～中性子星の観測と理論～ 研究活性化ワークショップ 2017
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Equation of state with kaon condensation and hyperons in dense matter

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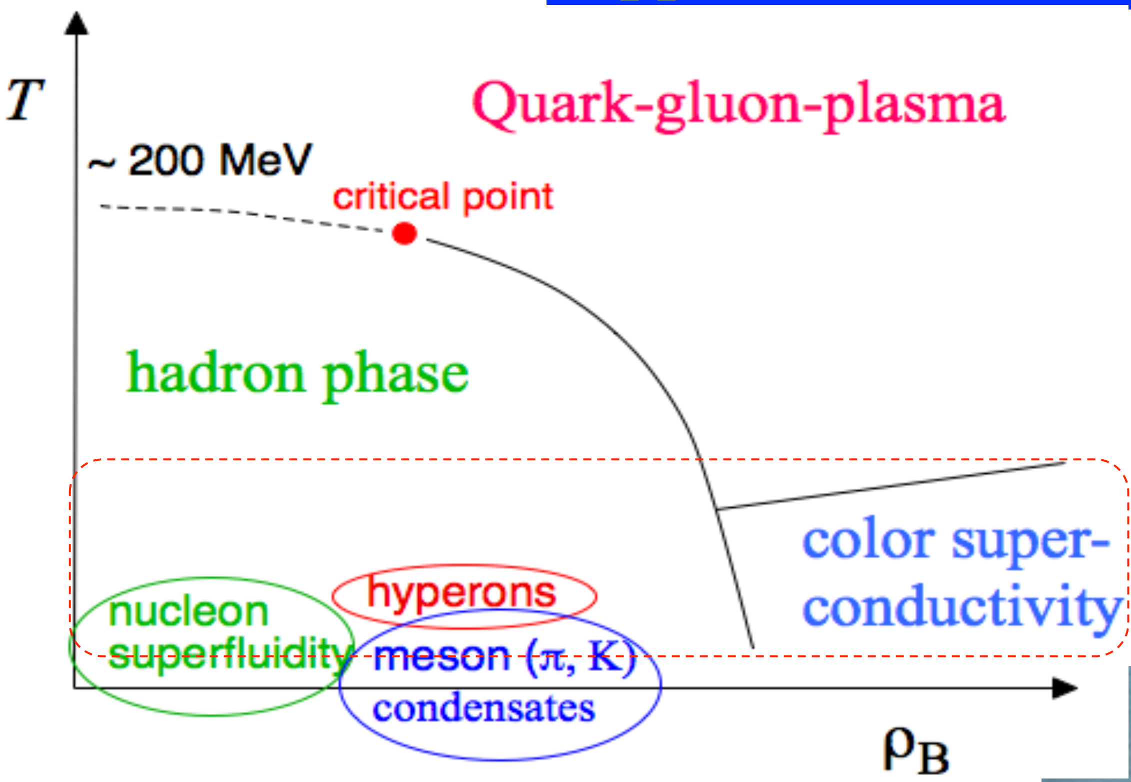
1. Introduction　1-1 High density matter in neutron stars

Appearance of strangeness quantum number



Stable infinite nuclear matter

Observations of neutron stars

(Xray, γ ray, neutrino, Gravitational wave . . .)

重力波観測（LIGO, Virgo）

X線観測 (NICER)

Experiments

J-PARC　[http://j-parc.jp/]

Various phases and Equation of state

Phase transition, phase equilibrium

High density QCD

1-2 highly dense matter and strangeness

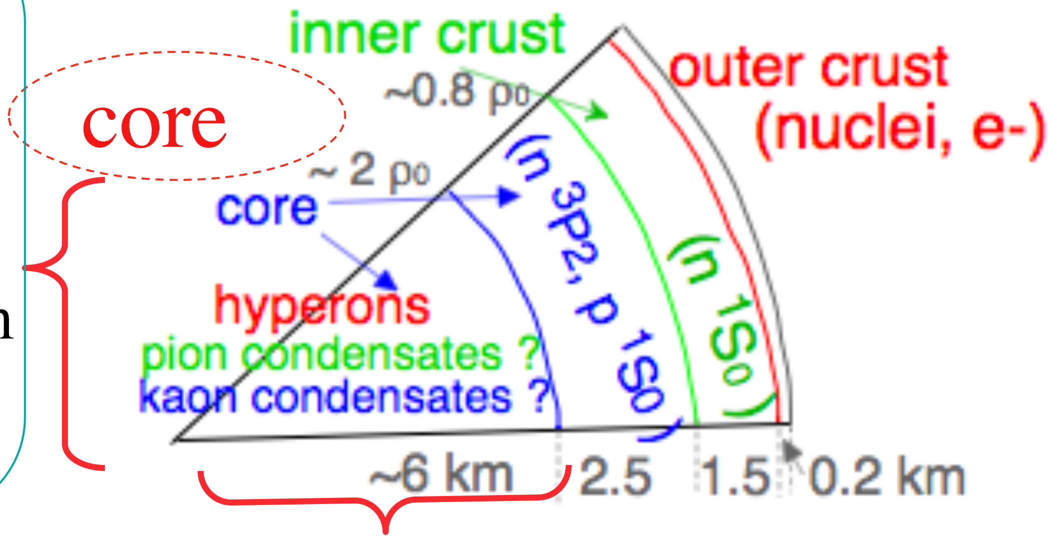
Neutron-star matter

(Saturation density : $\rho_0 = 0.17\ \mathrm{fm}^{-3}$
$\sim 2.8 \times 10^{14}\ \mathrm{g/cm}^3$)

- baryon number density:
  $\rho_B \geq 0.8\ \rho_0$
- composition nucleon (n, p), lepton (e^-, μ^-)

$n \leftrightharpoons p\ e^-\ (\bar{\nu}_e)$ β equilibrium

n-n $^3P_2$, p-p $^1S_0$ superfluid



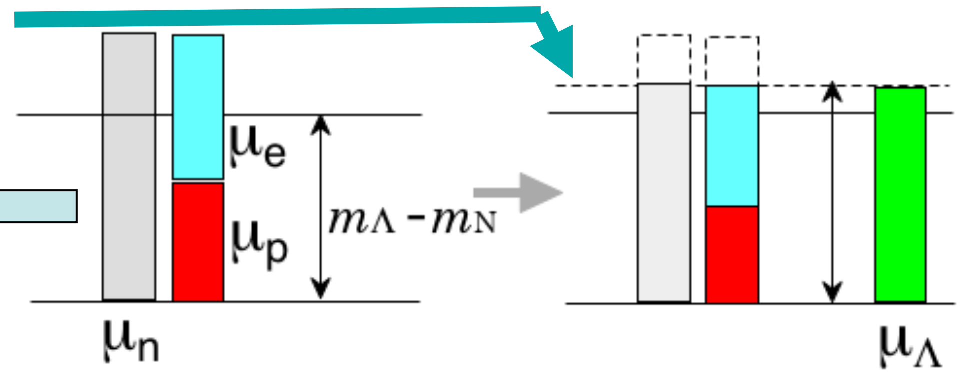
Hyperon-mixing At high density

$\rho_B \geq 2.5\ \rho_0$

$p + e^- \rightarrow \Lambda + \nu_e$

$n + e^- \rightarrow \Sigma^- + \nu_e$

Chemical equilibrium



(strangeness-changing weak interaction processes)

