【 YITP workshop "Nucleosynthesis and Evolution of Neutron Stars"
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Equation of state and neutrino emissivities with kaon condensates in hyperon-mixed matter

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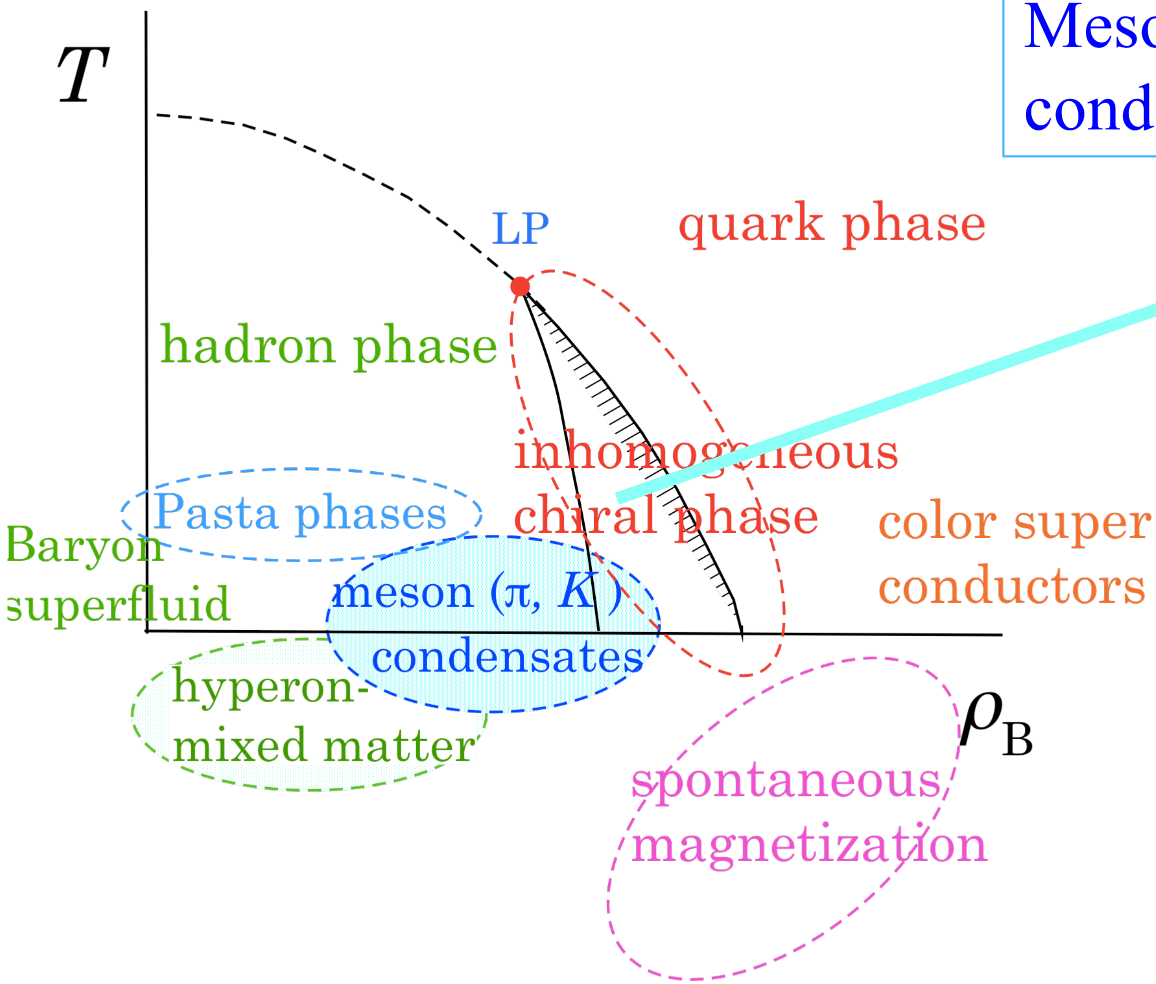
1. Introduction

1-1 Multi-strangeness in dense matter



Meson (Nambu-Goldstone boson) condensation

Kaon condensation (KC) in hyperon-mixed matter

(Y+K) phase

- Softening of EOS
→ meson-hadron dynamics
- Rapid cooling (ν emission)
→ weak reactions

Chiral symmetry

EOS with (Y+K) phase : Too softening problem
due to KC and hyperon-mixing (hyperon puzzle)
⇒ introduction of universal three-baryon repulsion (UTBR)

⇒ Consistent with observation of massive ($\sim 2M_\odot$) neutron stars

In this talk

- Overview of (Y+K) phase based on our interaction model

  bulk properties of compact stars with the (Y+K) phase

  M-R relation , M-$\rho_{B\ \mathrm{center}}$

- Emissivity for extra rapid cooling process

  (Kaon induced URCA)

  → Effects of KC on thermal evolution under the (Y+K)phase

  (cooling curve)

- Summary and Outlook

2. Formulation

2-1 model interaction

[T. Muto, T. Maruyama, and T. Tatsumi, Phys. Lett. B 820 (2021), 136587.
T. Muto, arXiv: 2411.09967v1 [nucl-th].]

