QUARK-HADRON MIXED PHASE WITH HYPERONS IN PROTO-NEUTRON STARS

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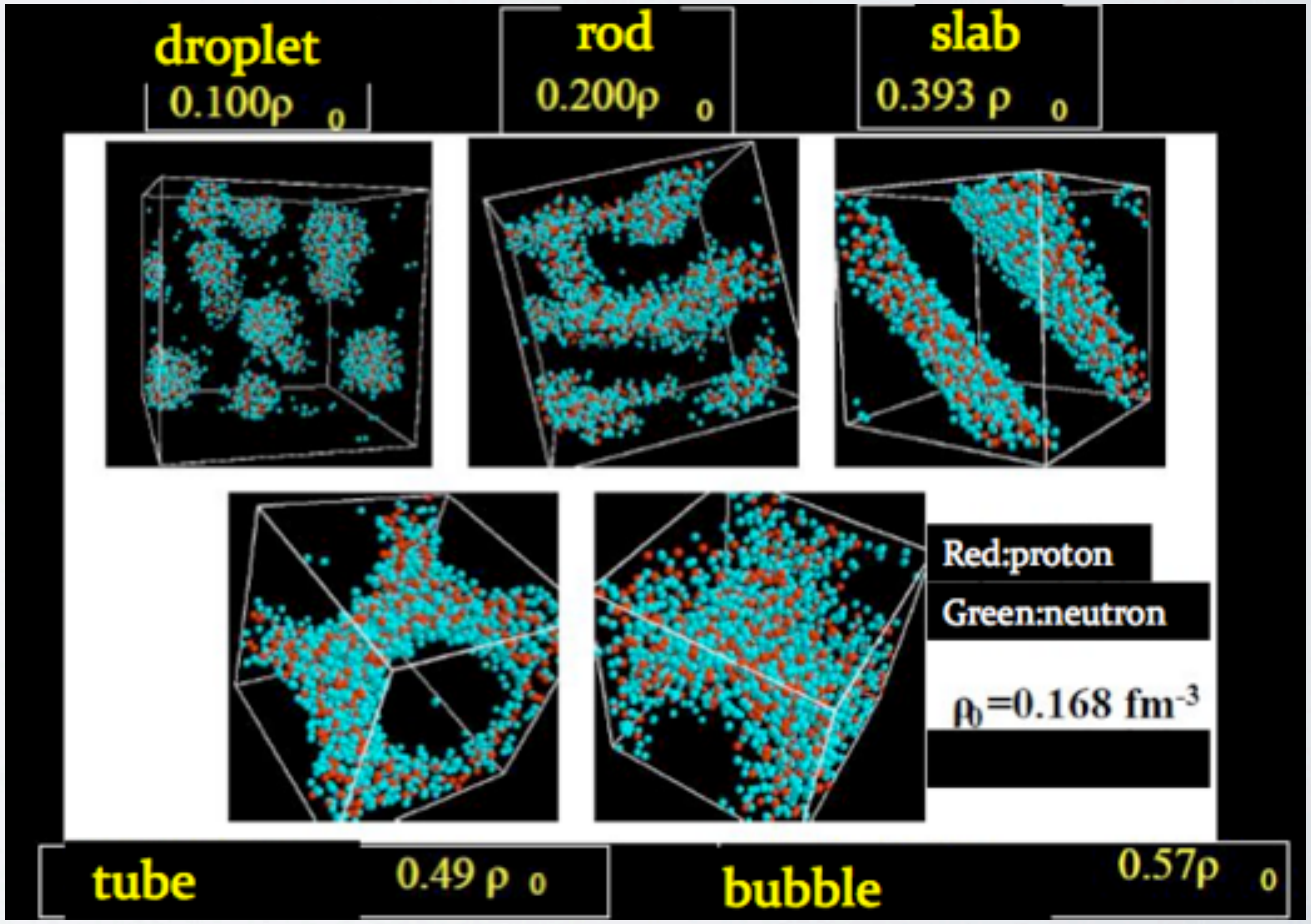
§1-1. INTRODUCTION

What is "pasta structure"?

↓

Non uniform structure on 1st order phase transition in multi-component system.

Depended on "density" and temperature", each charged particle clusterize automatically by "Coulomb interactions " and "surface tensions" ; i.e. finite size effects.
As a result, they construct non-uniform structures called as "pasta structures".



"Nucleon pasta " ref. Sonoda et al. 2008

§2-1. MOTIVATIONS

The problem of Soft Equation of State (EOS) with hyperons

Many hyperon EOS are not consistent with the observations of neutron stars Mass-Radius relations.

