# ダストを考慮した<br>宇宙初期における銀河モデル

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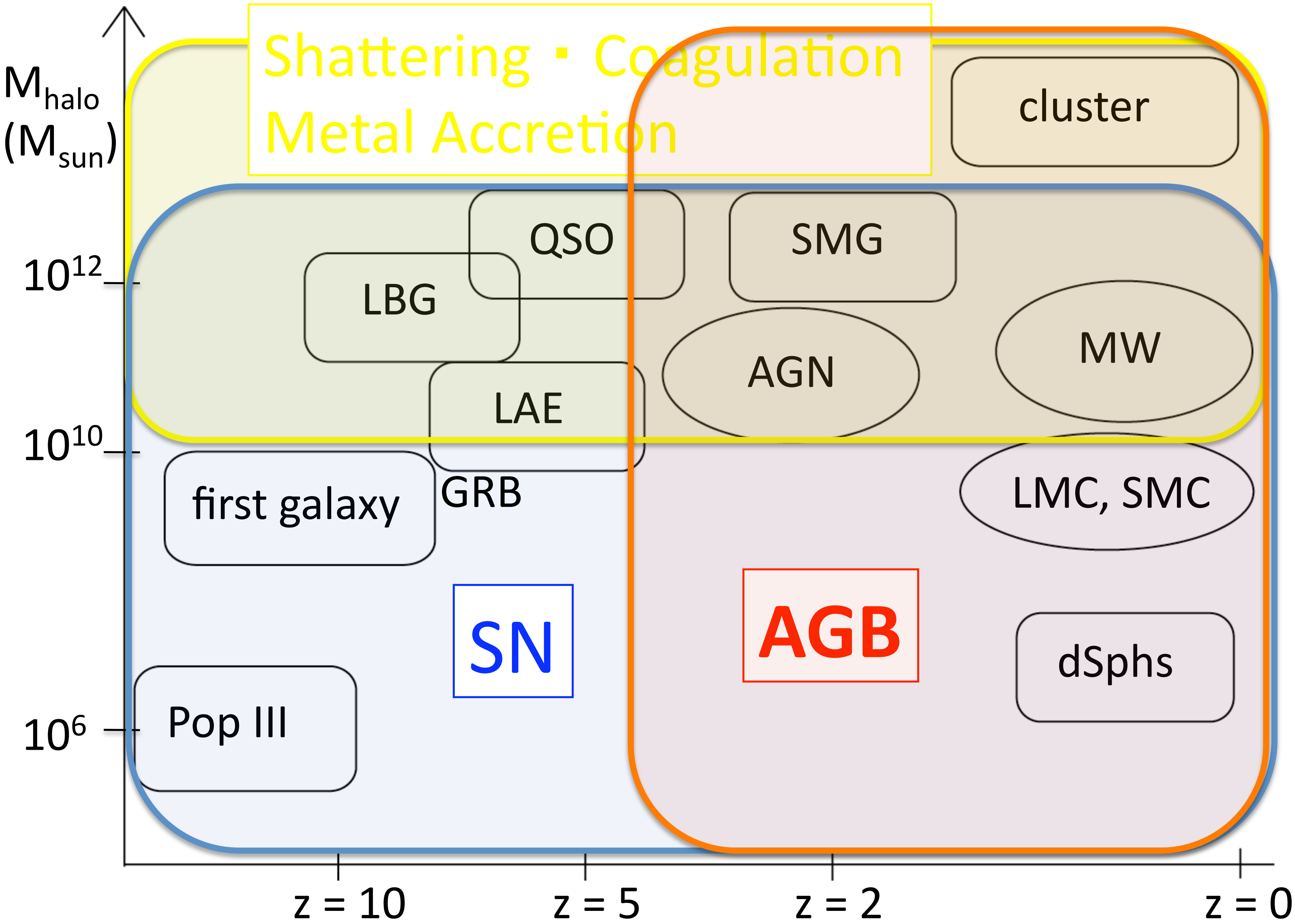
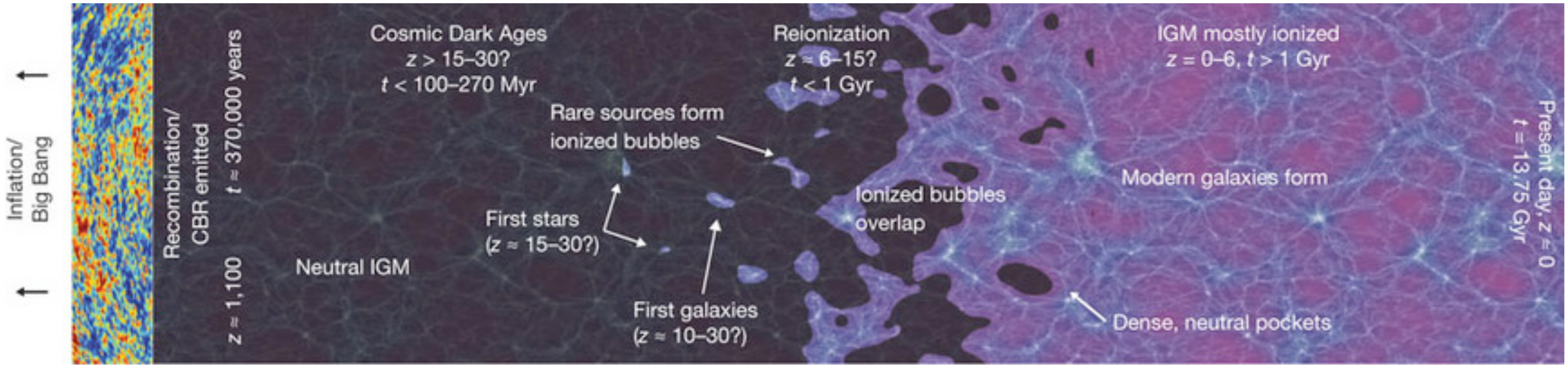

