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極めて金属量の低い星形成ガス雲中でのダスト成長と低質量星の形成

Nozawa et al. (2012, ApJ, 756, L35)

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wpi World Premier International Research Center Initiative
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1. Introduction

○ HMP ([Fe/H] < -5) and UMP ([Fe/H] < -4) stars

(Christlieb et al. 2002; Frebel et al. 2005; Norris et al. 2007)

Are these metal-poor stars the first generation or not?
How were these metal-poor low-mass stars formed?

➔ large excess of C, N, and O ($Z > 1.0\times10^{-3}\ Z_{sun}$)

○ Critical metallicity, Z_{crit}

– metal-line cooling (Bromm & Loeb 2003; Frebel et al. 2007)
➔ $Z_{crit} = \log_{10}(10^{[C/H]} + 0.3\times10^{[O/H]})$

– dust-emission cooling (Schneider et al. 2003; Omukai et al. 2005)
➔ $Z_{crit} = 10^{-6}\text{-}10^{-4}\ Z_{sun}$ (depends on $f_{dep} = M_{dust}/M_{metal}$)

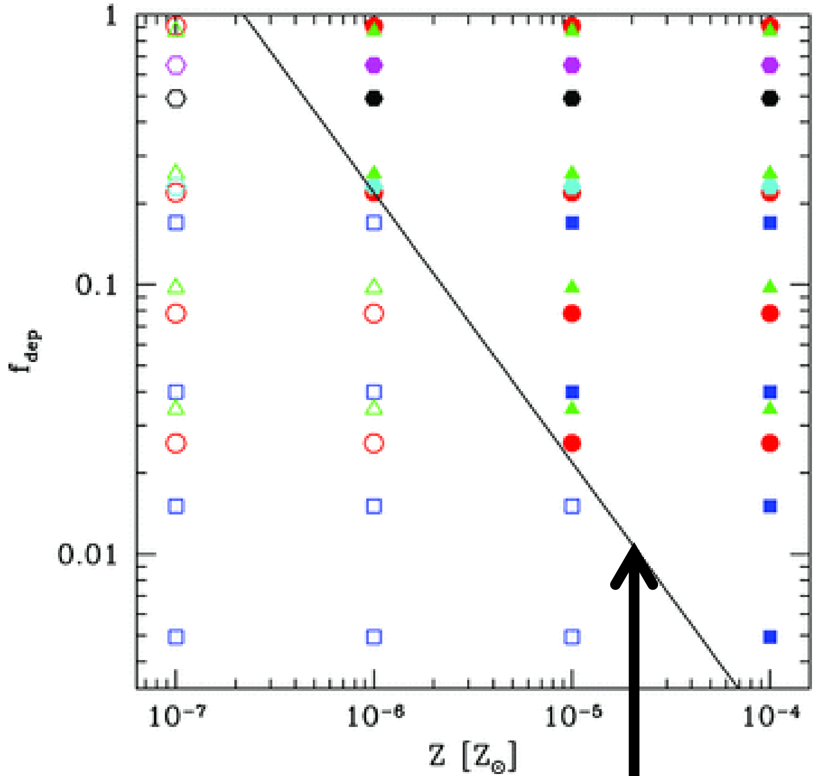
○ SDSS J102915+172927 with [Fe/H] = -4.99

(Caffau et al. 2011, see also Caffau et al. 2012)

➔ no excess of CNO (most primitive: $Z < 4.5\times10^{-5}\ Z_{sun}$)

2. Critical dust-to-gas ratio

Schneider et al. (2011)



*D*crit = Z fdep = 4.4x10^{-9}

- minimum condition above which the dust-induced fragmentation takes place ➔ *D* = Z fdep

$$\mathcal{S}\mathcal{D} > 1.4 \times 10^{-3}\mathrm{cm}^2/\mathrm{gr}\left[\frac{T}{10^3\mathrm{K}}\right]^{-1/2}\left[\frac{n_{\mathrm{H}}}{10^{12}\mathrm{cm}^{-3}}\right]^{-1/2}$$

