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Interplay of kaon condensation and hyperons in dense matter EOS

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1. Introduction

Multi-strangeness systems in neutron stars

Kaon condensation (BEC of antikaons)

Hyperon-mixed matter

(Λ, Σ, Ξ, ・・・ in the ground state)

・Rapid cooling of neutron stars ・Softening of EOS

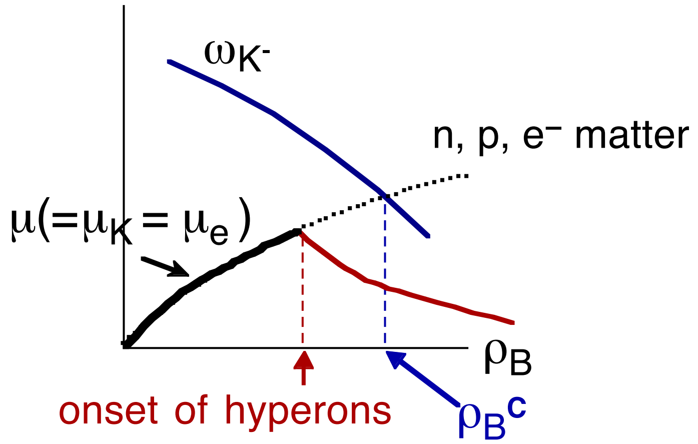
⇒ Strange matter (u, d, s quark matter)

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

(Relativistic Mean-Field theory)

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

・Possible appearance of kaons from hyperon matter depends on kaon-baryon interactions



(possibility of third family)

[S. Banik and D. Bandyopadhyay,
Phys. Rev. C 63 (2001) 035802; C64 (2001) 055805.]

(Quark Meson Coupling models)

[D. P. Menezes, P. K. Panda, C. Providencia, Phys. Rev. C 72 (2005) 035802.]

[C. Y. Ryu, C. H. Hyun, S. W. Hong, and B. T. Kim, Phys. Rev. C 75 (2007), 055804.]

(effect of δ meson)

[G.Y.Shao, Y.X.Liu, Phys. Rev. C82, 055801(2010).]

(effective chiral Lagrangian + phenomenological Baryon-Baryon int.

[T. Muto, Nucl. Phys. A754 (2005) 350; Phys. Rev. C77, 015810 (2008).]

⇒ theoretically $M_{max} < 2\,M_{\odot}$

⇕

Observations of massive neutron stars

$M(\mathrm{PSR\ J1614\text{-}2230}) = 1.97 \pm 0.04\,M_{\odot}$

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

$M(\mathrm{PSR\ J0348{+}0432}) = (2.01 \pm 0.04)\,M_{\odot}$

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

For hyperon-mixed matter

Phenomenological universal YNN, YYN, YYY repulsions

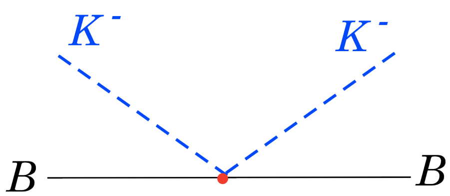
[S. Nishizaki, Y. Yamamoto and T. Takatsuka, Prog. Theor. Phys. 108 (2002) 703.]

→ Stiffening the EOS at high densities

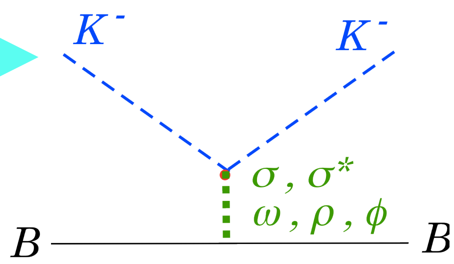
For kaon-Baryon interaction -ambiguity of S-wave $\bar{K}$-B int.

Two coupling schemes between nonlinear Kaon field and-Baryons

1. Contact Interaction ← Effective Chiral Lagrangian → **2. Meson-Exchange interaction**



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



medium effect

[T. Muto, T. Maruyama and T. Tatsumi, Phys. Rev. C79, 035207 (2009).]

---We consider dependence of (Y+K) phase (onset density, EOS) on K-Baryon coupling schemes within the RMF ---

2. Outline of the model

2-1. Baryon-Baryon interaction

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

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

Relativistic mean-field theory

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

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

parameters

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

--- NN interaction --- gross features of normal nuclei and nuclear matter

- saturation properties of nuclear matter (ρ_0 =0.153 fm^{-3})
- binding energy of nuclei and proton-mixing ratio
- density distributions of p and n

$g_{\sigma N}$=6.38

$g_{\omega N}$, $g_{\rho N}$ =8.71 =4.26

--- vector meson couplings for Y --- SU(6) symmetry

$$g_{\omega\Lambda} = g_{\omega\Sigma^-} = 2g_{\omega\Xi^-} = \frac{2}{3}g_{\omega N} \qquad g_{\phi\Lambda} = g_{\phi\Sigma^-} = \frac{1}{2}g_{\phi\Xi^-} = -\frac{\sqrt{2}}{3}g_{\omega N}$$

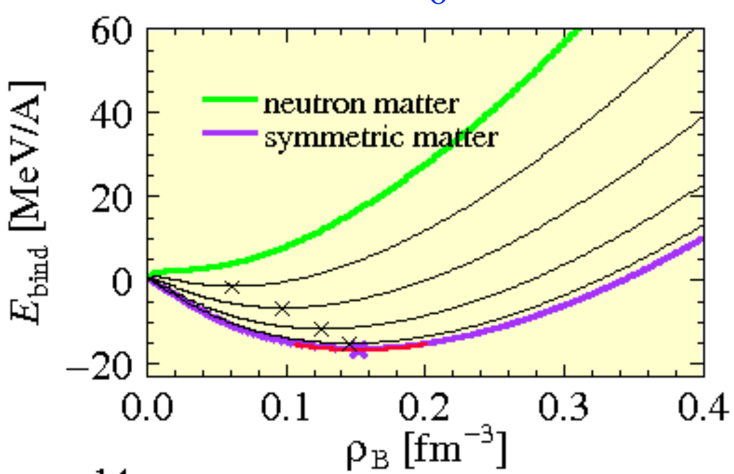
$$g_{\rho\Lambda} = 0 \qquad g_{\rho\Sigma^-} = 2g_{\rho\Xi^-} = 2g_{\rho N}$$

