Conversion of hadronic matter to quark matter in compact stars

[1] Shock Induced Conversion: PRD 93, 043018 (2016)

●**[2] Diffusion Induced Conversion: PRD 93, 043019 (2016)**

[3] Relativistic Conversion: under calculation

Shun Furusawa

Tokyo University of Science

(TUS) 東京理科大学

RIKEN iTHEMS

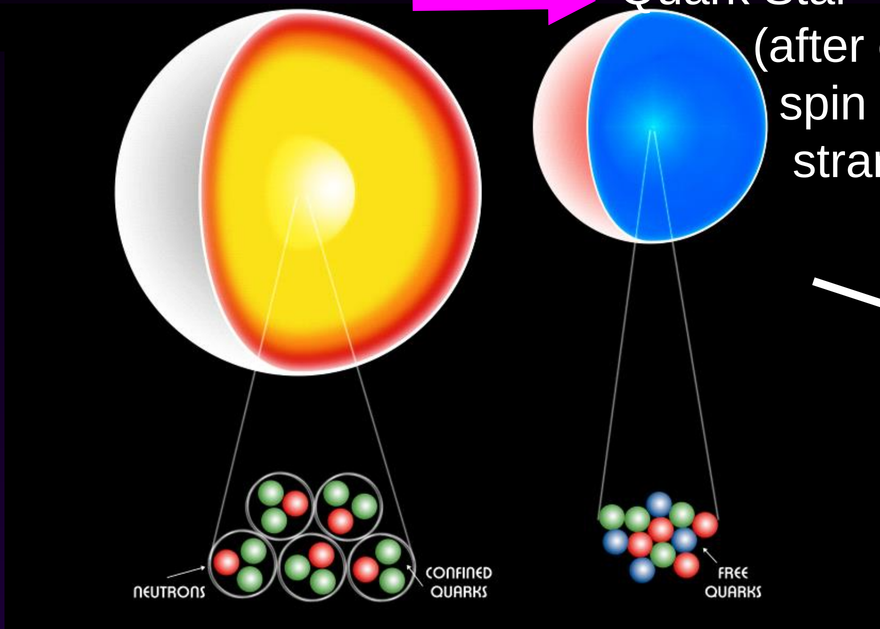
Shoichi Yamada (Waseda University)

Compact Stars in astrophysics

Core Collapse Supernova

Neutron Star

Quark Star
(after cooling, accretion,
spin down, merger,
strangelet capture, ….)



Black hole

Purpose of this project

To understand local process of quark matter formation with the help of combustion theory.

Compact Stars in astrophysics

Strange quark Stars

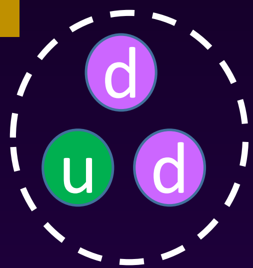
Neutron Stars

Hybrid stars

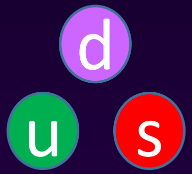
Pure quark stars

HM：neutrons, protons
(confined quarks)

3 quarks are confined
p=uud
n=udd



QM :deconfined quarks
(up, down, strange)



- Small Radius(~~RX J 1856.5–3754 R= 4-8 km ?~~ Drake '02)
- Rapid Cooling curves 3C 58 (Slane '02), MXB 1659-29 (Brwon'18)
- Super Giant Glitches (Spin up) of pulsars (Ma+'96)
- Quark Novae make GRB (Staff'07) and FRB (Shand'15)

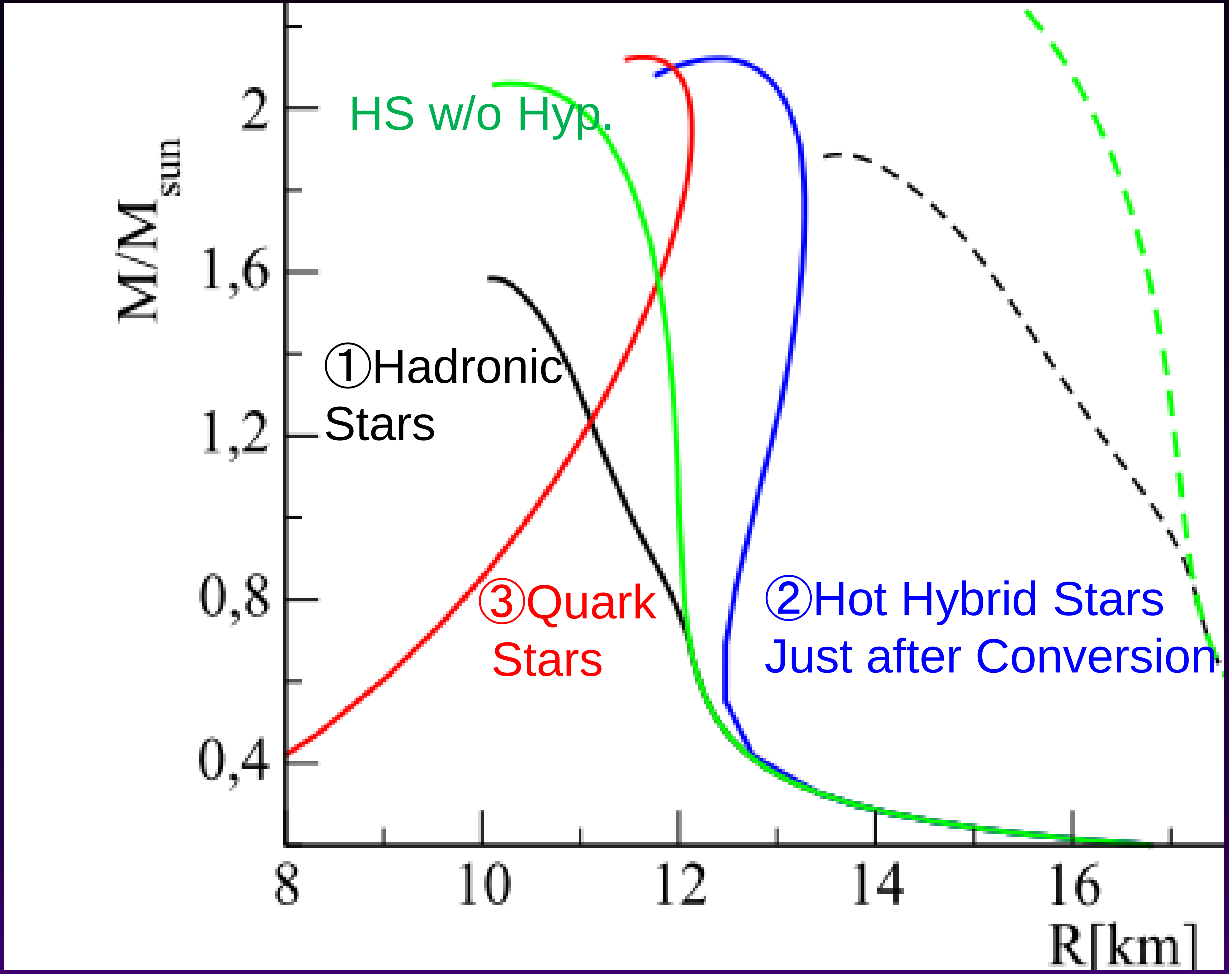
Compact Stars in astrophysics **Mass Radius Relation**

