基研研究会 2012.8.30-9.1

中性子星の構造と状態方程式
―観測が突きつける2つの深刻な問題―

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□2つの深刻な問題（→観測と矛盾）

問題1：EOSの劇的軟化（観測質量と矛盾）

問題2：速すぎる冷却（観測温度と矛盾）

□打開の方向

①ハドロン物質として、②ハドロン＋クォーク物質として

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＊玉垣良三、西崎滋、山本安夫、初田哲男氏、益田晃太各氏との共同研究

Two Serious Problems

(1) Dramatic Softening of NS EOS

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

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

$= (1.97 \pm 0.04)M_{\odot}$ 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

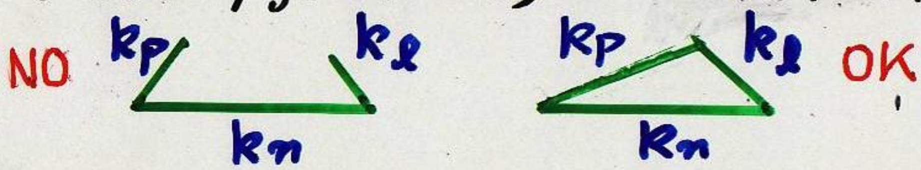
→ Problem 2

☐Problem 2: (2) Too rapid cooling

NS cooling due to ν-emission

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

- ο Modified URCA (Murca) --- Standard (slow)
  - $n + n \rightarrow p + n + \ell + \bar{\nu}_\ell$; $(\ell \equiv e^-, \mu^-)$
- ο Direct URCA (usual β-decay type) --- Non-standard (fast)
  - $n \rightarrow p + \ell + \bar{\nu}_\ell$, $p + \ell \rightarrow n + \nu_\ell$ (N-Durca)
  - ※ usually forbidden, but made possible for $y_p \geq 15\%$



  - $\Lambda \rightarrow p + \ell + \bar{\nu}_\ell$, $p + \ell \rightarrow \Lambda + \nu_\ell$ (Y-Durca)
  - $\Sigma^- \rightarrow \Lambda + \ell + \bar{\nu}_\ell$, $\Lambda + \ell \rightarrow \Sigma^- + \nu_\ell$ (〃)

Y-cooling

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

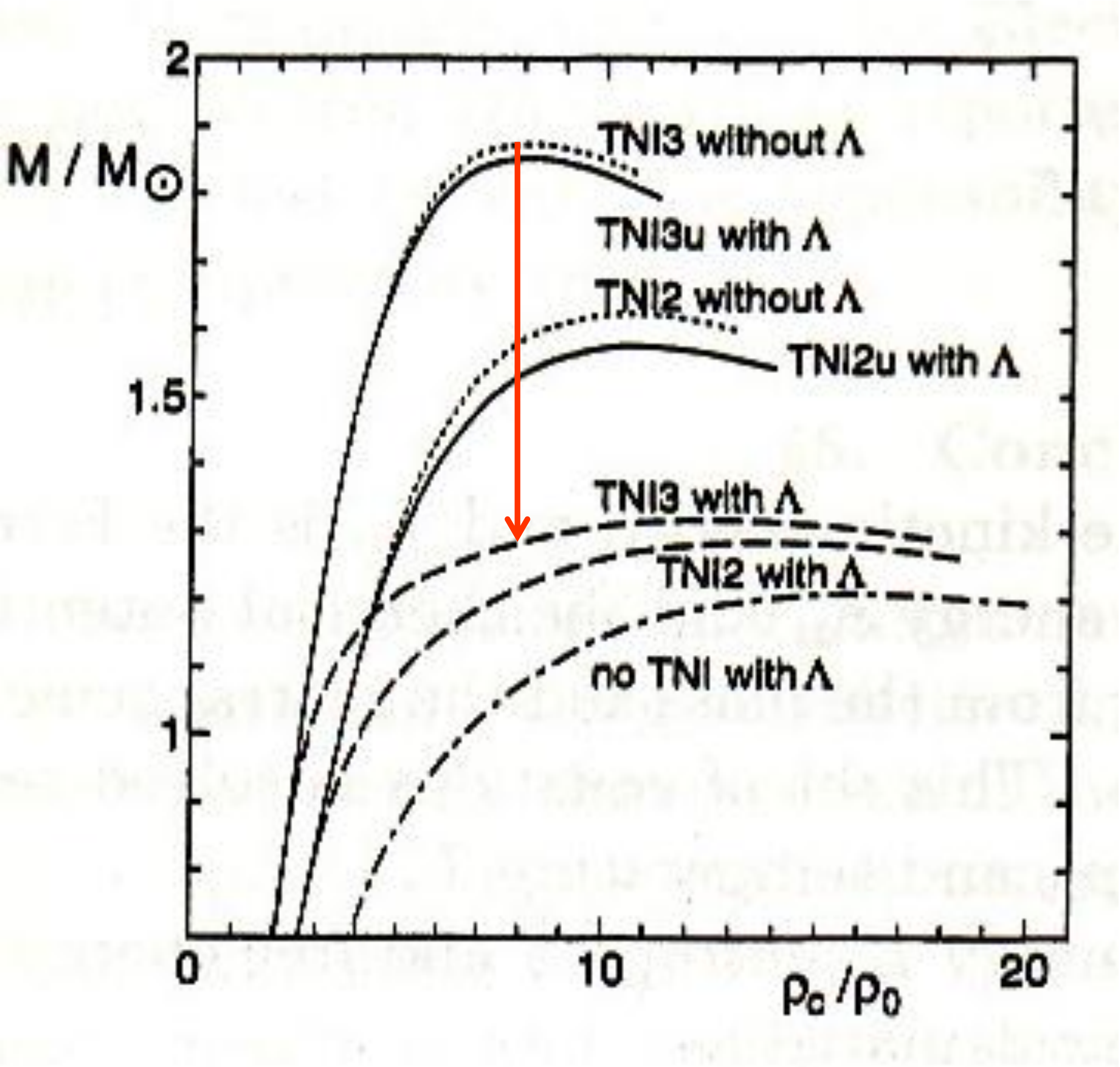
○ These problems are serious because of the points,

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!



Possible solution for the problem

(1) Problem 1: 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 "uneversally" on NN, YN and YY parts (universal 3-body force) is a promising candidate [1][2]