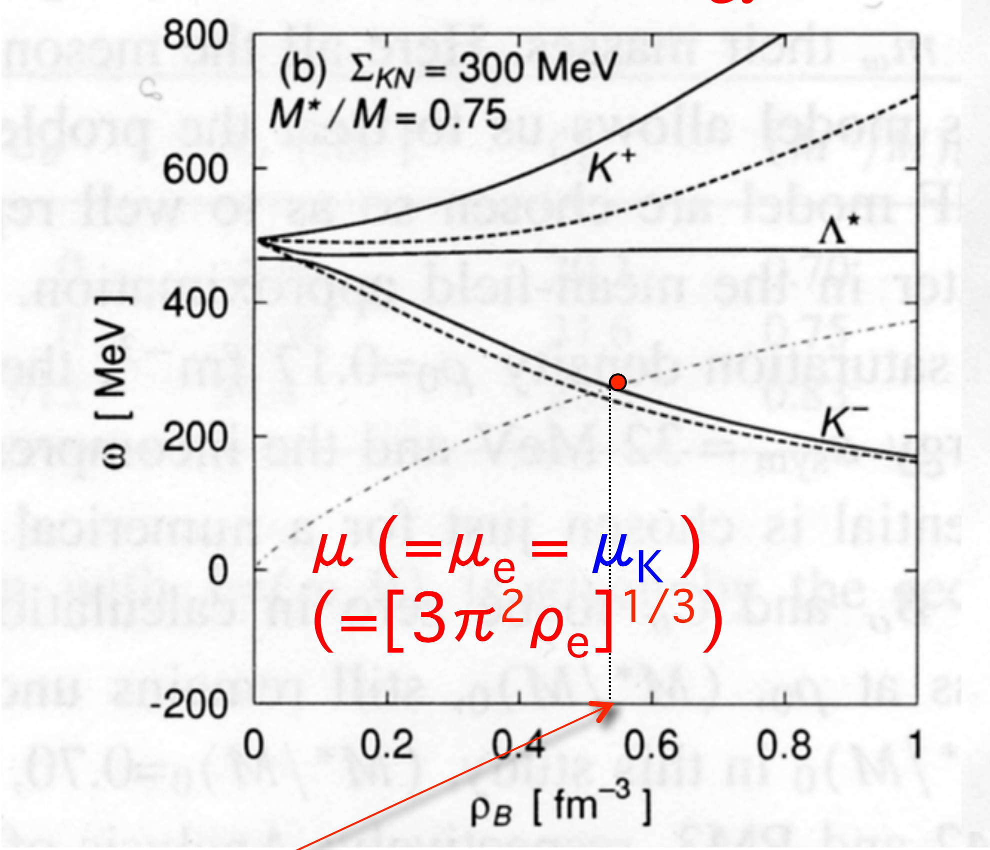
'hyperonic matter'

Hyperons (Λ[uds], Σ^-[dds], Ξ^-[dss]･･･) may be mixed.

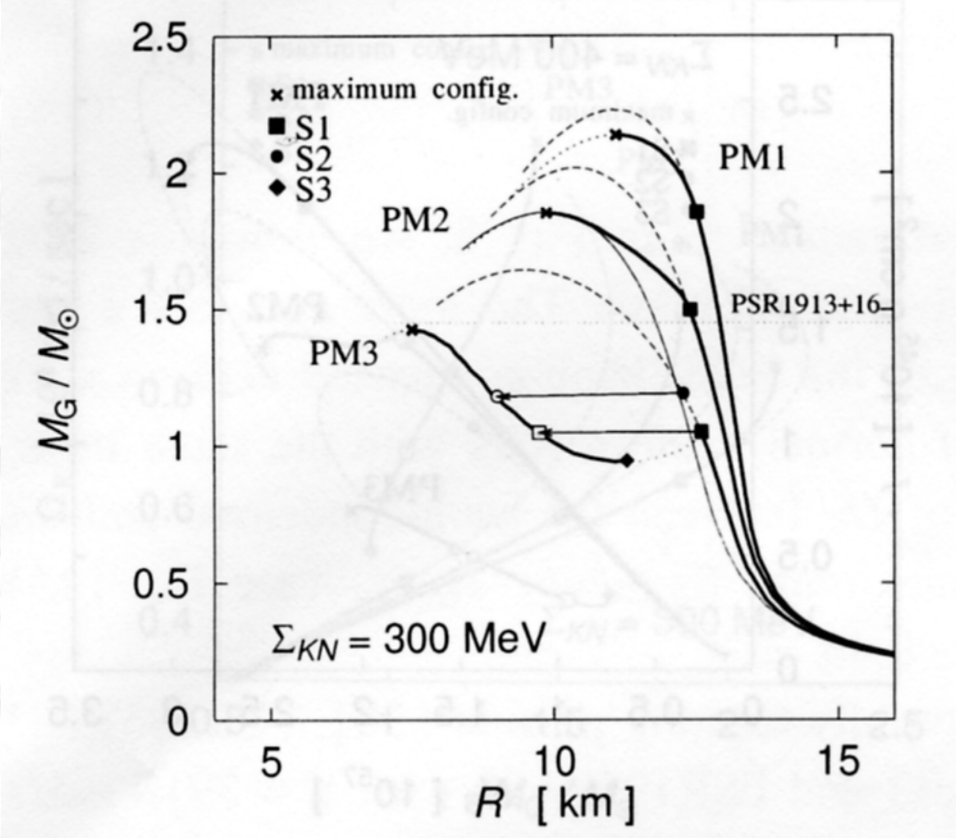
Kaon condensation in neutron-star matter (without hyperons)

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

Lowest Kaon energy



Gravitational mass-radius relations



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

$$f_K = 1/[e^{(\omega_K - \mu)/k_B T} - 1] \rightarrow \infty$$

Critical density $\rho_B{}^C = 3 \sim 4\ \rho_0$

Chemical equilibrium for weak processes

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

strangeness-nonconserving system

Multi-strangeness system in neutron stars

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

Kaon condensation (BEC of antikaons)

