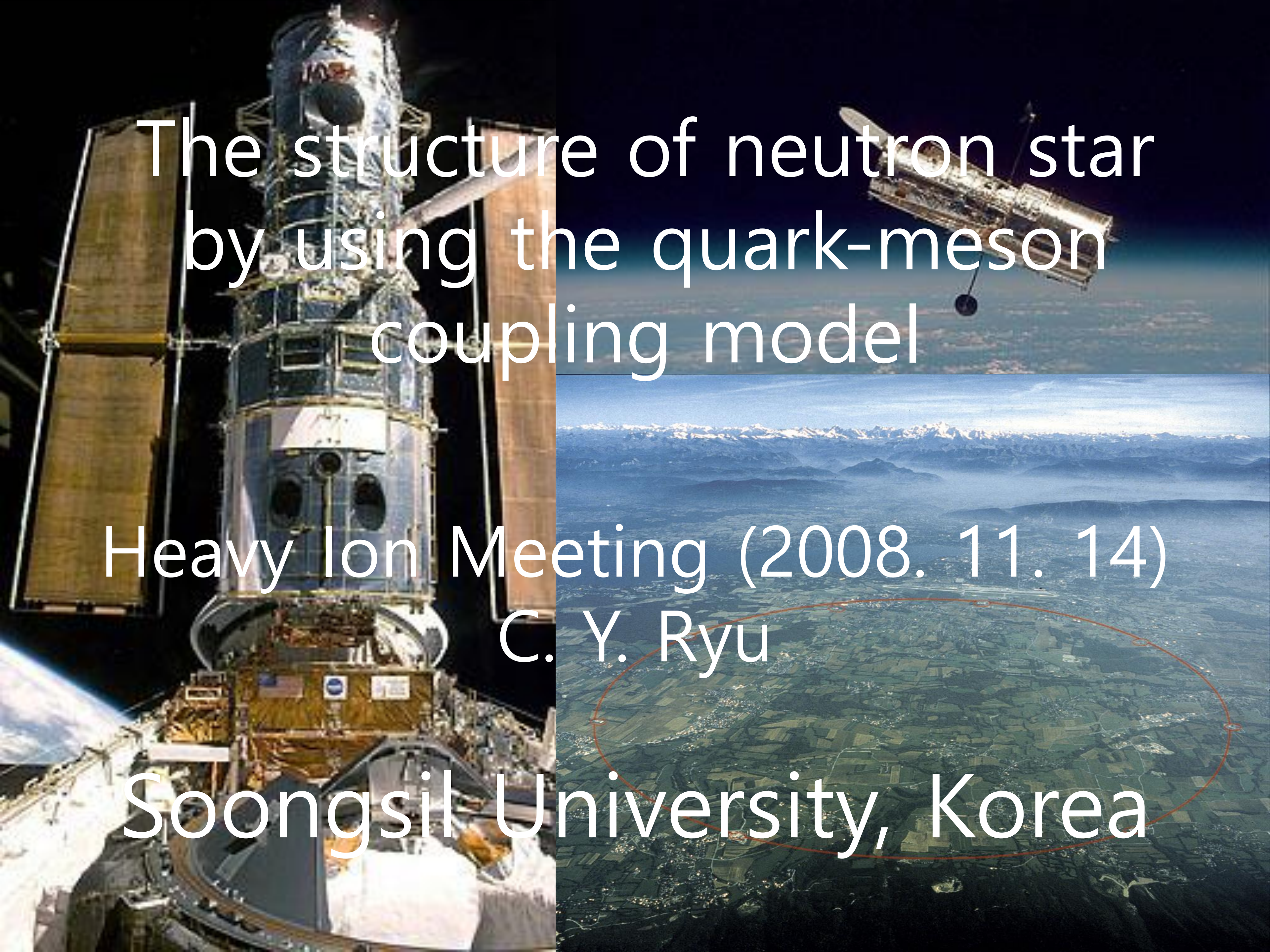


The structure of neutron star by using the quark-meson coupling model

Heavy Ion Meeting (2008. 11. 14)

C. Y. Ryu

Soongsil University, Korea

Outline

1. Introduction and motivation
   - Structure of neutron star
   - Mass and radius relation
   - The observed masses of neutrons star
   - Motivation

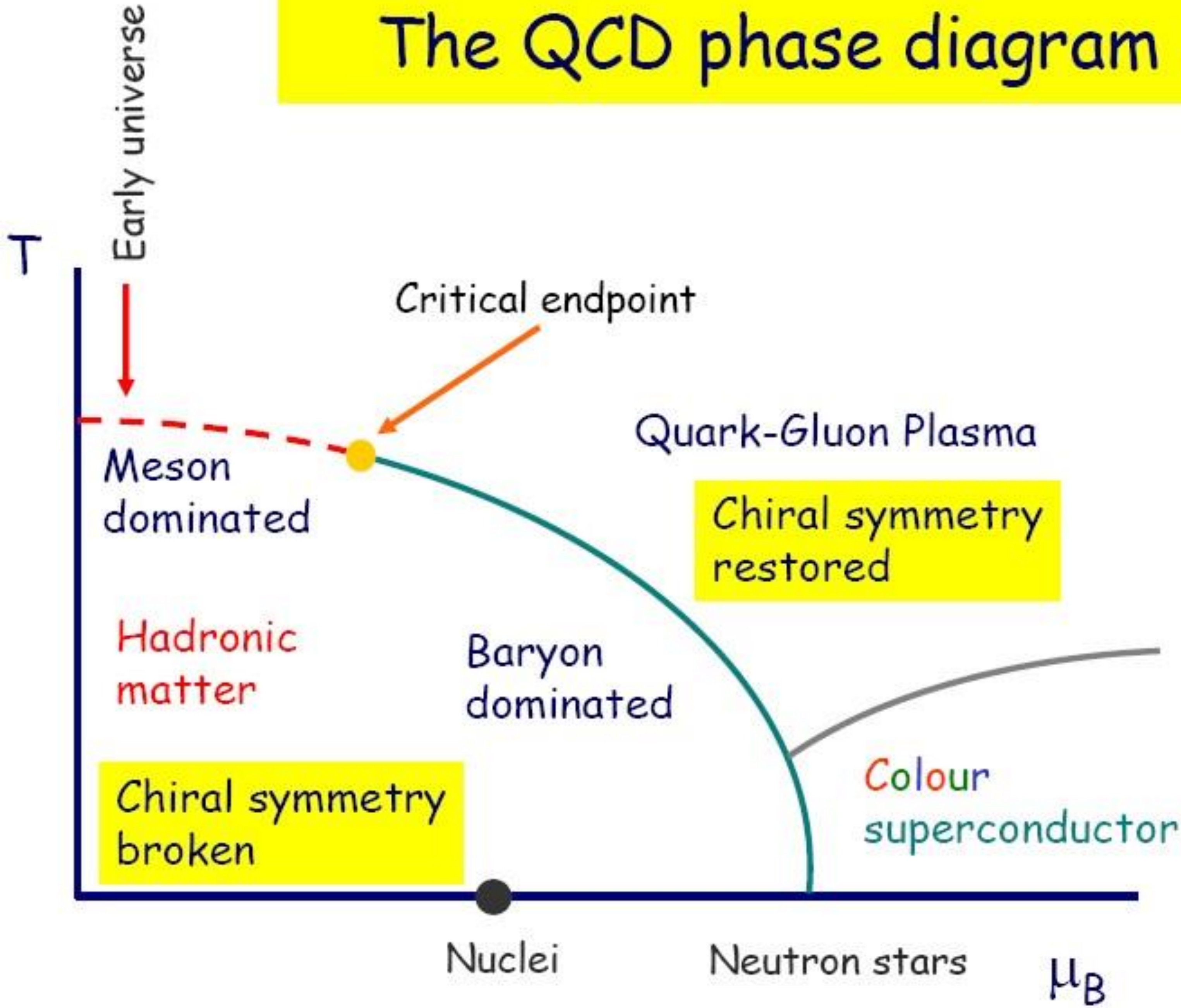
2. Theory
   - Quark-meson coupling model (dense matter)
   - Exotic phases
     : hyperons, kaon condensation
   - Finite temperature

