理研仁科センター連続講義・コースX（第3回）2013.7.26

原子核物理学連続講義・コースX－3

Baryonic Matter and Neutron Stars

（第3回）

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

6. Hyperon mixing and consequences on neutron stars (NSs)
    6-1. Hyperons as new constituents of NSs
    6-2. Too serious problems

7. Possible solution for the problem
    7-1. Too soft EOS (Problem 1)
    7-2. Too rapid cooling (Problem 2)

8. Recent topics ---- $2M_\odot$ problem
    8-1. Universal 3-body repulsion
    8-2. Hybrid NSs with quark degrees of freedom

9. Hot NSs at birth with hyperon mixing

□ Hyperons in NSs --- Earlier works

○ Suggestion for Y-mixing in NSs

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

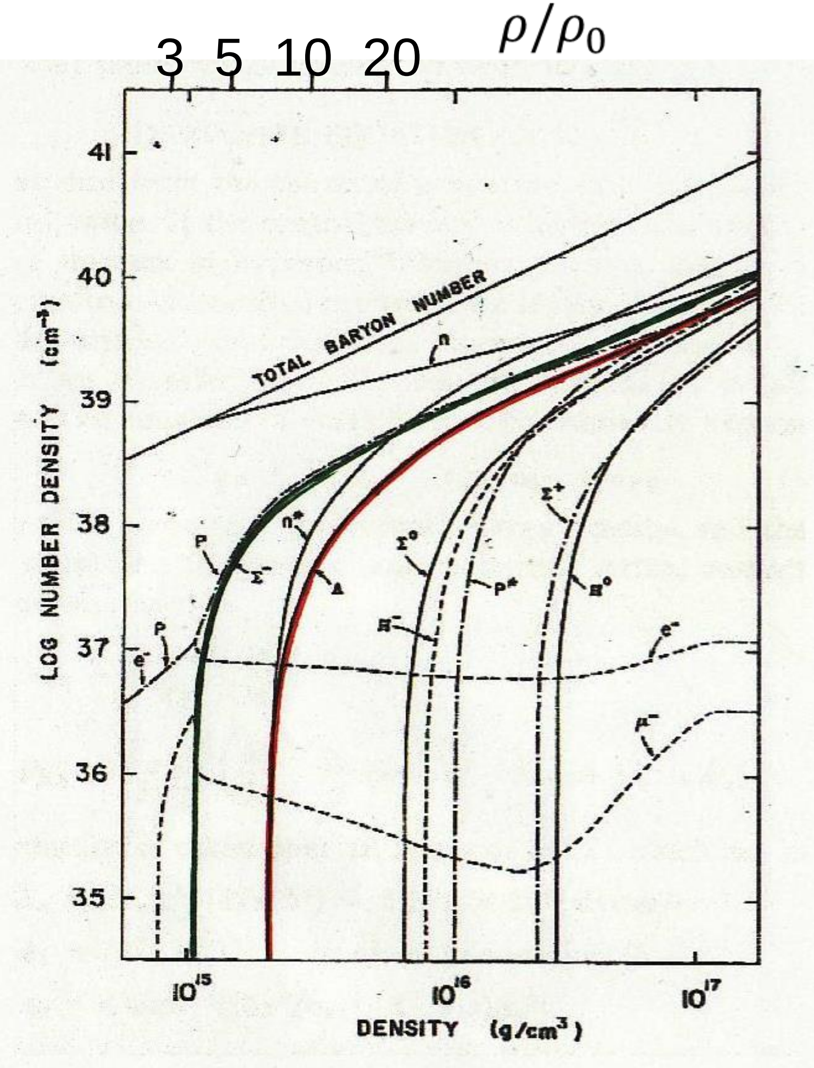
○ Attempts for Y-mixing calculation

- 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.

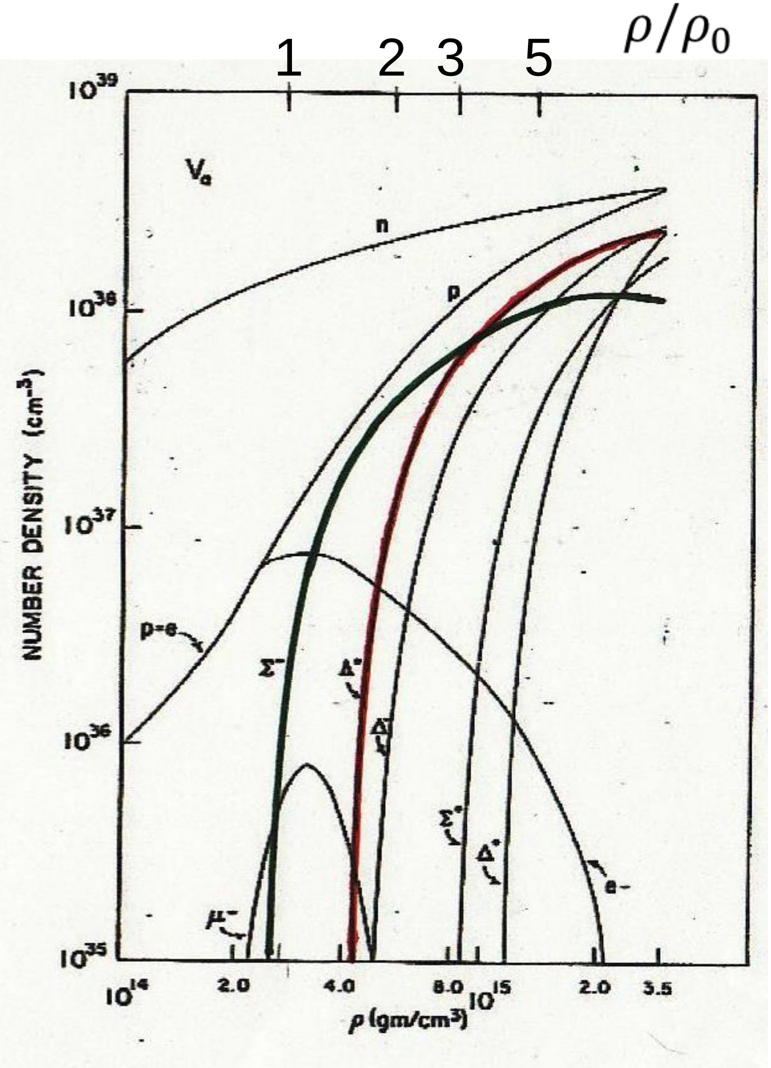
Baryon	M(Mev)	S	Comp.
n	940	0	udd
p	938	0	uud
Λ	1116	-1	$(uds-dus)/\sqrt{2}$
Σ^{+}	1189	-1	uus
Σ^{0}	1193	-1	$(uds+dus)/\sqrt{2}$
Σ^{-}	1197	-1	dds
Ξ^{0}	1315	-2	uss
Ξ^{-}	1321	-2	dss

○ 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;

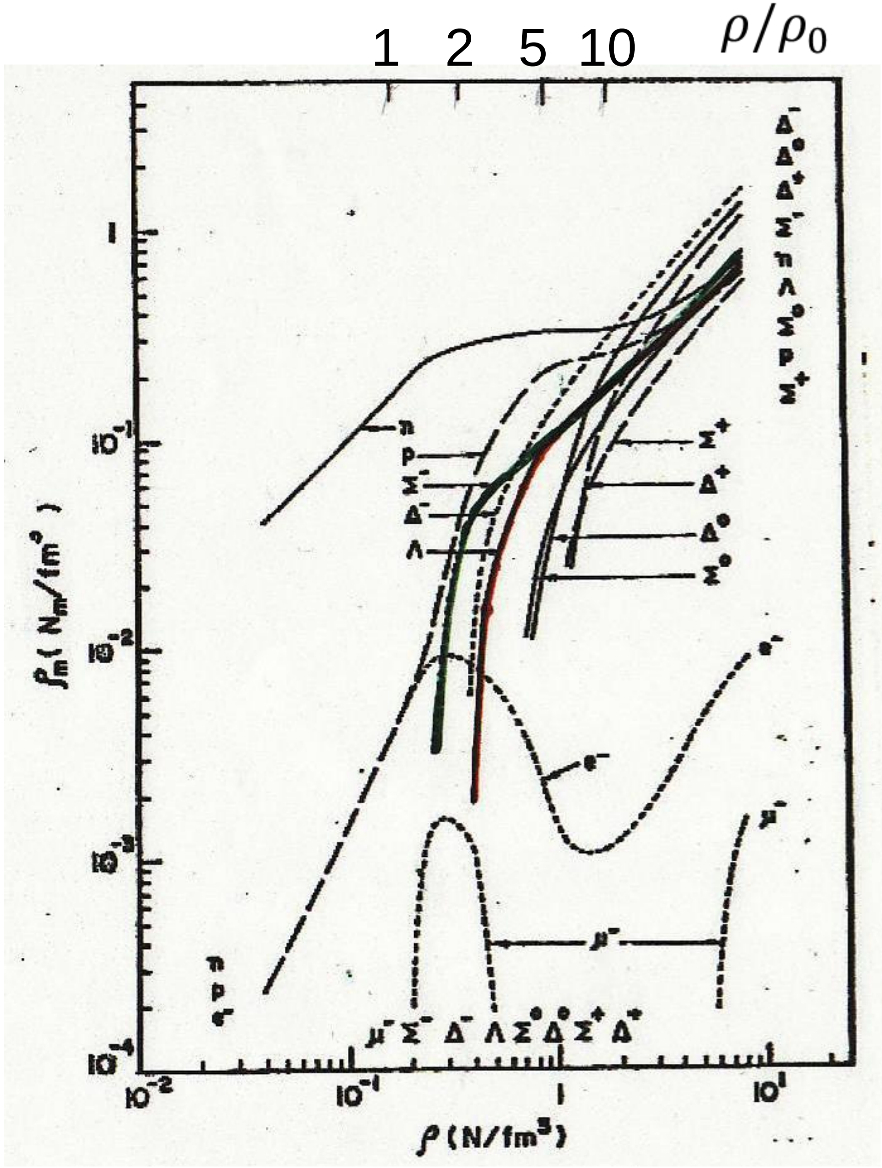
- T. Takatsuka, Prog. Theor. Phys. Suppl. No.156 (2004) 84.



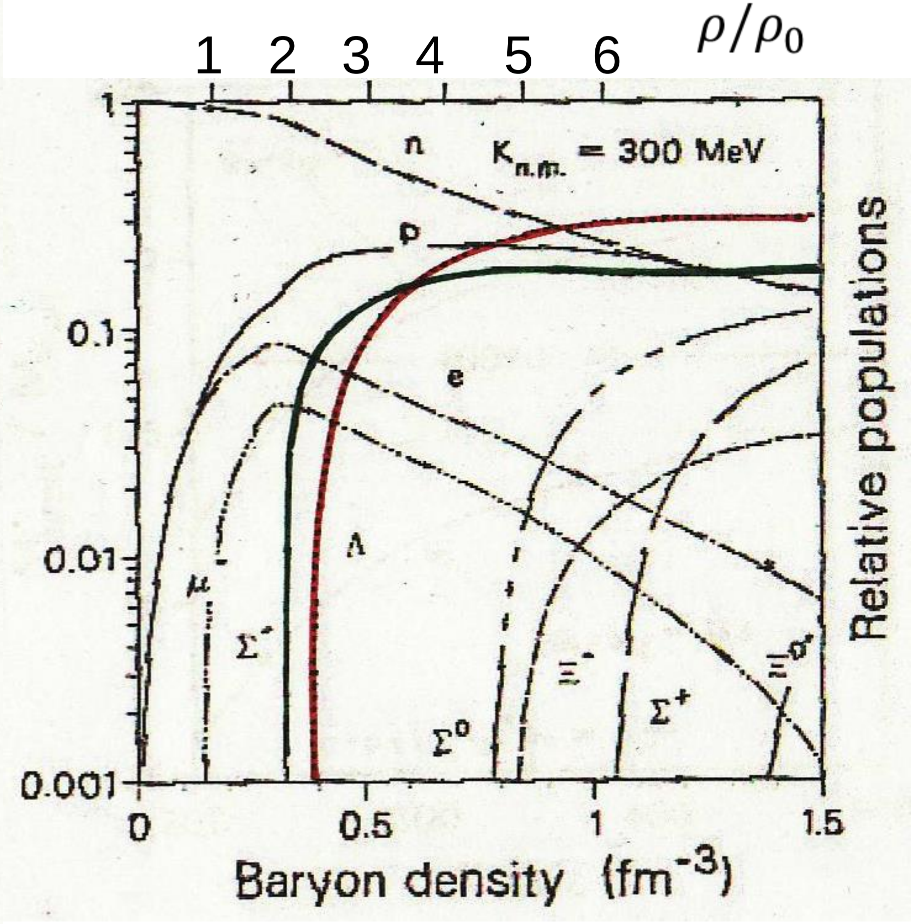
S. Tsuruta and A.G.W. Cameron,
Canadian Journal of Phys., 44 (1966) 1895.



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



V.R. Pandharipande, Nucl.Phys. A178 (1971)125.



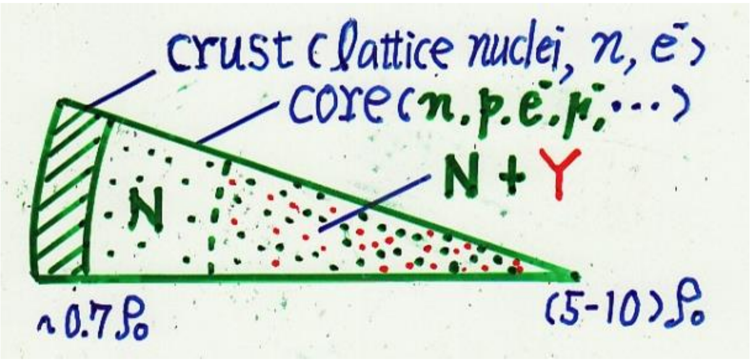
N.K. Glendenning, Nucl. Phys. A493 (1989) 521.

6. Hyperons mixing and consequences on neutron stars (NSs)

6-1. Hyperons as new constituents of NSs

Hyperons (Ys) are sure to appear !

Mechanism of Y-mixing



(1) K.E. only:

$$\frac{\hbar^2 {k_F}^2}{2m_n} = 61(\rho/\rho_0)^{2/3} = \Delta\mathrm{m} = m_\Lambda - m_n = 175\ \mathrm{MEV}$$

$$\rightarrow \rho_t(\Lambda) \simeq 5\rho_0 \qquad (\rho_0 = 0.17/fm^3;\ \text{nuclear density})$$

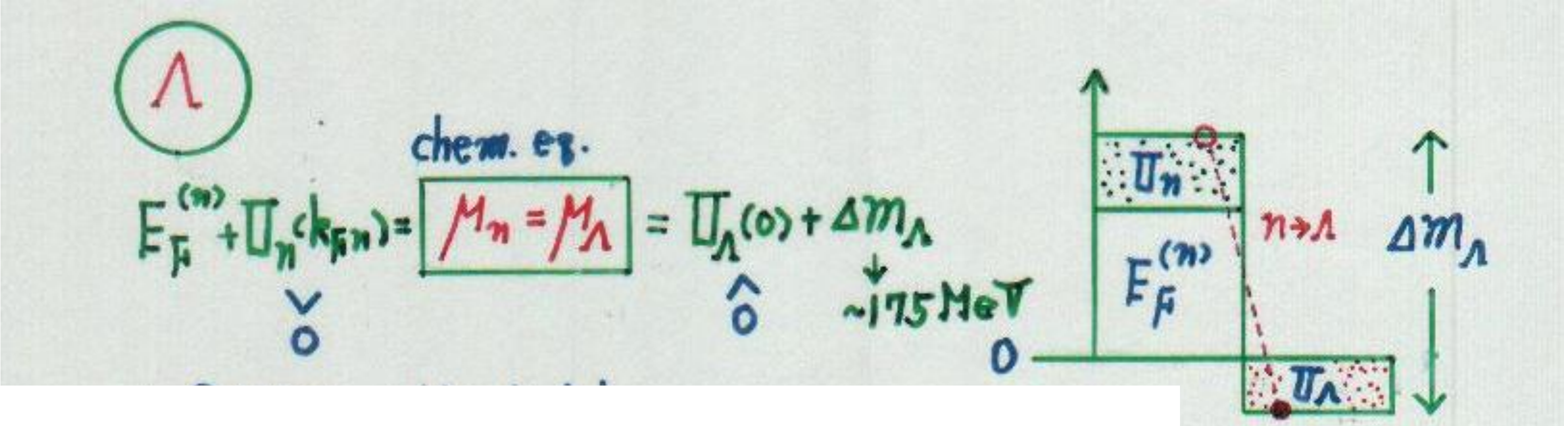
(2) Interaction is switched on:

Surely $\rho_t(\Lambda) < 5\rho_0$

because the effects of ΛN interaction is attractive

(← assured by the existence of Λ-hypernuclei in nature)

⇒ ρ_t is made lower by interactions:



chem. eq.

$$\underset{\overset{\vee}{0}}{E_F^{(n)}} + U_n(k_{Fn}) = \boxed{\mu_n = \mu_\Lambda} = \underset{\overset{\wedge}{0}}{U_\Lambda(0)} + \underset{\sim 175\,\mathrm{MeV}}{\underset{\downarrow}{\Delta m_\Lambda}}$$

* $\rho_t(\Lambda)$ is affected by

① ΛN int. ② NN int (Repulsion), (③ E_{sym})

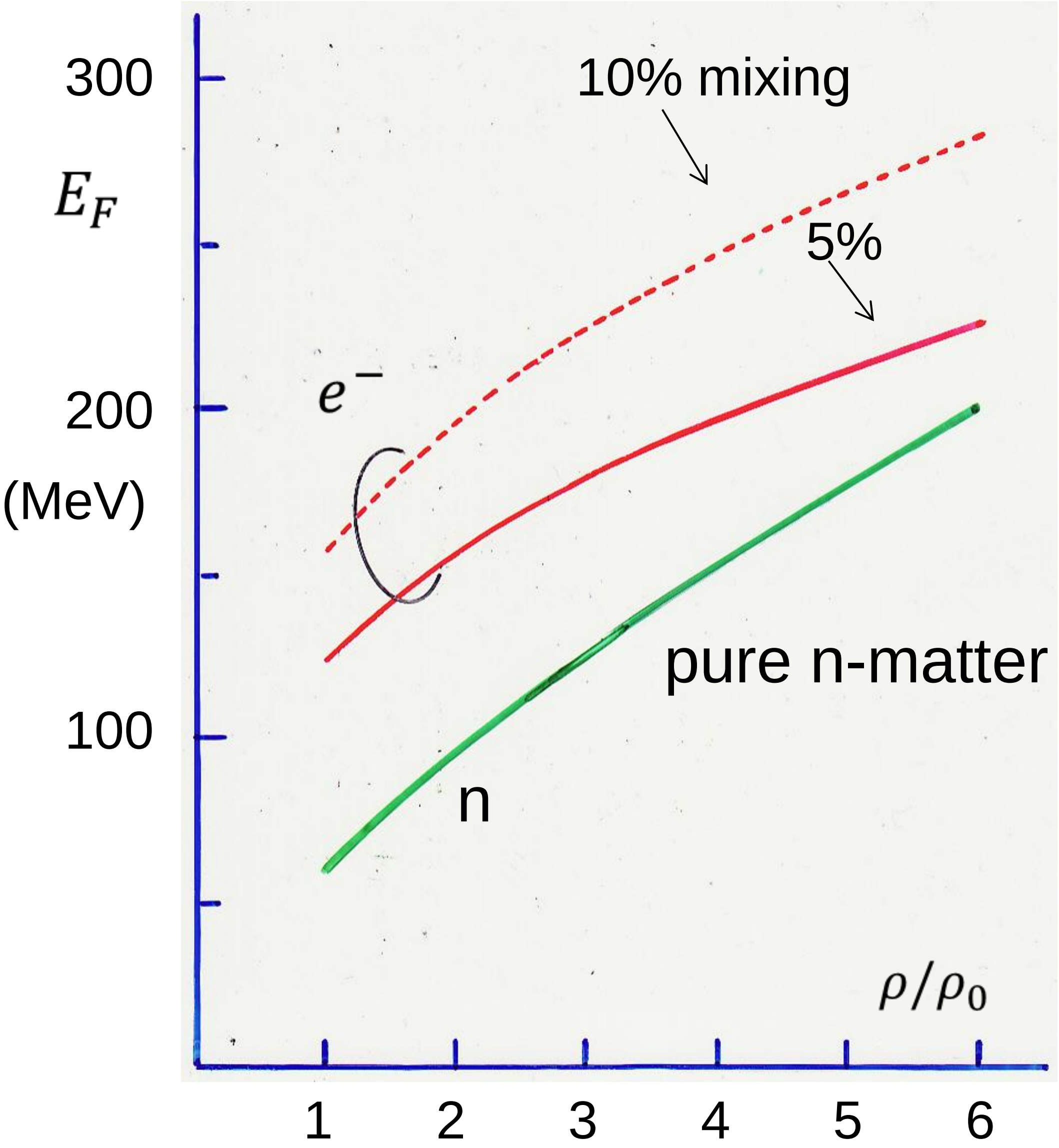
Σ⁻

$$E_F^{(n)} + U_n(k_{Fn}) + \underset{\sim 200 \times k_{Fe}/\mathrm{fm}^{-1}}{\underset{\downarrow}{E_F^{(e)}}} = \boxed{\mu_n + \mu_e = \mu_\Sigma} = U_\Sigma(0) + \underset{\sim 250\,\mathrm{MeV}}{\underset{\downarrow}{\Delta m_\Sigma}}$$

* $\rho_t(\Sigma^-)$ is determined by

① Σ^-N int. ② NN int. (Repulsion), ③ $E_{sym}(\to {E_F}^{(e)})$

Fermi energies

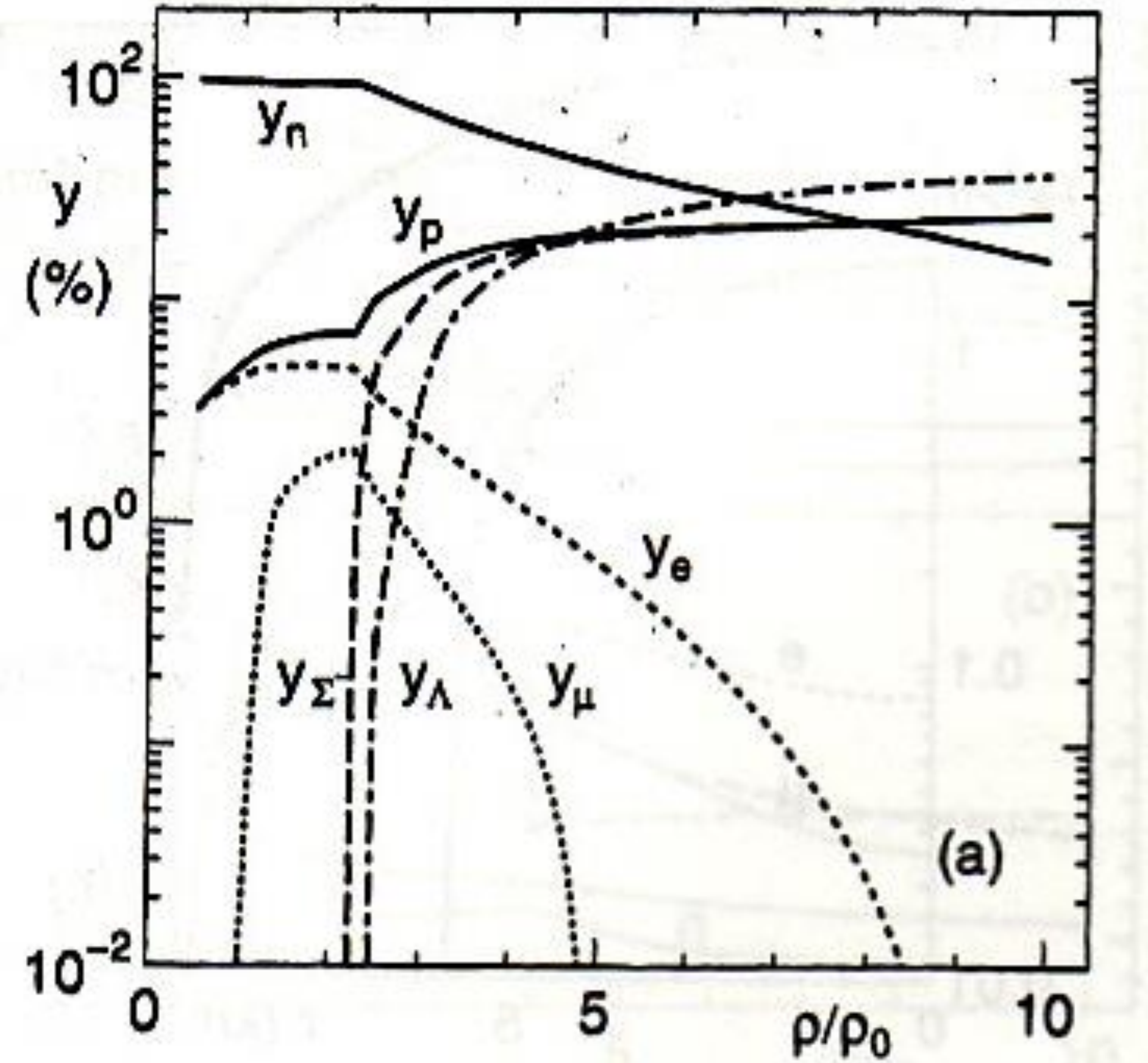


☐ Our approach to NS-matter with Y-mixing

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



○ So many works including ours have been devoted to the Y-mixing in neutron stars (NSs) (e.g. [3][4])

→ Hyperon surely participate in NS Cores (ρ_t(Y)$\sim 2\rho_0$, increasing population with ρ)

→ Standard picture for NS constituents; Old (n, p, e^-, μ^-) → Now (n, p, Y, e^-, μ^-)

→ NS properties should be discussed by taking account of Y degrees of freedom

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[3] M.Baldo, G.F. Burgio and H.-J. Schulze, Phys. Rev. C61 (2000) 055801

[4] I. Vidaña, A. Polls, A. Ramos, L. Engvik and M. Hjorth-Jensen, Phys. Rev. C62 (2000) 035801

Y-mixing,

Then

☐ What happens ?

