The low-mass star formation triggered by the early supernova explosions

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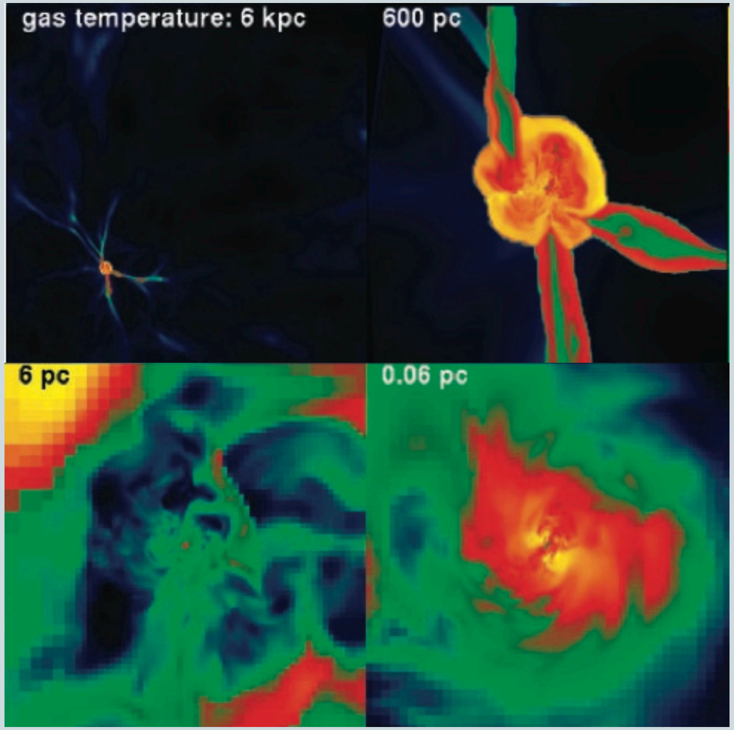
Oct 12 2012 The low-metallicity ISM @Göttingen

Massive Pop III Stars

First star (or Population III star)

- formed in metal-free gas
- massive ➔ SN explosion

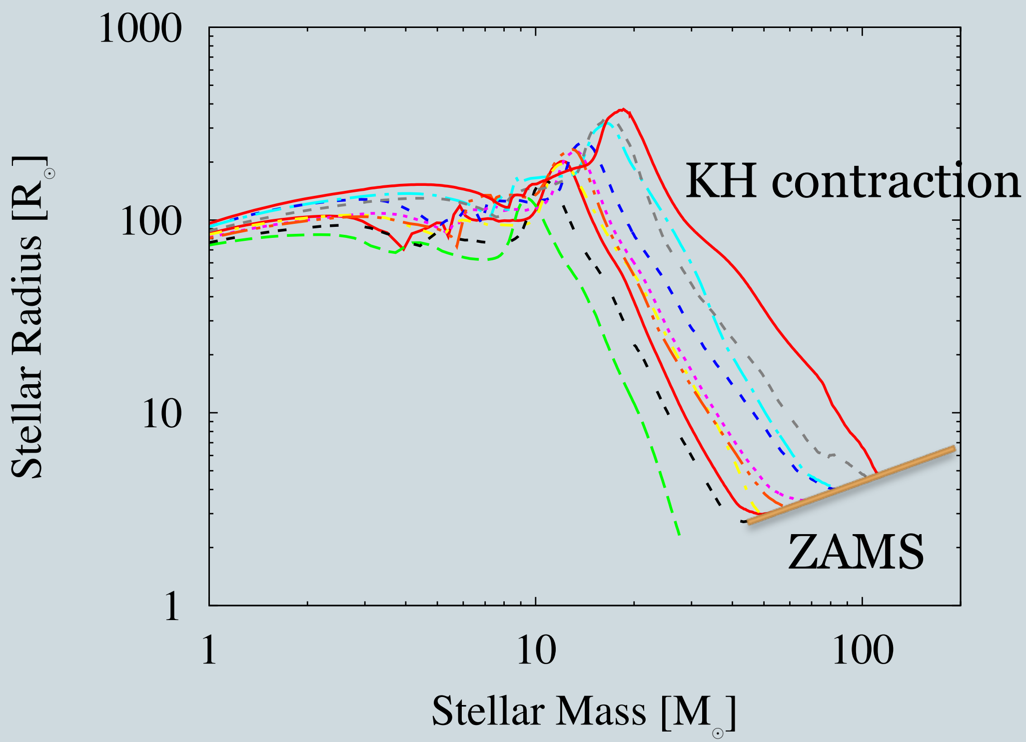
  e.g. Abel+ (2002); Bromm+ (2002)



Abel+ (2002)

- One cosmological simulation yields Pop III stars with 50-150 $M_\odot$

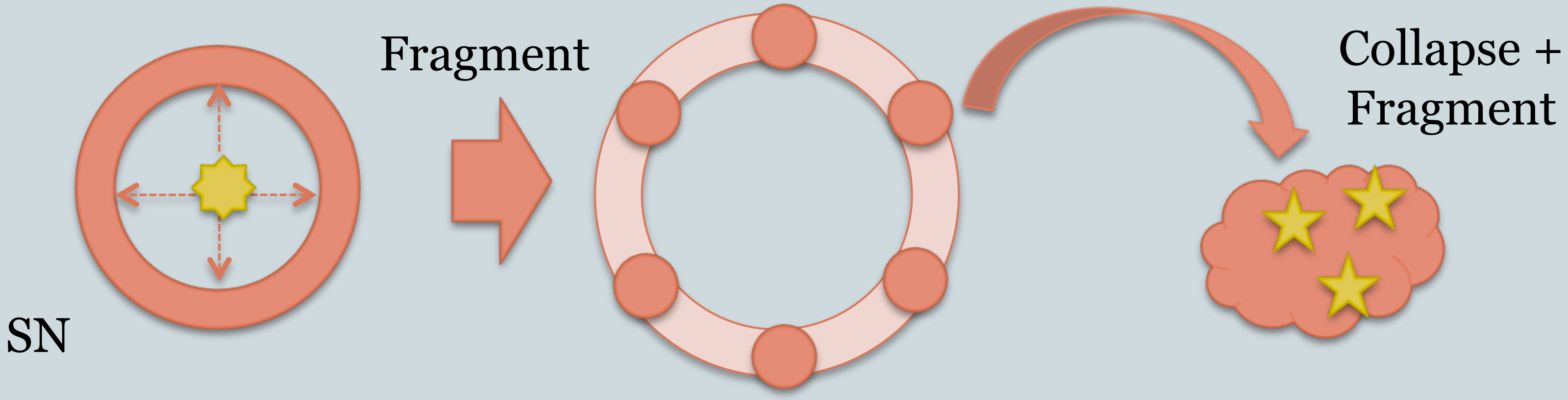
  Hirano+ in prep.



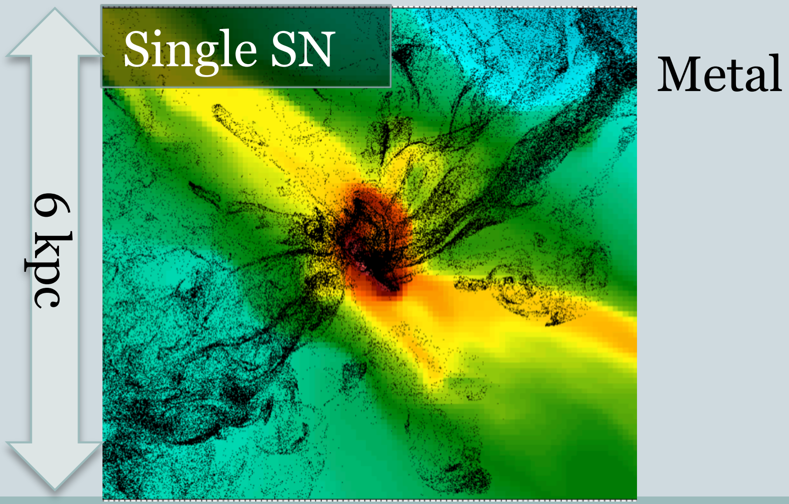
Hirano+ in prep.

Stellar Feedback by Pop III SN

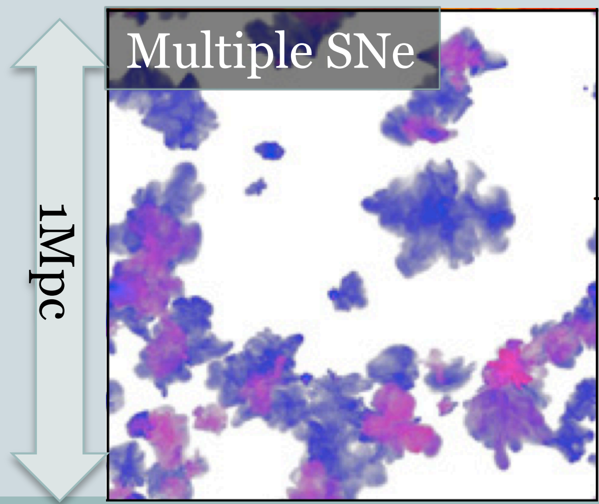
- Next-generation star formation (e.g. Machida+ 2005, Nagakura+ 2009)



- Dispersion of heavy elements into IGM and first galaxies



Ritter+ (2012)



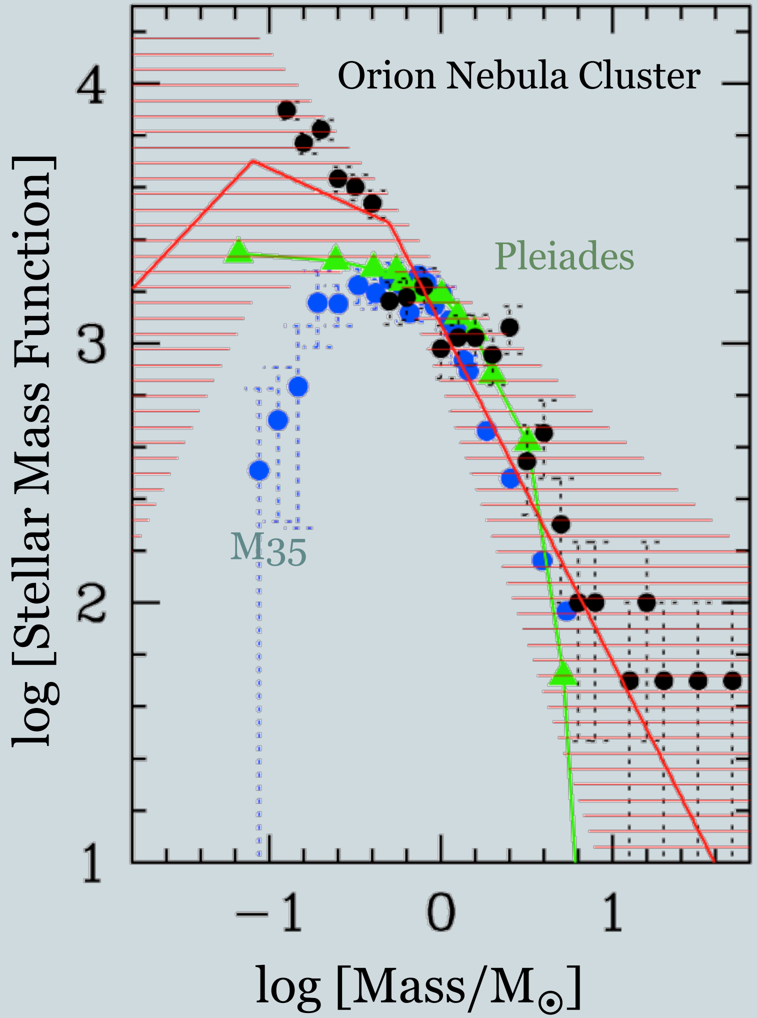
Wise+ (2012)

Present-Day IMF

Relating to star formation and metal dispersion…

- First stars are estimated to be massive (~100 $M_\odot$).
- Whereas, stars in Galaxy is typically low-mass (< 1 $M_\odot$).

