初代星・初代銀河研究会 2017 @ 呉

Condition for low-mass star formation in shock-compressed metal-poor clouds

D. Nakauchi, K. Omukai
(Tohoku TAP)
R. Schneider
SAPIENZA
UNIVERSITÀ DI ROMA

Sun 11 Feb 2018 in KNCT

TOHOKU
UNIVERSITY

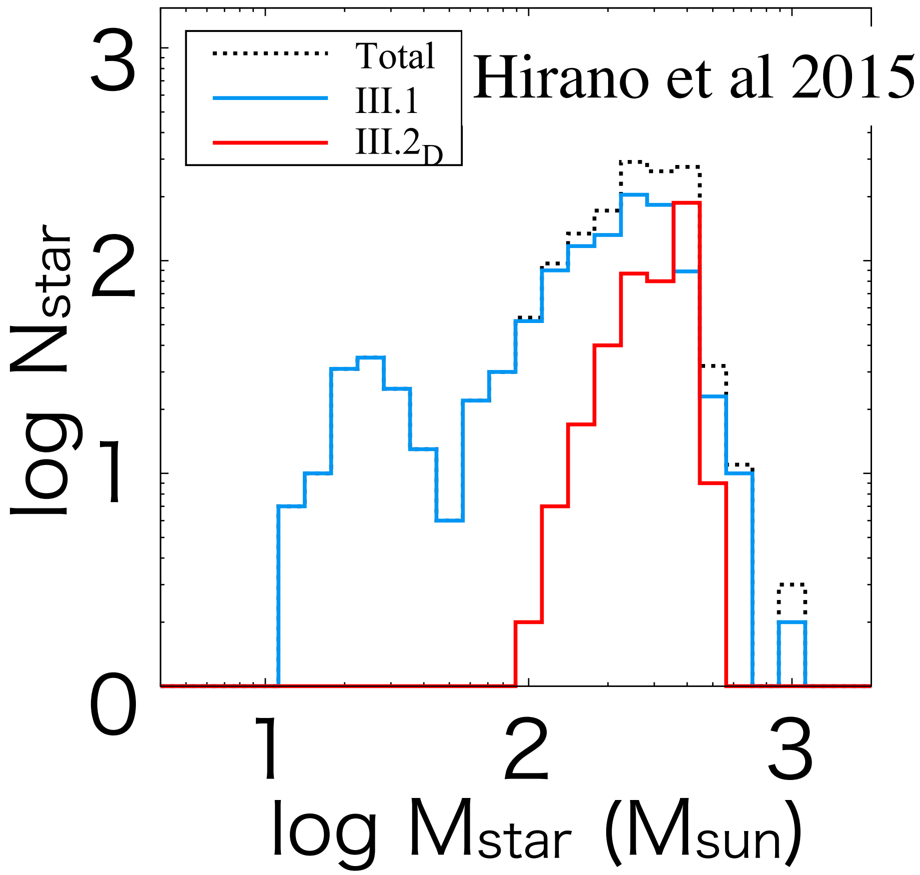
Theoretical Astrophysics
Tohoku University

Contents

1. Introduction

Transition in star formation mode

- **Pop III**: typically **massive,** 10-1000 $M_\odot$
- **Pop I, II**:
  low mass ($\lesssim M_\odot$) stars are broadly observed in the solar neighborhood, Galactic halo, and globular cluster etc.



＊Naively, cooling by **metal lines** and **dust emission** may play a role.

＊Especially, **dust** is indispensable for low mass star formation.

Broom&Loeb 2003
Schneider et al.
Omukai et al.

＊Above results are obtained for clouds collapsing by (self-)gravity from very low densities ~ 1 cm^{-3}.

Star formation in shock-compressed clouds

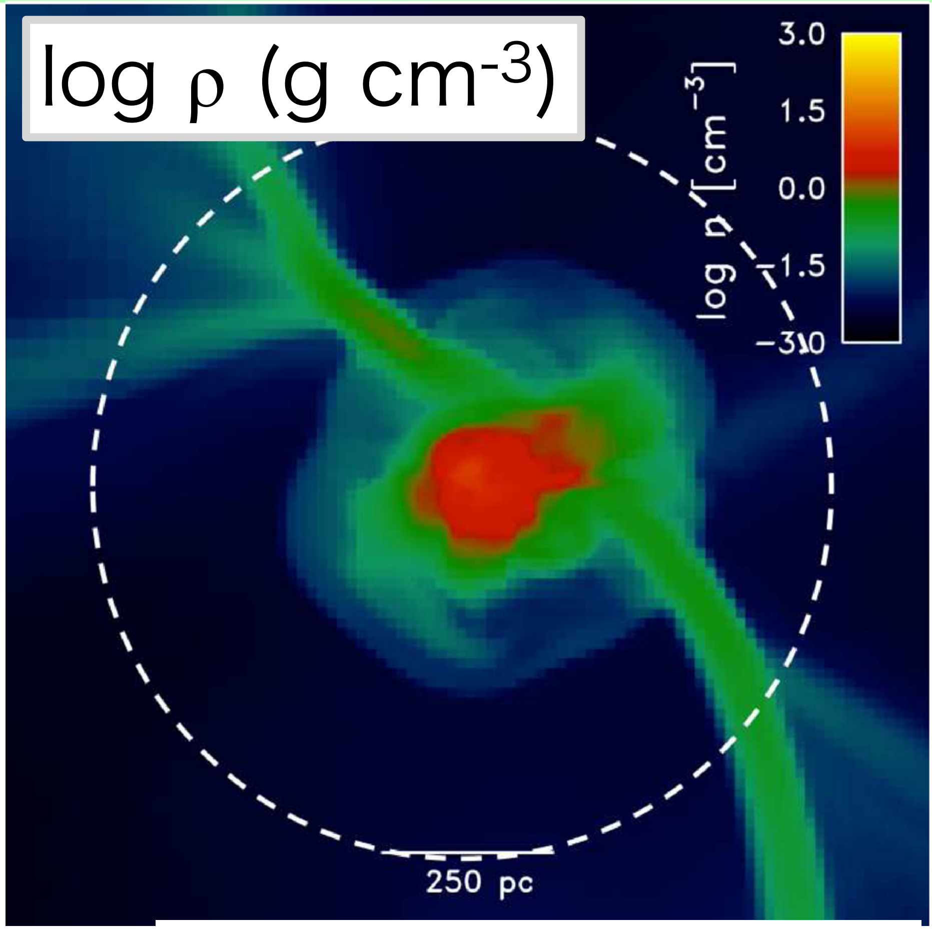
＊One zone calculation of shocked clouds in early galaxy formation.

Safranek-Shrader et al. 2010

- Initial density & temperature:

  $n_{H,1} = 4 \times 10^3 \ cm^{-3} \quad T_1 = 1.1 \times 10^4 \ K$

- If $Z/Z_{\odot} \sim 10^{-2.5}$, ~ solar mass fragments are formed by metal line cooling alone.