⇓

6-2. Two serious problems

Two Serious Problems

(1) Dramatic Softening of NS EOS

→ Contradicts observed mass (M_{obs}) of NSs:

$$M_{max} < M_{obs} = (1.44 \pm 0.002)M_{\odot} \text{ for PSR1913+16}$$
$$= (1.97 \pm 0.04)M_{\odot} \text{ for PSRJ1614-2230}$$

→ Problem 1

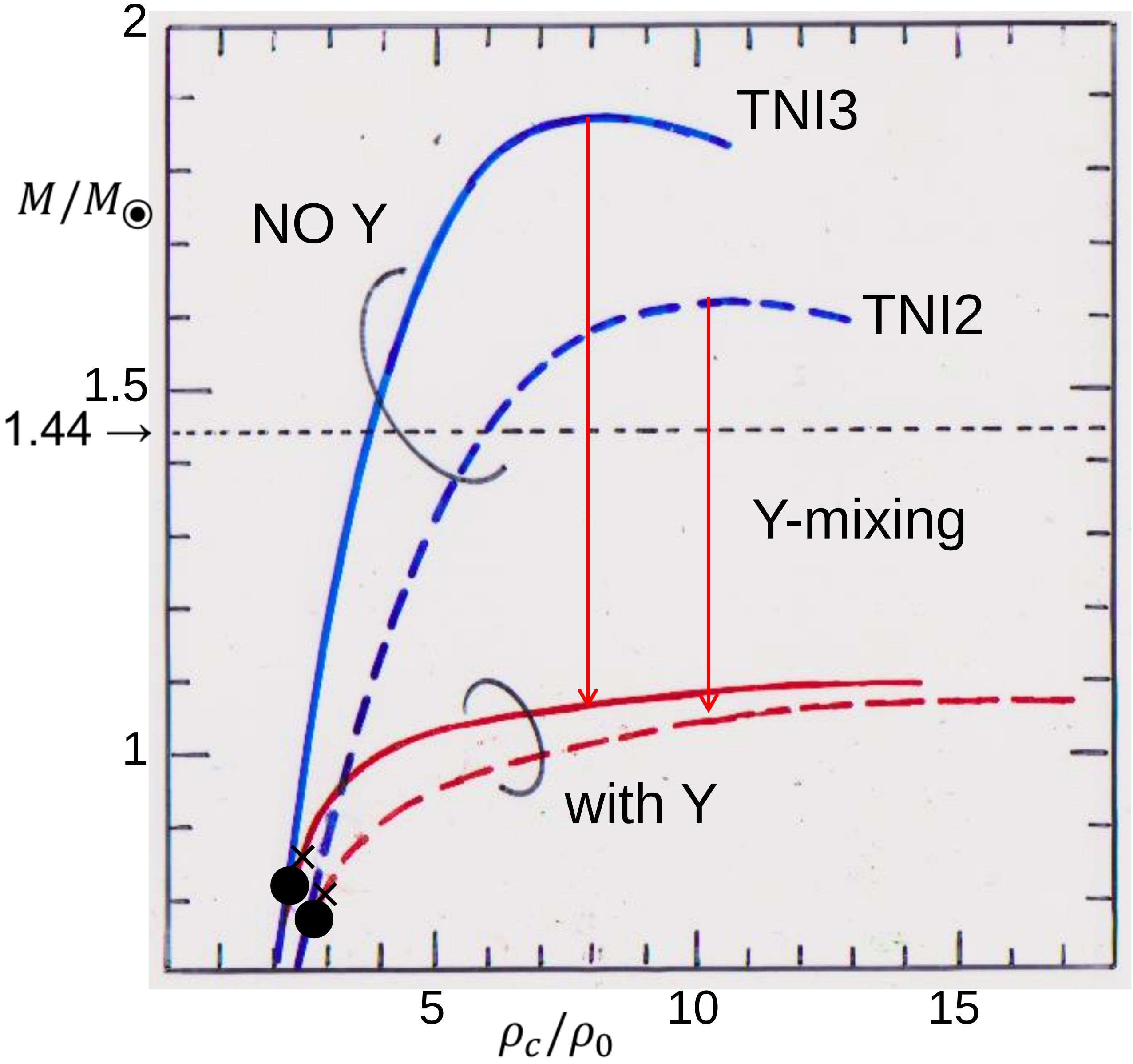
(2) Too rapid cooling

→ contradicts observed surface-temperature (T_s) of NSs:

- All of the NSs whose T_s are observed by thermal X-ray should have $M < M_{\odot}$----unlikely
- Thermal evolution of colder class NSs (Vela X-1, 3C58, Geminga, etc.) is very difficult to be explained

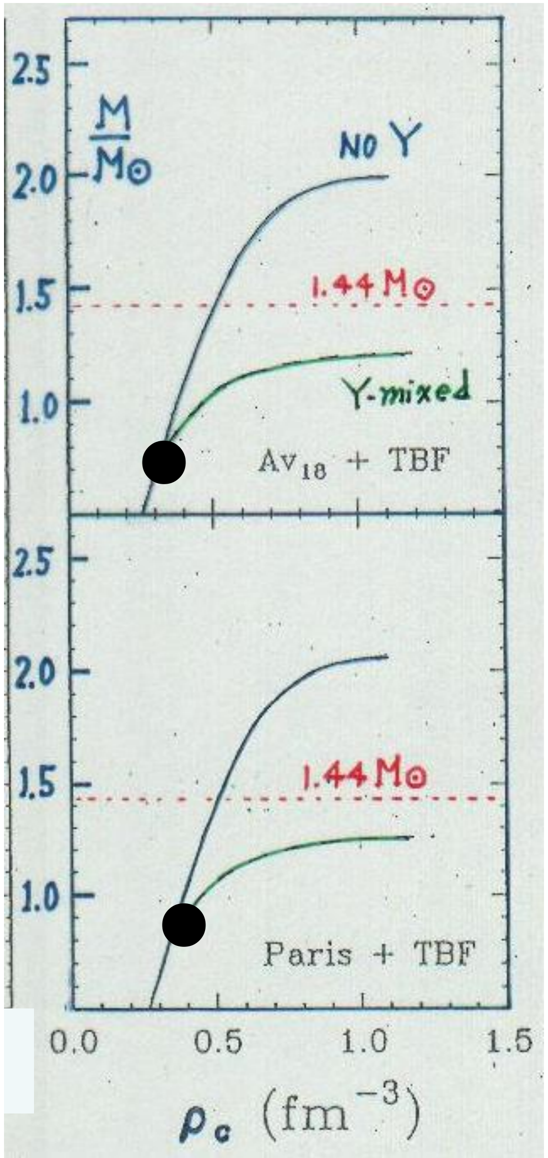
→ Problem 2

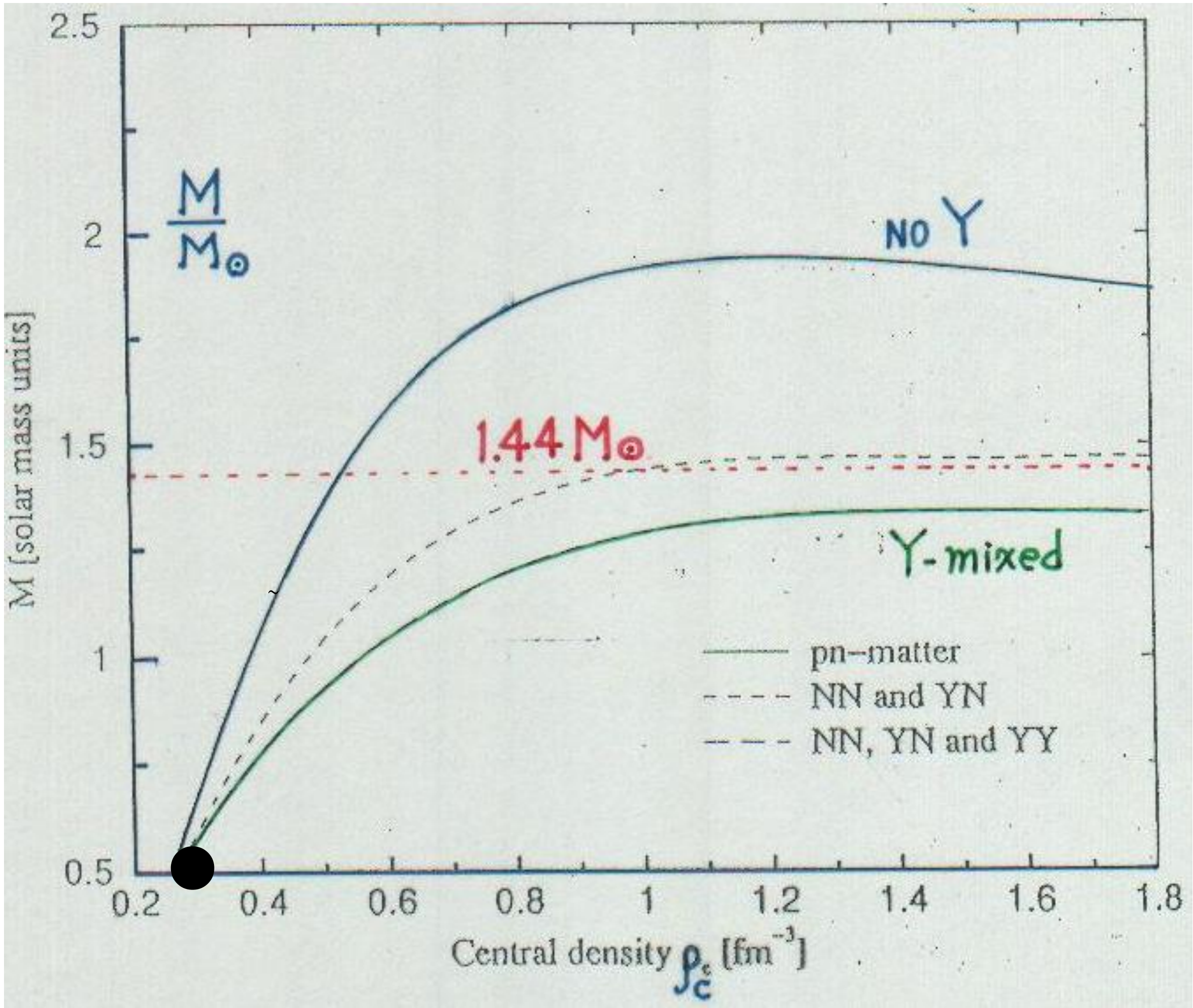
$M_{max} < M_{obs}$(Softened EOS by Y)



(1)

Strong Softening of the EOS

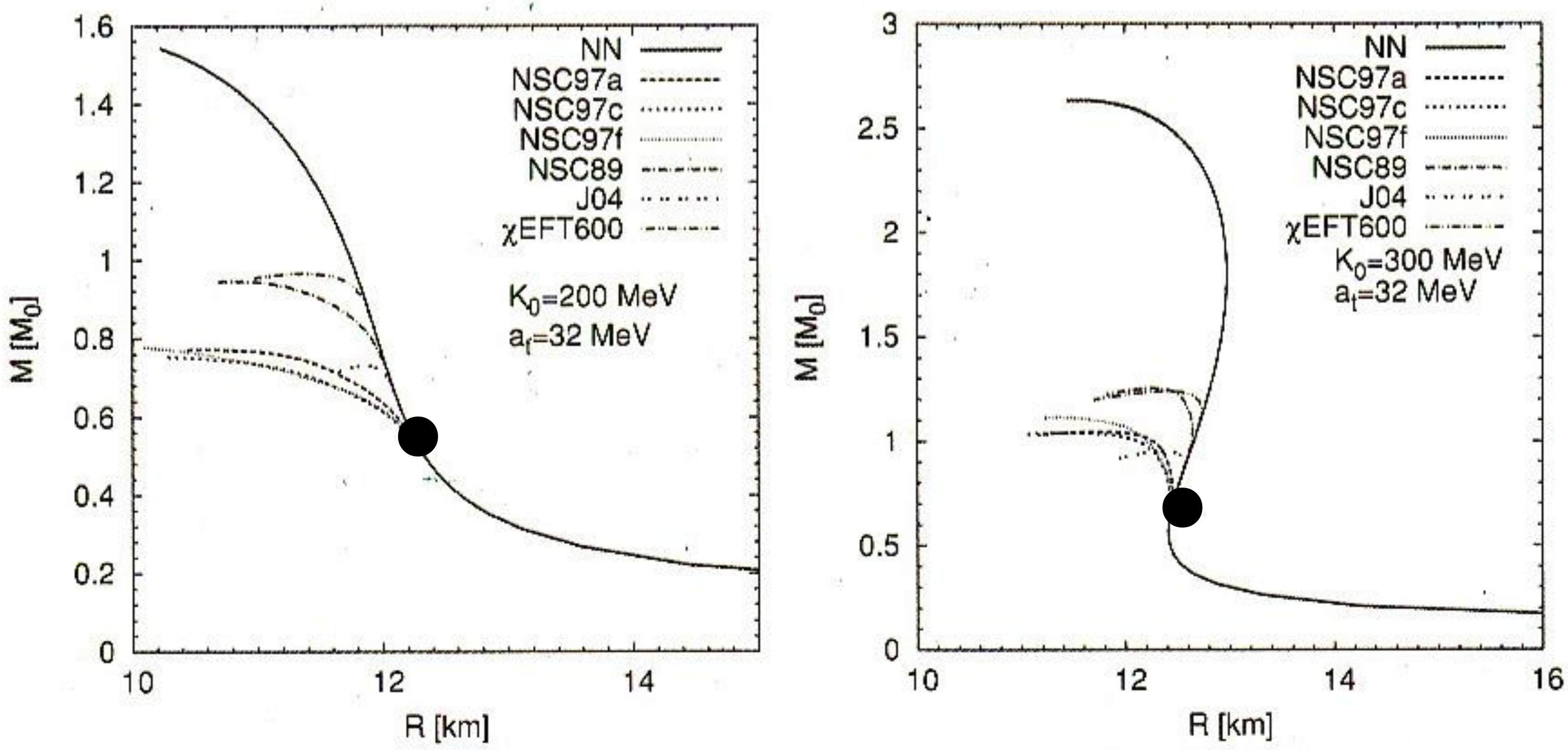




L-Vidana et al, P.R. C62 (2000) 035801

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

○ Hyperons are always present
→ profound consequence for NS-mass



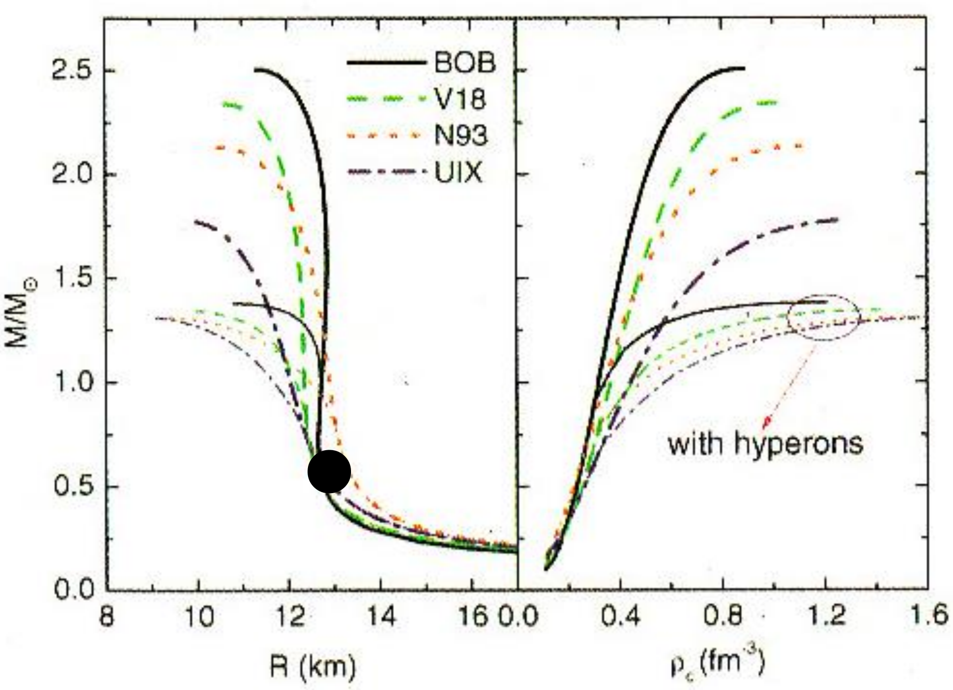
(a) $K_0 = 200$ MeV

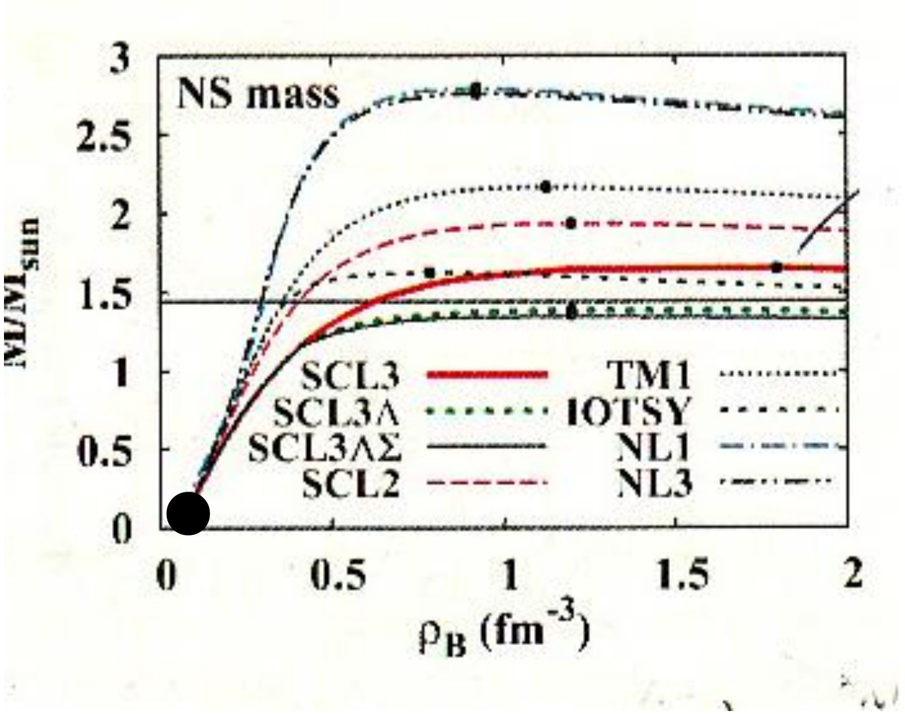
(b) $K_0 = 300$ MeV

H. Dapo, B-J. Schaefer and J. Wambach, Phys. Rev. C81 (2010) 035803

G-matrix with nucleonic 3-body force

Chiral SU(3) RMF

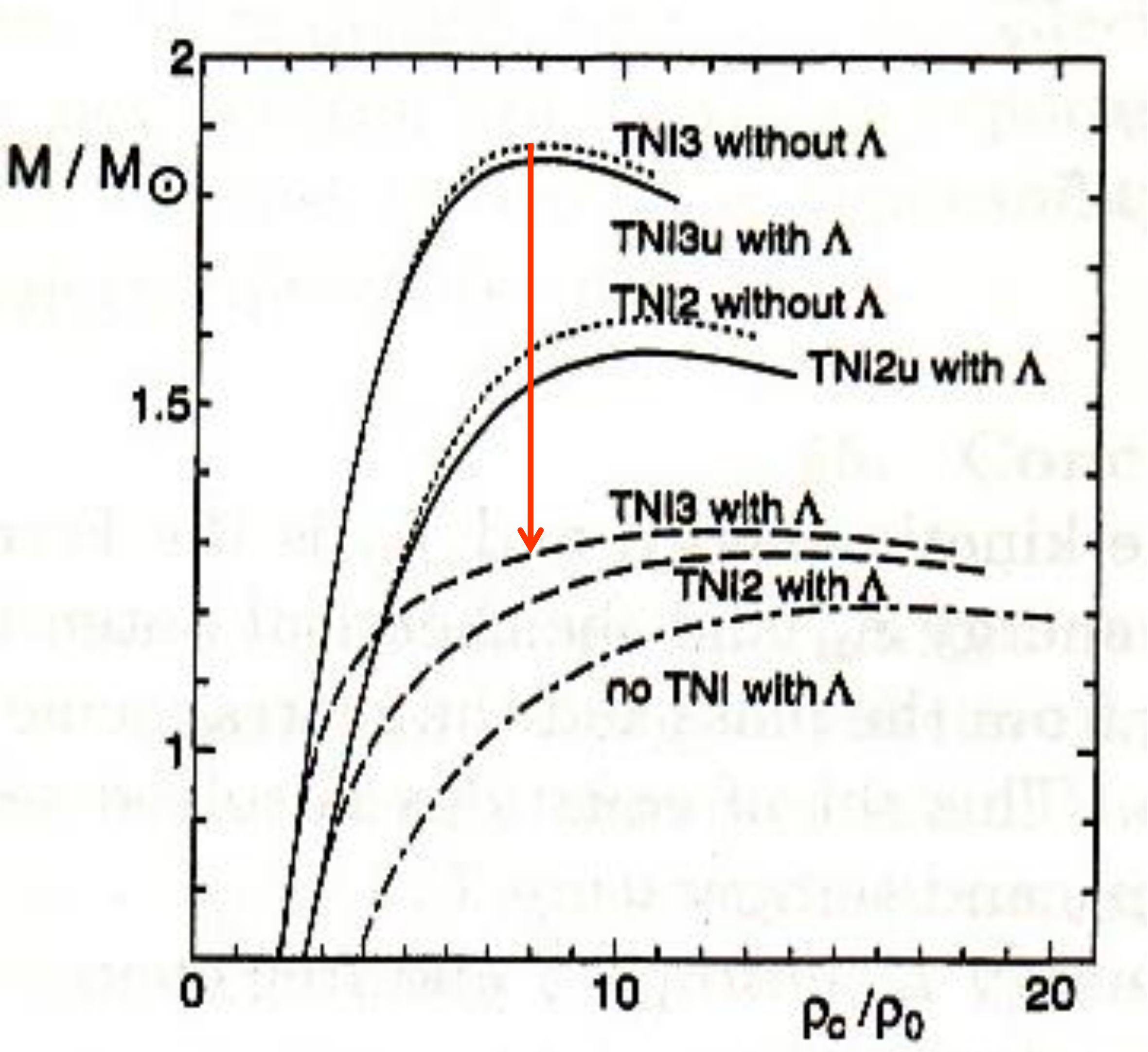




Z.H. Li and H.-J. Schulze, PR C78 (2008) 028801.

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

Even Λ-only mixing, situation is the same!



○ These problems are serious because of the points,

① Y surely participate in NSs → cannot be ignored

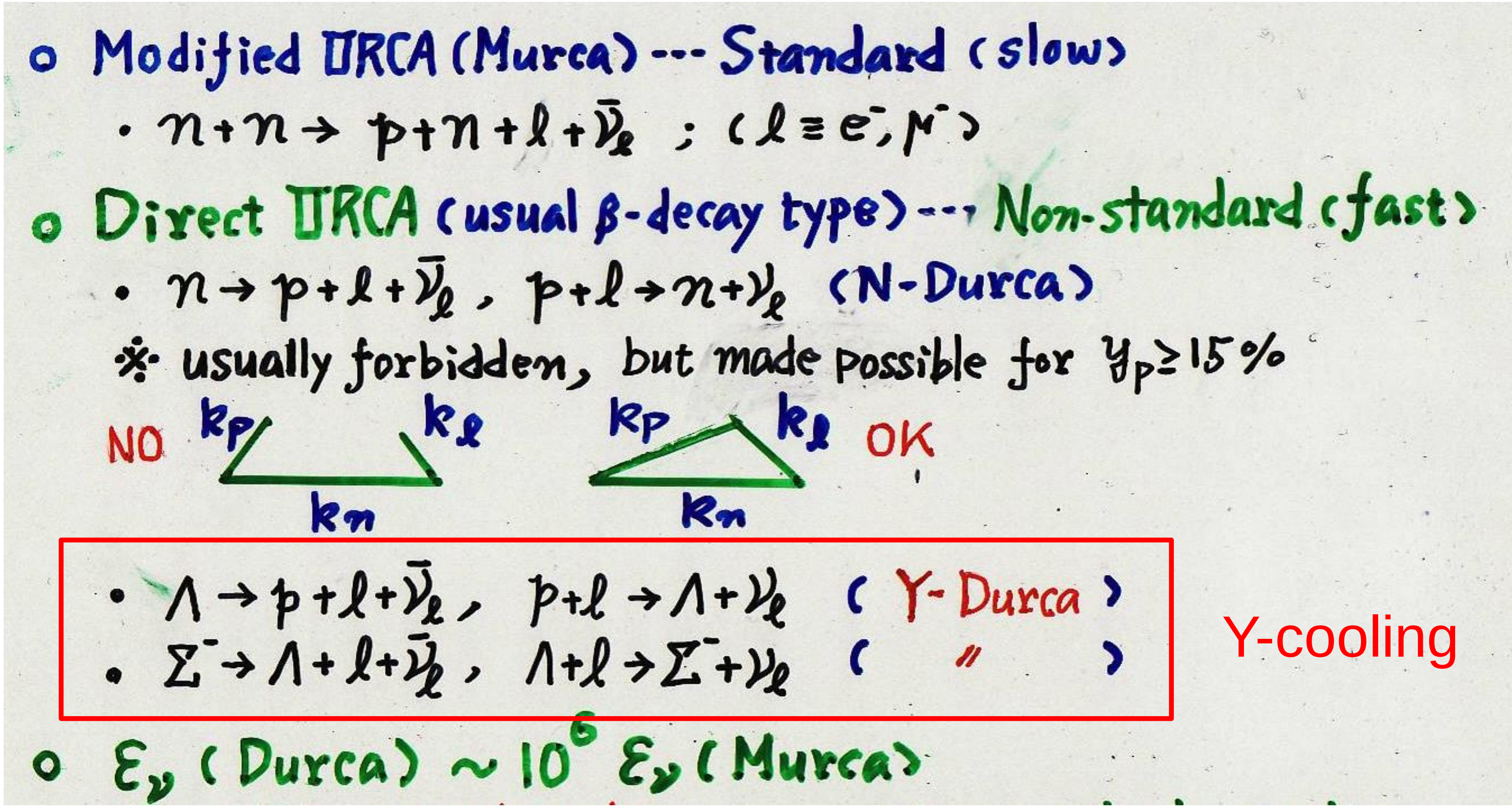
② Dilemma: Enhancement of NN repulsion → more developed Y-mixing → stronger softening effect → a good-for-nothing

③ Without Σ^--mixing (i.e. only Λ), the situation is unchanged

(2) Too rapid cooling

NS cooling due to ν-emission

（J. M. Lattimer et al.，PRL66（1991）2701）



- Modified URCA (Murca) --- Standard (slow)
  - $n+n \to p+n+l+\bar{\nu}_l$; ($l \equiv e^-, \mu^-$)
- Direct URCA (usual β-decay type) --- Non-standard (fast)
  - $n \to p+l+\bar{\nu}_l$, $p+l \to n+\nu_l$ (N-Durca)

※ usually forbidden, but made possible for $y_p \gtrsim 15\%$

- $\Lambda \to p+l+\bar{\nu}_l$, $p+l \to \Lambda+\nu_l$ (Y-Durca)
- $\Sigma^- \to \Lambda+l+\bar{\nu}_l$, $\Lambda+l \to \Sigma^-+\nu_l$ (〃)

Y-cooling

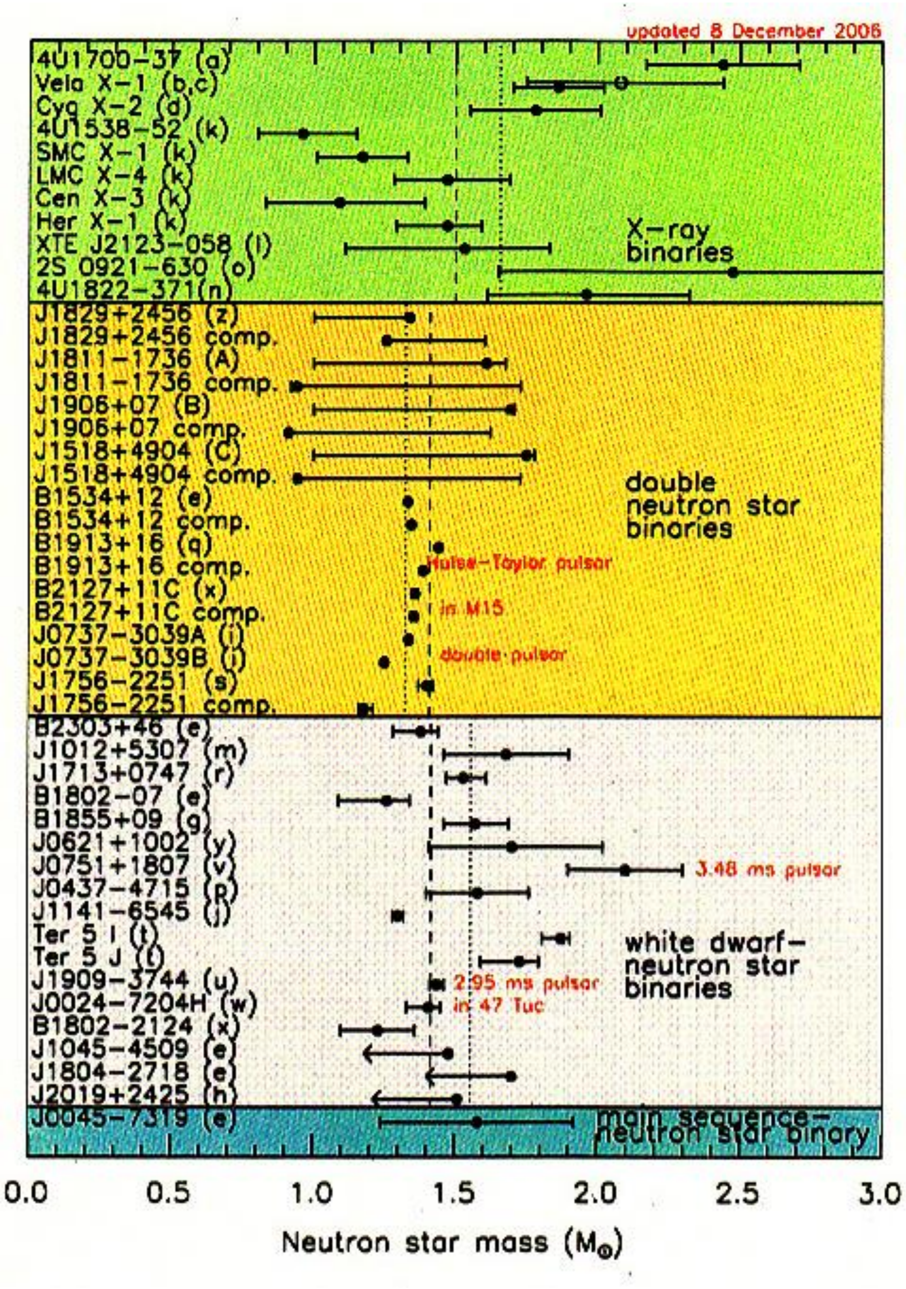
- ε_ν (Durca) $\sim 10^6$ ε_ν (Murca)

○ But, if directly applied, it causes a serious problem of “ too rapid cooling ” incompatible with NS surface-temperature observations.

