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「ストレンジネス・ハドロン合同」 2015.8.5　KEK東海キャンパス

Extremely Heavy Neutron Stars and the Equation of State

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

- ☐Background and motivation
- ☐Too-soft EOS due to Y ; ”Hyperon Crisis”
- ☐Massive NSs with univesal 3-body force
- ☐Massive NSs with hadron-quark crossover
- ☐Too-rapid cooling and necessity of Λ-super

NEUTRON STAR

Huge NUCLEUS

Y-mixed NSs → "HyperNSs"

"Cosmic Laboratory"

New paradigm
is comming !

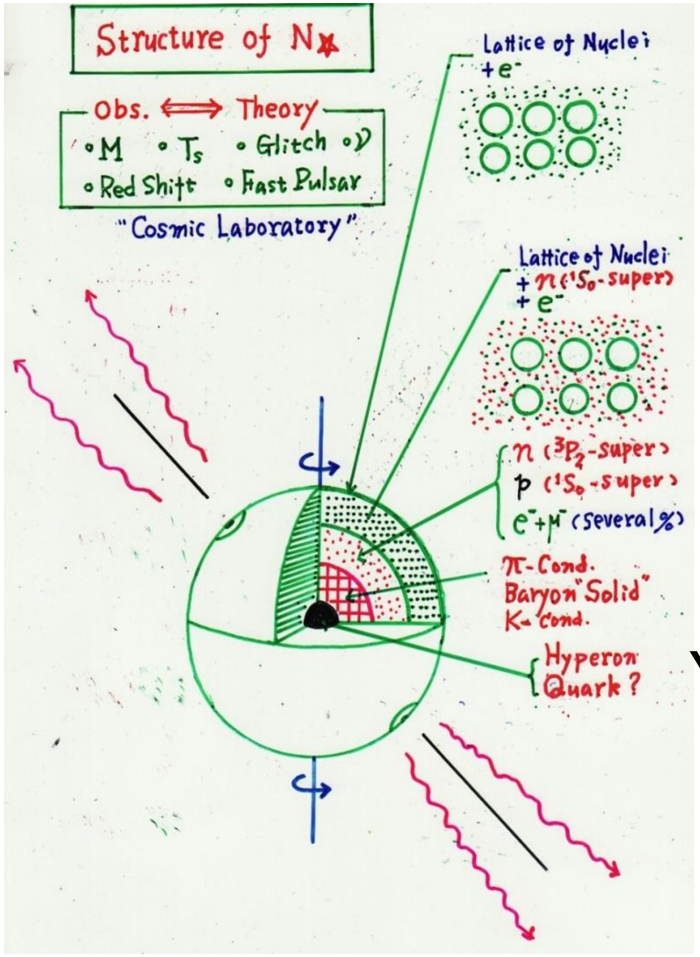
NUCLEUS

Y-mixed nuclei

→ Hypernuclei

Terrestrial Laboratory
(JPARK etc.)

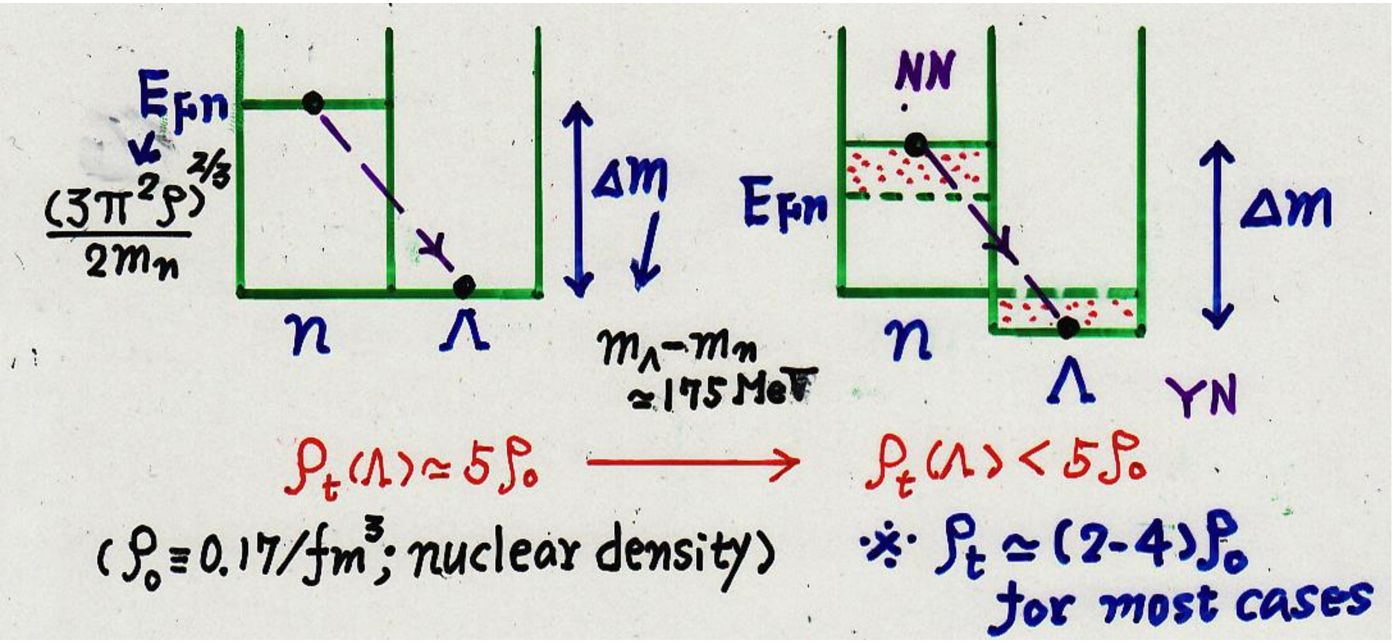
N,Y,Q



Y,Q

☐ Hyperon Mixing in NS cores

< K.E. only > < with interactions >



→ Hyperon (Y) surely participate in Neutron Star (NS) Cores

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

☐ 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)

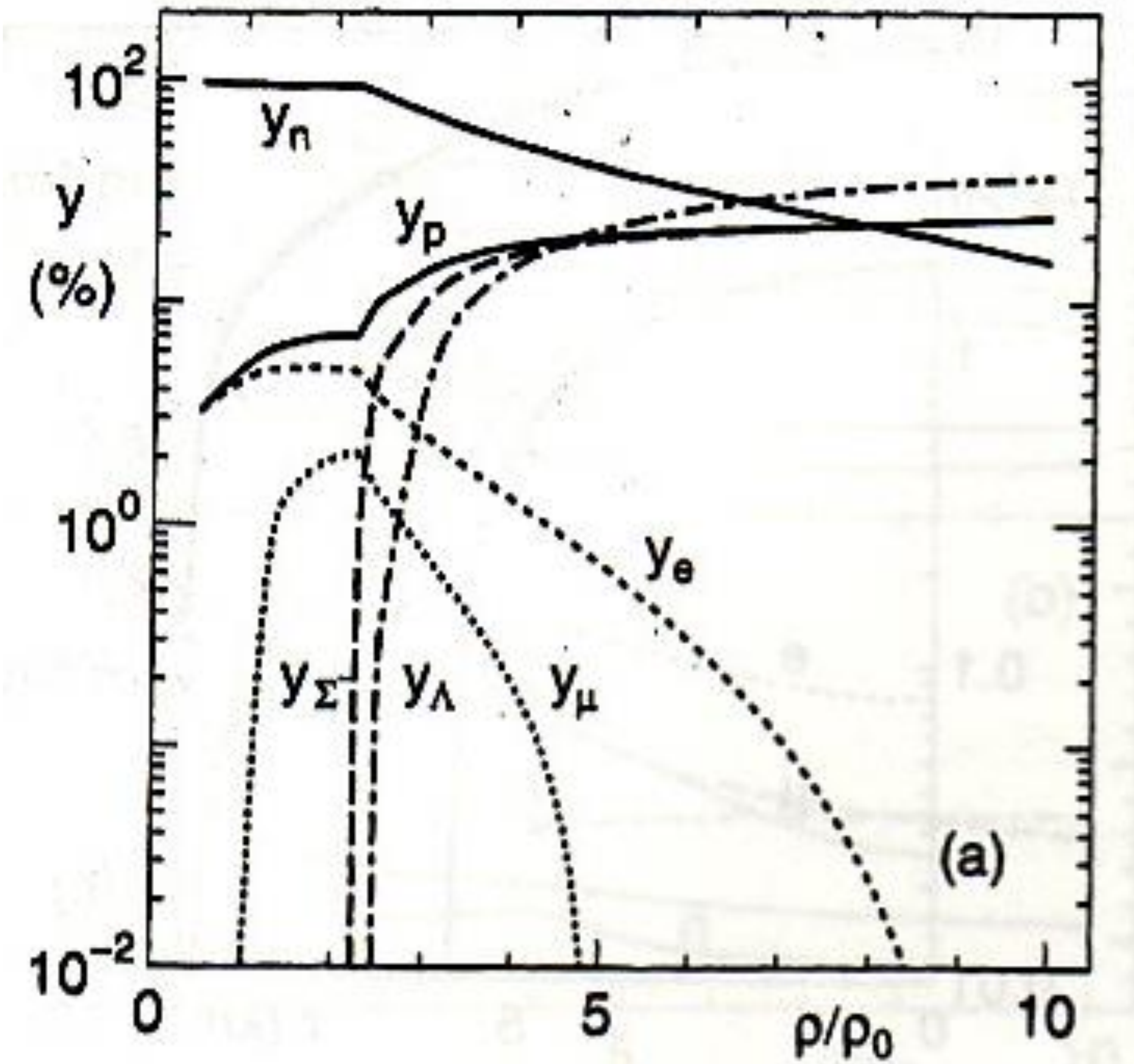
○ V+U satisfy the saturation property and symmetry energy at nuclear density

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



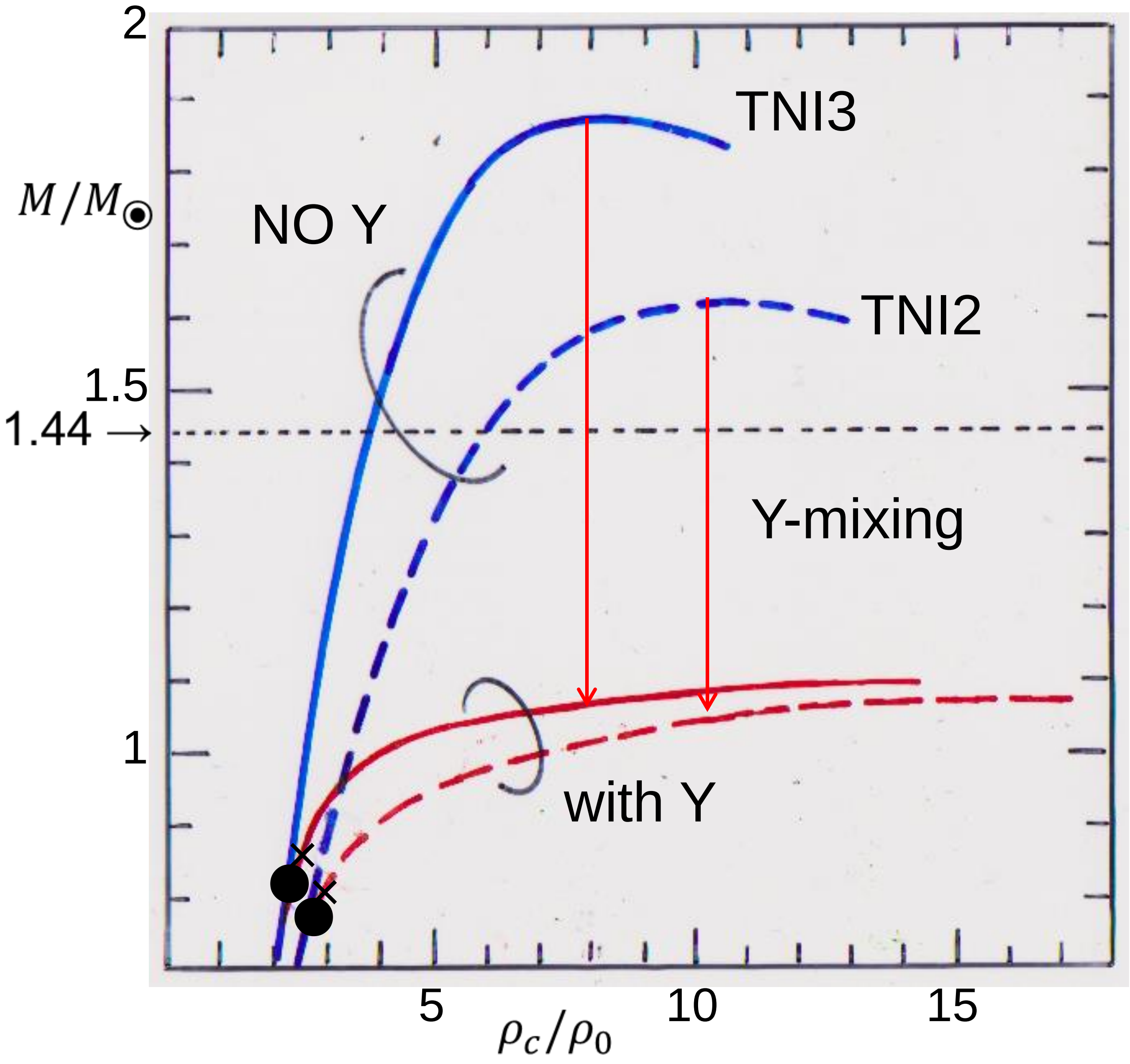
Then, What happens?

