# LOW-MASS STAR FORMATION INDUCED BY THE GROWTH OF DUST GRAINS IN LOW-METALLICITY GAS CLOUDS

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# Massive Pop III Stars

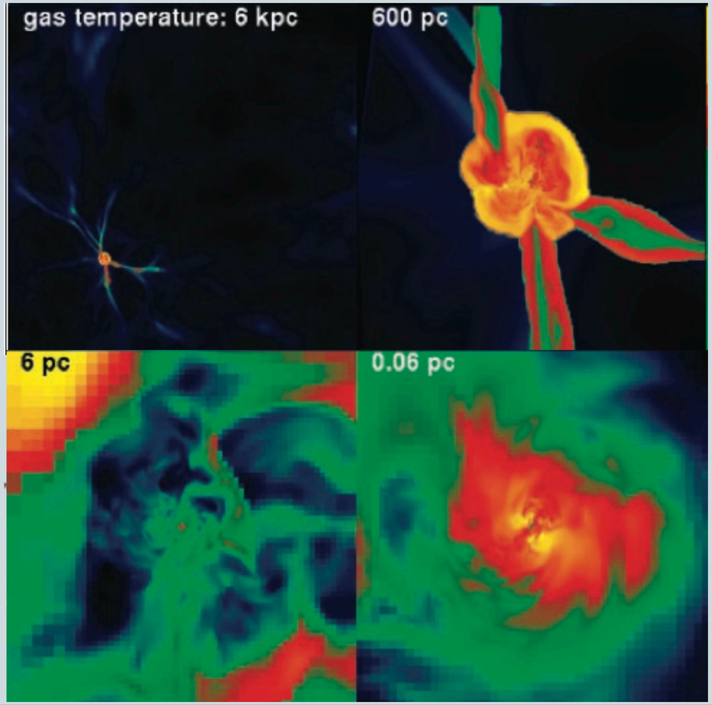
First star (or Population III star)

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

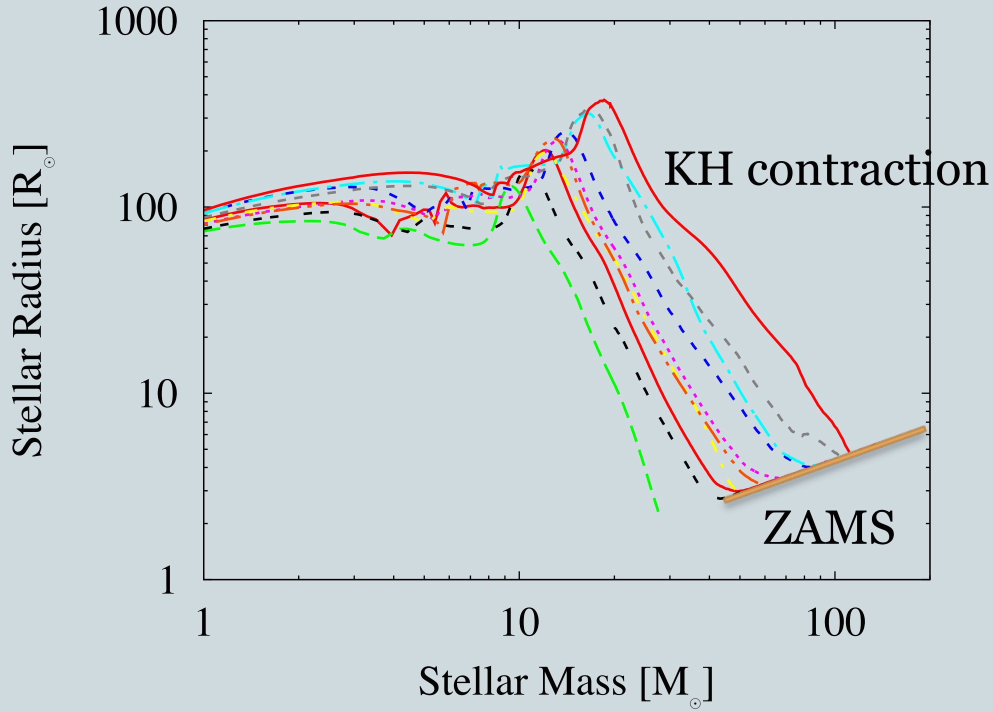
e.g. Abel+ (2002); Bromm+ (2002)

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

Hirano+ in prep.




