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Λ-Superfluidity under the Equation of State for massive Neutron Stars

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1. Introduction
2. Universal 3-body force U(SJM)
3. Hyperon cooling scenario for NSs
4. Λ-superfluidity
5. Summary

In collaboration with S.Nishizaki and Y.Akaishi

1. 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).

Two serious problems caused by Y-mixing

① Too-softened EOS
② Too-rapid cooling*

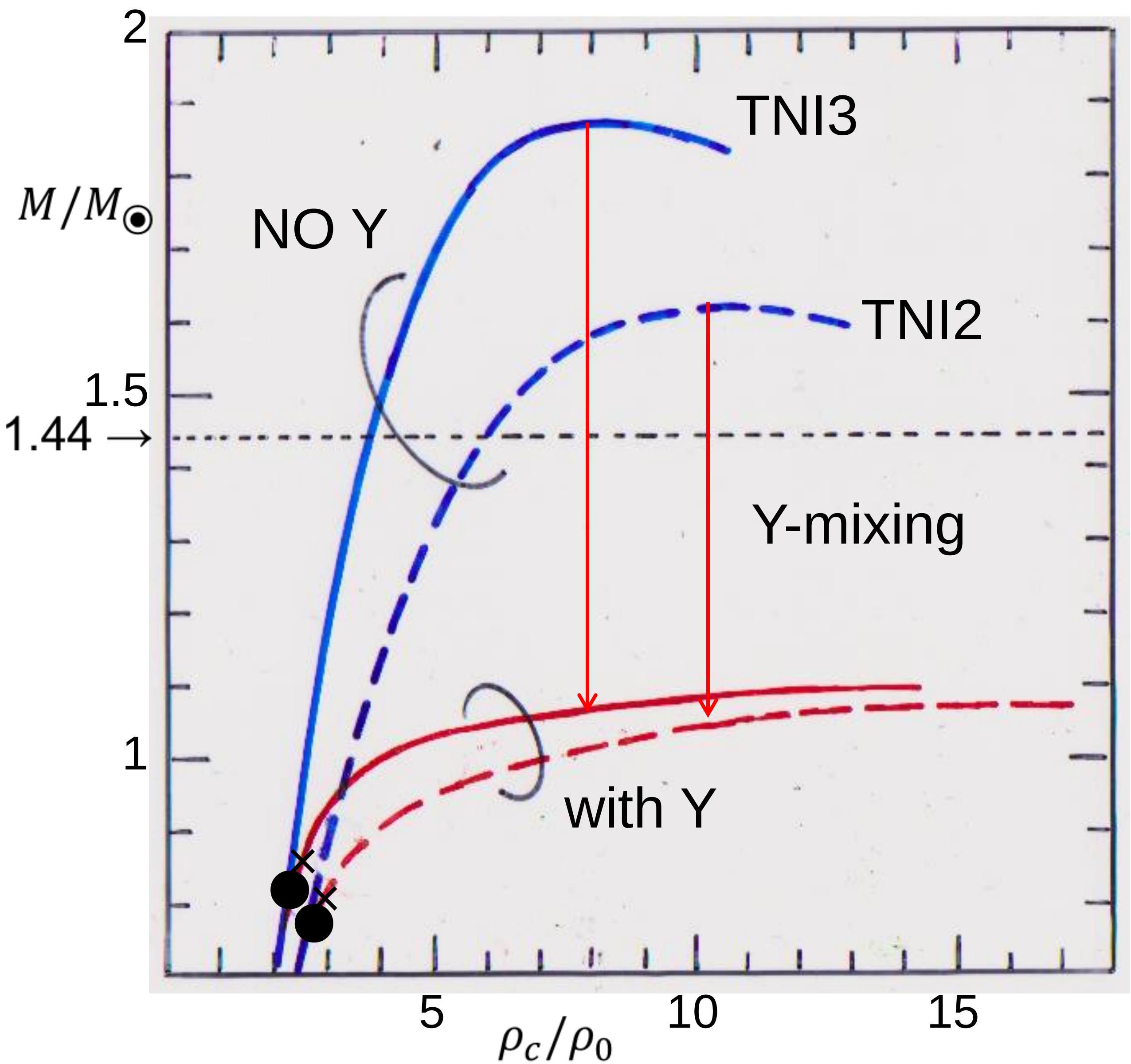
*Direct URCA is made possible by Y : YDurca, e.g.,

$\Lambda \longrightarrow p + e^- + \bar{\nu}$, $\quad p + e^- \longrightarrow \Lambda + \nu$

———————————————————

c.f.) Durca : $n \rightarrow p + e^- + \bar{\nu}$, and inverse process
Murca: $n + N \rightarrow p + N + e^- + \bar{\nu}$, and inv. pro.

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



Strong Softening of the EOS

After 2M_sun observations

Hyperon Crisis

(by T. Hatsuda)

☐ 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

N-part EOS; 3-body force from TNI

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

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

$$\tilde{V}_{TNR} = \tilde{V}_1 e^{-(r/\lambda_r)^2}(1 - e^{-\eta_1 \rho}), \tag{3}$$

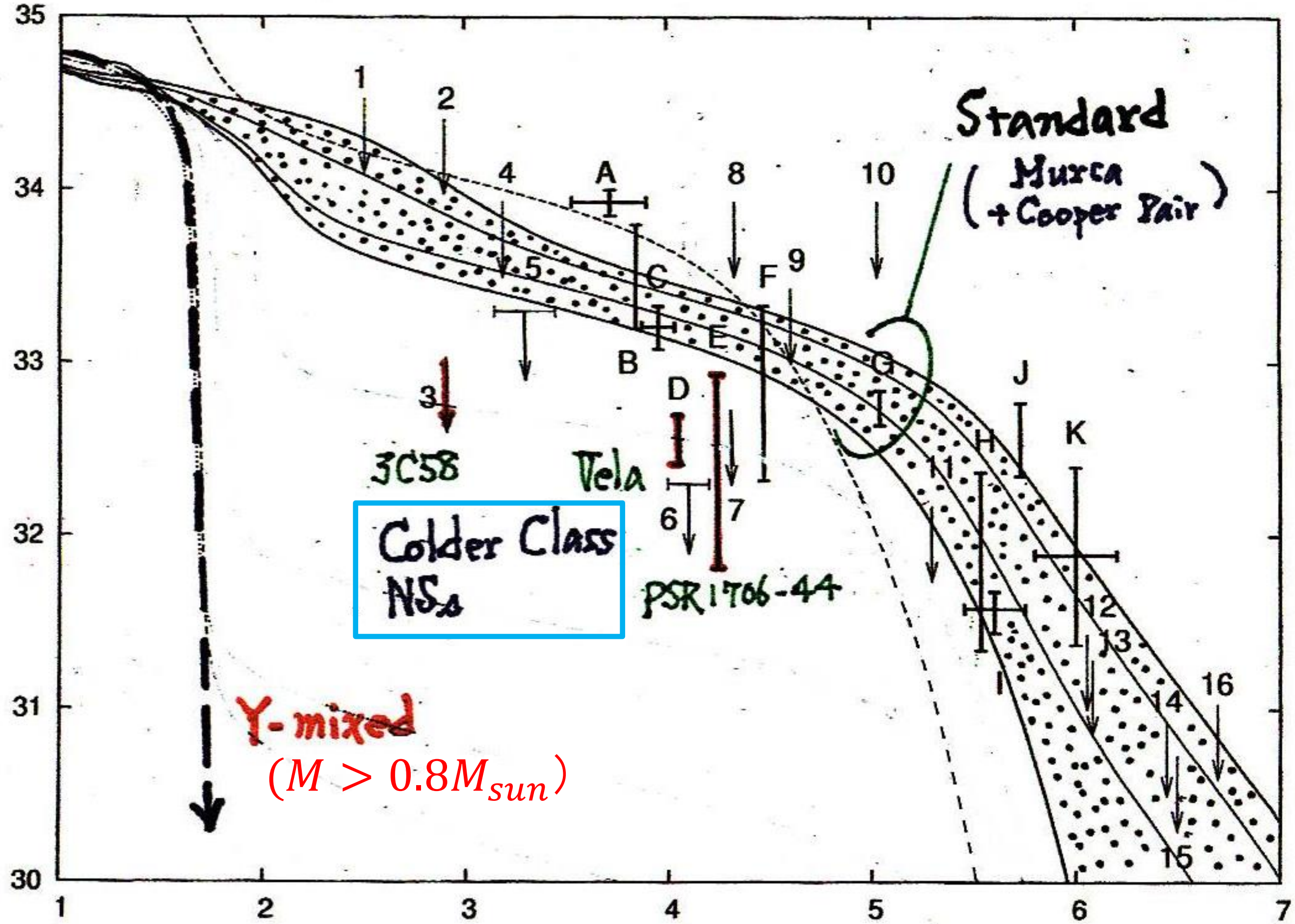
$$\tilde{V}_{TNA} = V_2 e^{-(r/\lambda_a)^2} \rho e^{-\eta_2 \rho} (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)^2. \tag{4}$$

