Quarks and Compact Stars (QCS2014)
KIAA, Peking Univ., Oct.20-22.2014

Massive Neutron Stars with Hadron-Quark Transient Core

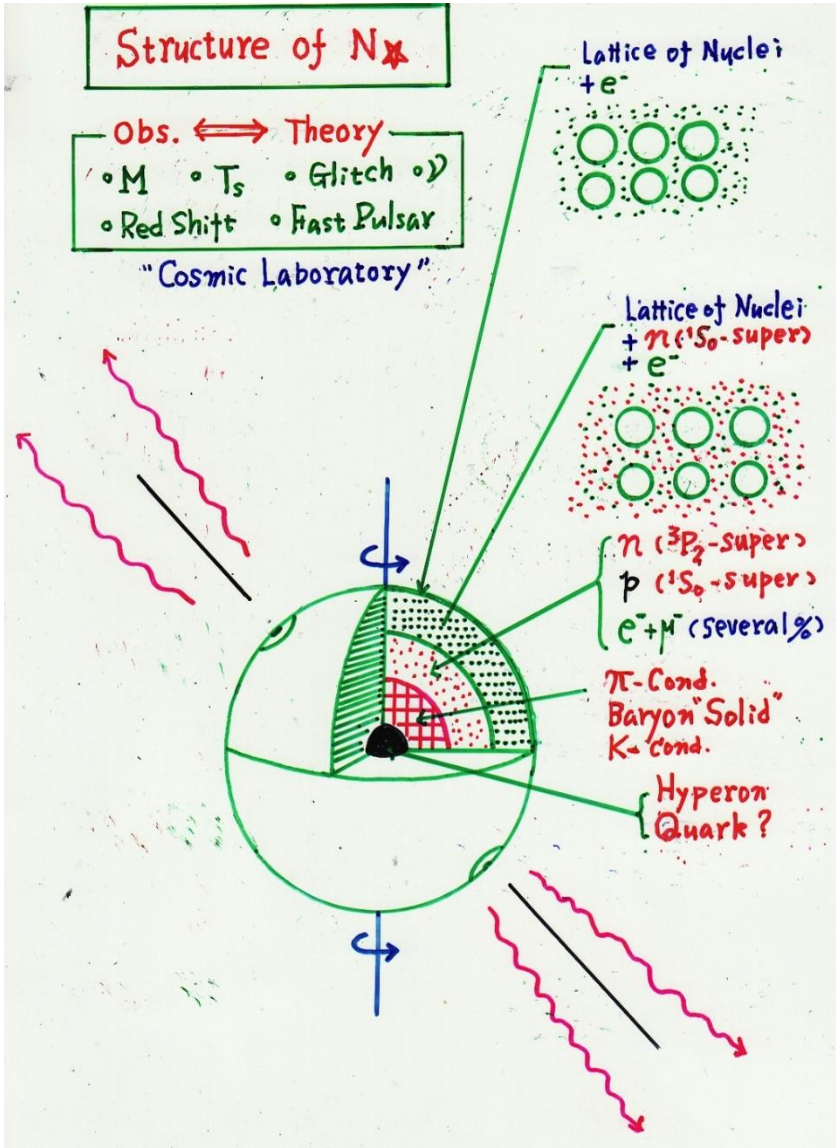
--- phenomenological approach by “3-window model”---

T. Takatsuka (RIKEN; Prof. Emeritus of Iwate Univ.)

☐Impact from Massive NS observations
☐Approach by 3-Window Model
☐Some results

In collaboration with T. Hatsuda and K. Masuda

1-2. Profile and structure of NSs



Mass $(1\sim2)\,M_\odot$

Radius $(10\sim20)$ Km

Temperature $\sim10^6$ K (surface),
$\sim10^8$ K (internal)

Pressure $(10^{29}\sim10^{31})$ atm (center)

Density $\sim10^6$ g/cc (surface),
$\sim10^{15}$ g/cc (center)

(5.5g/cc for earth, 1.4g/cc for sun)

Hyperon mixing

☐ Hyperons in NSs --- Earlier works

○ Suggestion for Y-mixing in NSs

- A.G.W. Cameron,
  Astrophys. J., 130 (1959) 884.

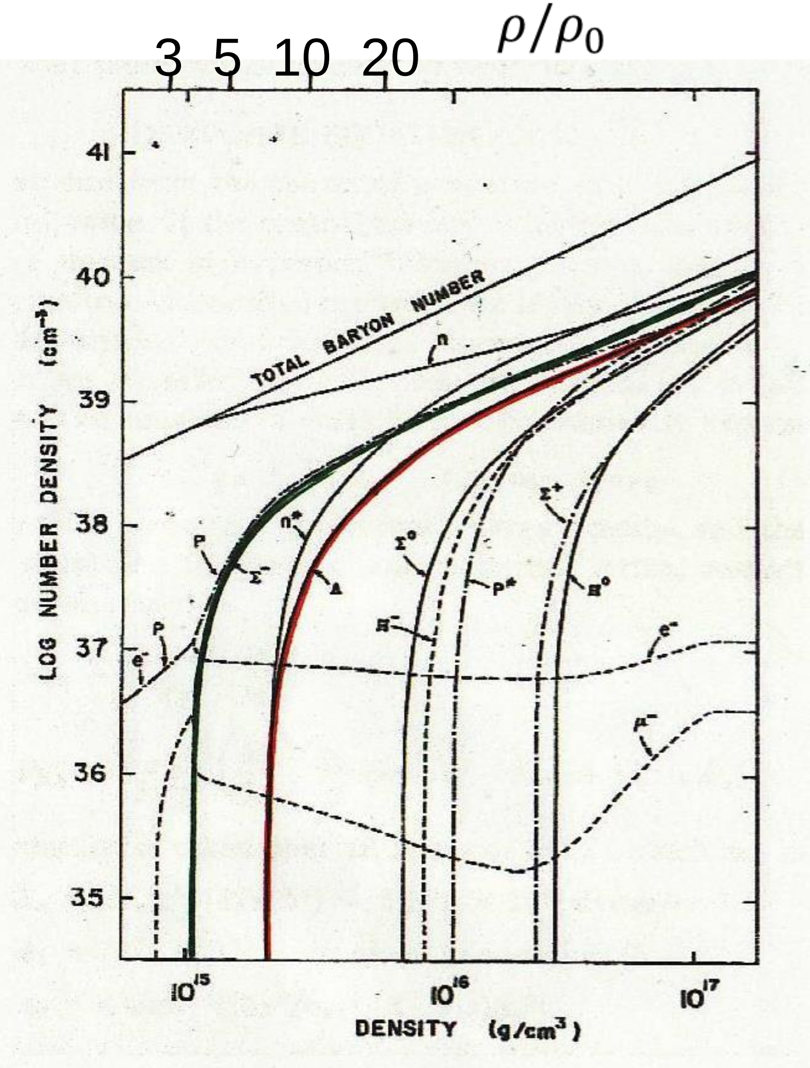
○ Attempts for Y-mixing calculation

- S. Tsuruta and A.G.W. Cameeron,
  Canadian Journal of Physics, 44 (1966) 1895.
- W.D. Langer and L.C. Rosen,
  Astrophysics and Space Science, 6 (1970) 217.
- V.R. Pandharipande,
  Nucl. Phys. A178 (1971) 123.
- N.K. Glendenning,
  Nucl. Phys. A493 (1989) 521.

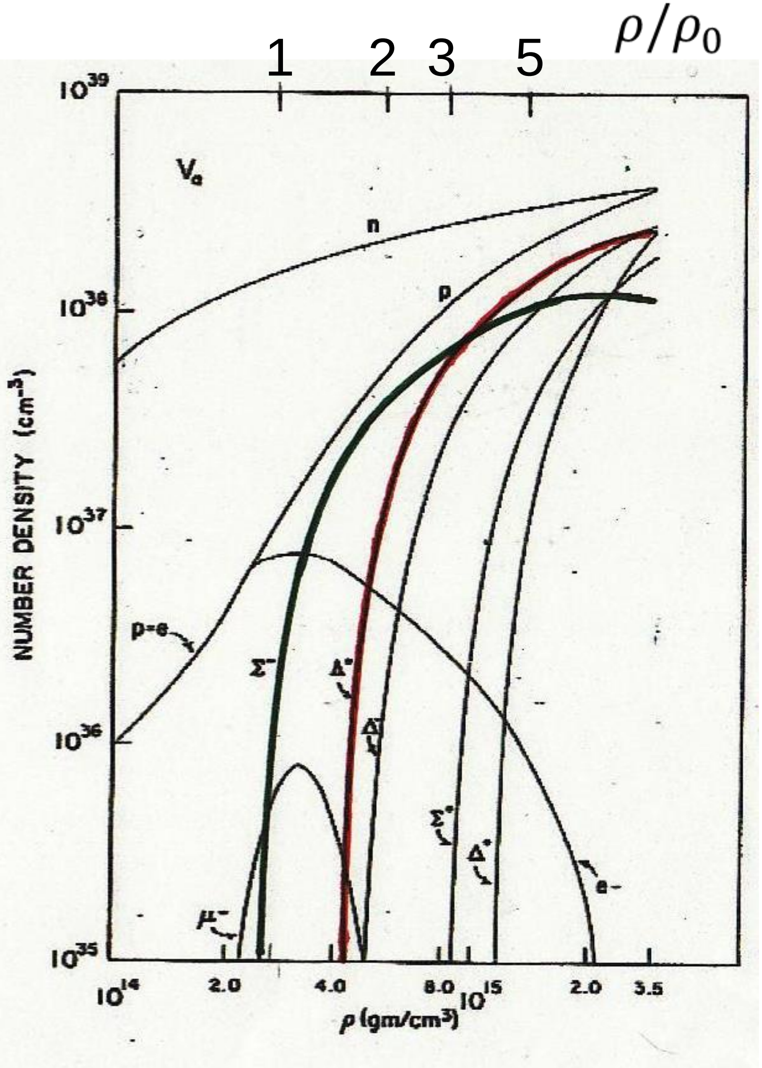
Baryon	M(Mev)	S	Comp.
n	940	0	udd
p	938	0	uud
Λ	1116	-1	(uds-dus)/$\sqrt{2}$
Σ^+	1189	-1	uus
Σ^0	1193	-1	(uds+dus)/$\sqrt{2}$
Σ^-	1197	-1	dds
Ξ^0	1315	-2	uss
Ξ^-	1321	-2	dss

○ From ～1995, many works stimulated by a progress of hypernuclear physics in laboratories and observations for NSs --- e.g. see references cited in a review;

- T. Takatsuka, Prog. Theor. Phys. Suppl. No.156 (2004) 84.



S. Tsuruta and A.G.W. Cameron,
Canadian Journal of Phys., 44 (1966) 1895.



W.D. Langer and L.C. Rosen,
Astrophysics and Space Science, 6
(1970) 217.

