Conversion of Baryonic Matter to Quark Matter

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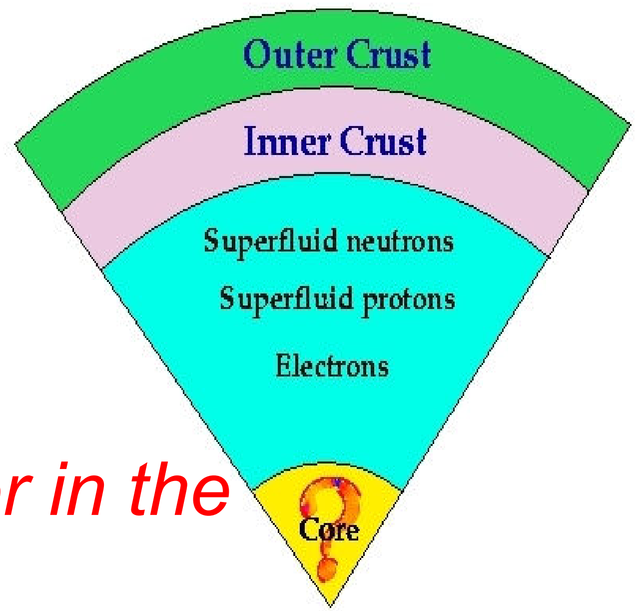
Neutron Star

- The remain after supernova explosion
- Discovered in 1967 as a pulsar
- Main components : neutron, proton, electron
- Mass : 1~2$M_\odot$
- Radius : ~10km
- Central density : ~10^{15} g/cm^3
- *It is not known the state of matter in the central region.*



quark / hyperon / pion-condensation …

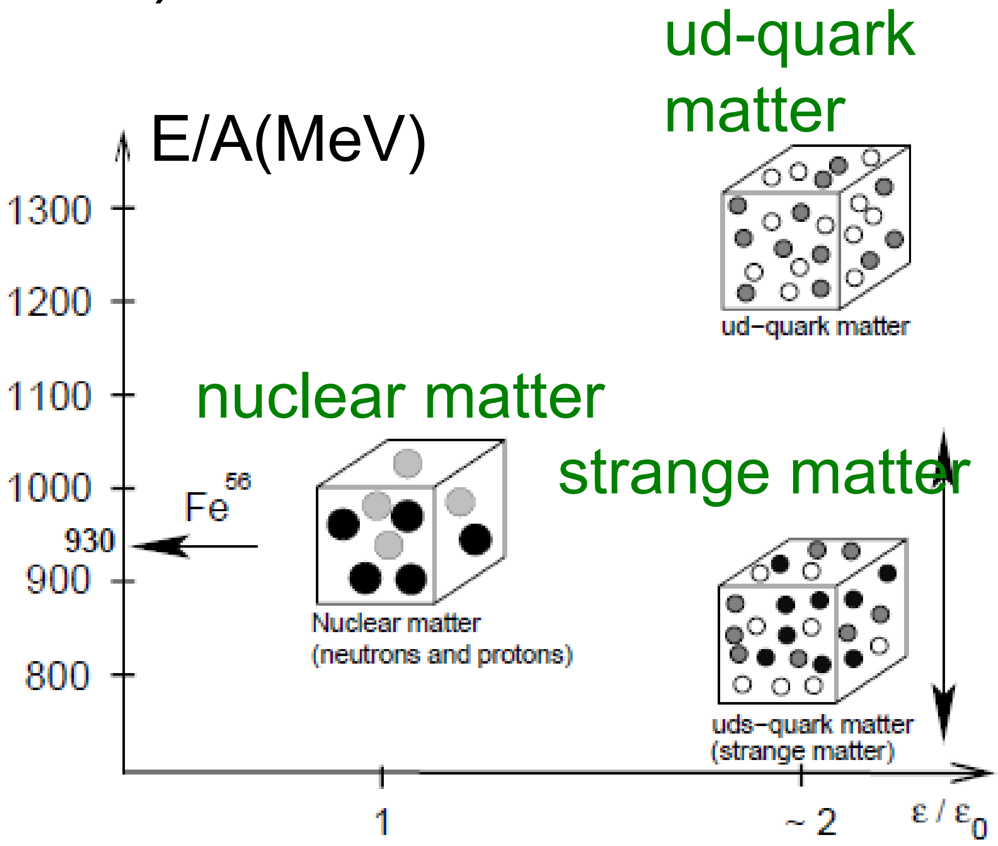
Strange Matter

- There may be quark phase in the central region of a neutron star.

- Witten's hypothesis (1984)

The strange matter that is composed of up, down and strange quarks is the true ground state of matter.

- *There needs to be a ratio of strange quarks to be stable.*



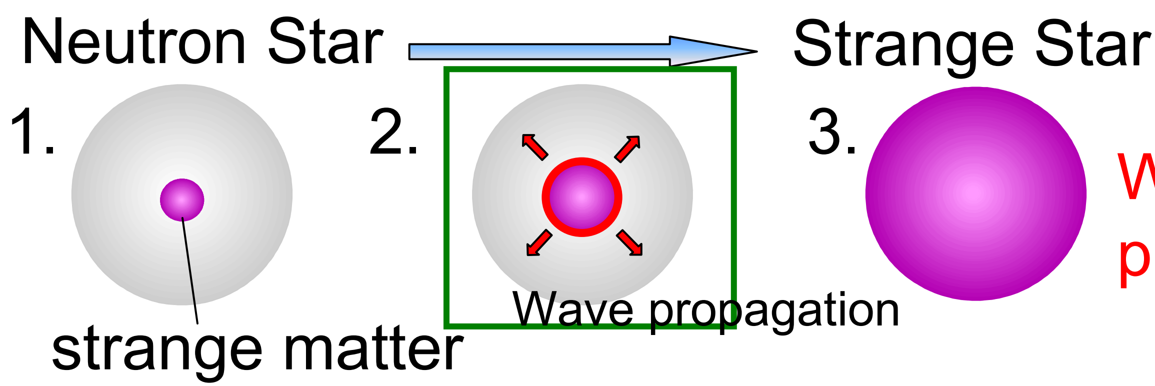
Strange Star

- The birth of a Strange Star

  1. *a stable strange matter appears in a neutron star (seeding process)*
  2. *the strange matter is eating up around nuclear matter*
  3. *whole star is changed into the strange matter*

     - catch a strange matter from the outside of a star
     - central density becomes higher than a critical density via spin down

     …



We study this conversion process itself.

