From Dust to Galaxies_6/29_IAP

The Role of Dust in the Early Universe

D. Yamasawa (Hokkaido University)

■ collaborators:
  A. Habe (Hokkaido University)
  T. Kozasa (Hokkaido University)
  T. Nozawa (IPMU, University of Tokyo)
  H. Hirashita (Academia Sinica)
  H. Umeda (University of Tokyo)
  K. Nomoto (IPMU, University of Tokyo)

■ references:
I: Protogalaxy Evolution (DY+ 2011, ApJ, 735, 44)
II: Reionization (in prepalation)

Table of Contents

INTRODUCTION

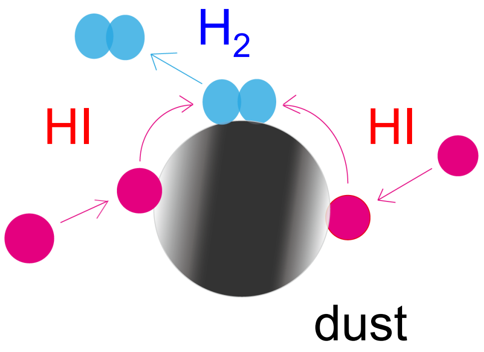
Role of Dust in Star Formation

■ 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.
- H_2 formation is due to collisions of hydrogen atoms to dust surface.
- The collsion rate depends on dust size, dust-to-gas mass ratio,Tgas, and ρgas.



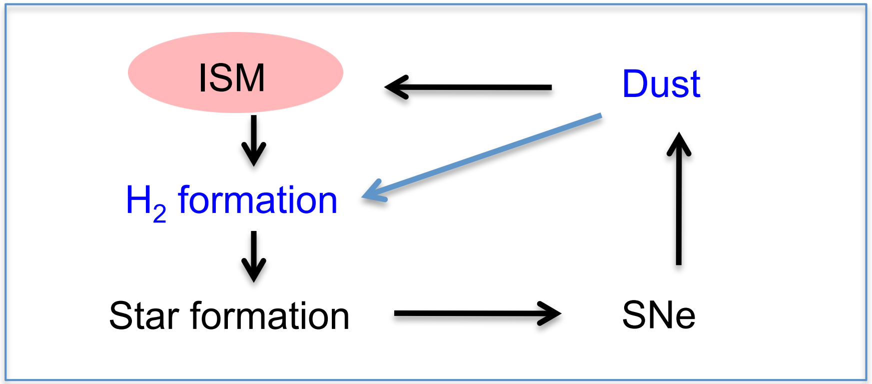
■ Dust size distribution in high redshift (z > 5) :

- This is different from Milky Way dust.
- This is because dominant dust origin is SNe.

Our Study

- We investigate time evolution of dust mass and dust size distribution in high z Universe, considering the dust production by SNe and dust destruction by sputtering in the high-velocity shocks driven by SNe.

- We consistently treat following processes in our one-zone model
  (i) the formation and size evolution of dust,
  (ii) the chemical reaction networks including H_2 formation both on the dust grains and in gas phase,
  (iii) gas cooling and heating
  (iv) the SFR based on H_2 mass .



MODEL

Dust Evolution (①/2)

■ Dust in the early Universe :

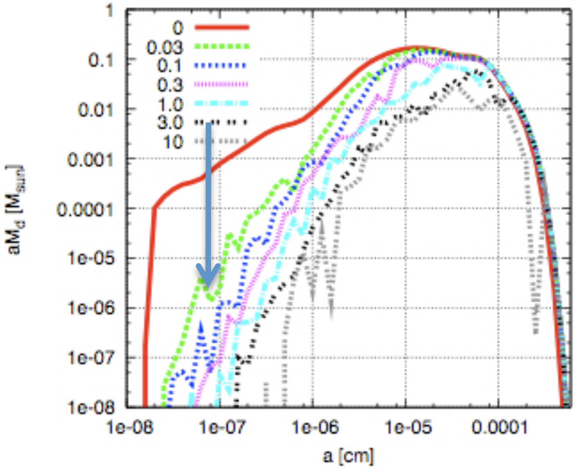
- SNe II are the source of dust in the early Universe (5 < z < 10)

  (Dwek+ 07; Gall+ 2011a, b, c; but see also Valiante+09; Dwek&Cherchneff 11; Valiante+11)
- Average size of SN dust is small.