3. Results

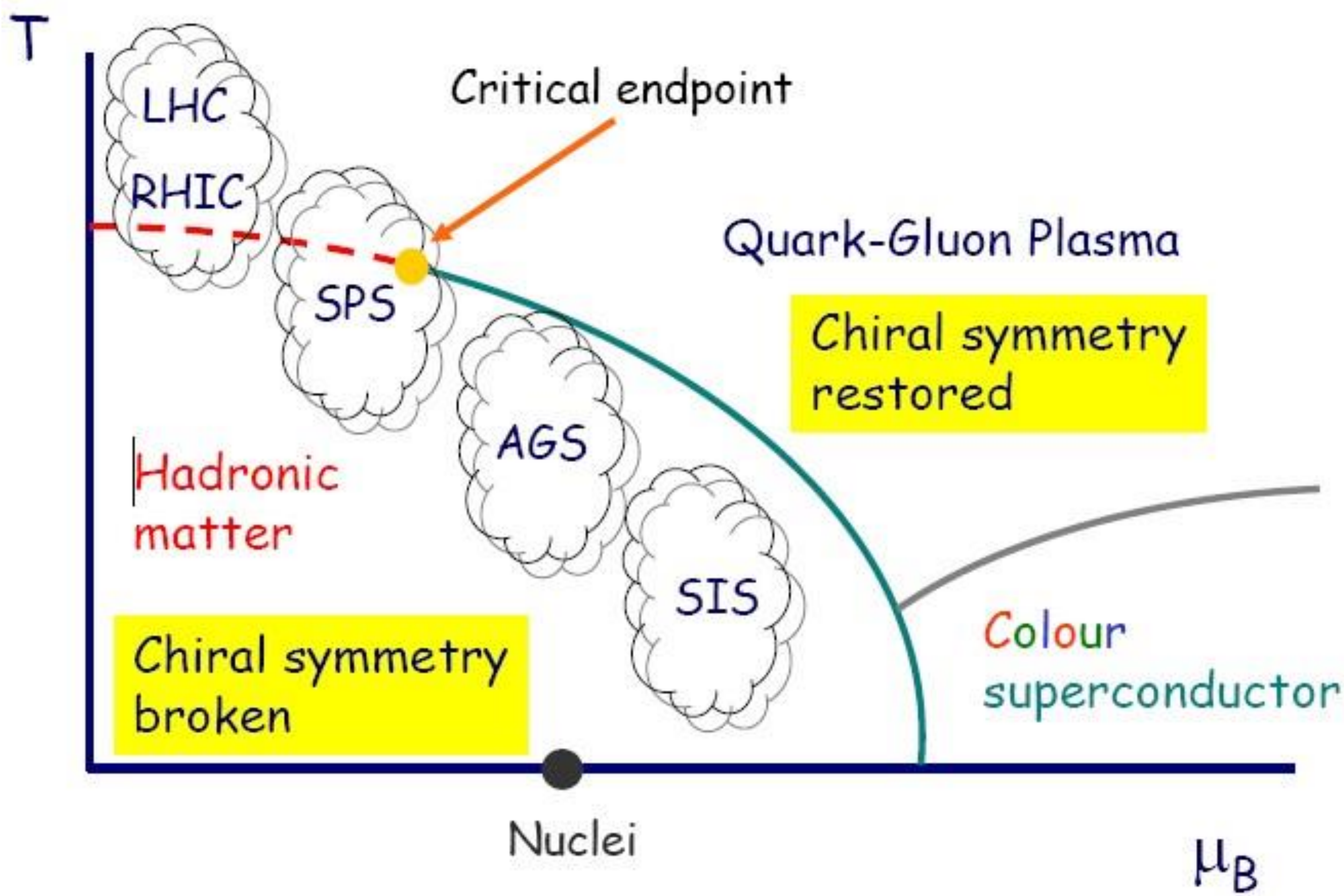
4. Summary

1.Introduction and motivation

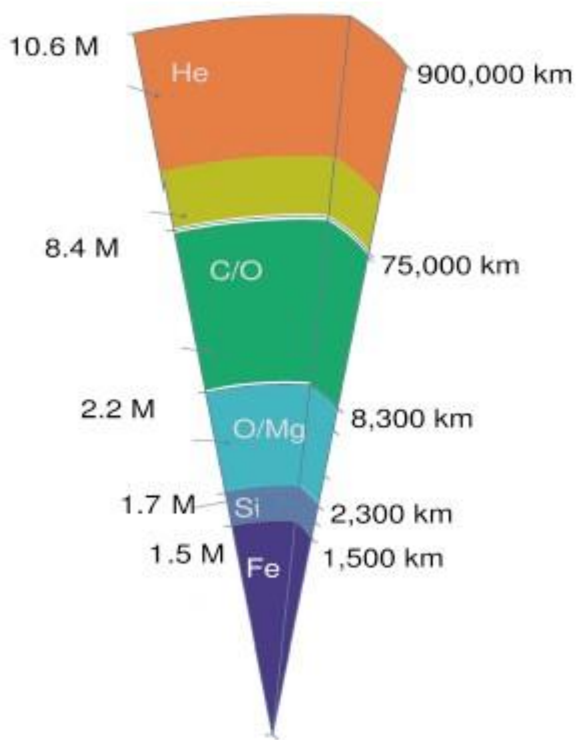
The QCD phase diagram



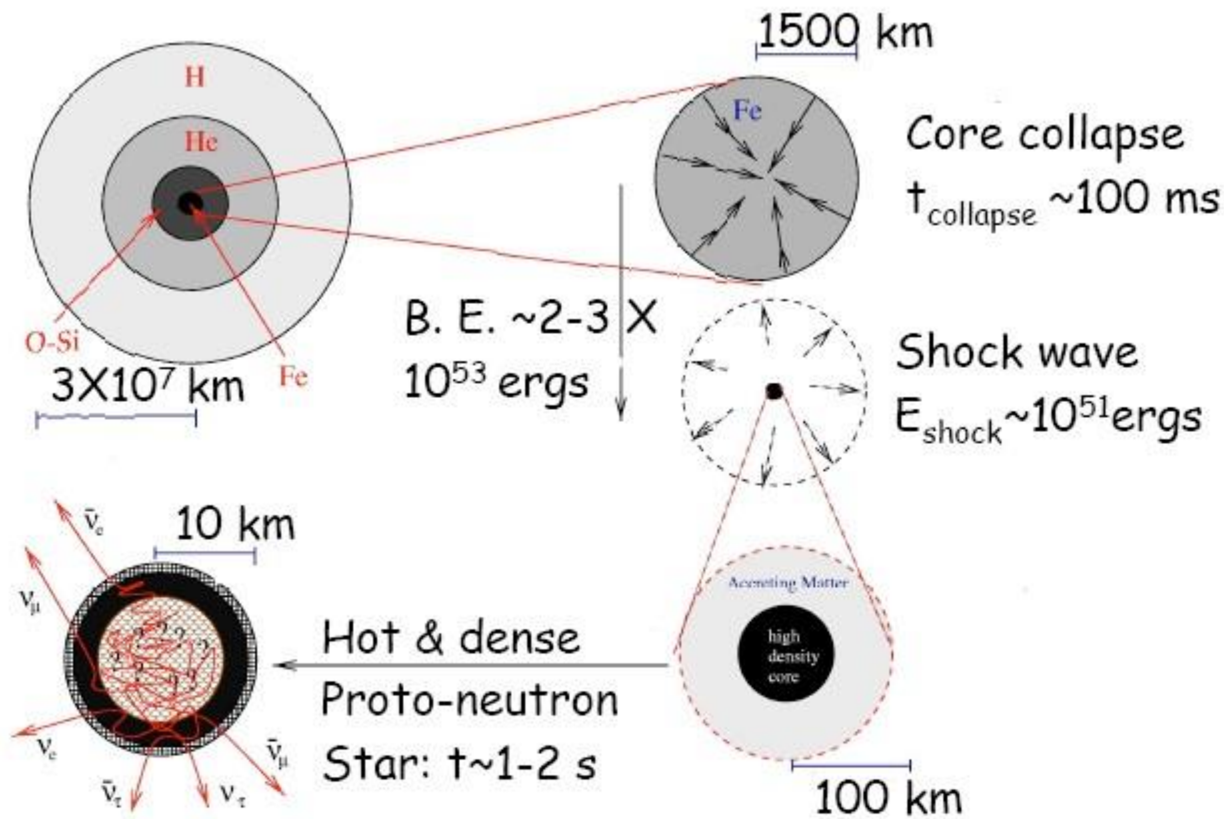
Hot and dense matter I
- Heavy ion collision