→ Serious problems

Ⅰ. Too-softened EOS

Ⅱ. Too-rapid cooling

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



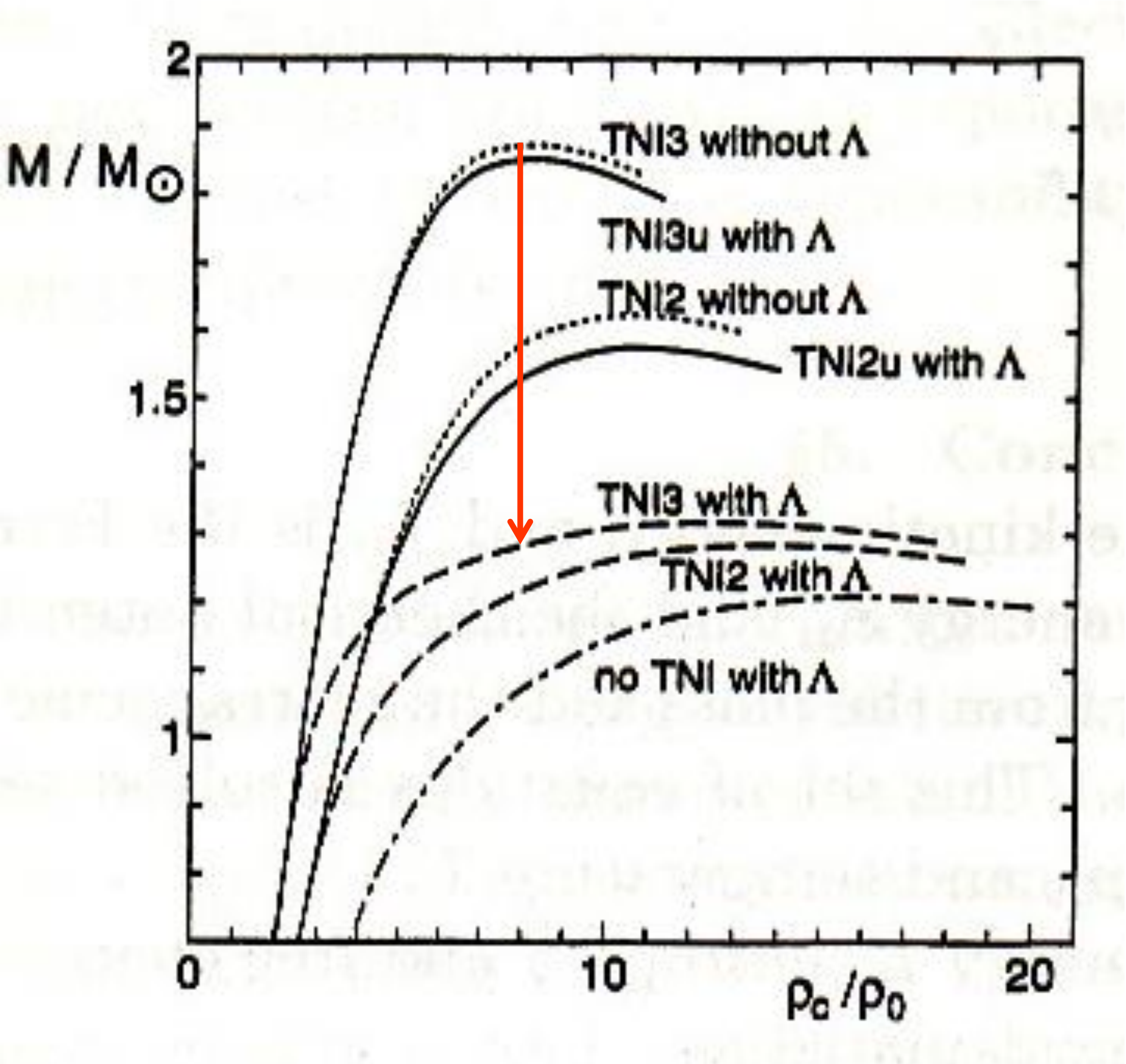
Strong Softening of the EOS

After 2M_sun observations

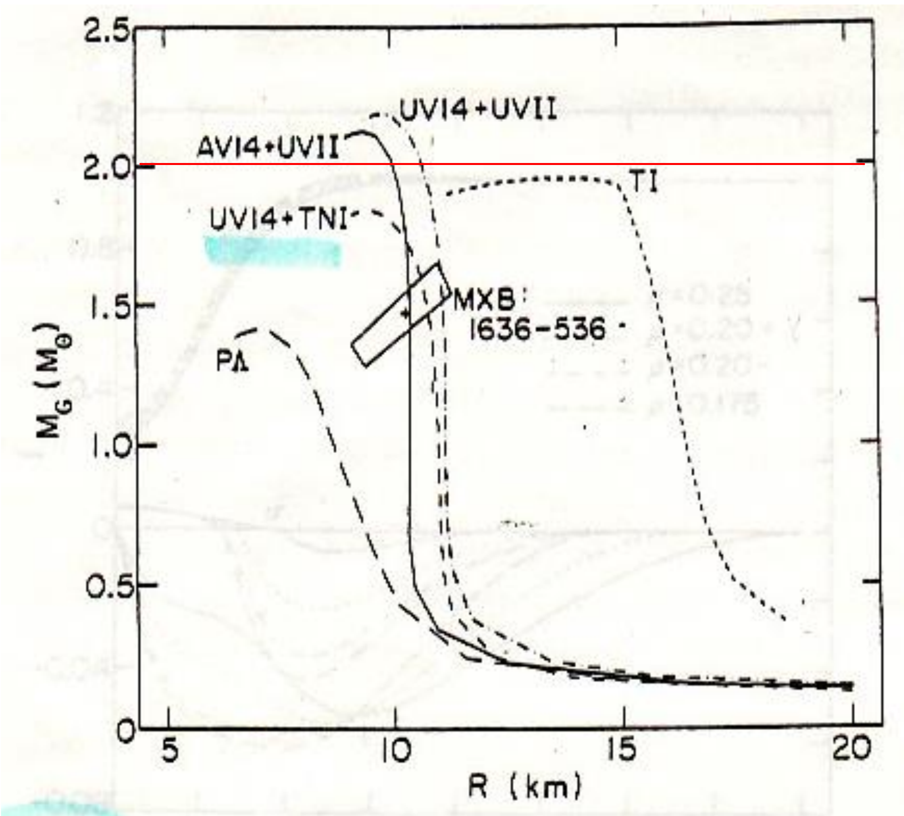
Hyperon Crisis

(by T. Hatsuda)

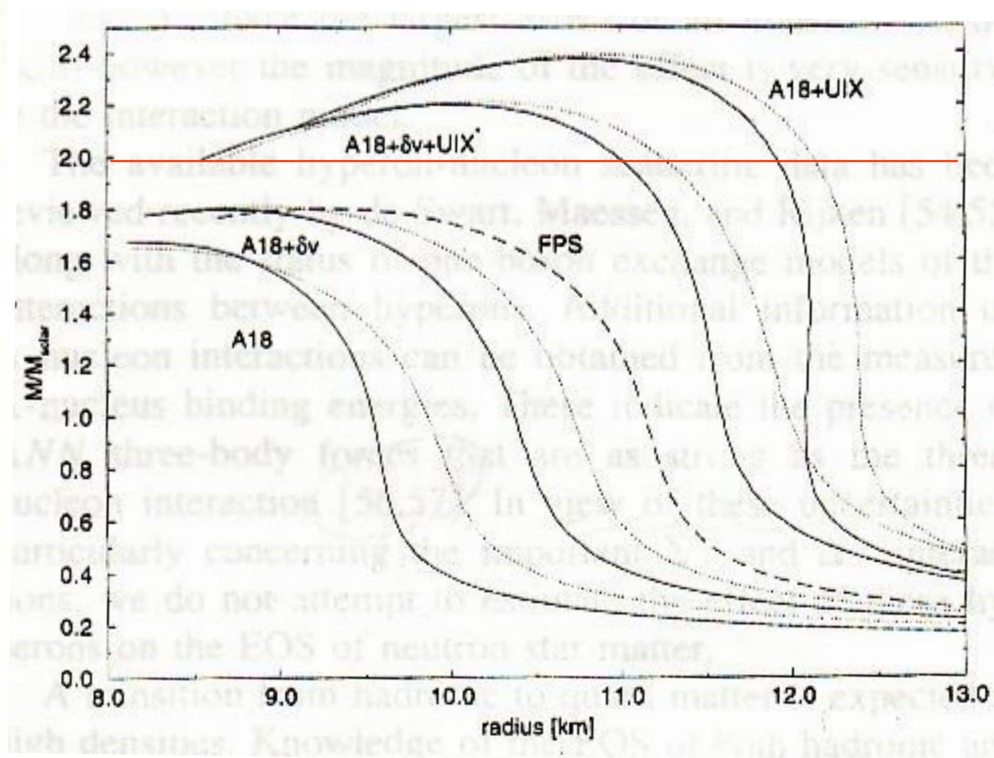
Even Λ-only mixing, situation is the same!



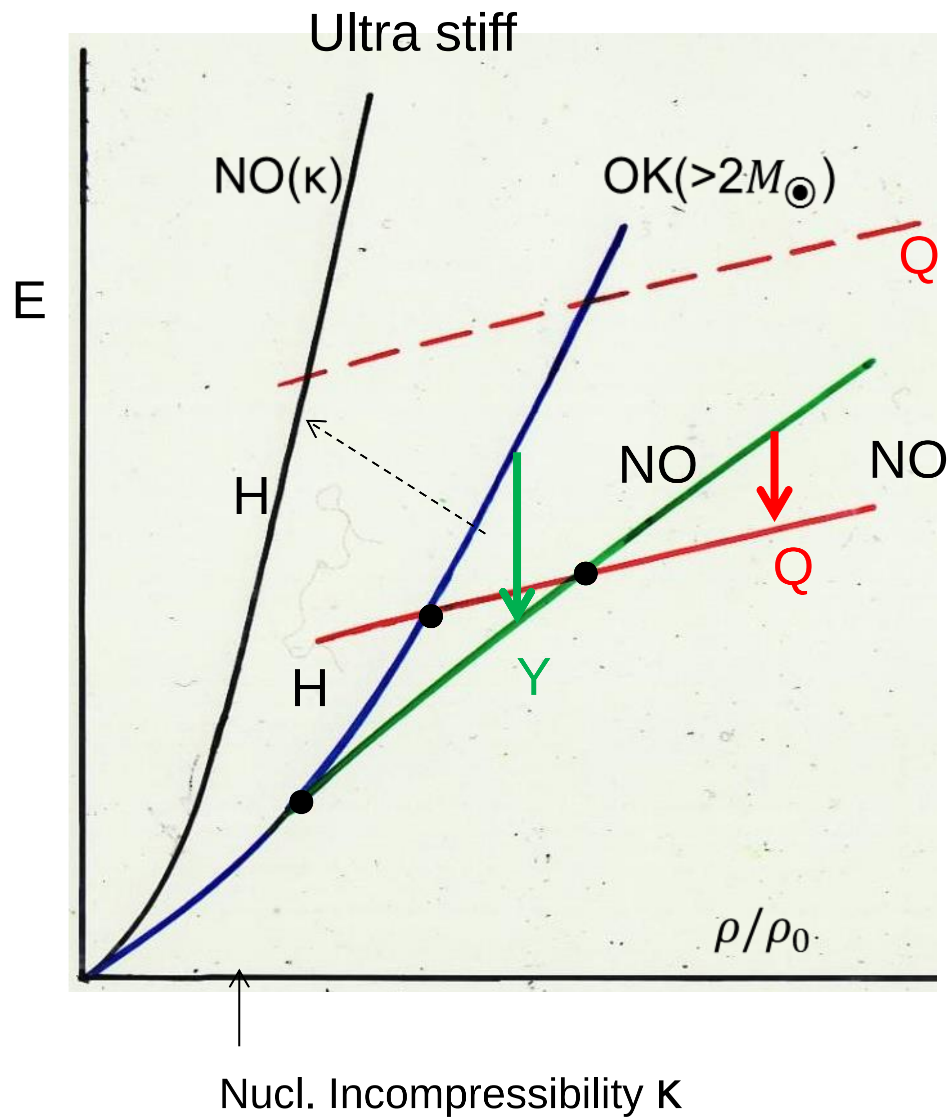
If no exotics, $M \geq 2M_{\odot}$ is possible



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.