■ Dust injected from SN II into ISM through a reverse shock :

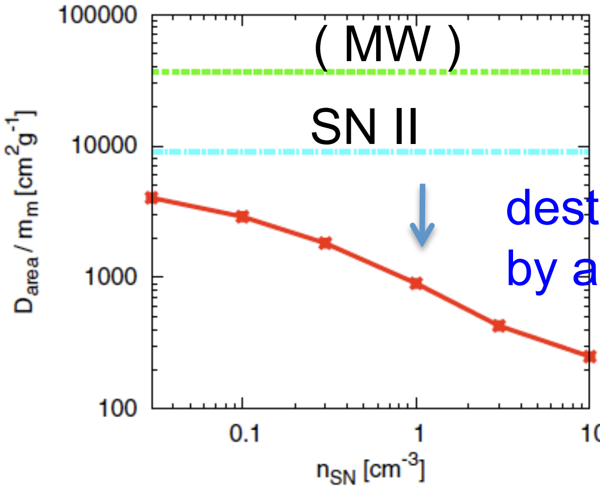
A reverse shock destroys dust.
This is more efficient in large n_{SN}.

$D_{area} = 4\pi a^2 f(a)\, da$



adopt:
the models by
Nozawa+ 07

(DY+11)



(Per SN II)

destruction
by a reverse shock

(DY+11)

n_{SN} : gas density around SN progenitor

MODEL

Dust Evolution (②/2)

■ Formulation of dust size evolution :

$$\begin{aligned}
\frac{\mathrm{d}\Delta M_{\mathrm{d},j}(a,t)}{\mathrm{d}t} = & \overline{\Delta M_{\mathrm{SN,d},j}}(a)\gamma_{\mathrm{SN}}(t) \\
& - \boxed{\frac{M_{\mathrm{swept}}}{M_{\mathrm{ISM}}(t)}\gamma_{\mathrm{SN}}(t)} \times \{\Delta M_{\mathrm{d},j}(a,t) \\
& - \int_0^\infty \mathrm{d}a'\eta_j(a,a')f_j(a',t)\rho_j\frac{4\pi}{3}a^3\} \\
& - \Psi(t)\frac{\Delta M_{\mathrm{d},j}(a,t)}{M_{\mathrm{ISM}}(t)} \qquad (9)
\end{aligned}$$

The injection rate from SNe II into ISM

$(= t_{\mathrm{swept}}^{-1})$

The destruction rate
of dust in ISM
by SN forward shocks

The dust incorporated
into stars in ISM

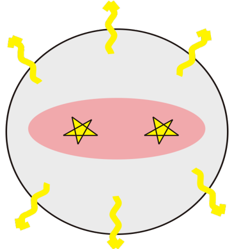
$\overline{\Delta M_{\mathrm{SN,d},j}}(a)$: The mass injected into ISM through a reverse shock per SN
(Nozawa+ 07)

$\eta_j(a,a')$: The conversion efficiency for dust grains in ISM through a forward shock
(Nozawa+ 06)

a' : a radii before the destruction
a : the radii after the destruction

MODEL

Galaxy One-zone Model (①/2)



■ Dark matter halo and physical state of gas :

- We assume (i) the DM halo as a singular isothermal sphere and (ii) the baryonic gas as a uniform, rotating gas disk

- Initial gas temparature : $T = T_{vir}$

$$T_{\rm vir} \equiv \frac{G\mu m_{\rm H} M_{\rm vir}}{3k_{\rm B} r_{\rm vir}}, \qquad (11)$$

- A rotation timescale, t_{cir} : $t_{\rm cir} \equiv \frac{2\pi r_{\rm disk}}{v_{\rm c}}.$

- The number density of H, n_H :

$$n_{\rm H} = \frac{M_{\rm H}}{\boxed{\pi r_{\rm disk}^2 2H m_{\rm H}}}. \qquad (16)$$

the typical volume of the galaxy

r_{disc} : the radius of disk
(Mo+ 98, λ = 0.04)
H : the typical scale height of Tgas
(Shakura & Sunyaev 88)

$$H = \sqrt{2}\frac{v_{\rm s}}{v_{\rm c}} r_{\rm disk} = \left(\frac{2T}{3T_{\rm vir}}\right)^{\frac{1}{2}} r_{\rm disk}$$