・Rapid cooling of neutron stars

・Softening of EOS

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

Hyperon puzzle

Theory

・Most of the models within 2-body B-B int. including (Y+K) phase predict $M_{max} < 2\ M_{\odot}$

Observations

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

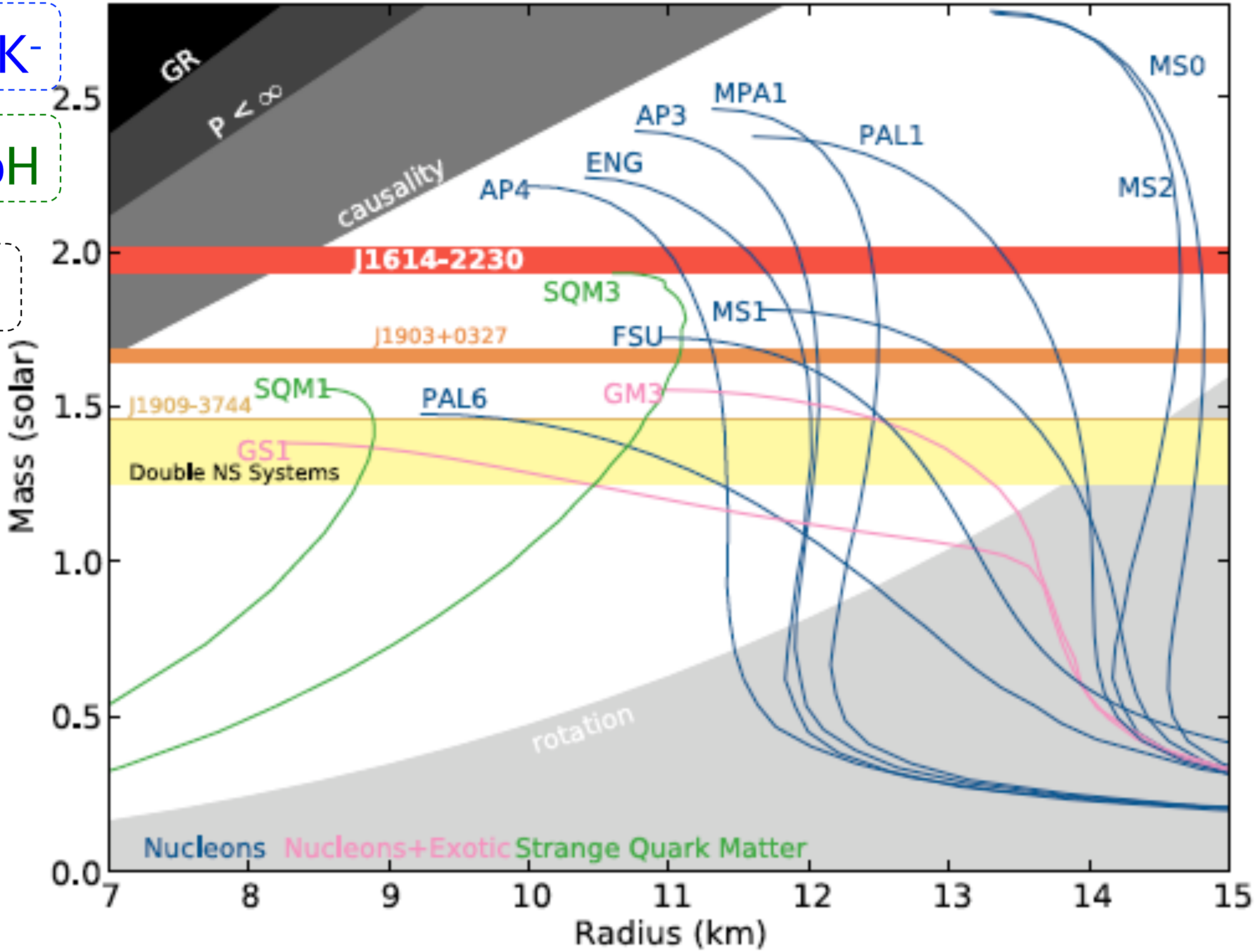
SQM: uds

GS1: npK$^-$

GM3: npH

AP4: np

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



1-3 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

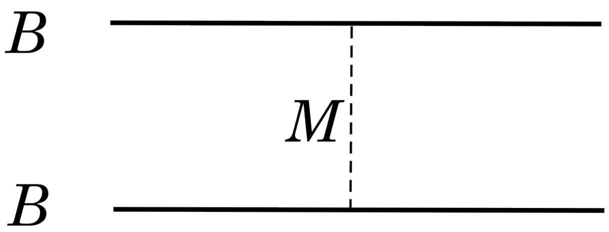
[K. Tsubakihara and A. Ohnishi, Nucl. Phys. A 914 (2013), 438; arXiv:1211.7208.]

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

2. Formulation

2.1 Interaction model

Baryon-Baryon interaction



Relativistic mean-field theory

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

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

Interaction Lagrangian

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

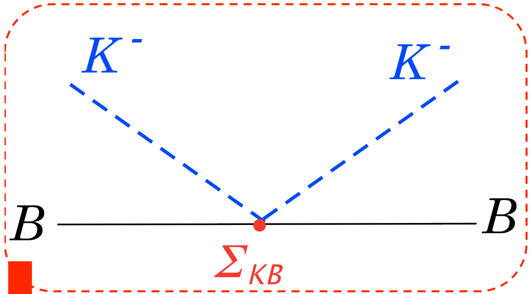
$$m_B^*(r) = m_B - g_{\sigma B}\sigma(r) - g_{\sigma^* B}\sigma^*(r)$$

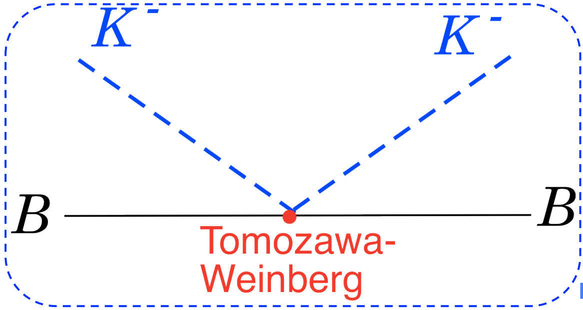
$$D^\mu \equiv \partial^\mu + ig_{\omega B}\omega^\mu + ig_{\rho B}\vec{\tau}\cdot\vec{R}^\mu + ig_{\phi B}\phi^\mu + iQA^\mu$$