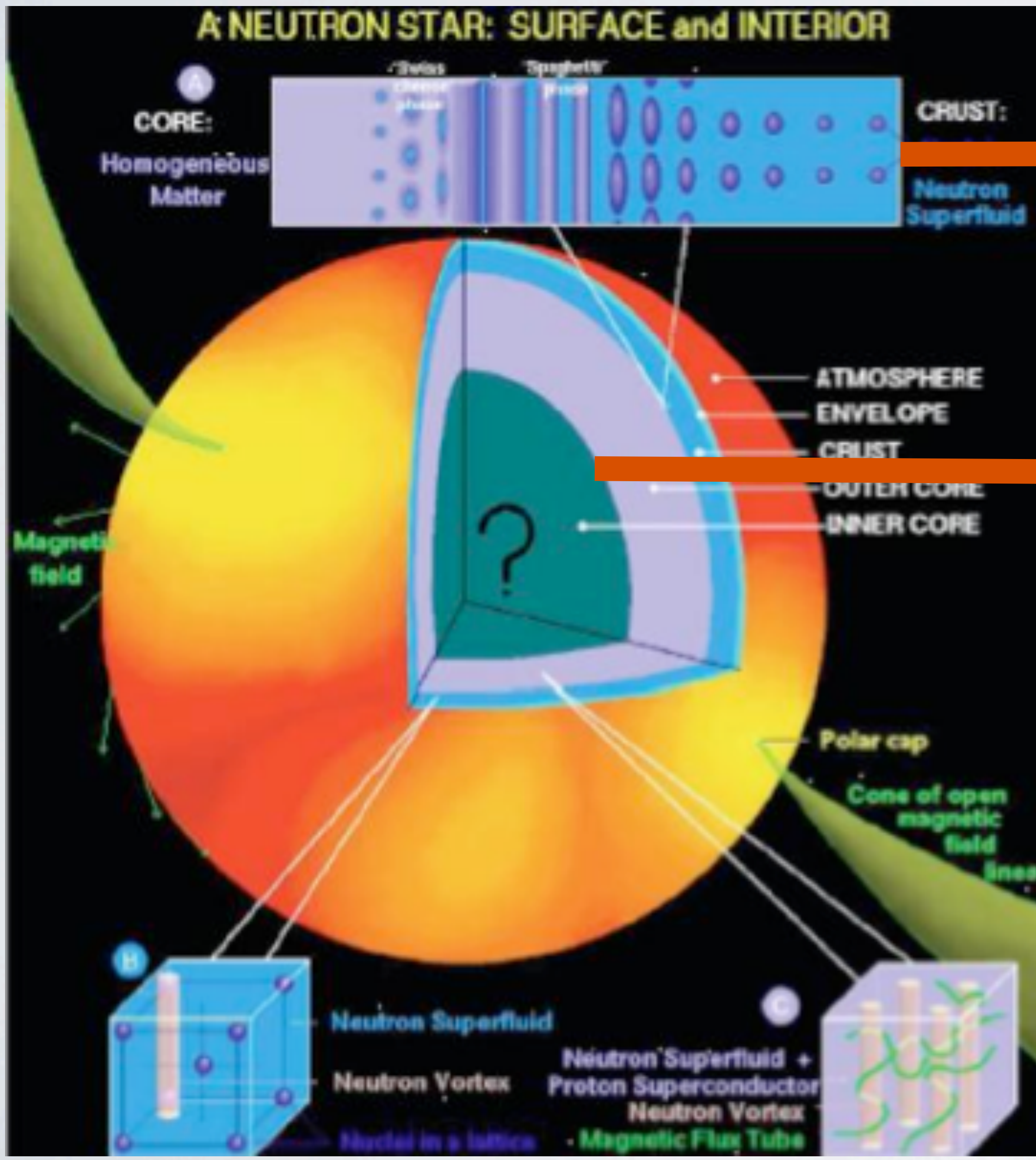
To solve this problems,

1. tree-body forces (Takatsuka & Tamagaki 2006)
2. relativistic effects (DBHF models)
3. quark-hadron phase transitions (Burgio et al. 2004) ←our study

We focus on the quark-hadron phase transition at finite temperature with neutrinos considering "finite size effects".

§2-2. MOTIVATION ②

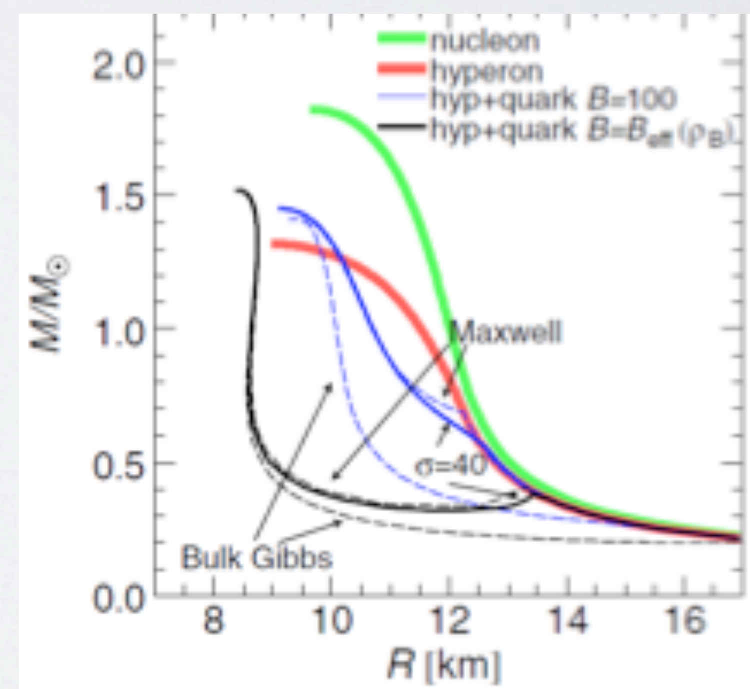
Quark-hadron pasta change "Mass-Radius relations" drastically.
It is very important for observations such as gravitational waves, cooling light curves.



credit: D. Page

Nucleon pasta change "**thin crust**" of NSs. Hence, it does not change the structure (M-R relations) so much.

Quark-hadron pasta change "**cores**" of NSs. Hence, it change the structure (M-R relations) drastically.



Maruyama et al. 2007

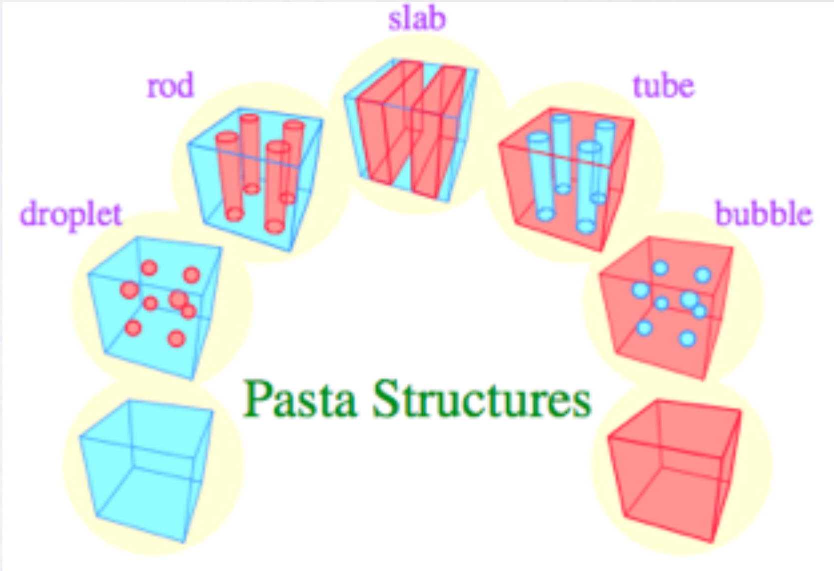
§3-1. FORMALISM ①

Hadron matter
Brueckner-Hartree-Fock model with hyperons (Baldo et al. 1998, Schulze et al. 1995)
NN interaction → Argonne V18 potential + UIX phenomenological three body forces
NY interaction → Nijmegen soft-core 89 potential
(We will update the interactions by the results of lattice QCD and/or J-PARC.)

+

Quark matter
Thermodynamic bag model ("bag constant" or "density dependent bag model")
(We will change this simple model to NJL model or pNJL model.)

We assume the pasta structures of the mixed phase as droplet, rod, slab, tube, and bubble under Wigner-Seitz cell approximation (right panel).