Abel+ (2002)

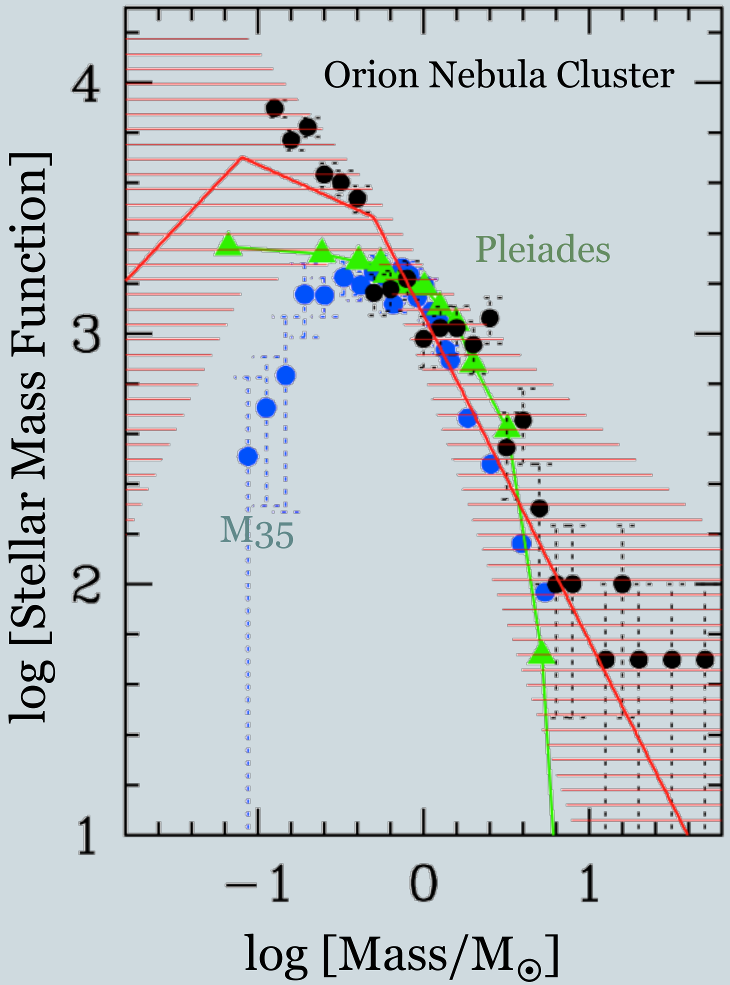



Hirano+ in prep.

# Present-Day IMF

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

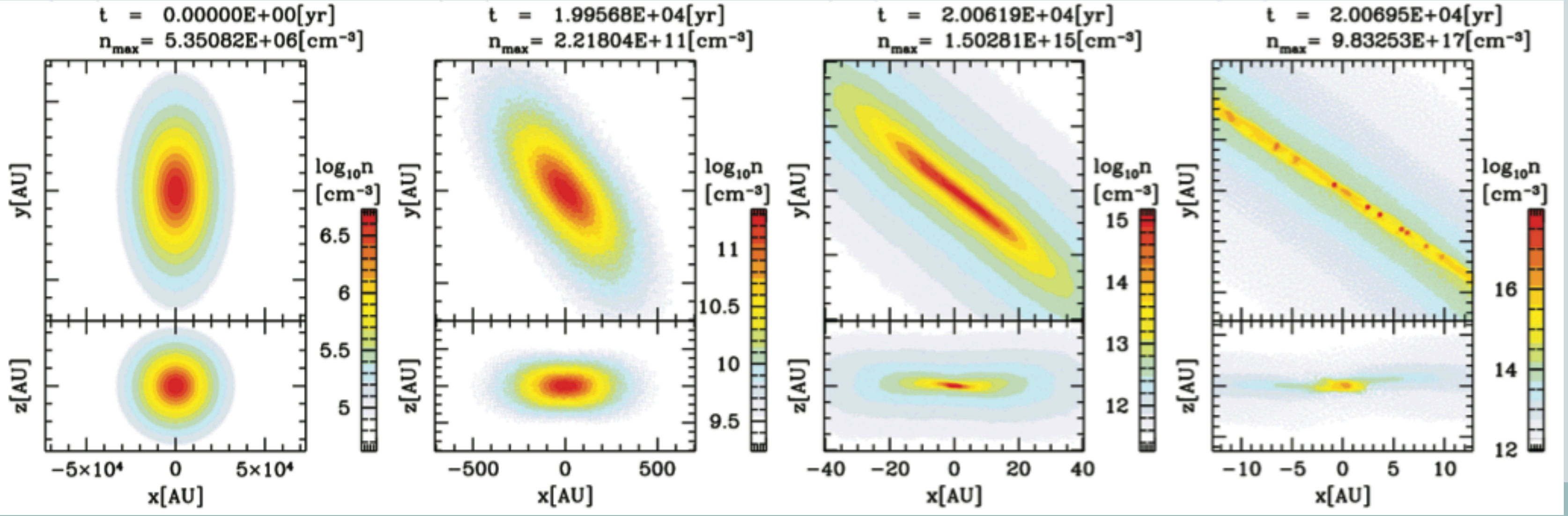
➔ When did transition of mass scale occur?