S : cross section per unit dust mass
D : dust-to-gas mass ratio

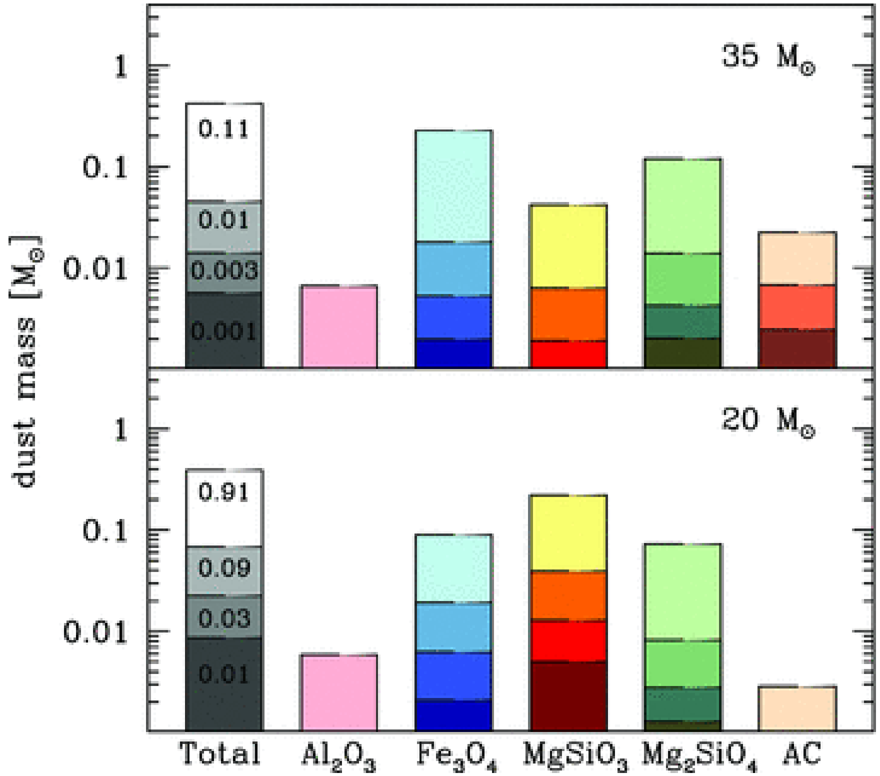
based on their dust model

$$\mathcal{D} > [2.6 - 6.3] \times 10^{-9}\left[\frac{T}{10^3\mathrm{K}}\right]^{-1/2}\left[\frac{n_{\mathrm{H}}}{10^{12}\mathrm{cm}^{-3}}\right]^{-1/2}$$

