【 中性子星の観測と理論 ー研究活性化ワークショップ 2023 ー
京都大学理学研究科セミナーハウス (9月6日 (水) – 8日 (金) , 2023 ） 】

Meson condensation in dense matter and implications for compact stars

武藤 巧（千葉工大）
Takumi Muto (Chiba Inst. Tech.)

1. Introduction

Meson condensation in dense matter

Multi-messenger

High-density QCD

- T-ρ_B phase diagram
  (+ strangeness, magnetic field, ⋯)
- various phases of hadronic matter and quark matter

Hadron phase

Pion condensation (π^c, π^0) (1970 ~)

Kaon condensation (K^-) (1986 ~)

in hyperon (Λ, Ξ, ⋯)-mixed matter

Chiral symmetry and its spontaneous breakdown

⇩

Nambu-Goldstone bosons (pseudo scalar)
→ coherent states

- Softening of EOS ⟷ Observations of massive $N_☆$
- Rapid cooling of neutron stars ⟶ Necessity of Baryon superfluidity

Observation of massive neutron stars (2010~)

M(PSR J1614-2230) = (1.97 ± 0.04) $M_\odot$

[P. Demorest et al., Nature 467 (2010) 1081.]

M(PSR J0348+0432) = (2.01 ± 0.04) $M_\odot$

[J. Antoniadis et al., Science 340, 6131 (2013).]

M(PSR J2215+5135) = (2.27 + 0.17-0.15) $M_\odot$

[M.Linares, T. Shahbaz, J.Casares, Astrophys. J. 859, 54 (2018).]

Millisecond pulsars in compact binaries

M(PSR J0740+6620) = (2.14 + 0.10-0.09) $M_\odot$
→ (2.08 ± 0.07) $M_\odot$

[H.T.Cromartie et al., Nat.Astron.4, 72(2020.)]

[E.Fonseca et al., Astrophys. J. Lett.915, L12 (2021)]

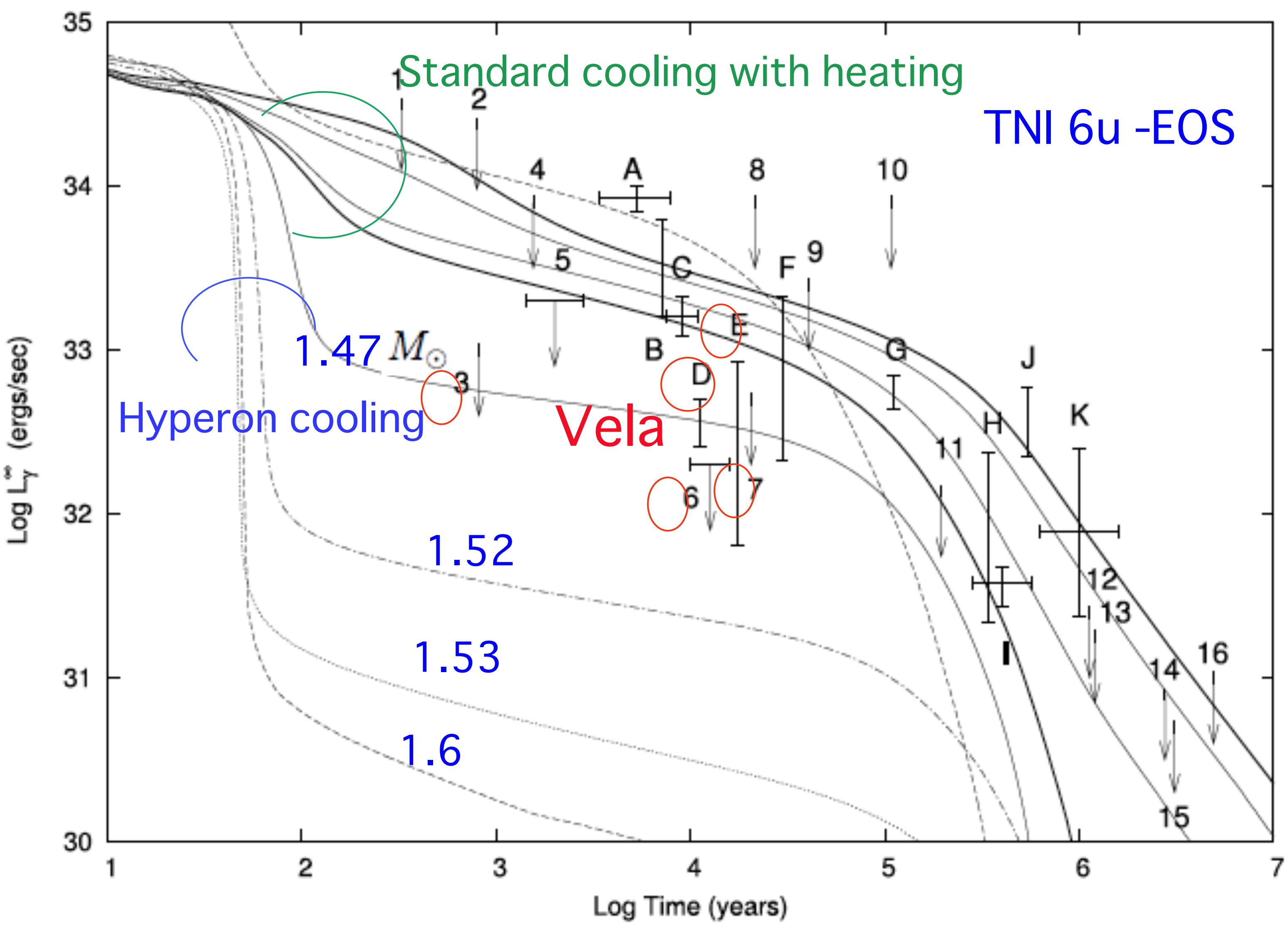
M(PSR J1810+1744) = (2.13 ± 0.04) $M_\odot$