Safranek-Shrader et al. 2014

- **BUT,**

  - H_2O, dust cooling and H_2 formation heating were missed.
  - Evolution after fragmentation was not studied.
  - Shock-compression may be frequent stellar wind, SN, and galaxy merger, etc…

Our study

＊Thermal evolution of shock-compressed clouds is studied

- by treating detailed chemical processes.
- by calculating the clump evolution after fragmentation.
- under various conditions.
  - Initial density: $4\ \mathrm{cm}^{-3} \le n_{\mathrm{H},1} \le 4 \times 10^4\ \mathrm{cm}^{-3}$
  - Initial temperature: $T_1 = 1.2 \times 10^4\ \mathrm{K}$ ($v_\mathrm{s} = 20\ \mathrm{km\ s}^{-1}$).
  - Metallicity: $0 < Z/\mathrm{Z}_\odot \le 10^{-2}$
  - External UV radiation: $0 \le J_{21} \le 10^4$

    ($J_{21} \sim 20$, in solar neighborhood)

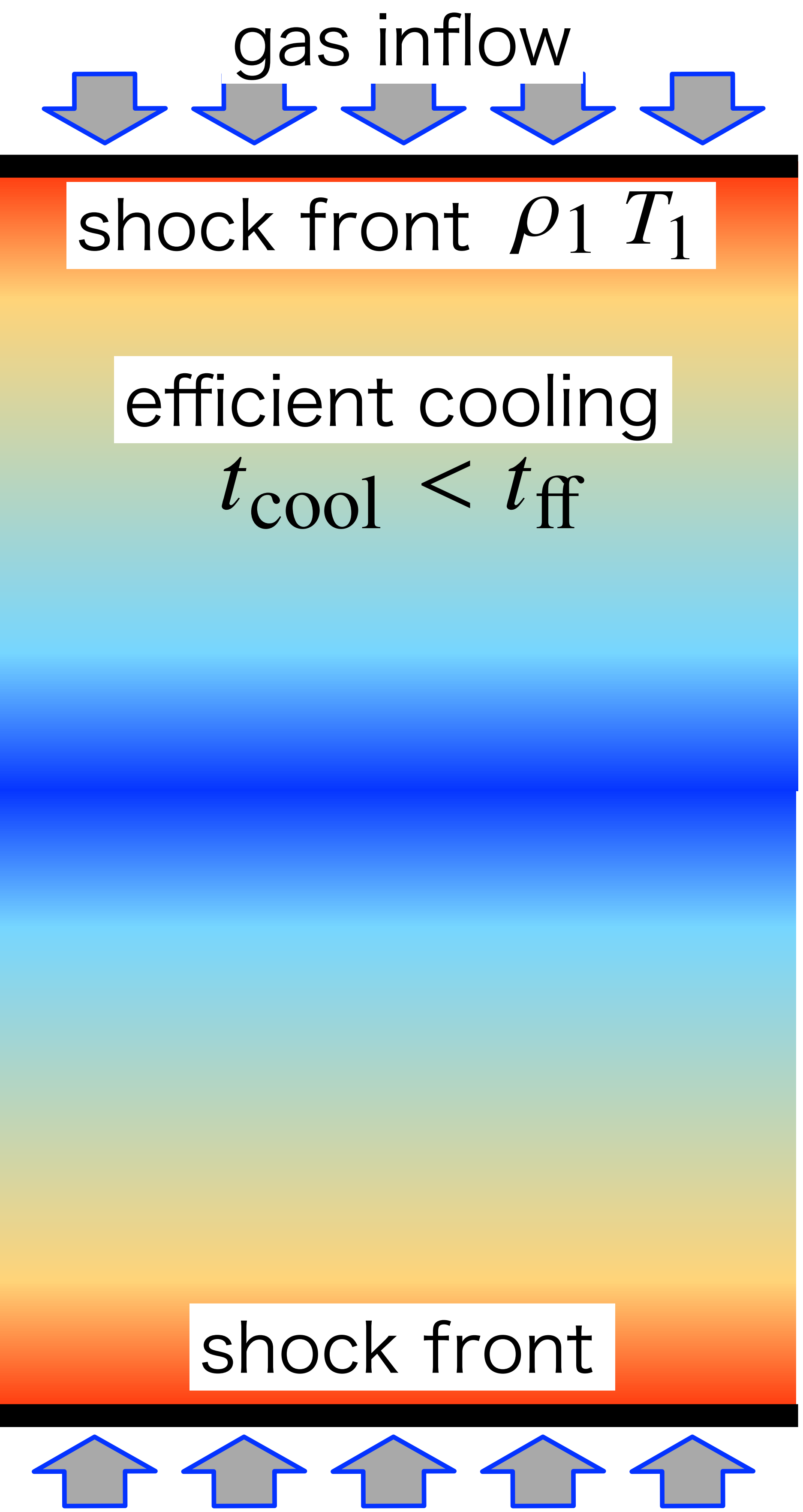
Condition for low-mass star formation is examined.

2. Methods

Basic equations
Fragmentation conditions

Evolution in shocked layers

Safranek-Shrader et al. 2010
Nakauchi et al. 2014



★ Shocked layers are assumed to be plane parallel and steady.

- EoM: $\rho_1 v_1^2 + P_1 = \rho v^2 + P,$
- Continuity: $\rho_1 v_1 = \rho v,$
- Energy: $\frac{de}{dt} = -P \frac{d}{dt}\left(\frac{1}{\rho}\right) - \Lambda_{\rm net},$

$$\Lambda_{\rm net} = \Lambda_{\rm line} + \Lambda_{\rm chem} + \Lambda_{\rm grain}$$

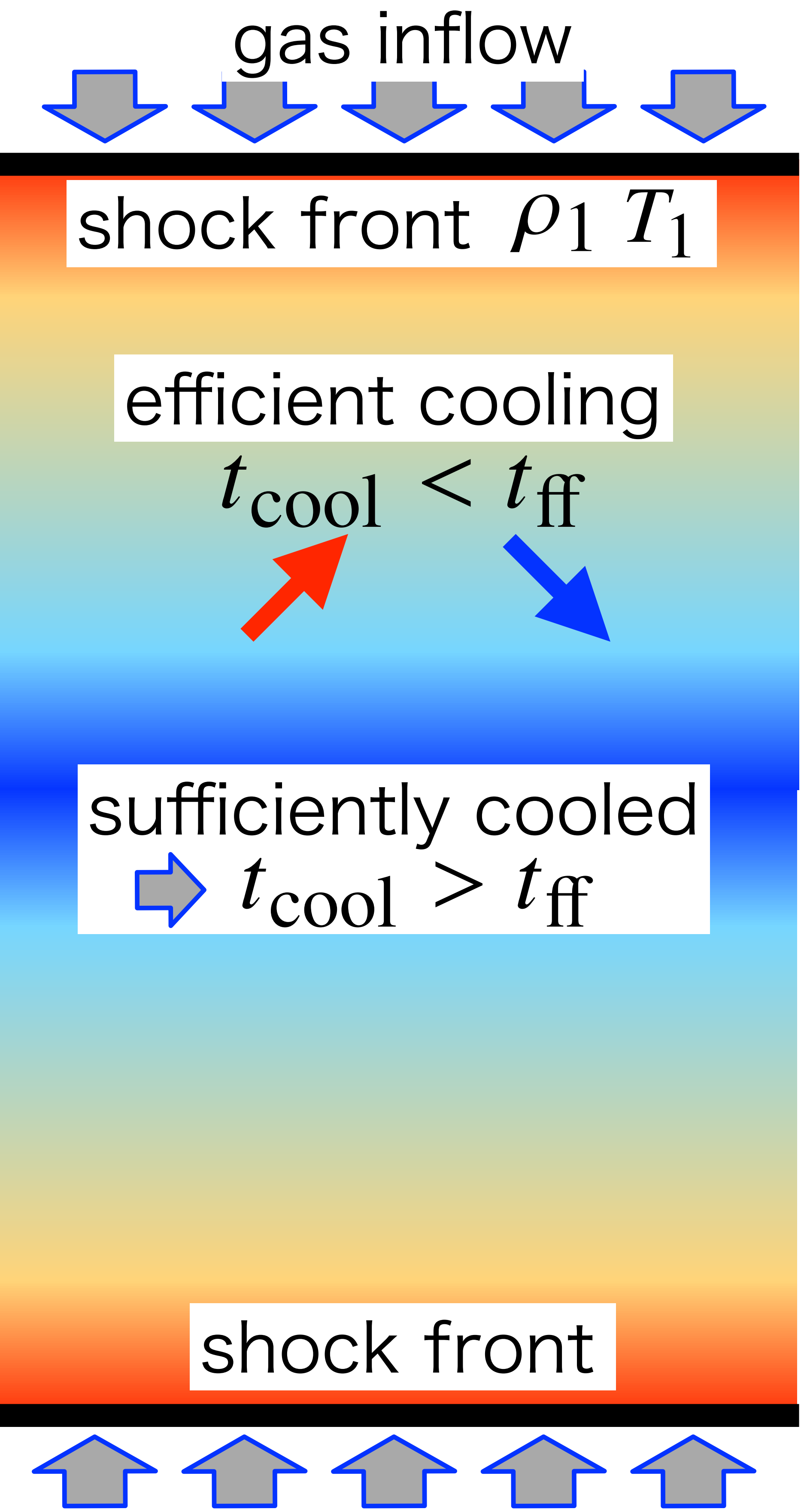
$\Lambda_{\rm line}$: line cooling by
H, H_2, HD, H_2O, CII, OI, etc.