In calculations of mixed phase, we consider
- charge neutrality
- chemical equilibrium
- baryon number conservation
- balance between "surface tension" and "Coulomb interaction"

§3-2. FORMALISM ②

Finite temperature technique

Hadron

Frozen Correlations Approximation

$$\varepsilon_i = \sqrt{m_i^2 + p^2} + U_i.$$

$$\mathcal{F}_H = \sum_i \{ \frac{g}{(2\pi)^3} \int_0^\infty \sqrt{m_i^2 + p^2} f_i(p)\ 4\pi p^2 dp + \frac{1}{2} U_i n_i \} - T s_H.$$

$$P_H = \sum_i \mu_i n_i - \mathcal{F}_H.$$

Quark

$$\epsilon_Q = B + \sum_f \epsilon_f,$$

$$\epsilon_f(\rho_f) = \frac{3m_f^4}{8\pi^2}\left[x_f(2x_f^2+1)\sqrt{1+x_f^2} - \mathrm{arsinh}x_f\right] - \alpha_s \frac{m_f^4}{\pi^3}\left[x_f^4 - \frac{3}{2}(x_f\sqrt{1+x_f^2} - \mathrm{arsinh}x_f)^2\right],$$

→

$$\epsilon_Q = \sum_q \frac{g}{(2\pi)^3} \int_0^\infty \sqrt{m_q^2 + p^2} f_q(p) 4\pi p^2 dp + B$$

$$\mathcal{F}_Q = \epsilon_Q - T s_Q$$

$$P_Q = \sum_q \mu_q n_q - \mathcal{F}_Q.$$

Total energy

$$E = \int_{V_H} d^3r\, \epsilon_H[\rho_i(\mathbf{r})] + \int_{V_Q} d^3r\, \epsilon_Q[\rho_f(\mathbf{r})] + E_e + E_C + \sigma S$$

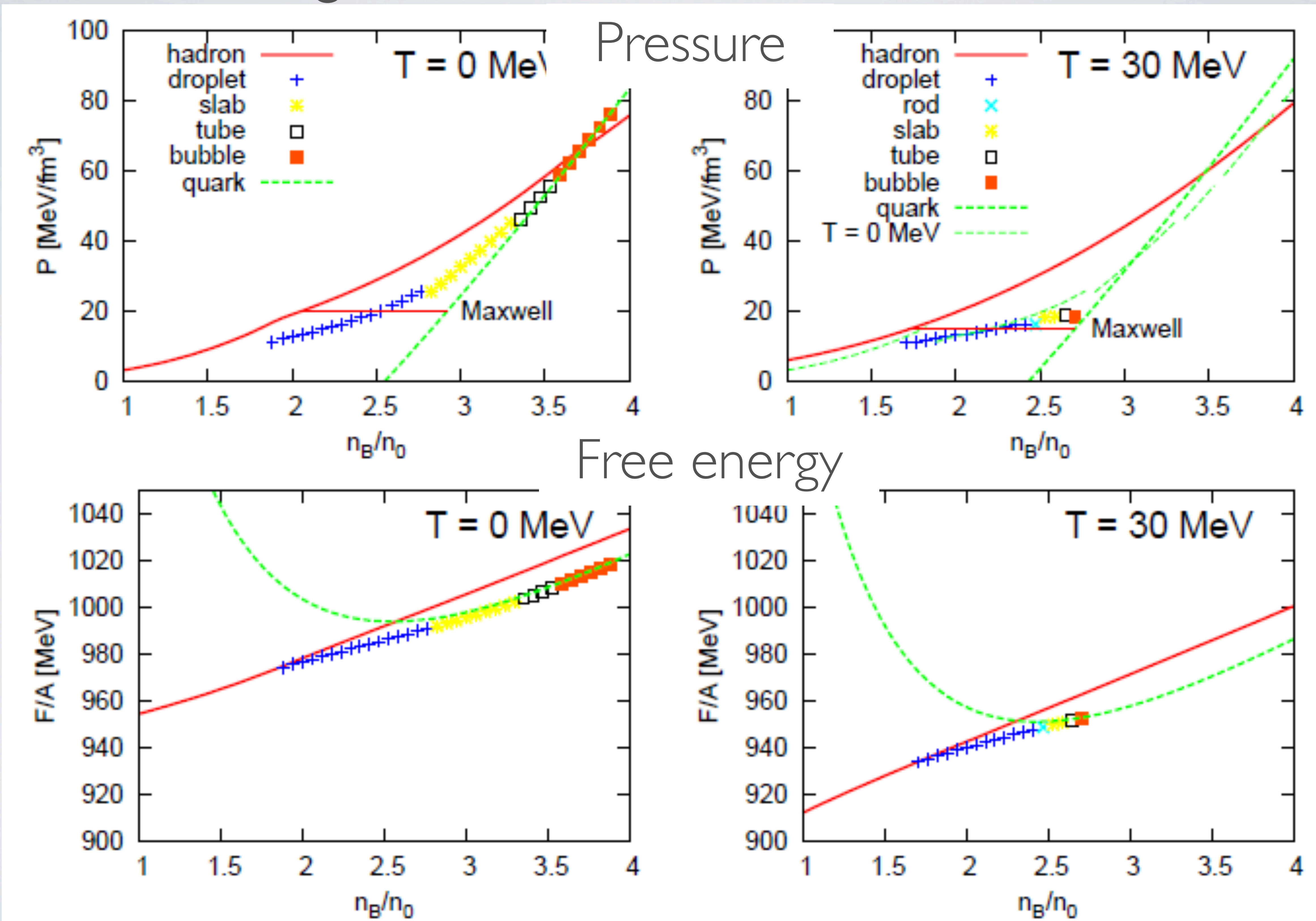
→

Free energy

$$F = \int_{V_H} d^3r\, f_H[\rho_i(\mathbf{r})] + \int_{V_Q} d^3r\, f_Q[\rho_q(\mathbf{r})] + F_e + E_C + \sigma S$$