☐ An origin for Universal 3-body force

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

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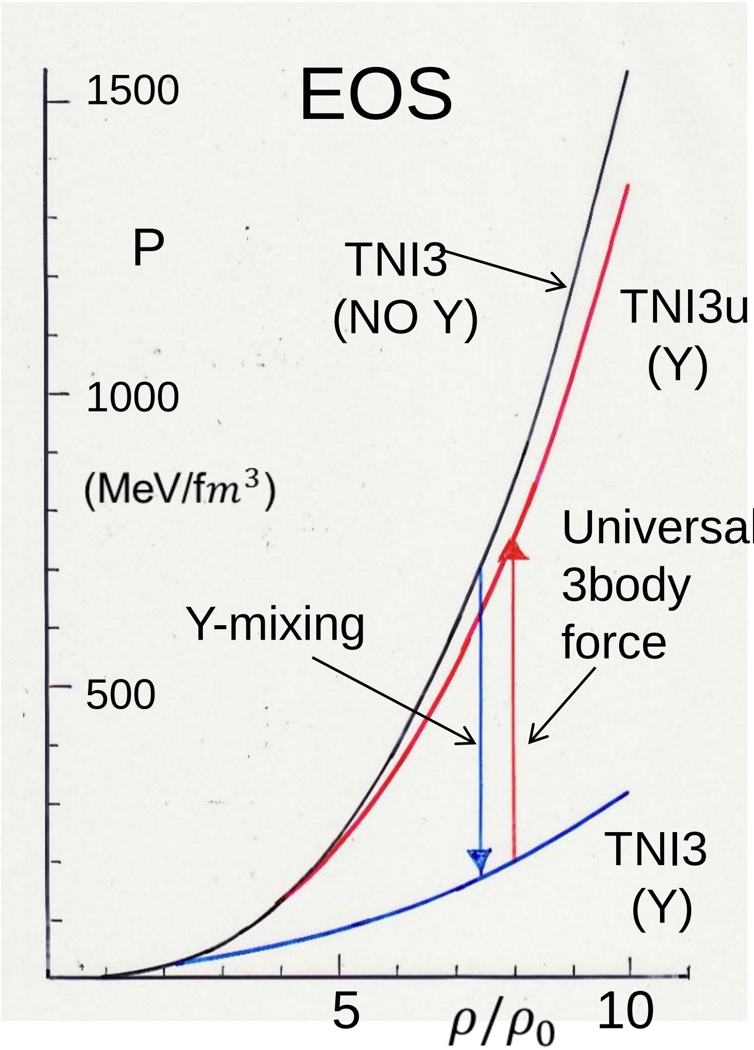
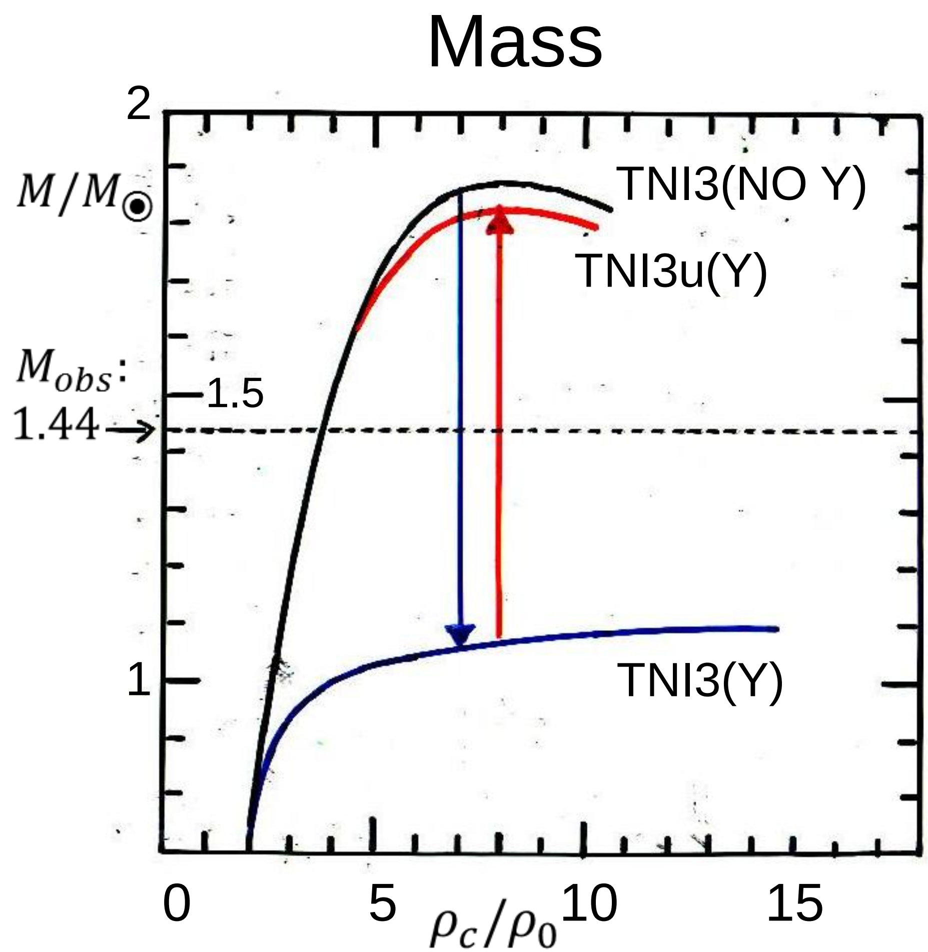
[5] T. Takatsuka, S. Nishizaki and R. Tamagaki, Proc. Int. Symp. "FM50"(AIP Conference proceedings, 2008) 209

Dramatic softening of EOS ⟶ Necessity of "Extra Repulsion"