[R. W. Romani et al., Astrophys. J. L. 908, L46 (2021).]

M(PSR J0952-0607) = (2.35 ± 0.17) $M_\odot$

[R. W. Romani et al., arXiv: 2207. 05124[astro-ph HE]]

[S. Tsuruta et al., Astrophys. J 691, 621(2009).]



E: PSR 1705-44

3: PSR J0205+6449 (in 3C 58)   6: RX J0007.0+7302 (in CTA 1)

7: PSR 1046-58

Present studies of meson condensation

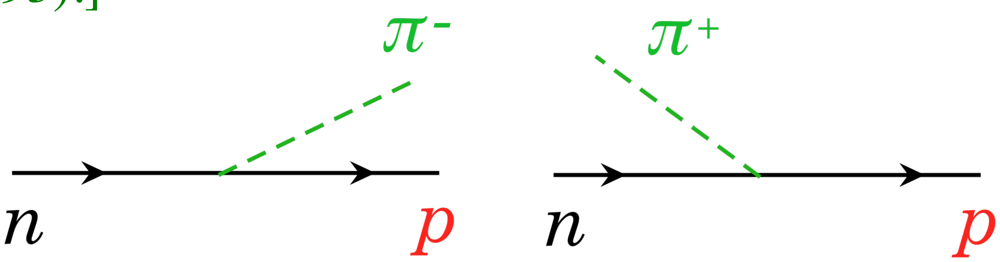
Pion condensation (π^c, π^0)

[G.Baym and D.K.Campbell,
Mesons in Nuclei, (ed M.Rho andD.H.Wilkinson) Vol. III, p.1031 (1979).]

[A.B.Migdal, E.E.Saperstein, M.A.Troitsky, and D.N.Voskresensky,
Phys. Rep.192 (1990), 179.]

[T. Kunihiro, T. Muto, T.Takatsuka, R.Tamagaki, and T.Tatsumi,
Prog. Theor. Phys. Supplement 112 (1993).]

Driving force: P-wave π-N int.



Quasi-baryons: $|\eta\rangle = \cos\phi|n\rangle - i\sin\phi|p\rangle$

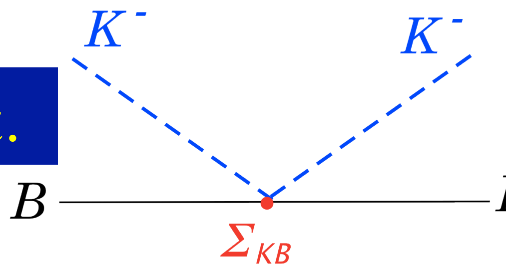
Pion properties are sensitive to medium effects.

Landau-Migdal parameter in spin-isospin channel

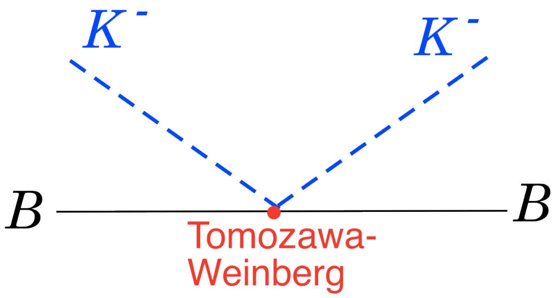
$$g' = (0.5 - 0.6)(f_{\pi NN}/m_\pi)^2$$

Kaon condensation (K^-)

Driving force: S wave KB int.