§4-1. RESULTS ①

NY et al. PRD2009b

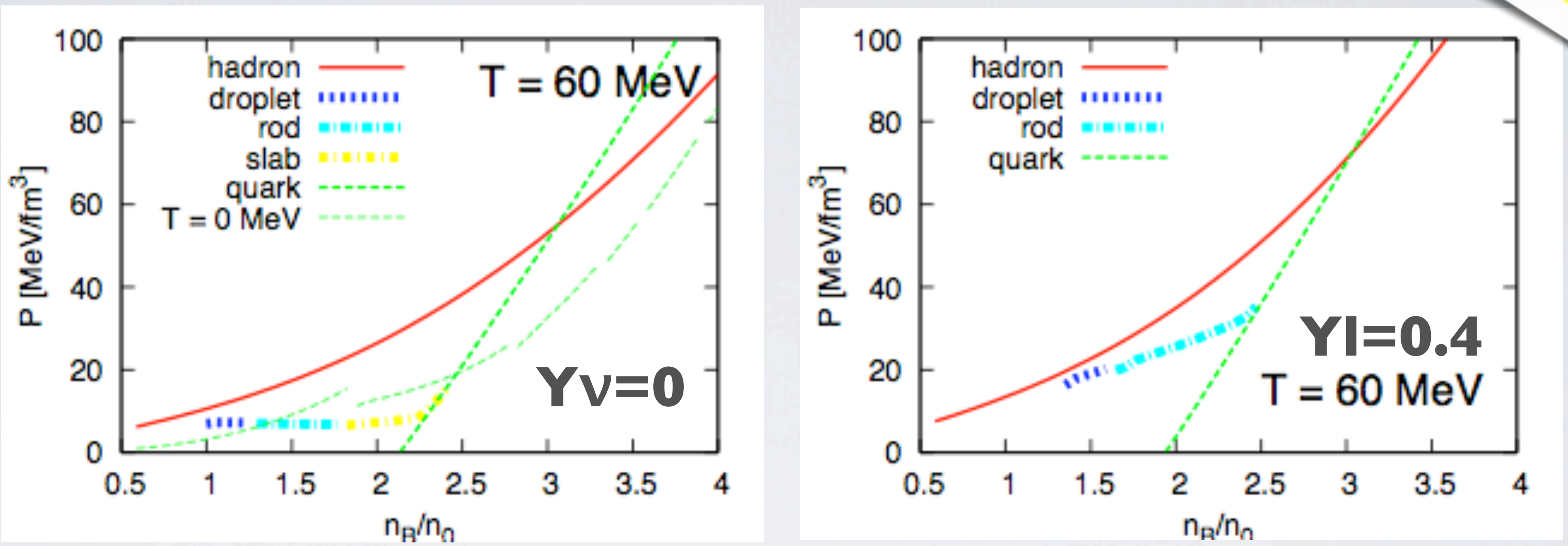


At high temperature → Maxwell-like mixed phase

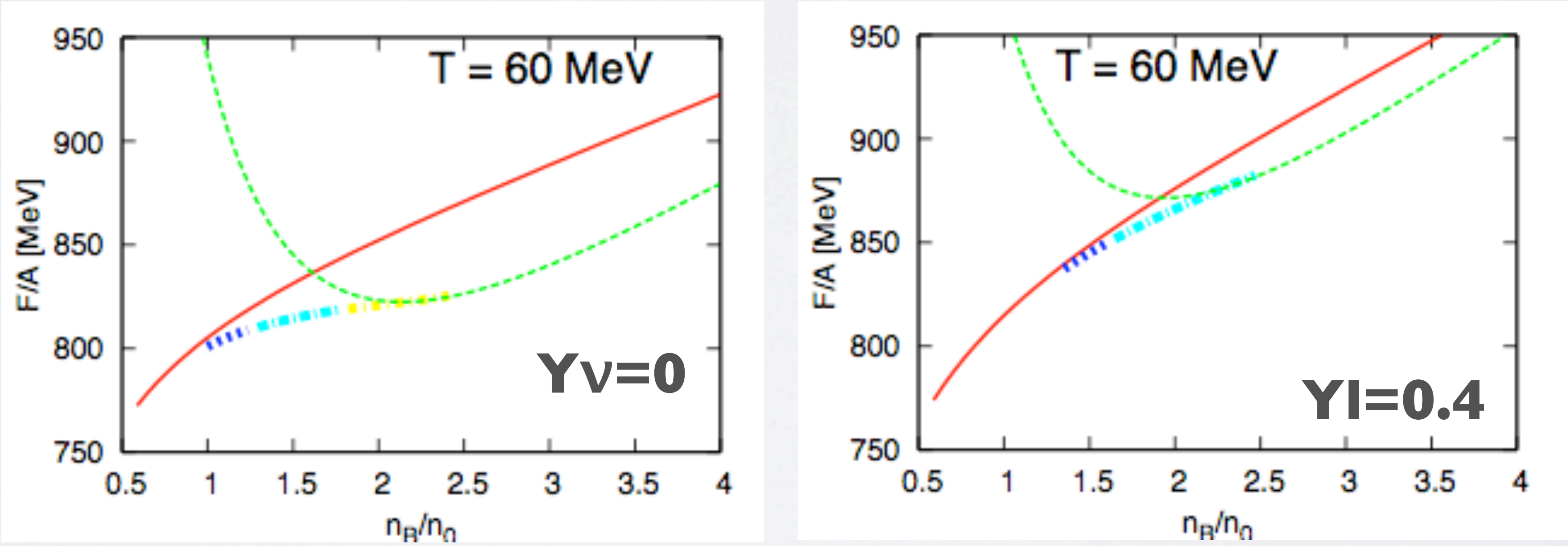
§4-2. RESULTS ②

Preliminary

Pressure



Free energy



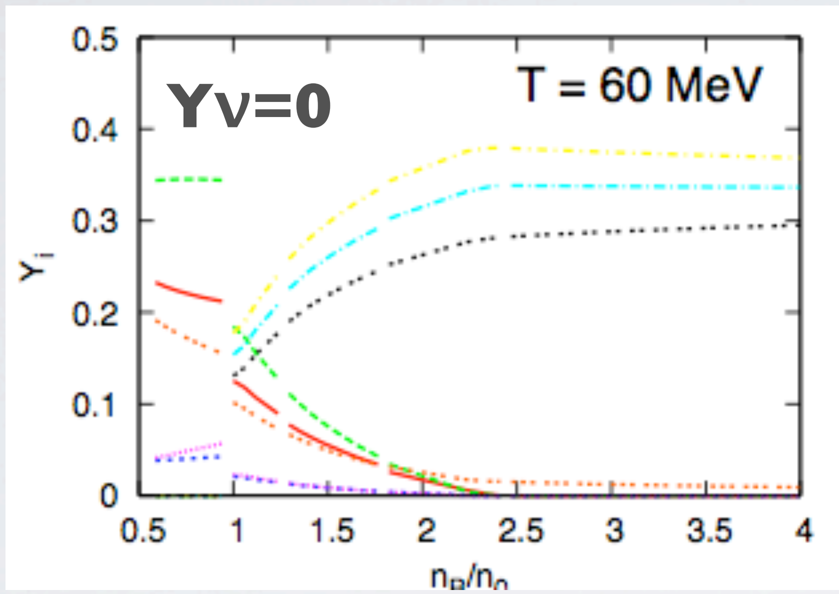
At high lepton fraction,
Maxwell-like mixed phase → Not Maxwell-like