Table I. Parameters of $\tilde{V}_{TNI}$, 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 $\tilde{V}_{RSC} + \tilde{V}_{TNI}$, 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

Thermal Evolution of NSs

Log L_ν^∞
(ergs/sec)



Log Time (years)

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

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(NNN)(i.e.,TNI byFriedman-Pandharipande*) : NNN ⟶ BBB

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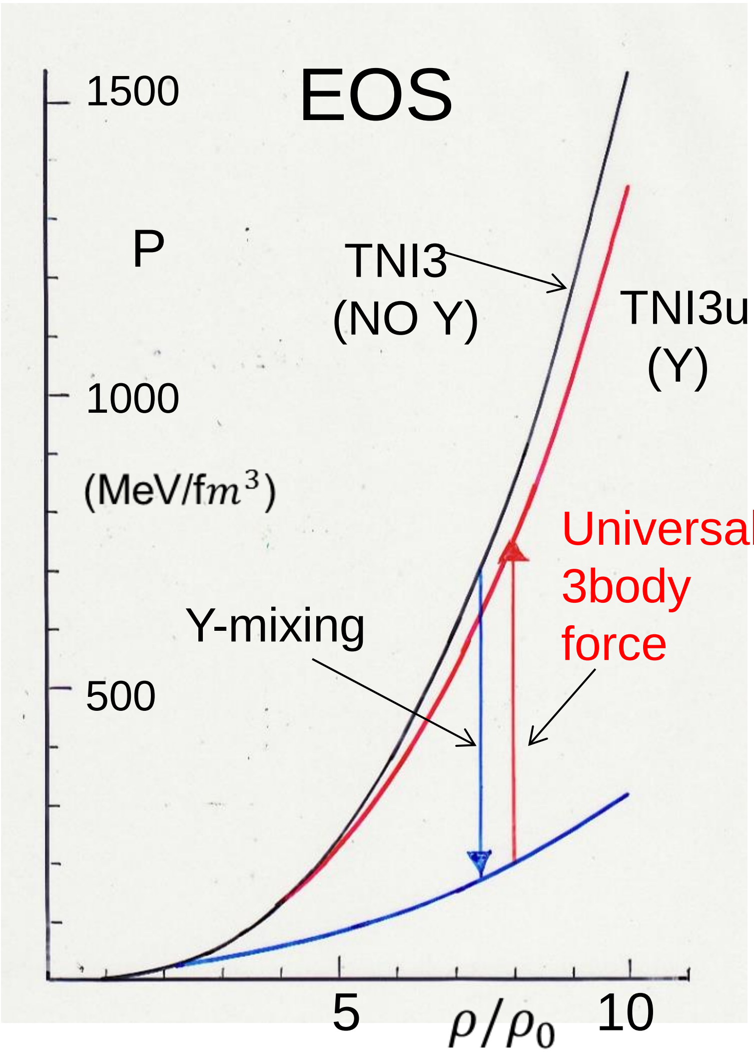
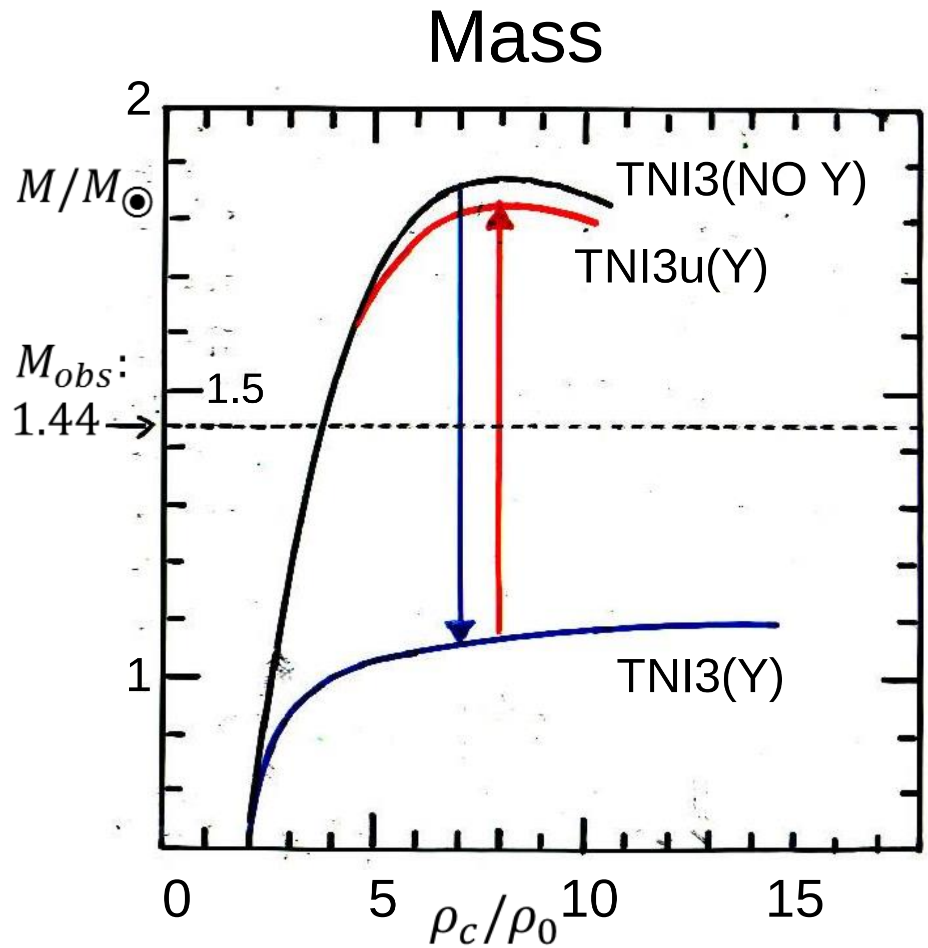
*) B. Friedmann and V. R. Pandharipande, Nucl.Phys. A361,502 (1981)

Dramatic softening of EOS ⟶ Necessity of "Extra Repulsion"





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

The aim here is to reinvestigate the existence or nonexistence problem of Λ-superfluid in NSs by taking the points:

1) Hyperon-mixed EOS with universal 3-body force, which is compatible with "2-solar-mass NSs"

U(BBB) ⟶ U(SJM) + TNA

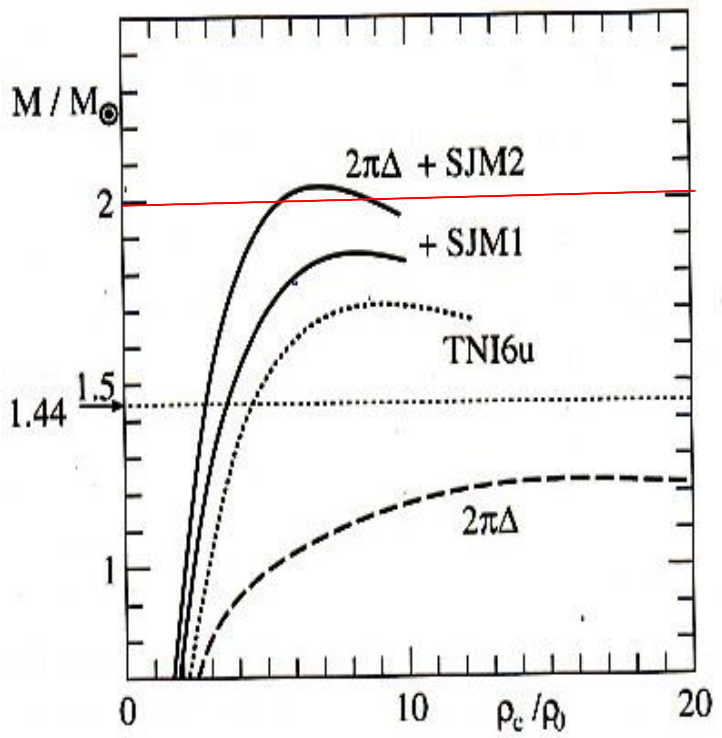
2) Pauli-suppression effects in ΛΛ—ΞN channel contributing to the additional attraction for the ΛΛ-pairing interaction .

2. Universal 3-body force

：U(SJM)

In the earlier works, U was introduced quite phenomenologically.,
but ,in 2008, U(SJM) from the Strihg-Junction Model for quark structure of baryons was constructed by R.Tamagaki [1], which is spin- and flavor-Independent and hence gives the universality to the 3-baryon force .

Actually it has been shown that the SJM 3-body force generates a EOS stiff enough to sustain the 2-solar-mass NSs, even under the Y-mixing [2].



