matter*).

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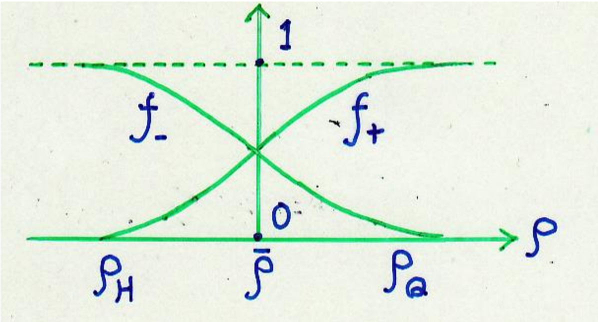
*)K.Masuda, T.Hatsuda and T.Takatsuka, ApJ 794,12 (2013)
K.Masuda, T.Hatsuda and T.Takatsuka, PTEP ,073D01 (2013)

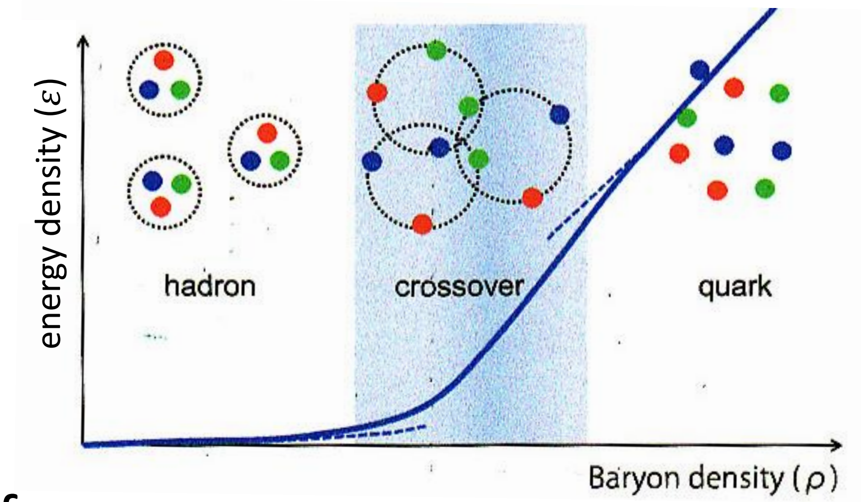
"H-Q crossover model"

○ From a view of "H-Q Crossover"

$$\varepsilon(\rho)_H = \varepsilon_H(\rho)f_-(\rho) + \varepsilon_Q(\rho)f_+(\rho),$$

$$f_\pm(\rho) = \frac{1}{2}\left\{1 + tanh\left(\frac{\rho-\bar{\rho}}{\Gamma}\right)\right\}$$



