Origin and Nature of Dust in the Early Universe

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Contents of this talk

1. Evidence of dust in the high-z universe

2. Dust formation in primordial SNe

3. Dust evolution in primordial SNRs

4. Extinction curves expected at high redshift

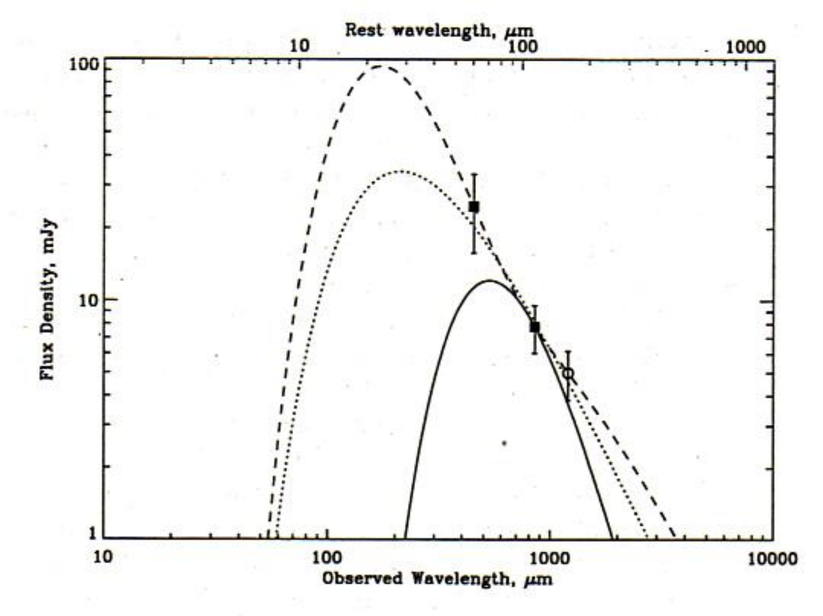
5. Role of dust in the early universe

1-1. A large amount of dust at z > 5

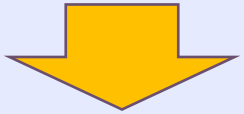
- 30% of z ＞ 5 quasars have shown the presence of large amounts of dust grains with mass larger than 10^8 Msun

(Bertoldi et al. 2003; Priddey et al. 2003; Robson et al. 2004; Beelen et al. 2006; Wang et al. 2008, Fan's talk)

SDSS J1148+5251 at z=6.4



Robson et al.
(2004, MNRAS, 351, L29)

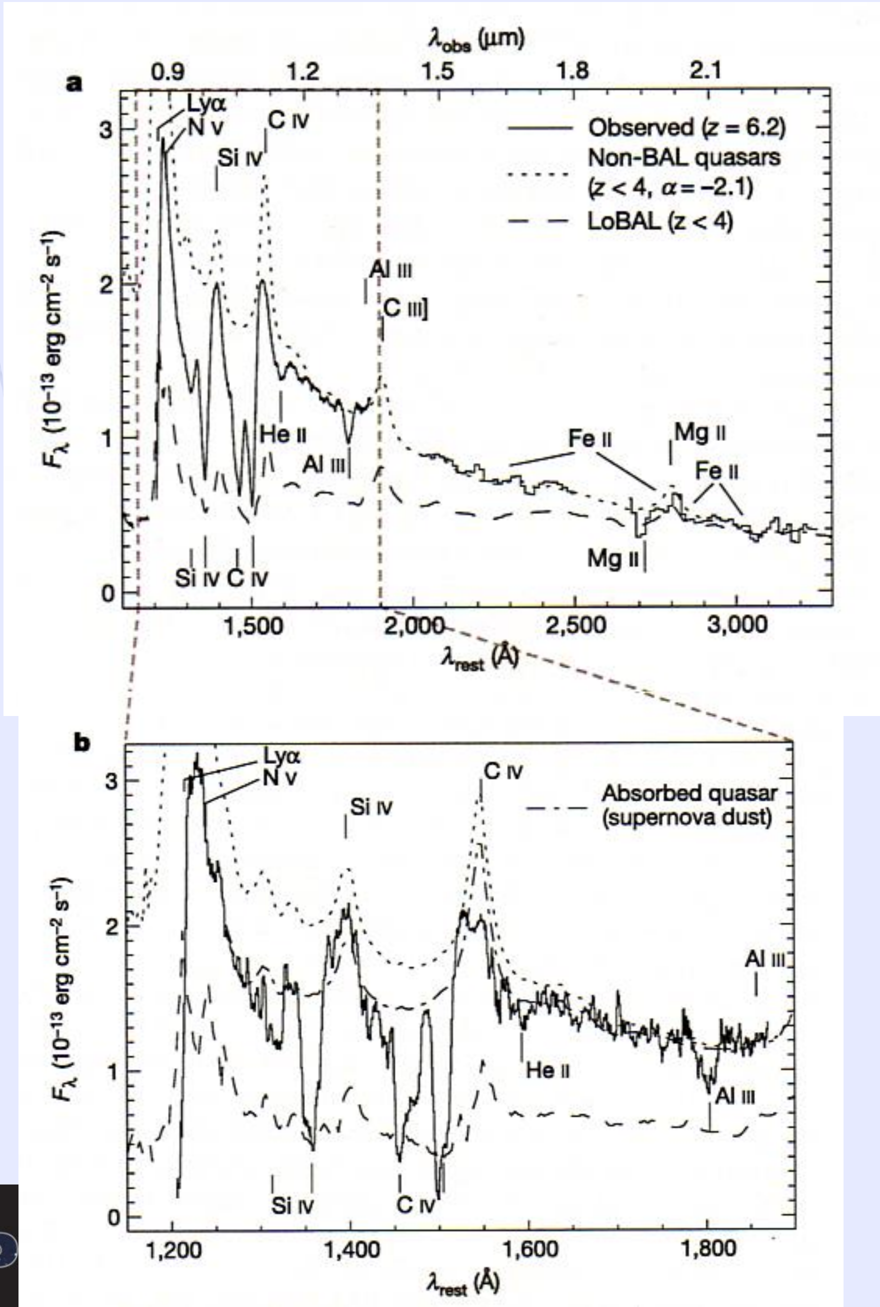


a rapid enrichment with dust formed in the ejecta of SNe

Dust of 0.1-1 M_{sun} per SN is required to form to explain a large content of dust at high-z galaxies

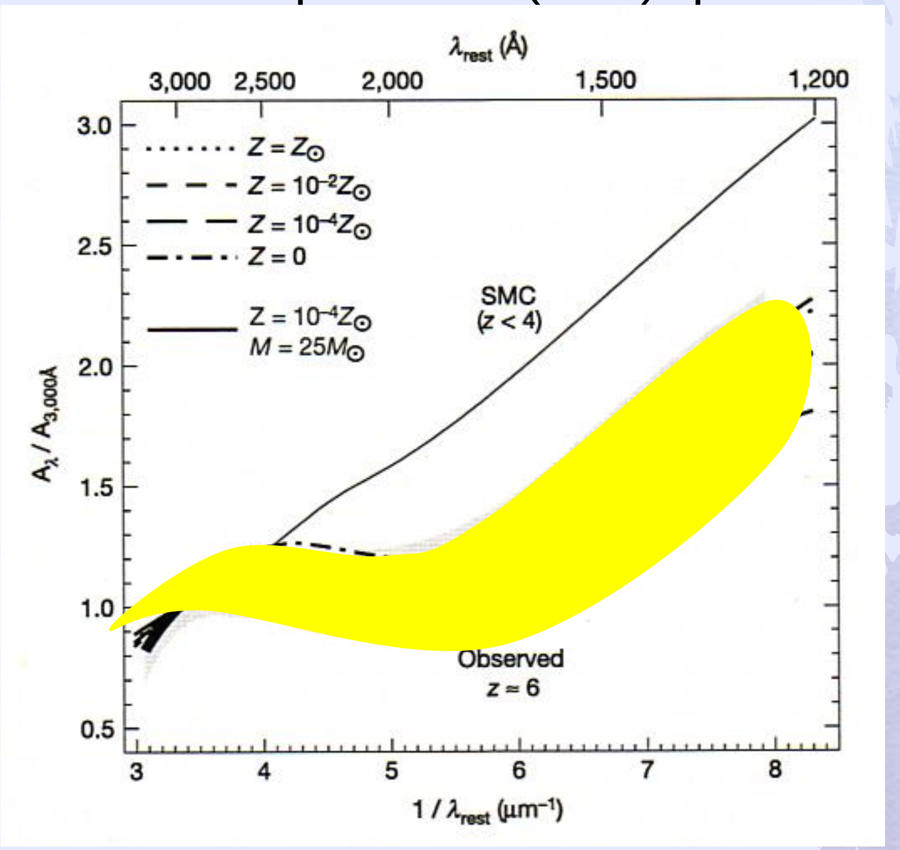
(Morgan & Edmunds 2003,
Maiolino et al. 2006;
Dwek et al. 2007, Dwek's Talk)

1-2. Extinction curves of high-z quasar



SDSS J1048+4637 at z=6.2

Broad absorption line (BAL) quasars



Maiolino et al.
(2004, Nature, 431, 533)

different dust properties from those in low redshifts

1-3. Role of dust in the early universe

- Dust absorbs stellar light and re-emits it by thermal radiation

  ➔ plays a crucial role in interpreting the SFR and the IMF of the early generation of stars from high-z observations

  (e.g., Loeb & Haiman 1998)

- Dust has great impacts on the formation processes of stars

  – providing additional cooling pathways of gas through thermal emission (e.g., Schneider et al. 2003, Omukai et al. 2005)

  – forming molecules (mainly H_2) on the surface (e.g., Cozax & Spaans 2004)

  – controlling the energy balance in the interstellar medium

1-4. Aim of our study

In the previous studies, the composition and size of dust are assumed to be the same as those in Galaxy, and the amount is treated as a parameter.

Absorption and thermal emission by dust grains are sensitive to the composition, size, and amount

It is essential to clarify the properties of dust in the early epoch of the universe!

We aim at revealing the composition and size, amount of dust by treating self-consistently the formation and destruction processes of dust.

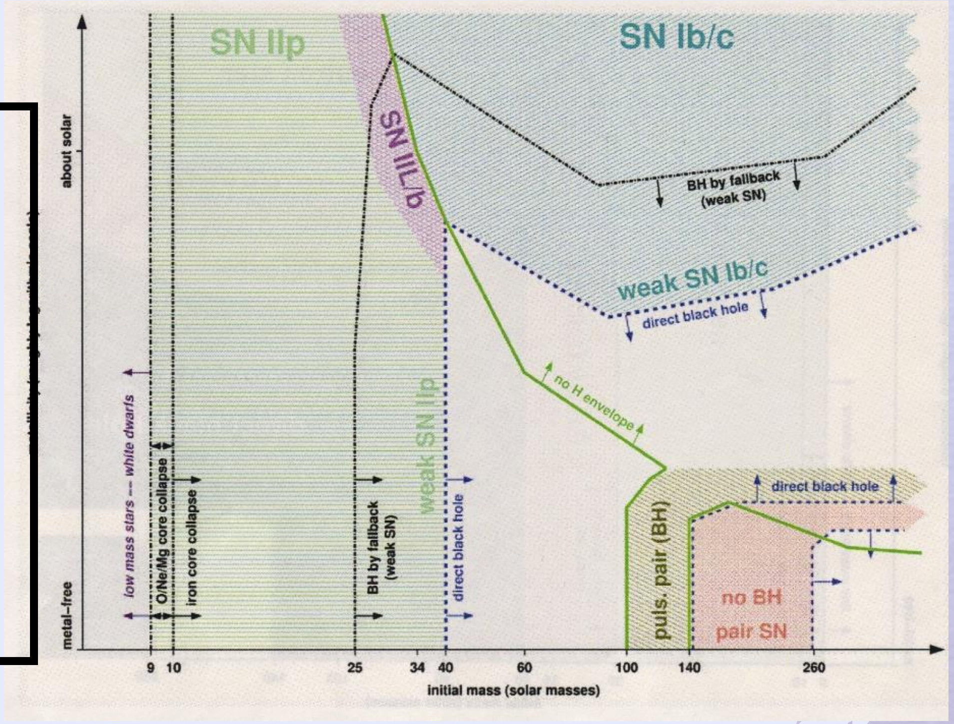
1-5. Sources of dust in the early universe