- Since NSs with $M \geq M_0$ have a Y-mixed core, most NSs (with $M < M_\odot$) are too cold to be observed by thermal X-rays----- unlikely?
- How to explain the existence of colder class NSs (such as Velax-1, 3C58, Geminga, etc.)

- ○ Observed mass of neutron stars

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



→ Remarks:

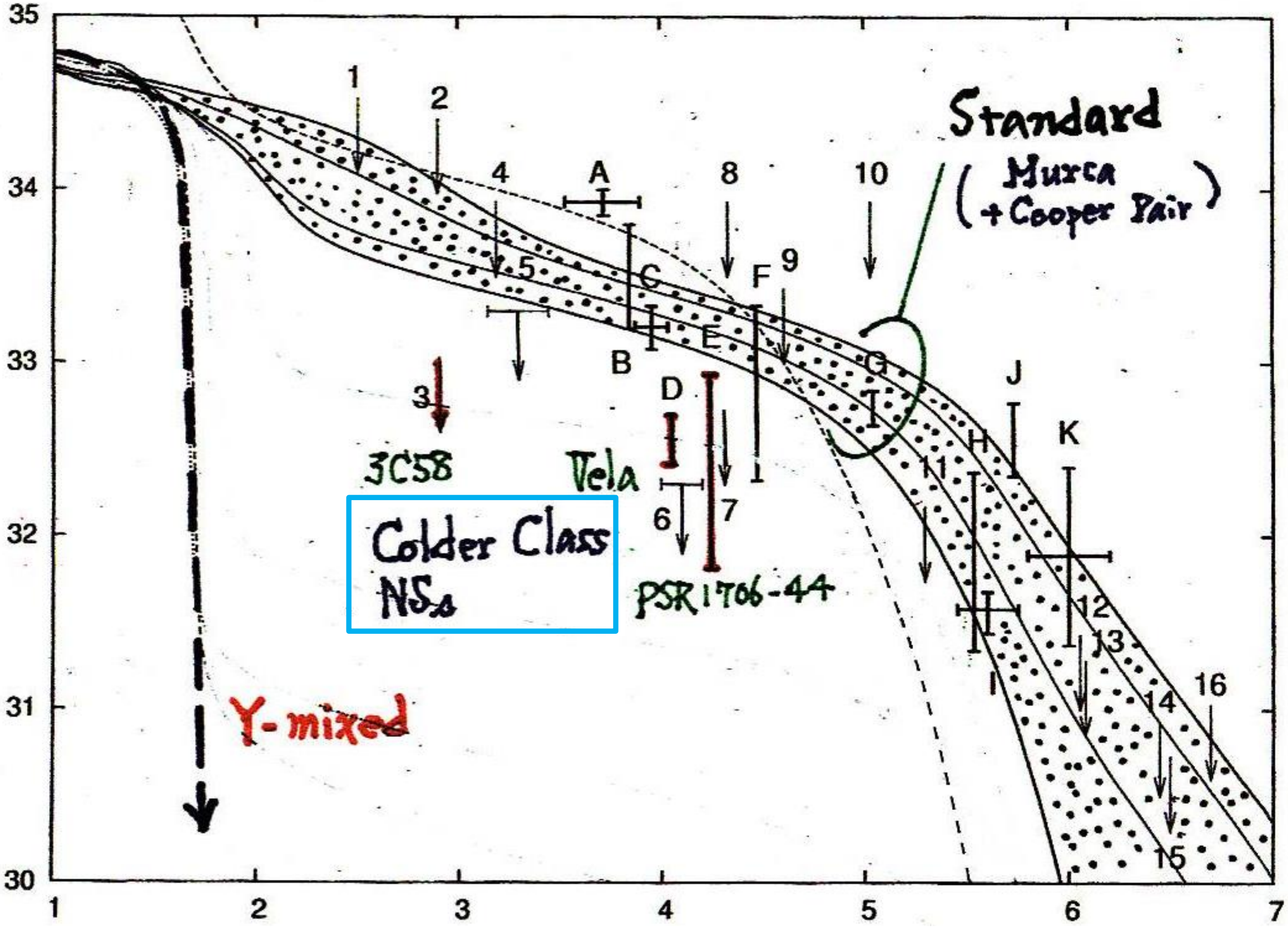
- ○ M_{obs} are mostly populated in (1.3-1.6) $M_\odot$

- ○ M_{max}(theory)≥1.44$M_\odot$

  (→ ~2.0$M_\odot$)

Thermal Evolution of NSs

Log L_ν^{∞}
(ergs/sec)



Log Time (years)

Tsuruta et al
Ap. J. 691
(2009) 621

7. Possible solution for the problem

Too soft EOS (Problem 1)

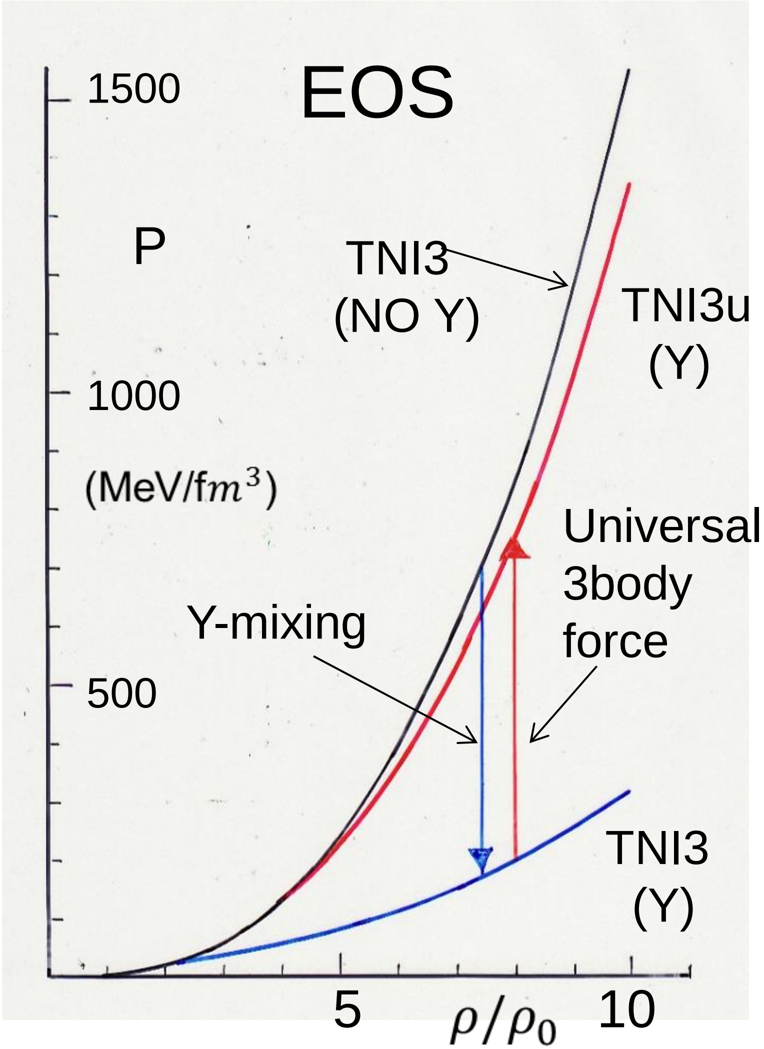
Dramatic softening of EOS⟶

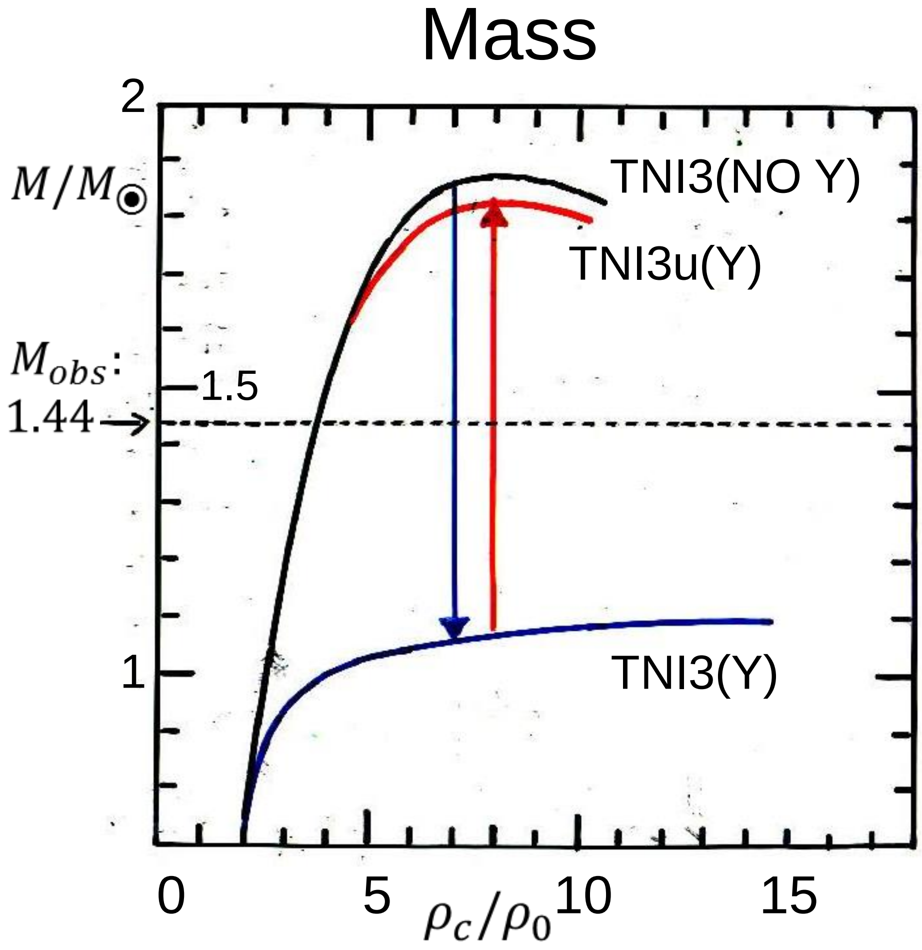
Universal 3-body force

The contradiction between theory and observation (M_max < M_obs) strongly suggests the necessity of some extra repulsion in dense hypernuclear systems

→ 3-body force repulsion acting “universaly” on NN,YNand YY parts (universal 3-body force) is a promising candidate [1][2]

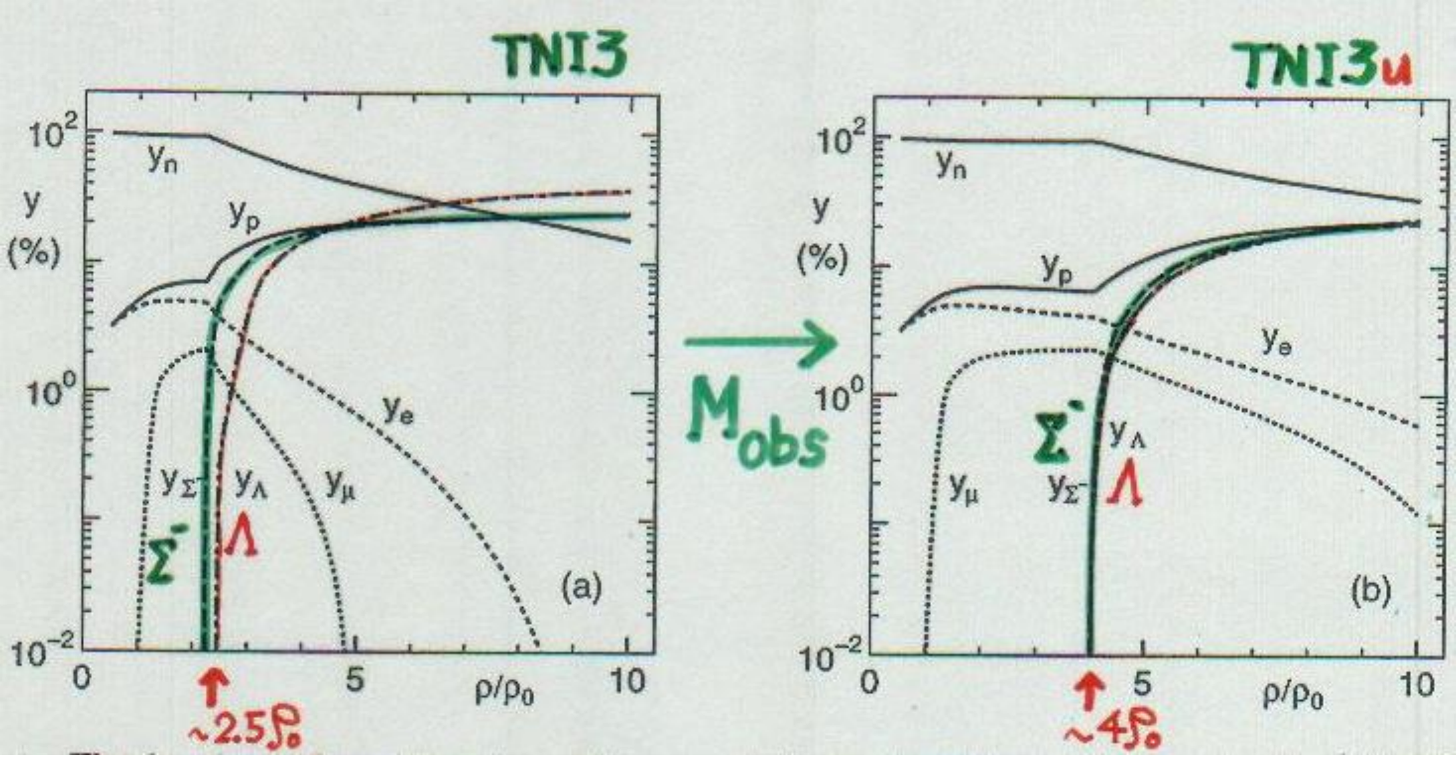
Dramatic softening of EOS ⟶ Necessity of “Extra Repulsion”





TNI3 ⟶ TNI3u: Universal inclusion of TNI3 repulsion

Univ. 3-body force → higher ρ_t(Y)



→ Y-mixed star
for $M > M_\odot$

→ Y-mixed star
for $M > 1.4M_\odot$

Too rapid cooling (Problem 2)

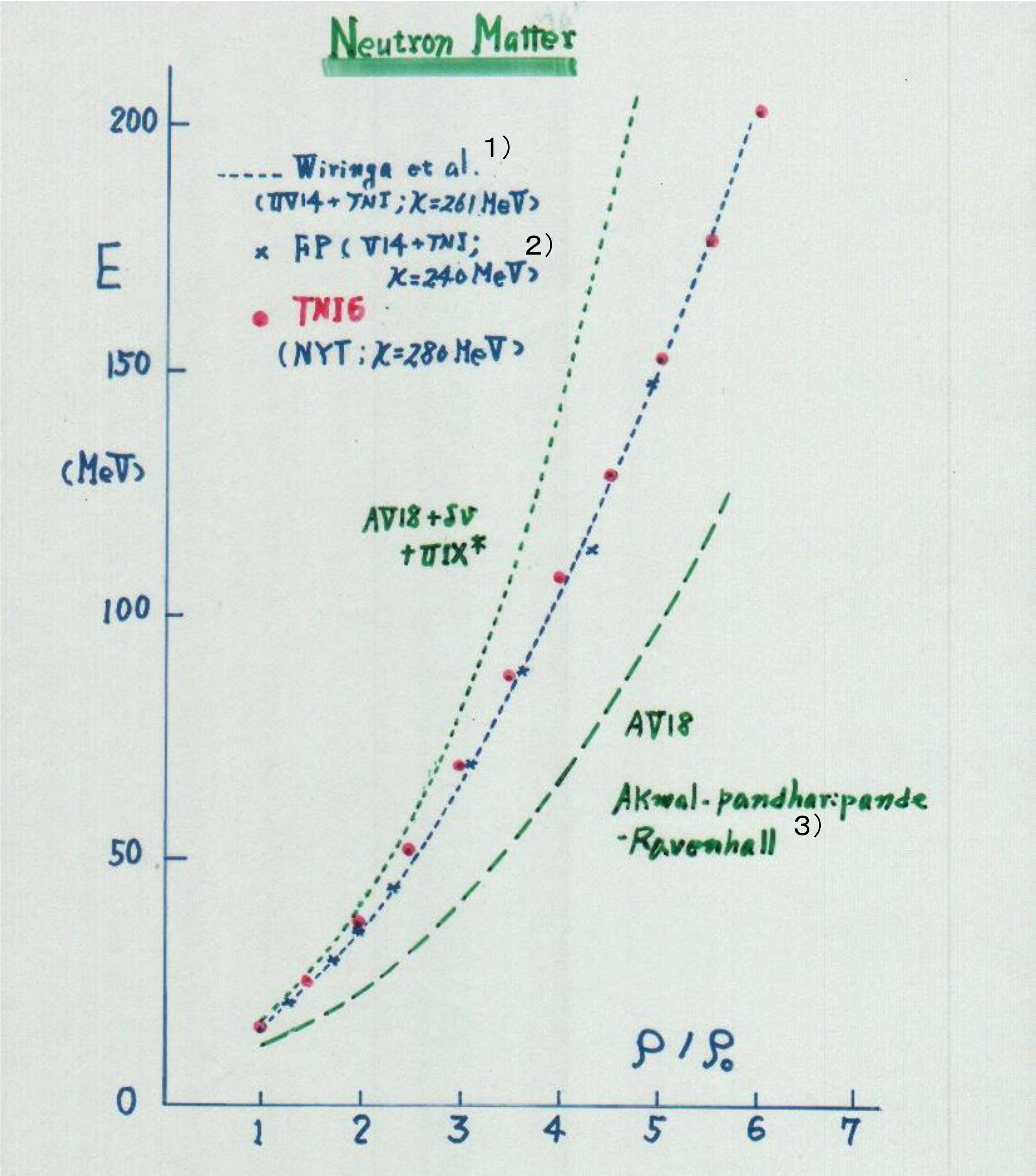
Too -rapid cooling → Hyperon superfluidity

NSs with M> 1.35 M_{sun} have a Y-mixed core. If Y-superfluidity is realized, it suppresses the efficient ν-emmision by Y-Durca (exp (-Δ/T))
→ moderate cooling consistent with colder class NSs

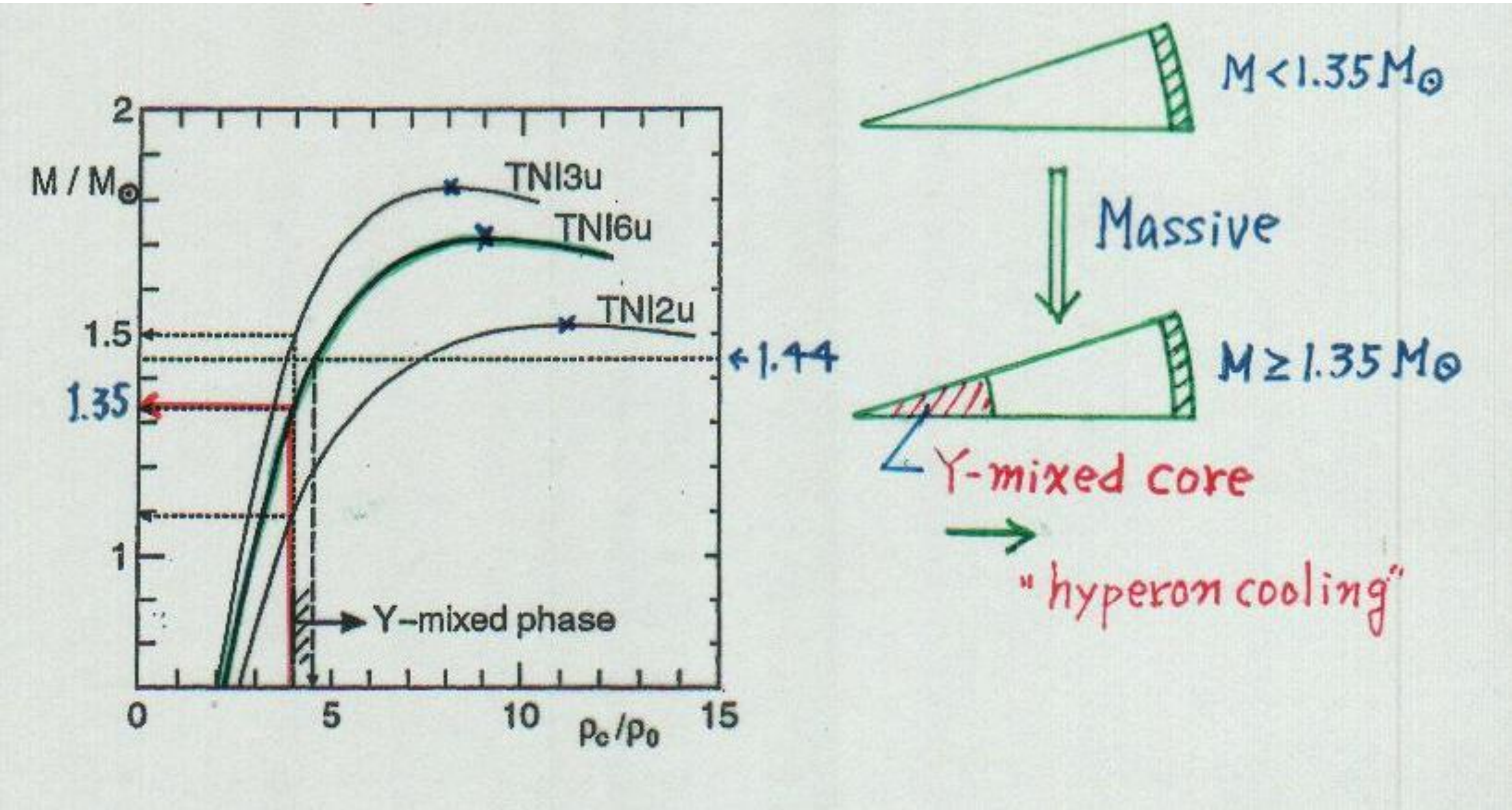
That is, a new scenario is

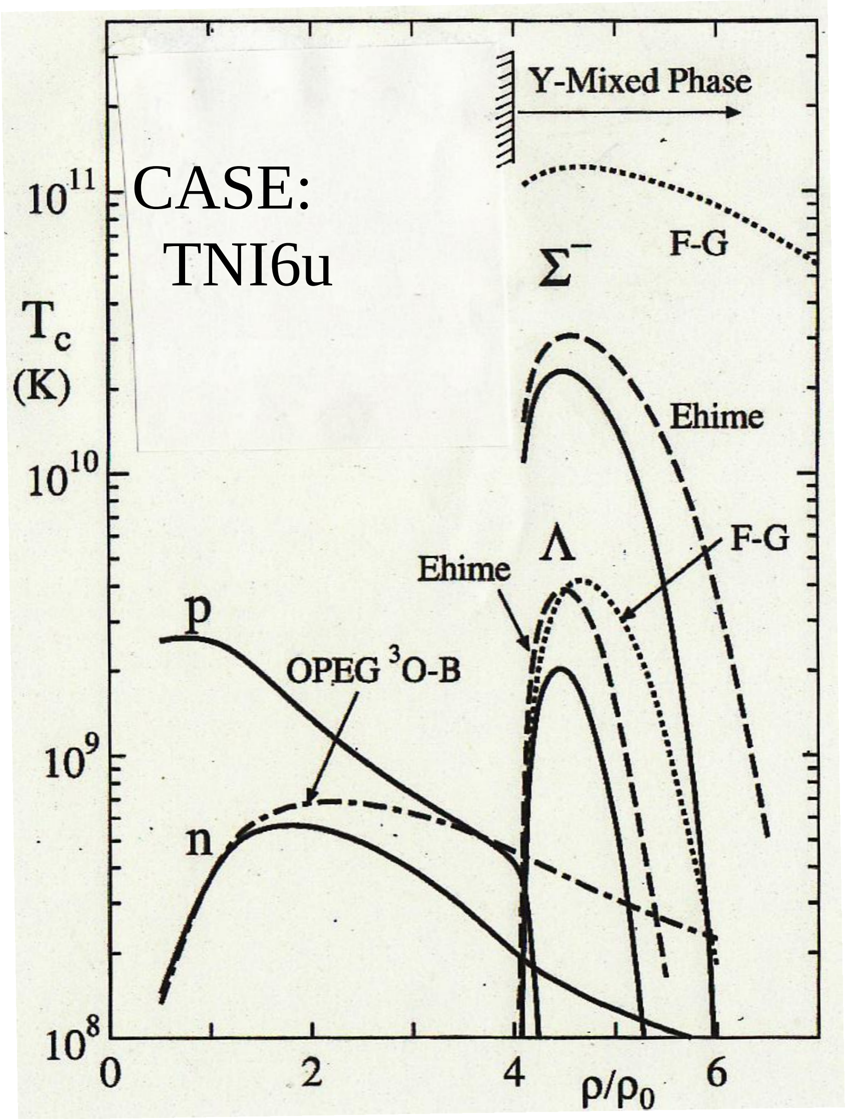
Lighter NSs → Warm (standard slow cooling of Murca)
Heavier NSs → Cool (nonstandard fast cooling of
YDurca ("hyperon cooling") + Y-super)
Massive NSs → Very Cold ("hyperon cooling")