■ A star formation law based on H_2 :

$$\Psi(t) = \frac{f_{\rm H_2}(t) M_{\rm H}(t)}{t_{\rm cir}(z_{\rm vir})}, \qquad (18)$$

f_{H2} : the molecular fraction
f_{H2} × M_H : the mass of H_2 in the galaxy

Galaxy One-zone Model (②/2)

■ Chemistry and cooling :

- the time evolution of H_2 fraction, f_{H2} :

$$\frac{\mathrm{d}f_{\mathrm{H_2}}}{\mathrm{d}t} = \left[\frac{\mathrm{d}f_{\mathrm{H_2}}}{\mathrm{d}t}\right]_{\mathrm{gas}} + \underline{\left[\frac{\mathrm{d}f_{\mathrm{H_2}}}{\mathrm{d}t}\right]_{\mathrm{dust}}} + \left[\frac{\mathrm{d}f_{\mathrm{H_2}}}{\mathrm{d}t}\right]_{\mathrm{dest}} + \left[\frac{\mathrm{d}f_{\mathrm{H_2}}}{\mathrm{d}t}\right]_{\mathrm{UV}} + \left[\frac{\mathrm{d}f_{\mathrm{H_2}}}{\mathrm{d}t}\right]_{\mathrm{star}}, \qquad (22)$$

H_2 formation on dust grains

- cooling (H_2 , H, H^+ , C_I , C_{II} , O_I) and heating (photoheating)

■ Formation of molecular hydrogen on dust grains :

$$\left[\frac{\mathrm{d}f_{\mathrm{H_2}}}{\mathrm{d}t}\right]_{\mathrm{dust}} = 2R_{\mathrm{dust}}\mathcal{D}n_{\mathrm{H}}f_0$$

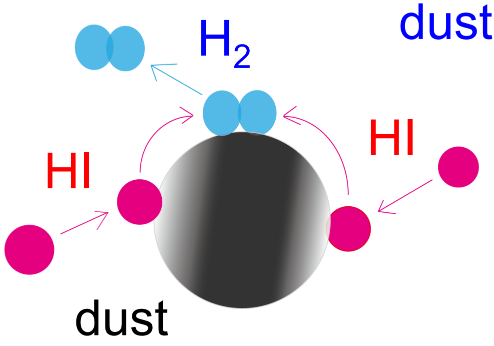
$$= \sum_j \int_0^\infty \underline{f_0 f_j(a)\pi a^2 \bar{v} S \mathrm{d}a}$$

the collision rate (30)
between the dust grains
and HI atoms

$$R_{\mathrm{dust}}(a)\mathcal{D} = \sum_j \int_0^\infty \left(\frac{3m_{\mathrm{H}}\bar{v}S}{8\underline{a}\rho_j}\right) \boxed{\left(\frac{4\pi a^3 \rho_j f_j(a)}{3n_{\mathrm{H}}m_{\mathrm{H}}}\right)} \mathrm{d}a. \qquad (33)$$

a : radius of dust

↑ dust-to-gas mass ratio



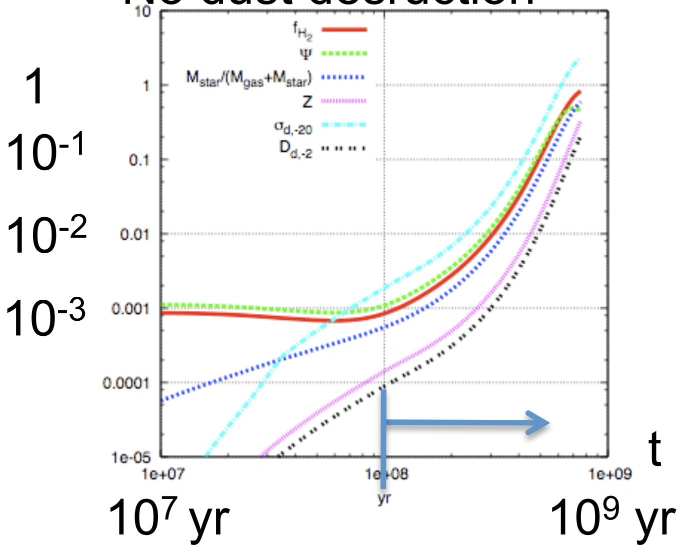
RESULTS

Galaxy Evolution

■ Time evolution of galaxy on dust models :