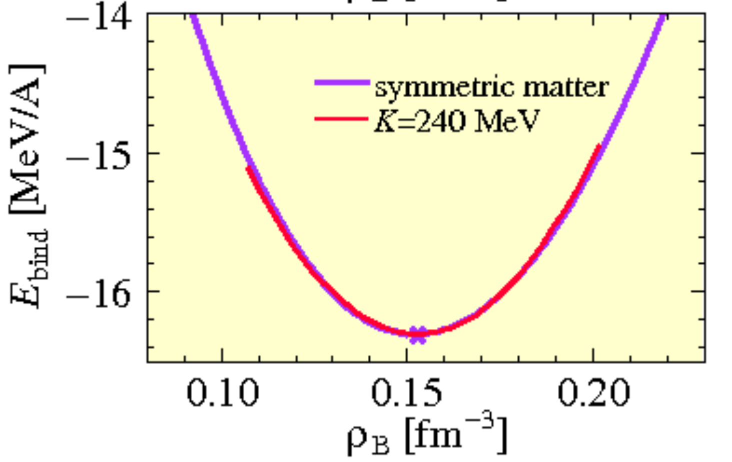
Choice of parameters

--- NN interaction ---

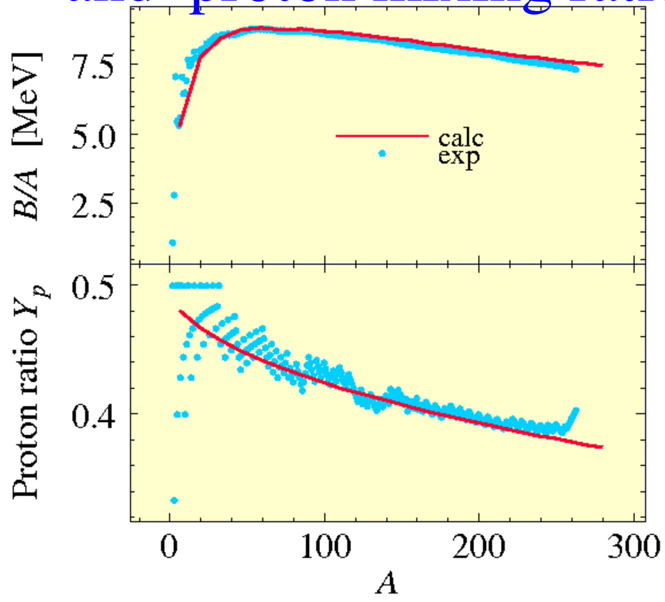
Saturation properties of nuclear matter

(ρ_0 =0.153 fm^{-3})

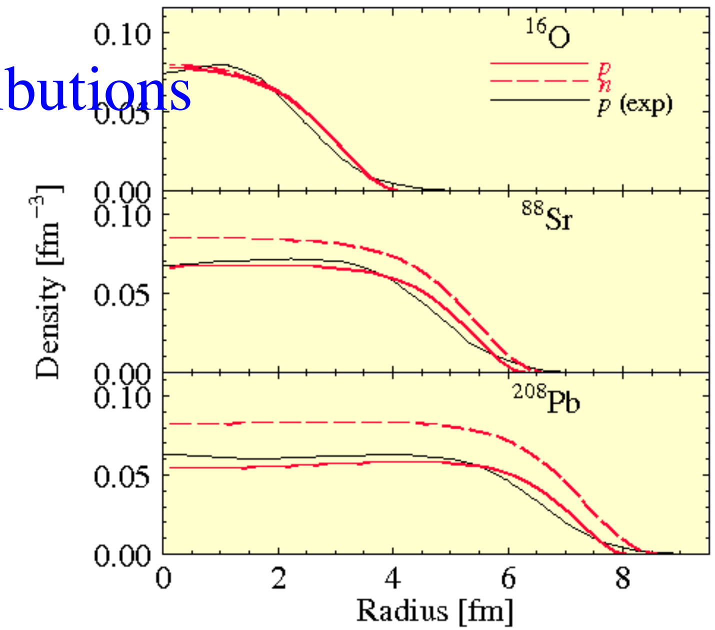




Binding energy of nuclei and proton mixing ratio



Density distributions of p and n



$g_{\sigma N}$ $g_{\omega N}$, $g_{\rho N}$

--- σ meson couplings for Y ---

Hyperon potentials deduced from hypernuclear experiments

(analysis of Λ single-particle orbitals)

$$U_\Lambda^N(\rho_0) = -g_{\sigma\Lambda}\sigma + g_{\omega\Lambda}\omega_0 = -27 \text{ MeV}$$ → $g_{\sigma\Lambda} = 3.84$

- (K^-, $\pi^\pm$) at BNL → T=3/2 state: strongly repulsive

[J. Dabrowski, Phys. Rev. C60 (1999), 025205.] $V_{\Sigma^-}(k_\Sigma) = V_0(k_\Sigma) - \frac{1}{2}V_1(k_\Sigma)\cdot\frac{Z-N}{A}$

23.5 MeV 80.4 MeV

- (π^-, K^+) at KEK [H. Noumi et al., , Phys. Rev. Lett. 89 (2002), 072301; ibid 90(2003), 049902(E).]

- analysis of Σ^- atoms : repulsive [C. J. Batty, E. Friedman, A. Gal, Phys. Rep. 287 (1997), 385.]

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

repulsive case → $g_{\sigma\Sigma^-} = 2.28$

$$U_{\Xi^-}^N(\rho_0) = -g_{\sigma\Xi^-}\sigma + g_{\omega\Xi^-}\omega_0 = -16 \text{ MeV}$$ → $g_{\sigma\Xi^-} = 2.0$

[T. Fukuda et al., Phys. Rev. C58 (1998), 1306., P. Khaustov et al., Phys. Rev. C61 (2000), 054603.]

--- σ* meson couplings for Y ---

$$g_{\sigma^* N} = g_{\sigma^*\Lambda} = g_{\sigma^*\Sigma^-} = g_{\sigma^*\Xi^-} = 0$$

2-2 $\overline{K}-B, \overline{K}-\overline{K}$ interactions

SU(3)$_L$× SU(3)$_R$ chiral effective Lagrangian

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

$$\mathcal{L}=\frac{1}{4}f^2\mathrm{Tr}\,\partial^\mu\Sigma^\dagger\partial_\mu\Sigma+\frac{1}{2}f^2\Lambda_{\chi SB}(\mathrm{Tr}\,M(\Sigma-1)+\mathrm{h.c.})$$
$$+\mathrm{Tr}\,\overline{\Psi}(i\partial\!\!\!/-m_B)\Psi+\mathrm{Tr}\,\overline{\Psi}i\gamma^\mu[V_\mu,\Psi]+D\mathrm{Tr}\,\overline{\Psi}\gamma^\mu\gamma^5\{A_\mu,\Psi\}$$
$$+F\mathrm{Tr}\,\overline{\Psi}\gamma^\mu\gamma^5[A_\mu,\Psi]+a_1\mathrm{Tr}\,\overline{\Psi}(\xi M^\dagger\xi+\mathrm{h.c.})\Psi$$
$$+a_2\mathrm{Tr}\,\overline{\Psi}\Psi(\xi M^\dagger\xi+\mathrm{h.c.})+a_3(\mathrm{Tr}\,M\Sigma+\mathrm{h.c.})\mathrm{Tr}\,\overline{\Psi}\Psi\ ,$$

Baryons

Ψ ⟹ (p, n, Λ, Ξ$^-$, Σ$^-$)

$$M=\mathrm{diag}(m_u,m_d,m_u)$$

Meson fields (K$^\pm$) $\Sigma\equiv e^{2i\Pi/f}$

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

Vector current $V^\mu=\frac{1}{2}(\xi^\dagger\partial^\mu\xi+\xi\partial^\mu\xi^\dagger)$

Axial-vector current $A^\mu=\frac{i}{2}(\xi^\dagger\partial^\mu\xi-\xi\partial^\mu\xi^\dagger)$

($\xi\equiv\Sigma^{1/2}=e^{i\pi_aT_a/f}$)

