[Workshop on Strangeness and charm in hadrons and dense matter
May 26 (Fri) , 2017, YITP, Kyoto Univ.)]

Interplay of kaon condensation and hyperons in nuclei and in neutron stars

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1. Introduction

Kaonic clusters and Strangeness physics

Kaonic nuclei

(Kaonic cluster)

・Chiral symmetry
and its spontaneous / explicit breaking

↓

$K^- pp$ experiments ⇄ In-medium $\bar{K}N$ dynamics

FINUDA [M. Agnello et al., Phys. Rev. Lett. 94 (2005) 212303;
Phys. Lett. B654(2007), 80.]

^{6}Li, ^{7}Li, ^{12}C + K^- stopped
$\rightarrow \Lambda\, p + \cdots$

$B = 115$ MeV, $\Gamma = 67$ MeV

DISTO Collaboration [T. Yamazaki et al., Phys.Rev.Lett.104, 132502 (2010).]

$(p\ p \rightarrow K^+ + K^- p\ p)$

$B = 105$ MeV, $\Gamma = 118$ MeV

E27 (J-PARC) [Y. Ichikawa et al., PTEP 2015, 021D01 (2015).]

$d(\pi^+, K^+)K^- pp$

$B = 95$ MeV, $\Gamma = 162$ MeV

E15 (J-PARC) [Y. Sada et al., PTEP 2016, 051D01 (2016).]

$^3\mathrm{He}\ (K^-,\ \Lambda p)n$

$B = 15$ MeV, $\Gamma = 110$ MeV

Finite system | Strangeness is conserved

Kaonic nuclei

↓

Multi- $\bar{K}$ nuclei

- dense and cold object ?
- Structure (composition, density distributions of kaons and baryons)

Multi-kaonic clusters

[T.Yamazaki, A. Dote, Y. Akaishi, Phys. Lett.B587, 167(2004).]

Bound state of multi K^- mesons

[T. Muto, T. Maruyama, and T. Tatsumi,
Phys. Rev. C79, 035207 (2009);
JPS Conf. Proceedings 1 (2014) 013081;
EPJ Web of Conferences 73 (2014) 05007.]

c.f., Meson-exchange models

[D. Gazda, E. Friedman, A. Gal, J. Mares,
Phys. Rev. C76, 055204 (2007);
Phys. Rev. C77, 045206 (2008).
Phys. Rev. C80, 035205 (2009).]

[S. Ohnishi, W. Horiuchi et al.,
JPS meeting (2016).]

Infinite matter

Kaon condensation in neutron stars

Coexistence of kaon condensation and hyperons (Y+K) phase

Strangeness is spontaneously generated by weak processes

- Softening of EOS
- Rapid cooling of neutron stars

I. Relation between Kaonic nuclei
and Kaon condensation in dense matter

II. Equation of state (EOS) with kaon condensation
in hyperon-mixed matter [(Y+K) phase]

- consistensy with massive neutron stars observations ($M_{max} \sim 2 M_{\odot}$)

Interaction model
for multi-strangeness system of kaons and baryons

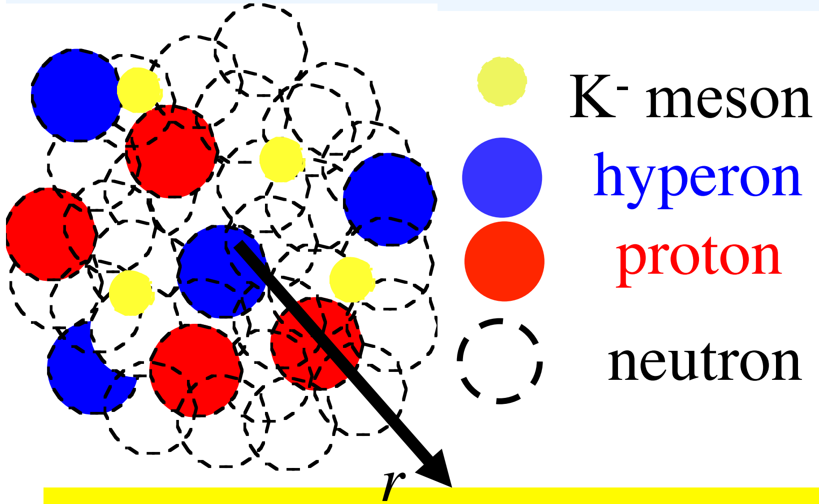
||

Effective chiral Lagrangian for $\bar{K}B$ and $\bar{K}\bar{K}$ interactions,
coupled with Relativistic Mean-field Theory for B-B interactions

K^- mesons and hyperons are taken into account together in a unified way for both finite nuclei and neutron stars within the same framework.

Density Functional description of $\bar{K}$ and Baryons in terms of density distribution functions

2. Multi-antikaonic nuclei



Assume : Spherical symmetry

Local density approximation for baryons

[Initial target nucleus] (A, Z)

Input K⁻ mesons : |S|

conservation

[strangeness] |S| : given

[e.m.charge] $Z - |S|$: constant

[baryon number] A: constant

Thermodynamic potential

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

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

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

$$\omega_{K^-} = \mu_Q - \mu_s$$

$$\mu_p = -(\mu_Q + \nu)$$

$$\mu_n = -\nu$$

$$\mu_\Lambda = -(\mu_s + \nu)$$

$$\mu_{\Sigma^-} = \mu_Q - \mu_s - \nu$$

$$\mu_{\Xi^-} = \mu_Q - 2\mu_s - \nu$$

Chemical equilibrium for strong processes

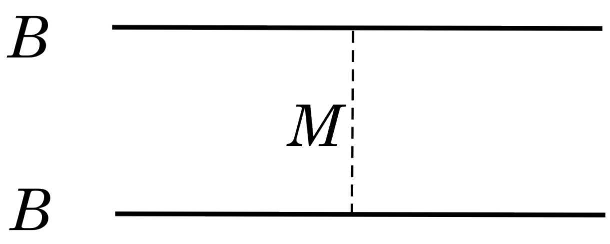
$$\omega_{K^-} + \mu_p = \mu_\Lambda$$

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

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

2.1 Interaction model

Baryon-Baryon interaction



Relativistic mean-field theory

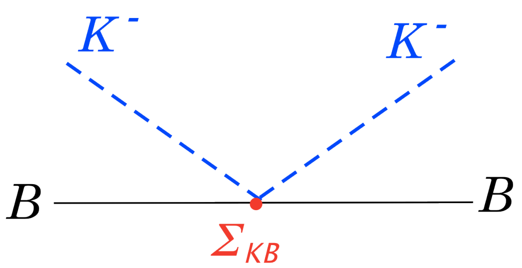
Baryons: $(p, n, \Lambda, \Sigma^-, \Xi^-)$

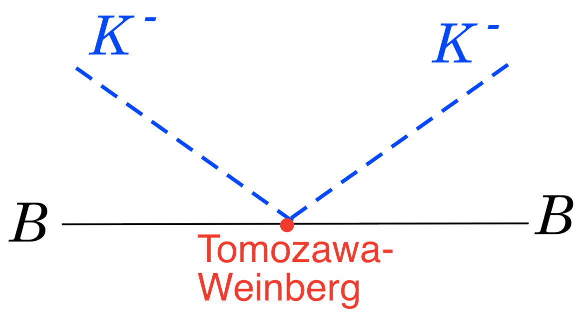
Mesons: $\sigma, \omega, \rho, \sigma^*, \phi$

$\overline{K}-B, \overline{K}-\overline{K}$ interactions

$SU(3)_L \times SU(3)_R$ chiral effective Lagrangian

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





Nonlinear K field

$$\Sigma \equiv e^{2i\Pi/f}$$

$$\Pi = \pi_a T_a = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & K^+ \\ 0 & 0 & 0 \\ K^- & 0 & 0 \end{pmatrix}$$

Classical K^- field

$$K^-(r) = \frac{f}{\sqrt{2}} \theta(r)$$

Meson decay constant

f =93 MeV

μ_K : kaon chemical potential

Thermodynamic potential *Ω*

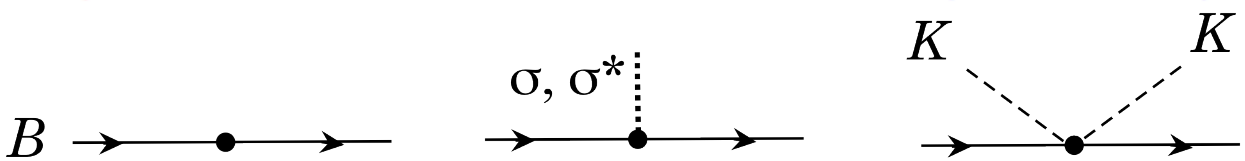
$$\Omega = \Omega_B + \Omega_K + \Omega_M + \Omega_{\rm Coulomb}$$