1) P.R. C38 (1988) 1010
2) N.P. A361 (1981) 502
3) P.R. C58 (1998) 1804



With or without Y-mixed core depends on M





CASE:
TNI6u

Critical Temperature T_c versus Density ρ

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

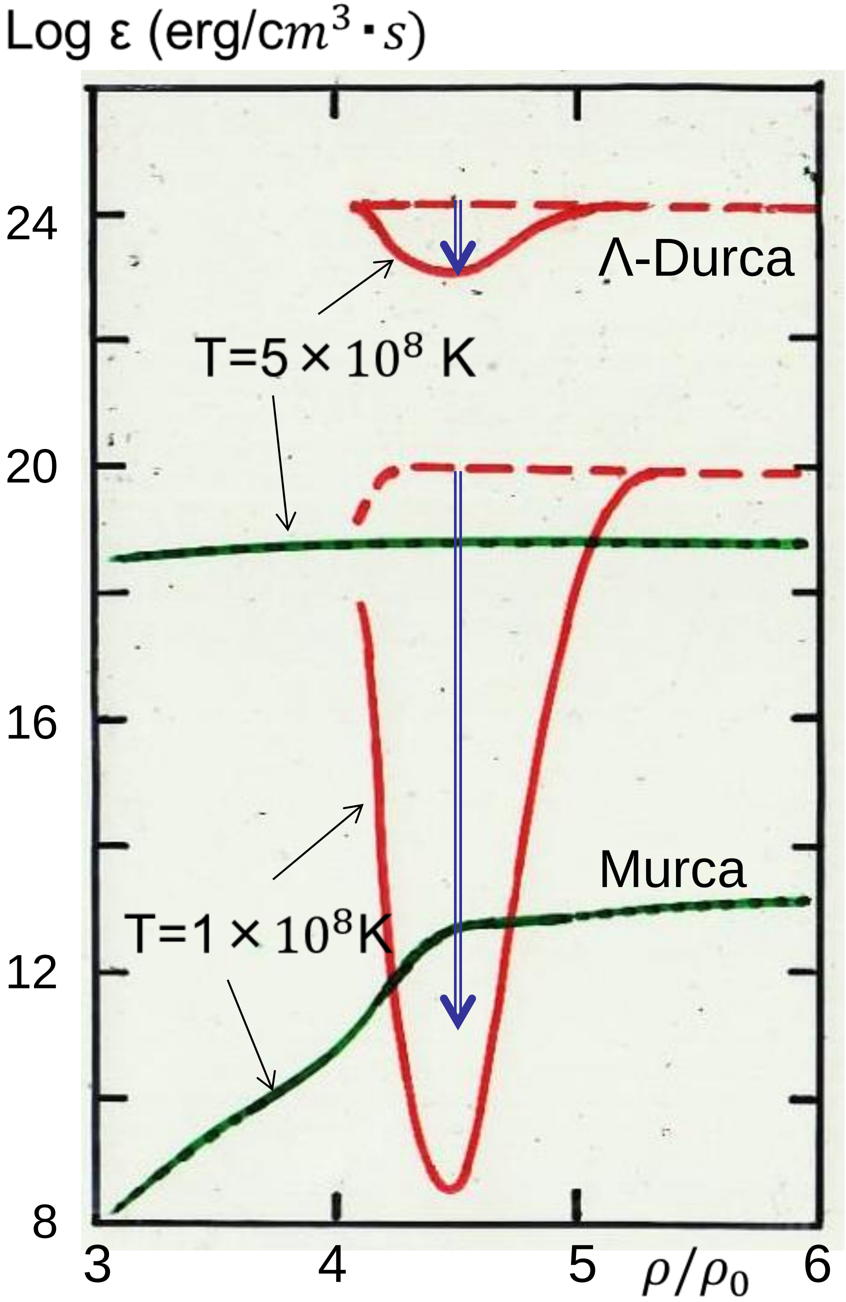
☐Pairing interactions:
n, p → OPEG-A pot.
Λ, Σ^- → ND-Soft
for solid lines

Suppression by Λ-Superfluidity

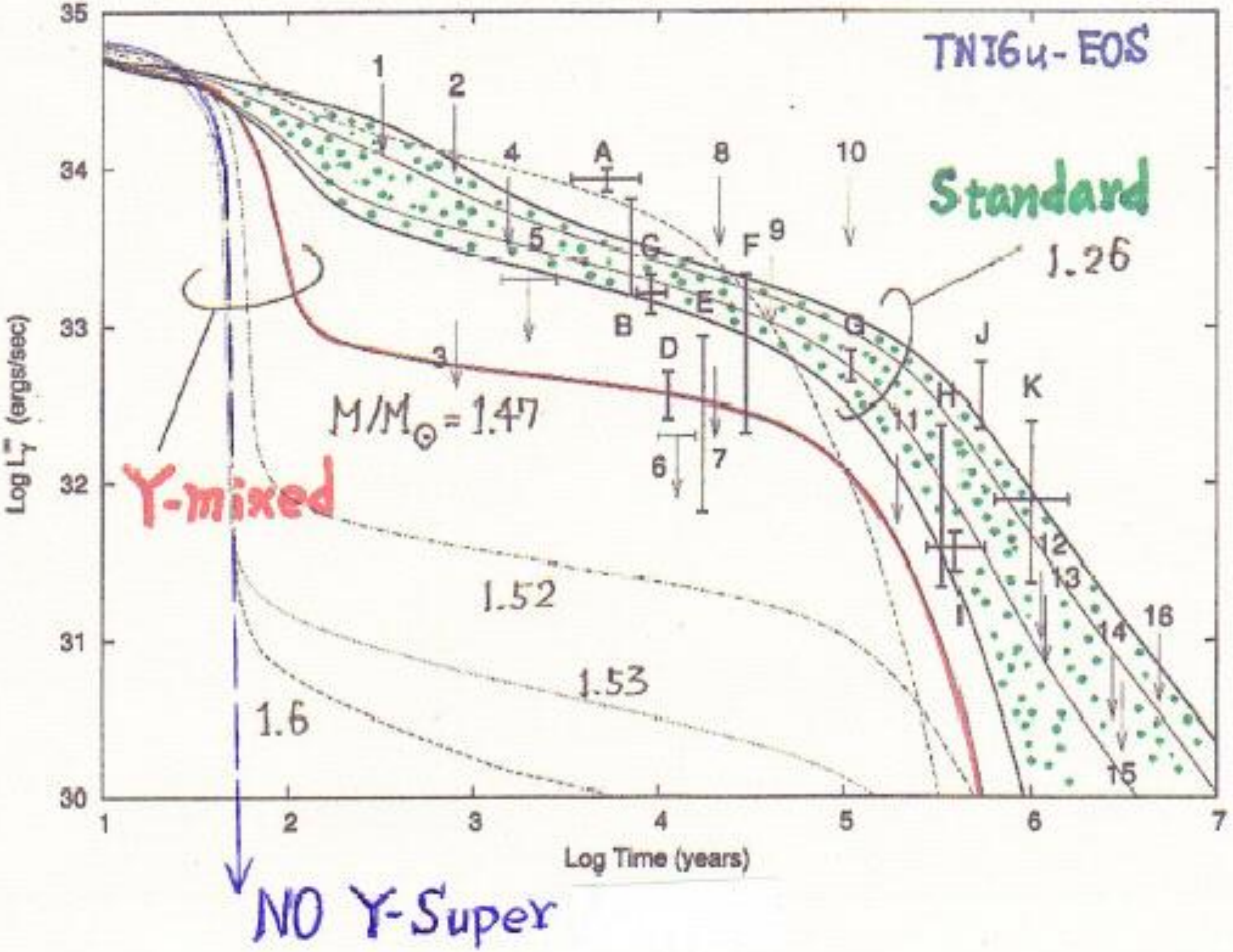
○ ε: ν-emissivity due to
Λ-Durca (Red)
Murca (Green)
dashed line: No suppression

○ T: internal temperature of NSs

T.Takatsuka,S.Nishizaki,Y.Yamamoto and R.Tamagaki,
Prog.Theor.Phys.115(2006)355



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



NAGARA event

NO Λ-super ! ⇒ Too-rapid cooling → break down of the hyperon cooling scenario

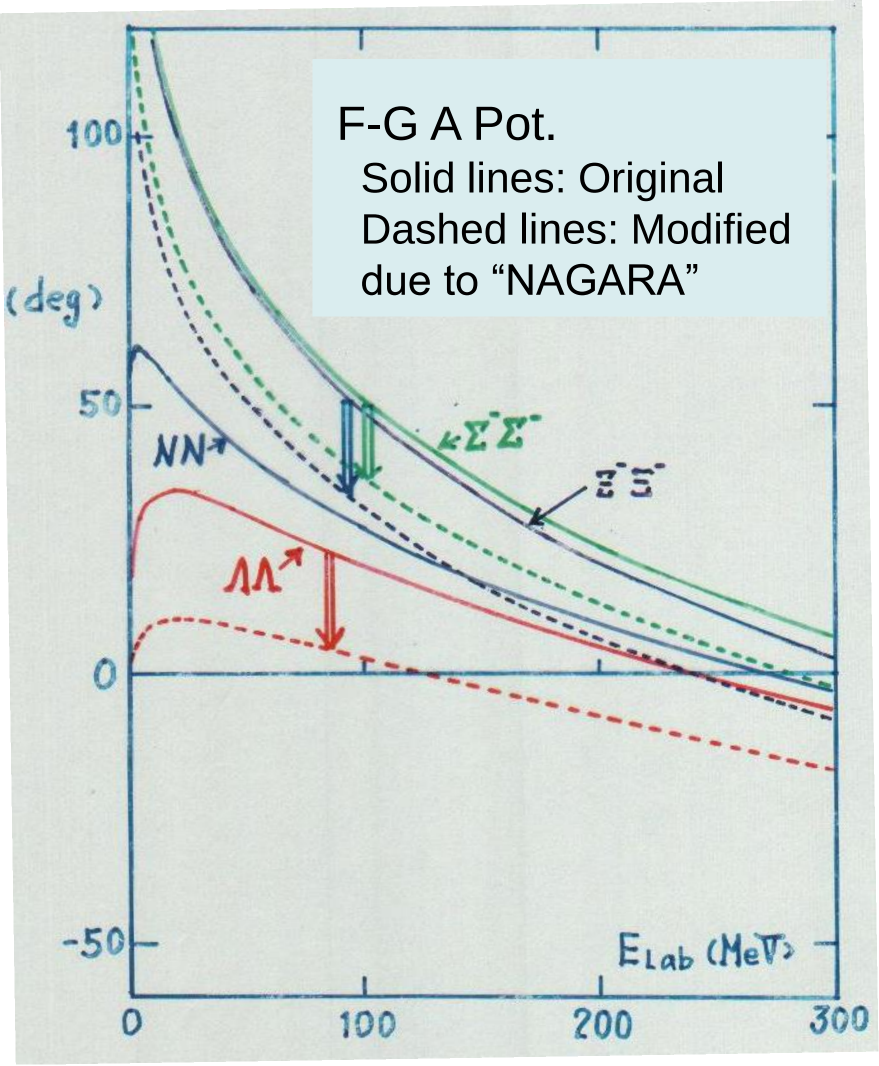
Need more careful investigations

○ sensitivity to ΛΛ int. → rearrangement effect, dependence on "α-core" ?

○ mechanism to enhance ΛΛ attraction

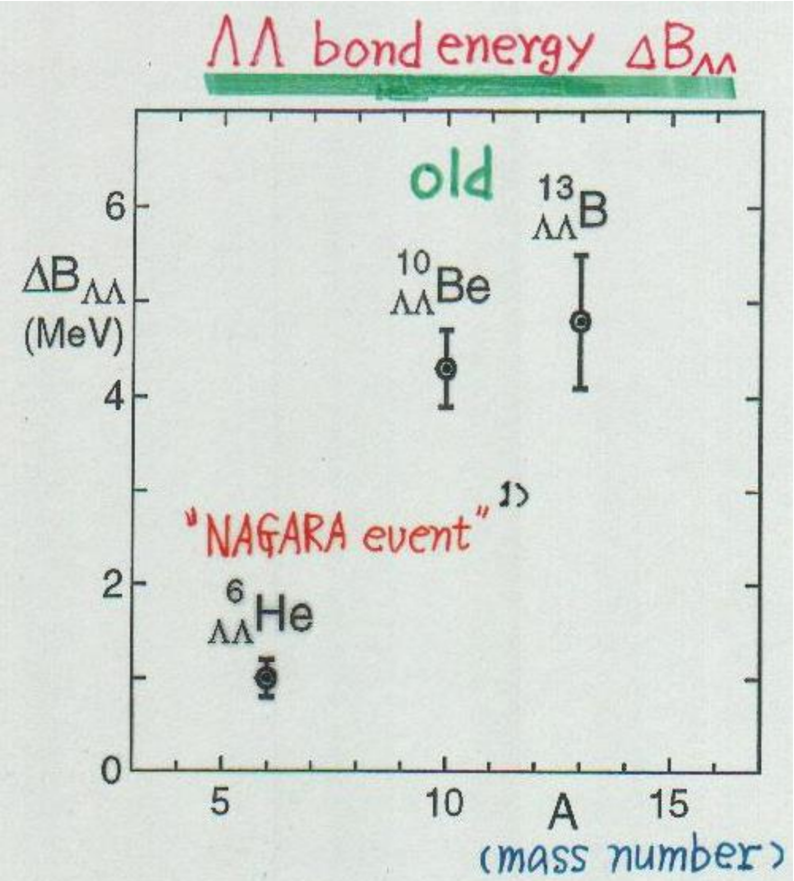
○ How about the A-dependence of ΛΛ bond energy?（J-PARC exp.is highly expected)

○ Especially,Lattice cal.study for ΛΛ int.



F-G A Pot.
Solid lines: Original
Dashed lines: Modified due to “NAGARA”

V(ND-soft)→ 0.5V(ND-soft) ; Hiyama


ΛΛ bond energy $\Delta B_{\Lambda\Lambda}$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2 \times B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

	$\Delta B_{\Lambda\Lambda}$ (MeV)
$^{13}_{\Lambda\Lambda}$B	4.8 ± 0.7
$^{10}_{\Lambda\Lambda}$Be	4.3 ± 0.4
$^{6}_{\Lambda\Lambda}$He	1.0 ± 0.2

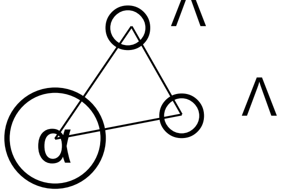
Takahashi et al., PRL 87 (2001) 212502

Nijmegen-D ΛΛ-pot.

(1) Original ($\eta_1 = \eta_2 = 1$):

$$V_{ND}{}^{\Lambda\Lambda}(r;\ {}^1S_0) = (10853.3 - 3 * 2035.1)\exp[-(\frac{r}{0.35})^2] * \eta_1$$
$$+(-187.01 - 3 * 32.166)\exp[-(\frac{r}{0.777})^2] * \eta_2$$
$$+(-21.337 - 3 * 0.19321)\exp[-(\frac{r}{1.342})^2] * \eta_2$$

(2) fitted by NAGARA: $\eta_1 = 0.45$, $\eta_2 = 0.5$ (← by Hiyama)



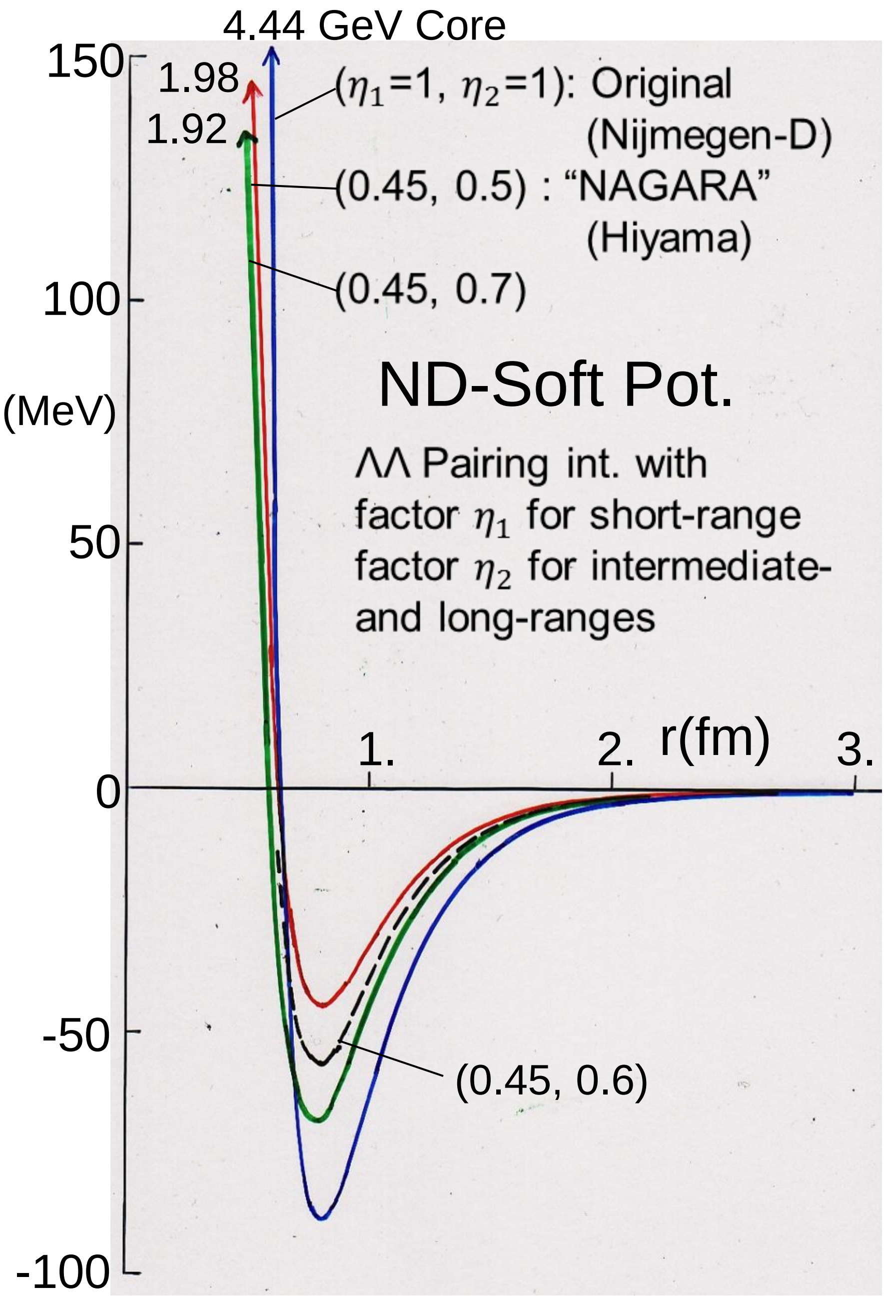
$B({}_{\Lambda\Lambda}{}^6He)$ by Hiyama
$B_{exp} = (-6.9 \pm 0.16)$ MeV

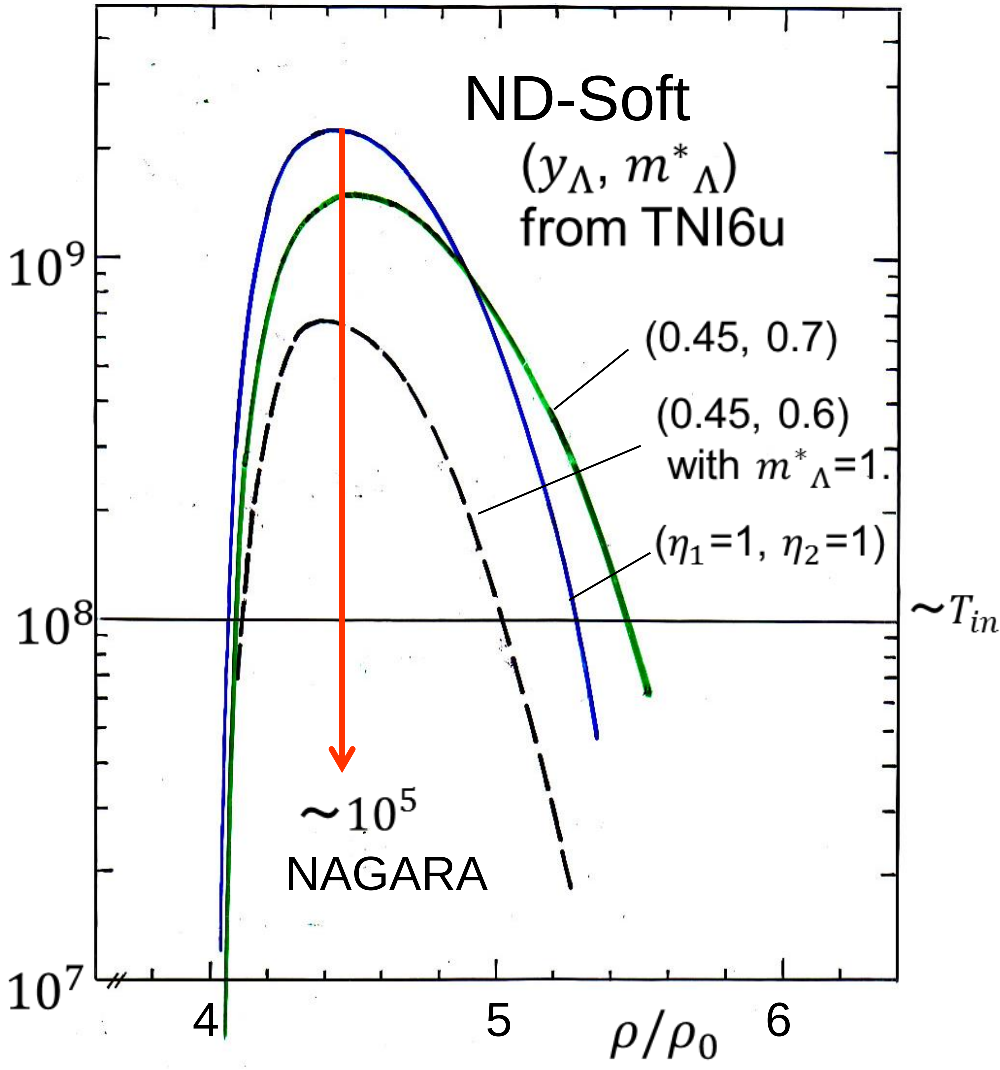
Variation of (η_1, η_2); B in MeV, $T_c{}^{max}$ in K

η_1	η_2	B (v.s. B_{exp})	$T_c{}^{max}$	(Λ-Super)
0.45	0.5	-7.263 (∼OK)	$<10^6$	(NO)
0.45	0.7	-8.96 (over)	1.5×10^9	(OK)
0.75	0.8	-8.43 (over)	4.0×10^8	(∼OK)
1.2	0.7	-6.80 (OK)	$<10^6$	(NO)

* How about the rearrangement effects?

Critical Temperature T_c v.s. ρ





present status of NS cooling

☐ Cooling processes:

- Murca (modified URCA)
- cooper-pair (pair breaking-formation)
- N-Durca (direct URCA)
- Exotic (Y,π,K,q, etc.) (Durca)

☐Observations:

detection---about 10, upper limmit---about 16

*hotter NSs(Puppis,CAS-A,RX J002+6246,PSR 0656+14, ---)

*colder NSs(Vela, PSR1706-44, 3C58, CTA-1, Vela-twin ---)

☐ Cooling Model

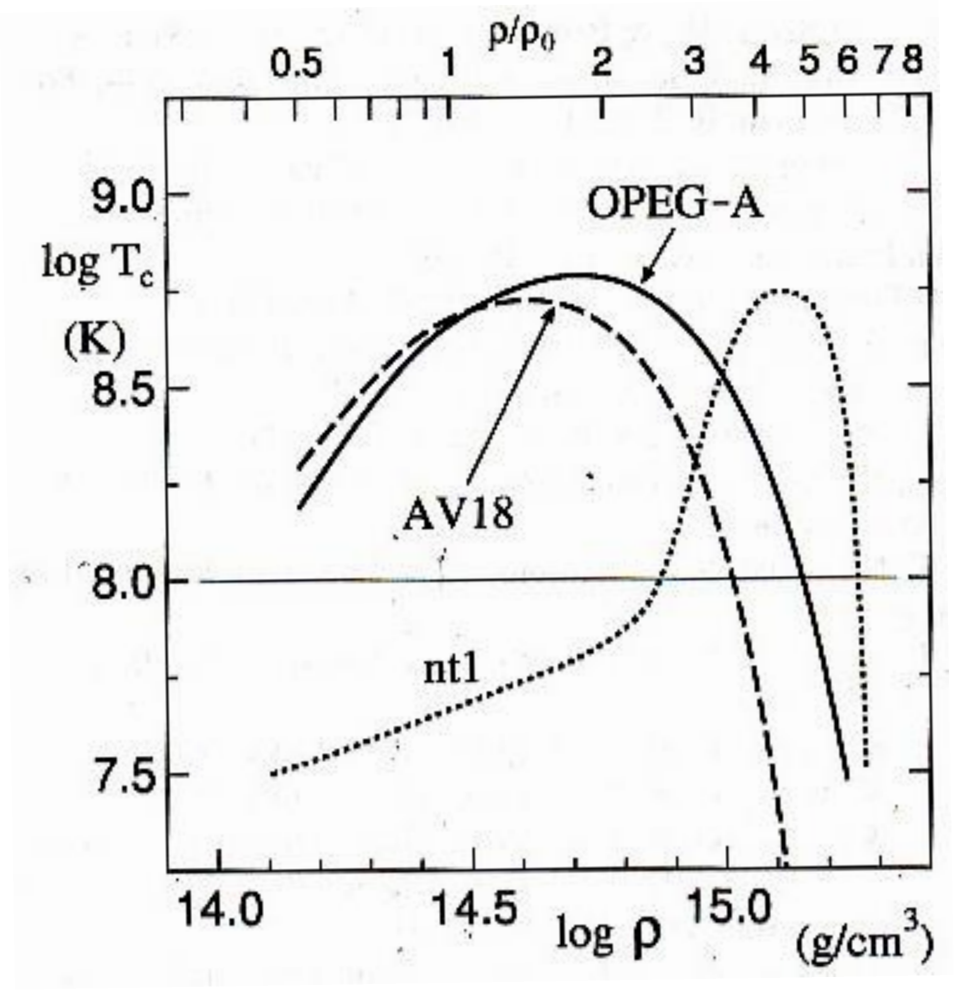
○ NO exiotics(minimal) verusus exisotics(non-standard)

○ Obs. Cold-class NSs → necessity of exotics

○ Vela (3C58) → exotic cooling(Y) + superfluidity(Y)

○ CAS-A → evidence of 3P2-super !

NO exotics scenario → assumption of extraordinal ρ-dependence of $T_c(^3P_2)$!



← Critical temperature of 3P2-Superfluid

○ nt1 from Gusakov, et al., A&A, 423 (2004) 1063.