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

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

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





Nonlinear K field

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

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

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

$$\mathcal{L} = \frac{1}{4} f^2 \mathrm{Tr}\,\partial^\mu \Sigma^\dagger \partial_\mu \Sigma + \frac{1}{2} f^2 \Lambda_{\chi SB} (\mathrm{Tr}\, M(\Sigma - 1) + \mathrm{h.c.})$$
$$+ \mathrm{Tr}\,\bar{\Psi}(i\not{\partial} - m_B)\Psi + \mathrm{Tr}\,\bar{\Psi} i\gamma^\mu [V_\mu, \Psi] + D\,\mathrm{Tr}\,\bar{\Psi}\gamma^\mu\gamma^5\{A_\mu, \Psi\}$$
$$+ F\,\mathrm{Tr}\,\bar{\Psi}\gamma^\mu\gamma^5 [A_\mu, \Psi] + a_1 \mathrm{Tr}\,\bar{\Psi}(\xi M^\dagger \xi + \mathrm{h.c.})\Psi$$
$$+ a_2 \mathrm{Tr}\,\bar{\Psi}\Psi(\xi M^\dagger \xi + \mathrm{h.c.}) + a_3 (\mathrm{Tr}\, M\Sigma + \mathrm{h.c.})\mathrm{Tr}\,\bar{\Psi}\Psi \,,$$

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

Vector current

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

Axial-vector current

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

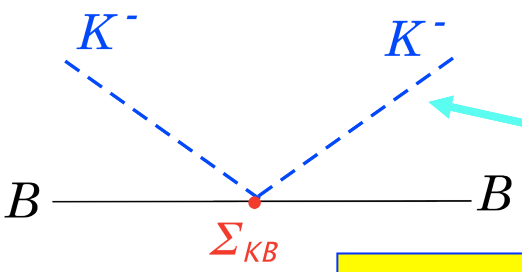
Classical K^- field

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

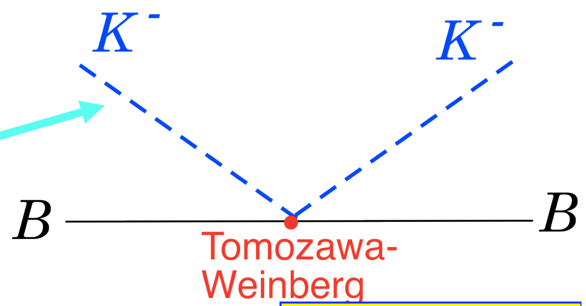
Meson decay constant f = 93 MeV

μ_K : kaon chemical potential

S wave KB interaction



Nonlinear K⁻ field



Scalar int.

$$m_K^{*2} \equiv m_K^2 - \frac{1}{f^2}\sum \rho_i^s \Sigma_{Ki} \quad (i = p, n, \Lambda, \Sigma^-, \Xi^-)$$

vector int.

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

2-2 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

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

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

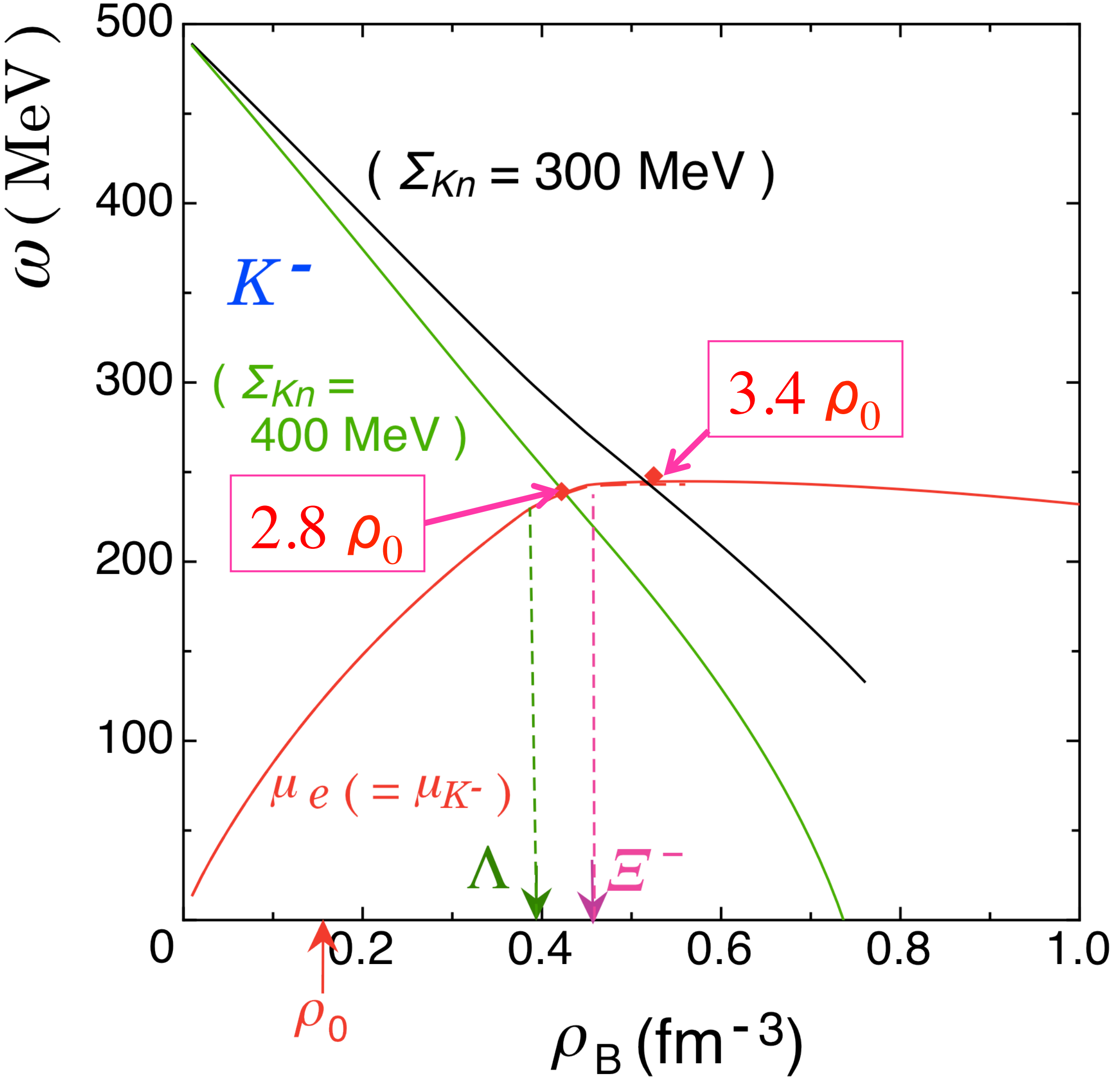
S-wave vector int.