TNI3 ⟶ TNI3u: Universal inclusion of TNI3 repulsion

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

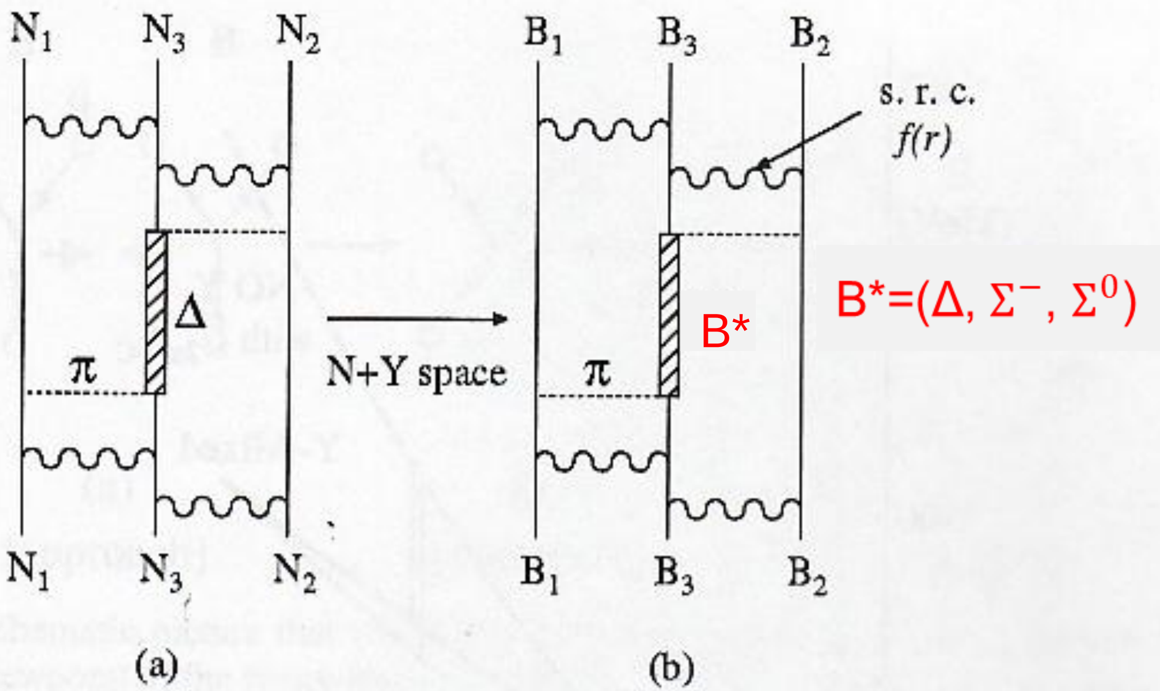
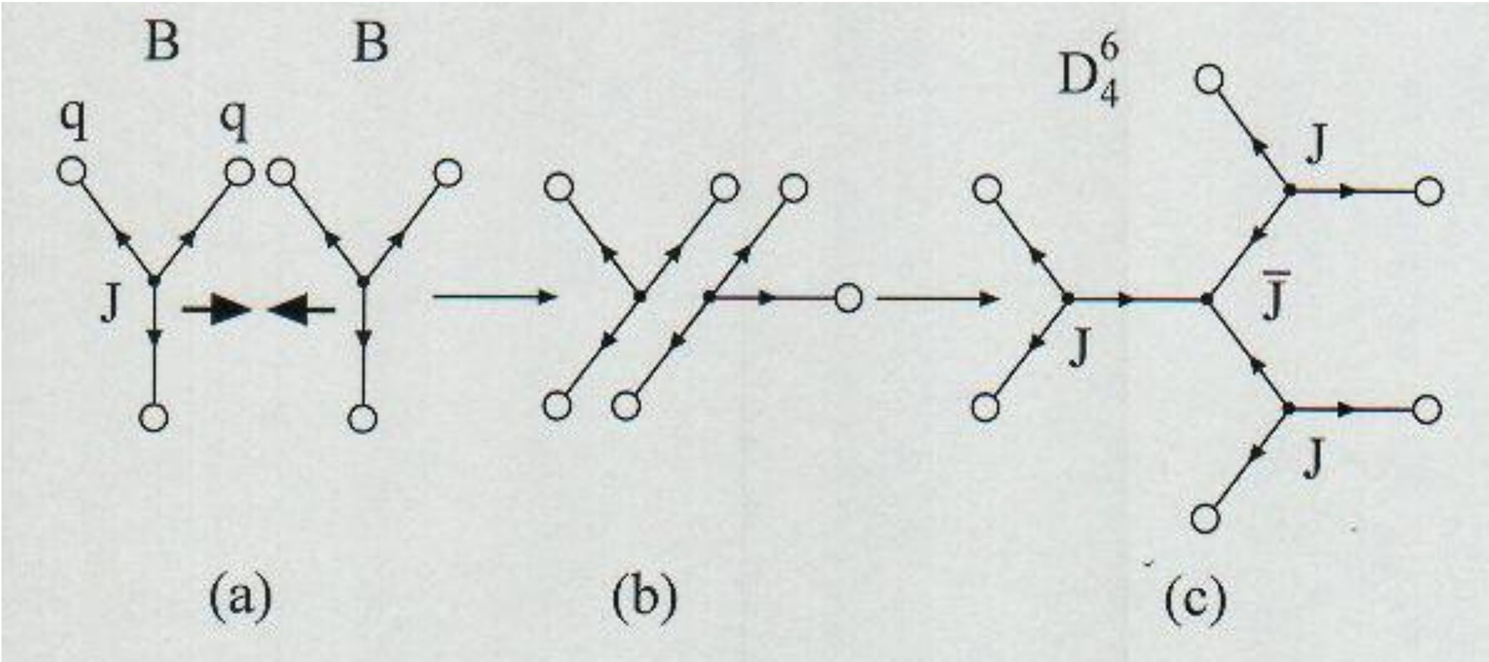


FIGURE 2. Extension of 3-body force from 2π-exchange via Δ excitation type ($2\pi\Delta$) in N-space (a) into $\{N+Y\}$ space (b), where B^* stands for Δ, Σ^{*-}, Σ^{*0} and $f(r)$ is the short-range correlation function.

○ 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
→ universal !

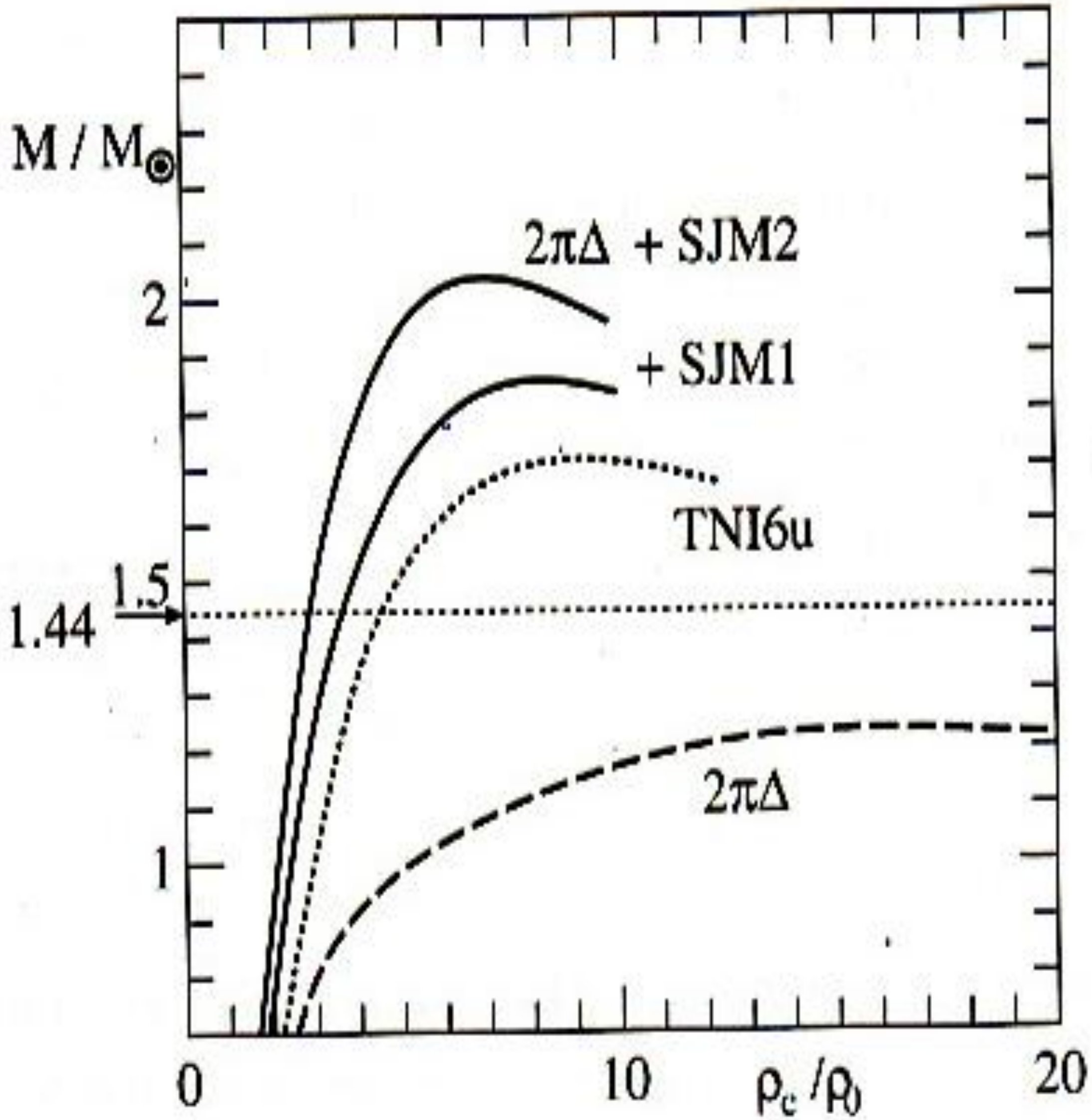


(a) 2B come in short distance
(b) Deformation (resistance)
(c) Fusion into 6-quark state

(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 ($2\pi\Delta$-type + SJM).