Omukai 2012 etc.

$\Lambda_{\rm chem}$: H_2 formation heating by
3-body & grain surface reactions,
etc.

Fragmentation condition

Elmegreen&Elmegreen 1978
Nakauchi et al. 2014



① $t_{\rm cool} > t_{\rm ff}$ $\quad t_{\rm cool} \equiv e/\Lambda_{\rm net}$

⇨ density perturbations grow in the layer.

② $t_{\rm sound} > t_{\rm ff}$ $\quad t_{\rm sound} = H_\rho / c_{\rm s}$

$H_\rho = \rho/(d\rho/dr)$: density scale height

⇨ fragment contracts by self-gravity.

Both ① & ② should be satisfied for the formation of self-gravitating clumps.

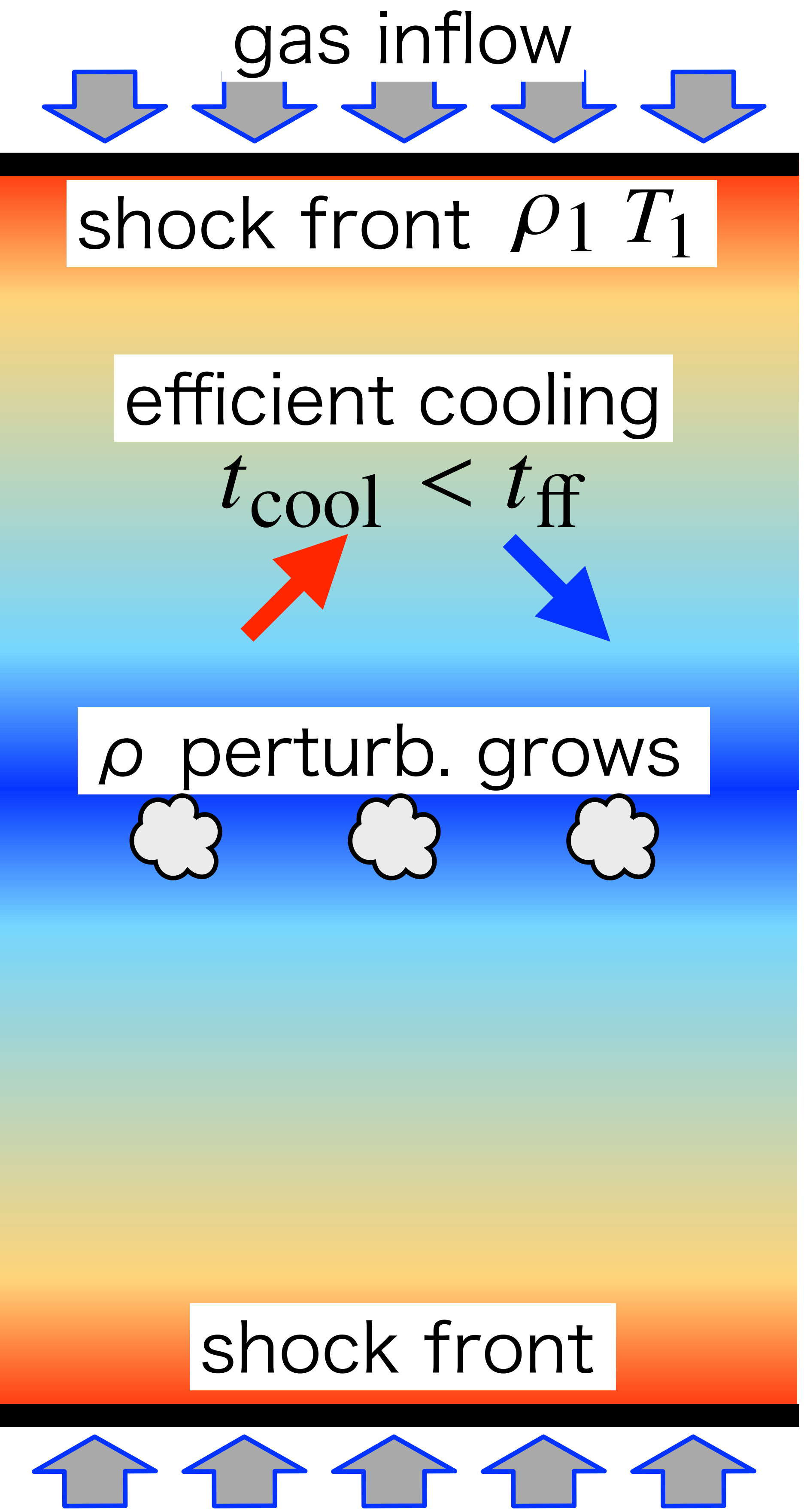
＊Fragment mass:

$$M_{\rm J}(\rho_{\rm frag}, T_{\rm frag}) \sim \rho_{\rm frag}\lambda_{\rm J}^3(\rho_{\rm frag}, T_{\rm frag})$$

$\lambda_{\rm J} = (\pi k_{\rm B} T / G\mu m_{\rm H}\rho)^{1/2}$: Jeans length

Fragmentation condition

Elmegreen&Elmegreen 1978
Nakauchi et al. 2014



① $t_{\rm cool} > t_{\rm ff}$ $t_{\rm cool} \equiv e/\Lambda_{\rm net}$

➡ density perturbations grow in the layer.

② $t_{\rm sound} > t_{\rm ff}$ $t_{\rm sound} = H_\rho/c_{\rm s}$

$H_\rho = \rho/(d\rho/dr)$: density scale height

➡ fragment contracts by self-gravity.

Both ① & ② should be satisfied for the formation of self-gravitating clumps.