[Baryon part]

$$\Omega_B = \sum_{b=p,n,\Lambda,\Sigma^-,\Xi^-} \int d^3r \left[2\int_0^{k_F(b)} \frac{d^3k}{(2\pi)^3}\sqrt{k^2 + M_b^{*2}} - \rho_b \sqrt{k_F(b)^2 + M_b^{*2}} \right]$$

Effective baryon mass

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



[kaon part]

$$\Omega_K = \int d^3r \left[f^2 m_K^2 (1-\cos\theta) - \frac{1}{2}(\omega_K - V_{\rm Coulomb})^2 f^2 \sin^2\theta + \frac{f^2}{2}(\nabla\theta)^2 \right]$$

$V_{\rm coulomb}$: Coulomb potential

$$\Omega_M = \int d^3r \left[\frac{1}{2}(\nabla\sigma)^2 + \frac{1}{2}m_\sigma^2\sigma^2 + U(\sigma) - \frac{1}{2}(\nabla\omega_0)^2 - \frac{1}{2}m_\omega^2\omega_0^2 - \frac{1}{2}(\nabla R_0)^2 - \frac{1}{2}m_\rho^2 R_0^2 \right]$$

$$\Omega_{\rm Coulomb} = \int d^3r \left[-\frac{1}{8\pi e^2}(\nabla V_{\rm Coulomb})^2 \right]$$

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

Classical K- field equation

$$\nabla^2\theta = \sin\theta\left[m_K^{*2} - 2(\omega_K - V_{\rm Coulomb})X_0 - (\omega_K - V_{\rm Coulomb})^2\cos\theta\right]$$

$$m_K^{*2} = m_K^2 - \frac{1}{f^2}\sum_{b=p,n,\Lambda,\Sigma^-,\Xi^-}\rho_b^s\Sigma_{Kb}$$

S wave KB scalar int.

$$X_0 \equiv \frac{1}{2f^2}\left(\rho_p + \frac{1}{2}\rho_n - \frac{1}{2}\rho_{\Sigma^-} - \rho_{\Xi^-}\right)$$

S wave KB vector int.

Coupling constants in RMF

g_{MB} (ρ_0 =0.153 fm^{-3}) (K=240 MeV)

--- NN interaction ---

gross features of normal nuclei and nuclear matter

--- vector meson couplings to Y ---

SU(6) symmetry

--- σ, σ* meson couplings for Y ---

M \ B	p	n	Λ	Ξ^-	Σ^-
σ	$g_{\sigma N}$= 6.38		3.84	1.94	2.28
ω	$g_{\omega N}$= 8.71		$2/3\ g_{\omega N}$	$1/3\ g_{\omega N}$	$2/3\ g_{\omega N}$
ρ	$g_{\rho N}$= 4.26			$g_{\rho N}$	$2g_{\rho N}$
ϕ			$-\sqrt{2}/3\ g_{\omega N}$	$-2\sqrt{2}/3\ g_{\omega N}$	$-\sqrt{2}/3\ g_{\omega N}$
σ^*			8.38	4.00	0

Hyperon potentials deduced from hypernuclear experiments

$$U_\Lambda^N(\rho_0) = -g_{\sigma\Lambda}\sigma + g_{\omega\Lambda}\omega_0 = -27\ \mathrm{MeV}$$

$g_{\sigma\Lambda} = 3.84$

$$U_{\Sigma^-}^N(\rho_0) = -g_{\sigma\Sigma^-}\sigma + g_{\omega\Sigma^-}\omega_0 = 23.5\ \mathrm{MeV}$$

: repulsive

$g_{\sigma\Sigma^-} = 2.28$

$$U_{\Xi^-}^N(\rho_0) = -g_{\sigma\Xi^-}\sigma + g_{\omega\Xi^-}\omega_0 = -14\ \mathrm{MeV}$$

$g_{\sigma\Xi^-} = 1.94$

--- σ, σ* meson couplings for Y ---

$$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) - 2B_{\Lambda}({}^{5}_{\Lambda}\mathrm{He})$$

Nagara event : $\Delta B_{\Lambda\Lambda}({}^{6}{}_{\Lambda\Lambda}\mathrm{He}) = 0.67 \pm 0.17$ MeV

[H.Takahashi et al., Phys. Rev.Lett. 87,212502 (2001).
J.K.Ahn et al., Phys. Rev. C88, 014003 (2013).]

gσΛ	gσ*Λ	$V_\Lambda(\rho_0)$ (MeV)	$B_{\Lambda\Lambda}({}^{6}{}_{\Lambda\Lambda}\mathrm{He})$ (MeV)	$B_{\Lambda}({}^{5}{}_{\Lambda}\mathrm{He})$ (MeV)	$\Delta B_{\Lambda\Lambda}({}^{6}{}_{\Lambda\Lambda}\mathrm{He})$ (MeV)
3.84	8.38	- 27	24.38	11.82	+ 0.74
	Exp.	- 27	6.91	3.12	+ 0.67

2.3 Multi-antikaonic nuclei (MKN)

For finite nuclei ($^{15}_{8}O$)

1. density distributions

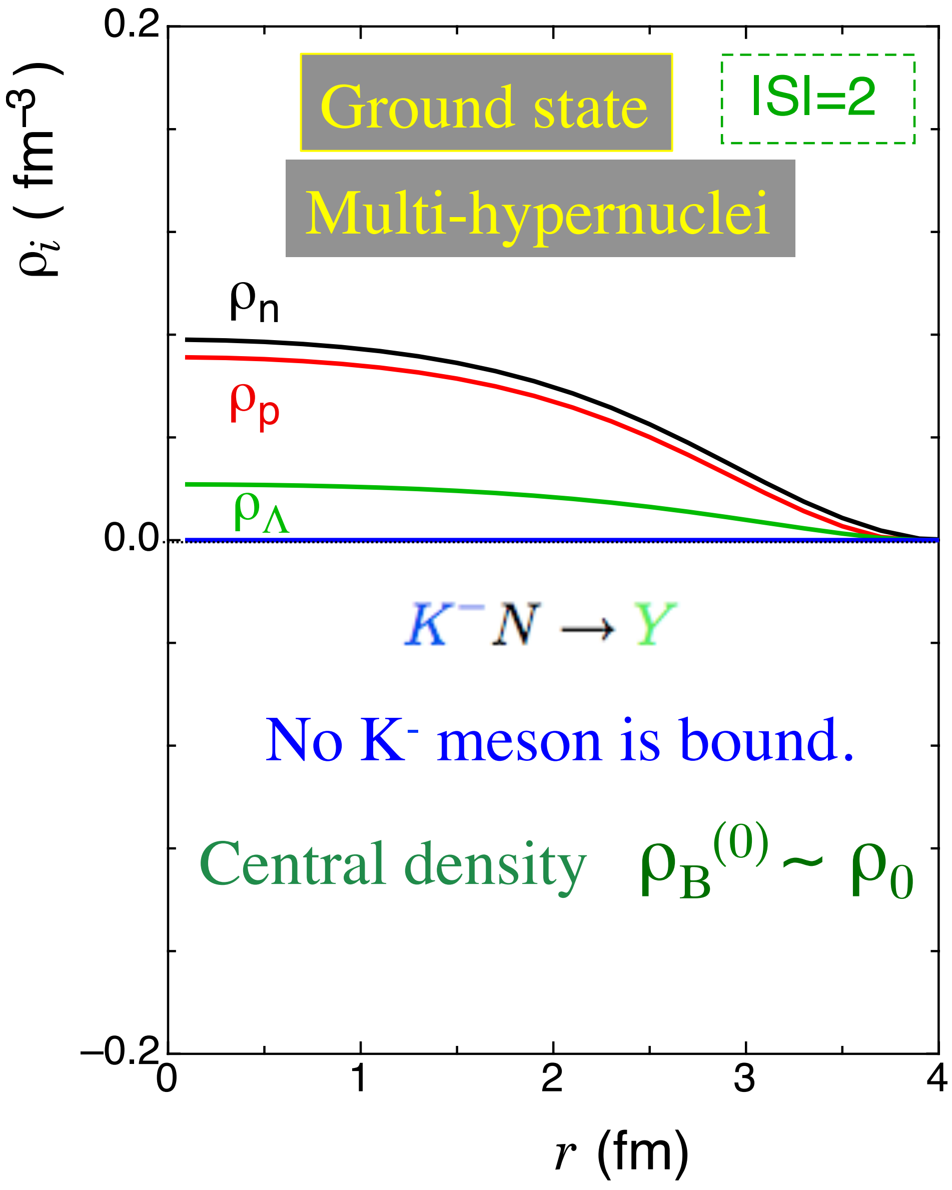
2. ground state of multi-strangeness nuclei