Shattering・Coagulation
Metal Accretion
M_halo (M_sun)
10^12
10^10
10^6
cluster
QSO
SMG
LBG
AGN
MW
LAE
GRB
first galaxy
LMC, SMC
SN
AGB
dSphs
Pop III
z = 10
z = 5
z = 2
z = 0

# Reionization




( Robertson+ 10 )

■ Observational constraints on reionization :

・Gun-Perterson test : reionization for $z > 6$

■ Reionizating photons :

・Most of the reionization radiation is expected to come from galaxies less than ～$10^{9.5}$ M_sun.

■ Star formation efficiency ( SFE ) :

・The stellar mass fraction, $M_{star}$ / ($M_{gas}$ + $M_{star}$ ) , is assumed to be constant independent of $M_{vir}$ in many previous analytic works.

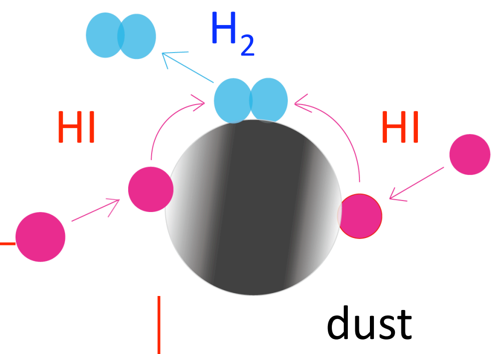
# Our Study

■ $H_2$ molecule is dominant coolant in the early Universe :

・Stars form in cool dense gas that is formed by $H_2$ cooling.

■ $H_2$ formation on dust is very quick than gas phase :

・ Dust is catalyst in $H_2$ formation.




■ We investigate the reionization history,
using our galaxy formation model
(Yamasawa et al. 2011)
in which we include a novel implementation of
dust size evolution by SNe
and the resulting $H_2$ formation on dust grains.

■ Because of $H_2$ formation rate on dust grains decreasing,
SFE decreases with small dark matter halo mass.

# Our Model

■ We consistently treat following processes :