Observation of Massive NSs

(2-solar-mass NSs)

⇓

○ How to explain such massive NS, with Y ?

○ 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

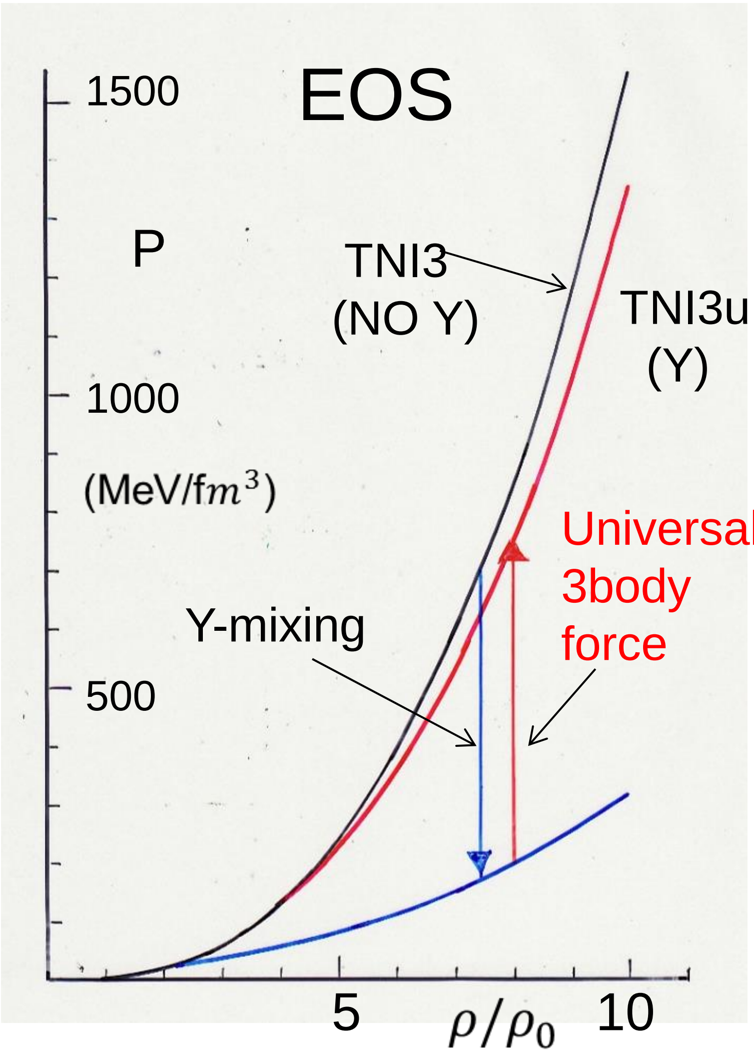
Possible candidate to solve the problem

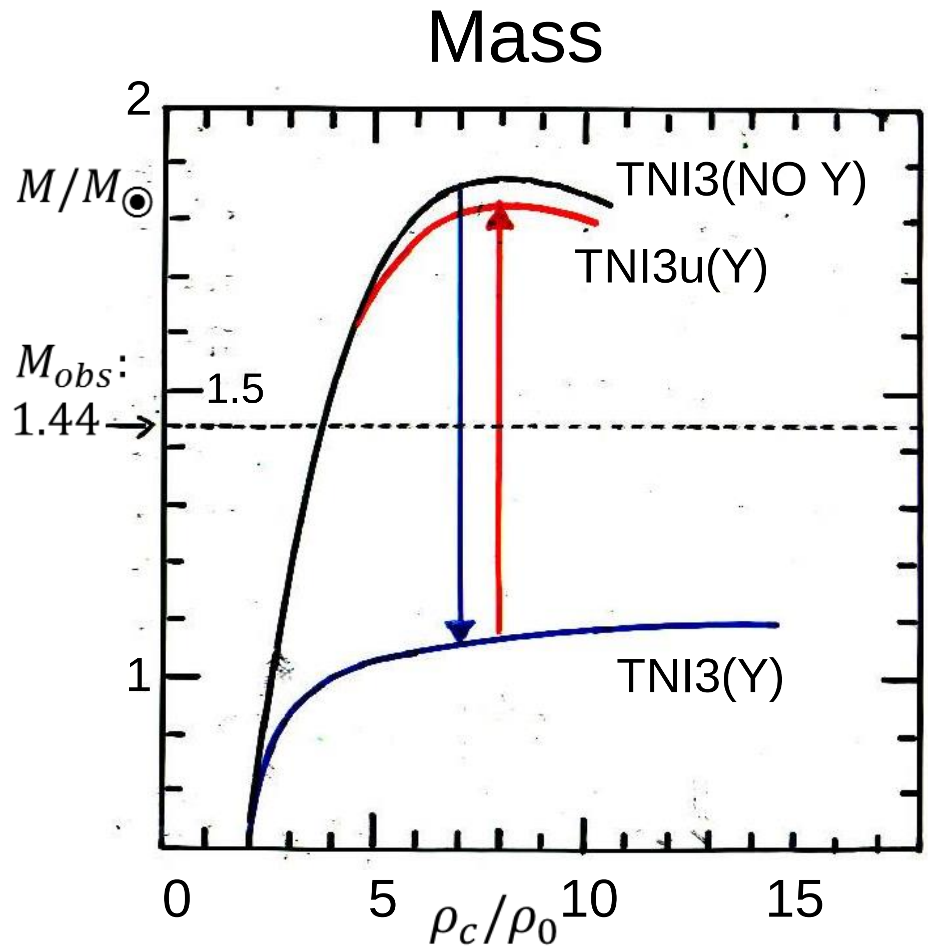
□ Universal 3-body force

an extended use of the phenomenological 3-body force U of Illinoi's type(Friedman-Pandharipande) :

NNN ⟶ BBB

Dramatic softening of EOS ⟶ Necessity of "Extra Repulsion"





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

A step forward to the origin of the Universal 3-Body Force, we consider at short d

SJM 3-Body Force (Tamagaki)

from the string-junction quark model of baryons ,which is based on the confinement (color degrees of freedom) and flavor-independent (namely,universal), and also for intermediate and long distances, an extended

2πΔ 3-Body Force (Fujita-Miyazawa type)

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

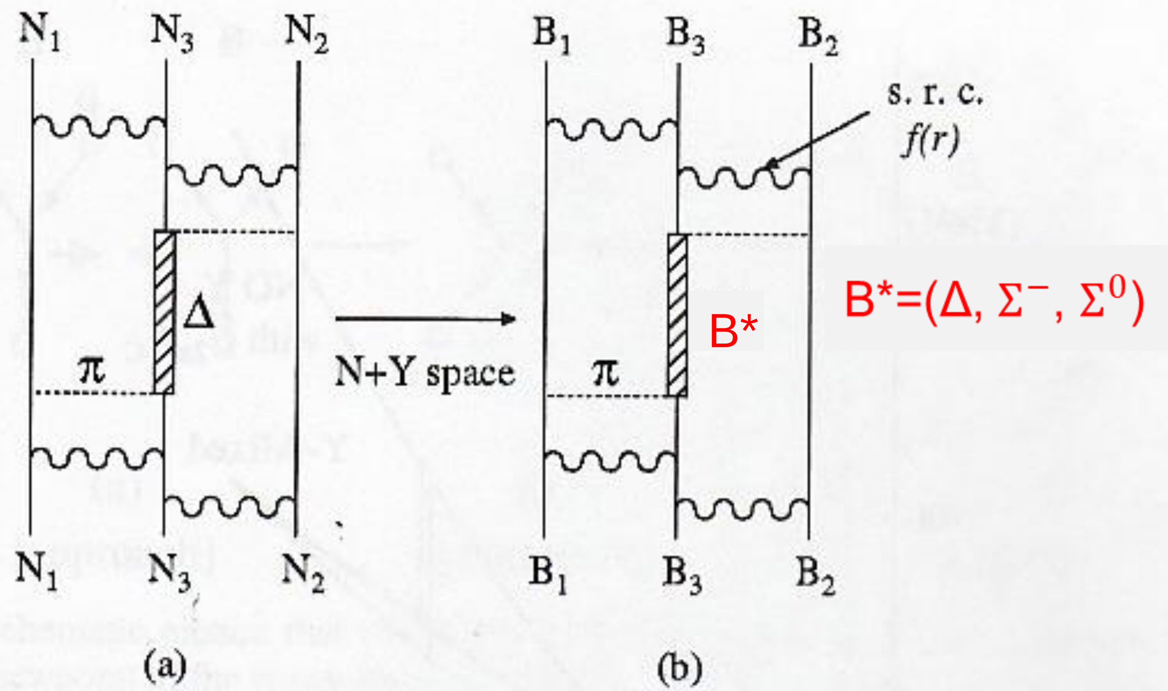
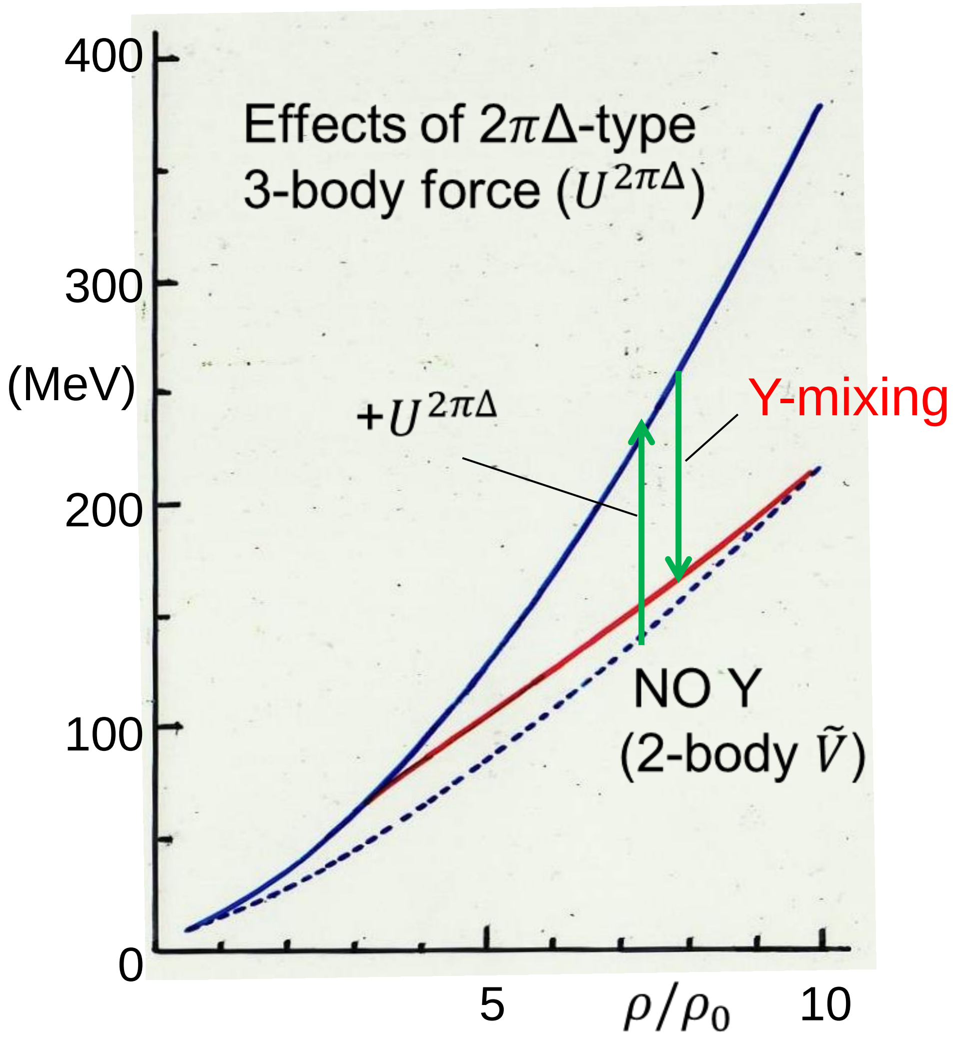