Scalar int.



vector int.

・Softening of EOS

[D.B. Kaplan and A. E. Nelson, Phys. Lett. B175 (1986), 57.]

[T. Tatsumi, Prog. Theor. Phys. 80, 22(1988).]

[C.-H.Lee, G.E.Brown, D.-P.Min, and M.Rho, Nucl. Phys. A585 (1995),401.]

[T. Muto and T. Tatsumi, Phys. Lett. B283(1992), 165.]
[H. Fujii, T. Maruyama, T. Muto, and T. Tatsumi, Nucl. Phys. A597 (1996), 645.]

chemical equilibrium
for weak processes

$$n \rightleftharpoons p\, K^-$$

・Rapid cooling of neutron stars

[H. Fujii, T. Muto, T. Tatsumi, R. Tamagaki,
Nucl. Phys. A578 (1994), 758; Phys. Rev. C 50 (1994), 3140.]

2. Overview of the present results on Kaon Condensation in hyperon (Y)-mixed matter [(Y+K) phase]

2-1 Our interaction model

[T. Muto, T. Maruyama, and T. Tatsumi, Phys. Lett. B 820 (2021), 136587.]

K-Baryon and K-K interactions : effective chiral Lagrangian

Baryon-Baryon interaction

Minimal Relativistic Mean-Field theory
(without nonlinear self-interactions
by mesons(σ, ω, ϱ ···)

Slope : $L \equiv 3\rho_0 \left(\frac{\partial S}{\partial \rho_B}\right)_{\rho_B=\rho_0}$ = (60 – 70) MeV

controls Stiffness of EOS from two-body B-B int.

Three-Baryon (many-body) forces

+ Universal Three-Baryon Repulsion (UTBR) : String-Junction Model 2
+ Three-Nucleon attraction (TNA)

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

The UTBR appropriately stiffen the EOS, consistent with recent observations of massive $N_\star$ (M and R. . .)

2-2 Lorentz invariant forms for UTBR

Conditions for the EOS

(1) Saturation properties of SNM

(2) Consistency with observations of massive N☆ M and R

(3) Causality condition $v_s < c$

$M_{\max} \gtrsim 2.0 M_\odot$

for stable star with gravitational mass $M \leq M_{\max}$

Lorentz scalar

TBR as energy density : $\mathcal{E}(\mathrm{TBR}) = -\mathcal{L}(\mathrm{TBR})$

$$\mathcal{E}(\mathrm{TBR}) = c_{m,n}(\bar{\psi}\psi)^m(\bar{\psi}\gamma^\mu\psi \cdot \bar{\psi}\gamma_\mu\psi)^n \qquad (m, n = 0, 1, \cdots)$$

$$\rightarrow c_3 \rho_B^s \rho_B{}^2 + c_4 \rho_B^2 [1 - \exp(-\eta \rho_B^2)]$$

: Covariant TBR

TBR3 TBR4

baryon density : $\rho_B = \sum_{b=p,n,\Lambda,\Xi^-,\Sigma^-} \rho_b$

baryon scalar density : $\rho_B^s = \sum_{b=p,n,\Lambda,\Xi^-,\Sigma^-} \rho_b^s$