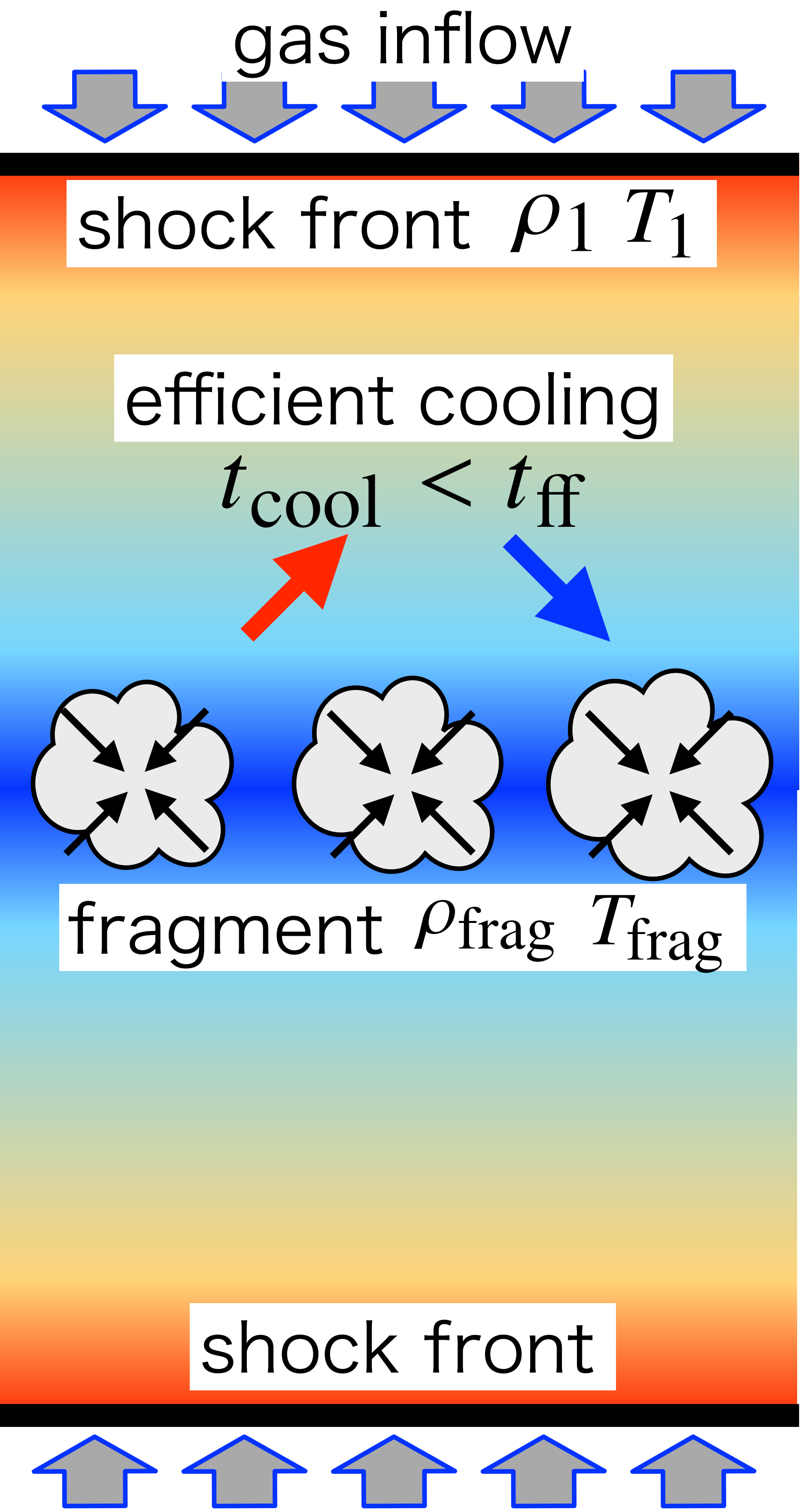
＊Fragment mass:

$$M_{\rm J}(\rho_{\rm frag}, T_{\rm frag}) \sim \rho_{\rm frag}\lambda_{\rm J}^3(\rho_{\rm frag}, T_{\rm frag})$$

$\lambda_{\rm J} = (\pi k_{\rm B}T/G\mu m_{\rm H}\rho)^{1/2}$: Jeans length

Fragmentation condition

Elmegreen&Elmegreen 1978
Nakauchi et al. 2014



① $t_{\rm cool} > t_{\rm ff}$ $\quad t_{\rm cool} \equiv e/\Lambda_{\rm net}$

➡ density perturbations grow in the layer.

② $t_{\rm sound} > t_{\rm ff}$ $\quad t_{\rm sound} = H_\rho / c_{\rm s}$

$H_\rho = \rho/(d\rho/dr)$: density scale height

➡ fragment contracts by self-gravity.

Both ① & ② should be satisfied for the formation of self-gravitating clumps.

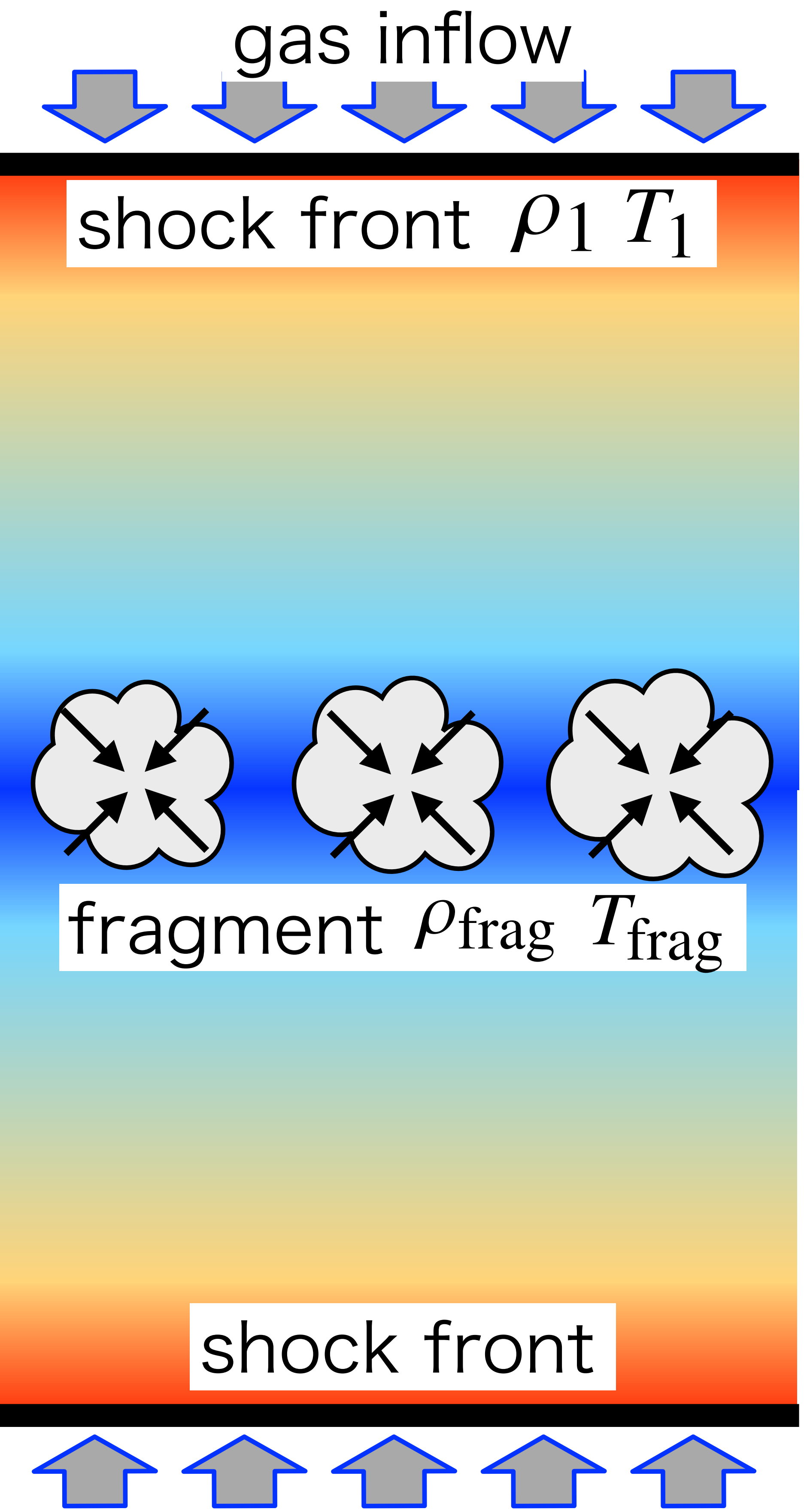
＊Fragment mass: $M_{\rm frag,shock}$

$$M_{\rm J}(\rho_{\rm frag}, T_{\rm frag}) \sim \rho_{\rm frag} \lambda_{\rm J}^3 (\rho_{\rm frag}, T_{\rm frag})$$

$\lambda_{\rm J} = (\pi k_{\rm B} T / G \mu m_{\rm H} \rho)^{1/2}$: Jeans length

Contraction by self-gravity

Omukai 2000, 2012
Omukai et al. 2005, 2010



★ Evolution in the cloud center is followed.