- **At z > 5, the main formation sites of dust are considered to be in the ejecta of supernovae (SNe)**

- **first stars (Population III stars) very massive**
  M =100-500 Msun

In the early universe

- **Type II SNe (SNe II)**
  ; M_{pr}=8−40 M_{sun}
- **pair-instability SNe**
  ; M_{pr}=140−260 M_{sun}



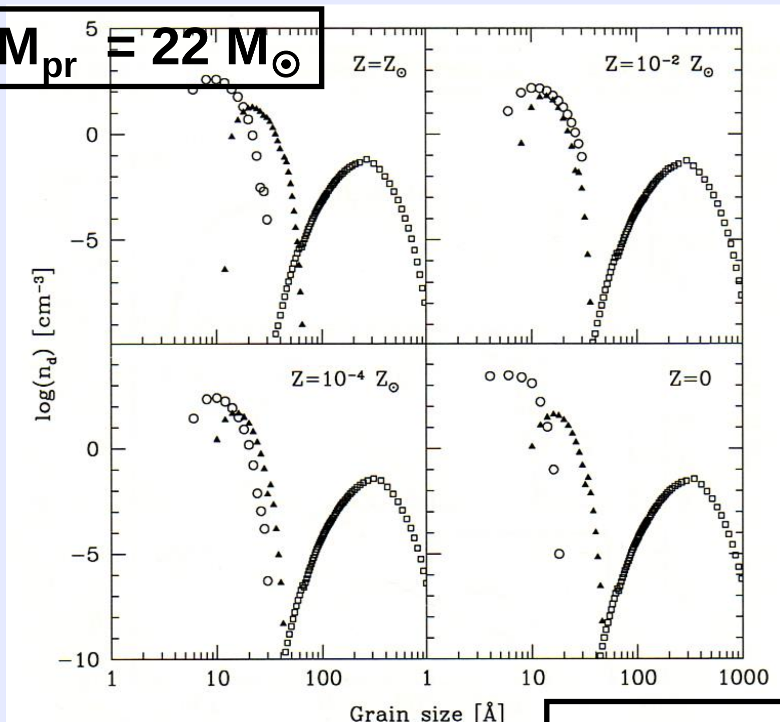
(Heger et al. 2003)

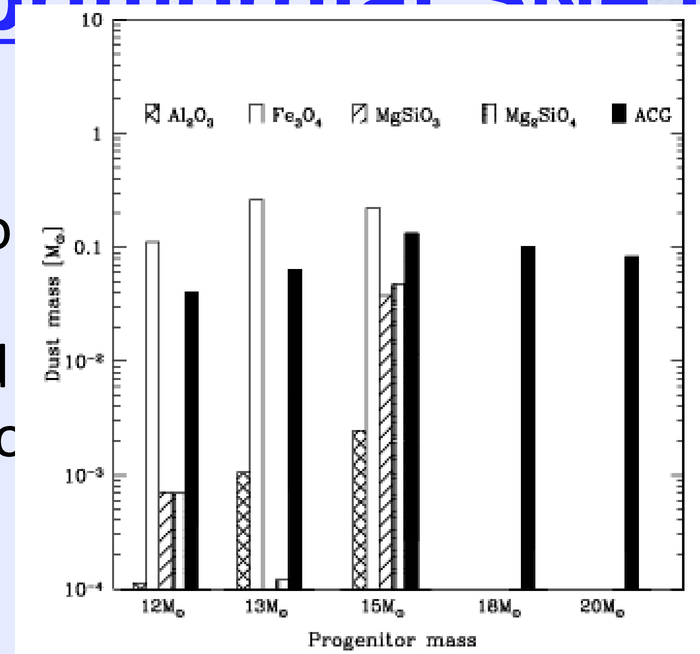
2-1. Dust formation in primordial SNe (1)

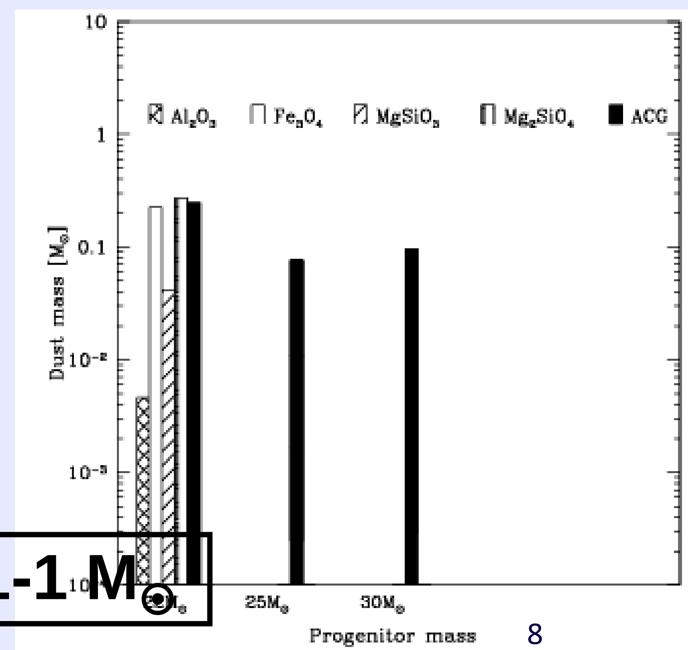
Todini & Ferrara (2001, MNRAS,

Type II SN model (Z = 0-0.02) by Woo
one-zone model within He core
formation and destruction of CO and
initial gas density and temperature fc

M_{pr} = 22 $M_{\odot}$







M_{dust} = 0.1-1 $M_{\odot}$

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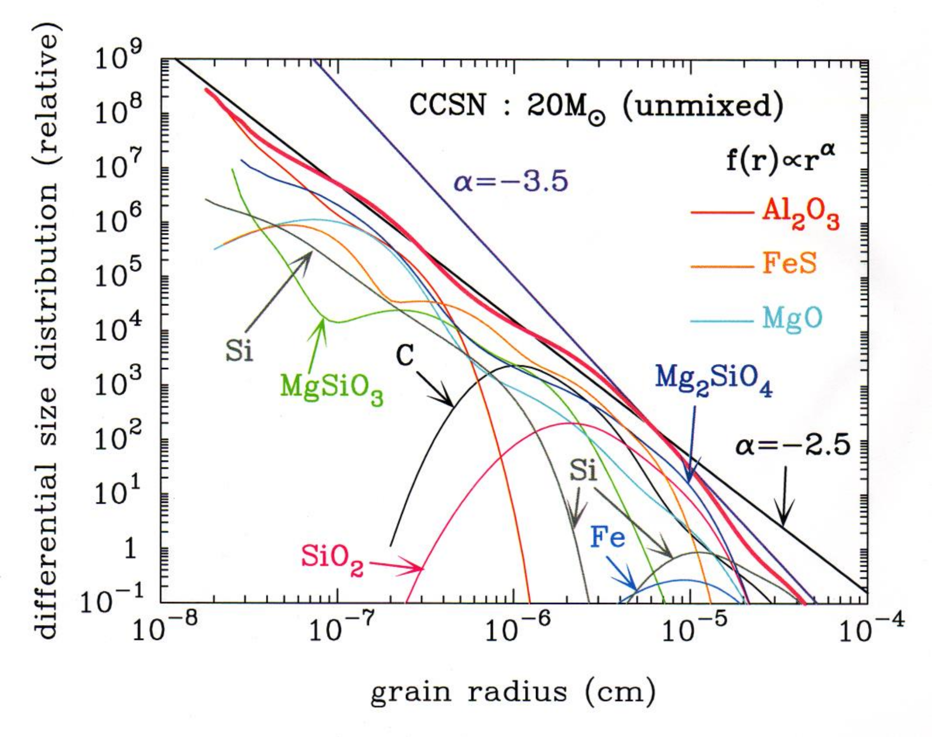
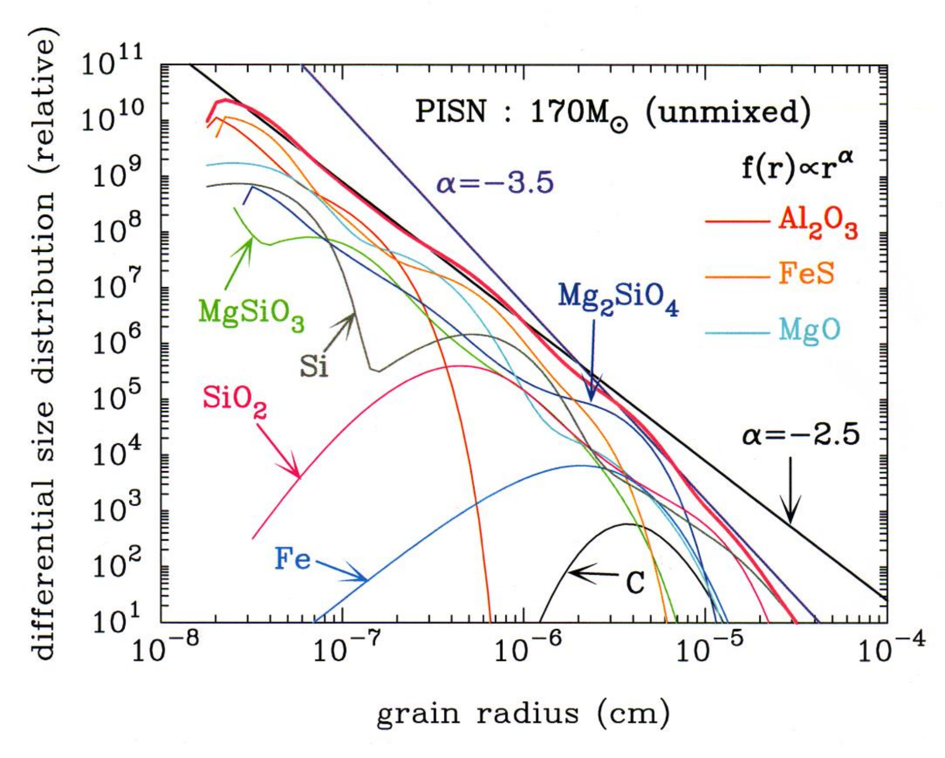
2-2. Dust formation in primordial SNe (2)

Nozawa et al. (2003, ApJ, 598, 785)

Type II SN (Z=0) and PISNe model by Umeda & Nomoto (2002)
mixing of elements within He-core ➔ two extreme cases
 unmixed case (onion-like structure)
 uniformly mixed case (retaining the density profile)
gas temperature; solving radiative transfer calculation
formation of CO and SiO molecules is complete

