Origin and Nature of Dust in the Early Universe

Takaya Nozawa

- Institute for the Physics and Mathematics of the Universe
- Graduate School of Science, Hokkaido University

Collaborators;

T. Kozasa (Hokkaido Univ.), H. Umeda (Univ. of Tokyo)
H. Hirashita (ASIAA), K. Maeda (IPMU), N. Tominaga (NAOJ)
K. Nomoto (Univ. of Tokyo, IPMU), A. Habe (Hokkaido Univ.)
E. Dwek (NASA Goddard Space Flight Center)
T. T. Takeuchi (Nagoya Univ.), T. T. Ishi (Kyoto Univ.)

Contents of this talk

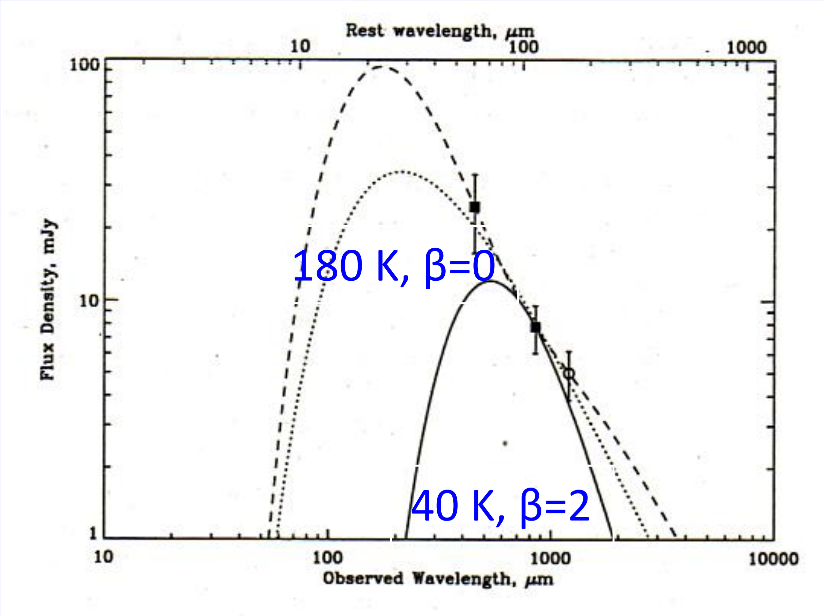
1. Introduction
2. Dust formation in primordial SNe
3. Dust evolution in primordial SNRs
4. Role of dust in the early universe
5. Extinction curves expected at high redshifts

1. Introduction

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. 2008a, 2008b)

SDSS J1148+5251 at z=6.4

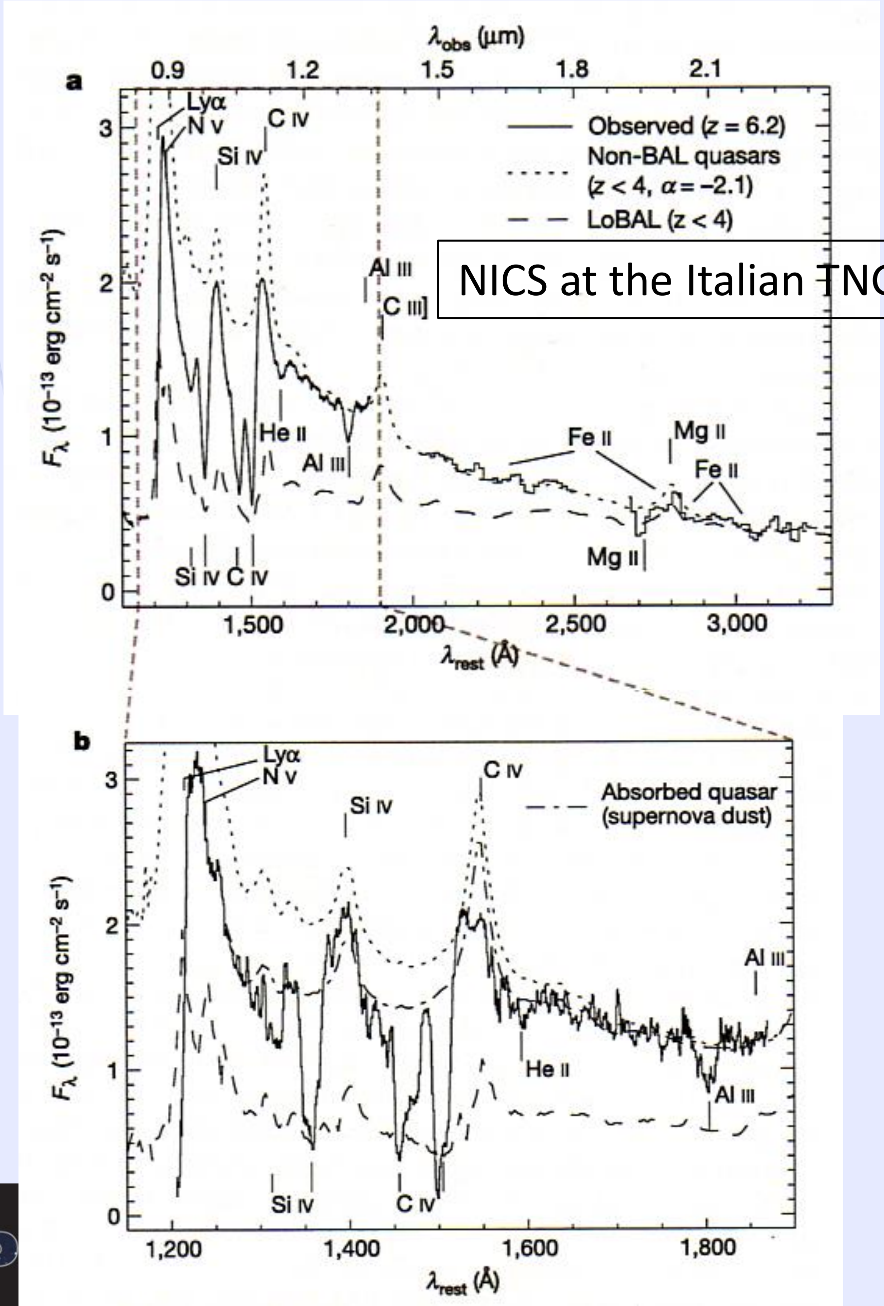


Robson et al.
(2004, MNRAS, 351, L29)

a rapid enrichment with dust formed in the ejecta of SNe

Dust of 0.1-1 Msun 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)

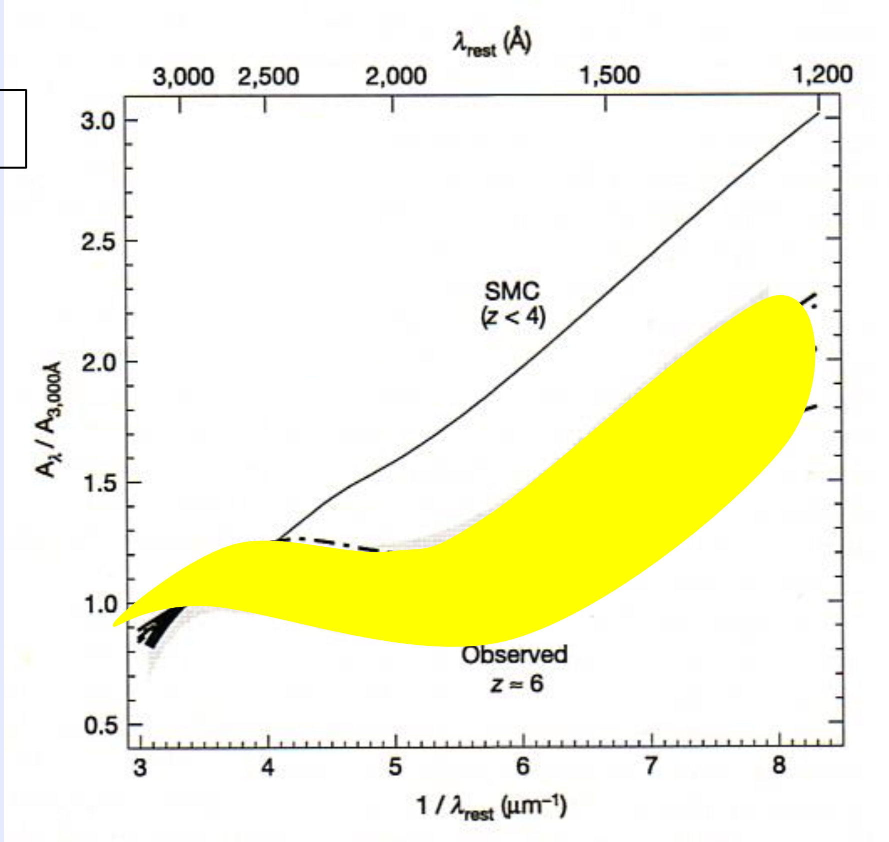
1-2. Extinction curve of high-z quasar



NICS at the Italian TNG

SDSS J1048+4637 at z=6.2

Broad absorption line (BAL) quasars



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

different dust properties from those at 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

