[基研研究会「ハドロン物質の諸相と状態方程式ー中性子星の観測に照らしてー」
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京都大学基礎物理学研究所・ 湯川記念館パナソニック国際交流ホール]

高密度ハドロン物質中での K中間子凝縮-ハイペロン共存と 中性子星観測との整合性

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1. Introduction

1-1 高密度ハドロン物質におけるストレンジネス

Kaon condensation in neutron stars

[T. Muto and T. Tatsumi, Phys. Lett. B283 (1992) 165.]

Chemical equilibrium for weak processes

$n \leftrightharpoons p\, K^-$ $\quad n \leftrightharpoons p\, e^- \; (\bar{\nu}_e)$

strangeness-nonconserving system

観測との関連

- Rapid cooling through neutrino emission
- Softening of the equation of state (EOS)

[H. Fujii, T. Maruyama, T. Muto , T. Tatsumi, Nucl. Phys. A597 (1996) 645.]

Kaon dynamics in nuclear matter

Deeply bound kaonic nuclear states

[Y.Akaishi and T.Yamazaki, Phys.Rev. C65 (2002) 044005.]

[A. Dote, H. Horiuchi et al., Phys. Lett. B 590 (2004) 51; Phys.Rev. C70 (2004) 044313.]

$\bar{K}$ nuclear clusters

[T.Yamazaki, A. Dote and Y.Akaishi, Phys.Lett. B 587 (2004) 167.]

1-2 Onset mechanism of kaon (K^-) condensation

Role of weak interaction processes

[T. Muto and T. Tatsumi, Phys. Lett. B283 (1992) 165.]
[G. E. Brown, K. Kubodera, M. Rho, V. Thorsson,
Phys. Lett. B. 291 (1992) 355.]

[Charge neutrality] $\rho_p - \rho_K - \rho_e = 0$

[Baryon number conservation] $\rho_p + \rho_n = \rho_B$

Effective energy density

$$\mathcal{E}^{\rm eff} = \mathcal{E} + \mu(\rho_p - \rho_K - \rho_e) + \nu(\rho_p + \rho_n)$$

μ: charge chemical potential

ν: baryon number chemical potential

$$\mu_a = \partial\mathcal{E}/\partial\rho_a \quad (a = p, n, K^-, e^-)$$

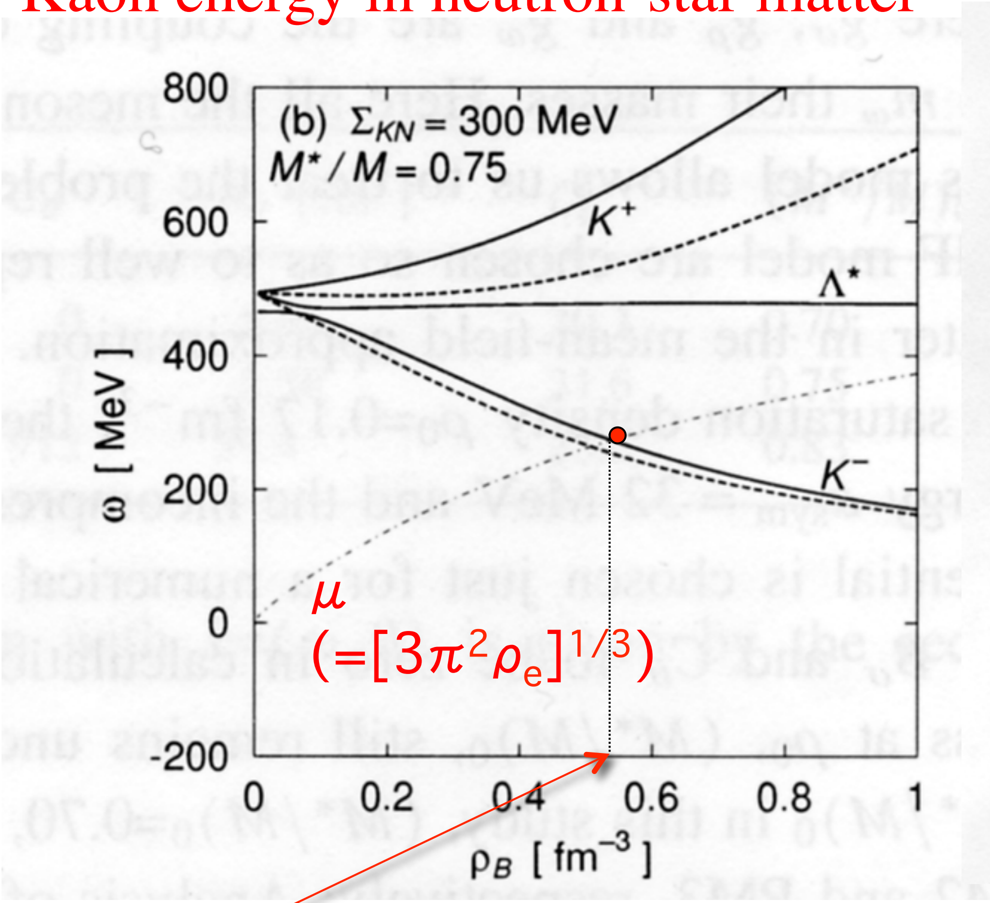
$$\mu_K = \mu_e = \mu_n - \mu_p = \mu$$
$$\mu_n = -\nu$$