2–solar- mass NSs with Y core
are possible !
(it was before the observations)

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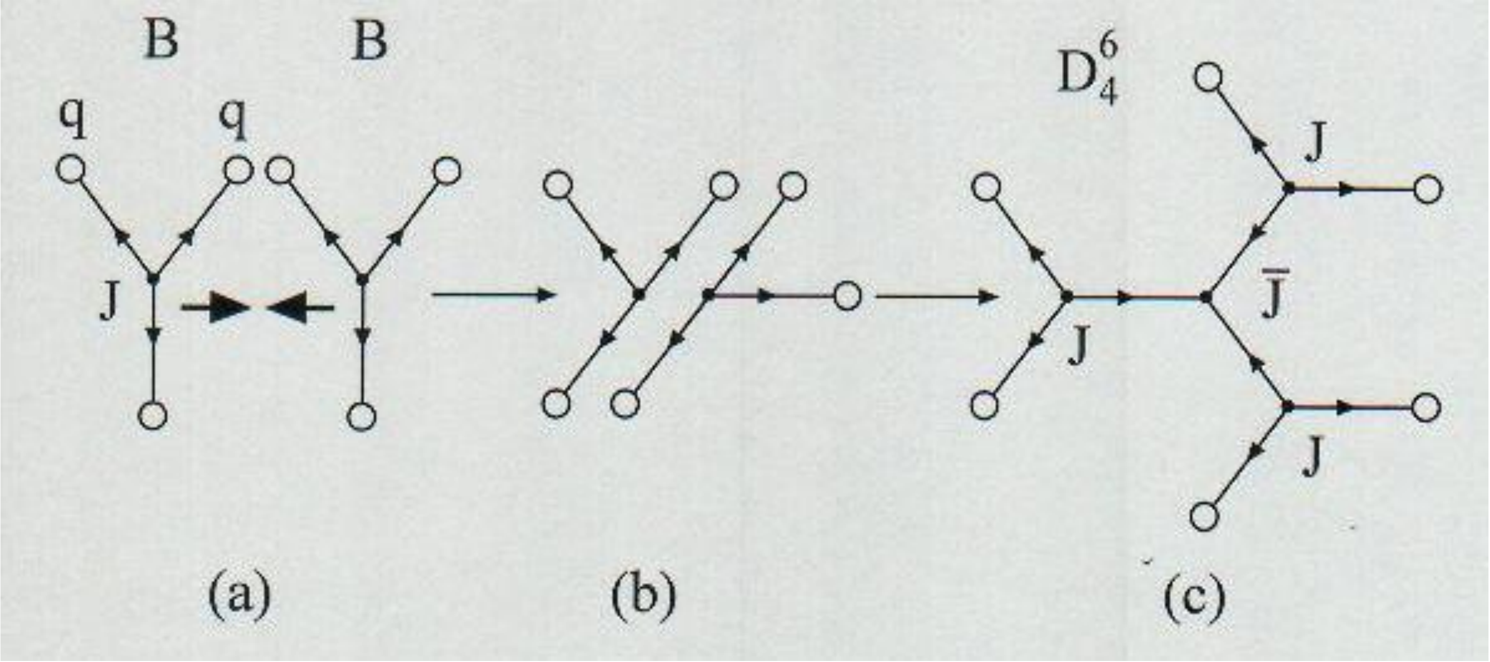
[1] R.Tamagaki, Prog.Theor.Phys.119 (2008) 963.
[2] T.Takatsuka ,S.Nishizaki and R.Tamagaki, AIP.Cof.Proc. 1011(2008) 209.

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

BBB interactions

Additionally 2GeV excitation → Height of 3-body pot.

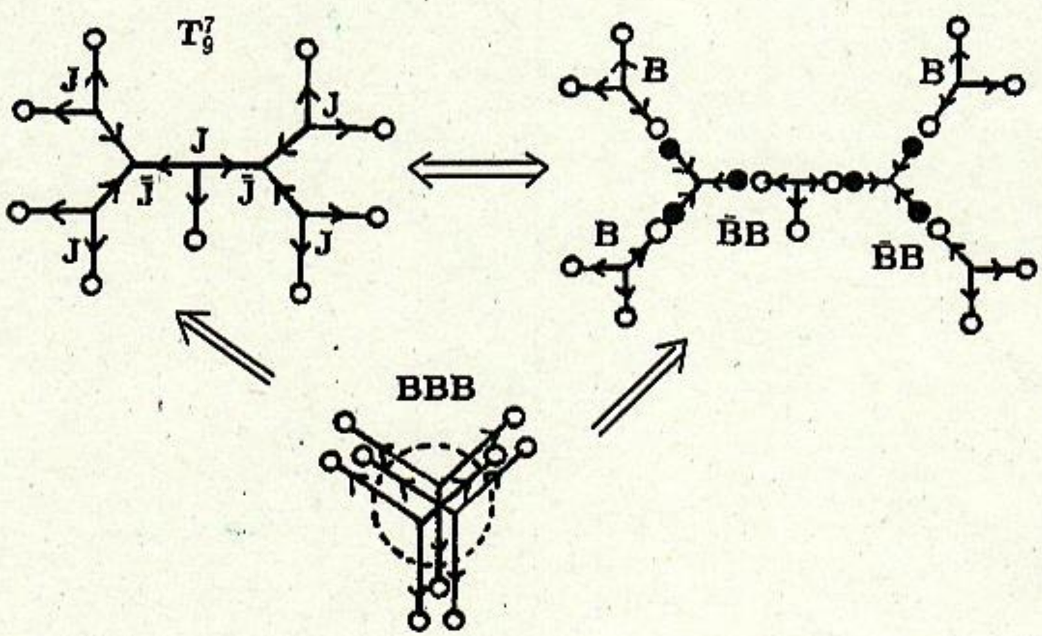


Fig. 7. Pictorial view of the exotic tribaryon and its preformation stage; (left) string-junction net of the tribaryon T^7_9, (right) $BBB(\bar{B}B)(\bar{B}B)$ states arising from the fission of the interjunction strings, and (bottom) an example illustrating one of many possible configurations for full overlap of BBB, where the dotted area indicates the formation region of a string-junction net. Such view is the unfolded-sheet drawing of the tribaryon having three-dimensional spread.

Universal 3-body force from SJM

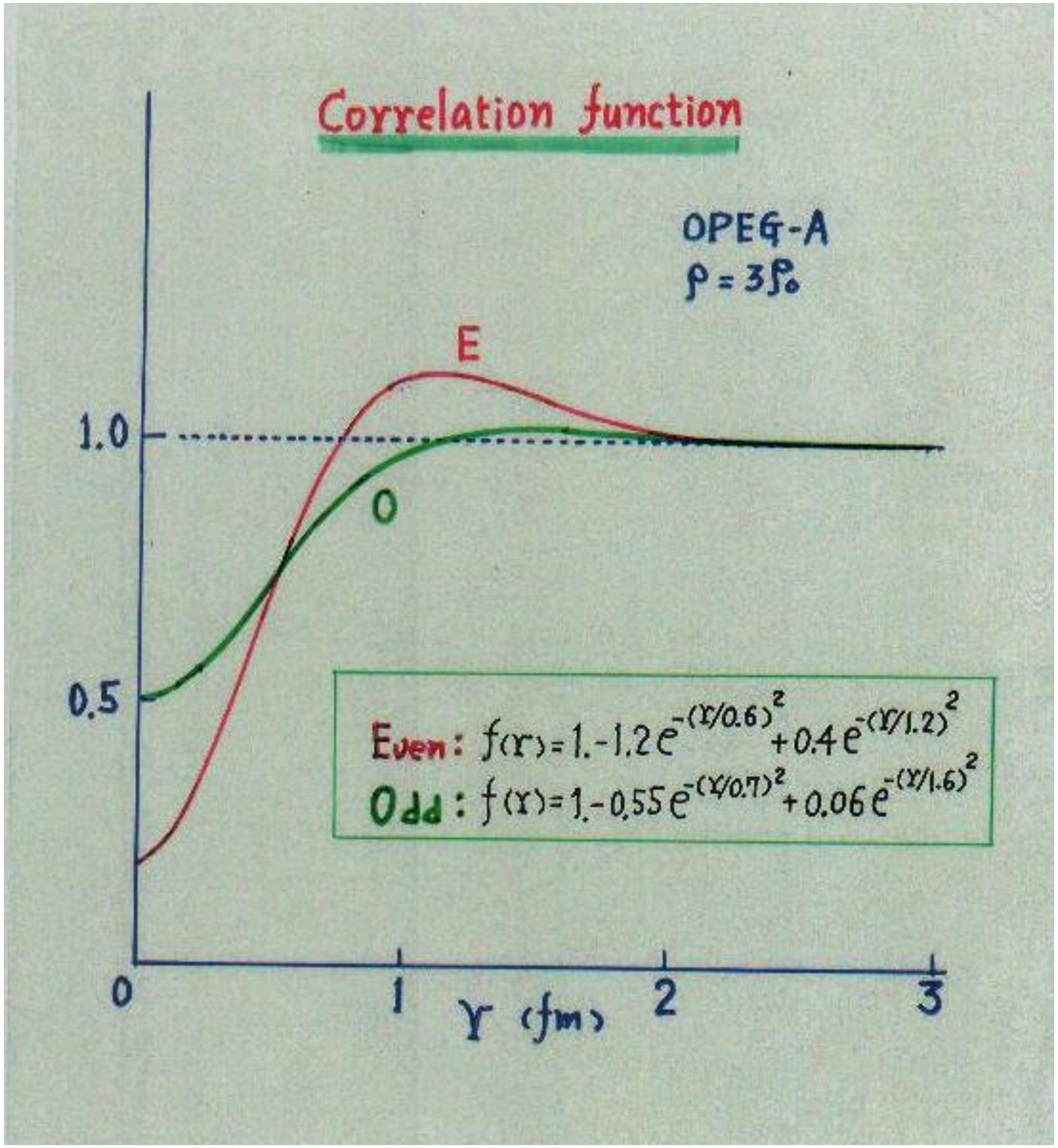
U(r; SJM) $= \frac{\rho W_0}{2\pi^2} \int_0^\infty dq q^2 j_0(qr) \{G_{SRC}(q)\}^2$