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

“Universal 3-body force” means ; “ repulsive and acting irrespective to BB pairs”

(2) Problem 2: Y-superfluidity

- ○ Y-mixing in NS cores → $M > 1.4M_{\odot}$
- ○ Y-superfluidity suppresses the efficient ν-emission by Y-Durca
  → not "too-rapid cooling" but moderate cooling consistent with colder class NSs

□ "NAGARA event" (${}^{6}_{\Lambda\Lambda}He$)

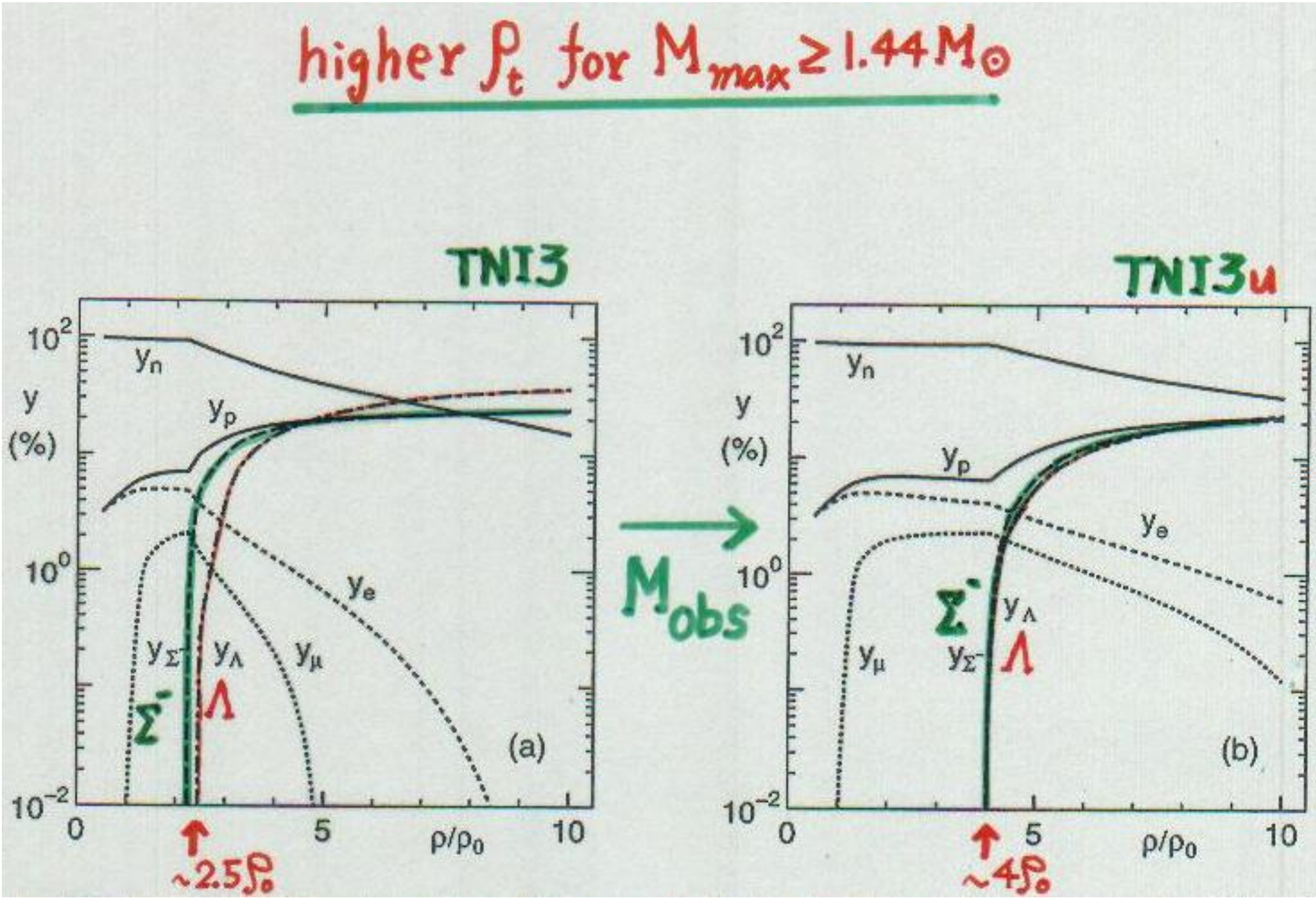
→ less attractive ΛΛ interaction
→ disappearance of Λ-superfluidity
→ break down of Y-cooling scenario

- ○ Direction to overcome the difficulty

☐ 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

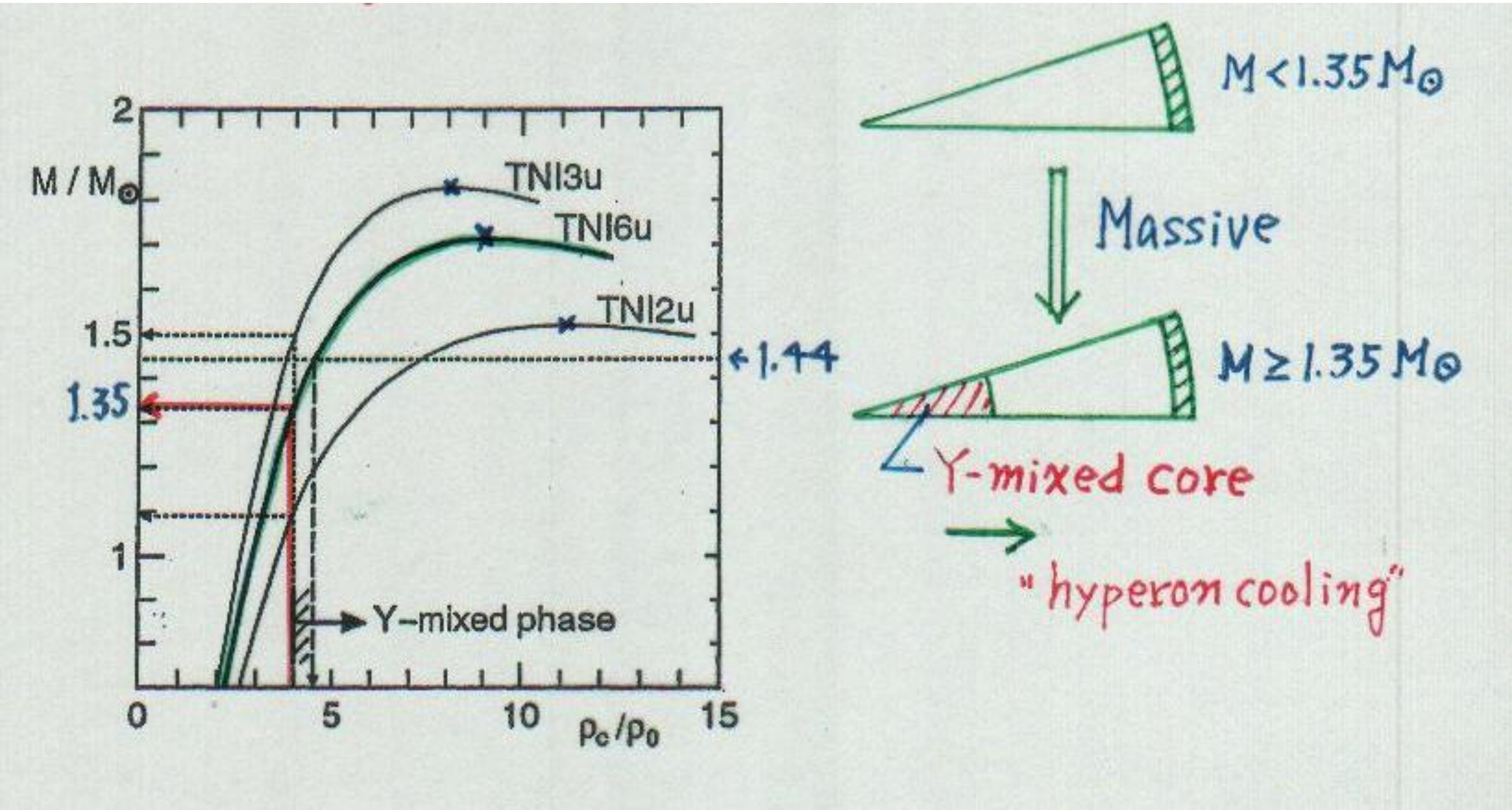
[1] S. Nishizaki, Y. Yamamoto and T. Takatsuka, Prog.Theor. Phys.105 (2001) 607; 108 (2002) 703
[2] T. Takatsuka, Prog. Theor. Phys. Suppl. No. 156 (2004) 84