Hot and dense matter II
- Proto-neutron star

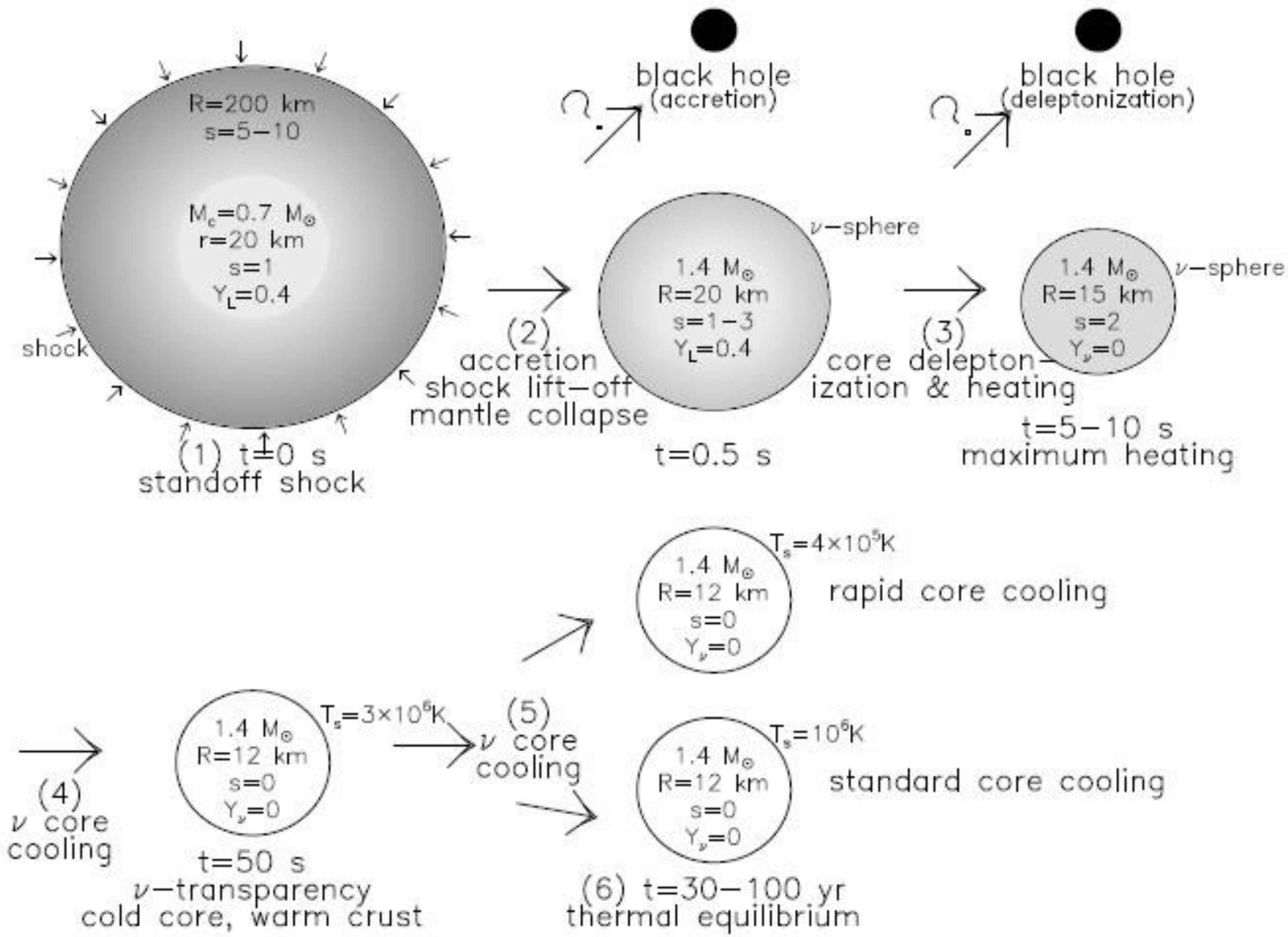


The structure of supernovae

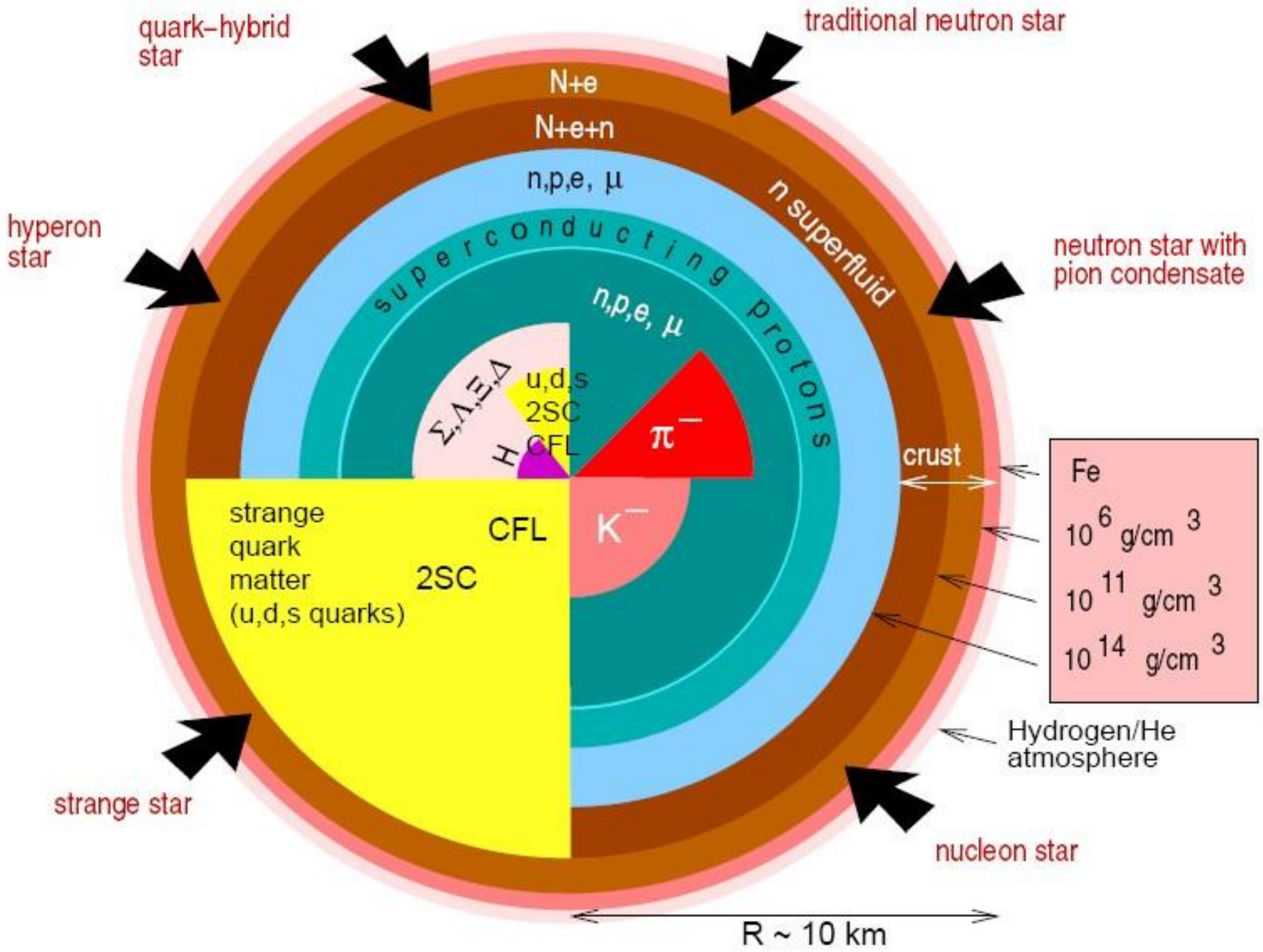


The production of proto-neutron star

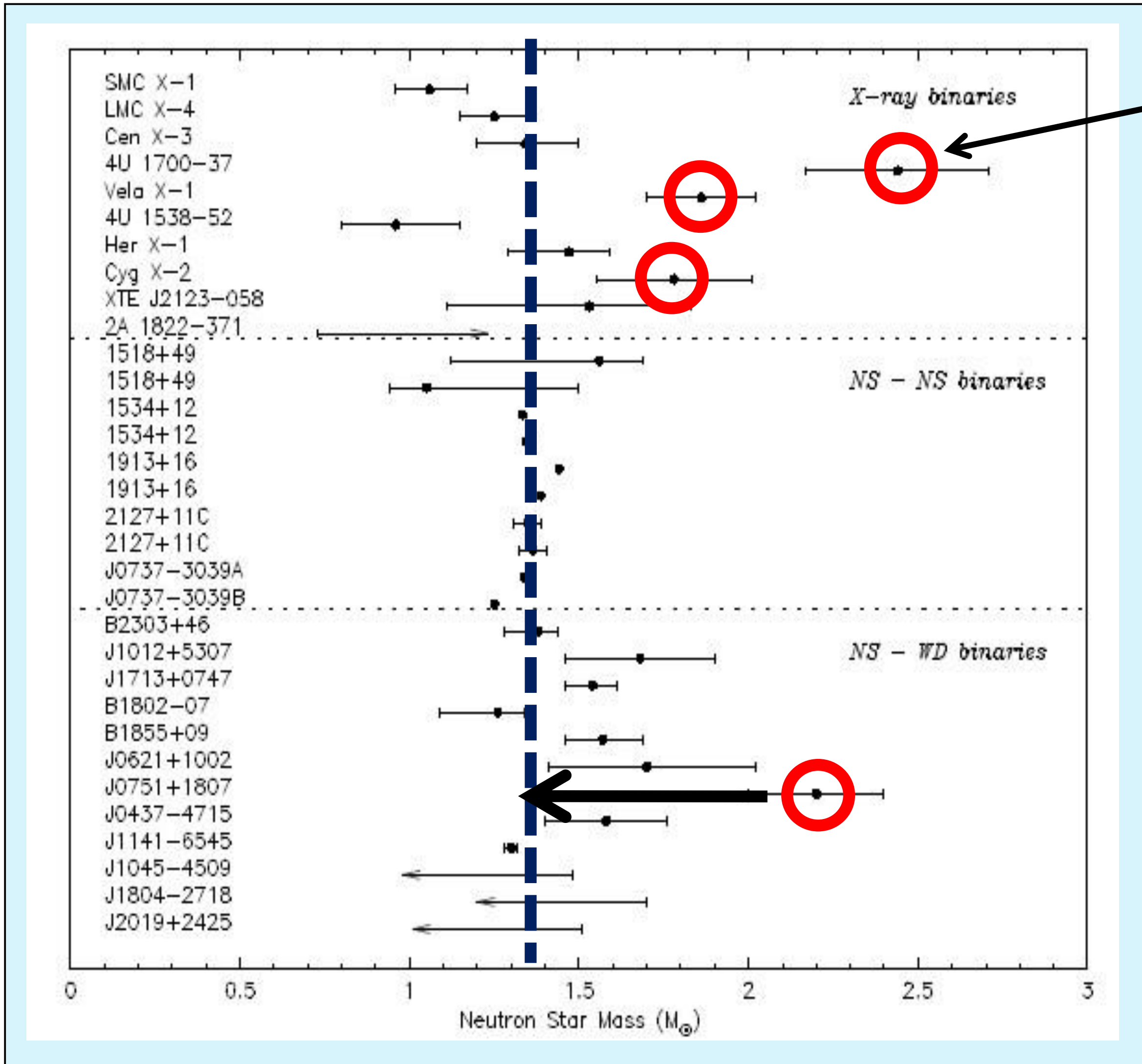
The production of neutron star



The structure of neutron star



The observed masses



Maybe, blackhole

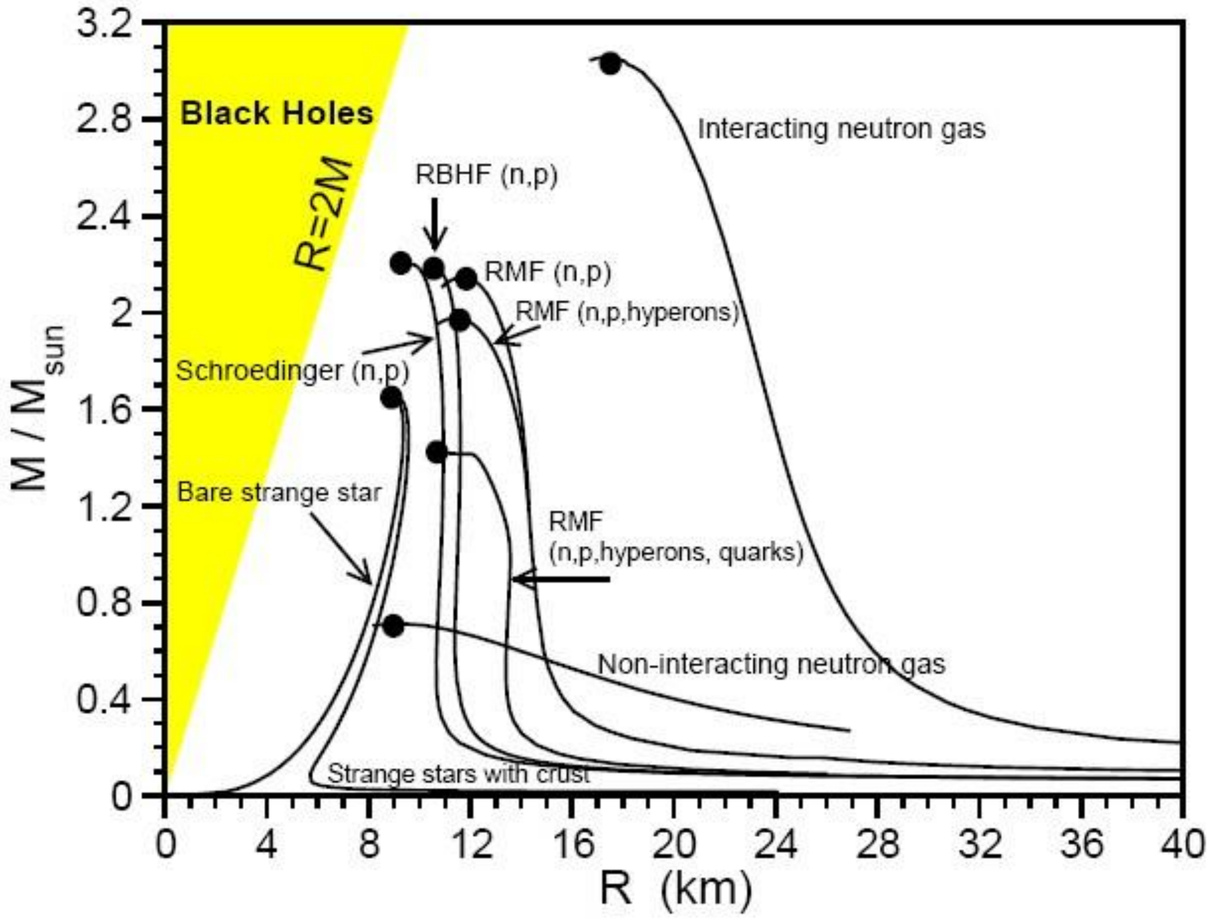
A. Van der Meer ***et al.***,

astro-ph:0707.280201(2007)

1) Best fit : 1.35 $M_\odot$

2) Recent observations : large masses

Motivation I

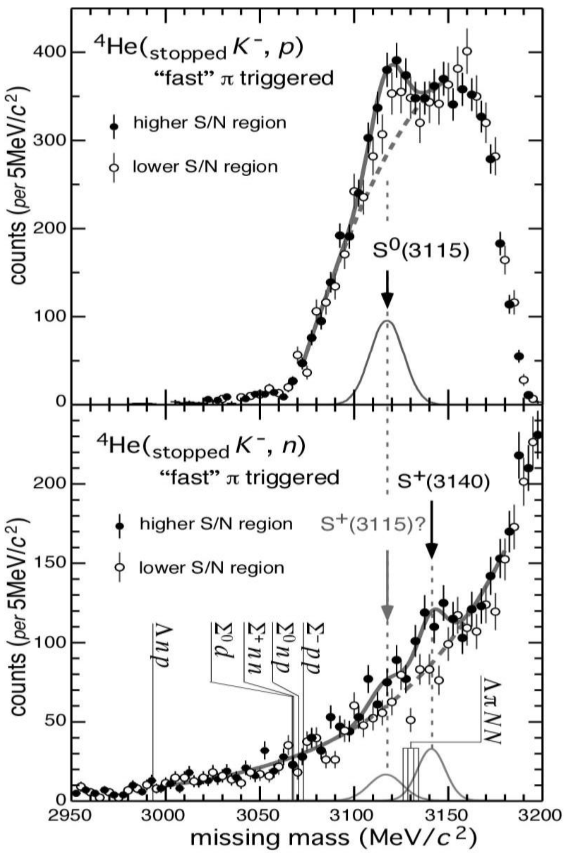


1) No strangeness : 2-3 M⊙

2) Strangeness : 1-2 M⊙
   - hyperons(Λ, Σ, Ξ)