Conversion Scenario

(arrow a) the diusion-induced conversion can take place anywhere below *Pc2*

To begin converting 3QM from BM, the stable strange quark matter seed is needed.

By diffusion of strange quark, combustion wave propagates.

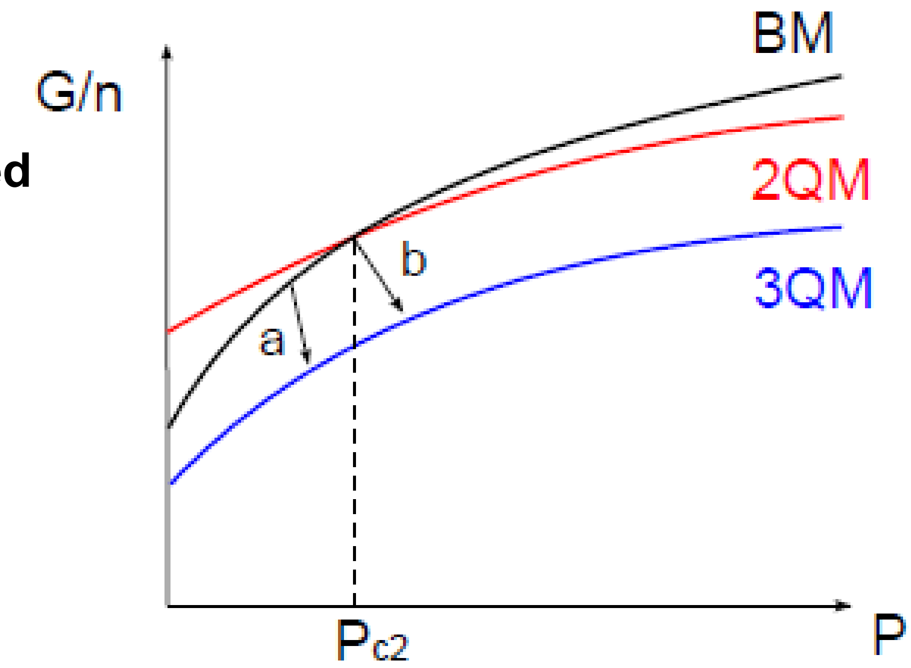
(arrow b) the shock-induced conversion occurs at *Pc2*

The ignition of combustion is critical density (change BM to 2QM, deconfinement).

BM : Baryonic matter

2QM : 2 flavor quark matter

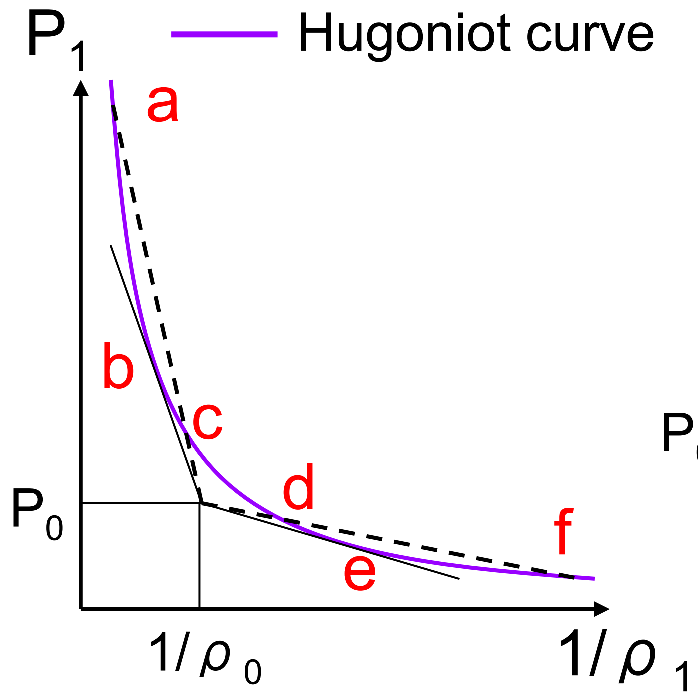
3QM : 3 flavor quark matter

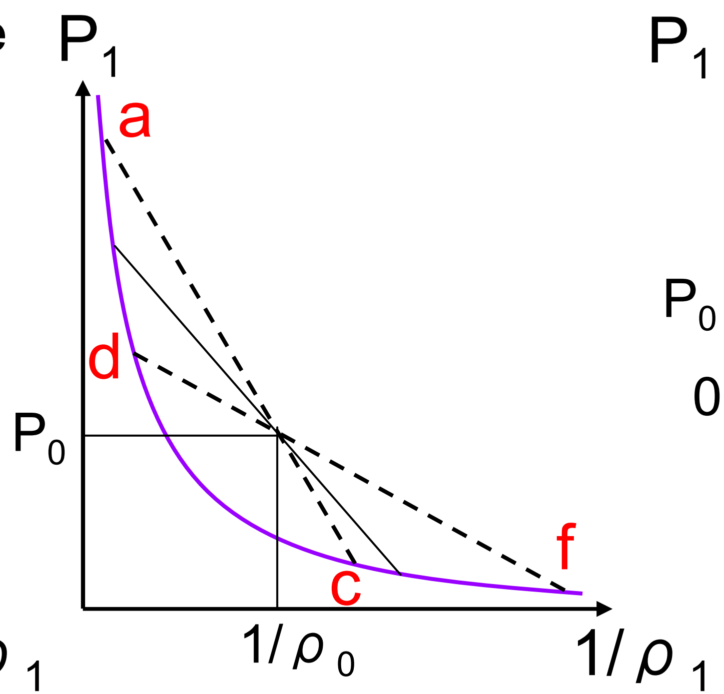


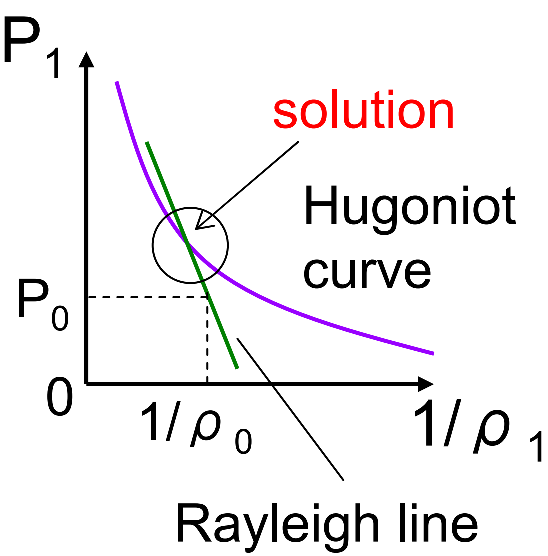
☆ Schematic pictures of the Gibbs free energy per baryon

