Hydrodynamical study on the conversion of hadronic matter to quark matter

Shock Induced Conversion
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Diffusion Induced Conversion
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The other work: Core Collapse Supernovae (5/30 FIGSS seminar)

05/10 2016 Astro Coffee

Introduction: Quark Stars

Strange quark Stars

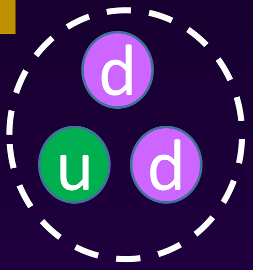
Neutron Stars

Hybrid stars

Pure quark stars

HM：neutrons, protons
(confined quarks)

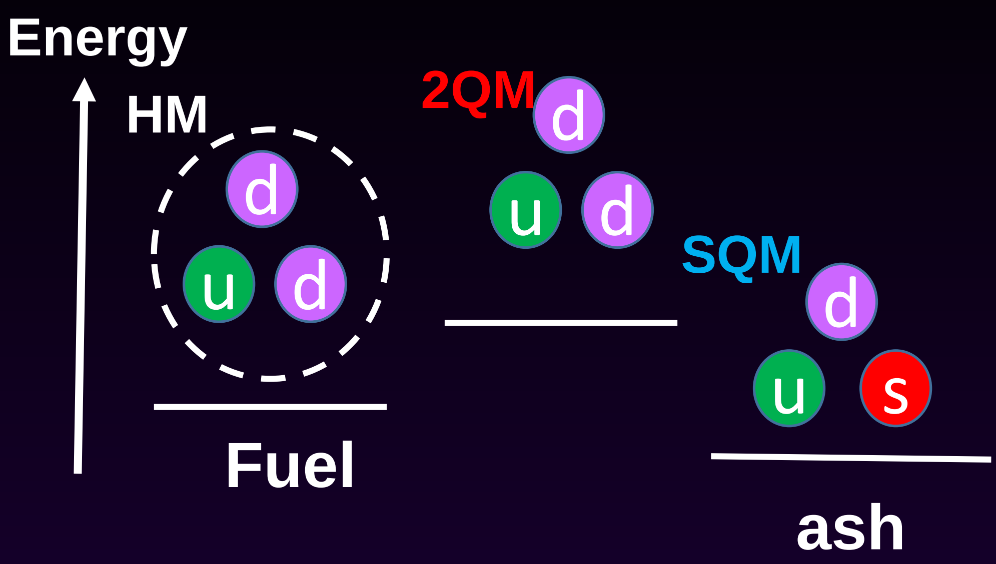
3 quarks are confined
p=uud
n=udd

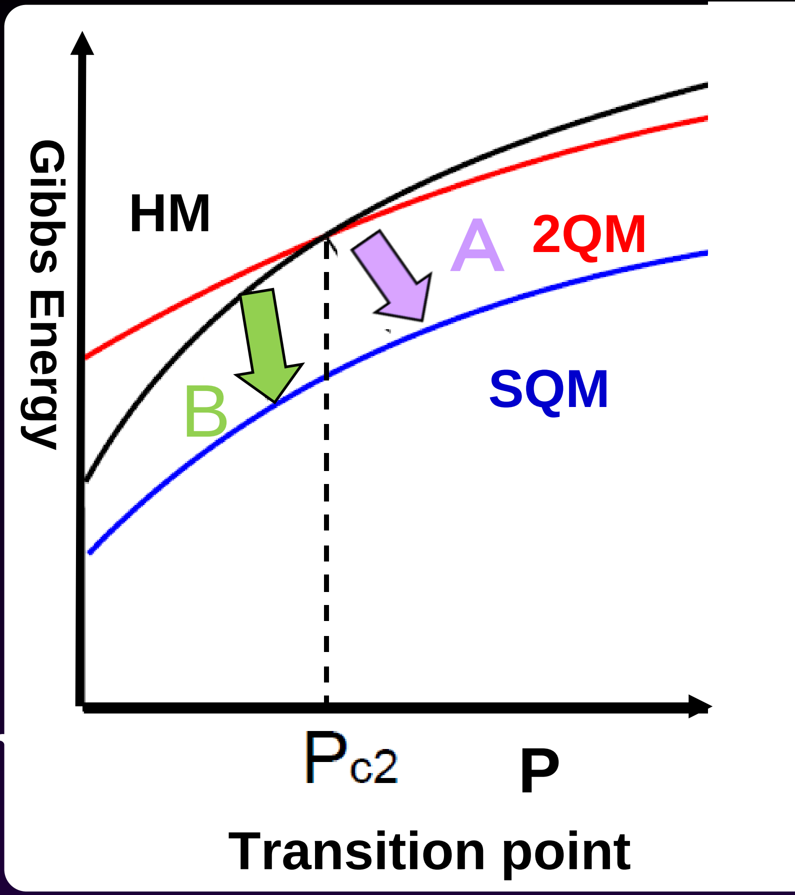


QM :deconfined quarks
(up, down, strange)

- **Mass Radius Relations**
- **different cooling curves**
- **Quark Nova (10^{53} erg neutrinos are emitted)**

Combustion to SQM





C,O ⇒ Ni_{56} (Type Ia SNe)