- Dynamics: $\frac{d\rho}{dt} = \frac{\rho}{t_{ff}}$,
- Energy: $\frac{de}{dt} = -P\frac{d}{dt}\left(\frac{1}{\rho}\right) - \Lambda_{net}$,

$$\Lambda_{net} = \Lambda_{line} + \Lambda_{chem} + \Lambda_{grain}$$

Below, we present the results for shocked clouds with

$n_{H,1} =$ $4\ cm^{-3}$ supernova remnant (SN)

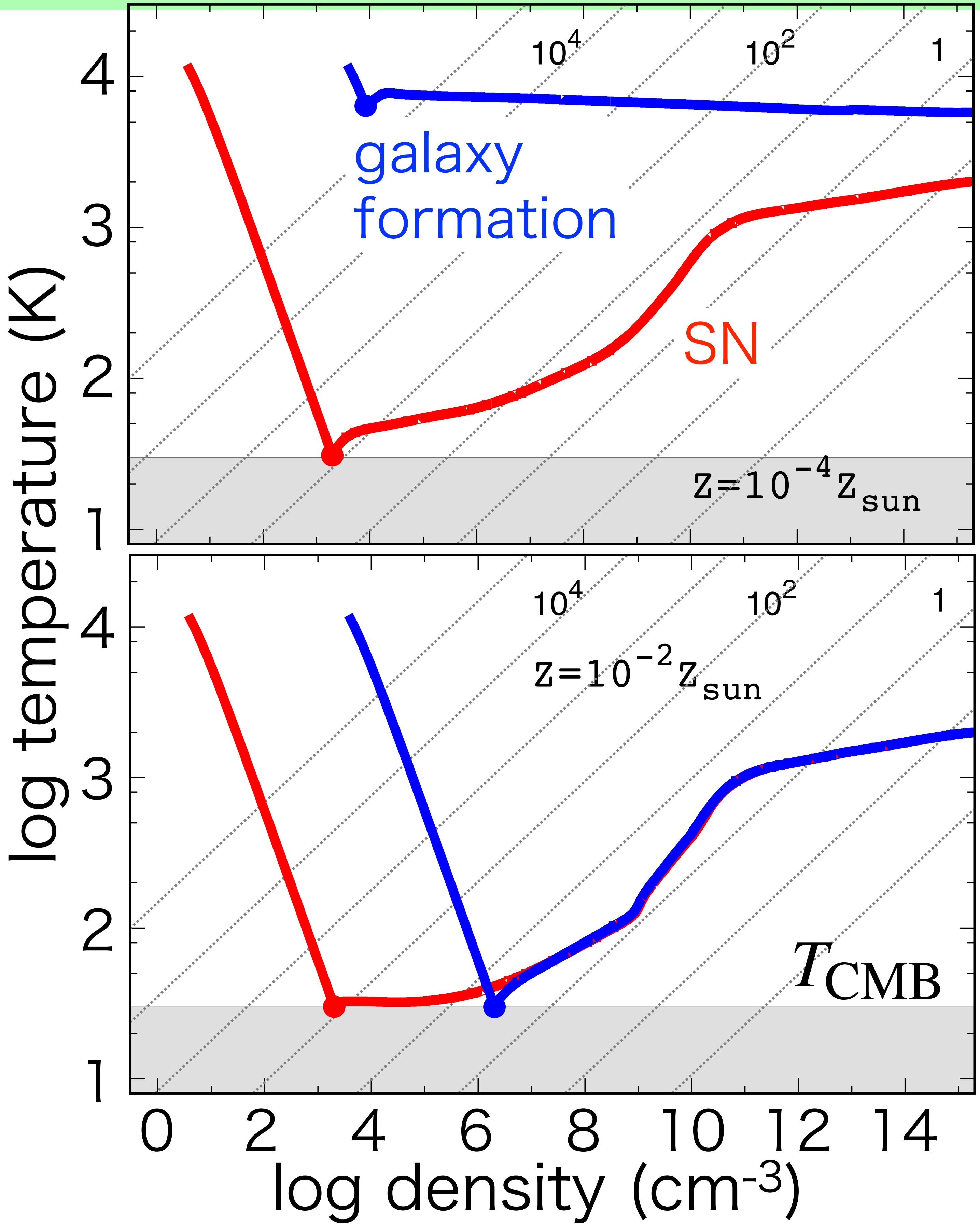
$4 \times 10^3\ cm^{-3}$ galaxy formation (GF)