GW170817⇒ **$R_{1.4} \lesssim$ 13.4 km, $M_{max} \sim$ 2.16 $M_\odot \pm$ 0.2 $M_\odot$,**

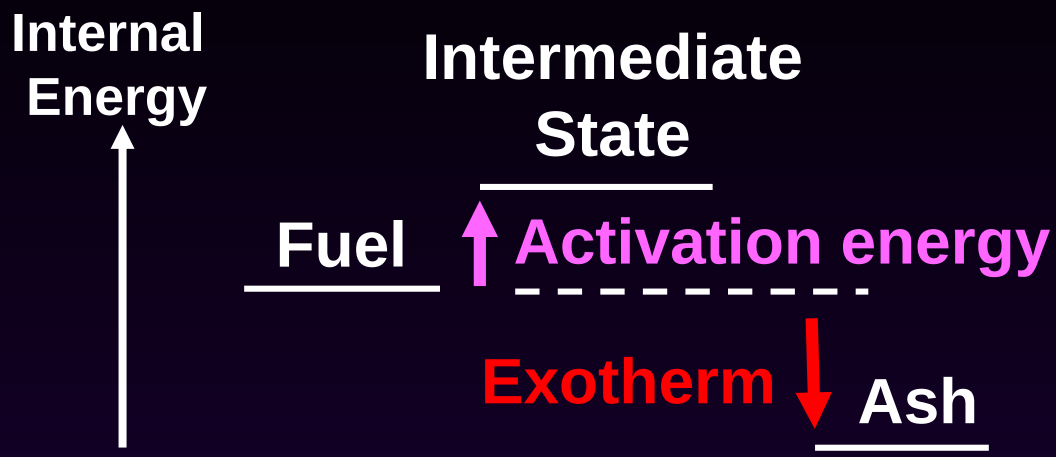
Twin-stars scenario: Hadron@low ρ & Quark@high ρ (Alfold+'13, Baym+19…)

Two Family Scenario：Hadron ⇒ Quark(Hybrid) (Drago+'14, Pietri+'19)