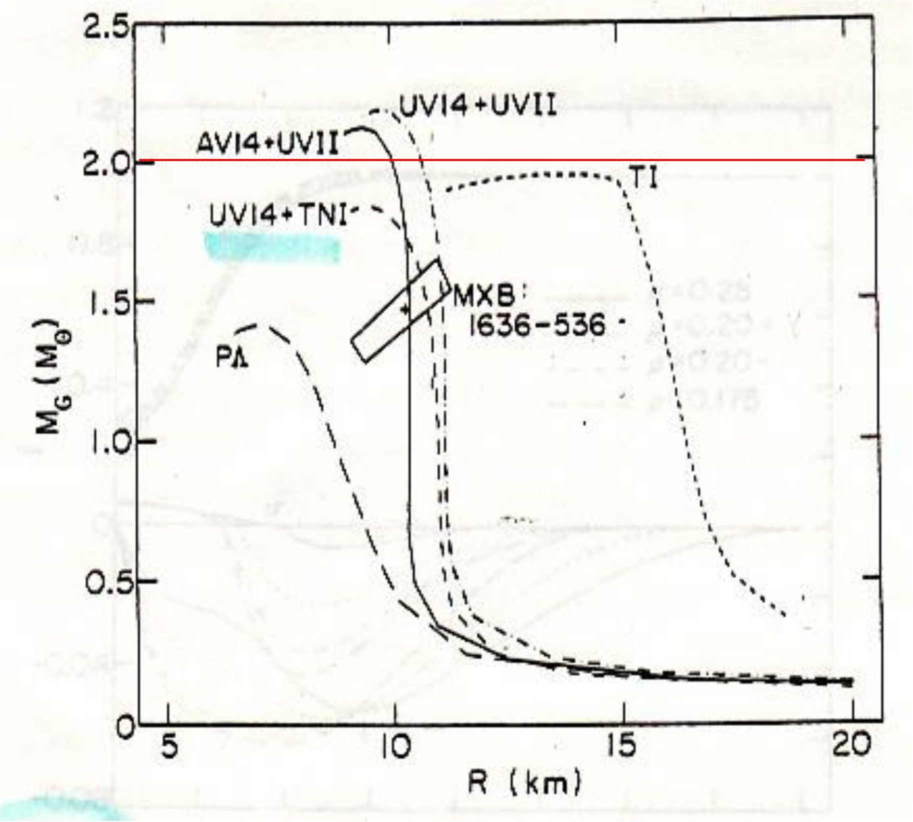
○ Extraordinal density dependence of 3P2-gap

8. Recent topics
--- $2M_{\odot}$ problem

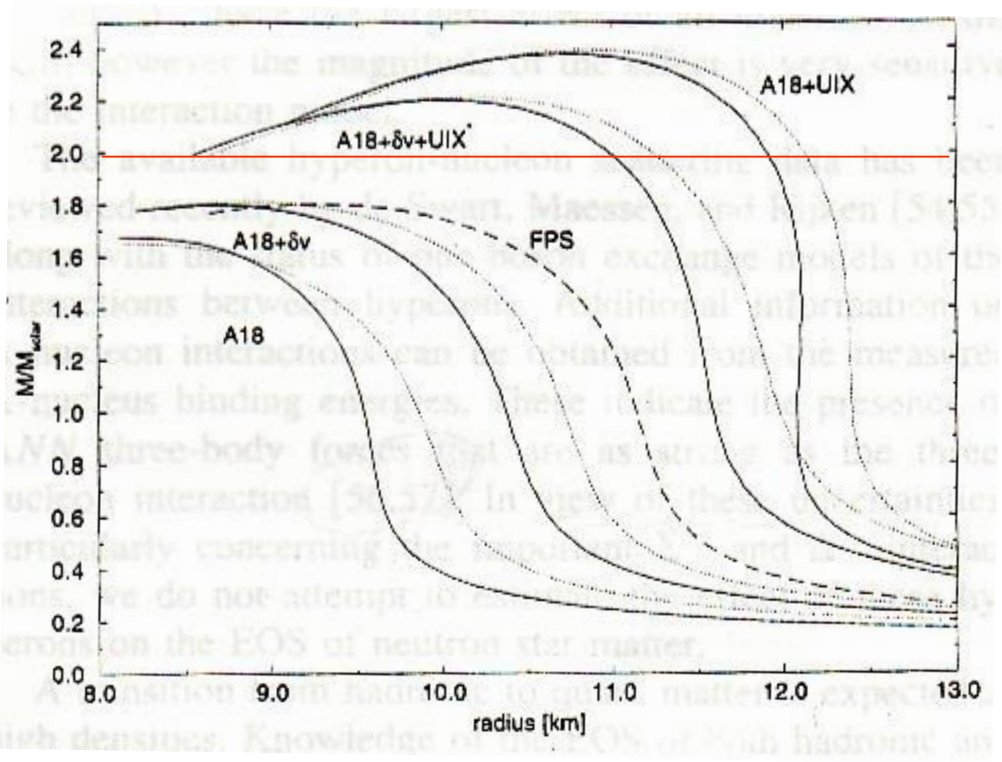
○ $M = (1.97 \pm 0.04)M_{\odot}$ for PSR J1614-2230 (P.B. Demorest et al., Nature 467 (2010) 1081)

○ $M = (2.01 \pm 0.04)M_{\odot}$ for PSR J0348+0432 (J. Antoniadis et al., arXiv: 1304.6875 [astro-ph. HE])

Without exotics, $M \geq 2M_\odot$ is possible



R.B. Wiringa, V. Fiks and A. Fabrocini, PR C38 (1988) 1010.



A. Akmal, V.R. Pandharipande and D.G. Ravenhall, PR C58 (1998) 1804.

8-1. Universal 3-body force

☐ {2πΔ-type + SJM} scheme

An origin of “universal 3-body force”

- “3-body force of extended 2πΔ-type”(at long and intermwdiate ranges) + “3-body force based on the string-junction quark model(SJM;at short distance) has been studied [5]

---

[5] T.Takatsuka,S.Nishizaki and R.Tamagaki, Proc.Int.Symp.”FM50”(AIP Conference proceedings, 2008)209

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

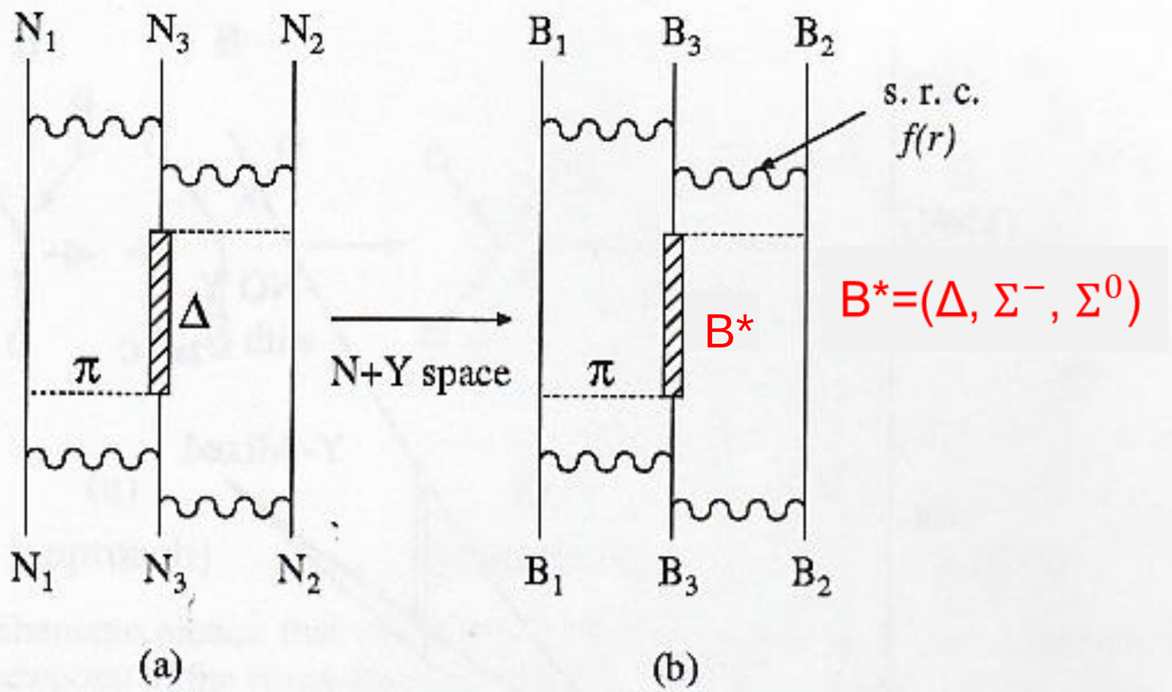
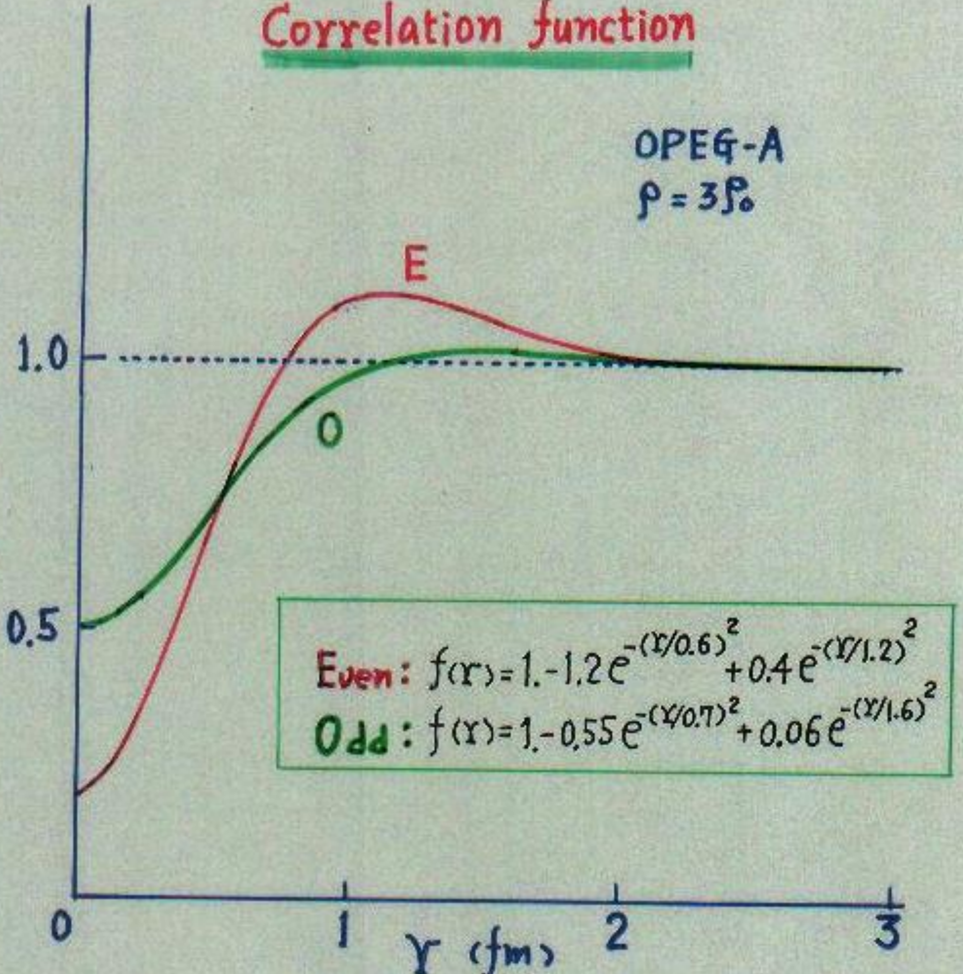


FIGURE 2. Extension of 3-body force from 2π-exchange via Δ excitation type ($2\pi\Delta$) in N-space (a) into $\{N+Y\}$ space (b), where B^* stands for Δ, Σ^{*-}, Σ^{*0} and $f(r)$ is the short-range correlation function.

○ 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

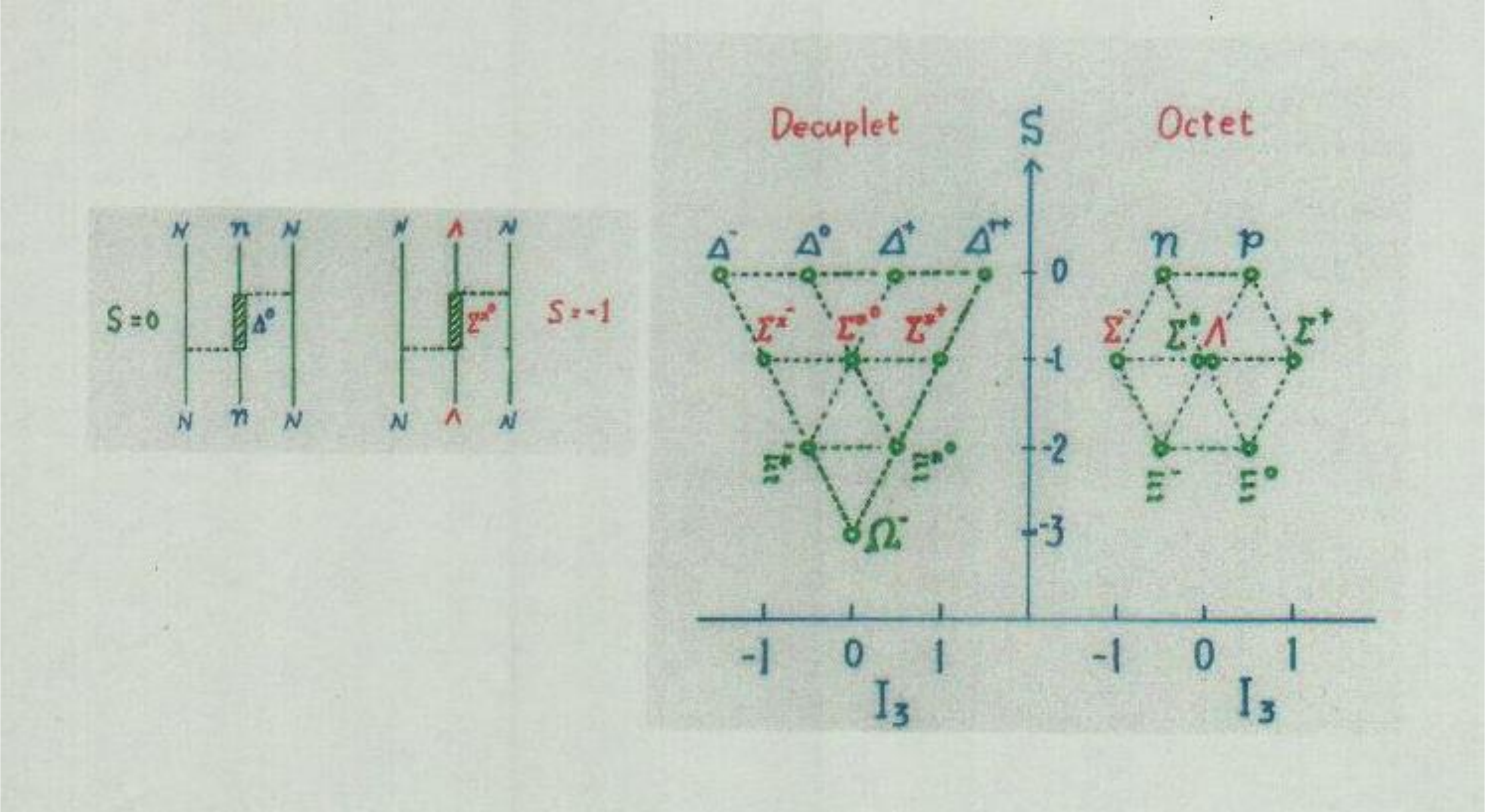
Correlation function



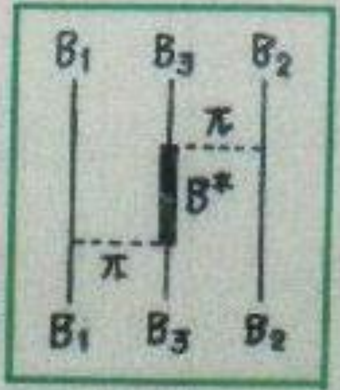
Even: $f(r) = 1. - 1.2\, e^{-(r/0.6)^2} + 0.4\, e^{-(r/1.2)^2}$

Odd: $f(r) = 1. - 0.55\, e^{-(r/0.7)^2} + 0.06\, e^{-(r/1.6)^2}$

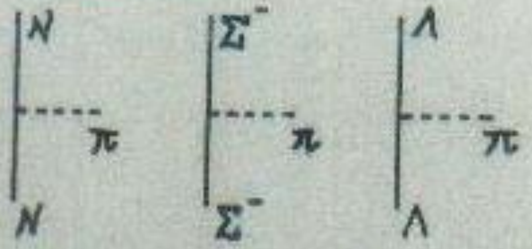
Extension to N+Y system



Extent of Contributions



(1) BBπ



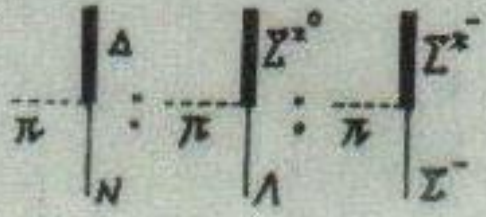
$\langle g_{NN\pi} \rangle$ $\langle g_{\Sigma^-\Sigma^-\pi} \rangle$ NO

$g_{\Sigma^-\Sigma^-\pi} = 2\alpha\, g_{NN\pi}$ (by OBE with SU(3) symm.)

$\alpha \simeq 0.49$ (Funabashi-Gifu), 0.52 (Ehime),
0.464 (Nijmegen)

$\Longrightarrow g_{\Sigma^-\Sigma^-\pi} \simeq g_{NN\pi} \Longrightarrow \tilde{V}^{(3B)}_{\Sigma^-\Sigma^-} \simeq \tilde{V}^{(3B)}_{\Sigma^- N} \simeq \tilde{V}^{(3B)}_{NN}$

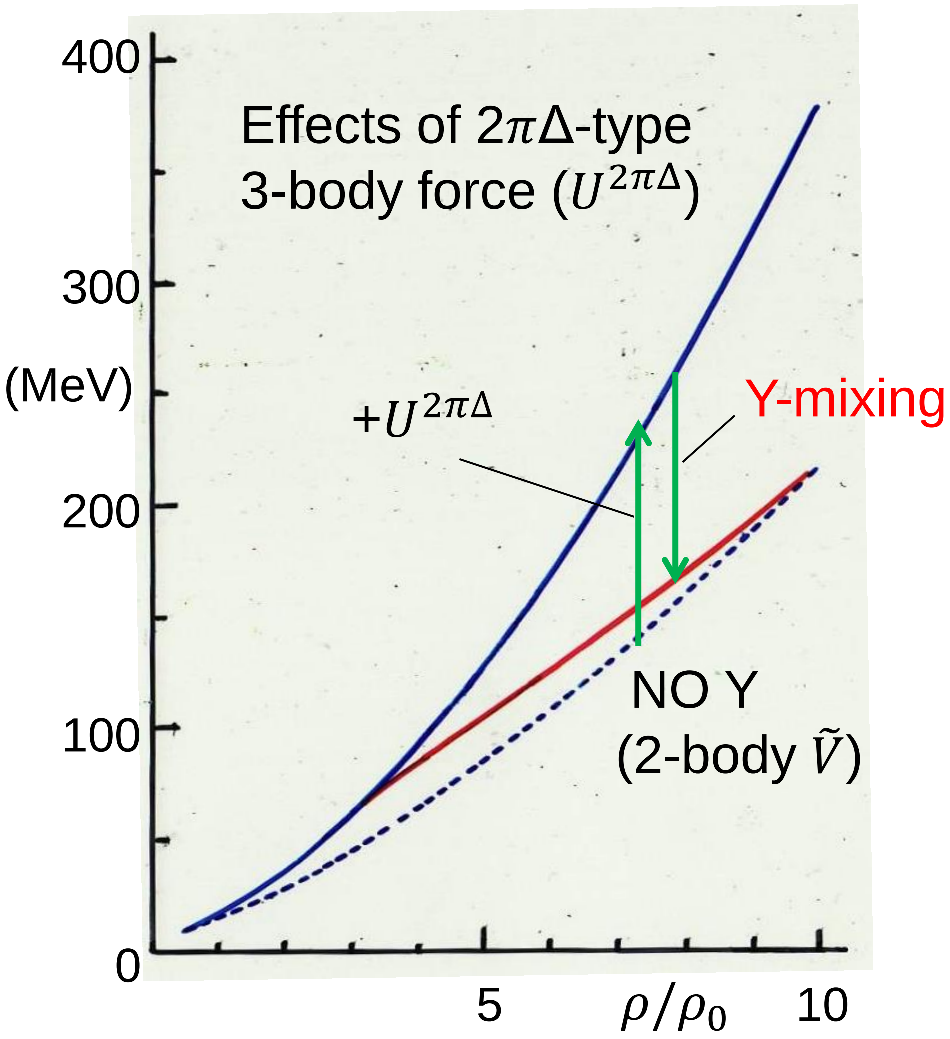
(2) BB*π



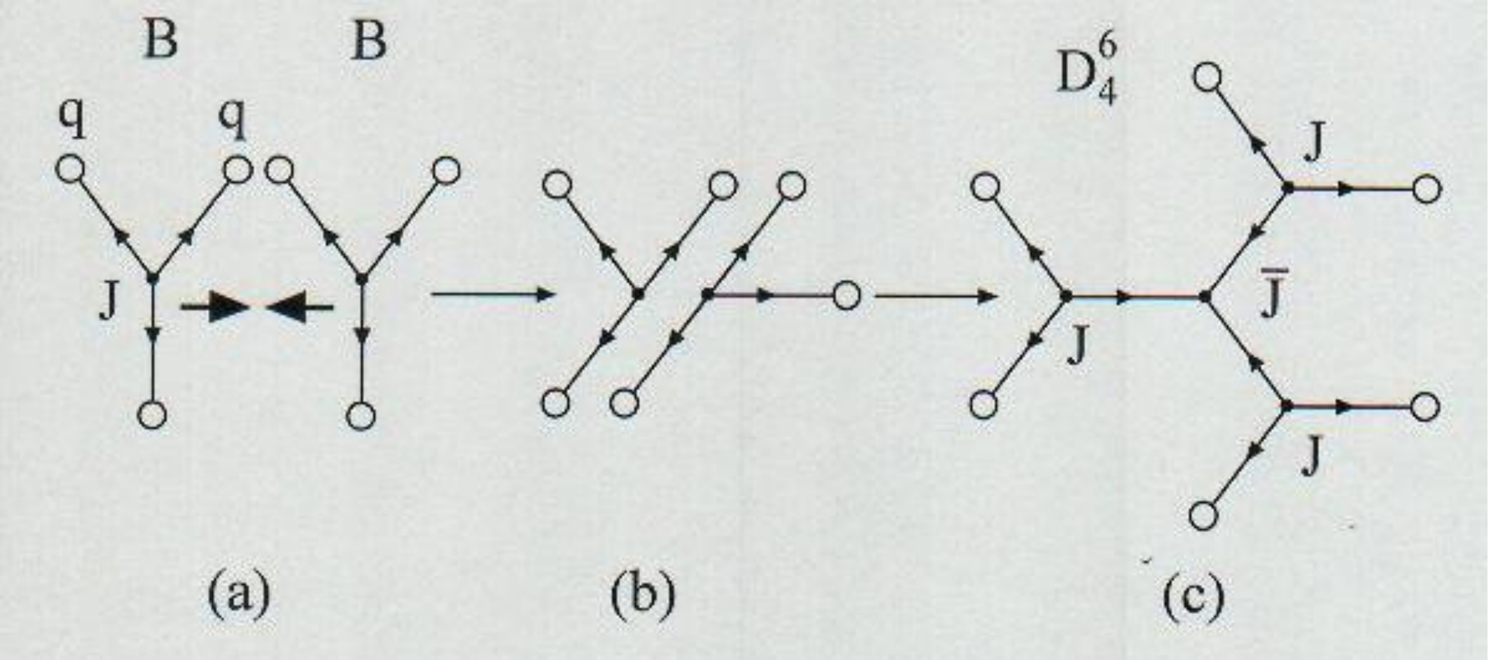
$= \frac{8}{3\sqrt{2}} : \frac{4}{\sqrt{6}} : \frac{2\sqrt{2}}{3} = 1 : \frac{\sqrt{3}}{2} : \frac{1}{2}$

(by quark model)

EOS of Neutron Star Matter



Repulsion from SJM-----flavor independent

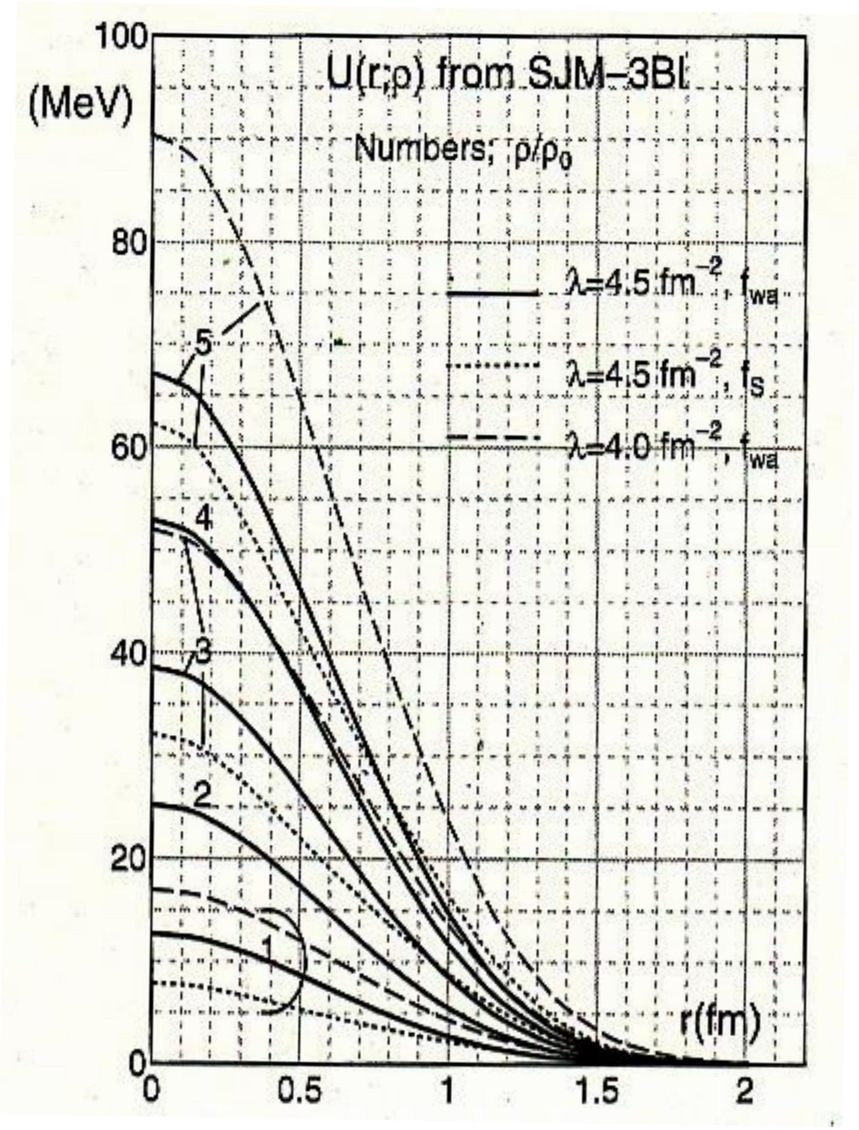


(a) 2B come in short distance
(b) Deformation (resistance)
(c) Fusion into 6-quark state

(by R. Tamagaki)

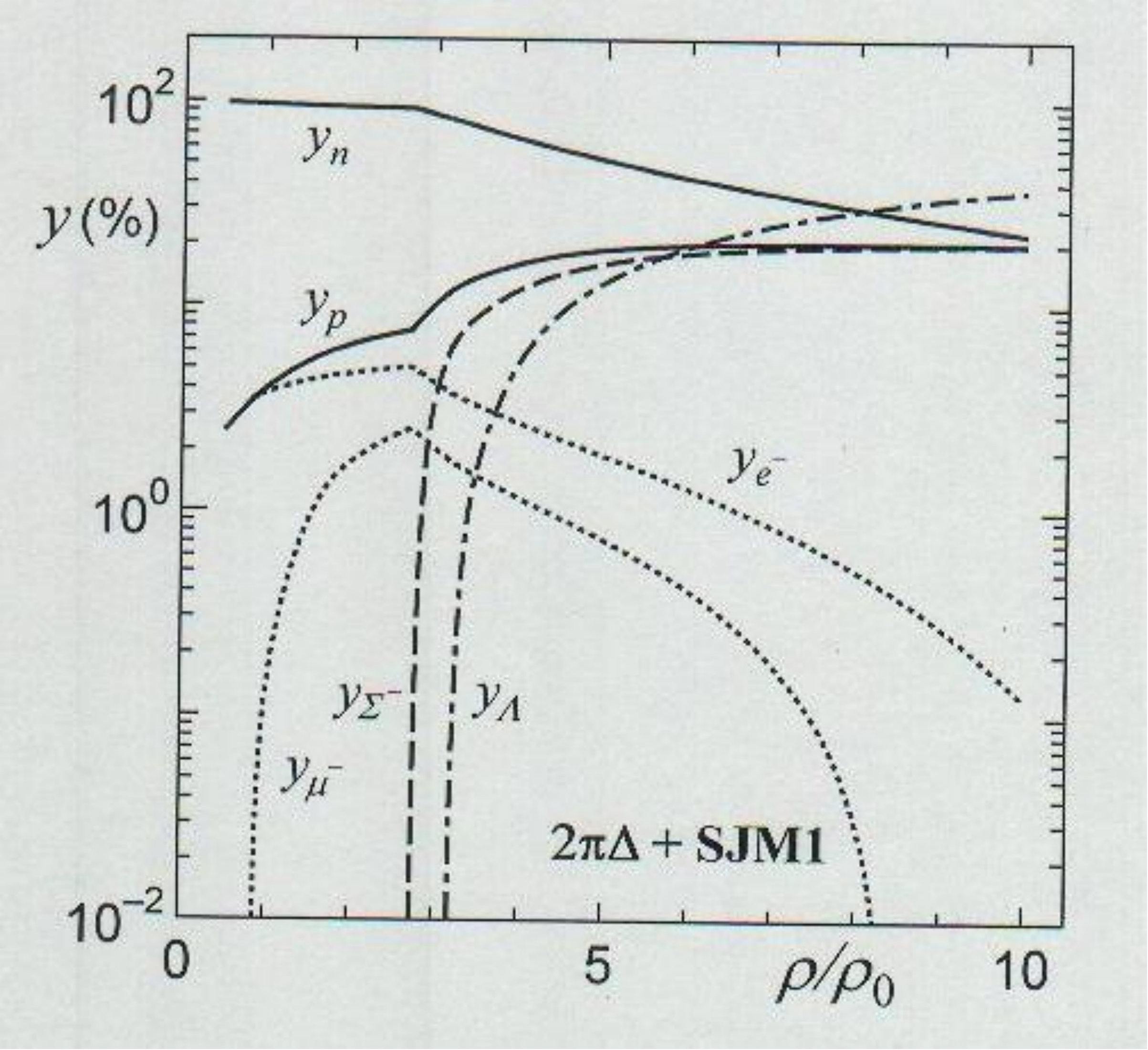
Prog. Theor. Phys. 119 (2008) 965.