☐ Our approach to NS-matter with Y-mixing

○ Matter composed of N (n, p), Y(Λ, Σ^-) and Leptons (e^-, μ^-)

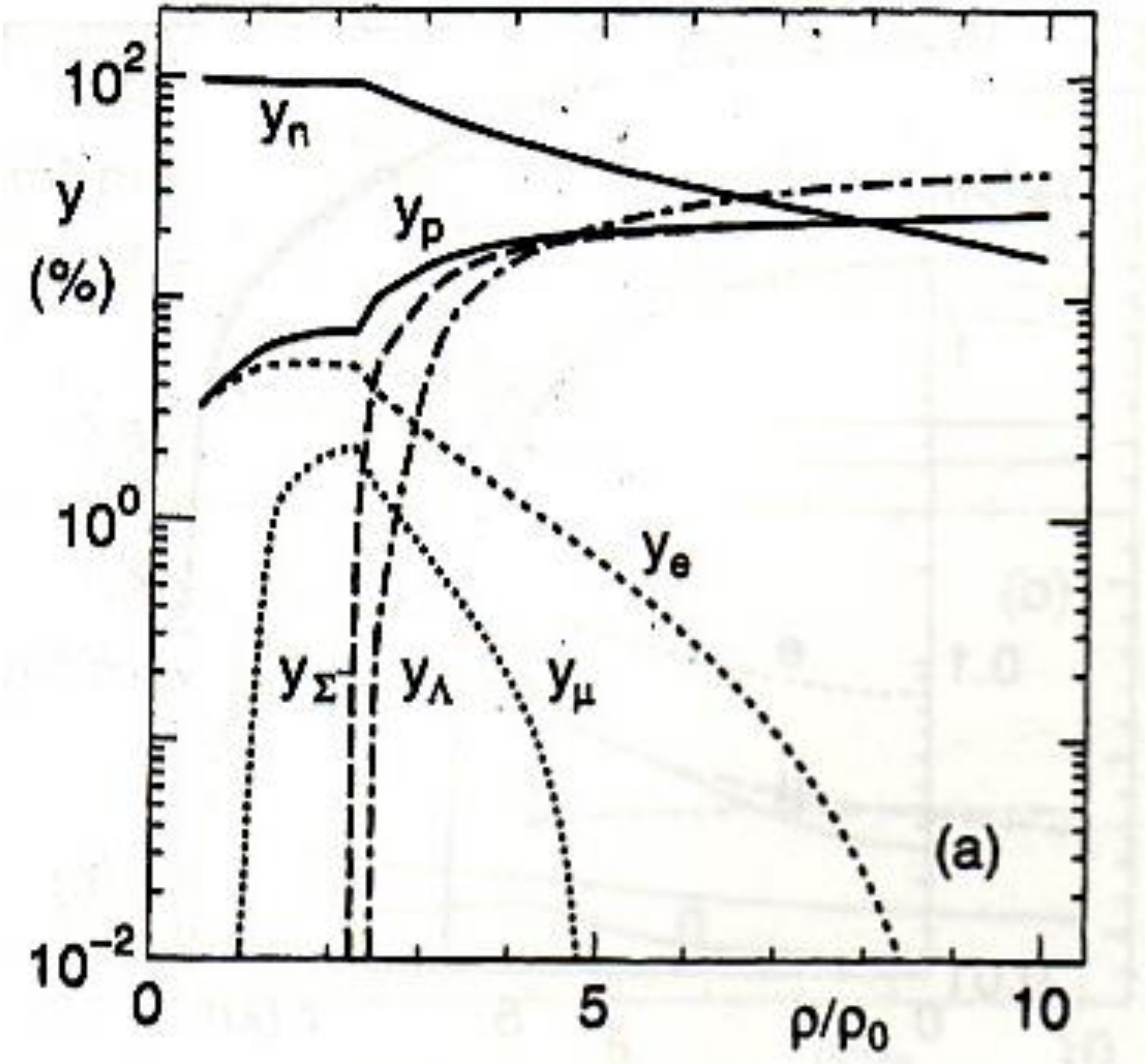
○ effective interaction approach based on G-matrix calculations, (effective int. V for NN, NY, YY)
Introduction of 3-body force U (TNI, phenomenological Illinoi-type, expressed as effective 2-body force)

○ 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 $\rho_t \sim (2\text{-}2.5)\rho_0$



Hyperon mixing in neutron stars(NSs)

○ sure to occur

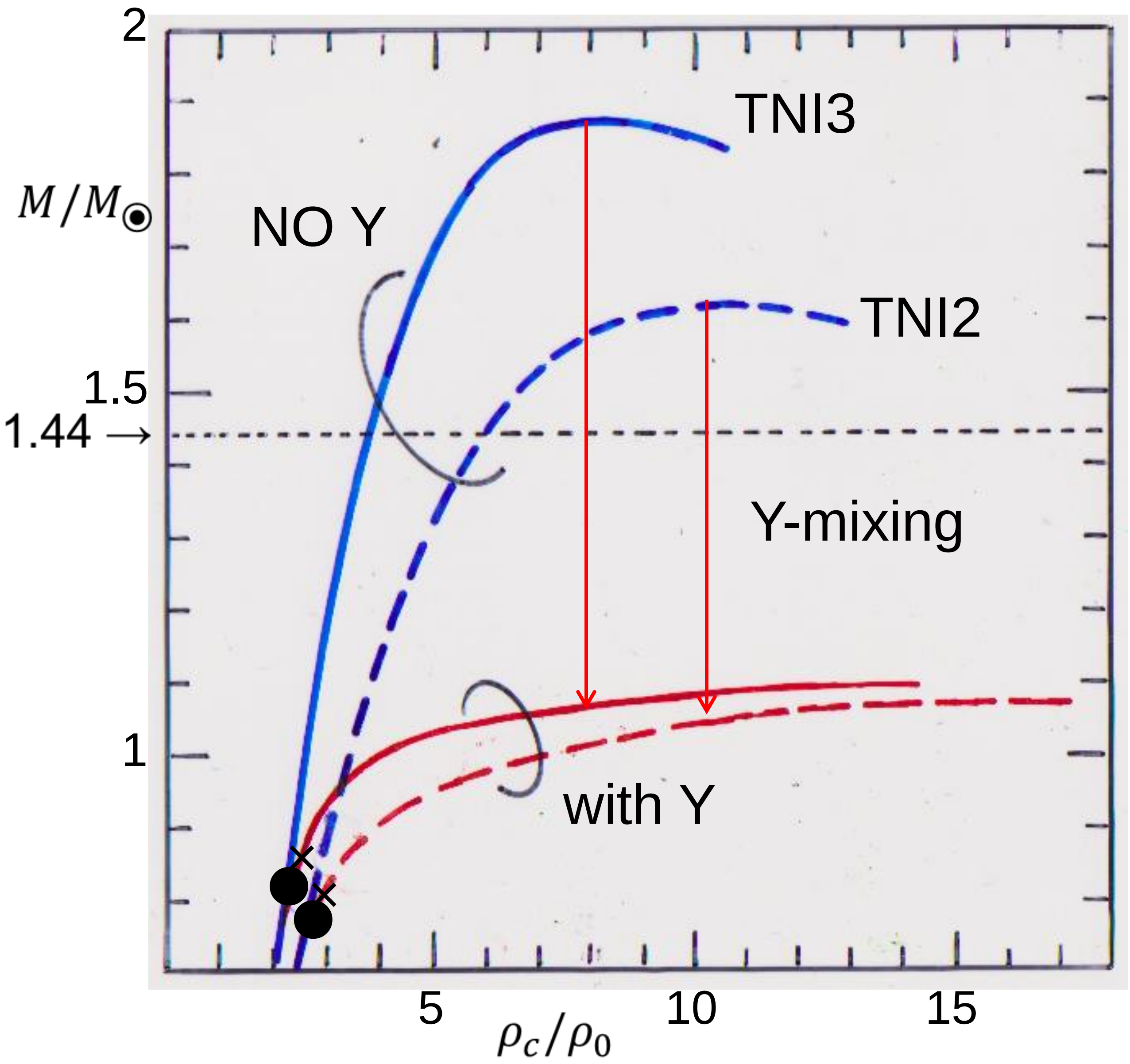
○ standard picture

OLD : n,p,e,μ → NOW : n,p,e,μ, Y

○ 2- problems

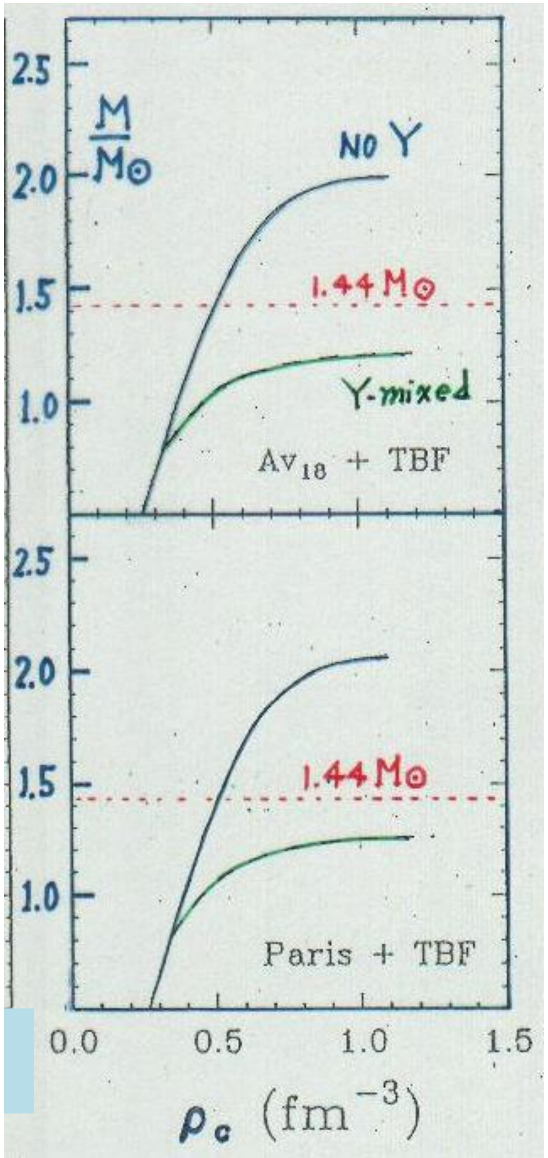
- strong softening effects on EOS
- too rapid cooling (Hyperon cooling)

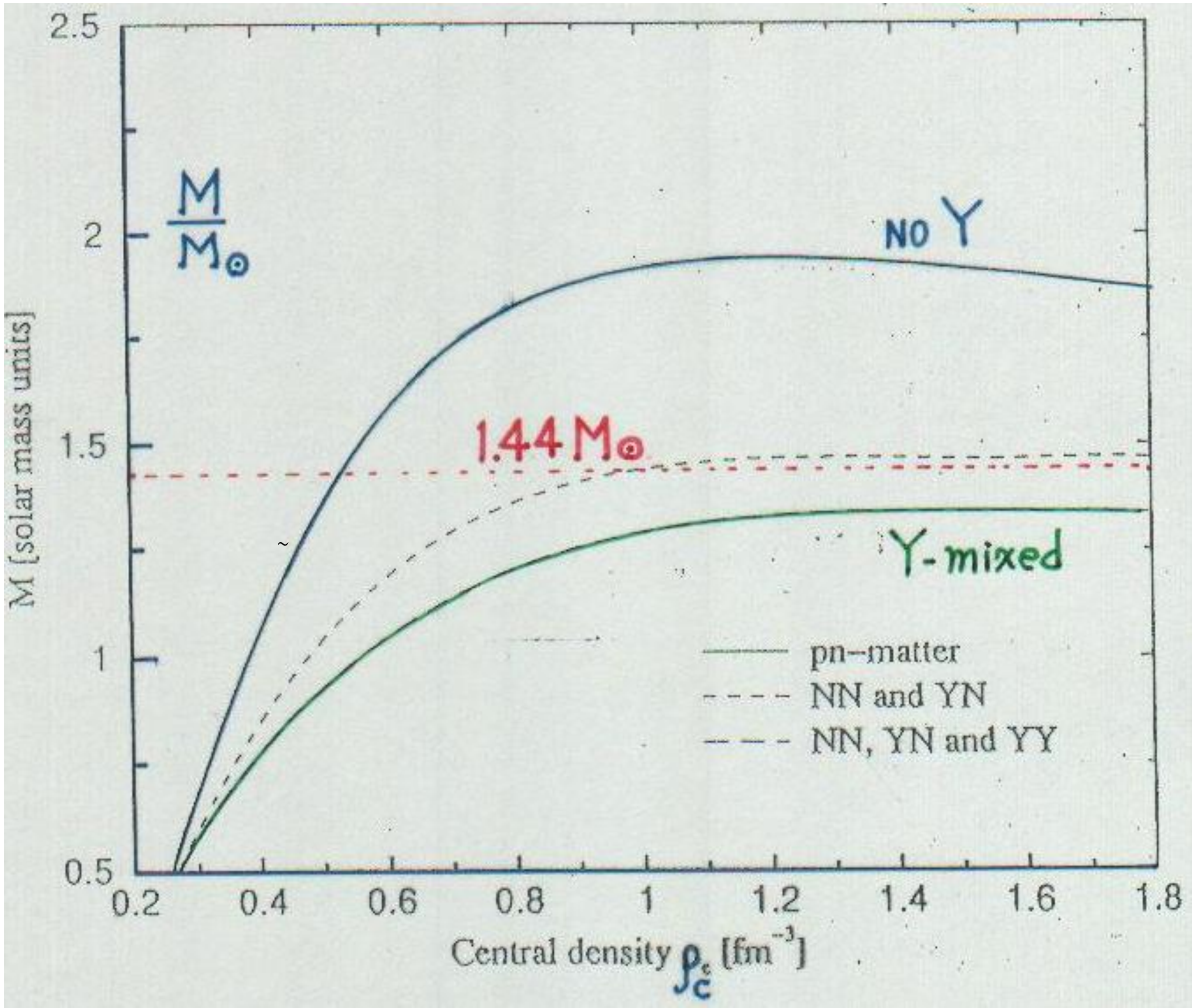
$M_{max} < M_{obs}$(Softened EOS by Y)