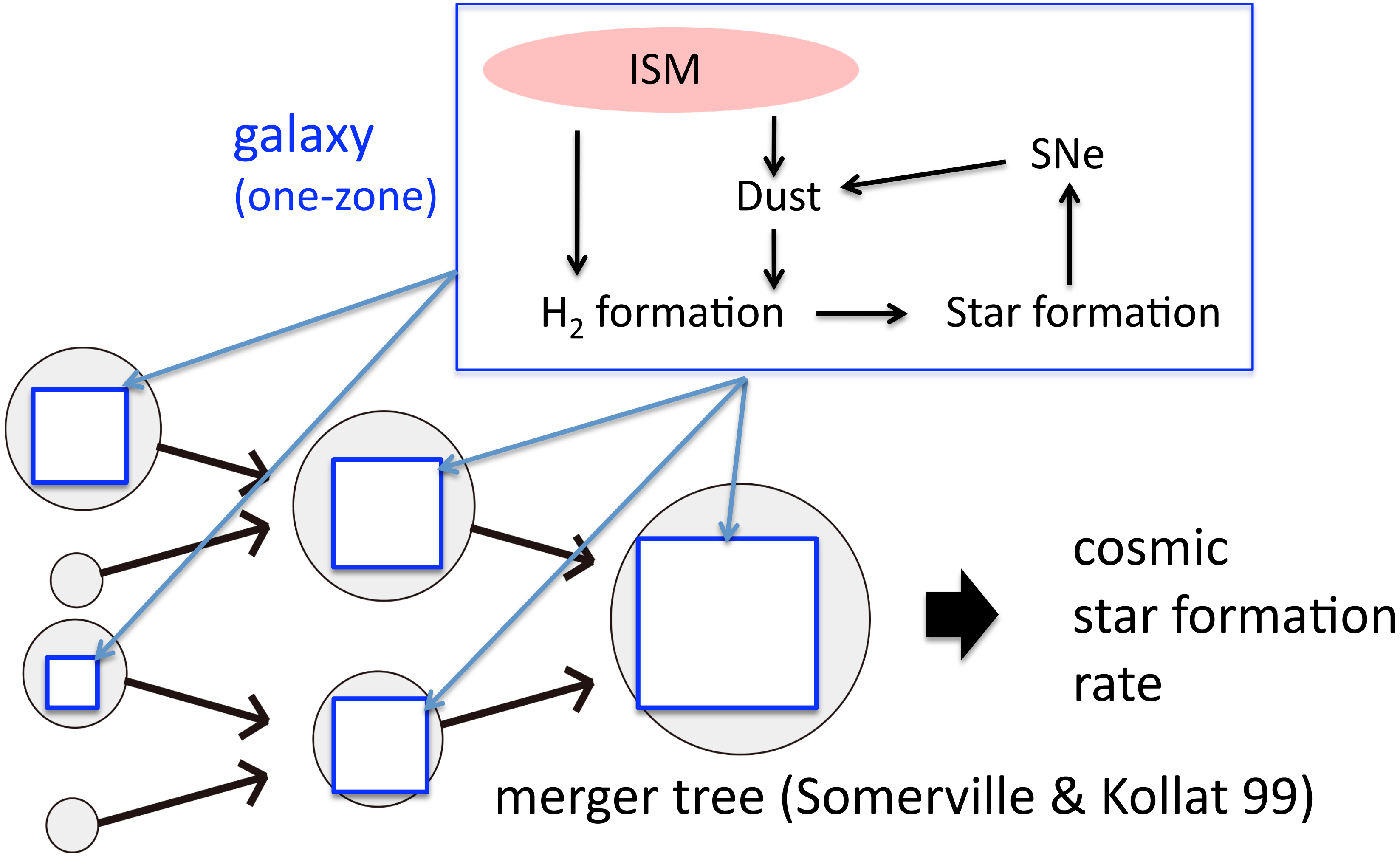
(i) the formation and size evolution of dust by SNe
(ii) time-dependent chemical reaction networks
including $H_2$ formation both on the dust grains and in gas phase
(iii) gas cooling and heating
(iv) the SFR proportional to $H_2$ mass

galaxy

+

(v) DM halo evolution - merger tree
(vi) IMF transition from Pop III to Pop II

# Our Model


ISM
galaxy
(one-zone)
SNe
Dust
$H_2$ formation
Star formation
cosmic
star formation
rate
merger tree (Somerville & Kollat 99)

# Star Formation Model

## ■ Critical dust-to-gas mass ratio, D_crit :

・We assume the IMF transition from Pop III to Pop II due to dust cooling.
( Schneider+ 03; Omukai+ 05; Schneider+ 06; Schneider and Omukai 10; Omukai+ 10 )