Combustion modes

- We can distinguish the combustion modes with the physical values of matter before and after the combustion.
- Mass & Momentum equations => *Rayleigh line*
- Mass & Energy equations => *Hugoniot curve*







a : strong detonation
f : strong deflagration
c : weak detonation
d : weak detonation
b,e : Jouget point

Our Motivation

- Study the converting process
  - solve the diffusion and reaction process with the motion of gases
  - We can decide only one combustion velocity and combustion mode

combustion mode

In this presentation, detonation case is treated.

strong detonation	strong deflagration
weak detonation	weak deflagration

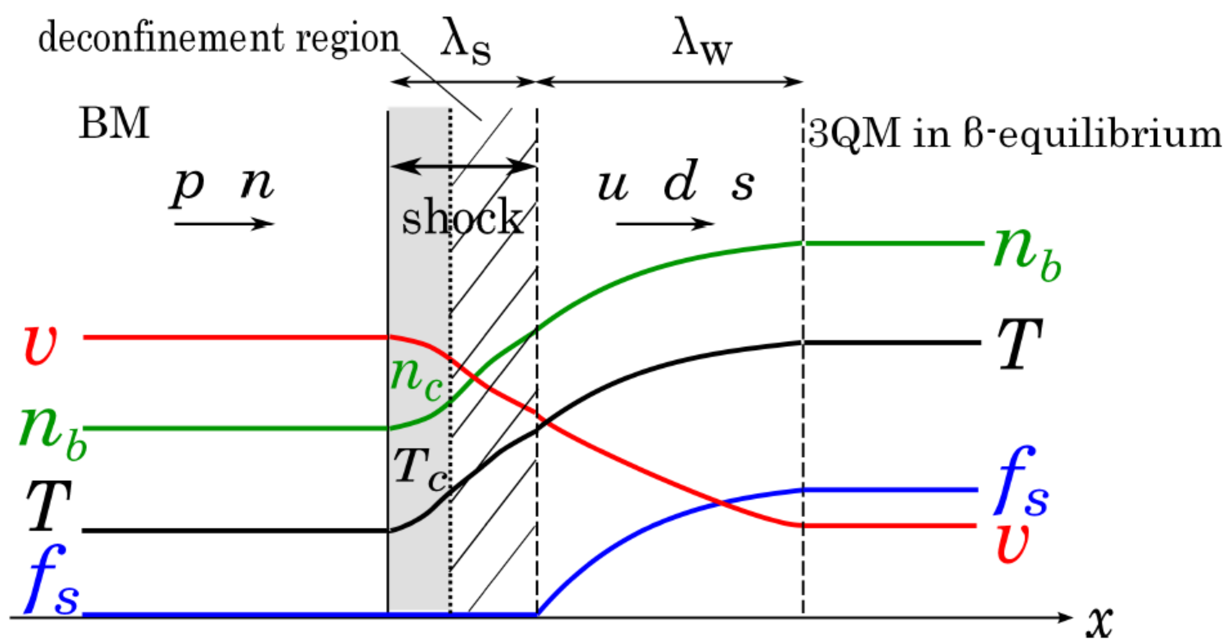
- Study the propagation of the combustion wave

(future work)

The combustion wave reach the surface of a star or not.

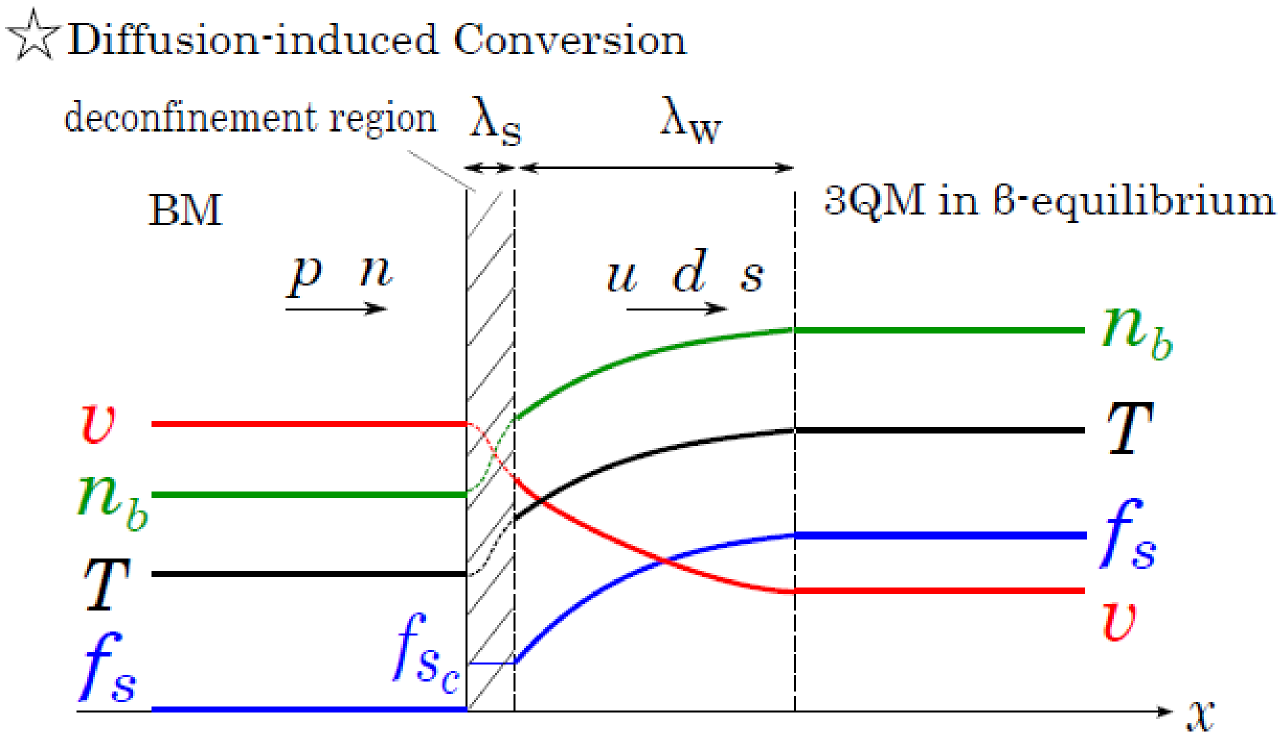
Schematic pictures of the conversion regions

☆Shock-induced Conversion



The shades stand for the deconnement regions, the widths of which are exaggerated in this picture. The hatched region in the right panel corresponds to the shock wave. Note that the deconnement commences inside the shock wave. The lines labeled as *v*, *nb*, *T* and *fs* represent the velocity, baryon number density, temperature and fraction of strange quarks, respectively.

