新学術領域「実験と観測で解き明かす中性子星の核物質」キックオフシンポジウム(2012.10.26-27、理研)

中性子星物質の状態方程式と冷却現象
EOS of NS-Matter and NS-cooling

T. Takatsuka (Iwate Univ.)

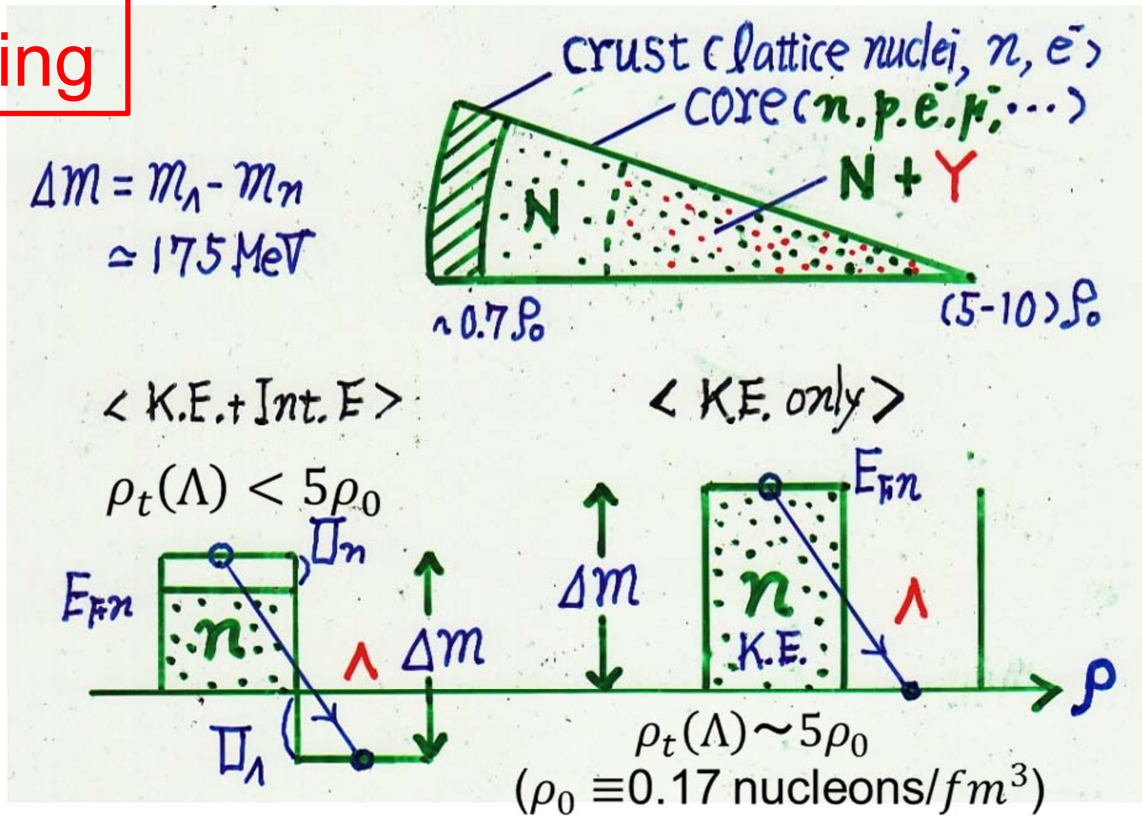
☐ Hyperons surely participate in NS cores
☐ NS Observations
→ Two serious problems:
(1) Strong softening of EOS
(2) Too-rapid Cooling
→ feedback to the physics of hadrons and quarks
☐ Summary

In collaboration with R. Tamagaki, S. Nishizaki, Y. Yamamoto, T. Hatsuda and M. Masuda

1. Hyperons surely participate in neutron star cores

Hyperon-mixing

Δm
$= m_\Lambda - m_n$
$\simeq 175 MeV$



(1) K.E. only : K.E.+$m_n = \mu_n = \mu_\Lambda = m_\Lambda$

$61(\rho/\rho_0)^{2/3}$ MeV $\rightarrow$ $\rho_t(\Lambda) \sim 5\rho_0$

(2) K.E.+ Int. E: K.E. + $U_n + m_N = \mu_n = \mu_\Lambda = m_\Lambda + U_\Lambda$

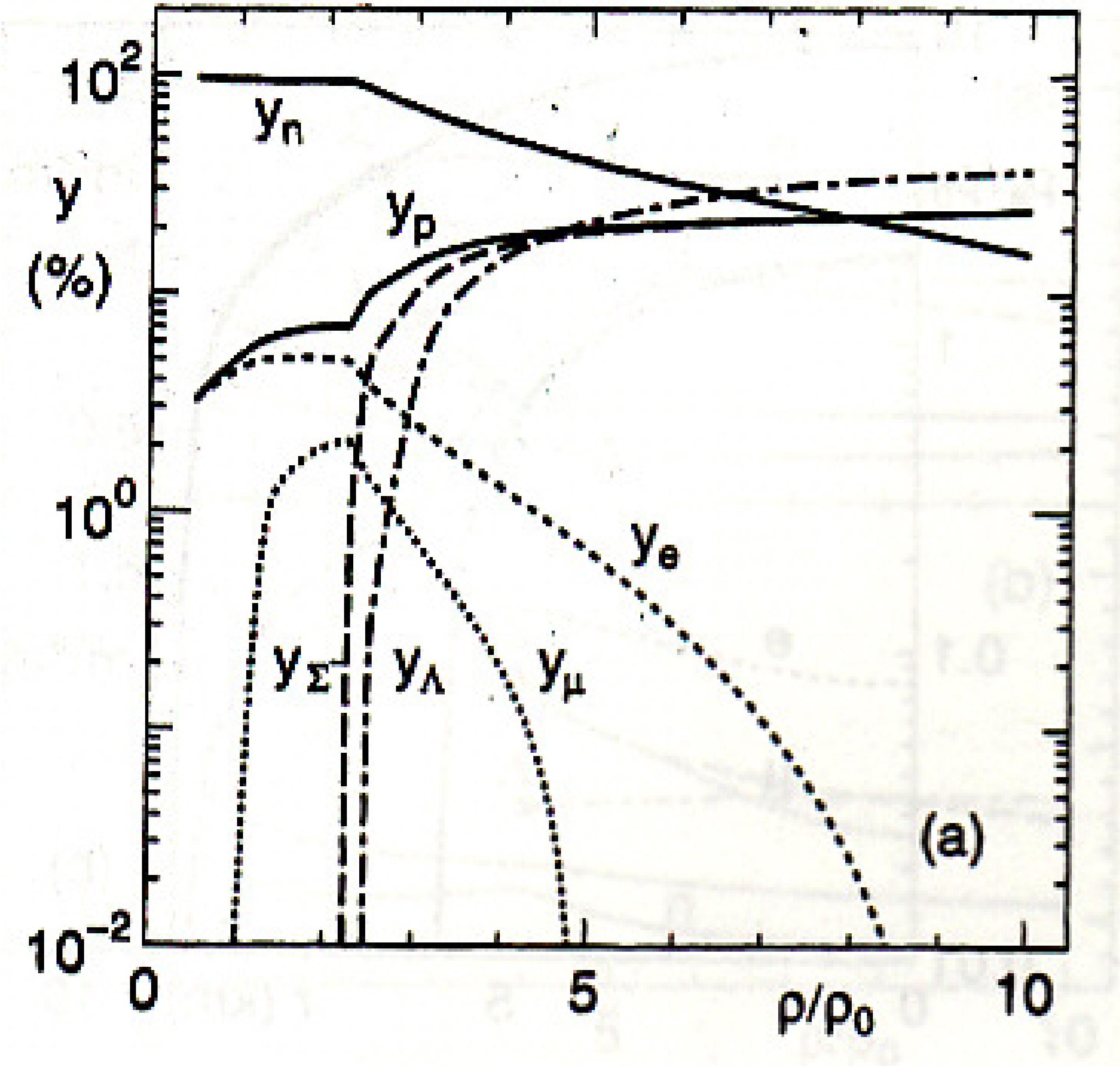
$U_\Lambda < 0$ (assured by the existence of Λ-hypernuclei),
and $U_n > 0 \rightarrow \rho_t(\Lambda) \ll 5\rho_0$ is expected

☐ 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

2. What happens ?

Two Serious Problems

(1) Dramatic Softening of NS EOS

$\longrightarrow$ Contradicts observed mass (M_{obs}) of NSs:

