8th International Conference on Quarks and Nuclear Physics (QNP 2018)
[Tsukuba Ibaraki, Japan, November 13(Tue)-17(Sat), 2018]

Parallel Session 16D2

Effects of Universal Three-Body Repulsion on Kaon Condensation in Hyperonic Matter

Takumi Muto (Chiba Institute of Technology)
Toshiki Maruyama (JAEA)
Toshitaka Tatsumi (Kyoto Univ.)
Tatsuyuki Takatsuka（Iwate Univ. / Riken）

1. Introduction   Multi-strangeness system

In neutron stars

Kaon condensation

Hyperon-mixed matter

- Softening of EOS
- Rapid cooling of neutron stars

In nuclei

Kaonic nuclei FINUDA

DISTO Collaboration

E15, E27 at J-PARC

Hypernuclei J-PARC, Jlab . . .

- $\bar{K}-B$, B-B int.

Observational constraints

Detection of Gravitational waves from neutron star mergers (GW170817)

[B.P.Abott et al., (LIGO and Virgo Collaboration), Phys. Rev. Lett. 119, 161101 (2017) ; 121, 161101(2018).]

Tidal deformabilities of compact stars → EOS, radius

X-ray observation by NICER → Mass and radius of neutron stars

Observation of massive neutron stars

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

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

[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).]

Coexistence of kaon condensation and hyperons [(Y+K) phase] necessarily leads to very soft EOS

For hyperon-mixed matter (Hyperon puzzle)

Necessity of universal three-body force (UTBF)

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

We study repulsive effects of the UTBF on the EOS of the (Y+K) phase

← parameters from saturation properties of symmetric matter

Interaction model

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

[T. Muto, T. Maruyama, and T. Tatsumi, JPS Conf. Proceedings 17, 102003 (2017).]
[T. Muto, T. Maruyama,,T. Tatsumi, and T. Takatsuka, JPS Conf. Proceedings 20, 011038(2018).]

+String-Junction Model for UTBF.

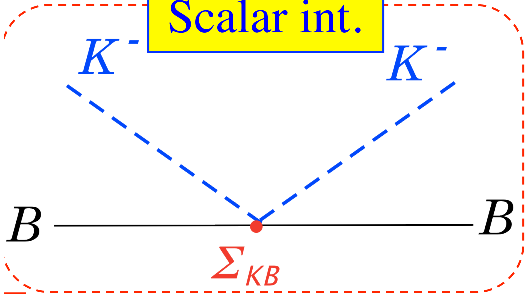
2. Formulation for the (Y+K) phase

2-1 $\bar{K}-B, \bar{K}-\bar{K}$ interactions

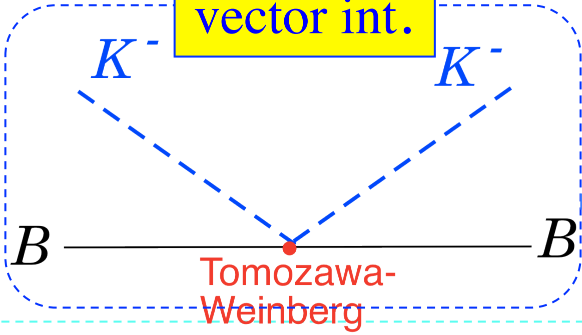
[D. B. Kaplan and A. E. Nelson, Phys. Lett. B 175 (1986) 57.]

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

Scalar int.



vector int.