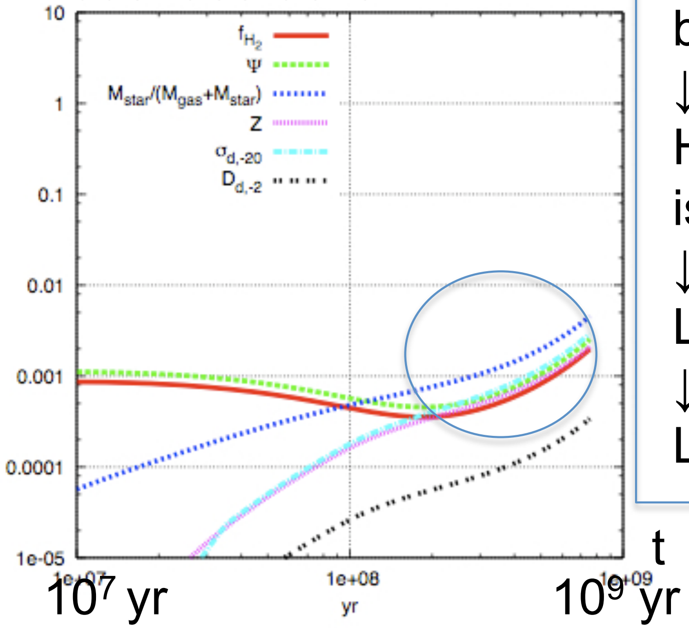
- $M_{vir} = 10^9\ M_{sun}$, $z_{vir} = 10$, $n_{SN} = 1\ cm^{-3}$:

No dust desruction



the H_2 formation on dust grains

dust desruction



(DY+11)

SNe
↓
Dust destruction
by reverse shocks
↓
H2 formation
is suppressed.
↓
Low SFR
↓
Low SNe

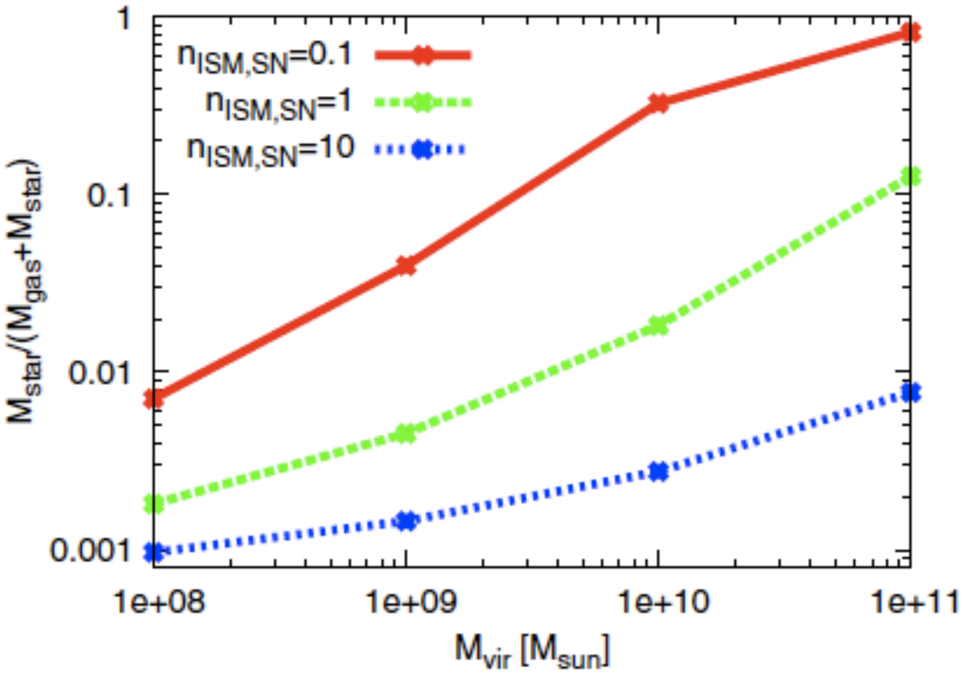
reverse	×	○
forward	×	○

- The dust destruction by the reverse shocks is very effective and suppresses H_2 formation on dust grains.