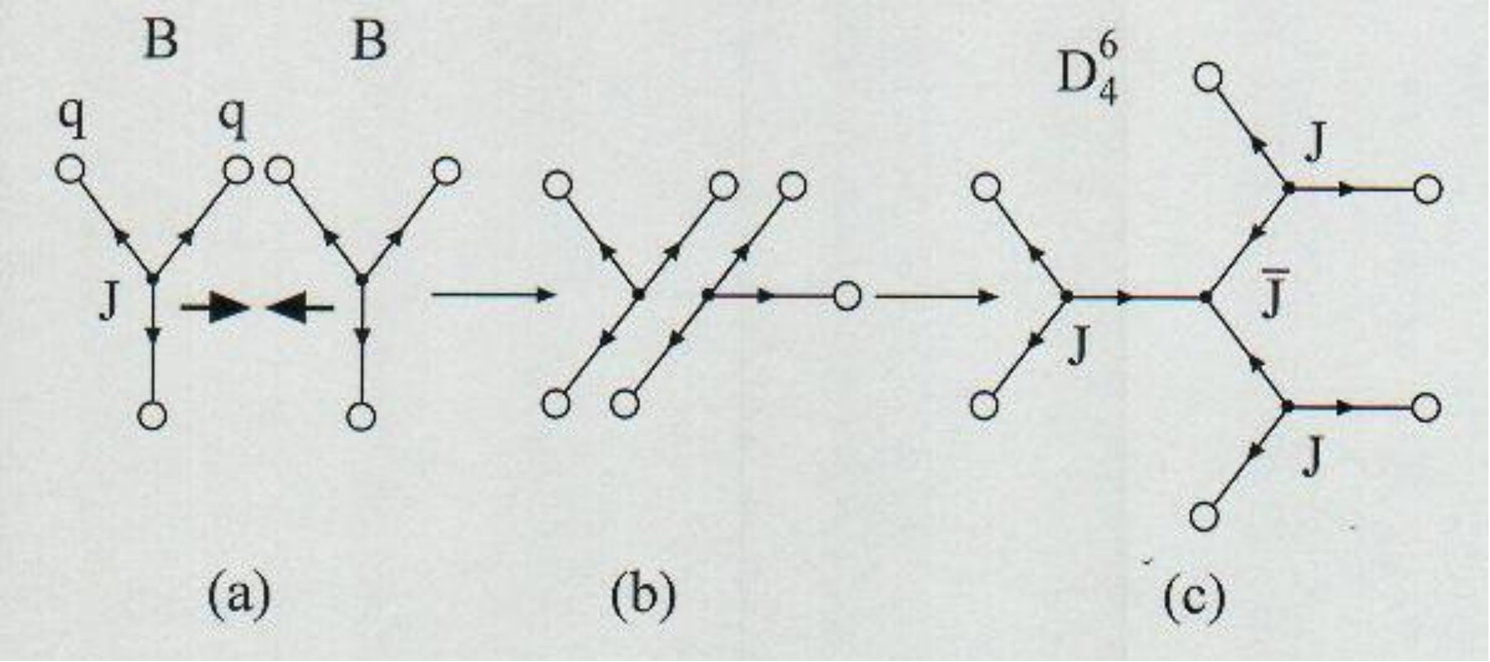
FIGURE 2. Extension of 3-body force from 2π-exchange via Δ excitation type ($2\pi\Delta$) in N-space (a) into $\{N+Y\}$ space (b), where B^* stands for Δ, Σ^{*-}, Σ^{*0} and $f(r)$ is the short-range correlation function.

○ 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

EOS of Neutron Star Matter



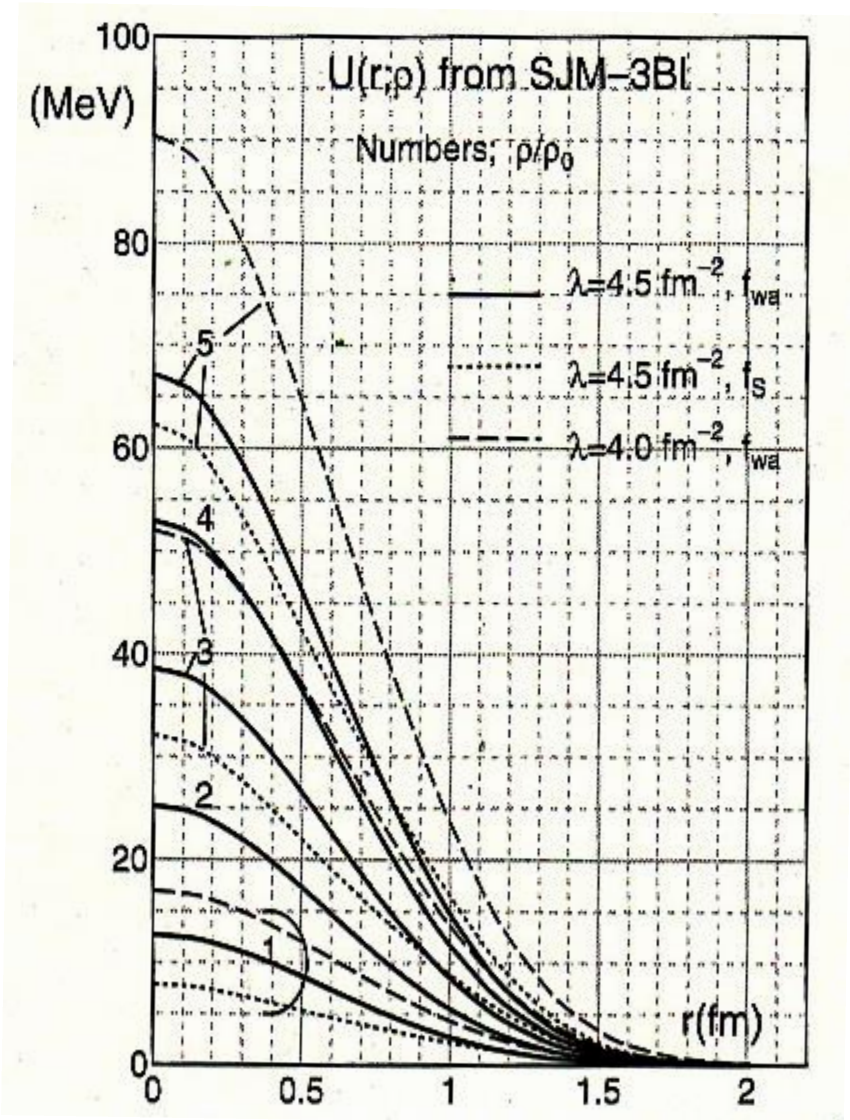
Repulsion from SJM-----flavor independent



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

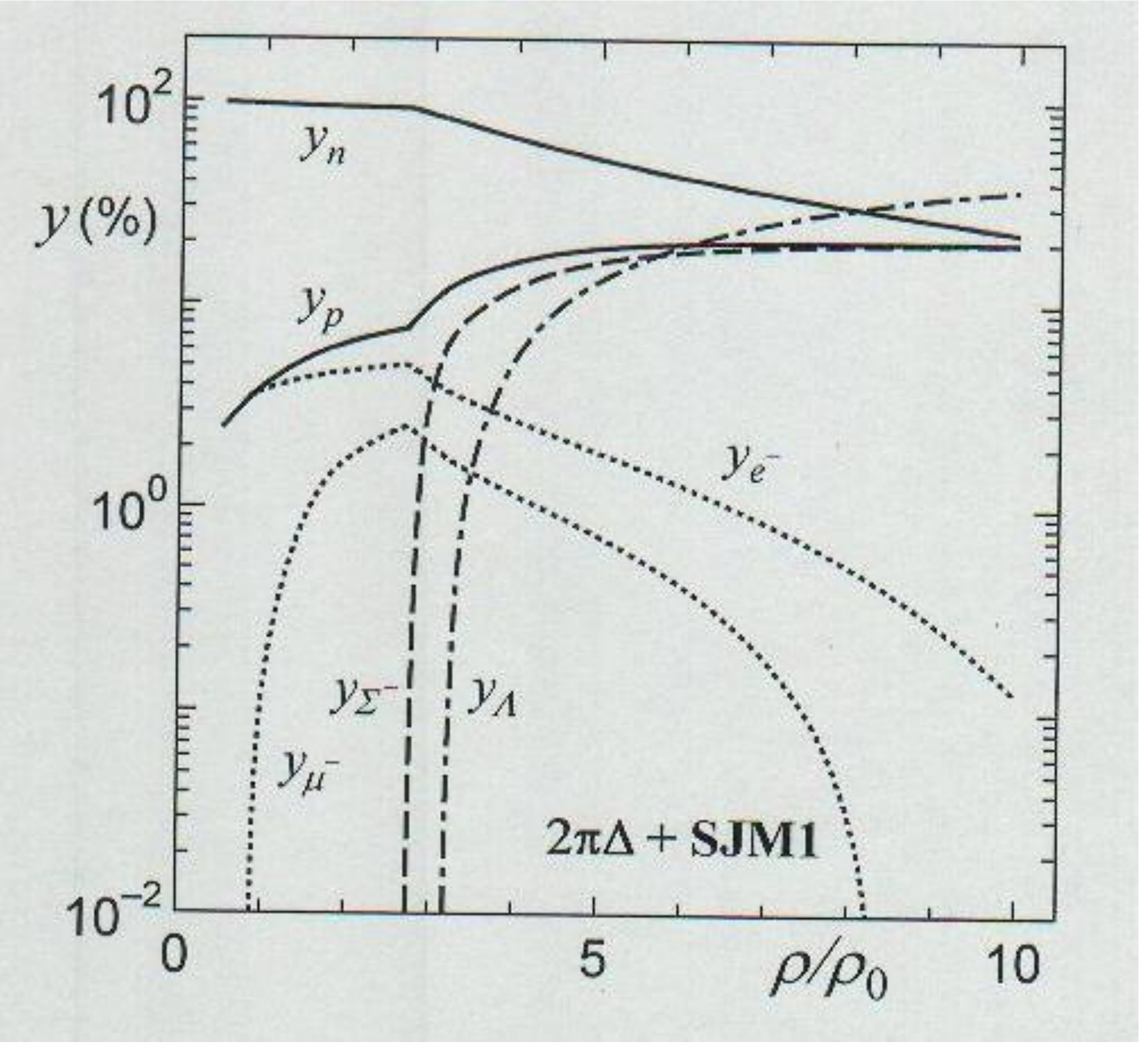
(by R. Tamagaki)
Prog. Theor. Phys. 119 (2008) 965.