3. Results

Thermal evolution without/with dust
with UV radiation

Fragment mass

Thermal evolution without dust



Isobaric contraction

T ↘ $T_{CMB} = 30$ K

Fragmentation

$M_{frag,shock}$ ~ 100 $M_\odot$ in SN

~ 10 $M_\odot$ in GF

for 10^{-2} $Z_\odot$

Gravitational contraction

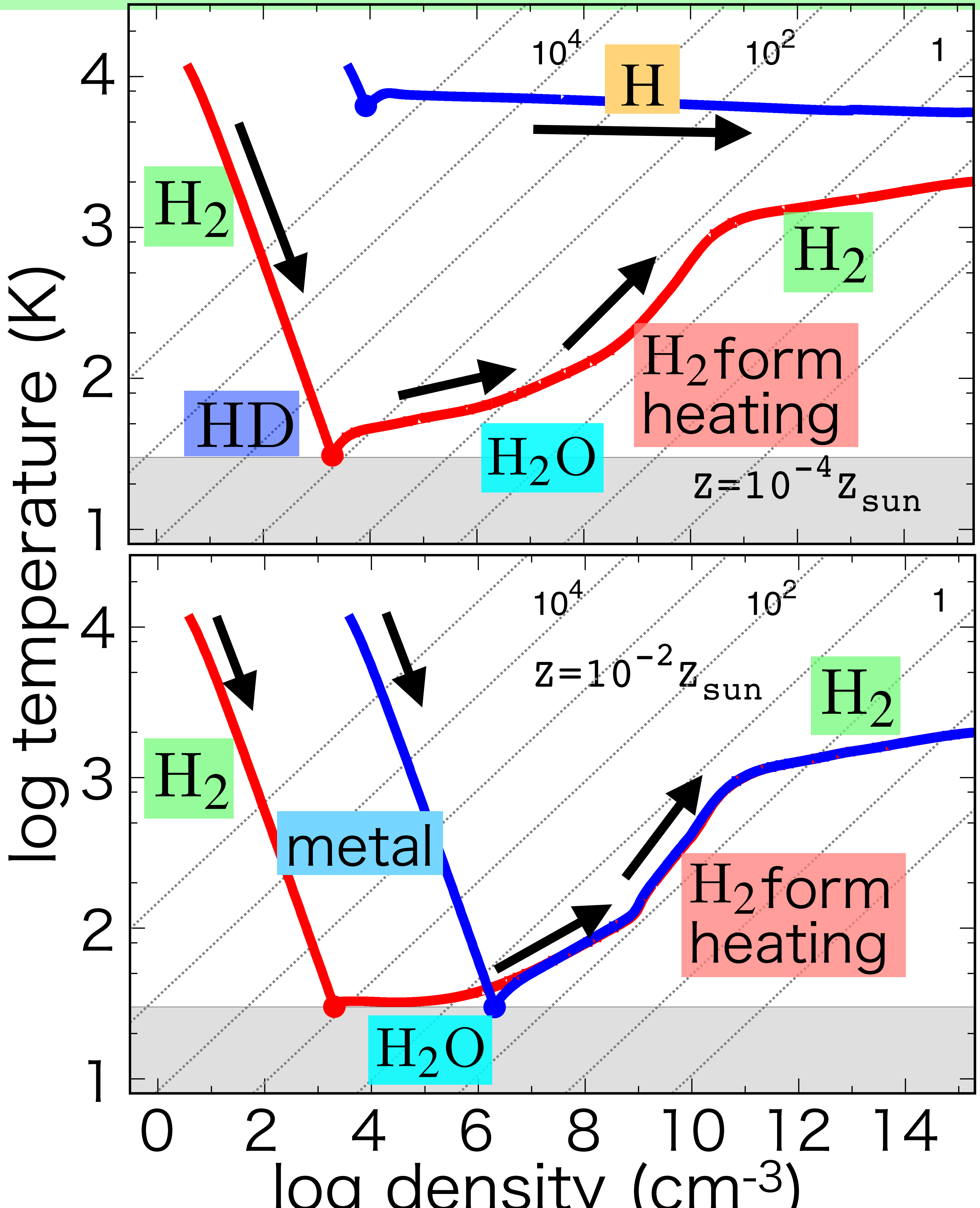
T ↗↗

In GF, H_2 suffers from collisional dissociation.

⇨ Gas can not cool below ~ 8000 K without metals.

$M_{frag,shock} \gtrsim 10^5$ $M_\odot$

Thermal evolution without dust



Isobaric contraction

$T \searrow T_{CMB} = 30$ K

Fragmentation

$M_{frag,shock} \sim 100\ M_\odot$ in SN

$\sim 10\ M_\odot$ in GF

for $10^{-2}\ Z_\odot$

Gravitational contraction

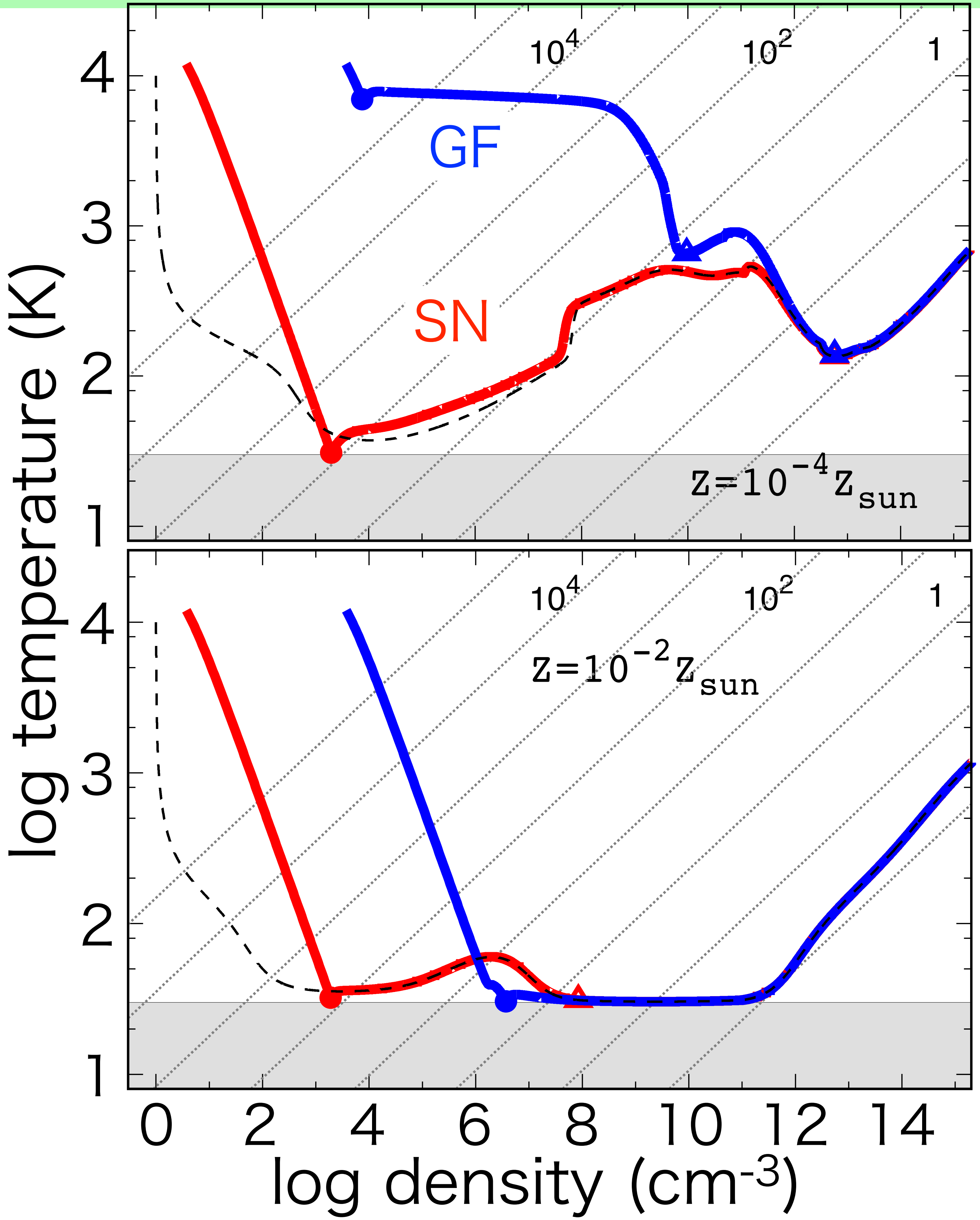
$T \nearrow\nearrow$

In GF, H_2 suffers from collisional dissociation.

Gas can not cool below ~ 8000 K without metals.

$M_{frag,shock} \gtrsim 10^5\ M_\odot$

Thermal evolution with dust



Before fragmentation, dust has little effect.

After fragmentation, thermal track is altered dramatically.