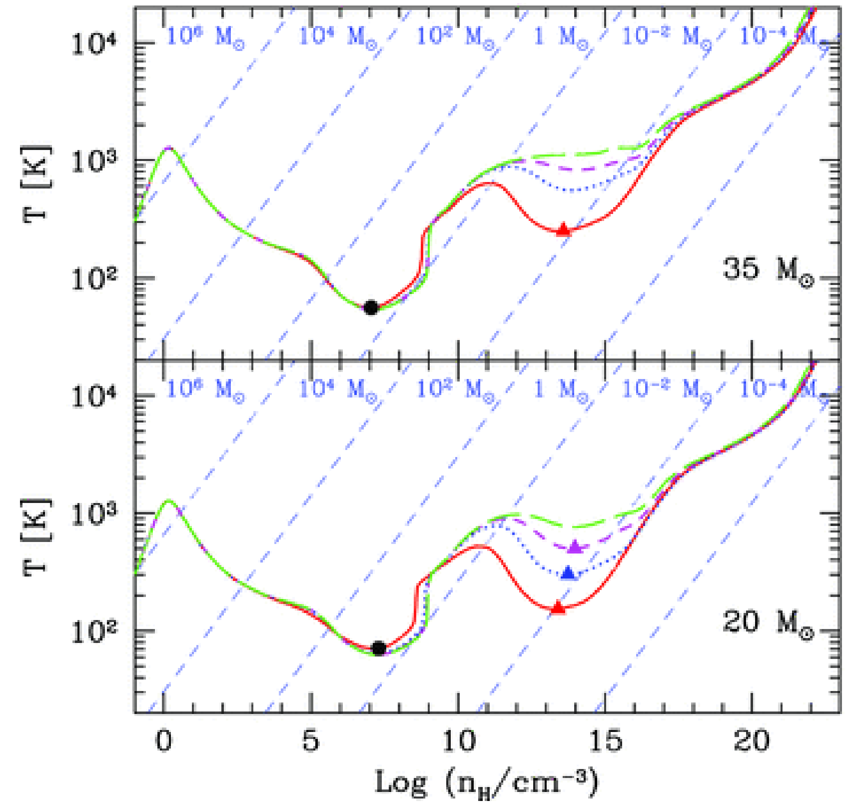
The cloud-fragmentation depends on depletion factor fdep, and it is suppressed when the reverse shock destroys too much dust