PIETRI+, '19



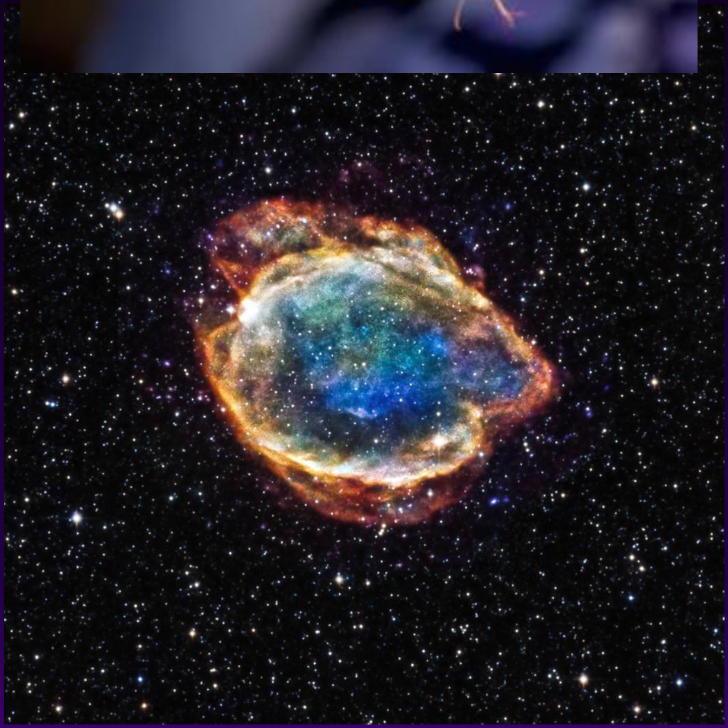
Combustion



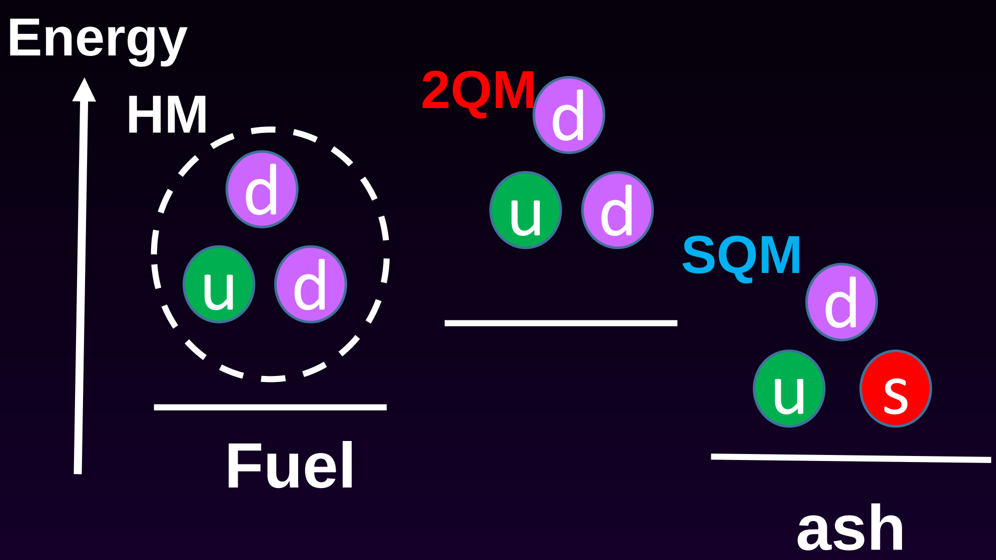
C,H, O_2 ⇒ CO_2, H_2O
(Chemical Reaction)

C,O ⇒ Ni
(Nuclear Reaction, Type Ia SNe)

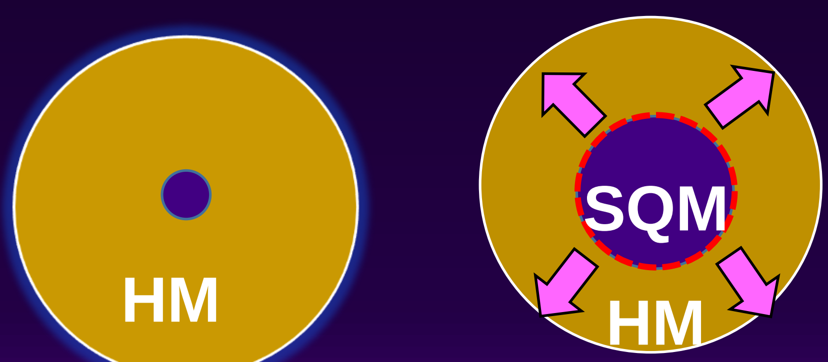
Energy obstacle:
Thermal energy (Activation Energy)