➔ When did transition of mass scale occur?



Kroupa (2002)

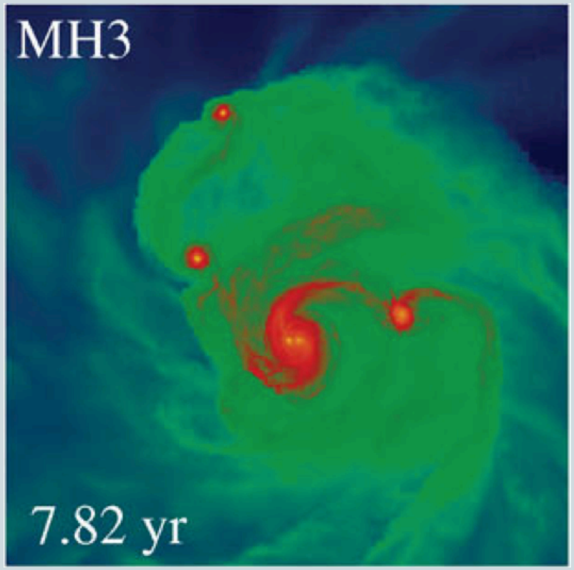
Transition of Mass Scale

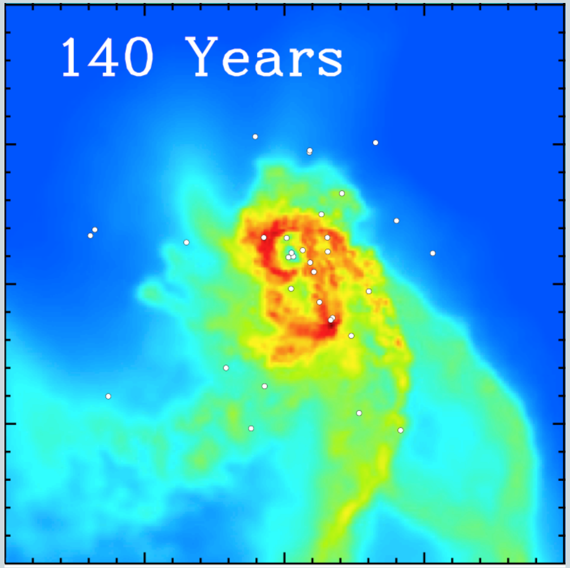
How & when did low-mass stars first form?

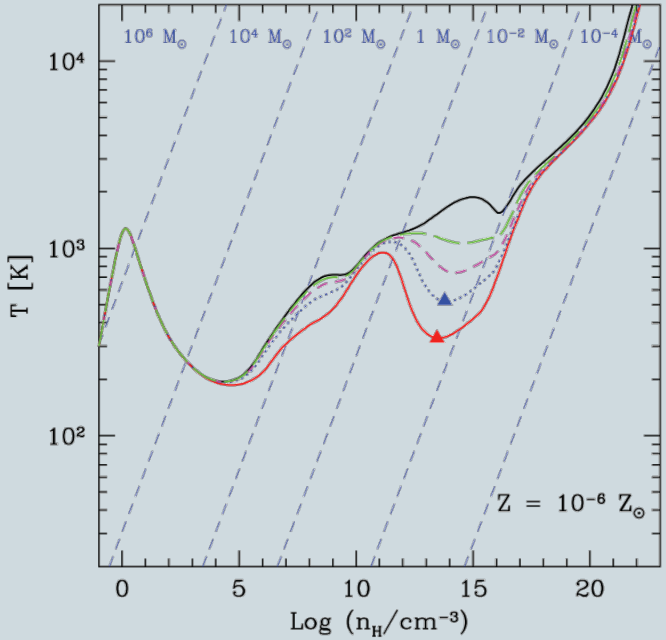
- Some researchers consider various scenarios.

due to Turbulence, Rotation | due to purely Metallicity

Metal-Free | Low-Metallicity + Dust







Greif+ (2012) | Dopcke+ (2011) | Schneider+ (2012)

Transition of Mass Scale

How & when did low-mass stars first form?

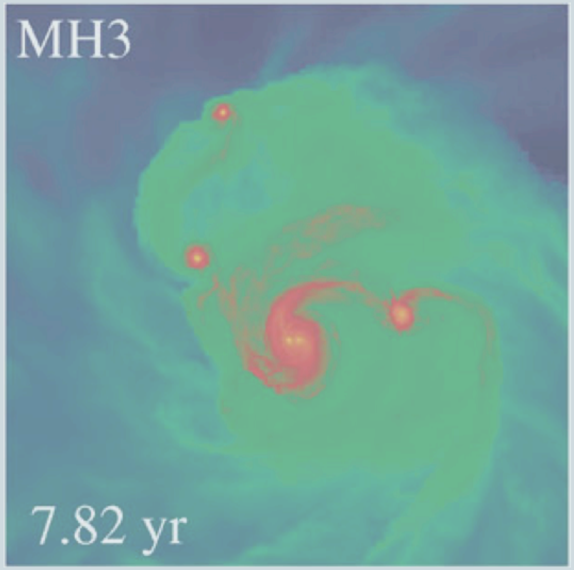
- In this work, we search minimal condition for low-mass star formation.

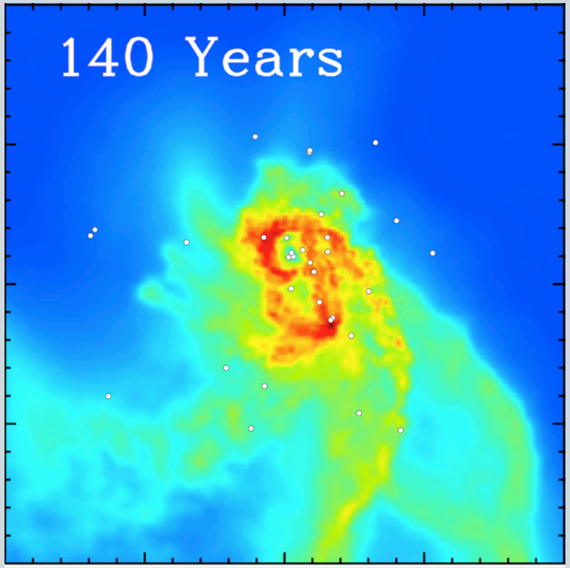
due to Turbulence, Rotation

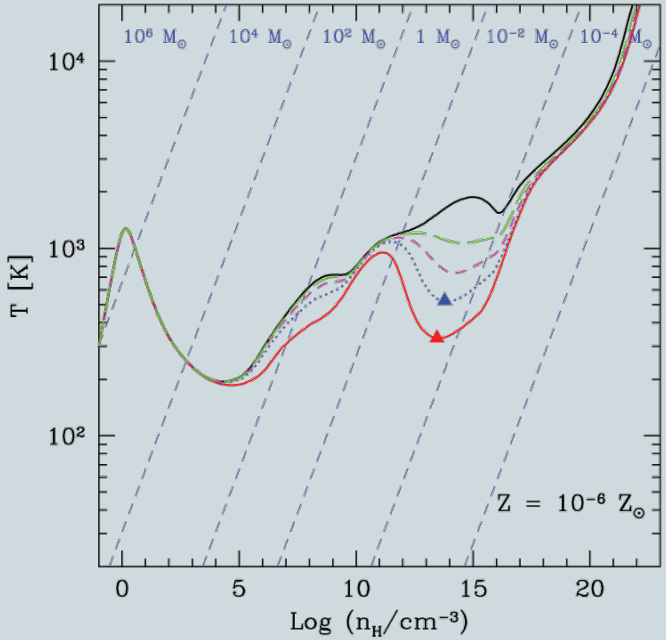
due to purely Metallicity

Metal-Free

Low-Metallicity + Dust







Greif+ (2012)

Dopcke+ (2011)

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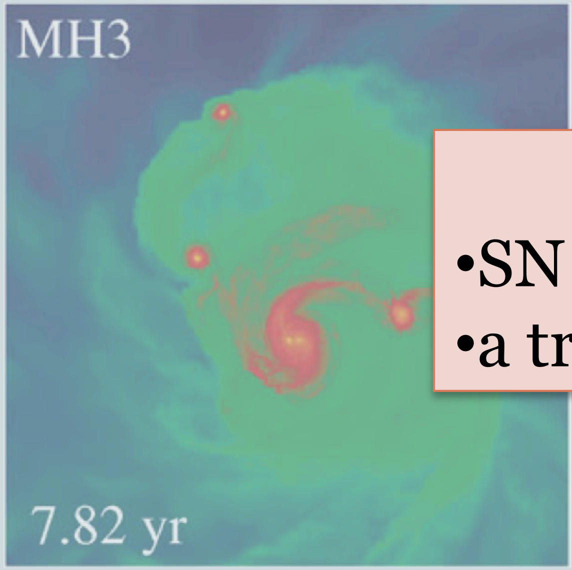
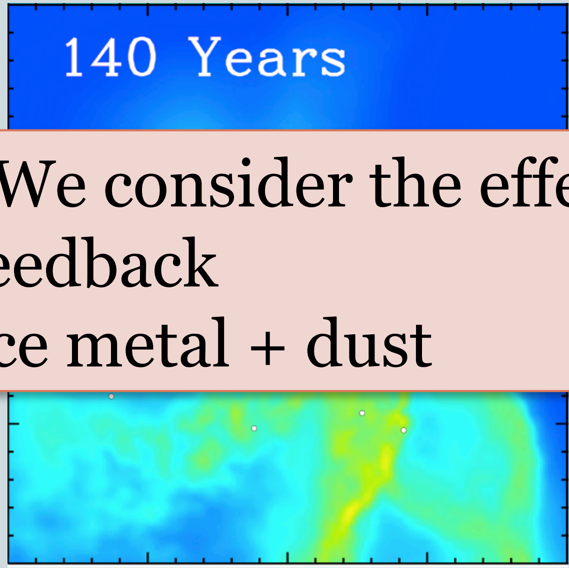
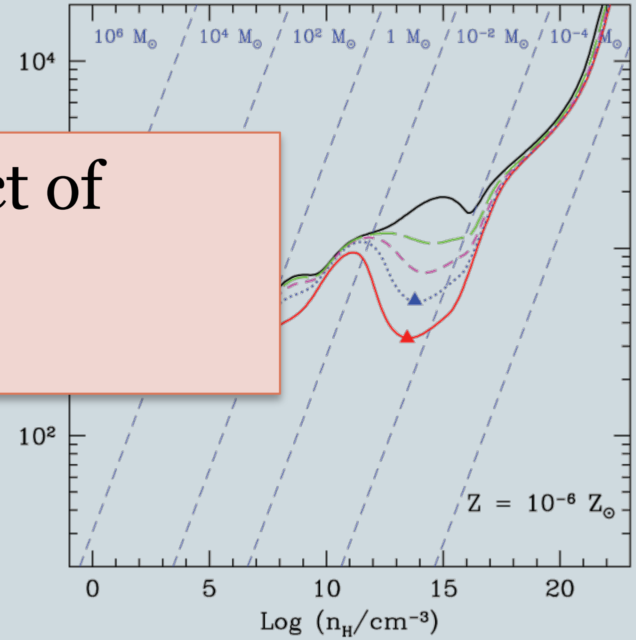






We consider the effect of

- SN feedback
- a trace metal + dust

Greif+ (2012) Dopcke+ (2011) Schneider+ (2012)

Part I
Low-mass star formation triggered by early supernova explosions

Collaborators:

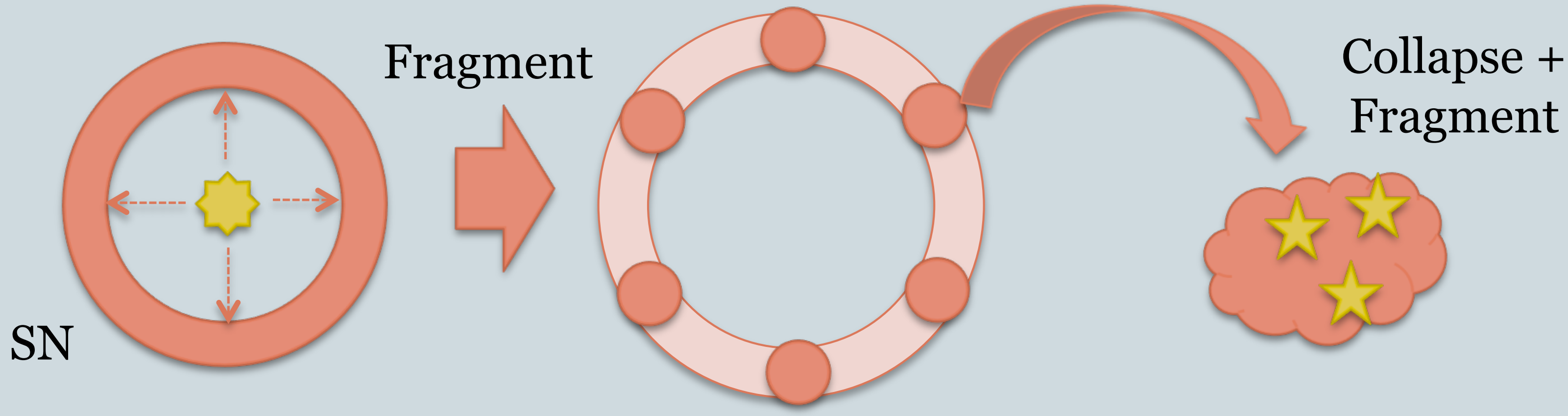
Naoki Yoshida (Tokyo), Tetsu Kitayama (Toho)

GC, Yoshida, & Kitayama (2012), submitted to ApJ, arxiv:1203.0820

Question:
Can the Pop III supernovae trigger the low-mass star formation?

Method

- Star formation triggered by SN of early generation stars



Evolution of SN shell

1D Hydrodynamic calculation
(Spherically symmetric)
- Hydrodynamics
- Self-gravity
- Non-eq. chemistry
- Radiative cooling

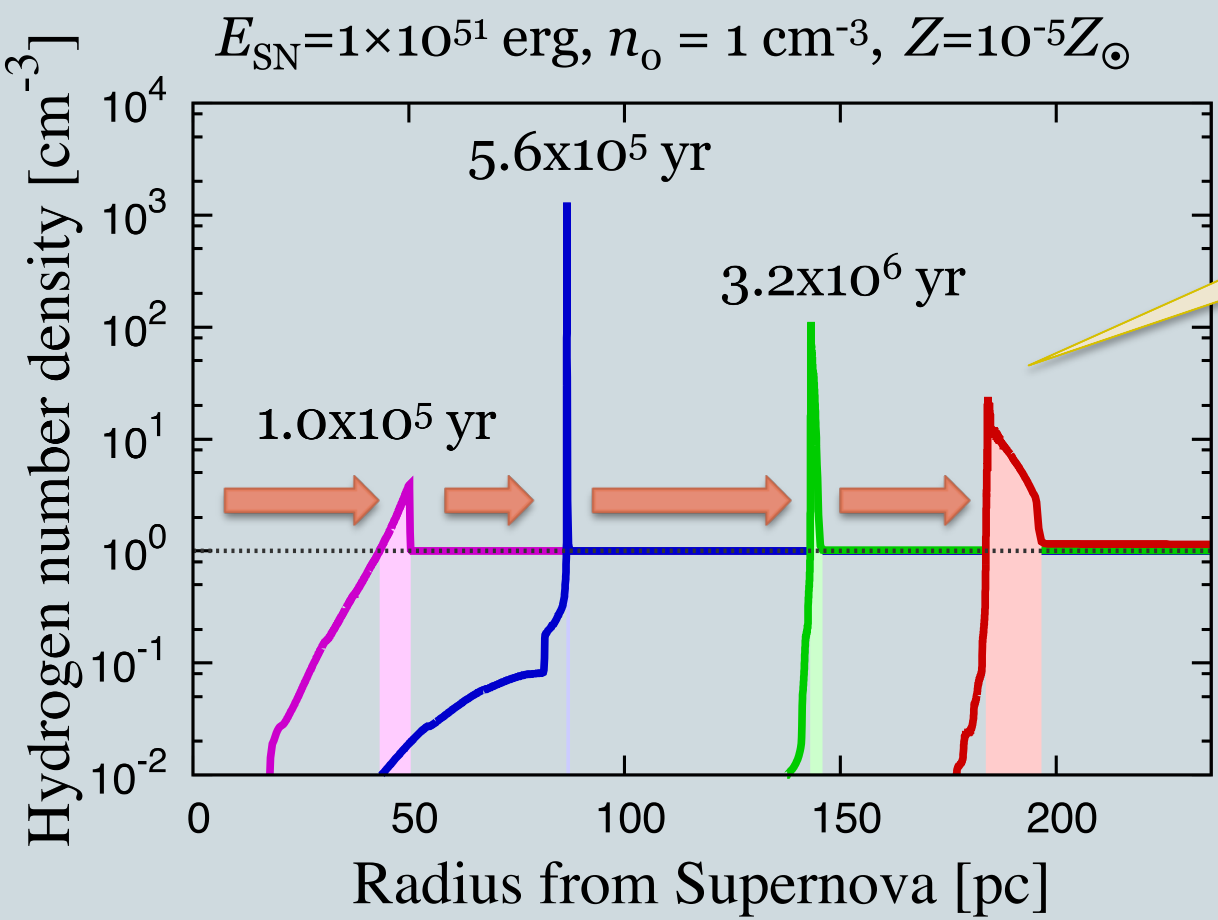
→ Fragment →

Collapse of fragments

One-zone calculation
(Spherical collapse)
- Self-gravity
- Non-eq. chemistry
- Radiative cooling
- Radiative transfer

Results: Evolution of SN Shell

- Evolution of SNR in low-metallicity ISM



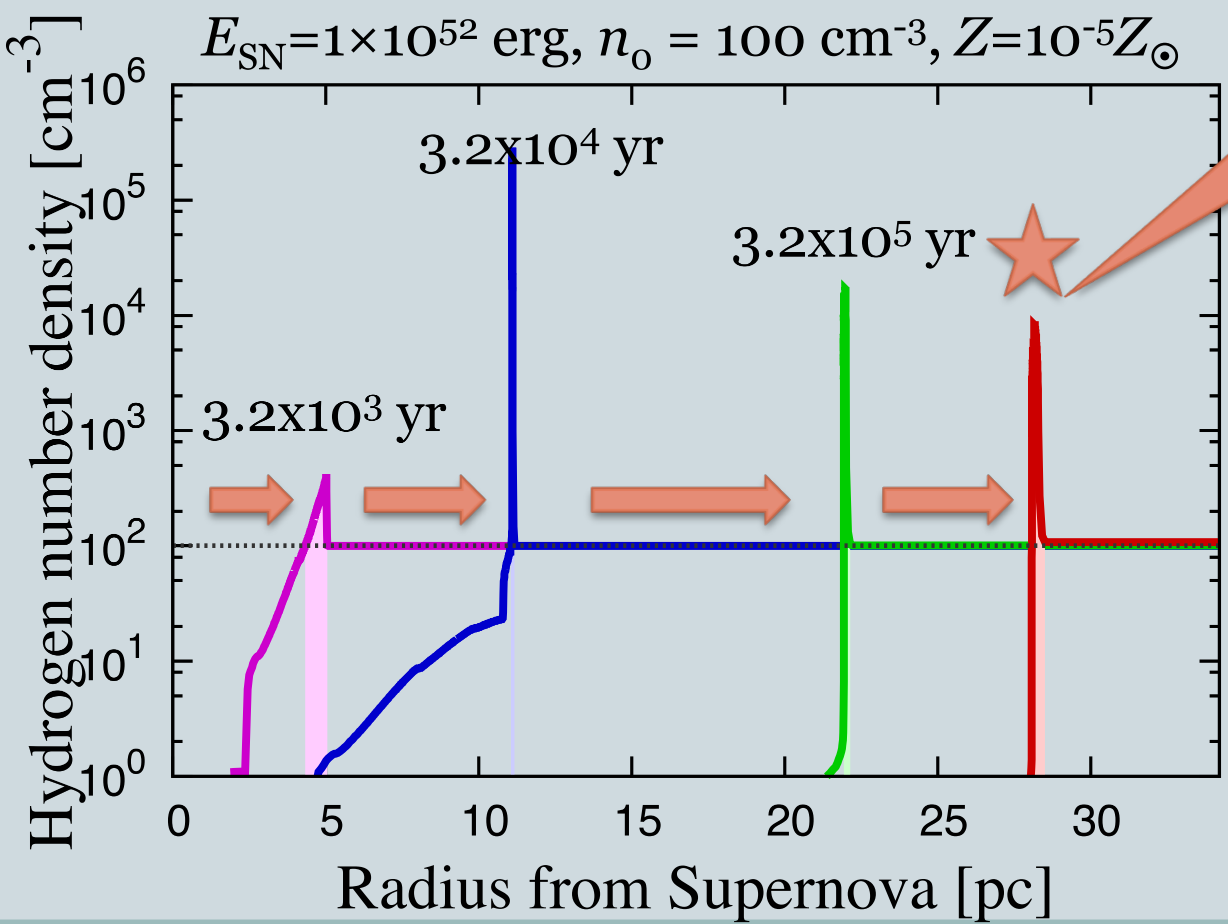
Gravitational instability
t=1.0x10^{7} yr

It is unclear whether the fragments form in the shell or not.

The time for fragmentation is comparable with halo dynamical time (~10^{7} yr)

Results: Evolution of SN Shell

- Evolution of SNR in low-metallicity ISM



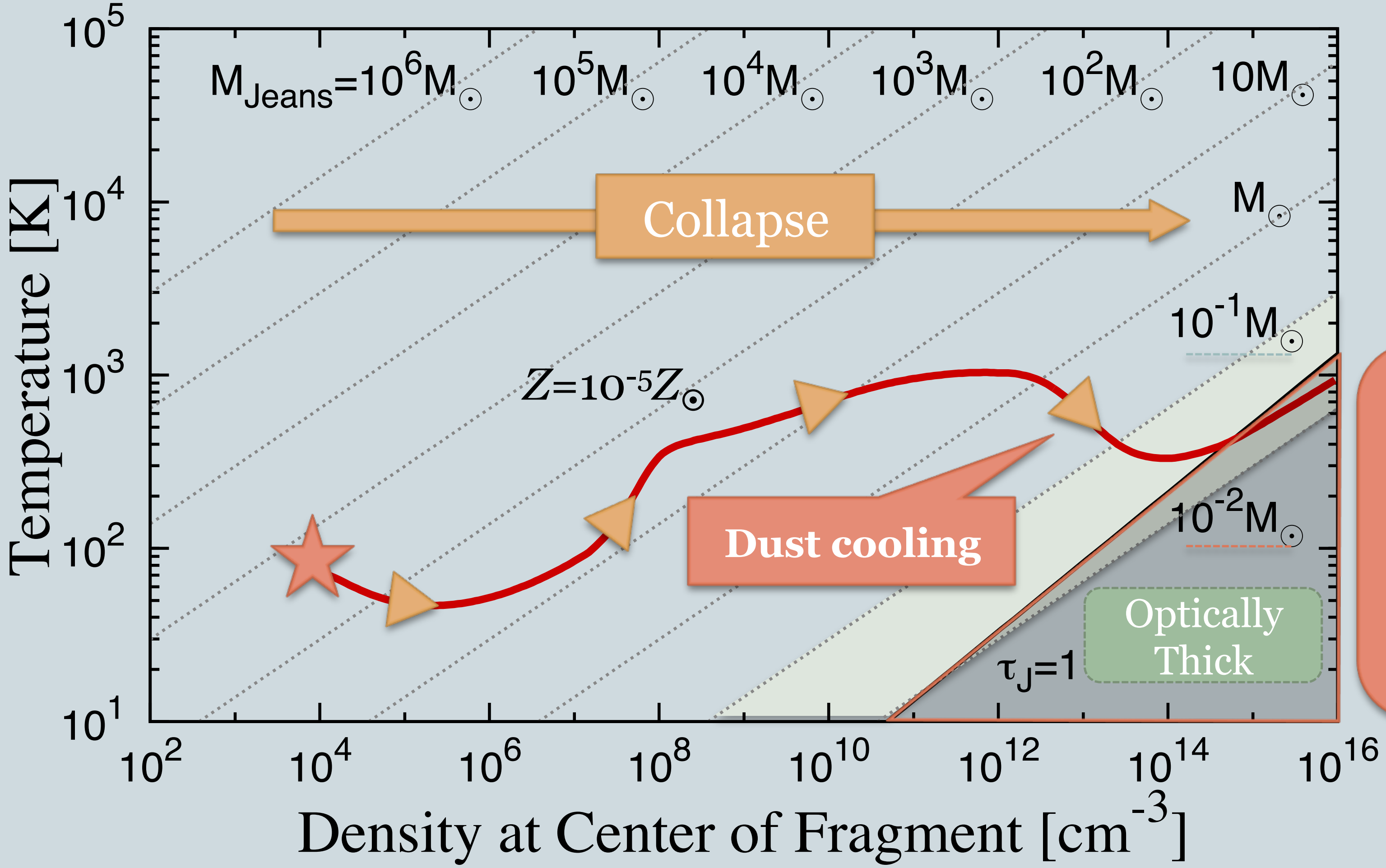
Gravitational instability
t=8.3x10^5 yr

Fragment forms!