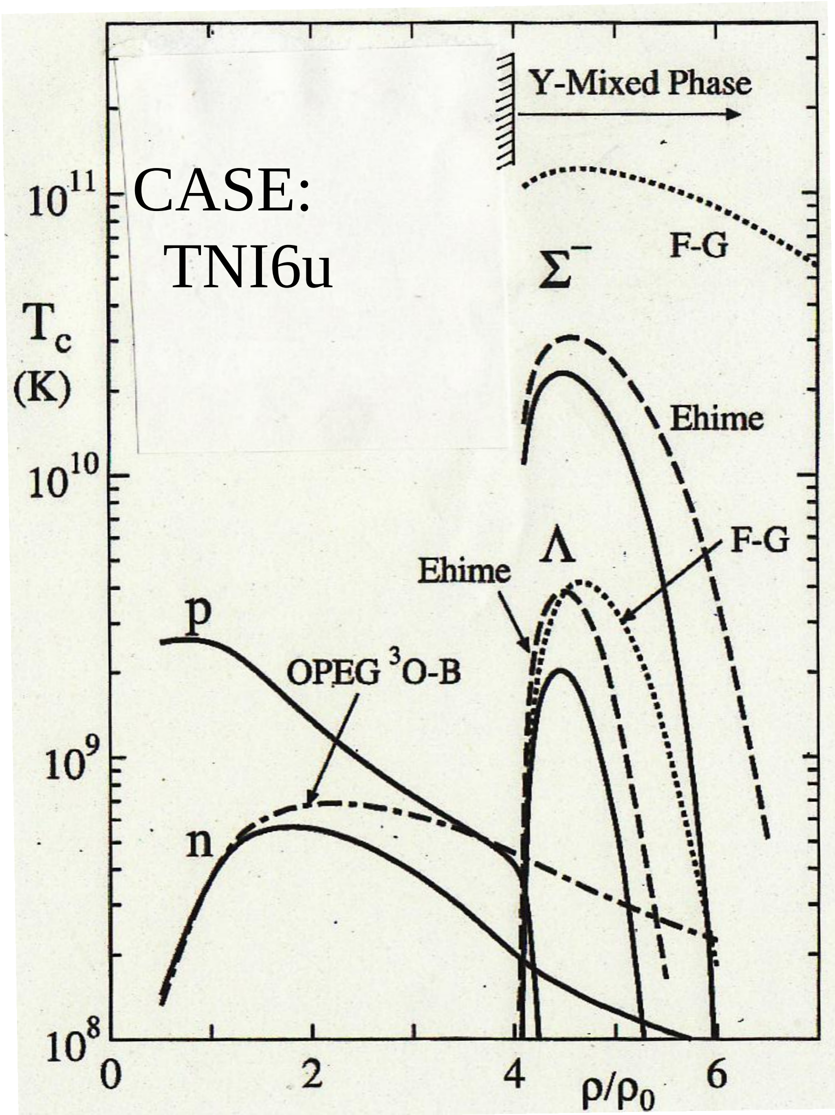


→ Y-mixed star for $M > M_\odot$

→ Y-mixed star for $M > 1.4 M_\odot$

With or without Y-mixed core depends on M

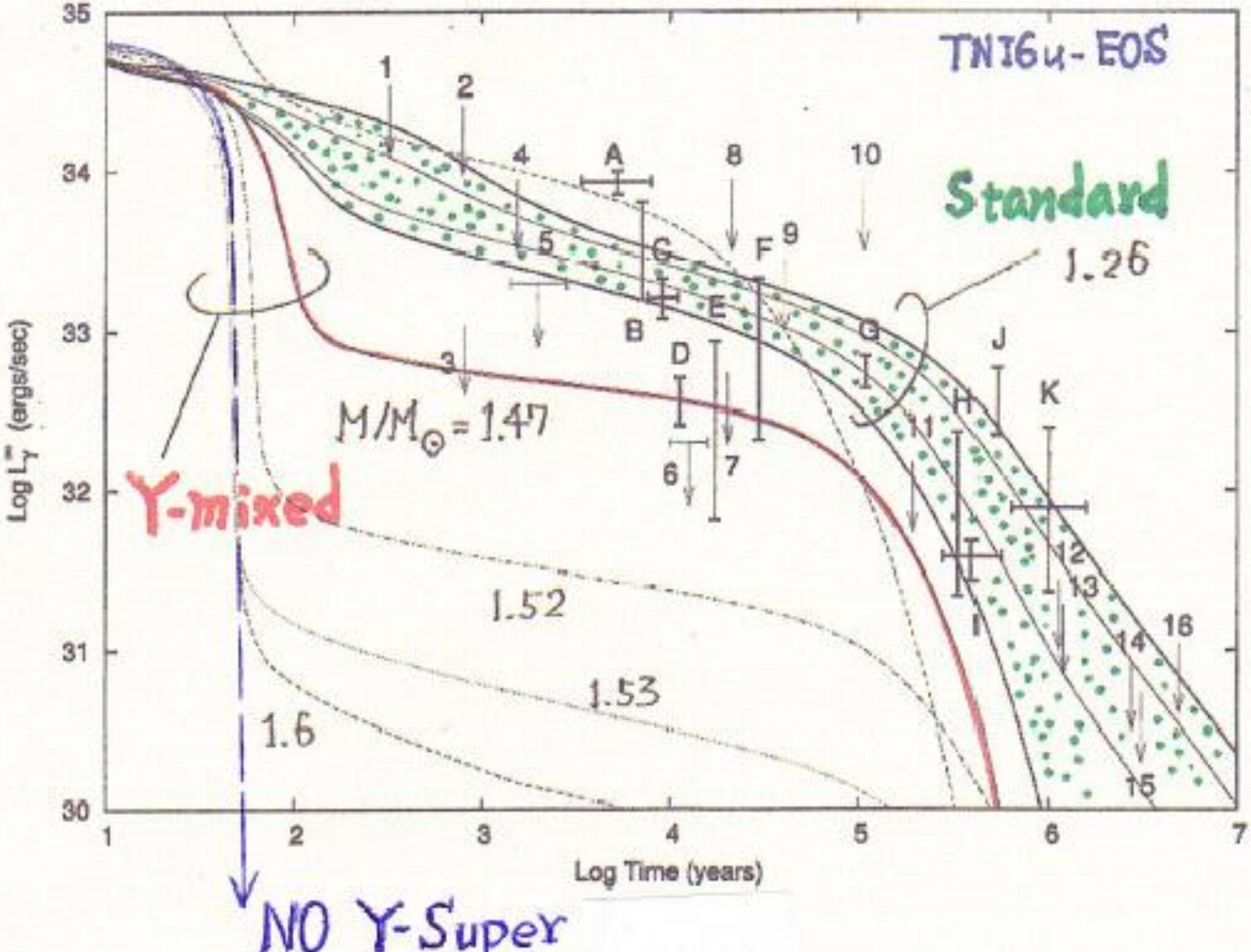




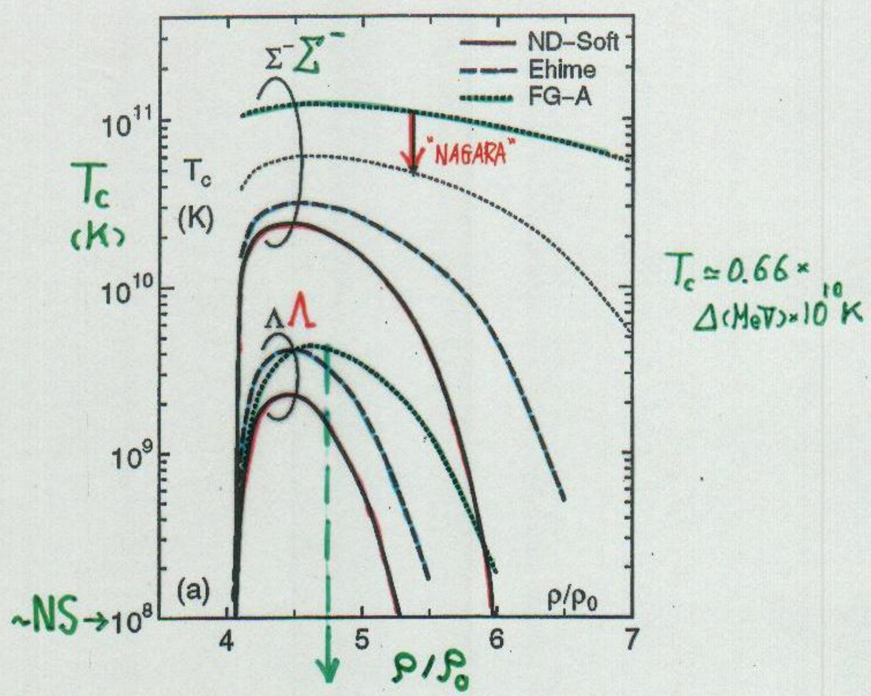
Critical Temperature T_c versus Density ρ