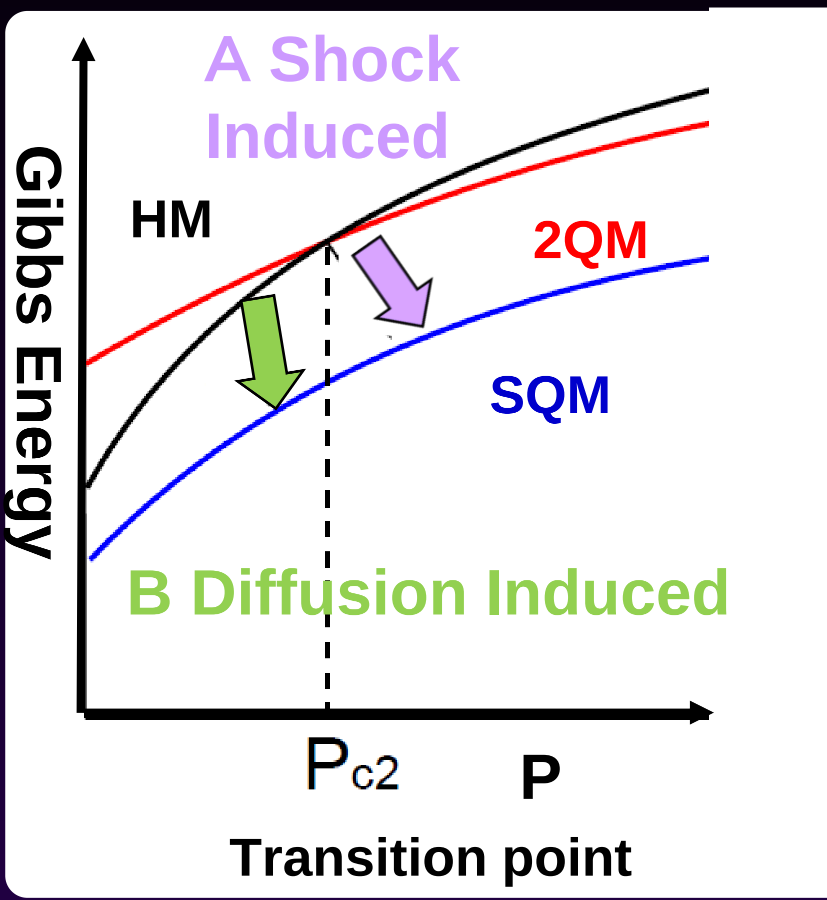


Combustion to SQM

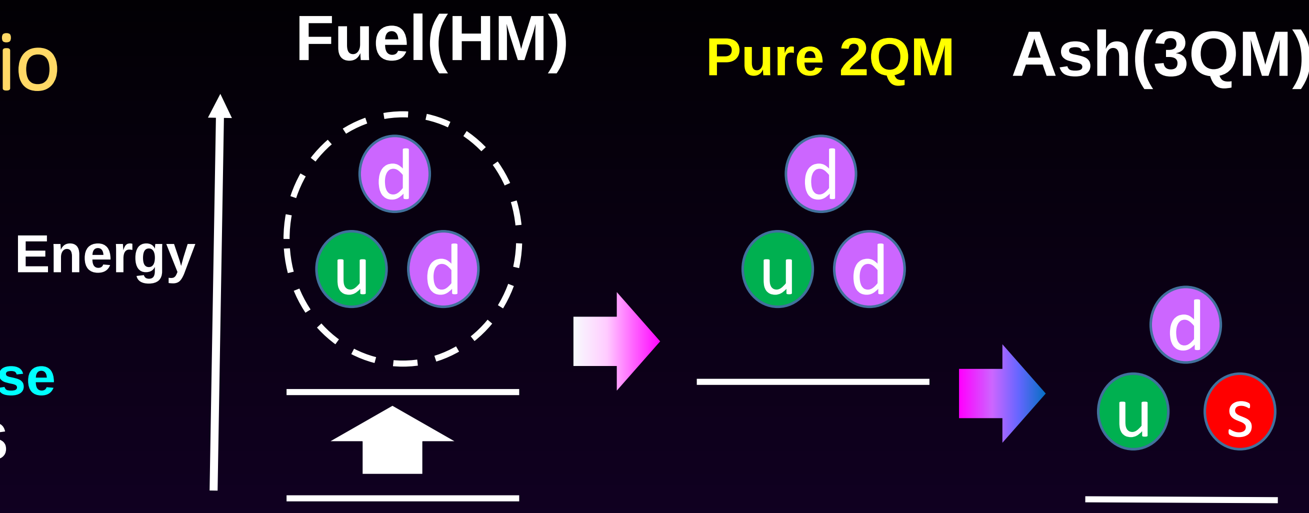


Energy obstacle:
Chemical energies of ud quarks





Ignition Scenario

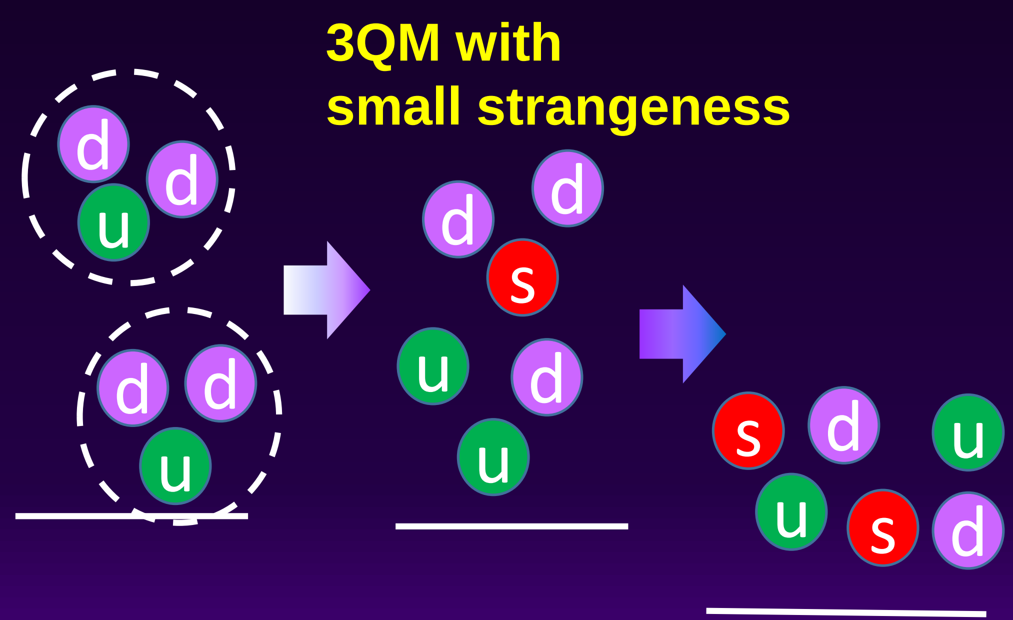


A. Shock induced Case

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

B. Diffusion induced Case

- Following Shock induced
- Capture of strangelets
- Hyperon deconfinement



Combustion in 1 dimensional steady flow

Initial States ⇒ Conservation laws ⇒ Final states

Mass flux

Momentum flux

Energy flux