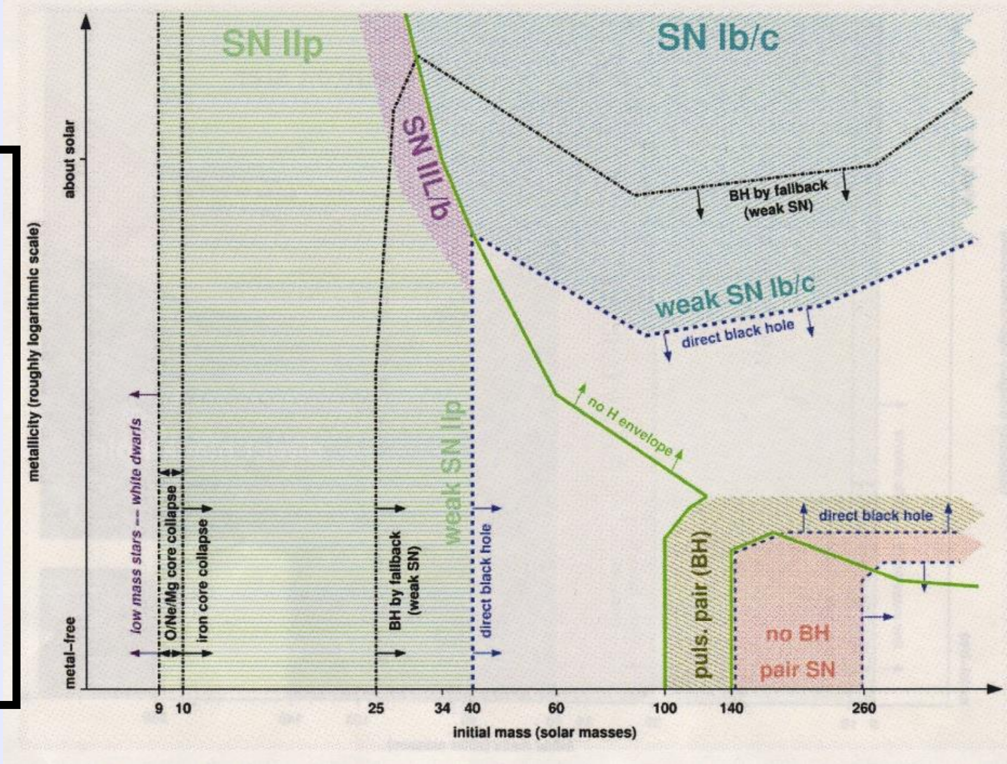
1-5. Sources of dust in the early universe

- 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
  $M = 100\text{–}500\ M_{\rm sun}$

In the early universe

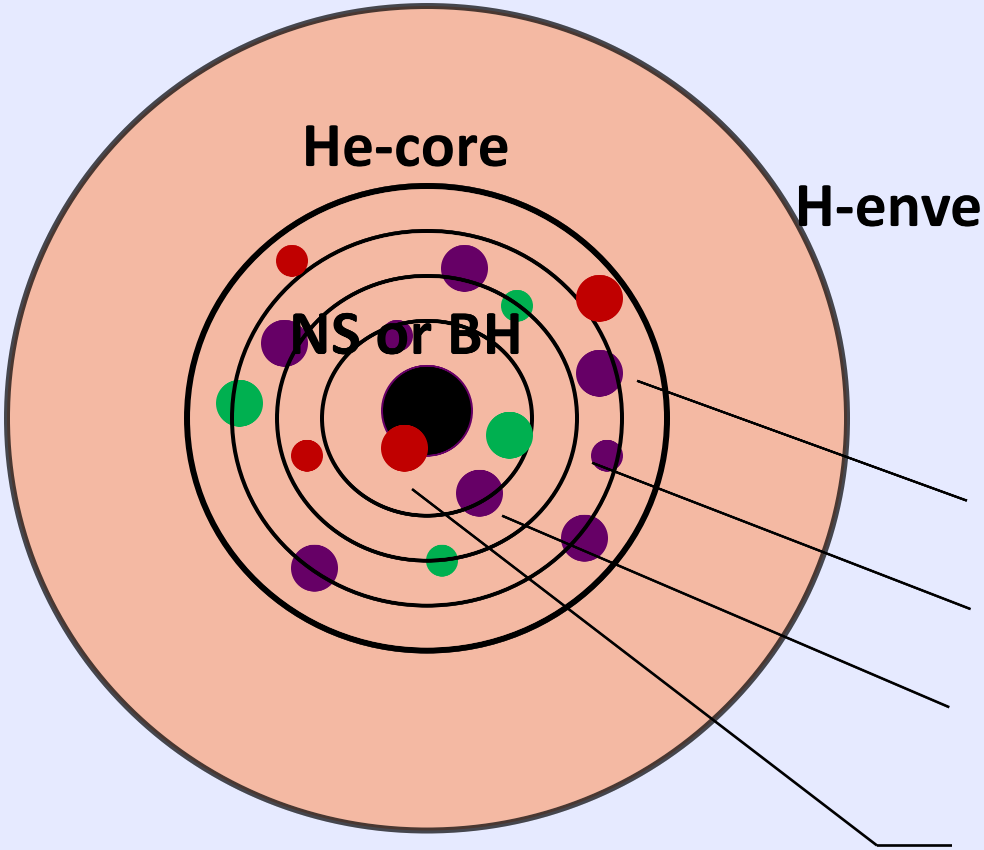
- **Type II SNe (SNe II)**
  ; $M_{\rm pr} = 8\text{–}40\ M_{\rm sun}$
- **pair-instability SNe**
  ; $M_{\rm pr} = 140\text{–}260\ M_{\rm sun}$



(Heger et al. 2003, 591, 288)

2. Dust Formation in Primordial SNe

at ~1 days



He-core

H-envelope

NS or BH

He–layer (C>O)

O–Ne-Mg layer

Si–S layer

Fe–Ni layer

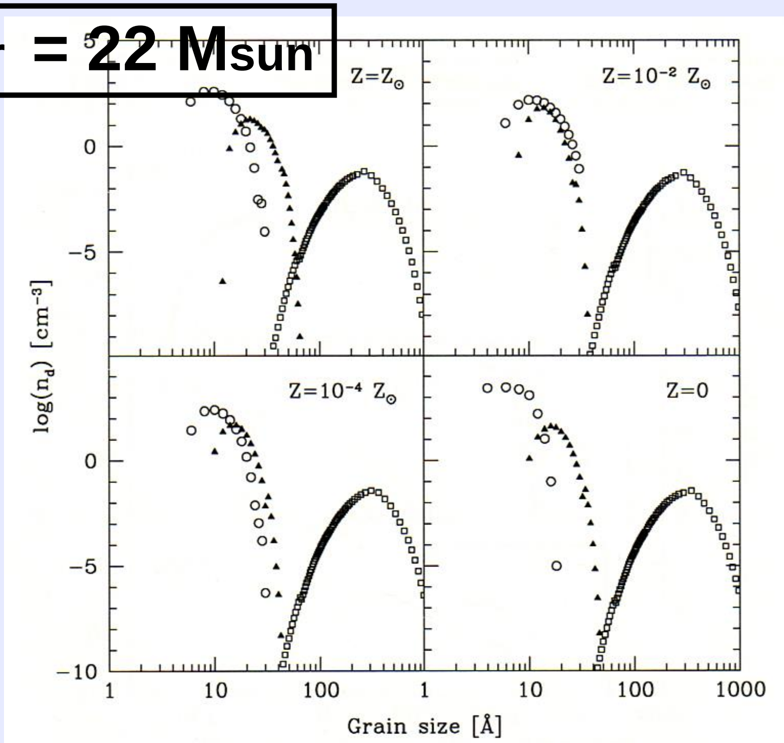
Dust formation
at ~1-3 years
after explosion

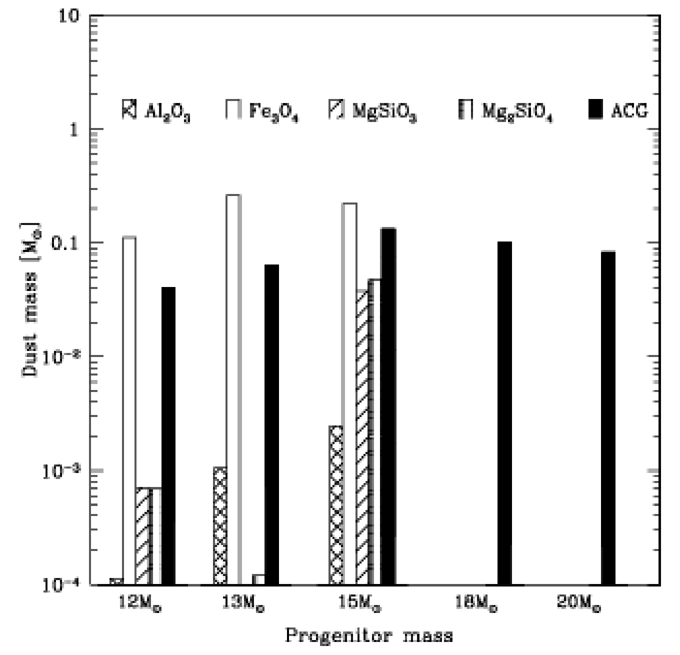
2-1. Dust formation in primordial SNe (1)

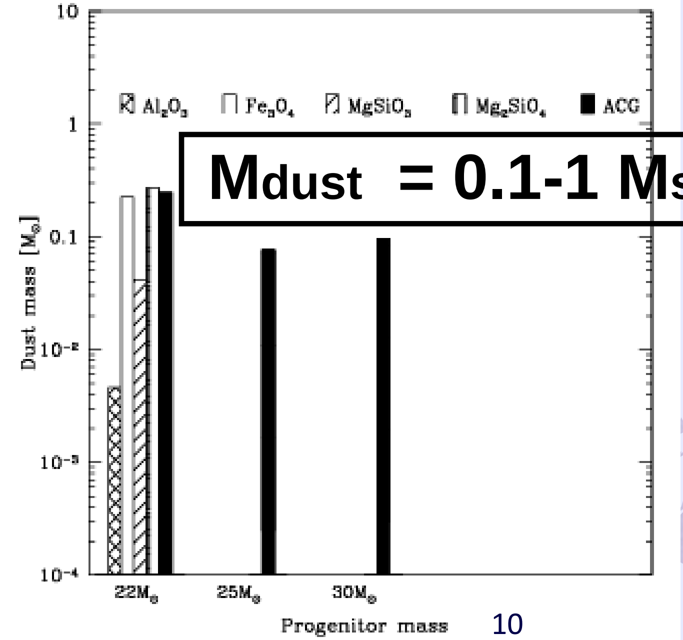
Todini & Ferrara (2001, MNRAS,

- SNe II (M = 12-30 Msun, Z = 0-0.02) 5)
- one-zone model within He core
- formation and destruction of CO an
- initial gas density and temperature