## ■ IMF transition :

| Dust | DM halo | IMF | SFR |
|---|---|---|---|
| $D < D_{crit}$ | $T_{vir} < 10000$ K | Pop III.1 ( 100 - 500 $M_{sun}$ ) | ( Machacek+ 03 ) |
| | $T_{vir} \geqq 10000$ K | Pop III.2 ( 10 - 100 $M_{sun}$ ) | $\Psi(t) = \frac{f_{H_2}(t) M_H(t)}{t_{cir}(z_{vir})}$ |
| $D \geqq D_{crit}$ | | Pop II ( 0.1 - 60 $M_{sun}$ ) | ( Our model ) |

all slope index : -2.35

# Reionization Model

## ■ Ionizing photons, $n_{ion}$ , emitted by massive stars (Greif & Bromm 06):

$$\frac{1}{n_b}\frac{dn_{\rm ion}(z)}{dz} = \frac{1}{\rho_{\rm m}}\frac{\Omega_{\rm m}}{\Omega_{\rm b}}\left\{\sum_i f_{{\rm esc},i}\eta_{{\rm ion},i}\Psi_{*,i}(z)\right\}\left|\frac{dt}{dz}\right|$$

cosmic SFR (per $Mpc^3$)

i : popIII.1, popIII.2, popII

$n_{\rm ion}$ : comoving density of ionizing photons
$f_{\rm esc}$ : escape fraction
$\eta_{\rm ion}$ : number of ionizing photons emitted per stellar baryon

- Ionizing photon number per stellar mass for Pop III.2 stars is 10 times larger than that for Pop II stars (Schaerer 02).
- Pop III.2 stars are very effective to the reionization.

## ■ Evolution of ionized volume fraction, $Q_{ion}$ (Wyithe & Loeb 03):

$$\frac{dQ_{\rm ion}(z)}{dz} = \frac{1}{n_{\rm b}}\frac{dn_{\rm ion}(z)}{dz} - \alpha_{\rm B} n_{\rm b} C(z) Q^2_{\rm ion}(z)(1+z)^3\left|\frac{dt}{dz}\right|$$

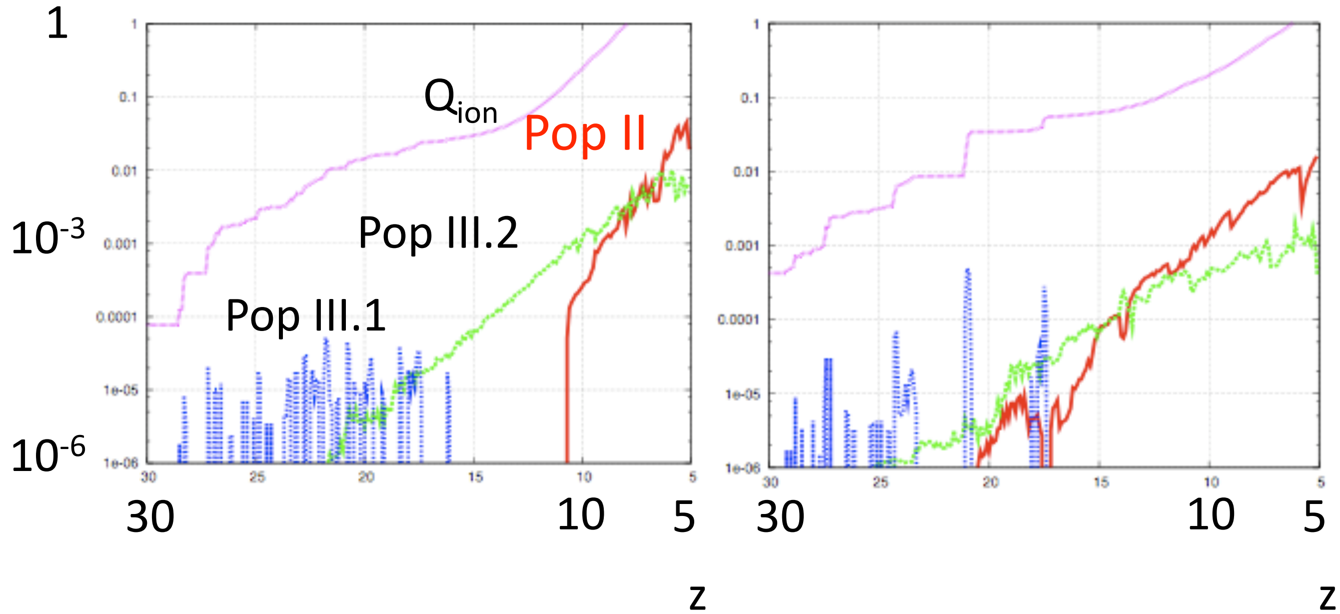
ionization　　recombination

$Q_{\rm ion}$ : volume fraction of ionizing regions
$\alpha_B$ : recombination coefficient
$C(z)$ : clumping factor