S-wave scalar int.

3. Numerical Results

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

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



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

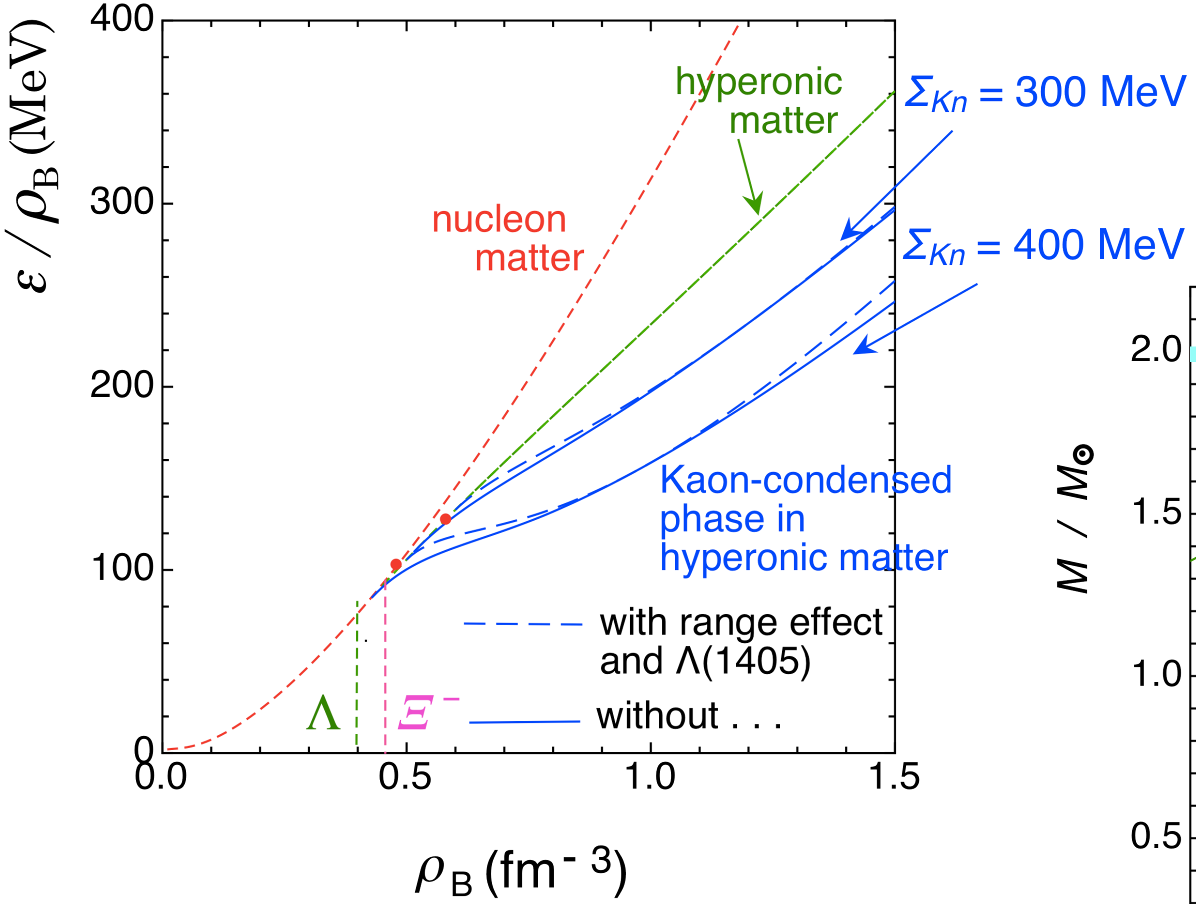
$$\omega = \mu_K (= \mu_{e^-} = \mu)$$