$C+O_2 \Rightarrow CO_2$ (Terrestrial combustion

A Shock induced Case

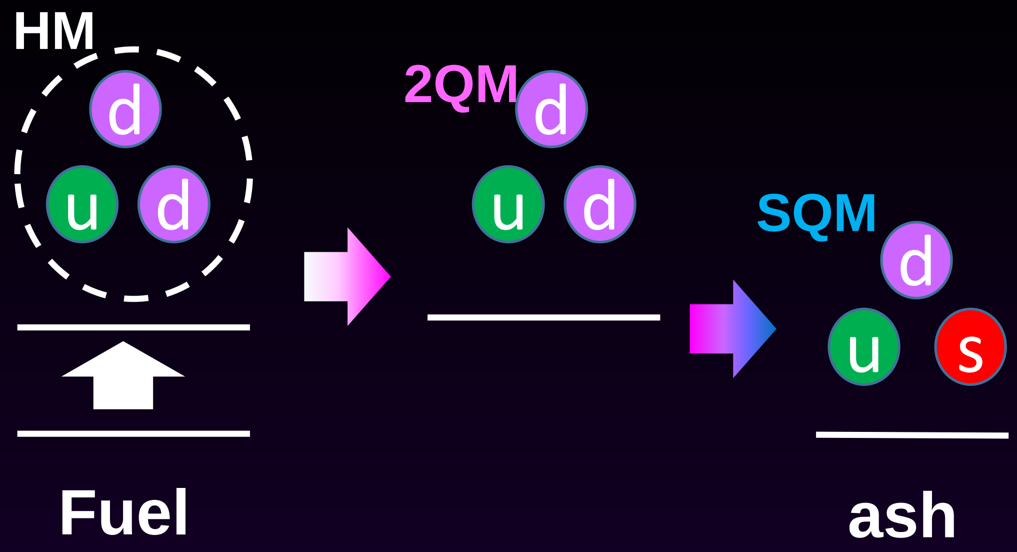
HM ⇒ 2QM ⇒ SQM

B Diffusion induced Case

HM⇒SQM with small strangeness ⇒ SQM

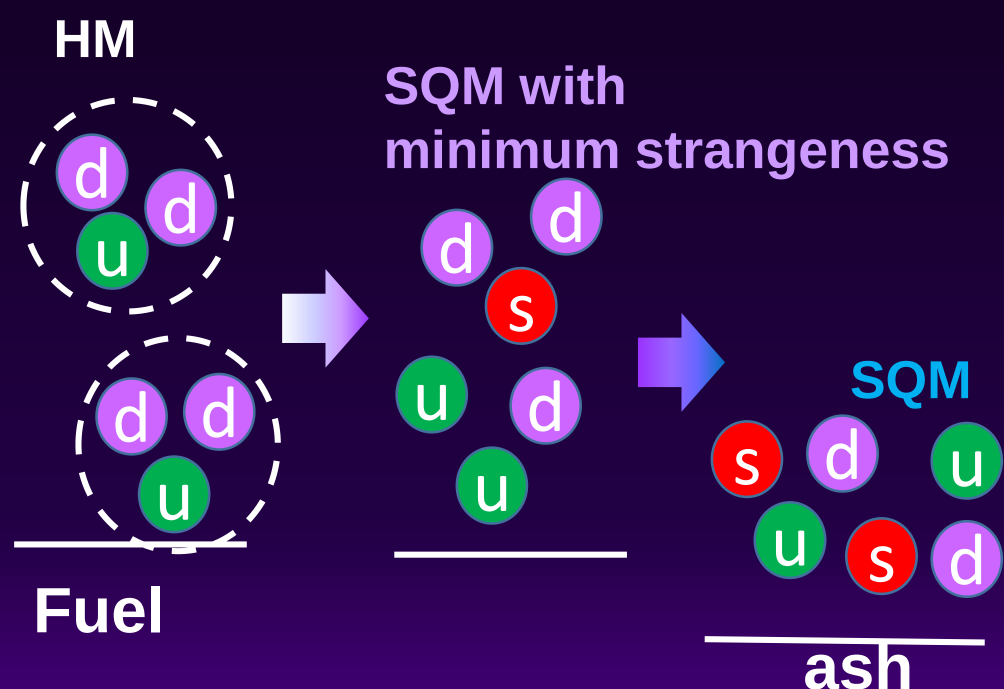
A. Shock induced Case

- Spin Down of (P)NS
- Accretion on (P)NS
- Merger of compact stars

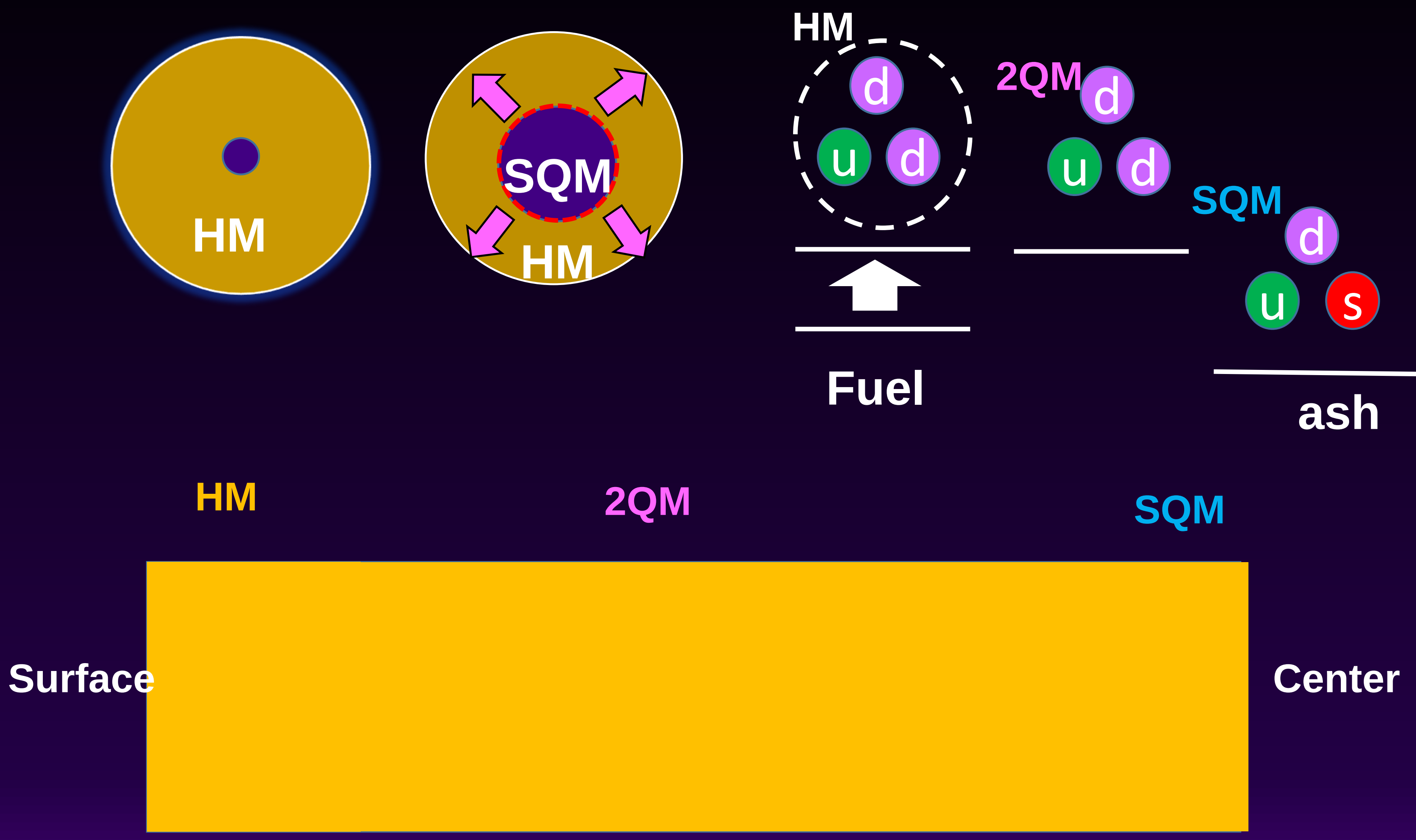


B. Diffusion induced Case

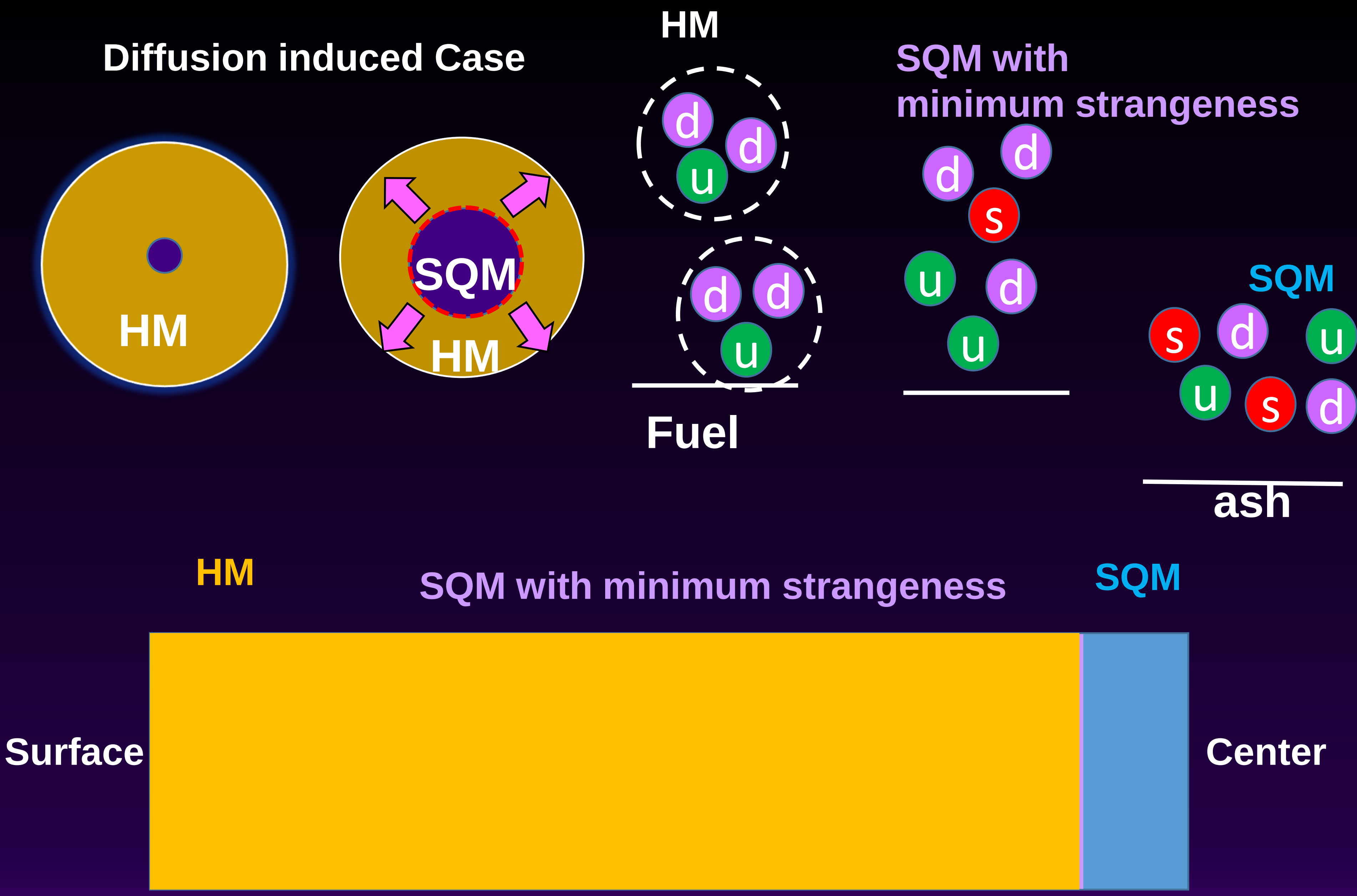
- Following Shock induced
- Capture of strangelets