Go to next step
---- the evolution of the fragments, using
•density
•temperature
•chemical composition
averaged over the shell

Results: Evolution of Fragment

- Evolution of SNR in low-metallicity ISM

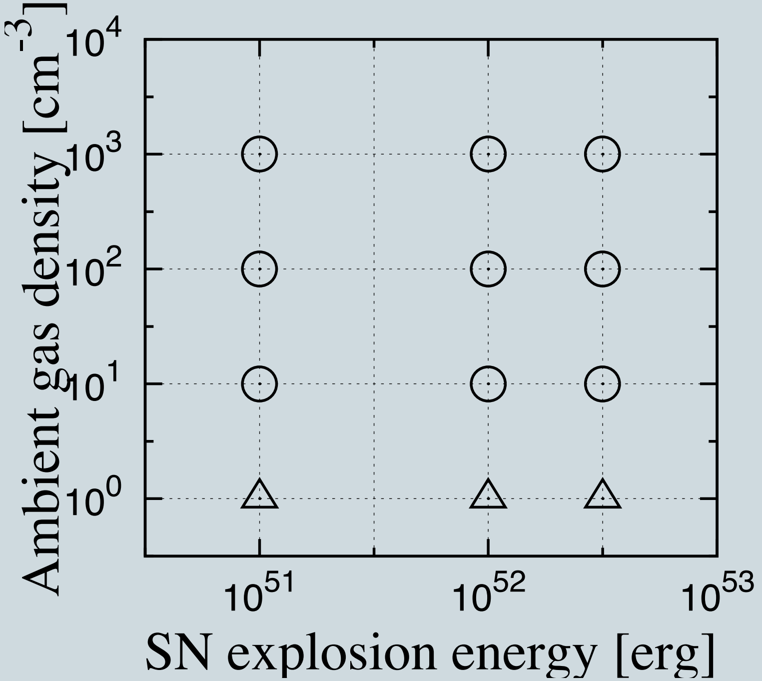


Low-mass protostar 0.1-0.01 $M_\odot$ is formed!

Results of Part I

- We investigate the effect of the stellar feedback (early SN explosion) on low-mass star formation.
- For ambient gas density $n_H > 10\ cm^{-3}$, the shell fragments to form low-mass protostar with 0.1—0.01 $M_\odot$.
  - Dust cooling plays important role for low-mass star formation.
- For ambient gas density, $n_H < 10\ cm^{-3}$, it is uncertain whether the shell fragments or not.
  - Three-dimensional simulations are required.

$Z = 1.0 \times 10^{-5} Z_\odot,\ 4.5 \times 10^{-5} Z_\odot$



○: low-mass protostars form
△: uncertain

Question:
Can the Pop III supernovae trigger the low-mass star formation?

Answer: Yes!
Stars with $M<0.1\ M_\odot$ can form for ambient gas densities $n_H>10\ cm^{-3}$

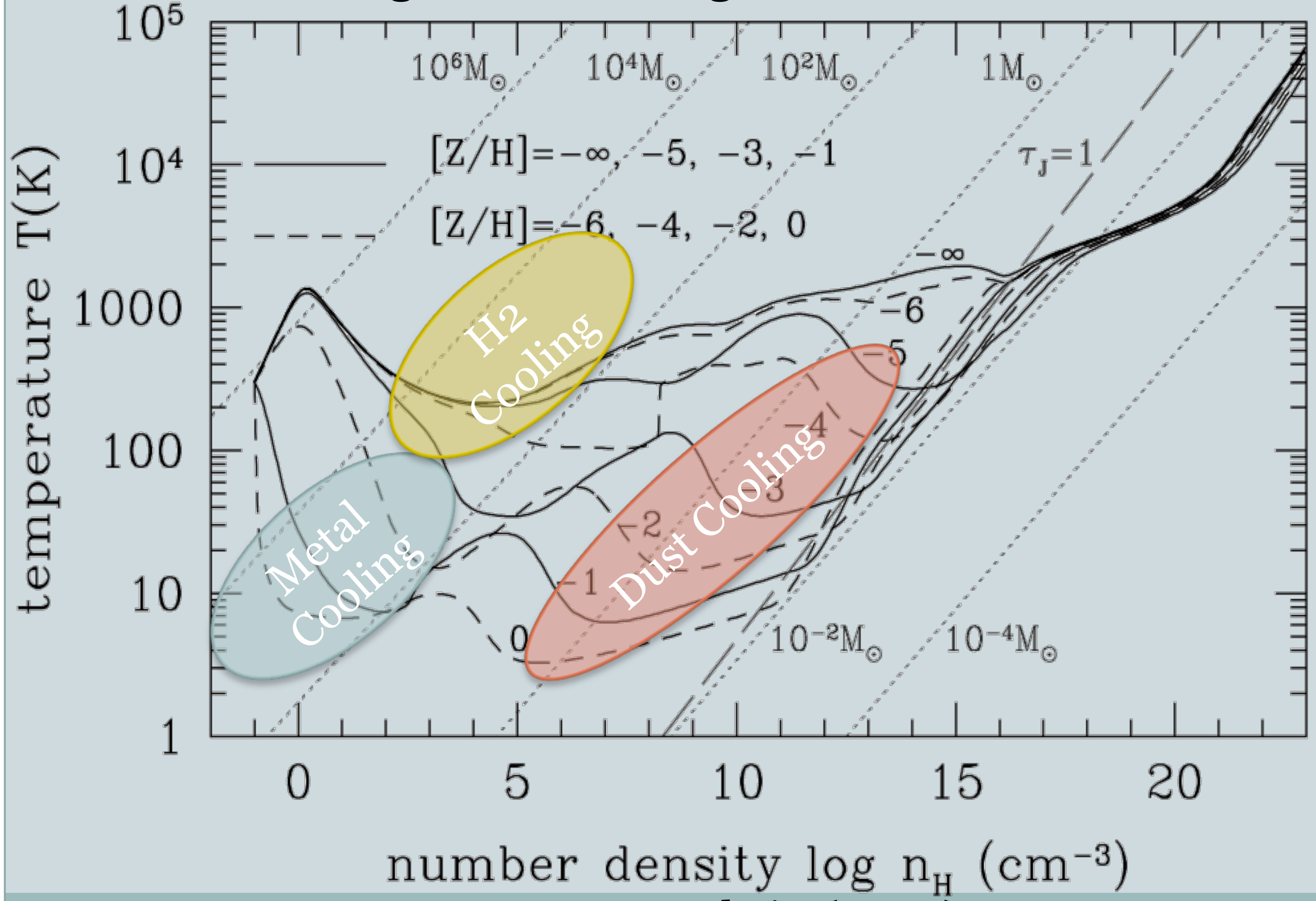
Part II
Evolution of a collapsing gas cloud considering growth of dust grains

Collaborators:
Takaya Nozawa (KIPMU), Naoki Yoshida (Tokyo)

GC, Nozawa & Yoshida (2012), in prep

Three Different Mass Scales

- In no rotating or turbulent gas cloud



Omukai+ (2005)

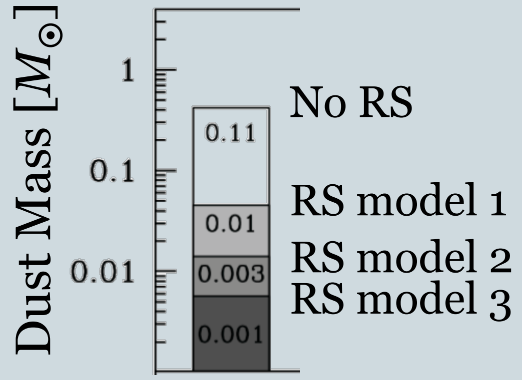
H_2 cooling
$M_{Jeans} \sim 10^3 M_\odot$
e.g. Abel+ (2002)

Metal cooling
$M_{Jeans} \sim 10^3 M_\odot$
e.g. Bromm+ (2001)

Dust cooling
$M_{Jeans} \sim 10^{-1} M_\odot$
e.g. Larson (2005)

SNR as a Site of Dust Formation/Destruction

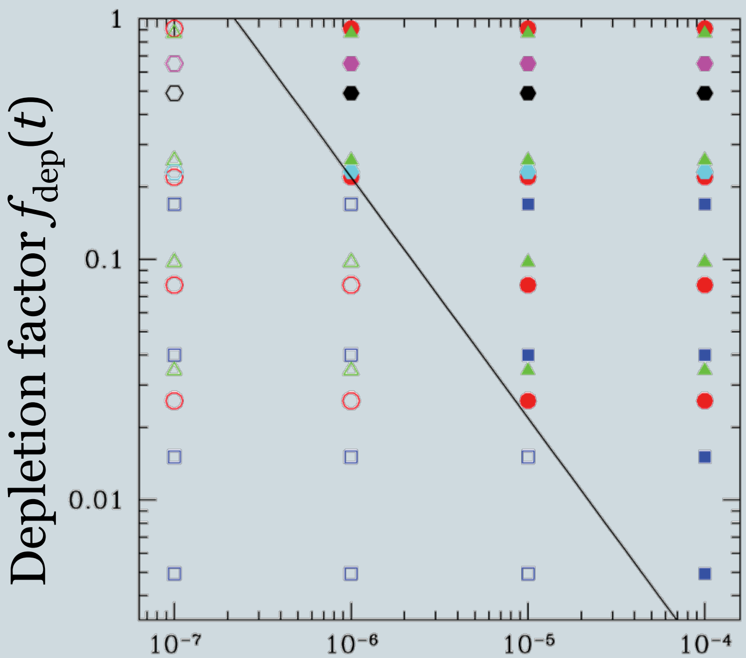
- First dust was formed in Pop III SNR.
  Todini & Ferrara 2001; Nozawa+ 2003;
- Simultaneously, grains are destroyed by the reverse shock (RS).
  Bianchi & Schneider 2007; Nozawa+ 2007



- By taking dust destruction into consideration, Schneider+ (2012, MNRAS 419, 1566) found that the condition for low-mass star formation:

$$\mathcal{SD} > 1.4 \times 10^{-3}\ \mathrm{cm^2\,g^{-1}} \left(\frac{T}{10^3\ \mathrm{K}}\right)^{-1/2} \left(\frac{n_\mathrm{H}}{10^{12}\ \mathrm{cm^{-3}}}\right)^{-1/2}$$