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

Nonlinear K field

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

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

$$\xi \equiv \Sigma^{1/2} = e^{i\pi_a T_a / f}$$

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

Vector current

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

Axial-vector current

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

Classical K^- field

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

Meson decay constant

f = 93 MeV

μ_K : kaon chemical potential

2-2. Baryon-Baryon interaction

Relativistic mean-field theory

- intermediate and long-range part → point-like : RMF

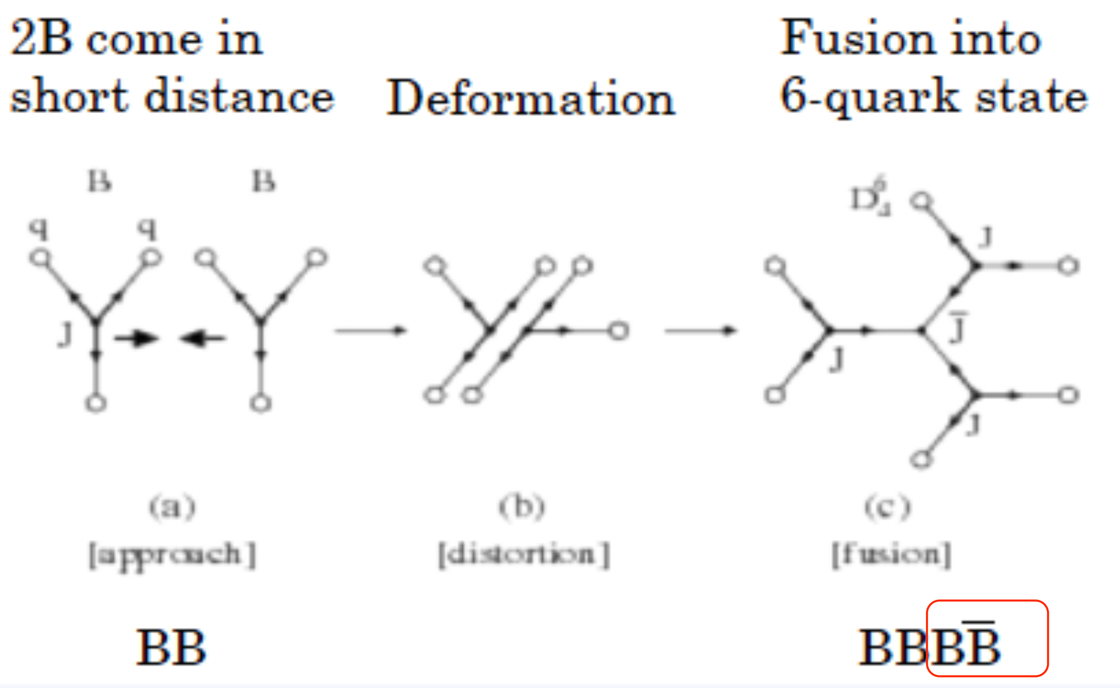
Baryons: $(p, n, \Lambda, \Sigma^-, \Xi^-)$ Mesons: $\sigma, \omega, \rho, \sigma^*, \phi$

- Short range part → quark structure of Baryon :

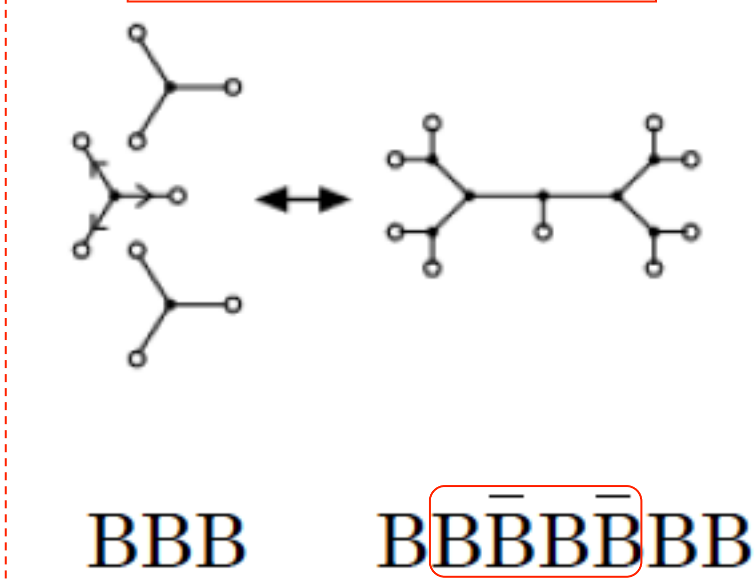
String Junction Model (Flavor-independent three-body repulsion)