$M_{max} < M_{obs} = (1.44 \pm 0.002)M_{\odot}$ for PSR1913+16

$= (1.97 \pm 0.04)M_{\odot}$ for PSRJ1614-2230

$\longrightarrow$ Problem 1

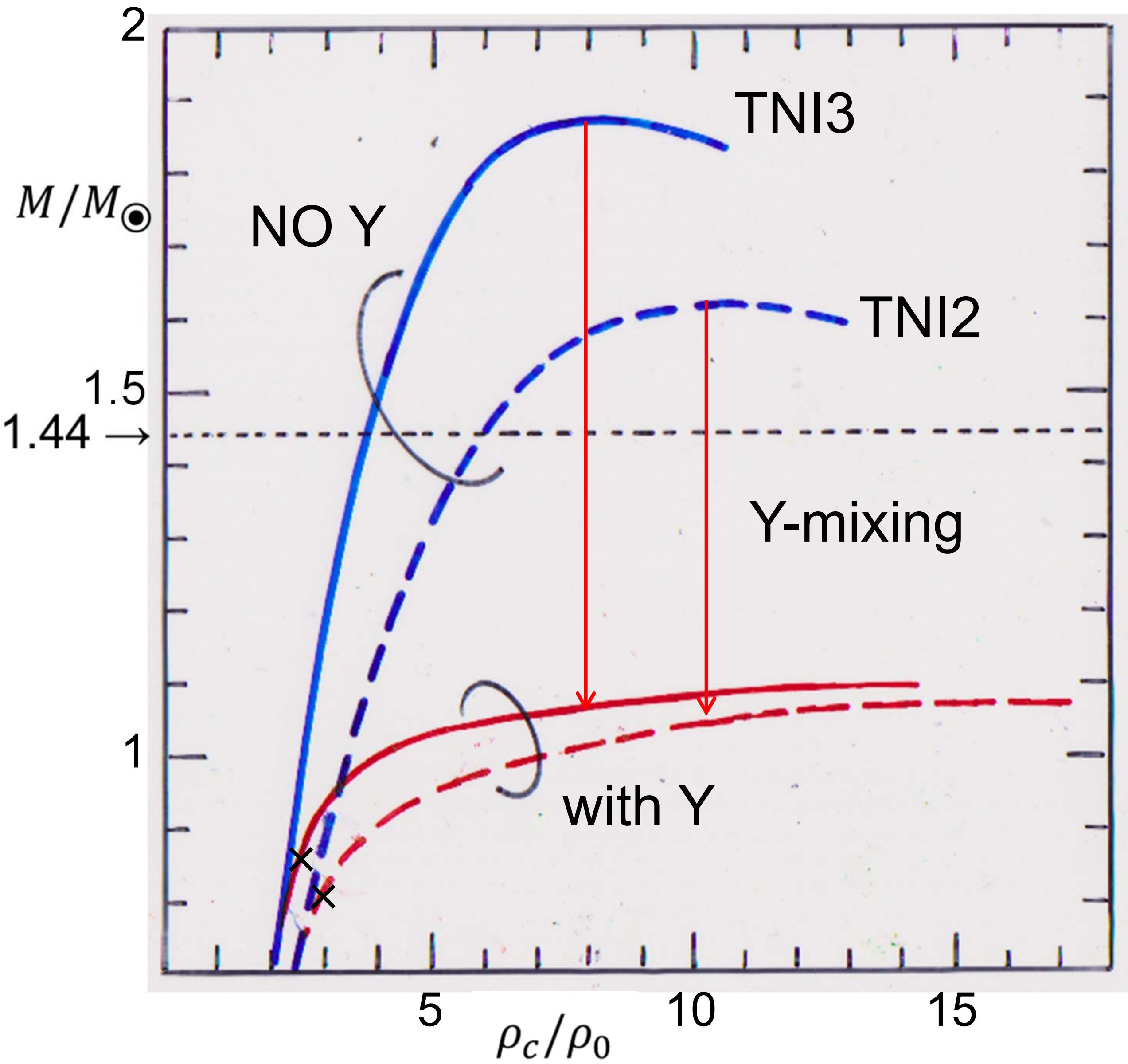
(2) Too rapid cooling

$\longrightarrow$ 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

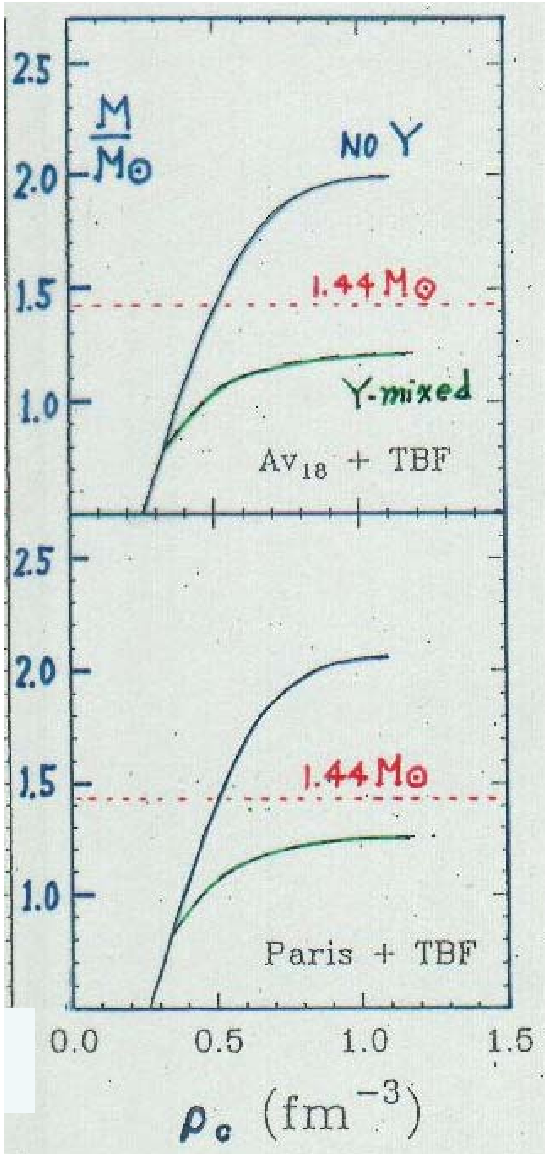
$\longrightarrow$ Problem 2

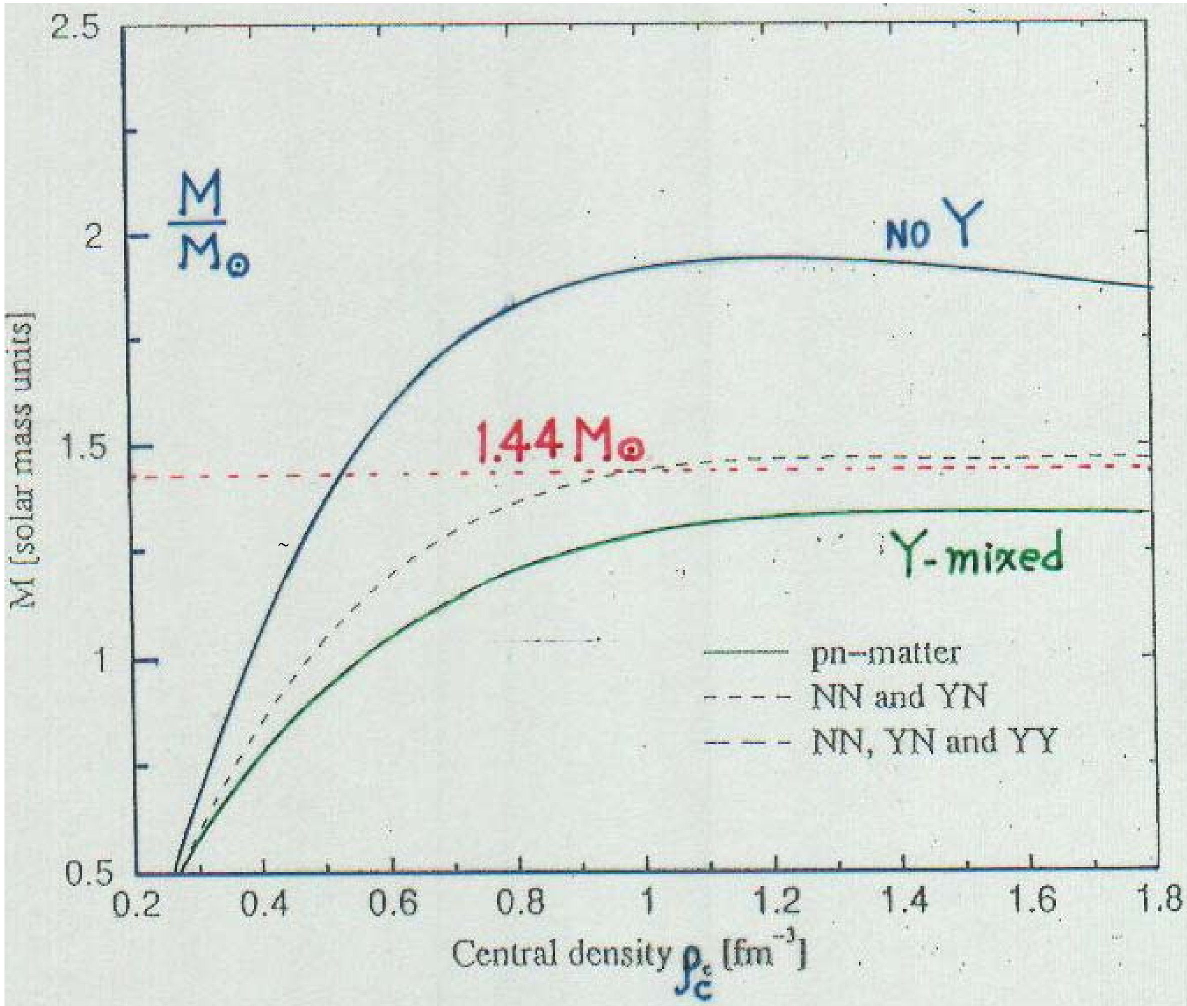
$M_{max} < M_{obs}$(Softened EOS by Y)



(1)