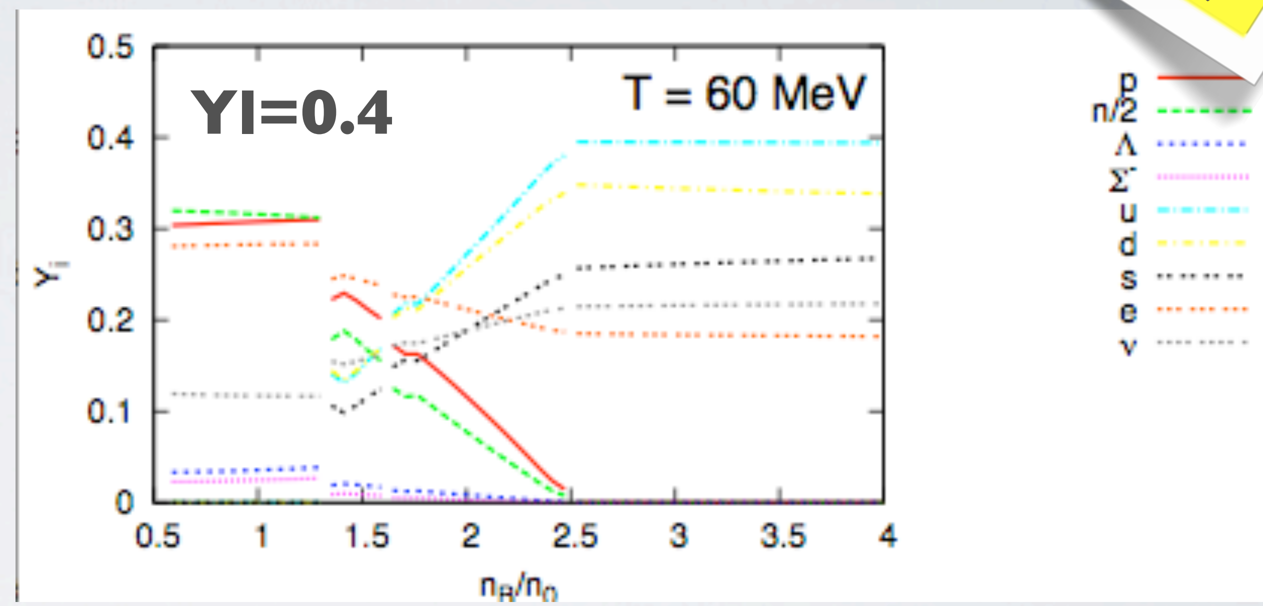
§4-3. RESULTS ③

Preliminary

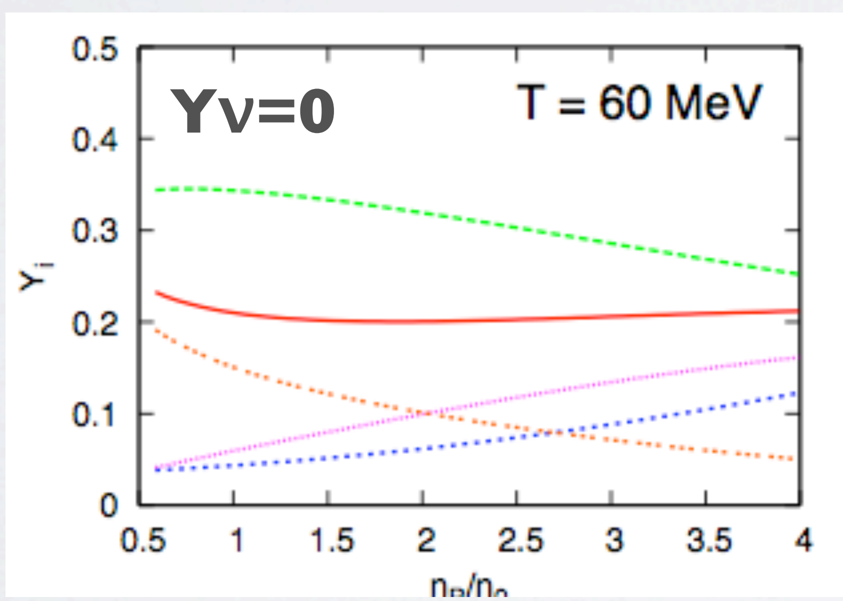
Compositions

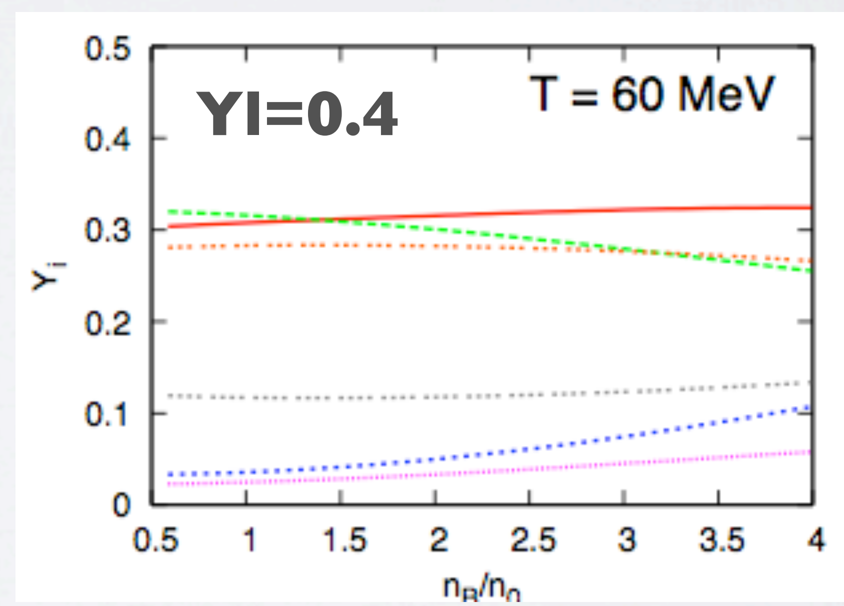
with quarks





without quarks



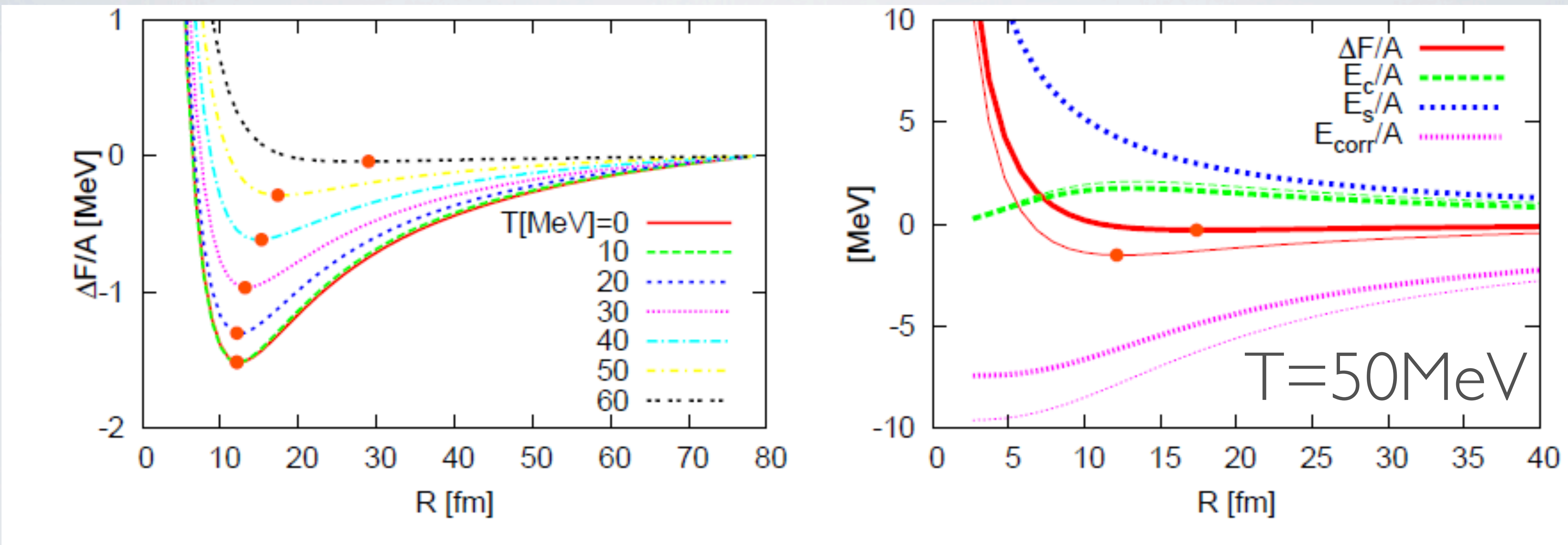