K-Baryon and K-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.]

Classical Kaon field :

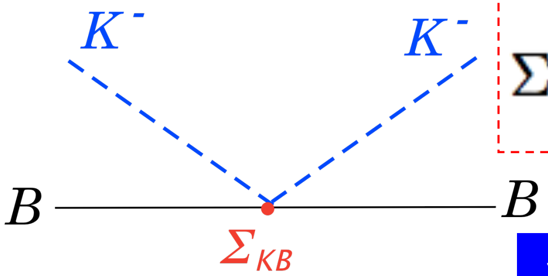
$$\langle K^- \rangle = \frac{f}{\sqrt{2}} \theta e^{-i\mu_K t}$$

θ : chiral angle

μ_K : kaon chemical potential

$f = 93$ MeV : meson decay const.

S wave KB interaction

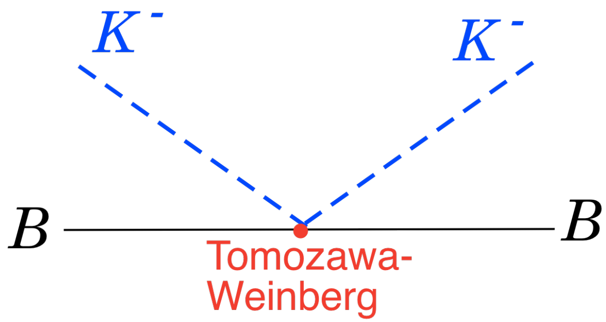


Scalar int.

$$\Sigma_{Kb} \equiv \frac{1}{2}(m_u + m_s)\langle b|(\bar{u}u + \bar{s}s)|b\rangle$$

We take

$\Sigma_{Kn} = (300 - 400)$ MeV



vector int.

Baryon-Baryon interaction

Minimal Relativistic Mean-Field theory

Meson-exchange (σ, ω, ρ …) → two-body force
(without nonlinear self-interactions)

Slope : $L \equiv 3\rho_0 \left(\frac{\partial S}{\partial \rho_B} \right)_{\rho_B=\rho_0}$

= (60 – 70) MeV

↓

controls Stiffness of EOS from two-body B-B int.

+ Three-Baryon (many-body) forces

Universal Three-Baryon Repulsion (UTBR)