$(= \rho W_0 \ (\pi/2\lambda)^{3/2}$ exp$(-\lambda r^2/2)$ for no correlation

$G_{SRC}(q) = 4\pi \int_0^\infty dr r^2 \, {f_L}^2(r) e^{-\lambda r^2} j_0(qr)$

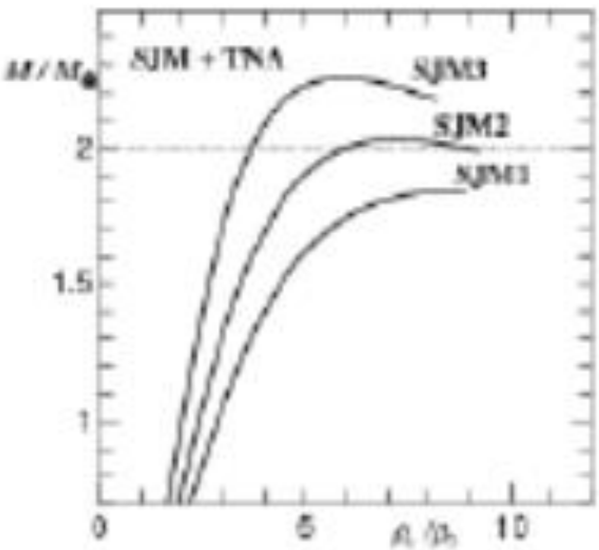
SJM→ $W_0 \cong$ 2GeV

parameter: λ=4.5, 4.0, 3.5 fm^{-2} for SJM1, SJM2 and SJM3

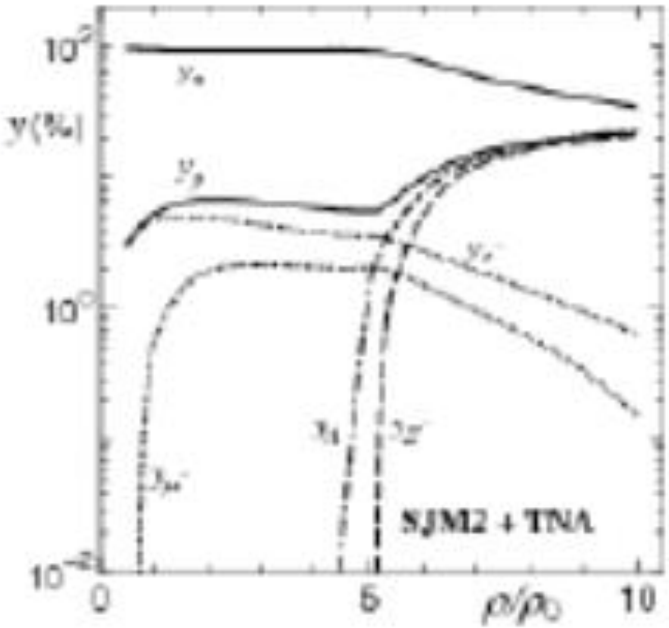


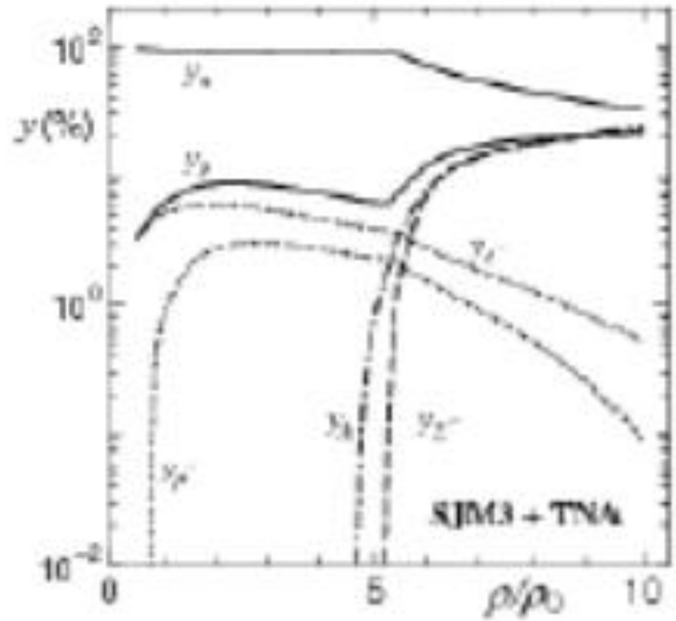
Correlation function
OPEG-A
ρ = 3ρ₀
E
O
1.0
0.5
0
1
2
3
r (fm)
Even: f(r) = 1. − 1.2 e^−(r/0.6)² + 0.4 e^−(r/1.2)²
Odd: f(r) = 1. − 0.55 e^−(r/0.7)² + 0.06 e^−(r/1.6)²

TNA is introduced to reproduce the saturation property of symmetric nuclear matter

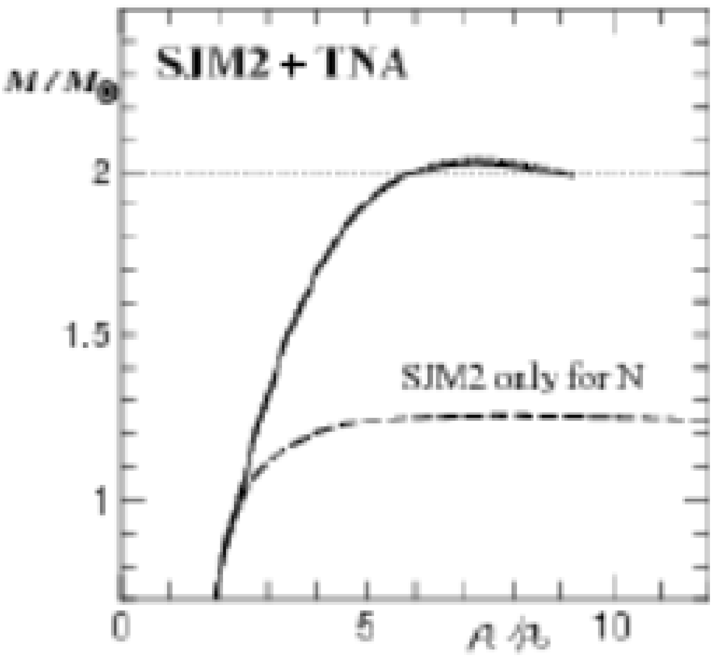


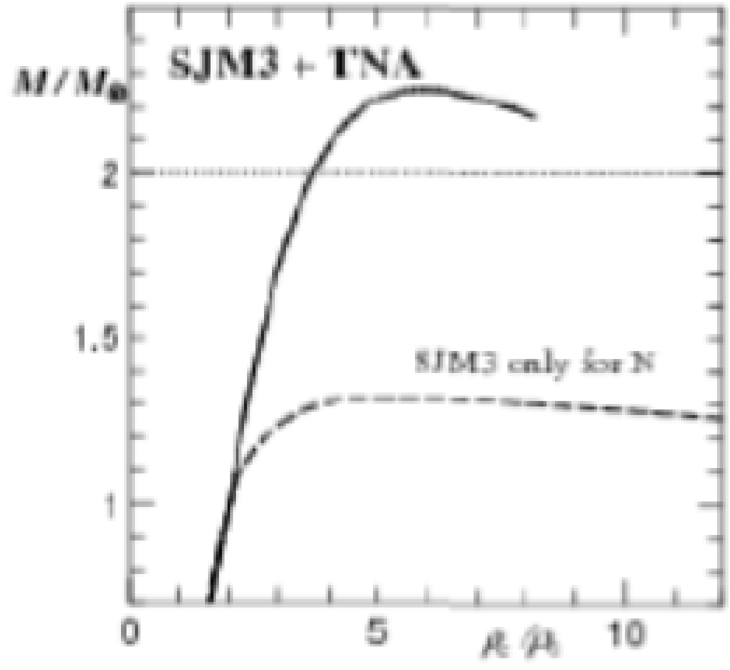
	M_{max}/M_S
SJM1	1.84
SJM2	2.03
SJM3	2.25