- Hyperon matter are suppressed with quarks.
- Electron fraction is enhanced at neutrino trapped matter.

§4-4. RESULTS ④

NY et al. PRD2009b

Stability curve of "droplet" structure at $n=2n_0$



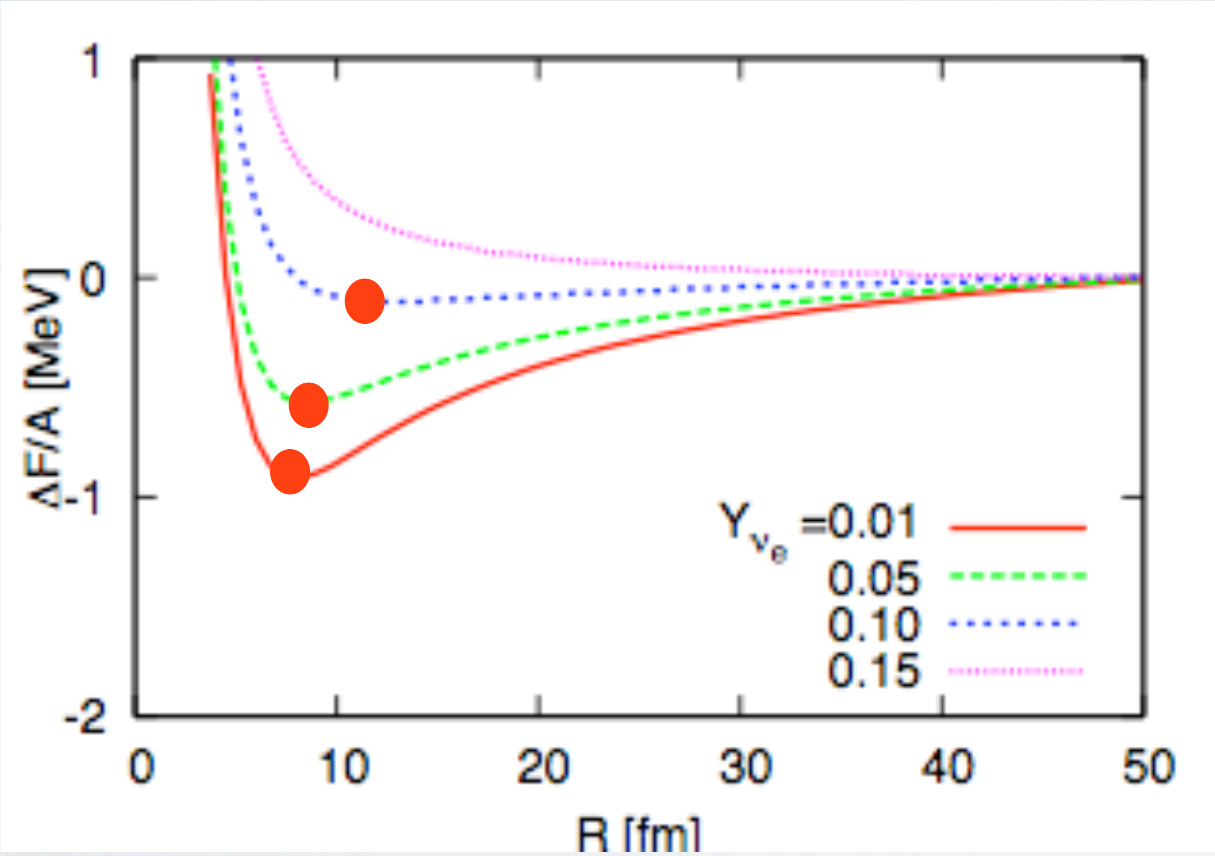
The mixed phase becomes unstable over ∼T=60 MeV .