Kroupa (2002)

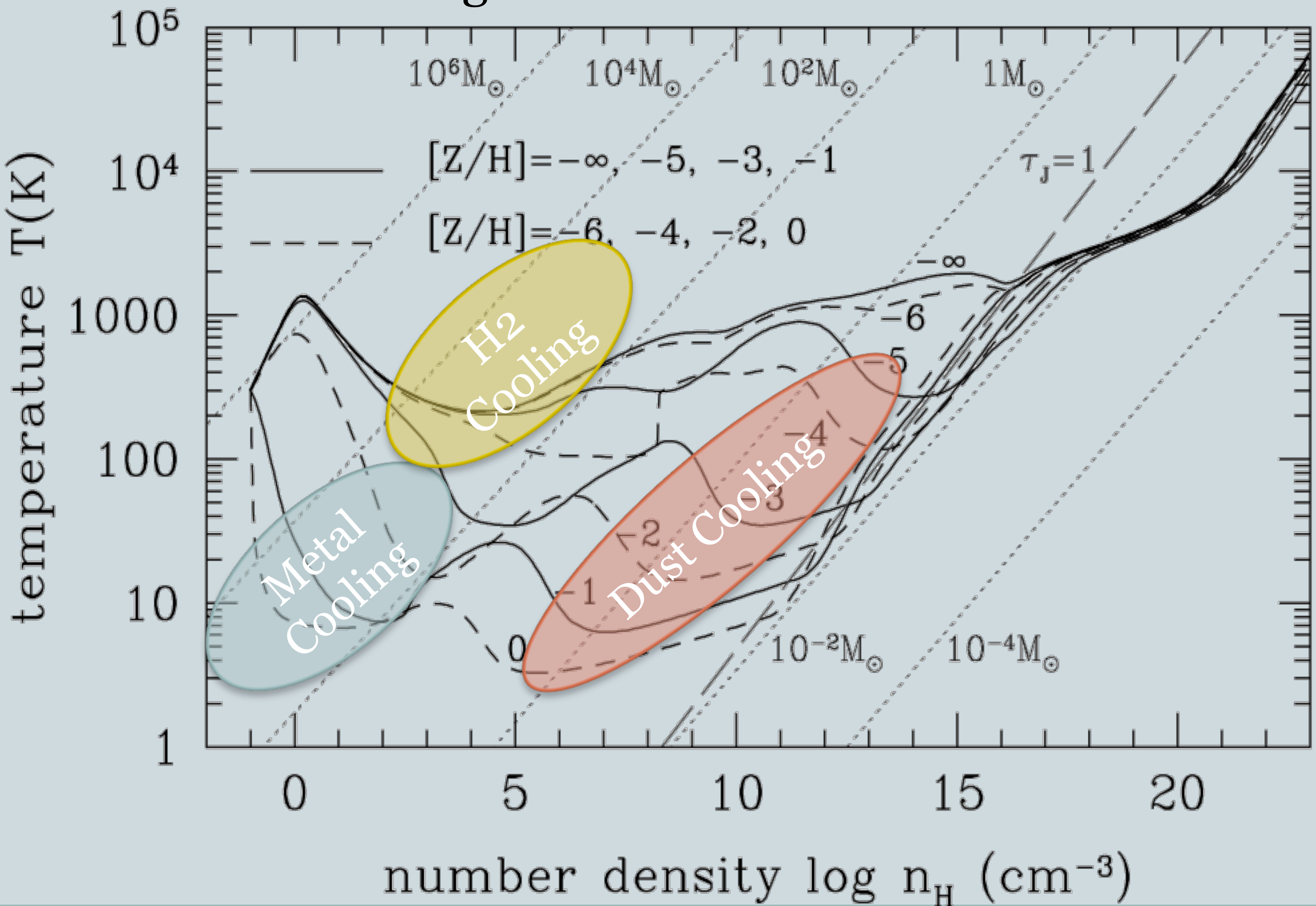
# Formation of Pop II Stars

- Various chemical reactions and cooling/heating mechanisms determine the evolution of collapsing gas clouds.
  - $H_2$ cooling
  - HD cooling
  - Dust cooling
- Cooling can trigger fragmentation of the clouds.
- ➢ Low-mass star formation



# Three Different Mass Scales

- Radiative cooling




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

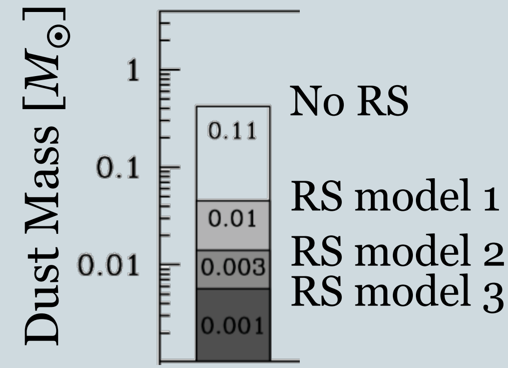
Metal cooling
$M_{Jeans} \sim 10^3 M_\odot$
e.g. Bromm+ (2001)

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

Omukai+ (2005)