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

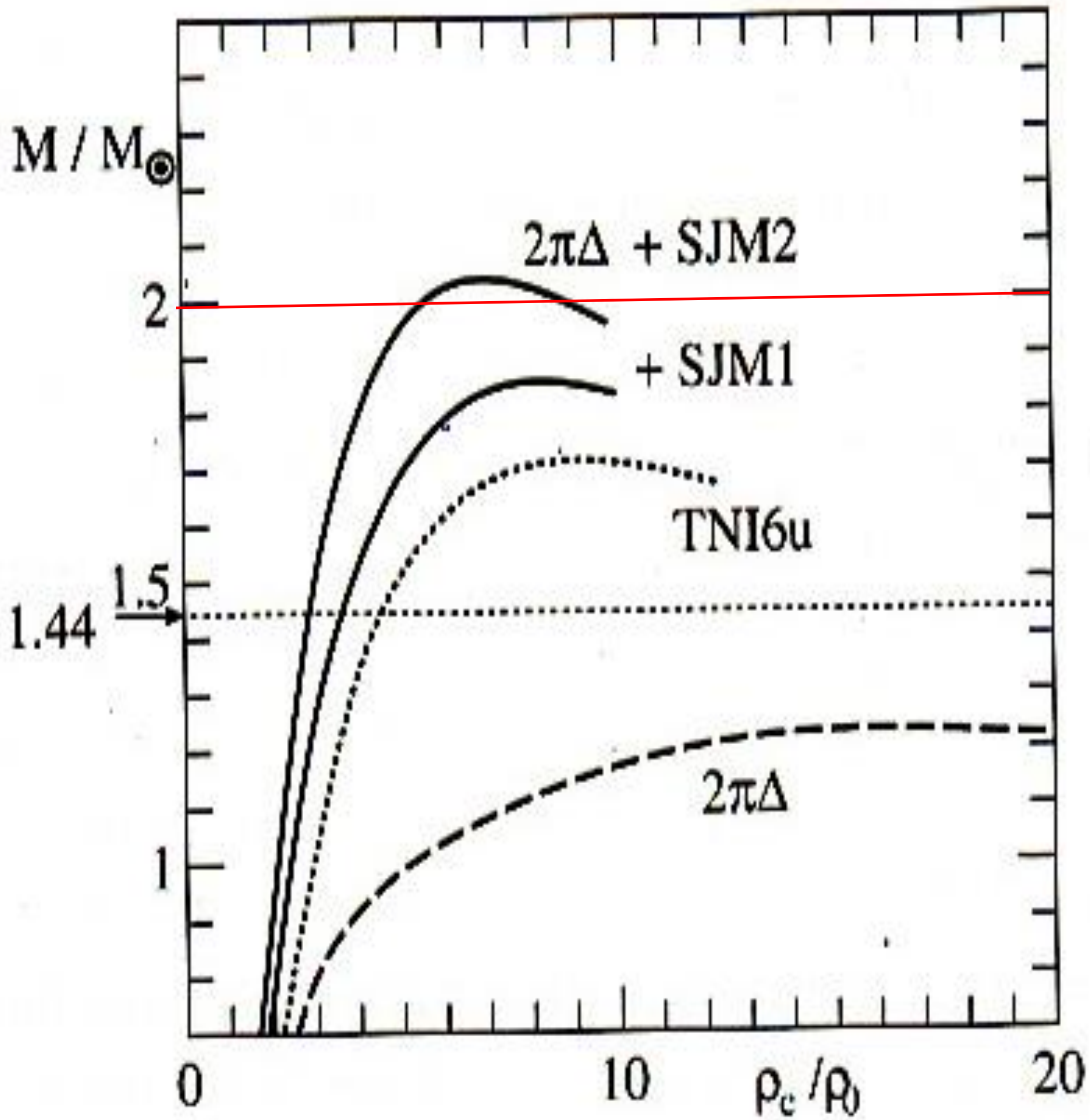


R. Tamagaki, Prog. Theor. Phys. 119 (2008) 965.

Fraction of constituents in Y-mixed NSs



Mass v.s. Central Density



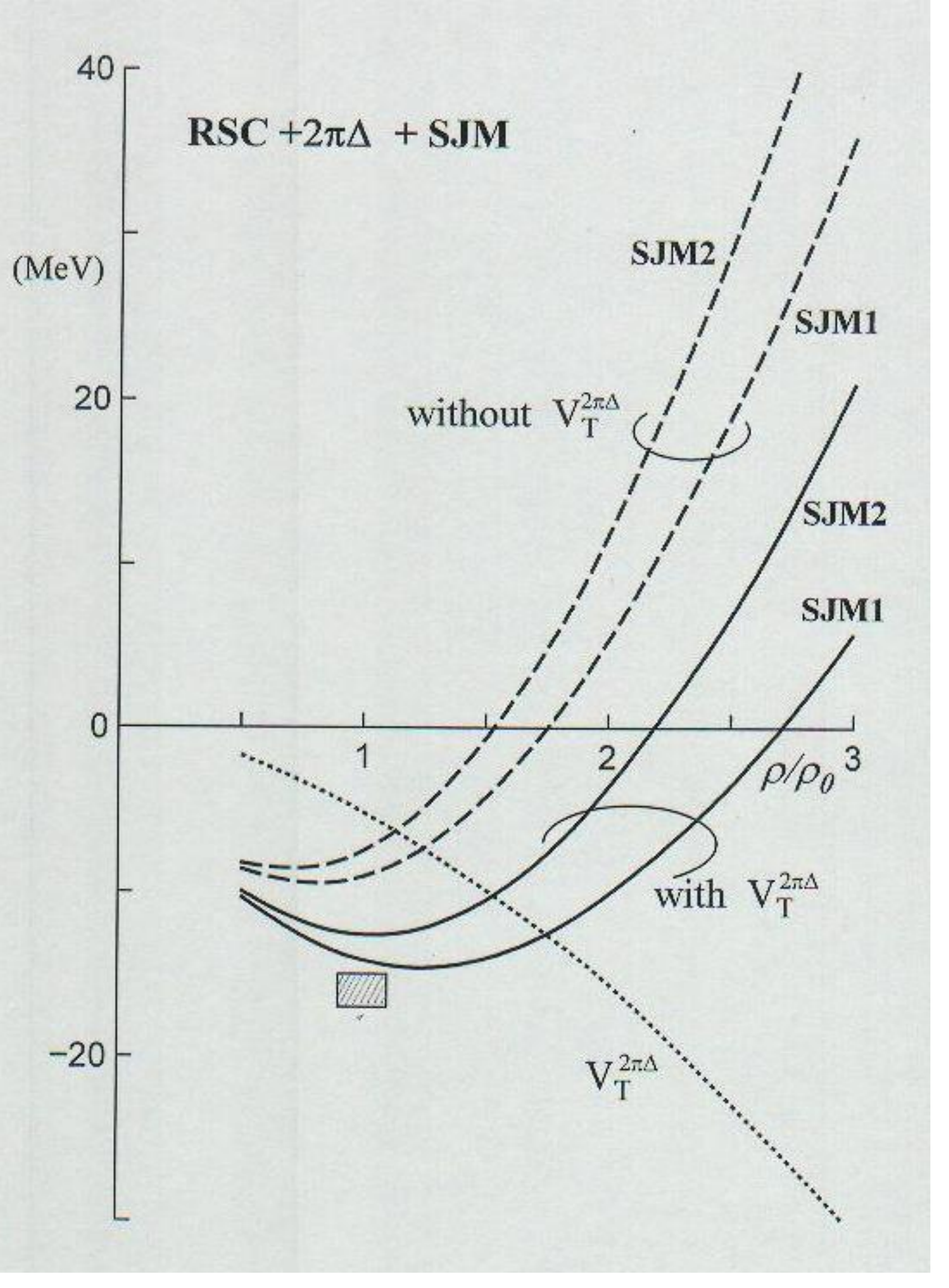
NS-mass from 2-body force + ”universal” 3-body force (2πΔ-type + SJM).

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

(Before observations)

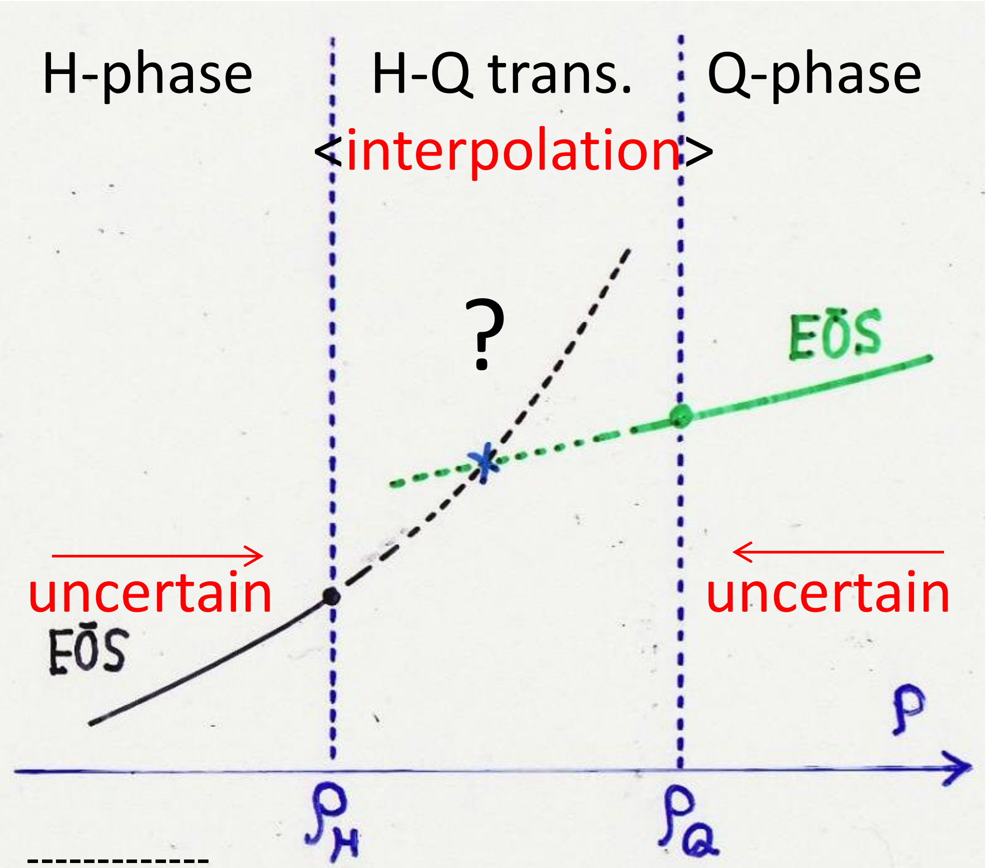
T.Takatsuka,S.Nishizaki and R.Tamagaki, AIP Conference Proceedings 1011 (2008) 209.

Symmetric Nuclear Matter



☐ Possibility of quark matter in NSs *)

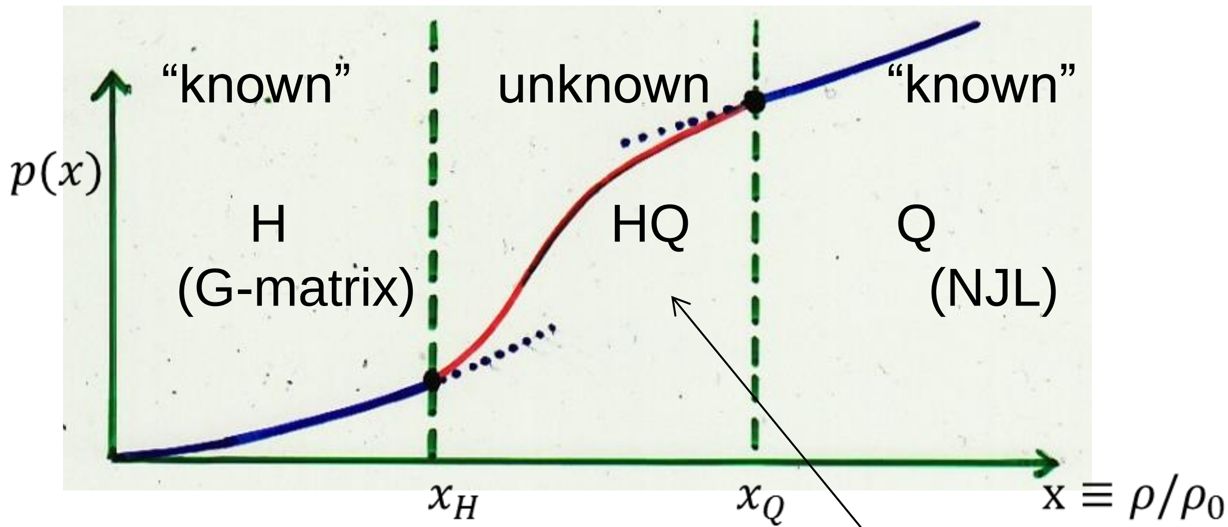
A way of approach



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

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.