(1)

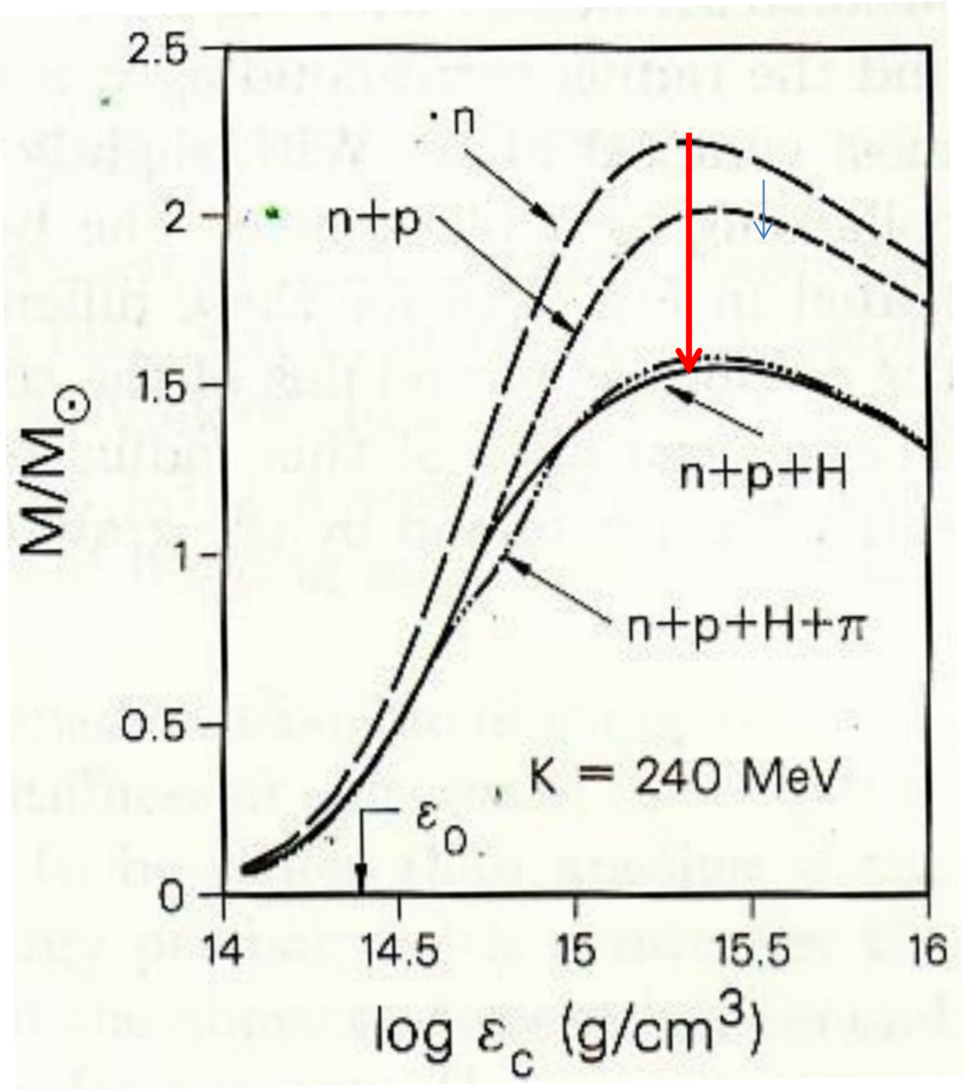
Strong Softening of the EOS





L-Vidana et al, P.R. C62 (2000) 035801

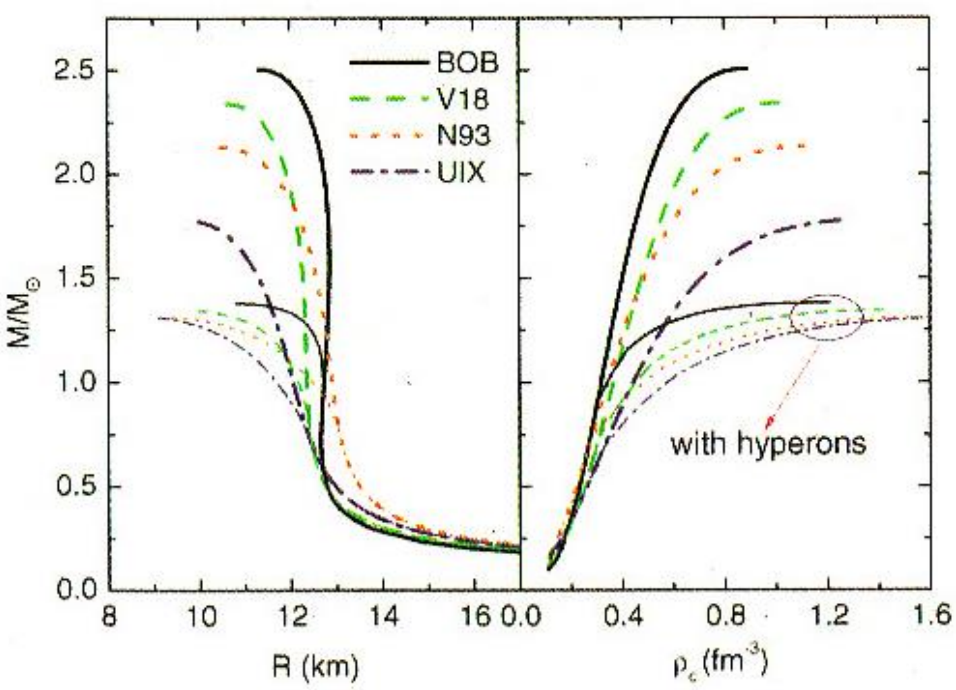
M. Baldo et al, P.R. C61 (2000) 055801



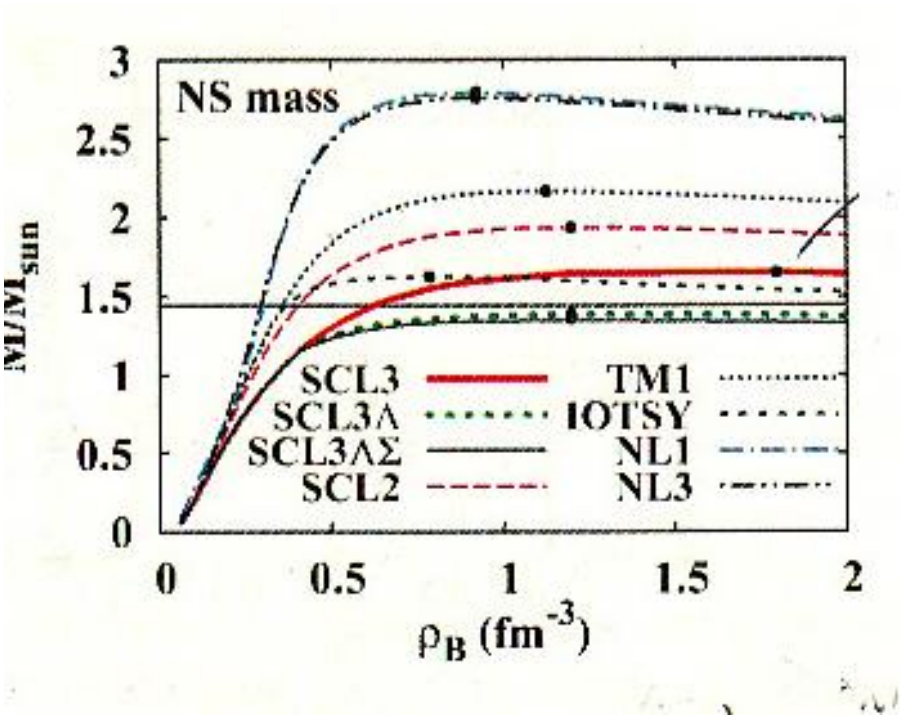
N.K. Glendenning, Nucl. Phys. A493 (1989) 521.

G-matrix with nucleonic 3-body force

Chiral SU(3) RMF

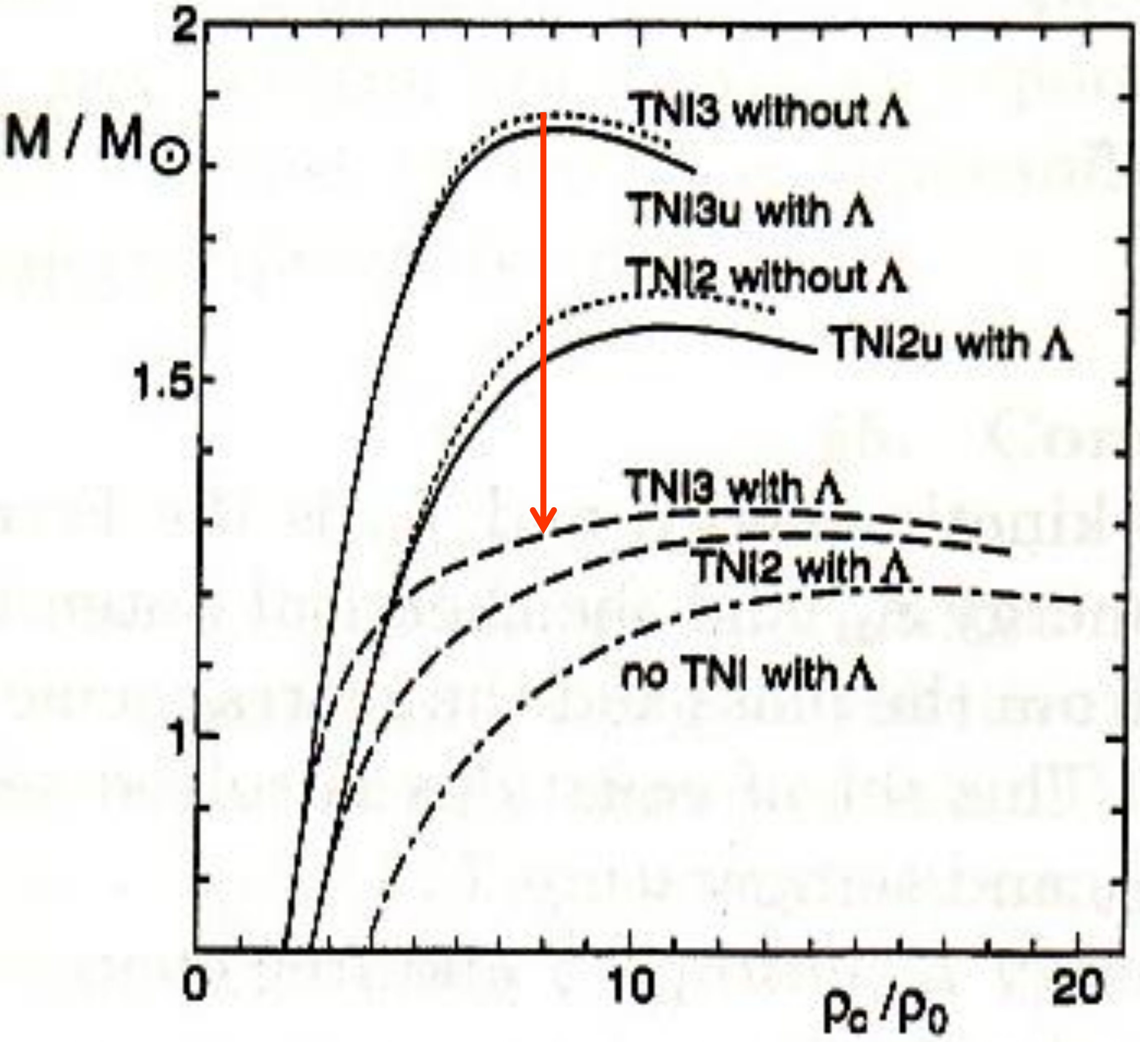


Z.H. Li and H.-J. Schulze, PR C78 (2008) 028801.