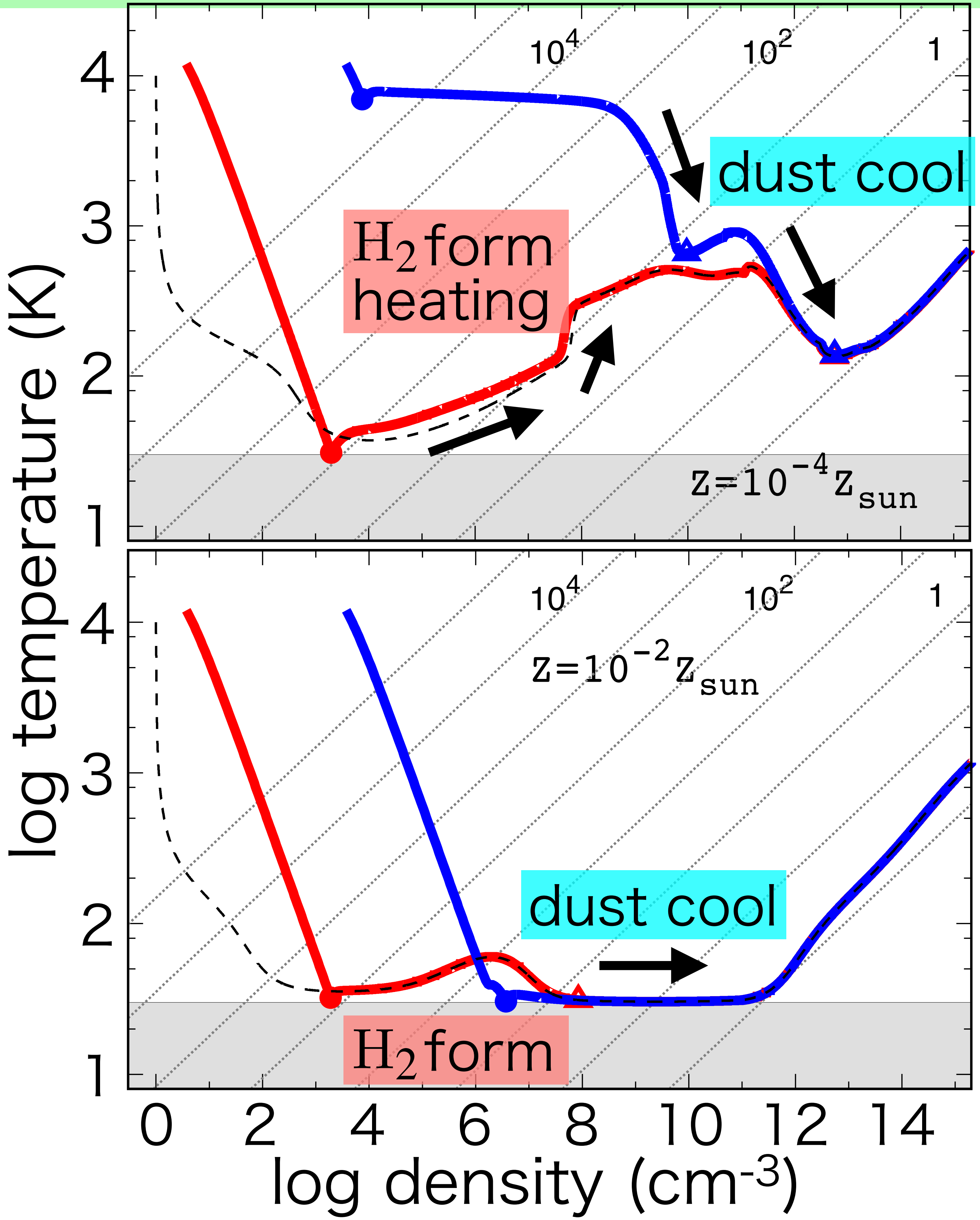
Dust cooling leads to rapid T drop & re-fragmentation.

⇨ Sub-solar mass fragments are formed.

$(M_{\rm frag, dust} \sim 0.01\text{-}1 \ M_\odot)$

*This is not true for $10^{-2} \ Z_\odot$ in galaxy formation.

Thermal evolution with dust



Before fragmentation, dust has little effect.

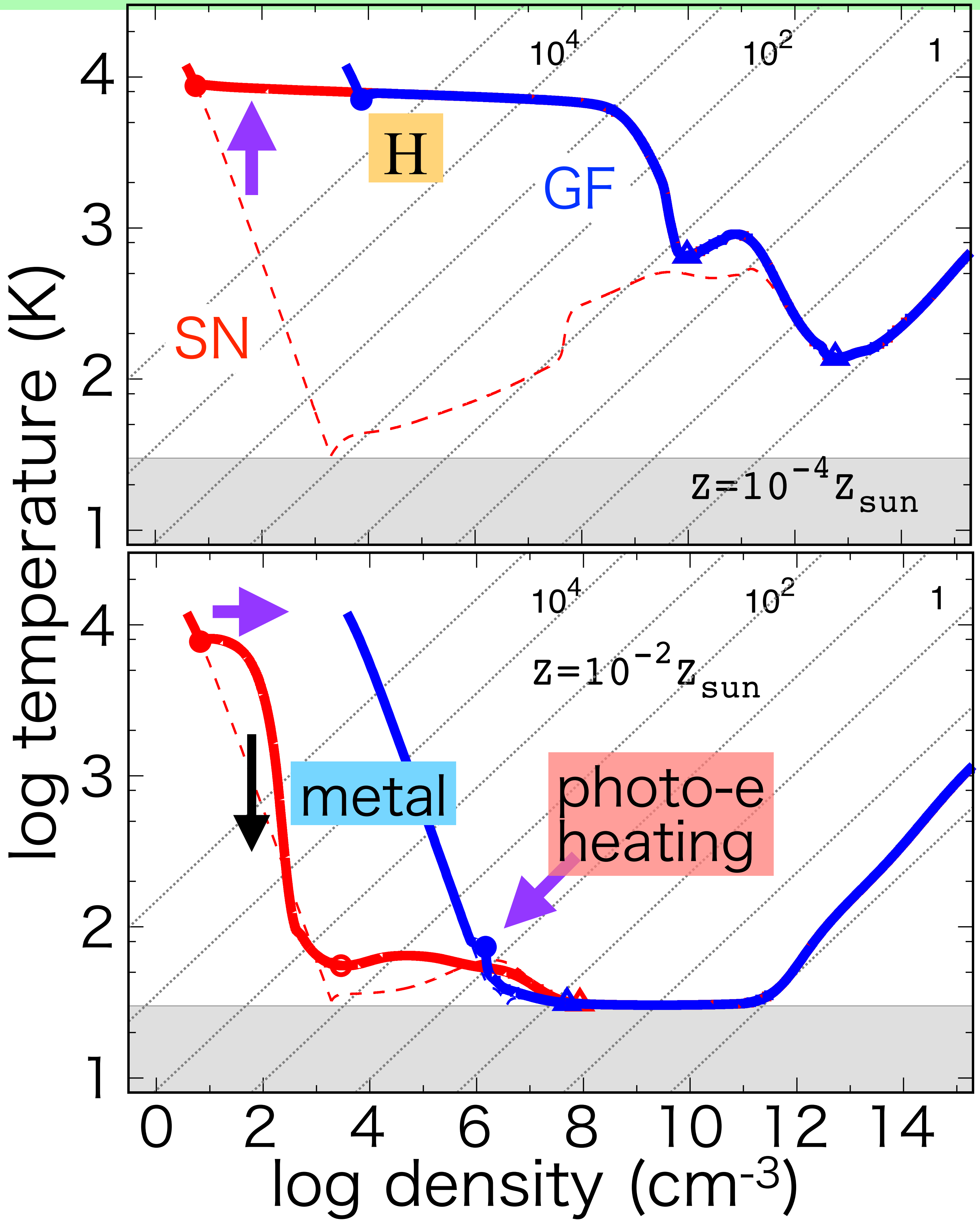
After fragmentation, thermal track is altered dramatically.

Dust cooling leads to rapid T drop & re-fragmentation.

⇨ Sub-solar mass fragments are formed.
$(M_{\rm frag,dust} \sim 0.01\text{-}1 \ {\rm M}_\odot)$

*This is not true for $10^{-2}\ Z_\odot$ in galaxy formation.

Thermal evolution with UV radiation



UV effect is explicit in SN.