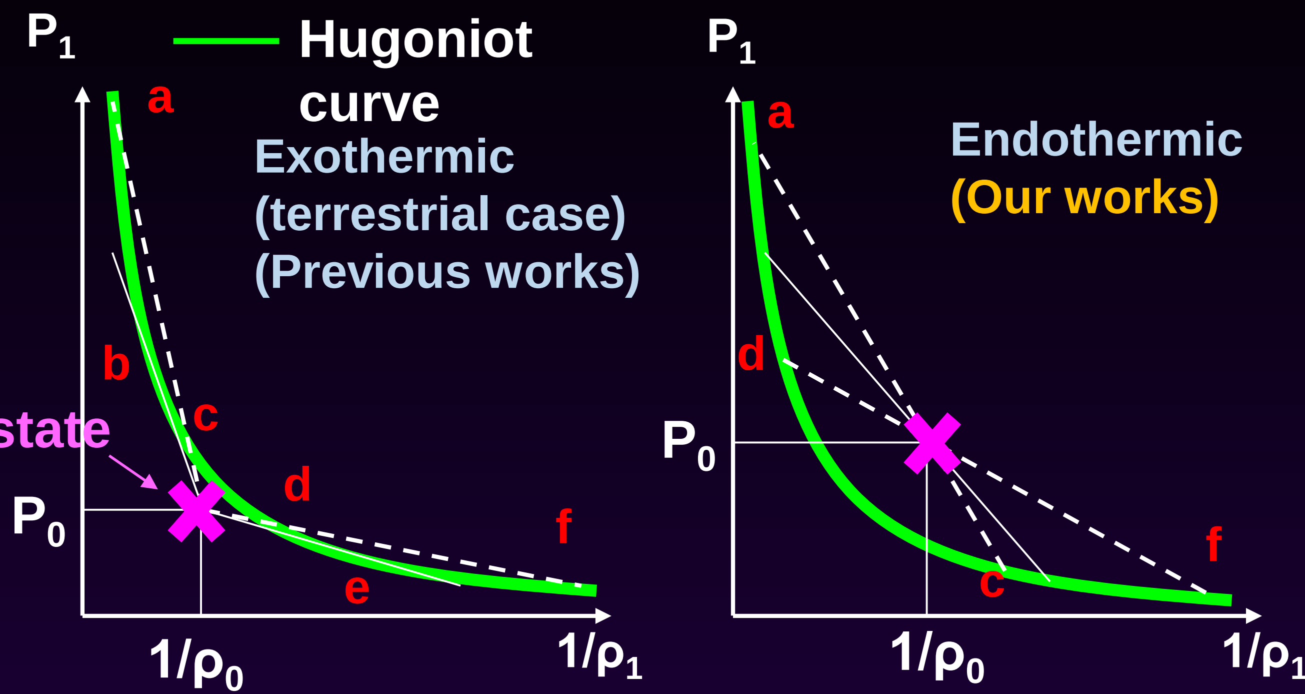
Shock induced Case



Diffusion induced Case



Combustion modes



$u_0 > c_{s0}$

$u_1 < c_{s1}$ a: strong detonation

$u_1 > c_{s1}$ c: weak detonation

$u_0 < c_{s0}$

$u_1 < c_{s1}$ d: weak deflagration

$u_1 > c_{s1}$ f: strong deflagration

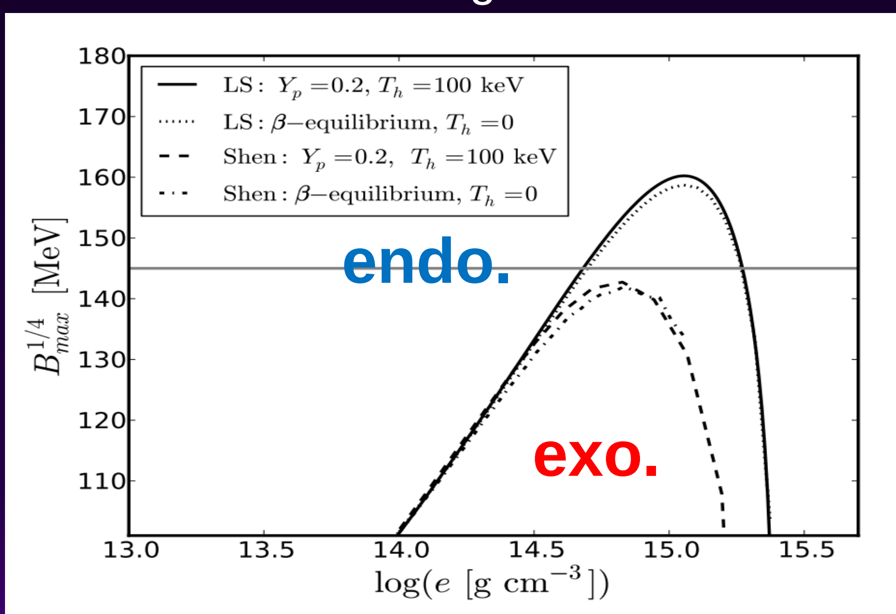
b,e: Jouget point $u_1 = c_{s1}$

Previous works (Olint '87, Benvenuto' 89 Mishustin '14, Drago '15)

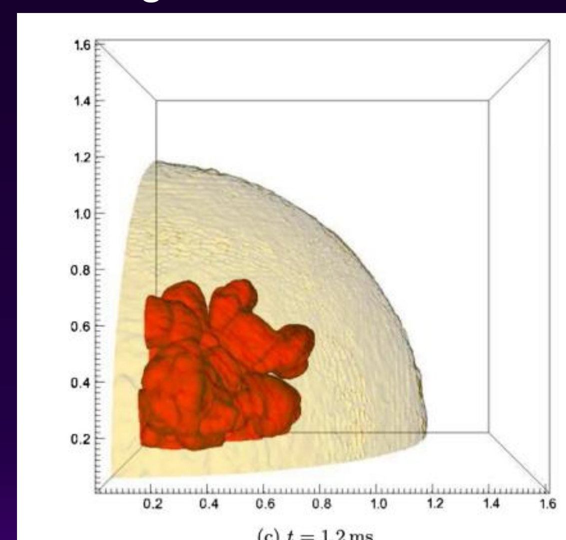
- Structures inside the front are not solved.

- Endothermic case is neglected in reference to terrestrial combustion

Herzog '11



Pagliara '13



Previous works

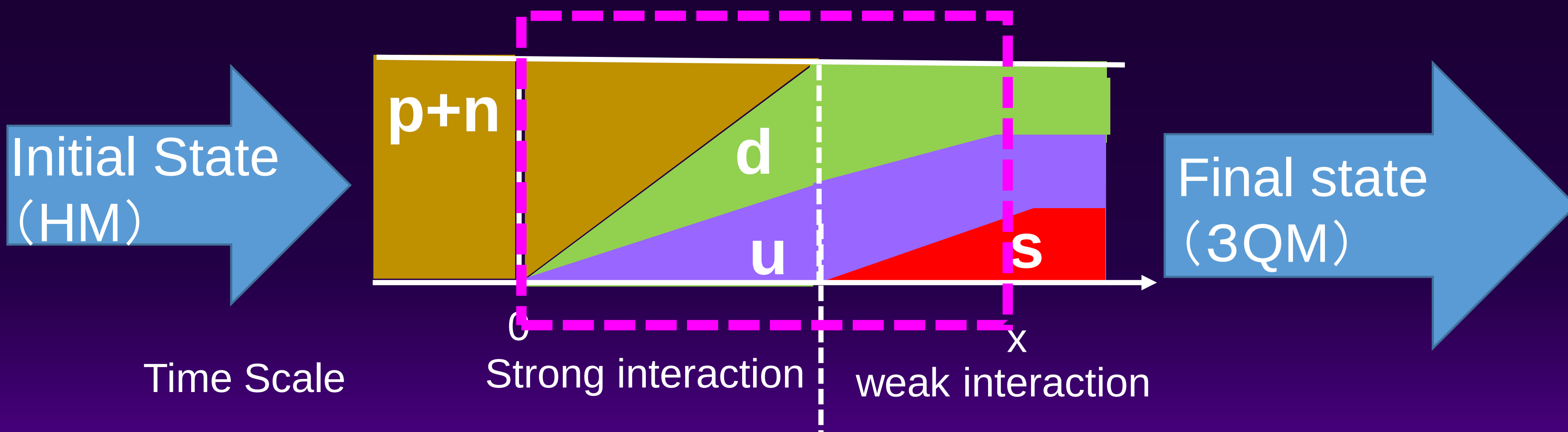
- Structures inside the front are not solved.
- Endothermic case is neglected due to a strained interpretation.