2-3. Dust formed in the unmixed ejecta

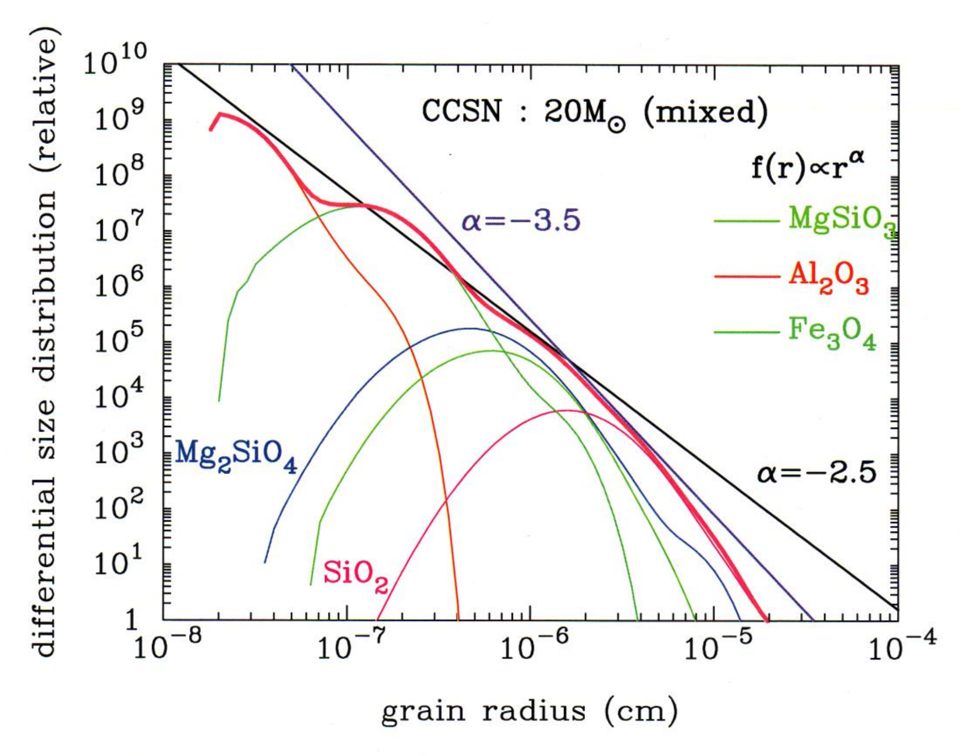


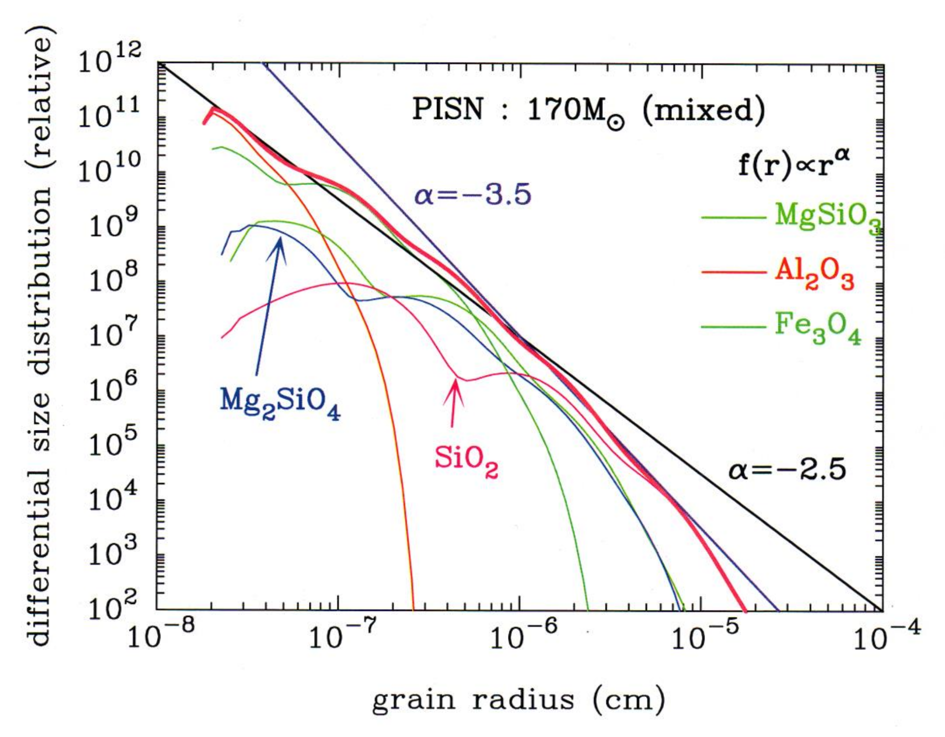


- Various species of dust form, reflecting the elemental composition of each layer.

- C, SiO2, and Fe grains are lognormal-like with relatively large average radii, while other grains are power-law-like.

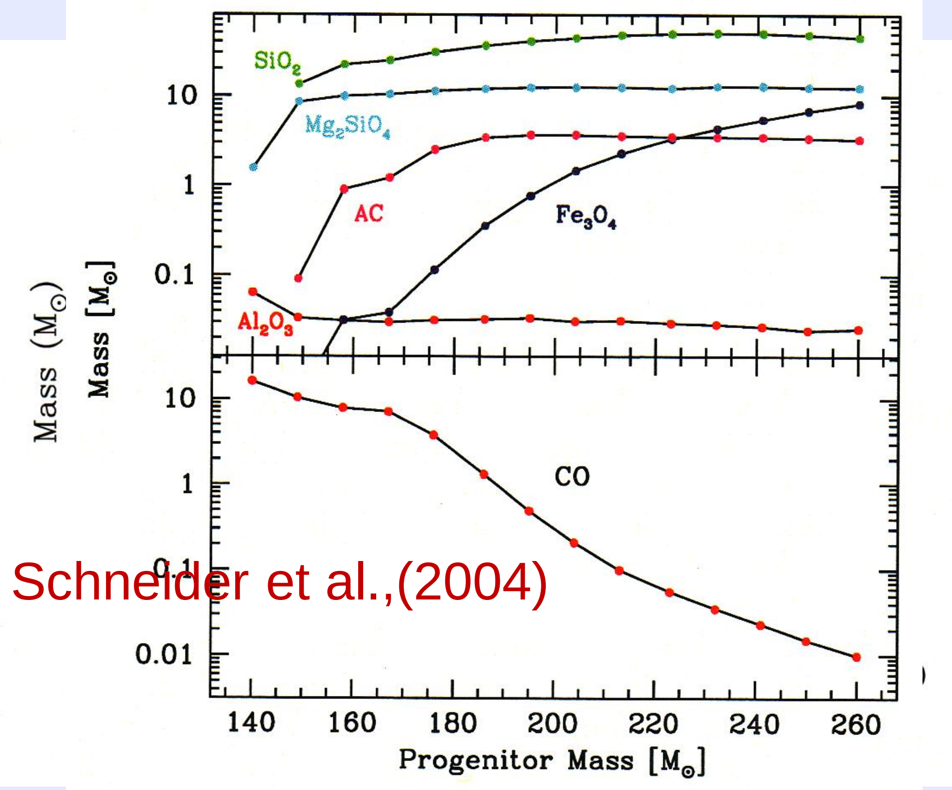
2-4. Dust formed in the mixed ejecta



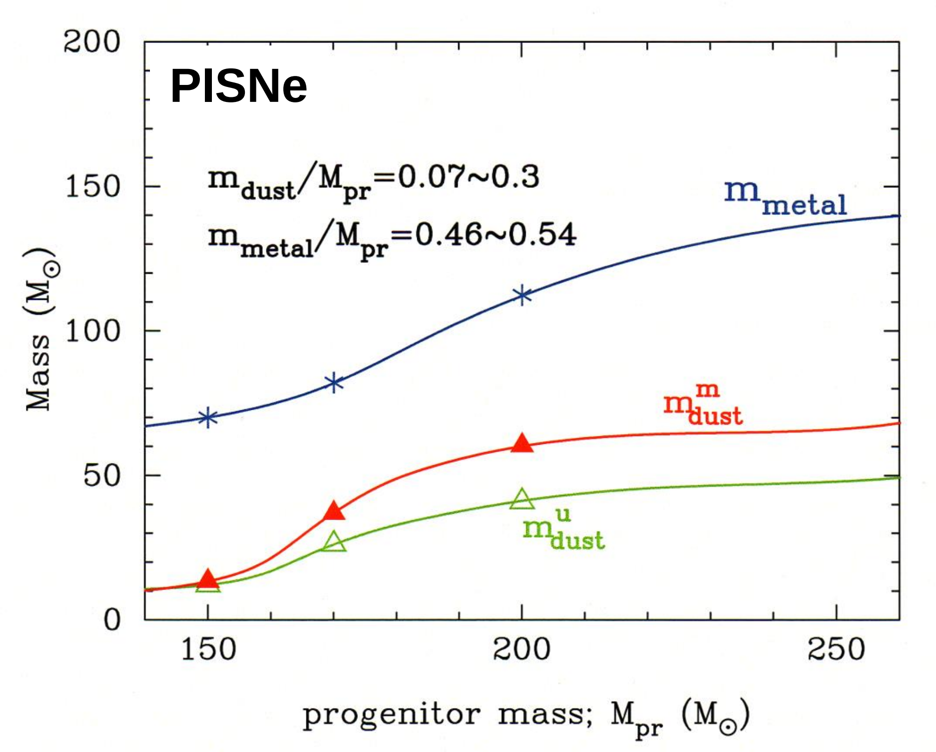


- Because oxygen is rich, only silicate（$MgSiO_3$, Mg_2SiO_4, SiO_2）and oxides（Fe_3O_4, Al_2O_3）form.
- The size distribution of each dust species except for Al_2O_3 is lognormal-like

2-5. Total mass of dust formed



Schneider et al.,(2004)



- Total dust mass increases with increasing progenitor mass
  SNe II：M_{dust} = 0.1-2 Msun PISNe：M_{dust} = 10-60 Msun
- Dust mass for the mixed case is generally larger than for the unmixed case

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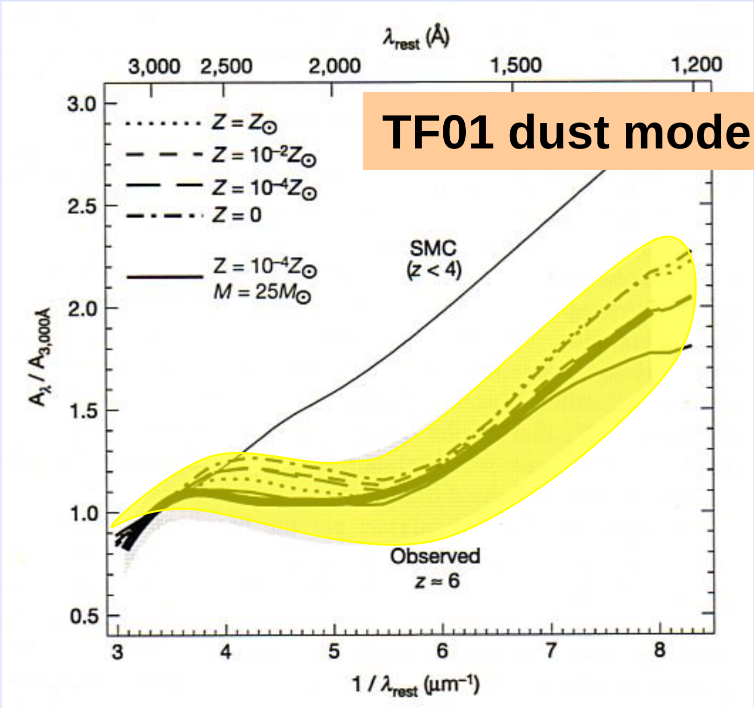
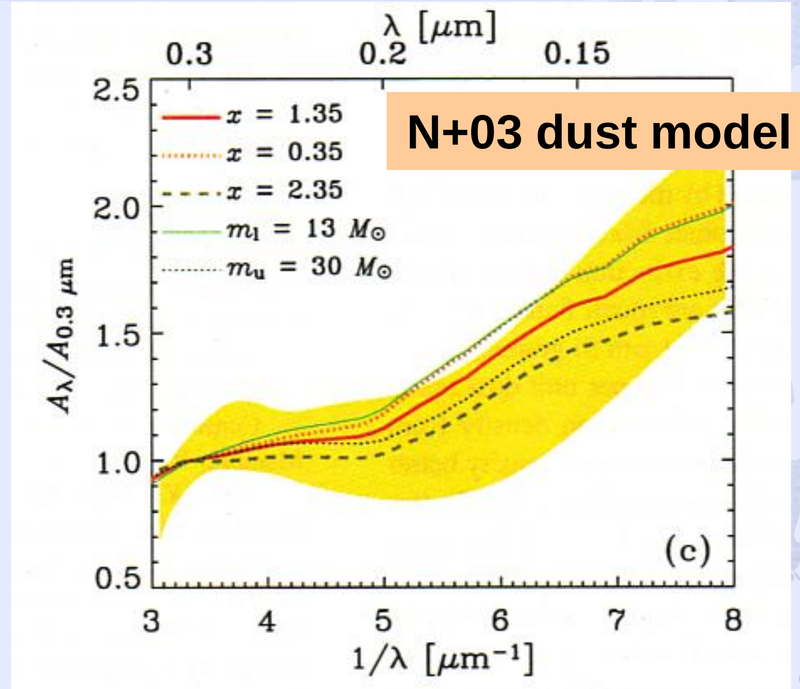
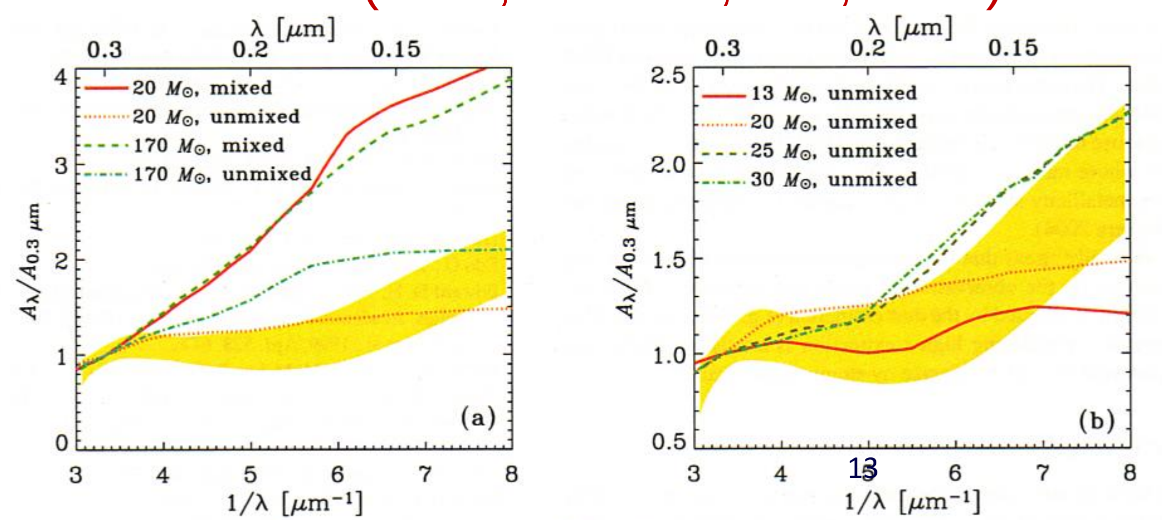
2-6. Extinction curves from SN dust