   - kaon condensation
   - quark matter(u, d, s)

Motivation II

– Deeply bound kaonic nuclear states



KEK PS-E471 (2004)

Ramos & E. Oset, Nucl. Phys. A671 (2000)
V. K. Magas, E.Oset, A.Ramos, H.Toki, nucl-th/0611098
Chirally-motivated potentials

Shallow optical potential $V_0 \approx -50$ MeV

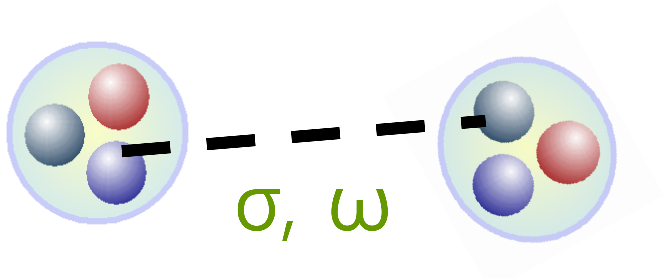
Deep optical potential $V_0 \approx -120$ MeV

Y. Akaishi & T. Yamazaki, PRC65 (2002)
N. Kaiser, P.B. Siegel & W. Weise, NPA594 (1995)
J. Mares, E.Friedman and A. Gal,Nucl.Phys.A770 (2006)

Motivation III

- Model dependency
  - Haron degree of freedom :
    Quantum Hadrodynamics (QHD)