3. Numerical Results

3-2 EOS in β-equilibrated matter

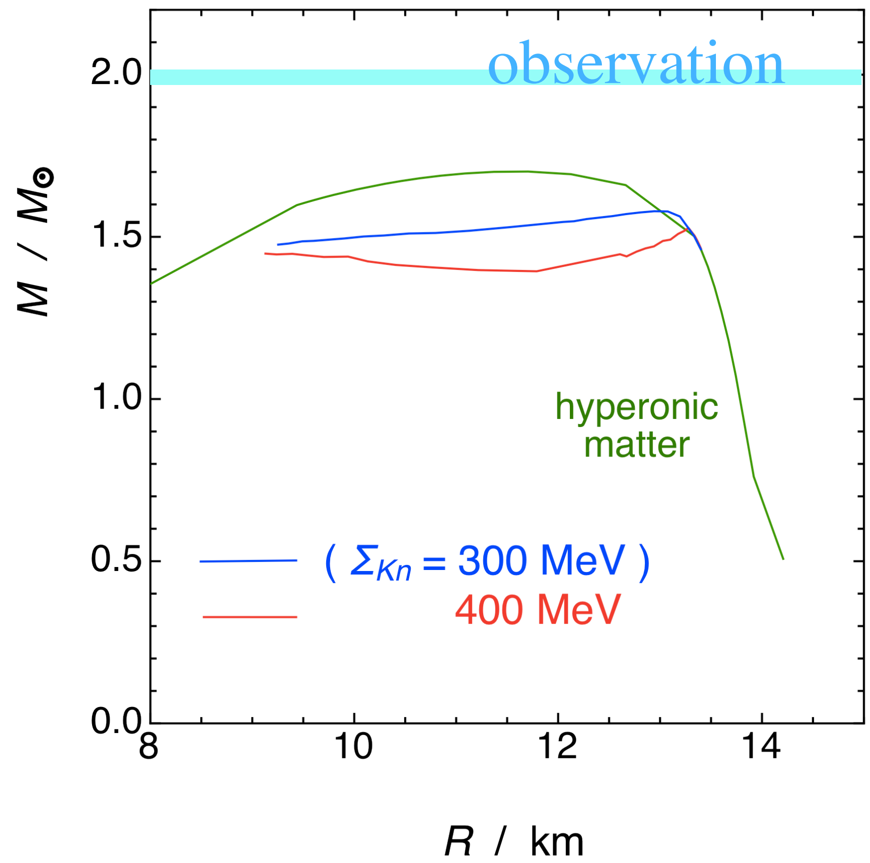
Energy per particle

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



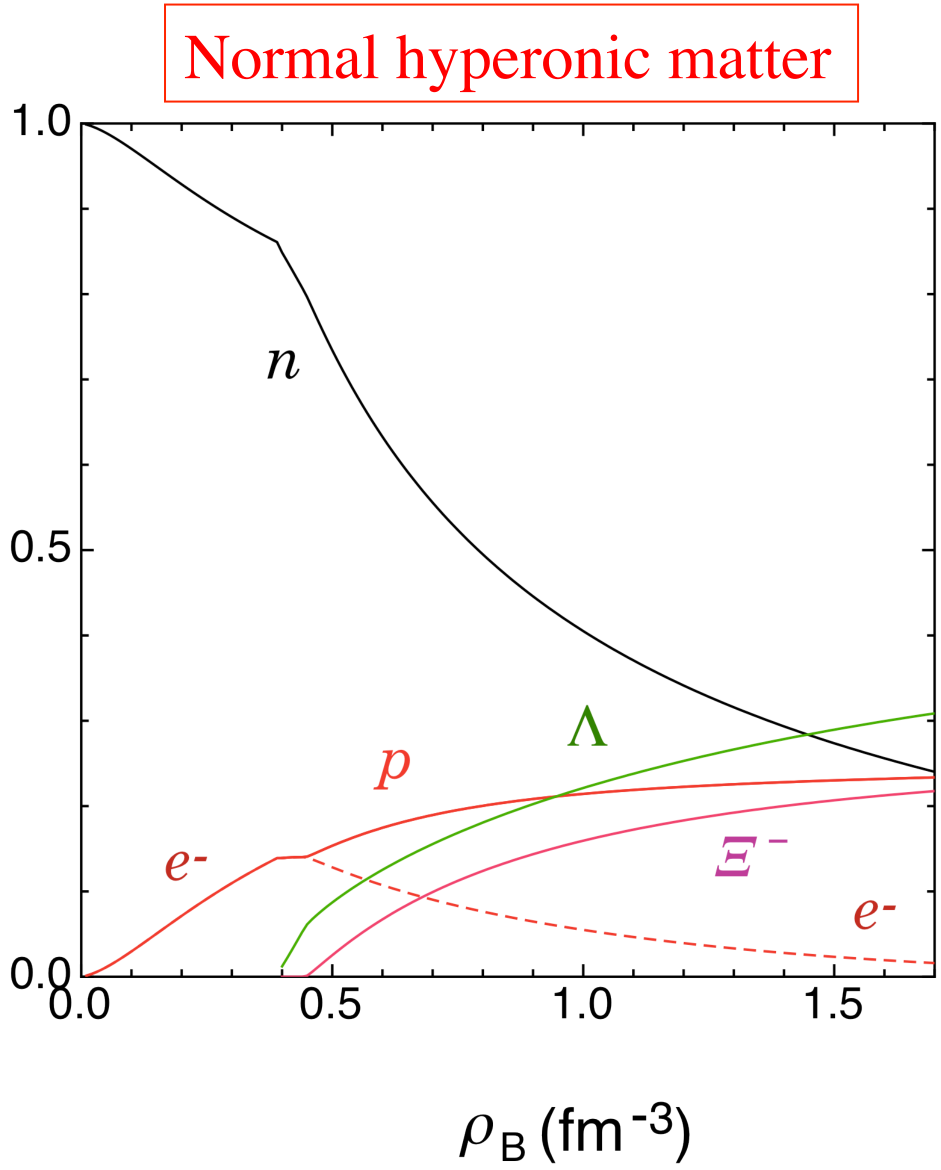
c.f. ($\Sigma_{KN} \sim 280$ MeV for $\langle N|\bar{s}s|N\rangle \sim 0$)