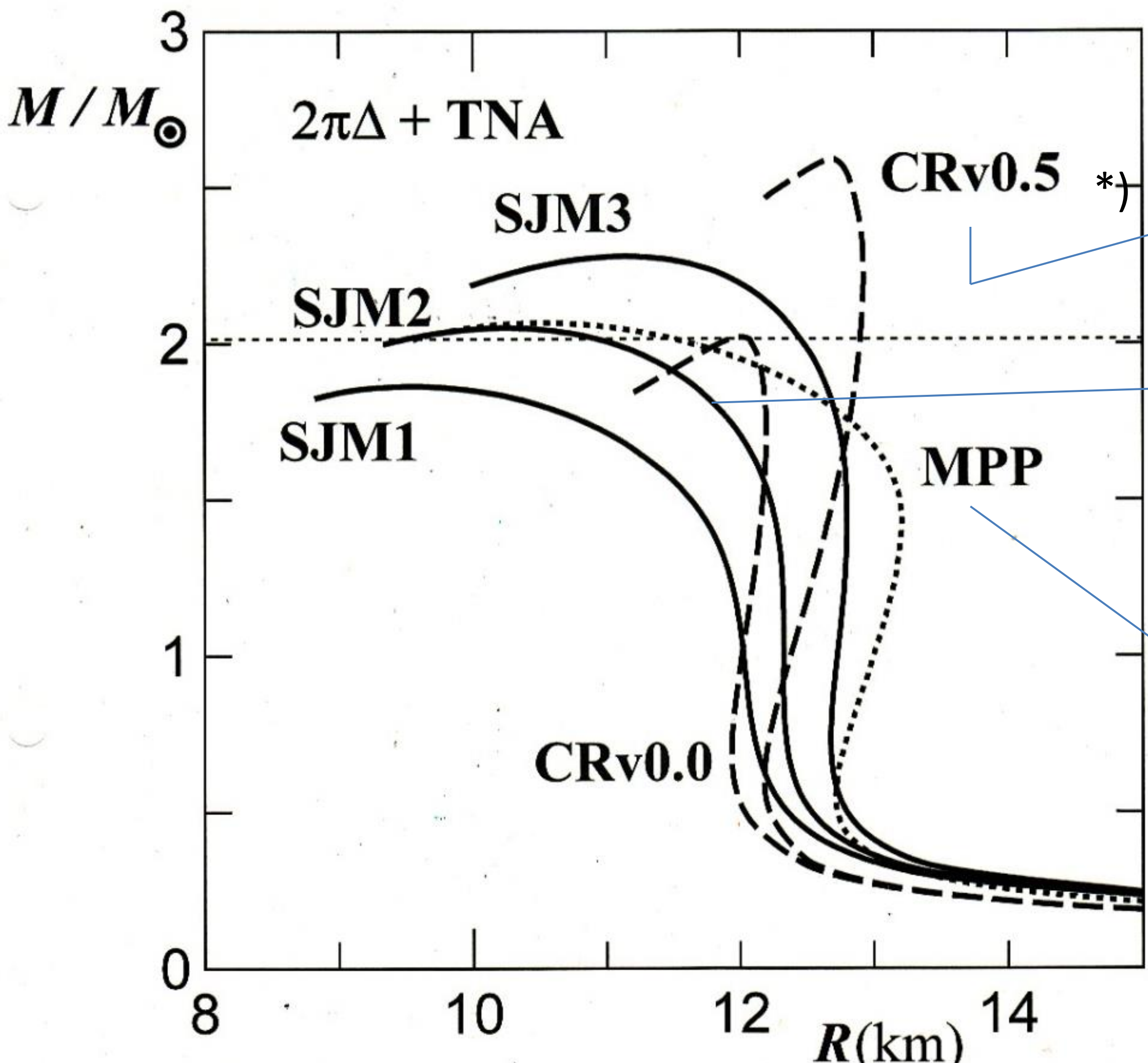


○ Pressure $P(\rho)$ is derived from

$$P(\rho) = \rho^2 \partial(\varepsilon(\rho)/\rho)/\partial\rho$$

・K. Masuda, T. Hatsuda and T. Takatsuka, ApJ. 794 (2013) 12; PTEP 073D01 (2013).

Possible NS Models (e.g.)



K.Masuda,T.Hatsuda and T.Takatsuka, PTEP. 073D01 ((2013).

T.Takatsuka, S.Nishizaki and R.Tamagaki, AIP Cof. Proc. 1011 (2008).

Y. Yamamoto, T. Furumoto,,N. Yasutake and T.A.Rijken, Submitted to EPJ (Talk in this Conference).

Summary

(1) We have discussed that one of the solution for "Hyperon Crisis " problem would be the universal 3-body force, in the case of pure hadronic framework .

(2) Larger symmetry energy acts for the appearance of Σ^- and on the other hand, larger Σ^-n repulsion act against the appearance. Thus the Y population is so much influenced by these effects, but the NS maximum mass is found to be almost unaffected. In this sense, Λs play an essential role in the softening of the EOS.

(3) In the framework to introduce explicitly a quark degrees of freedom, a hadron-quark crossover model would be another promising candidate.

Any way , we need more studies.