K. Tsubakihara, H. Maekawa, H. Matsumiya and A. Ohnishi, PR C81 (2010) 065206.

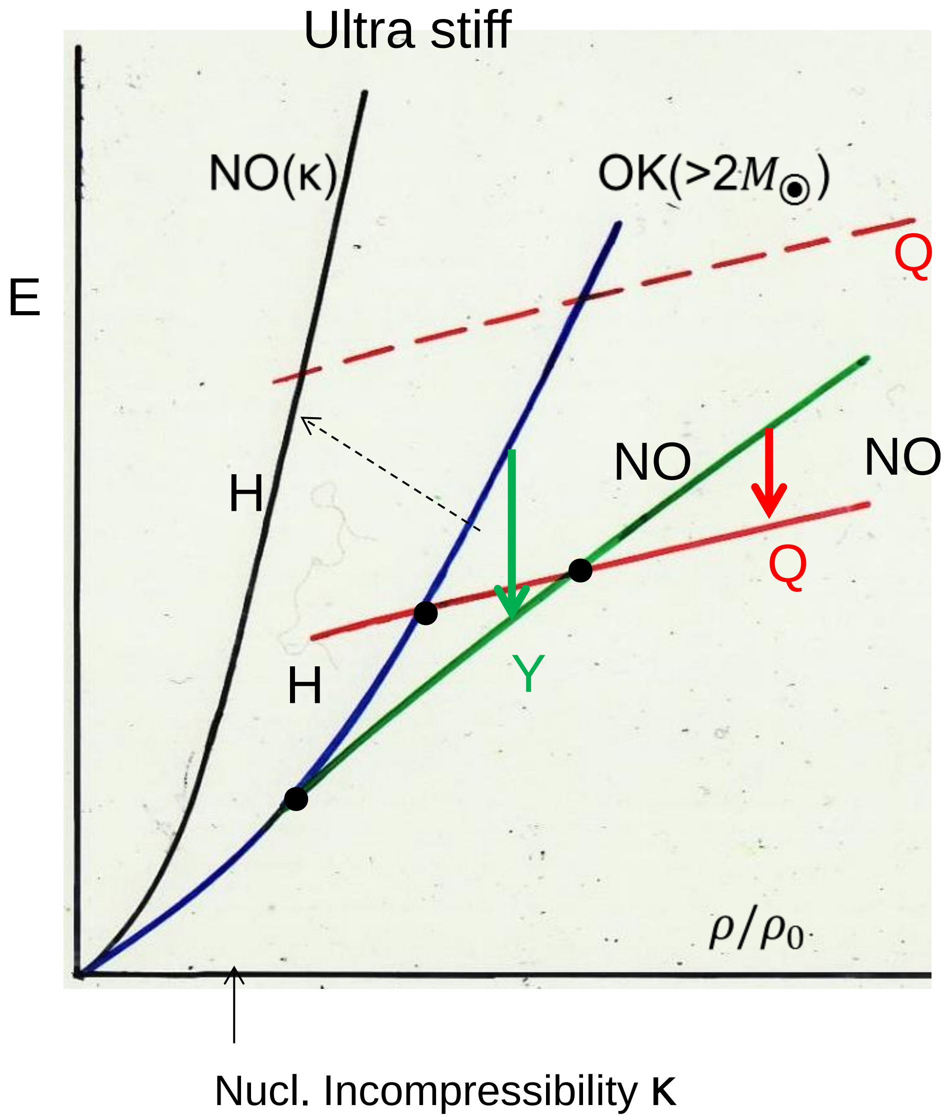
Even Λ-only mixing, situation is the same!



Recent Observation of Two-Solar-Mass Neutron Stars

↓ Impact !

Indeed,
“Hyperon Crisis!”



Observation of Massive NSs

(2-solar-mass NSs)

⇓

○ How to explain such massive NSs?

○ NO Q-matt. (Q-deg. of freedom) in NSs?

We consider the possibility in two frameworks:

① Pure hadronic (H) matter

② With Q-degrees of freedom

Seroius conflict between theory (soft; Y-mixing) and observation (stiff; two-solar-mass NSs),i.e., Hyperon Crisis

↓

Something are missing

↓

Deeper insights in hadron physics
and QCD

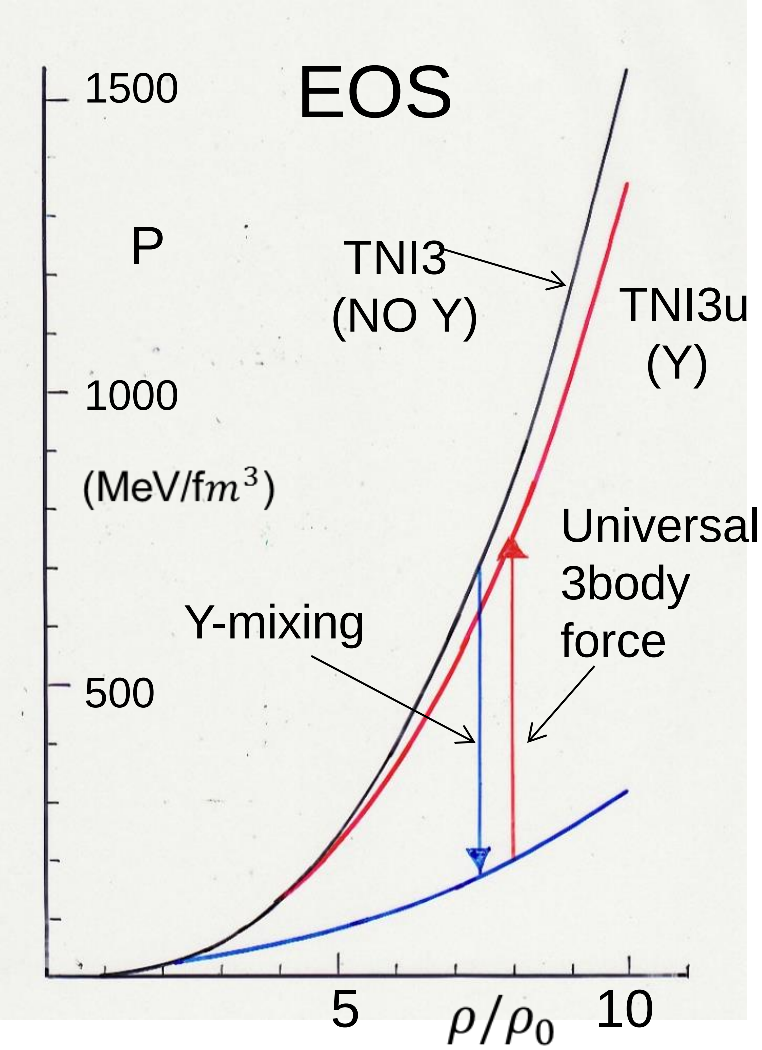
①Pure hadronic matter framework

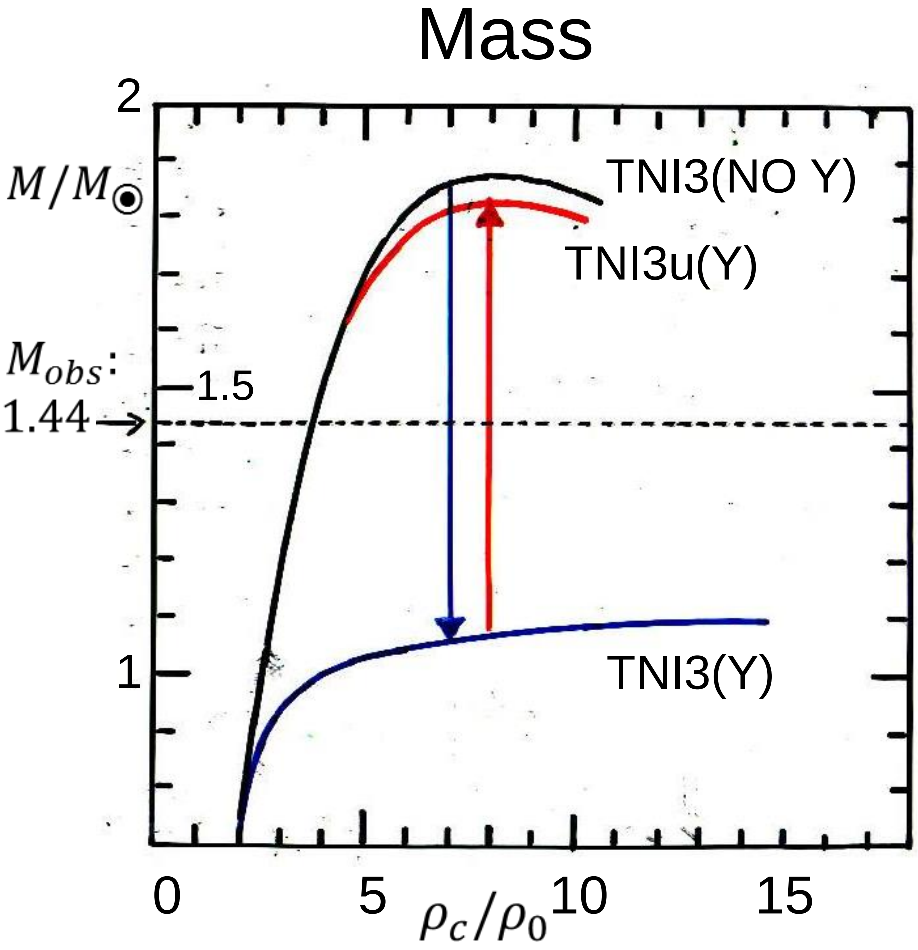
Universal introduction of 3-body force to (N+Y)-matter

S.Nishizaki,Y.Yamamoto and T.Takatsuka
Prog.Theor.Phys. 105(2001)607;108(2002)703

- ○phenomenological (F-P type)
- ○2πΔ＋SJM

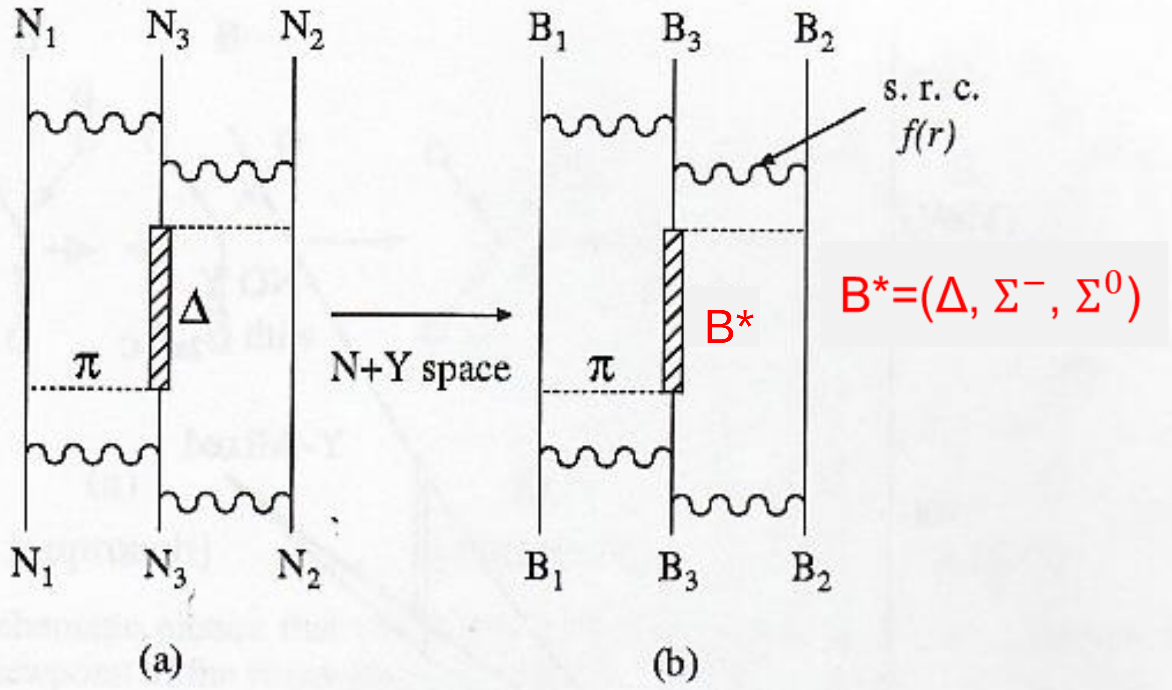
Dramatic softening of EOS ⟶ Necessity of "Extra Repulsion"