Mpr = 22 Msun







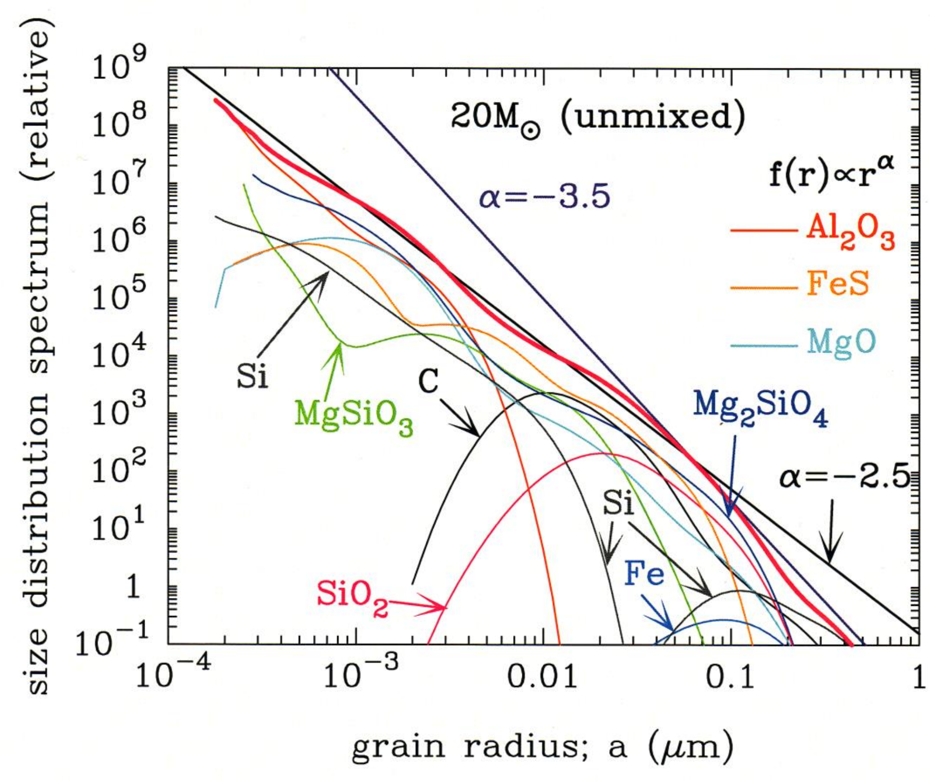
Mdust = 0.1-1 Msun

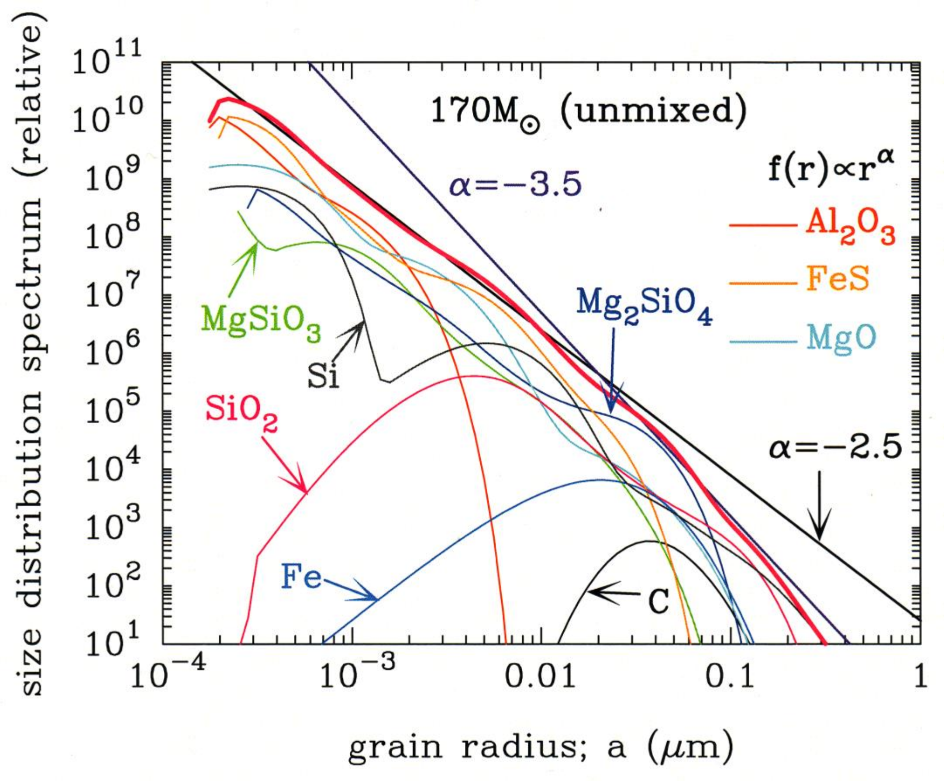
2-2. Dust formation in primordial SNe (2)

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

- SNe II (M = 13, 20, 25, 30 M_{sun}, Z=0)
  PISNe (M = 150, 170, 200 M_{sun})   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
  - C / O > 1 ➔ all O atoms are locked into CO
  - C / O < 1 ➔ all C atoms are locked into CO
  - Si / O < 1 ➔ all Si atoms are locked into SiO

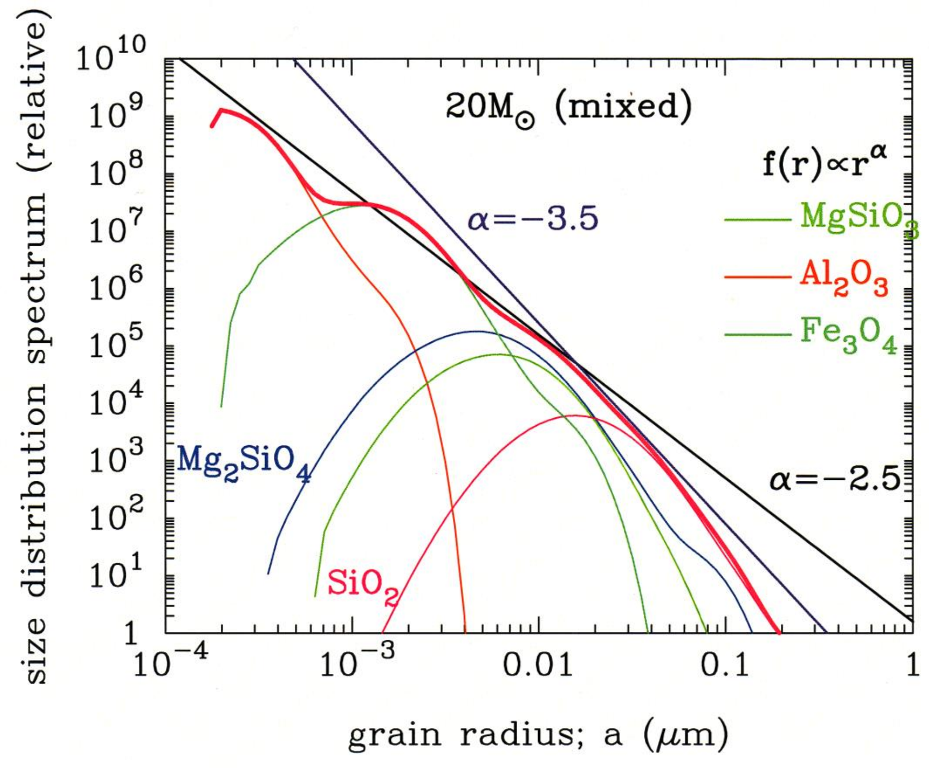
2-3. Dust formed in the unmixed ejecta

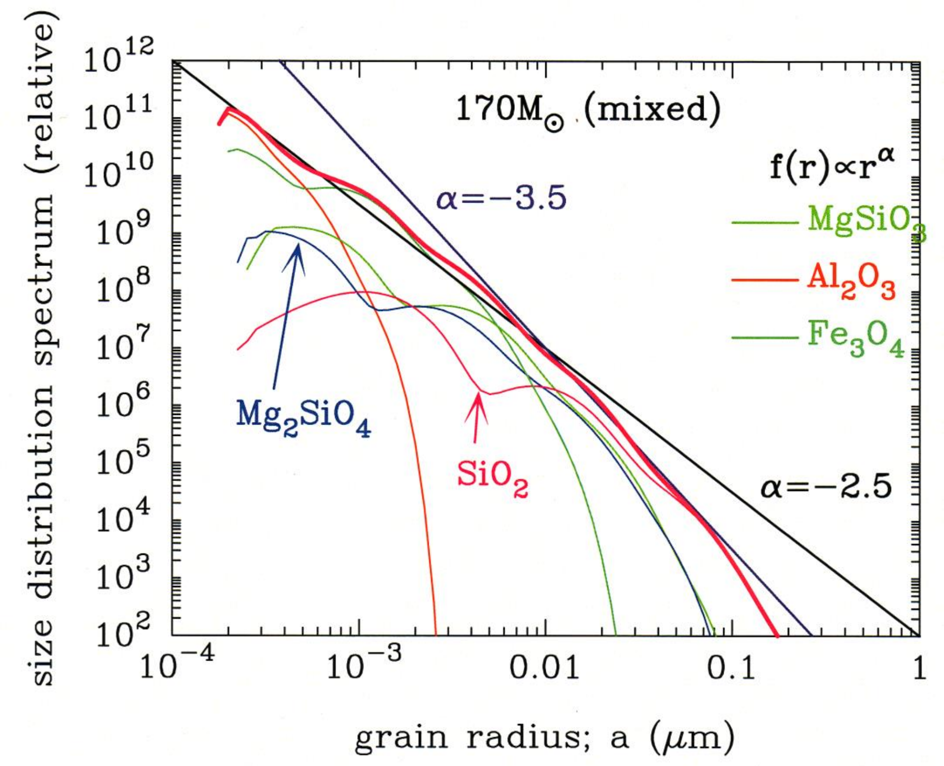




- Various dust species (C, $MgSiO_3$, Mg_2SiO_4, SiO_2, Al_2O_3, MgO, Si, FeS, Fe) form in the unmixed ejecta, reflecting the elemental composition in each layer.
- C, SiO_2, and Fe grains are lognormal-like size distribution with relatively large radii, while other grains are power-law-like one.