Strong Softening of the EOS

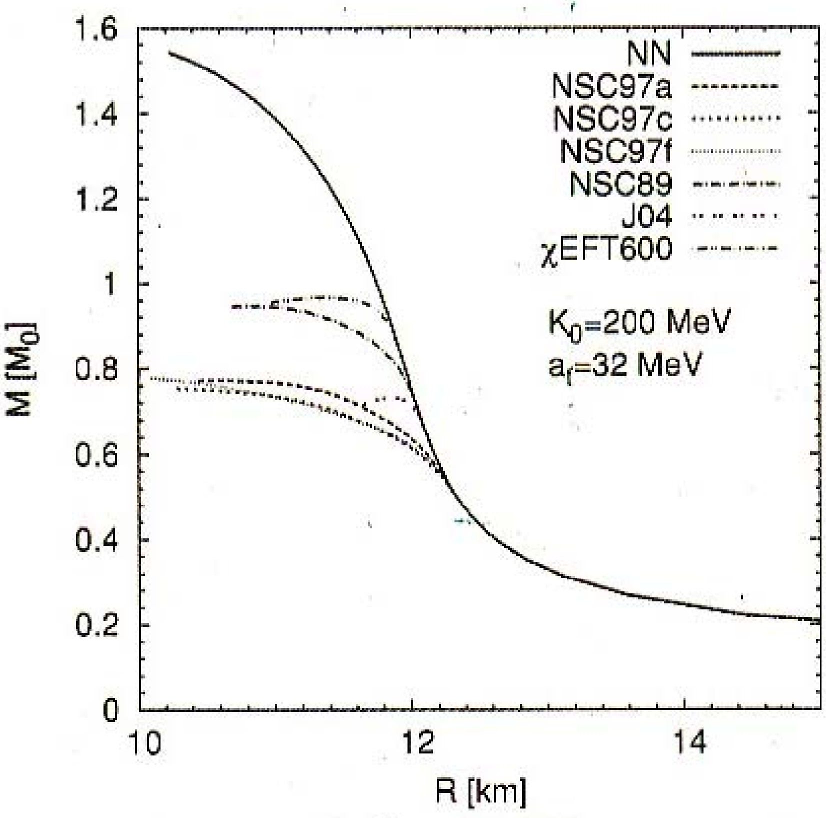




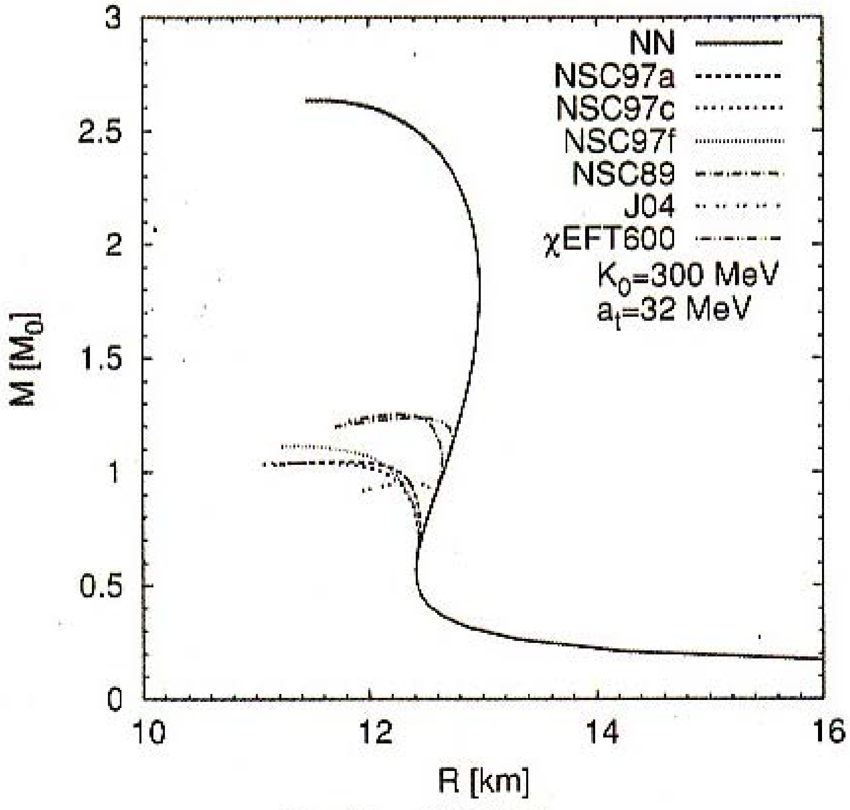
↑ L-Vidana et al, P.R. C62 (2000) 035801

← 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

(2) Too rapid cooling

NS cooling due to ν-emission

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

○ Modified URCA (Murca) --- Standard (slow)

• $n + n \to p + n + \ell + \bar{\nu}_\ell$; $(\ell = e^-, \mu^-)$

○ Direct URCA (usual β-decay type) --- Non-standard (fast)

• $n \to p + \ell + \bar{\nu}_\ell$, $p + \ell \to n + \nu_\ell$ (N-Durca)

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

• $\Lambda \to p + \ell + \bar{\nu}_\ell$, $p + \ell \to \Lambda + \nu_\ell$ (Y-Durca)

• $\Sigma^- \to \Lambda + \ell + \bar{\nu}_\ell$, $\Lambda + \ell \to \Sigma^- + \nu_\ell$ (〃)

Y-cooling

○ ε_ν (Durca) $\sim 10^6\ \varepsilon_\nu$ (Murca)

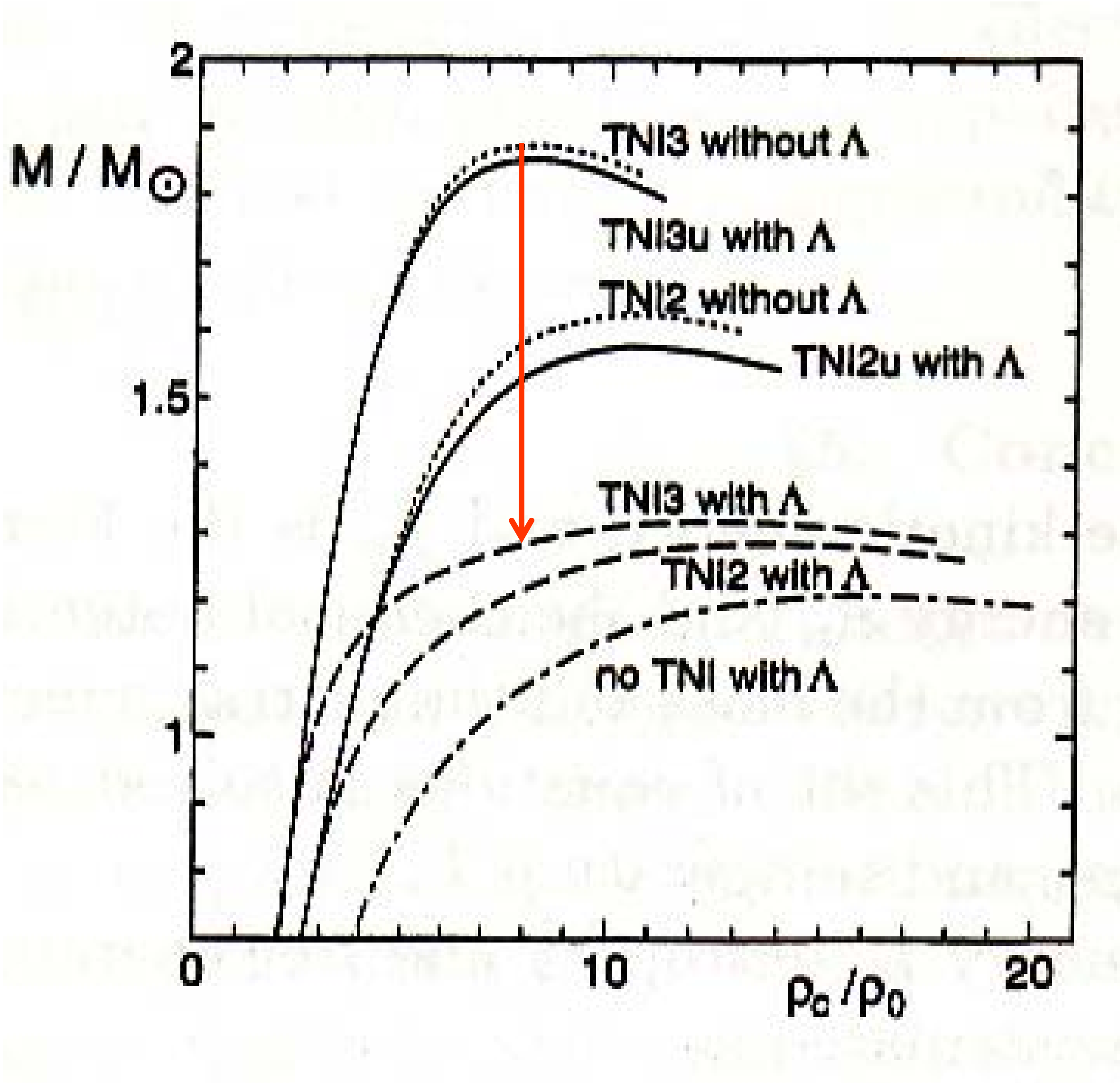
○ But, if directly applied, it causes a serious problem of " too rapid cooling " incompatible with NS surface-temperature observations.

- 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.)

○ 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

Even Λ-only mixing, situation is the same!



3. Possible solution for the problem

Problem 1:

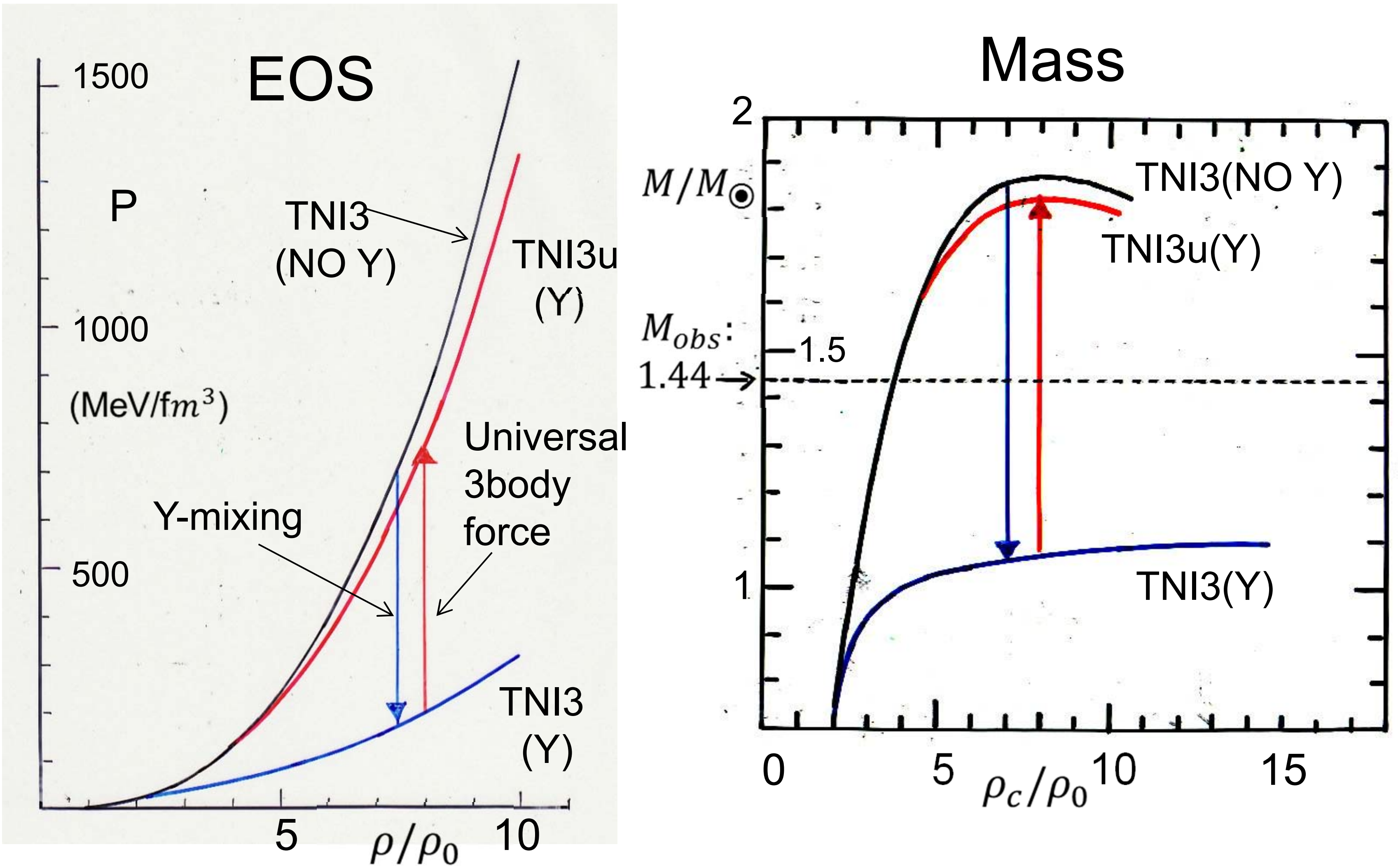
Dramatic softening of EOS⟶

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

Comment 1 :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]