Chemical equilibrium for weak processes

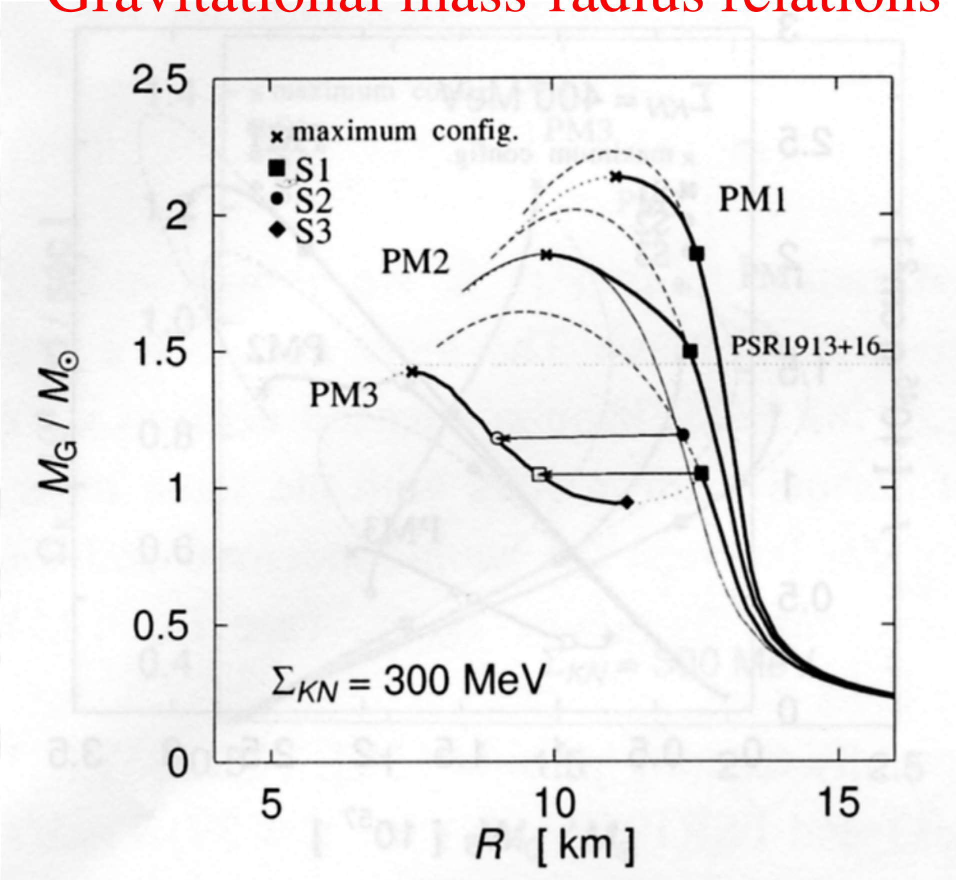
$$n \rightleftharpoons p\ K^-$$
$$n \rightleftharpoons p\ e^-\ (\bar{\nu}_e)$$

[H. Fujii, T. Maruyama, T. Muto, T. Tatsumi, Nucl. Phys. A 597 (1996) 645.]

Kaon energy in neutron-star matter



Gravitational mass-radius relations



$\omega(\rho_B^C)=\mu$

$$\Rightarrow \quad f_K = 1/[e^{(\omega_K-\mu)/k_BT}-1] \to \infty$$

Critical density $\rho_B^C = 3\sim4\ \rho_0$

Chemical equilibrium for weak processes

$$n \rightleftharpoons p\ K^- \qquad n \rightleftharpoons p\ e^-\ (\bar{\nu}_e)$$

strangeness-nonconserving system

1-3 Interplay between antikaons and hyperons

(1) 化学組成の変化が臨界密度に与える効果　　$\omega(\rho_B^C)=\mu$

[P.J.Ellis, R.Knorren and M.Prakash, Phys. Rev. C52(1995),3470.
J. Schaffner and I.N.Mishustin, Phys. Rev. C53(1996), 1416.]

A critical density of K^- condensation is shifted to higher density in the presence of (negatively charged) hyperons.

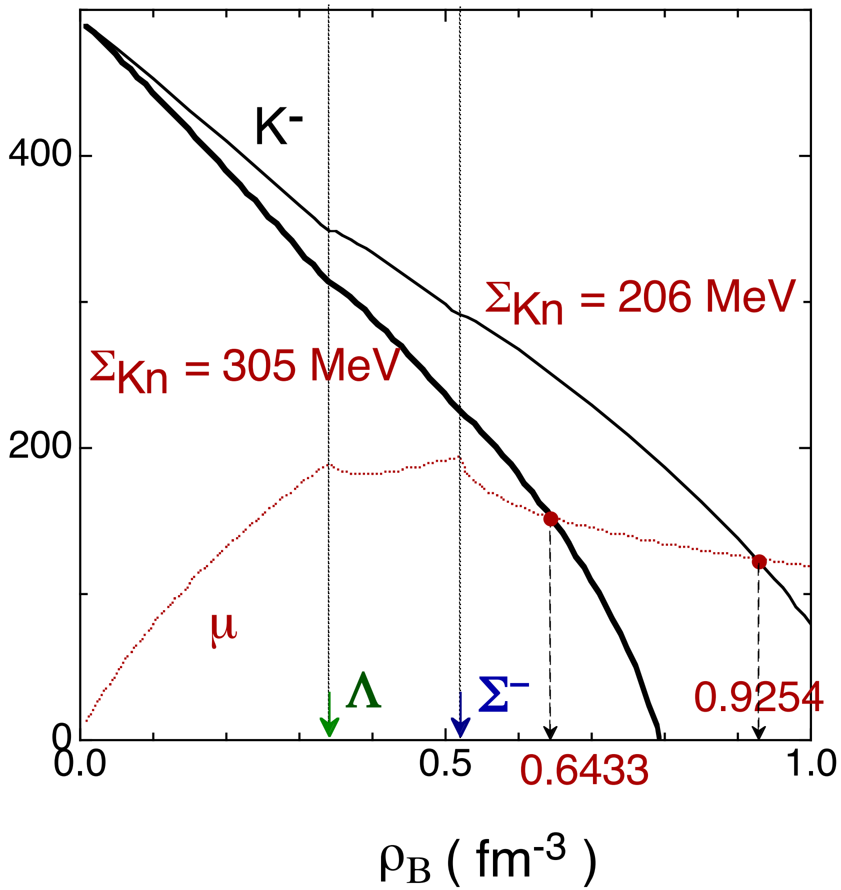
(2) S-wave kaon-baryon interactions

が K- mesonsや hyperons の出現に及ぼす効果

scalar interaction
simulated by U_{K^-} (depth of K^- optical potential)

⬍

vector interaction
(Tomozawa- Weinberg terms)



有限系(原子核)に, ストレンジネス |S| を一定にして与えたとき,
系の ground state に占める K^- mesons と hyperon の割合を求める。

A possible existence of antikaonic nuclear bound states
with hyperon-mixing for finite nuclei
within the RMF framework

Strangeness nuclear physics (J-PARC, JLab . . .)

Kaonic nuclei [Y.Akaishi and T.Yamazaki, Phys.Rev. C65 (2002) 044005.]

→ Multi kaonic nuclear cluster

High energy

$(p\, p \to K^+ + K^- p\, p)$

$(p\, p \to K^+ K^+ + K^- K^- p\, p)$

[M. Hassanvand, Y.Akaishi, T.Yamazaki, Phys.Rev. C84, 015207 (2011).]

