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Effects of Three-Body Repulsive Forces on Kaon Condensates in Hyperon-Mixed Matter

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1. Introduction

1-1 Multi-strangeness systems in neutron stars

Hyperon-mixed matter (Λ, Σ, Ξ, ・・・ in the ground state)

Kaon condensation (BEC of antikaons)

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

- Rapid cooling of neutron stars
- Softening of EOS

⇅ Observational constraints

X-rays from pulsars, LMXB, … → surface temperature of compact stars

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

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

↕

Observation of massive neutron stars

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

M(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).]

Possible Solutions to the " Hyperon Puzzle"

・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.]

Three-baryon repulsion (TNR) is necessary in order to stiffen the EOS at high densities.

Around the saturation density ρ_0 ($\sim$0.16 fm^{-3})

Saturation of symmetric nuclear matter needs

Three-nucleon attraction (TNA) for $\rho_B \lesssim \rho_0$

Three-nucleon repulsion (TNR) for $\rho_B \gtrsim \rho_0$

Experimental evidence of three-nucleon interaction around saturation density ρ_0 ($\sim$0.16 fm^{-3})

- Fujita-Miyazawa 3-body force : (0.5 – 1) MeV in B(^{3}H) = 8.5 MeV
- *N*-*d* elastic scattering [E_{in} = (100 – 200) MeV] at RIKEN (SMART), RCNP (Ring Cyclotron)

[H. Sakai et al., Phys. Rev. Lett. 84, 5288 (2000).
K.Sekiguchi et al., Phys.Rev.C65, 034003 (2002); Phys.Rev.Lett.95, 0162301(2005).]

- neutron drip line in neutron-rich nuclei

[T. Otsuka et al., Phys. Rev. Lett. 105, 032501 (2010).]

For 3-body int., Three-Nucleon-Attraction (TNA) + Universal Three-Baryon Force (UTBF) are introduced.

TNA [B. Friedman and V. R. Pandharipande, Nucl. Phys. A361, 502(1981)]

$$\mathcal{E}(\mathrm{TNA})/\rho_{\mathrm{B}} = \gamma_2 \rho_{\mathrm{B}}^2 \exp[-\gamma_3 \rho_{\mathrm{B}}] \left[3 - 2\left(\frac{\rho_n - \rho_p}{\rho_{\mathrm{B}}}\right)^2\right]$$

UTBF Effective two-body int. based on String-Junction Model 2
[R. Tamagaki, Prog. Theor. Phys. 119 (2008), 965.]

$$E(\mathrm{UTBF}) = C \cdot \rho_{\mathrm{B}}^2 (1 + 0.024\rho_{\mathrm{B}}/\rho_0)$$

SJM2: $\eta_C = 0.50$ fm
(range of repulsive core)

For 2-body int.,
the minimal Relativistic Mean-Field (RMF) theory
without introduction of the nonlinear self-interacting σ potential U(σ):

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

: not included

We study the effects of the 3-body baryon forces (TNA + UTBF) on the EOS of the (Y+K) phase.

Interaction model

Effective chiral Lagrangian for $\overline{K}B$ and $\overline{K}\overline{K}$ interactions coupled with the RMF [without U(σ)] for B-B int.

+ (TNA + UTBF)

Meson-N Coupling constants are refitted to satisfy the saturation properties of symmetric nuclear matter (SNM)

(ρ_0 =0.16 fm^{-3}) (E_B=16.3 MeV) (K=240 MeV) (S_0=31.5 MeV)

For TNA $\gamma_2 = -1607$ MeV・fm^6 $\gamma_3 = 18$ fm^3

$$\mathcal{E}(\mathrm{TNA})/\rho_{\mathrm{B}} = \gamma_2 \rho_{\mathrm{B}}^2 \exp[-\gamma_3 \rho_{\mathrm{B}}]\left[3 - 2\left(\frac{\rho_n - \rho_p}{\rho_{\mathrm{B}}}\right)^2\right]$$