Hyperons appear at $(4.5-5.5)\rho_0$

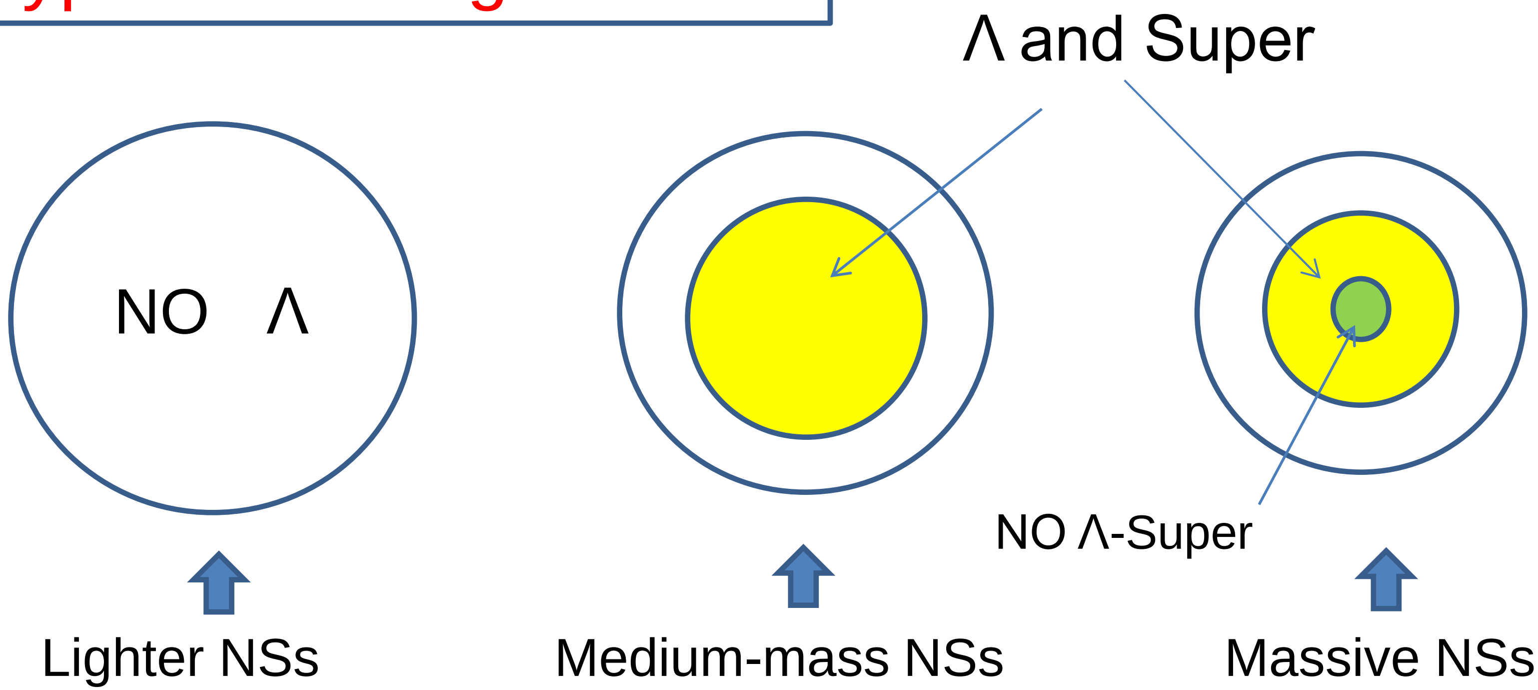




Necessity of universal repulsion

3. Hyperon cooling scenario

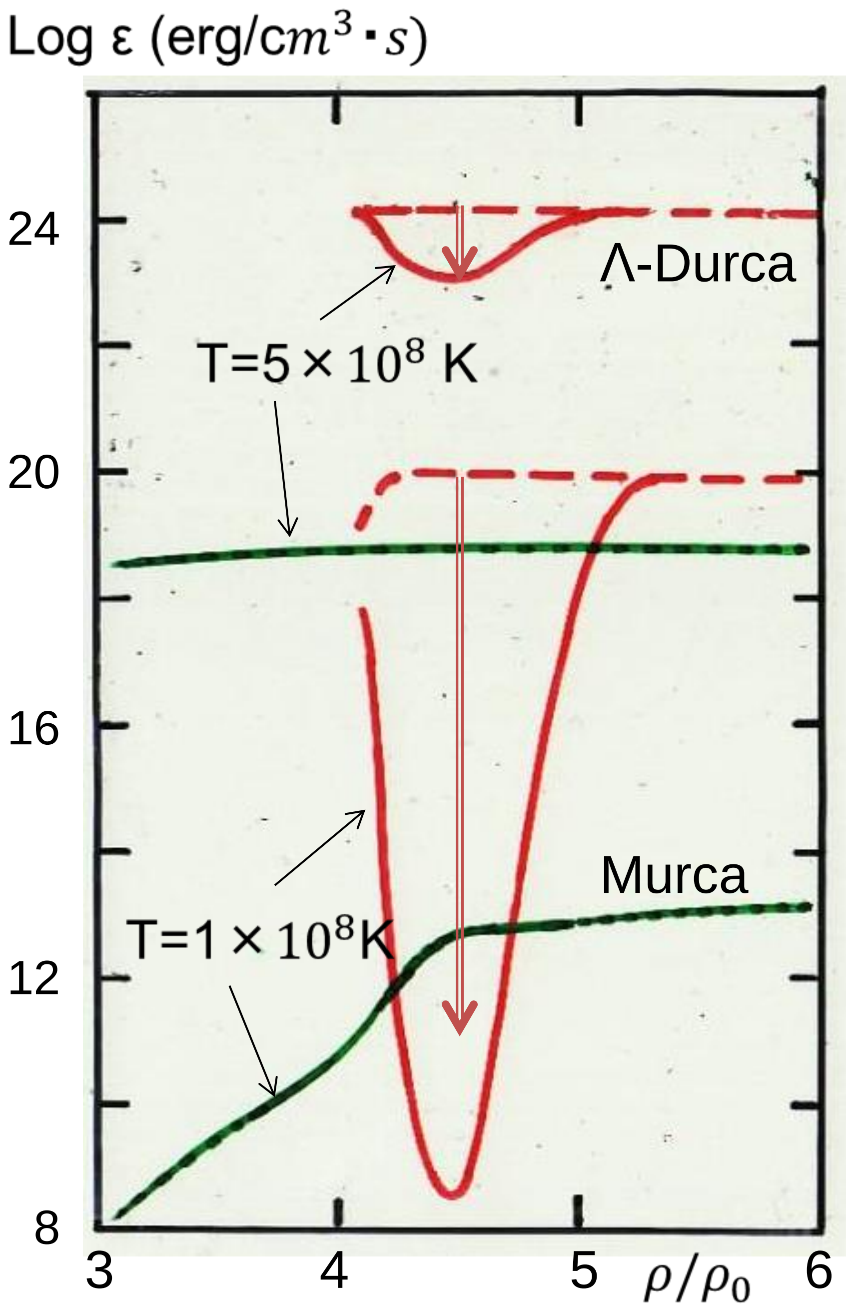
Hyperon cooling scenario



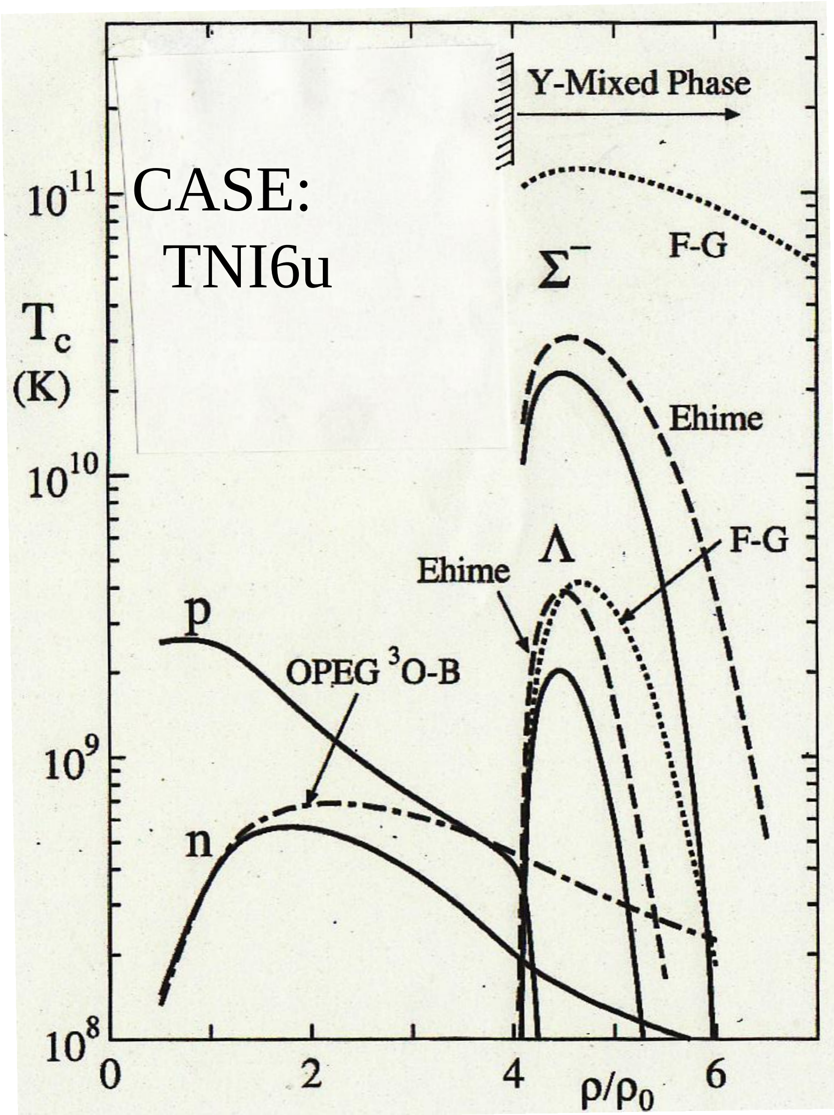
< Warm >	< Cool >	< Ultra cool>
Standard cooling by Modified URCA	Y-Cooling with superfluid supressionn	Rapid Y-cooling

Suppression by Λ-Superfluidity

- ε: ν-emissivity due to
  Λ-Durca (Red)
  Murca (Green)
  dashed line: No suppression
- T: internal temperature of NSs