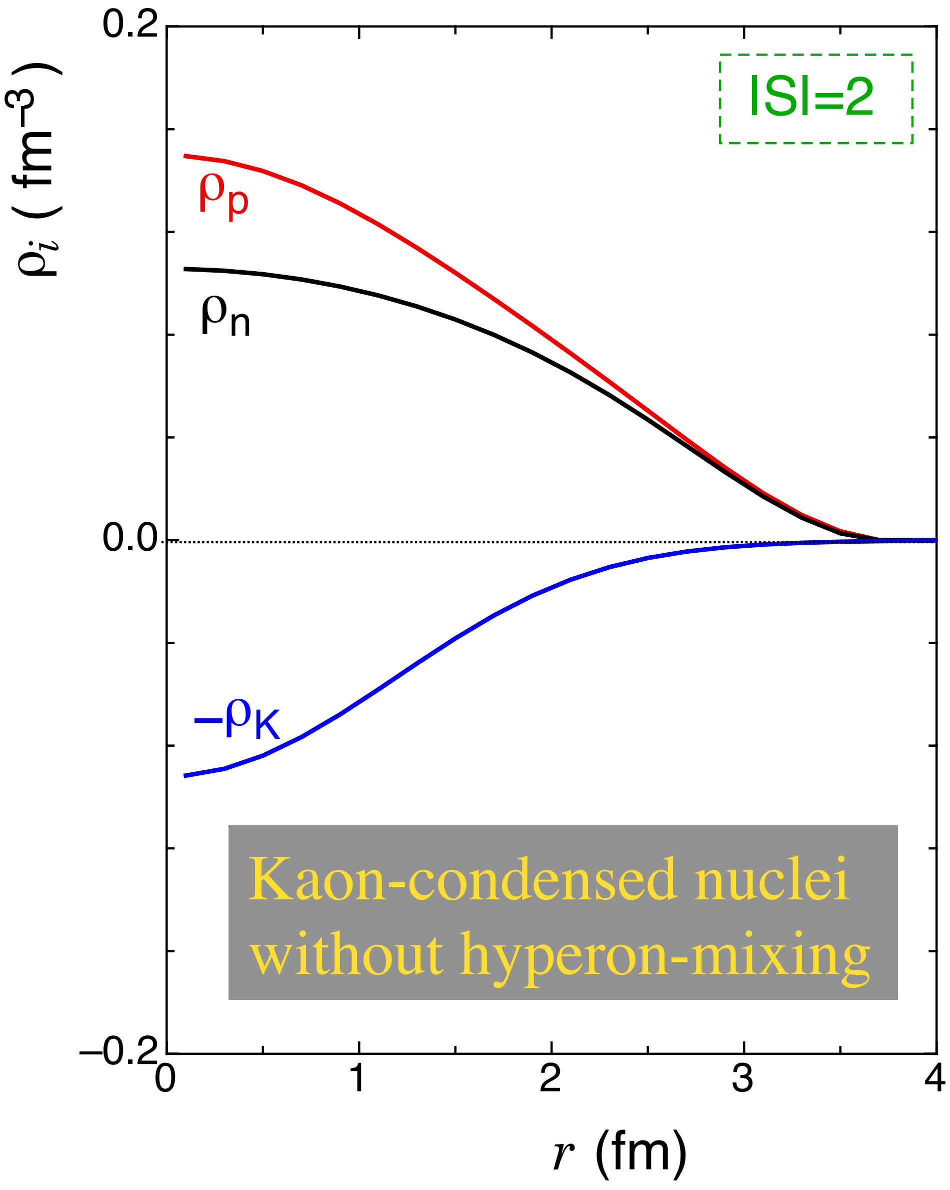
[T. Muto, T. Maruyama, and T. Tatsumi, Phys. Rev. C79, 035207 (2009).]
[T. Muto, T. Maruyama, and T. Tatsumi, JPS Conf. Proceedings 1 (2014) 013081;
EPJ Web of Conferences 73 (2014) 05007.]

c.f., Meson-exchange models [D. Gazda, E. Friedman, A. Gal, J. Mares,
Phys. Rev. C76, 055204 (2007);
Phys. Rev. C77, 045206 (2008).
Phys. Rev. C80, 035205 (2009).]

density distributions

A=15, Z=8 ($^{15}_{8}O$) $U_K = -80$ MeV   ($\Sigma_{Kn} \sim 300$ MeV)