Schematic pictures of the conversion regions



The shades stand for the deconnement regions, the widths of which are exaggerated in this picture. Following the deconnement, the -equilibration of QM, in which strange quarks become populated, occurs as long as a certain fraction of strangeness (denoted as *sc* in the gure) already exists at the interface.

Toy Model (Detonation Type)

- Diffusion and Reaction of Strange matter

$$v\frac{df_s}{dx} - D\frac{d^2 f_s}{dx^2} = \frac{f_{s,f} - f_s}{\tau},$$

D: diffusion constant

τ : reaction time

fs: strange quark fraction

fs,f: strange quark fraction of ash region (3QM in beta-equilibrium)

- Motion of gases

$$\rho v = \rho_i v_i \; (= \rho_f v_f),$$

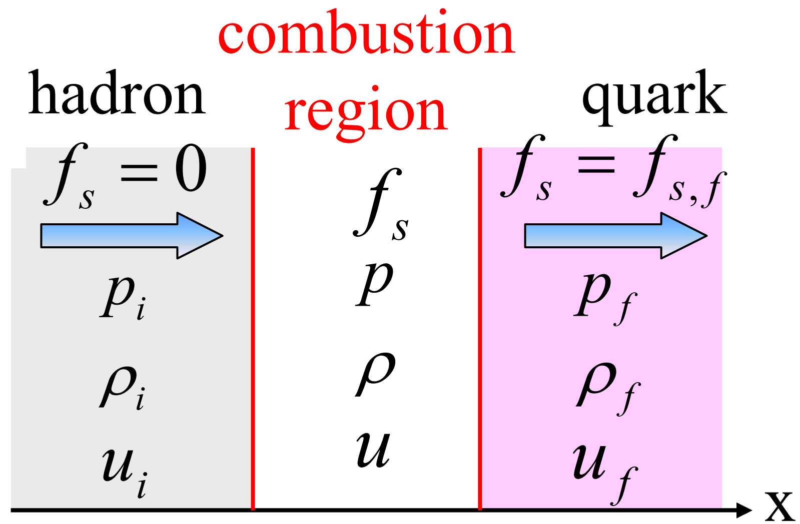
$$P + \rho v^2 - \nu\frac{dv}{dx} = P_i + \rho_i v_i^2 \; (= P_f + \rho_f v_f^2),$$

$$h + \frac{1}{2}v^2 - \nu v\frac{dv}{dx} = h_i + \frac{1}{2}v_i^2 \; (= h_f + \frac{1}{2}v_f^2),$$

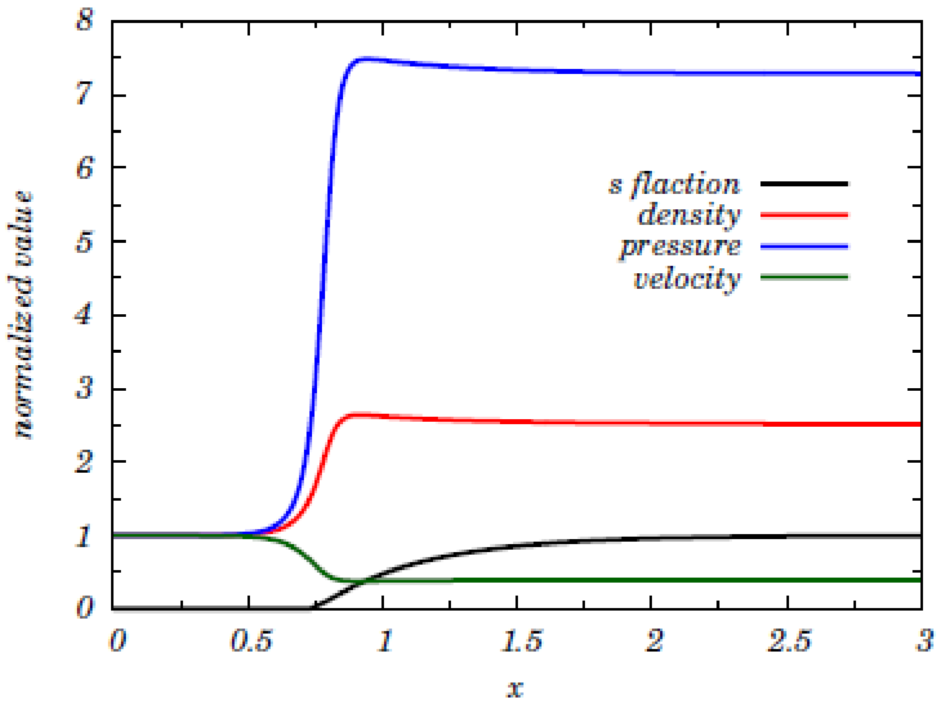
- EOS

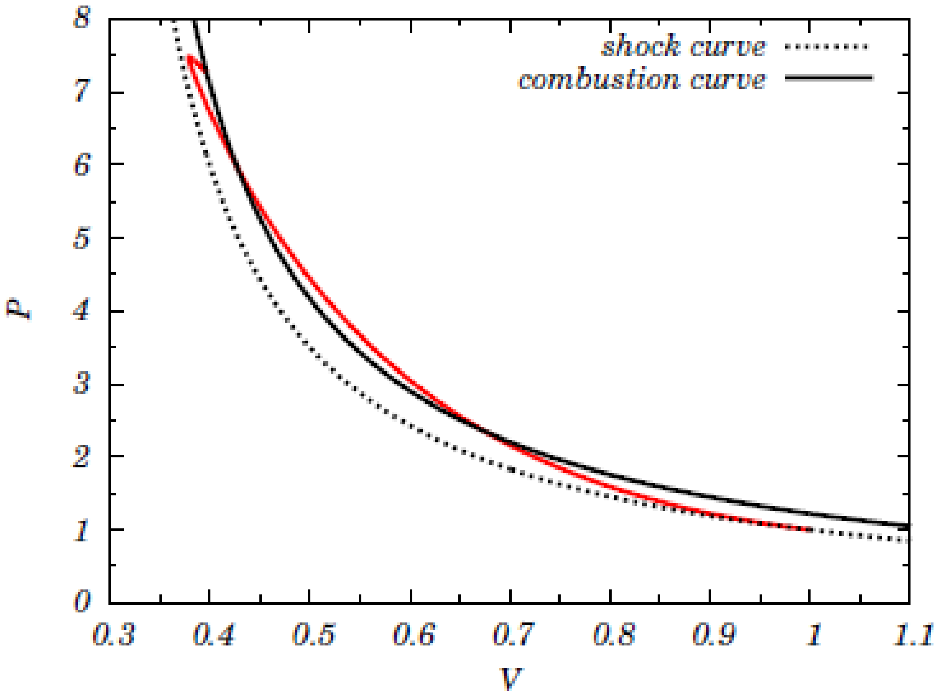
$$P = (\gamma - 1)\rho(\epsilon + \bar{f}_s e),$$