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

: String-Junction Model 2

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

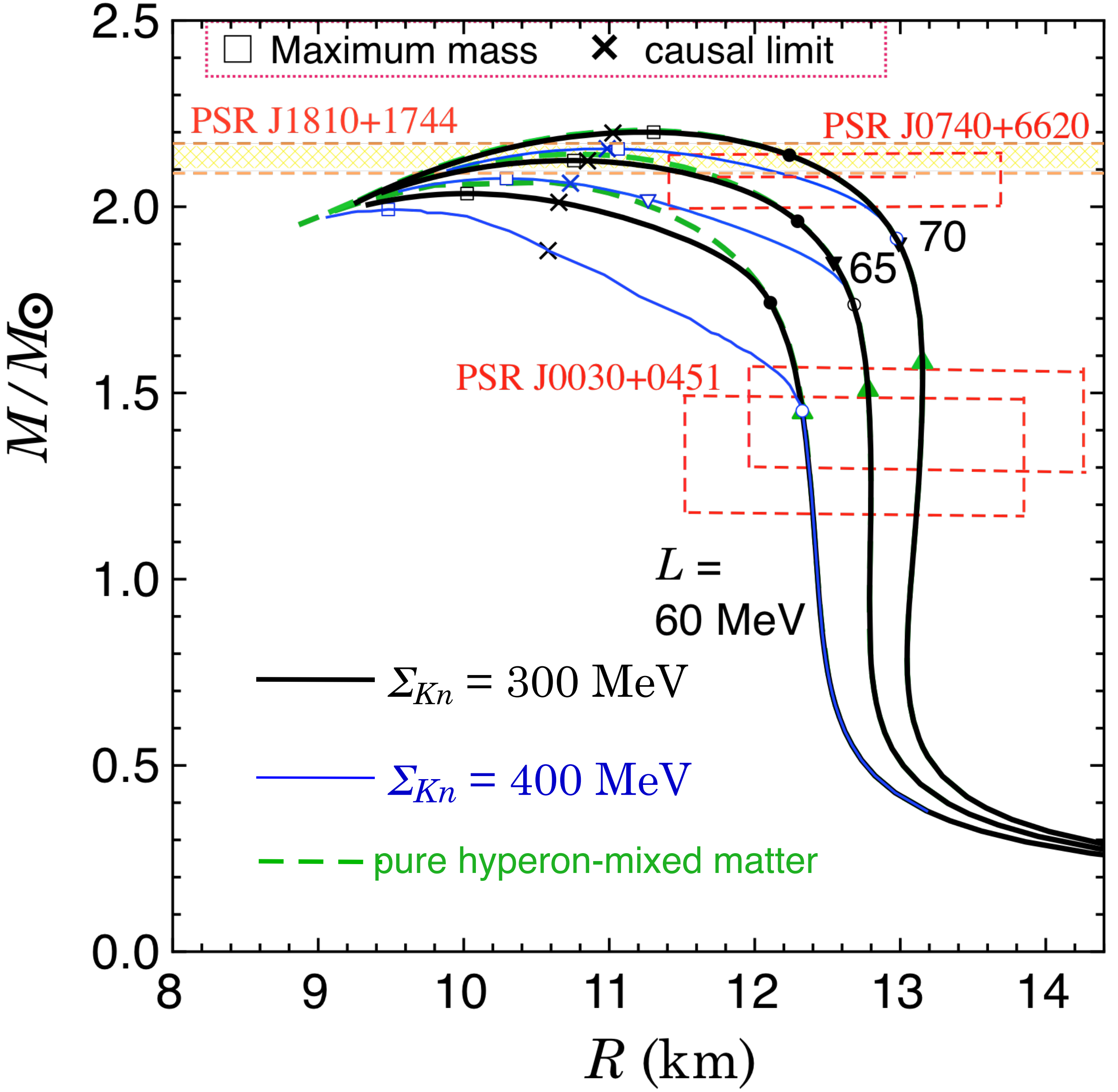
→ Density-dependent effective two-baryon force

+ Three-Nucleon attraction (TNA)

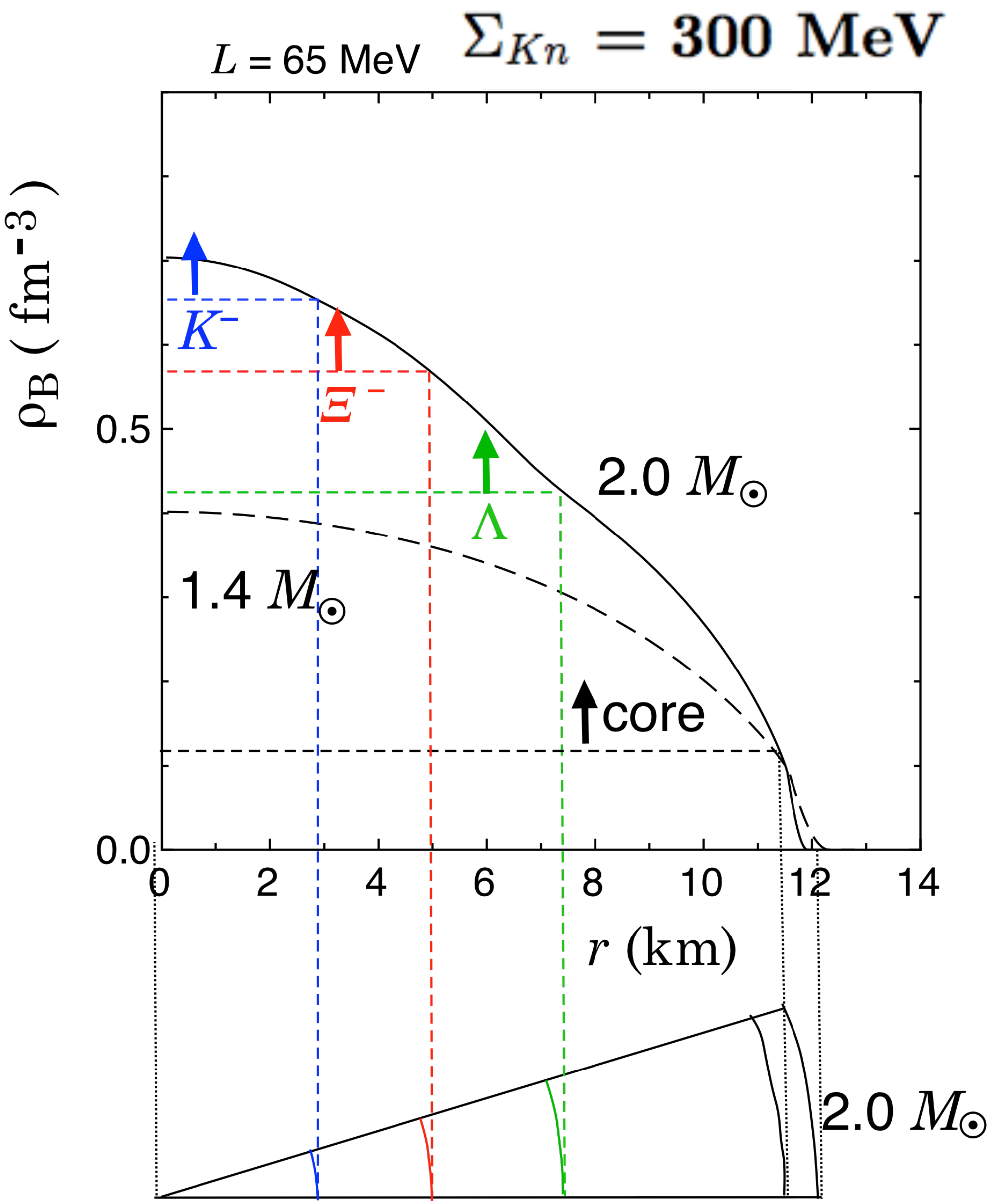
[c.f., I. E. Lagaris and V. R. Pandharipande, Nucl. Phys. A359(1981),349.]