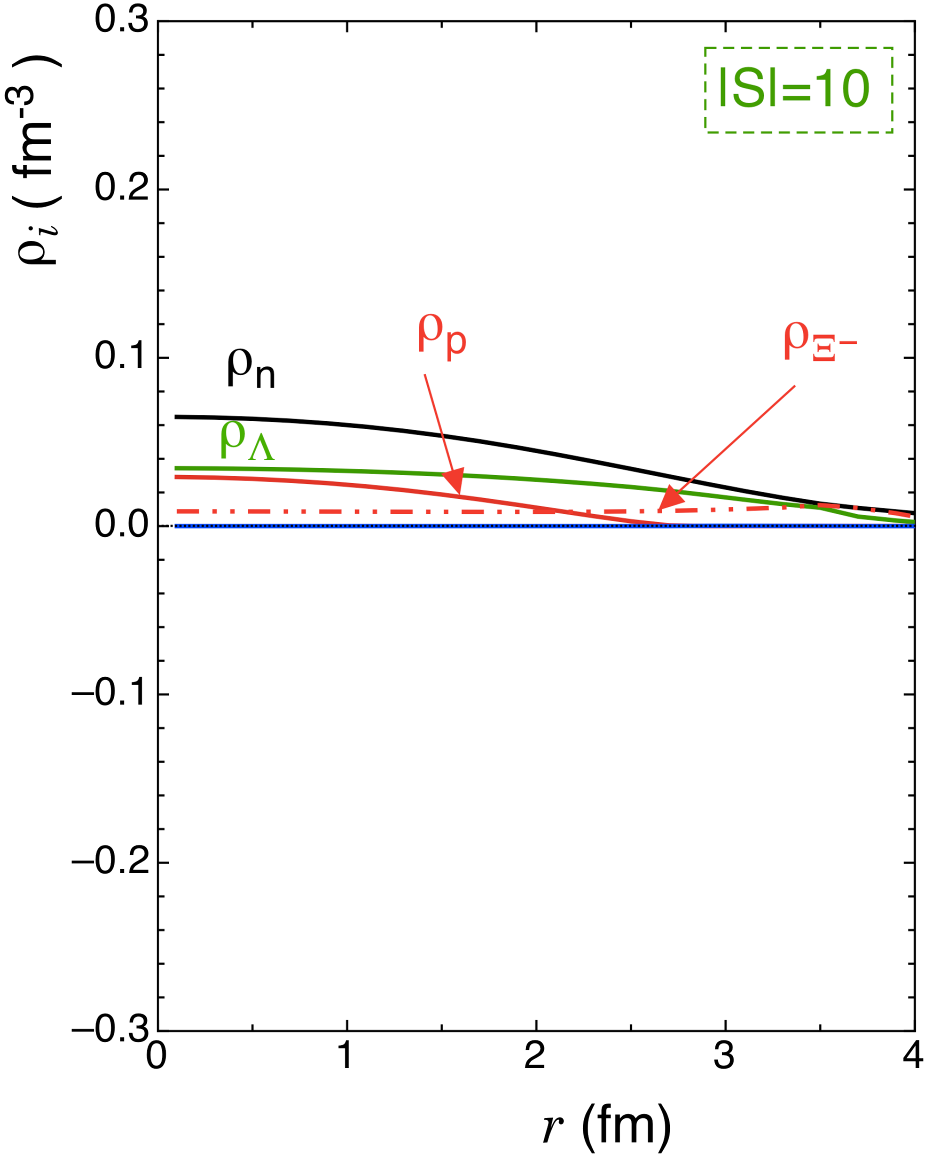




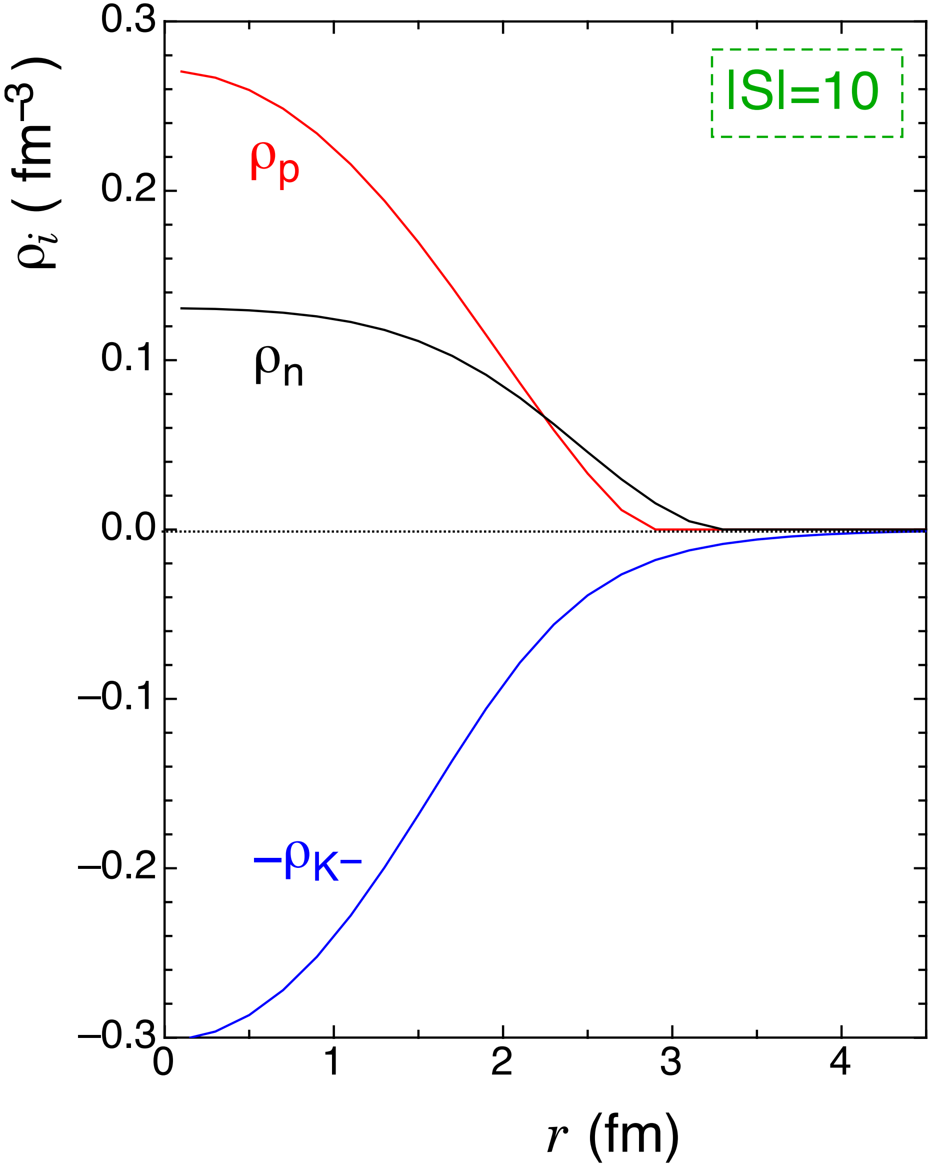
$U_K = -80$ MeV

Density distributions

Ground state

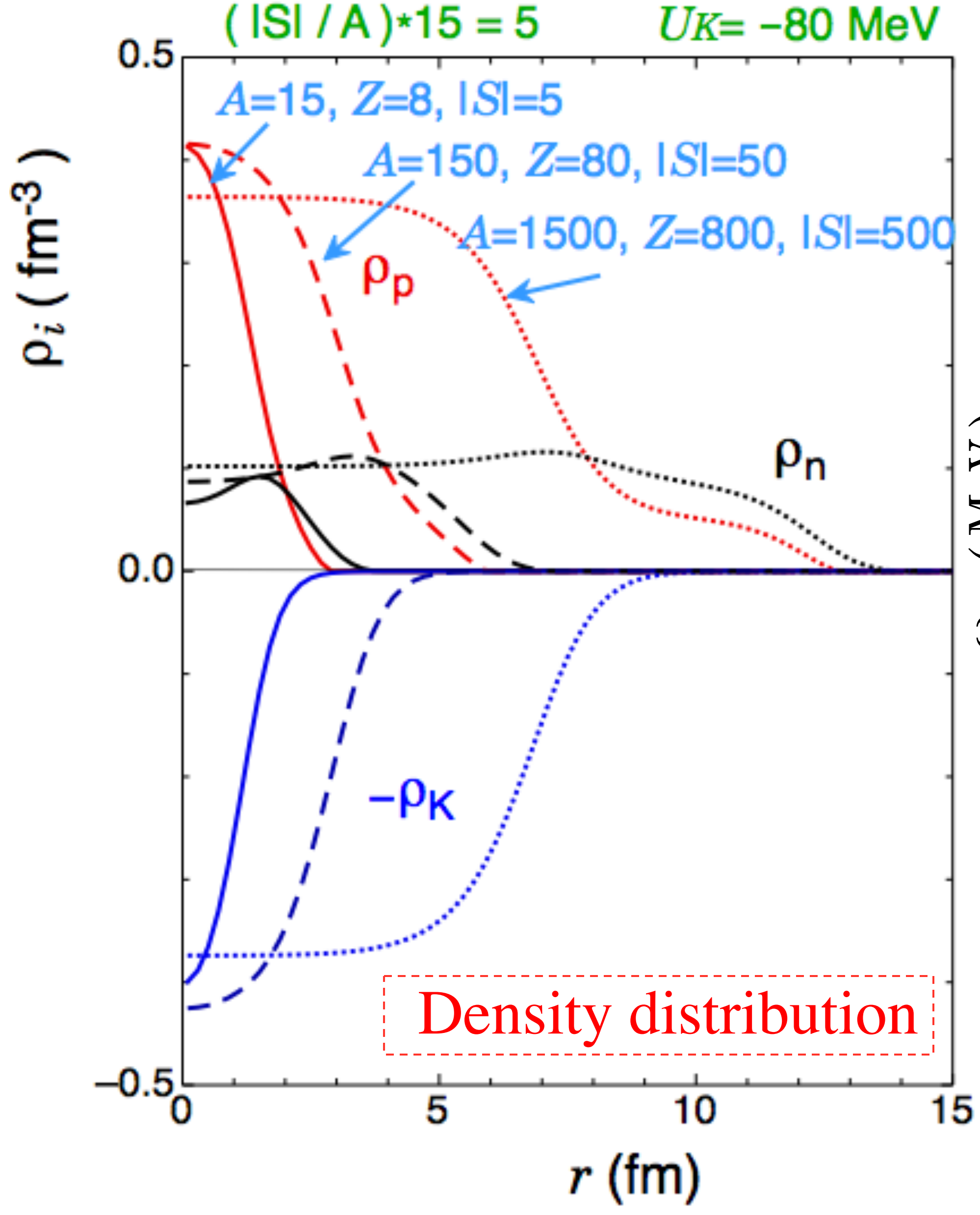


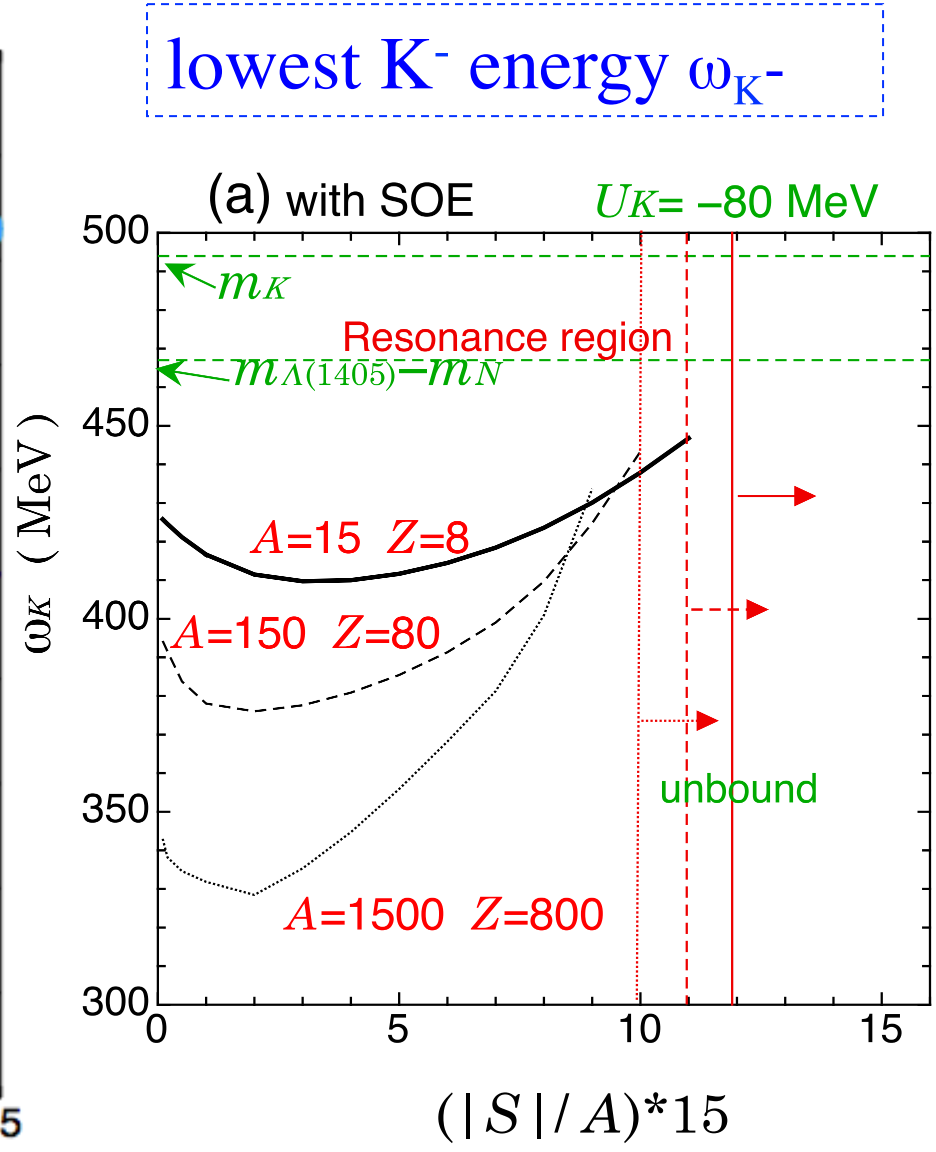
Without hyperon-mixing



condensation in dense matter

3.1 Increasing *A* with |*S*| / *A* and *Z* / *A* fixed





3.2 Comparison with kaon condensation in neutron stars

Finite system formed in laboratory

Antikaons do not receive much $\bar{K}-B$ attraction ← Finite effects of nuclei

$\omega_{K^-} > \mu_\Lambda - \mu_p$

$\omega_{K^-} = \mu_Q - \mu_s$

hard to satisfy

Chemical equilibrium for strong processes

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

Ground state: multi-hypernuclei

In neutron stars

Antikaons receive much $\bar{K}-B$ attraction ← dense infinite matter

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 : $\omega_{K^-} = \mu = \mu_n - \mu_p = O(m_\pi)$

Off-shell for high densities

Ground state: (Y+K) phase

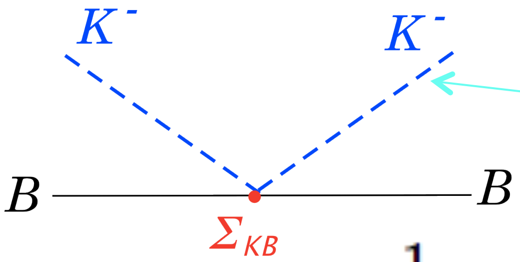
4. kaon condensation