ΛΛ hypernuclei, Ξ hypernuclei …

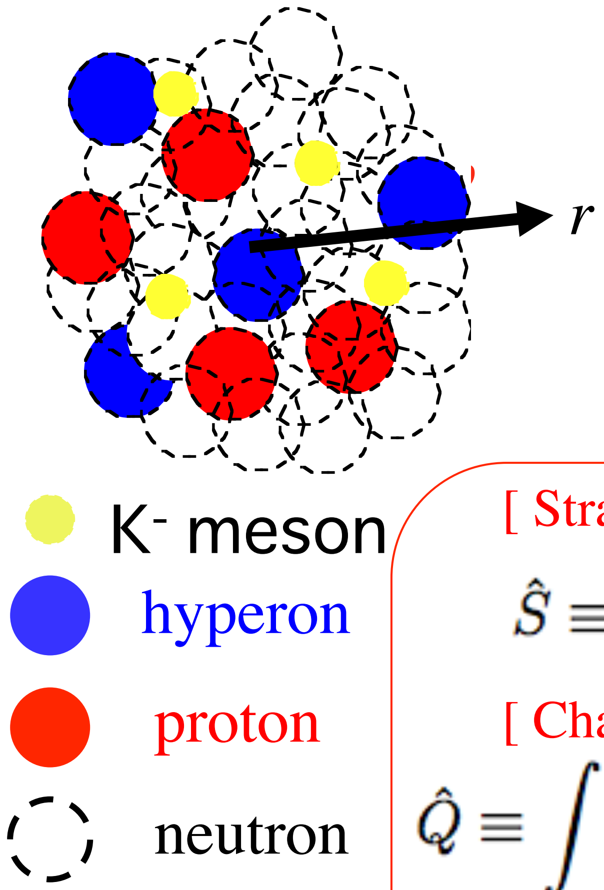
K^- meson とハイペロンの自由度を同時に考慮した
multi-strangeness system

Relation to Kaon condensation in hyperon-mixed matter

2. Formulation

2-1 Outline of Kaon-condensed hypernuclei

Multi-$\bar{K}$ Nuclei



[Initial target nucleus]

$A = N + Z$: mass number

Z: the number of proton

$|S|$: the number of the embedded K^-

Assume : Spherical symmetry

Local density approximation for baryons

$(p, n, \Lambda, \Sigma^-, \Xi^-)$

[Strangeness conservation]

$$\hat{S} \equiv \int d^3r \, (\rho_{K^-}(r) + \rho_{\Lambda}(r) + \rho_{\Sigma^-}(r) + 2\rho_{\Xi^-}(r)) = |S|$$

[Charge conservation]

$$\hat{Q} \equiv \int d^3r \, (\rho_p(r) - \rho_{K^-}(r) - \rho_{\Sigma^-}(r) - \rho_{\Xi^-}(r)) = Z - |S|$$

[Baryon number conservation]

$$\hat{N}_B \equiv \int d^3r \, (\rho_p(r) + \rho_n(r) + \rho_{\Lambda}(r) + \rho_{\Sigma^-}(r) + \rho_{\Xi^-}(r)) = A$$

2. Formulation

Mesons: $\sigma, \omega, \rho, \sigma^*, \phi$

2-2 Baryon-Baryon interaction

$B = (p, n, \Lambda, \Sigma^-, \Xi^-)$

$$\mathcal{L}_{B,M} = \sum_B \overline{B}(i\gamma^\mu D_\mu - m_B^*)B + \frac{1}{2}\left(\partial^\mu\sigma\partial_\mu\sigma - m_\sigma^2\sigma^2\right) - U(\sigma) + \frac{1}{2}\left(\partial^\mu\sigma^*\partial_\mu\sigma^* - m_{\sigma^*}^2\sigma^{*2}\right)$$
$$- \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}R^{\mu\nu}R_{\mu\nu} + \frac{1}{2}m_\rho^2 R^\mu R_\mu - \frac{1}{4}\phi^{\mu\nu}\phi_{\mu\nu} + \frac{1}{2}m_\phi^2\phi^\mu\phi_\mu$$
$$- \frac{1}{4}F^{\mu\nu}F_{\mu\nu} ,$$

$$m_B^*(r) = m_B - g_{\sigma B}\sigma(r) - g_{\sigma^* B}\sigma^*(r)$$

$$D^\mu \equiv \partial^\mu + ig_{\omega B}\omega^\mu + ig_{\rho B}\vec{\tau}\cdot\vec{R}^\mu + ig_{\phi B}\phi^\mu + iQA^\mu$$

2-3 $\overline{K}-N, \overline{K}-\overline{K}$ interactions

Nonlinear chiral effective Lagrangian

[D. B. Kaplan and A. E. Nelson, Phys. Lett. B 175 (1986) 57.]

Meson fields ($K^\pm$) (nonlinear representation)

Condensate assumption

(K^- mesons are condensed in the lowest energy state) → $\langle K^- \rangle = \frac{f}{\sqrt{2}}\theta(\mathbf{r})$

Meson decay const. $f = 93$ MeV

Kaonic part of the Lagrangian density

$$
\begin{aligned}
\mathcal{L}_{KB} &= \frac{1}{2}\left\{1+\left(\frac{\sin\theta}{\theta}\right)^2\right\}\partial^\mu K^+\partial_\mu K^- + \frac{1-\left(\frac{\sin\theta}{\theta}\right)^2}{2f^2\theta^2}\left\{(K^+\partial_\mu K^-)^2+(K^-\partial_\mu K^+)^2\right\} \\
&- \left[m_K^2 - \frac{1}{f^2}\sum_{B=p,n,\Lambda,\Sigma^-,\Xi^-}\Sigma_{KB}\bar{B}B)\right]\left(\frac{\sin(\theta/2)}{\theta/2}\right)^2 K^+K^- \\
&+ i\frac{1}{2f^2}\left(\bar{p}\gamma^\mu p + \frac{1}{2}\bar{n}\gamma^\mu n - \frac{1}{2}\bar{\Sigma}^-\gamma^\mu\Sigma^- - \bar{\Xi}^-\gamma^\mu\Xi^-\right)\left(\frac{\sin(\theta/2)}{\theta/2}\right)^2(K^+\partial_\mu K^- - \partial_\mu K^+K^-)
\end{aligned}
$$