# SNR as a Site of Dust Formation/Destruction

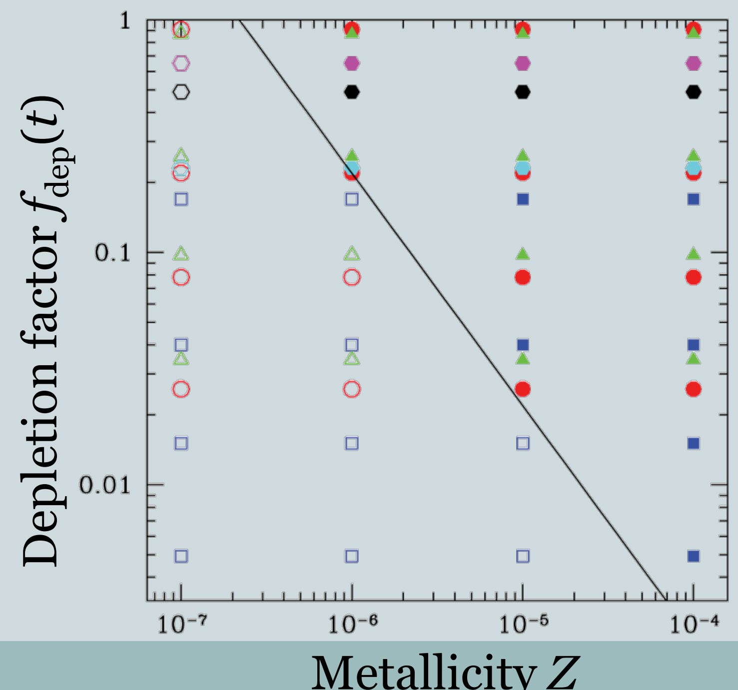
- First dust was formed in Pop III SNR.
  Todini & Ferrara 2001; Nozawa+ 2003;
- Simultaneously, grains are destroyed by the reverse shock (RS).
  Bianchi & Schneider 2007; Nozawa+ 2007




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

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

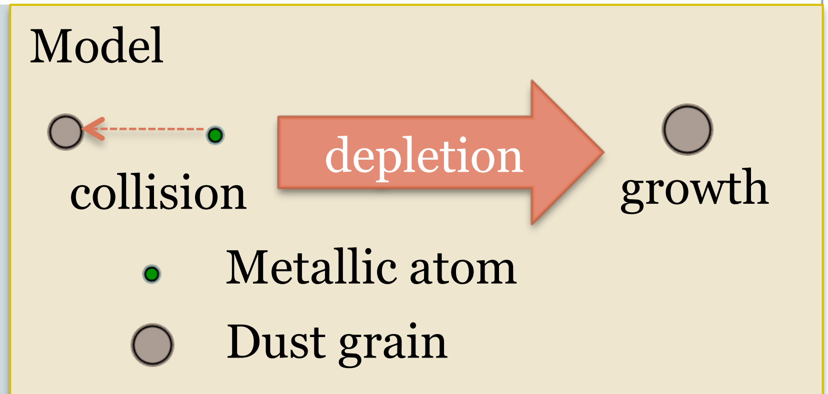
$\mathcal{S}$ : geometrical cross-section per unit dust mass
$\mathcal{D}=Zf_\mathrm{dep}$ : dust-to-gas mass ratio after destruction

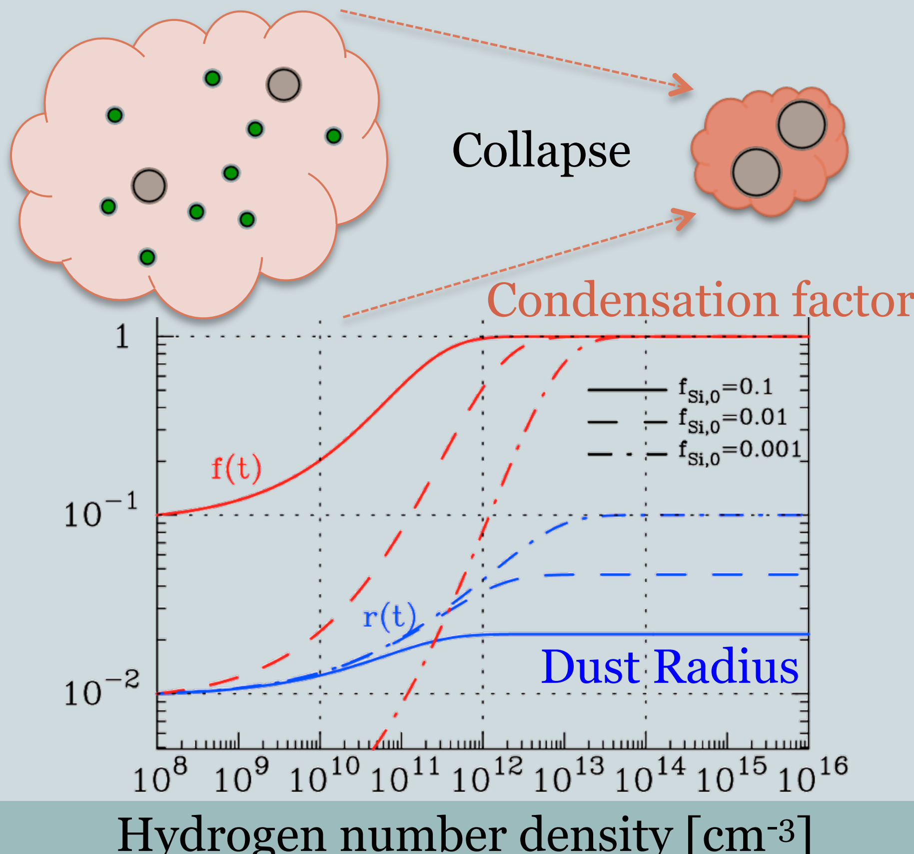



see also Schneider+ (2012, MNRAS 423, 60)