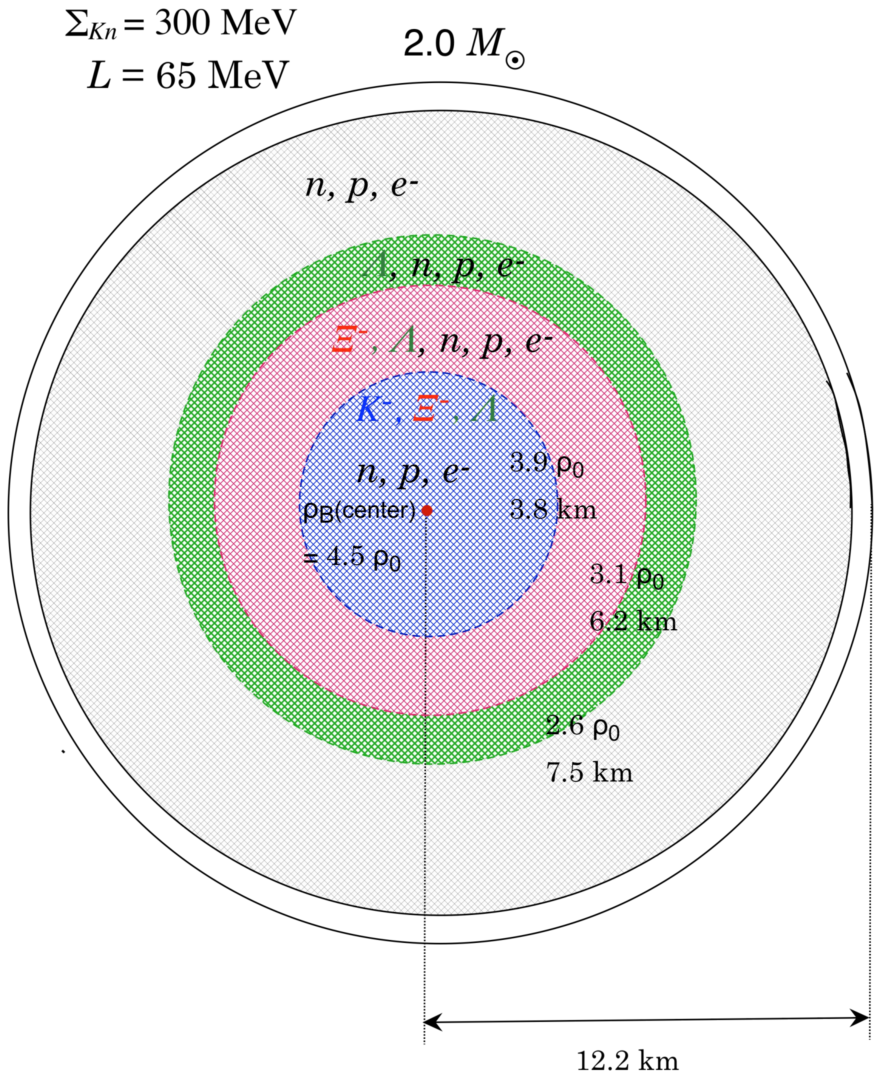
3. Bulk properties of compact stars with the (Y+K) phase