Classical K$^-$ field

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

Meson decay constant

f =93 MeV

μ_K : kaon chemical potential

Kaonic part of the Lagrangian density

$$\mathcal{L}_{KB} = \frac{1}{2}f^2\mu^2\sin^2\theta - f^2 m_K^{*2}(1-\cos\theta) + 2X_0\mu f^2(1-\cos\theta)$$

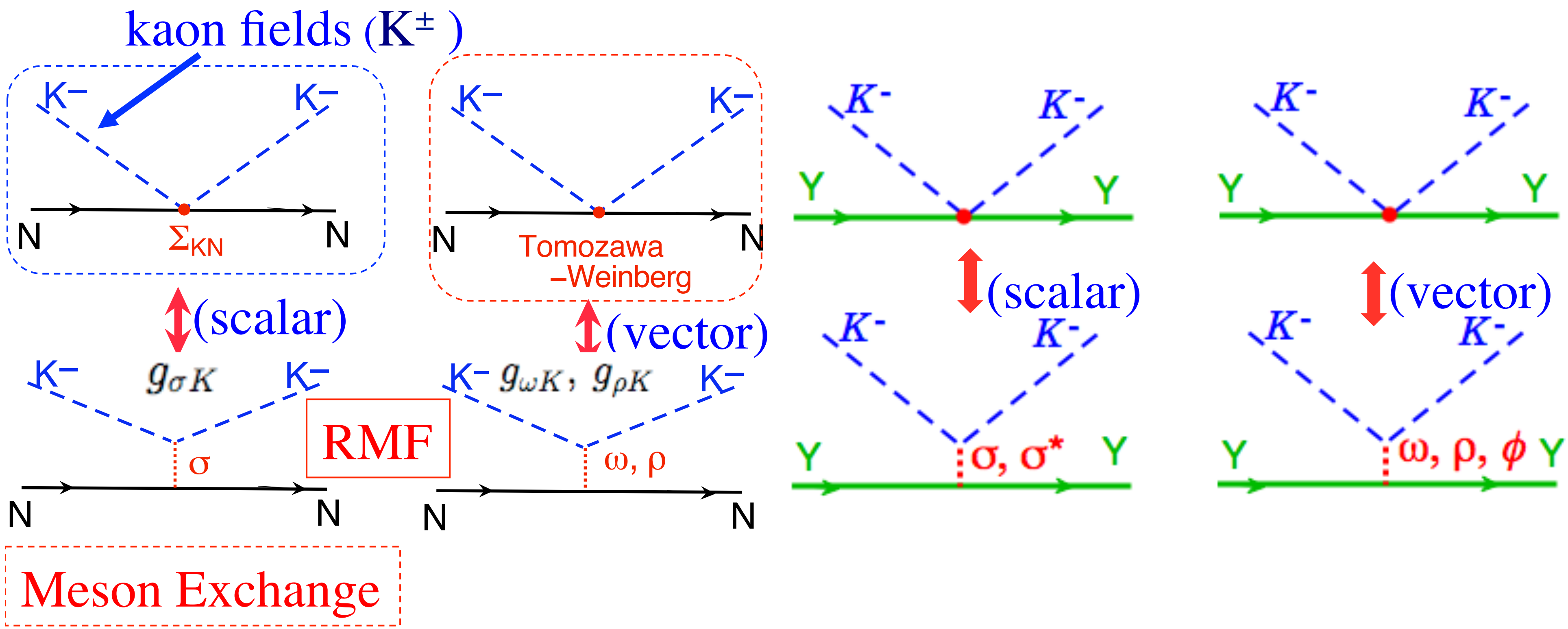
S wave scalar int.

S wave vector int.

Contact Int.

$$m_K^{*2} \equiv m_K^2 - \frac{1}{f^2}\sum \rho_i^s \Sigma_{Ki} \qquad X_0 \equiv \frac{1}{2f^2}\left(\rho_p + \frac{1}{2}\rho_n - \frac{1}{2}\rho_{\Sigma^-} - \rho_{\Xi^-}\right)$$

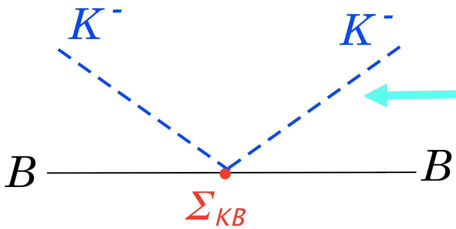
$(i = p, n, \Lambda, \Sigma^-, \Xi^-)$

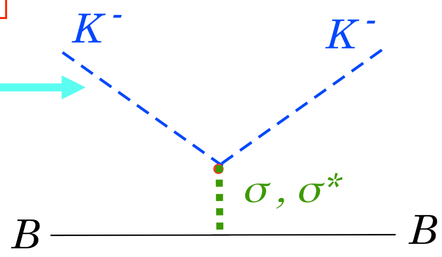


K-B coupling schemes

Contact K-B interaction | **S wave scalar int.** | **Meson-exchange (ME)**

Nonlinear K⁻ field





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

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

$$\begin{aligned} m_K^{*2} &\equiv m_K^2 - 2m_K(g_{\sigma K}\sigma + g_{\sigma^* K}\sigma^*) \\ &\simeq m_K^2 + 2g_{\sigma K}\frac{m_K}{m_\sigma^2}\frac{dU}{d\sigma} - \frac{1}{f^2}\sum_i \rho_i^s \Sigma_{Ki} \\ &- (2fm_K)^2\left(\frac{g_{\sigma K}^2}{m_\sigma^2} + \frac{g_{\sigma^* K}^2}{m_{\sigma^*}^2}\right)(1-\cos\theta) \end{aligned}$$

Scalar mean fields

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

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

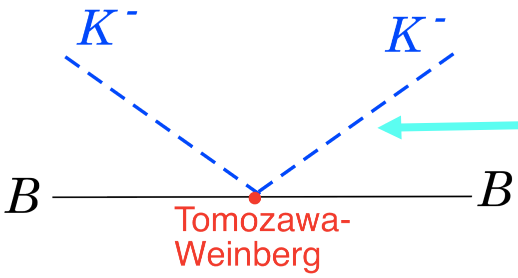
Nonlinear σ self-interaction potential : $U(\sigma) = bm_N(g_{\sigma N}\sigma)^3/3 + c(g_{\sigma N}\sigma)^4/4$

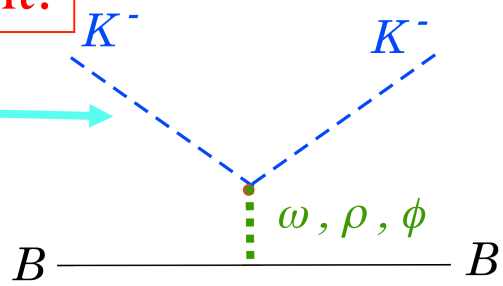
Contact K-B interaction

Meson-exchange (ME)

S wave vector int.