3. Birth conditions of SDSS J102915+172927

dust mass and composition



thermal evolution of clouds

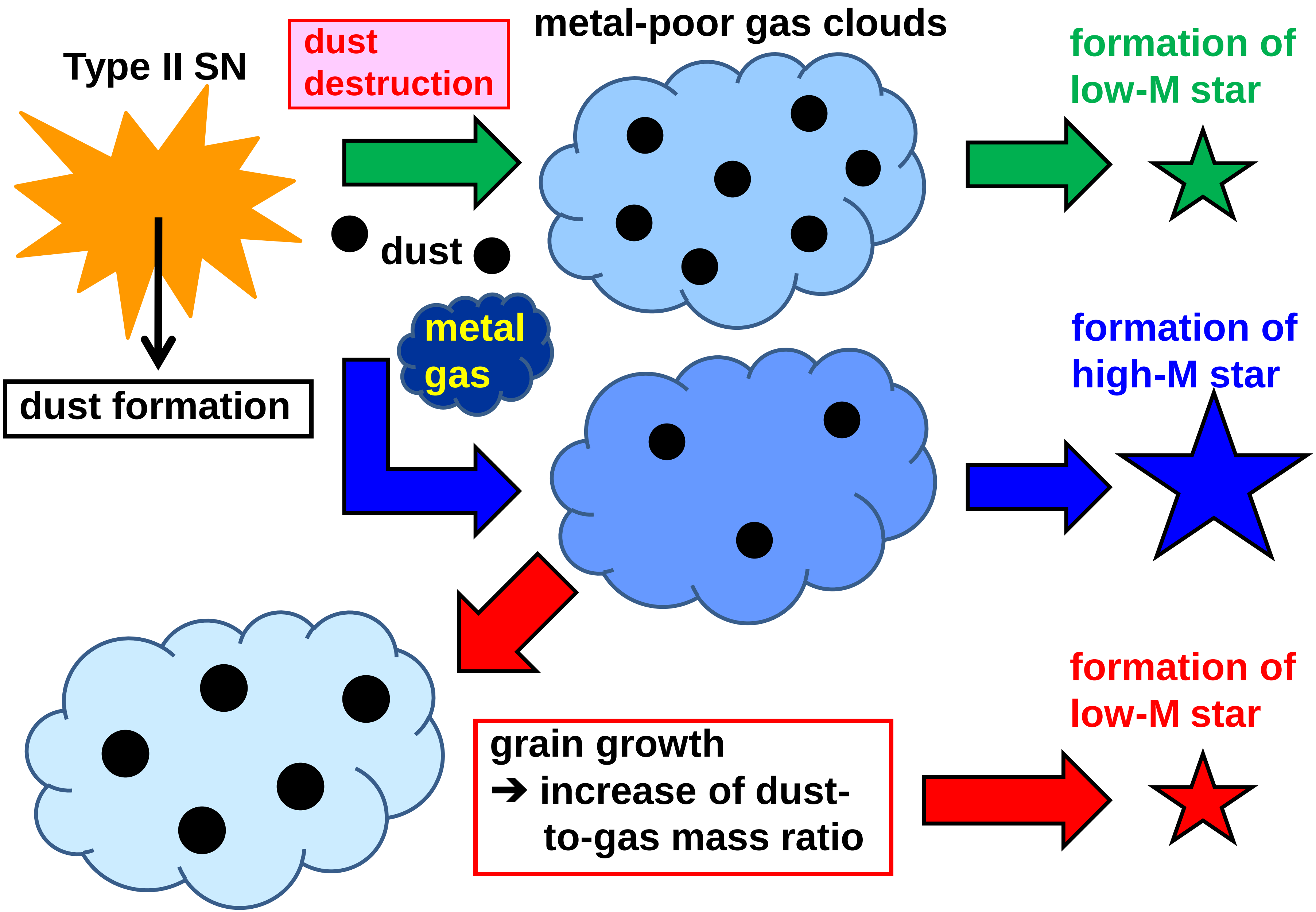


Schneider et al. (2012)

– **fragmentation occurs at $n_H = 10^{12}$-10^{14} cm^{-3} if $f_{dep} > 0.01$**

➔ **if dust formation in SNe is less efficient or strong dust destruction occur, only $M > 8\ M_{sun}$ fragments can form**

4. Aim of this study



5. Model of grain growth in collapsing clouds

・Time evolution of gas density (collapsing with free-fall time)

$$c_i(t) = c_{i,0} \left(1 - \frac{t - t_0}{2\tau_0^{\rm ff}}\right)^{-2}$$

initial single radius: $r_{i,0}$
initial dust abundance: $f_{i,0}$
abundance of element i: A_i

・equation of mass conservation

$$c_i(t) = c_i^{\rm gas}(t) + c_i^{\rm dust}(t).$$

→

$$f_i(t) = 1 - Y_i(t) = f_{i,0} X_i^3(t),$$

・growth rate of grain radius

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

$f_i(t) = c_i^{\rm dust}(t) / c_i(t)$
$Y_i(t) = c_i^{\rm gas}(t) / c_i(t)$
$X_i(t) = r_i(t) / r_{i,0}$