# Critical dust-to-gas mass ratio, D_crit

■ cosmic SFR and reionization ( $Q_{ion}$ = 1 ) :

D_crit = 10^-4 D_crit = 10^-5




reionization ( $Q_{ion}$ = 1 ) :

ψ_Pop II

ψ_Pop III.2

ψ_Pop III.1

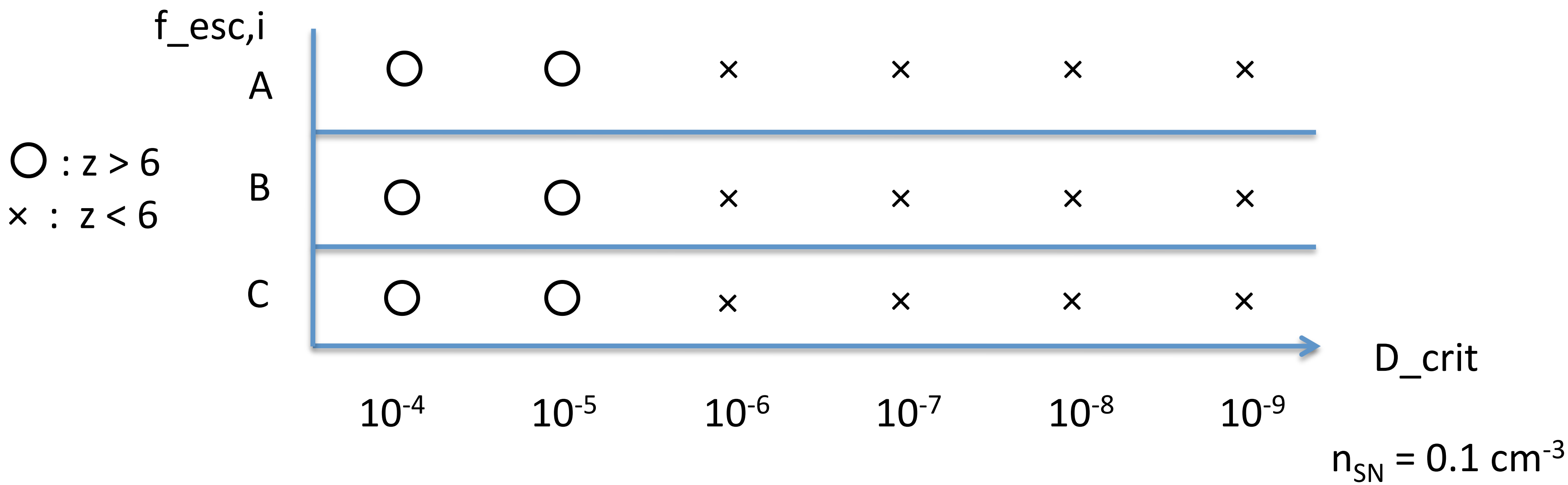
Q_ion

ψ ( M_sun / yr / $Mpc^3$ )

$n_{SN}$ : 0.1 $cm^{-3}$

- Small D_crit → early transition from Pop III to Pop II → late reionization epoch
  note: ionizing photon per Pop III mass > ionizing per Pop II mass