Gravitational Mass – radius R relations



Density distributions --- L = 65 MeV ---



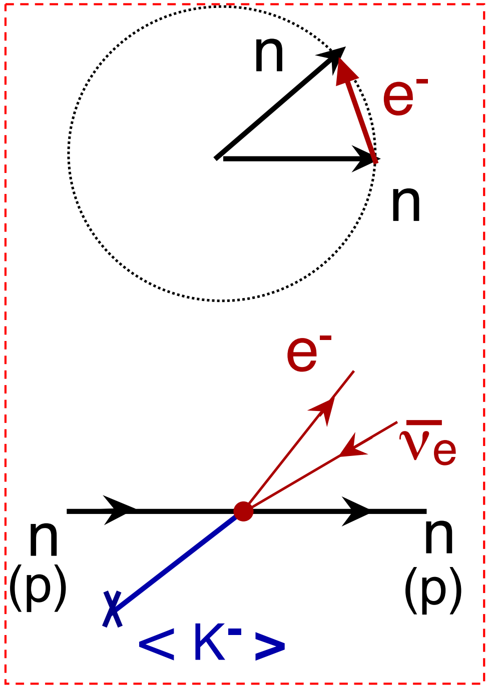


4. Unified description of EOS with (Y+K) phase and neutron-star cooling in the context of chiral symmetry

Rapid cooling mechanisms via neutrino emission

[T. Tatsumi, Prog. Theor. Phys. 80 (1988), 22.]

[H. Fujii, T. Muto, T. Tatsumi, R. Tamagaki,
Nucl. Phys. A578 (1994), 758; Phys. Rev. C 50 (1994), 3140.]



Kaon-induced Urca process (KU)

$$n \ (p) + \langle K^- \rangle \rightarrow n \ (p) + e^- + \bar{\nu}_e \ ,$$
$$n \ (p) + e^- \rightarrow n \ (p) + \langle K^- \rangle + \nu_e$$

Weak Hamiltonian $H_W = \frac{G_F}{\sqrt{2}} J_h^{\mu\dagger} l_\mu + \mathrm{h.c.}$

Hadron current $J_{\rm h}^\mu = \cos\theta_c (V_{1+i2}^\mu - A_{1+i2}^\mu) + \sin\theta_c (V_{4+i5}^\mu - A_{4+i5}^\mu)$

Chiral-transformed

$$\widetilde{J}_{\rm h}^\mu = \hat{U}_K^{-1} J_{\rm h}^\mu \hat{U}_K$$
$$= e^{-i\mu_K t}\Big[\cos\theta_c \Big\{ (V_{1+i2}^\mu - A_{1+i2}^\mu)\cos(\theta/2) + i(V_{6-i7}^\mu - A_{6-i7}^\mu)\sin(\theta/2) \Big\}$$
$$+ \sin\theta_c \Big\{ (V_4^\mu - A_4^\mu) + i\cos\theta (V_5^\mu - A_5^\mu) - \frac{i}{2}\sin\theta \Big(V_3^\mu - A_3^\mu + \sqrt{3}(V_8^\mu - A_8^\mu)\Big)\Big\}\Big]$$