$$\rho_i v_i = \rho_f v_f = j \quad (1)$$

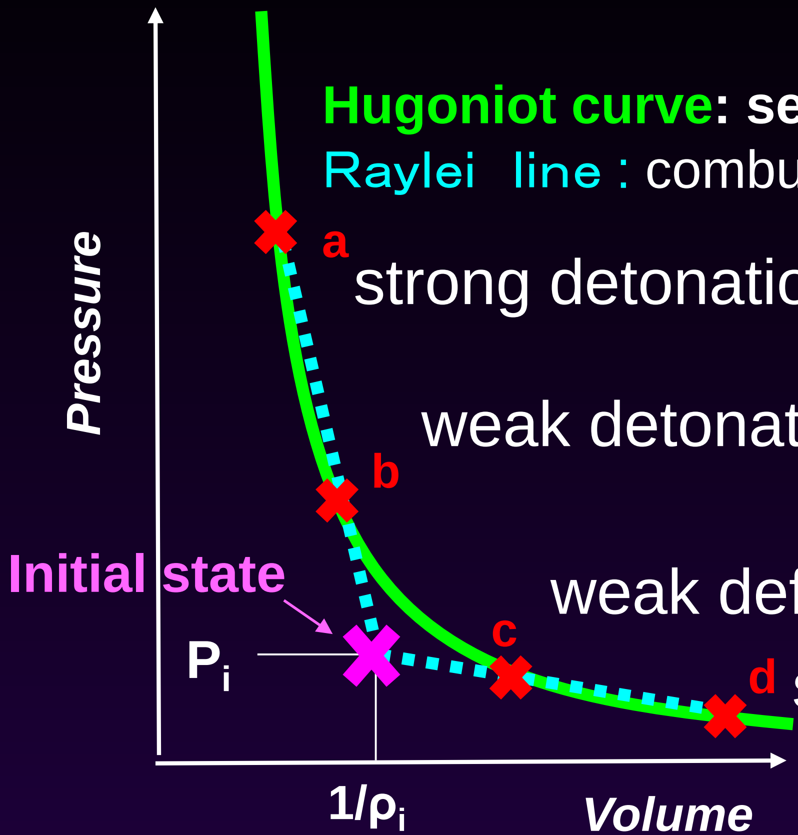
$$P_i + \rho_i v_i^2 = P_f + \rho_f v_f^2 \quad (2)$$

$$\epsilon_i + P_i/\rho_i + \frac{1}{2} v_i^2 = \epsilon_f + P_f/\rho_f + \frac{1}{2} v_f^2 \quad (3)$$

Combustion modes

Hugoniot curve: set of final state for various initial velocity u_i

Raylei line : combustion trajectory for specific u_i



strong detonation $u_i > c_{si}, u_f < c_{sf}$

weak detonation $u_i > c_{si}, u_f > c_{sf}$

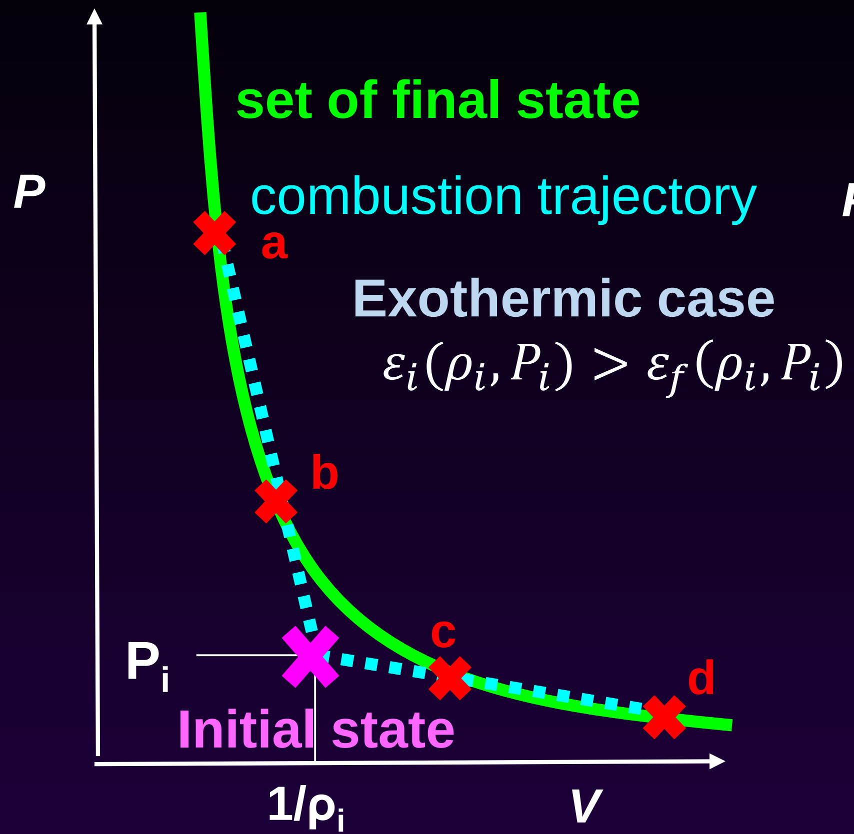
weak deflagration $u_i < c_{si}, u_f < c_{sf}$