# Grain Growth in a Collapsing Gas Cloud

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



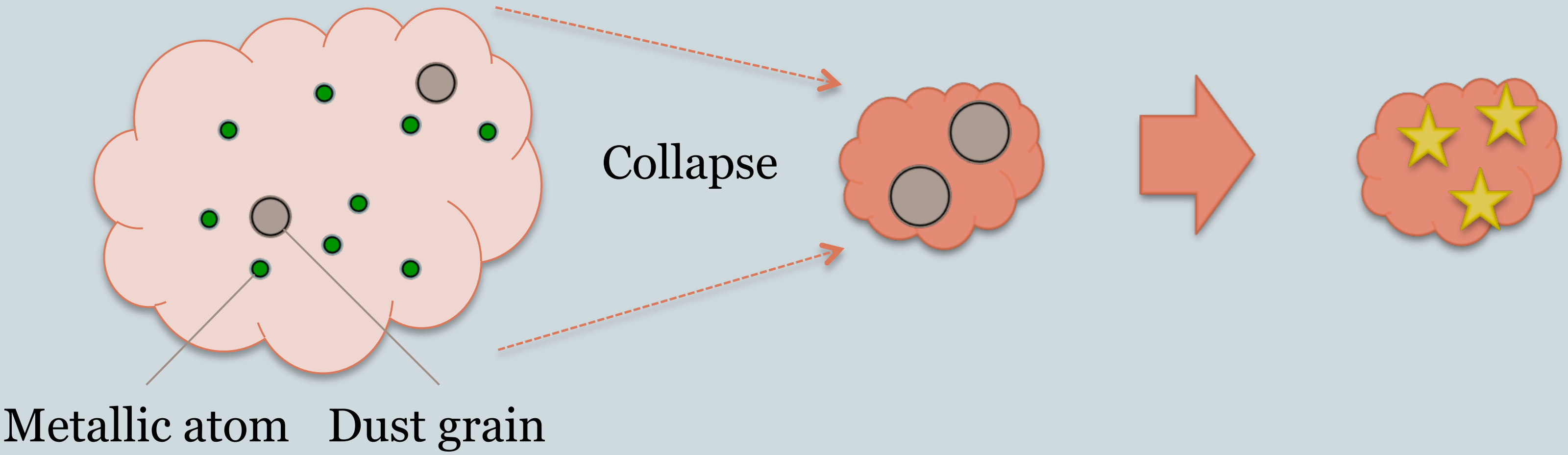




- They show that all of metallic atoms eventually deplete on grains in certain models.
- We further investigate whether dust cooling affect the thermal evolution of collapsing gas cloud.