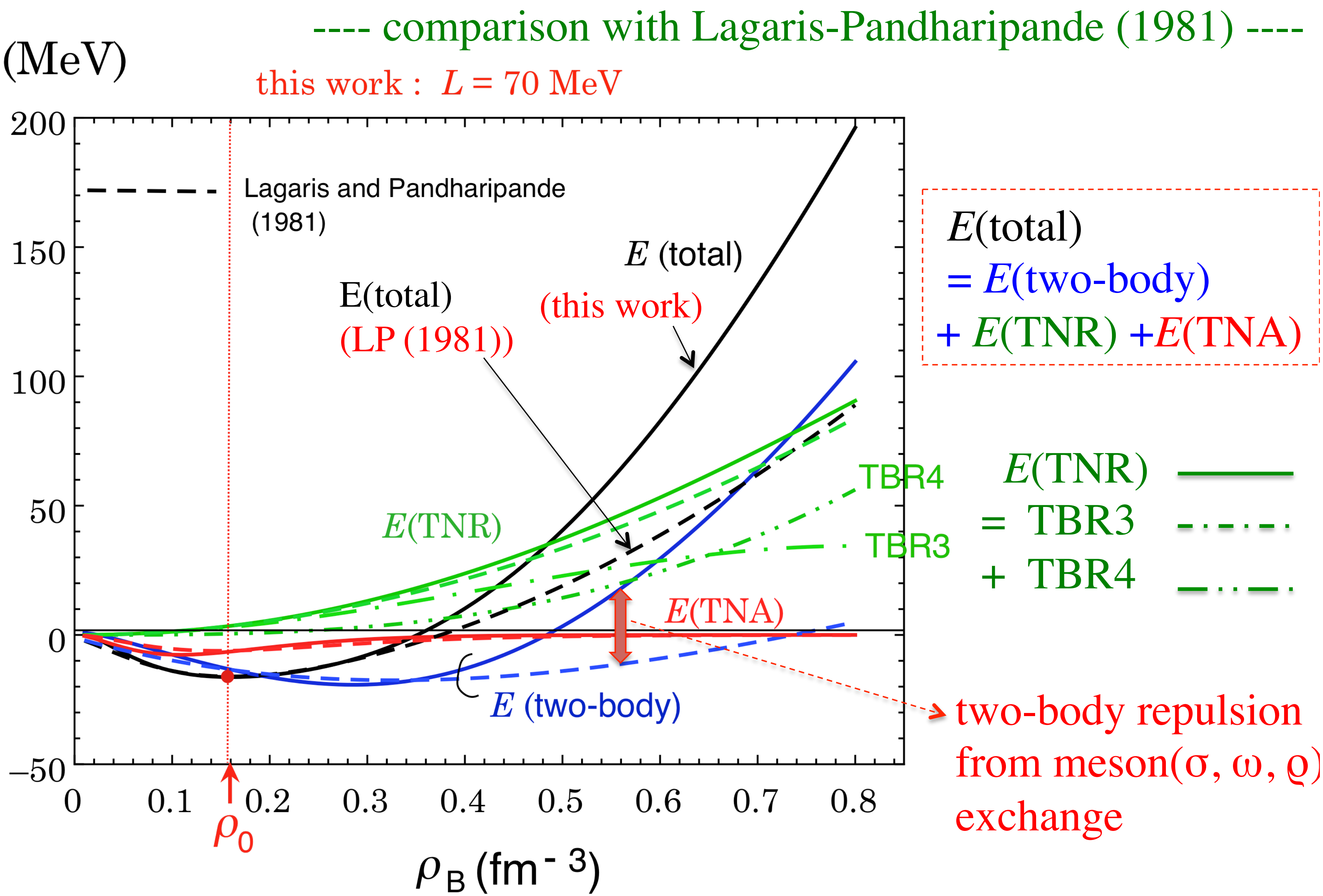
$$\rho_b^s = \frac{2}{(2\pi)^3} \int_{|\mathbf{p}| \leq p_F(b)} d^3\mathbf{p} \frac{\widetilde{M}_b^*}{(|\mathbf{p}|^2 + \widetilde{M}_b^{*2})^{1/2}}$$

(effective baryon mass)