$$\bar{f}_s = f_s / f_{s,f}$$



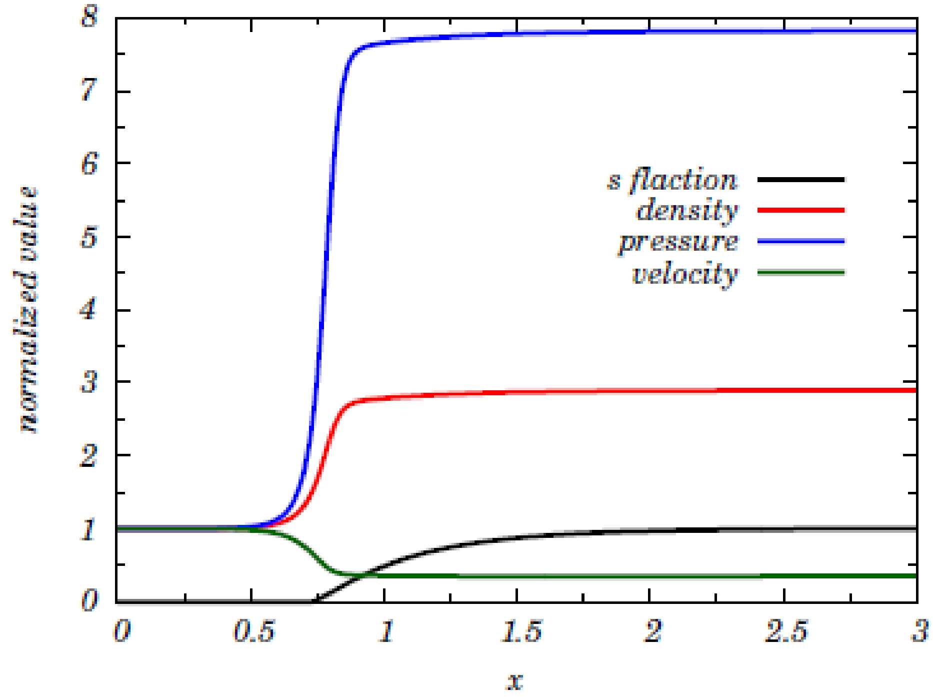
Toy Model (Exothermic case)

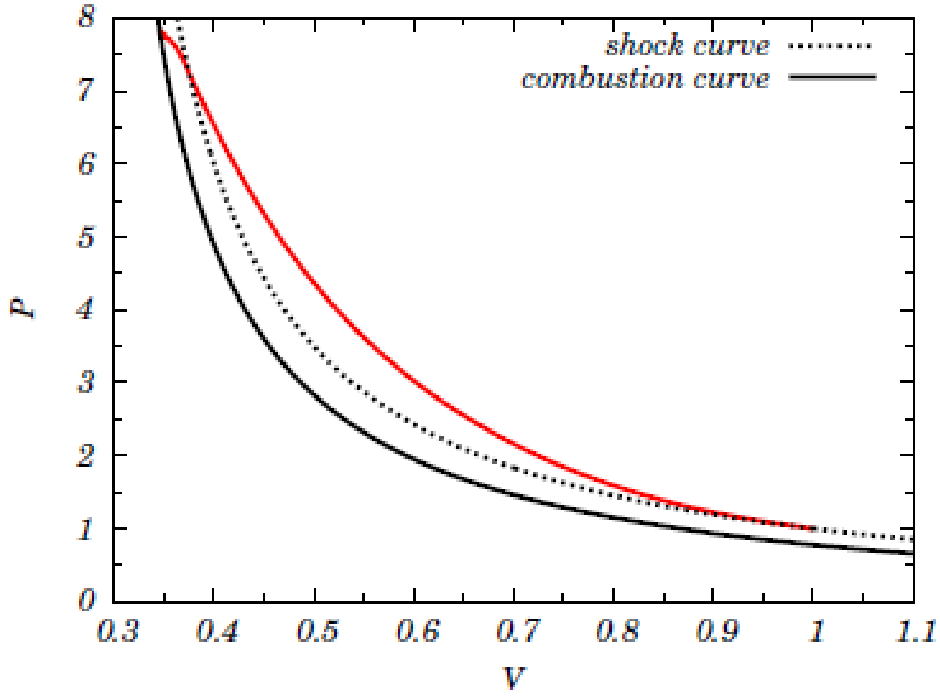




The evolution of physical quantities of shock-induced scenario (left figure). The density reaches critical one and strangeness appears.
In the right figure, P-V diagram is shown.

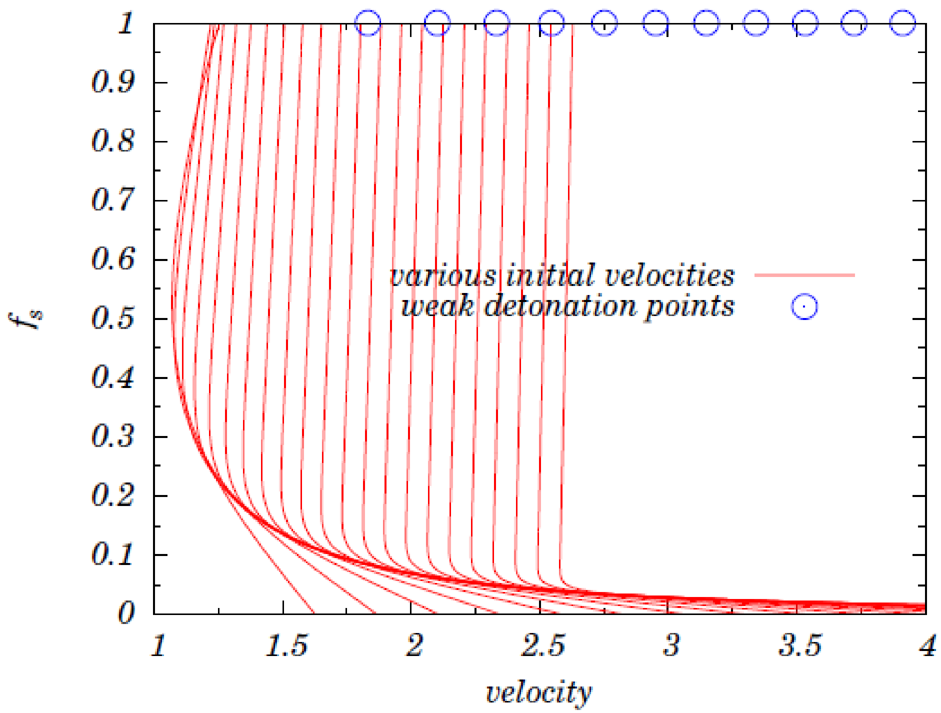
Toy Model (Endothermic case)