Motivation of Our works:

1, What happens inside combustion front when QS is formed?

2, Which combustion modes are realized for the two scenarios.

3, **List up all possible structures inside the front for wide ranges of parameter s in EOS of QM and initial condition.**



QM EOS (Farhi et al. 84, Fischer et al. 10)

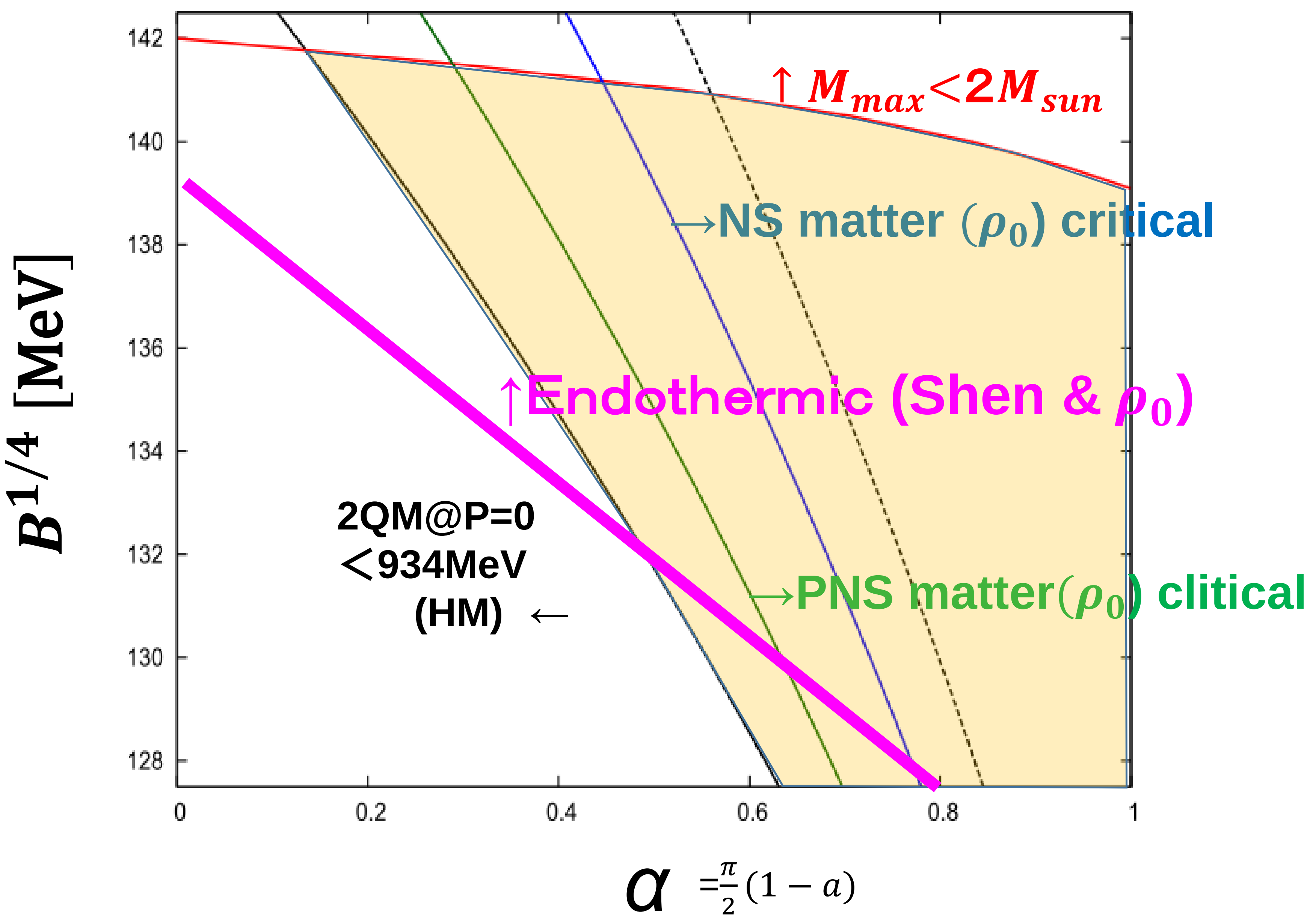
MIT Bag Model
Larger Bag constant ⇒softer
Larger Strong Coupling Constant α ⇒stiffer

$$P = \sum_{f=u,d,s} P_f - B$$

$$\epsilon = \sum_f \epsilon_f + B.$$

$$P_f(\alpha_s) = P_f(0) - \left[\frac{7}{60}T^4\pi^2\frac{50\alpha_s}{21\pi} + \frac{2\alpha_s}{\pi}\left(\frac{1}{2}T^2\mu_f^2 + \frac{\mu_f^4}{4\pi^2}\right)\right]$$

Parameters in QM EOS



Model Shock Induced case

- 1D Steady flow
- Conservation Eq. of Hydrodynamics with viscos terms
- β equilibration ($\tau = 10^{-8}$s)

$$u\frac{df_s}{dx} = \frac{f_s^{eq} - f_s}{\tau}$$

$$\rho v = \text{Const.}$$

$$P + \rho v^2 - \nu\frac{dv}{dx} = \text{Const.}$$

$$h + \frac{1}{2}v^2 - \frac{\nu}{\rho}\frac{dv}{dx} = \text{Const.}$$

・PNS HM

(Shen EOS '11)

$Y_{lep} = 0.3$

$T_i = 10\text{MeV}$ $\rho_i = 3\times10^{14}\, g/cm^3$

・QM (T.Fischer 10)

Bag Model（B:Bagconstant）＋

Strong interaction(α: coupling c.)

・Mixed Phase in the front

・Volume Fraction of QM and HM

QM: HM= r :（1-r）

・Global Charge Neutrality

$$\mu_p = 2\mu_{up} + \mu_{dn}$$

$$\mu_n = \mu_{up} + 2\mu_{dn}$$

$$P^H = P^Q$$

$$T^H = T^Q$$

Complete-Deconfinement Case

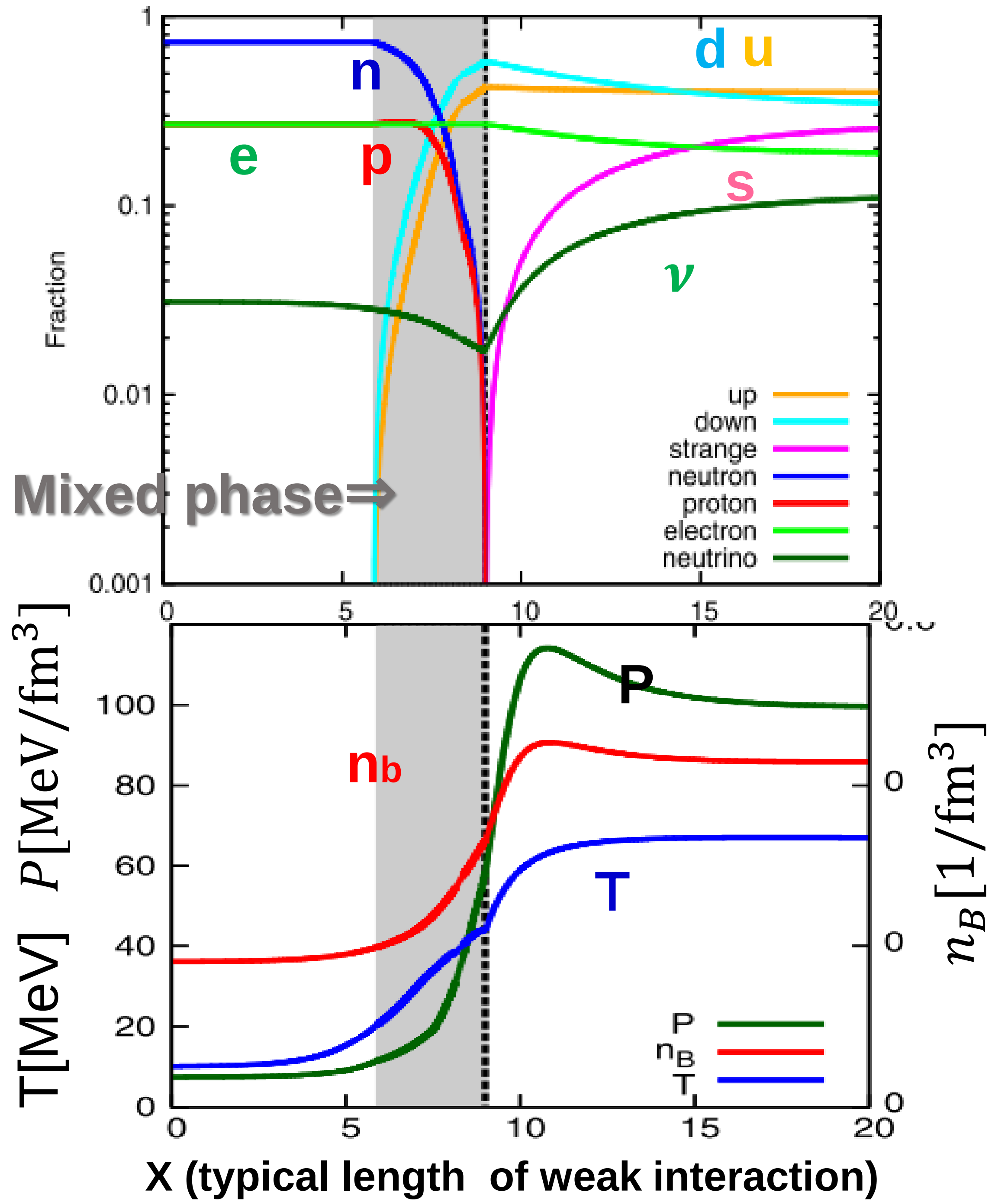
$B^{1/4} = 140$ [MeV]
$\alpha_s = 0.4$
$M_i = 3.0$