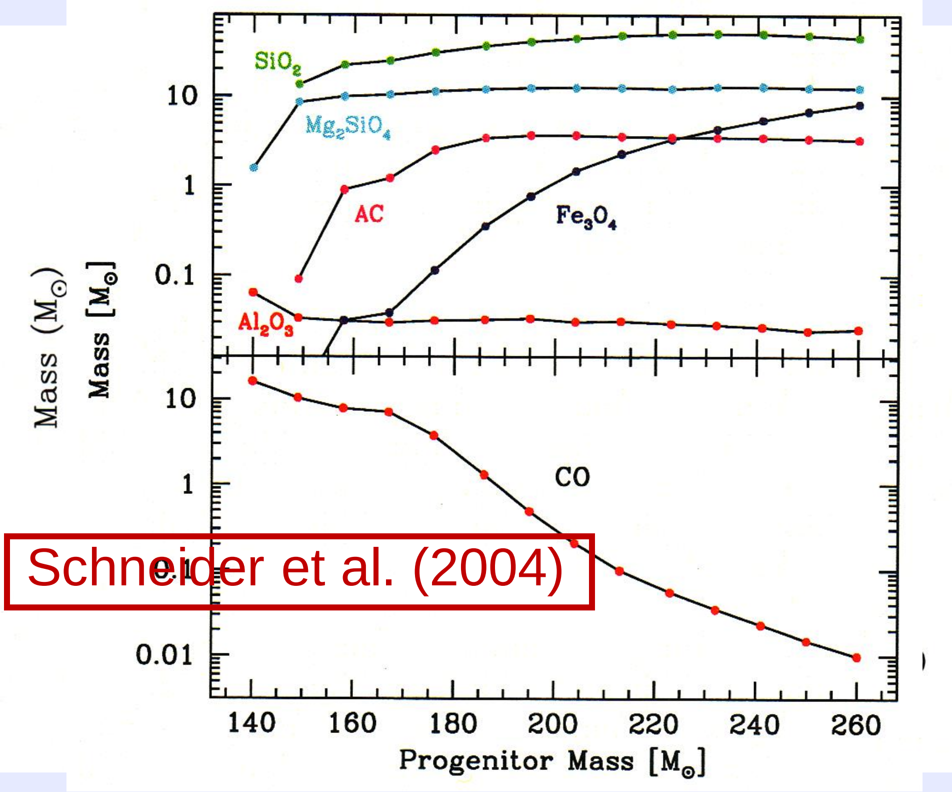
2-4. Dust formed in the mixed ejecta



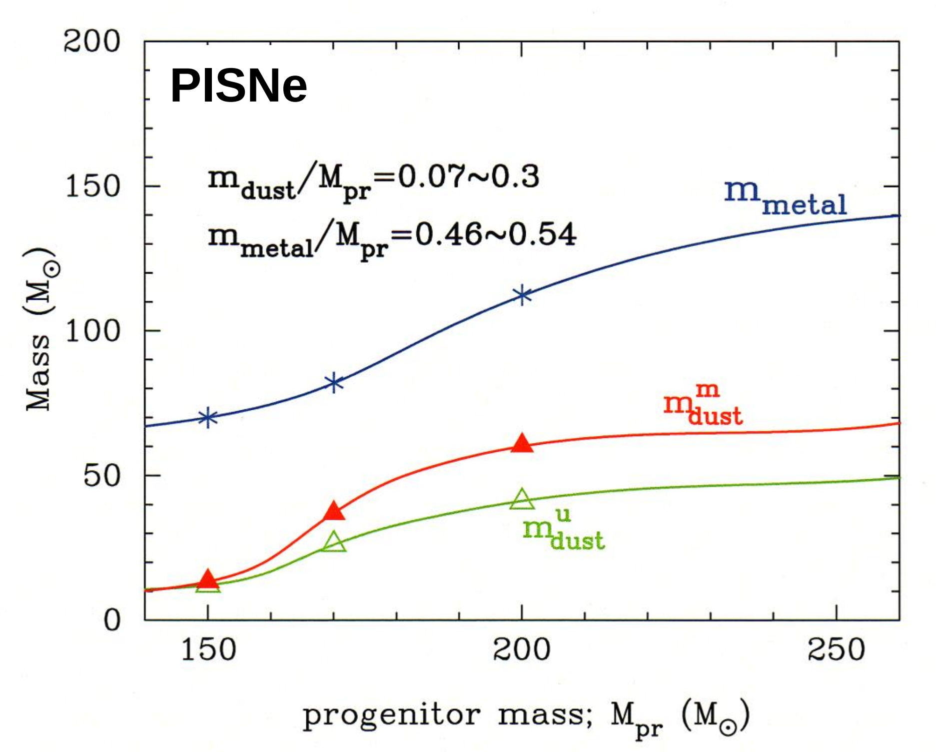


- Because O atoms are richer, only silicate（$MgSiO_3$, Mg_2SiO_4, SiO_2）and oxides（Fe_3O_4, Al_2O_3）form.
- The size distribution of each dust species except for Al_2O_3 is lognormal-like

2-5. Total mass of dust formed



Schneider et al. (2004)



m_{dust}/M_{pr}=0.07~0.3

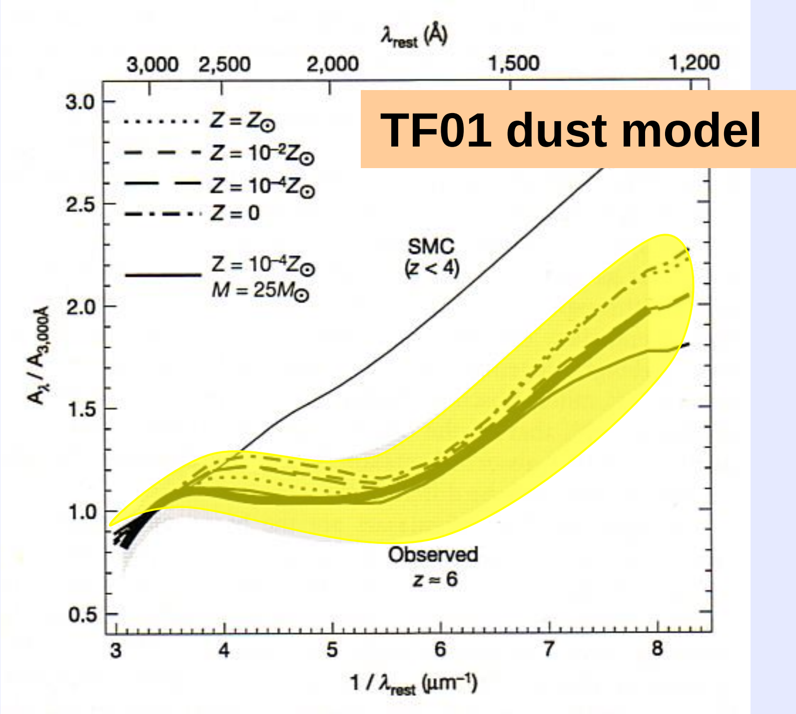
m_{metal}/M_{pr}=0.46~0.54

- Total dust mass increases with increasing progenitor mass

  SNe II ： M_{dust} = 0.1-2 M_{sun} PISNe ： M_{dust} = 10-60 M_{sun}

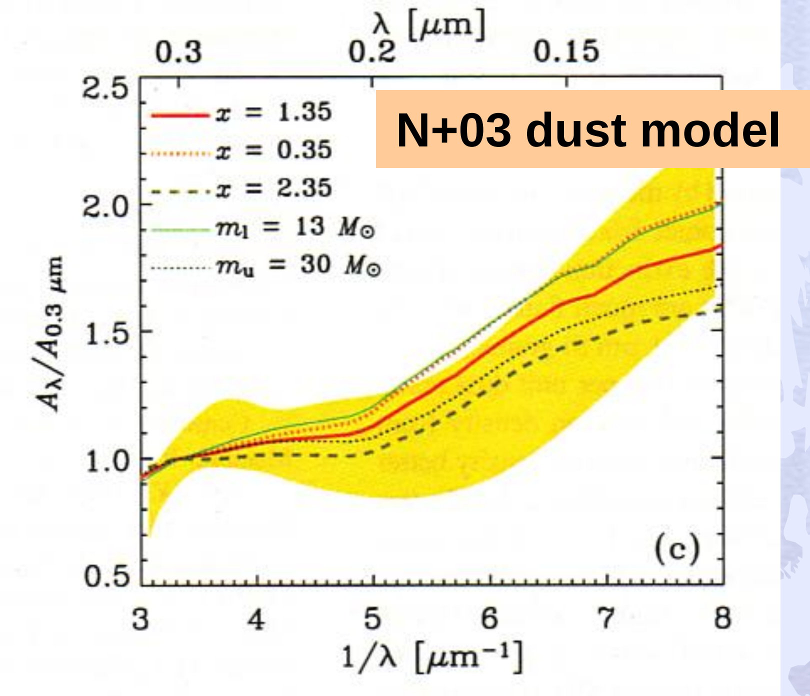
- Dust mass for the mixed case is generally larger than for the unmixed case