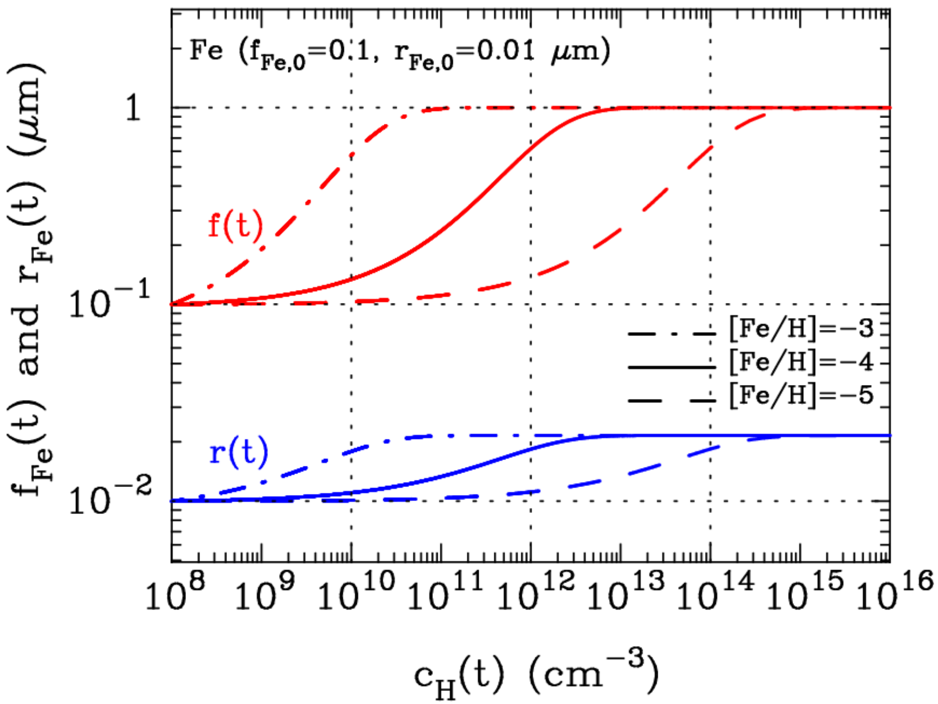
→

$$X_i(t) = 1 + \frac{2\tau_0^{\rm ff}}{\tau_{i,0}^{\rm gg}} \int_0^u \frac{Y(u')}{(1 - u')^2} du',$$

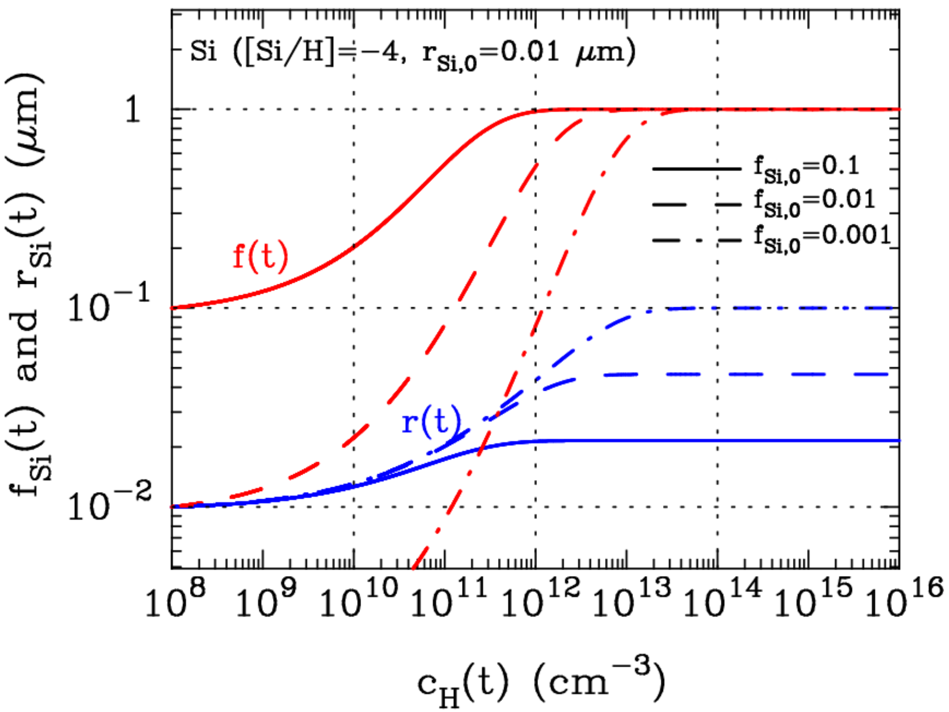
- grain species: Fe and Si grains (not consider C grains)
- gas temperature: $T_{\rm gas}$ = 1000 K, sticking probability: s = 1

6. Grain growth in metal-poor gas clouds

growth of Fe grains



growth of Si grains



— **grain growth activates in the gas clouds with [Fe/H] = -5**

— **the gas density at which f_{Fe} reaches > 0.5 is higher for a lower Fe abundance**