○ Quark Matter phase *)

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

$$L_{NJL} = \bar{q}(i\partial\!\!\!/ - m)q + \frac{1}{2} G_S \sum_{\alpha=0}^{8}\{(\bar{q}\lambda^{\alpha}q)^2 + (\bar{q}\lambda^{\alpha}i\gamma_5 q)^2\}$$
$$+G_D\{det\bar{q}(1+\gamma_5)q + h.c.\} - \frac{1}{2} g_V (\bar{q}\gamma^{\mu}q)^2$$

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

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

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

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

(2) Hadron-Quark Crossover Model

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

☐ Motivation

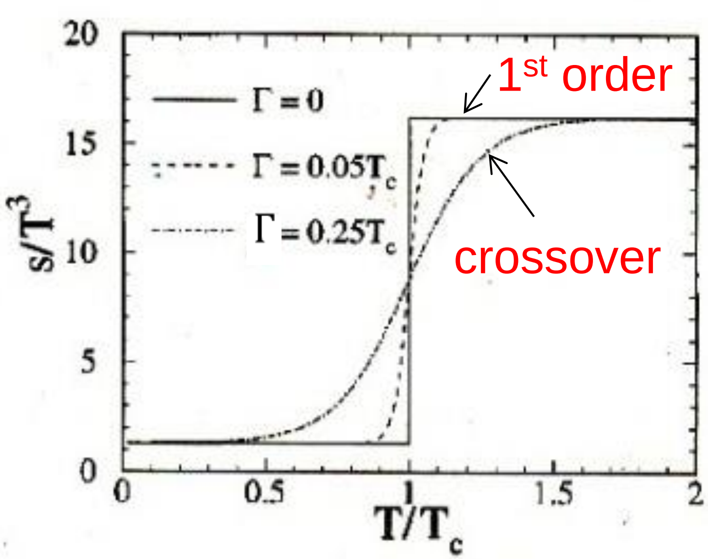
○ QCD Phase diagram:

μ=0, T≠0 → aspect of H-Q crossover transition at T_c～200 MeV
→ well descrived by the parameterization (*)

$$s(T) = s_H(T)\omega_H(T) + s_Q(T)\omega_Q(T)$$

$\omega_H(T) + \omega_Q(T) = 1$, e.g., $\omega_Q(T) = \{1 + \tan h(T - T_c)/\Gamma\}]/2$

$\rightarrow p(\mathrm{T}) = \int_0^T s(t)dt,\ e(T) = T_s(T) - p(T)$



○ Correspondence

T increase → K.E. increase
μ(or ρ) increase → K.E. increase
of constituent particles
common

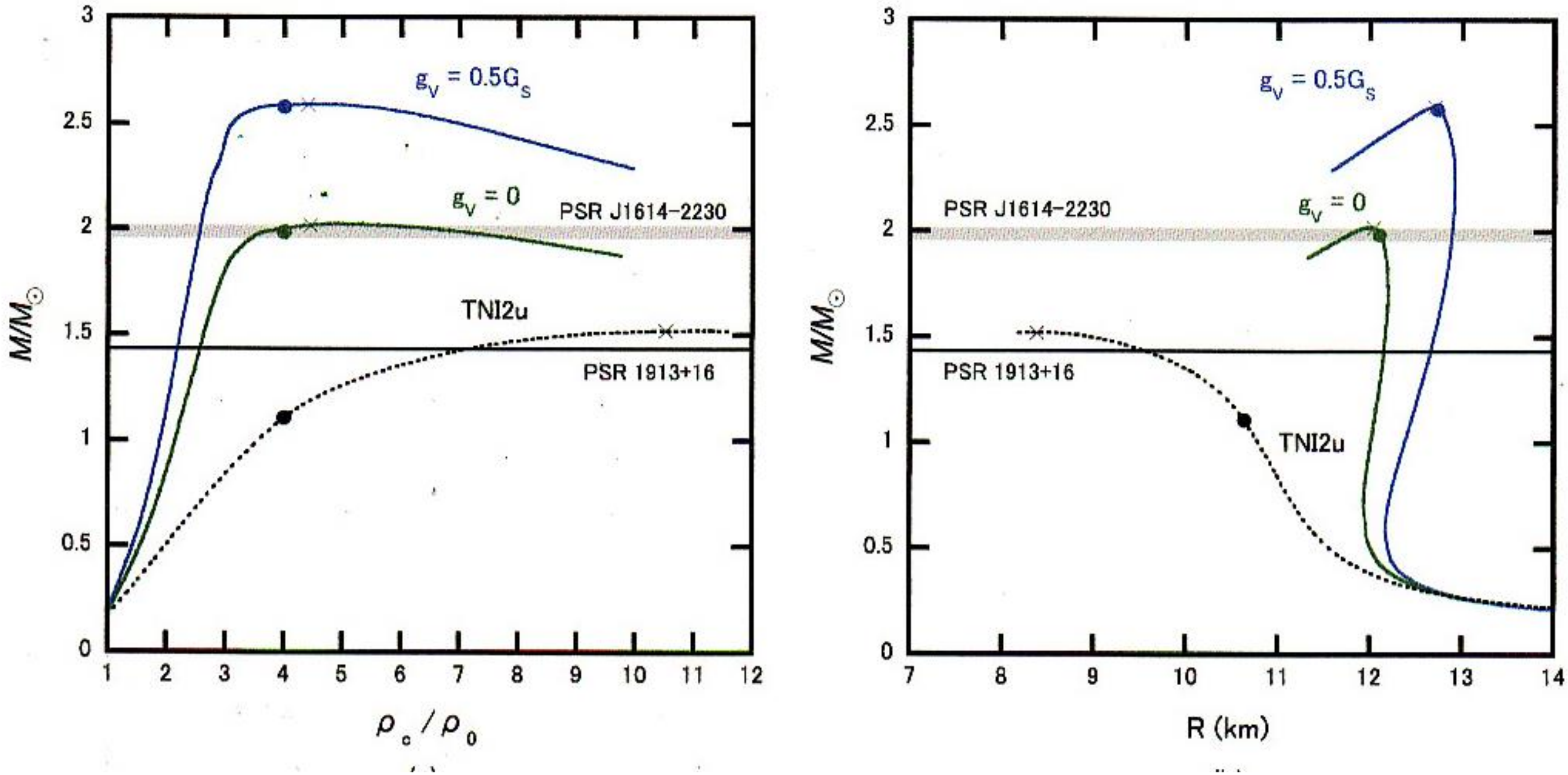
○ Taking analogy, assume for μ≠0 crossover case

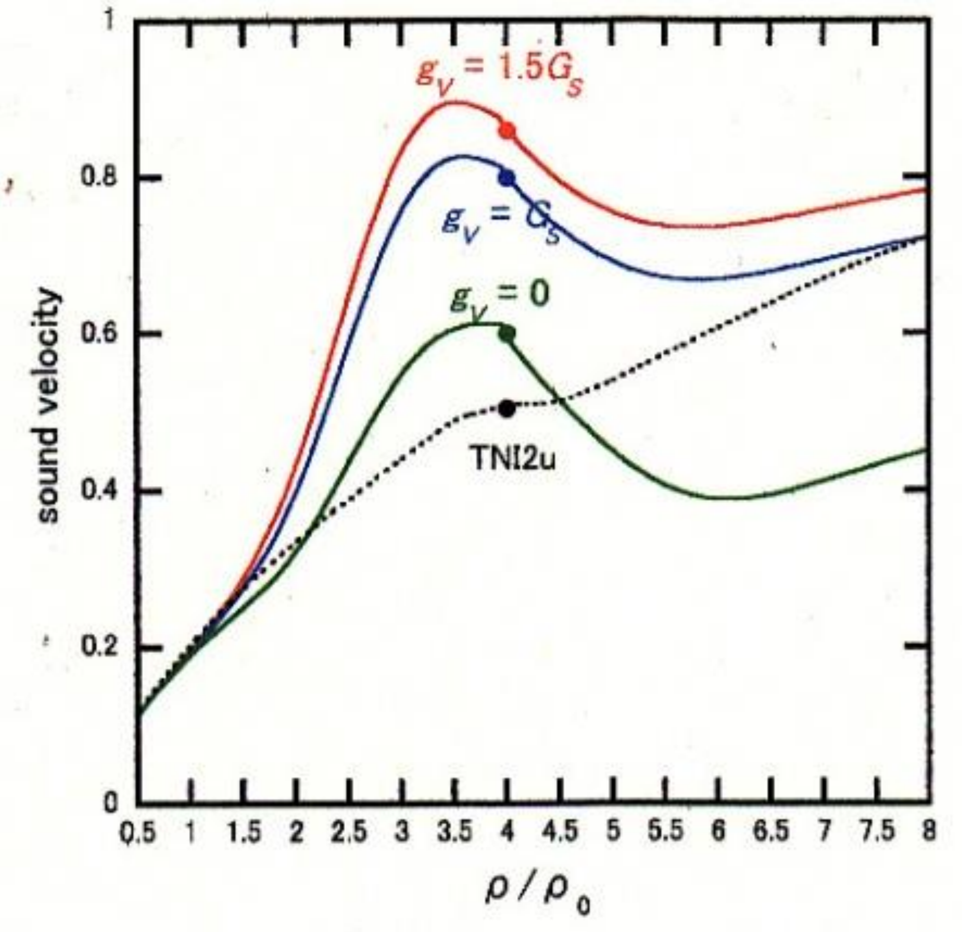
$$\hat{F}(\rho, T; Y_l) = \hat{F}_{\mathrm{HL}}(\rho, T; Y_l) w_-(\rho, T) + \hat{F}_{\mathrm{QL}}(\rho, T; Y_l) w_+(\rho, T).$$

$$w_\pm(\rho, T) \rightarrow w_\pm(\rho) = \frac{1}{2}\left(1 \pm \tanh\left(\frac{\rho - \bar{\rho}}{\Gamma}\right)\right),$$

(*) M. Asakawa and T. Hatsuda, Phys. Rev. D55 (1997) 4488.