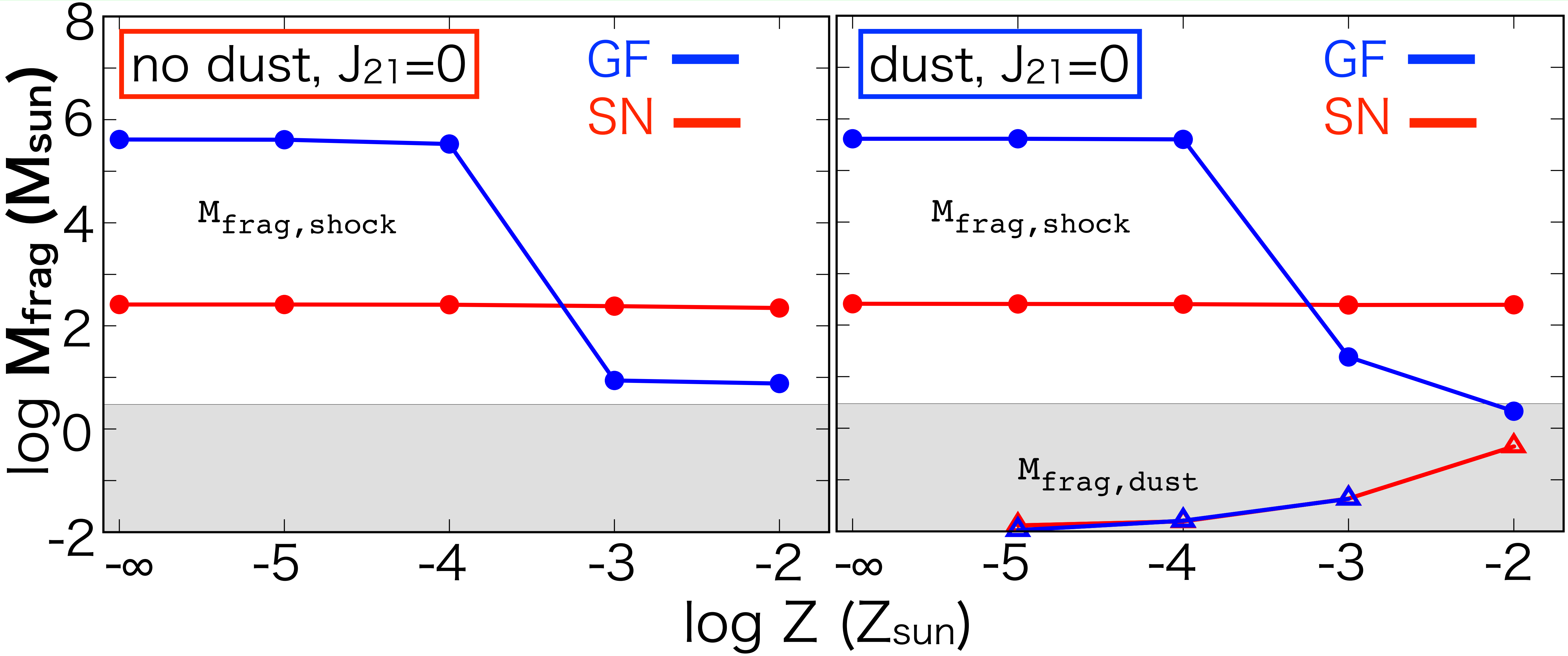
By H_2 photodissociation, gas can not cool below 8000K.

For $10^{-2}\ Z_\odot$, re-fragmentation occurs multiple times by metal/dust cooling.

In galaxy formation, little effect is seen.

Photoelectrons emitted from grains heat gas at 10^5-10^6 cm^{-3}.

Fragment mass: with no UV



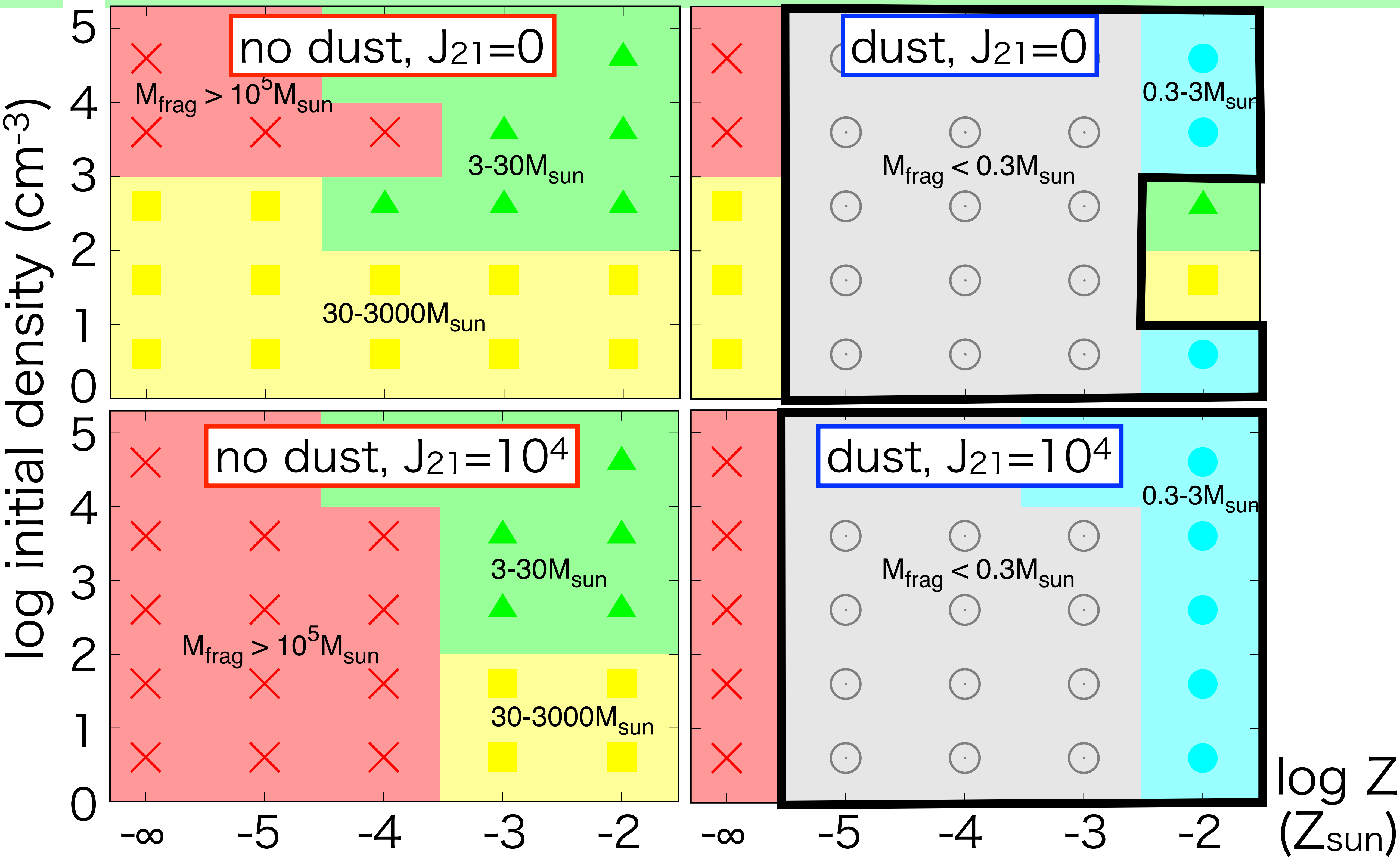
∗In GF, $M_{\mathrm{frag,shock}} > 10^5\ \mathrm{M}_\odot$ ↘ $\sim 10\ \mathrm{M}_\odot$ at 10^{-4}-$10^{-3}\ \mathrm{Z}_\odot$.

∗In SN, $M_{\mathrm{frag,shock}} \sim 100\ \mathrm{M}_\odot$ for all metallicities.

∗Sub-solar mass fragments are formed by dust cooling even in a very metal-poor cloud $\gtrsim 10^{-5}\ \mathrm{Z}_\odot$.

∗UV hardly changes these trends.

Condition for low mass star formation



Dust is indispensable for low-mass star formation in shock-compressed clouds.

Summary

∗Thermal evolution of a shock-compressed cloud is studied.

∗Isobaric contract ➡ fragmentation ➡ gravitational contract.

-In GF, $M_{\rm frag,shock} > 10^5\ \rm M_\odot$ ↘ $\sim 10\ \rm M_\odot$ at 10^{-4}-$10^{-3}\ \rm Z_\odot$.

-In SN, $M_{\rm frag,shock} \sim 100\ \rm M_\odot$ for all metallicities.

∗Dust cooling drives rapid T drop & re-fragmentation.

⇨ Sub-solar mass fragment is formed for $\gtrsim 10^{-5}\ \rm Z_\odot$.

∗UV hardly changes these trends.

∗Dust is indispensable for low-mass star formation in shock-compressed clouds.