As $f_{Si,0}$ decreases,

— **higher gas densities are needed to achieve f_{Si} > 0.5**

— **final grain radii are larger when all Si atoms are used**

7. Critical metal abundances

fragmentation of cloud occurs at $c_H = 10^{12}$-10^{14} cm^{-3}
➔ before reading this density, growth must be significant

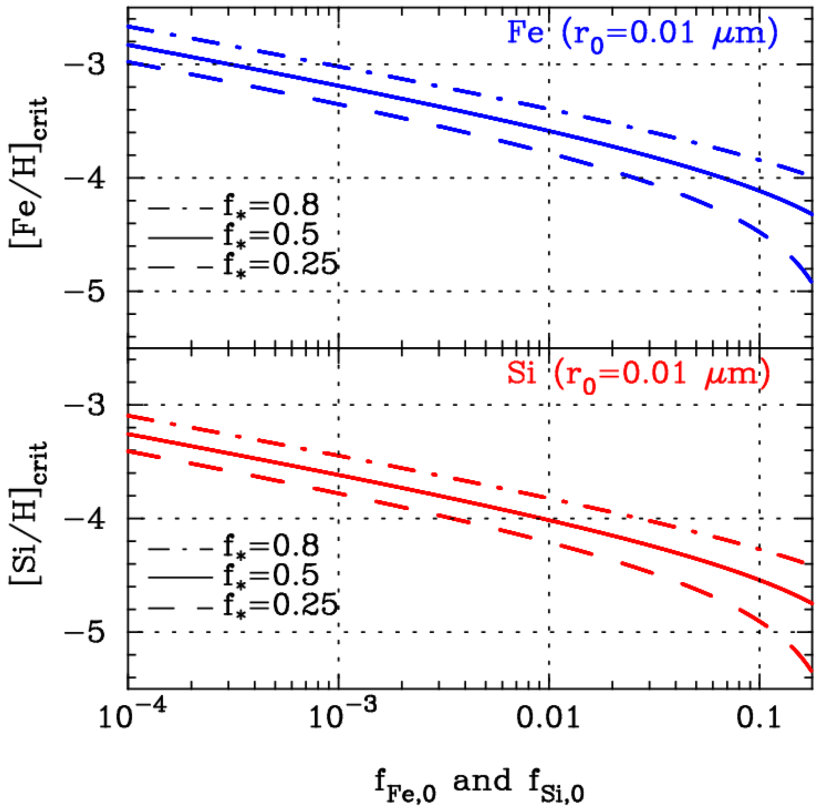
・ critical metal abundance:

above which the grain growth can affect formation of low-mass stars

$$A_{i,\mathrm{crit}} \simeq 10^{-9}\, K_i \left(\frac{r_{i,0}}{0.01\ \mu\mathrm{m}} \right) \left(\frac{10^{12}\ \mathrm{cm}^{-3}}{c_{\mathrm{H},*}} \right)^{\frac{1}{2}}$$

where $K_i(f_{i,0}, f_{i,*}) = f_{i,0}^{-\frac{1}{3}} \int_{f_{i,0}}^{f_{i,*}} \frac{dy}{1-y^3},$