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

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

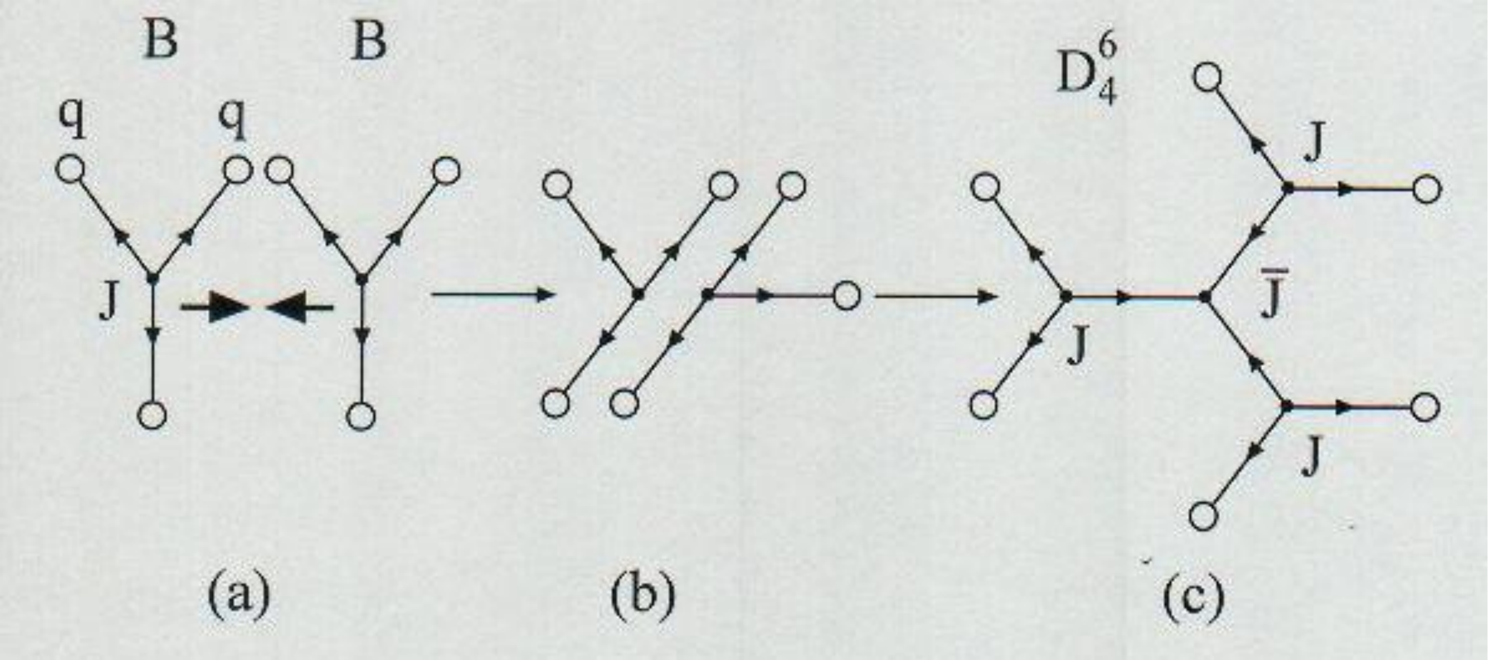


$B^*=(\Delta, \Sigma^-, \Sigma^0)$

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



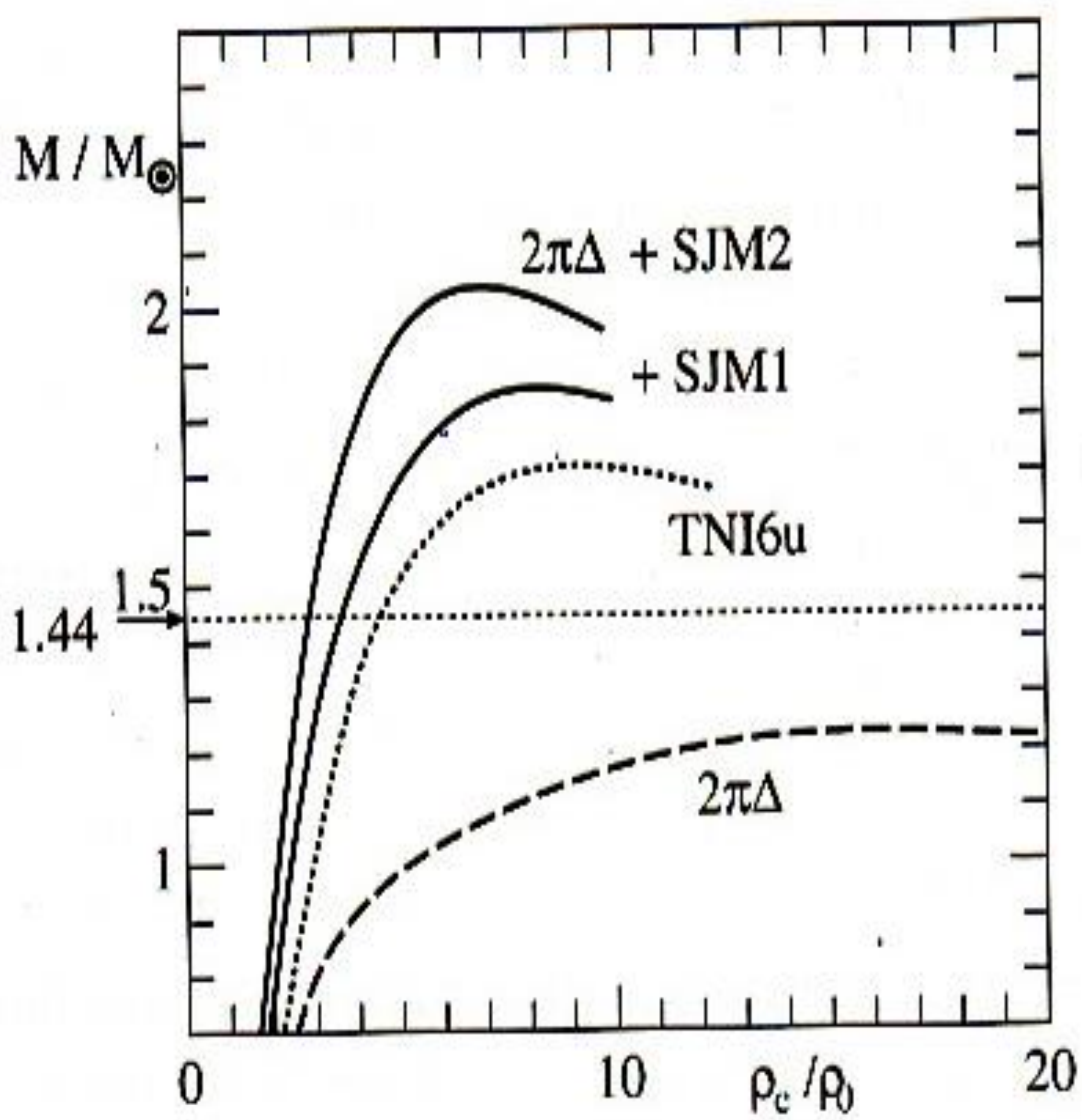
(a) 2B come in short distance
(b) Deformation (resistance)
(c) Fusion into 6-quark state

(by R. Tamagaki)

Prog. Theor. Phys. 119 (2008) 965.

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

Mass v.s. Central Density



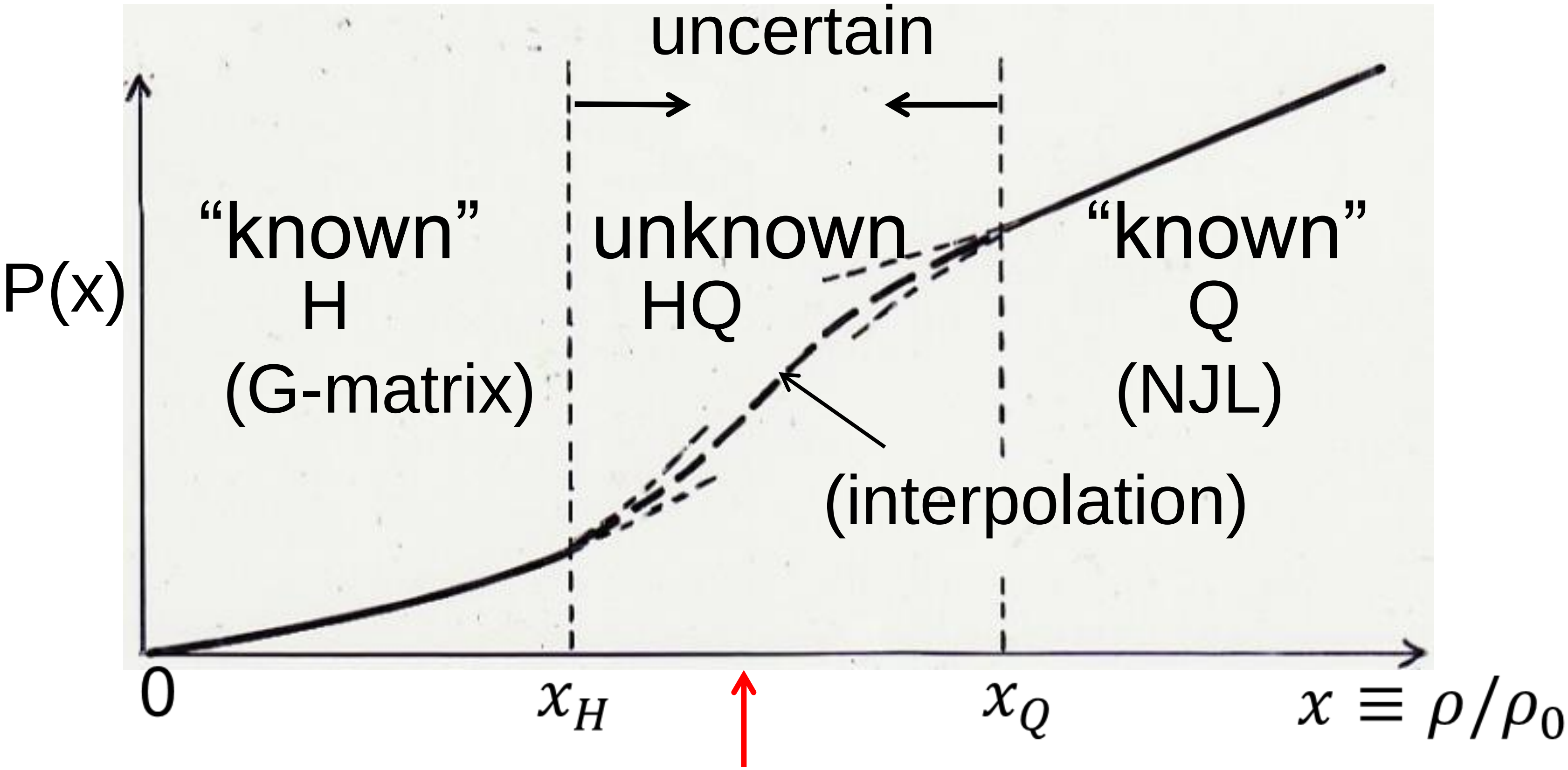
NS-mass from 2-body force + ”universal” 3-body force (2πΔ-type + SJM).

$M_{max} > 2M_\odot$ is possible.

T.Takatsuka,S.Nishizaki and R.Tamagaki, AIP Conference Proceedings 1011 (2008) 209.

② Inclusion of quark degrees of freedom

3-Window Model



uncertain

"known"
H
(G-matrix)

unknown
HQ

"known"
Q
(NJL)

(interpolation)

Deconfinement and confinement
are concerned

Constraints on EOS

☐Symm.Nucl.Matt.
・Saturation :ρ=ρ0=0.17nucleons/fm**3
E=Eb=-16MeV
・Incompressibility: κ=~(180-260)MeV
・Symm.energy : Esym=~(25-35)MeV
・Slope parameter L=~(50-100) MeV

☐Neutron Star Matt.