Nonlinear K⁻ field





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

$$\begin{aligned} X_0 &\equiv g_{\omega K}\omega_0 + g_{\rho K}R_0 + g_{\phi K}\phi_0 \\ &= \frac{1}{2f^2}\left(\rho_p + \frac{1}{2}\rho_n - \frac{1}{2}\rho_{\Sigma^-} - \rho_{\Xi^-}\right) \\ &- 2f^2\mu\left(\frac{{g_{\omega K}}^2}{m_\omega^2} + \frac{{g_{\rho^* K}}^2}{m_{\rho^*}^2} + \frac{{g_{\phi K}}^2}{m_\phi^2}\right)(1-\cos\theta) \end{aligned}$$

Vector mean fields

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

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

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

Meson-Kaon coupling parameters

--- vector meson couplings for Kaon ---

Corresponding to the Tomozawa-Weinberg term

$$X_0 \equiv g_{\omega K}\omega_0 + g_{\rho K}R_0 + g_{\phi K}\phi_0 \quad \sim \frac{1}{2f^2}\left(\rho_p + \frac{1}{2}\rho_n - \frac{1}{2}\rho_{\Sigma^-} - \rho_{\Xi^-}\right)$$

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega N} + \frac{g_{\rho K}}{m_\rho^2}g_{\rho N}\right) = 1 \quad \text{for } p$$

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega N} - \frac{g_{\rho K}}{m_\rho^2}g_{\rho N}\right) = \frac{1}{2} \quad \text{for } n$$

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega\Lambda} + \frac{g_{\rho K}}{m_\rho^2}g_{\rho\Lambda} + \frac{g_{\phi K}}{m_\phi^2}g_{\phi\Lambda}\right) = 0 \quad \text{for } \Lambda$$

$$g_{\omega K} = 3.05$$
$$g_{\rho K} = 2.00$$
$$g_{\phi K} = 7.33$$

automatically satisfied

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega\Sigma^-} - \frac{g_{\rho K}}{m_\rho^2}g_{\rho\Sigma^-} + \frac{g_{\phi K}}{m_\phi^2}g_{\phi\Sigma^-}\right) = -\frac{1}{2} \quad \text{for } \Sigma^-$$

$$2f^2\left(\frac{g_{\omega K}}{m_\omega^2}g_{\omega\Xi^-} - \frac{g_{\rho K}}{m_\rho^2}g_{\rho\Xi^-} + \frac{g_{\phi K}}{m_\phi^2}g_{\phi\Xi^-}\right) = -1 \quad \text{for } \Xi^-$$

quark – isospin counting rule

SU(6) symmetry

$$g_{\omega K} = g_{\omega N}/3 = 2.90$$
$$g_{\rho K} = g_{\rho N} = 4.26$$
$$g_{\phi K} = 6.04/\sqrt{2}$$

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. ($2\mu X_0$)

S-wave scalar int. (m_K^{*2})

Charge neutrality condition

$$\partial\mathcal{E}^{\rm eff}/\partial\mu = 0$$

chemical equilibrium for weak processes

$$\partial\mathcal{E}^{\rm eff}/\partial\rho_a = 0 \quad (a = p, n, \Lambda, \Xi^-, \Sigma^-)$$

with $\rho_p + \rho_n + \rho_\Lambda + \rho_{\Xi^-} + \rho_{\Sigma^-} = \rho_{\rm B}$

$n \rightleftharpoons p\ K^-$

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

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

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

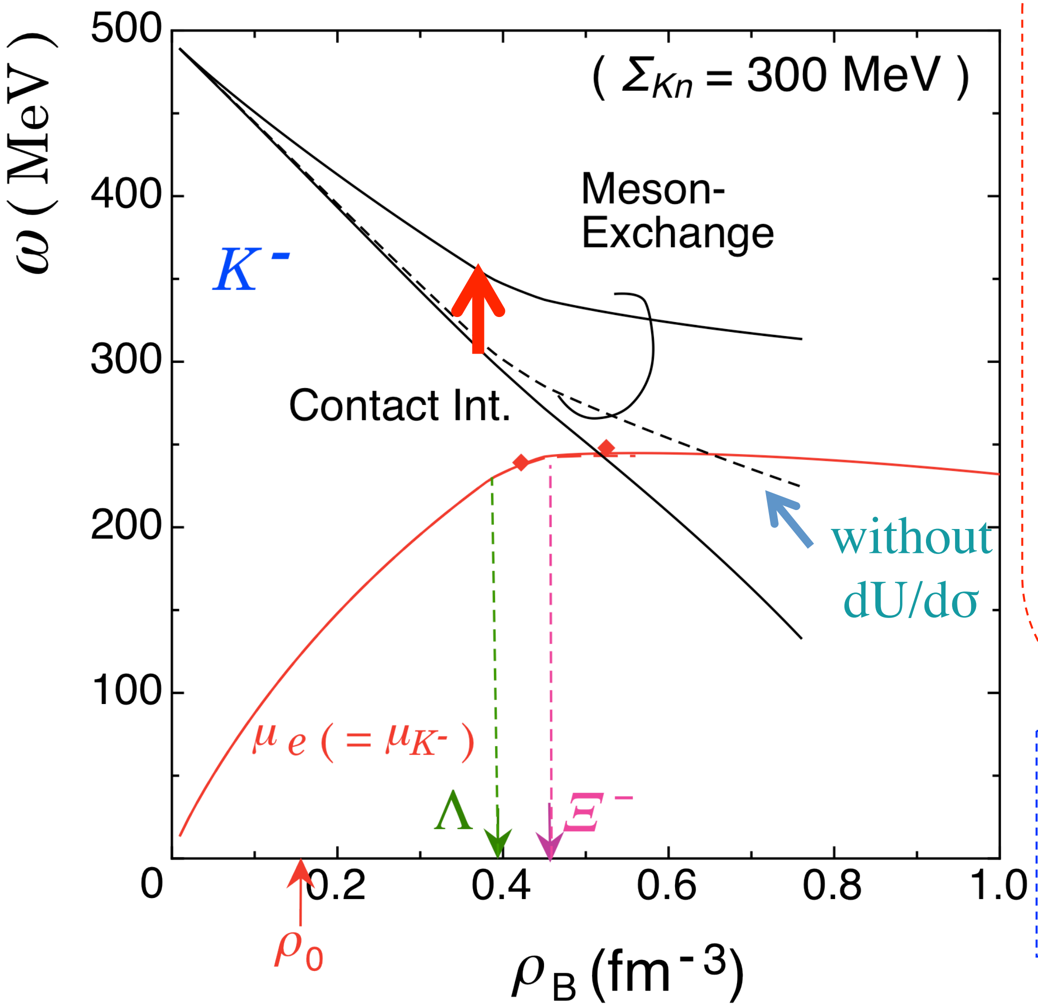
$\Lambda\ e^- \rightleftharpoons \Xi^-\ (\nu_e)$

3. Results

3-1 Kaon lowest energy *ω in hyperonic matter* and onset density of kaon condensation

ω: Pole of kaon propagator

$$D_K^{-1} = \omega^2 + 2X_0\omega - m_K^{*2} = 0$$



Meson-Exchange

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

$$\simeq m_K^2 + 2g_{\sigma K}\frac{m_K}{m_\sigma^2}\frac{dU}{d\sigma} - \frac{1}{f^2}\sum_i \rho_i^s \Sigma_{Ki}$$