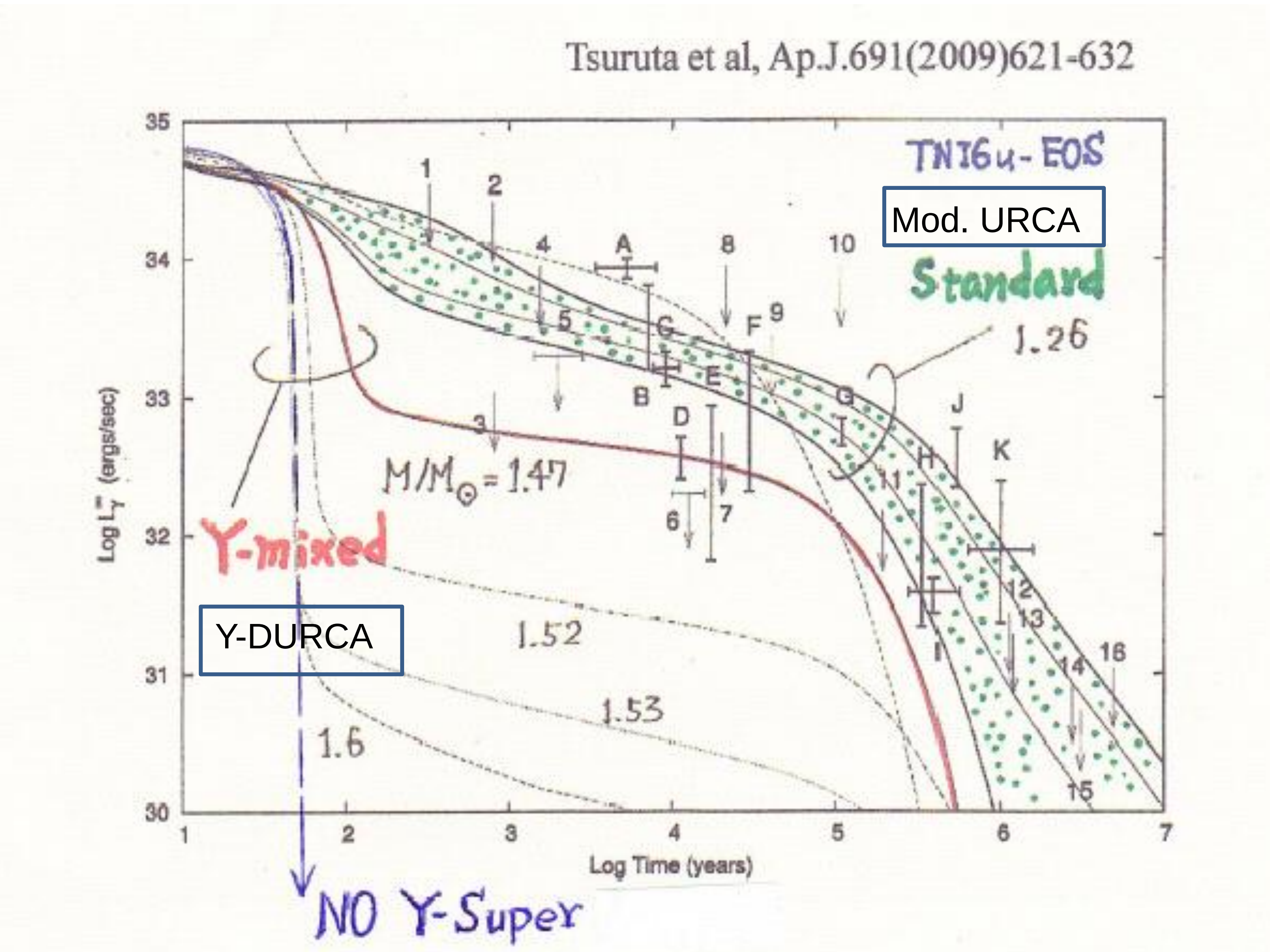
T.Takatsuka,S.Nishizaki,Y.Yamamoto and R.Tamagaki, Prog.Theor.Phys.115(2006)355



Critical Temperature T_c versus Density ρ

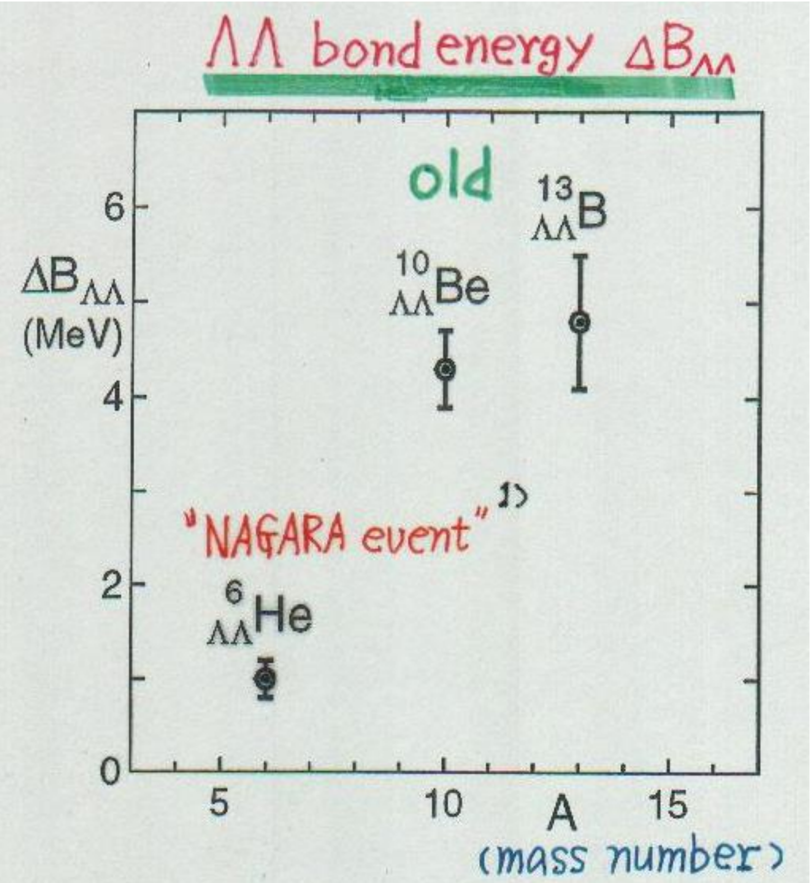
□Pairing type:
- n → 3P2
- p, Λ, Σ^- → 1S0

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


Tsuruta et al, Ap.J.691(2009)621-632
TN I6u - EOS
Mod. URCA
Standard
1.26
$M/M_{\odot} = 1.47$
1.52
1.53
1.6
Y-mixed
Y-DURCA
NO Y-Super
Log L_{γ}^{∞} (ergs/sec)
Log Time (years)

NO Λ-super due to "NAGARA"