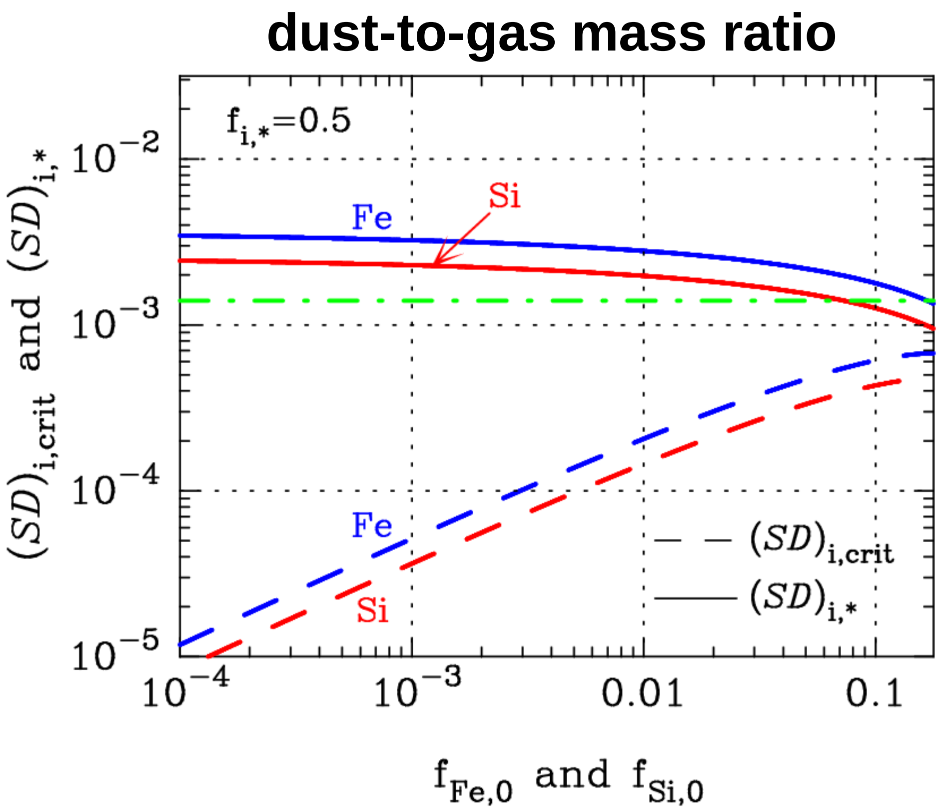
critical metal abundances



— A_{crit} is higher for a higher $f_{i,*}$ and/or for a lower $f_{i,0}$

— for $f_{i,*}$ = 0.5 and 0.001 < $f_{i,0}$ < 0.1,
-4.12 < [Fe/H] < -3.2, -4.6 < [Si/H] < -3.3
ref. [Si/H] = -4.27 for SDSS J102915+2729

8. Dust-to-gas mass ratio



・ dust-to-gas mass ratio

$$(\mathcal{SD})_{i,\mathrm{crit}} = 3 f_{i,0} A_{i,\mathrm{crit}} m_i / 4 \rho_i r_{i,0} \mu m_{\mathrm{H}}$$

$$(\mathcal{SD})_{i,*} = (\mathcal{SD})_{i,\mathrm{crit}} (f_{i,*}/f_{i,0})^{2/3}$$

・ total metallicity

$$Z \simeq (5 - 50) \times 10^{-6} \left(\frac{0.2}{\mathcal{R}} \right) Z_{\odot},$$

R **: mass ratio of refractory elements to all heavy elements**

formation of low-mass stars with $Z < 4.5\mathrm{x}10^{-5}$ Z_{sun} can be possible?