within empirical values

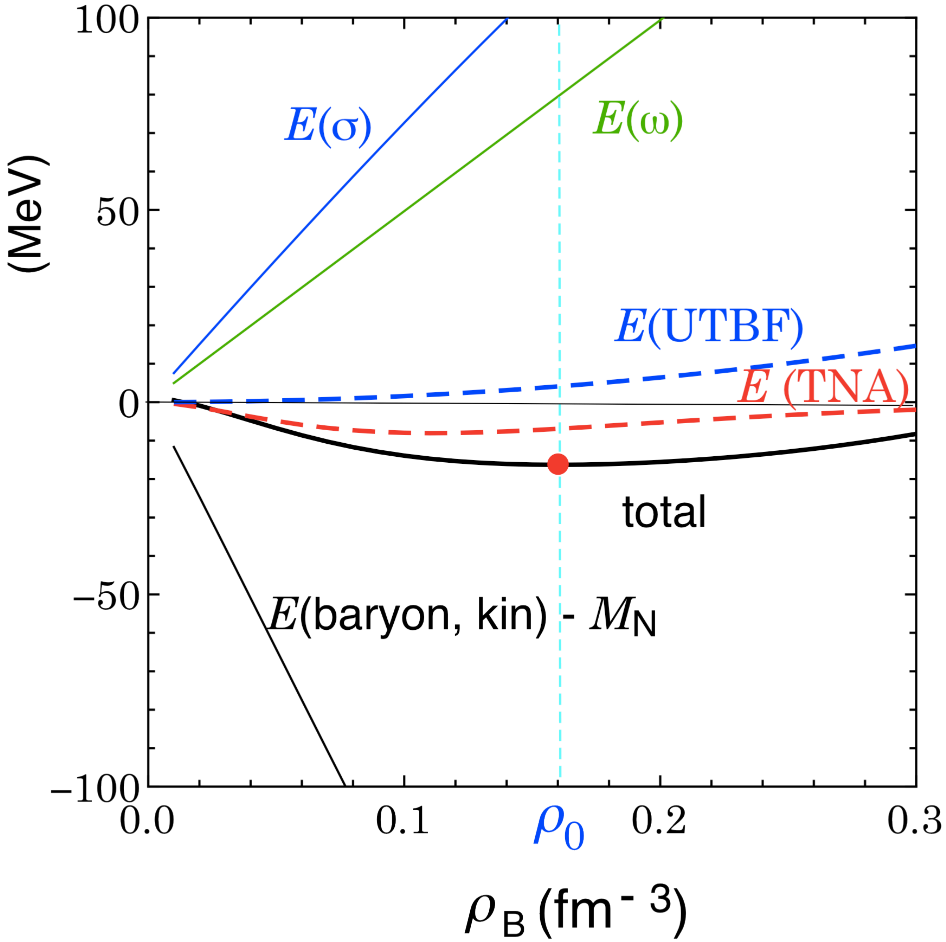
	$g_{\sigma N}$	$g_{\omega N}$	$g_{\rho N}$	$\langle\sigma\rangle_0$ (MeV)	$\langle\omega\rangle_0$ (MeV)	M_N^*/M_N	S_0 (MeV)	L (MeV)
present	5.63	8.90	3.33	41.6	17.9	0.75	31.5	64.0
previous	6.24	8.44	4.27	32.8	16.9	0.78	33.7	93.0

Saturation of symmetric nuclear matter

$$E(\text{total}) = E(\text{baryon, kin}) + E(\sigma) + E(\omega) + E(\text{TNA}) + E(\text{UTBF})$$

$$E(\text{baryon, kin}) = \frac{1}{\rho_B} \sum_{b=p,n} \frac{2}{(2\pi)^3} \int_{|\vec{p}| \le p_F(b)} d^3|\vec{p}| (|\vec{p}|^2 + M_b^{*2})^{1/2}$$

energy contribution



$$M_b^* = M_N - g_{\sigma N}\sigma$$

(effective nucleon mass)

$$E(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2 / \rho_B$$

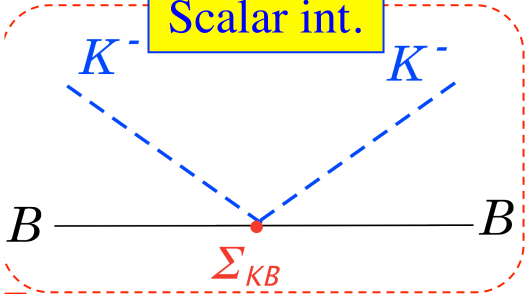
$$E(\omega) = \frac{1}{2} m_\omega^2 \omega_0^2 / \rho_B$$

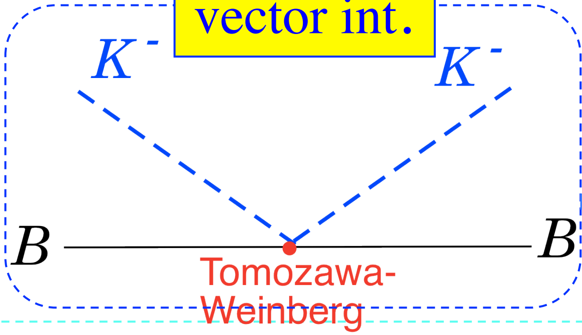
2. Formulation for the (Y+K) phase

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





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

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

Coupling constants in RMF g_{MB} with TNA + SJM2 (without SJM2)