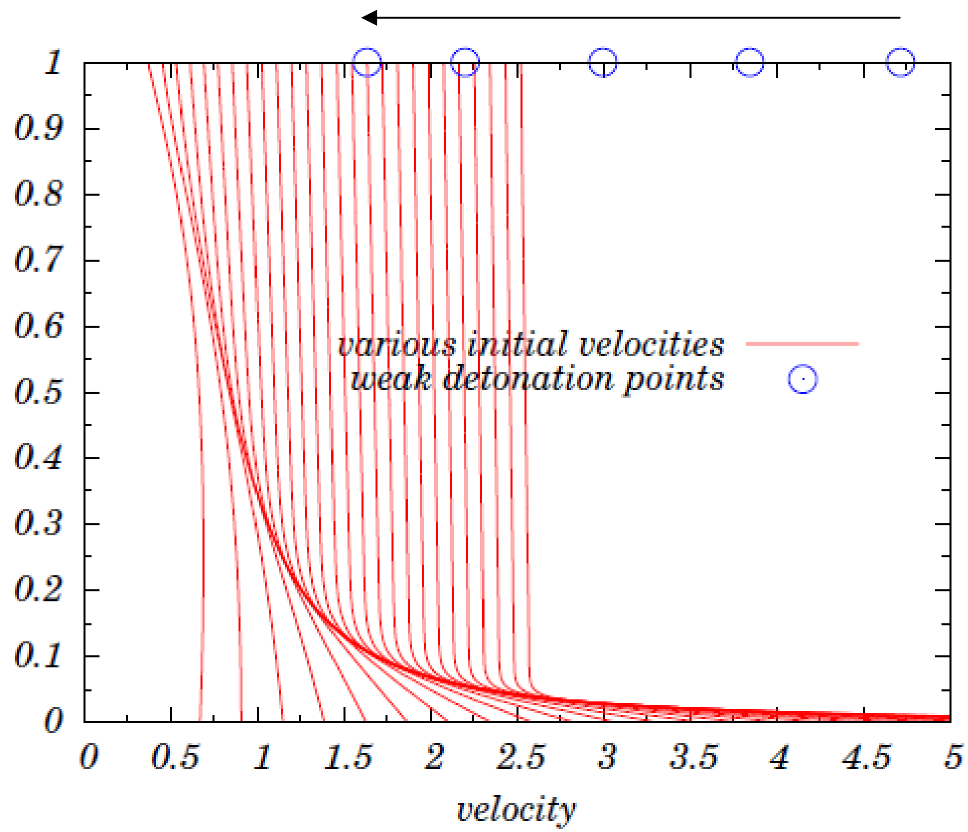
The evolution of physical quantities of teh endothermic case (left gure) and the P-V diagram (right gure).

Possibility of other combustion modes



weak detonation mode is impossible!

Weak detonation points for slower initial velosity

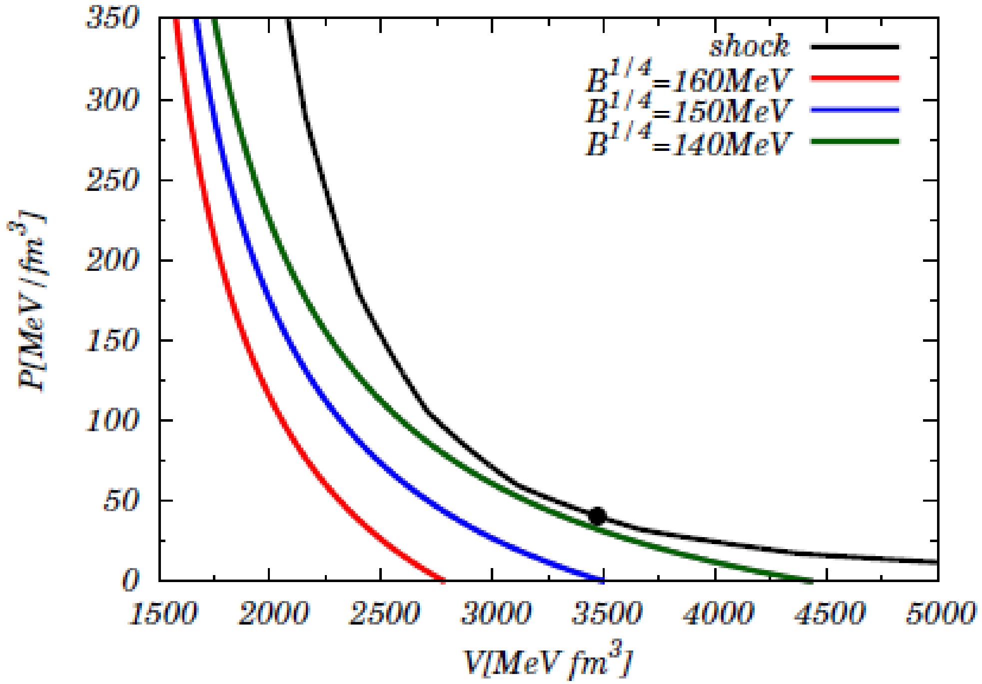


Realistic Case

We use Shen EOS (BM) and Bag Model (3QM)