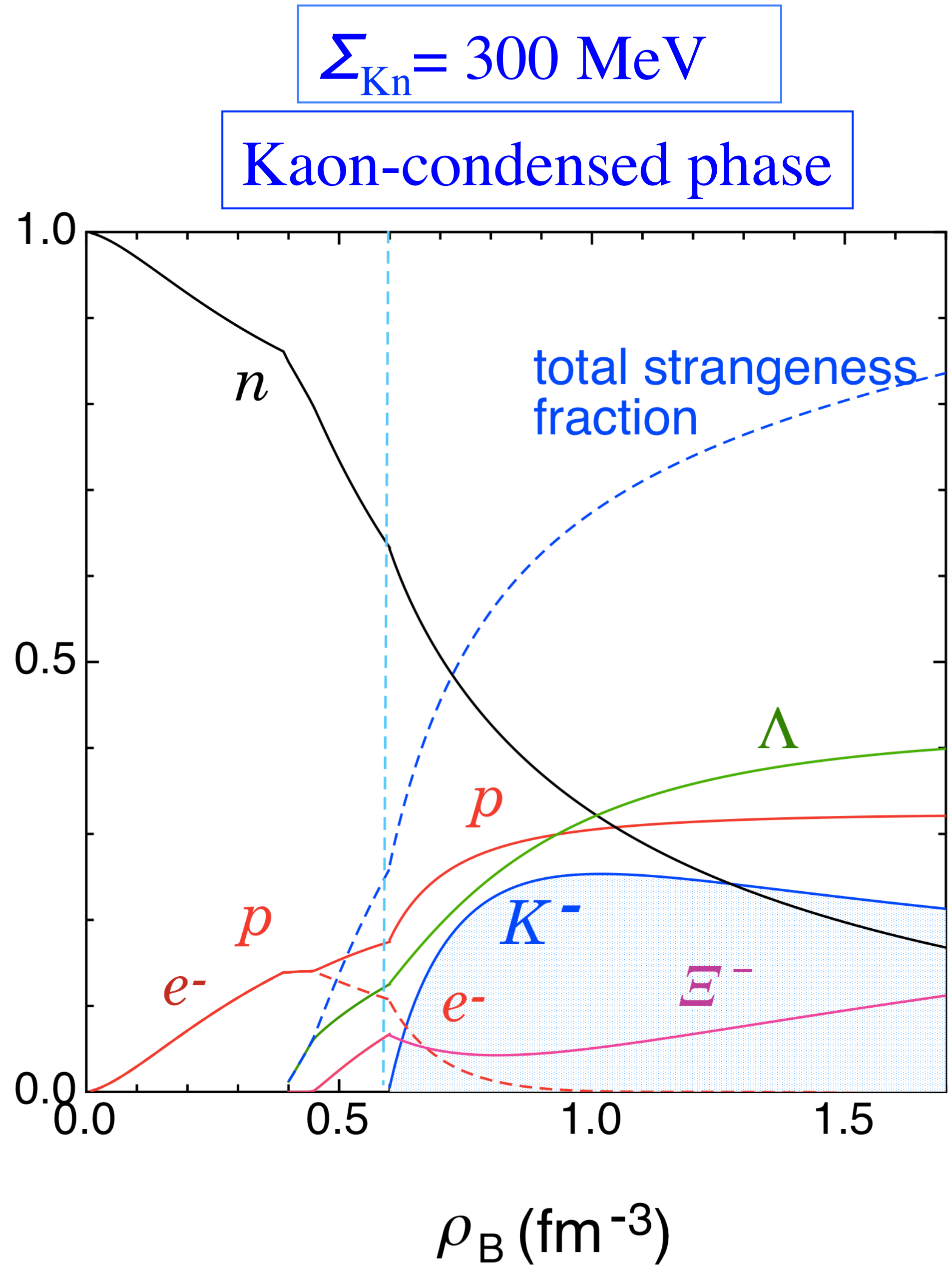
Mass –Radius relation



3-3 Particle fractions

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



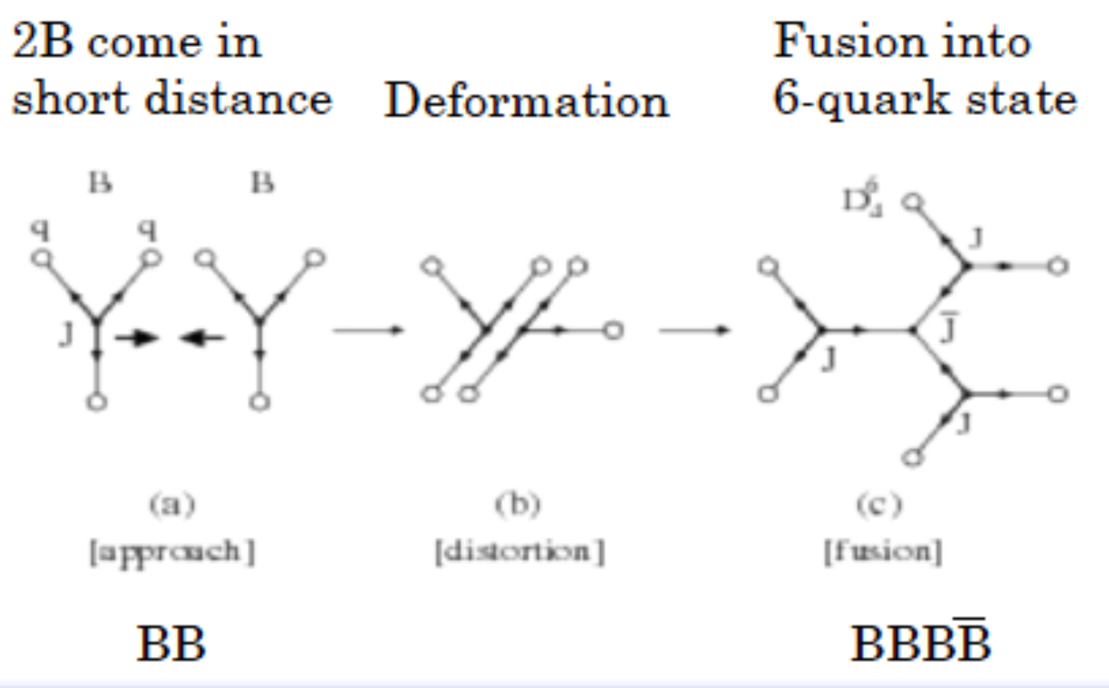


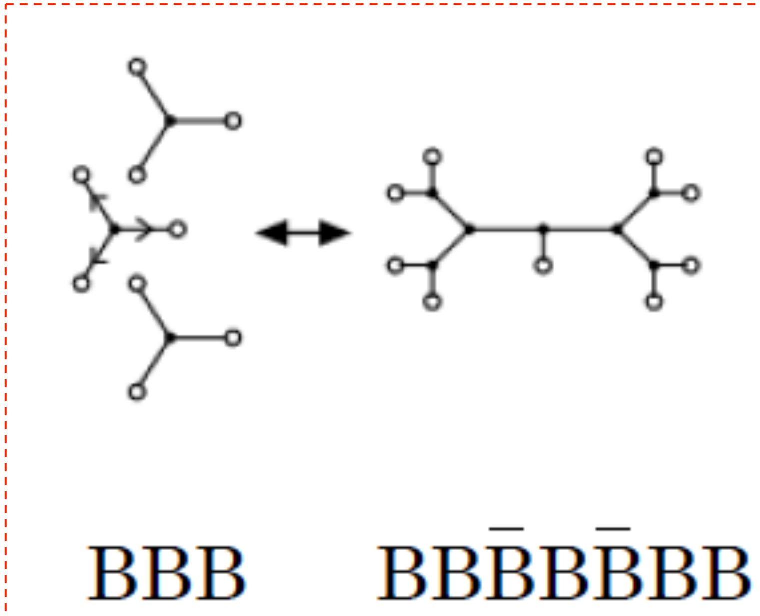
4. Effects of universal three-body repulsion with String Junction Model (Flavor-independent three-body repulsion)

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

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

B-B-B interactions





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

W_0 ~ 2 GeV

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

Effective 2-body potential

short-range correlation function

$$U_{\rm SJM}(r;\rho_{\rm B}) = \rho_{\rm B}\int d^3\mathbf{r}_3 W(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) f^2(\mathbf{r}_1-\mathbf{r}_3) f^2(\mathbf{r}_2-\mathbf{r}_3)$$

$$= \rho_{\rm B} W_0 \int d^3\mathbf{r}_3 f^2(\mathbf{r}_1-\mathbf{r}_3) g(\mathbf{r}_1-\mathbf{r}_3) f^2(\mathbf{r}_2-\mathbf{r}_3) g(\mathbf{r}_2-\mathbf{r}_3)$$

$$= \rho_{\rm B}\frac{W_0}{(2\pi)^3}\int d^3\mathbf{q}\, e^{-i\mathbf{q}\cdot\mathbf{r}}\int d^3\mathbf{q}_1 h(\mathbf{q}_1)G(\mathbf{q}_1)\int d^3\mathbf{q}_2 h(\mathbf{q}_2)G(\mathbf{q}_2)$$