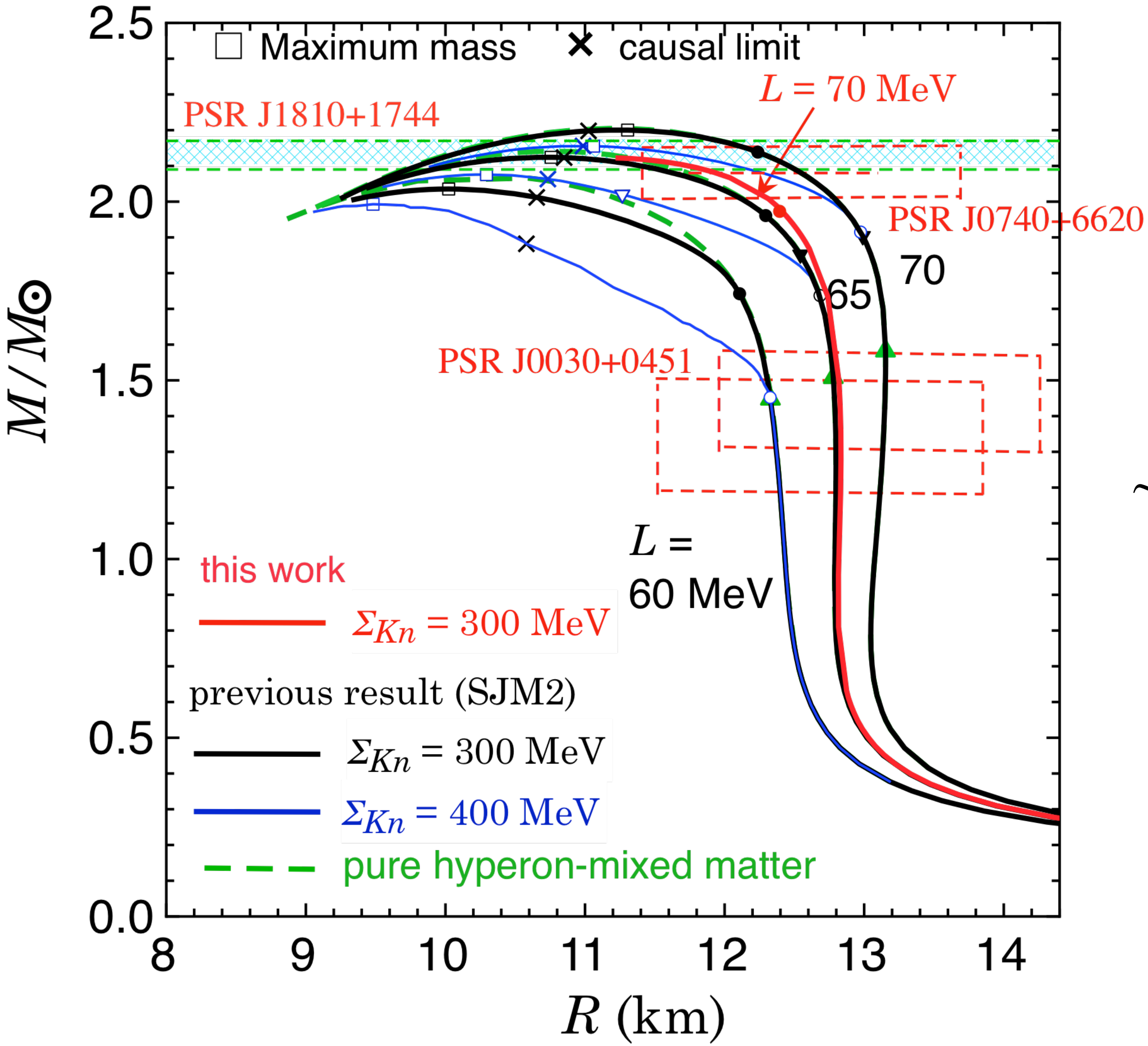
$$\widetilde{M}_b^* = M_b - g_{\sigma b}\sigma - g_{\sigma^* b}\sigma^* - \Sigma_{Kb}(1 - \cos\theta)$$