2-6. Extinction curves from SN dust



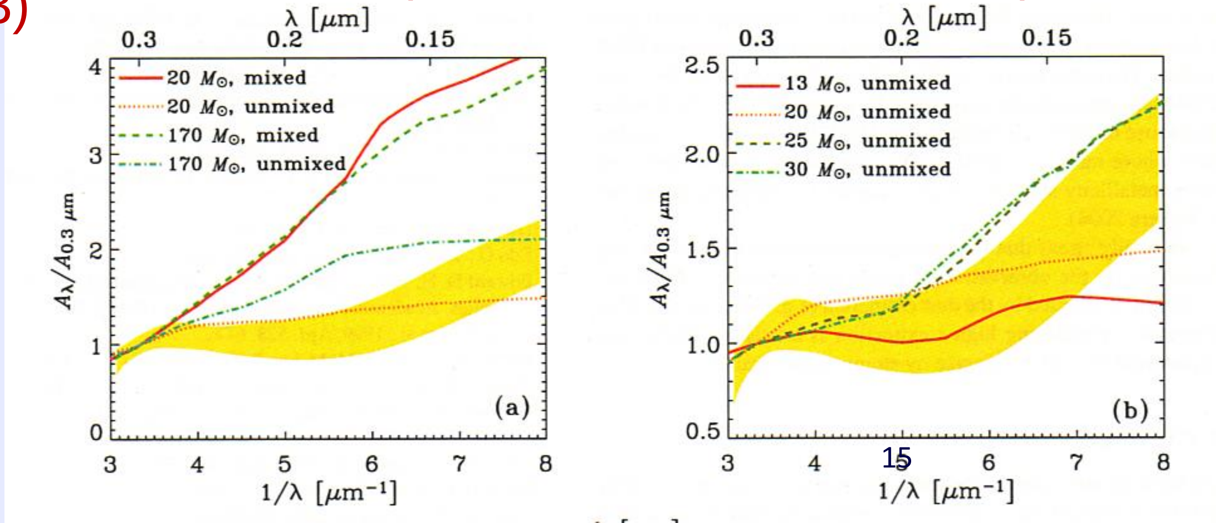
TF01 dust model

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



N+03 dust model

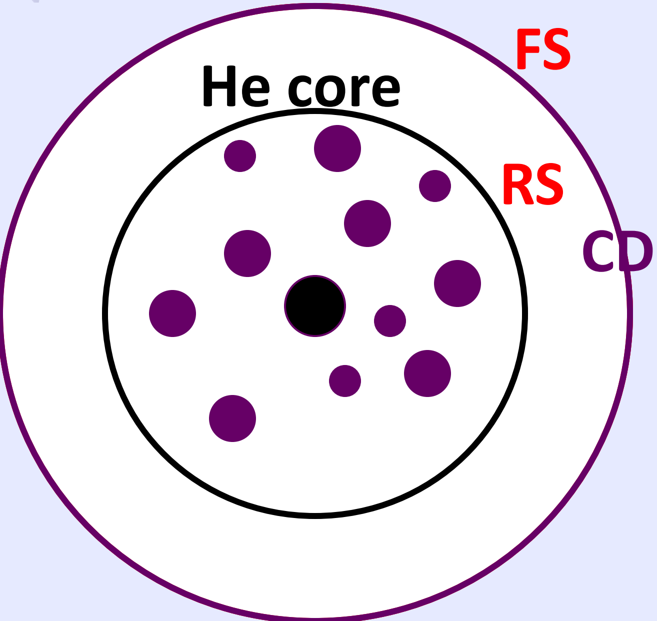
Hirashita et al.
(2005, MNRAS, 357, 1077)



3. Dust Evolution in Primordial SNRs

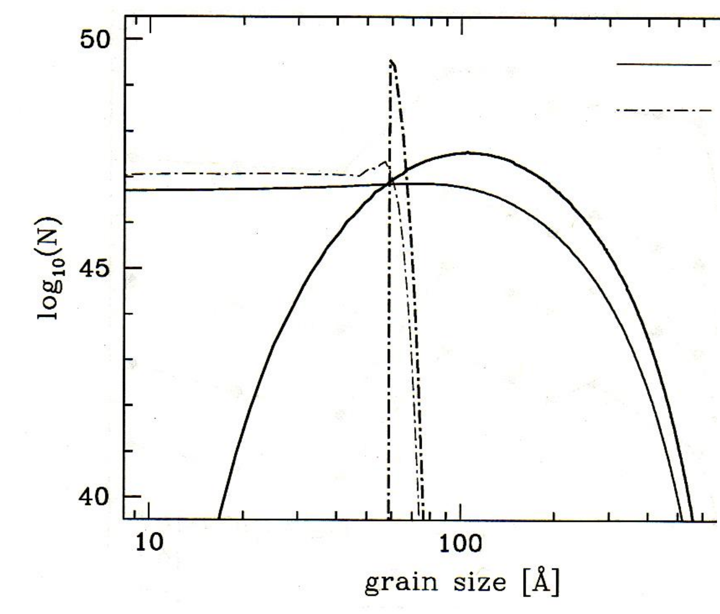
$T = (1\text{-}2) \times 10^4$ K

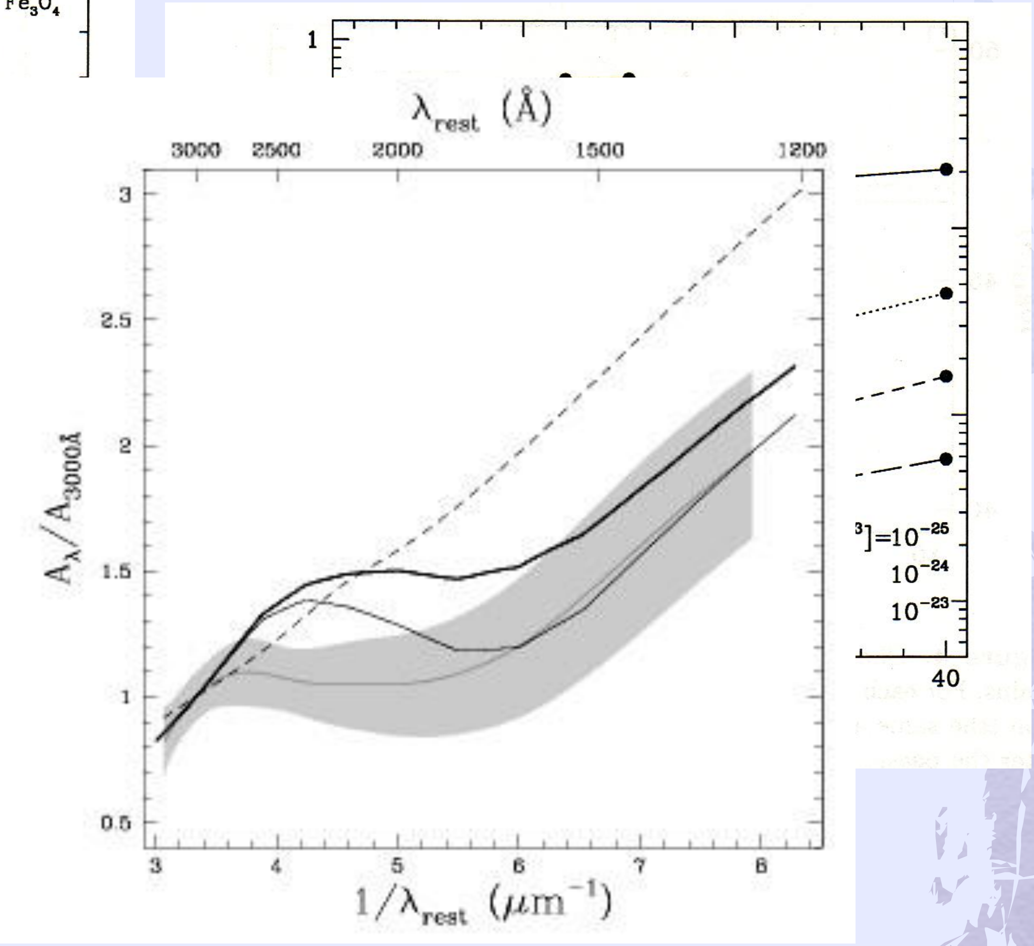
$n_H = 0.1\text{-}1$ cm^{-3}



3-1. Bianchi & Schneider's calculation

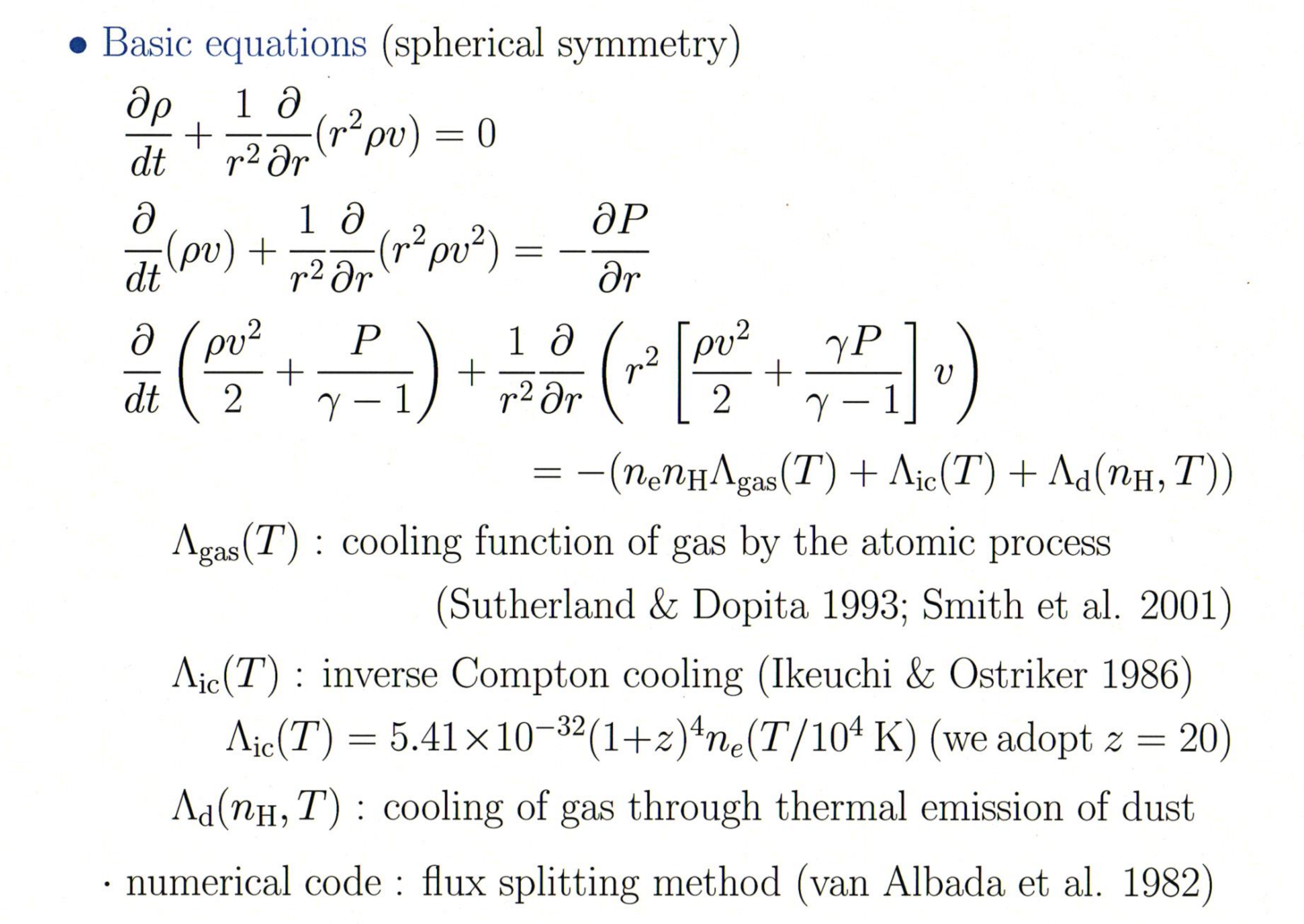
Bianchi & Schneider (2007, MNRAS, 378, 973)





semi-analytical model
neglecting motion of dust
t < ~10^5 yr

3-2-1. Time evolution of shock wave



- Basic equations (spherical symmetry)