strong deflagration $u_i < c_{si}, u_f > c_{sf}$

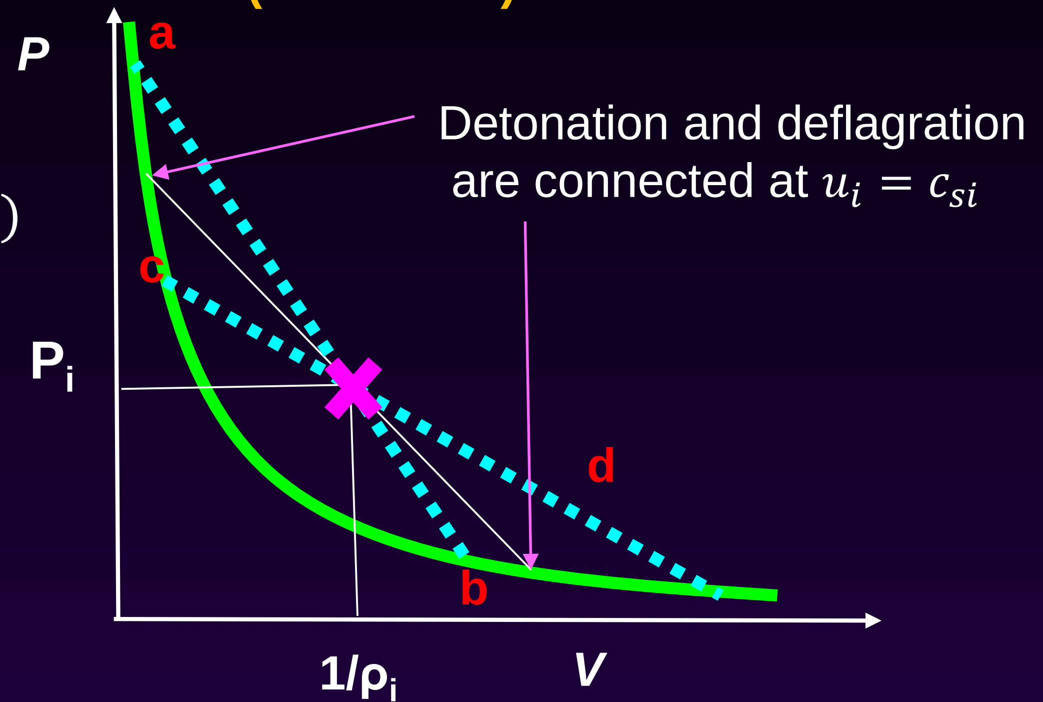
Exothermic case $\varepsilon_i(\rho_i, P_i) > \varepsilon_f(\rho_i, P_i)$

- **Previous works**
- **Type Ia SNe (C,O ⇒Ni_{56})**
- Terrestrial Case（Hydrocarbon +O_2 ⇒ CO_2, H_2O)

Combustion modes



Endothermic $\varepsilon_i(\rho_i, P_i) < \varepsilon_f(\rho_i, P_i)$
(Our works)



a: strong detonation $u_i > c_{si}, u_f < c_{sf}$

b: weak detonation $u_i > c_{si}, u_f > c_{sf}$

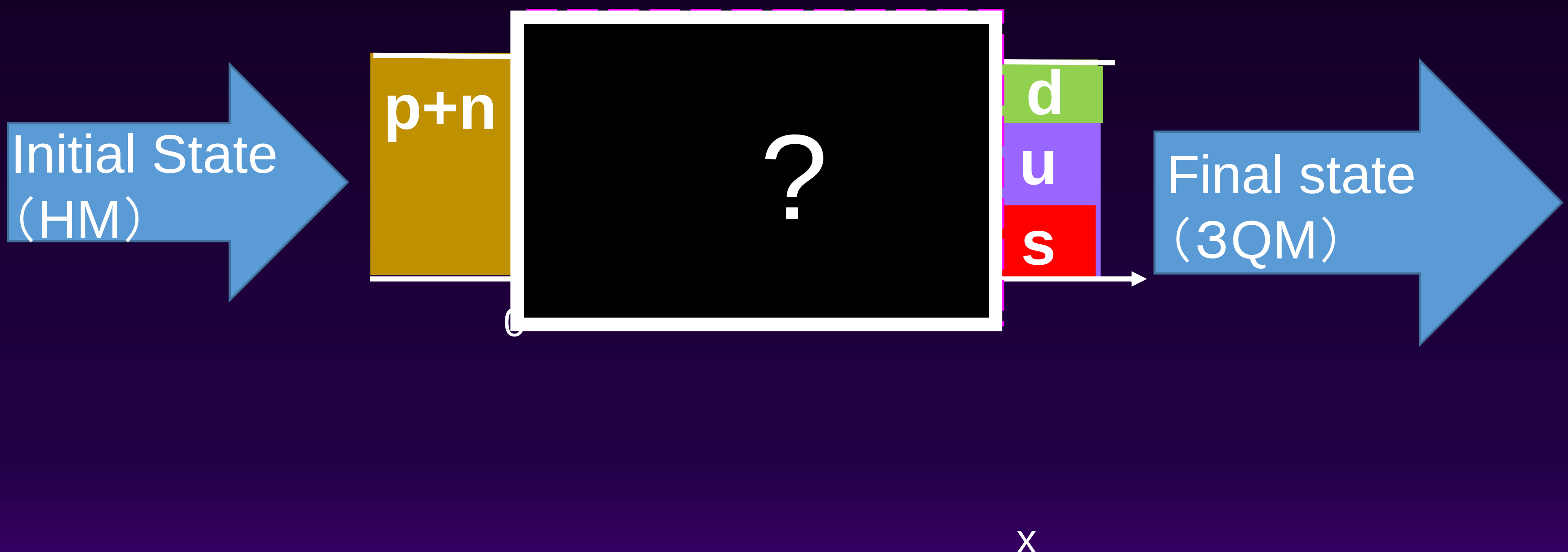
c: weak deflagration $u_i < c_{si}, u_f < c_{sf}$

d: strong deflagration $u_i < c_{si}, u_f > c_{sf}$

Motivation of this work

1, What happens inside combustion front when quark phase is formed both in exothermic and endothermic cases?

2, Which combustion mode is realized?



Model of diffusion induced case

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

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

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

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

$$\epsilon + P/\rho + \frac{1}{2}v^2 = \text{Const.}$$

・Hadronic Matter

Shen EOS '11

$Y_{lep} = 0.3,\ T_0 = 10$ MeV

$\rho_0 = 3.0 \times 10^{14}\ \mathrm{g/cm^3}$

・Quark matter

Bag Model（B:Bagconstant）＋

Strong interaction(α: coupling c.)