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[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

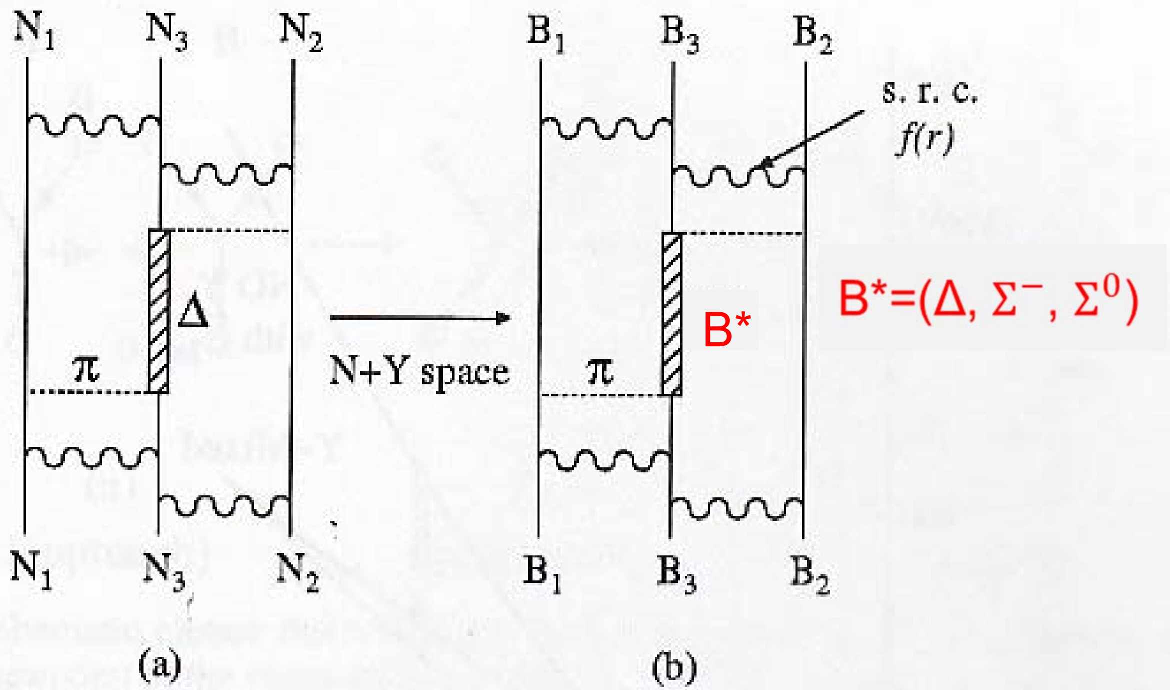
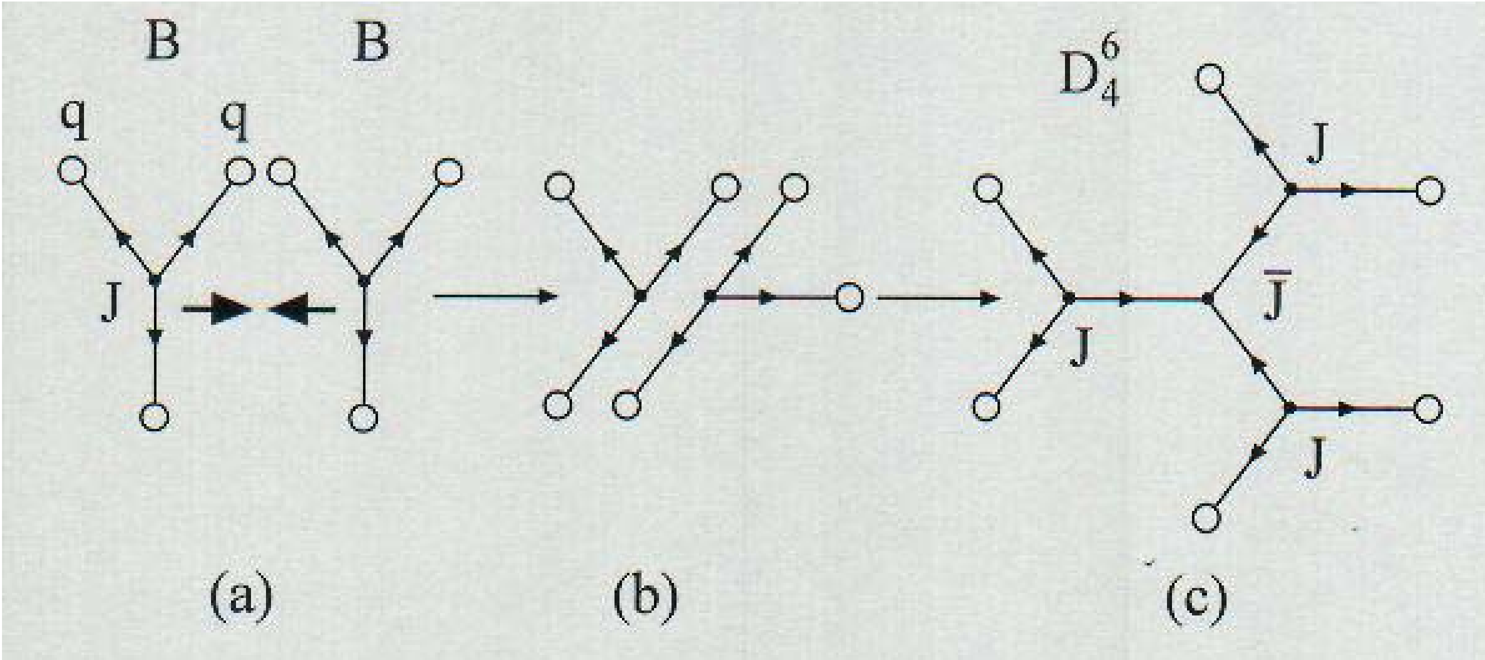


FIGURE 2. Extension of 3-body force from 2π-exchange via Δ excitation type ($2\pi\Delta$) in N-space (a) into $\{N+Y\}$ space (b), where B^* stands for Δ, Σ^{*-}, Σ^{*0} and $f(r)$ is the short-range correlation function.

○ 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

Repulsion from SJM-----flavor independent

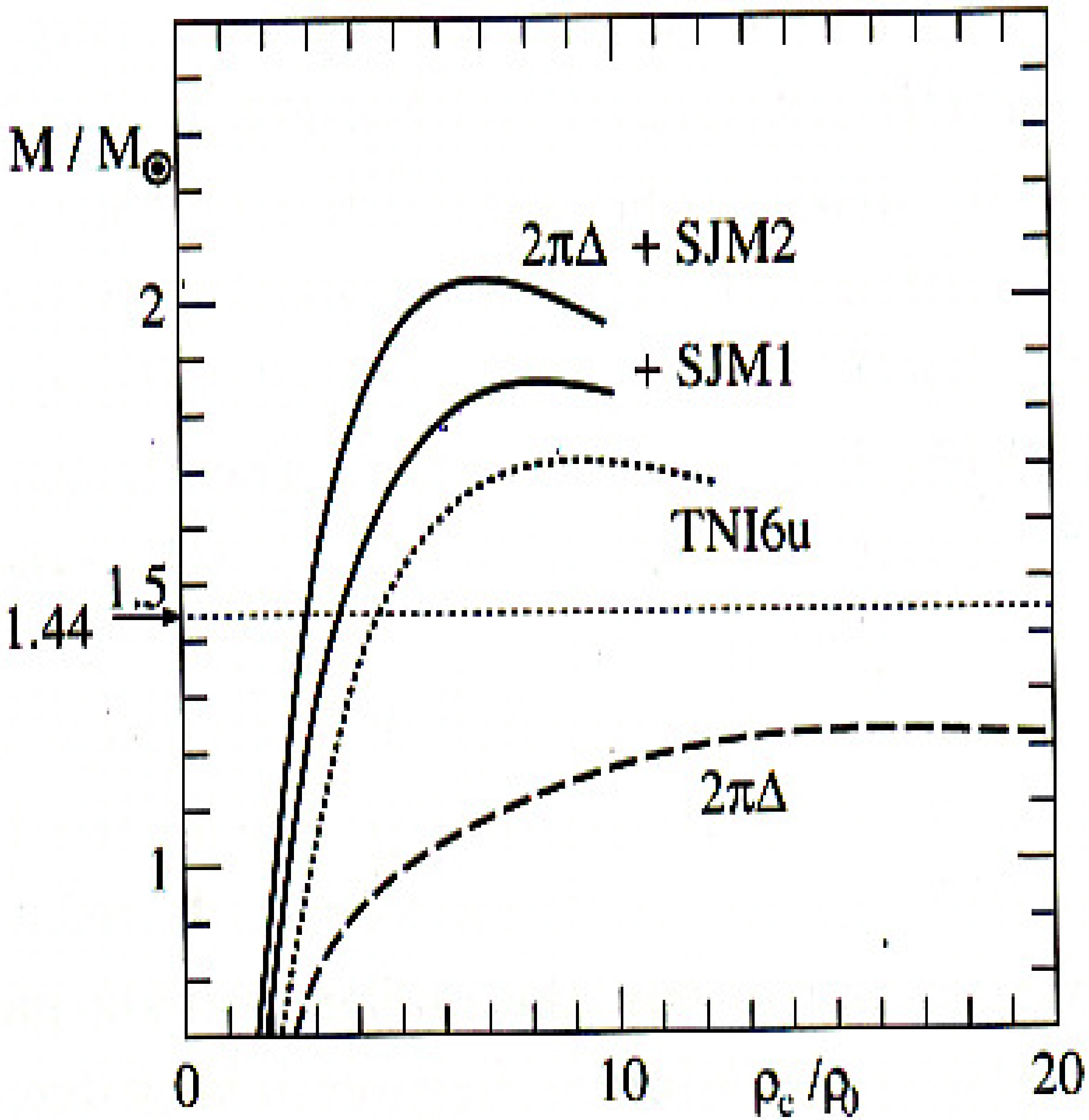


(a) 2B come in short distance
(b) Deformation (resistance)
(c) Fusion into 6-quark state

(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.