・Mmax G.T. ~ 2-Solar- Mass
・Sound velocity L.T. Light velocity
・Radius=~(10-12)Km

☐ Approach by 3-window model

(1) Interpolation function assumed $x \equiv \rho/\rho_0$:

$$\varepsilon_{HQ}(x) = Ax^5 + Bx^4 + Cx^3 + Dx^2 + Ex + F$$

$$p_{HQ}(x) = x^2 \frac{\partial}{\partial x}(\varepsilon_{HQ}(x)/x)$$

(2) -conditions:

$$\varepsilon_{HQ}(x_H) = \varepsilon_H(x_H), \quad \varepsilon_{HQ}(x_Q) = \varepsilon_Q(x_Q)$$

$$p_{HQ}(x_H) = p_H(x_H), \quad p_{HQ}(x_Q) = p_Q(x_Q)$$

$$p'_{HQ}(x_H) = p'_H(x_H), \; p'_{HQ}(x_Q) = p'_Q(x_Q)$$

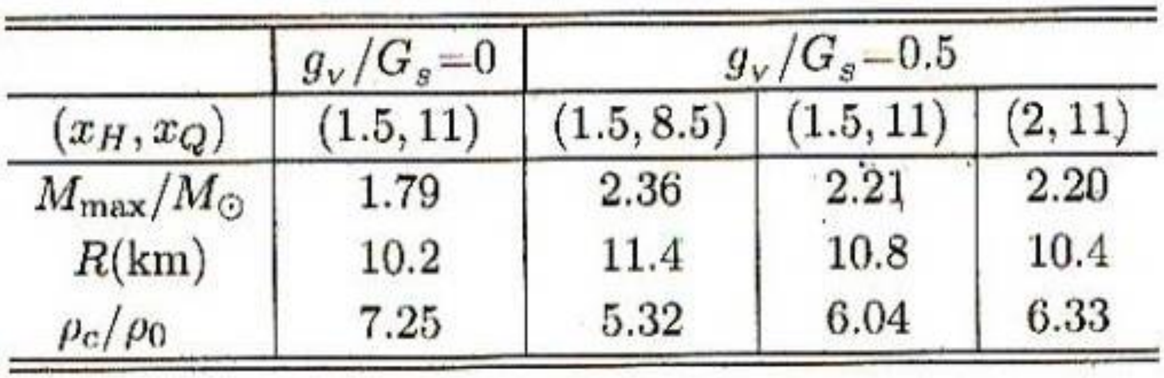
(c.f. $p(x) = \frac{\partial}{\partial x}\varepsilon(x) - \varepsilon(x)$

$\rightarrow \varepsilon'_{HQ}(x_H) = \varepsilon'_H(x_H), \; \varepsilon'_{HQ}(x_Q) = \varepsilon'_Q(x_Q)$)

(3) Selection of $\varepsilon_{HQ}(x)$:

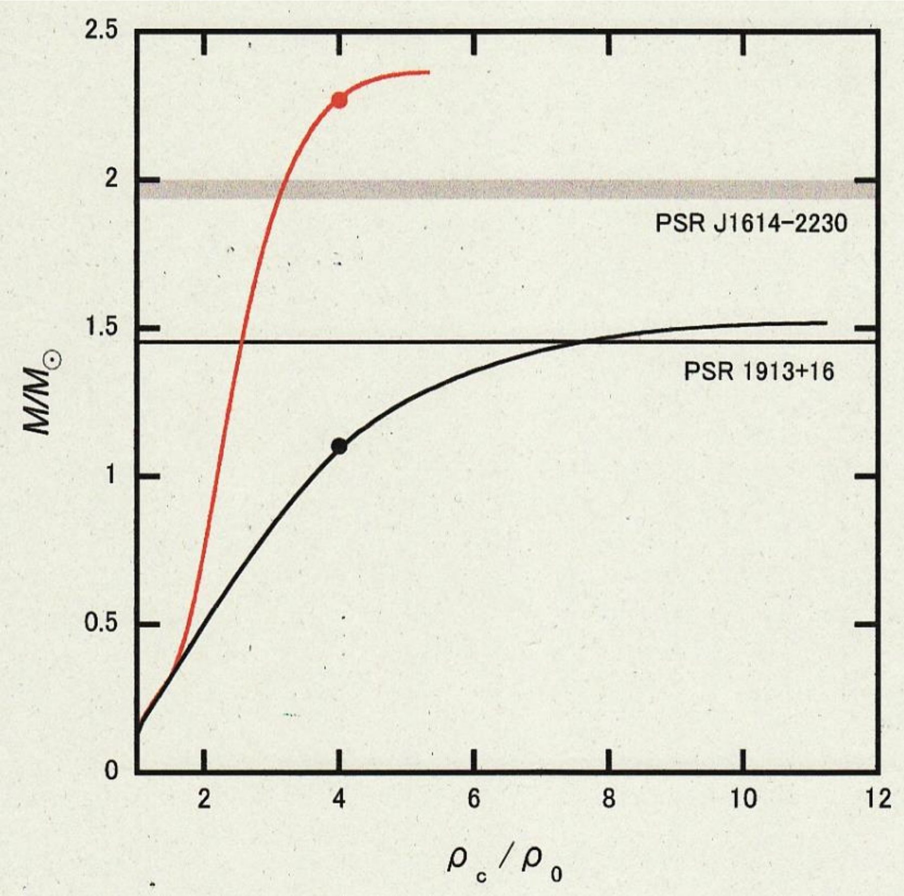
- ○ Onset of quark degrees of freedom, $x_H > 1$
- ○ Thermodynamic stability, $p_{HQ}(x) > 0, \;\; p'_{HQ}(x) > 0$
- ○ Causality, $\frac{v_s}{c} < 1$

☐ Some results

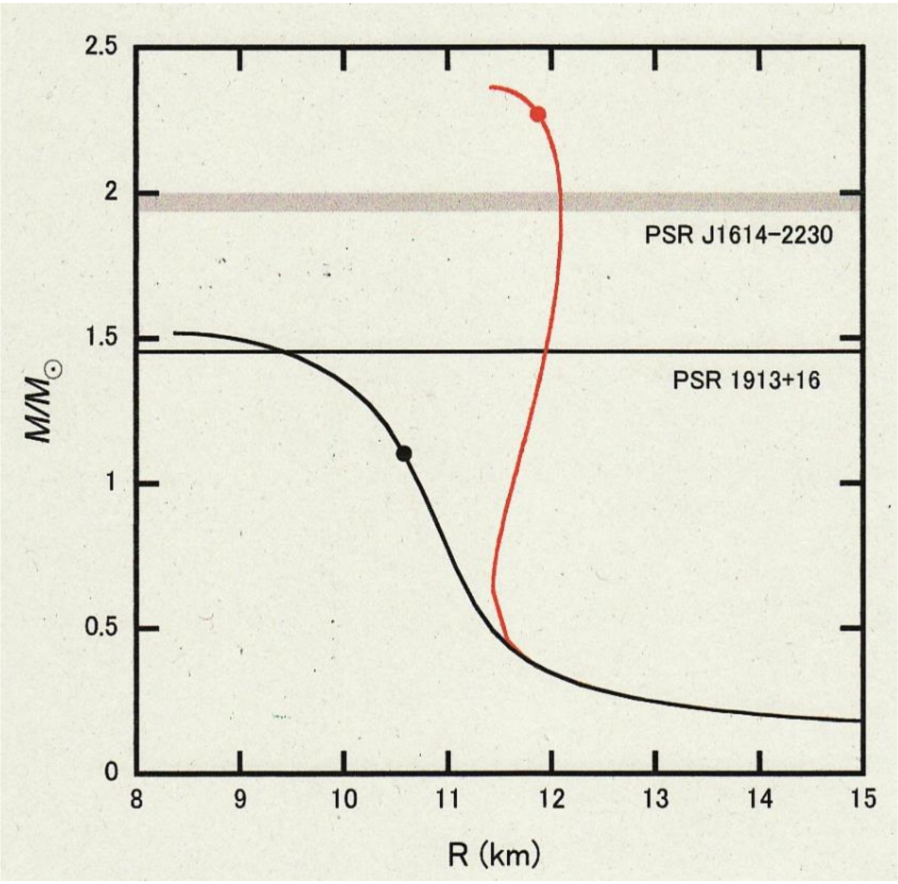


	$g_V/G_s=0$	$g_V/G_s=0.5$		
(x_H, x_Q)	$(1.5, 11)$	$(1.5, 8.5)$	$(1.5, 11)$	$(2, 11)$
$M_{\max}/M_\odot$	1.79	2.36	2.21	2.20
R(km)	10.2	11.4	10.8	10.4
ρ_c/ρ_0	7.25	5.32	6.04	6.33

$M - \rho_c$


2.5
2
1.5
1
0.5
0
$M/M_\odot$
2
4
6
8
10
12
ρ_c/ρ_0
PSR J1614−2230
PSR 1913+16

$M - R$


2.5
2
1.5
1
0.5
0
$M/M_\odot$
8
9
10
11
12
13
14
15
R (km)
PSR J1614−2230
PSR 1913+16

Summary

1) The 3-window model suggests the possibility of 2-solar-mass NSs with H-Q transient core, as far as quark degrees of freedom sets in at rather low density and the Q-EOS is stiff.

   Present results support those from a crossover picture in our preceeding work.

2) So, possible candidates to solve the “Hyperon Crisis” problem:

∗ pure hadronic scheme -→ Universal 3-body force repulsion
∗ hadron + quark scheme --→ NSs with H-Q transient core

3) Finally, we want to stress that 2-solar-mass NSs do not exclude the H-Q transition in NS cores.

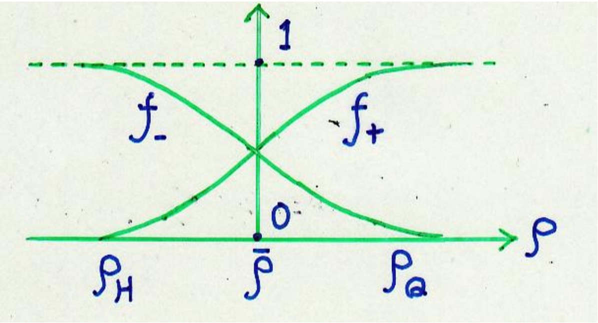
Appendix

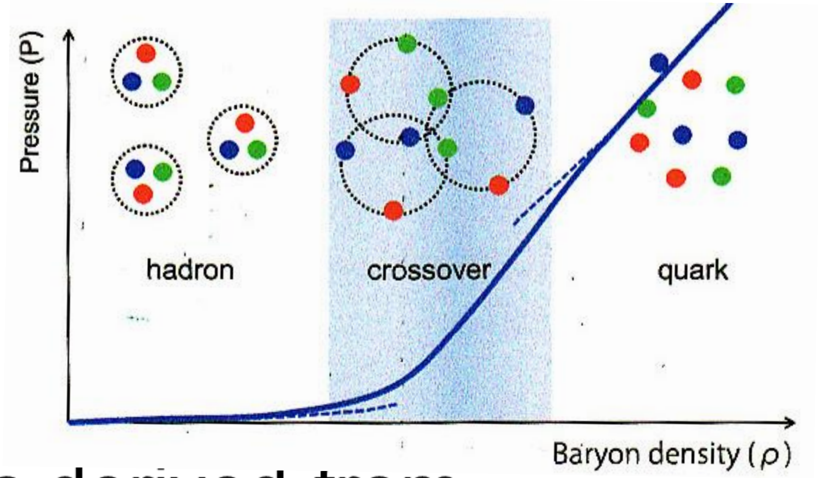
“H-Q crossover model”

○ From a view of “H-Q Crossover”