3. Numerical Results

3-1 Energy per particle in SNM



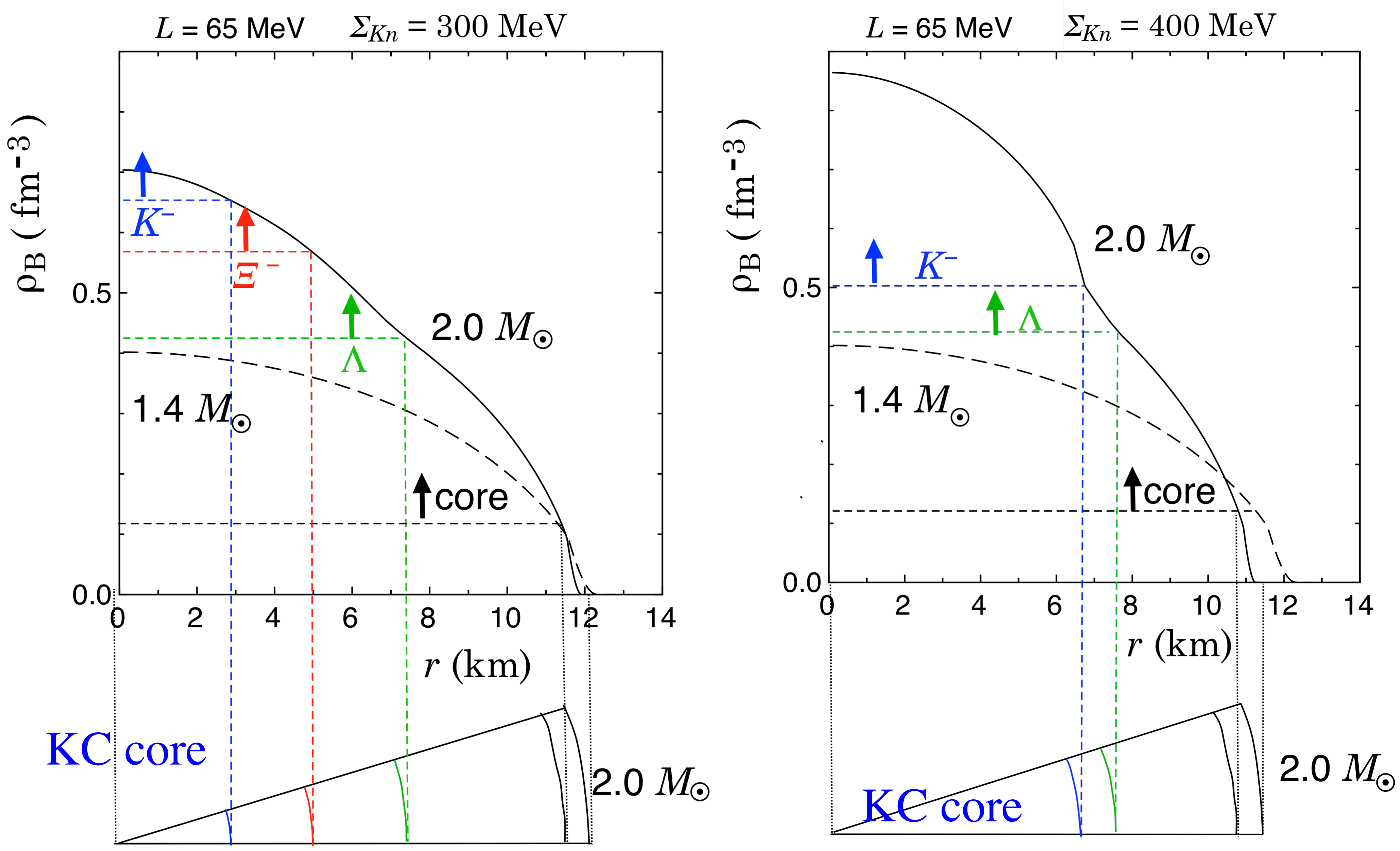
3-2 Gravitational Mass – radius R relations