Maiolino et al.,
(2004, Nature, 431, 533)



Hirashita, T. N. et al.
(2005, MNRAS, 357, 1077)



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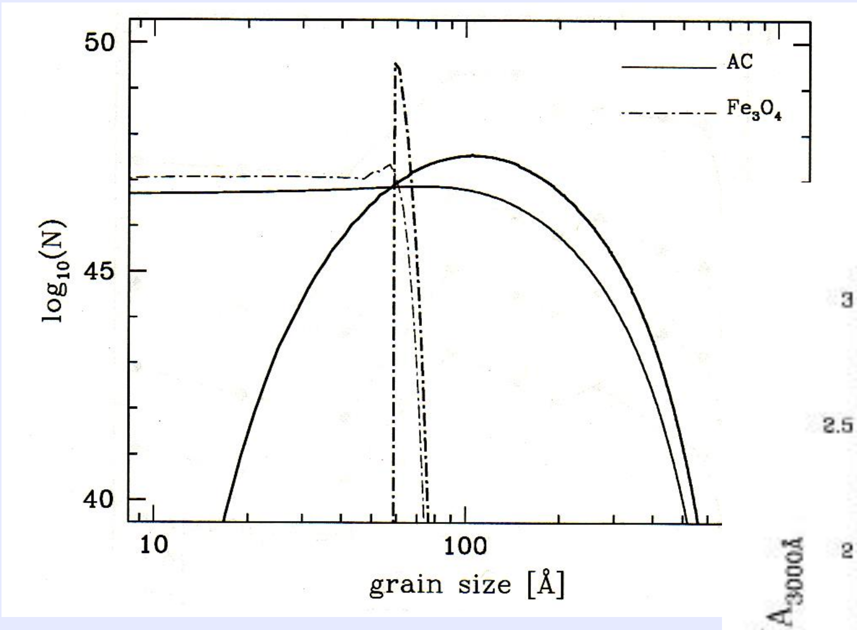
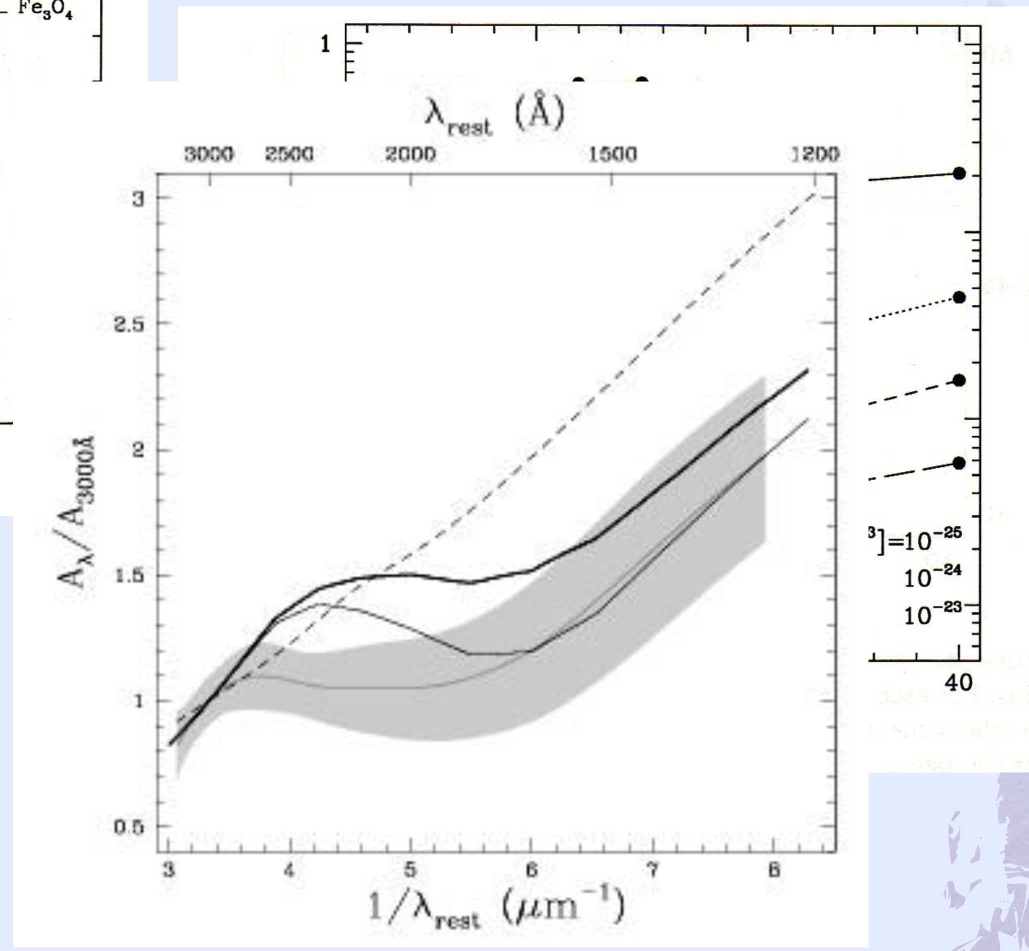
3-1. Bianchi & Schneider's calculation

Bianchi & Schneider, (2007, MNRAS, 378, 973)





Semi-analytical model
neglecting gas drag
t < ~10^5 yr

3-2-1. Time evolution of SNRs

- Basic equations (spherical symmetry)

$$\frac{\partial \rho}{dt} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v) = 0$$

$$\frac{\partial}{dt}(\rho v) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v^2) = -\frac{\partial P}{\partial r}$$

$$\frac{\partial}{dt}\left(\frac{\rho v^2}{2} + \frac{P}{\gamma - 1}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left[\frac{\rho v^2}{2} + \frac{\gamma P}{\gamma - 1}\right] v\right)$$

$$= -(n_e n_H \Lambda_{gas}(T) + \Lambda_{ic}(T) + \Lambda_d(n_H, T))$$

$\Lambda_{gas}(T)$: cooling function of gas by the atomic process (Sutherland & Dopita 1993; Smith et al. 2001)

$\Lambda_{ic}(T)$: inverse Compton cooling (Ikeuchi & Ostriker 1986)

$$\Lambda_{ic}(T) = 5.41 \times 10^{-32} (1+z)^4 n_e (T/10^4 \text{ K}) \text{ (we adopt } z = 20)$$

$\Lambda_d(n_H, T)$: cooling of gas through thermal emission of dust

· numerical code : flux splitting method (van Albada et al. 1982)

3-2-2. Physics of dust in SNRs

- deceleration of dust due to drag force (Baines et al. 1965)

$$\frac{dw_{\rm d}}{dt} = -\frac{3kT}{2a\rho_{\rm d}} \sum_i n_i G_i(s_i) \quad (s_i^2 = m_i w_d^2 / 2kT)$$

$w_{\rm d}$; velocity of dust relative to gas

$\rho_{\rm d}$; bulk density of a grain

n_i ; number density of gas species i

$$G_i(s_i) \approx \frac{8 s_i}{3\sqrt{\pi}} \left(1 + \frac{9\pi}{64} s_i^2\right)^{\frac{1}{2}} \quad \text{(Draine \& Salpeter 1979)}$$

- dust destruction by sputtering (e.g., Dwek et al. 1996)

$$\frac{da}{dt} = -\frac{m_{\rm sp}}{2\rho_{\rm d}} \sum_i n_i \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} \frac{e^{-s_i^2}}{2 s_i} \int_{\epsilon_{\rm th}}^{\infty} \sqrt{\epsilon_i} e^{-\epsilon_i} \sinh(2 s_i \sqrt{\epsilon_i}) Y_i^0(E_i) d\epsilon_i$$

$Y_i^0(E_i = \epsilon_i kT)$; sputtering yield at normal incidence

$m_{\rm sp}$; average mass of the sputtered atoms

3-2-3. Initial conditions

○ Models of Pop III SNe (Umeda & Nomoto 2002)

- M_{pr}=13, 20, 25, and 30 $M_\odot$ (E_{51}=1)

○ The ambient medium (e.g., Kitayama et al. 2004)

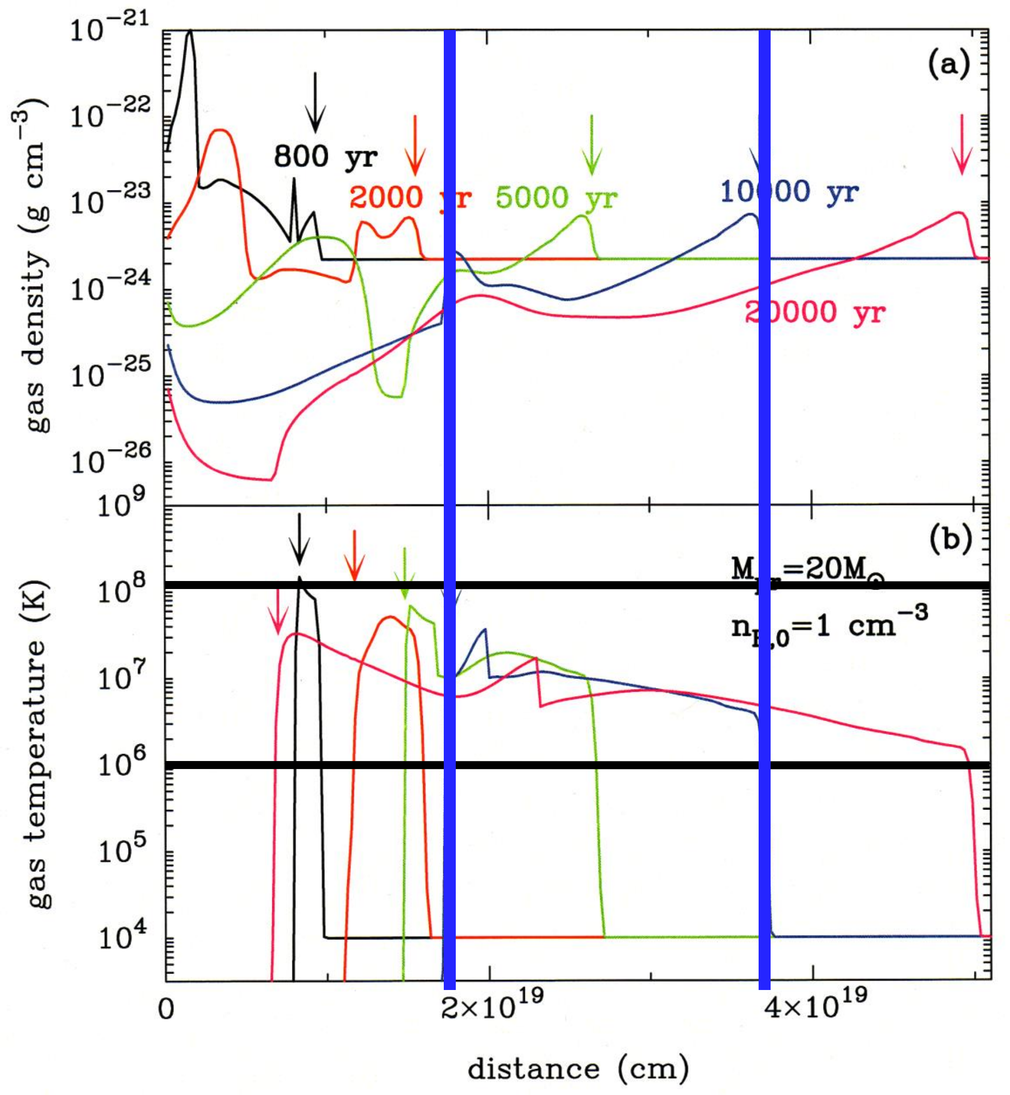
- gas temperature ; $T = 10^4$ K
- gas density ; **$n_{H,0}$ = 0.1, 1, and 10 cm^{-3}**

○ Dust in the He core (Nozawa et al. 2003)

- size distribution and spatial distribution of each grain species formed in the ejecta
- dust grains → test particles

The calculation is performed from 10 yr up to ~10^6 yr.