①shock compression
HM(x<6)

②deconfinement starts
@x~6 HM& 2QM

③deconfinement finishes
@x~9 2QM

④3QM toward β eq.
(9<x<20) 3QM



Incomplete-Deconfinement Case

$B^{1/4} = 140$ [MeV]

$\alpha_s = 0.6$

$M_i = 3.0$

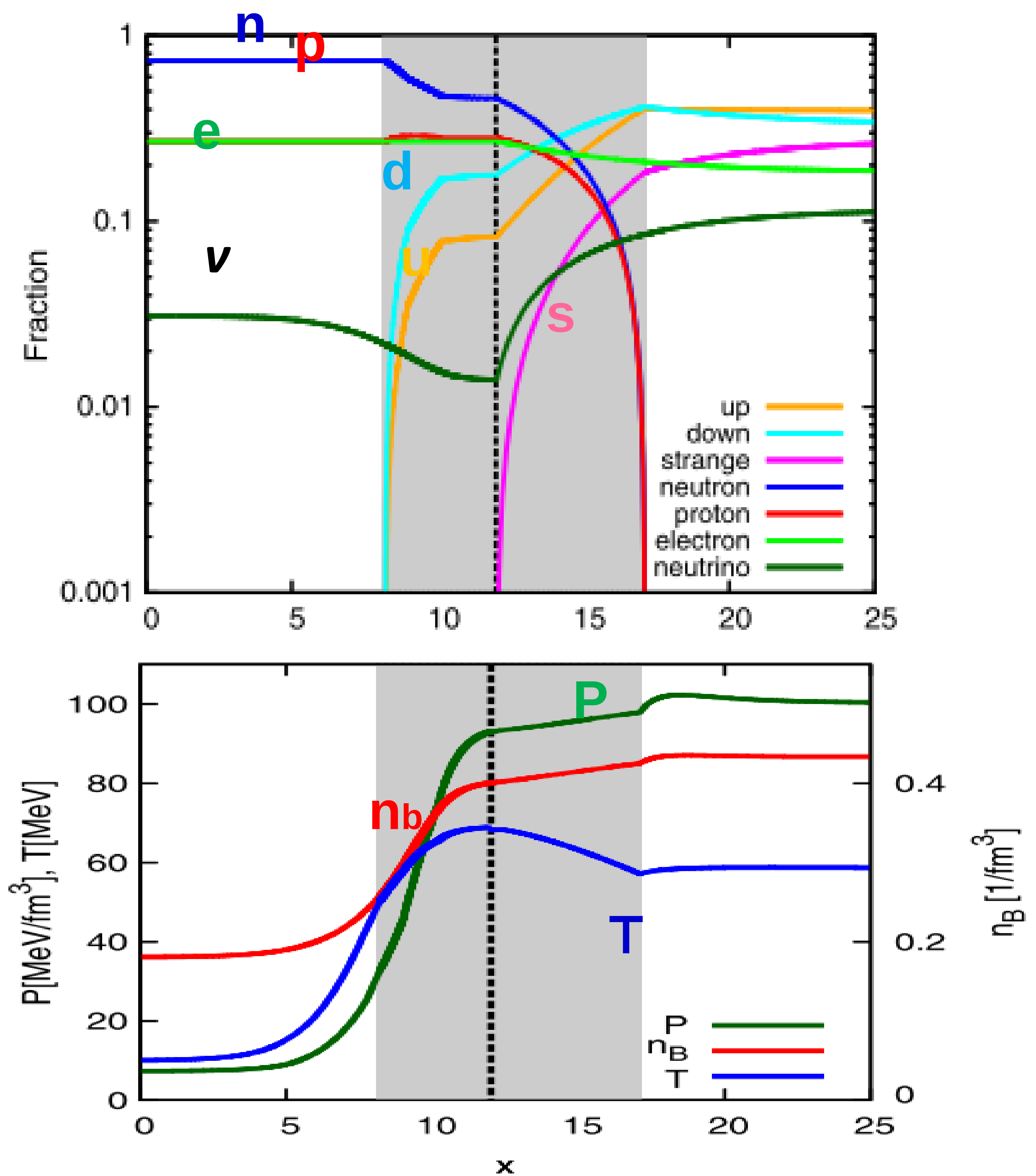
①shock compression HM(x<7.5)

②deconfinement starts @x~7.5 HM& 2QM

③shock compression stop and s quarks appear @（x~12）

③deconfinement finishes @x~12 3QM

④3QM toward β eq. (18<x<30) 3QM



2, Model diffusion induced case

- **1D Steady flow（local analysis）**
- **Conservation Eq. of Hydrodynamics**
- **Diffusion Equation of Strange quarks**

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

$$\rho v = \text{Const.}$$

$$P + \rho v^2 = \text{Const.}$$

$$h + \frac{1}{2}v^2 = \text{Const.}$$

・PNS HM

(Shen EOS ’11)

$Y_{lep} = 0.3$

$T_0 = 10MeV$ $\rho_0 = 3\times10^{14}\, g/cm^3$

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$$\mu_p = 2\mu_{up} + \mu_{dn}$$

$$\mu_n = \mu_{up} + 2\mu_{dn}$$

$$P^H = P^Q$$

$$T^H = T^Q$$

Result

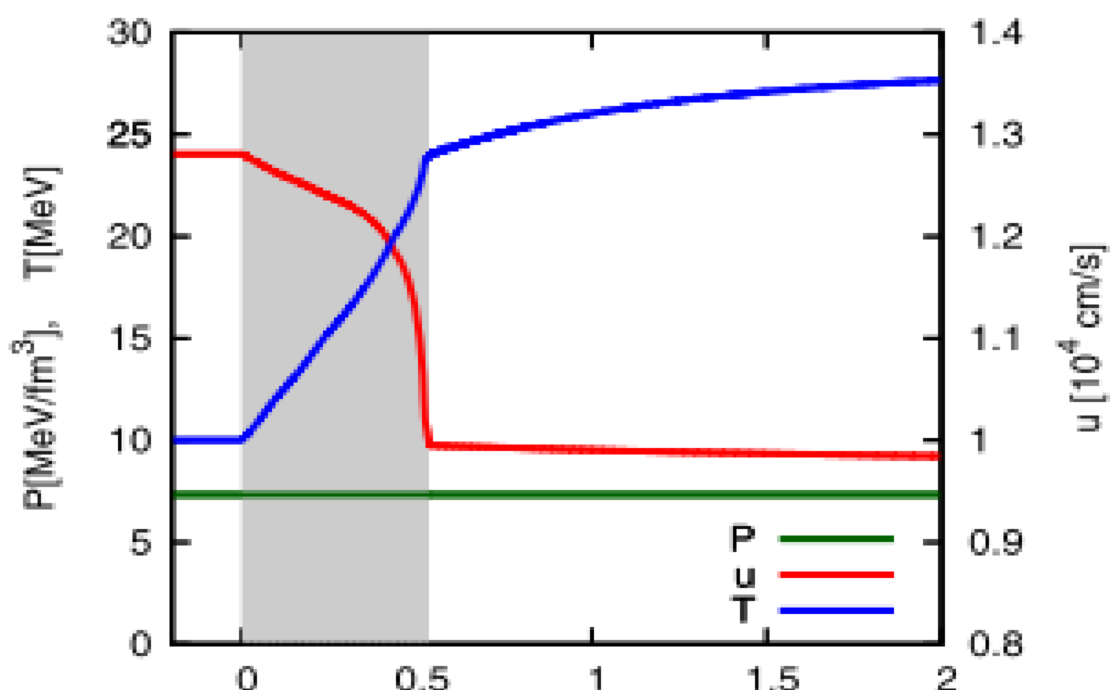
$(B^{1/4} = 140\ [\mathrm{MeV}]\ \ \alpha_s = 0.4\ )$