$$P(\rho) = P_H(\rho) f_-(\rho) + P_Q(\rho) f_+(\rho),$$

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

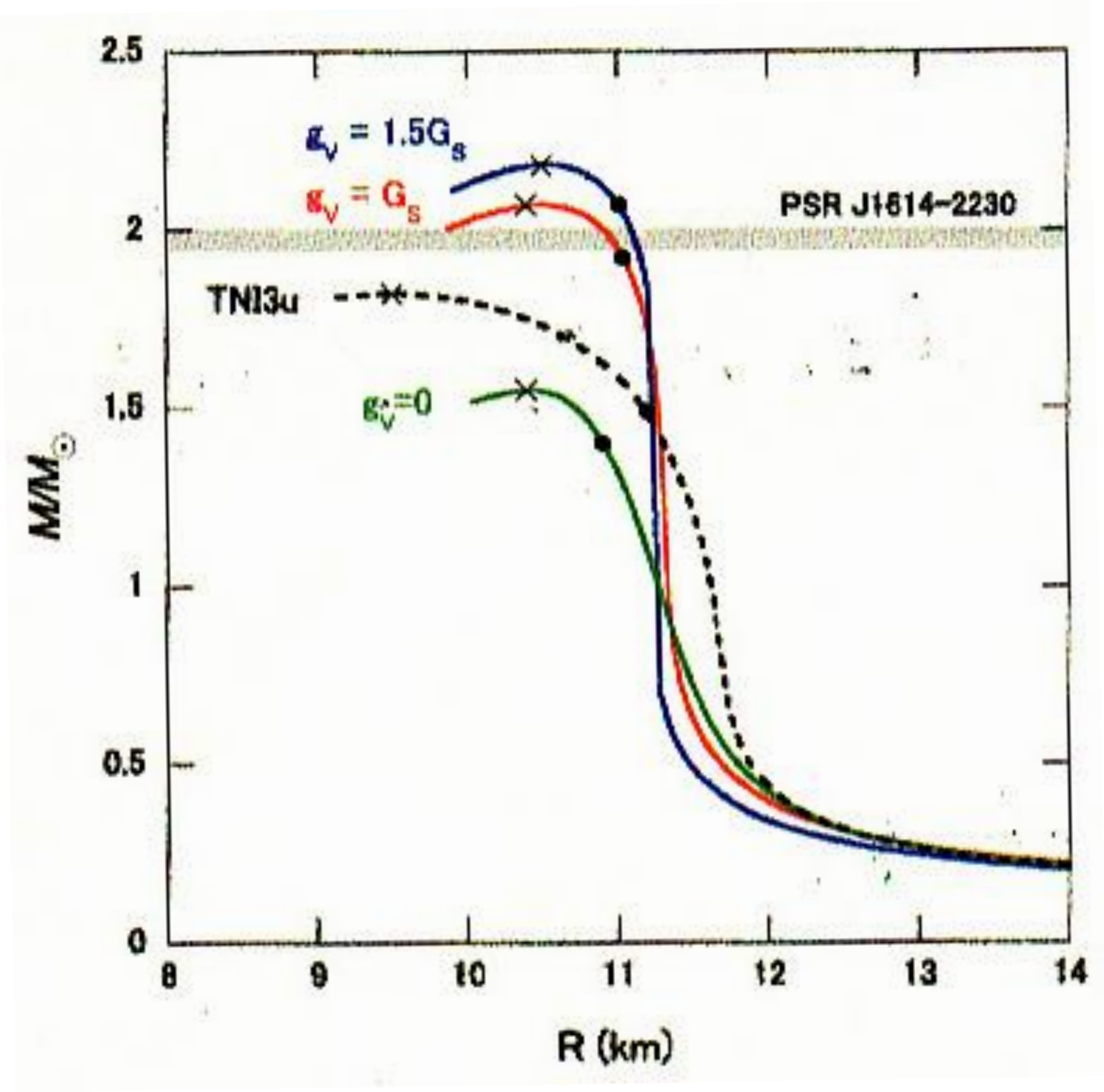




○ energy density ε(ρ) is derived from

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

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

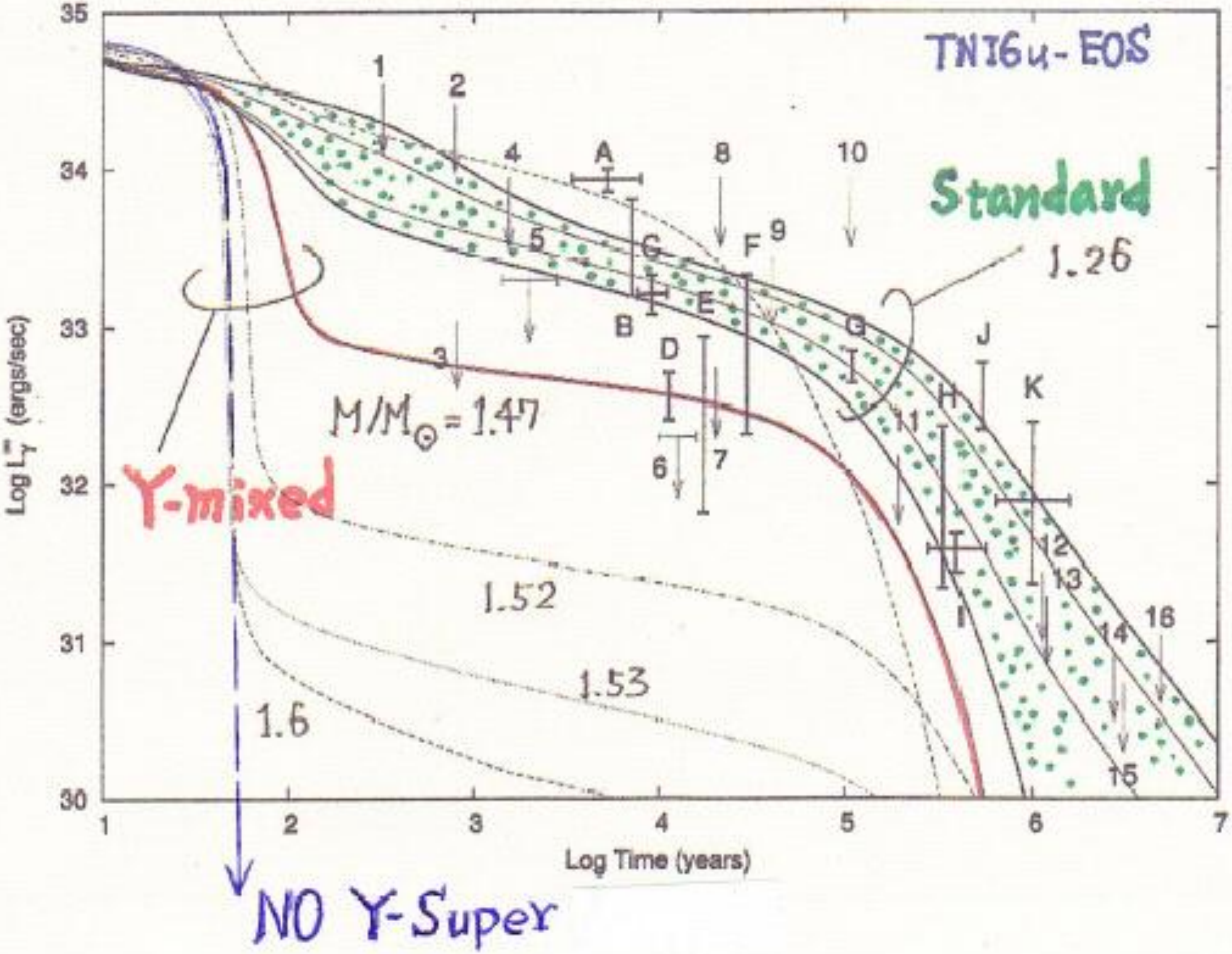


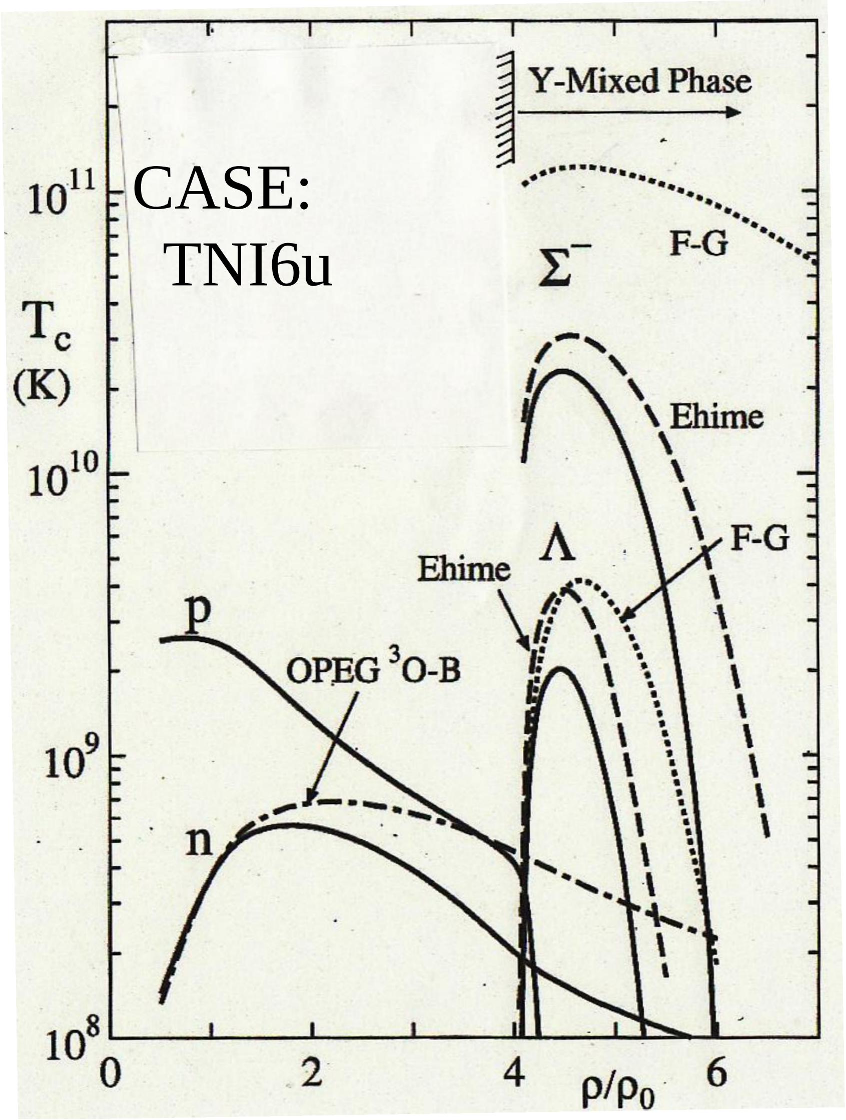
Mass v.s. Radius

$M_{max} > 2M_\odot$

Is possible

Tsuruta et al, Ap.J.691(2009)621-632





CASE:
TNI6u

Critical Temperature T_c versus Density ρ

☐Pairing type:
n → 3P2
p, Λ, Σ^- → 1S0

☐Pairing interactions:
n, p → OPEG-A pot.
Λ, Σ^- → ND-Soft
for solid lines

○ Observed mass of neutron stars

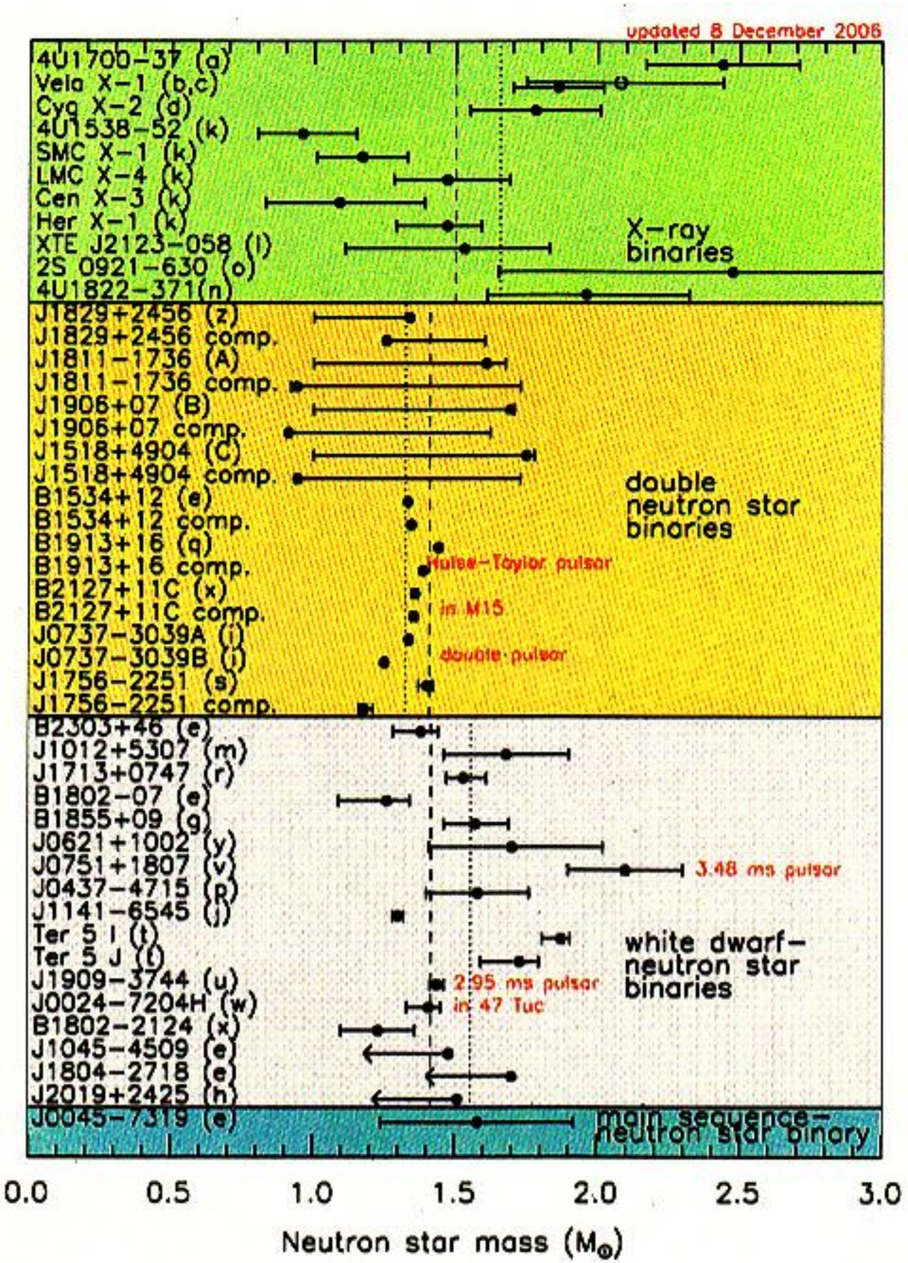
J.M. Lattimer and
M. Prakash
Phys. Rep. 442
(2007) 109-165