  - Quark degree of freedom :
    Quark-meson coupling model (QMC) model

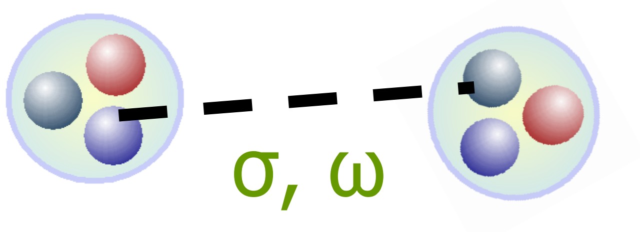


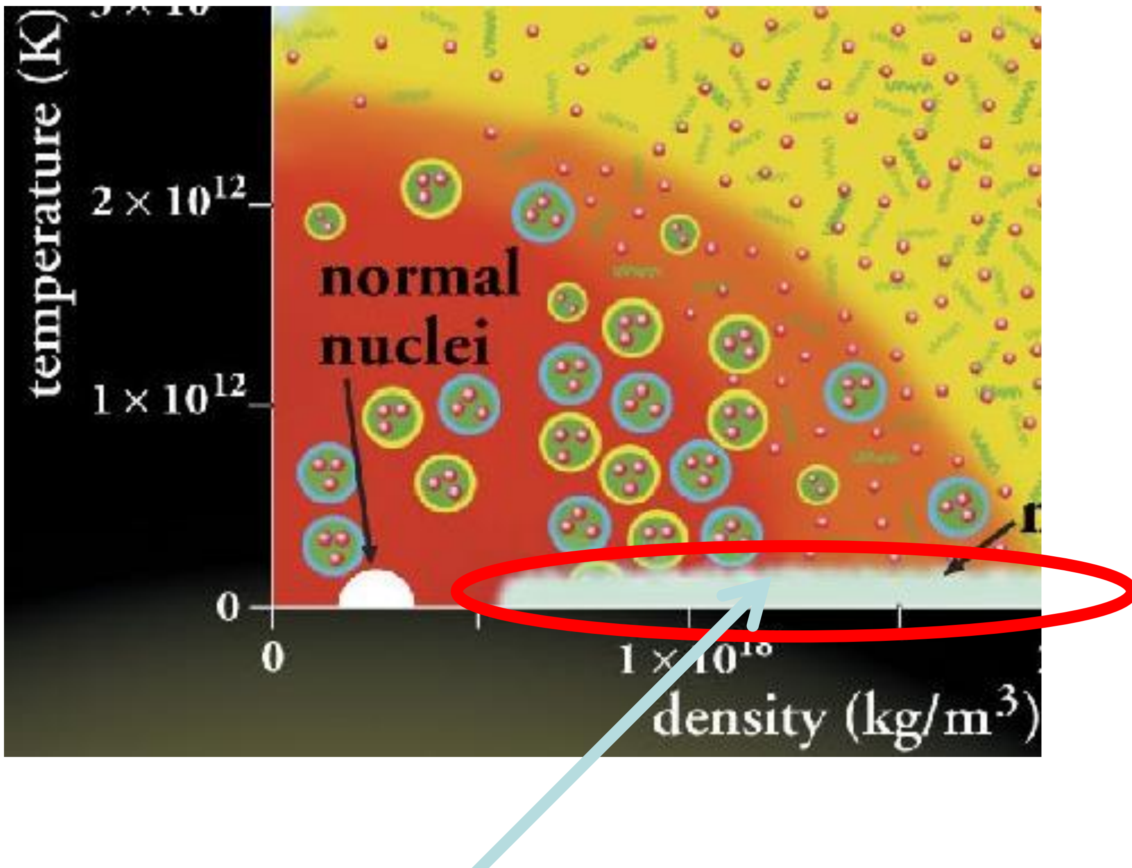
2. Theory

Quark-meson coupling model - MIT bag + mean fields

Quark-meson coupling (QMC) model

MIT bag + σ, ω mesons





Neutron star

The QMC model at saturation

1) Infinite, static and uniform matter

2) The properties of nuclear matter

- **Saturation density** ρ_0 **= 0.17 fm^{-3}**
- **Binding energy** $B/A = \varepsilon/\rho - m_N$ **= 16 MeV**
- **Effective mass of a nucleon** m_N^*/m_N **= 0.7 - 0.8 (0.78)**
- **Compression modulus** K^{-1} **= 200 - 300 MeV**
- **Symmetric energy** a_{sym} **= 32.5 MeV**

3) **The Lagrangian of QMC model for infinite nuclear matter**

$$\mathcal{L} = \bar{\psi}_N[i\gamma_\mu\partial^\mu - g_\omega\gamma_0\omega^0) - m_N^*(\sigma)]\psi_N - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega^0\omega_0$$

QMC model for hyperonic matter

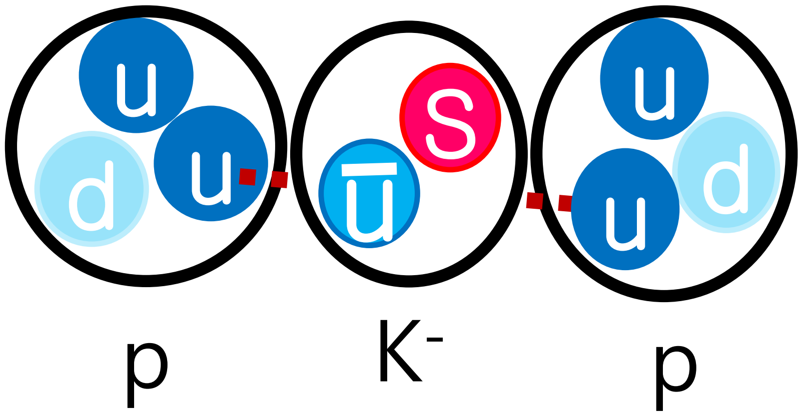
Lagrangian density for baryon octet and leptons

$$L = \sum_B \bar{\psi}_B[i\gamma\cdot\partial - m_B^*(\sigma,\sigma^*) - \gamma^0(g_{\omega B}\omega_0 + g_{\phi B}\phi_0 + \frac{1}{2}g_{\rho B}\tau_z\rho_{03})]\psi_B$$
$$+\frac{1}{2}(m_\sigma^2\sigma^2 + m_{\sigma^*}^2\sigma^{*2} + m_\omega^2\omega_0^2 + m_\phi^2\phi_0^2 + m_\rho^2\rho_{03}^2)$$
$$+\sum_l \bar{\psi}_l(i\gamma\cdot\partial - m_l)\psi_l$$

σ–ω–ρ(only u(d) quark)
\+ σ*(980) –φ(1050) (only s quark)

Baryon octet : p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-, ***lepton :* e,** μ

Naive picture of K^- potential



1) OZI rule : s-quark does not interact with u and d quarks

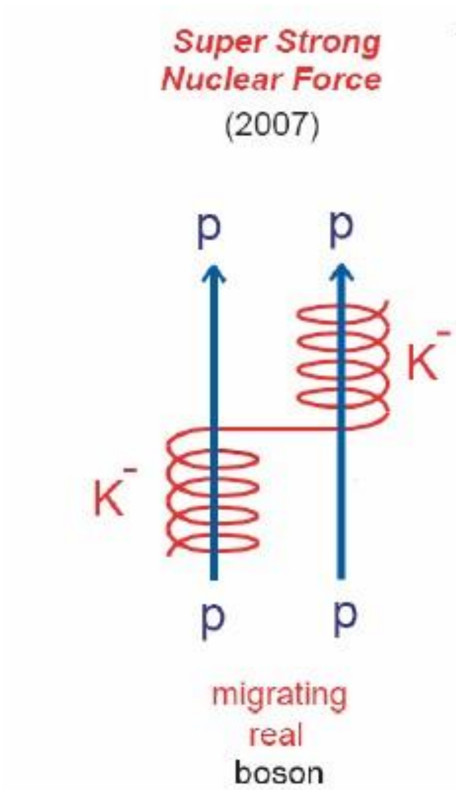
2) Antiparticle may feel very strong attraction.

$$[\gamma^\mu(i\partial_\mu - g_\omega \omega_\mu) - (M - g_\sigma \sigma)]\psi = 0$$

3) Potential of particle
   Scalar (attractive)+ Vector (repulsive)

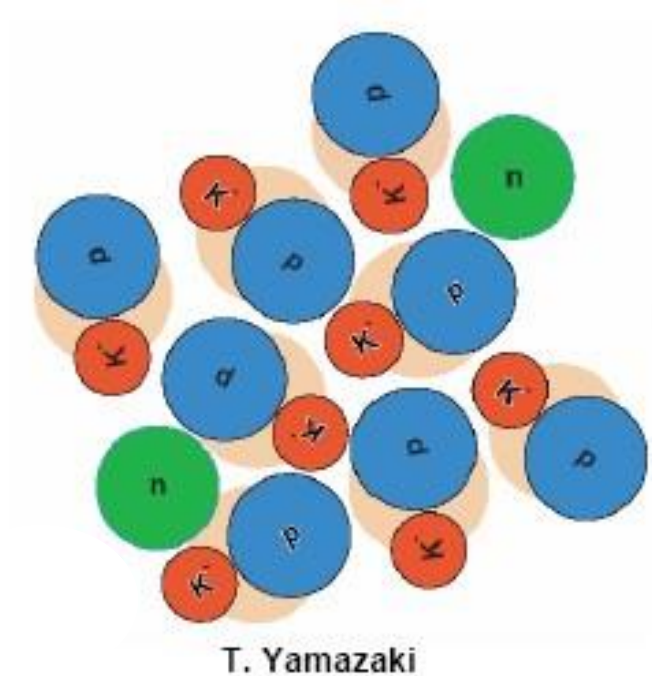
4) Potential of antiparticle – strong attraction
   Scalar (attractive)+ Vector (attractive)