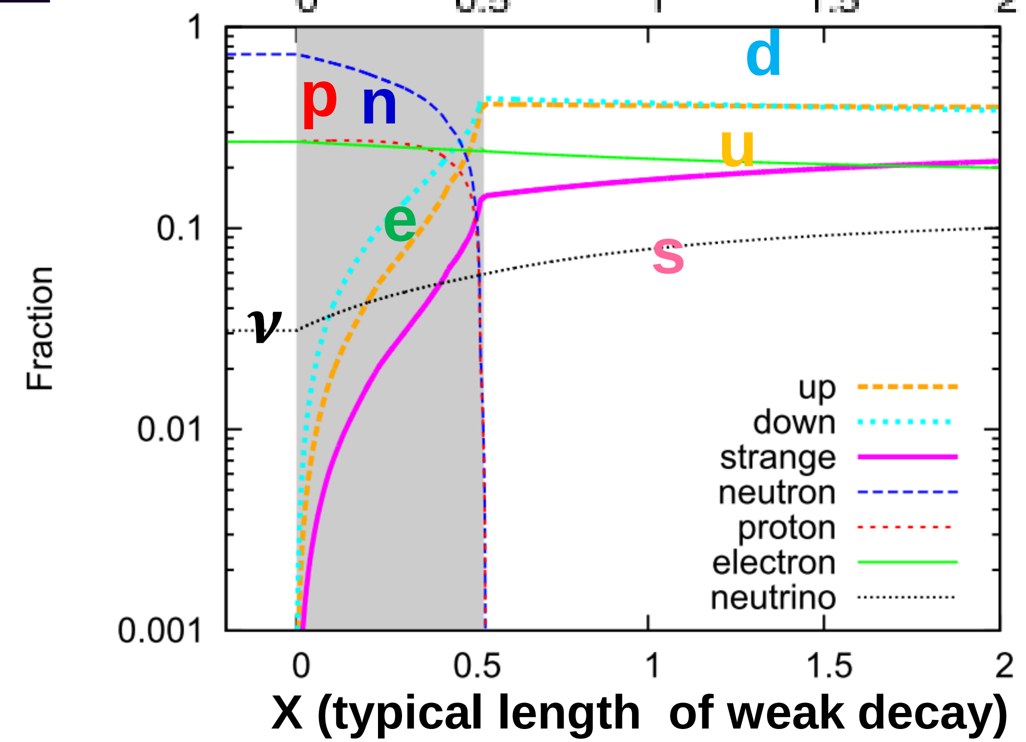
x=0 start of deconfinemet

x~0.5 end of deconfinement

x>0.5 equilibration to 3QM

$u_i = 2.3\ *\ 10^4\ \mathrm{cm/s}$

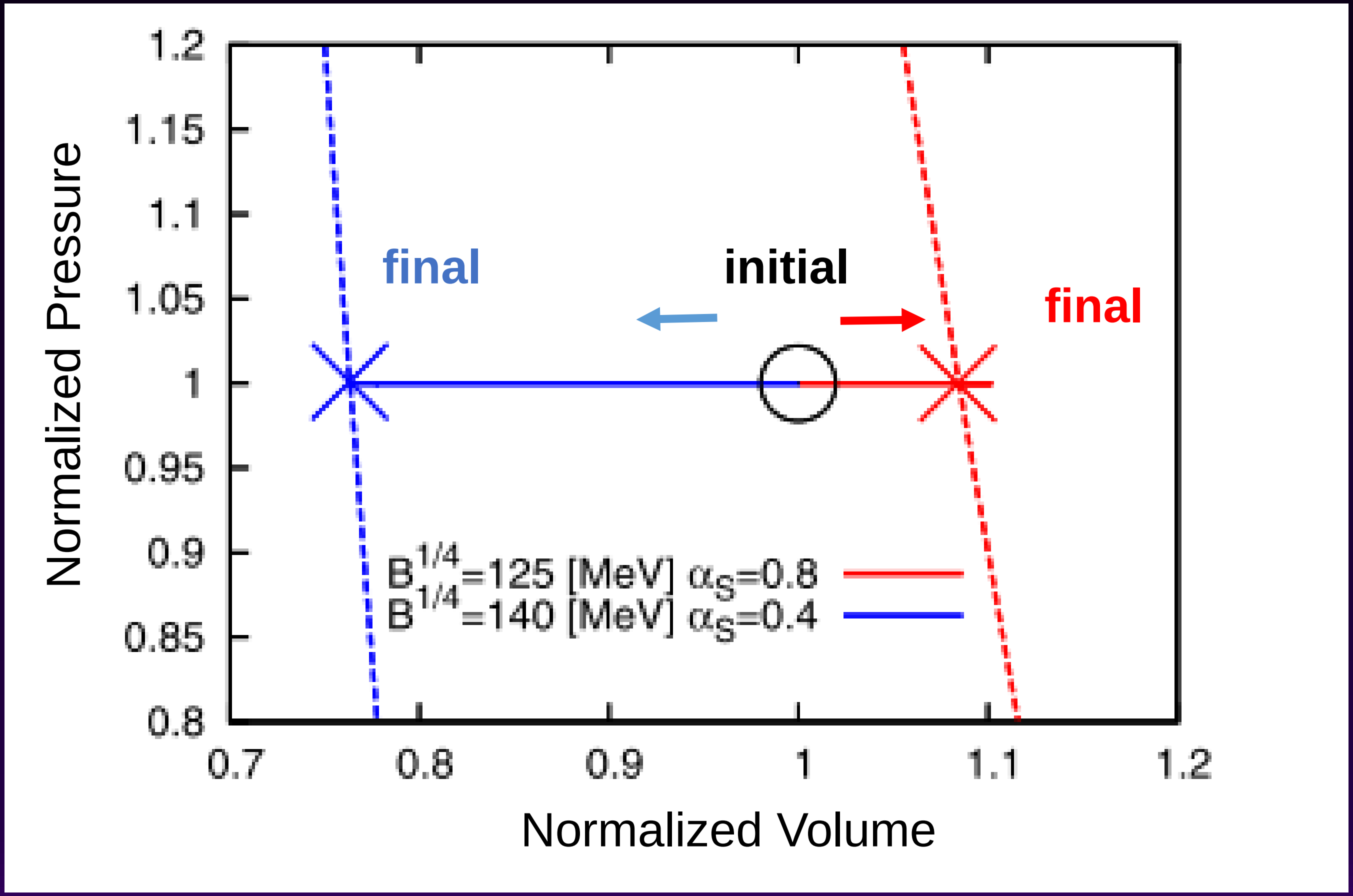




Result :Evolution of component in the front
$(B^{1/4} = 140\ [\mathrm{MeV}]\ \ \alpha_s = 0.4\ )$

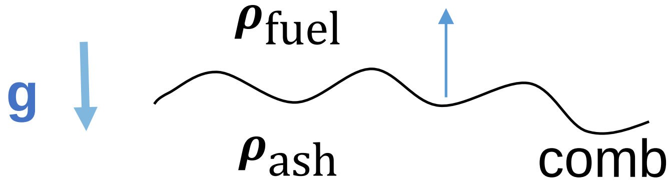
Endothermic
$B^{1/4} = 140\ [\mathrm{MeV}]\ \ \alpha_s = 0.4$