→ Mixed phase disappear at high temperature

§4-5. RESULTS ⑤

Preliminary

Stability curve of “slab” structure at n=2.5n_0



cf. density dependent bag model

$$B(\rho) = B_\infty + (B_0 - B_\infty)\exp\left[-\beta\left(\frac{\rho}{\rho_0}\right)^2\right]$$

with $B_\infty = 50\ \mathrm{MeV/fm^3}$, $B_0 = 400\ \mathrm{MeV/fm^3}$,

Nicotra et al. 2006

With neutrinos, the mixed phase becomes unstable over ∼Yν=0,1 .

→ Mixed phase disappear at high neutrino fractions.

§5-1. SUMMARY

We study the quark-hadron mixed phase at finite temperature with neutrinos considering "finite size effects".

Main result is

At high temperature, Mixed phase → unstable	At high lepton fraction, Mixed phase → unstable

These results will change the dynamical simulation of supernovae, or black hole formations, and evolutional simulations of proto-neutron stars. Now, we are analyzing the results.

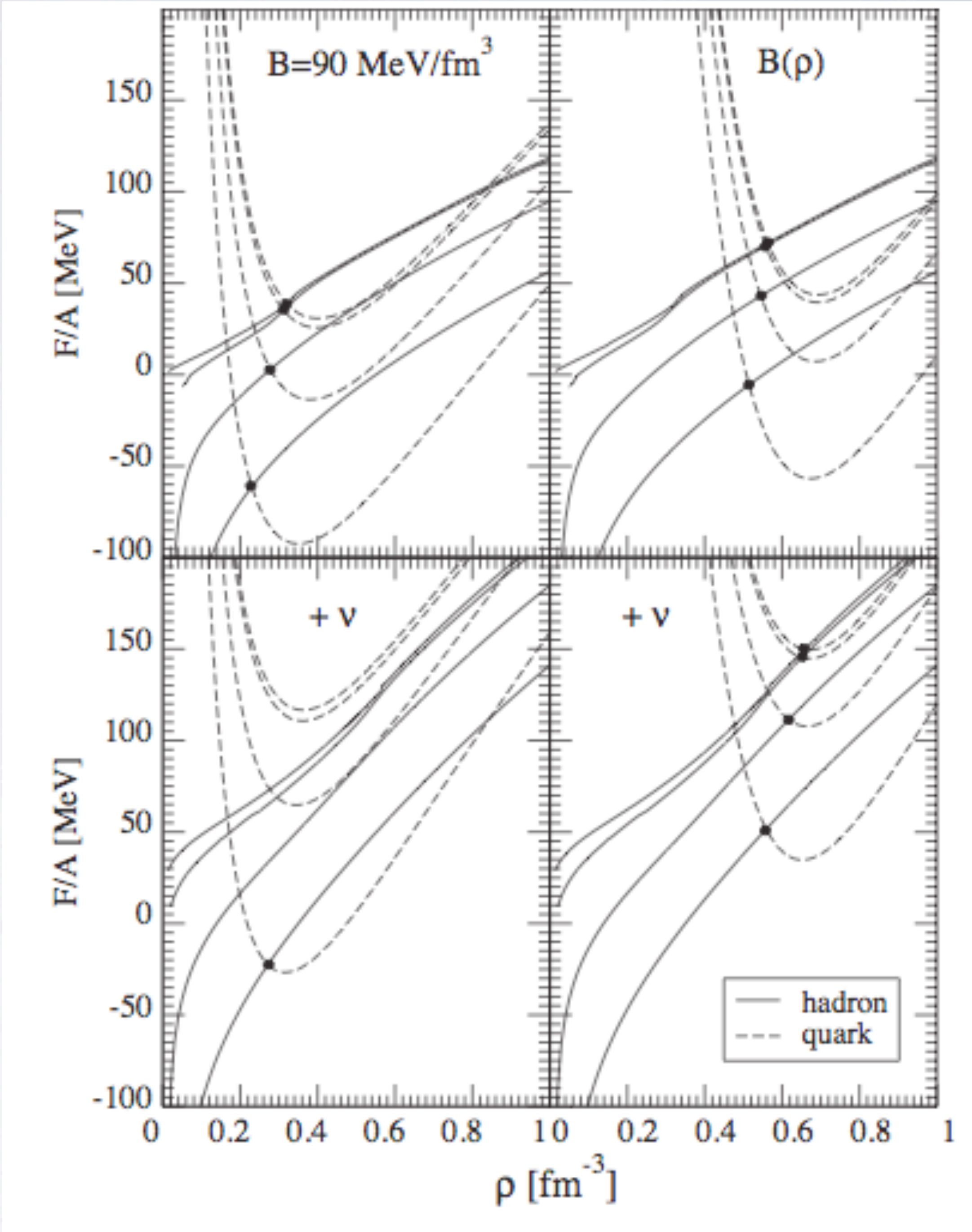
If the quark-hadron phase transition occurs in supernovae, it may not have the mixed phase. But, it will appear in the proto-neutron stars along the ejections of neutrinos,

Danke !