**Question:**
Can the grain growth enhance the fragmentation?

# Method

- Evolution of a collapsing gas cloud considering grain growth

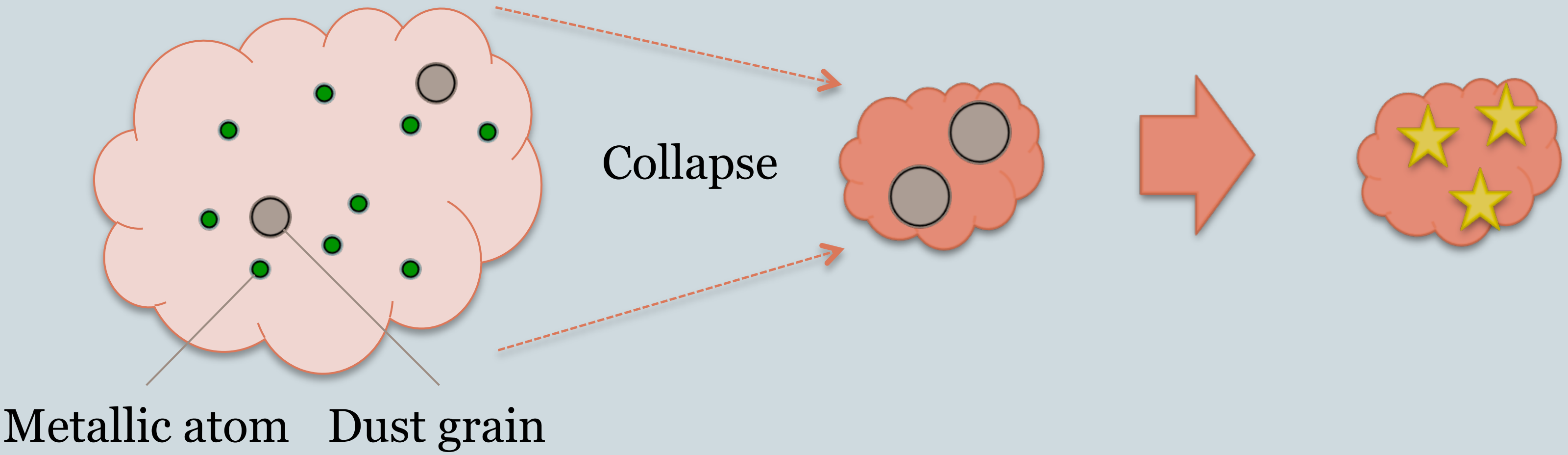



**Collapse of fragments**

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

# Method

- Evolution of a collapsing gas cloud considering grain growth



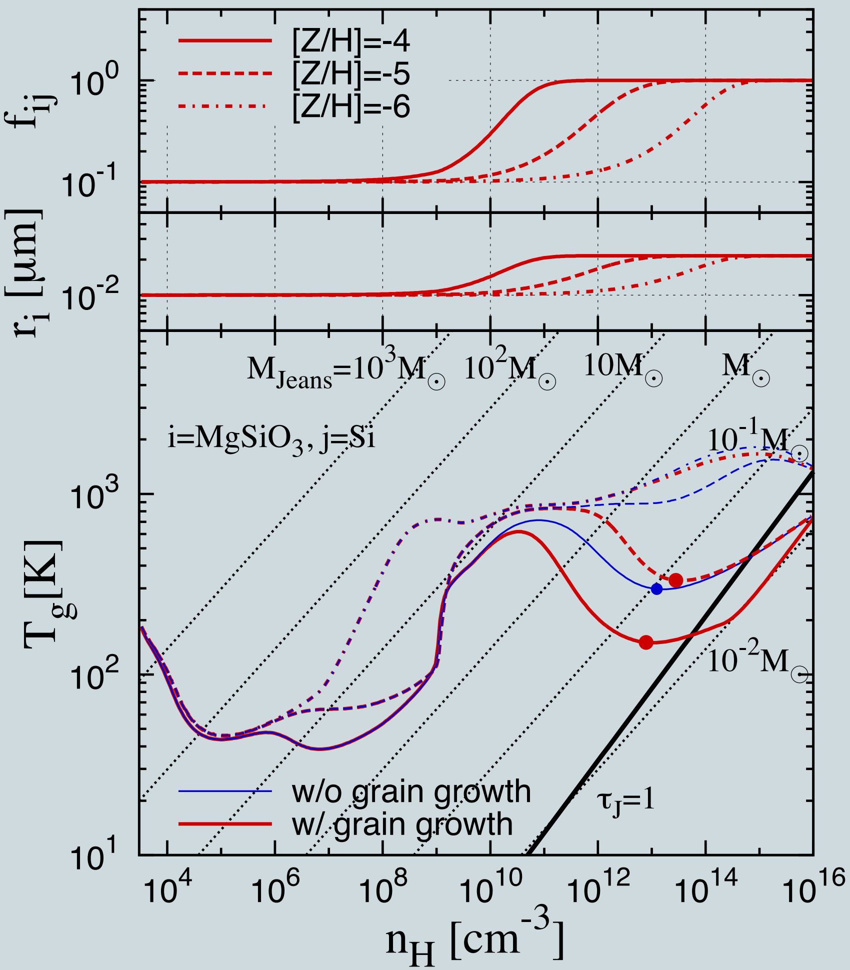

- We consider $MgSiO_3$ grains.

Assumptions:

- Dust grains are spherical and have the same size.
- Si atoms are accreted onto $MgSiO_3$ grains.

# Results: Metallicity Dependence

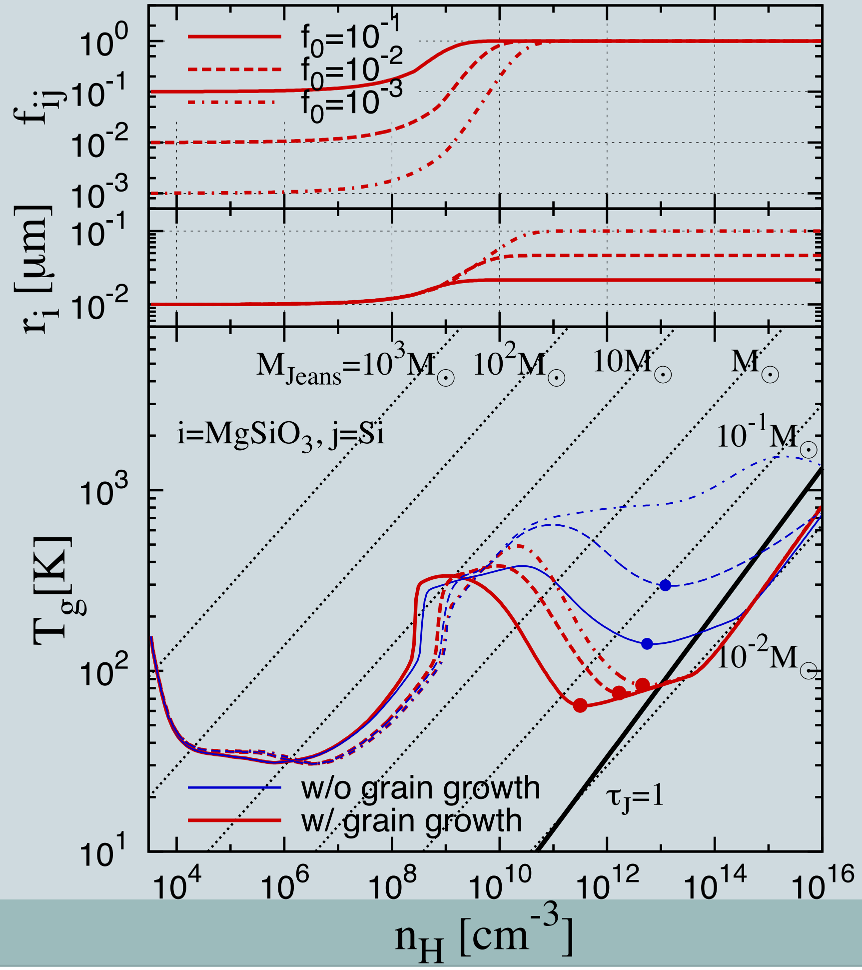
- Initial grain radius of $MgSiO_3$ 0.01 μm
- Initial condensation factor of Si 0.1
- All Si atoms are accreted onto $MgSiO_3$ grains before the cloud becomes optically thick.
- Dust thermal emission increases.
- For metallicity $Z=10^{-5}\,Z_\odot$, low-mass fragments form in our model w/ grain growth and not in our model w/o grain growth.