Covariant TBR
with L = 70 MeV

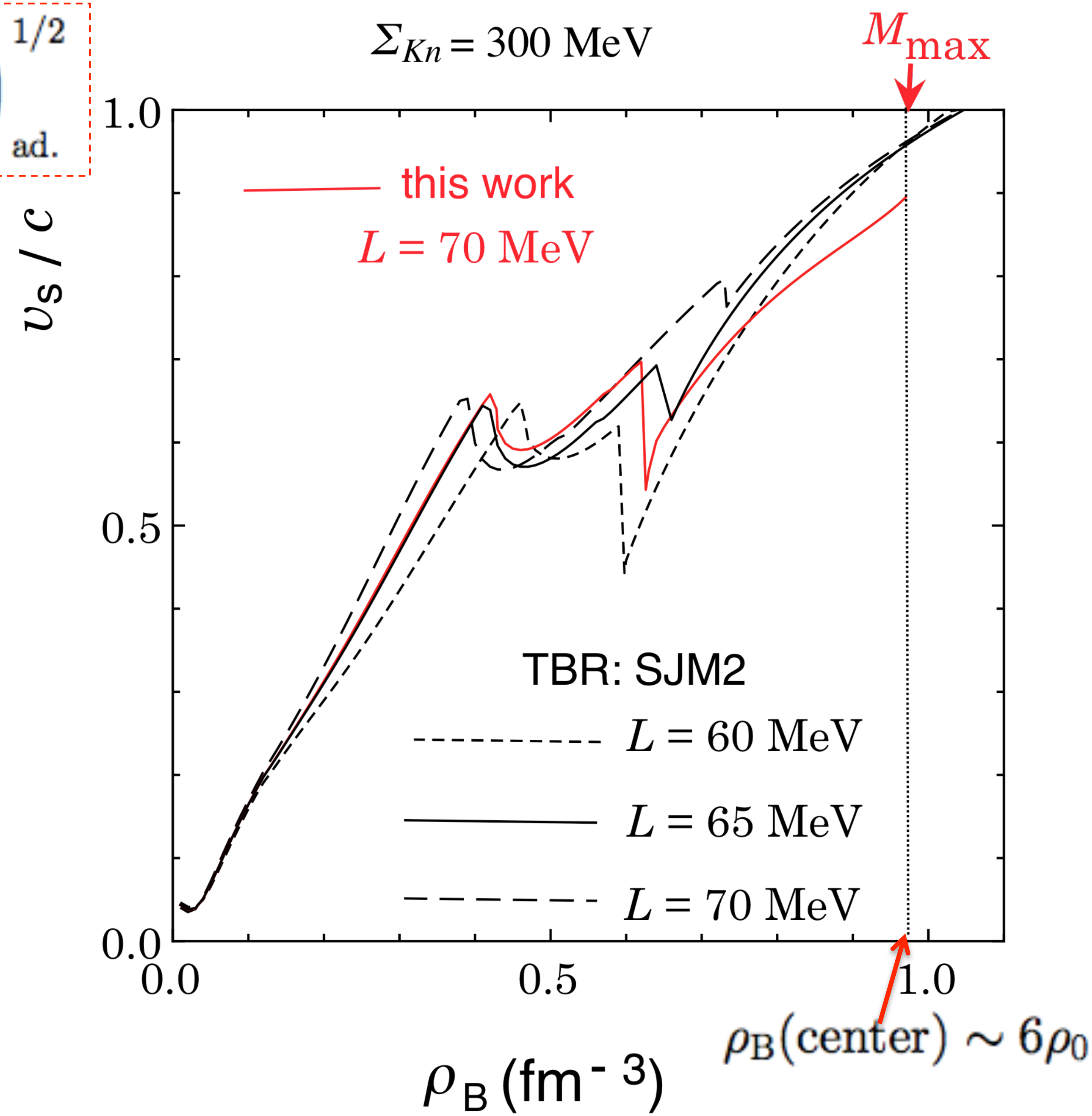
~ TBR(SJM2)
with L = 65 MeV

3-3 Density distributions --- L = 65 MeV ---



3-4 Sound velocity (v_s) squared – baryon density ϱ_B

$$v_s = \left(\frac{dP}{d\mathcal{E}}\right)^{1/2}_{\rm ad.}$$



4. Short Summary

Lorentz-scalar form of the TBR (Covariant TBR), combined with the Minimal RMF and TNA, has been obtained consistently with

- saturation properties of SNM,
- causality condition
- observations of massive compact stars.

In order to be consistent with causality condition,

E (TBR) ~ E (two-body) for SNM at high densities ~ (0.7-0.8) fm^{-3}

Observationally, the EOS including the (Y+K) phase with Covariant TBR predicts higher *L* (~70 MeV) in order to be consistent with observation of massive compact stars.

5. Outlook

5-1 Outlook Role of pion condensation

EOS

Possible coexistence of PC and KC (π-K condensation)

From heavy-ion collisions, the EOS may be softer for $\rho_B = (2-4.5)\rho_0$

[P. Danielewicz, R.Lacey, W.G.Lynch, Science 298, 1592 (2002).]

PC and KC couple with p-wave

→ Validity of Universal three-baryon repulsion (UTBR) and consistency withMassive $N_{☆}$ observations