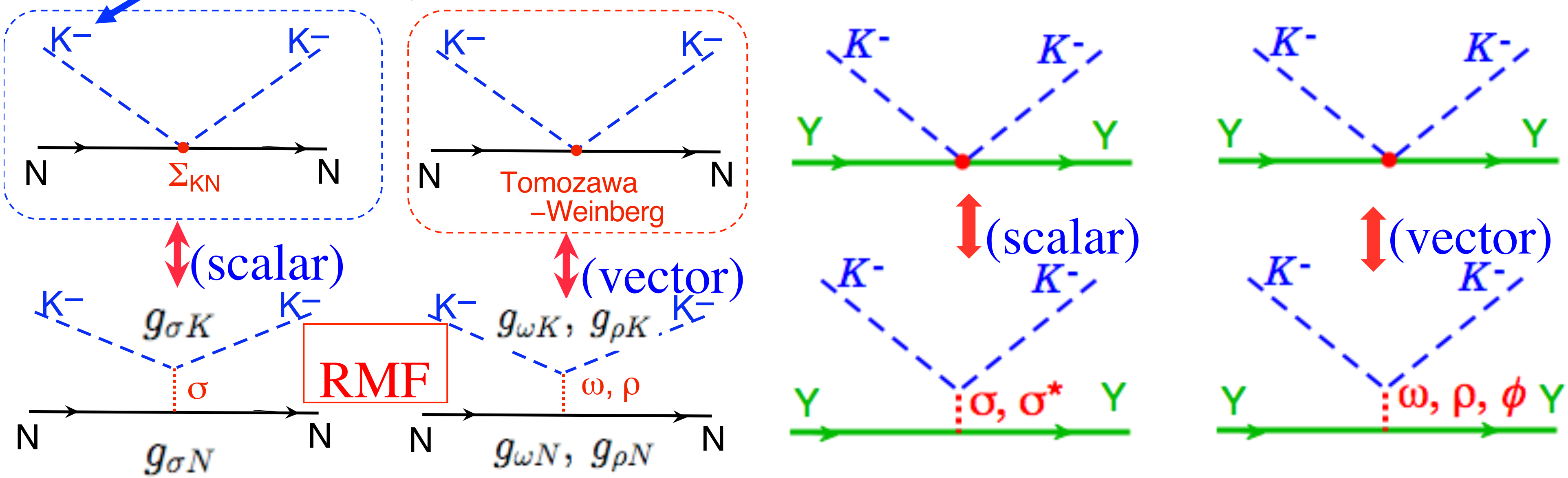
S-wave scalar int.

$$m_K^{*2} \equiv m_K^2 - 2g_{\sigma K}m_K\sigma - 2g_{\sigma^* K}m_K\sigma^*$$

S-wave vector int.

$$X_0 \equiv g_{\omega K}\omega_0 + g_{\rho K}R_0 + g_{\phi K}\phi_0$$

kaon fields ($K^\pm$) (nonlinear representation)



2-4 Thermodynamic potential

$$\Omega = \int d^3r \mathcal{H}(r) + \mu_s \hat{S} + \mu_Q \hat{Q} + \nu \hat{N}_B$$

$\delta\Omega = 0$ as $\rho_a \to \rho_a + \delta\rho_a$

$(a = K^-, p, n, \Lambda, \Sigma^-, \Xi^-)$

$$\omega_{K^-} = \mu_Q - \mu_s$$
$$\mu_p = -(\mu_Q + \nu) \qquad \mu_{\Sigma^-} = \mu_Q - \mu_s - \nu$$
$$\mu_n = -\nu \qquad \mu_{\Xi^-} = \mu_Q - 2\mu_s - \nu$$
$$\mu_\Lambda = -(\mu_s + \nu)$$

Chemical equilibrium for strong processes

$$\omega_{K^-} + \mu_p = \mu_\Lambda$$
$$\omega_{K^-} + \mu_n = \mu_{\Sigma^-}$$
$$\omega_{K^-} + \mu_\Lambda = \mu_{\Xi^-}$$

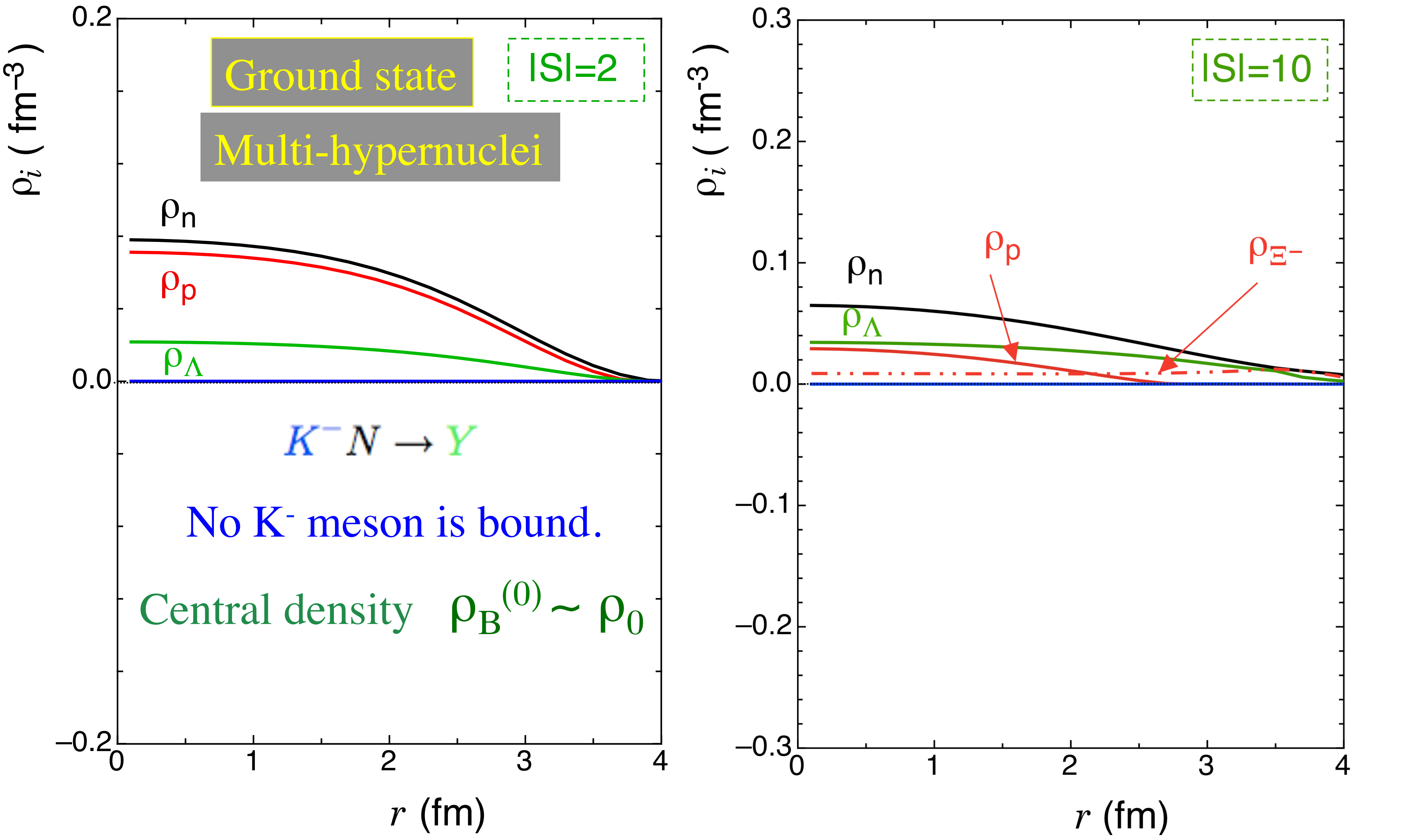
Take into account of nonmesonic processes,