RESULTS

SFE vs. DM Halo Mass

■ SFR is very suppresed in our model with dust desruction,
and stellar mass fraction is very low at t～0.8 Gyr.
note : SFE can be well characterized by stellar mass fraction.



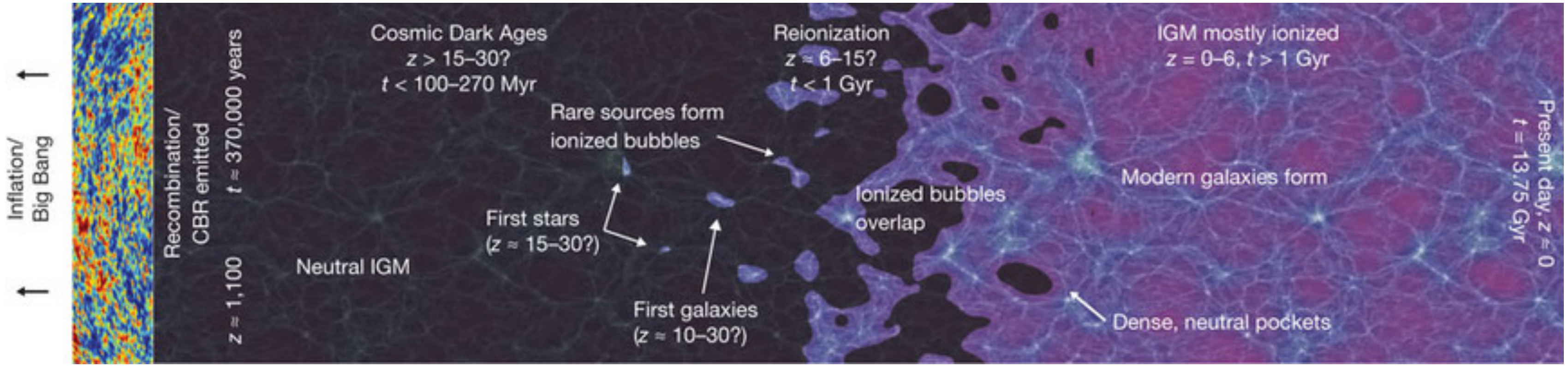
■ SFE is large for large M_{vir} :

The gas cools the T_{CMB} ～ 40 K in all M_{vir}.
Tvir increase with M_{vir}.
↓
The final gas density becomes higher because of smaller H / r_{disc} .
↓
This results in more rapid H_2 formation.
↓
This enhances the SFR.

Table of Contents

INTRODUCTION

Reionization in the Universe



(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 ∼$10^{9.5}$ Msun.

■ Star formation efficiency (SFE) :