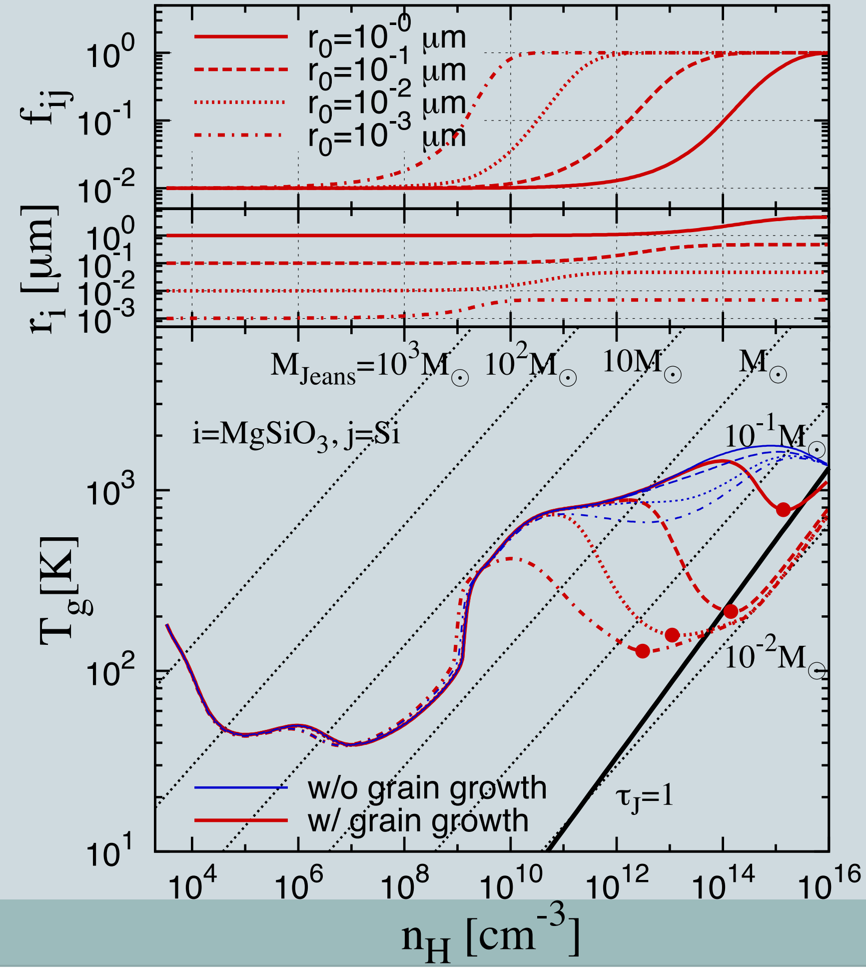
# Results

$Z = 10^{-4} Z_{\odot}$

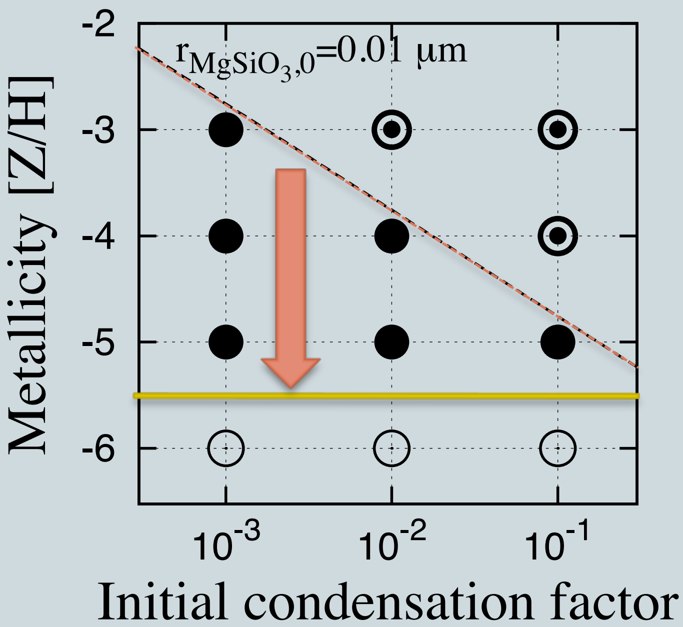
- condensation factor dependence




- grain radius dependence



# Results: Critical abundance




- Initial grain radius of $MgSiO_3$ 0.01 μm
- Initial condensation factor of Si 0.001—0.1

⊙ fragment in both models w/ and w/o grain growth

● fragment in models w/ grain growth

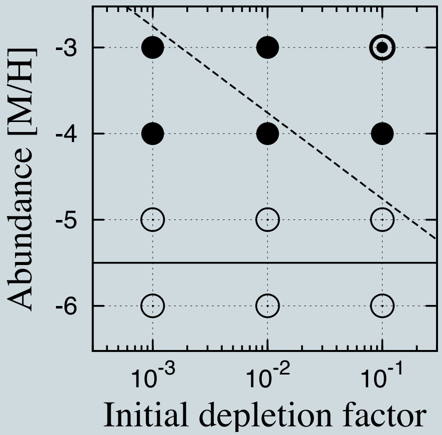
○ no fragments

critical metallicity presented by Schneider+ (2012)

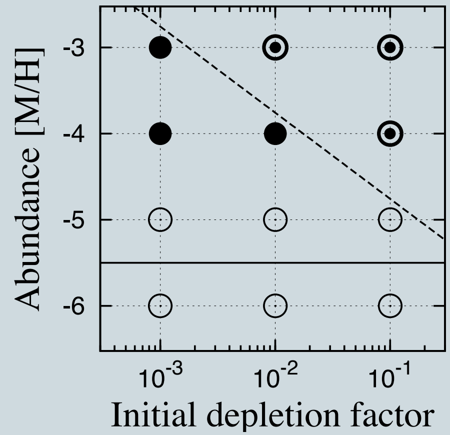
present work

# Results: Critical abundance

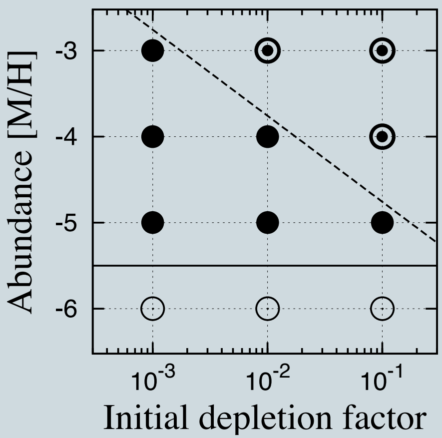
Initial grain radius 1 µm



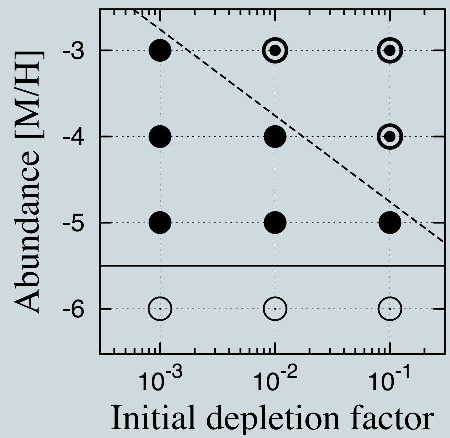

0.1 µm




0.01 µm




0.001 µm




- Initial grain radius of $MgSiO_3$ 0.001--1 µm
- Initial condensation factor of Si 0.001—0.1
  - Grain radius ↑
  - number density of grains ↓ (if mass density of dust is fixed)
  - critical metallicity ↑
- Critical metallicity
  - [Z/H]~-5.5 $r_0$=0.001, 0.01 µm
  - [Z/H]~-4.5 $r_0$=0.1, 1 µm

**Question:**
Can the grain growth enhance the fragmentation?

**Answer: Yes!**
Critical metallicity changes into
[Z/H]~-5.5 for the initial grain radius 0.001—0.01 μm
[Z/H]~-4.5 for the initial grain radius 0.1—1 μm

# Summary

- We study the evolution of collapsing gas cloud, considering the growth of dust grains.
- Due to grain growth, the fragmentation condition dramatically changes.
  - Lower initial abundances are required in models w/ grain growth.
  - Critical metallicity for formation of low-mass fragments
    - [Z/H]~-5.5 for the initial grain radius 0.001—0.01 μm
    - [Z/H]~-4.5 for the initial grain radius 0.1—1 μm

Future Works:

- Calculations including multiple dust species
- Three-dimensional simulations to follow the fragmentation
- Cosmological simulations
  - Evolution of dust-to-gas mass ratio in the first galaxies

# Appendix

# 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

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