3-3-1. Temperature and density of gas



(Nozawa et al. 2007, ApJ, 666, 955)

Model : M_{pr}=20 $M_\odot$ (E_{51}=1)

$n_{H,0}$ = 1 cm^{-3}

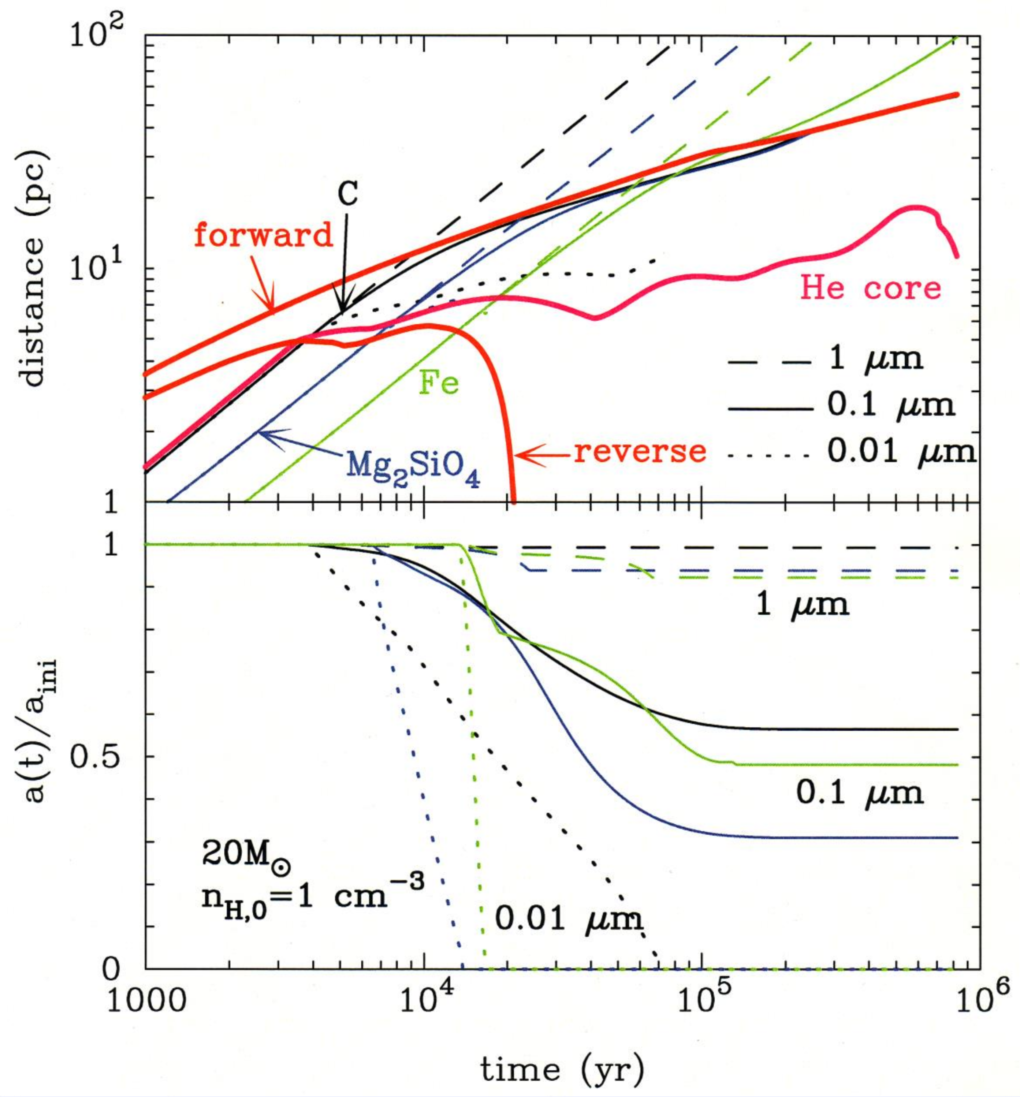
Downward-pointing arrows:
forward shock in upper panel
reverse shock in lower panel

The temperature of the gas swept up by the shocks
➔ 10^6-10^8 K

↓

Dust grains residing in this hot gas are eroded by sputtering

3-3-2. Evolution of dust in SNRs



(Nozawa et al. 2007, ApJ, 666, 955)

Model : M_{pr}=20 $M_\odot$ (E_{51}=1)

$n_{H,0}$ = 1 cm^{-3}

Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

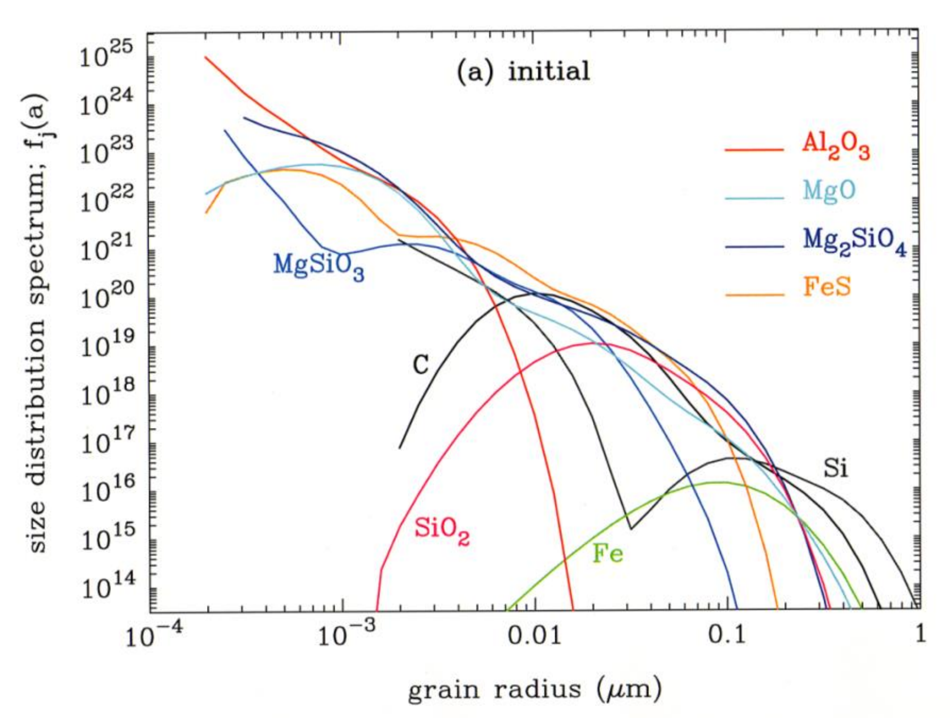
The evolution of dust heavily depends on the initial radius and composition

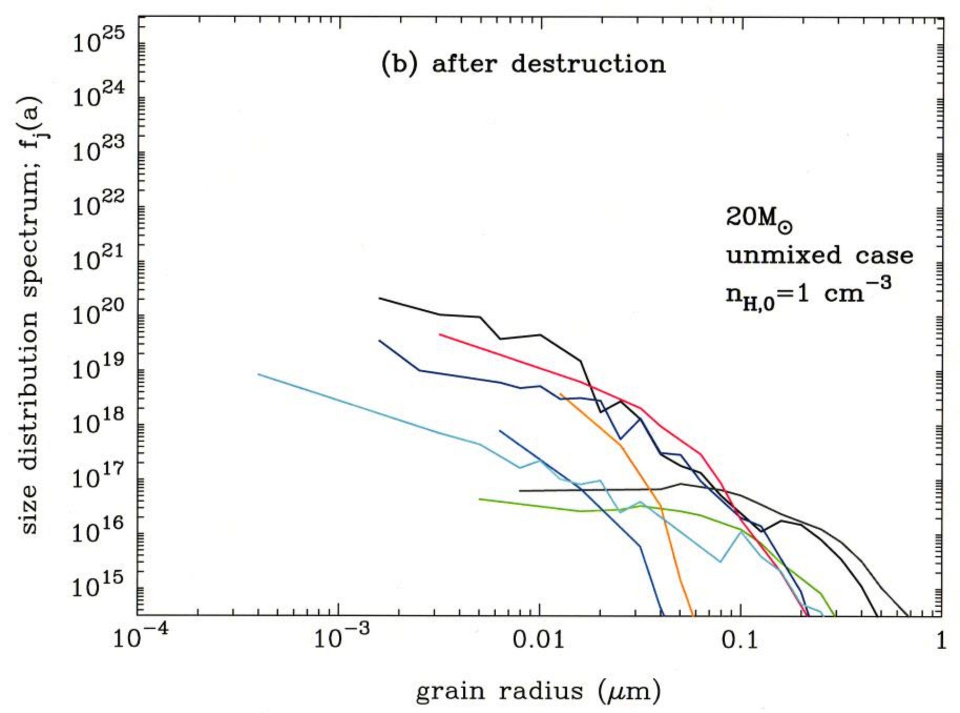
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed

a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell

a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

3-4. Size distribution of surviving dust

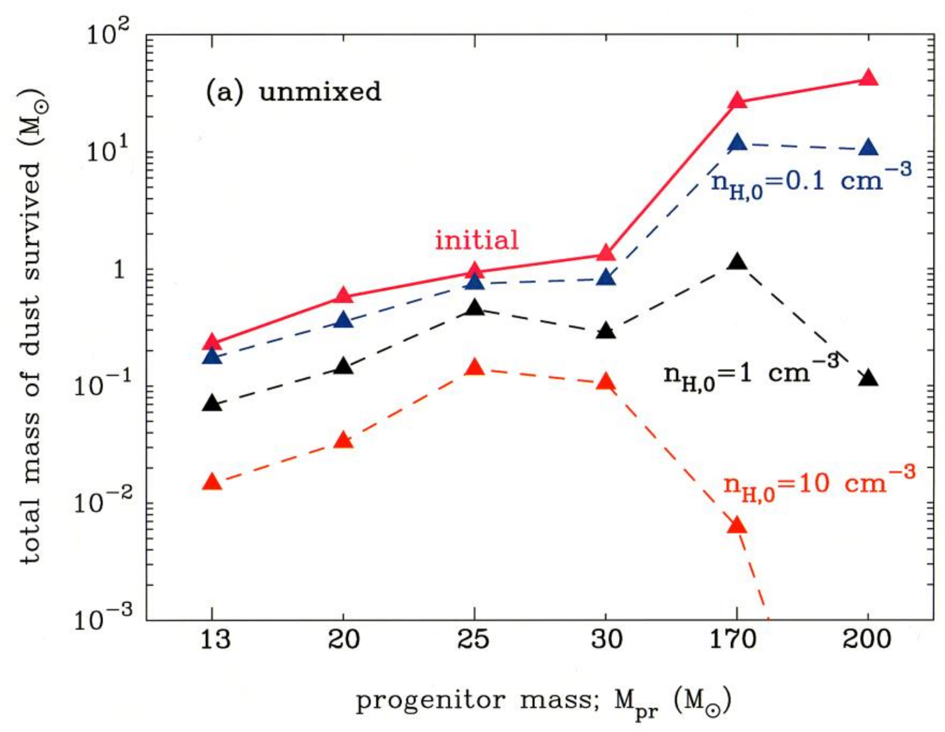


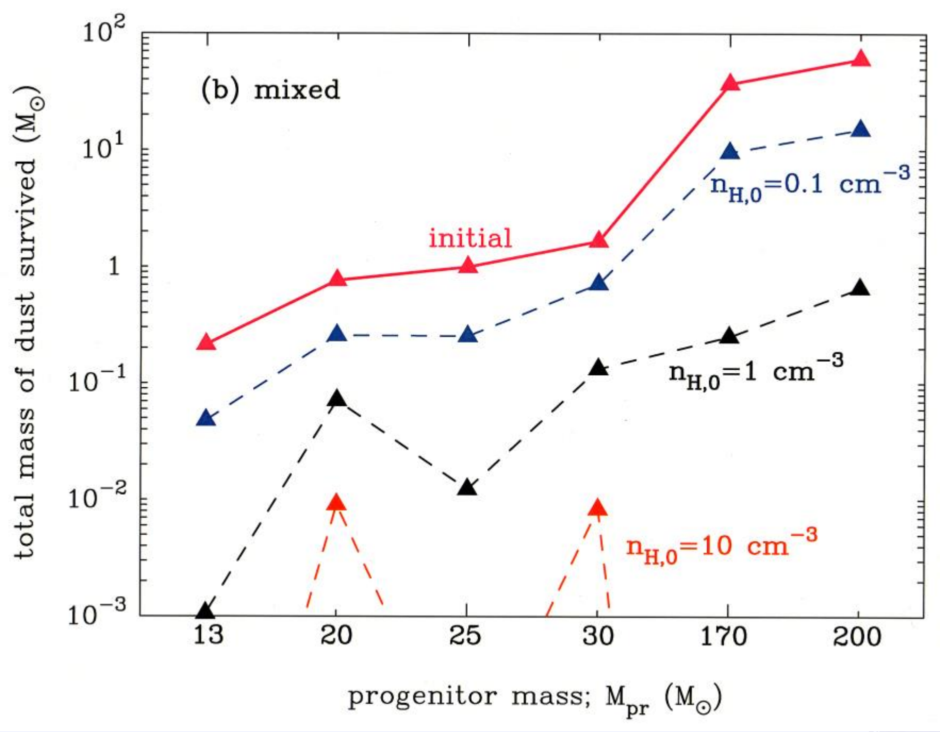


The size distribution of surviving dust is greatly deficient in small-sized grains, compared with that at its formation

→ **Dust in the early universe is dominated by large grains**

3-5. Total mass of surviving dust





Total mass of dust surviving the destruction for Type II SNRs;
0.1-0.8 $M_\odot$ for the unmixed grain model ($n_{H,0}$ = 0.1-1 cm^{-3})
0.06-0.7 $M_\odot$ for the mixed grain model ($n_{H,0}$ = 0.1 cm^{-3})

➔ **high enough to explain dust content at high-z galaxies**
(Morgan & Edmunds 2003, Maiolino et al. 2006; Dwek et al. 2007)

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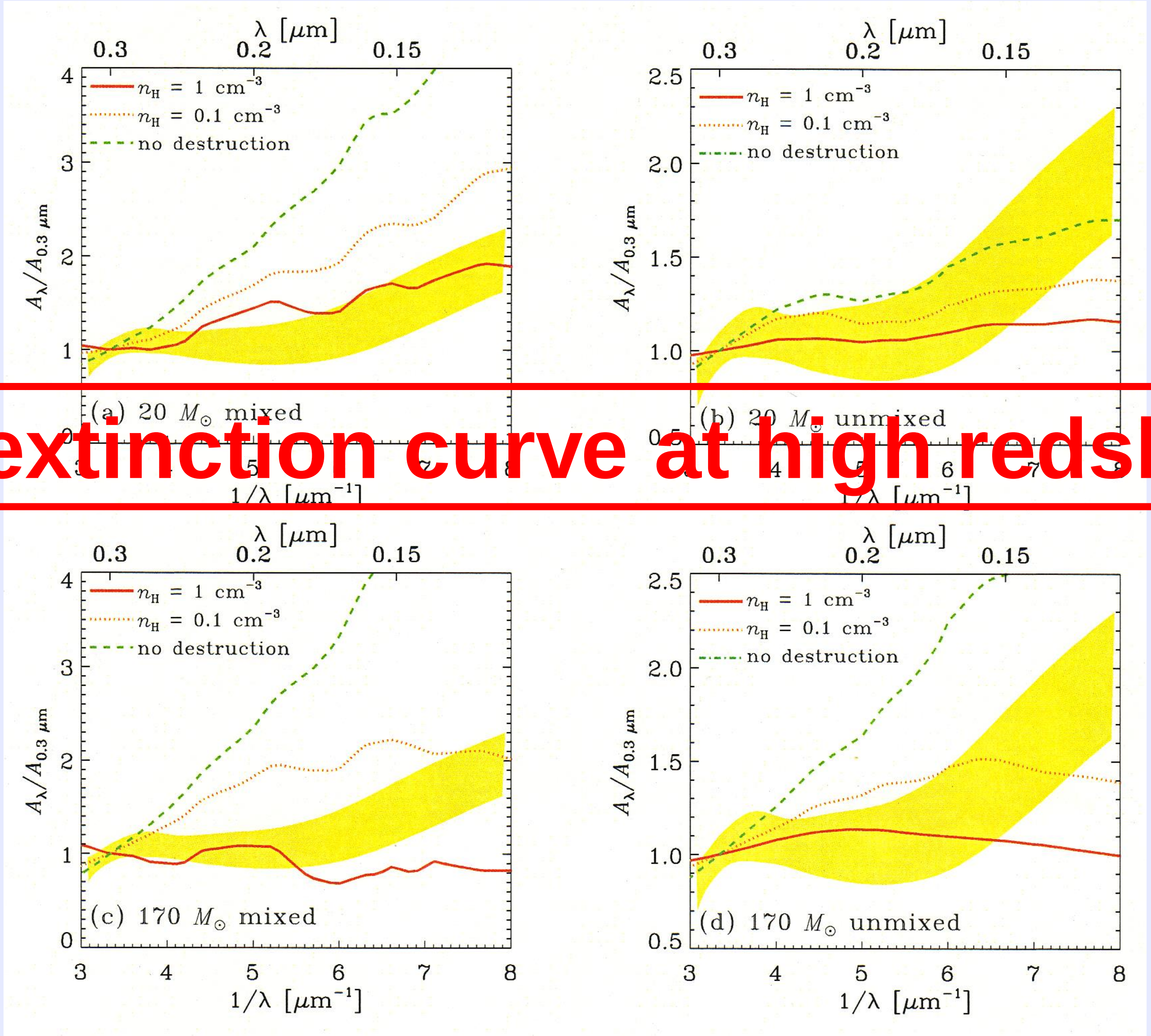
4-1. Flattened extinction curves



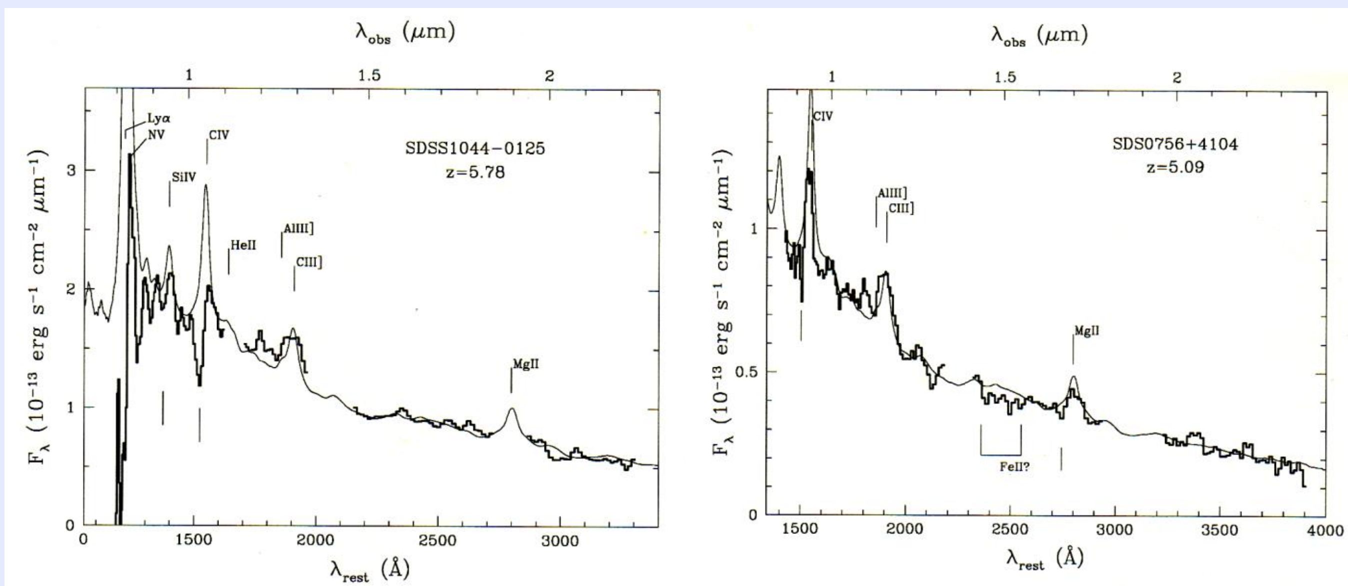
flat extinction curve at high redshifts !

Hitashita, T. N. et al. (2008, 384, 1725, MNRAS)

4-2. Extinction in high-z BAL quasars

Source	z	$t(\infty) - t(z)$ Gyr	M_d 10^8 $M_\odot$	$\dot{M}_*$ (min) $M_\odot$ yr^{-1}	L_{FIR} 10^{10} $L_\odot$	M_{bh} 10^9 $M_\odot$	$\dot{M}_{acc}$ $M_\odot$ yr^{-1}
SDSS J1306+0356	5.99	0.99 (0.70)	2.6 (1.8)	26	520 (370)	4.4 (3.0)	95 (65)
SDSS J1044−0125	5.74	1.04 (0.74)	4.2 (3.0)	41	870 (610)	5.6 (4.0)	125 (85)
SDSS J0756+4104	5.09	1.21 (0.86)	9.6 (6.9)	80	1970 (1410)	2.1 (1.4)	45 (30)
SDSS J0338+0021	5.07	1.22 (0.87)	8.5 (6.1)	70	1750 (1250)	2.1 (1.4)	45 (30)
SDSS J1030+0524	6.28	0.93 (0.66)	<1.4 (1.0)	–	<280 (200)	4.4 (3.0)	95 (65)
SDSS J0836+0054	5.82	1.02 (0.73)	<2.1 (1.5)	–	<430 (300)	7.6 (5.2)	165 (115)
RD J0301+0020	5.50	1.10 (0.78)	1.4 (1.0)	13	290 (200)	0.06 (0.04)	1.4 (0.9)
SDSS J2216+0013	4.99	1.25 (0.89)	<2.0 (1.4)	–	<410 (300)	1.9 (1.4)	40 (30)

Priddey et al. (2003, MNRAS, 344, L74)



Maiolino et al. (2004, A&A, 420, 889)