Comment 2 : Quark degrees of freedom

2M$_{sun}$ NS → high central density

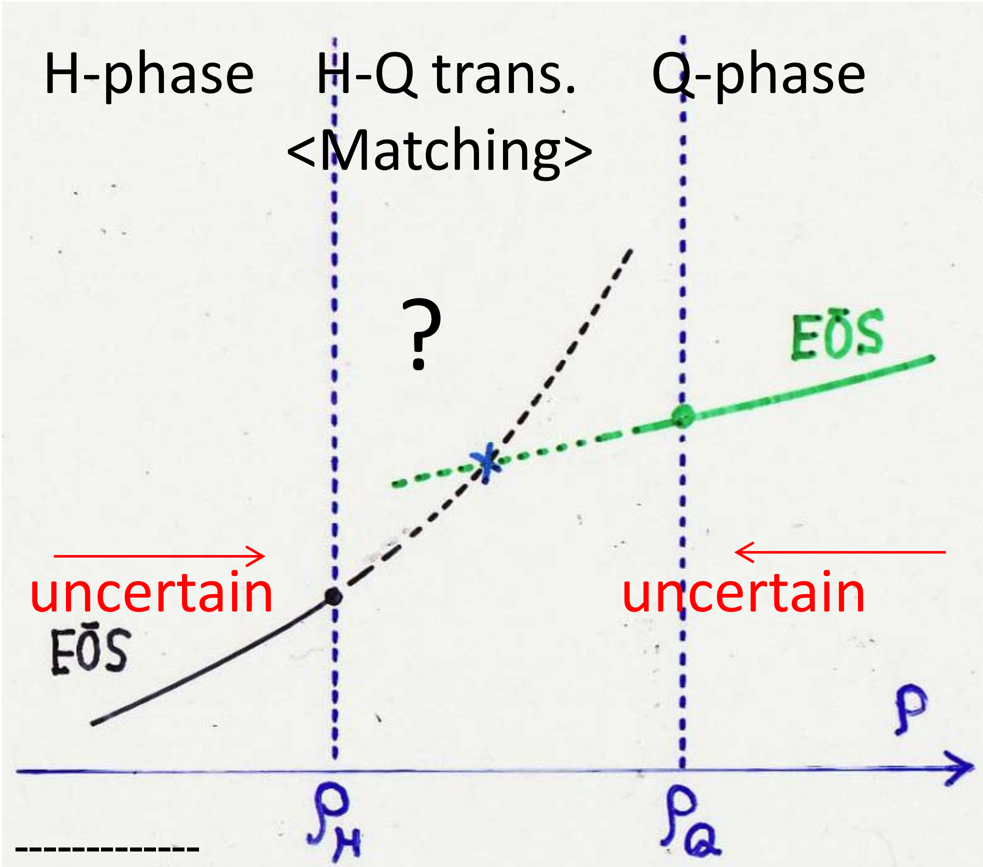
→ possibility of a hybrid star

From a view of "smooth crossover" in the hadron - quark phase transition, a possibility of hybrid stars (NSs with quark matt. core)

Is disscused→ 2M$_{sun}$ is possible under the conditions ;1) crossover proceeds in rather low densities,2) strongly correlated quark 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

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*) [6] T. Takatsuka, T. Hatsuda and K. Masuda, Proc. of "OMEG11" (Nov.14-17, 2001, RIKAEN)

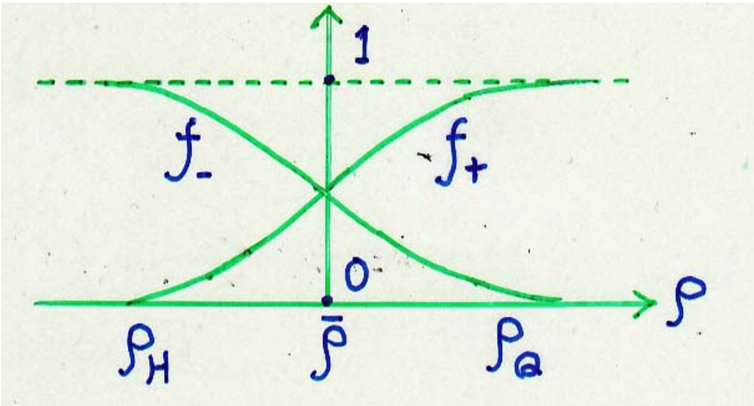
[7] K. Masuda, T. Hatsuda and T. Takatsuka, arxiv:1205.362 [nucl-th.]

☐ Interpolation between H- and Q-phases

○ 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

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

□ Quark Matter phase

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

$$L_{NJL} = \bar{q}(i\not{\partial} - m)q + \frac{1}{2} G_S \sum_{\alpha=0}^{8} \{(\bar{q}\lambda^{\alpha} q)^2 + (\bar{q}\lambda^{\alpha} i\gamma_5 q)^2\}$$
$$+ G_D \{det\bar{q}(1+\gamma_5)q + h.c.\} - \frac{1}{2} g_V (\bar{q}\gamma^{\mu} q)^2$$

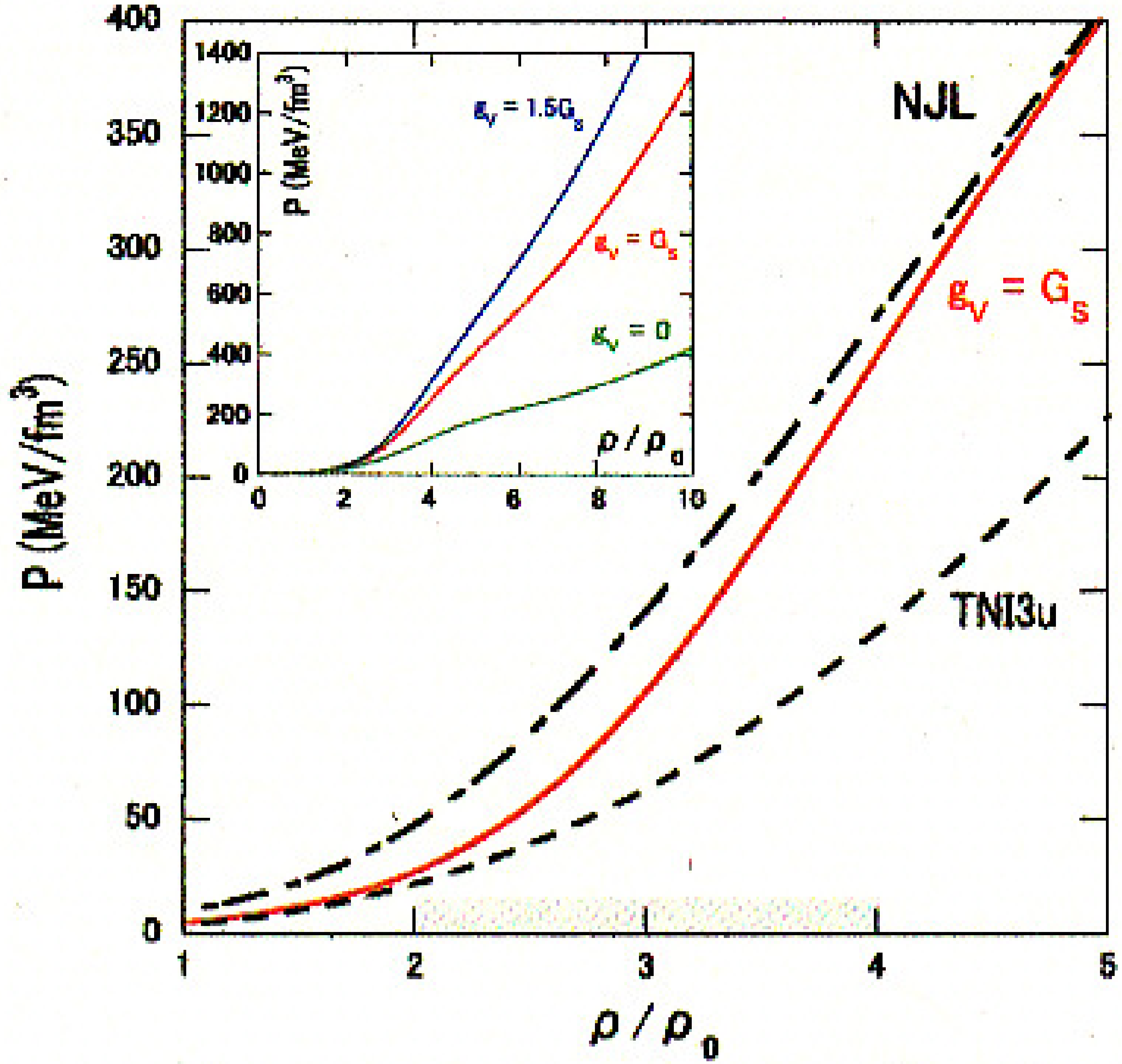
with $q \equiv \{q_i; i = u, d, s\}$ $m \equiv \{m_i\}$

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

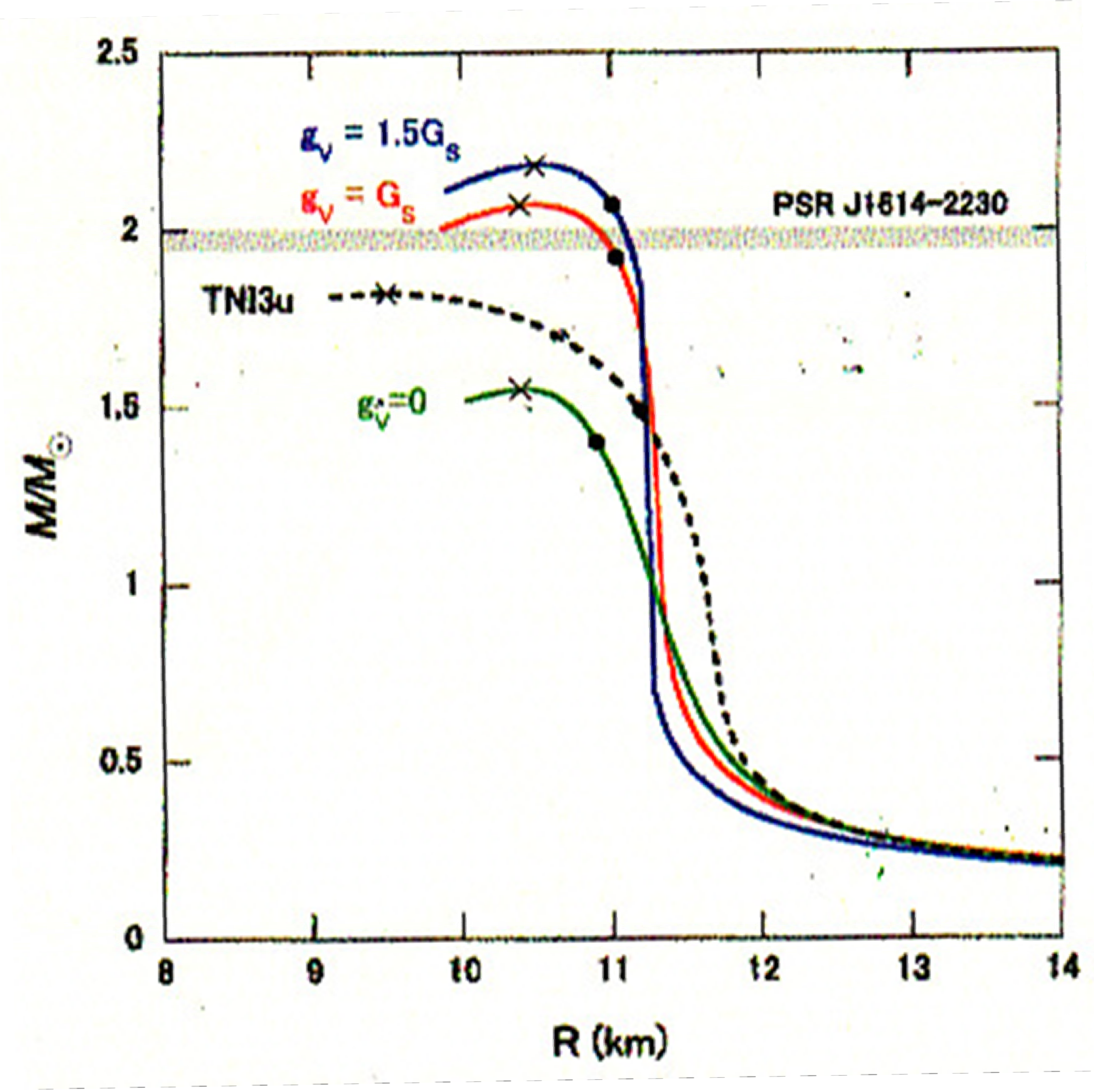
Λ = 631.4 MeV, $G_S \Lambda^2 = 1835$, $G_D \Lambda^2 = 9.29$
$m_u = m_d = 5.5$ MeV, $m_s = 135.7$ MeV