(T.Fischer 10)

・Mixed Phase in the front

・Volume Fraction of QM and HM

QM: HM= r :（1-r）

・Global Charge Neutrality

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

$$P^H = P^Q$$
$$T^H = T^Q$$

Inside of Combustion front

QM EOS:

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

$\alpha_s = 0.4$

(endothermic regime)

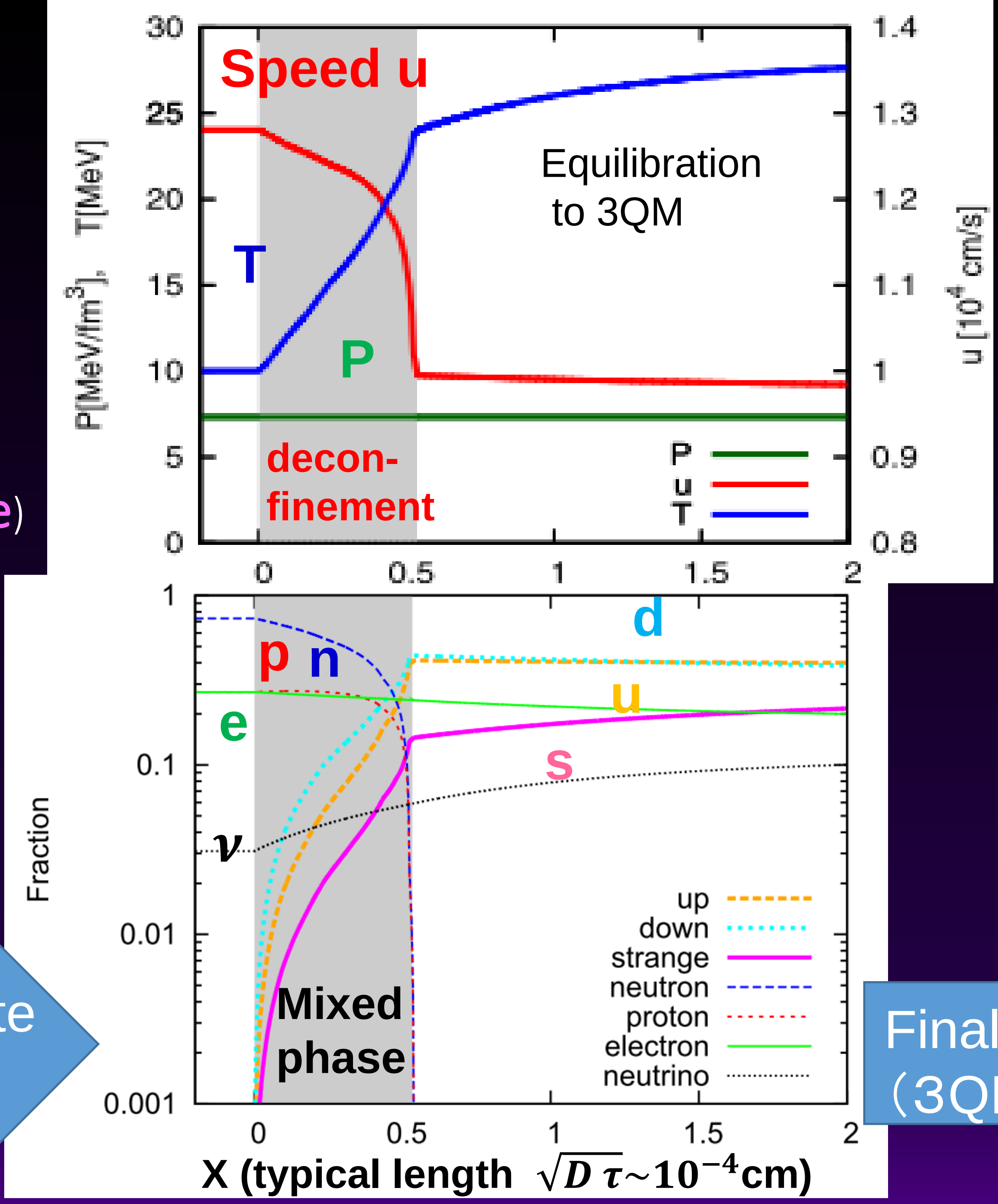
Initial: PNS matter

$T = 10$ MeV

$\rho = 3 \times 10^{14}$ [g/cm^3]