B \ M	p	n	Λ	Ξ^-	Σ^-
σ	$g_{\sigma N}$= 5.63 (6.24)		3.20(3.73)	1.61(1.88)	1.98(2.19)
ω	$g_{\omega N}$= 8.90 (8.44)		$2/3\ g_{\omega N}$	$1/3\ g_{\omega N}$	$2/3\ g_{\omega N}$
ρ	$g_{\rho N}$= 3.33 (4.27)			$g_{\rho N}$	$2g_{\rho N}$
ϕ			$-\sqrt{2/3}\ g_{\omega N}$	$-2\sqrt{2/3}\ g_{\omega N}$	$-\sqrt{2/3}\ g_{\omega N}$
σ *			7.2	4.0	0

-- NN interaction --

Saturation of nuclear matter

(ρ_0 =0.16 fm^{-3})

(E_B=16.3 MeV)

(K=240 MeV)

(S_0=31.5 MeV)

--- vector meson couplings to Y ---

SU(6) symmetry

--- σ, σ* meson couplings for Y ---

Hyperon potentials deduced from hypernuclear experiments

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

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

: repulsive

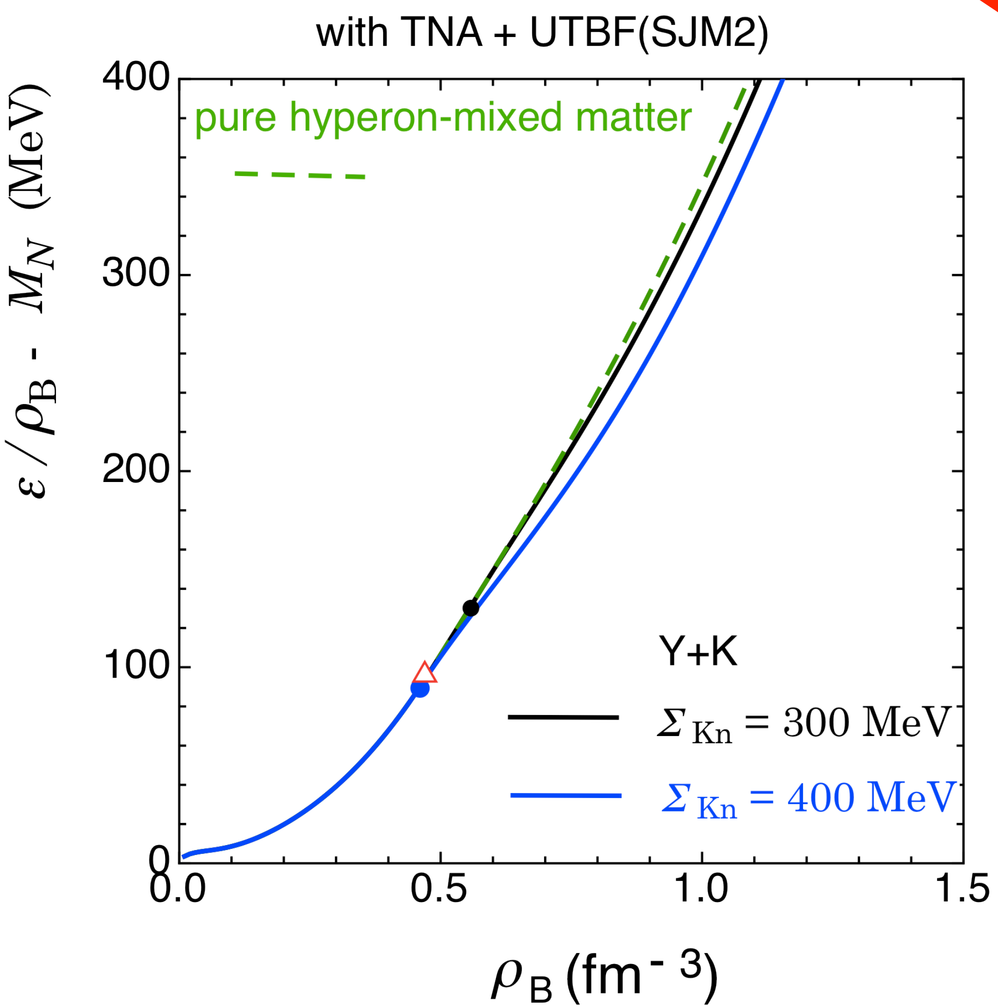
$$U_{\Xi^-}^N(\rho_0) = -g_{\sigma\Xi^-}\sigma + g_{\omega\Xi^-}\omega_0 = -14\ \text{MeV}$$