- □Pairing type:
  - n → 3P2
  - p, Λ, Σ^- → 1S0
- □Pairing interactions:
  - n, p → OPEG-A pot.
  - Λ, Σ^- → ND-Soft for solid lines

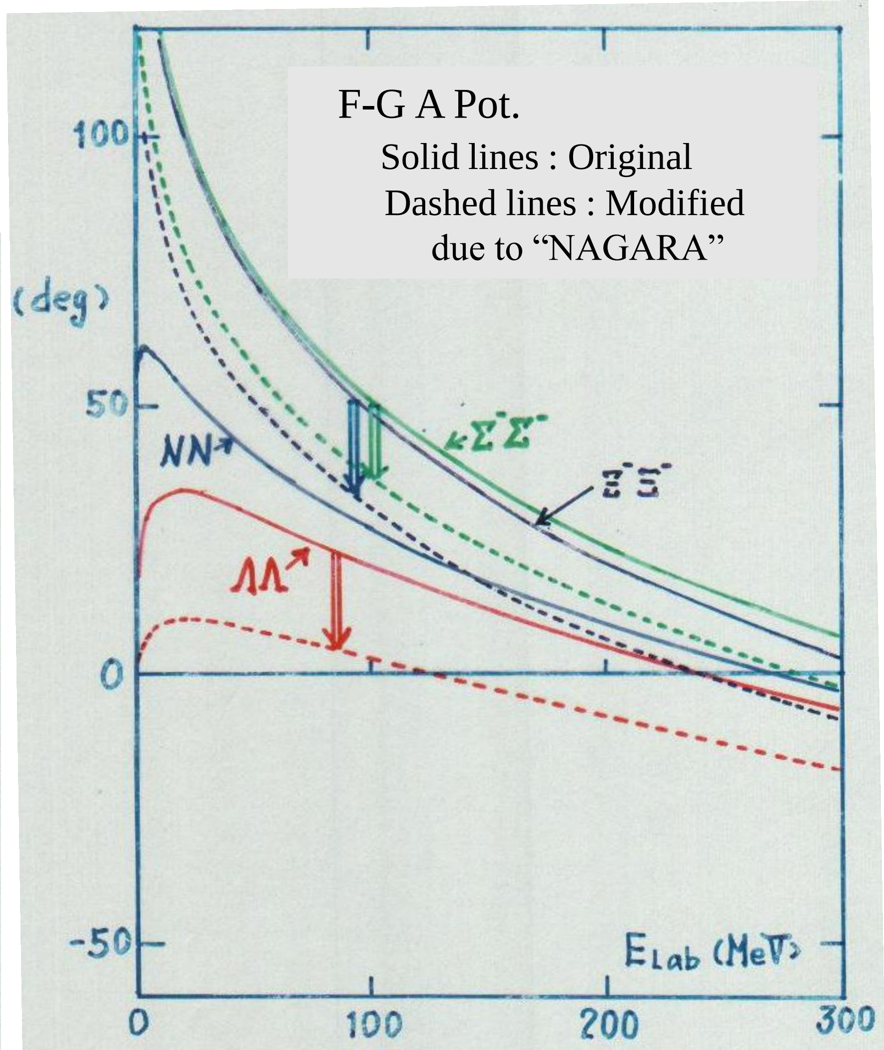
Tsuruta et al, Ap.J.691(2009)621-632



Less attractive YY int. suggested by “NAGARA”