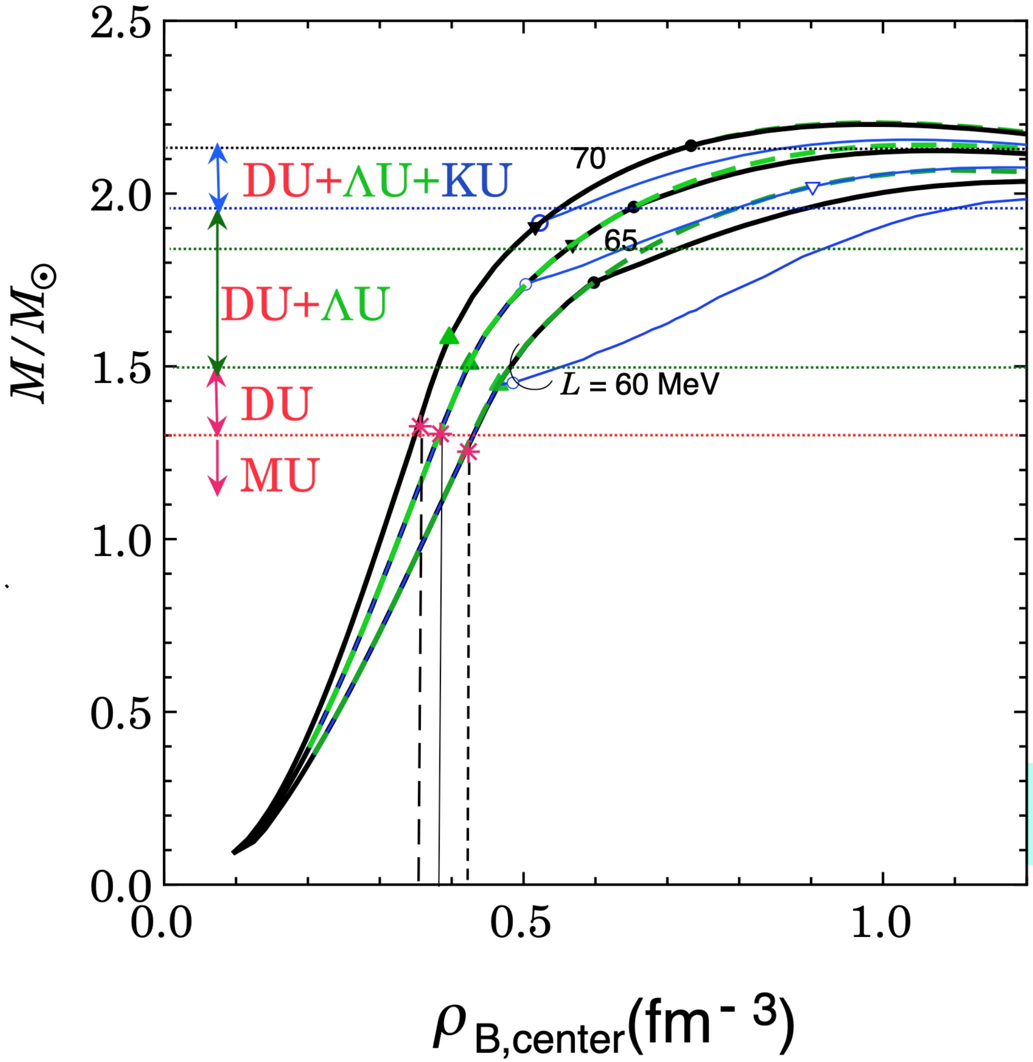
Emissivity for the (KU) process

$$\epsilon(\mathrm{KU}) = (4.1 \times 10^{25}) \left(\frac{m_N^*}{m_N}\right)^2 \frac{\mu_K}{m_\pi} \sin^2\theta T_9^6 \quad (\mathrm{erg}\cdot\mathrm{cm}^{-3}\cdot\mathrm{s}^{-1})$$

$$\begin{aligned} \epsilon(\mathrm{kaon-induced\ Urca})/\epsilon(\mathrm{modified\ Urca}) &= O(\mu_n/T)^2 \\ &\sim 10^{6-8} \end{aligned}$$

Gravitational Mass – baryon density at the center

e.g. $L = 65$ MeV, $\Sigma_{Kn} = 300$ MeV case



[Modified Urca process (MU)] $M \lesssim 1.3M_\odot$

$$n + n \to n + p + e^- + \bar{\nu}_e\ ,$$
$$n + p + e^- \to n + n + \nu_e$$

[Direct Urca process (DU)] $1.3M_\odot \lesssim M \lesssim 1.5M_\odot$

$$n \to p + e^- + \bar{\nu}_e\ ,$$
$$p + e^- \to n + \nu_e$$

[hyperon (Λ) Urca process (ΛU)] $1.5M_\odot \lesssim M \lesssim 1.96M_\odot$

$$\Lambda \to p + e^- + \bar{\nu}_e$$
$$p + e^- \to \Lambda + \nu_e$$

[hyperon (Ξ$^-$) Urca process (Ξ$^-$U)]