$$\Lambda\Lambda \rightleftarrows \Xi^- p \qquad \Lambda\Sigma^- \rightleftarrows \Xi^- n$$

in addition to mesonic process $K^-\Lambda \rightleftarrows \Xi^-$

3. Numerical results 3-1 density distributions

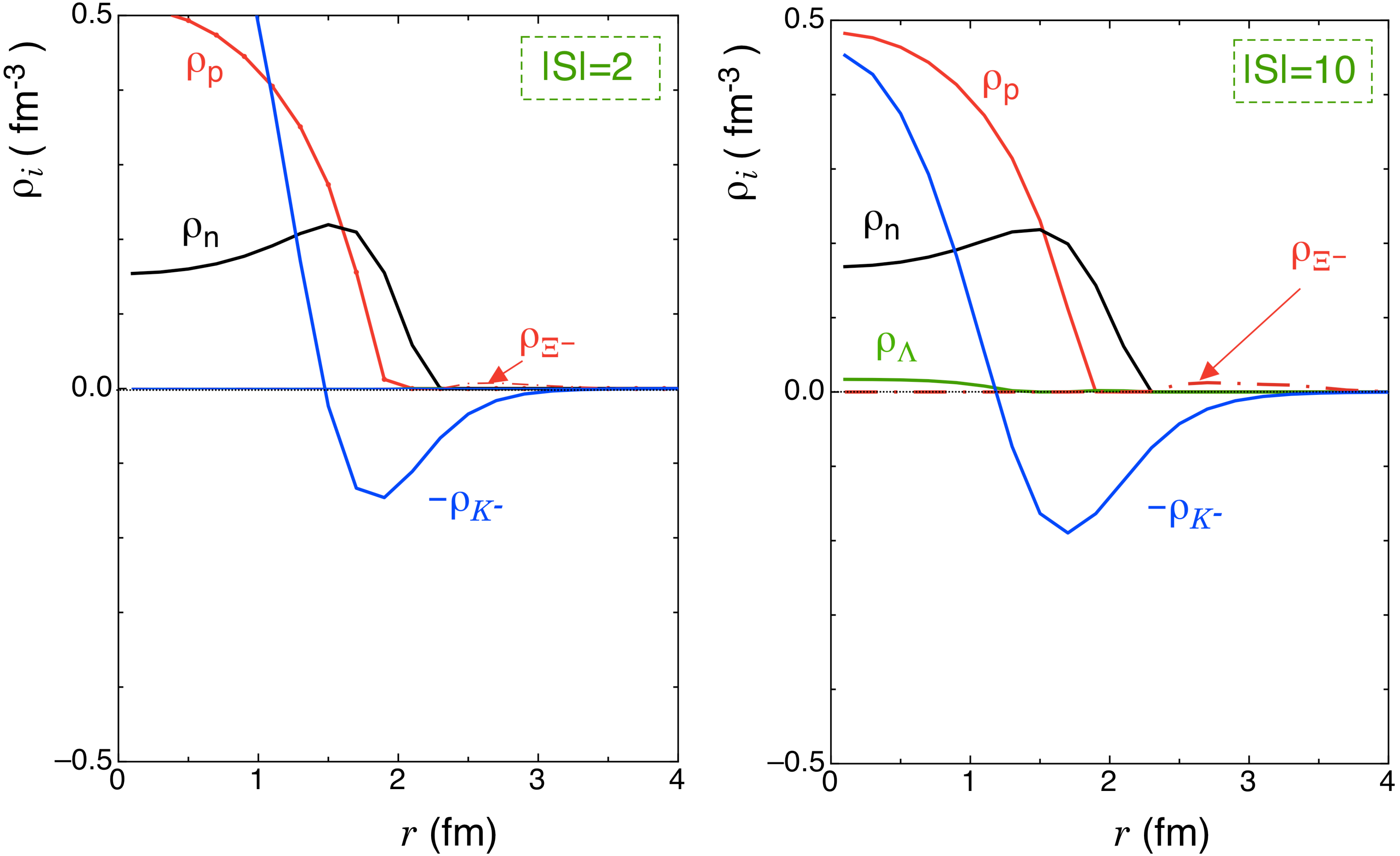
A=15, Z=8 ($^{15}_{8}\mathrm{O}$) $U_K = -80$ MeV ($\Sigma_{KN} \sim 330$ MeV)



$U_K = -180$ MeV (extremely attractive)

Density distributions

Ground state



$\overline{K}$- Baryon interactions in K⁻ field equation

$\delta\Omega/\delta\theta(r) = 0$

K⁻ field equation

$\widetilde{\omega}_{K^-} = \omega_{K^-} - V_{\rm Coul}$

$$\nabla^2\theta = \sin\theta\Big[\big(m_K^2 - 2g_{\sigma K}m_K\sigma - 2g_{\sigma^* K}m_K\sigma^*\big) - 2\widetilde{\omega}_{K^-}(g_{\omega K}\omega_0 + g_{\rho K}R_0 + g_{\phi K}\phi_0) - \widetilde{\omega}^2_{K^-}\cos\theta\Big]$$

S-wave scalar int.

$$m_K^{*2} \equiv m_K^2 - 2g_{\sigma K}m_K\sigma - 2g_{\sigma^* K}m_K\sigma^*$$

$$\big(\ U_{K^-} = -g_{\sigma K}\sigma - g_{\omega K}\omega_0\ \big)$$

S-wave vector int.

$$X_0 \equiv g_{\omega K}\omega_0 + g_{\rho K}R_0 + g_{\phi K}\phi_0$$

Chiral symmetry

$$\sim \frac{1}{2f^2}\left(\rho_p + \frac{1}{2}\rho_n - \frac{1}{2}\rho_{\Sigma^-} - \rho_{\Xi^-}\right)$$

repulsion for Σ^- and Ξ^- hyperons

In the presence of K⁻ mesons,

- Mixing of Σ^- and Ξ^- hyperons are unfavored.