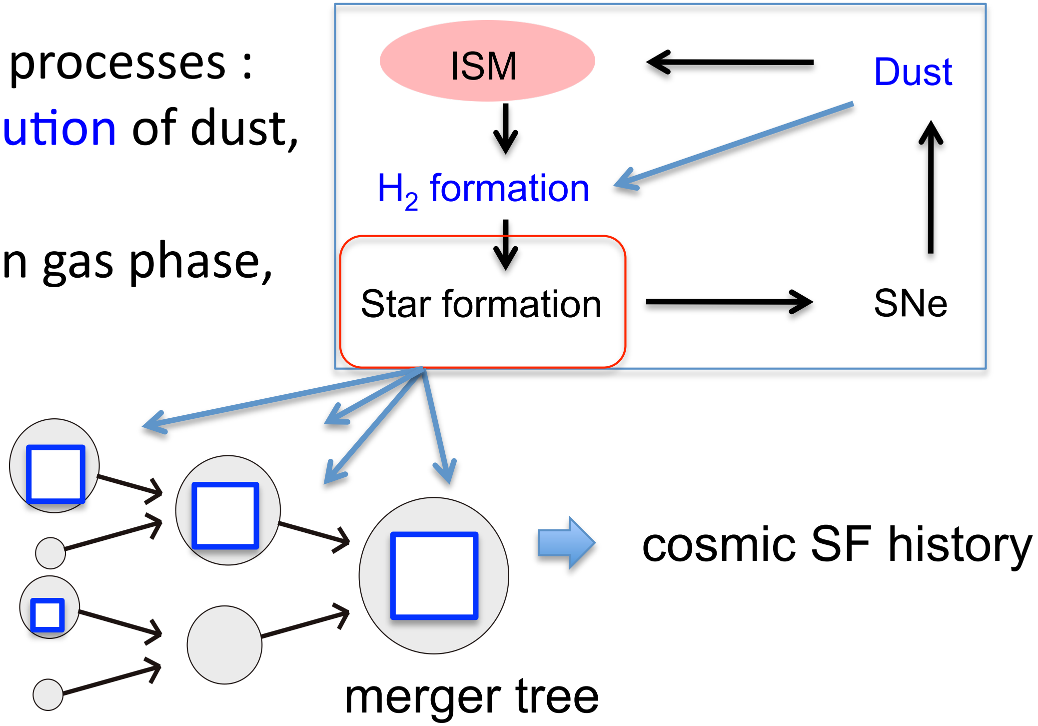
- The stellar mass fraction, $M_{star} / (M_{gas} + M_{star})$, is assumed to be constant independent of M_{vir} in previous analytic works.

Our Study

- We study reionization by our one-zone protogalaxy model which includes dust production and dust size evolution.

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

- We consistently treat following processes :
  (i) the formation and size evolution of dust,
  (ii) H_2 formation
  both on the dust grains and in gas phase,
  (iii) gas cooling and heating
  (iv) the SFR based on H_2 mass
  and
  (v) DM halo evolution
  (vi) IMF transition
  from Pop III to Pop II



ISM

Dust

H_2 formation

Star formation

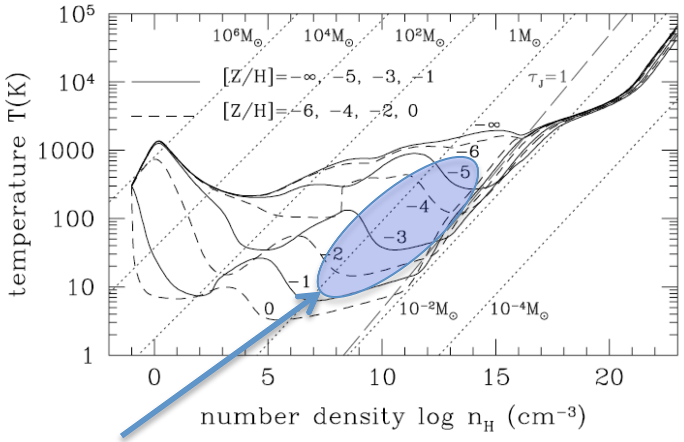
SNe

cosmic SF history

merger tree

MODEL

Pop III.1 and Pop III.2



dust cooling

(Omukai+ 05)

■ 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

- Ionizing photons, n_{ion} , emitted by massive stars :

$$\frac{1}{n_{\rm b}}\frac{dn_{\rm ion}(z)}{dz} = \frac{1}{\rho_{\rm m}}\frac{\Omega_{\rm m}}{\Omega_{\rm b}} f_{\rm esc}\underline{\eta_{\rm ion}}\,\underbrace{\Psi_*(z)}_{\text{cosmic SFR (per Mpc}^3\text{)}}\left|\frac{dt}{dz}\right|$$

$n_{\rm ion}$: 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.