in β-equilibrated matter (Neutron stars)

II. Equation of state (EOS) with kaon condensation in hyperon-mixed matter [(Y+K) phase]

4.1 Driving force and onset density of kaon condensation

uniform condensation

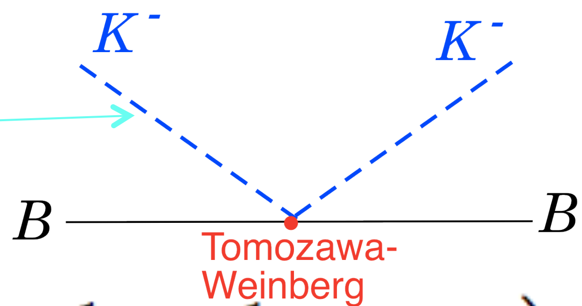
S wave KB scalar int.



Nonlinear K^- field

$$K^{\pm} = \frac{f}{\sqrt{2}}\theta \exp(\pm i\mu_K t)$$

S wave KB vector int.



$$m_K^{*2} \equiv m_K^2 - \frac{1}{f^2}\sum_i \rho_i^s \Sigma_{Ki}$$

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

$$X_0 \equiv \frac{1}{2f^2}\left(\rho_p + \frac{1}{2}\rho_n - \frac{1}{2}\rho_{\Sigma^-} - \rho_{\Xi^-}\right)$$

Effective energy density

$$\mathcal{E}^{\rm eff}(\theta, \mu, \rho_p, \rho_n, \rho_\Lambda, \rho_{\Xi^-}, \rho_{\Sigma^-}, \rho_e) = \mathcal{E} + \mu(\rho_p - \rho_{\Xi^-} - \rho_{\Sigma^-} - \rho_{K^-} - \rho_e)$$

Charge neutrality

Classical K$^-$ field equation $\partial\mathcal{E}^{\rm eff}/\partial\theta = 0$

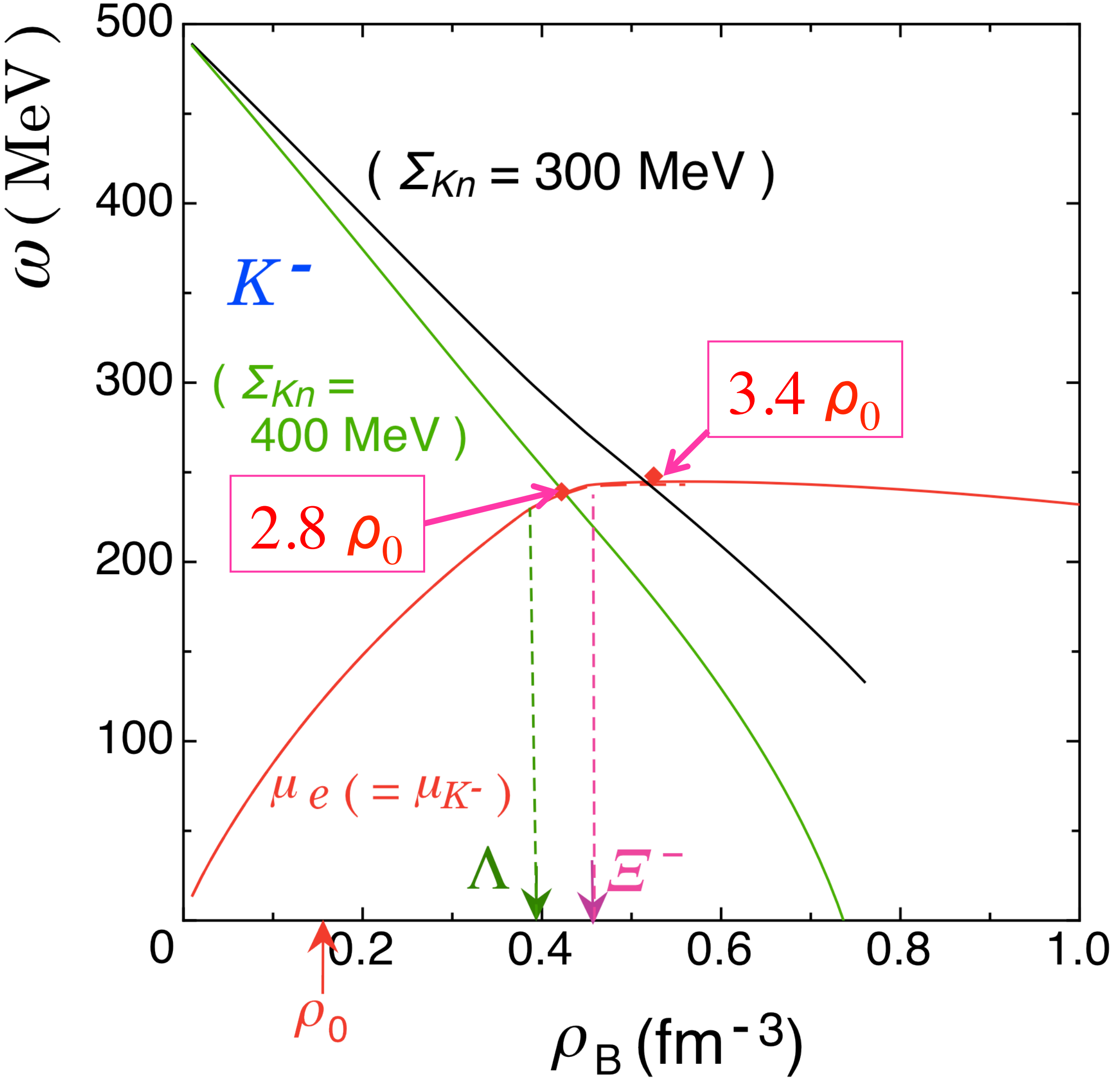
$$\mu^2\cos\theta + 2\mu X_0 - m_K^{*2} = 0$$

S-wave vector int.