Equations of motion for meson fields

Scalar mean fields

$$-\nabla^2\sigma+m_\sigma^2\sigma=-\frac{dU}{d\sigma}+g_{\sigma N}(\rho_p^s+\rho_n^s)+g_{\sigma\Lambda}\rho_\Lambda^s+g_{\sigma\Sigma^-}\rho_{\Sigma^-}^s+g_{\sigma\Xi^-}\rho_{\Xi^-}^s+2f^2g_{\sigma K}m_K(1-\cos\theta)$$

$$-\nabla^2\sigma^*+m_{\sigma^*}^2\sigma^*=g_{\sigma^*\Lambda}\rho_\Lambda^s+g_{\sigma^*\Sigma^-}\rho_{\Sigma^-}^s+g_{\sigma^*\Xi^-}\rho_{\Xi^-}^s+2f^2g_{\sigma^*K}m_K(1-\cos\theta)$$

Vector mean fields

$$-\nabla^2\omega_0+m_\omega^2\omega_0=g_{\omega N}(\rho_p+\rho_n)+g_{\omega\Lambda}\rho_\Lambda+g_{\omega\Sigma^-}\rho_{\Sigma^-}+g_{\omega\Xi^-}\rho_{\Xi^-}-2f^2g_{\omega K}\widetilde{\omega}_K(1-\cos\theta)$$

$$-\nabla^2R_0+m_\rho^2R_0=g_{\rho N}(\rho_p-\rho_n)+g_{\rho\Lambda}\rho_\Lambda-g_{\rho\Sigma^-}\rho_{\Sigma^-}-g_{\rho\Xi^-}\rho_{\Xi^-}-2f^2g_{\rho K}\widetilde{\omega}_K(1-\cos\theta)$$

$$-\nabla^2\phi_0+m_\phi^2\phi_0=g_{\phi\Lambda}\rho_\Lambda+g_{\phi\Sigma^-}\rho_{\Sigma^-}+g_{\phi\Xi^-}\rho_{\Xi^-}-2f^2g_{\phi K}\widetilde{\omega}_K(1-\cos\theta)$$

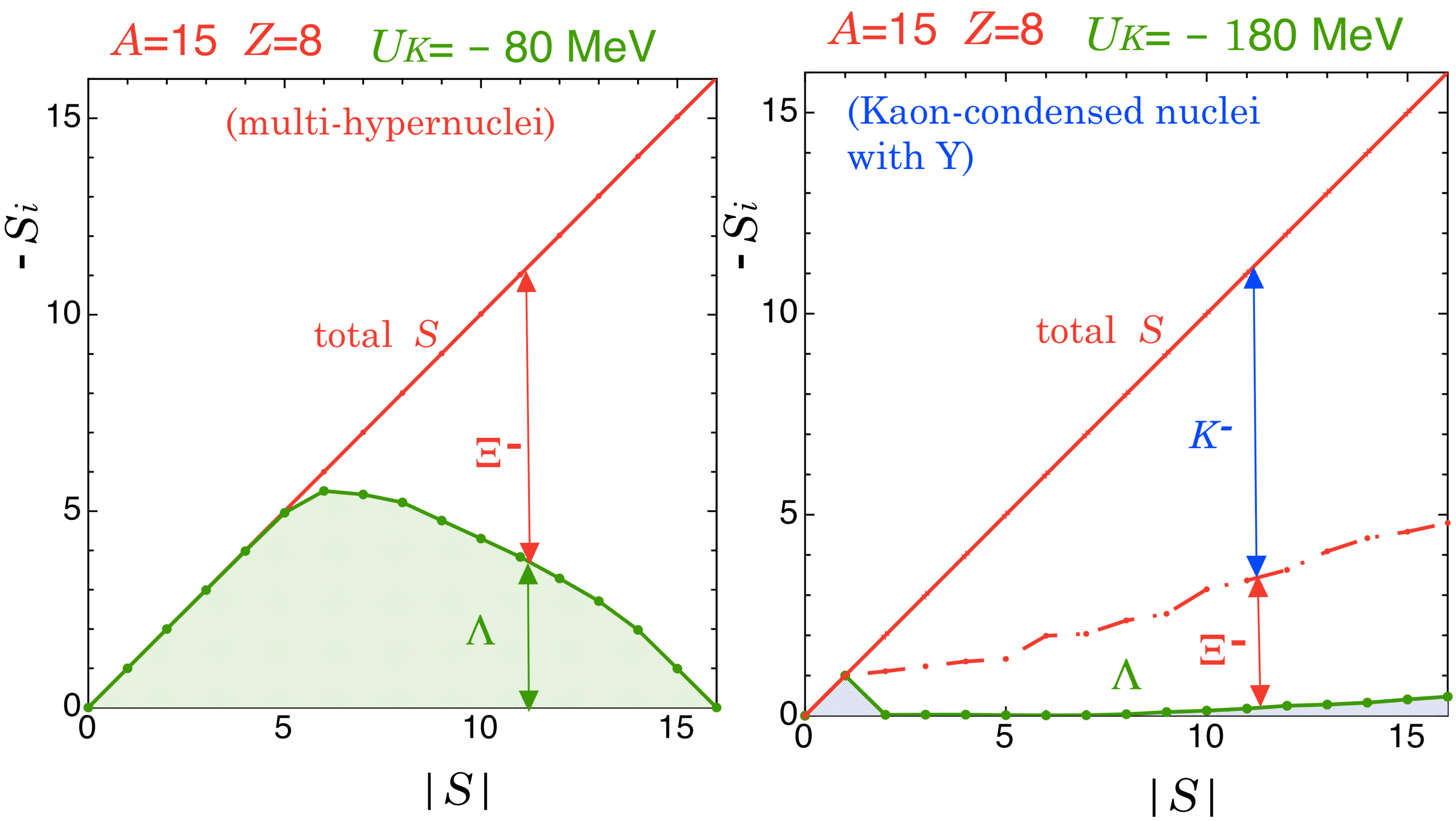
Coulomb field $\nabla^2V_{\rm Coul}=4\pi e^2(\rho_p-\rho_{\Sigma^-}-\rho_{\Xi^-}-\rho_{K^-})$