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

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



B-B-B interactions



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

$W_0 \sim 2$ GeV

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

$\lambda = 1/\eta_C^2$

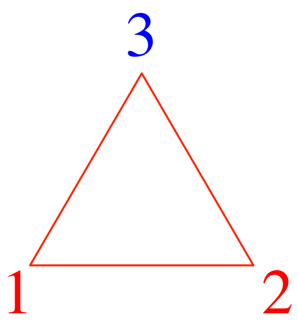
$\eta_C = 0.5$ fm for SJM2

(range of repulsive core)

Effective 2-body potential

short-range correlation function

$$\begin{aligned} U_{\mathrm{SJM}}(r;\rho_{\mathrm{B}}) &= \rho_{\mathrm{B}} \int d^3\mathbf{r}_3 W(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) f^2(\mathbf{r}_1 - \mathbf{r}_3) f^2(\mathbf{r}_2 - \mathbf{r}_3) \\ &= \rho_{\mathrm{B}} W_0 \int d^3\mathbf{r}_3 f^2(\mathbf{r}_1 - \mathbf{r}_3) g(\mathbf{r}_1 - \mathbf{r}_3) f^2(\mathbf{r}_2 - \mathbf{r}_3) g(\mathbf{r}_2 - \mathbf{r}_3) \\ &= \rho_{\mathrm{B}} \frac{W_0}{(2\pi)^3} \int d^3\mathbf{q} e^{-i\mathbf{q}\cdot\mathbf{r}} \int d^3\mathbf{q}_1 h(\mathbf{q}_1) G(\mathbf{q}_1) \int d^3\mathbf{q}_2 h(\mathbf{q}_2) G(\mathbf{q}_2) \end{aligned}$$



$$U_{\mathrm{SJM}}(r;\rho_{\mathrm{B}}) \simeq V \rho_{\mathrm{B}} \left(1 + c\frac{\rho_{\mathrm{B}}}{\rho_0}\right) e^{-\alpha r^2}$$

$V = 95$ MeV・fm^3

$c = 0.024$

$\alpha = 1.35$ fm^{-2}

for SJM2

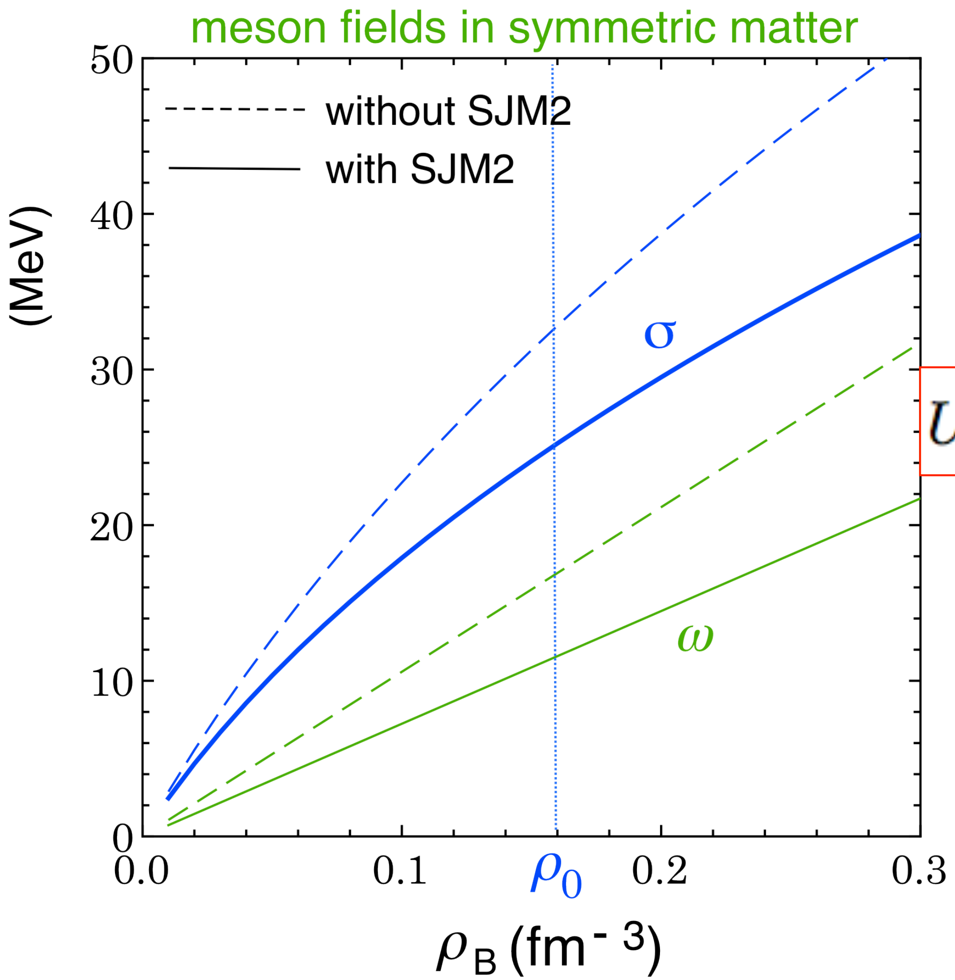
$$\widetilde{U}_{\mathrm{SJM}}(r;\rho_{\mathrm{B}}) = f_{\mathrm{SRC}}(r) U_{\mathrm{SJM}}(r;\rho_{\mathrm{B}})$$