# Critical dust-to-gas mass ratio, D_crit

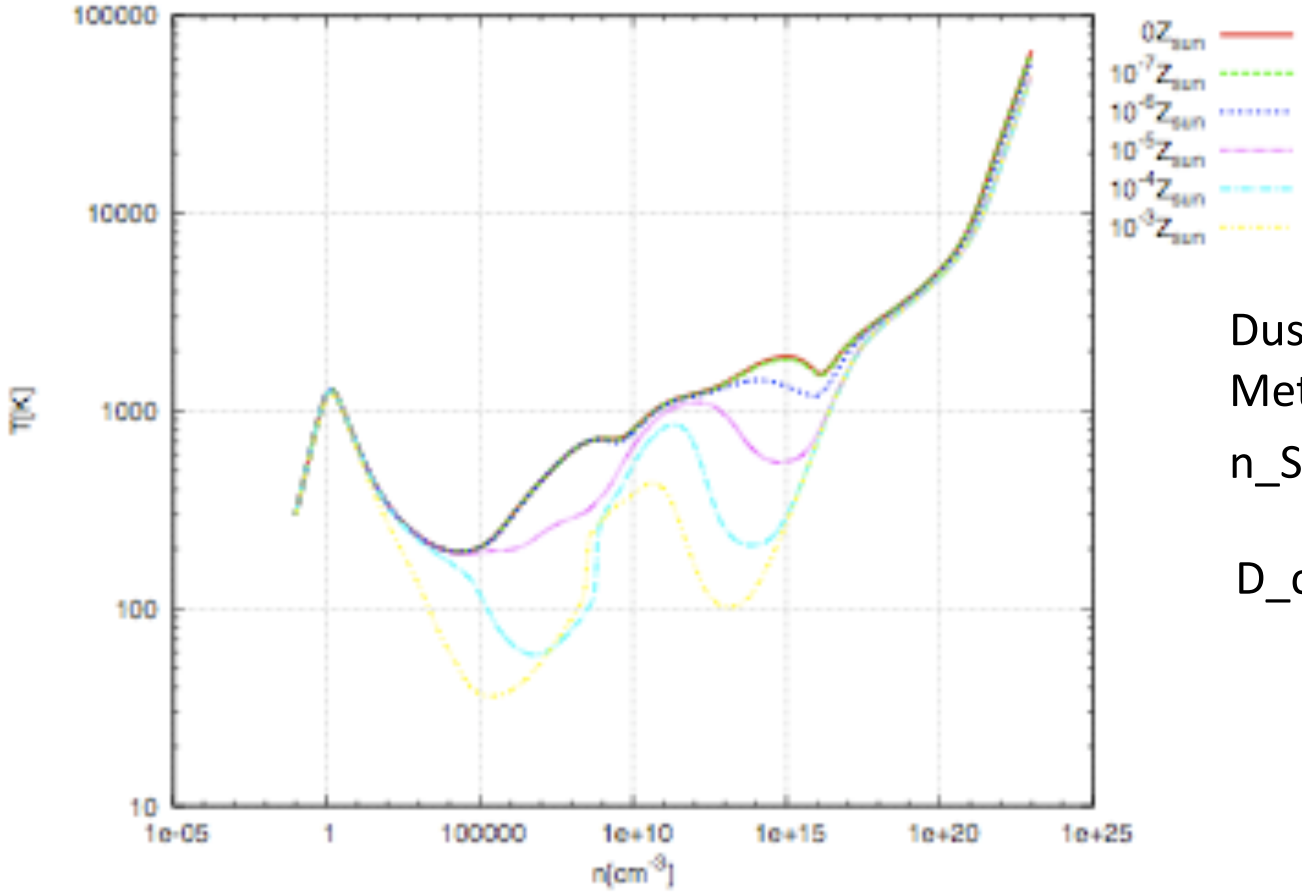



A : f_esc,popIII.2 = 0.1, f_esc,popII = 0.3 ( Greif and Bromm 06 )
B : f_esc,popIII.2 = 0.5, f_esc,popII = 0.6 ( Wise and Cen 09, cosmological )
C : f_esc,popIII.2 = 0.7, f_esc,popII = 0.8 ( Wise and Cen 09, isolated )

- In the cases of D_crit > 10^-5 ,
  reionization occurs at z > 6 independent of escape fraction, f_esc,i .

# IMF transition

question :
Which value is critical dust-to-gas ratio in the early universe?
( Schneider+, **arXiv:1109.2900** )




Dust : Nozawa+ 07
Metal : Umeda & Nomoto 02
n_SN = 0.1 cm^-3

D_crit = f_dep * Z_crit [Z_sun]
= 0.12 * 10^(-5) * 0.02
∼ 2*10^(-8)

# Summary

■ We investigate the reionization history,
using our galaxy formation model (Yamasawa et al. 2011)
in which we include a novel implementation of
dust size evolution and the resulting $H_2$ formation on dust grains.

- We show cosmic star formation efficiency is low,
  because $H_2$ formation rate on dust grains is supressed by dust destruction
  by SN reverse shocks.
- We show range of parameters where reionization have completed until z = 6.
  In the cases of critical dust-to-gas mass ratio, D_crit ≧ 10^-5,
  reionization completes before z = 6.
  This is independent of escape fraction, f_esc,i.
- Thermal evolution of clouds for our dust model shows a dust-to-gas mass ratio,
  D_crit = f_dep × Z_crit = 0.052 × 10^-5 × 0.02 ~ 10^-8.
  Our result shows need of additional reioniation sources or top-heavy IMF
  in z > 6 for cosmological reionization.

■ We conclude that not only the amount but also the size distribution of dust
strongly affects the cosmic star formation efficiency and
the IMF transition from Pop III to Pop II.