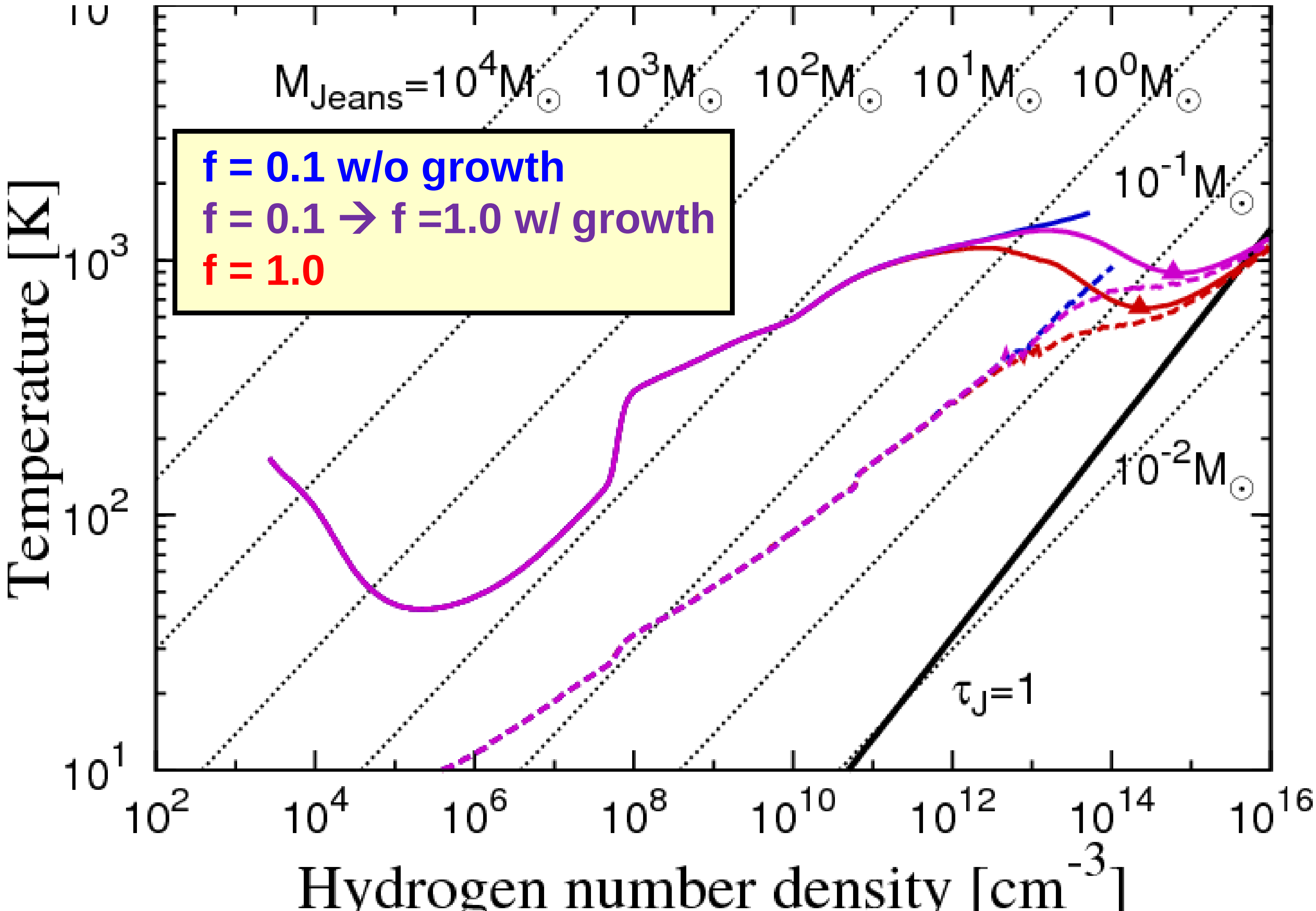
– $(SD)_{i,crit}$ is well below the minimum value for the dust-induced fragmentation, whereas $(SD)_{i,*}$ exceeds this value

➔ grain growth enhances *SD* in the clouds and enable the gas fragmentation into sub-solar mass clumps

9. Fragmentation by metal-line cooling

$MgSiO_3$ grain

Chiaki, TN, Yoshida (2012, in prep.)



10. Summary

- Growth of Fe and Si grains can operate efficiently even in collapsing clouds with [Fe, Si/H] ~ -5

- The critical abundances above which grain growth could induce the gas fragmentation is [X/H] ~ -4.5

- Even if the initial dust-to-gas mass ratio is well below the minimum value for dust-induced fragmentation, grain growth increases the dust mass high enough to cause the gas fragmentation into low-mass clumps

- As long as the critical abundance is satisfied, grain growth could play an important role in the formation of low-mass stars with metallicity as low as 10^{-5} Z_{sun}