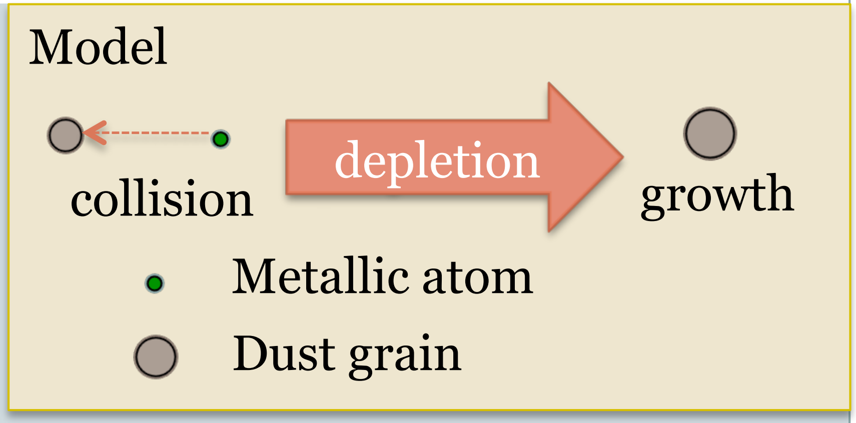
S : geometrical cross-section per unit dust mass
$\mathcal{D}=Zf_{dep}$: dust-to-gas mass ratio after destruction

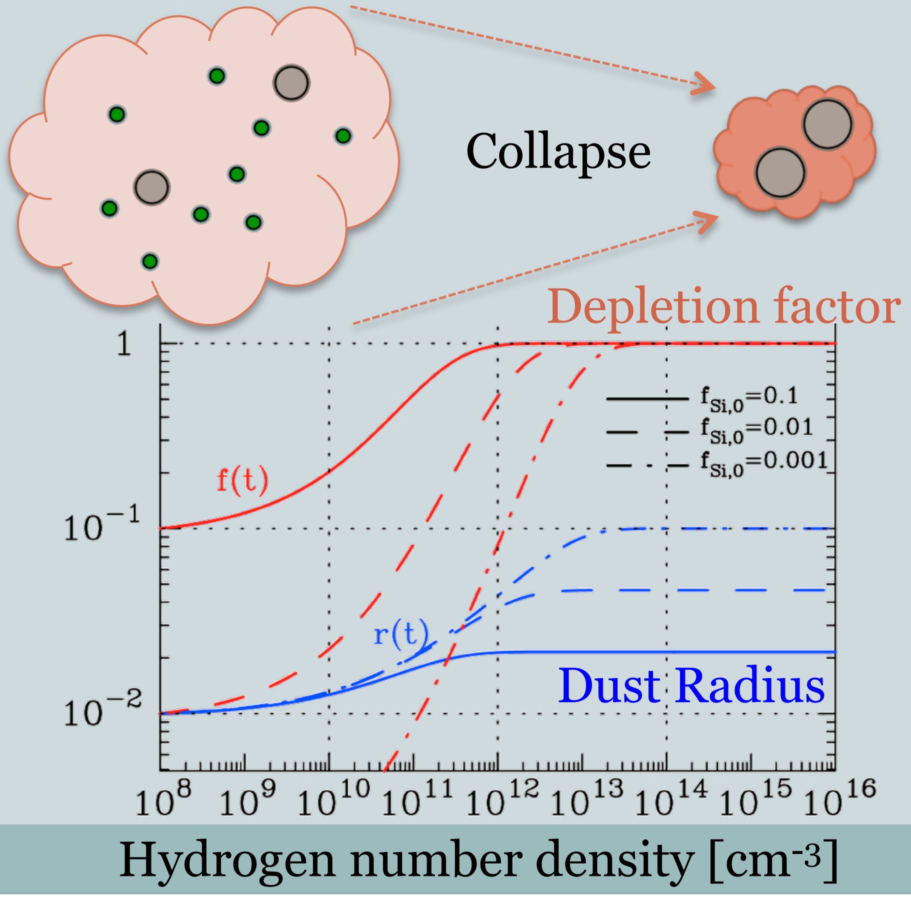


see also Schneider+ (2012, MNRAS 423, 60)

Grain Growth in a Collapsing Gas Cloud

- Nozawa+ (2012) suggest that the grain growth in a collapsing gas can modify the fragmentation condition.



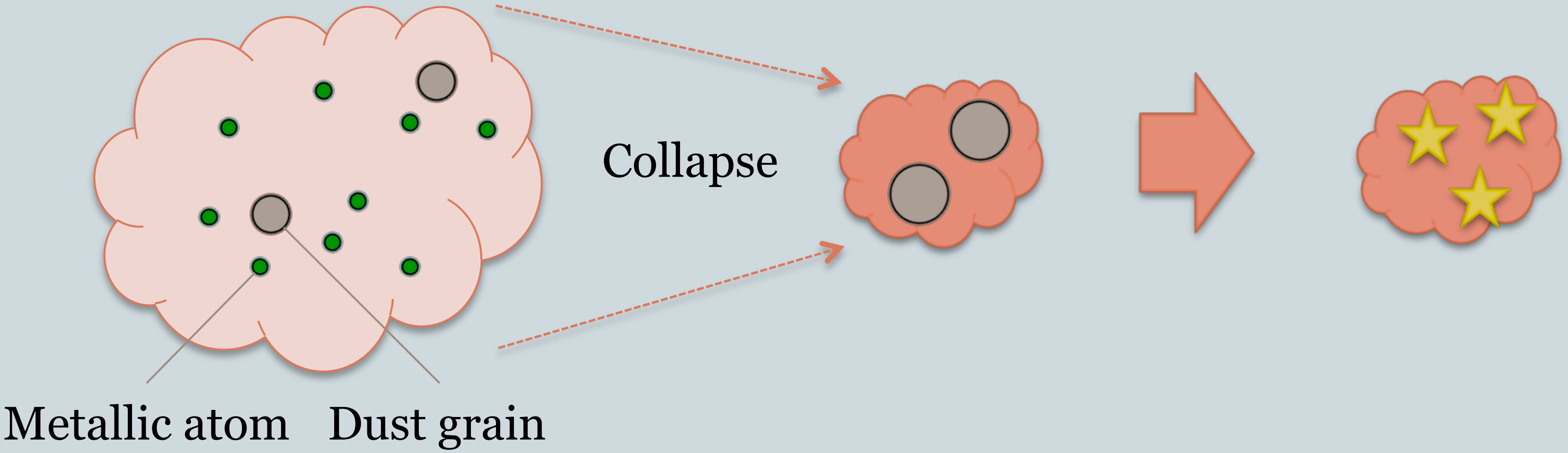


- They show that all of metallic atoms eventually deplete on grains in certain models.
- We further investigate whether dust cooling affect the thermal evolution of collapsing gas cloud.

Question:
Can the grain growth enhance the fragmentation?

Method

- Evolution of a collapsing gas cloud considering grain growth

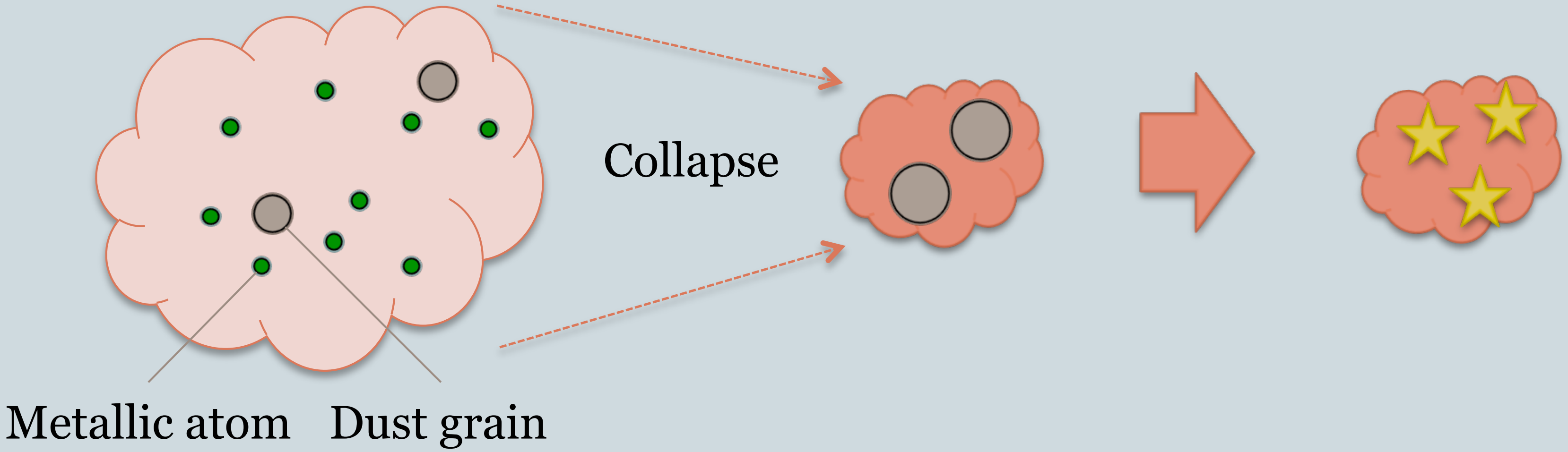


Collapse of fragments

One-zone calculation (Spherical collapse)	Simultaneously solve
•Self-gravity	•Grain growth
•Non-eq. chemistry	•Dust temperature
•Radiative cooling	•Dust cooling
•Radiative transfer	•Dust opacity
	consistently!

Method

- Evolution of a collapsing gas cloud considering grain growth

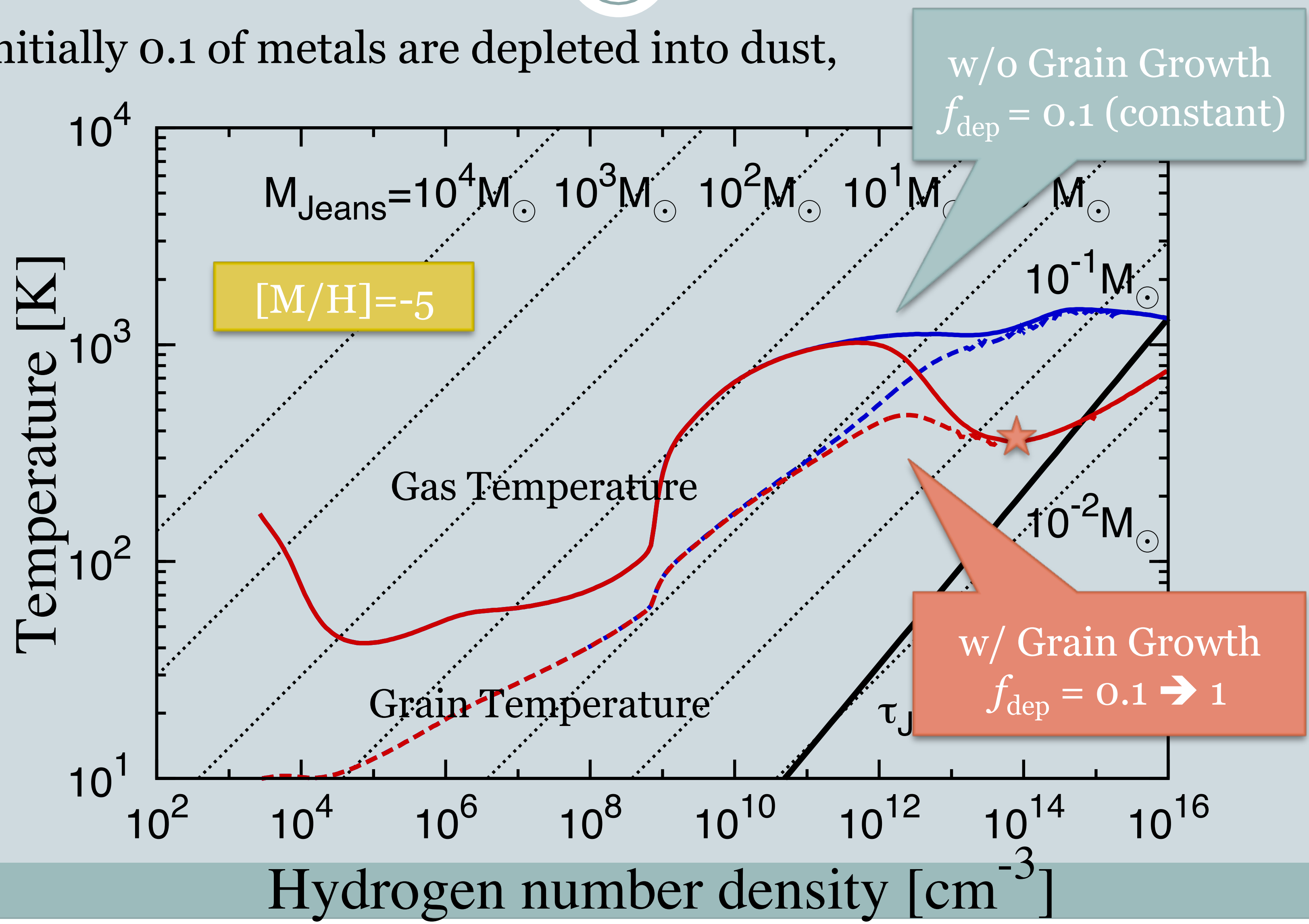


- To find minimal conditions, we first include silicate ($MgSiO_3$) dust.
- We assume that the dust grains are spherical and have the same size.