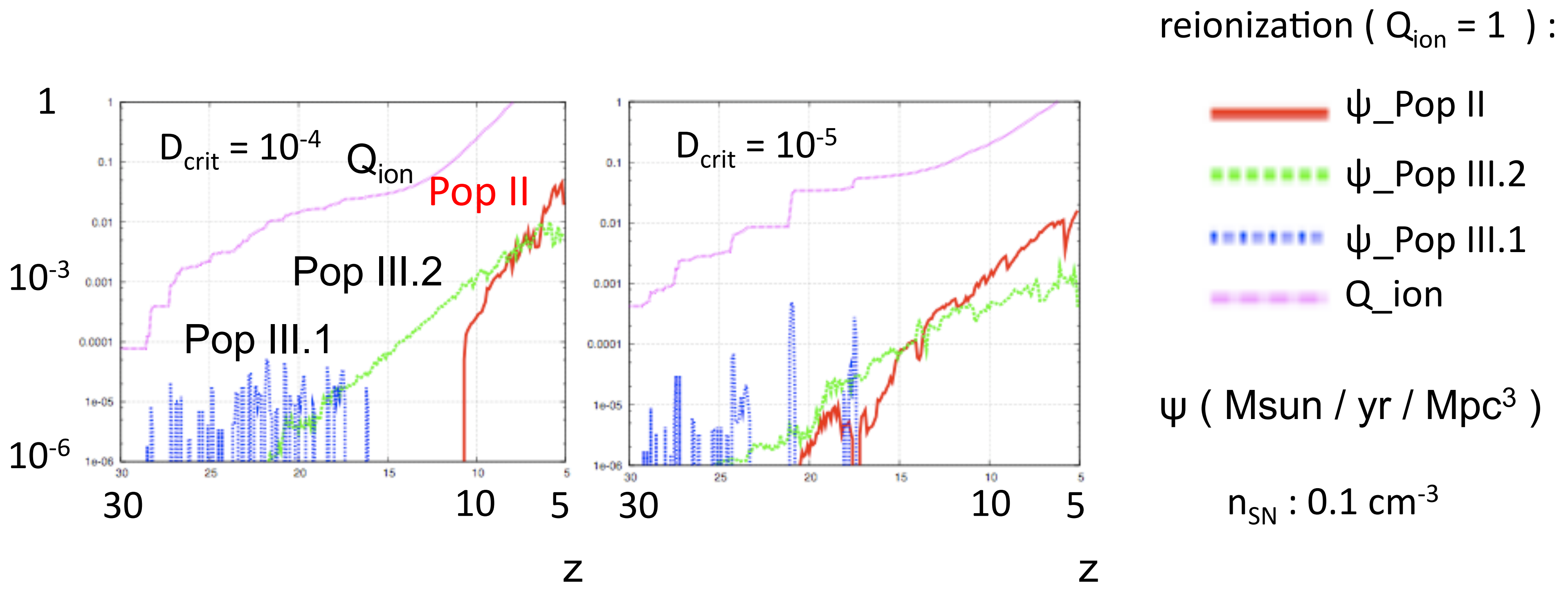
- Evolution of ionized volume fraction, Q_{ion} :

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

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

RESULTS

Reionization and Dcrit



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

ψ (Msun / yr / Mpc^3)

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

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

RESULTS

Reionization and Dcrit

■ reionization ($Q_{ion} = 1$) :

○ : $z > 6$
× : $z < 6$

f_{esc} \ D_{crit}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}
A	○	○	×	×	×	×
B	○	○	×	×	×	×
C	○	○	×	×	×	×

$n_{SN} = 0.1\ \mathrm{cm}^{-3}$

A : Pop III.2 : f_{esc} = 10%, Pop II : f_{esc} = 30% (Greif and Bromm 06)
B : Pop III.2 : f_{esc} = 50%, Pop II : f_{esc} = 60% (Wise and Cen 09, cosmological)
C : Pop III.2 : f_{esc} = 70%, Pop II : f_{esc} = 80% (Wise and Cen 09, isolated)

- In the cases of $D_{crit} > 10^{-5}$,
  reionization occurs at $z > 6$ independent of escape fraction, f_{esc} .

SUMMARY

I: Protogalaxy Evolution :

We conclude that
the amount and the size distribution of dust
strongly affects the evolution of galaxies in the early Universe,
since SF activity depends on H_2 formation on dust grains.

- We show that H_2 formation is suppressed by the dust destruction, especially by the reverse shocks in SNRs.

II. Reionizarion :

We study reionization by our galaxy model
and find that, in the cases of $D_{crit} > 10^{-5}$,
reionization occurs at $z > 6$ independent of other parameters.

- This result show that study of critical dust-to-gas mass ratio is very important for reionization process.