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

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

$$\frac{\partial}{dt}\left(\frac{\rho v^2}{2} + \frac{P}{\gamma - 1}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left[\frac{\rho v^2}{2} + \frac{\gamma P}{\gamma - 1}\right] v\right)$$
$$= -(n_{\rm e} n_{\rm H} \Lambda_{\rm gas}(T) + \Lambda_{\rm ic}(T) + \Lambda_{\rm d}(n_{\rm H}, T))$$

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

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

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

$\Lambda_{\rm d}(n_{\rm H}, T)$: cooling of gas through thermal emission of dust

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

3-2-2. Initial condition for shock wave

○ SN ejecta models (Umeda & Nomoto 2002)

- SNe II : Mpr=13, 20, 25, 30 Msun ($E_{51}=1$)
- PISNe : Mpr=170 ($E_{51}=20$), 200 Msun ($E_{51}=28$)

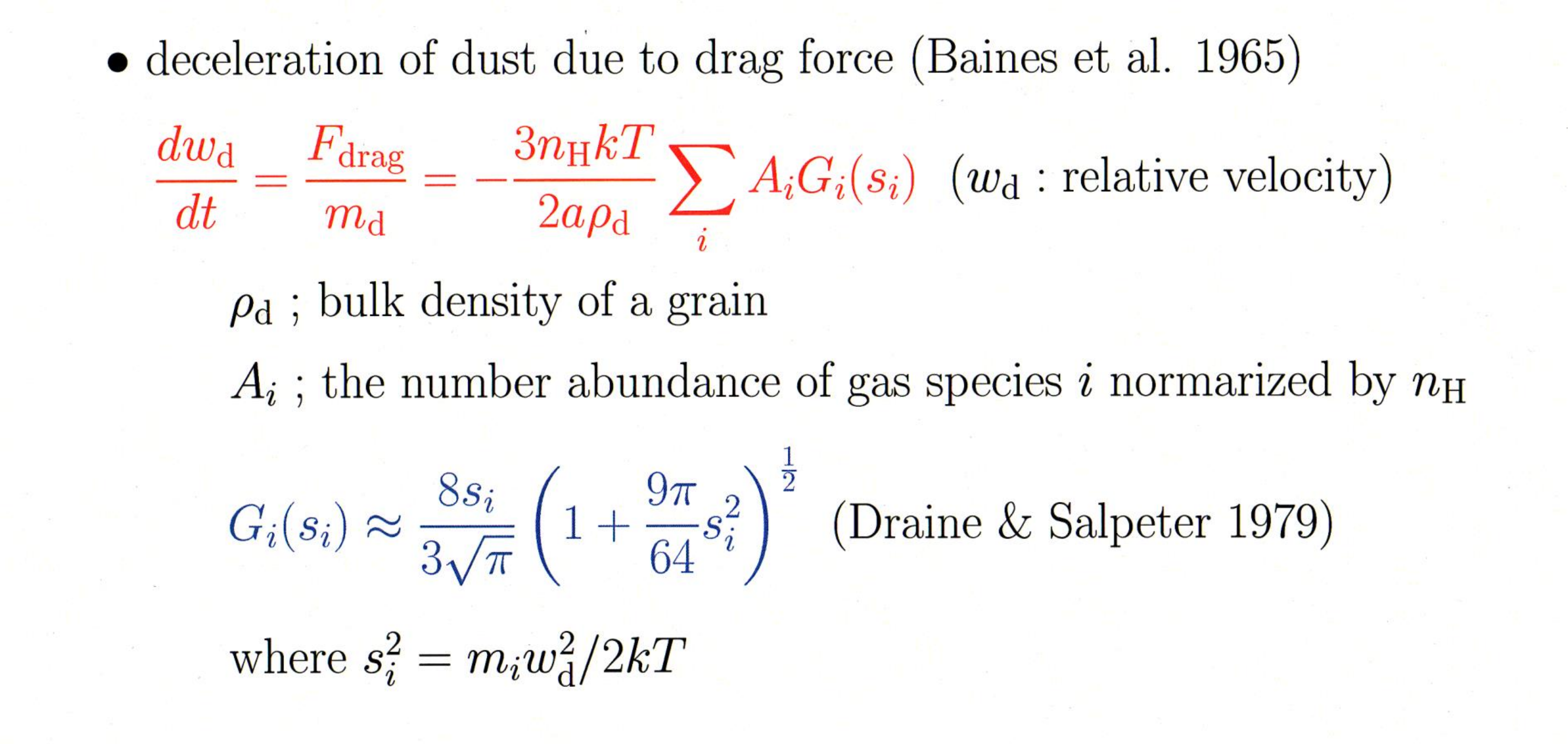
○ The ambient medium

- primordial composition (uniform)
- gas temperature ; T = 10^4 K
- gas density ; **$n_{H,0}$ = 0.1, 1, and 10 cm^{-3}**
  (e.g., Kitayama et al. 2004; Machida et al. 2005)

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

3-3. Dynamics of dust

- dust model : results of dust formation calculations
- treating (spherical) dust grains as test particles
- neglecting the effects of charge of dust



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

$$\frac{dw_{\mathrm{d}}}{dt} = \frac{F_{\mathrm{drag}}}{m_{\mathrm{d}}} = -\frac{3n_{\mathrm{H}}kT}{2a\rho_{\mathrm{d}}}\sum_i A_i G_i(s_i) \quad (w_{\mathrm{d}} : \text{relative velocity})$$

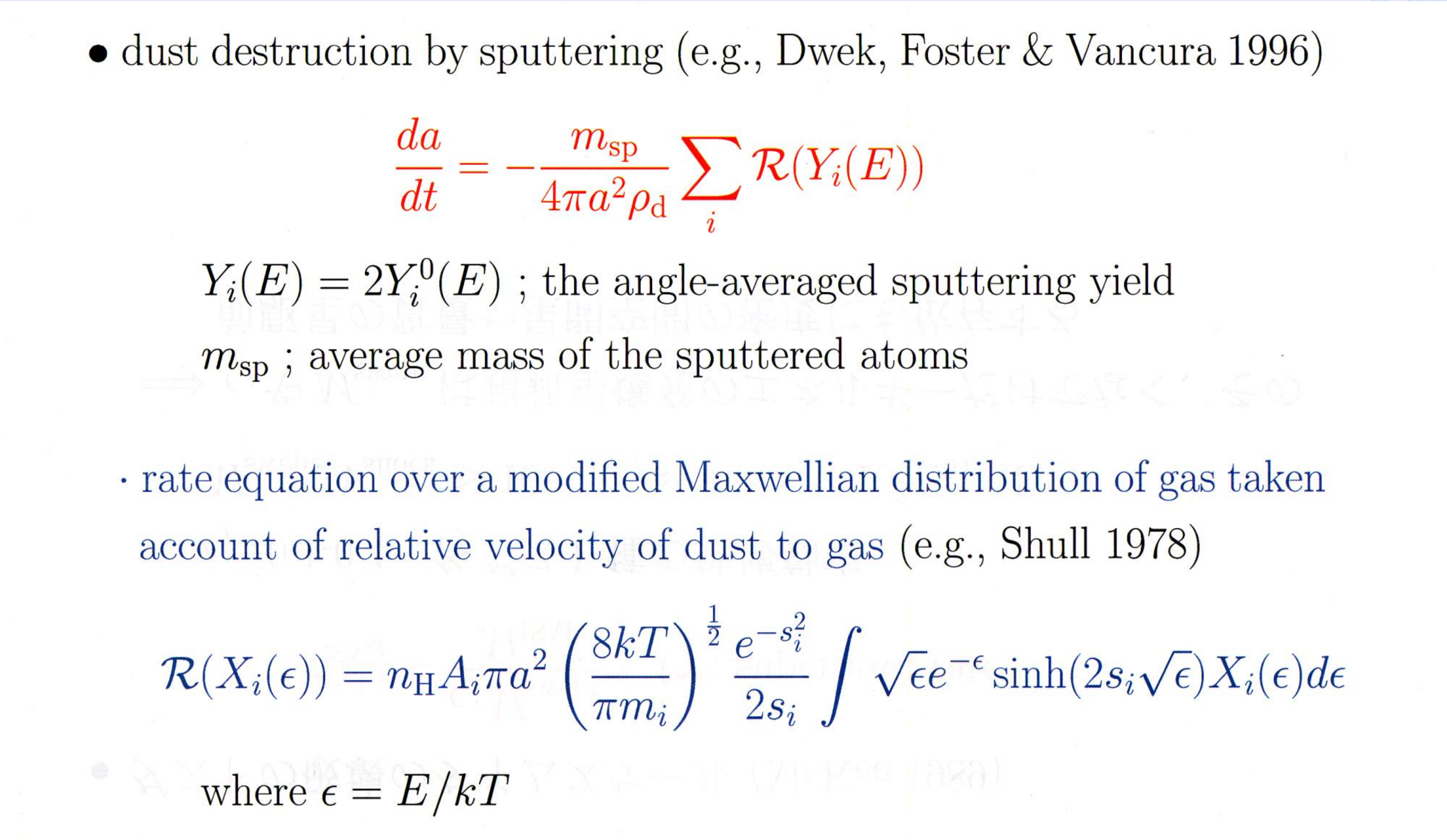
ρ_{d} ; bulk density of a grain

A_i ; the number abundance of gas species i normarized by n_{H}

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

where $s_i^2 = m_i w_{\mathrm{d}}^2/2kT$

3-4-1. Erosion rate of dust by sputtering



- dust destruction by sputtering (e.g., Dwek, Foster & Vancura 1996)

$$\frac{da}{dt} = -\frac{m_{\rm sp}}{4\pi a^2 \rho_{\rm d}} \sum_i \mathcal{R}(Y_i(E))$$