→ Remarks:

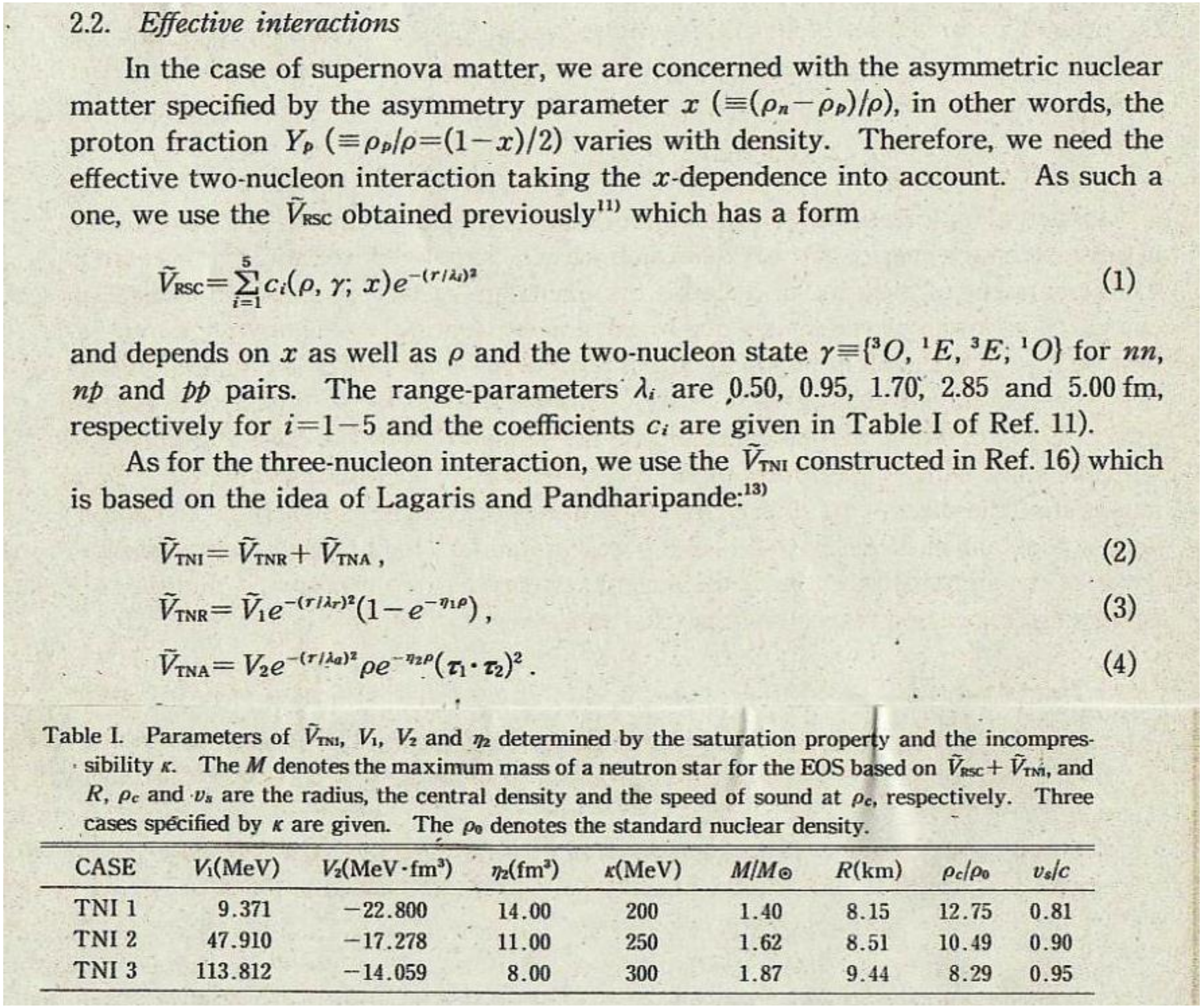
○ M_{obs} are mostly populated in (1.3-1.6) $M_\odot$

○ M_{max}(theory)≥1.44$M_\odot$

(→ ~2.0$M_\odot$)



H-EOS



2.2. *Effective interactions*

In the case of supernova matter, we are concerned with the asymmetric nuclear matter specified by the asymmetry parameter x $(\equiv(\rho_n-\rho_p)/\rho)$, in other words, the proton fraction Y_p $(\equiv\rho_p/\rho=(1-x)/2)$ varies with density. Therefore, we need the effective two-nucleon interaction taking the x-dependence into account. As such a one, we use the $\tilde{V}_{\mathrm{RSC}}$ obtained previously[11] which has a form

$$\tilde{V}_{\mathrm{RSC}}=\sum_{i=1}^{5}c_i(\rho,\gamma;x)e^{-(r/\lambda_i)^2} \tag{1}$$

and depends on x as well as ρ and the two-nucleon state $\gamma\equiv\{{}^3O,{}^1E,{}^3E,{}^1O\}$ for nn, np and pp pairs. The range-parameters λ_i are 0.50, 0.95, 1.70, 2.85 and 5.00 fm, respectively for $i=1-5$ and the coefficients c_i are given in Table I of Ref. 11).

As for the three-nucleon interaction, we use the $\tilde{V}_{\mathrm{TNI}}$ constructed in Ref. 16) which is based on the idea of Lagaris and Pandharipande:[13]

$$\tilde{V}_{\mathrm{TNI}}=\tilde{V}_{\mathrm{TNR}}+\tilde{V}_{\mathrm{TNA}}\,, \tag{2}$$

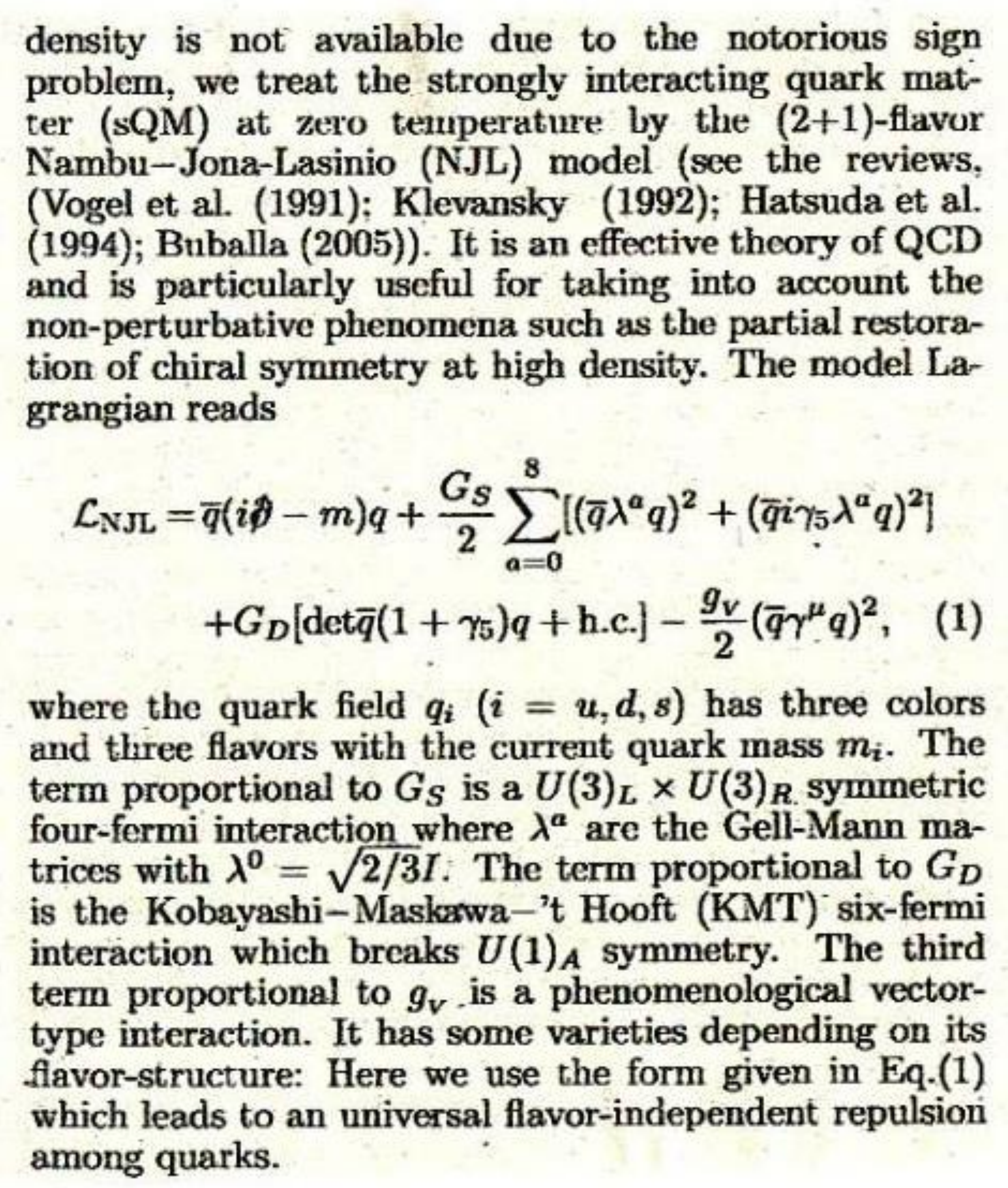
$$\tilde{V}_{\mathrm{TNR}}=\tilde{V}_1e^{-(r/\lambda_r)^2}(1-e^{-\eta_1\rho})\,, \tag{3}$$

$$\tilde{V}_{\mathrm{TNA}}=V_2e^{-(r/\lambda_a)^2}\rho e^{-\eta_2\rho}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)^2\,. \tag{4}$$

Table I. Parameters of $\tilde{V}_{\mathrm{TNI}}$, V_1, V_2 and η_2 determined by the saturation property and the incompressibility κ. The M denotes the maximum mass of a neutron star for the EOS based on $\tilde{V}_{\mathrm{RSC}}+\tilde{V}_{\mathrm{TNI}}$, and R, ρ_c and v_s are the radius, the central density and the speed of sound at ρ_c, respectively. Three cases specified by κ are given. The ρ_0 denotes the standard nuclear density.

CASE	V_1(MeV)	V_2(MeV·fm^3)	η_2(fm^3)	κ(MeV)	$M/M_\odot$	R(km)	ρ_c/ρ_0	v_s/c
TNI 1	9.371	−22.800	14.00	200	1.40	8.15	12.75	0.81
TNI 2	47.910	−17.278	11.00	250	1.62	8.51	10.49	0.90
TNI 3	113.812	−14.059	8.00	300	1.87	9.44	8.29	0.95

Q-EOS



density is not available due to the notorious sign problem, we treat the strongly interacting quark matter (sQM) at zero temperature by the (2+1)-flavor Nambu–Jona-Lasinio (NJL) model (see the reviews, (Vogel et al. (1991); Klevansky (1992); Hatsuda et al. (1994); Buballa (2005)). It is an effective theory of QCD and is particularly useful for taking into account the non-perturbative phenomena such as the partial restoration of chiral symmetry at high density. The model Lagrangian reads

$$\mathcal{L}_{\mathrm{NJL}} = \bar{q}(i\partial\!\!\!/ - m)q + \frac{G_S}{2}\sum_{a=0}^{8}[(\bar{q}\lambda^a q)^2 + (\bar{q}i\gamma_5\lambda^a q)^2]$$

$$+G_D[\det\bar{q}(1+\gamma_5)q + \mathrm{h.c.}] - \frac{g_V}{2}(\bar{q}\gamma^\mu q)^2, \quad (1)$$

where the quark field q_i $(i = u, d, s)$ has three colors and three flavors with the current quark mass m_i. The term proportional to G_S is a $U(3)_L \times U(3)_R$ symmetric four-fermi interaction where λ^a are the Gell-Mann matrices with $\lambda^0 = \sqrt{2/3}I$. The term proportional to G_D is the Kobayashi–Maskawa–'t Hooft (KMT) six-fermi interaction which breaks $U(1)_A$ symmetry. The third term proportional to g_V is a phenomenological vector-type interaction. It has some varieties depending on its flavor-structure: Here we use the form given in Eq.(1) which leads to an universal flavor-independent repulsion among quarks.