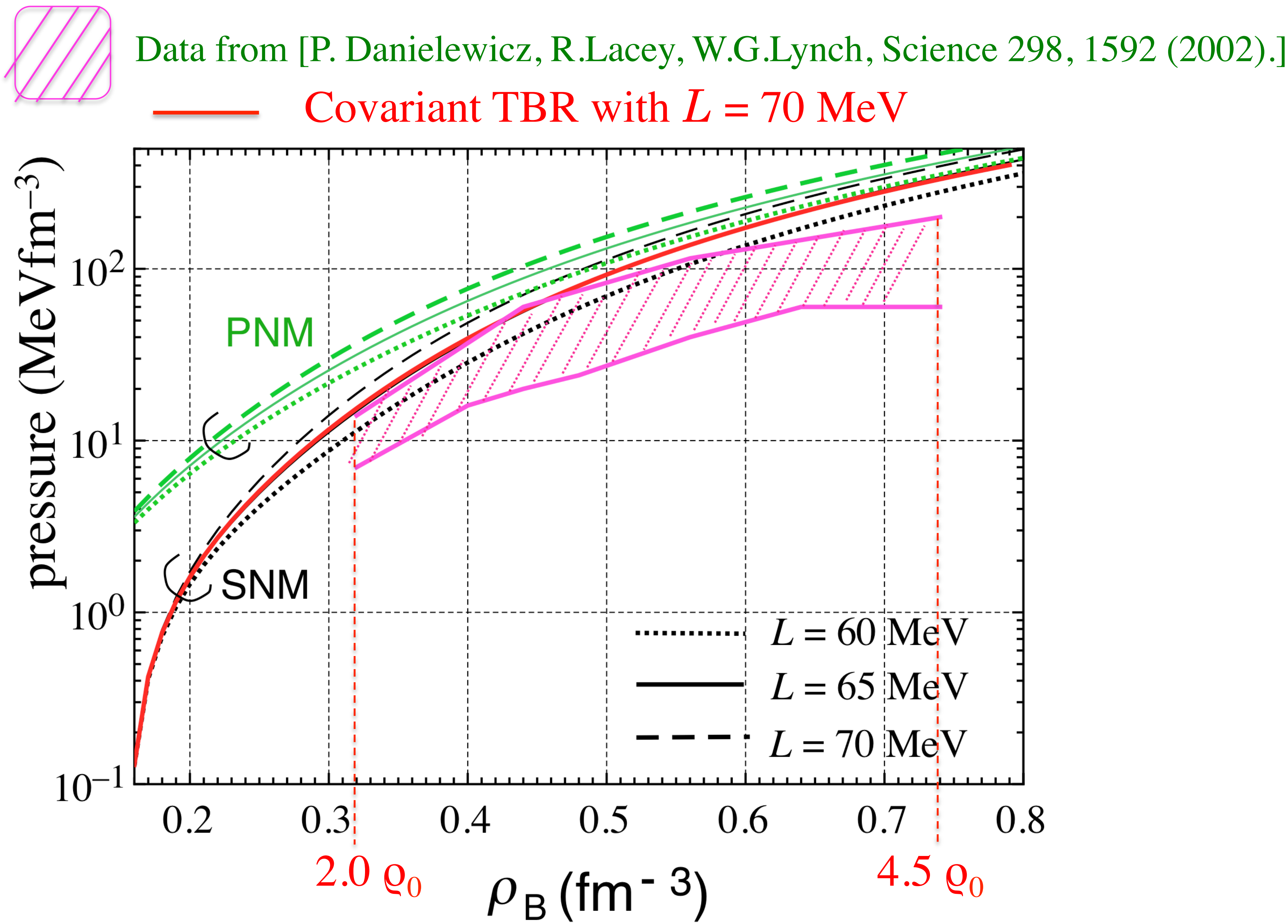
Rapid cooling mechanisms

Baryon superfluidity in the presence of KC or π-K condensation is needed in order to suppress too rapid neutrino emissivity.

5-2 Phenomena specific to meson condensation

- Response to rotation and strong magnetic field as superfluidity / superconductivity
- Response to radial/nonradial oscillations

Pressure in Symmetric Nuclear Matter



5-3 Outlook Role of MC in Hadron– Quark crossover

hadron matter ⟶ quark matter

H-Q crossover ← **Meson condensation**

[K.Masuda, T. Hatsuda, T.Takatsuka,
Astrophys. J. 764,12 (2013); PTEP 2016, 021D01(2016).]

[G. Baym, T. Hatsuda, T. Kojo, P.D.Powell, Y.Song, T.Takatsuka,
Rept. Prog. Phys. 81, 056902 (2018).]

Nonlinear representation of NG octet bosons (elementary fields)

$$U = \exp(2i\Pi/f)$$

$$\Pi = \pi_a T_a = \frac{1}{\sqrt{2}} \begin{pmatrix} \pi^0/\sqrt{2} + \eta/\sqrt{6} & \pi^+ & K^+ \\ \pi^- & -\pi^0/\sqrt{2} + \eta/\sqrt{6} & K^0 \\ K^- & \overline{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

↓

$$\xi \equiv U^{1/2}$$

↓

Meson vector current

$$V_\mu \equiv \frac{1}{2}(\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger)$$

Meson axial-vector current

$$A_\mu \equiv \frac{i}{2}(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)$$

Hadron phase

$$
\begin{aligned}
\mathcal{L}_{K,B} &= \frac{1}{4} f^2 \, \mathrm{Tr}(\partial^\mu U^\dagger \partial_\mu U) + \frac{1}{2} f^2 \Lambda_{\chi\mathrm{SB}} (\mathrm{Tr} M(U-1) + \mathrm{h.c.}) \\
&+ \mathrm{Tr}\overline{\Psi}(i\gamma^\mu \partial_\mu - M_B)\Psi + \mathrm{Tr}\overline{\Psi} i\gamma^\mu [V_\mu, \Psi] + D\mathrm{Tr}\overline{\Psi}\gamma^\mu\gamma^5\{A_\mu, \Psi\} \\
&+ F\mathrm{Tr}\overline{\Psi}\gamma^\mu\gamma^5[A_\mu, \Psi] + a_1 \mathrm{Tr}\overline{\Psi}(\xi M^\dagger \xi + \mathrm{h.c.})\Psi \\
&+ a_2 \mathrm{Tr}\overline{\Psi}\Psi(\xi M^\dagger \xi + \mathrm{h.c.}) + a_3(\mathrm{Tr} MU + \mathrm{h.c.})\mathrm{Tr}\overline{\Psi}\Psi,
\end{aligned}
$$

Octet Baryons

$$
\Psi = \begin{pmatrix} \Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & \Sigma^+ & p \\ \Sigma^- & -\Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}
$$

Quark phase

$$
\mathcal{L}_{M,q} = \frac{1}{4} f^2 \mathrm{Tr}(\partial^\mu U^\dagger \partial_\mu U) + \bar{q}(i\gamma^\mu D_\mu + g_A \gamma^\mu A_\mu \gamma_5 - M) q
$$

Quark fields $q^T = (u, d, s)$ $\qquad D_\mu \equiv \partial_\mu + V_\mu$