Importance of refitting the parameters to reproduce the saturation properties of symmetric nuclear matter

Saturation of nuclear matter

(ρ_0 =0.16 fm^{-3}) (E_B=16.3 MeV)

(K=240 MeV) (S_0=32.6 MeV)



Repulsive contribution (+ 4MeV) from UTBF [E(SJM2)] to the binding energy

[Nonlinear σ self-int. potential]

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

$\langle\sigma\rangle$, $\langle\omega\rangle$, $g_{\sigma N}$, $g_{\omega N}$: small

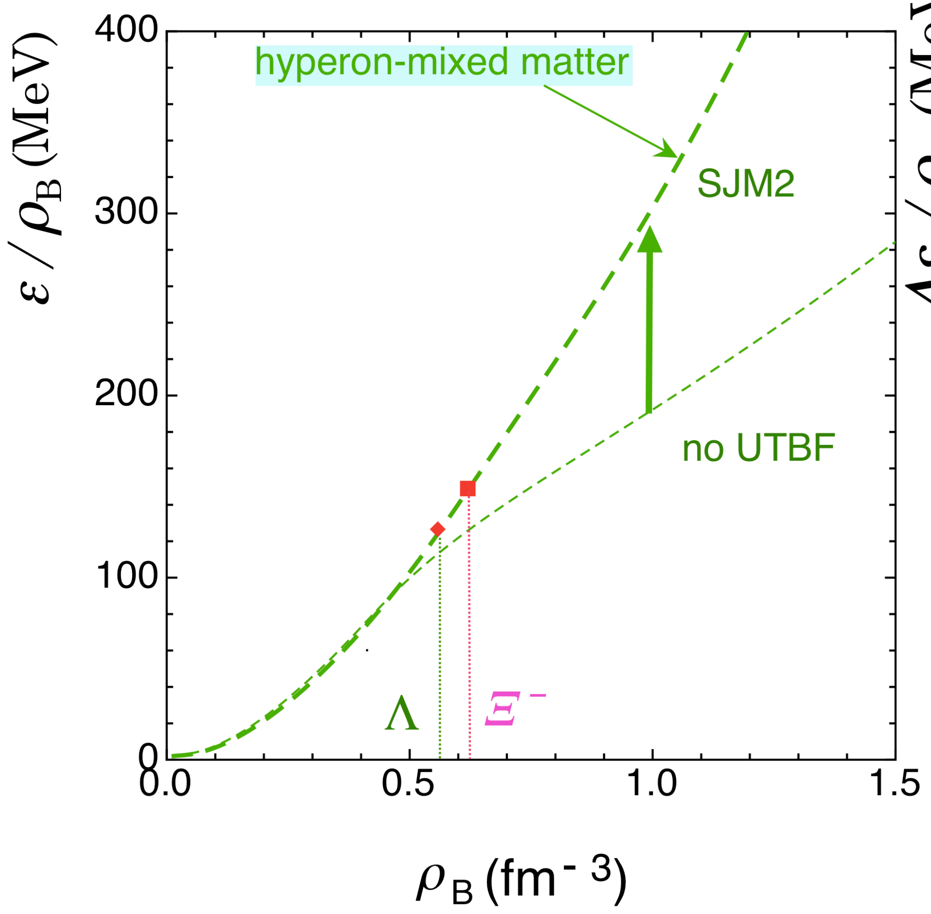
as compared with the case without SJM2

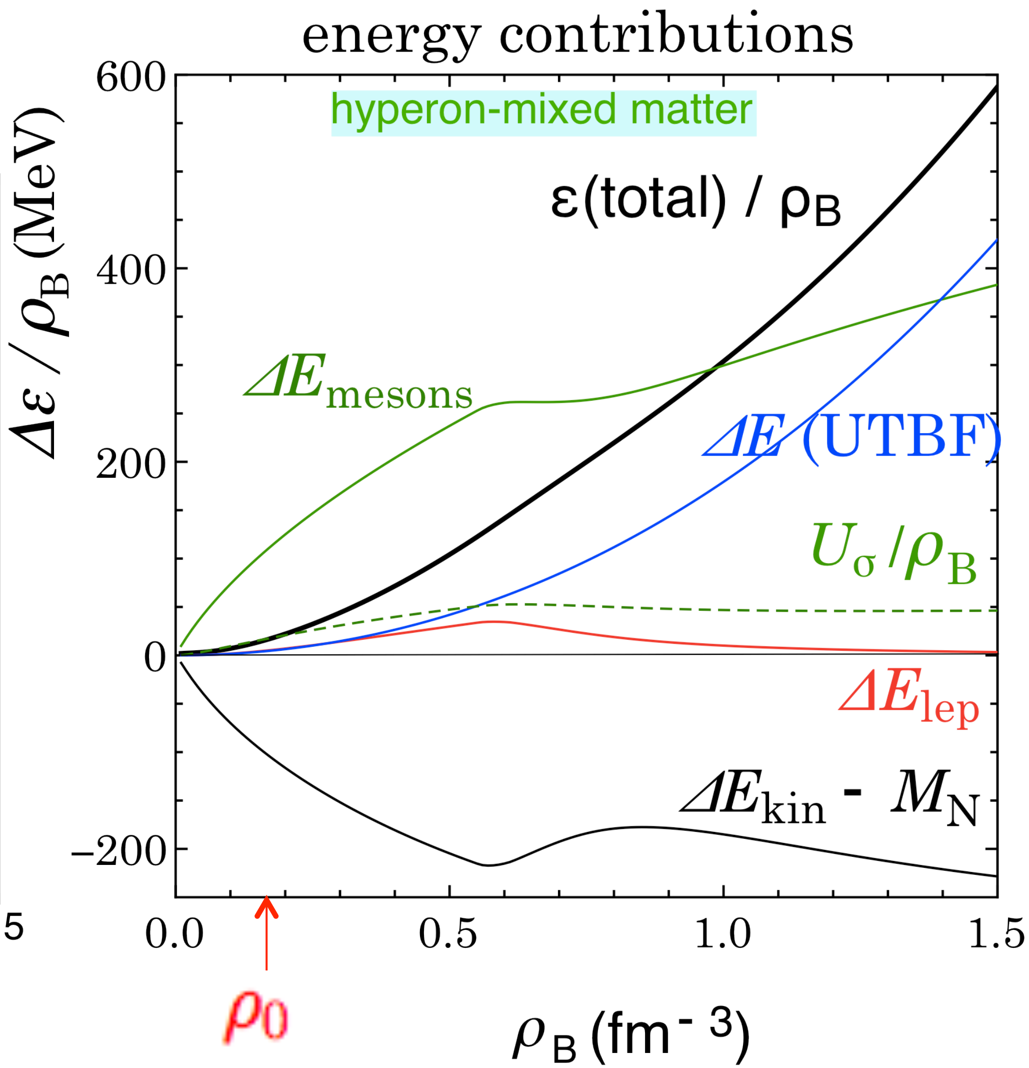
Repulsive effects of the mesons on the EOS become moderate.