$$\Xi^- \to \Lambda + e^- + \bar{\nu}_e,$$
$$\Lambda + e^- \to \Xi^- + \nu_e$$

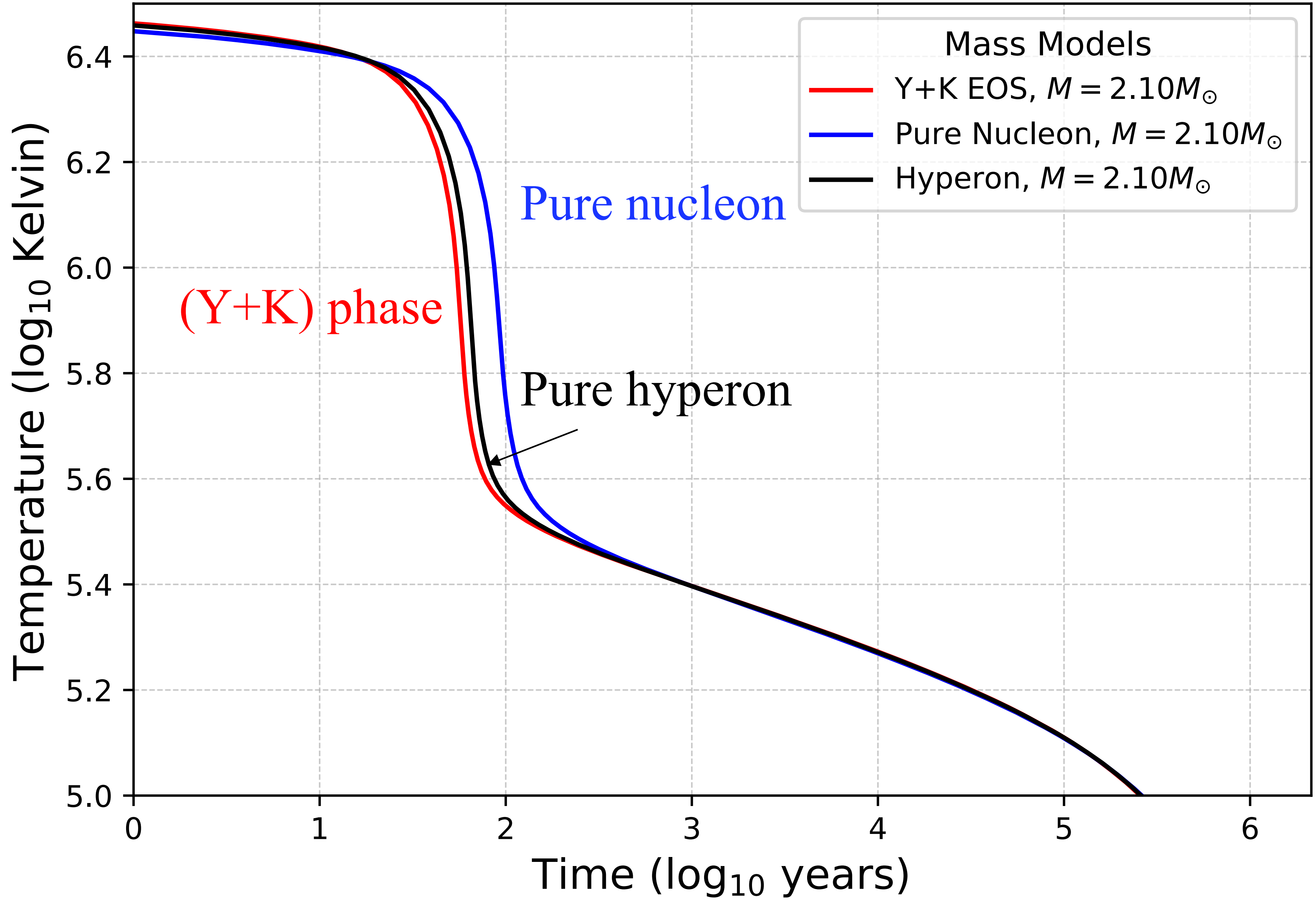
[Kaon-induced Urca process (KU)] $1.96M_\odot \lesssim M \lesssim M_{max}(= 2.12M_\odot)$

$$N + \langle K^- \rangle \to N + e^- + \bar{\nu}_e$$
$$N + e^- \to N + \langle K^- \rangle + \nu_e$$

Time evolution of surface temperature

[from Bhavnesh et al.2025]