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

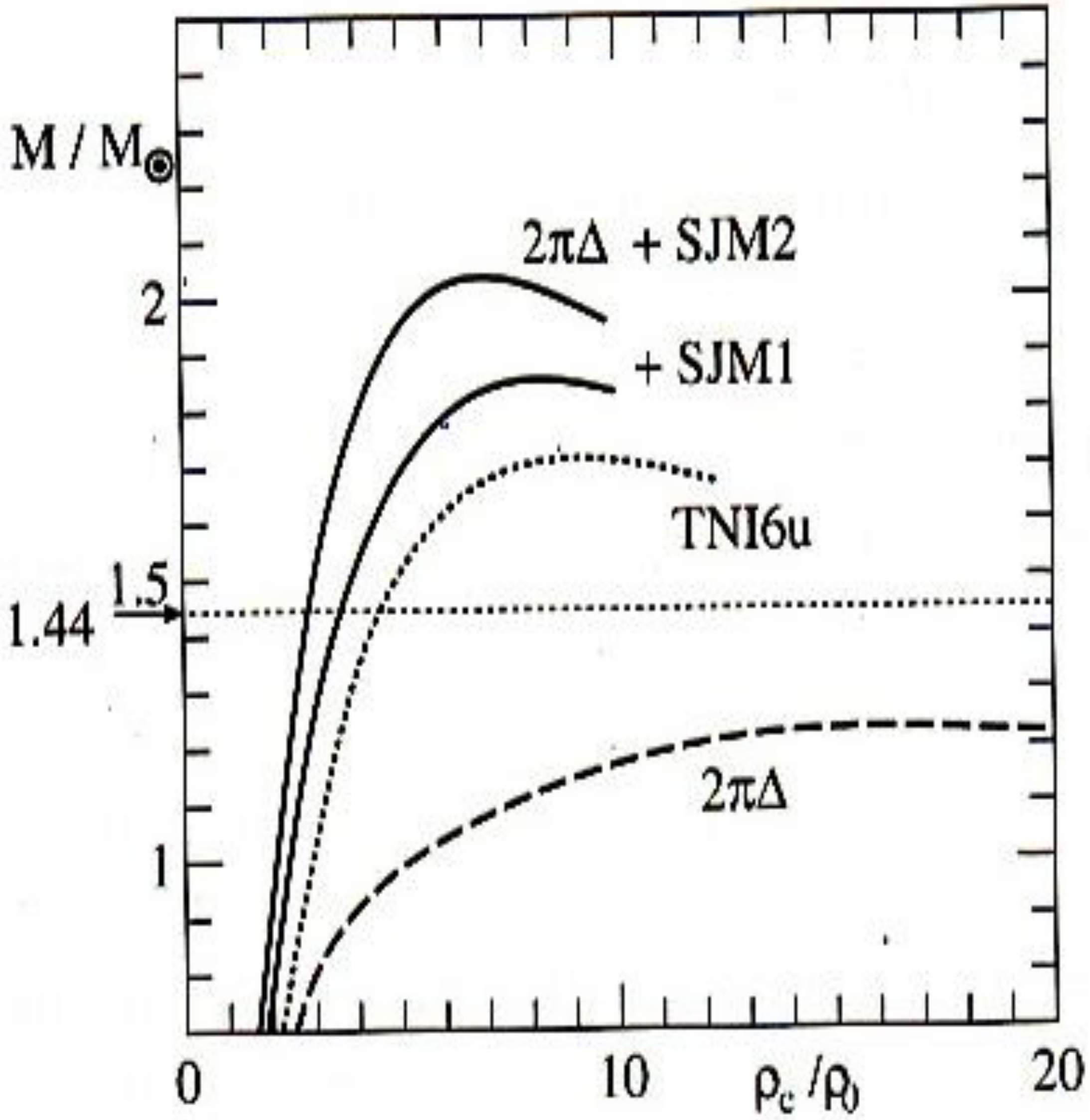


R. Tamagaki, Prog. Theor. Phys. 119 (2008) 965.

Fraction of constituents in Y-mixed NSs



Mass v.s. Central Density



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

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

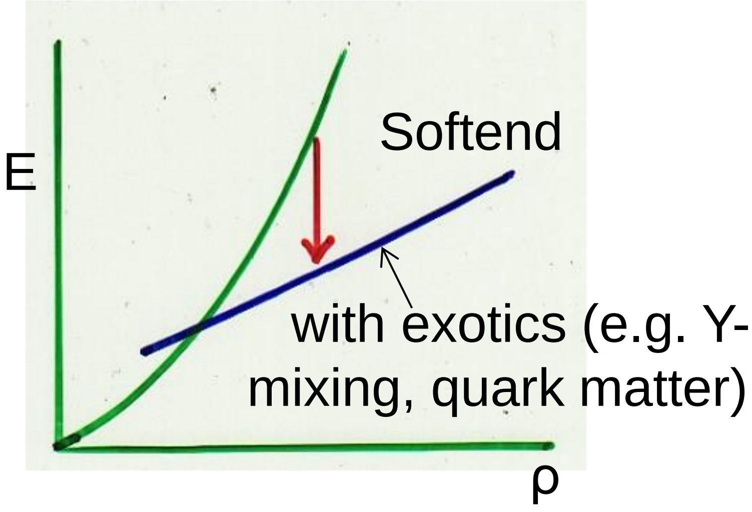
8-2. Hybrid stars with quark degrees of freedom

Introduction

○ Obs. Of $2M_{\odot} - NS$
○ NO exotics: $M_{max} \geq 2M_{\odot}$ is possible

○ with exotics → Softened EOS → NO($M_{max} \ll 2M_{\odot}$)

○ Then, no exotics?



☐ In a pure hadronic level, “universal 3-body repulsion” can be a solution. How about the quark degrees of freedom

☐ Remarks

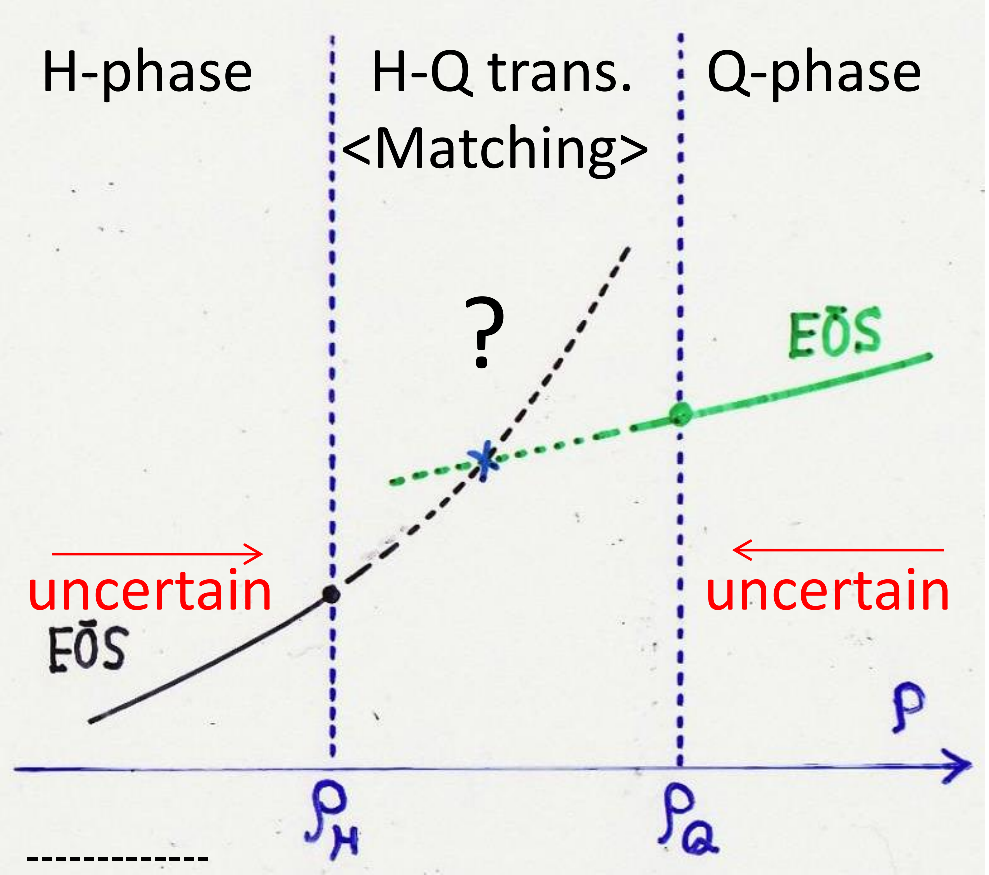
(1) hadrons are composed of quarks and have a finite size
→ point-like picture gets uncertain as ρ goes higher

(2) Quark matter framework gets uncertain with decreasing ρ due to the confinement－deconfinement transition

(3) Usual Gibbs condition is not necessarily applicable

☐ Possibility of quark matter in NSs *)

A way of approach



☐ H: point particle
+ interaction
→ G-Matrix, Variational

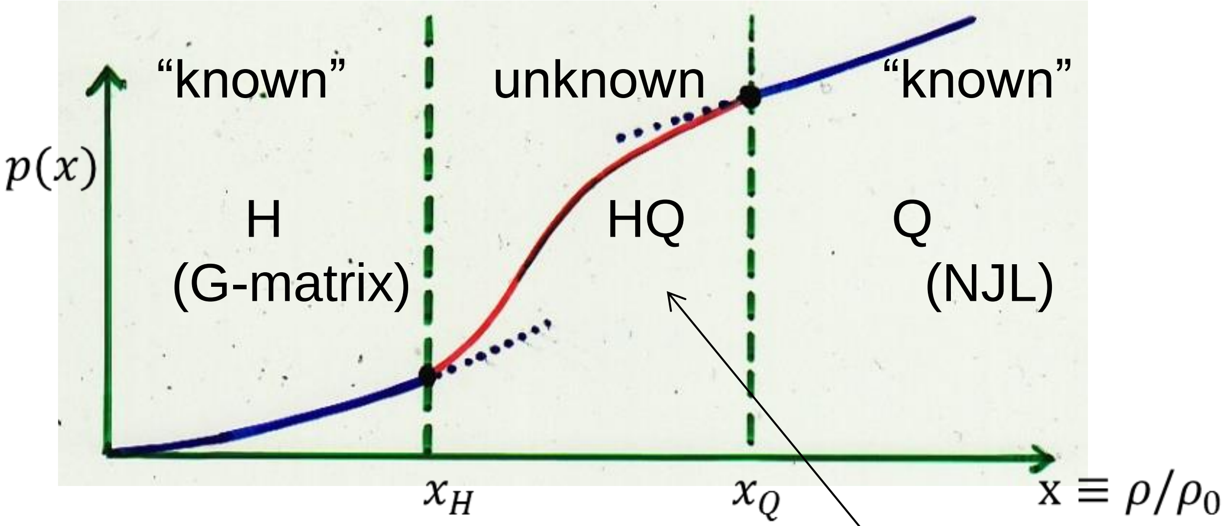
☐ Q: q-matter + asymptotic
freedom

☐ HQ Phase transition
Cross point (Maxwell, Gibbs) → not necessarily reliable

☐ Need new strategy

- T. Takatsuka, T. Hatsuda and K. Masuda, AIP Conference Proceedings 1484 (Melvile, N.Y. 2012) 406.
- K. Masuda, T. Hatsuda and T. Takatsuka, ApJ 794 (2013) 12.

(1) “3-window model”



not by Gibbs condition, but by phenomenological interpolation

① $p(x) = a^m + bx^n + c$ $\quad \left(p = x^2 \frac{\partial\left(\frac{\varepsilon}{x}\right)}{\partial x}\right)$

② $\varepsilon(x) = \frac{a}{m-1} x^m + \frac{b}{n-1} x^n - c + dx$

③ Conditions

(i) thermodynamic stability: $\frac{\partial p}{\partial x} > 0$

(ii) sound velocity: $v_z \leq c$

④ Determination of (a, b, c, d)

$$p(x_H) = p_H \quad , p(x_Q) = p_Q$$
$$\varepsilon(x_H) = \varepsilon_H \quad , \quad \varepsilon(x_Q) = \varepsilon_Q$$

- T. Takatsuka, “Genshikaku Kenkyu” Vol.57 (2013) 270.

Some results for NS models

JEOS	x_H	x_s	H-EOS	Q-EOS	m	n	$M_{max}/M_{\odot}$	R/k_m	ρ_c/ρ_0
1	1.5	5.5	TNI2u	$g_v = 0.5G_s$	0.2	-2.6	2.61	13.38	3.99
2	1.5	6.0	〃	〃	〃	〃	2.59	13.27	3.90
3	1.5	7.0	〃	〃	〃	〃	2.53	12.08	4.52
4	1.5	8.0	〃	〃	〃	〃	2.48	12.56	4.35
5	1.5	7.0	〃	$g_v = 1.5G_s$	〃	〃	3.08	13.73	3.34
6	1.5	7.0	〃	$g_v = 1.0G_s$	〃	〃	2.86	13.28	3.94
7	1.5	7.0	〃	$g_v = 0.$	〃	〃	1.99	12.30	4.85
8	1.5	7.0	〃	$g_v = 0.5G_s$	2.6	-0.2	2.62	13.44	4.05
9	1.5	7.0	〃	〃	1.2	-1.2	2.61	13.44	3.73

Dependence on (m, n)

$$p(x) = ax^m + bx^n + c$$

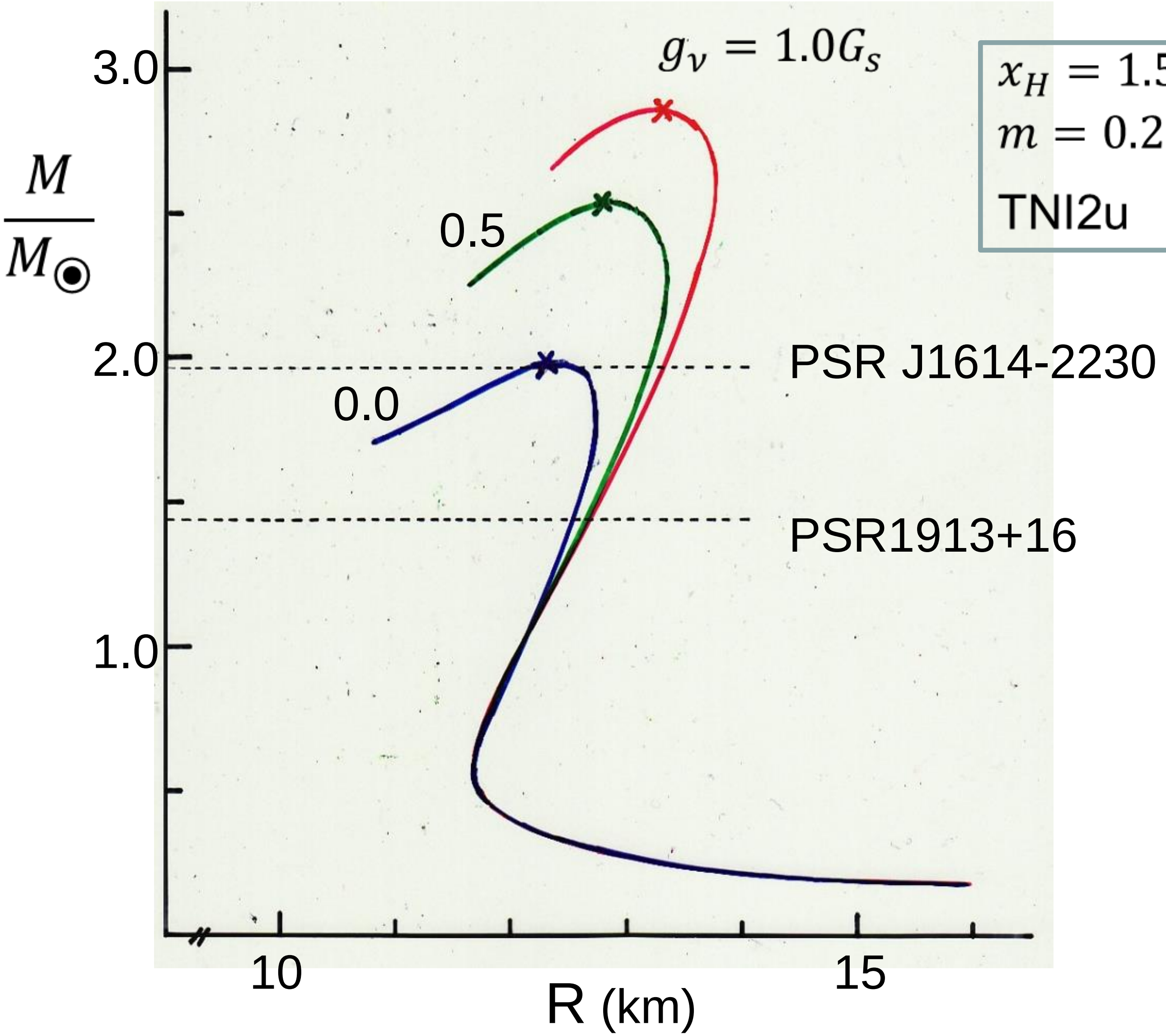
H-EOS: TNI2u

Q-EOS: NJL, $g_v = 0.5G_s$

$x_H = 1.5,$ $x_Q = 7.0$

(m,	n)	$\frac{M_{max}}{M_\odot}$	$\frac{R}{km}$	ρ_c/ρ_0
0.2	-2.6	2.53	12.8	4.5
2.6	-0.2	2.62	13.4	4.1
1.2	-1.2	2.61	13.4	3.7