  ← The dust size distribution has little effect on the thermal evolution of collapsing clouds (Hirashita & Omukai 2009).

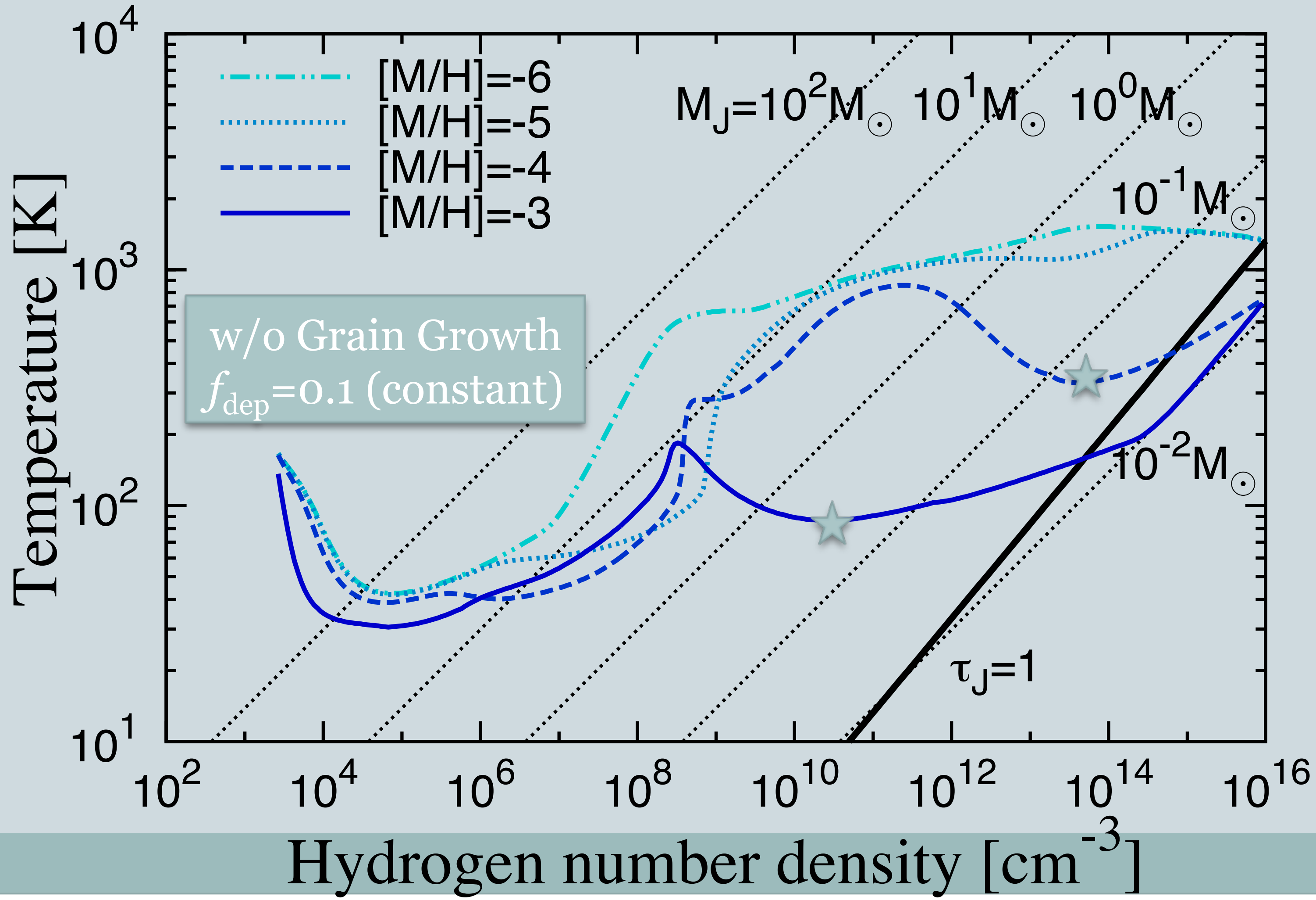
Results: w/ vs. w/o Grain Growth

- If initially 0.1 of metals are depleted into dust,



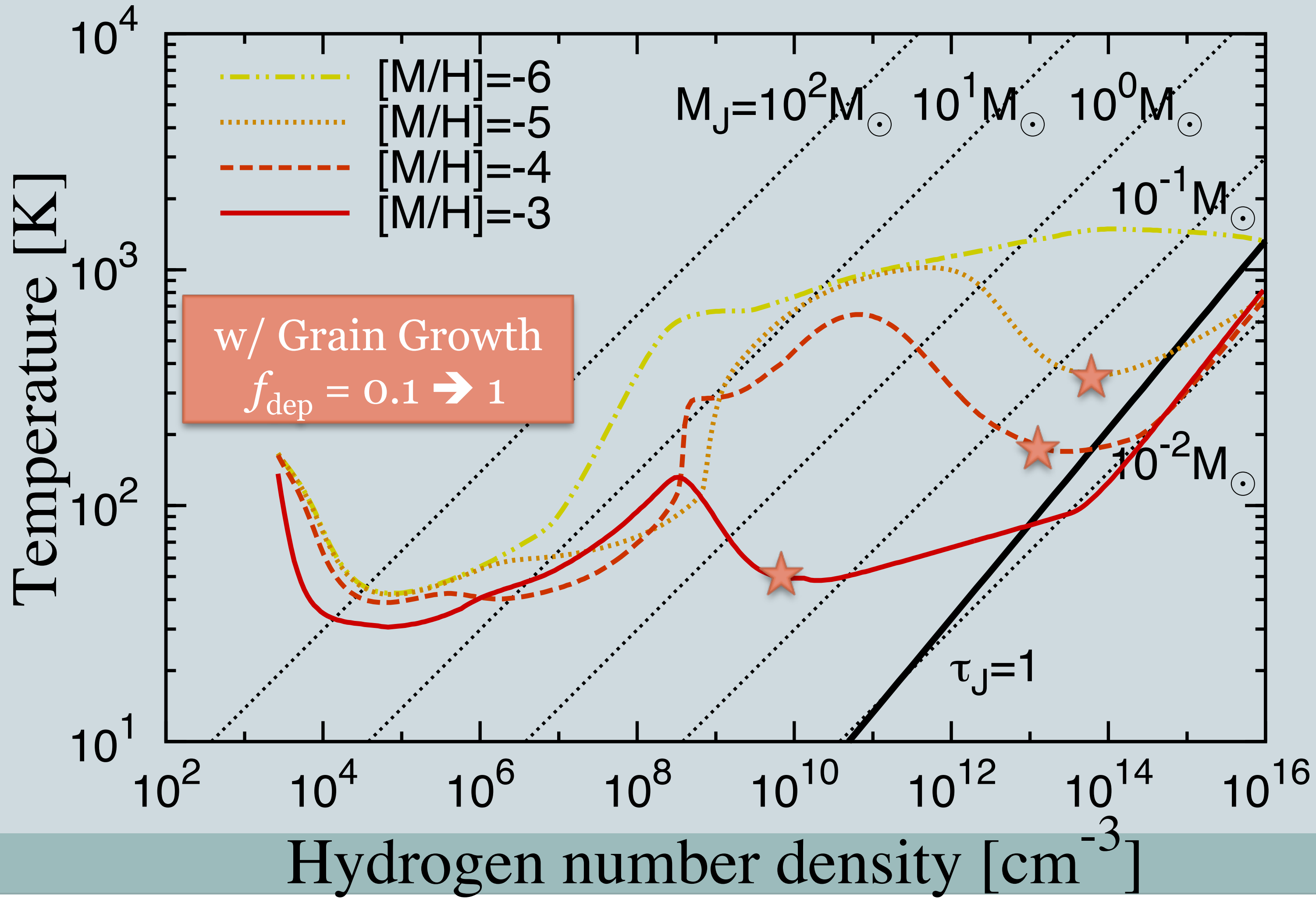
Results: Metallicity Dependence

- When we do NOT consider the grain growth:

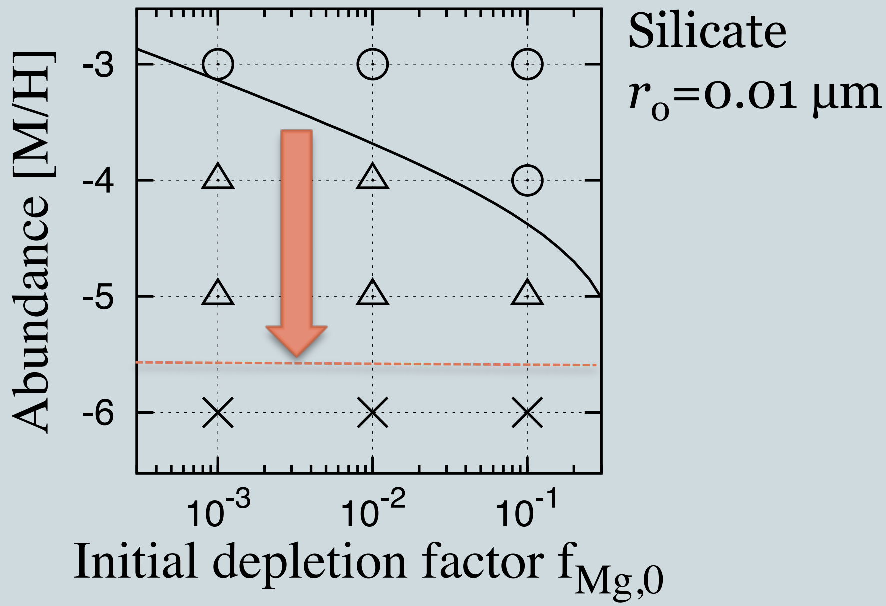


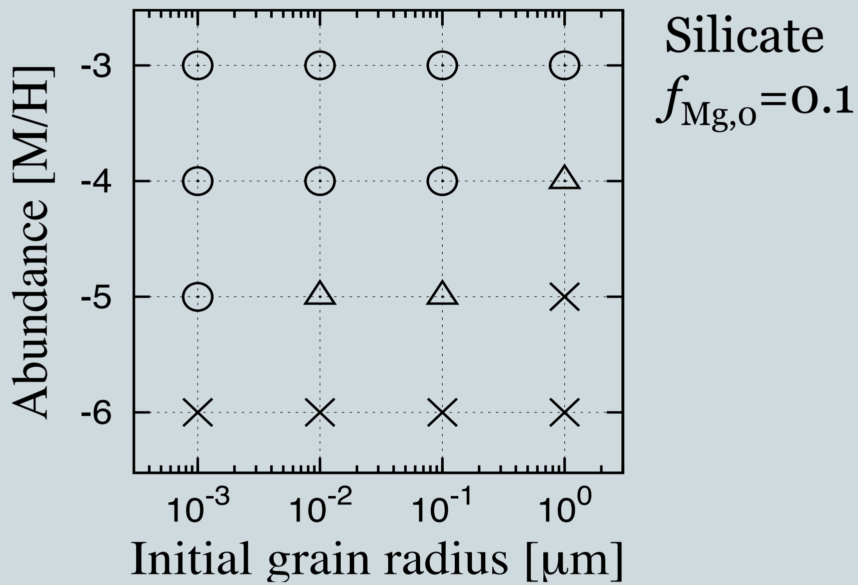
Results: Metallicity Dependence

- When we consider the grain growth:



Results: Critical abundance





—— fragmentation condition (Schneider+ 2012; Nozawa+ 2012)

○: fragment in both models w/ and w/o grain growth

△: fragment in models w/ grain growth

×: no fragments

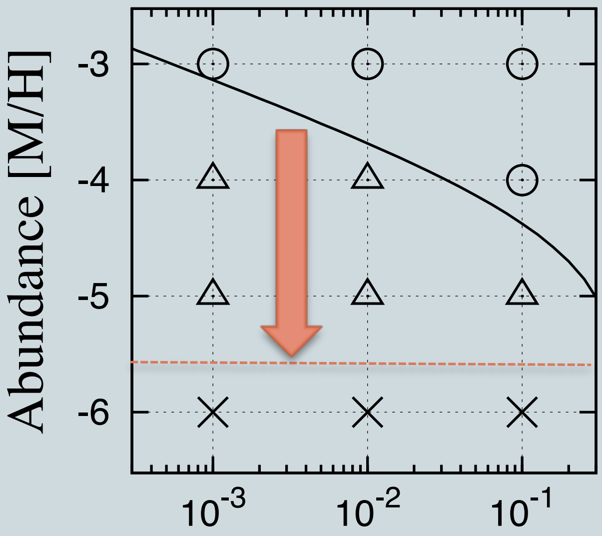
- Dust radius ↑

⇒ Total surface area ↓

(total dust mass is constant)

⇒ Cooling efficiency ↓

Result of Part II



Initial depletion factor $f_{Mg,0}$

Silicate

r_0=0.01 μm

—— fragmentation condition (Schneider+ 2012; Nozawa+ 2012)

○: fragment in both models w/ and w/o grain growth

△: fragment in models w/ grain growth

×: no fragments

- We study the evolution of collapsing gas cloud, considering the growth of dust grains.
- Even when we include only $MgSiO_3$, the fragmentation condition dramatically changes!
  - Lower initial abundances are required in models w/ grain growth.
- Gas Clouds fragment with [M/H] $\gtrsim$ -5.5 when we consider grain growth.

Question:
Can the grain growth enhance the fragmentation?

Answer: Yes!
Low-mass protostars can form for [M/H]>-5.5 (r_{dust}<1 μm)

Summary

- We investigate the stellar feedback of early SN explosion.
  - especially, star formation (and metal pollution of the ISM)
  - Low-mass star can be formed in extremely metal-poor environment.
- Furthermore, we study the effect of grain growth on the evolution of collapsing gas cloud.
  - Grain growth is crucial for low-mass star formation in the early universe.

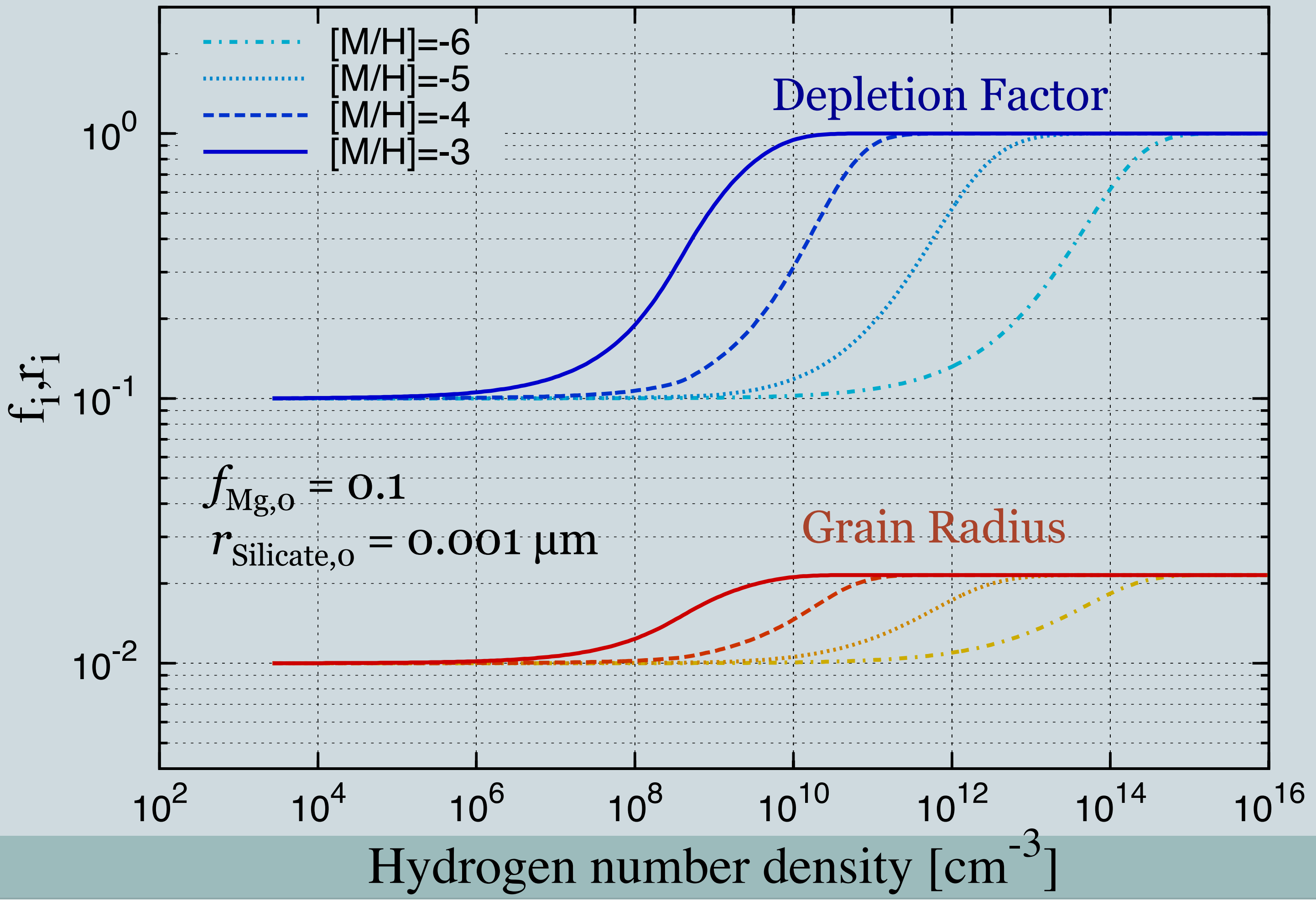
Future Works:

- In the latter work, we include $MgSiO_3$ (refractory, large κ) ➔ consider the effect of other dust species.
- Three-dimensional calculations are required to confirm the predictions from our model.