1. As the bag constant becomes larger, the Hugoniot curve for combustion moves down-wards.

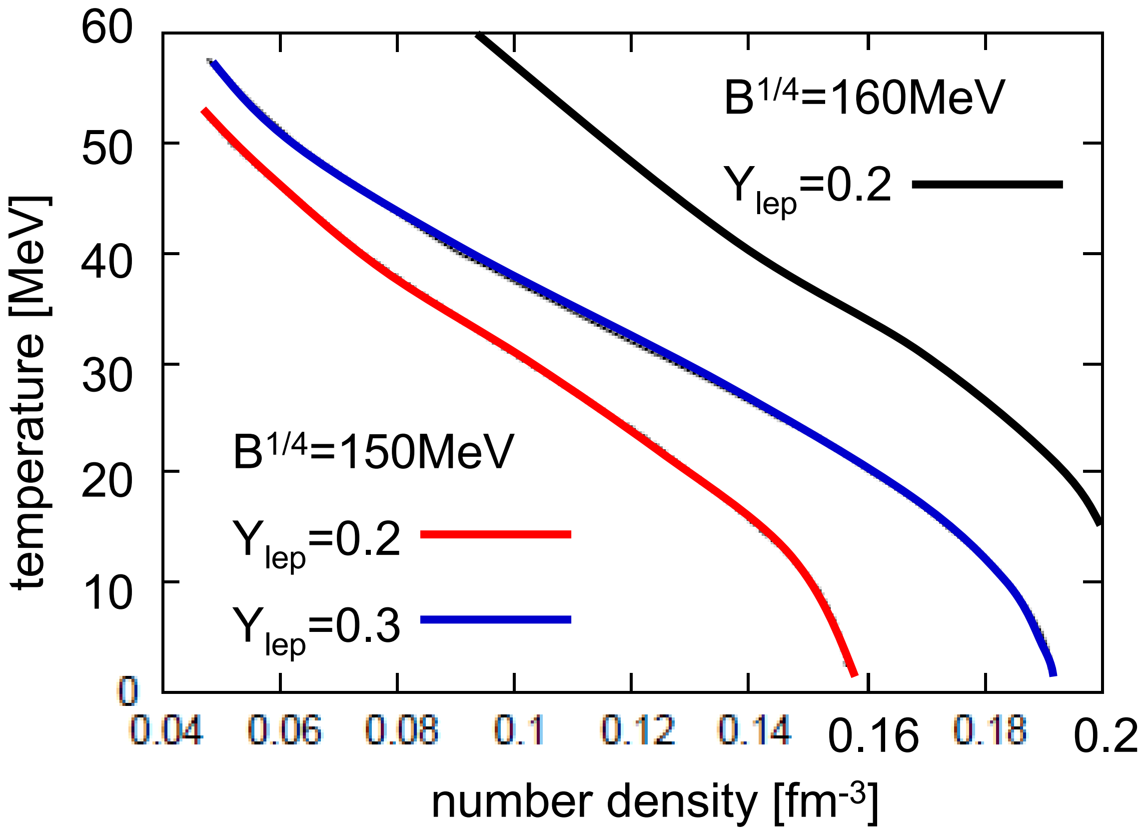
2. For *B*1=4 > 140MeV the Hugoniot curve for combustion runs always below the Hugoniot curve for shock wave.