3. Numerical Results

3-1. Effects of universal three-body repulsion with SJM2

Energy /baryon in pure hyperon-mixed matter

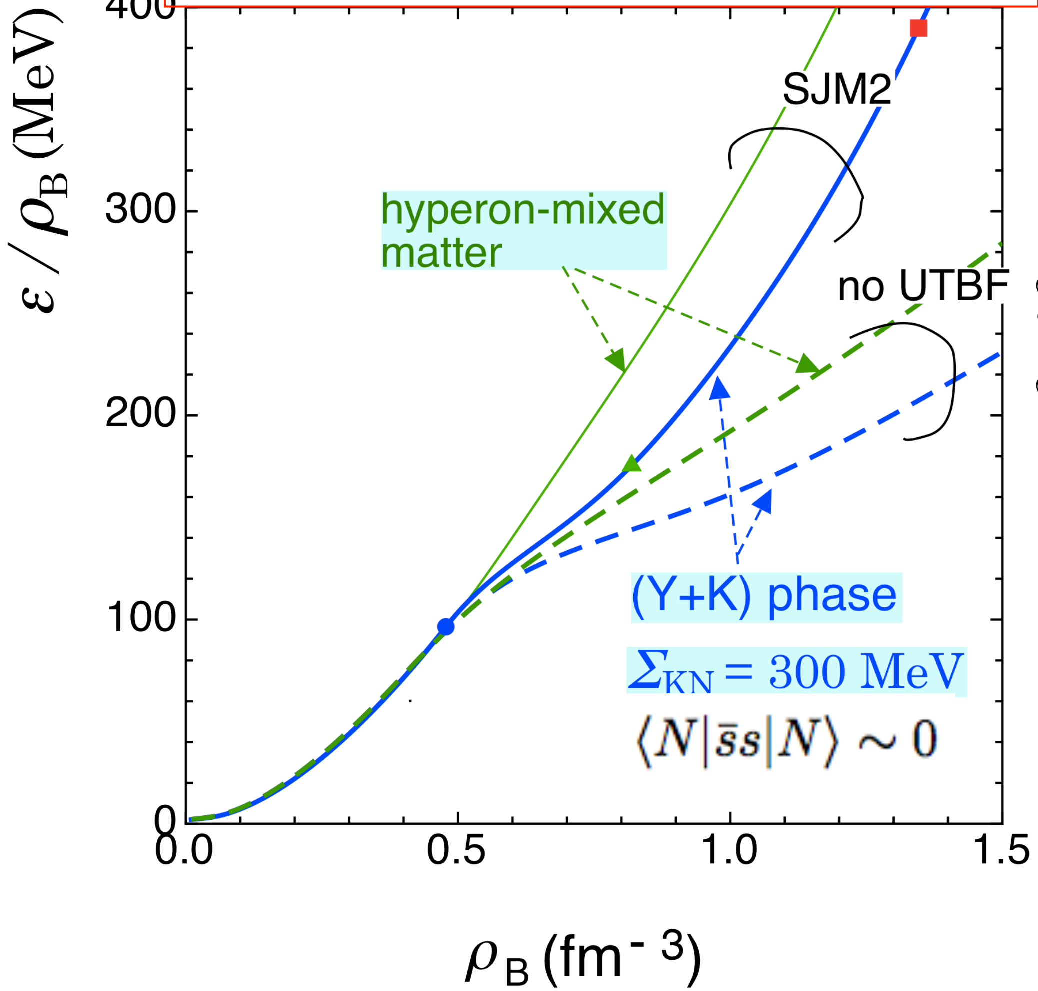




3-1. Effects of universal three-body repulsion with SJM2

Energy /baryon in (Y+K) phase

Kaon condensates compete with hyperons (Λ, Ξ^-, ...) .