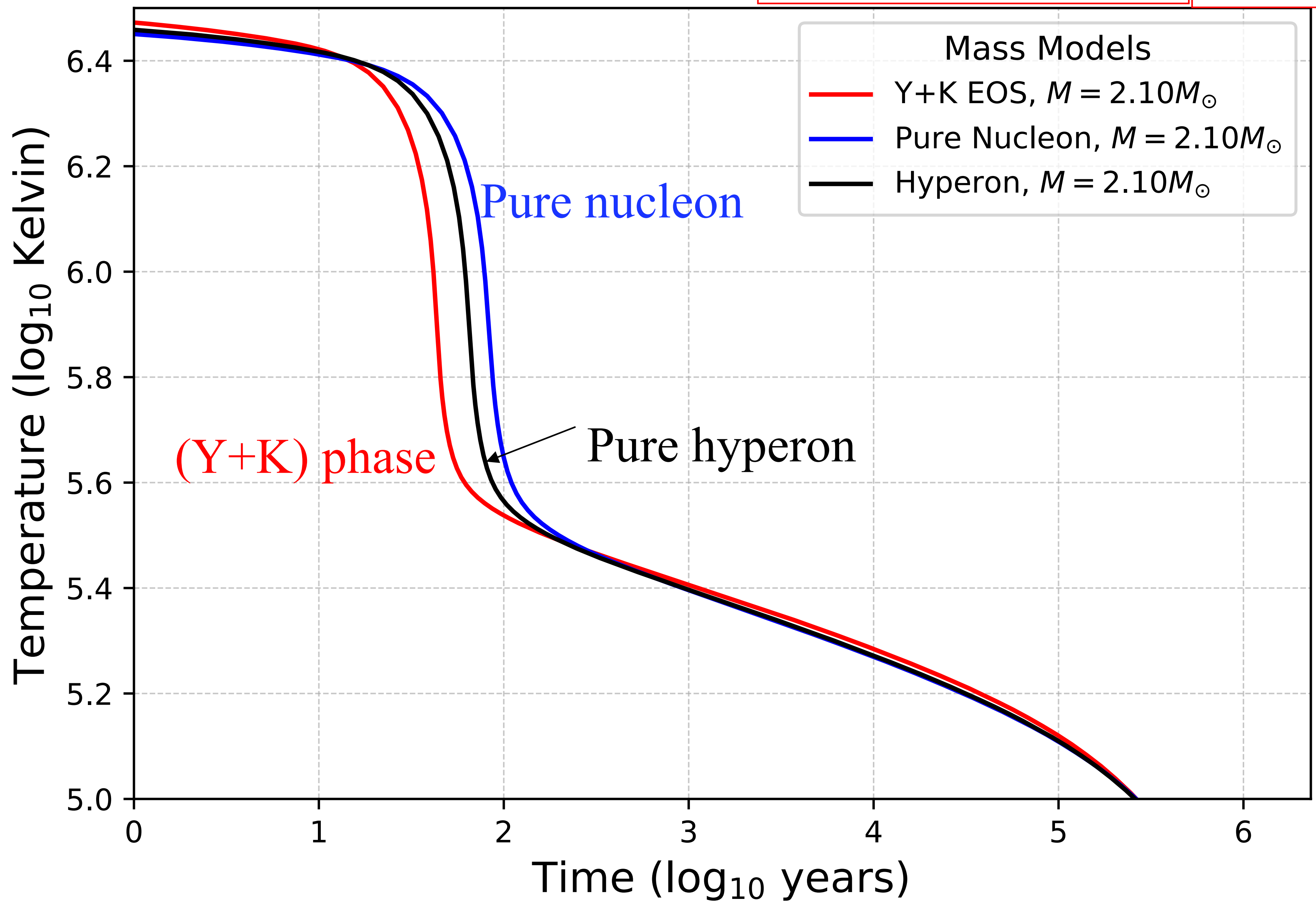
$M = 2.1 M_\odot$ *Y + K Model with* $\Sigma_{Kn} = 300$ MeV $L = 65$ MeV



Time evolution of surface temperature

[from Bhavnesh et al.2025]

$M = 2.1 M_\odot$ $Y + K$ *Model with* $\Sigma_{Kn} = 400$ MeV $L = 65$ MeV



5. Summary and outlook

・We have overviewed the (Y+K) phase based on our interaction model

bulk properties of compact stars with the (Y+K) phase

M-R relation , internal structure for matter composition

M-$\rho_{B\ center}$

Unified description on the basis of chiral symmetry

・We have overviewed emissivity for extra rapid cooling process

(Kaon induced URCA)

→ We have considered

Effects of KC on thermal evolution under the (Y+K)phase

(cooling curve)

5. Summary and outlook

"Kaon-induced n Λ Urca" process [nΛ-KU]

$$n + \langle K^- \rangle \rightarrow \Lambda + e^- + \bar{\nu}_e$$
$$\Lambda + e^- \rightarrow n + \langle K^- \rangle + \nu_e$$

$$\propto \cos^2\theta_C \sin^2(\theta/2)$$

・Proton-rich, electron-less

→How do these features affect
the cooling mechanisms in kaon condensates ?

Effects of thermal conductivity, baryon superfluidity in the (Y+K) phase on the cooling history of neutron stars

in progress with A. Dohi, T. Noda,
and B.Bhavnesh

Thank you
for your attention !