Exothermic
$B^{1/4} = 125[\mathrm{MeV}]\ \ \alpha_s = 0.8$



Both cases show weak deflagrations

STABILITY OF THE COMBUSTION FRONT



$\alpha = \rho_{\rm ash}/\rho_{\rm fuel}$ **<1 exothermic**
>1 endothermic

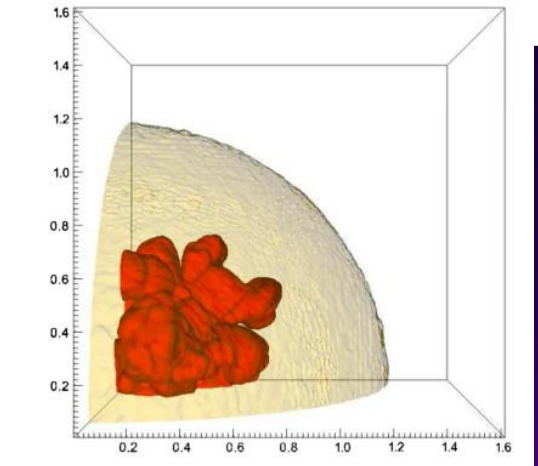
combustion front $y = f(x,t)$

x

$$\omega = \frac{1}{1+\alpha}\left(-1 \pm \sqrt{\frac{1}{\alpha} + 1 - \alpha + g\frac{(1-\alpha^2)}{v_f^2 k} - \sigma\frac{(1+\alpha)k}{\rho_f v_f^2}}\right) v_f k$$

gravity surface effect

α<1 exothermic ⇒ ω real part>0 (σ=0) ⇒unstable (previous works)
α>1 endothermic ⇒ω real part<0 (any σ) ⇒stable （our work）



(c) $t = 1.2\,\mathrm{ms}$

3D simulation
in Exothermic regime
(Pagliara '13)

⇒spherical propagation in endothermic?

Summary

We have cleared the structure of combustion front.

●**The type of combustion**

- **diffusion induced case: weak deflagration**
- **shock induced case: strong detonation**

● **Even in Endothermic Case, Combustion can take place !!**

- **Conversion front of deflagration is stable in Endothermic Case**

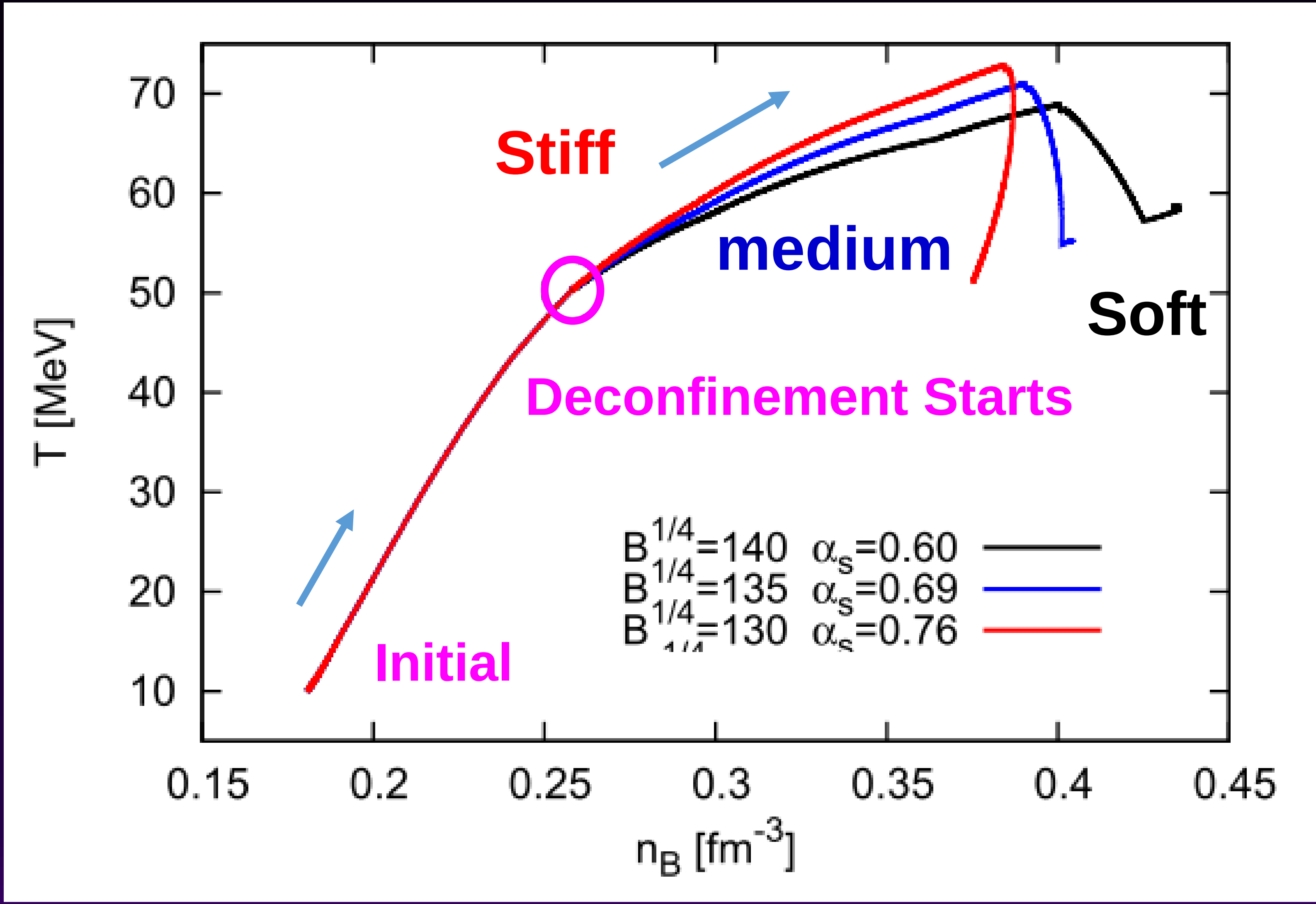
● There are some conversion patterns

- Complete- or Incomplete- deconfinement

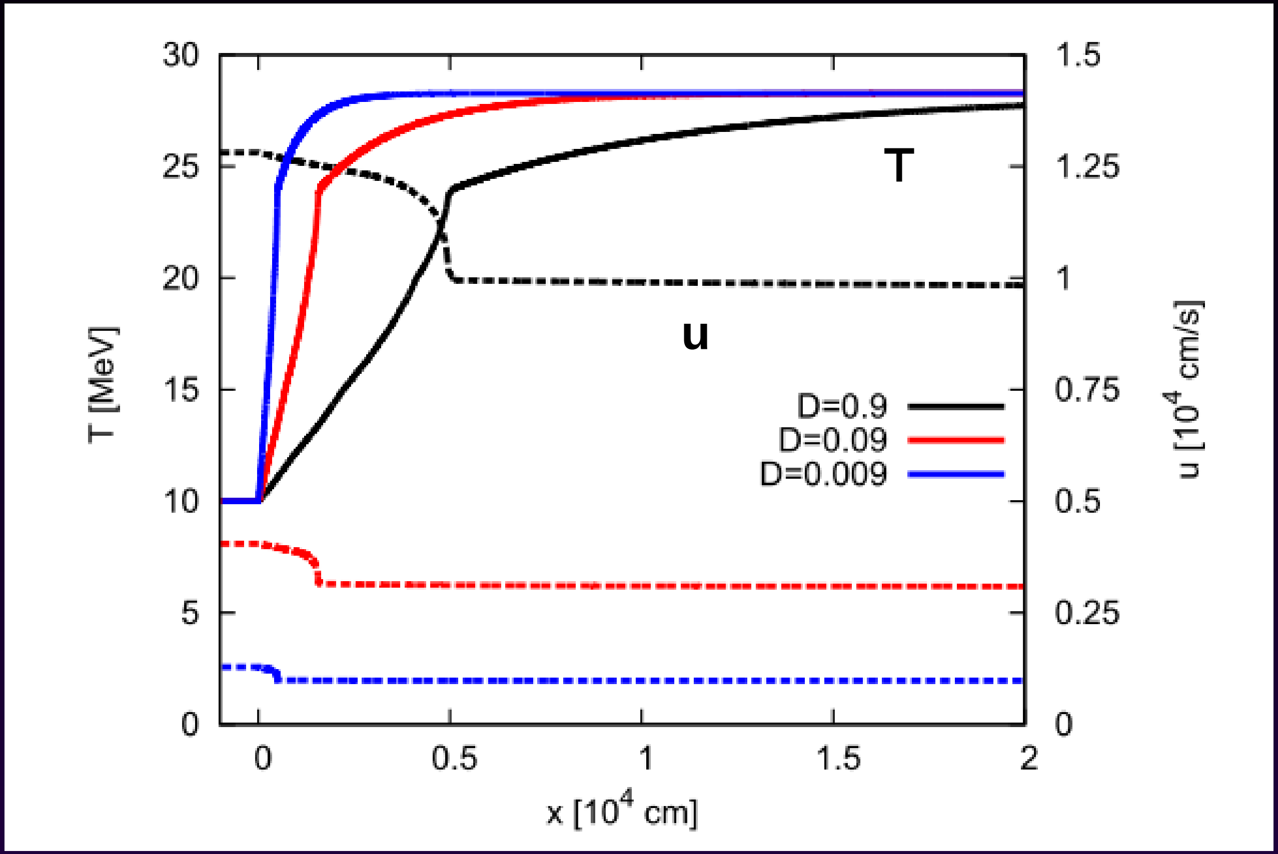
Future Works

- **dependence of Surface tension, EoS of HM（underway）**
- **Conversion from Hyperonic to 3QM and 3QM to HM**
- **Dynamical Simulation from NS to QS.**