$Y_i(E) = 2Y_i^0(E)$; the angle-averaged sputtering yield

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

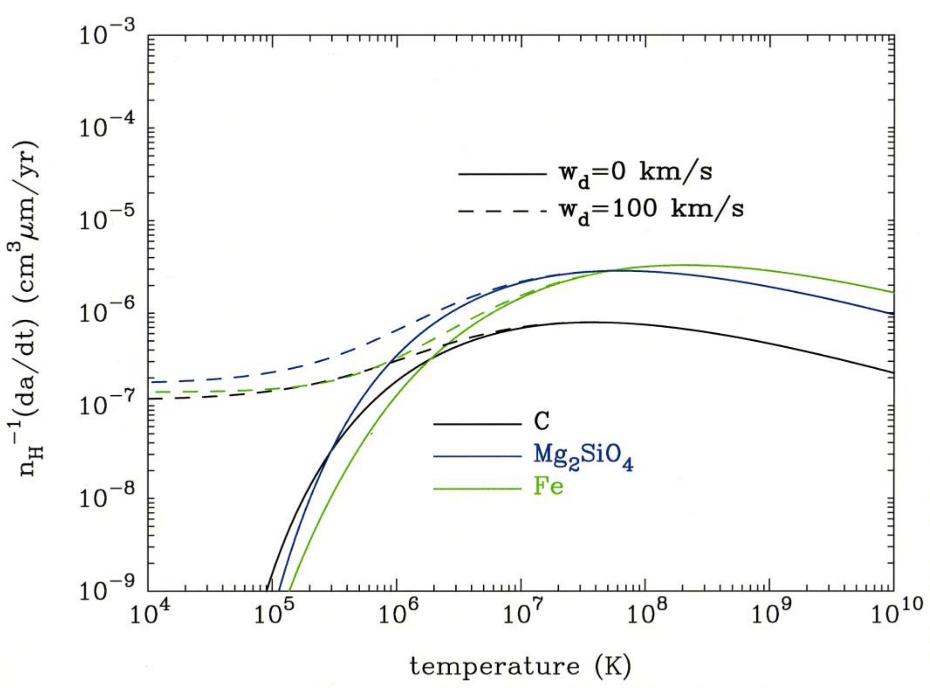
- rate equation over a modified Maxwellian distribution of gas taken account of relative velocity of dust to gas (e.g., Shull 1978)

$$\mathcal{R}(X_i(\epsilon)) = n_{\rm H} A_i \pi a^2 \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} \frac{e^{-s_i^2}}{2s_i} \int \sqrt{\epsilon} e^{-\epsilon} \sinh(2s_i\sqrt{\epsilon}) X_i(\epsilon) d\epsilon$$

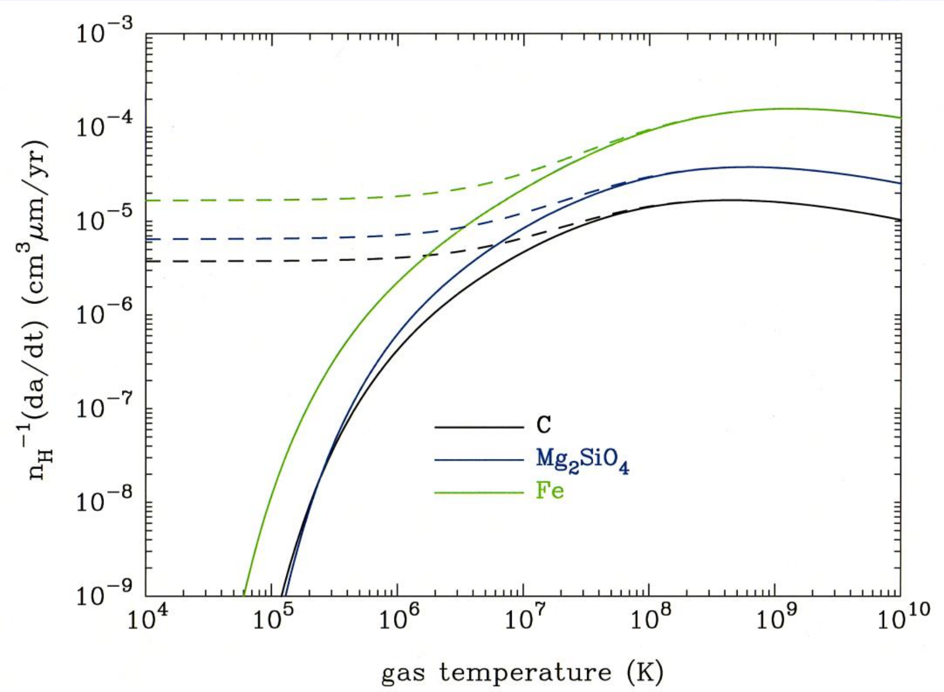
where $\epsilon = E/kT$

3-4-2. Erosion rate of dust by sputtering

for primordial composition gas



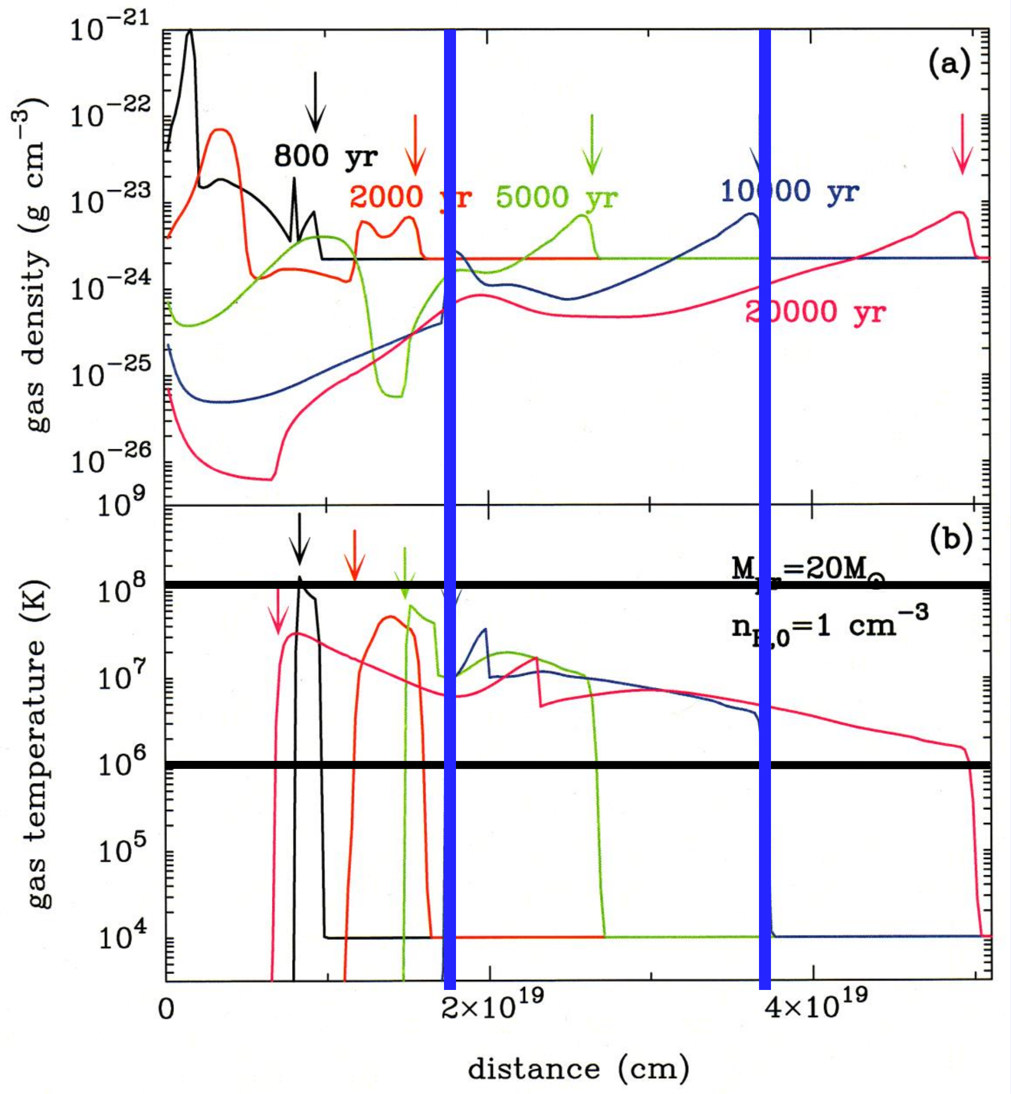
for oxygen ions



- the erosion rate by sputtering quickly increases above 10^5 K and peaks at 10^7 -10^8 K

- **da / dt ∼ 10^{-6} n_H μm yr^{-1} cm^3 for T > 10^6 K and primordial gas**

3-5-1. Temperature and density of gas



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

Model : M_{pr}=20 M_{sun} (E_{51}=1)