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

$V = 95$ MeV・fm^3

$c = 0.024$

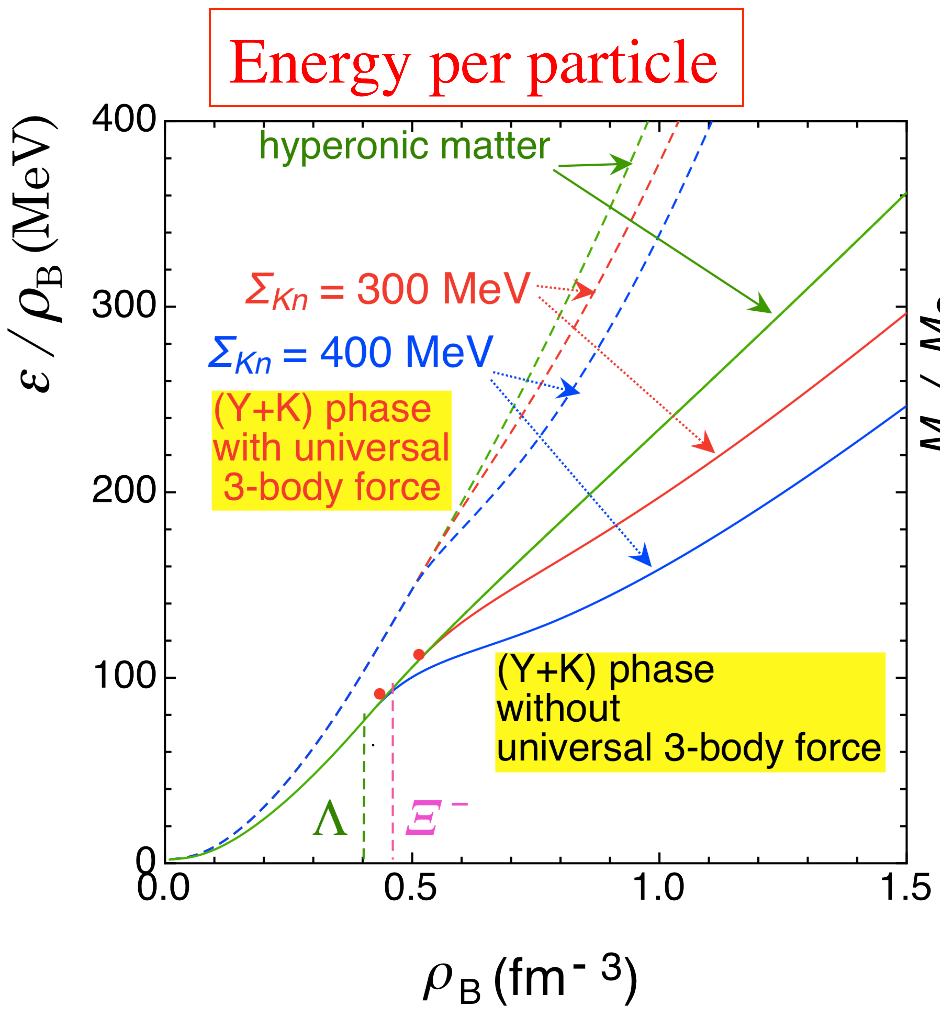
$\alpha = 1.35$ fm^{-2}

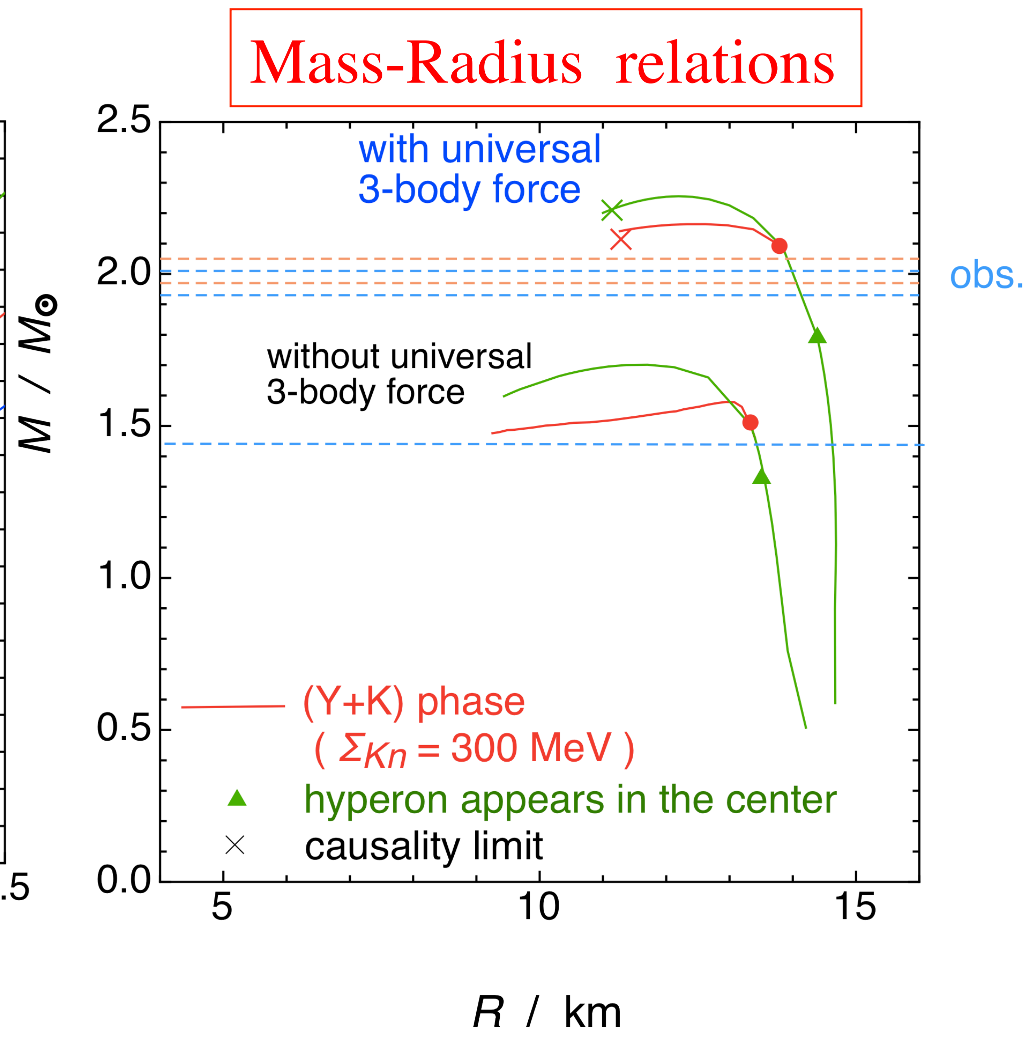
for SJM2

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

- 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





[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).]

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

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

5. Summary

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.

$M_{max} > 2M_\odot$

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

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 ($\rho_B \lesssim 2\rho_0$)

for Supernova explosions   Heavy-ion collisions

- Radius is too large ($\sim$14 km for $1.7M_\odot$)