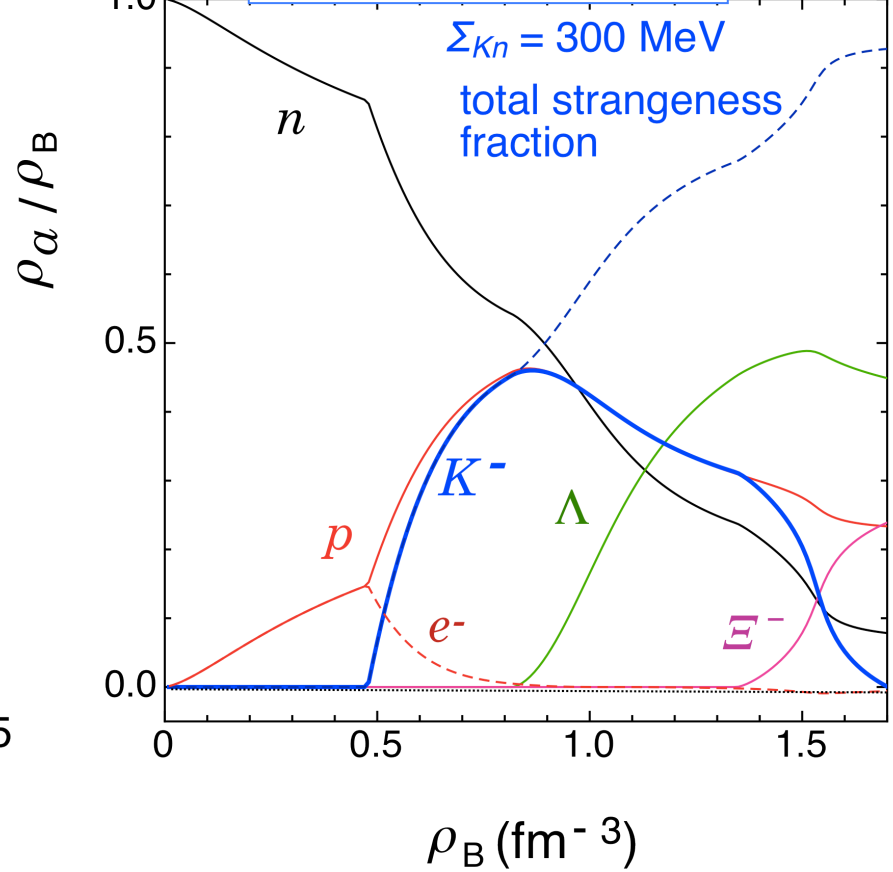


Onset of Λ :