$T = 0\text{MeV},\ \rho = 5.0 \times 10^{14}\text{g/cm}^3$

Transition density

$$\mu_B = \mu_Q \qquad T_B = T_Q \qquad P_B = P_Q$$

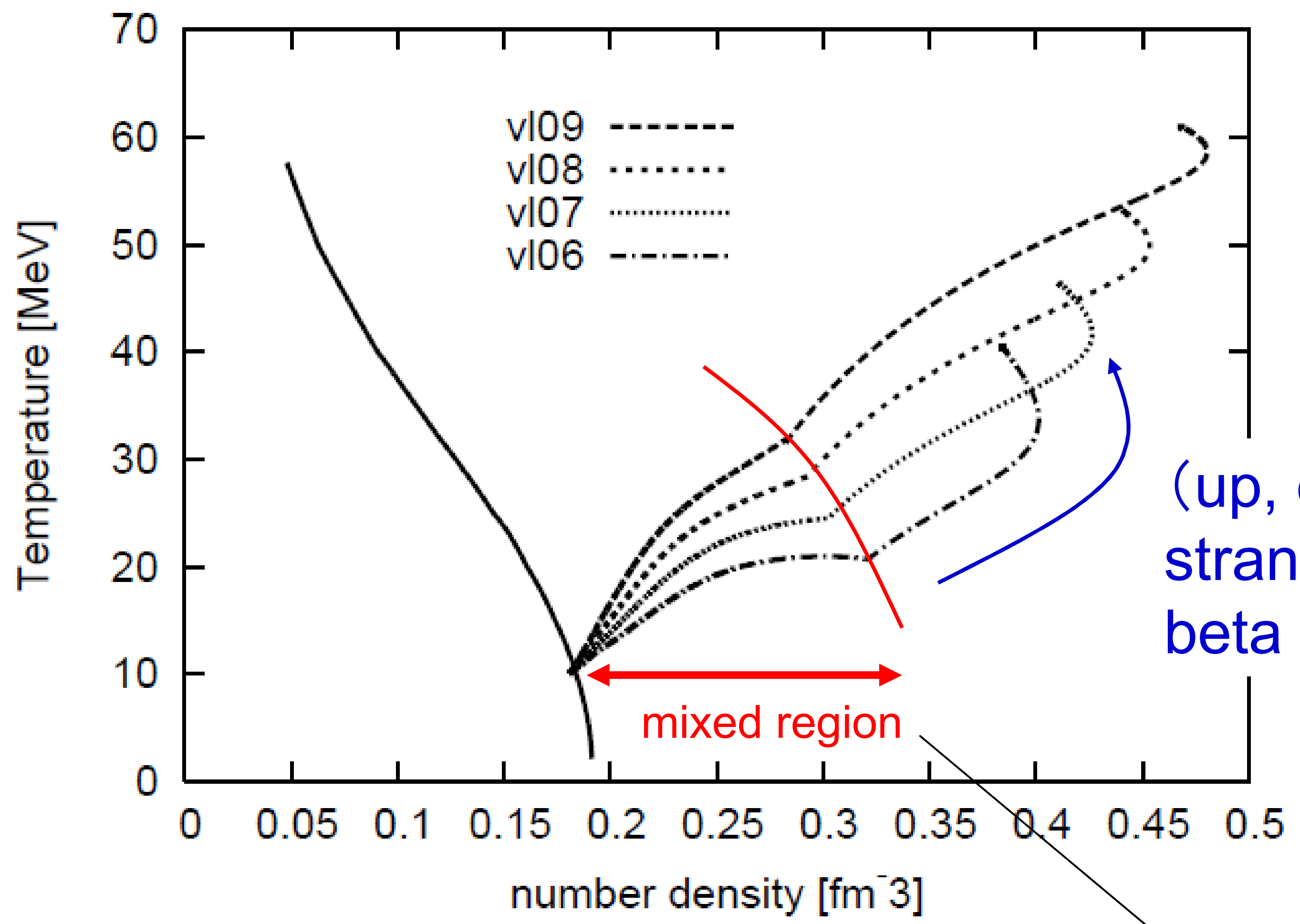


Hadron : Shen EOS

Quark : Bag Model

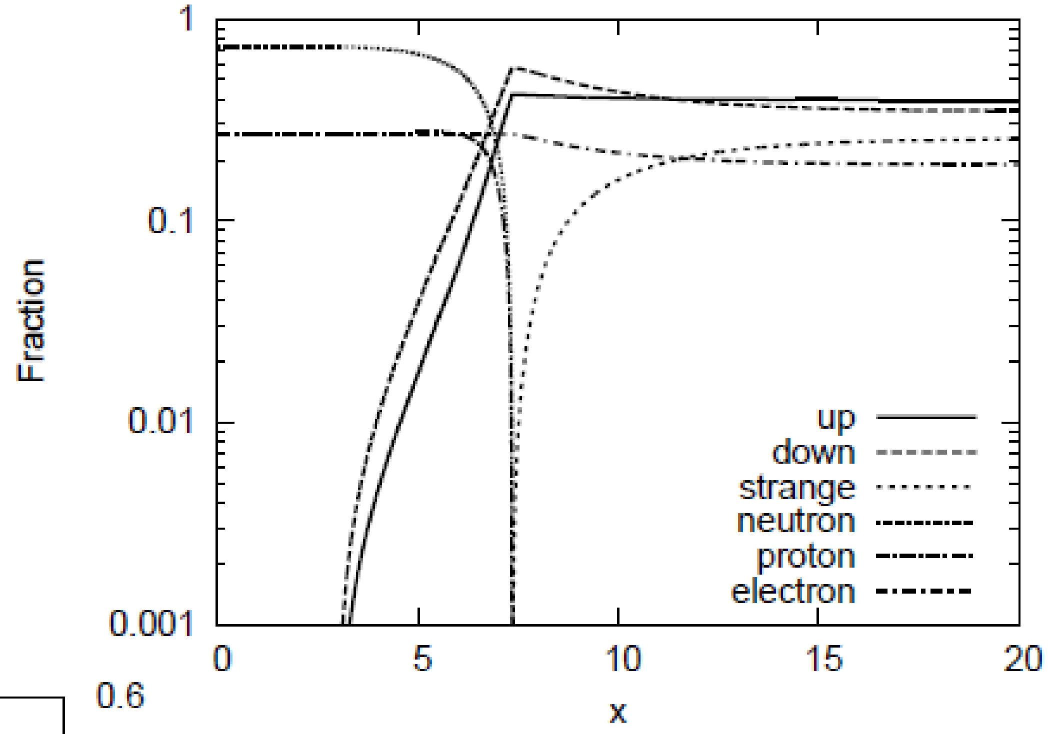
Bag const. ↑ : transition density ↑

Conversion Region



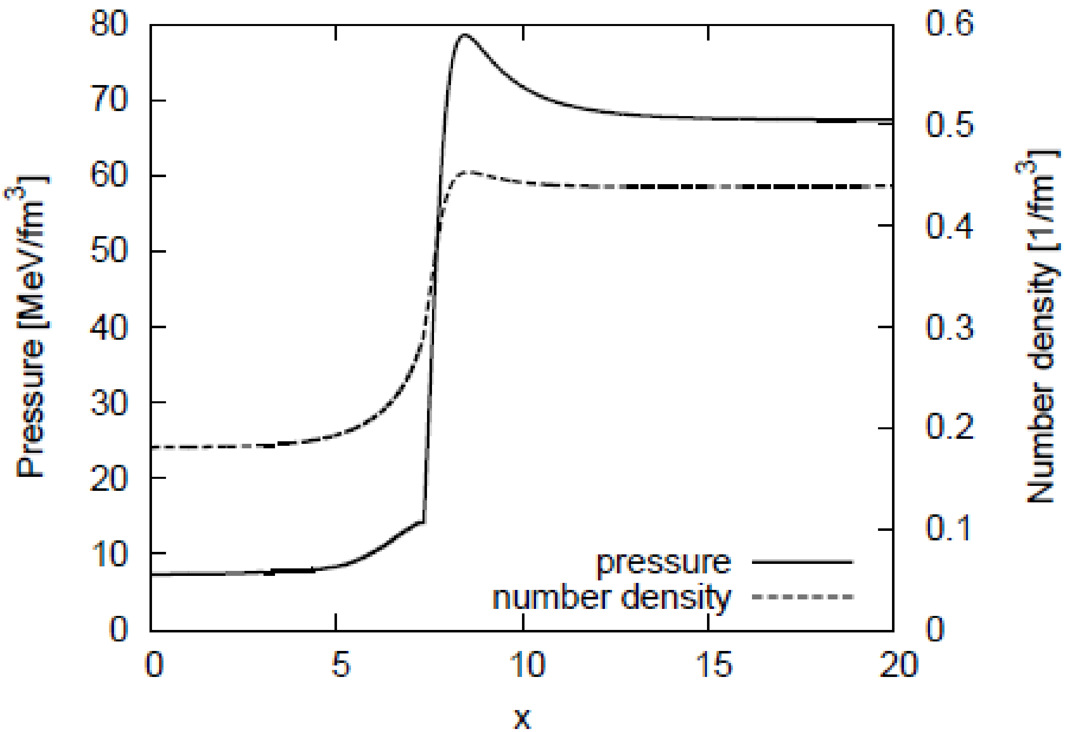
（up, down, strange quark ） beta equilibrium

Slower velocity, Wider region



Fraction evolutions

Physical value evolutions



Summary

- We disscus about structure of combustion from baryonic matter to 3 flavor quark matter in beta-equilibrium.
- The combustion of detonation type is triggered by the critical density (deconfiment).
- In the case Shen EOS and Bag model is used, the hugoniot curve appears in the below part compared by the initial point.
- The ash temperature is about several $\times$10MeV.

Future Work

Calculation of wave propergation dynamically

It is kown well that the exothermic detonation of spherical wave appears in the Jouget point. But in our case, the hugoniot curve is in the bottom region. It is interesting that what type of combustion mode happens.

Various Conversion Scenarios