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

$$\Sigma_{KN} = \frac{2m_K f^2 g_{\sigma K} g_{\sigma N}}{m_\sigma^2}$$

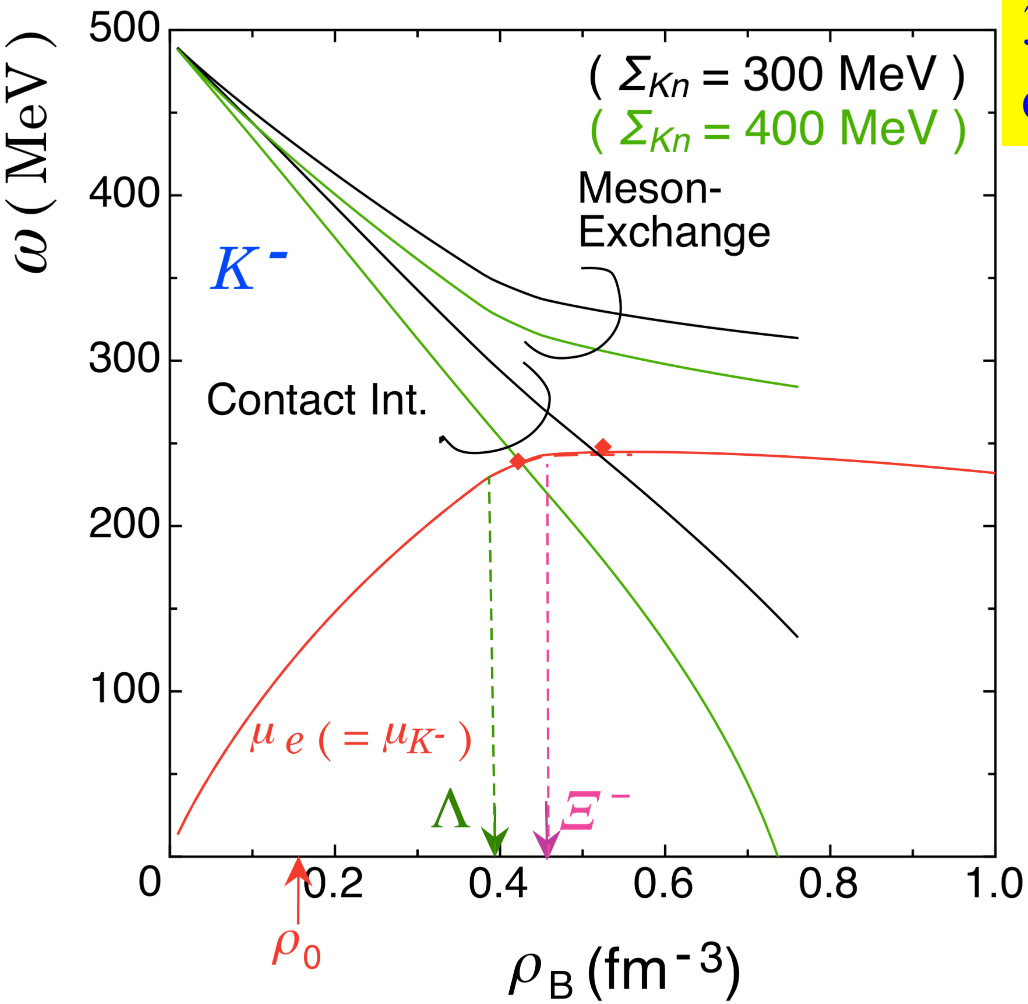
$$\Sigma_{KY} \equiv 2f^2 m_K \left(\frac{g_{\sigma K} g_{\sigma Y}}{m_\sigma^2} + \frac{g_{\sigma^* K} g_{\sigma^* Y}}{m_{\sigma^*}^2}\right)$$

$$(Y = \Lambda, \Sigma^-, \Xi^-)$$

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

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

3.2 Dependence of Onset density on S-wave KB scalar int. Σ_{Kn}



K$^-$ optical potential depth at ρ_0

$$U_K = -(g_{\sigma K}\sigma + g_{\omega K}\omega_0)$$

$$\Sigma_{KN} = \frac{2 m_K f^2 g_{\sigma K} g_{\sigma N}}{m_\sigma^2}$$

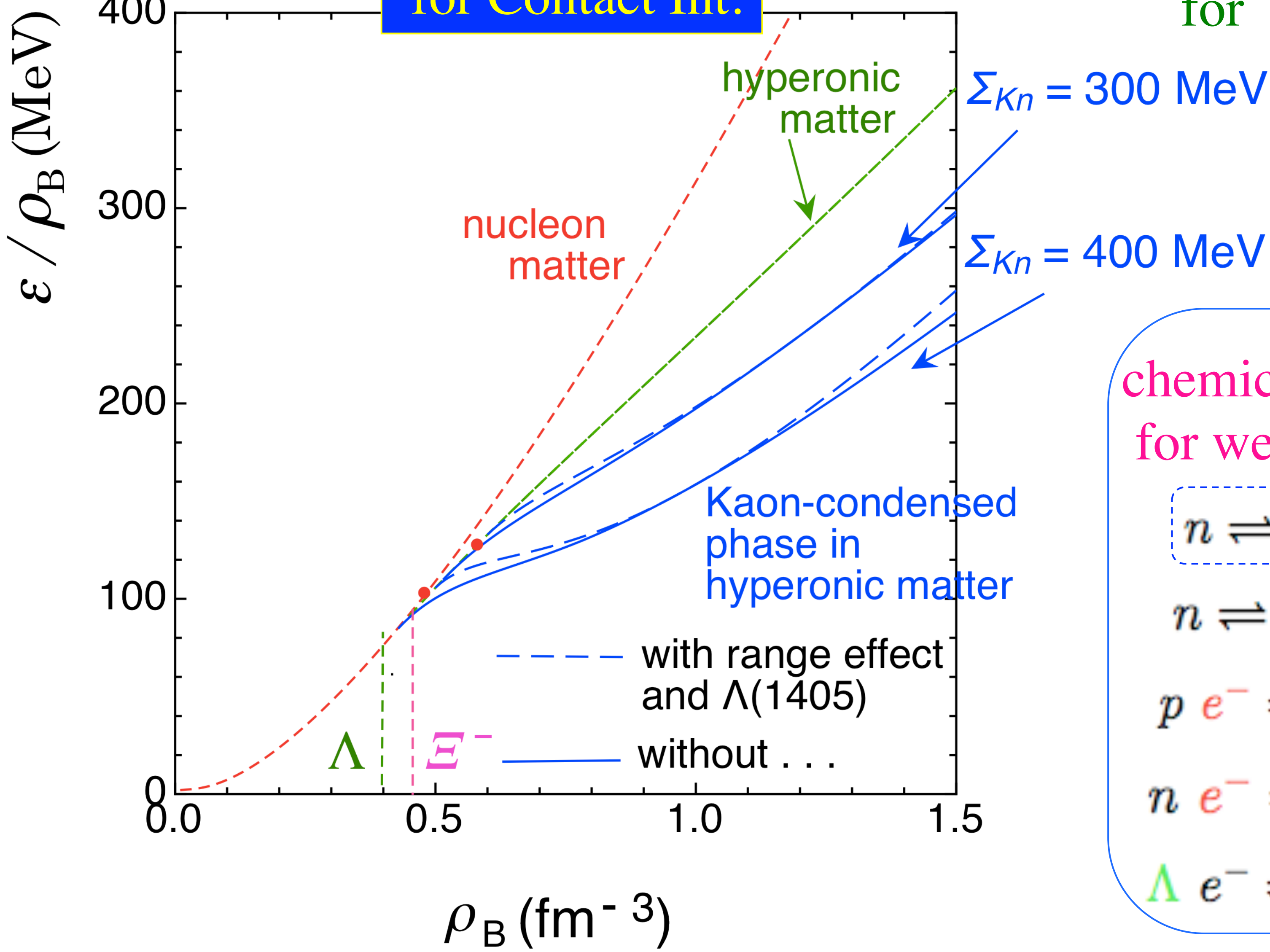
U_{K^-} (MeV)	Σ_{Kn} (MeV)	ρ_B^C (ME)	ρ_B^C (CI)
− 77	300	−	3.4 ρ_0 (0.52 fm^{-3})
− 87	400	−	2.8 ρ_0 (0.43 fm^{-3})
− 100	542	5.7 ρ_0 (0.87 fm^{-3})	2.4 ρ_0 (0.37 fm^{-3})

3-3 EOS in β-equilibrated matter

Energy per particle

for Contact Int.