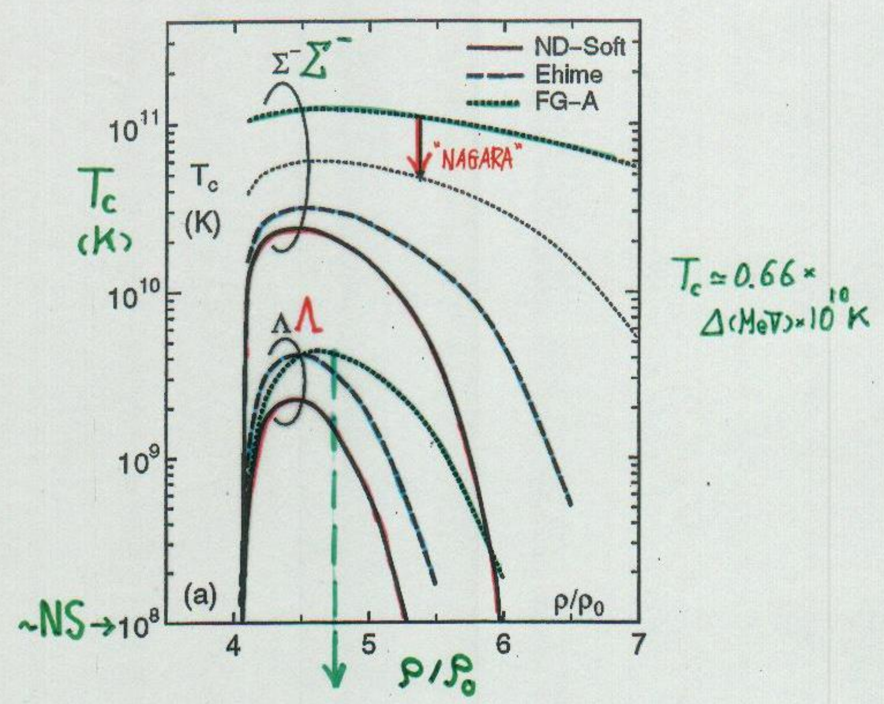
A-dependence ? →



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

	$\Delta B_{\Lambda\Lambda}$ (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) 21250



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

4. Reviving Λ-Superfluidity

Three elements in gap equations

- Here, we note the 3-elements (Fermi momentum k^{FB}, effective mass m_B^* and pairing interaction) to control the energy gap.

$$\Delta_B(k) = -\frac{1}{\pi}\int k'^2 dk' \langle k' | V_{BB}(^1S_0) | k \rangle \times \frac{\Delta_B(k')}{\sqrt{\tilde{\varepsilon}_B^2(k') + \Delta_B^2(k')}}$$

$$\tilde{\varepsilon}_B(k') \equiv \varepsilon_B(k') - \varepsilon_B(k_{FB}) \simeq \hbar^2(k'^2 - k_{FB}^2)/2m_B^*$$

#) For 3P2 NN pairing, the situation is similar, although the gap equation becomes complex due to the 3P2-3F2 tensor-coupling.

NS Model from SJM

U（BBB）	M_{max}/M_{sun}	R/km	ρ_c/ρ_0
SJM2+TNA	2.03	9.9	7.4
SJM3+TNA	2.26	10.9	5.8

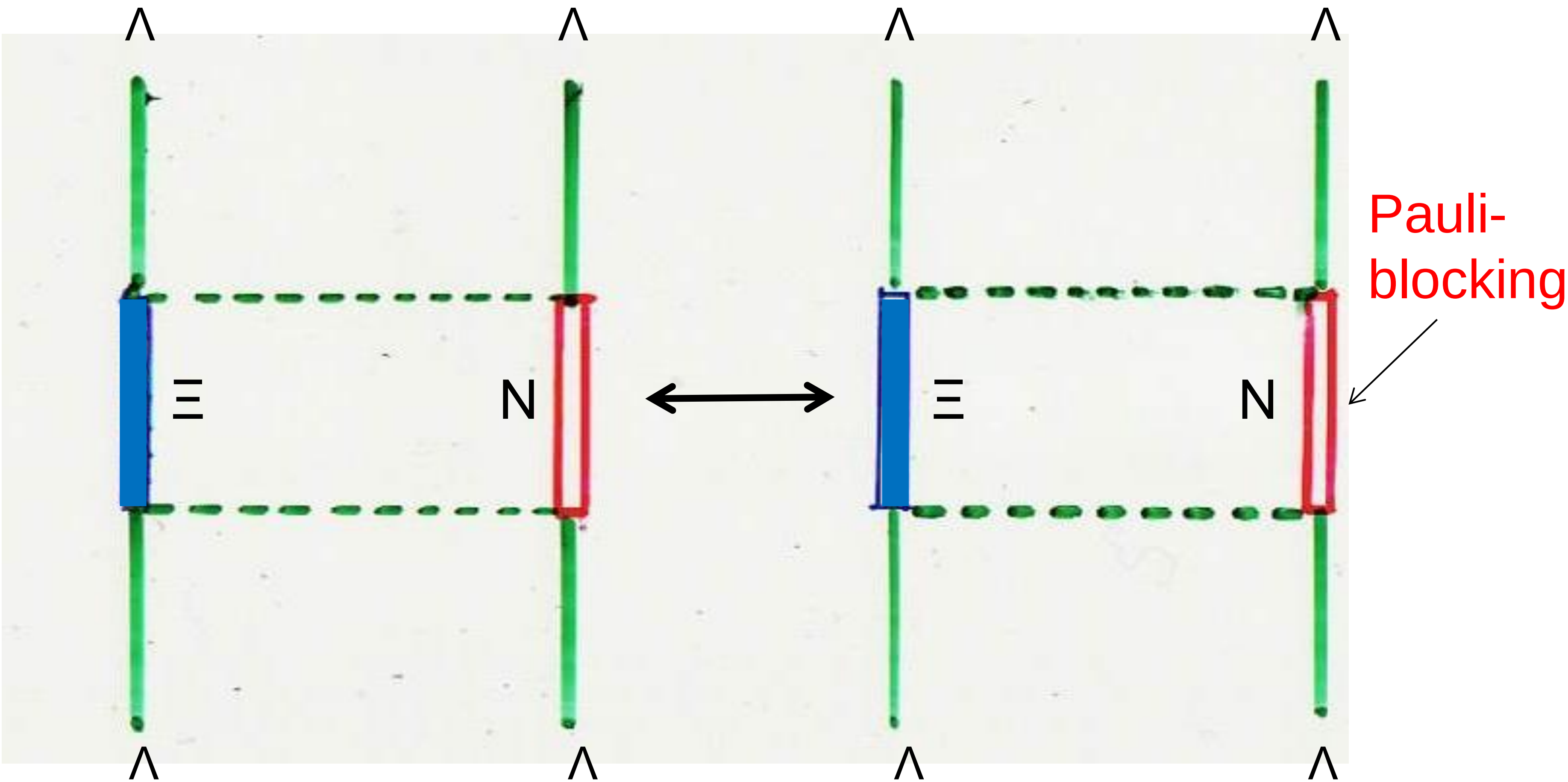
We study the energy gap Δ of Λ by using single-particle quantities under the EOS compatible with 2-solar mass NSs.

Mixing ratio (y) and effective-mass parameter(m^*) ; SJM2+TNA

ρ/ρ_0	y(Λ) in%	$m^*(\Lambda)$	Y(n) in %	m^*(n)
4.5	0.02	0.828	94.5	0.615
4.6	0.25	0.834		
4.8	0.93	0.847		
5.0	1.71	0.859	92.7	0.602
5.2	2.57	0.869		
5.4	3.79	0.872		
5.5	4.47	0.871	86.6	0.586
5.6	5.16	0.870		
5.8	6.55	0.866		
6.0	7.93	0.860	76.6	0.568