Strong force of K^- N and kaon condensation



T. Yamazaki & Y. Akaishi,
Proc. Japan Academy B 83 (2007) 144

K^- pp system



Kaon condensation in medium

The RMF for kaon and antikaon

Lagrangian density for baryon octet and leptons

$$L = \sum_B \bar{\psi}_B[i\gamma\cdot\partial - m_B^*(\sigma,\sigma^*) - \gamma^0(g_{\omega B}\omega_0 + g_{\phi B}\phi_0 + \frac{1}{2}g_{\rho B}\tau_z\rho_{03})]\psi_B$$
$$+\frac{1}{2}(m_\sigma^2\sigma^2 + m_{\sigma^*}^2\sigma^{*2} + m_\omega^2\omega_0^2 + m_\phi^2\phi_0^2 + m_\rho^2\rho_{03}^2)$$
$$+\sum_l \bar{\psi}_l(i\gamma\cdot\partial - m_l)\psi_l$$

Langrangian density for kaon

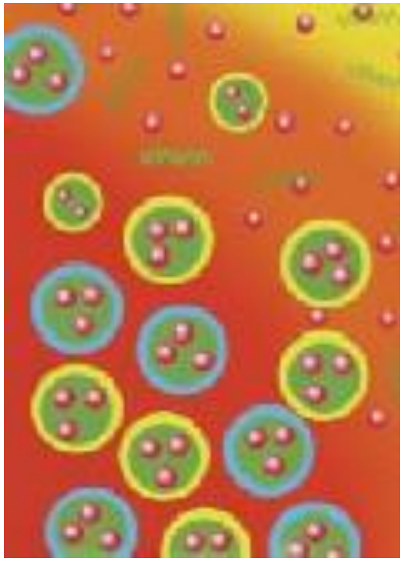
$$L_K = D_\mu^* K^* D^\mu K - {m_K^*}^2 K^* K$$

$$D_\mu = \partial_\mu + i g_{\omega K}\omega_\mu - i g_{\phi K}\phi_\mu + i g_{\rho K}\boldsymbol{\tau}\cdot\rho_\mu$$

$$m_K^* = m_K - g_{\sigma K}\sigma - g_{\sigma^* K}\sigma^*$$

The potential of K^- : U_{K-} = - gσ – g ω_0

The QMC model at finite temperature



1. Thermodynamic grand potential :

$$\Omega = \varepsilon - TS - \mu\rho$$

2. Pressure is

$$P = \frac{1}{3}\frac{\gamma}{(2\pi)^3}\int d^3k \frac{k^2}{\sqrt{k^2 + {M_N^*}^2}}(f_B + \bar{f}_B) + \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{2}m_\sigma^2\sigma^2$$

Where

$$f_B = \frac{1}{e^{(\epsilon^* - \mu_B^*)/T} + 1} \qquad \bar{f}_B = \frac{1}{e^{(\epsilon^* + \mu_B^*)/T} + 1}$$

3. The condition for equilibrium – **minimize Ω** or **maximize P.**

$$\frac{\partial P}{\partial \sigma} = \left(\frac{\partial P}{\partial M_N^*}\right)_{\mu_B, T}\frac{\partial M_N^*}{\partial \sigma} + \left(\frac{\partial P}{\partial \sigma}\right)_{M_N^*} = 0.$$

TOV equation

- Macroscopic part – General relativity
  - Einstein field equation : $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = - 8\pi G T_{\mu\nu}$$

Static and spherical symmetric neutron star (Schwarzschild metric)

Static perfect fluid
Diag $T_{\mu\nu}$ = (ε, p, p, p)

  - TOV equation : $$\frac{dP}{dr} = -\frac{G}{r} \frac{[\epsilon + P][M + 4\pi r^3 P]}{(r - 2GM)}$$

- Microsopic part – QMC model
  - equation of state (pressure, energy density)

The conditions in neutron star

1) Baryon number conservation : $$\rho_{tot} = \sum_B \rho_B$$

2) Charge neutrality : $$q_{tot} = \sum_B q_B \rho_B + \sum_l q_l \rho_l$$

3) chemical equilibrium (Λ, Σ, Ξ)

$$\mu_{\Sigma^-} = \mu_{\Xi^-} = \mu_n + \mu_e \qquad \mu_\Lambda = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_n$$

$$\mu_n = \mu_p + \mu_e \qquad \mu_p = \mu_{\Sigma^+}$$

※ The condition for K^- condensation

$$\mu_K = \mu_e$$

Eq. of state in kaon+hyperonic matter

The energy density :

$$\begin{aligned}\epsilon \;=\; & \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\phi^2\phi_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 \\ & + \sum_B \frac{2J_B+1}{2\pi^2}\int_0^{k_B}[k^2 + m_B^{*\,2}]^{1/2}k^2 dk + \sum_l \frac{1}{\pi^2}\int_0^{k_l}[k^2 + m_l^2]^{1/2}k^2 dk \\ & + m_K^* n_K\end{aligned}$$

The pressure :

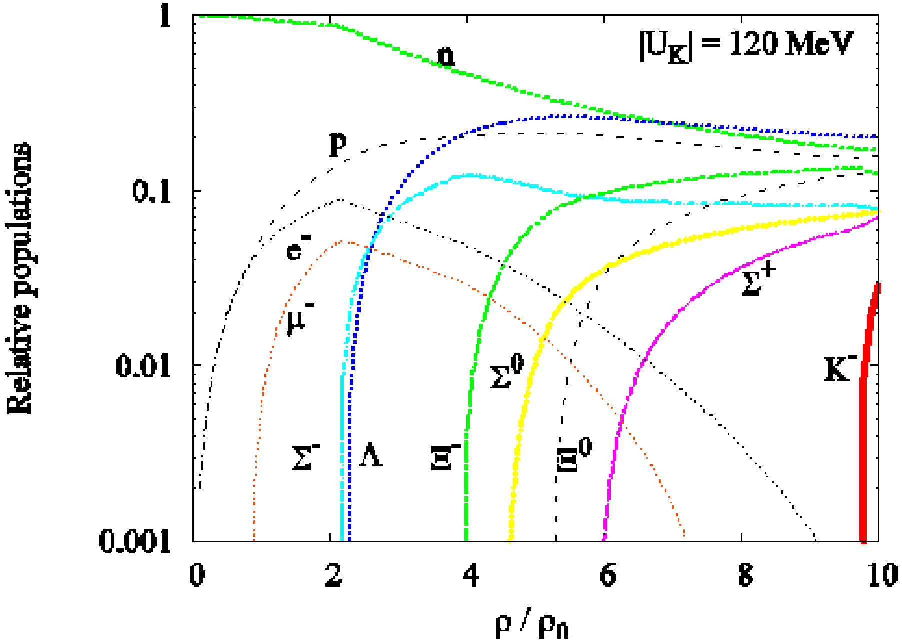
$$\begin{aligned}P \;=\; & -\frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\phi^2\phi_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 \\ & + \frac{1}{3}\sum_B \frac{2J_B+1}{2\pi^2}\int_0^{k_B}\frac{k^4 dk}{[k^2 + m_B^{*\,2}]^{1/2}} + \frac{1}{3}\sum_l \frac{1}{\pi^2}\int_0^{k_l}\frac{k^4 dk}{[k^2 + m_l^2]^{1/2}}\end{aligned}$$