○ 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

Problem 2 :

Too -rapid cooling → Hyperon superfluidity

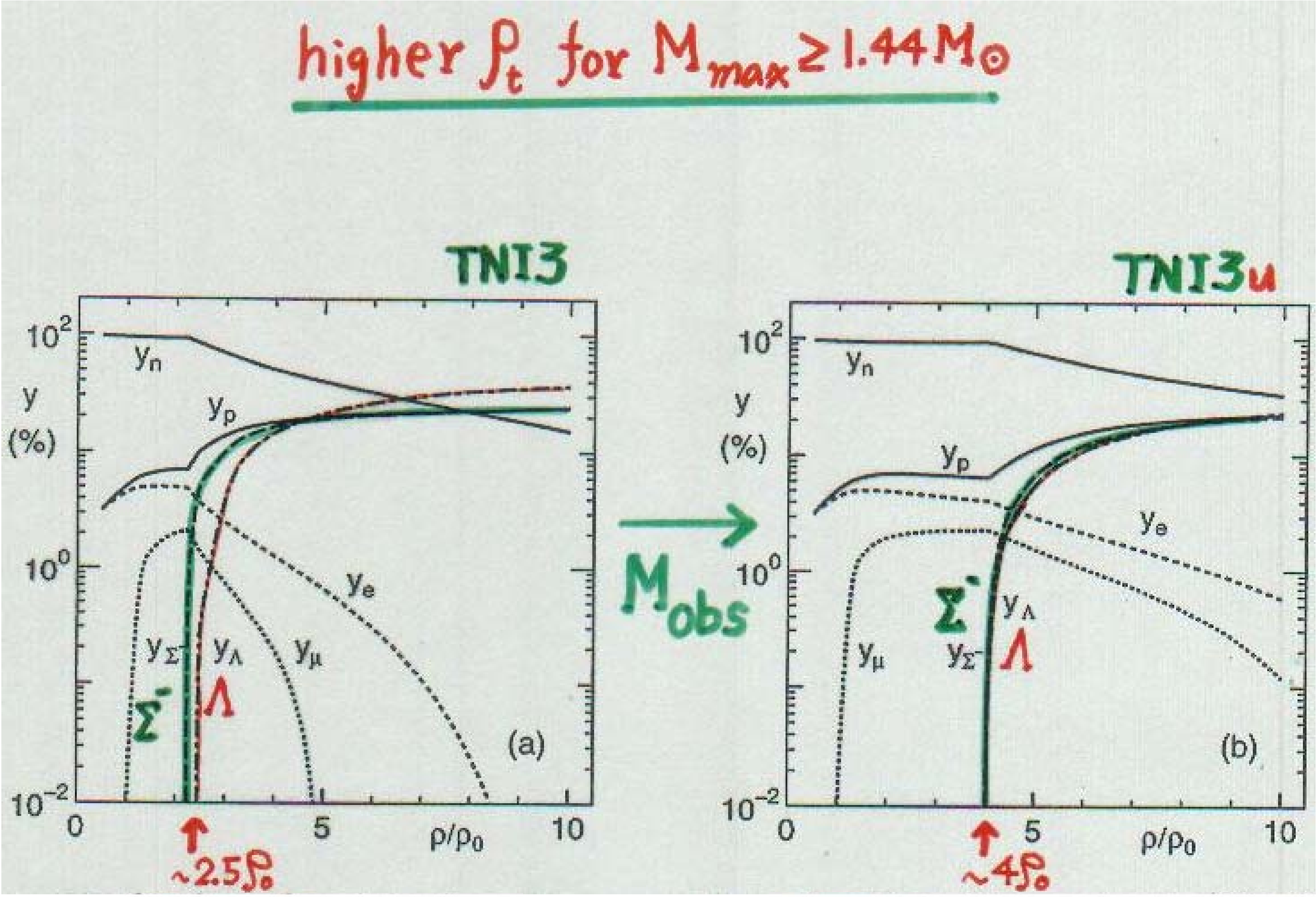
NSs with M> 1.35 M_{sun} have a Y-mixed core. If Y-superfluidity is realized ,it suppresses the efficient ν-emmision by Y-Durca ($\exp(-\Delta/T)$)

→ moderate cooling consistent with colder class NSs

That is, a new scenario is

Lighter NSs → standard slow cooling of MUrca

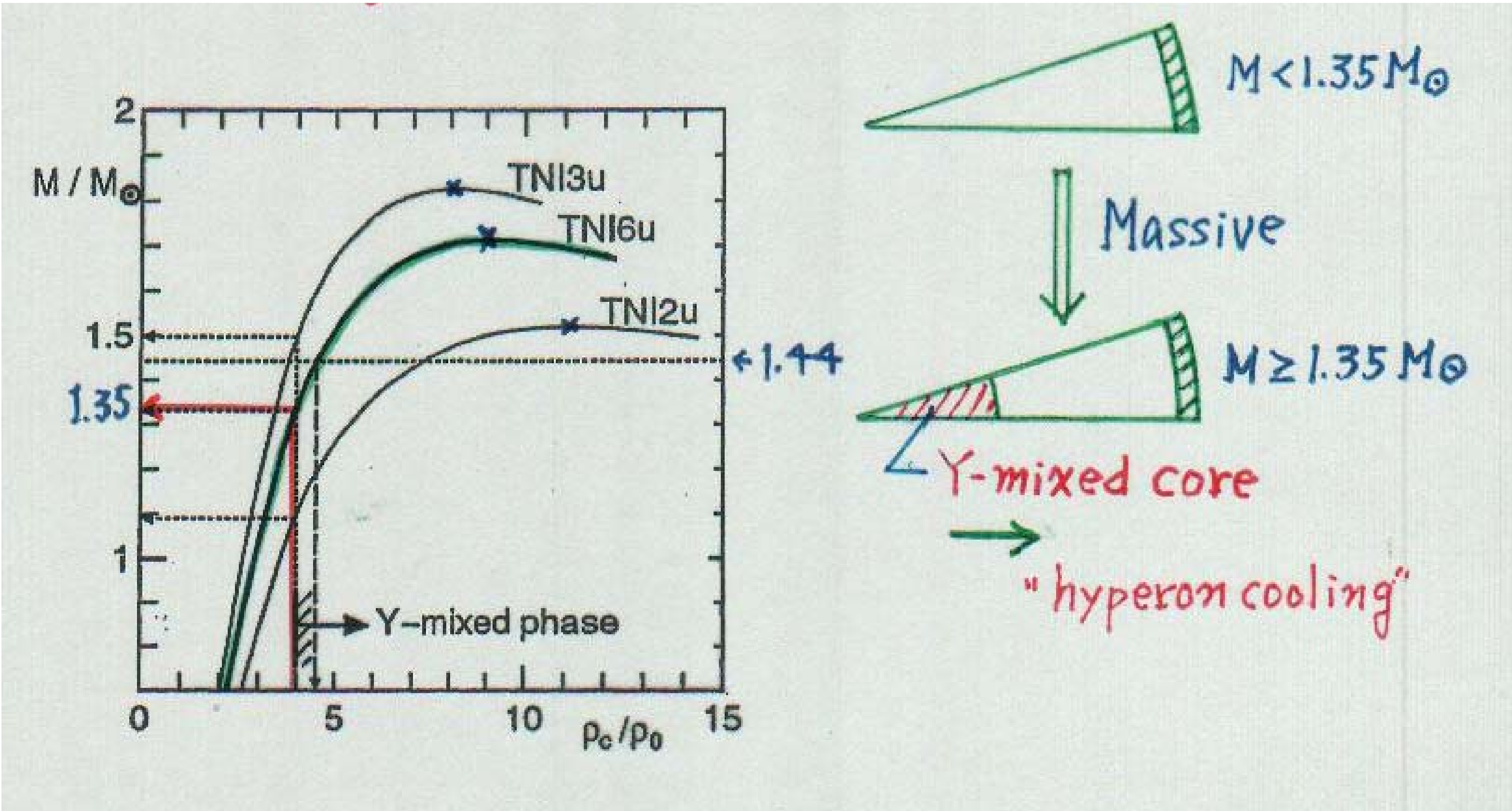
Heavier NSs → nonstandard fast cooling of YDurca ("hyperon cooling")