EOS dependence



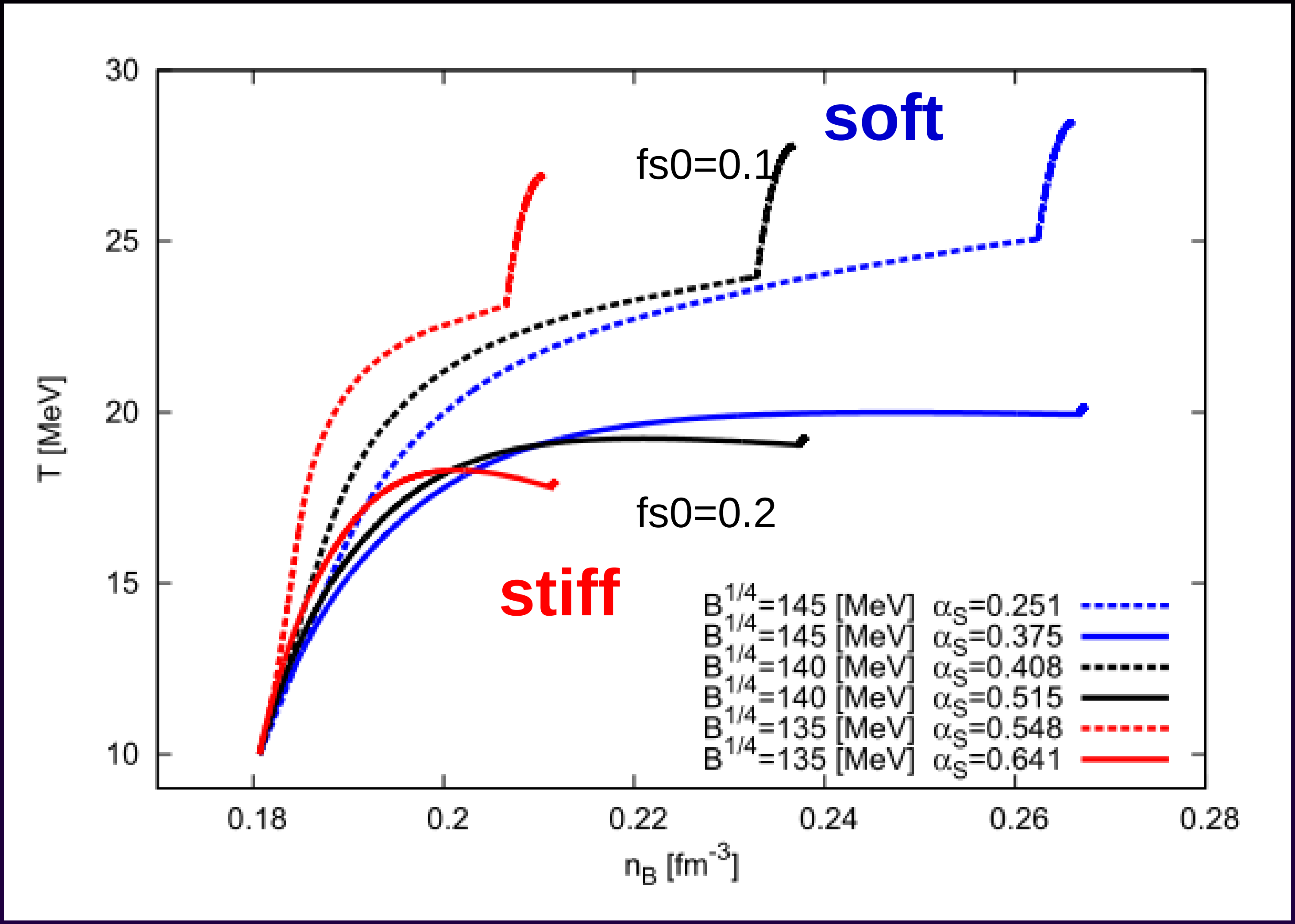
Diffusion Constant Dependence



$u_i \propto \sqrt{D} \propto \mu/T$

Front velocities are highly dependent on T & ρ

EOS dependence



$u_i \sim 4.3 \times 10^4$ cm/s for fs=0.1

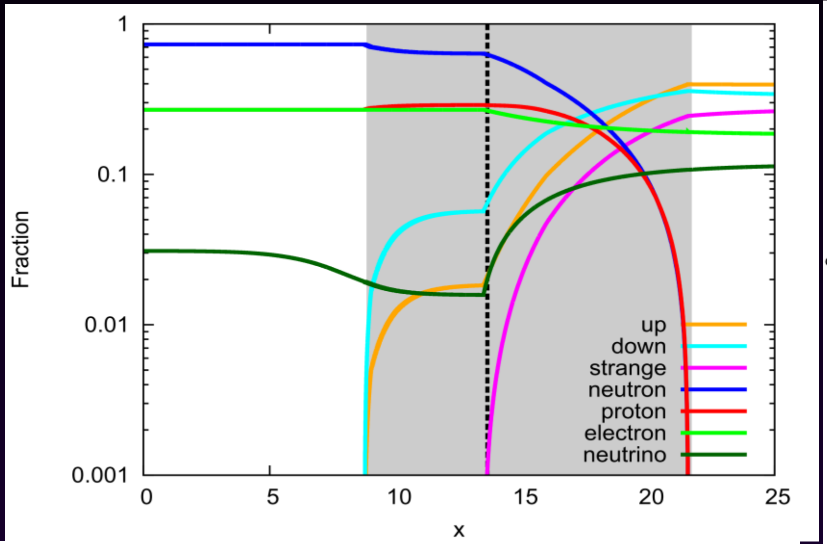
$u_i \sim 11.6 \times 10^4$ cm/s for fs=0.2

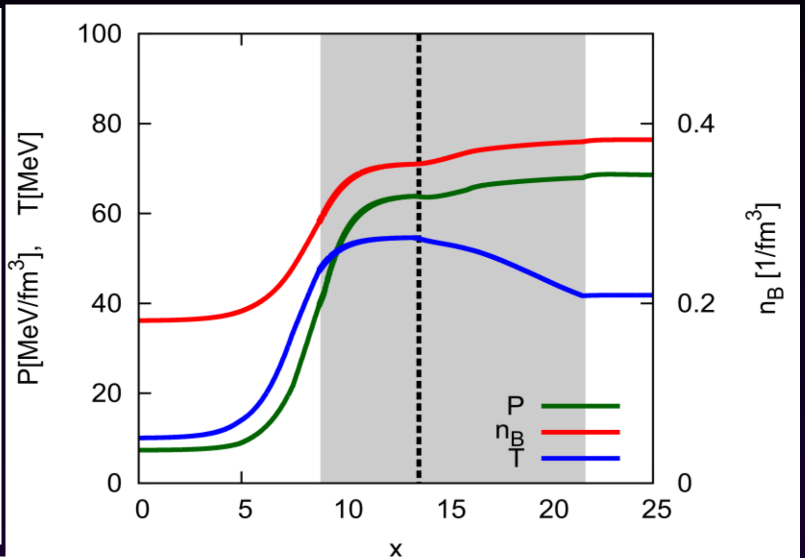
.Combustion velocity depends on Fraction of Strangeness at x=0.

Relativistic scheme

$B^{1/4} = 140$ [MeV], $\alpha_s = 0.6$ and $M_i = 2.5$

Non-rela





Rela