The presence of K^- condensates (θ) leads to a negative contribution to vector mean fields (ω_0, R_0, ϕ_0) . ⟹ $X_0\equiv g_{\omega K}\omega_0+g_{\rho K}R_0+g_{\phi K}\phi_0$ <0

The number density of K- mesons

$$\rho_{K^-}=\widetilde{\omega}_{K^-}f^2\sin^2\theta+2f^2X_0(1-\cos\theta)<0 \quad \text{for } X_0<<0 .$$

3-2 Strangeness fraction



4. 中性子星内部のK中間子凝縮との関係

実験室系　バリオン, K-中間子の密度分布は自己無撞着に求まる。

$U_K = -80$ MeV　バリオン密度 $\rho \sim \rho_0$

満たしにくい

Chemical equilibrium for strong processes

$K^- p \rightleftharpoons \Lambda, \quad K^- \Lambda \rightleftharpoons \Xi^-, \quad K^- n \rightleftharpoons \Sigma^-$

無限系

中性子星内部　高密度のバリオン系

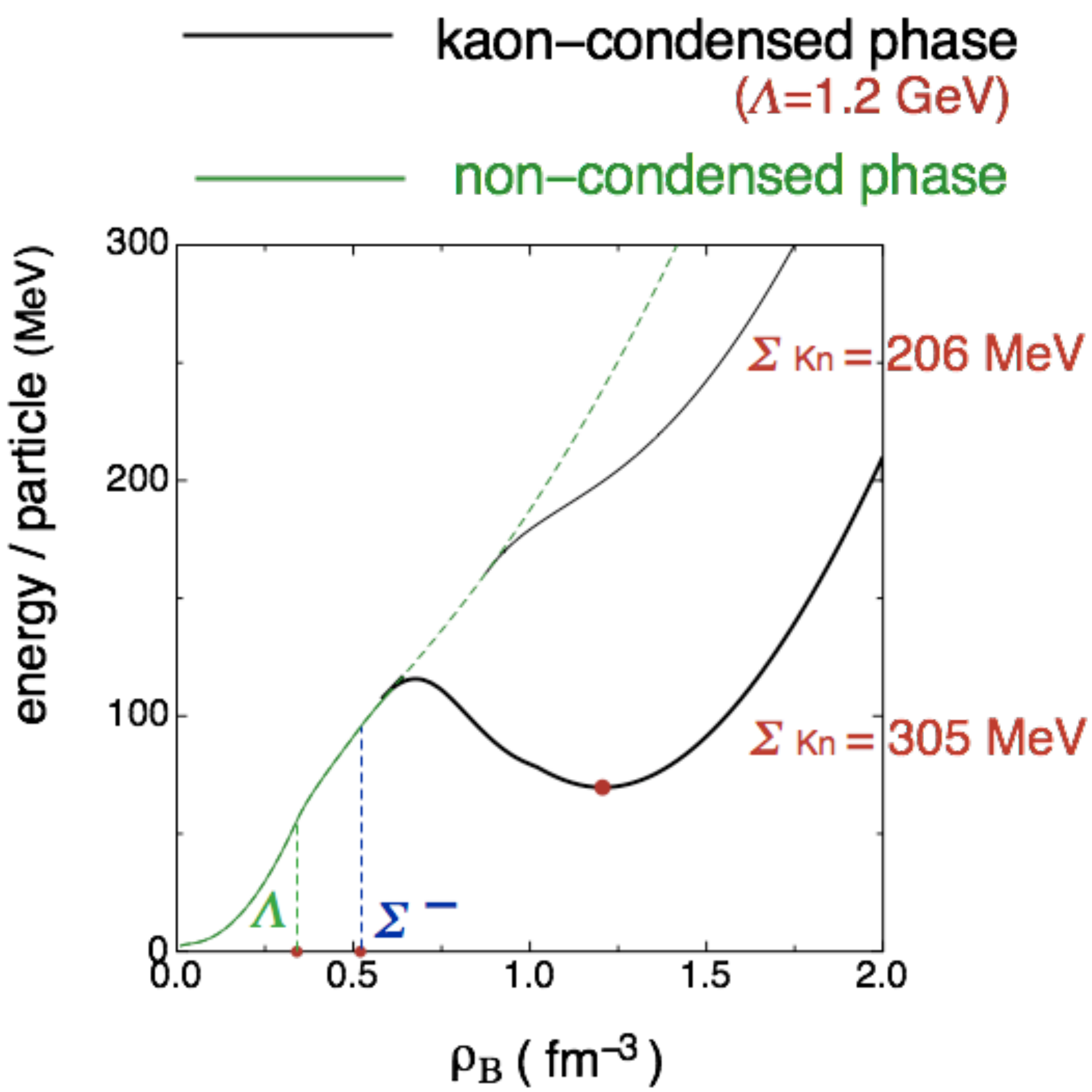
chemical equilibrium for weak processes

$n \rightleftharpoons p\, K^- \qquad p\, e^- \rightleftharpoons \Lambda\ (\nu_e) \qquad n\, e^- \rightleftharpoons \Sigma^-\ (\nu_e)$

$n \rightleftharpoons p\, e^-\ (\bar{\nu}_e) \qquad \Lambda\, e^- \rightleftharpoons \Xi^-\ (\nu_e)$