3. Numerical Results

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

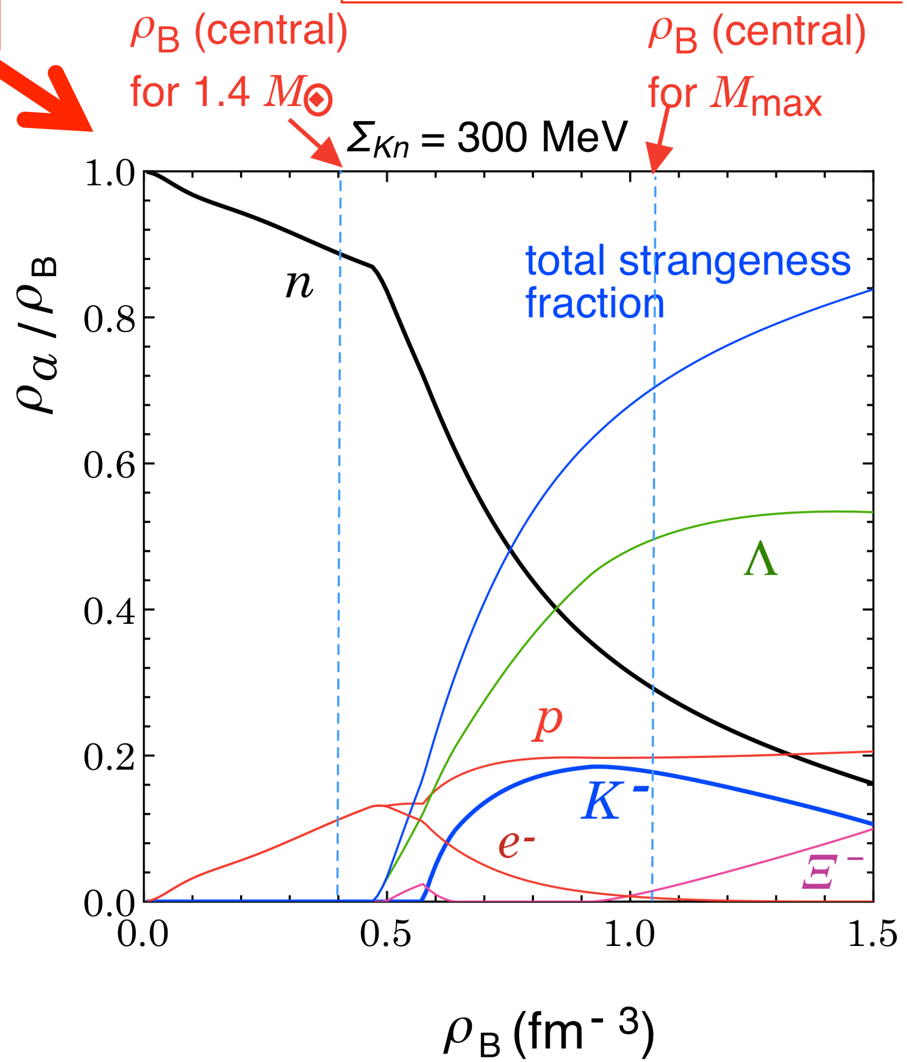
Energy /baryon in (Y+K) phase

Kaon condensates compete with Ξ^- hyperons

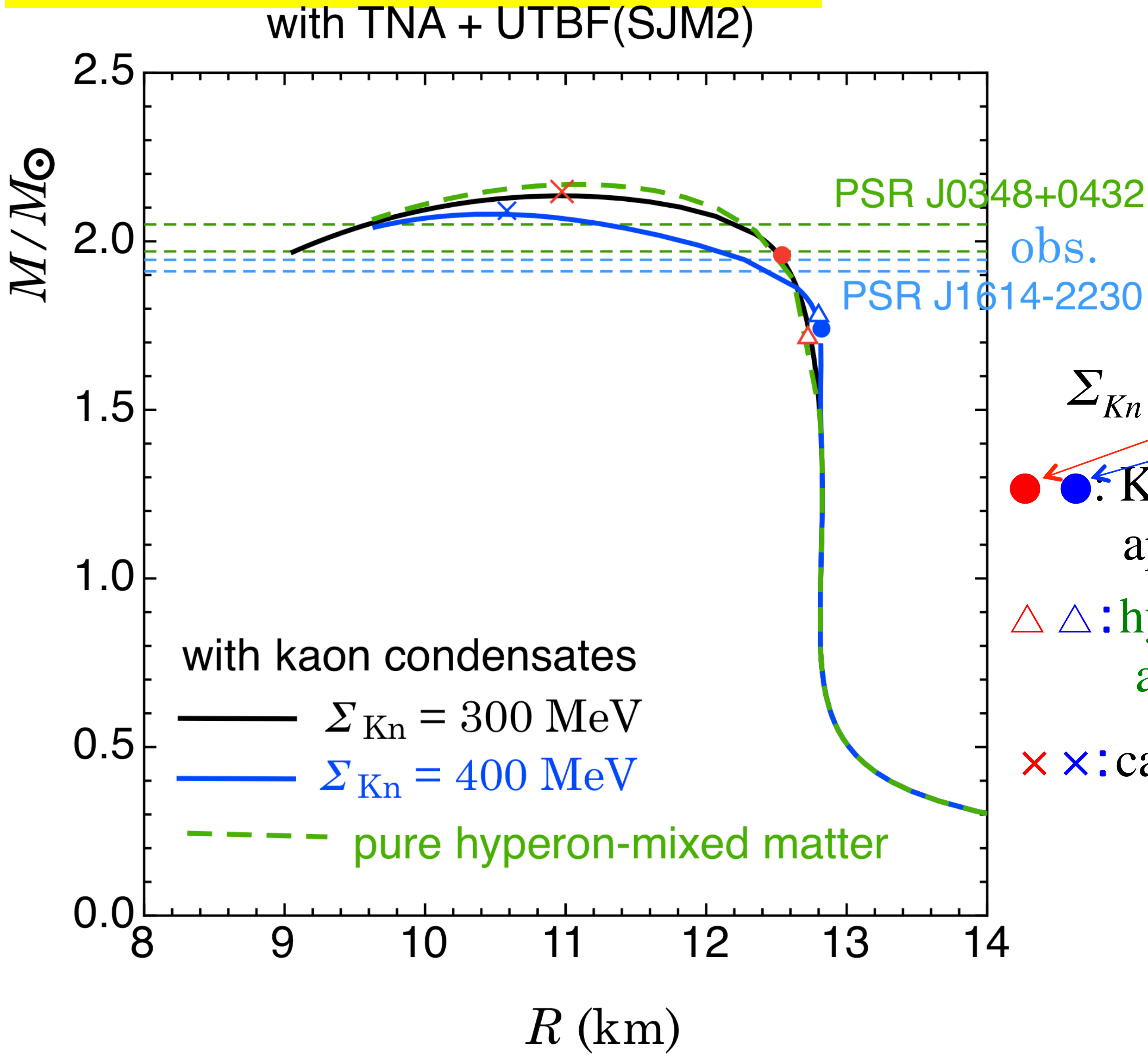


Particle fractions

Onset of Λ : $\mu_n = \mu_p + \mu_e = \mu_\Lambda$



3-3 Gravitational mass – Radius



Σ_{Kn} = 300 (400) MeV

● ●: Kaon condensates appear

△ △: hyperon (Λ) appears

× ×: causality limit

	Σ_{Kn} = 300 MeV	$M/M_{\odot}$	R (km)	Σ_{Kn} = 400 MeV	$M/M_{\odot}$	R (km)
K- appearing in the center		1.94	12.6		1.73	12.8
Maximum mass		2.14	11.0		2.08	10.6

Compact stars with (Y+K) phase: $M = (1.7 - 2.1)\ M_{\odot}$

$R = (13 - 11)$ km

4. Summary and concluding remarks

By setting the parameters to reproduce the saturation properties of symmetric matter including the three-body interactions, TNA + UTBF, in addition to minimal RMF without introducing U(σ), we considered the repulsive effects of the UTBF (SJM2), on a possible coexistence of kaon condensates and hyperons [(Y+K) phase] .

Results

Σ_{KN} = 300 MeV case ($\langle N|\bar{s}s|N\rangle \sim 0$) $\rho_B^c(K^-) = 3.6\rho_0$

Σ_{KN} = 400 MeV case ($y \equiv 2\langle N|\bar{s}s|N\rangle / \langle N|\bar{u}u + \bar{d}d|N\rangle \sim 0.4$) $\rho_B^c(K^-) = 2.9\rho_0$

・In the (Y+K) phase, kaons compete with Ξ^- 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 due to kaon condensates leads to slow decrease in M as R increases.

・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.

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

The heavy neutron stars can exist within a hadron picture including kaon condensates and hyperon-mixing.

・For the canonical mass ($\sim 1.4 M_\odot$) stars, even hyperons (Λ . . .) do not appear in the core .

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

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

Thank you !