Appendix

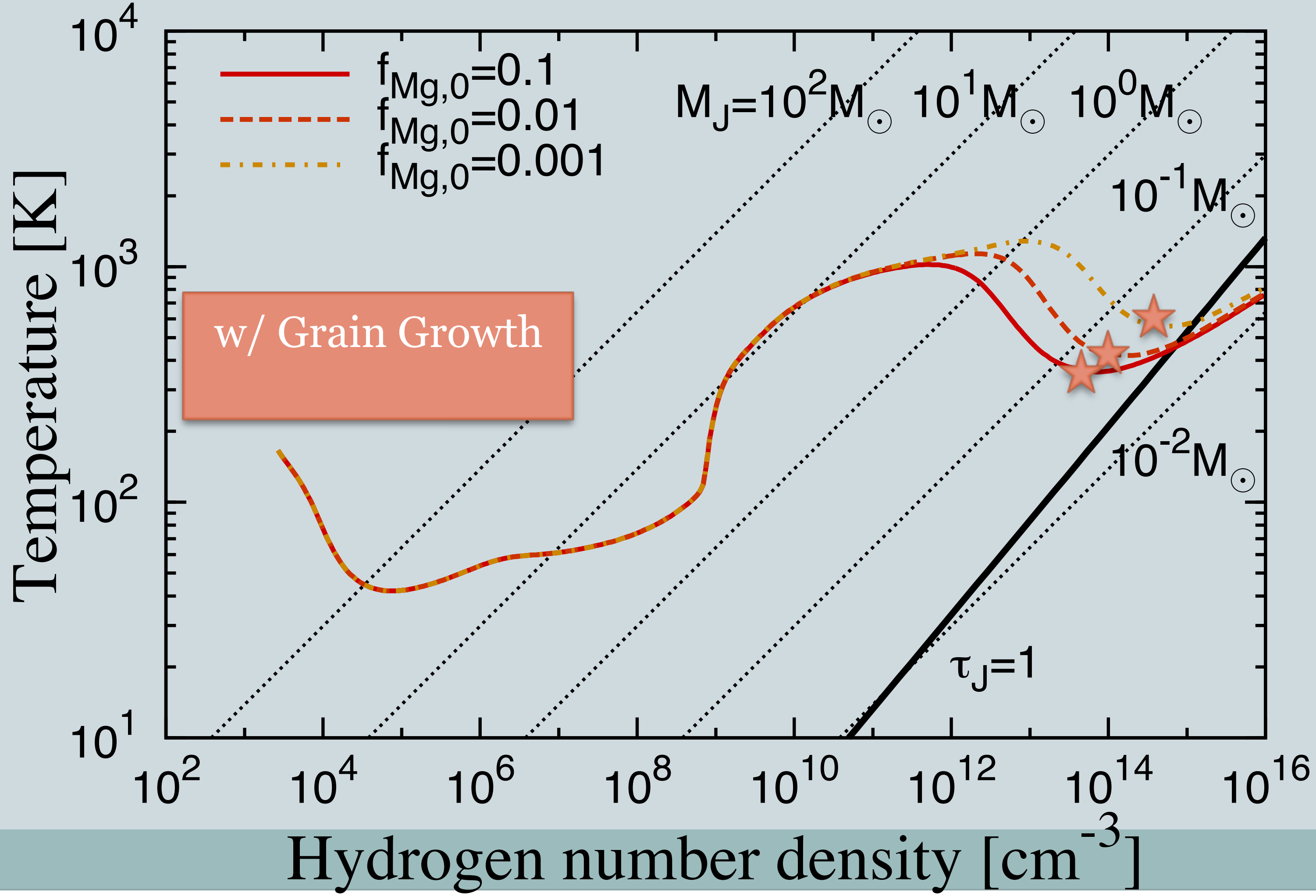
Results: Metallicity Dependence

- $MgSiO_3$



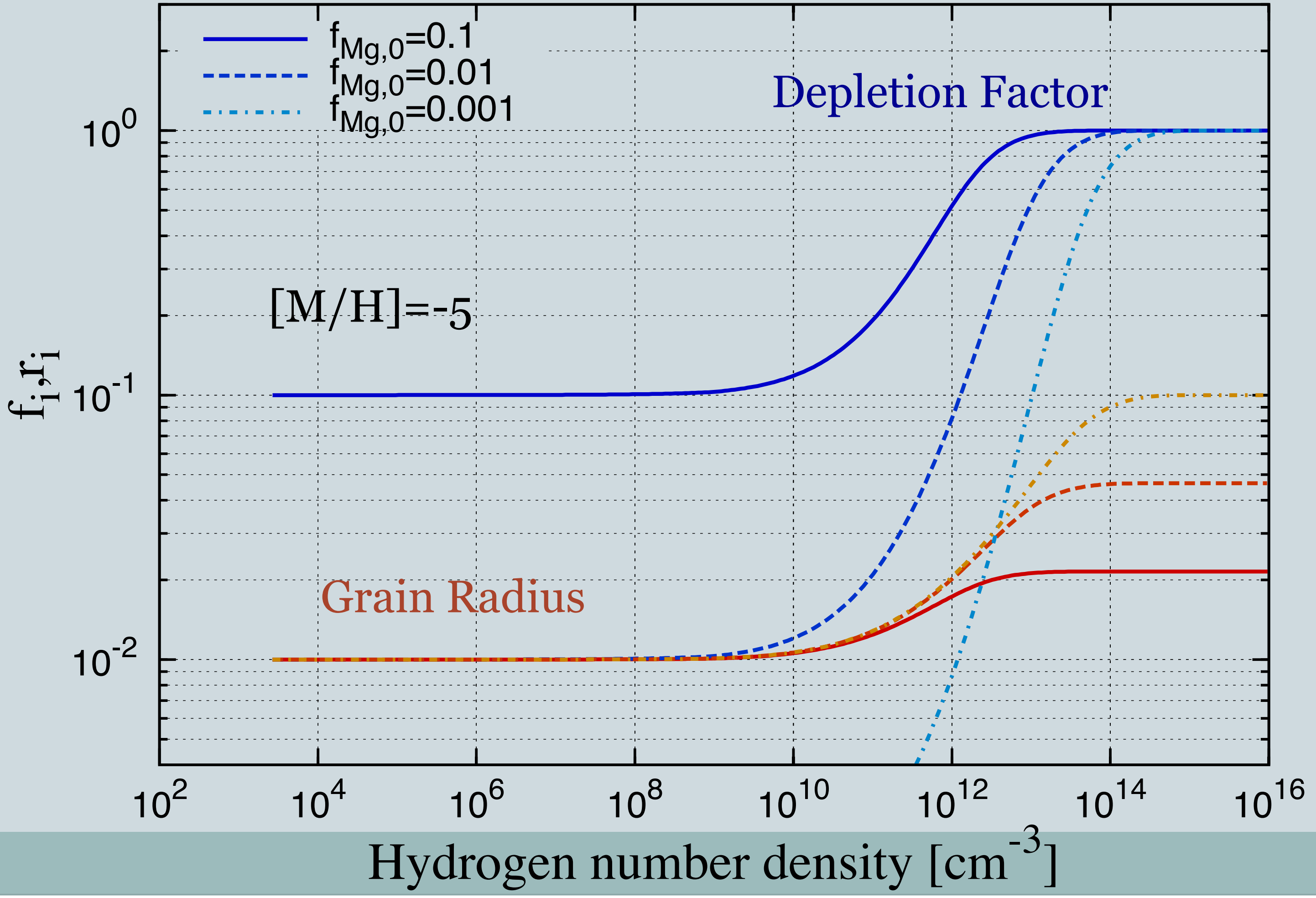
Results: Initial Depletion Factor Dependence

- $r_{Mg,0}$=0.01 μm, [M/H]=-5



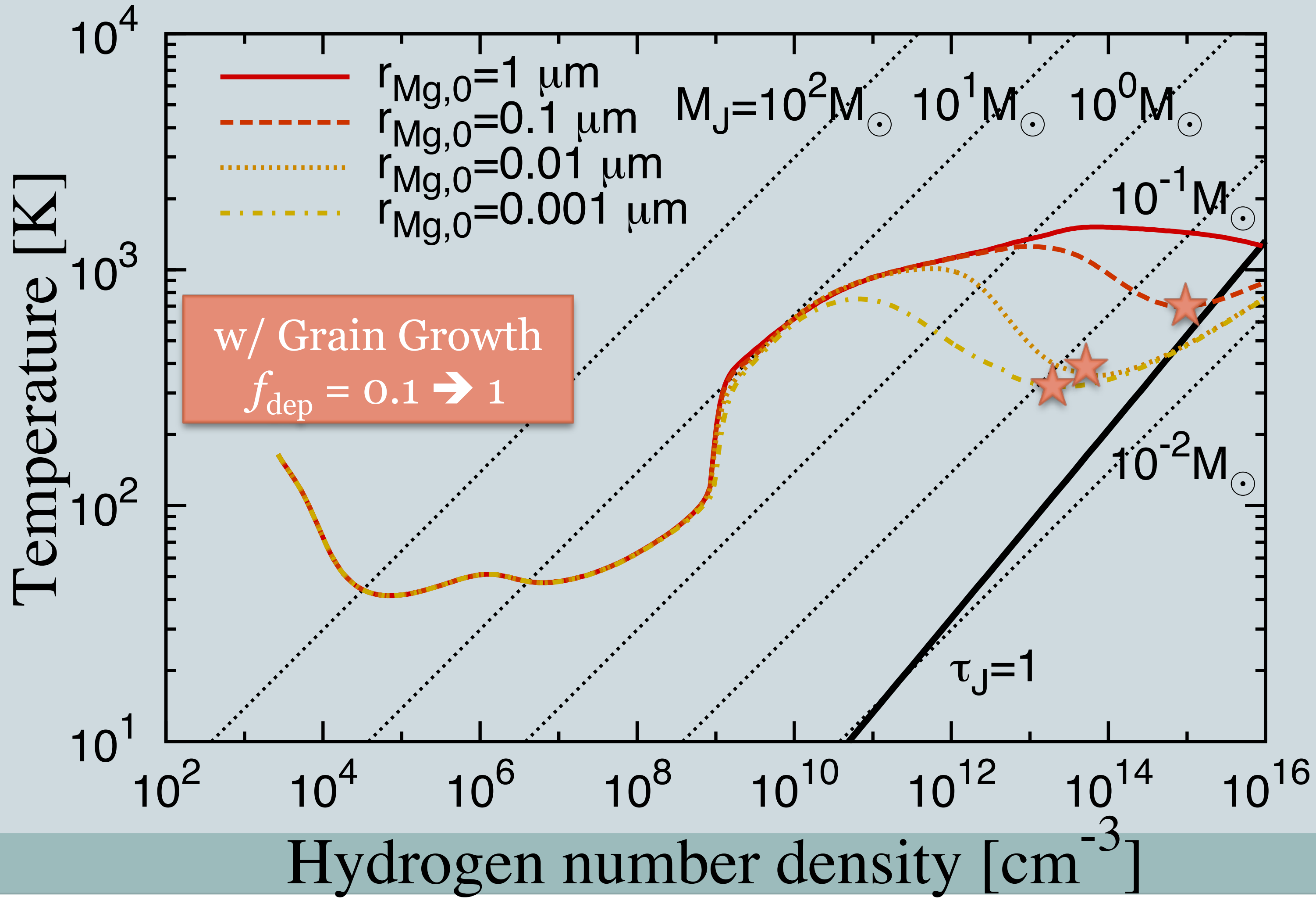
Results: Initial Depletion Factor Dependence

- $MgSiO_3$



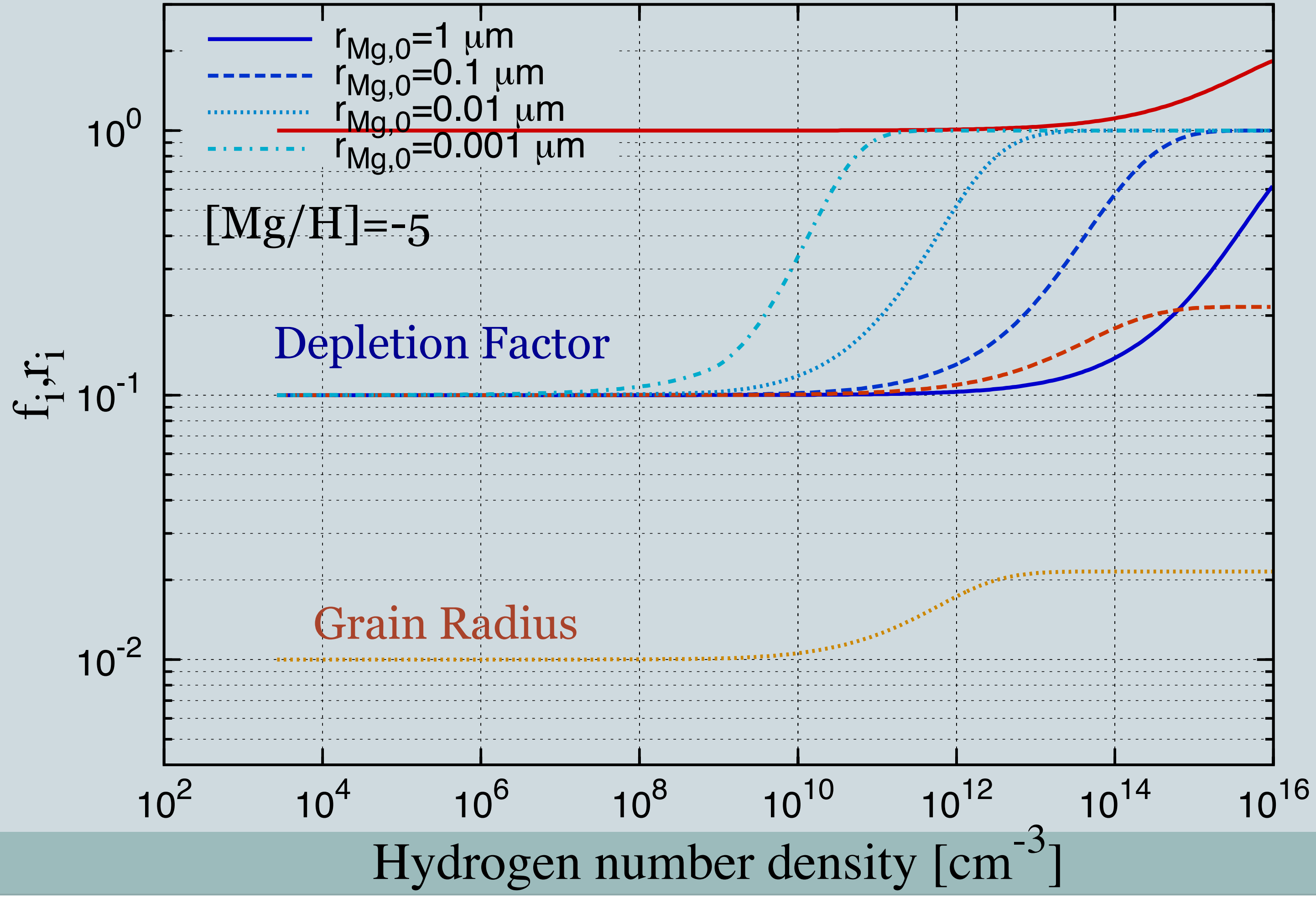
Results: Initial Grain Radius Dependence

- $f_{Mg,0}$=0.1, [Mg/H]=-5



Results: Initial Grain Radius Dependence

- $MgSiO_3$



Models

- Grain growth model (see Nozawa+ 03, 12)

$$\frac{dr_i}{dt} = s_i \left(\frac{4\pi}{3} a_{i,0}^3\right) \left(\frac{kT_{\rm gas}}{2\pi m_i}\right)^{\frac{1}{2}} c_i^{\rm gas}(t) \left(1 - \frac{1}{S_i}\sqrt{\frac{T_{\rm dust}}{T_{\rm gas}}}\right)$$

- Dust temperature/dust cooling

$$\begin{aligned} \Gamma_{\gamma\to\rm d} + \Gamma_{\rm g\to d} &= \Lambda_{\rm d\to\gamma} \\ \Gamma_{\rm g\to d} &= \Lambda_{\rm d\to\gamma} - \Gamma_{\gamma\to\rm d} \\ n_{\rm d} n_{\rm H} \sigma_{\rm d} \langle v_{\rm g} \rangle (2kT_{\rm g} - 2kT_{\rm d}) &= 4\rho_{\rm d} \sigma T_{\rm d}^4 \kappa_{\rm d} f_{\rm cont} \end{aligned}$$

Dust Species