3. Results

The population of particles in neutron star

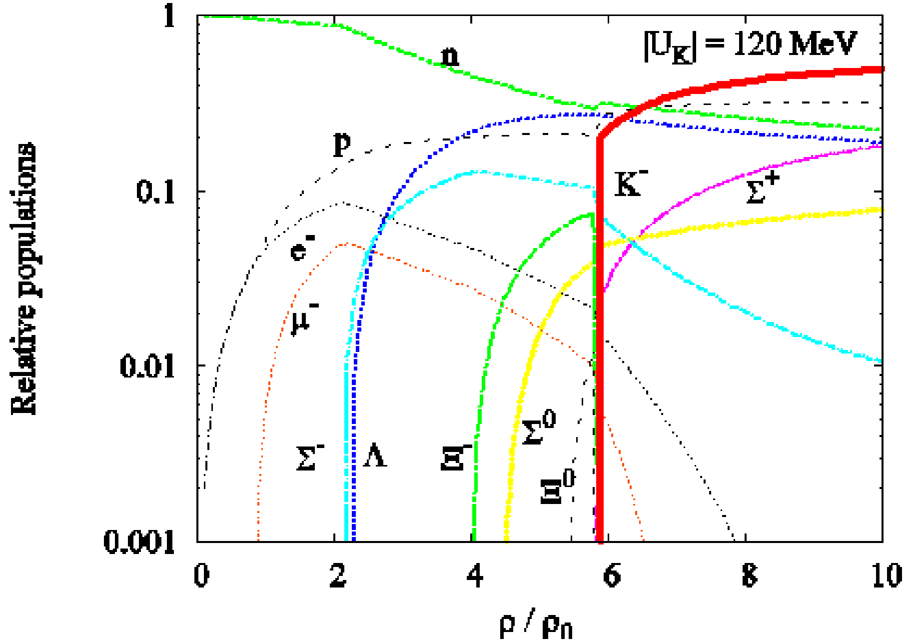
$$U_{K^-}(\rho_0) = -120\ \text{MeV}$$

QHD



$$\rho_c = 9.8\rho_0$$

MQMC

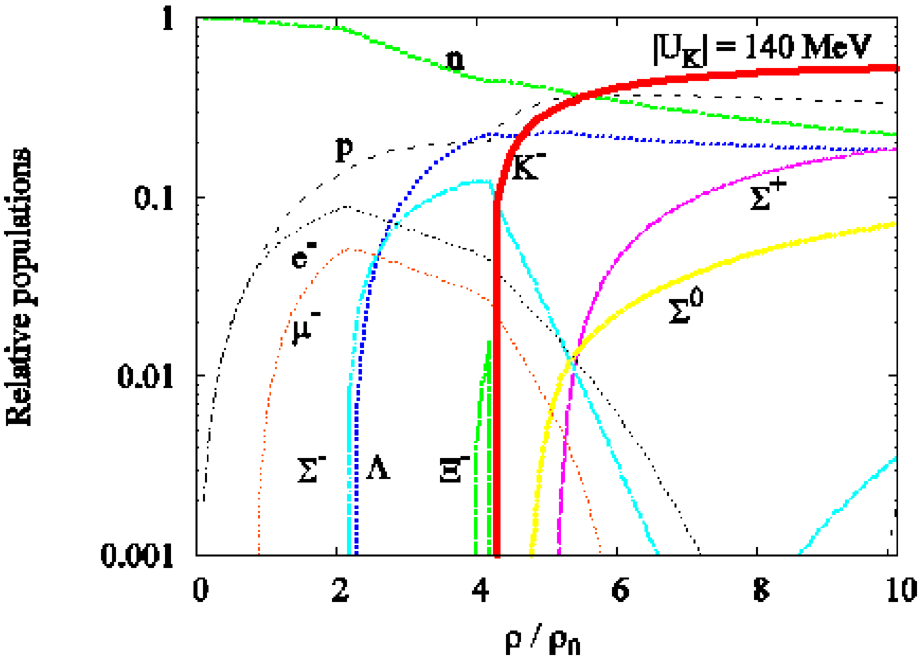


$$\rho_c = 5.9\rho_0$$

The population of particles in neutron star

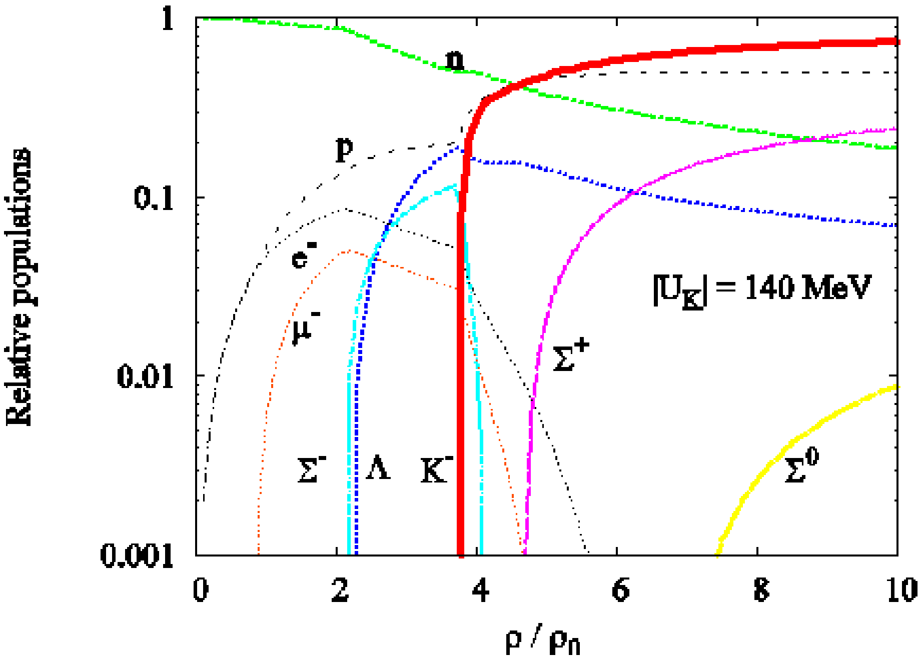
$$U_{K^-}(\rho_0) = \text{-}140\ \text{MeV}$$