Larger m^* for Λ ⟶ works for a realization of Λ-super

ΛΛ—ΞN coupling

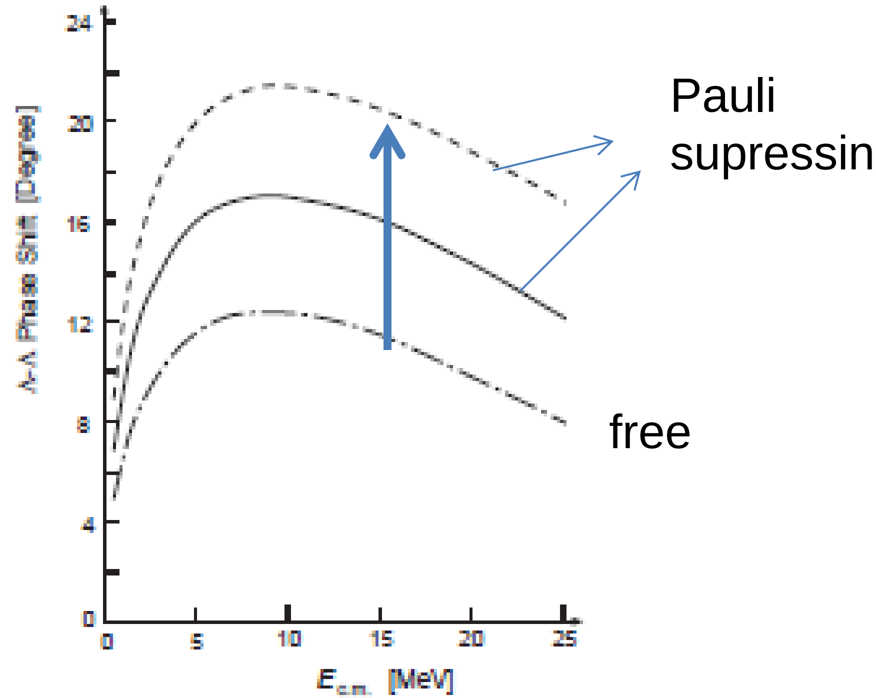


In free space in medium

$V_{\Lambda\Lambda}$ is more attractive than $\tilde{V}_{\Lambda\Lambda}$

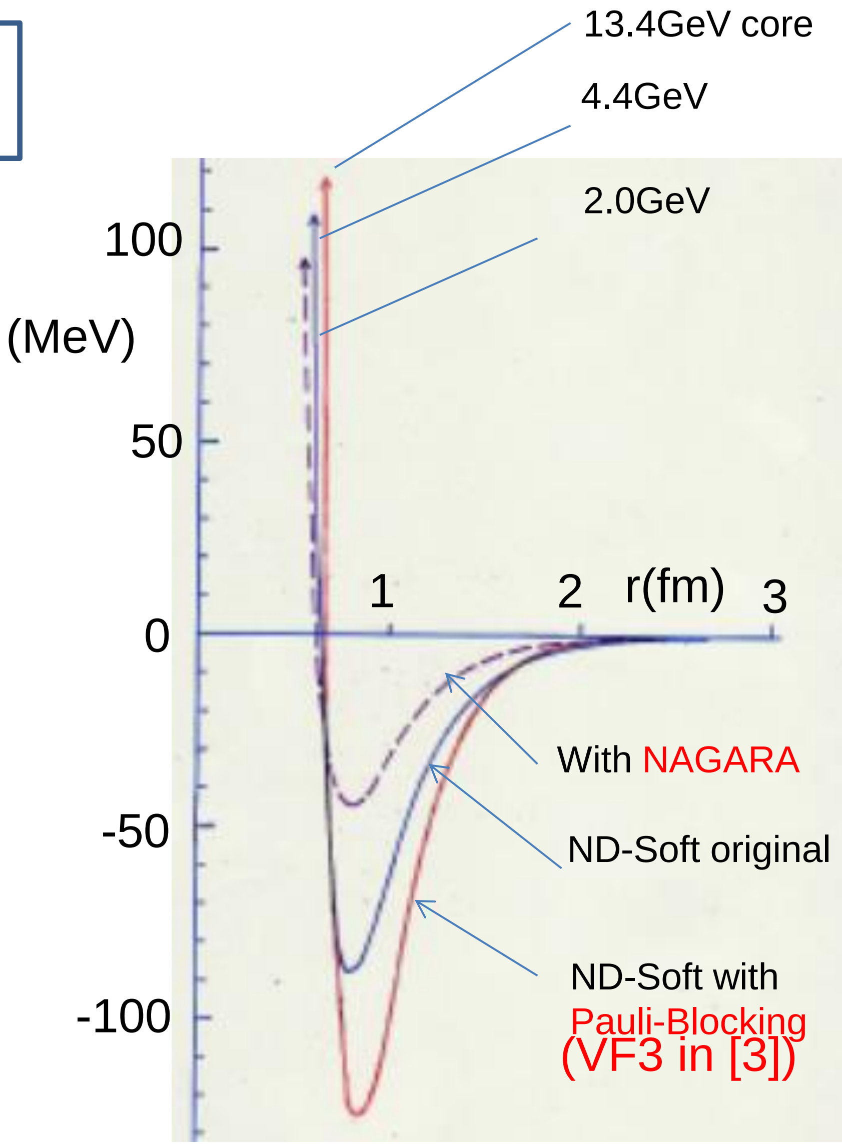
We need further investigations,i.e.,

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



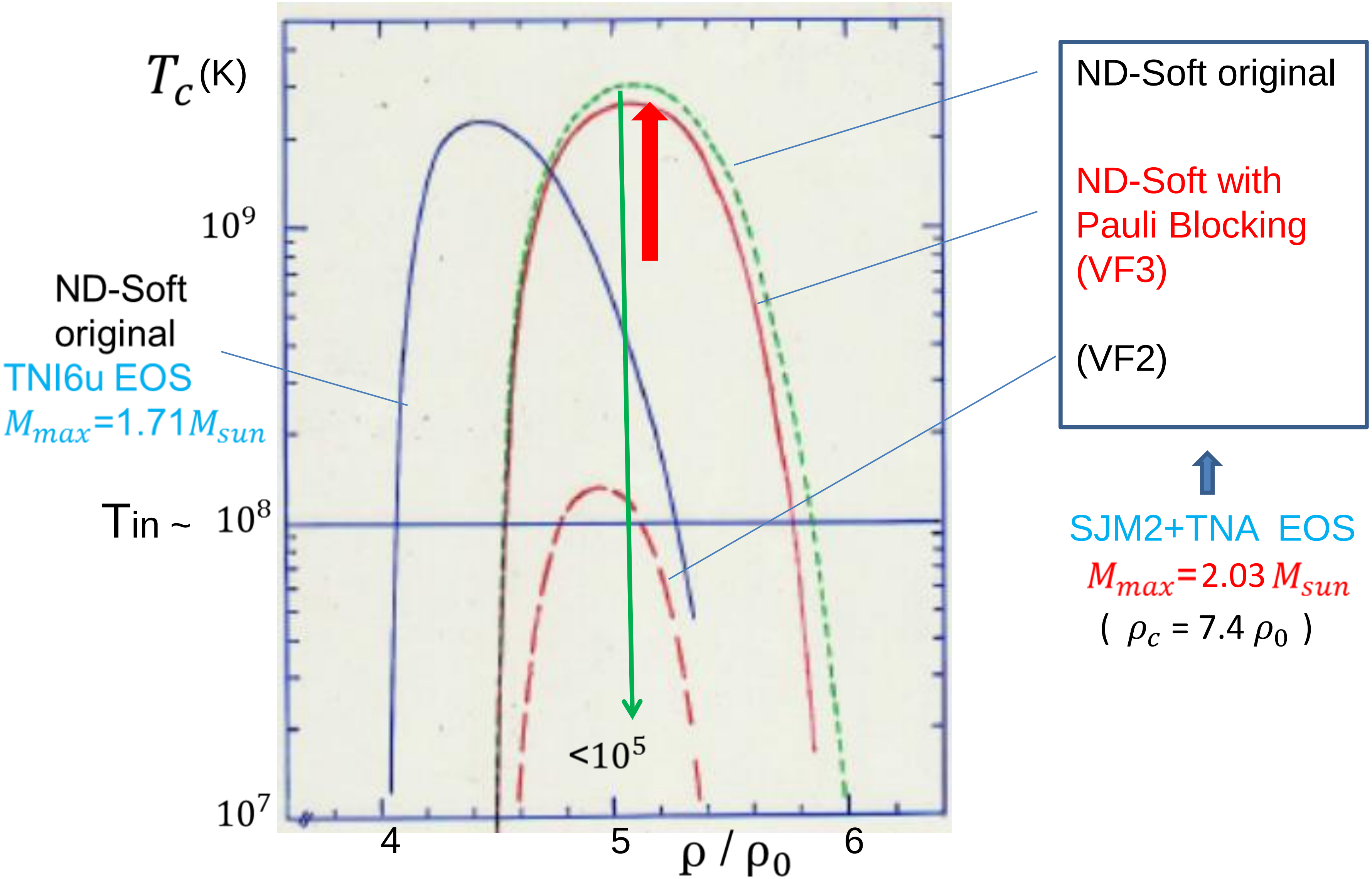
K.S.Myint ,S.Shinmura and Y.Akaishi, Eur.Phys.J.A16 (2003) 21

ΛΛ Pot.



{3}K.S.Myint,S.Shinmura
And Y.Akaishi ,
Eur.Phys.J.A16(2003)21

Critical Temperature of Λ-Superfluid



5. Summary

Due to the Y-mixing in NS cores, we are faced to the serious problems; too-softened EOS and too-rapid cooling . The former is made more serious by recent observation of very massive 2-solar-mass NSs.
These two problems have to be solved at the same time.

In the case of pure hadronic framework . the universal 3-body force is a solution for the former problem.

For the problem of too-rapid Y-cooling, a central concern is how to revive the Λ-superfluidity , consistently with NAGARA event. .We find this is possible by taking account of the Pauli-Blocking effects for ΛΛ-ΞN coupling.