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

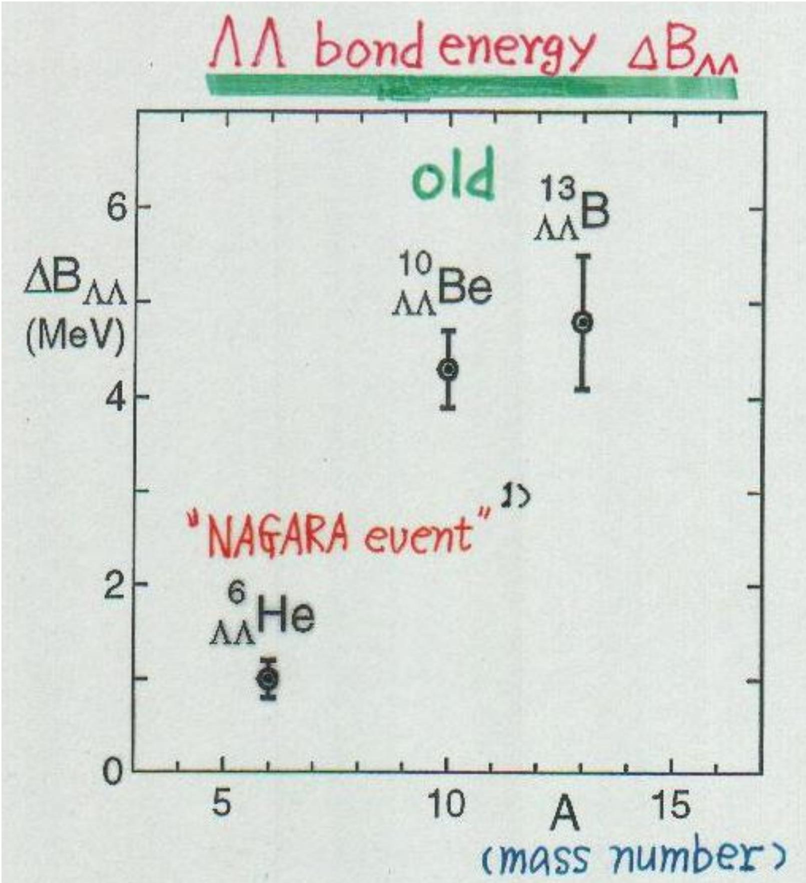


V(ND-soft)→ 0.5V(ND-soft) ; Hiyama

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?



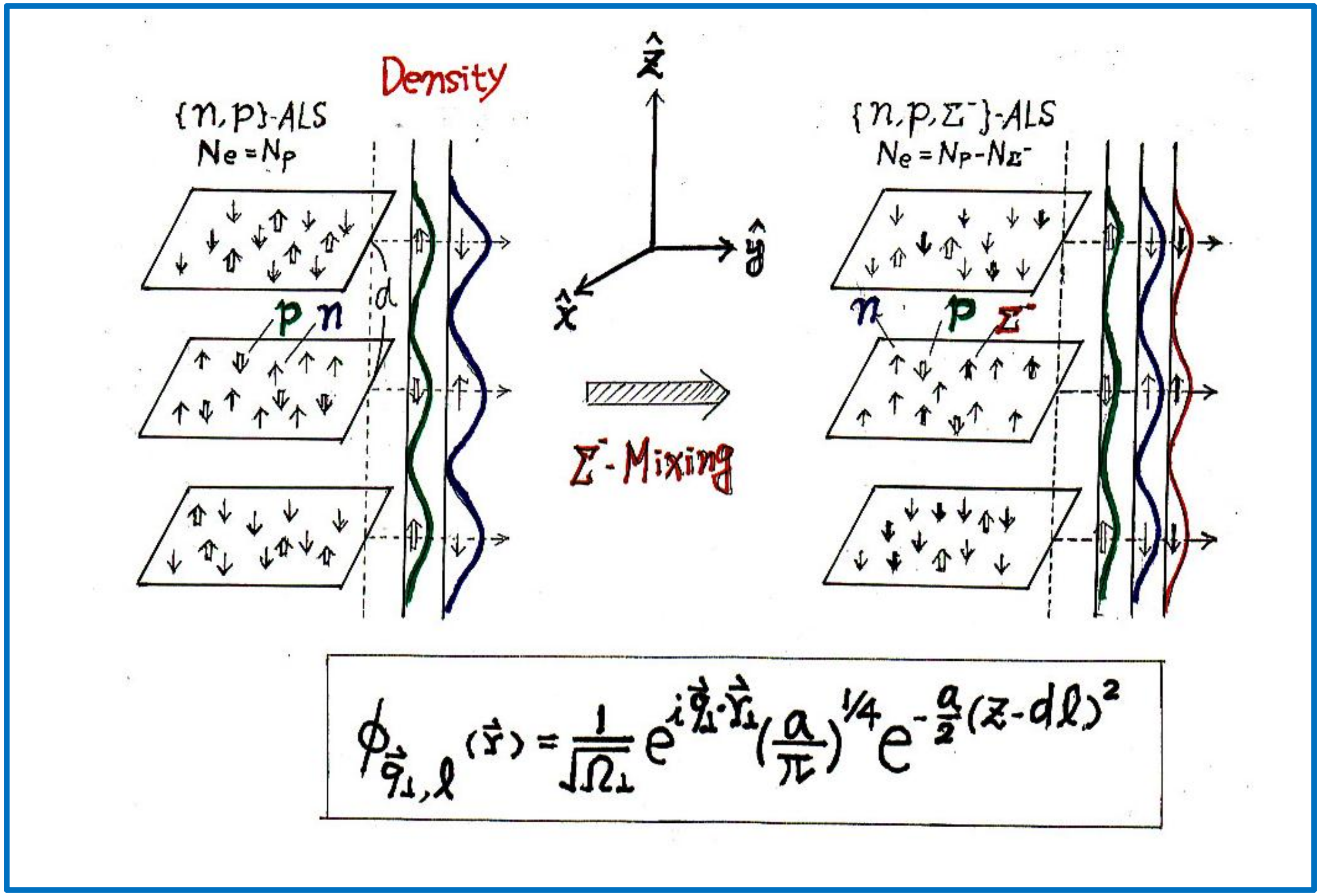
$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2 \times B_{\Lambda}({}^{A-1}_{\Lambda}Z)$

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

(2) Delay the Λ-appearance and "pion cooling"

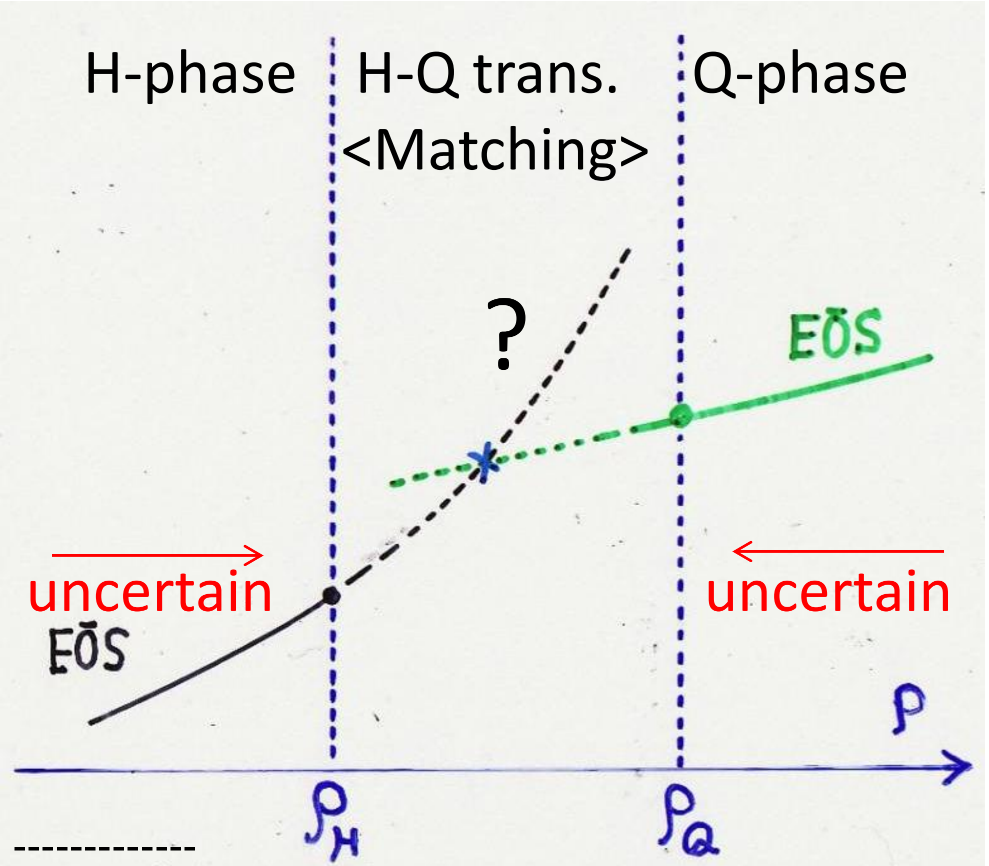
Baryonic ALS structure under π^0 Condensation
(Σ^- are localized but Λ are not localized and uniformly distributed)



$$\phi_{\vec{q}_\perp, l}(\vec{r}) = \frac{1}{\sqrt{\Omega_\perp}} e^{i \vec{q}_\perp \cdot \vec{r}_\perp} \left(\frac{a}{\pi}\right)^{1/4} e^{-\frac{a}{2}(z - dl)^2}$$