S-wave scalar int.

Lowest kaon energy ω *in hyperonic matter* and onset density of kaon condensation

Coexistence of Kaon condensates and hyperons



(Y+K) phase

chemical equilibrium for weak processes

$n \rightleftharpoons p\ K^-$

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

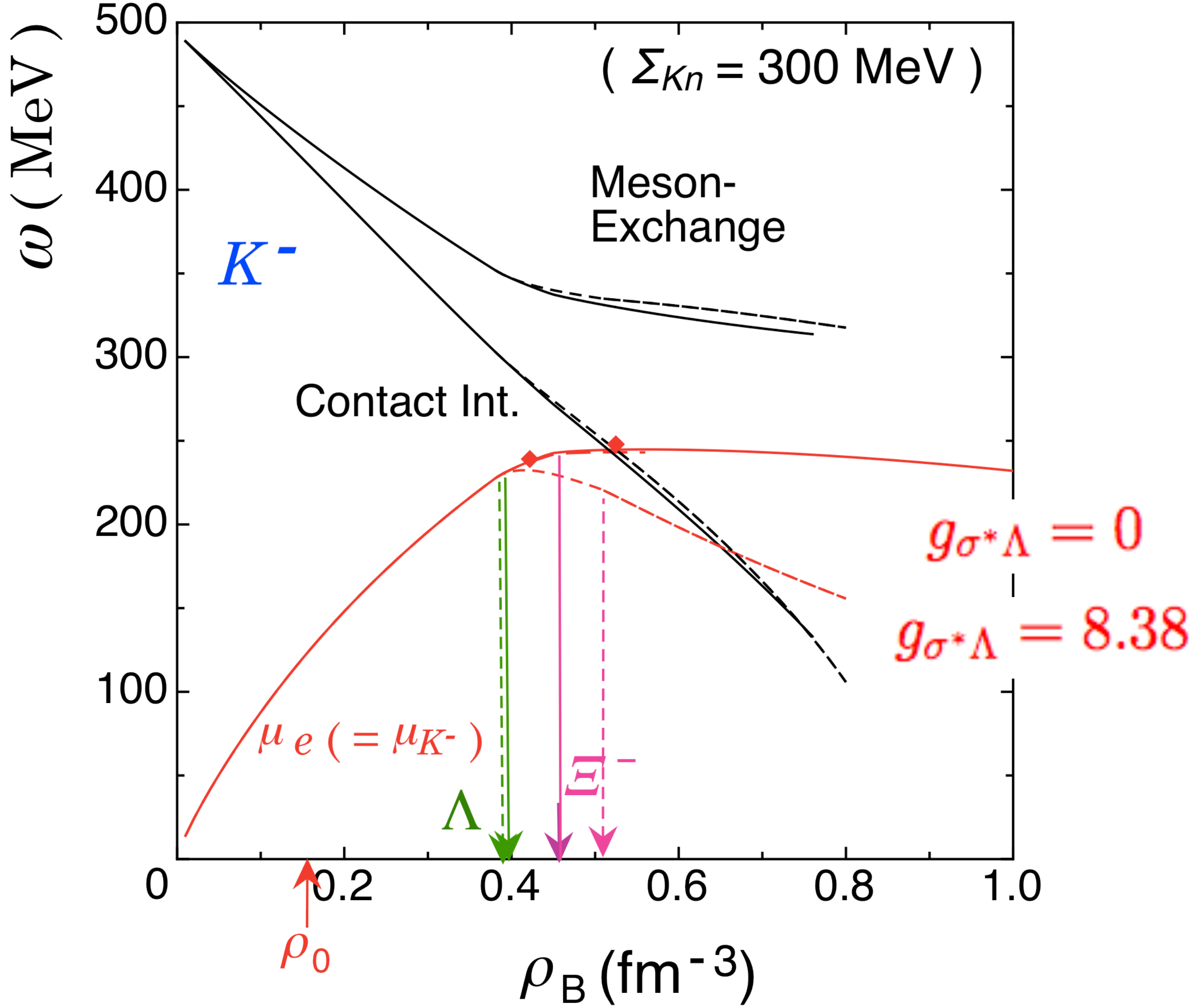
$p\ e^- \rightleftharpoons \Lambda\ (\nu_e)$