4-3. Extinction curves of low-z AGNs

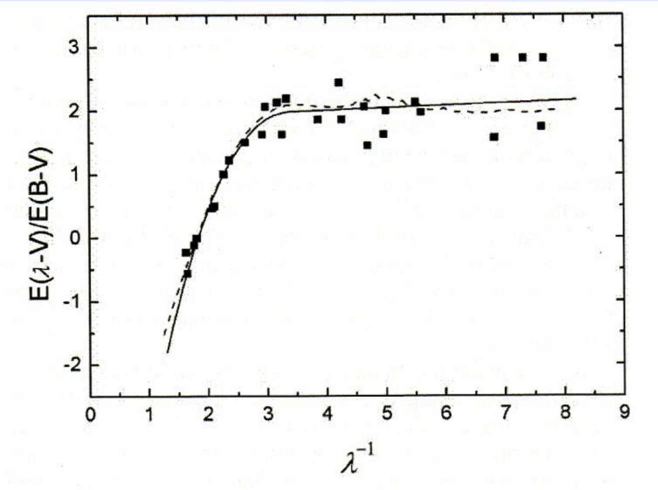
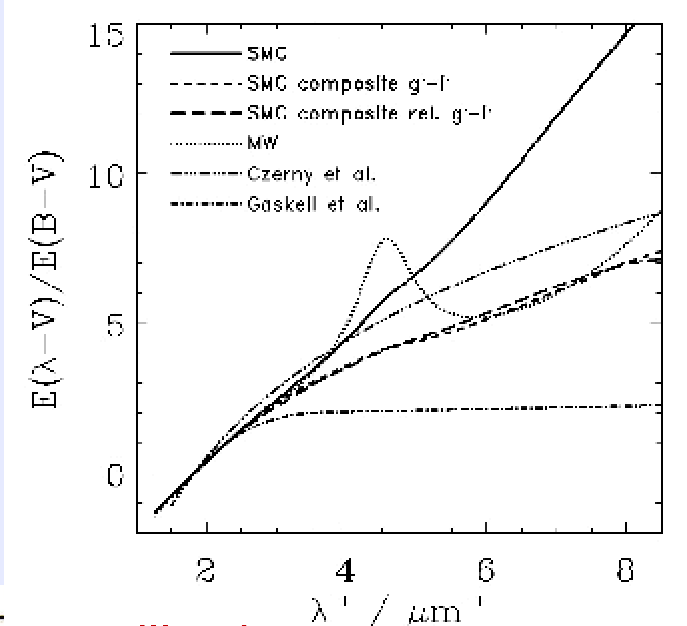
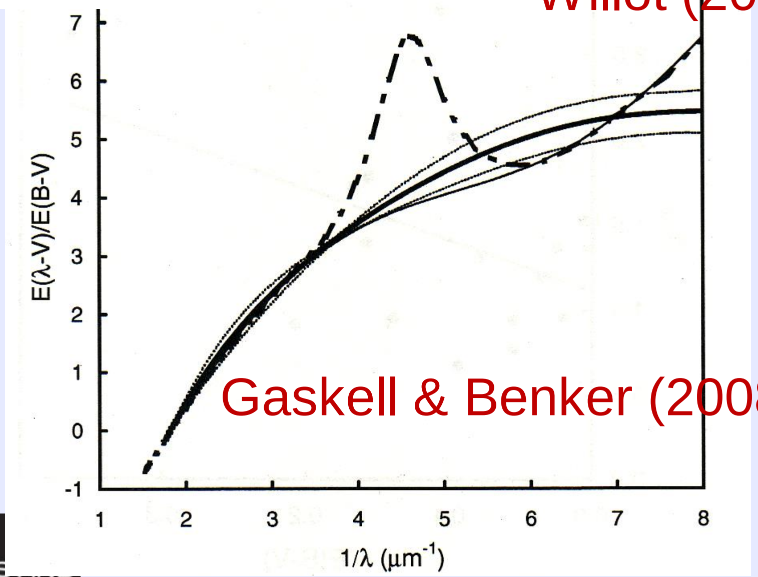


FIG. 6.—AGN extinction curves (*squares*) plotted together with a model

Gaskell et al.
(2004, ApJ, 616, 147)



Willot (2005, ApJ, 627 L201)

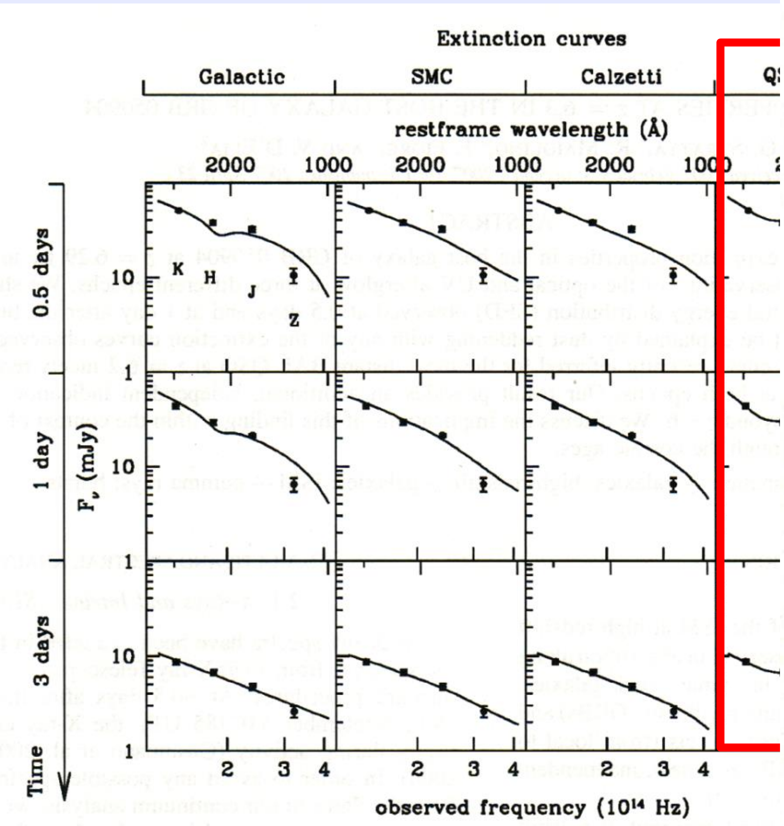


Gaskell & Benker (2008, astro-ph/0711.1013)

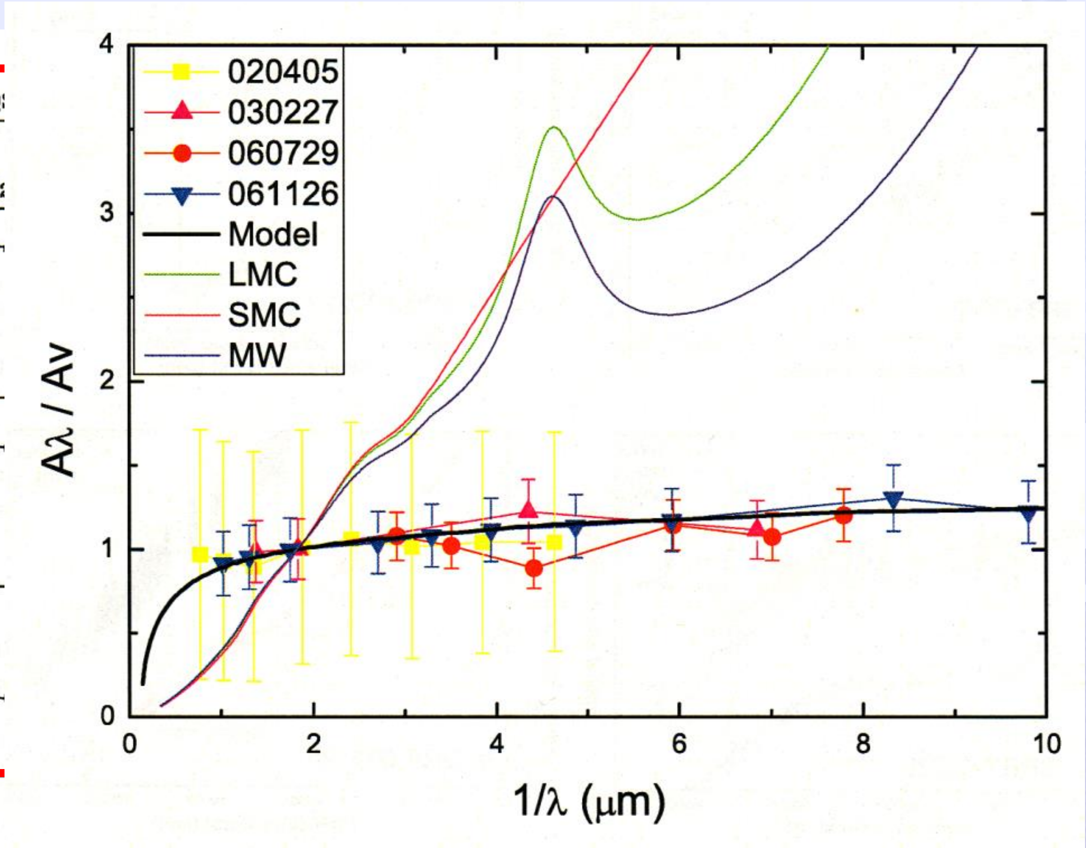
4-4. Extinction curves from GRBs

Watson's Talk

GRB 050904 at z=6.3



Stratta et al. (2007, ApJ, 661, L9)



Li et al. (2008, astro-ph/0712.2622)

coagulation of grains in dense clouds
evaporation of smaller grains by GRB
destruction of small grains by shock