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



chemical equilibrium for weak processes

$n \rightleftharpoons p\, K^-$

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

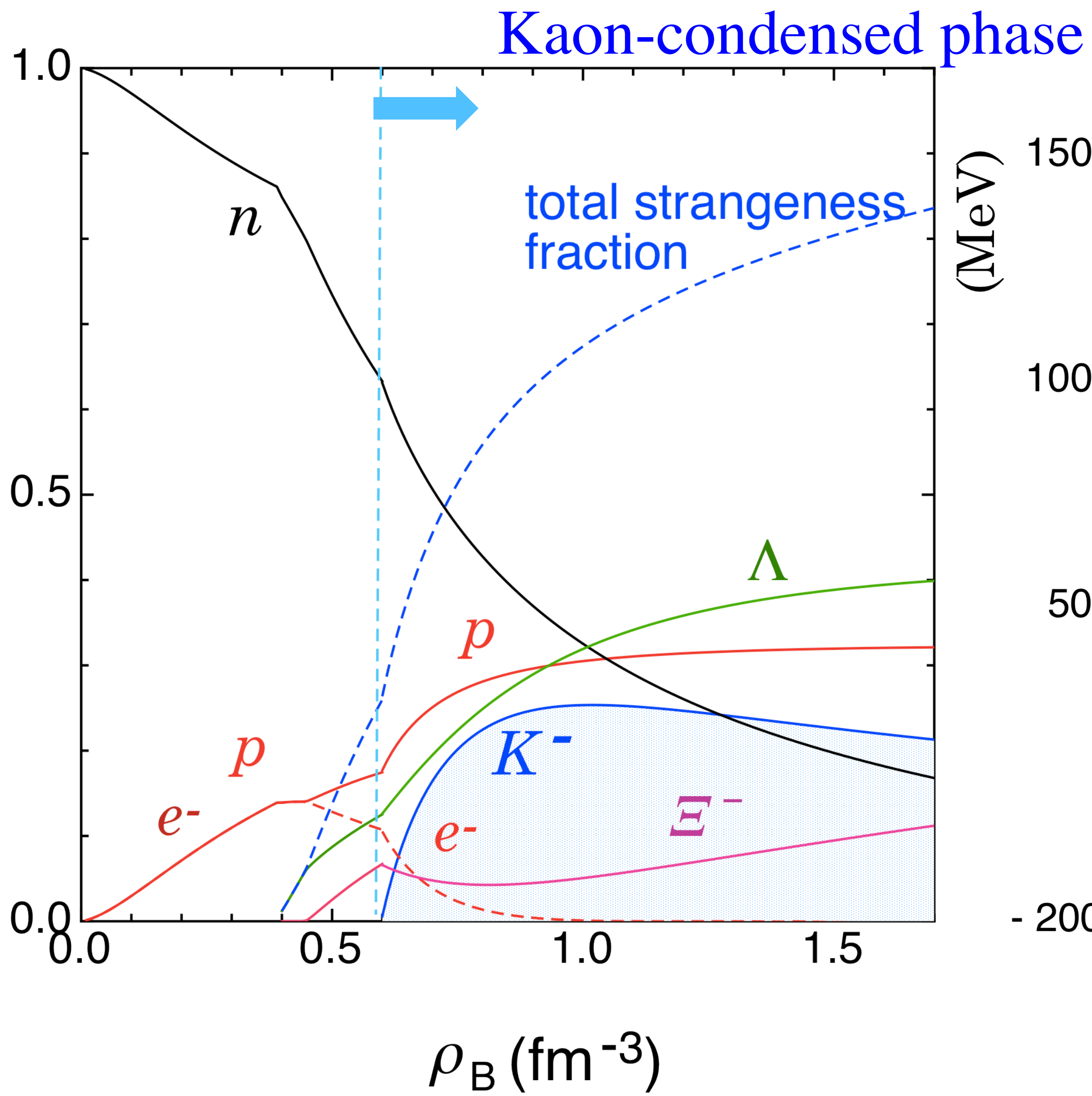
$p\, e^- \rightleftharpoons \Lambda \; (\nu_e)$

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

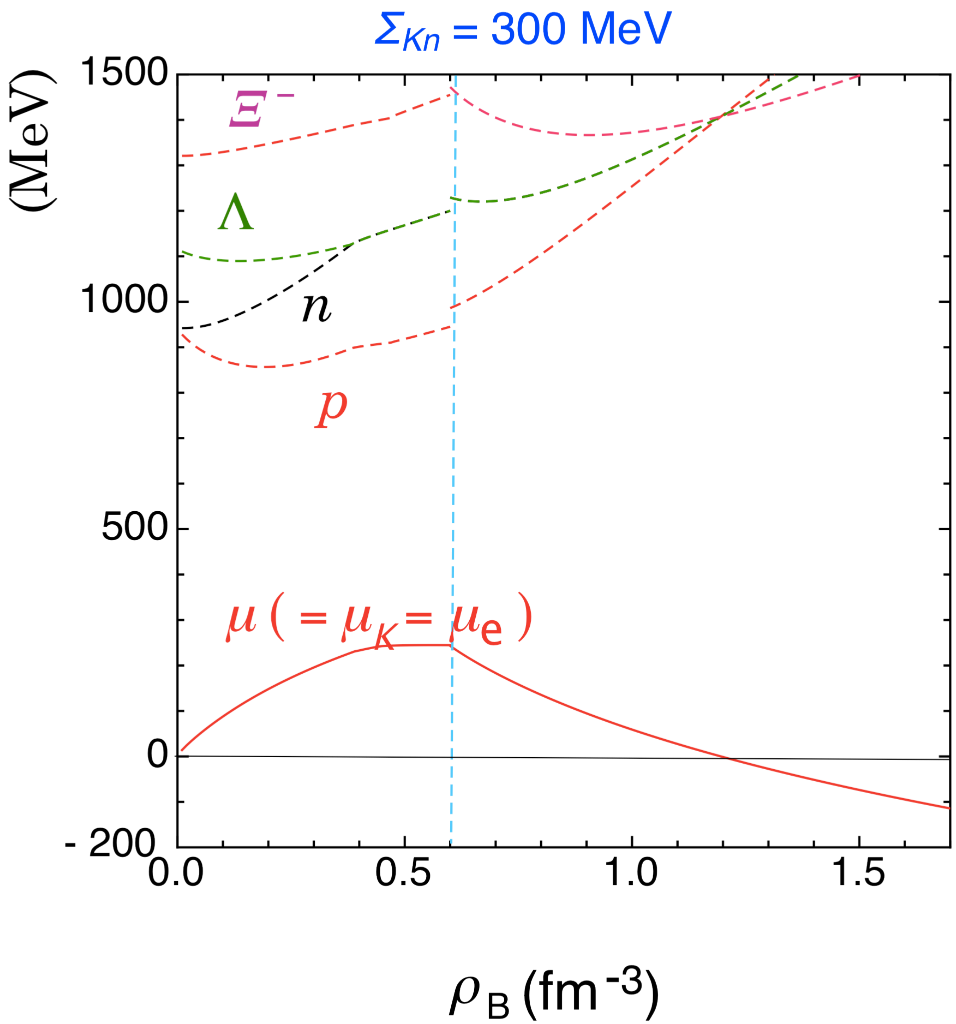
$\Lambda\, e^- \rightleftharpoons \Xi^- \; (\nu_e)$