$Y_l = 0.3$

$u_i = 2.3 \; * \; 10^4$ cm/s



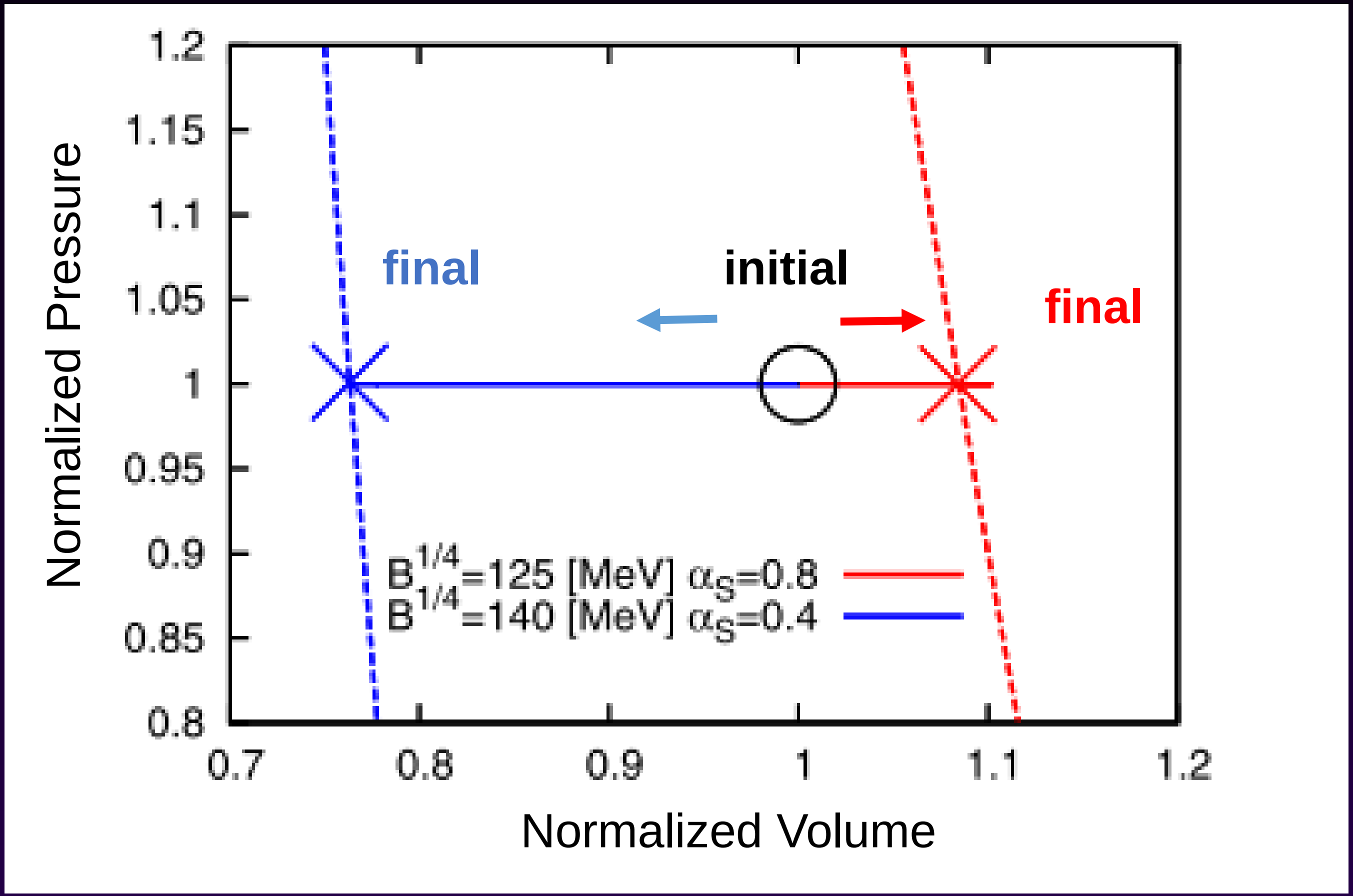
Initial State (HM)

Final state (3QM)

Combustion lines in (V,P) for both cases

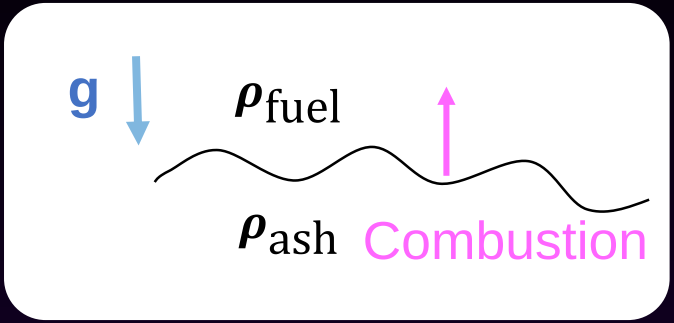
Endothermic $B^{1/4} = 140\ [\mathrm{MeV}]\ \ \alpha_s = 0.4$

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



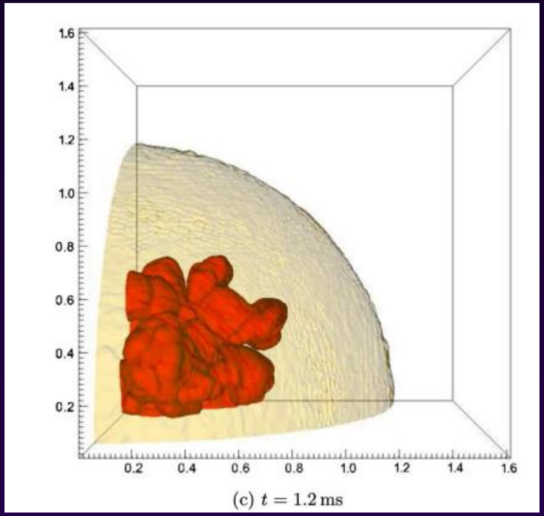
Weak deflagrations are realized in both cases.

STABILITY OF THE COMBUSTION FRONT



$\rho_{\rm ash}/\rho_{\rm fuel}$<1
(exothermic)
Type Ia,
Terrestrial Combustion
⇒unstable

$\rho_{\rm ash}/\rho_{\rm fuel}$ >1
(endothermic)
⇒ stable



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

In Previous work,
3D simulation (Pagliara ’13),
the combustion is stopped
by hand in Endothermic regime.

⇒ may be steady combustion in endothermic (future work)

Summary

We have cleared the structure of combustion front.

●The type of combustion

- **diffusion induced case: weak deflagration**

(･shock induced case: strong detonation see SF+ PRD 93,043018 ’16**)**

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

Future Works

- **Relativistic formulation（underway）**
- **dependence and update of HM EOS, QM EOS, Transition condition**