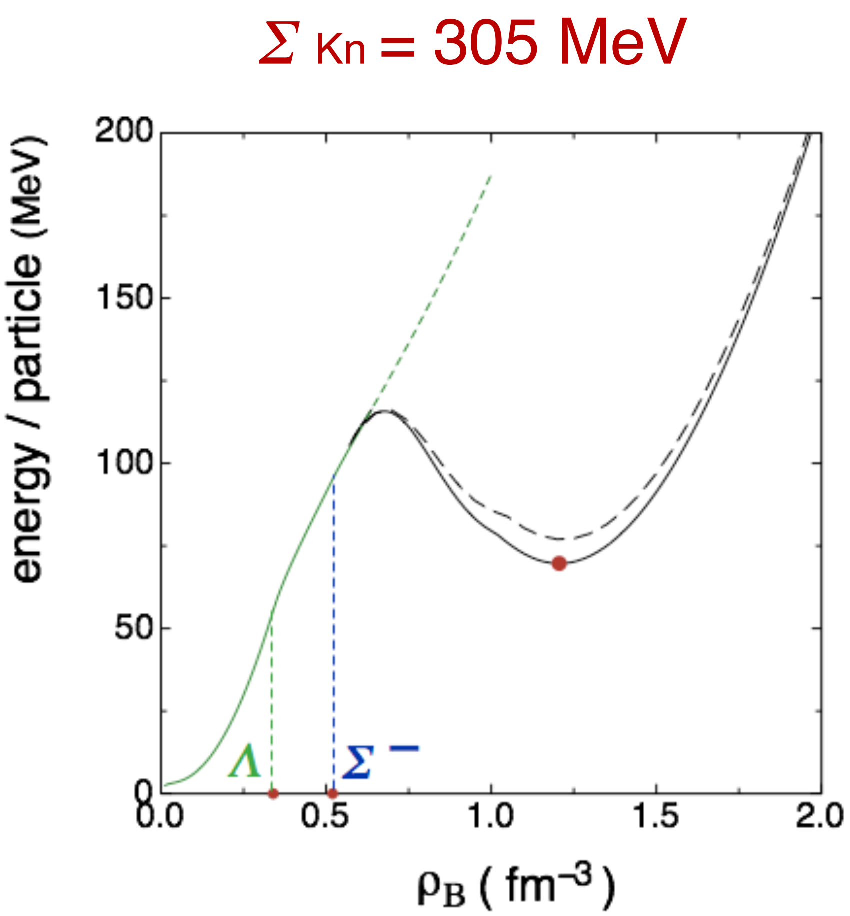
K^- chemical potential : $\omega_{K^-} = \mu = \mu_n - \mu_p < 0$ for high densities

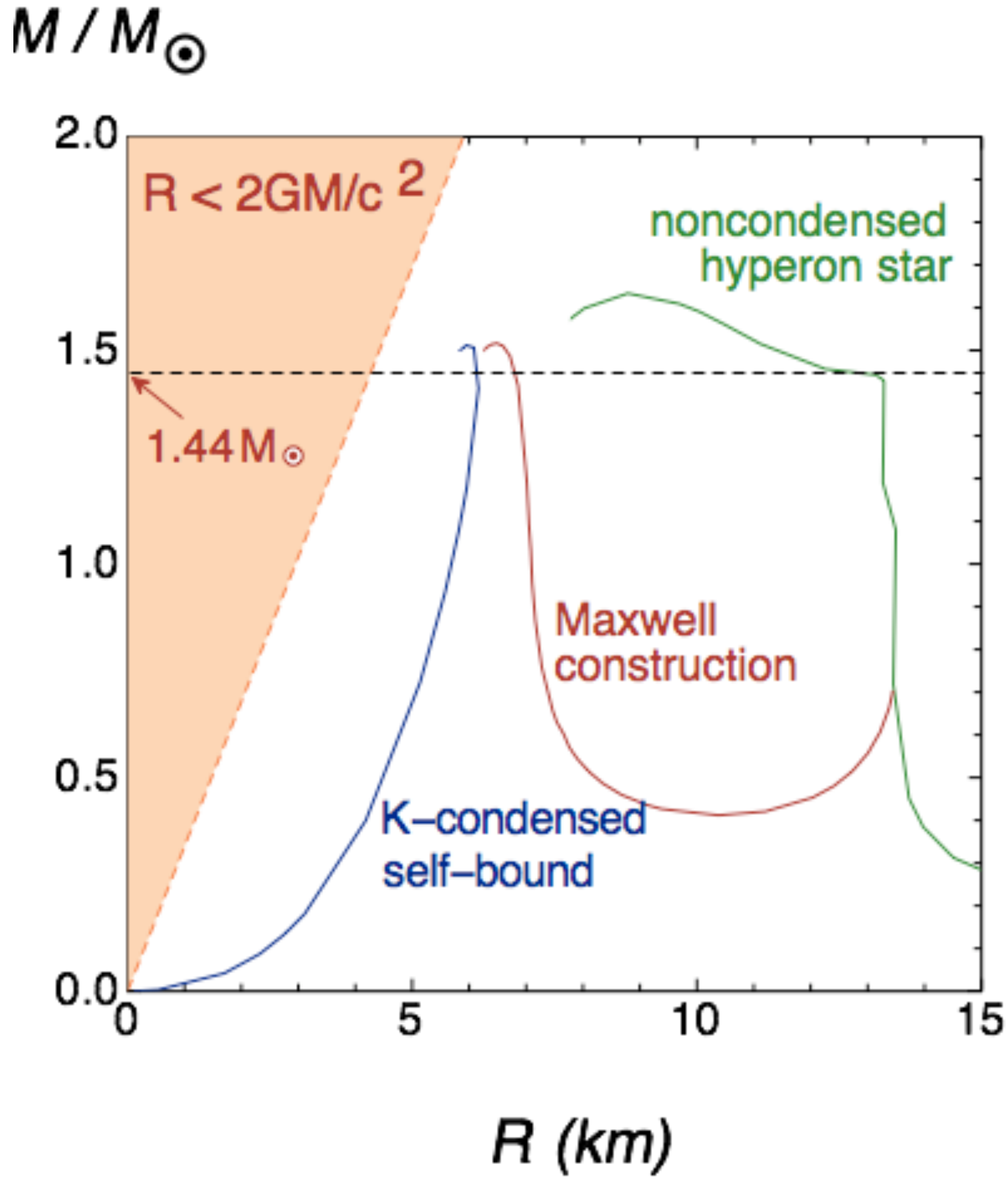
EOS of kaon condensation in hyperonic matter



Self-bound object with kaon condensates

Gravitational Mass - Radius relations





5. Summary and outlook

We have considered a possible existence of kaonic bound nuclei with hyperon-mixing in a framework of the RMF combined with nonlinear effective chiral Lagrangian for $\bar{K}-B$ and $\bar{K}-\bar{K}$ interactions.

For moderate U_{K^-} (= - 80 MeV), the ground state is given by multi-hypernuclei without bound K^- mesons.

Ξ^- -mixing becomes dominant for large |S|.

For extremely attractive U_{K^-} (= - 180 MeV), K^- mesons are bound with slightly mixed Λ hyperons and Ξ^-.

K^- mesons: near the center , Ξ^- : at the outer region

The presence of K^- condensates (θ) leads to a negative contribution to vector mean fields (ω_0, R_0, ϕ_0) .

EOS of kaon condensation in hyperonic matter

- hyperon-mixing
- S-wave and p-wave kaon-baryon interactions

➡ Considerable softening of the EOS

高密度でのバリオン間の斥力を強める効果

K-バリオン間の引力を弱める効果