Σ_{Kn}= 300 MeV

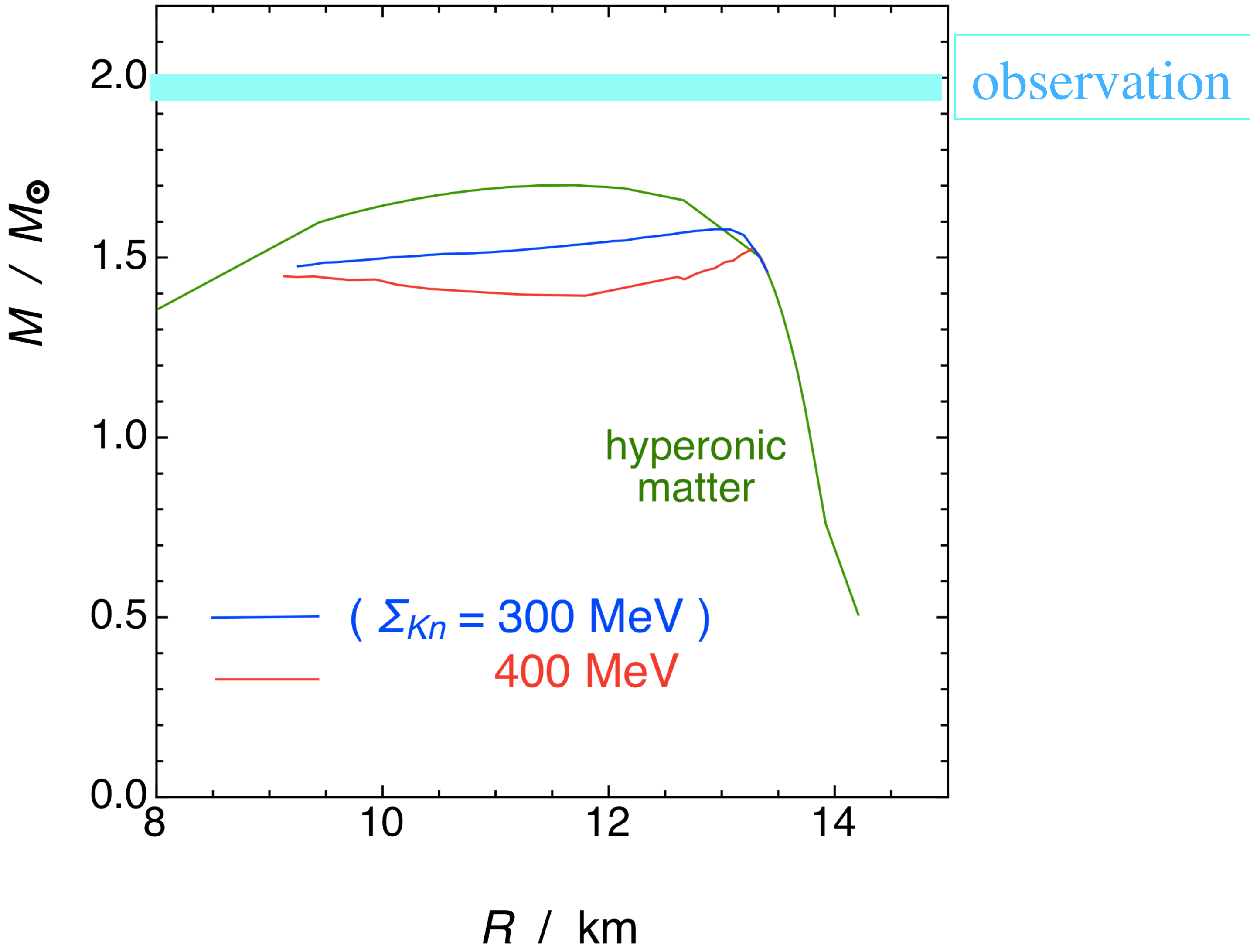
Particle fractions



chemical potentials



Gravitational Mass –Radius relatiosn



4. Short Summary

K- B Meson-Exchange int.

σ self-interaction potential

$$U(\sigma) = bm_N(g_{\sigma N}\sigma)^3/3 + c(g_{\sigma N}\sigma)^4/4$$

- $dU/d\sigma$ from nonlinear scalar self-int.potential : repulsive   universal result ?

c.f. [P.J.Ellis, R.Knorren and M.Prakash, Phys. Rev. C52(1995), 3470.]

→ Push up the onset density of kaon condensation

- K-ω, ρ, ϕ meson coupling terms in the E.O.M.of vector mean-fields weaken the K-B vector attraction in the K-condensed phase.

↓

(Y+K) phase is unlikely for $U_K \sim -75$MeV ($\Sigma_{KN} \sim 280$ MeV) ←

(Recent Lattie QCD)

$\bar{s}s$ content in the nucleon is small

[R. D. Young, A. W. Thomas, Nucl. Phys. A844(2010) 266c.]

K- B Contact int.

(Y+K) phase is likely to occur even for $U_K \sim -75$MeV($\Sigma_{KN} \sim 280$ MeV) , leading to softening the EOS steadily.

5. Discussion

Effects leading to stiff EOS of (Y+K) phase at high density

(1) Baryon-baryon sector

(i) Phenomenological universal YNN, YYN, YYY repulsions

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

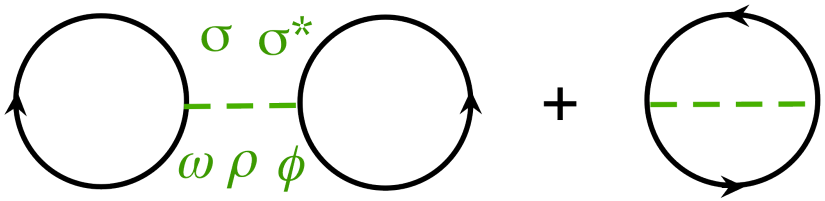
[R. Tamagaki, Prog. Theor. Phys. 119 (2008), 965.] : String-Junction model

(cf : RMF extended to BMM, MMM type diagrams)
[K. Tsubakihara and A. Ohnishi, Nucl. Phys. A 914 (2013), 438; arXiv:1211.7208.]