$M \geq 2M_{\odot}$ is realized

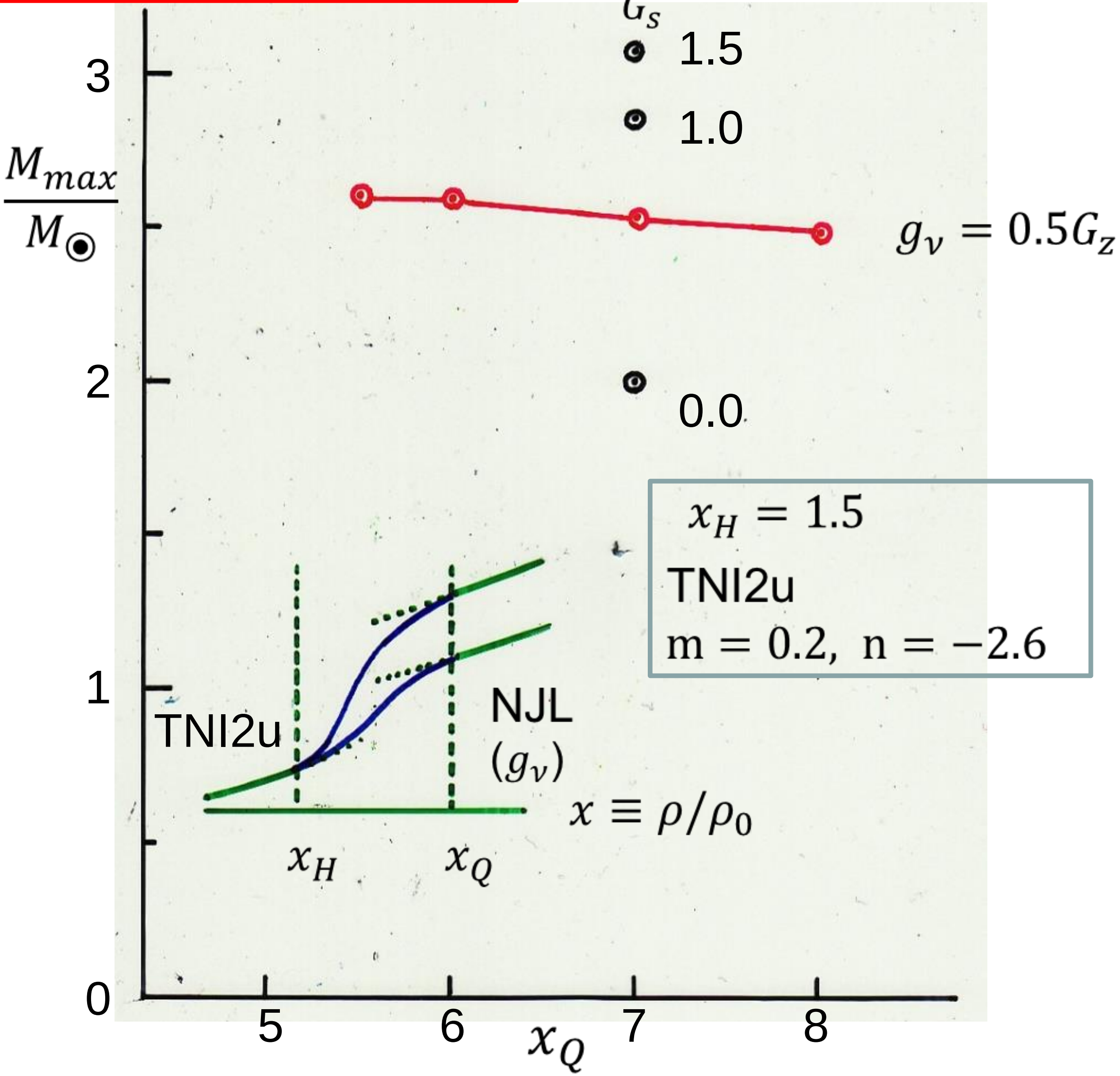


$x_H = 1.5, \quad x_Q = 7$

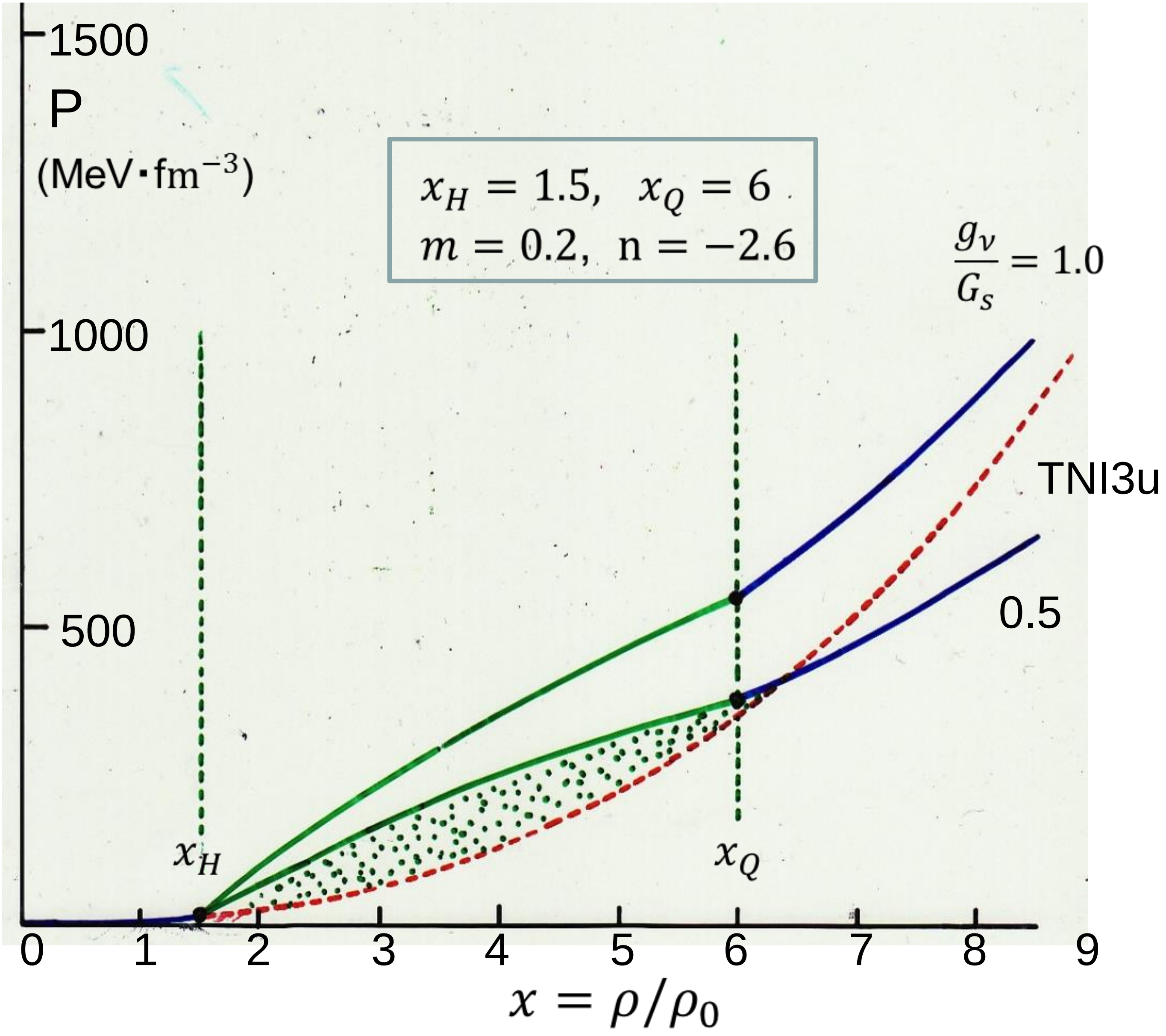
$m = 0.2, \quad \mathrm{n} = -2.6$

TNI2u

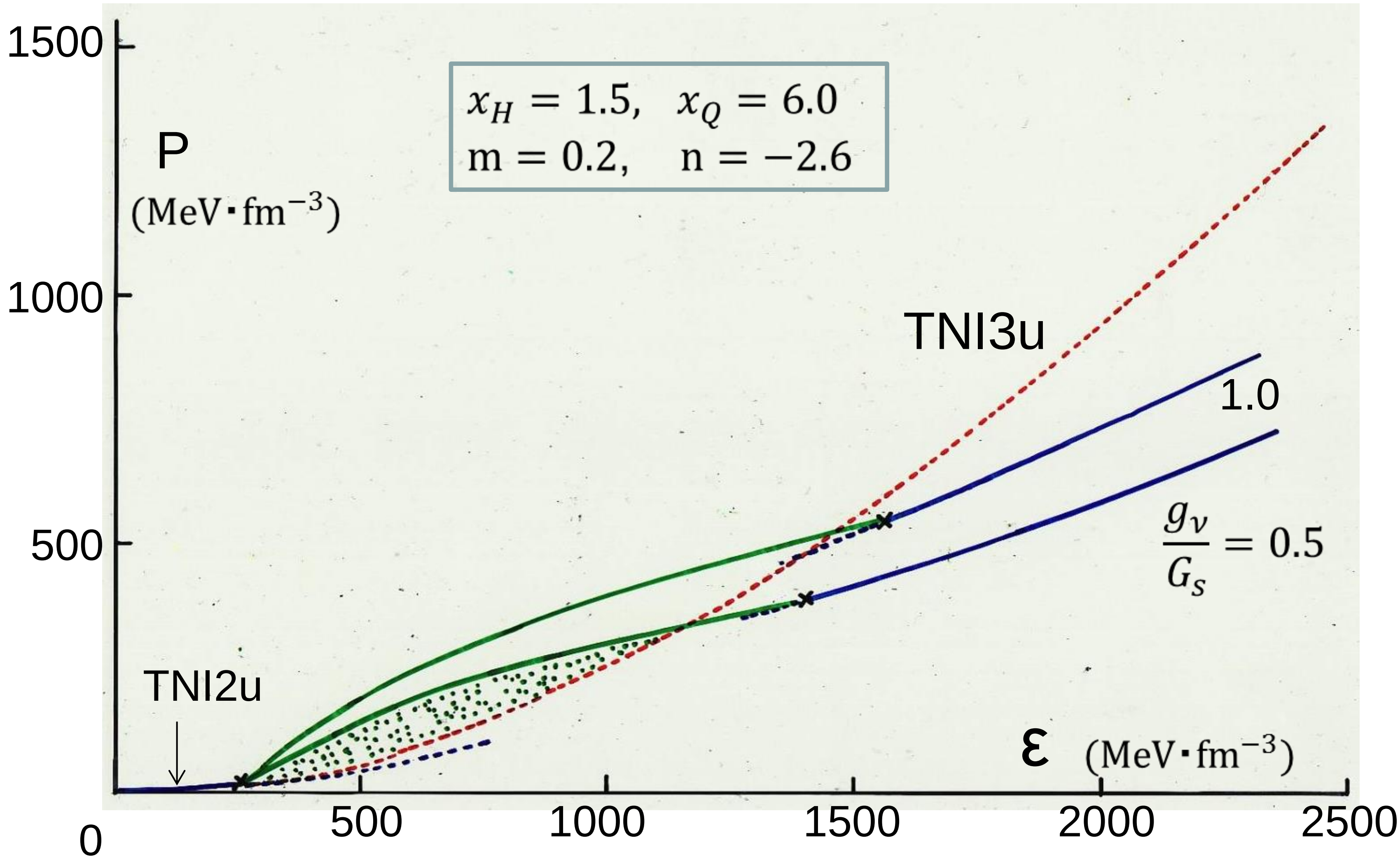
Dependence on x_Q , g_ν



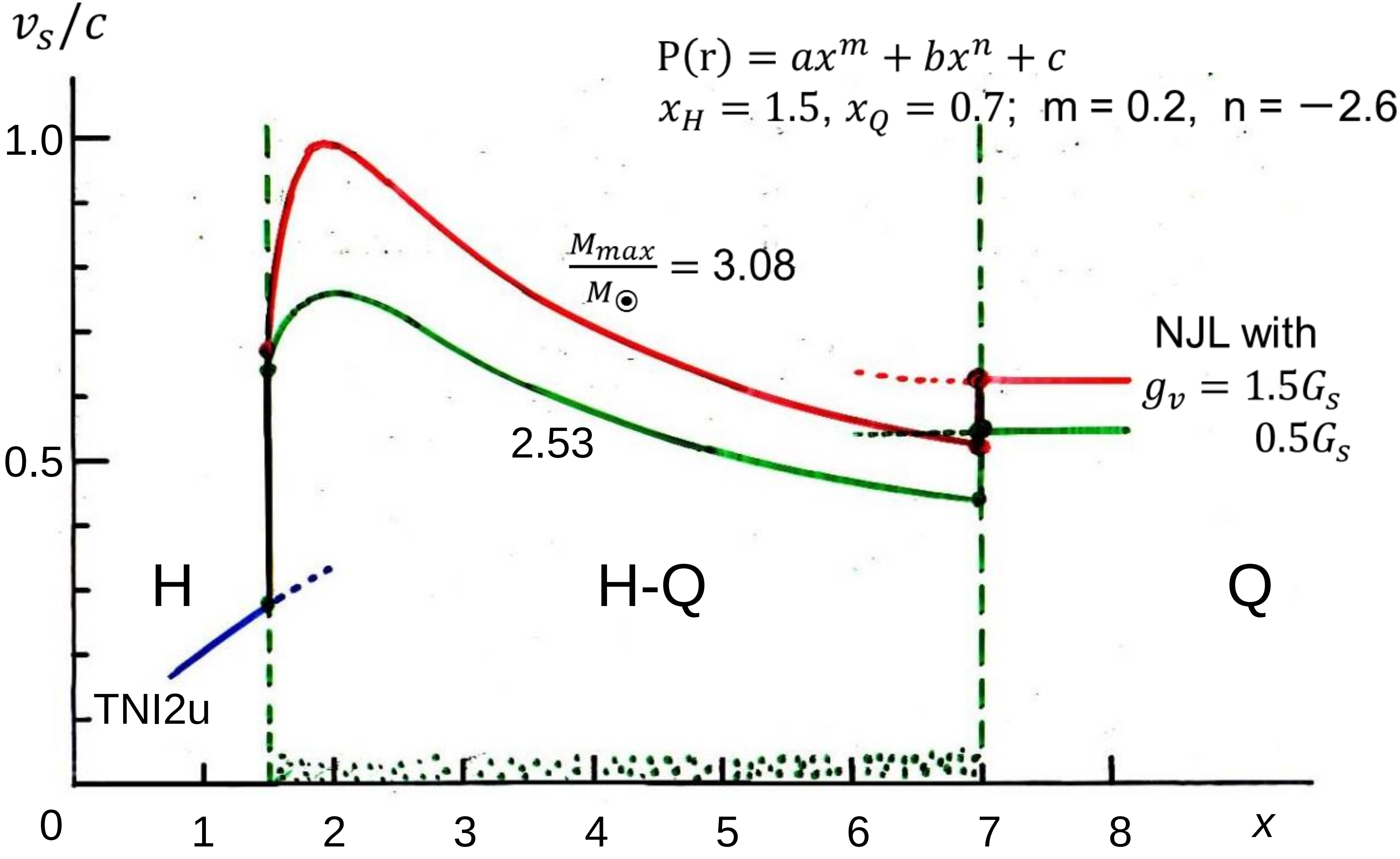
Stiffened EOS at $\rho\sim(2-5)\rho_0$ is a key to $M_{max} \geq 2M_{\odot}$



Stiffening of EOS due to H-Q transition



Sound Velocity

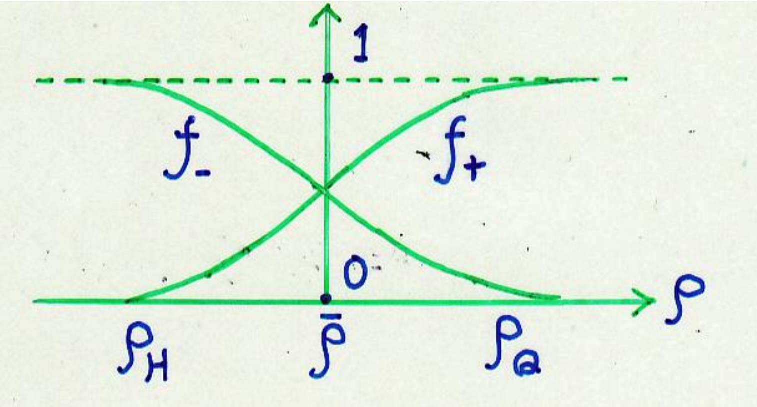


(2) "H-Q crossover model"

○ From a view of "H-Q Crossover"

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

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



*) Asakawa-Hatsuda
P.R. D55(1997)
4488

○ 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).

○ Quark Matter phase

- ○ (2 + 1) -flavor NJL model with vector interaction

$$L_{NJL} = \bar{q}(i\not{\partial} - m)q + \frac{1}{2}G_S \sum_{\alpha=0}^{8}\{(\bar{q}\lambda^{\alpha}q)^2 + (\bar{q}\lambda^{\alpha}i\gamma_5 q)^2\}$$

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

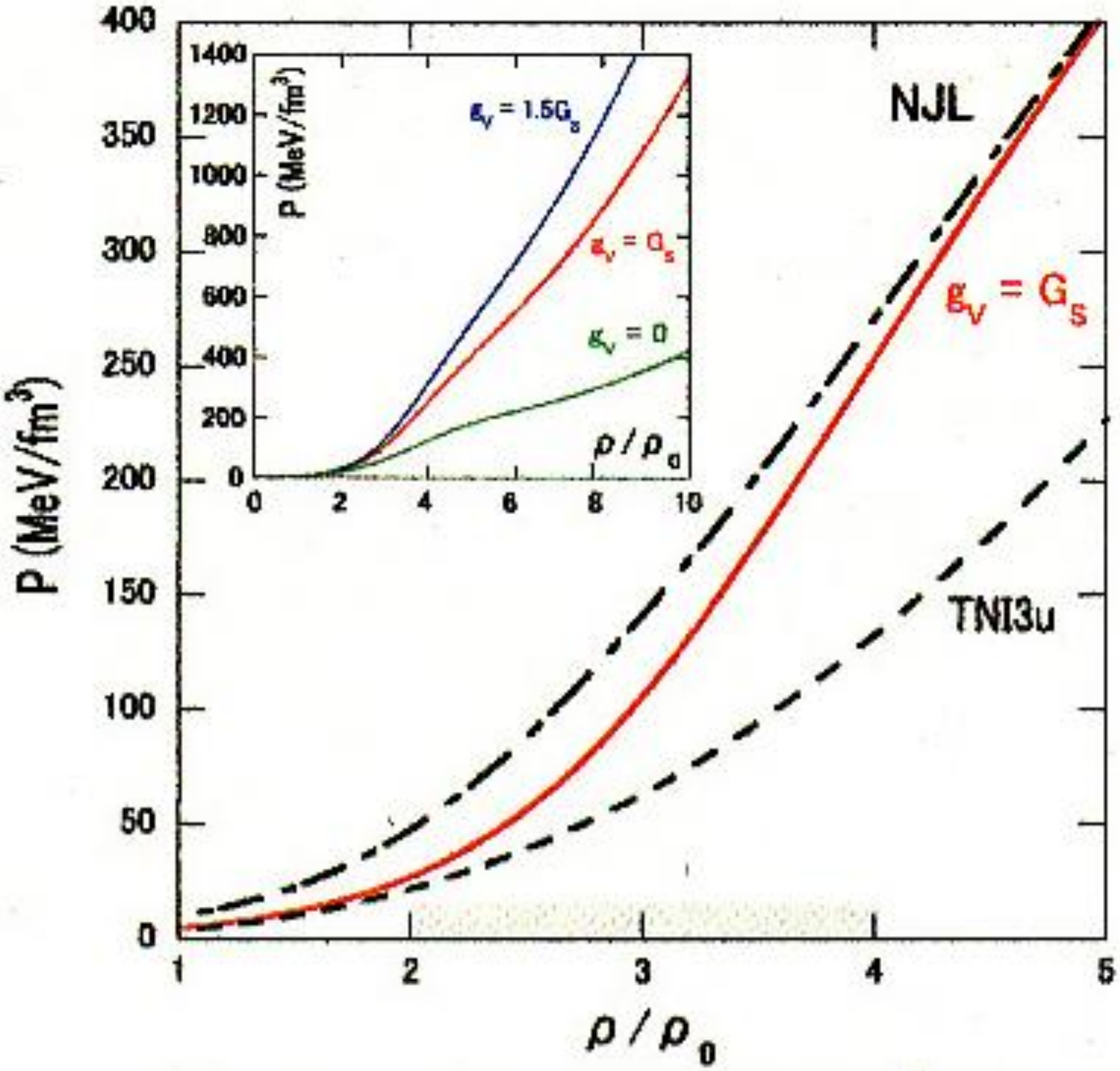
with $q \equiv \{q_i; i = u, d, s\}$ $m \equiv \{m_i\}$

- ○ Hatsuda-Kunihiro parameter set (Phys. Rep - 247 (1994) 221)

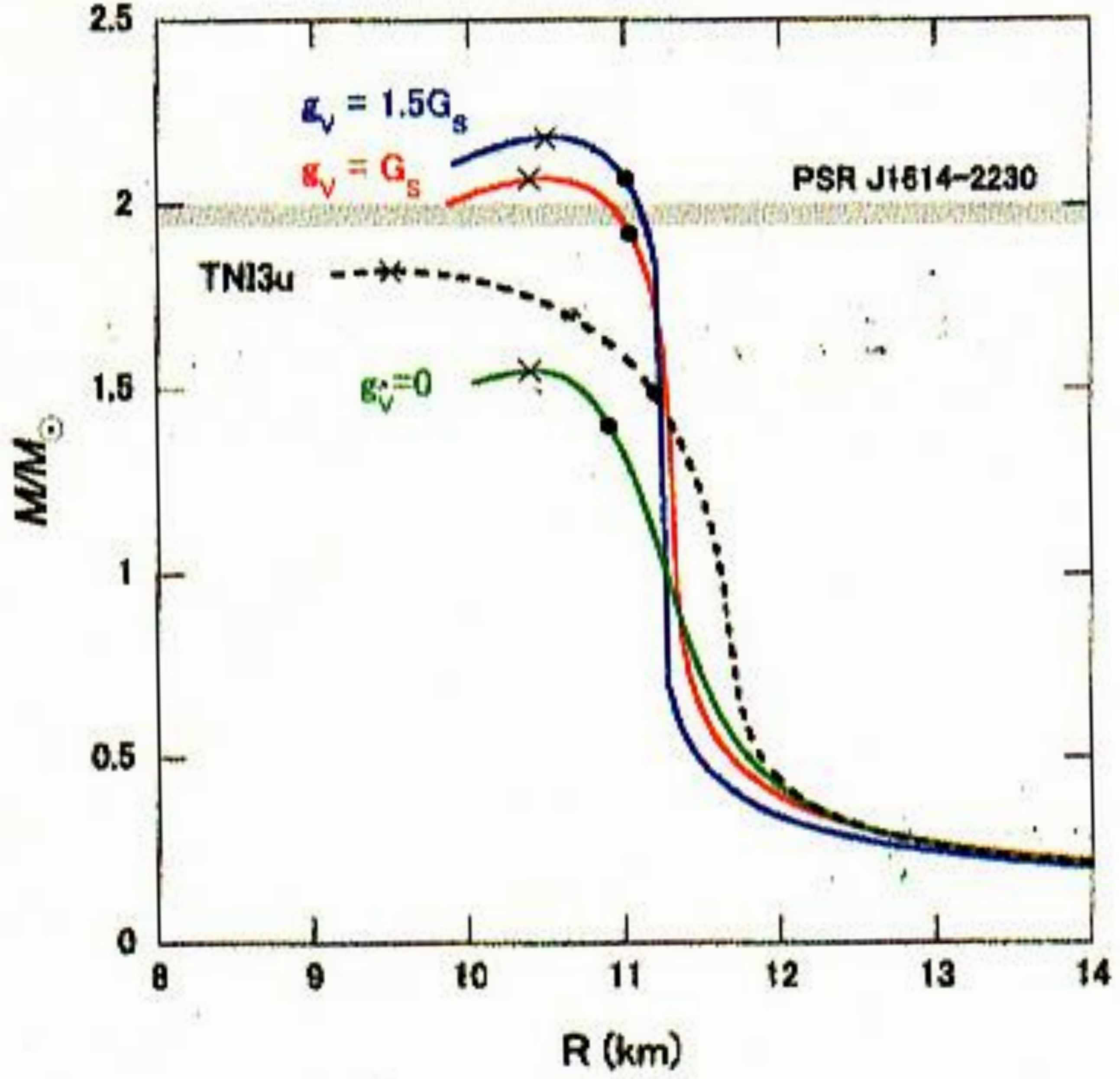
Λ = 631.4 MeV, $G_S\Lambda^2 = 1835$, $G_D\Lambda^2 = 9.29$
$m_u = m_d = 5.5$ MeV, $m_s = 135.7$ MeV

- ○ g_V is not well determined, but it is suggested that g_V can be comparable or even larger than g_S
→ we take

$$\frac{g_V}{g_S} \sim (0 - 1.5)$$



Pressure v.s. density



Mass v.s. Radius

$M_{max} > 2M_\odot$

Is possible

Remarks

$M_{max} \geq 2M_{\odot}$ is possible under the condition:

① H-Q transition sets on at relatively low density $(\rho \sim 1.5\rho_0)$

② Quark matter is strongly correlated (with repulsive effects)

Short summary

☐ Two-solar mass problem with hyperons

(A) pure hadron framework

"universal 3-body force" is one of the solution

* study on the origin is the next important subject

(B) "hadron + quark" framework

Introduction of Q-degrees of freedom from a view of "3-window model" and "H-Q crossover model" is another promising solution

☐ Too-rapid cooling problem with hyperons

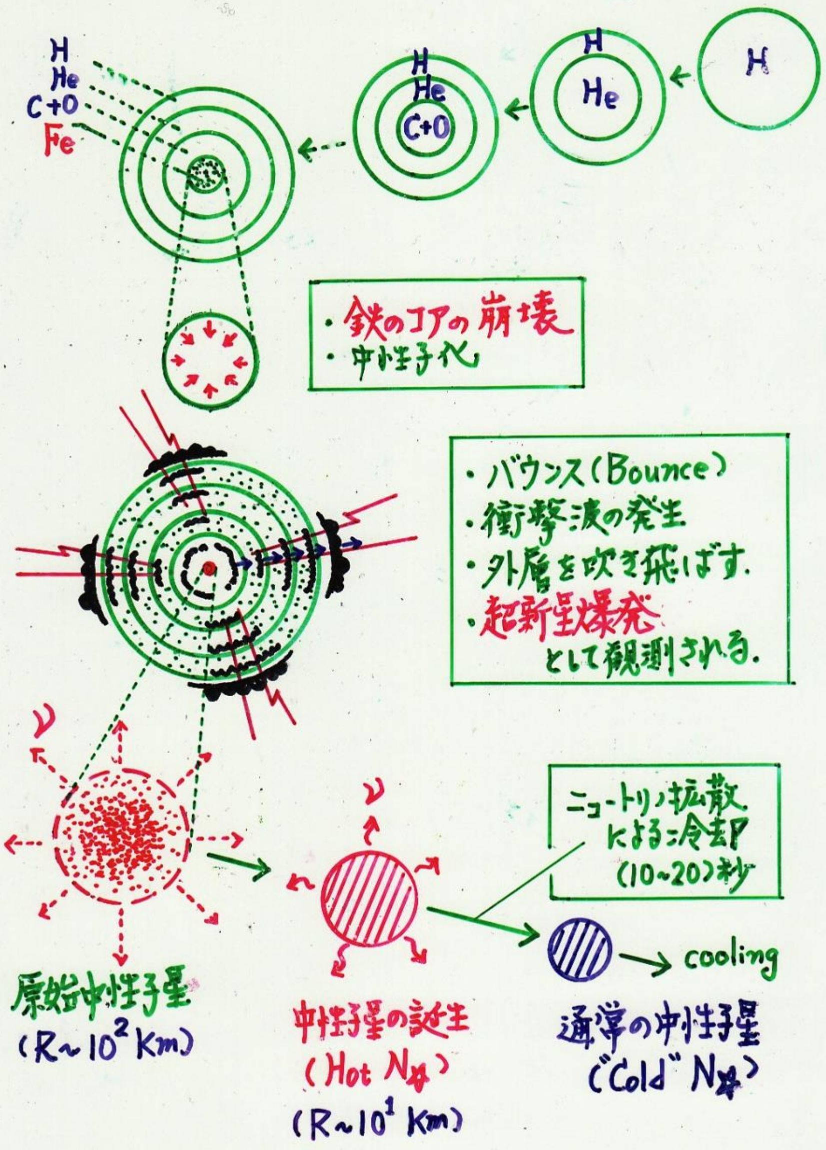
necessity of hyperon superfluidity →yes?, no?

→ more careful investigation; ΛΛ interaction from NGARA, effects to enhance the attraction

→ other possibilities

☐ We have to solve the two problems challenged by NSs at the same time

9. Hot NSs at birth with hyperon mixing



- 鉄のコアの崩壊
- 中性子化

- バウンス(Bounce)
- 衝撃波の発生
- 外層を吹き飛ばす.
- 超新星爆発
  として観測される.

ニュートリノ拡散
による冷却
(10~20)秒

☐ Effective Interaction Approach (EIA) at Finite-Temperature (*T*>0) [1]

☐ EIA at *T*>0

Consists of

(a) solving the HF equation at *T*>0 under the conservation of total nucleon number (*N*)

(b) using a *T*-independent effective interaction $\tilde{V}$ (or *G*-mitrix at *T*=0; *G*(0)) based on the *G*-matrix calculation with bare interaction *V*

$$\varepsilon_\alpha = t_\alpha + \sum_\beta f_\beta R_e[< \alpha\beta|W|\alpha\beta - \beta\alpha >] \text{ with } W \equiv \tilde{V} \text{ or } G(0)$$

$$\sum_\alpha f_\alpha = N \text{ with } f_\alpha \equiv \frac{1}{1+e^{(\varepsilon_\alpha-\mu)/T}}. \qquad (1)$$

☐ EBA (Extended Brueckner approach (*T*>0))

$$G(T) = V + V\frac{Q(T)}{e(T)}G(T) \qquad (2)$$

together with (1), where $e = \varepsilon_\alpha + \varepsilon_\beta - \varepsilon_{\alpha'} - \varepsilon_{\beta'} + i\,\epsilon$.

☐ Thermodynamic Quantities

$$\boxed{\begin{gathered} E = \sum_{\alpha} f_\alpha(\varepsilon_\alpha + t_\alpha)/2N \\ S = -\sum_\alpha\{(1-f_\alpha)\ln(1-f_\alpha) + f_\alpha \ln f_\alpha\}/N \\ F = E - TS \\ P = \rho^2 \frac{\partial F}{\partial \rho} \end{gathered}} \qquad (3)$$

☐ Calculations and Results

○ effective-mass approximation for ε_α

$$\boxed{\varepsilon_\alpha \simeq \tilde{\varepsilon}_\alpha(k_\alpha) = U_0 + t_\alpha/m^*,\ m^* = m_N{}^*/m_N} \qquad (4)$$

○ Angle-averaged Pauli operator ($Q \to \bar{Q}$)

○ QTQ-method

○ V→Mongan's separable pot.

---

[1] T. Takatsuka and J. Hiura, Prog. Theor. Phys. 79 (1988) 268.

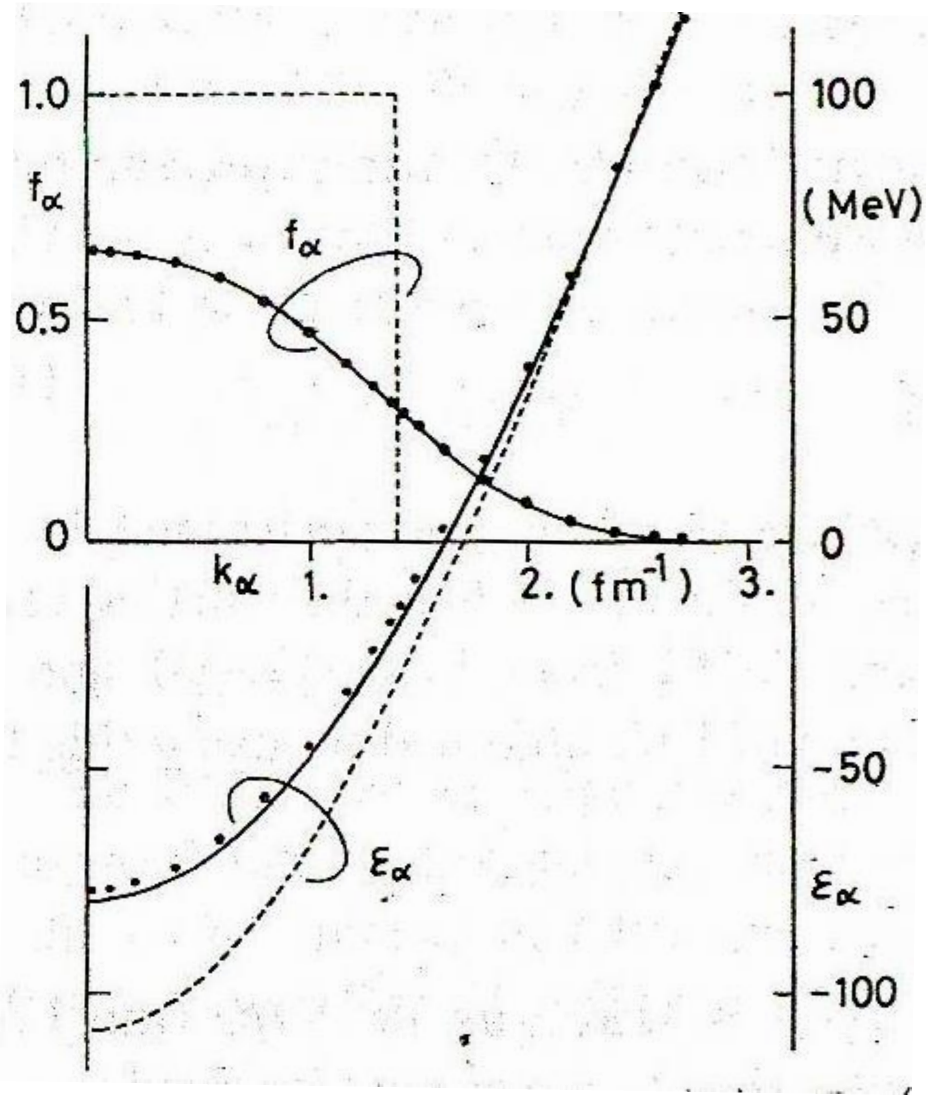
[2] T.R. Mongan, Phys. Rev. 178 (1969) 1597.