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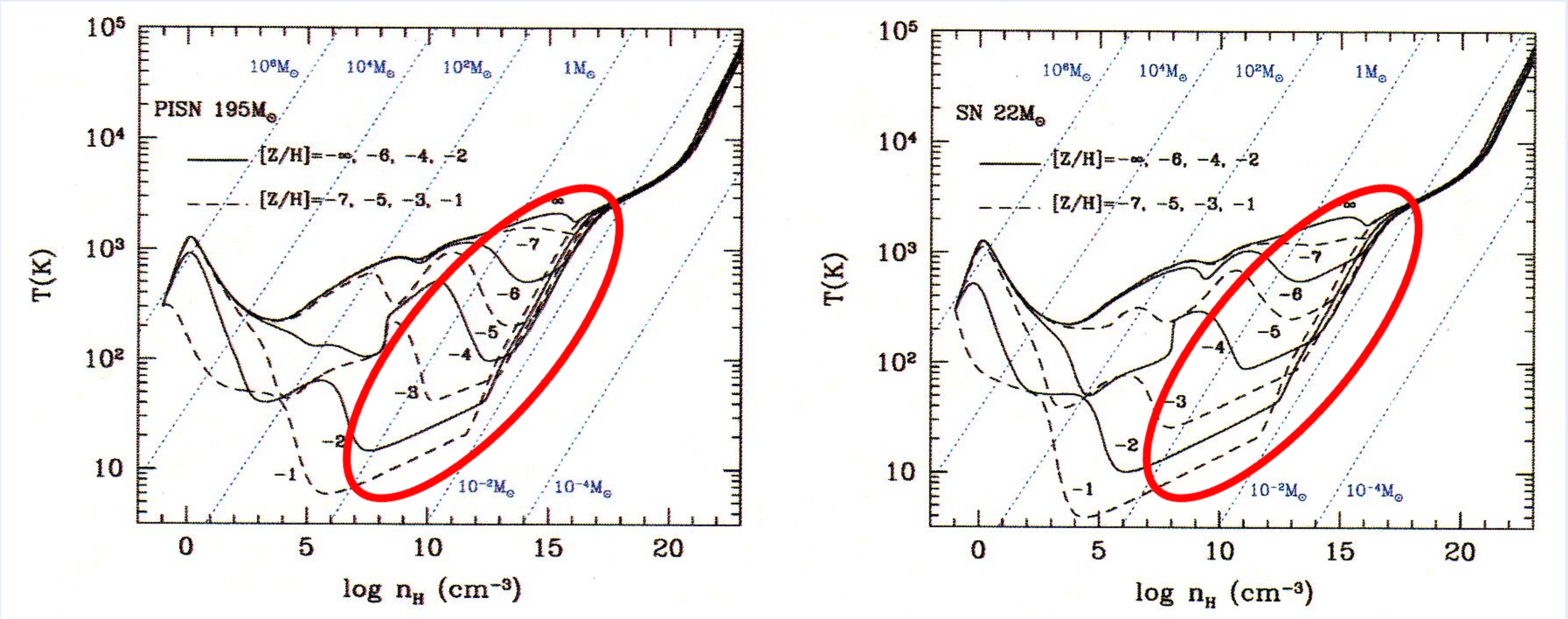
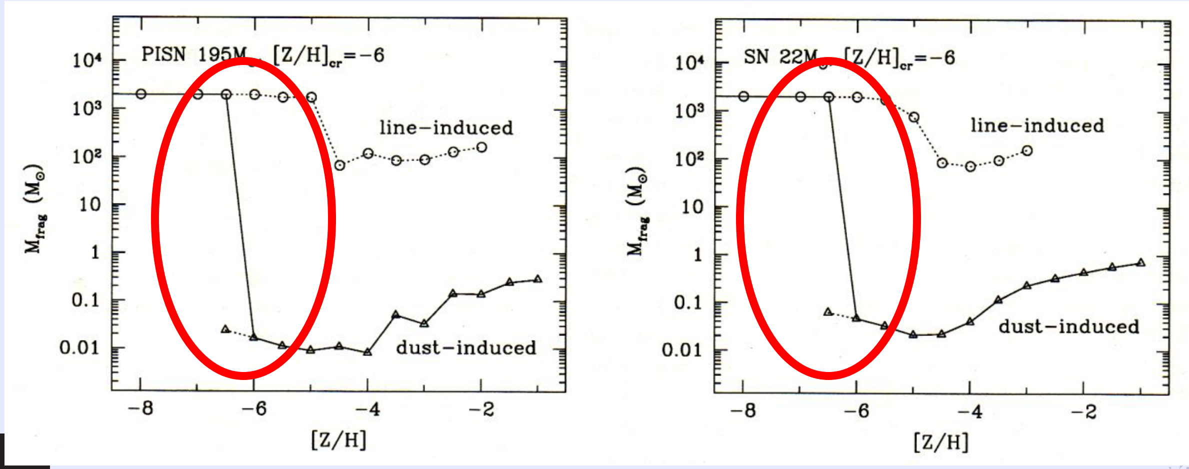
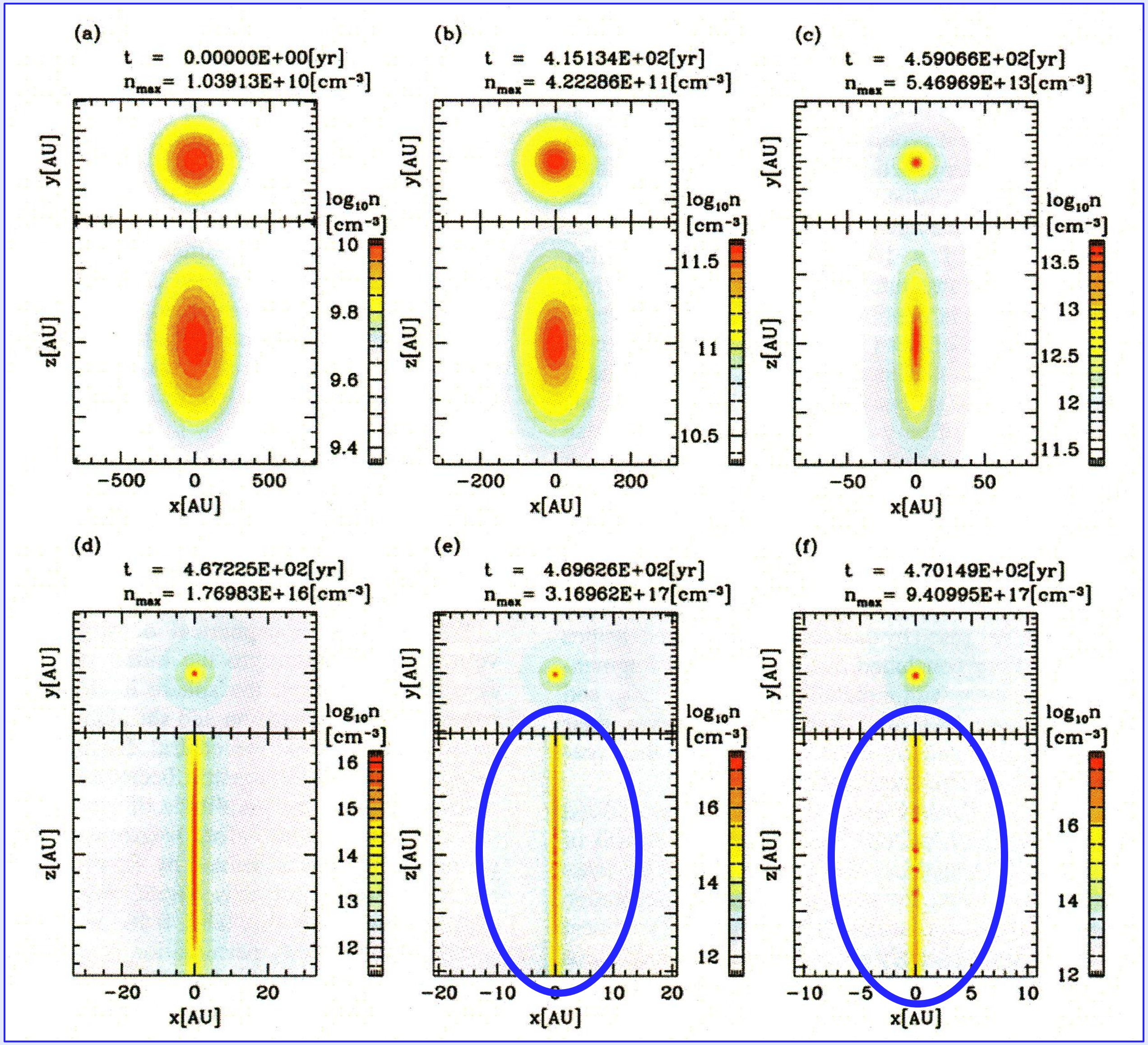
5-1. Critical metallicity

Schneider et al. (2006, MNRAS, 378, 973)
Schneider's Poster V03





5-2. 3-D simulation of star-forming cloud



Tsuribe & Omukai (2006, ApJ, 378, 973)

5-3. Impacts of dust on Pop II.5 stars

Population II.5 stars : the 2nd-generation stars formed in the dense shell of Pop III SNRs

(Mackey et al. 2003; Salvattera et al. 2004; Machida et al. 2005)

dust grains surviving the destruction but not injected into the ISM are piled up in the dense shell in 10^5-10^6 yr

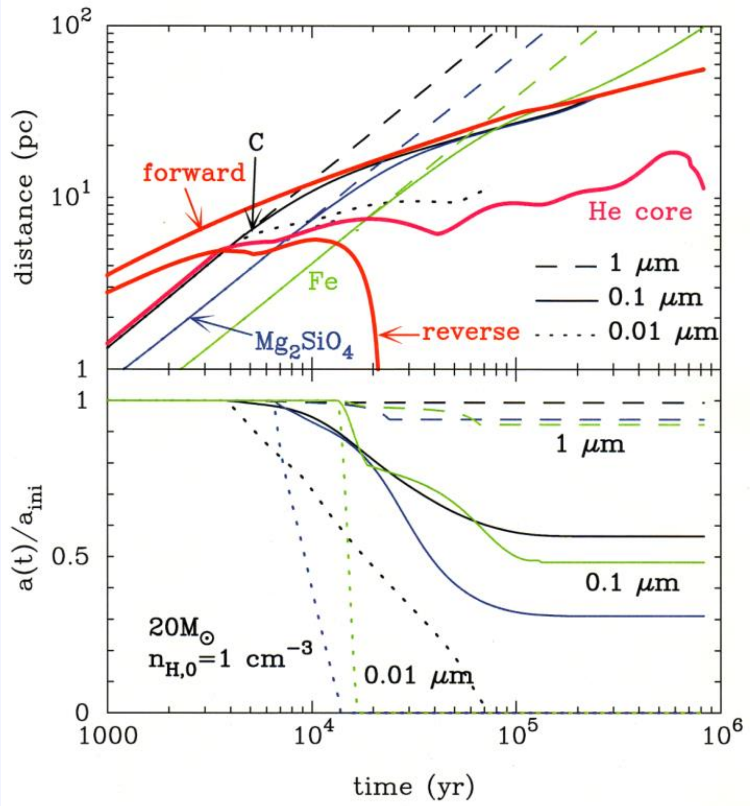
↓

- elemental composition of these piled-up grains

  ➔ elemental abundance of Population II.5 stars

metallicity and metal abundance patte

comparing with observations of HMP a



5-4. Elemental abundance in the shell (2)

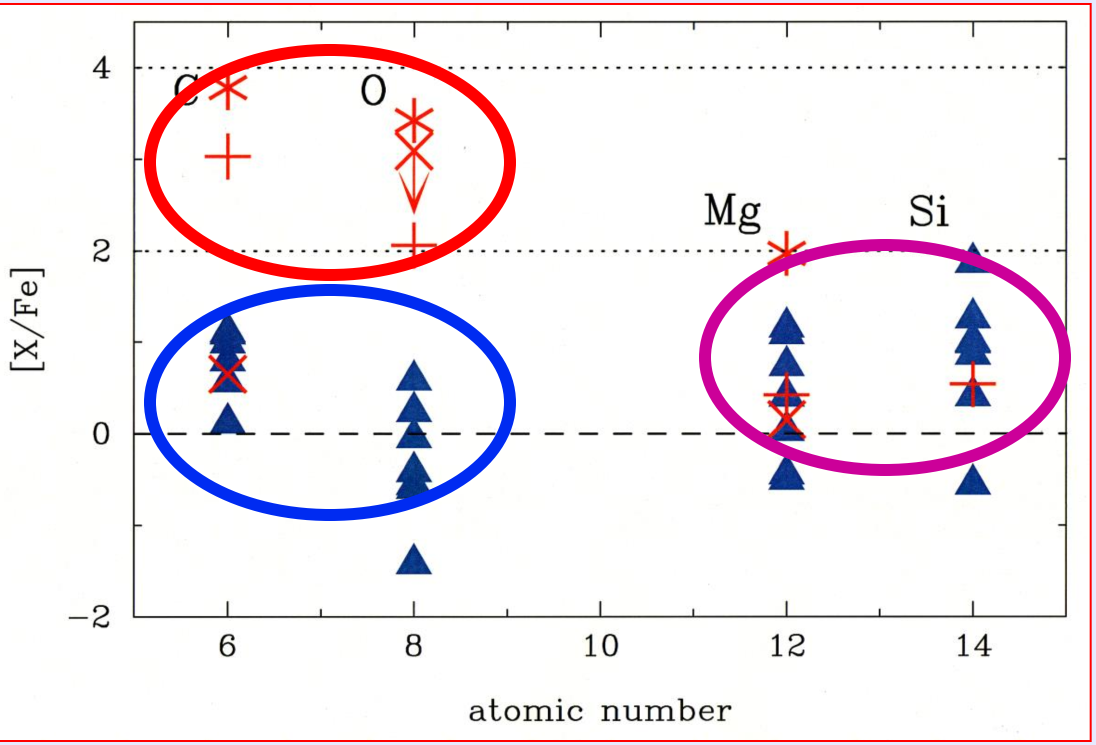
M_{pr} ($M_\odot$)	[Fe/H]	[C/Fe]	[O/Fe]	[Mg/Fe]	[S			$\log(Z/Z_\odot)$
				$n_{H,0} = 0.1$ cm				
13	−6.43	−0.274	−0.699	−0.230	1.92	−2.60	0.239	−5.89
20	−5.20	0.117	−0.595	0.034	0.410	−1.97	0.242	−5.44
25	−5.90	1.11	−1.42	−0.500	−0.552	−0.563	0.242	−5.55
30	−5.56	0.566	−0.043	0.739	0.866	0.905	0.242	−5.33
				$n_{H,0} = 1$ cm^{-3}				
13	−5.15	1.11	−0.555	−0.459	1.01	–	−2.18	−4.72
20	−5.53	0.992	0.585	1.16	1.87	–	0.200	−4.68
25	−5.23	1.09	−0.412	0.407	0.989	–	0.241	−4.79
30	−5.11	0.797	0.242	1.09	1.26	−5.72	0.242	−4.60
13	−4.13							−4.40
20	−4.92							−4.09
25	−5.10							−3.91
30	−5.11	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	−3.84

metallicity of shell

$Z > Z_{cr} = 10^{-6} Z_\odot$

[Fe/H] = -5.62 (HE0107-5240; Collet et al. 2006)
[Fe/H] = -5.96 (HE1327-2326; Frebel et al. 2008)
[Fe/H] = -4.75 (HE0557-4840; Noris et al. 2007)
3-D corrected

5-4. Elemental abundance in the shell (3)



$-6 < [Fe/H] < -5$
$0 < [Mg, Si/Fe] < 2$

↓

Elemental composition of dust piled up in the shell can reproduce abundance patterns in HMP stars

The transport of dust segregated from metal-rich gas can be responsible for the elemental composition of Population II.5 stars formed in the dense SN shell.

Summary of this talk

1. The fate of newly formed dust within primordial SNRs strongly **depends on the initial radii and compositions.**
2. Size distribution of dust surviving in SNRs is **weighted to large size.**
3. **Extinction curves** in the early universe is expected to be **flat.**
4. Dust grains in the early universe play crucial roles in the formation of metal-deficient low-mass stars.
5. Dust formed in the ejecta has **great impacts on the composition and formation of Population II.5 stars.**