(ii) relativistic Hartree-Fock

Introduction of tensor coupling of vector mesons

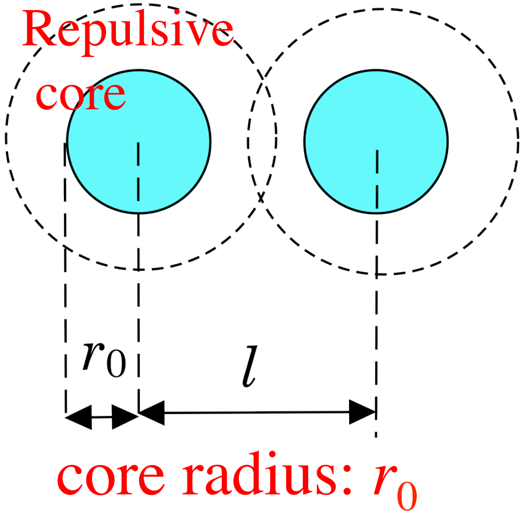
Cf. for hyperonic matter,
[T. Miyatsu, T. Katayama, K. Saito, Phys. Lett.B709 242(2012).]



Suppression of hyperons ?

(2) Finite-size effects of baryons in Hadron phase

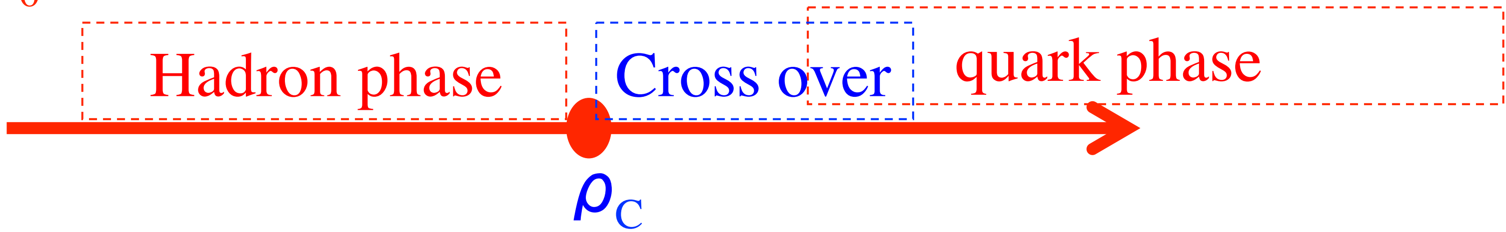
- Excluded volume effect of baryons → Stiffening the EOS
- limitation of hadron picture
  and necessity of cross over between hadron and quark phases



$$\frac{1}{\rho_B} = V/N = l^3 \qquad l_0 = 1/\rho_0^{1/3} = 1.8\ \mathrm{fm}$$

Hadron picture $\quad \rho_B \lesssim \rho_c = 1/(2r_0)^3$

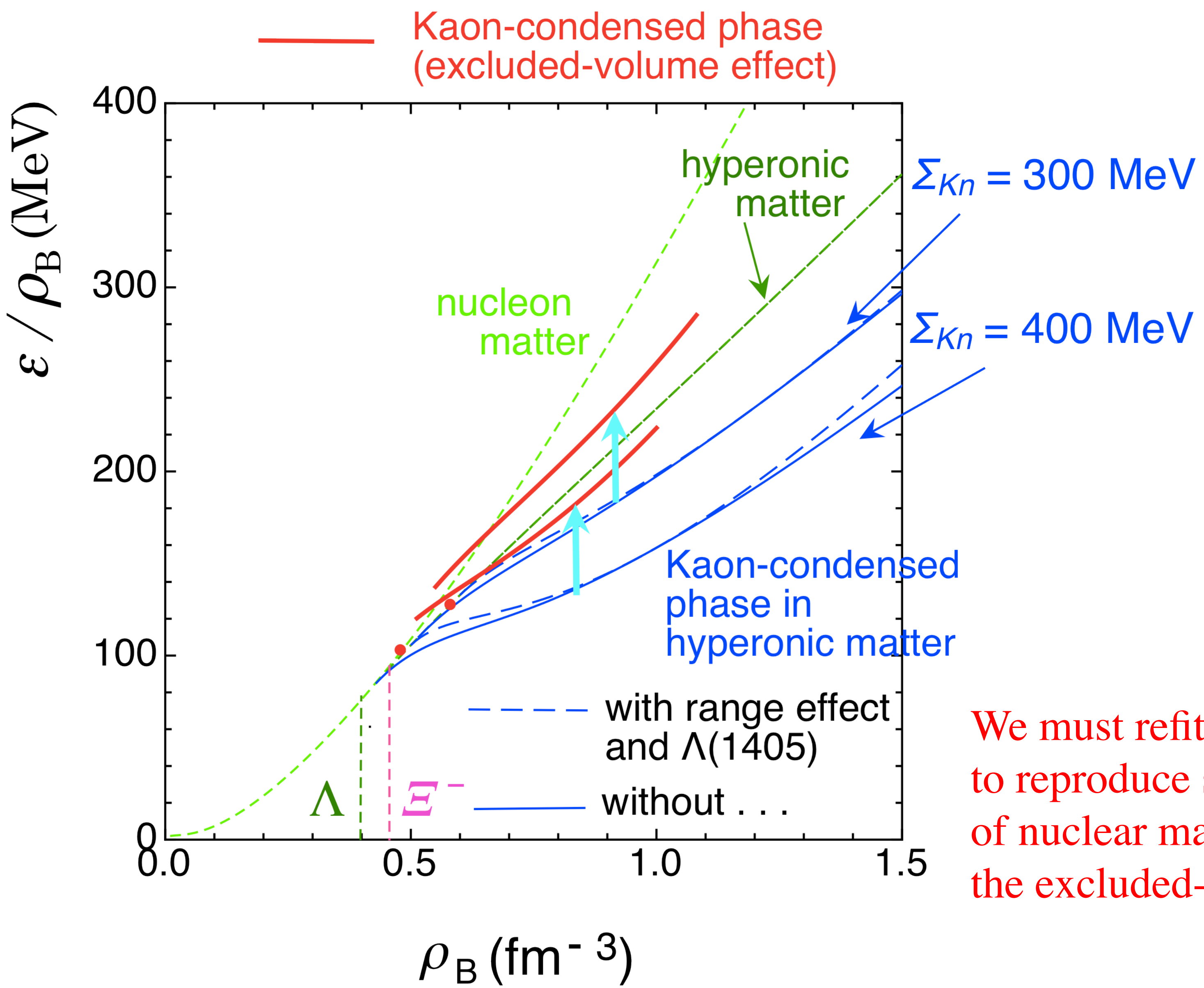
$= 1.0\ \mathrm{fm}^{-3}$ for $r_0 = 0.5$ fm



→ Introduction of excluded-volume effect of baryons for (Y+K) phase

- Preliminary result on the EOS

Preliminary result : EOS of kaon-condensated phase with excluded-volume effect



We must refit the parameters to reproduce saturation properties of nuclear matter within the excluded-volume formalism .

・Validity of hadron picture
based on excluded-volume mechanism for baryons

Future issues

・connecting hadron phase and quark phase →
taking into account of Crossover region

c.f. [K. Masuda, T. Hatsuda, T. Takatsuka, Astrophys. J. Lett. 764, 12 (2013).]

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Coexistence of kaon-condensates and hyperons for hadronic phase ➡ Strange quark matter (kaon-condensates in quark matter)