Single-particle energy (ε_α) and occupation probability (f_α)

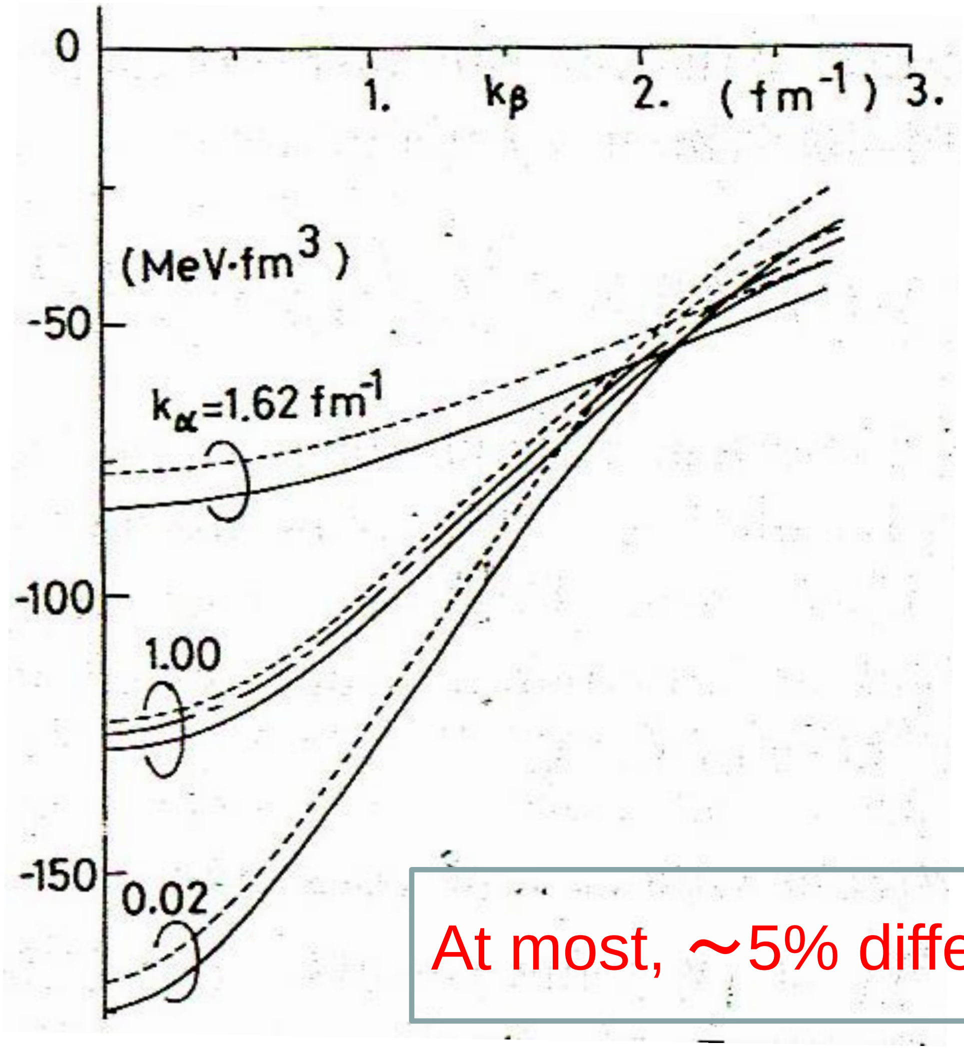
○ ρ≃1.1ρ_0

○ solid (dashed) line for *T*=40 (0) MeV

○ solid circles for EBA



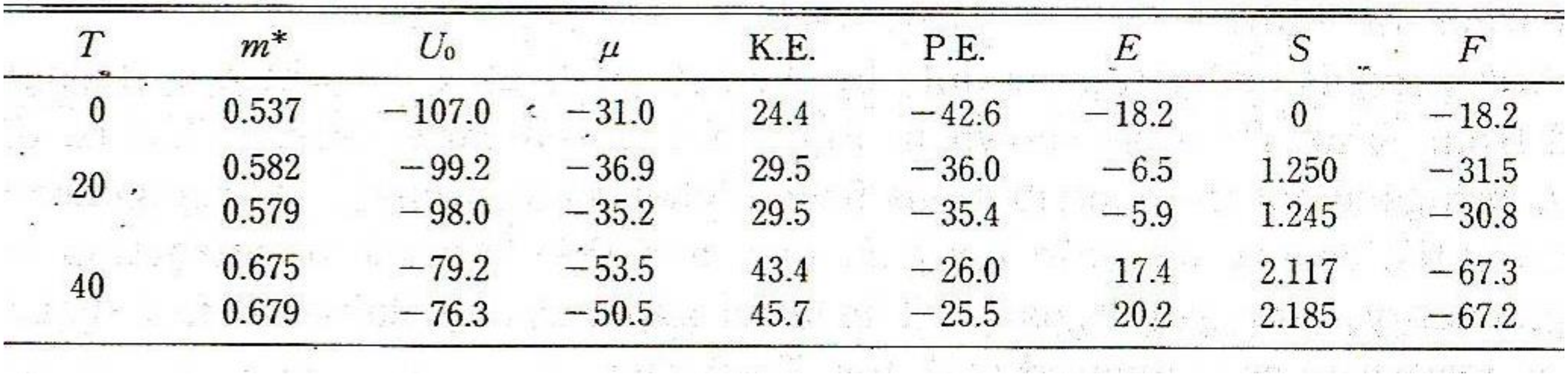
Weak *T*-dep. of *G*(*T*)



- ○ $\bar{G}(k_\alpha, k_\beta; T)$:
  angle-averaged *G*
- ○ ρ=1.1ρ_0, *T*=40MeV
- ○ solid (dashed) line for
  T=40(0)MeV
- ○ dash-dotted line for
  $\bar{Q}(T) \rightarrow \bar{Q}(0)$

At most, ∼5% difference even for T=40MeV!

Single and bulk quantities



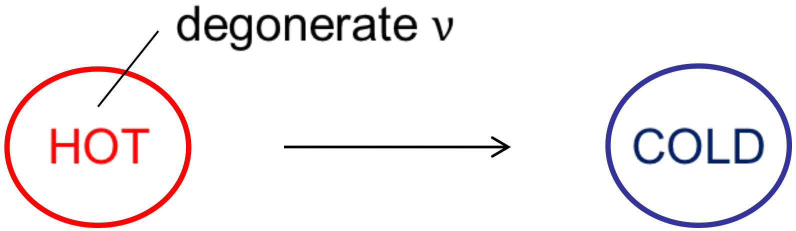
T	m^*	U_0	μ	K.E.	P.E.	E	S	F
0	0.537	−107.0	−31.0	24.4	−42.6	−18.2	0	−18.2
20	0.582	−99.2	−36.9	29.5	−36.0	−6.5	1.250	−31.5
	0.579	−98.0	−35.2	29.5	−35.4	−5.9	1.245	−30.8
40	0.675	−79.2	−53.5	43.4	−26.0	17.4	2.117	−67.3
	0.679	−76.3	−50.5	45.7	−25.5	20.2	2.185	−67.2

○ ρ≃1.1ρ_0

○ BA (Brueckner approach),
BA (extended Brueckner approach),
EIA (effective interaction approach)

☐ Hyperon-Mixed Supernova Matter (SM)

☐ Characteristics of supernova matter



HOT	COLD
T=10～30MeV	T = 0
n, p, Y, e^-, μ^-, ν	n, p, Y, e^-, μ^-
S = 0.1～1.5 (constant)	S = 0
Y_l = 0.3-0.4 (constant)	Y_l～0.05

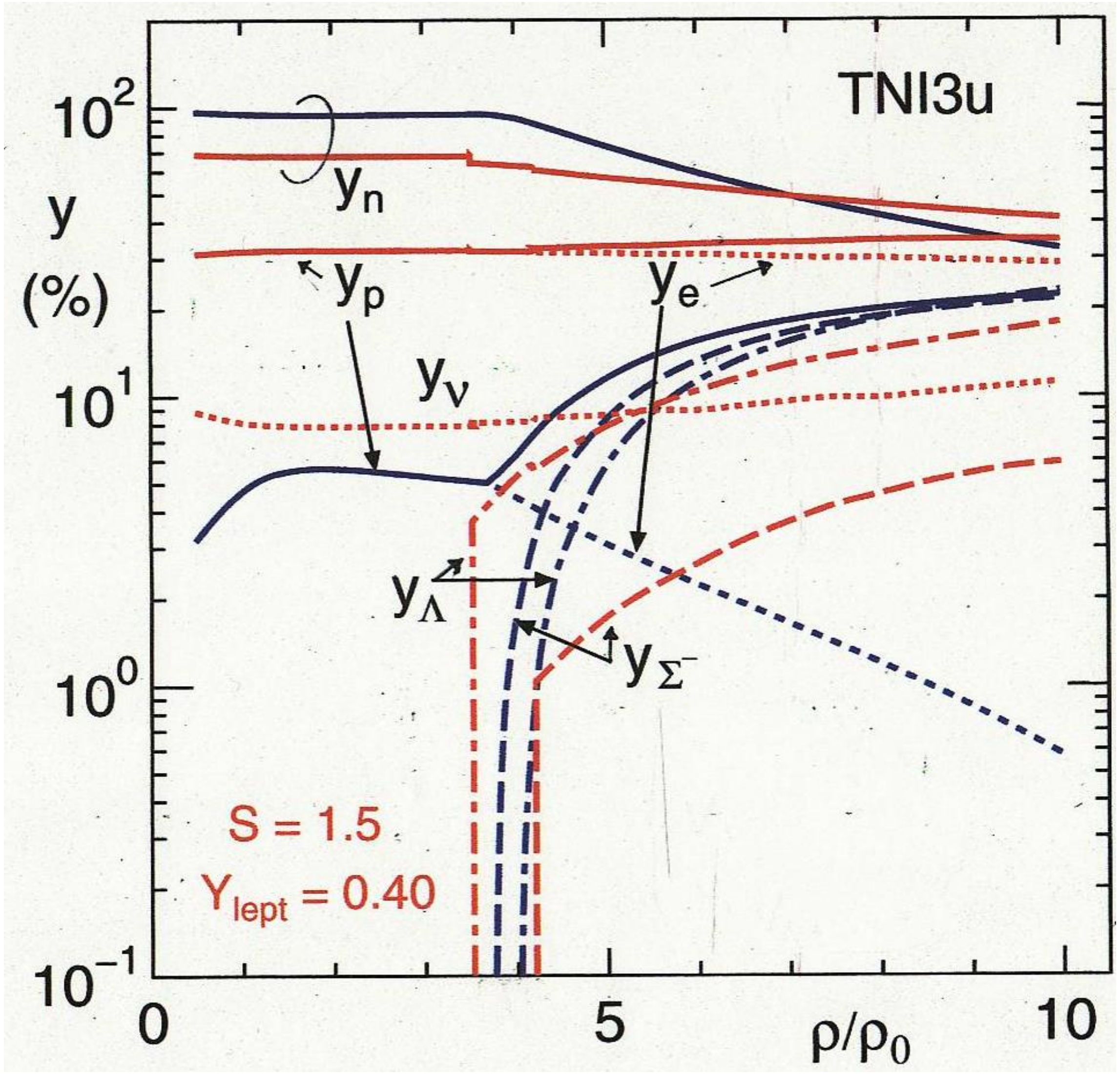
☐ Y-mixing in SM

○ EIA

○ effective *NN* pot. from *G*-matrix cal. With RSC
effective *YN*, *YY* pot. From *G*-matrix with Nijmegen type-D

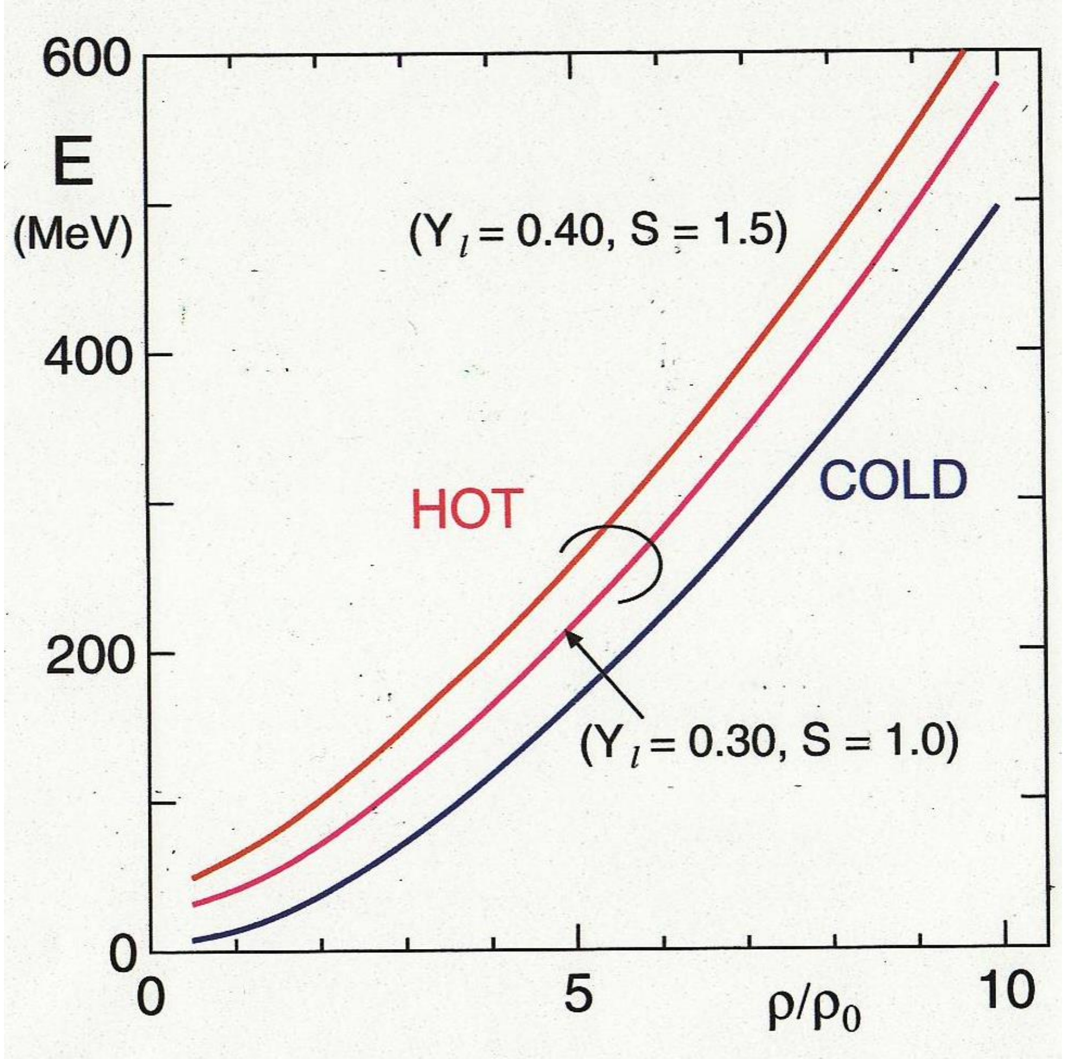
○ Introduction of 3-body force (Illinoi's type, TNI)

TNI2 → κ = 250MeV, TNI3 → κ = 300MeV
TNIu → universal inclusion of TNI to all the baryons (*N*, *Y*).



Composition and Population

- ○ Red (black) lines for SM (NSM)



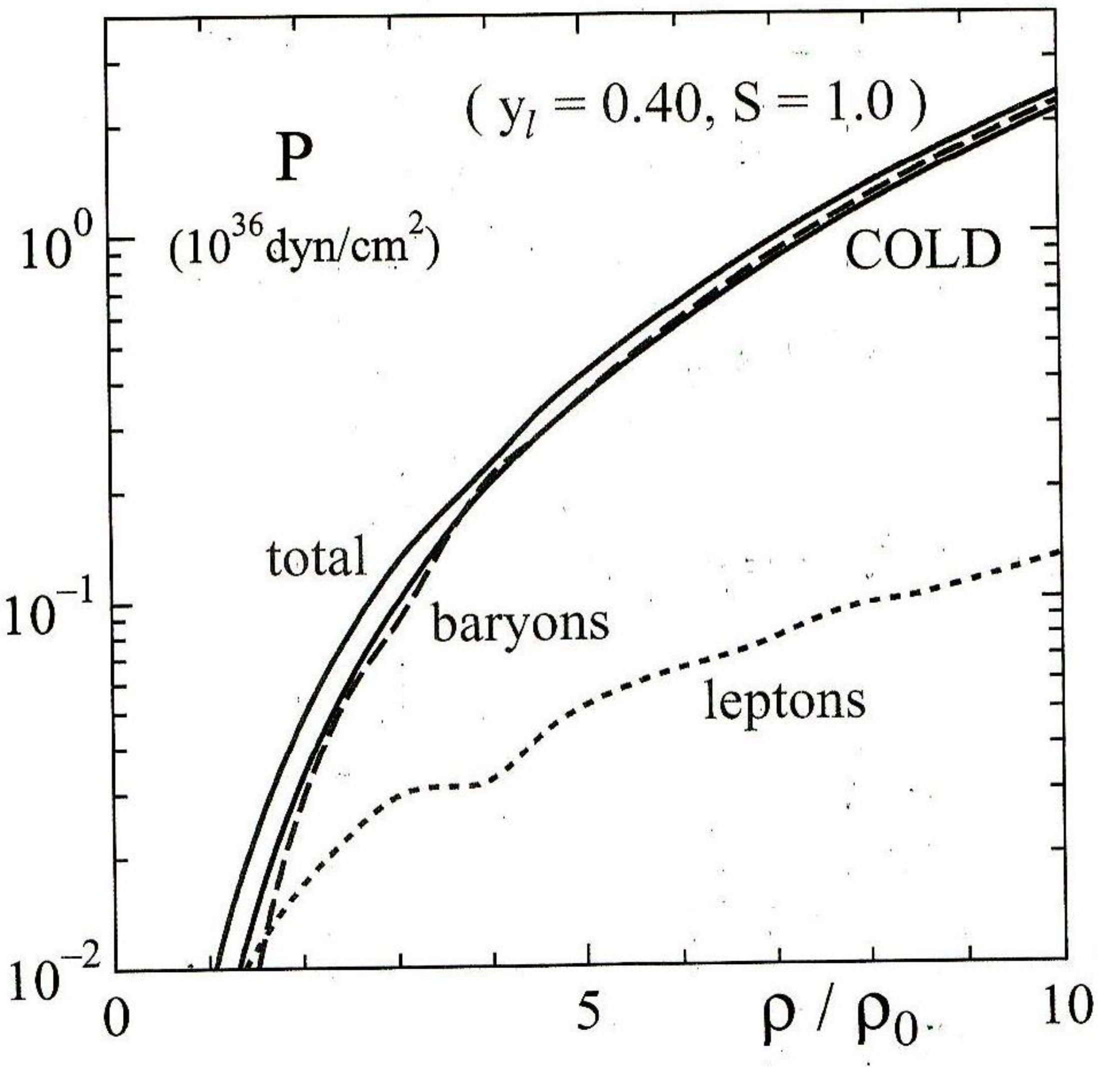
Internal energy

○ HOT: SM with *Y*
COLD: NSM with *Y*

○ TNI3u case

Pressure

○ TNI3u case



Maximum-mass NSs

(TNI3u)

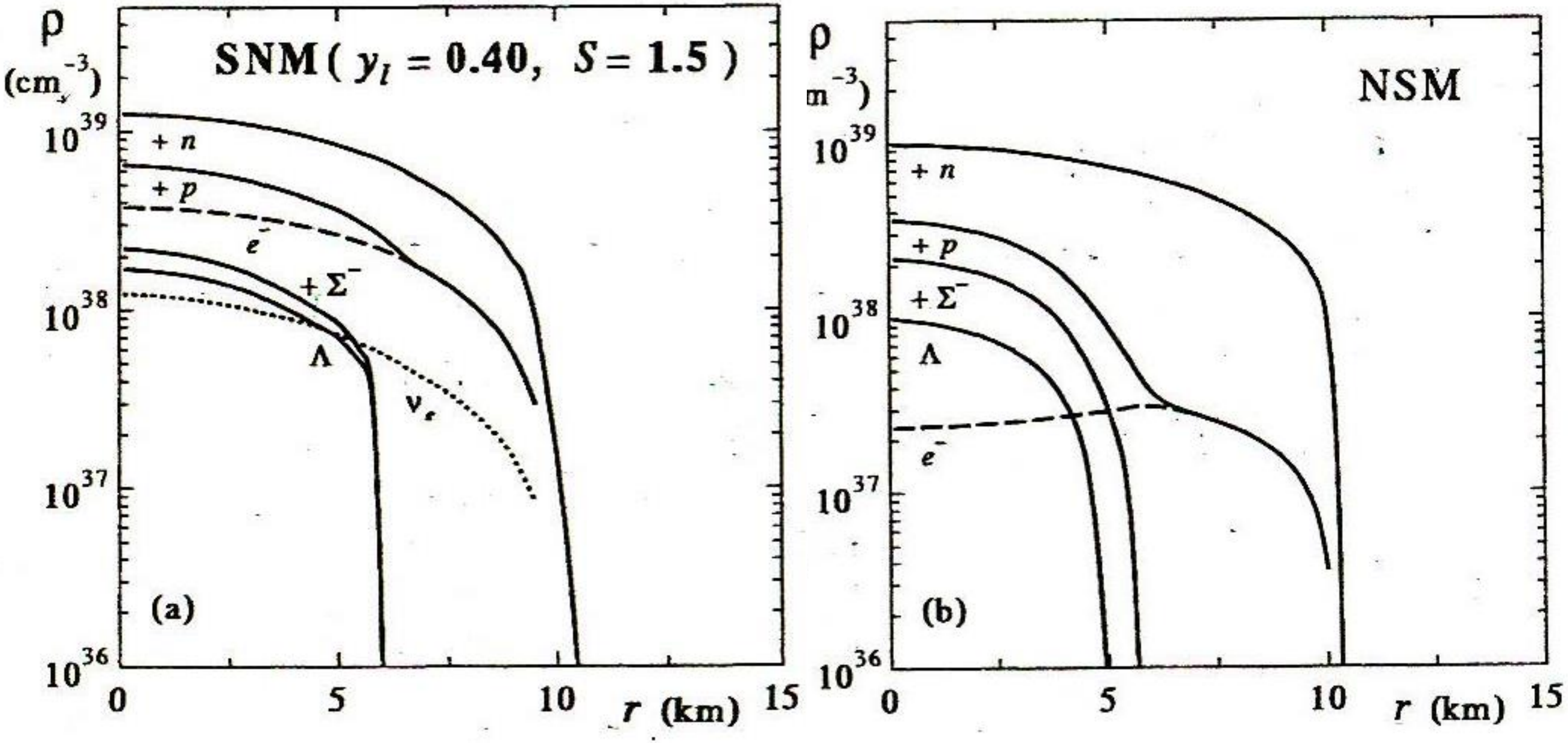
	NSM T=0	SM y_l=0.30 S=1.0	SM y_l=0.40 S=1.5
$M_{max}/M_{\odot}$	1.82	1.84	1.84
R(km)	9.55	10.49	10.81
ρ_c/ρ_0	8.26	7.75	7.11
$N_B(10^{57})$	2.54	2.48	2.41

Density profile of composition

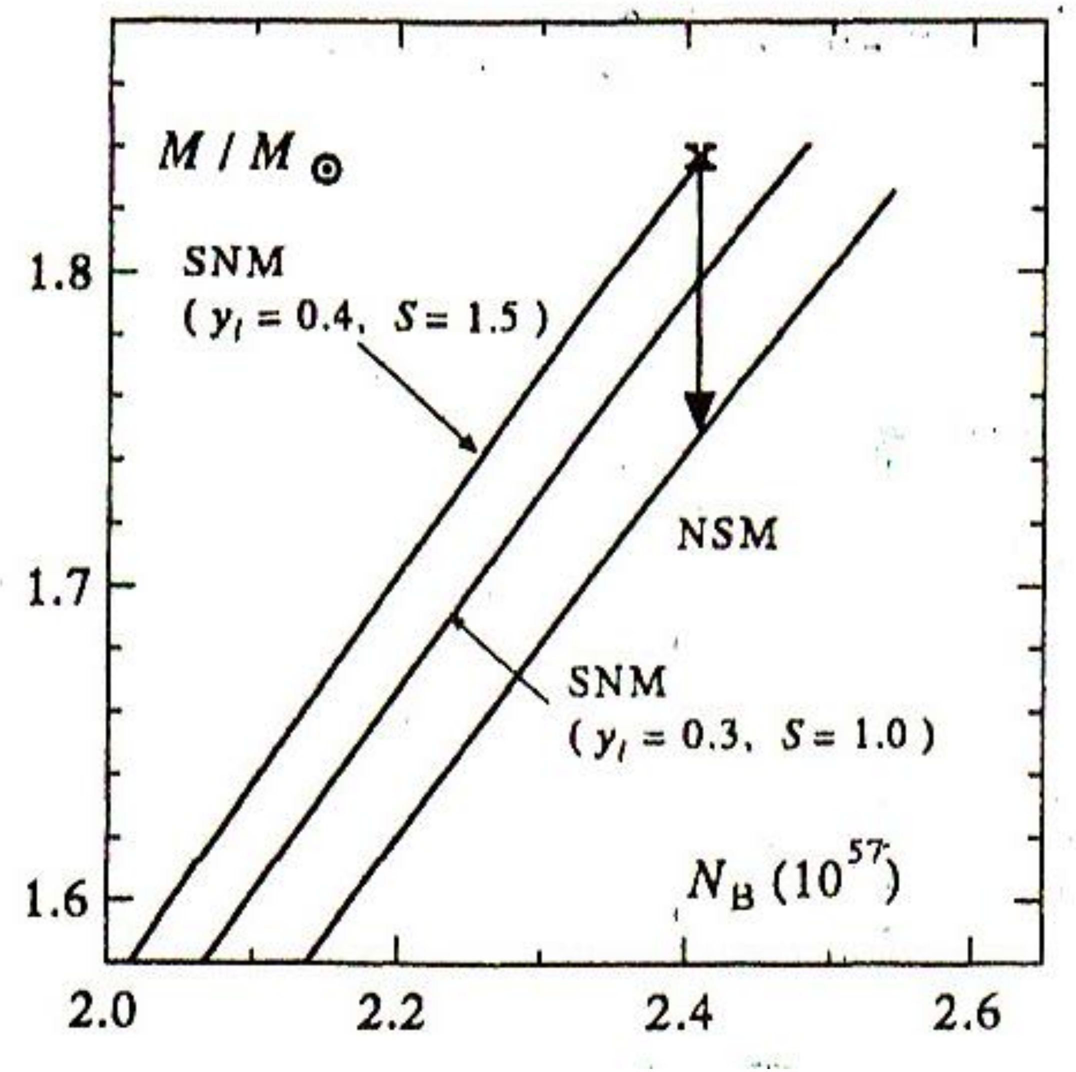
(TNI3u)

HOT

COLD



Thermal evolution and maximum mass



(TNI3u)

Short summary

○ Effective interaction approach at T>0 (T>0 EIA) provides us with a good approximation method for finite-temperature G-matrix approach

○ NSs with Y-mixing at hot birth stage have characteristics as compared with those at cold evolved stage:

- ･populations of p and e^- are enlarged, Σ^--mixing is suppressed and Λ–mixing is almost unchanged.
- ･The central density (ρ_c) is decreased and the radius (R) is increased.
- ･The maximum mass (M_{max}) of hot NSs restricts importantly that of cold NSs, under the condition of total baryon number conservation through their thermal evolution.

○ It is a forthcoming subject to study characteristics of hot NSs by the EOS compatible with $2M_{\odot}$-problem.