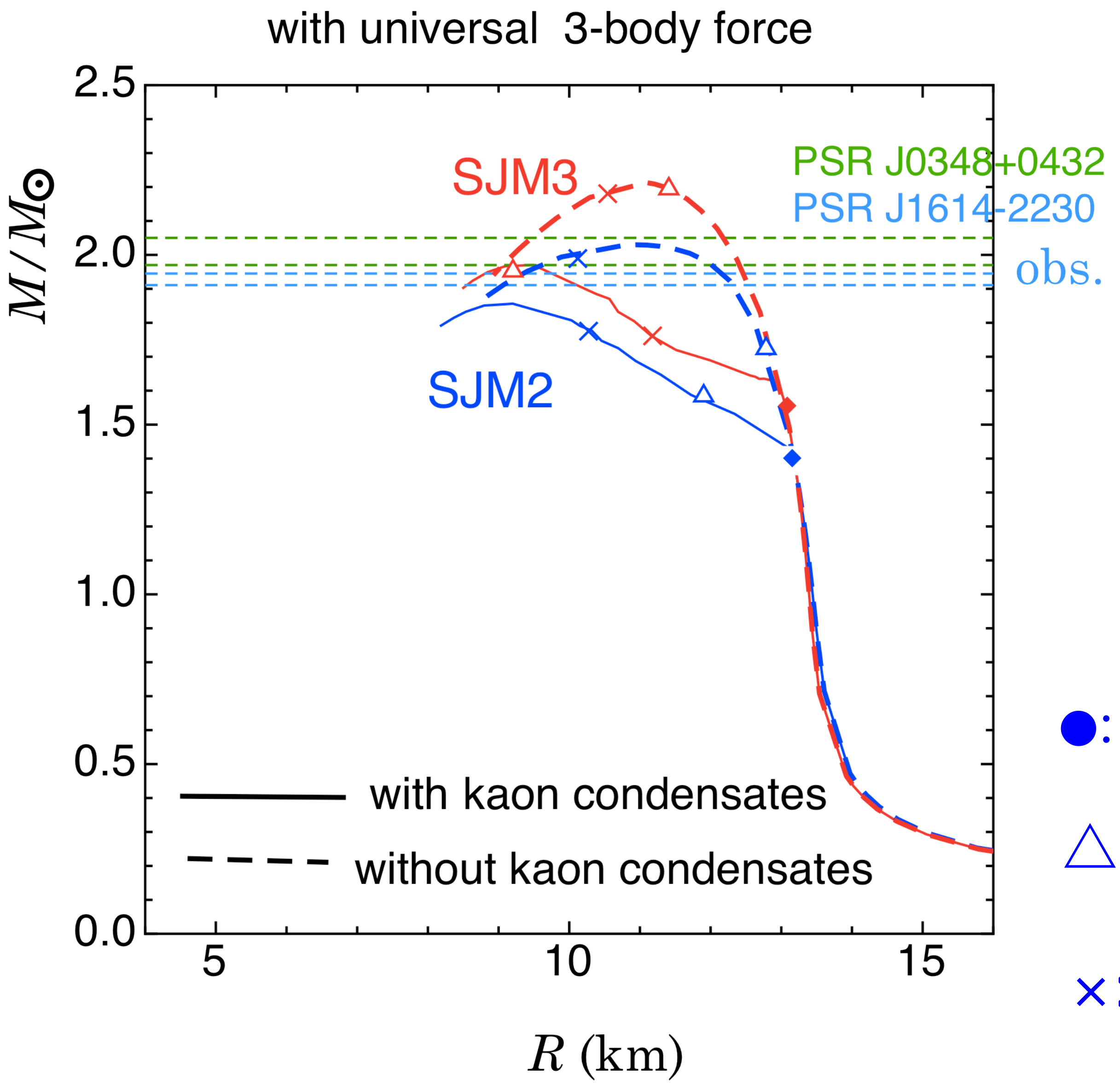
$$\mu_n = \mu_p + \mu_e = \mu_\Lambda$$

Onset of Ξ^- :

$$\mu_n = \mu_{\Xi^-} - \mu_e$$



3-3 Gravitational mass – Radius



(range of repulsive core)

SJM2: $\eta_C = 0.50$ fm

SJM3: $\eta_C = 0.53$ fm

$\Sigma_{KN} = 300$ MeV

●: Kaon condensates appear

△: hyperon (Λ) appears

×: causality limit

4. Summary and concluding remarks

By refitting the parameters to reproduce the saturation properties of symmetric matter including the repulsive energy contribution from the UTBF at ρ_0, we considered the effects of the Universal Three-Body Force, based on the String Junction Model (SJM2, 3), on a possible coexistence of kaon condensates and hyperons [(Y+K) phase] .

Results

Σ_{KN} = 300 MeV case ($\langle N|\bar{s}s|N\rangle \sim 0$)

・Onset density of hyperons (Λ and Ξ^-) is pushed up to higher densities,

⇨ Kaon condensation appears ($\sim 3\rho_0$) prior to hyperon-mixing.

In the (Y+K) phase, kaons compete with hyperons rather than they coexist.

・Kaon-baryon attraction does not directly suffer from the repulsive effects of the UTBF.

→ Softening of the EOS of the (Y+K) phase is still large.

Future issues

・Effects of the TNA (three-nucleon attraction) at ρ_0 .

・ validity of universal 3-body repulsion at high densities

Consistent interaction model with UTBF within the RMF.

⟺ Quark Pauli effects [C. Nakamoto, Y. Suzuki, Phys.Rev. C94, 035803 (2016).]]

Lattice QCD results (T. Hatsuda , Hal QCD)

・Properties of kaon-condensates in hadronic phase and quark (CFL) phase

↓

・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).]
[T.Kojo, P.D.Powel, Y.Song, G.Baym, Phys. Rev. 91, 045003 (2015).]

Thank you !