2-solar –mass NSs are possible





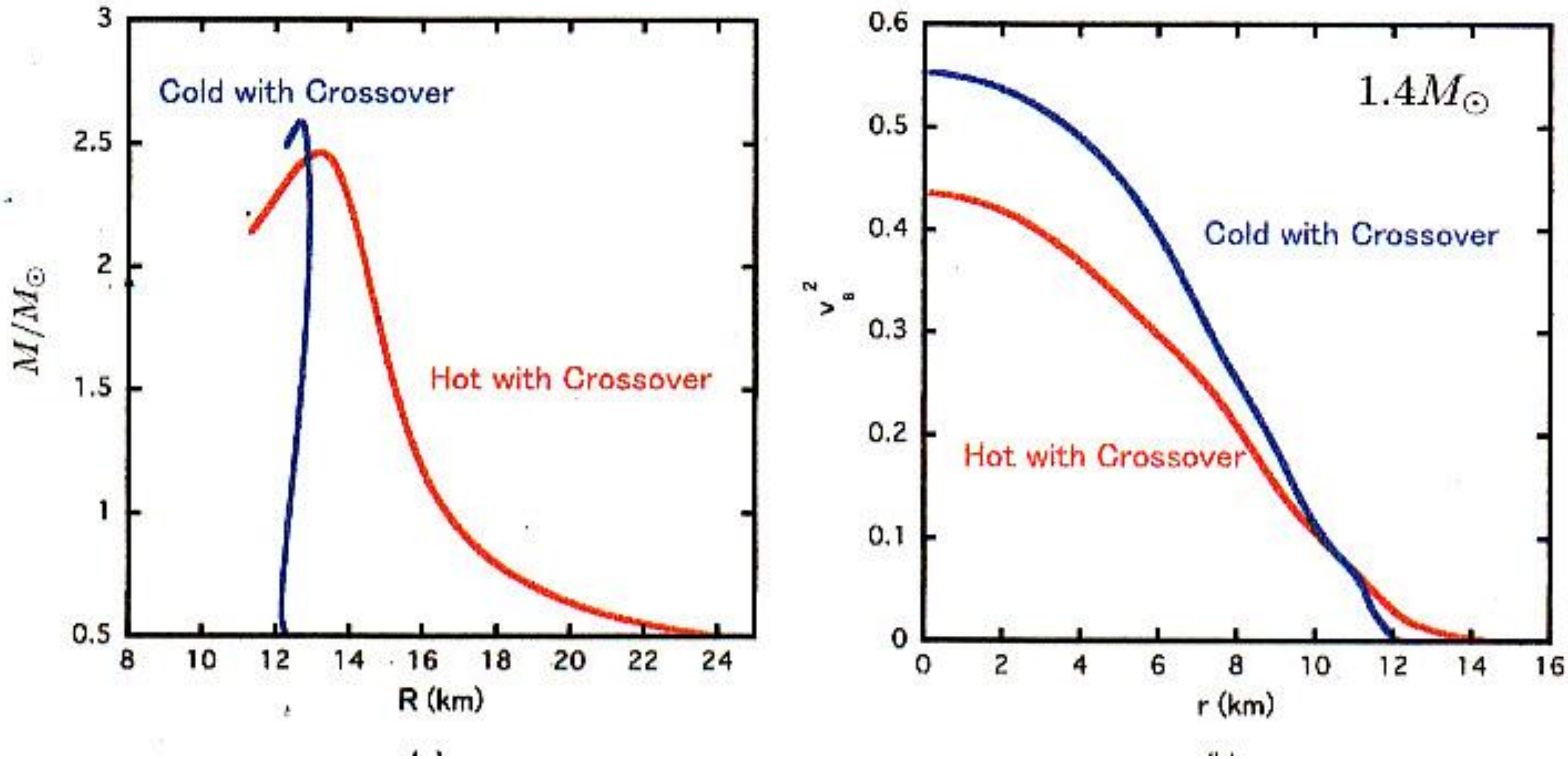
Sound velocity

Application of our EOS with crossover (named “CRover”) to hot NSs at birth

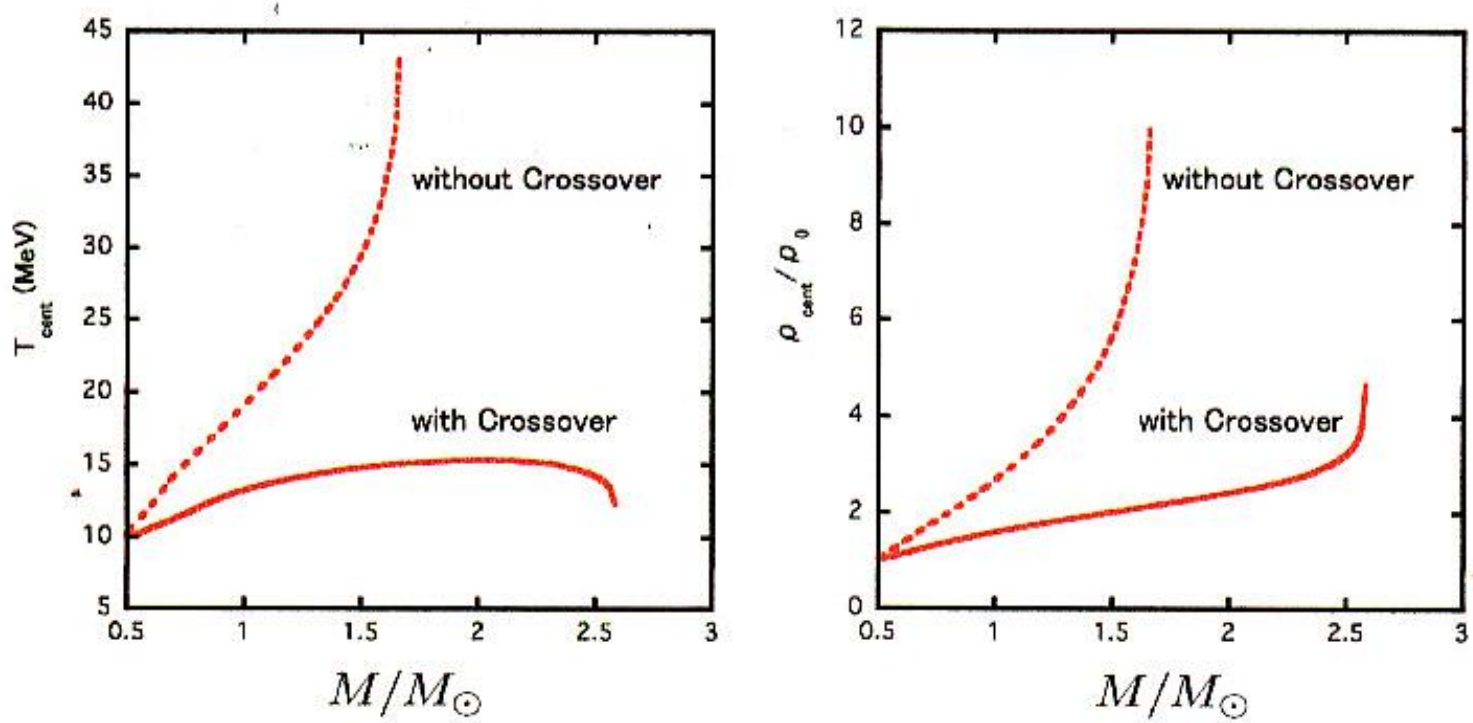
It is found that the H-Q crossover plays important roles not only to generate a stiff EOS compatible with extremely heavy NSs but also to lower the internal temperature of hot NSs

It is noteworthy that hot NSs interestingly constrain The maximum mass of cold NSs.

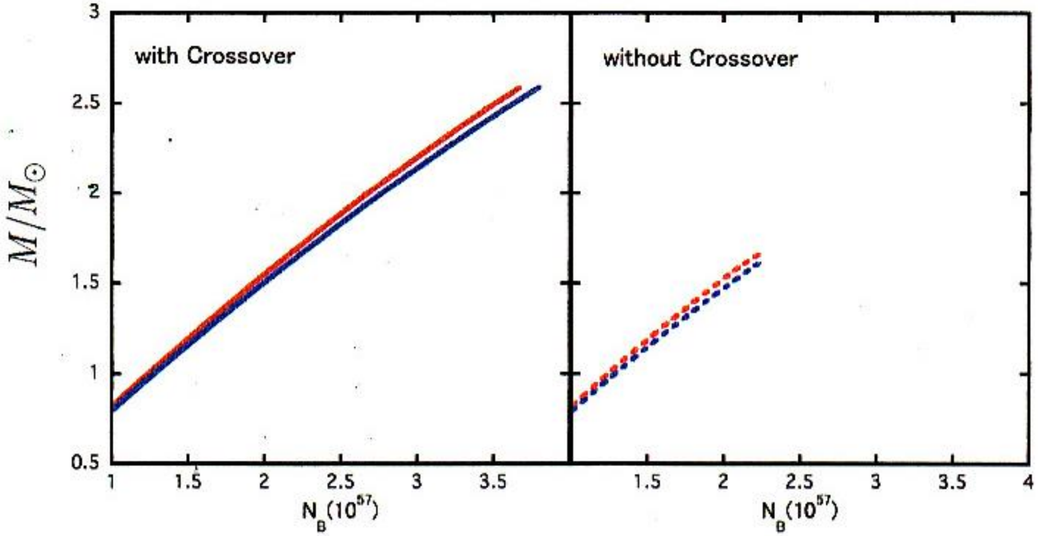
K.Masuda, T.Hatsuda and T.Takatsuka, submitted to PTEP



Cold with Crossover
Hot with Crossover
$M/M_{\odot}$
R (km)
3
2.5
2
1.5
1
0.5
8
10
12
14
16
18
20
22
24
$1.4M_{\odot}$
Cold with Crossover
Hot with Crossover
v_s^2
r (km)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16

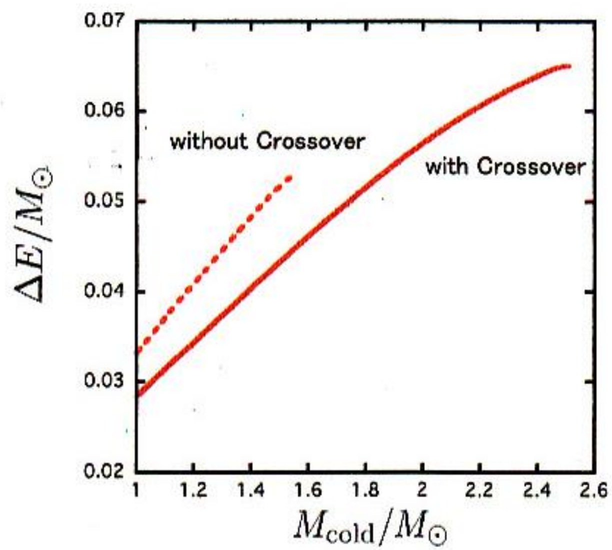


45
40
35
30
25
20
15
10
5
0.5
1
1.5
2
2.5
3
T_{cent} (MeV)
without Crossover
with Crossover
$M/M_\odot$
12
10
8
6
4
2
0
ρ_{cent}/ρ_0
without Crossover
with Crossover
$M/M_\odot$



with Crossover
without Crossover
$M/M_{\odot}$
$N_B(10^{57})$
$N_B(10^{57})$

(a)



without Crossover
with Crossover
$\Delta E/M_{\odot}$
$M_{\rm cold}/M_{\odot}$

Too-rapid cooling of NSs with Y-mixing

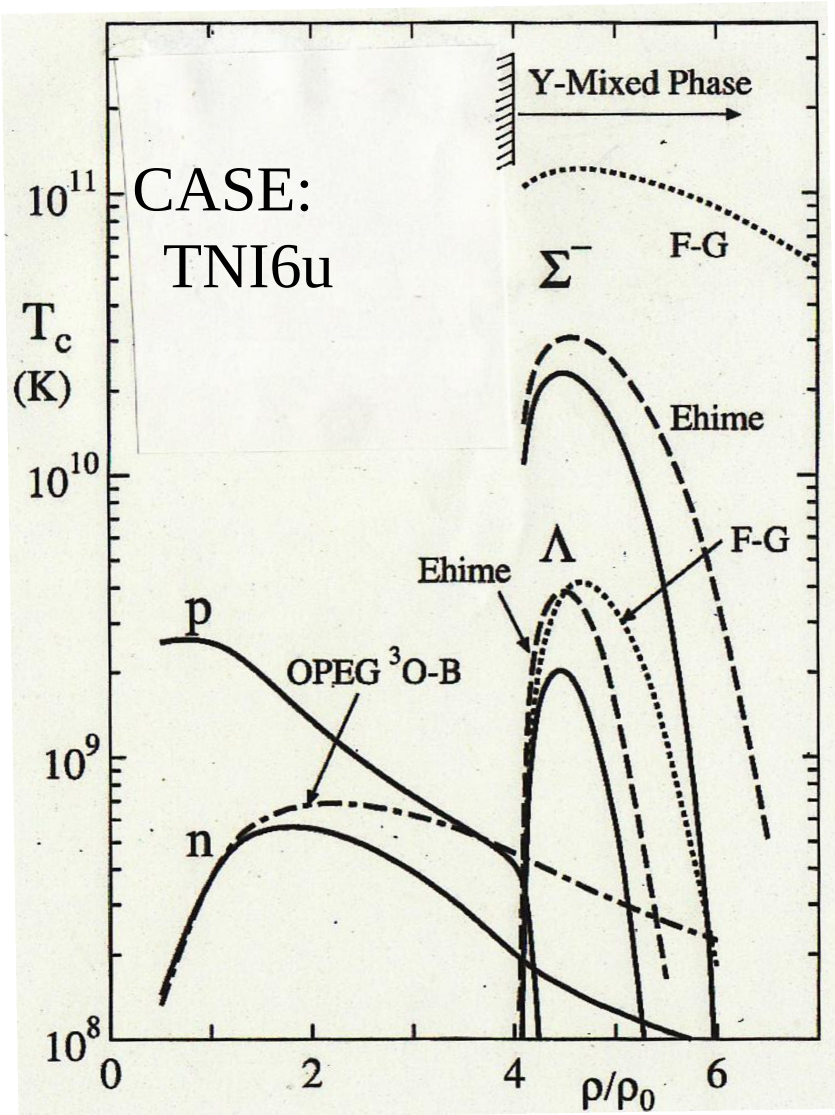
Direct URCA is made possible by Y(YDurca, e.g.,

$\Lambda \longrightarrow$ p+ e^- + v-bar , p + e^- $\longrightarrow \Lambda$ + v

———————————————

c.f.) Durca : n → p + e^- + v-bar, and inverse process

Murca: n + N → p + N + e^- + v-bar , and inv. pro.



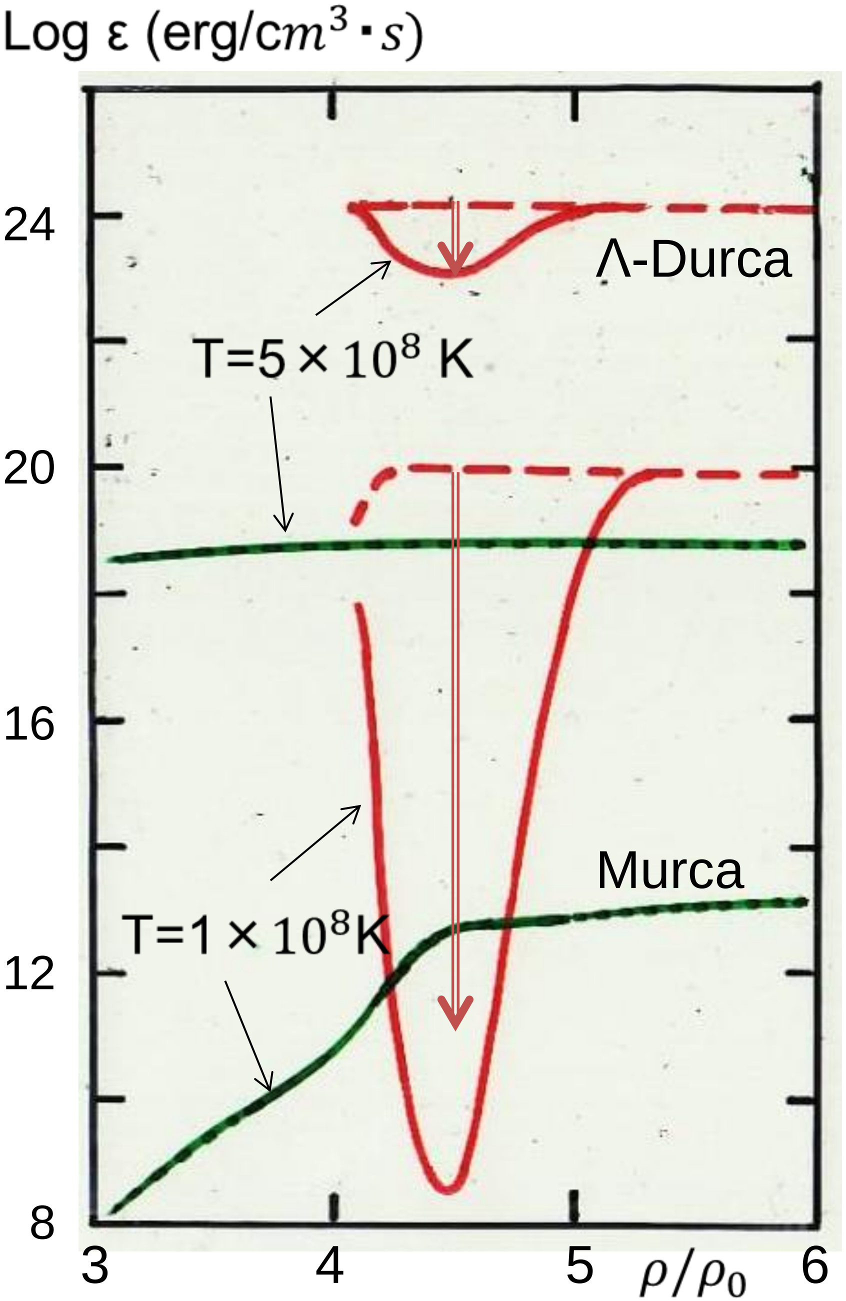
Critical Temperature T_c versus Density ρ