QHD



$\rho_c = 4.3\rho_0$

MQMC

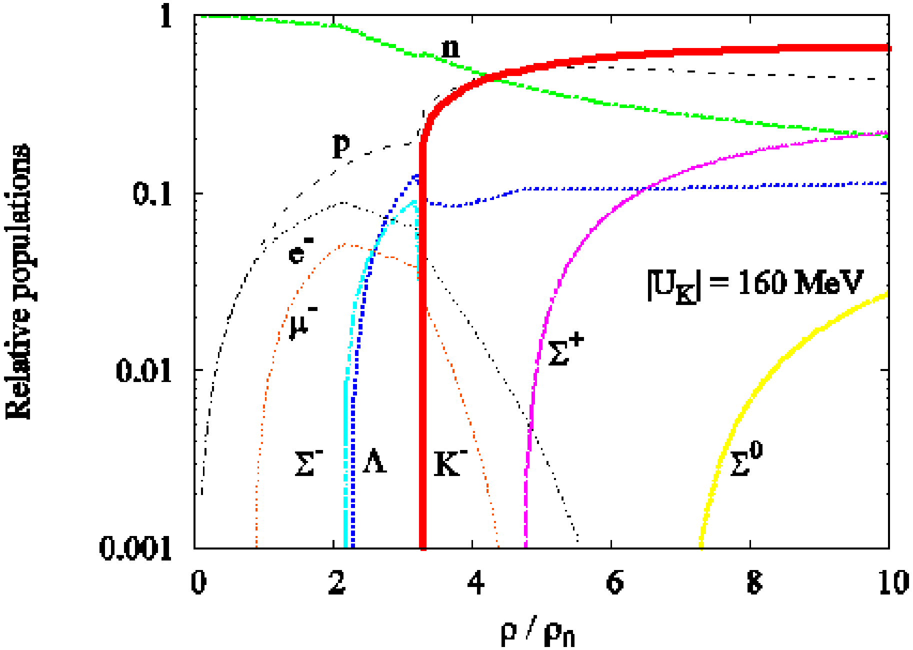


$\rho_c = 3.8\rho_0$

The population of particles in neutron star

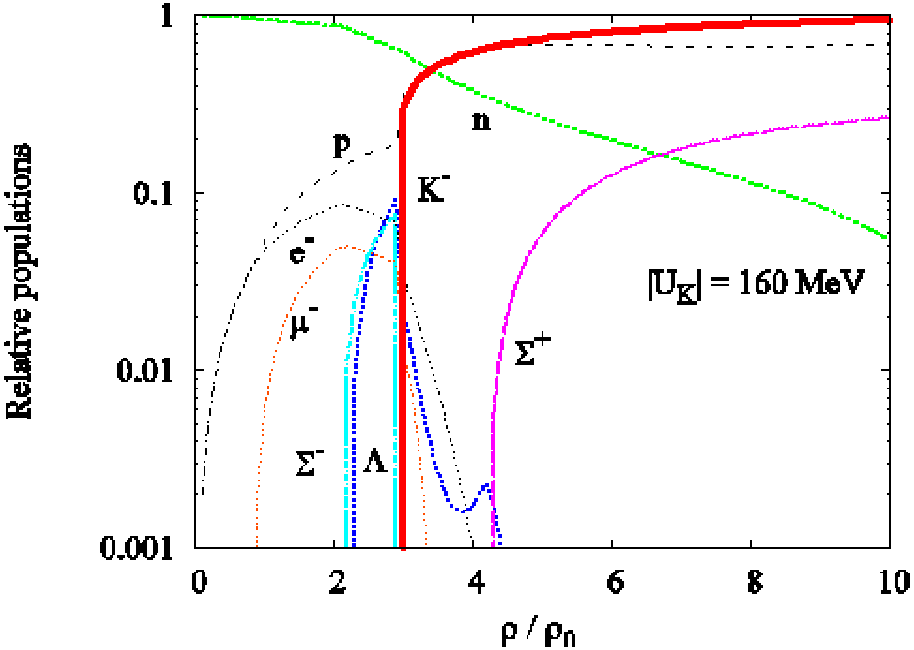
$$U_{K^-}(\rho_0) = \text{-160 MeV}$$

QHD



$\rho_c = 3.3\rho_0$

MQMC

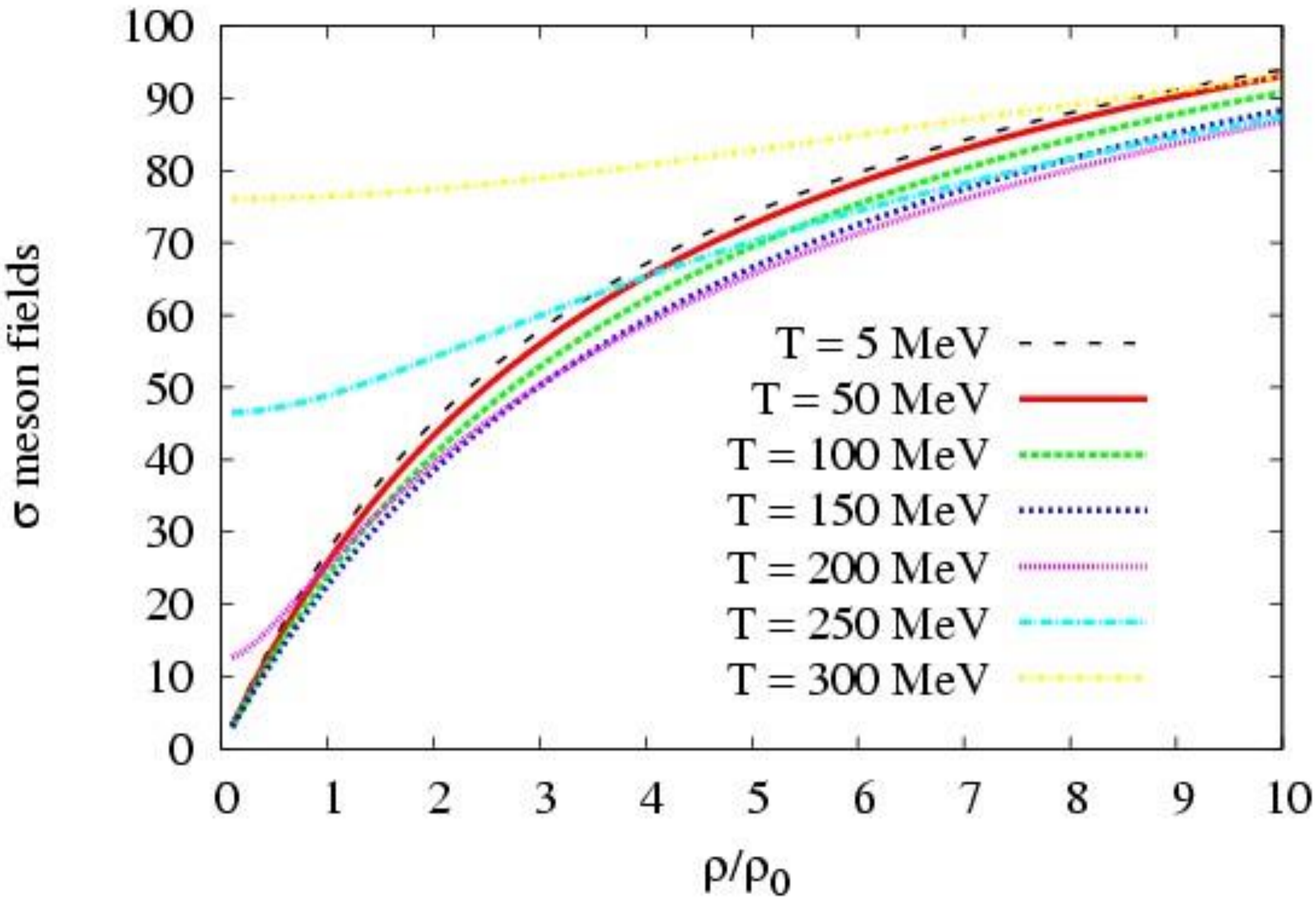


$\rho_c = 3.0\rho_0$

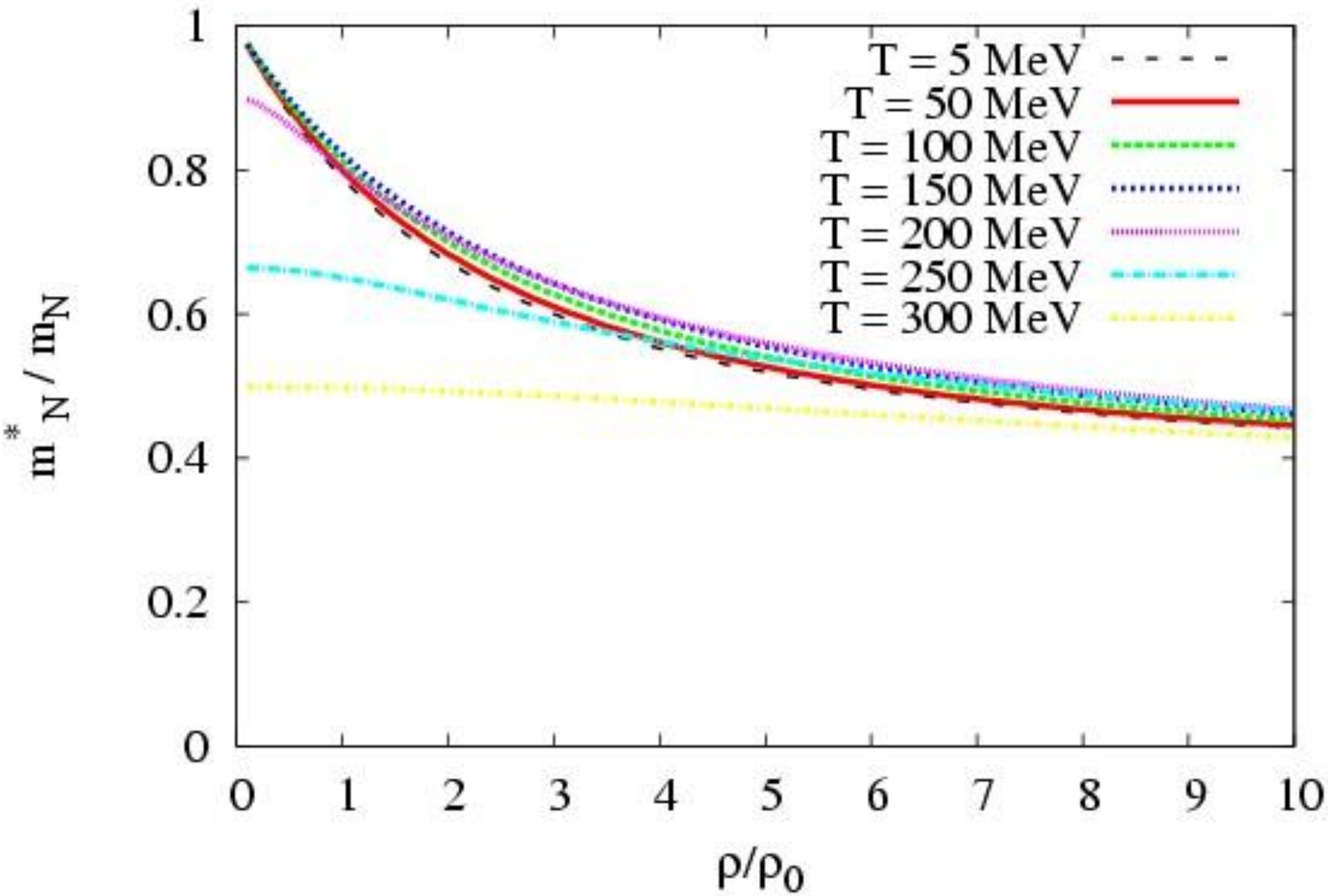
The mass of a neutron star and kaon condensation

	$M/M_{\odot}$	ρ_{crit}/ρ_0 for Kaon Condensation	References	
QHD (GM2)	1.645	3.37	Knorren et al	
QHD (GM2)	1.646	5.10	Knorren et al	
QHD (GM1)	1.649	2.23	Banik et al	
QMC	1.94	4.0	Menezes et al	
QHD (Our)	1.46	4.3		$U_{K^-}(\rho_0)$ = -140 MeV
MQMC (Our)	1.52	3.8		$U_{K^-}(\rho_0)$ = -140 MeV

σmeson fields at finite temperature



The effective masses of a nucleon at finite temperature



Summaries

1. Hadronic phases : QHD and QMC models
   i) Proto-neutron star – 2.0 solar mass
   ii) Hyperons - 1.6-7 Solar mass
   iii) Kaon condensation – 1.4-5 solar mass
   But, we can see the model dependency in both.

2. All results depend on the coupling constants and the potentials of kaon and baryons.
   – Experiment has to confirm them.

3. **If the observed mass is larger than 2.0 solar mass, all exotic phases are ruled out(?).**

4. **Finite temperature – symmetric matter**