$n\ e^- \rightleftharpoons \Sigma^-\ (\nu_e)$

$\Lambda\ e^- \rightleftharpoons \Xi^-\ (\nu_e)$

Onset condition of Kaon condensation

$$\omega_{K^-} = \mu_Q (= \mu_e = \mu_n - \mu_p)$$

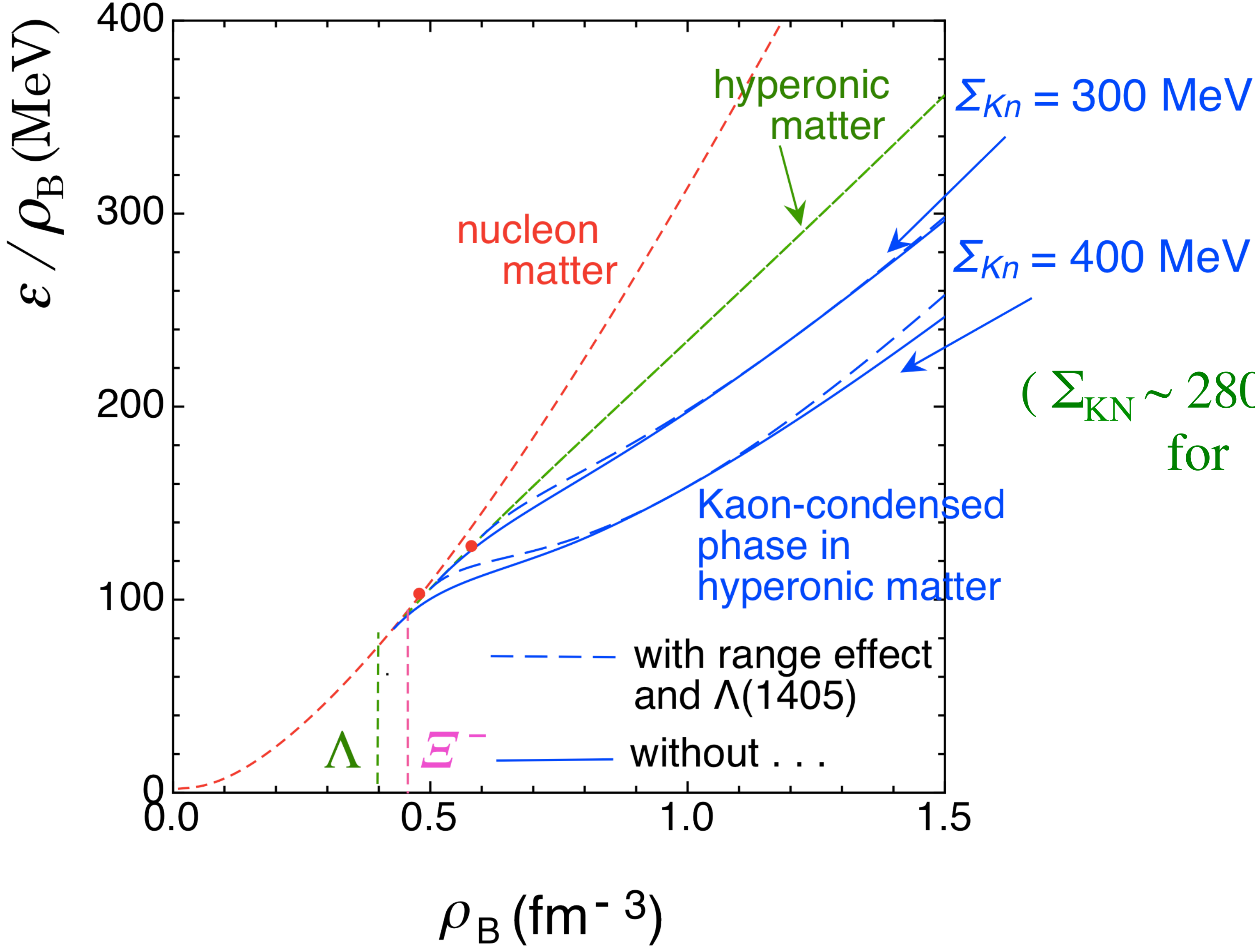


(Σ_{Kn} = 300 MeV)
Meson-
Exchange
K^-
Contact Int.
$g_{\sigma^*\Lambda} = 0$
$g_{\sigma^*\Lambda} = 8.38$
$\mu_e\ (= \mu_{K^-})$
Λ
Ξ^-
ω (MeV)
500
400
300
200
100
0
0.2
0.4
0.6
0.8
1.0
ρ_0
ρ_B (fm^{-3})

4.2 EOS of (Y+K) phase in β-equilibrated matter

Energy per particle

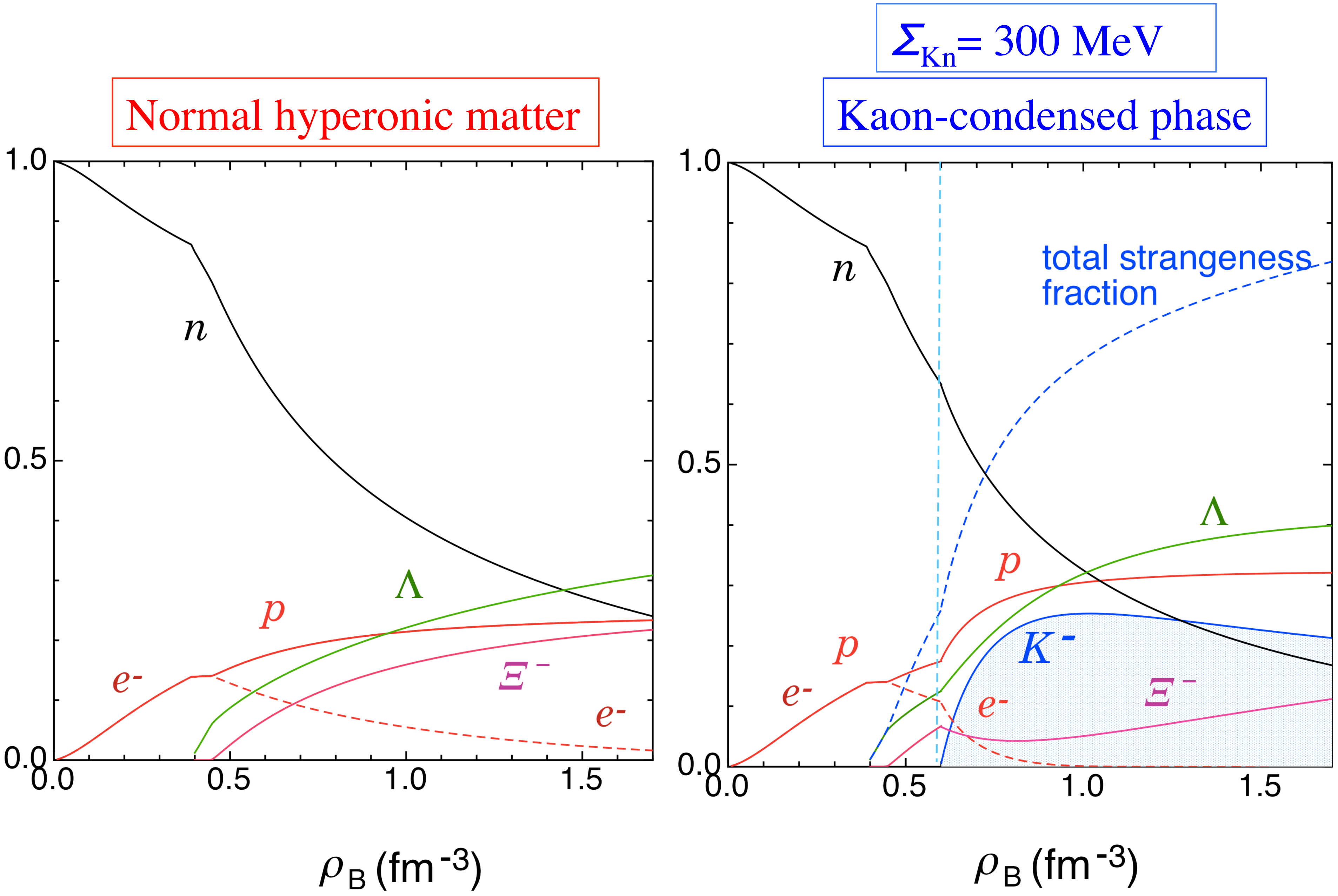
--- without universal 3-body repulsions ---



($\Sigma_{KN} \sim 280$ MeV for $\langle N | \bar{s}s | N \rangle \sim 0$)

Particle fractions

--- without universal 3-body repulsions ---



4.3 Possible Solutions to the " Hyperon Puzzle"

Many-body repulsion effects on EOS at high densities

➡ Stiffening the EOS at high densities

- Universal YNN, YYN, YYY repulsions

[S. Nishizaki, Y. Yamamoto and T. Takatsuka, Prog. Theor. Phys. 108 (2002) 703.]

[R. Tamagaki, Prog. Theor. Phys. 119 (2008), 965.] : String-Junction model

- Multi-pomeron exchange potential

[Y. Yamamoto, T. Furumoto, N. Yasutake, and Th.A. Rijken, Phys. Rev. C 90, 045805 (2014).]

- RMF extended to BMM, MMM type diagrams

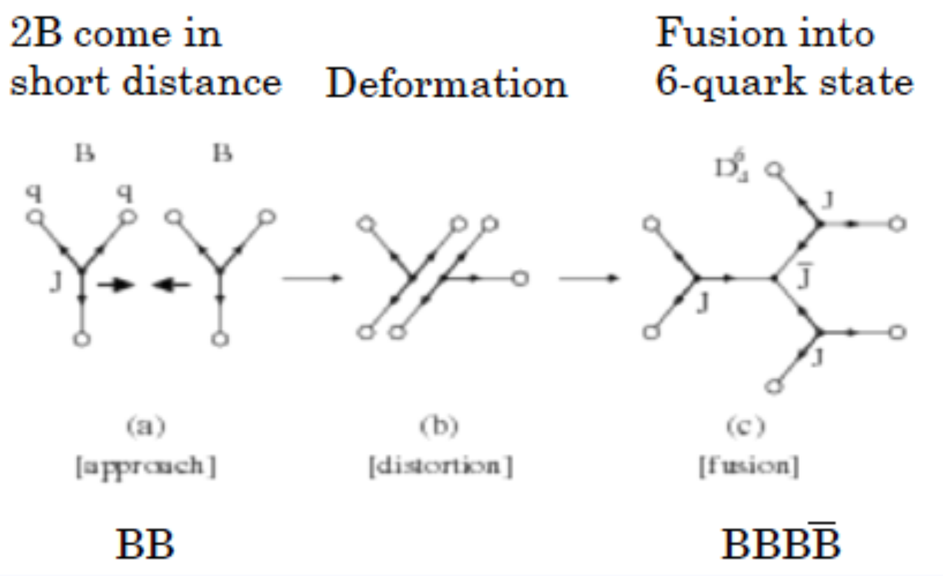
[K. Tsubakihara and A. Ohnishi, Nucl. Phys. A 914 (2013), 438; arXiv:1211.7208.]

We consider the (Y+K) phase by taking into account the universal three-body repulsion introduced by the String-junction model.