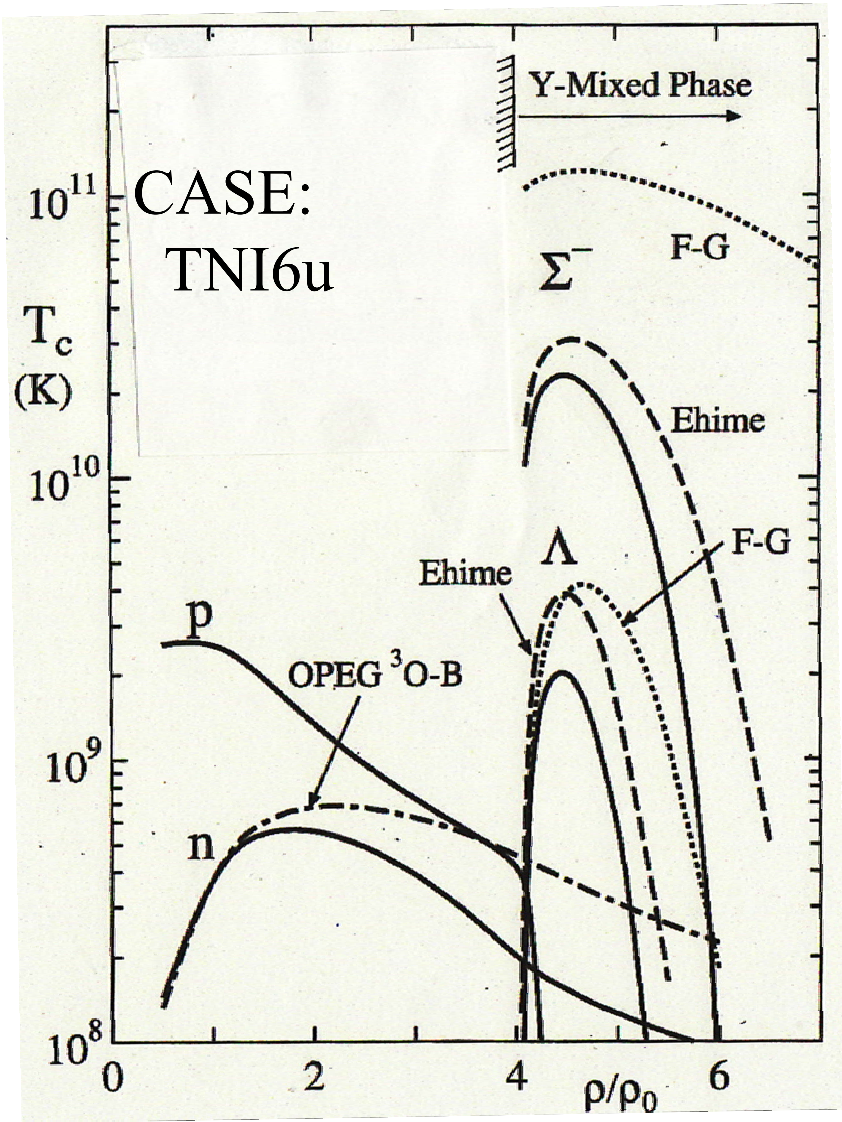


→ Y-mixed star for $M > M_{\odot}$

→ Y-mixed star for $M > 1.4M_{\odot}$

With or without Y-mixed core depends on M

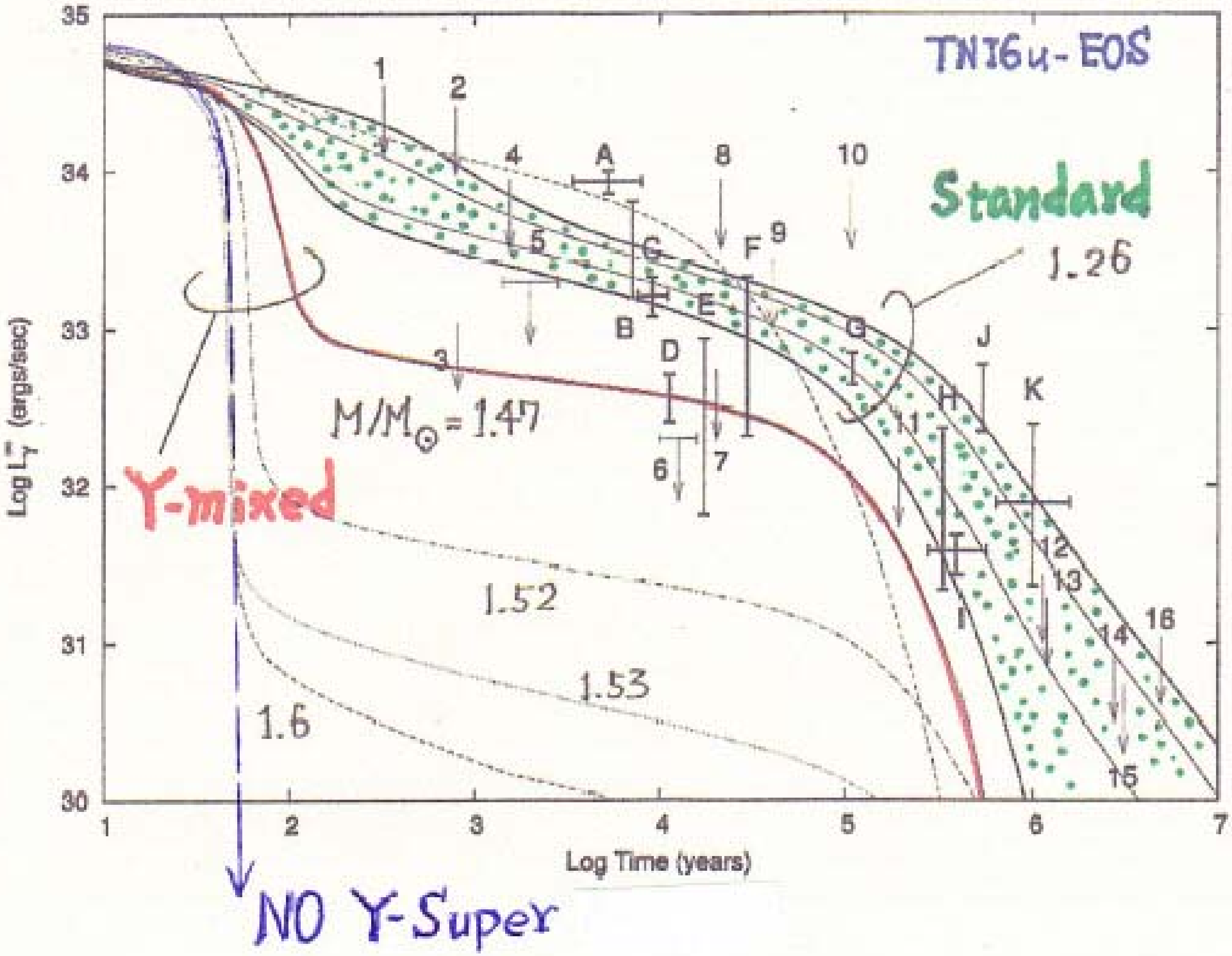




Critical Temperature T_c versus Density ρ

- □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



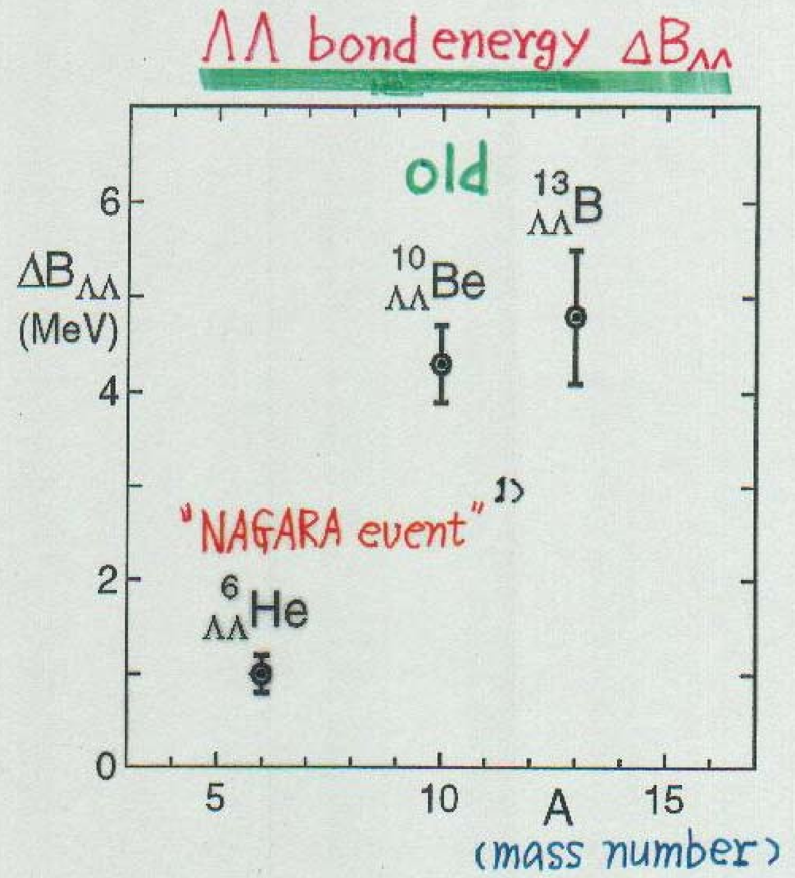
NO Λ-super ⇒ Too-rapid cooling →
break down of the hyperon cooling scenario

How to overcome the problem ?

NO Λ-super due to
"NAGARA"

1) "NAGARA event" → directly means "less attractive ΛΛ interaction?

- How about the A-dependence of ΛΛ bond energy?
- Repulsive effects of 3-body force?