- □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

With and without Y core depends on M

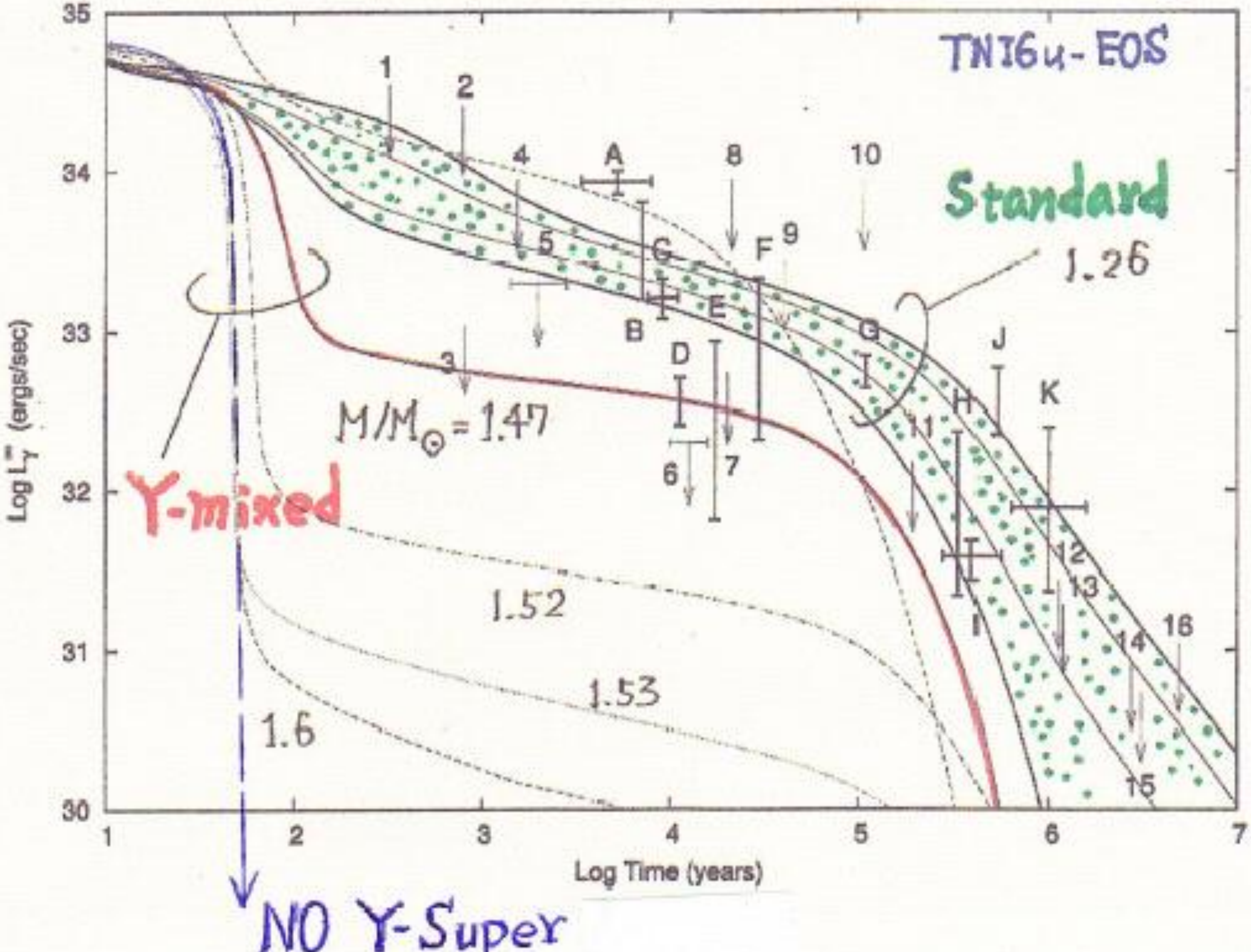
Too -rapid cooling → Hyperon superfluidity

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

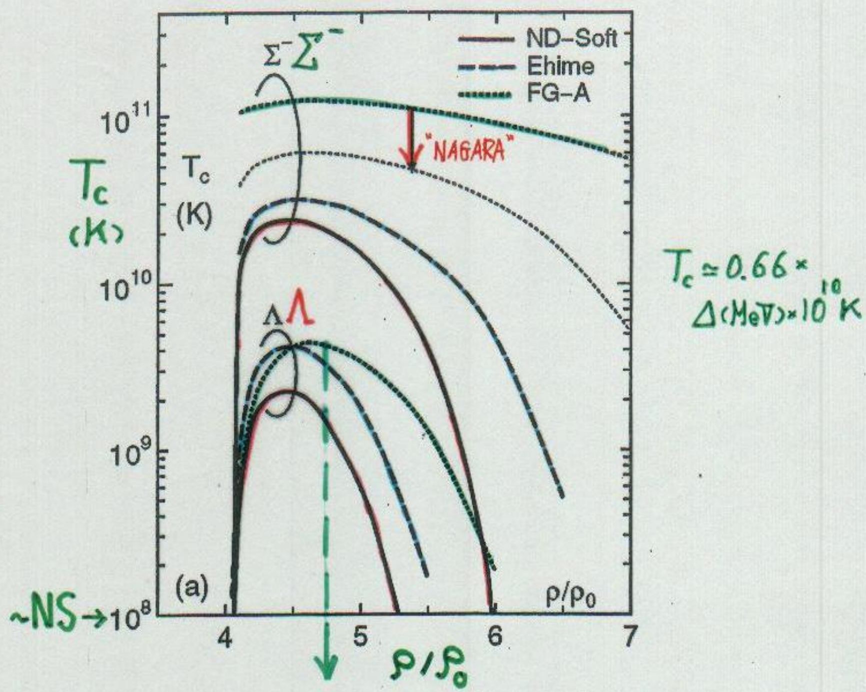
Lighter NSs → Warm (standard slow cooling of Murca)
Heavier NSs → Cool (nonstandard fast cooling of YDurca (“hyperon cooling”) + Y-super)
Massive NSs → Very Cold (“hyperon cooling”)

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

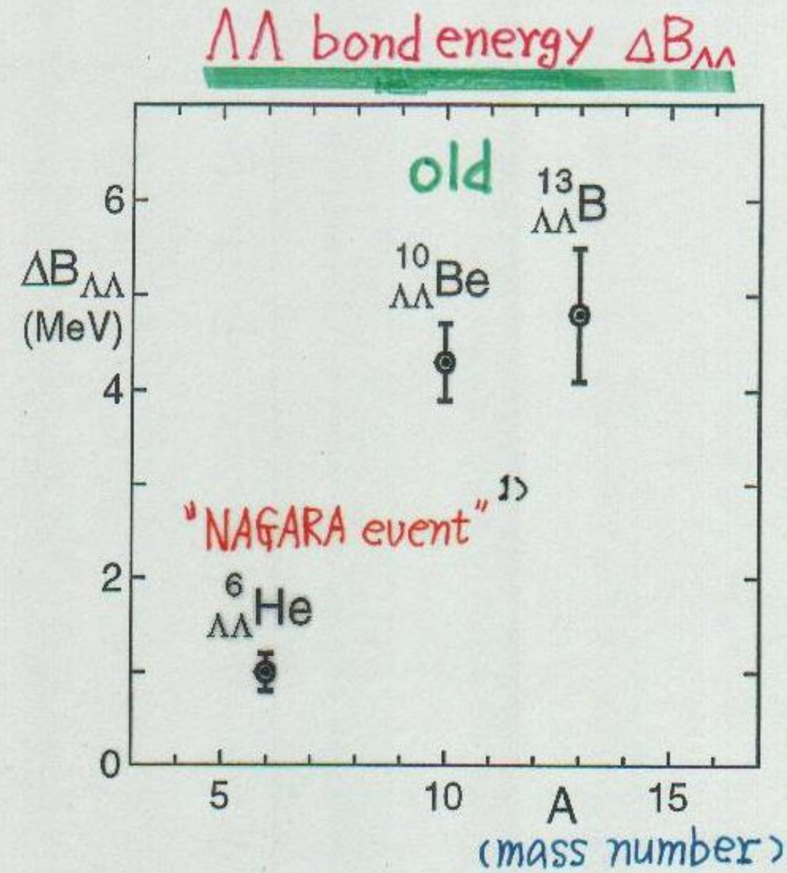


NO Λ-super due to "NAGARA"

A-dependence ? →



- Y-superfluids are realized
- Hyperon cooling scenario is Okay



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

	$\Delta B_{\Lambda\Lambda}$ (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

1) Takahasi et al., PRL 87 (2001) 2125

NAGARA event

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

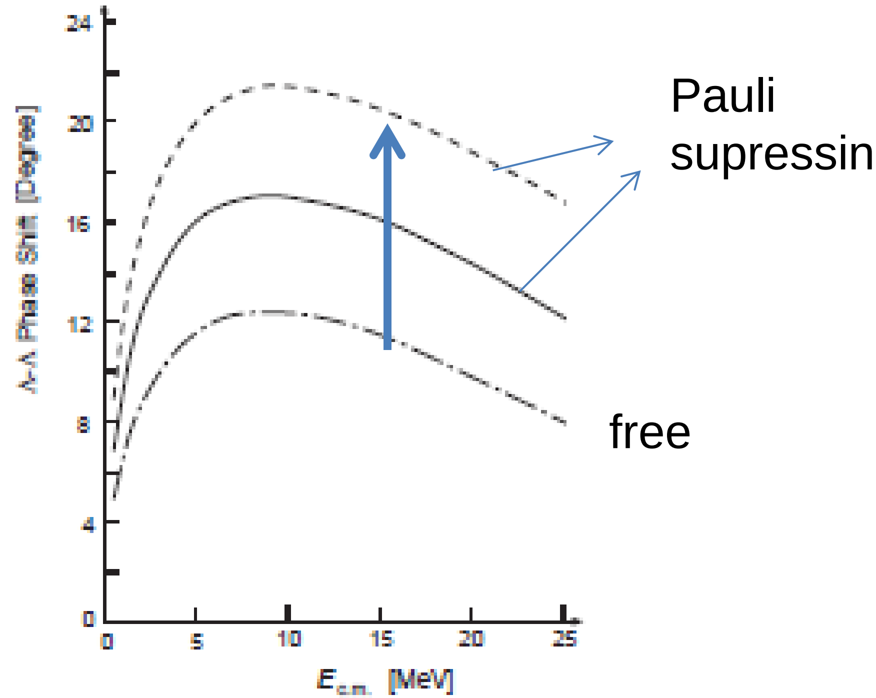
Need more careful investigations

- ○ 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.

We need further investigations,i.e.,

a) A-dependence
b) Checking the validity of ΛΛ-bond energy extraction
c) Including other missing effects to enhance ΛΛ attraction

e.g.
ΛΛ—ΞN coupling effects in medium



K.S.Myint ,S.Shinmura and Y.Akaishi, Eur.Phys.J.A16 (2003) 21

Summary

Due to the Y-mixing sure to occur in NS cores, we are faced to the serious problems, too-softened EOS and too-rapid cooling .

The former is so to speak , ”hyperon crisis” , considering recent observations of very massive 2-solar-mass NSs. Possible solution would be ,universal 3-body force in the case of pure hadronic framework , and hadron- quark crossover transition when quark degrees of freedom is taken into account.

To get out from the problem of too-rapid cooling, a central concern would be in the point how we revive the Λ-superfluidity ,reconciling ΛΛ-hypernucleiar data.