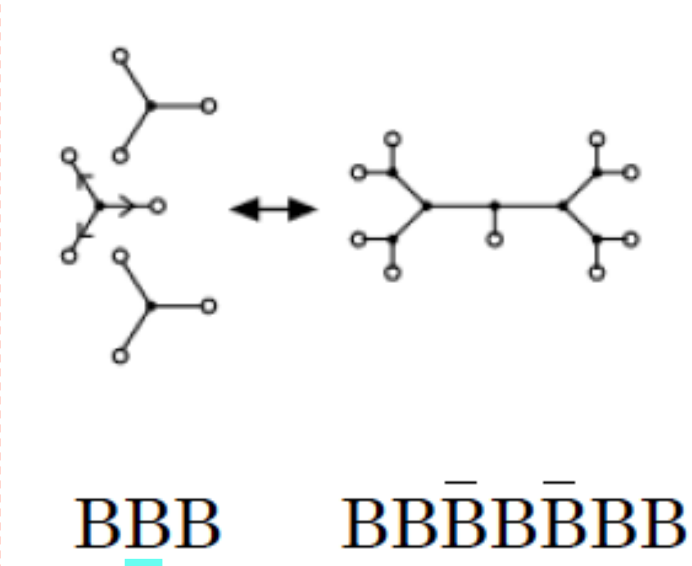
4.4 Effects of universal three-body repulsion with String Junction Model (Flavor-independent three-body repulsion)

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

Energy-barrier (~2 GeV) →
Repulsive core of B-B interactions



B-B-B interactions



W_0 ~ 2 GeV

Relative w. f.

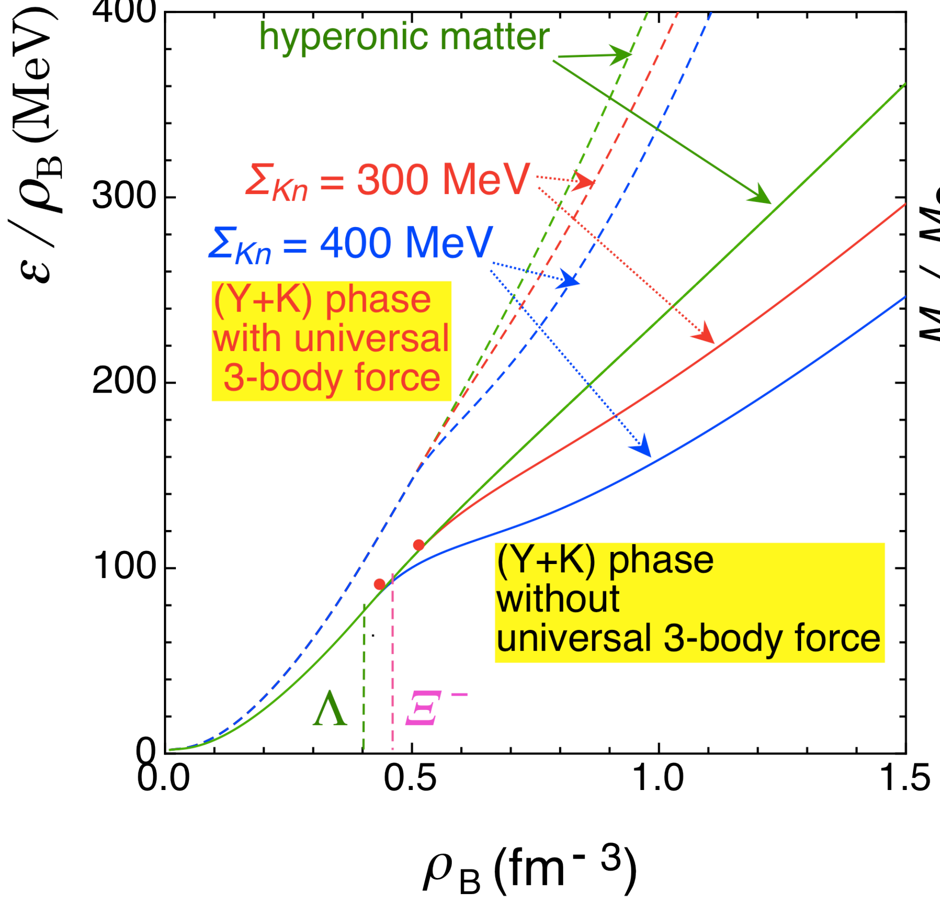
$$W(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) = W_0 g(\mathbf{r}_1 - \mathbf{r}_3) g(\mathbf{r}_2 - \mathbf{r}_3)$$

$$g(\mathbf{r}_i - \mathbf{r}_j) = \exp(-\lambda(\mathbf{r}_i - \mathbf{r}_j)^2)$$

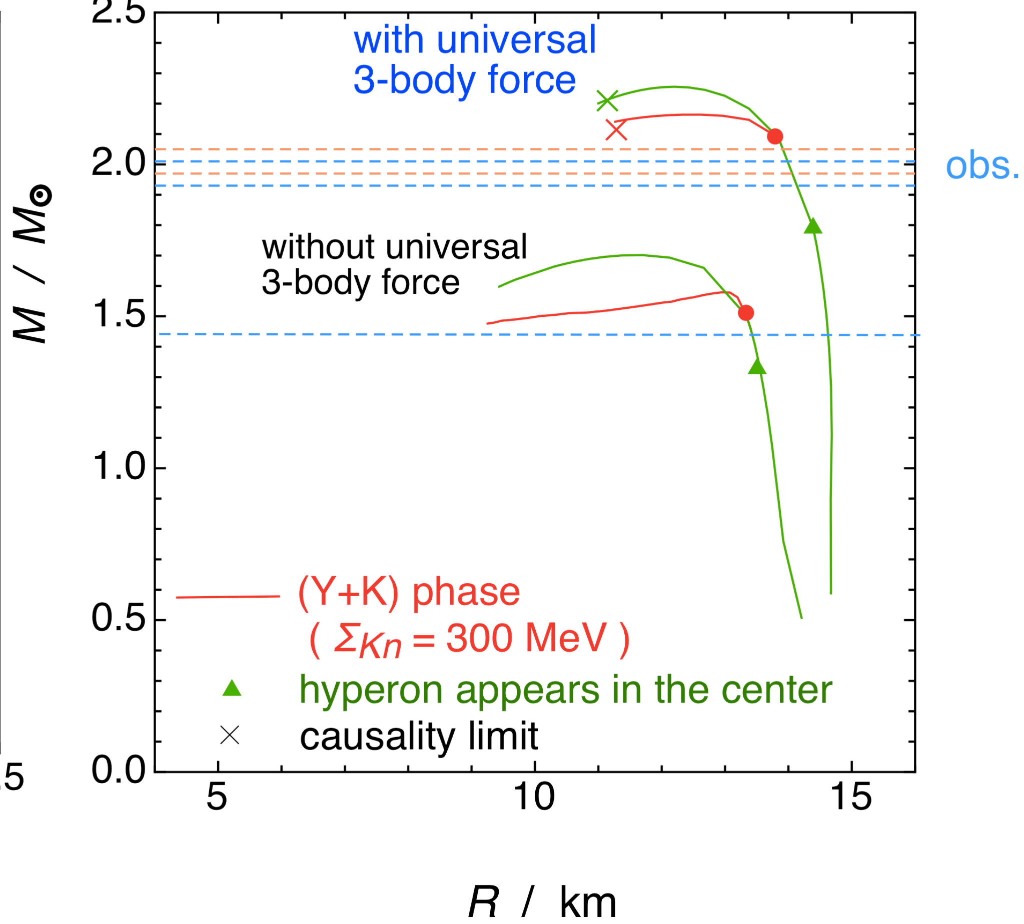
- Short range part → quark structure of Baryon : String Junction Model
- intermediate and long-range part → point-like : RMF

Effects of universal three-body repulsion with SJM2

Energy per particle



Mass-Radius relations



[P. Demorest, T.Pennucci, S. Ransom, M. Roberts and J.W.T.Hessels, Nature 467 (2010) 1081.]

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

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

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

5. Concluding remarks

I. Relation between Kaonic nuclei and Kaon condensation in neutron stars

Strangeness-conserving
Finite-size effect

Chemical equil. for weak processes
infinite matter $\omega_{K^-} = O$ (200 MeV)
Ground state: (Y+K) phase

II. Equation of state (EOS) with kaon condensation in hyperon-mixed matter [(Y+K) phase]

- Universal 3-body repulsion leads to a stiff EOS with (Y+K) phase.
- Kaon condensates appear in the center of the core only for neutron stars near the maximum mass.

$\Rightarrow M_{\max} > 2M_{\odot}$

Problem :

- derivation of universal 3-body repulsion at high densities
- Consistency of a stiff EOS at very high densities with soft EOS for lower densities ($\rho_B \lesssim 2\rho_0$)

relevant to SN explosions   Heavy-ion collisions

Thank you !