APPENDIX

§5-2. DISCUSSION

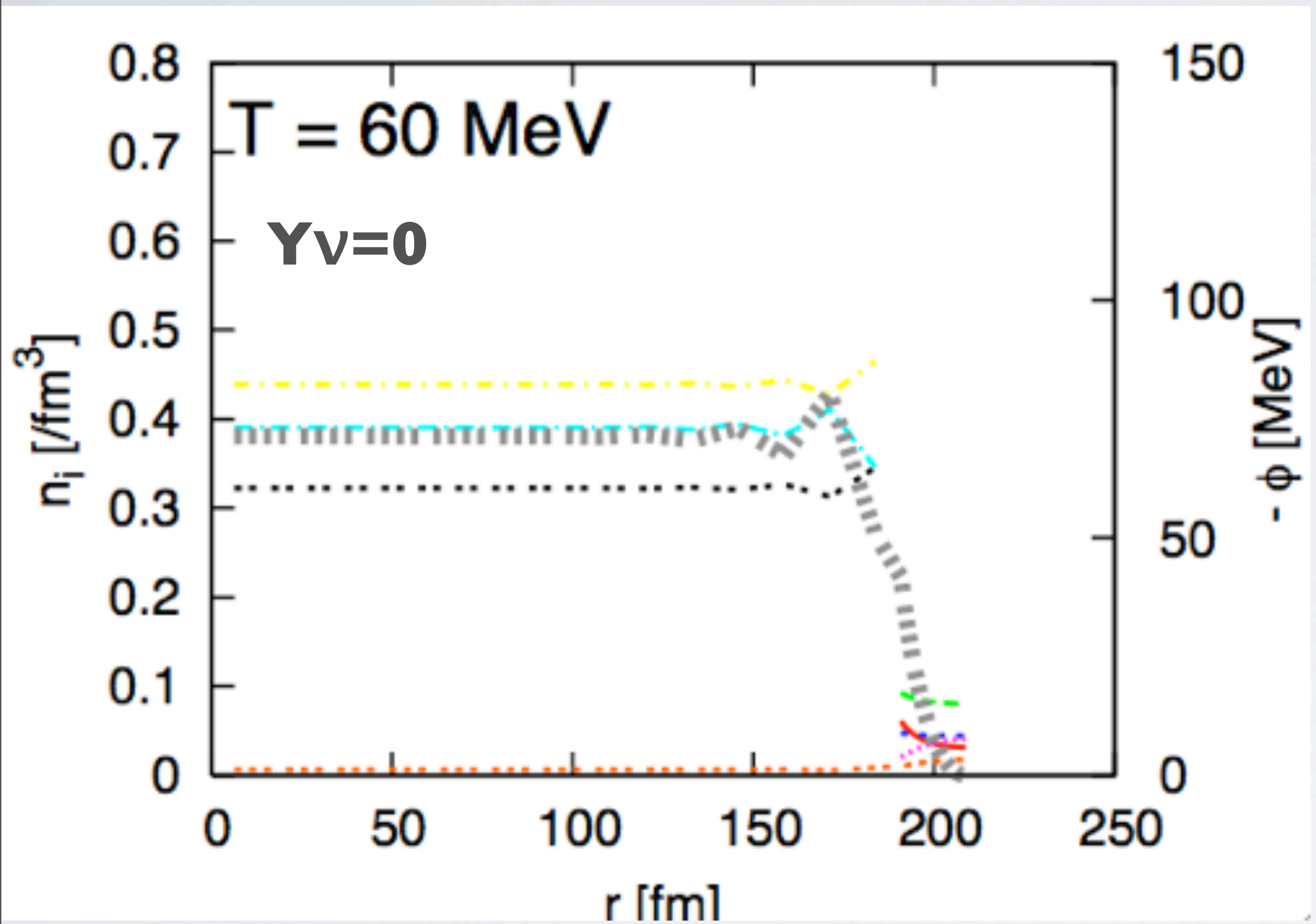
In this study, temperature is too high (T=60 MeV) for PNSs. At lower temperature, we can not find any phase transitions. However, if we change the quark model from constant bag model to density dependent bag model or other models, we will find mixed phases (see right panels).

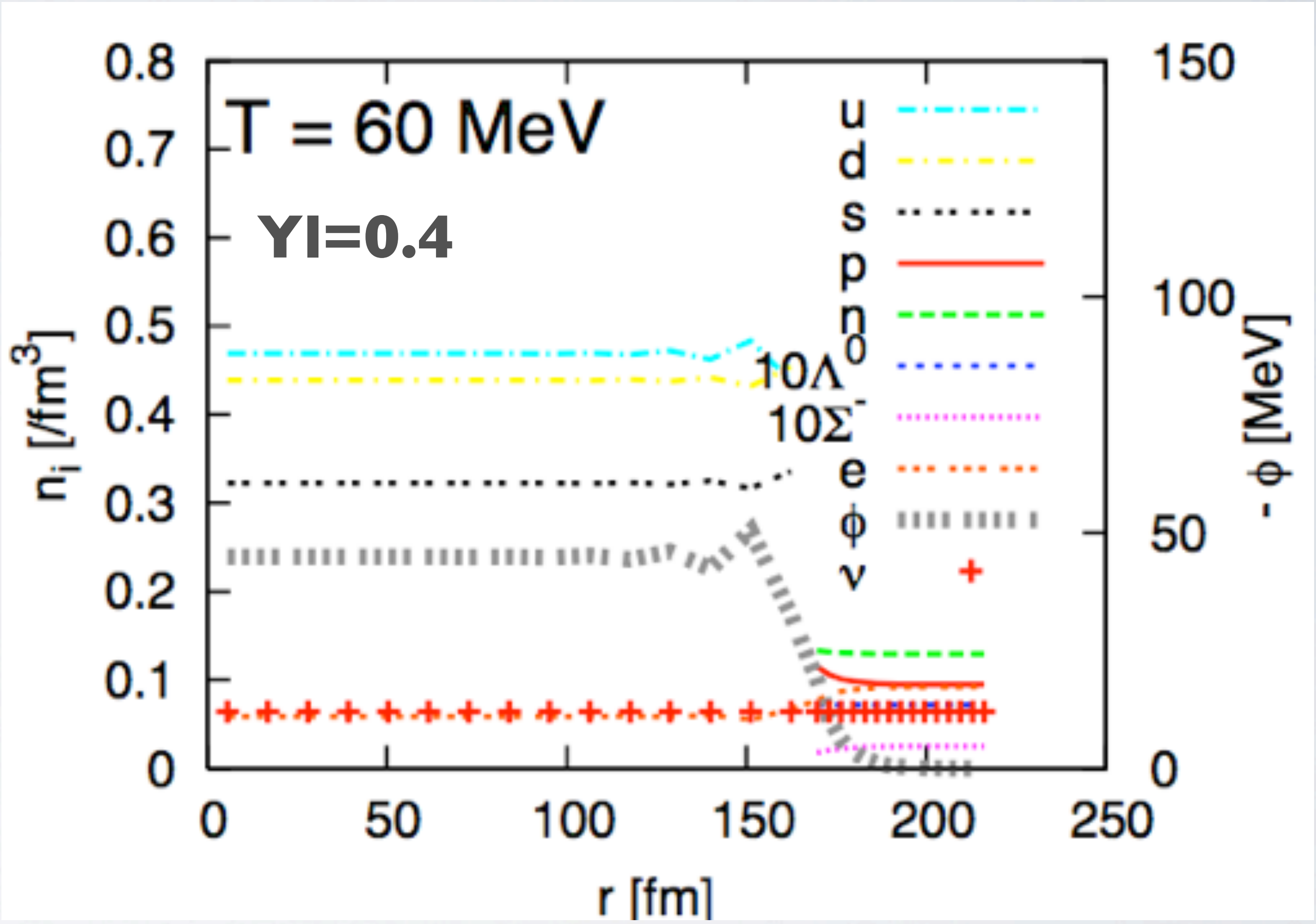


Nicotra et al. 2006

§OTHER RESULTS①

Profiles of "rod" structure at n=2n_0





- Profiles are almost flat because of high temperature.