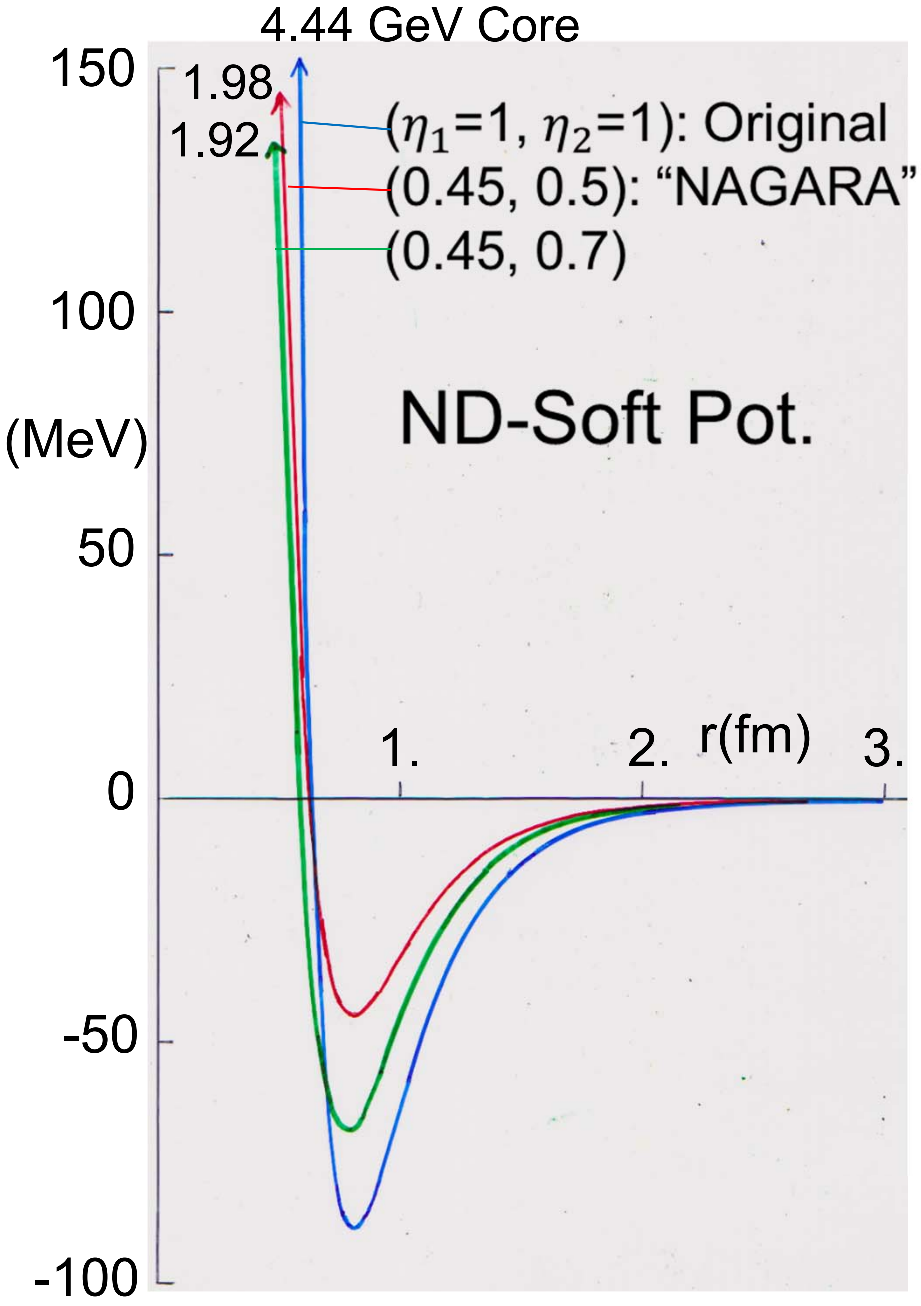


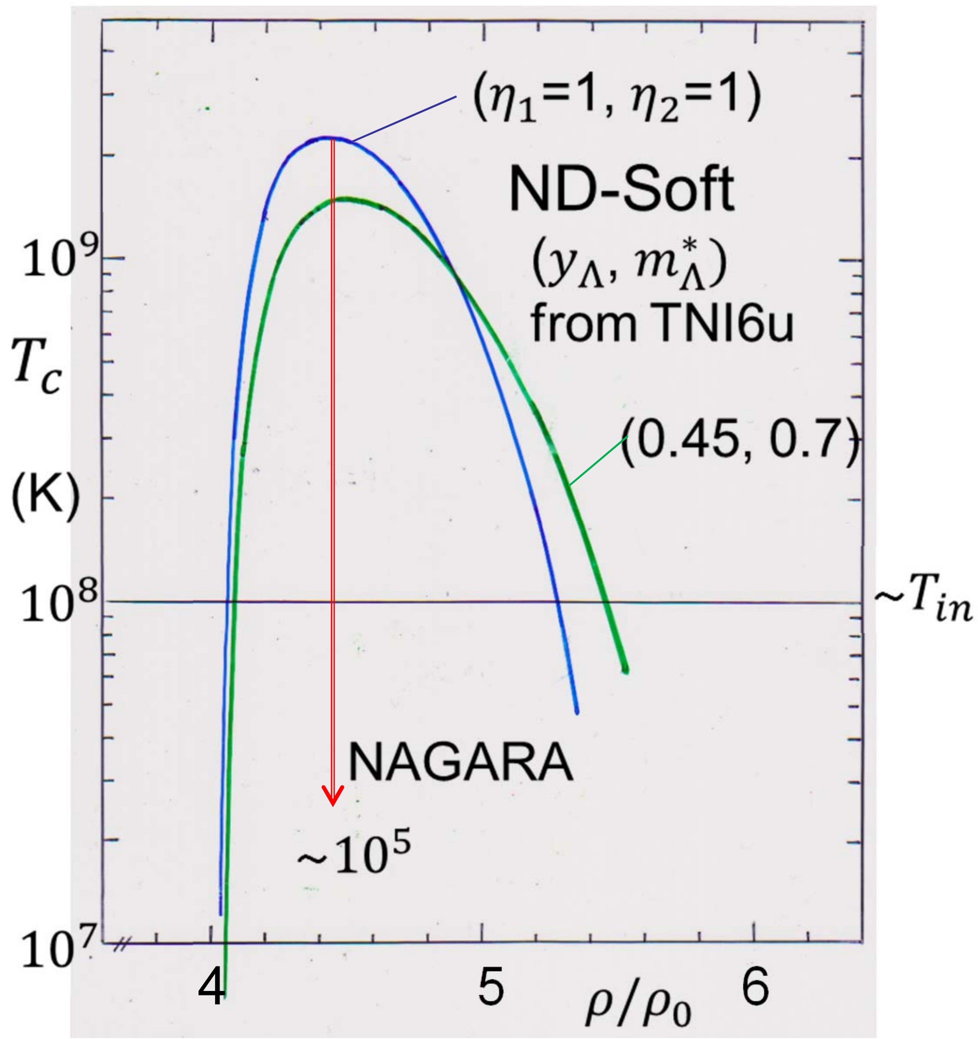
$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2 \times B_{\Lambda}({}^{A-1}_{\Lambda}Z)$

	$\Delta B_{\Lambda\Lambda}$ (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[...]

Critical Temperature T_c v.s. ρ





Brief summary 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,3C58,CTA-1,Geminga,Vela,Vela-twin ---)

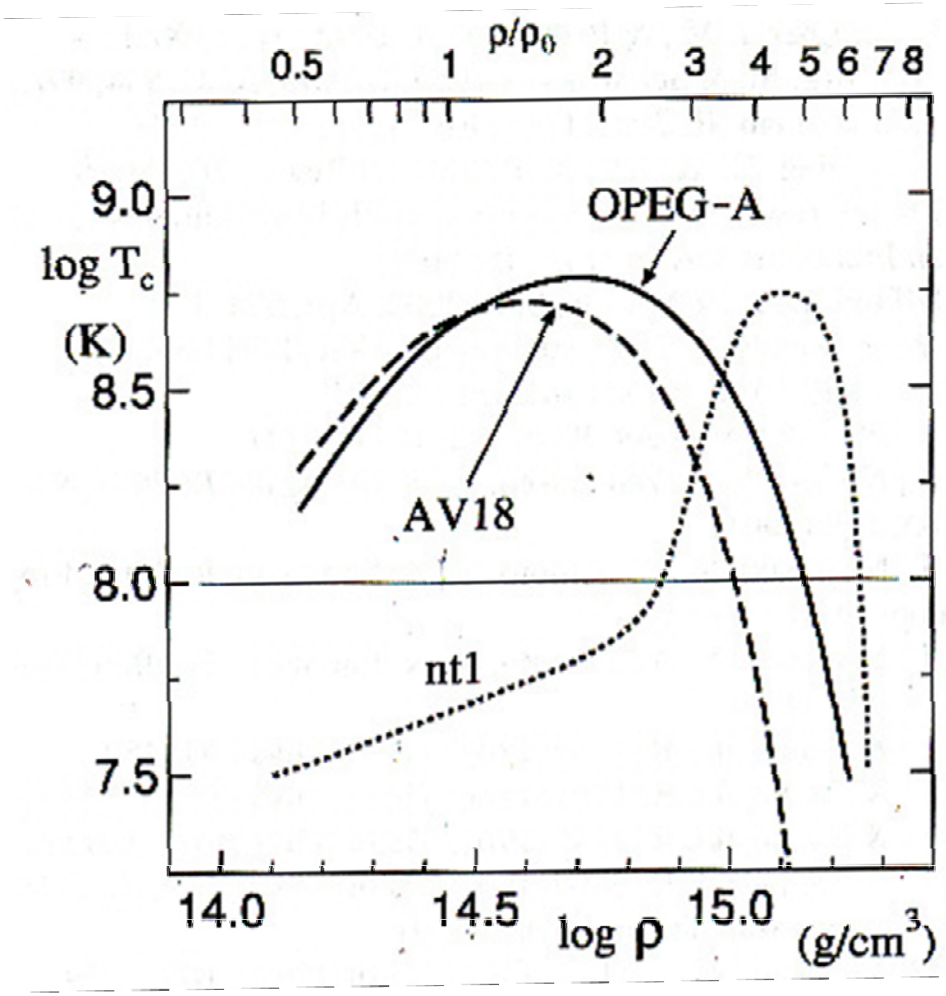
☐ Cooling Model

○ 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 !



← Critical temperature of 3P2-Superfluid

- nt1 from Gusakov, et al., A&A, 423 (2004) 1063.
- Extraordinal density dependence of 3P2-gap

☐ Summary

NS obs. $\underset{\longleftarrow}{\overset{\text{feedback}}{\longrightarrow}}$ Theory

<table>
<tr><td colspan="2" rowspan="2">Theory
(with exp.)</td><td colspan="2">Old standard (n, p, e^-, μ^-) $\rightarrow$ New standard (n, p, Y, e^-, μ^-)</td></tr>
<tr><td>Dramaticly softened EOS</td><td>Extremely efficient ν-emission</td></tr>
<tr><td colspan="2">Obs.</td><td>$2M_\odot$-NS !</td><td>Cooler NSs !</td></tr>
<tr><td rowspan="2">challenges to solution and open problems</td><td>H</td><td>・Universal 3-body force (→OK)
・What is the origin
(→ new subject)
・Other candidates?</td><td>・Y-Durca + Y-super (→OK)
・"NAGARA"→ NO Λ-super
(→ breakdown of the scenario?)
・Very sensitive to ΛΛ int.
(→ demands (A-dep.,?
effects missing in ΛΛ?))</td></tr>
<tr><td>H+Q</td><td>・EOS from H-Q crossover
(→ OK), with conditions
(proceeds at (2-4)ρ_0,
strongly correlated q-matter
・instruction from QGP
・Other possibility</td><td>・Most NSs ($M \le 1.9M_\odot$) are free
from Y-Durca(→OK)
・How to explain cooler NSs
(→ open; π cond.?)
・How about ν-emission from H-Q
phase? (→ new subject)</td></tr>
</table>

Remark: We have to solve the two serious problems at the same time !