☐ 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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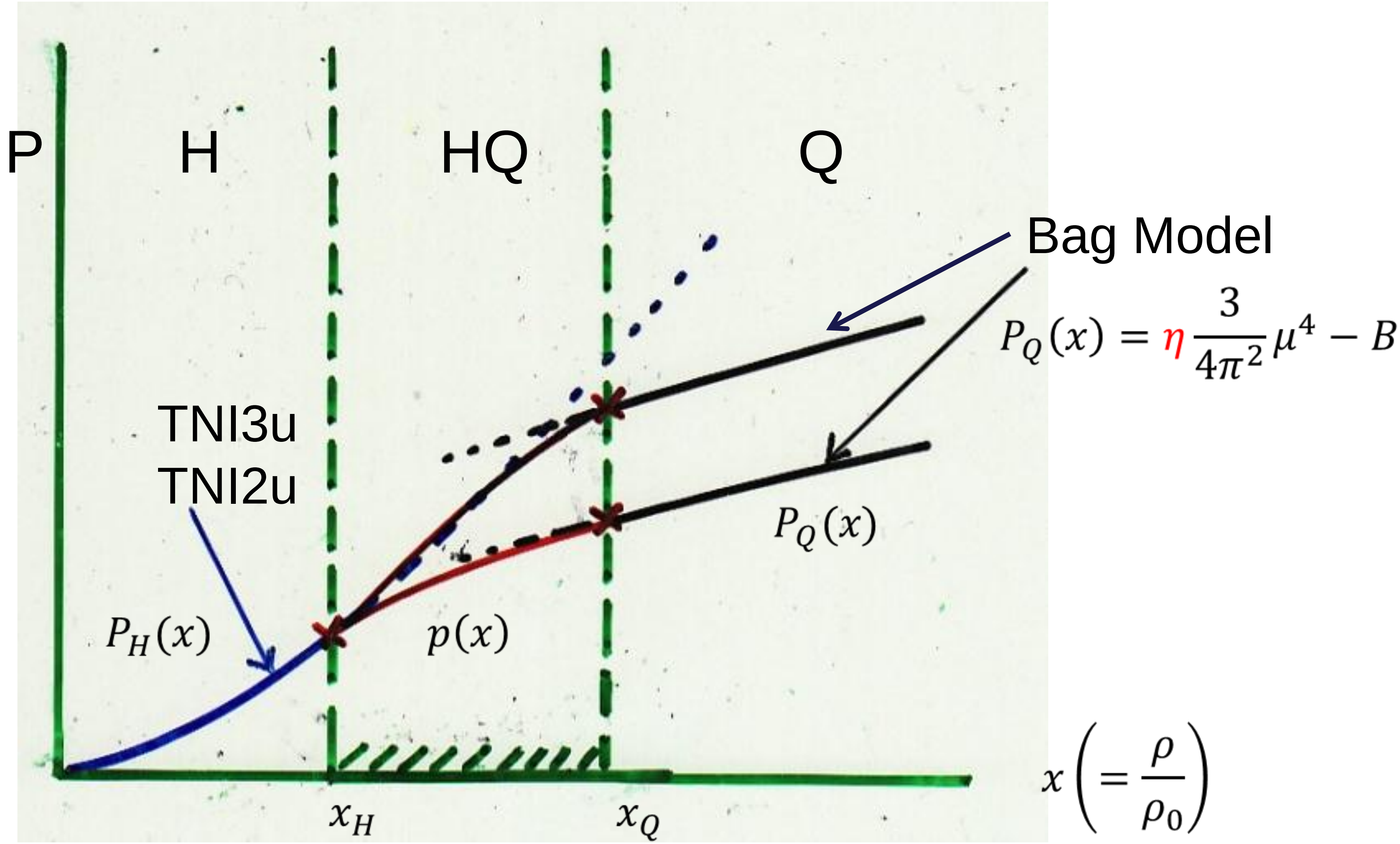
*) [6] T. Takatsuka, T. Hatsuda and K. Masuda, Proc. of "OMEG11" (Nov.14-17, 2001, RIKAEN)
[7] K. Masuda, T. Hatsuda and T. Takatsuka, arxiv:1205.362 [nucl-th.]

☐ Interpolation and Matching

(H-HQ-Q window model)



- $p(x) = ax^{5/2} + bx^2 + c$ (assumed)
- $\varepsilon(x)$ from $p(x) = x^2 \partial(\frac{\varepsilon(x)}{x})/\partial x$
  (to satisfy the thermodynamic relation)
- 4 conditions:

$$P = P_H, \quad \varepsilon = \varepsilon_H, \qquad \text{at} \quad x = x_H$$
$$P = P_Q, \quad \varepsilon = \varepsilon_Q, \qquad \text{at} \quad x = x_Q$$

  (→ assure the smooth matching for $\varepsilon(x)$)
- Stability condition: $\frac{\partial p}{\partial x} > 0$

Some results

H-EOS: TNI3u, TNI2u, Q-EOS: $\eta = 1.3,\ B^{1/4} = 100$ MeV

	$x_H = 2$、 $x_Q = 4$			$x_H = 2,\ x_Q = 6$		
H-EOS	M_{max}	R	ρ_c	M_{max}	R	ρ_c
TNI3u	2.13	11.28	5.64	2.10	11.34	5.68
TNI2u	2.15	11.27	5.64	2.14	11.30	5.65

(M_{max} in $M_{\odot}$, R in km, ρ_c in ρ_0)

* $2M_{\odot}$ – NSs are possible!

□打開の方向（まとめにかえて）

質量問題

その１:「ハドロン物質」枠組で → 普遍3体力斥力によりハイペロン混在でも
$M_{max} > 2M_{\odot}$

その２:「ハドロン＋クォーク物質」（ハイブリッド星）枠組で
→ ハドロン・クォーク転移が比較的低密度域
$\rho \sim (2-4)\rho_0$で進行し、且、硬い（強相関）クォーク物質、により$M_{max} > 2M_{\odot}$

冷却問題

その１: Nagara event → directly mean "less attractive ΛΛ int.?"
＊Mass-dependence?
＊Contribution from 3-body force? etc.

その２:「ハドロン物質」枠組で
→ ハイペロン混在ALS構造（Λ混在をおくらせる、π凝縮冷却の復活！）

その３:「ハドロン＋クォーク物質」枠組で
→ ハイペロン冷却の回避、クォーク冷却は効かない。
Velax-1等の問題は残る。