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

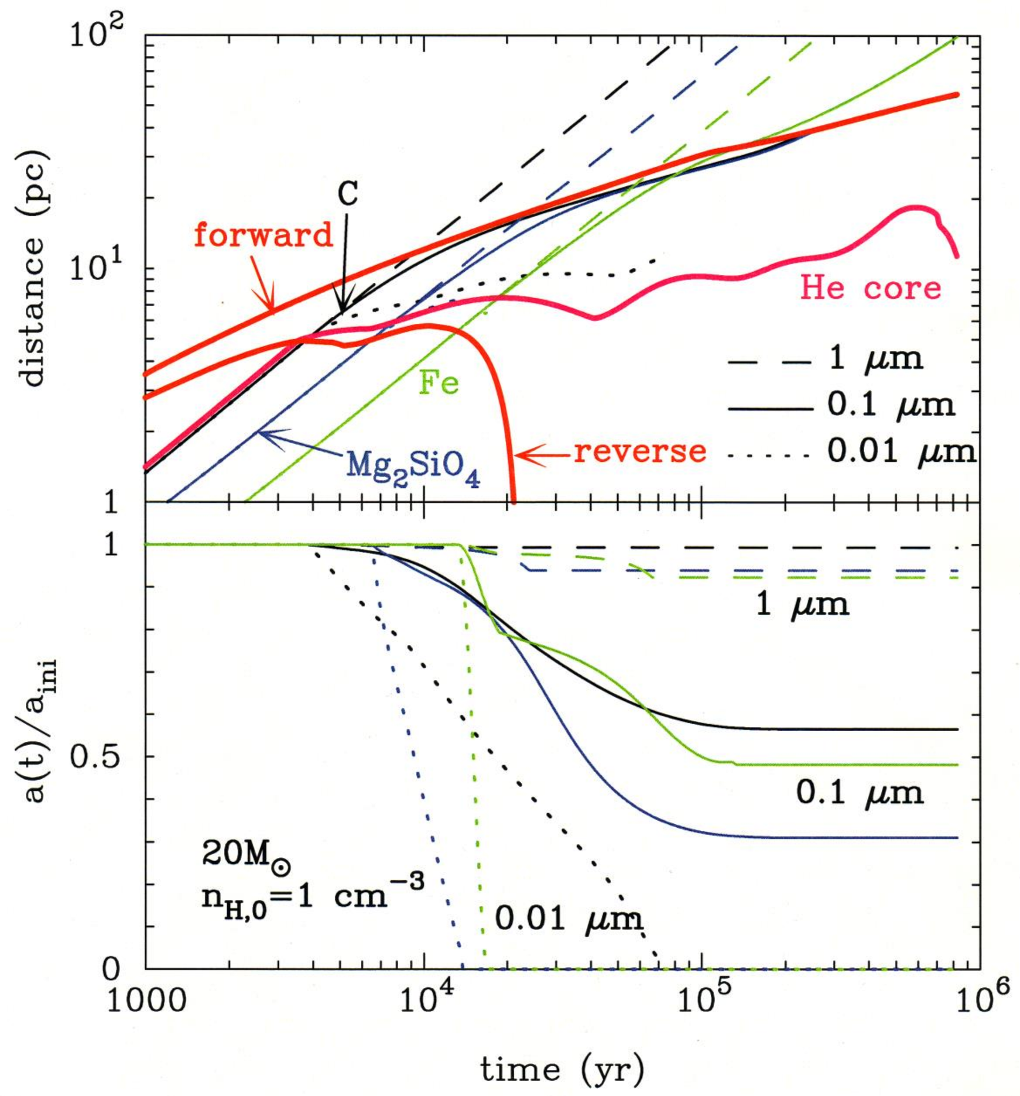
Downward-pointing arrows:
forward shock in upper panel
reverse shock in lower panel

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

3-5-2. Evolution of dust in SNRs



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

Model : Mpr=20 Msun (E_{51}=1)

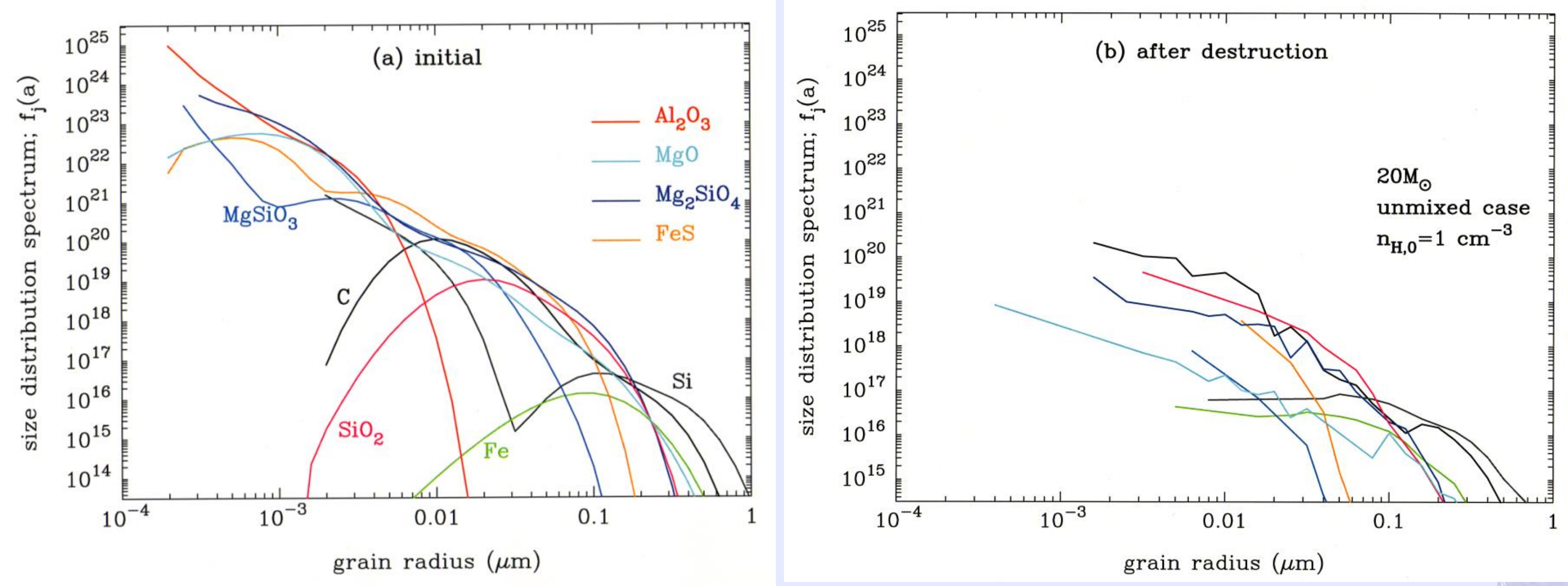
$n_{H,0}$ = 1 cm^{-3}

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

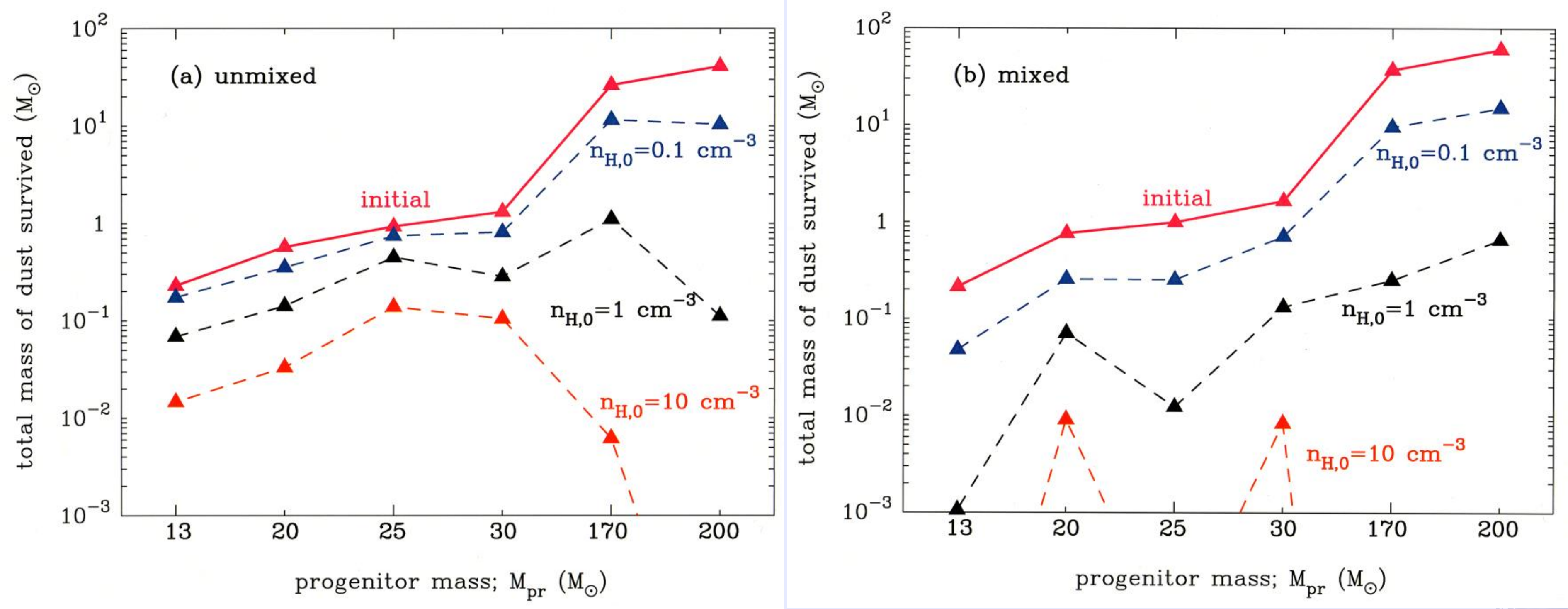
3-5-3. Size distribution of surviving dust



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**

3-5-4. Total mass of surviving dust



Total mass of dust surviving the destruction for Type II SNRs;

0.1-0.8 Msun for the unmixed grain model ($n_{H,0}$ = 0.1-1 cm^{-3})

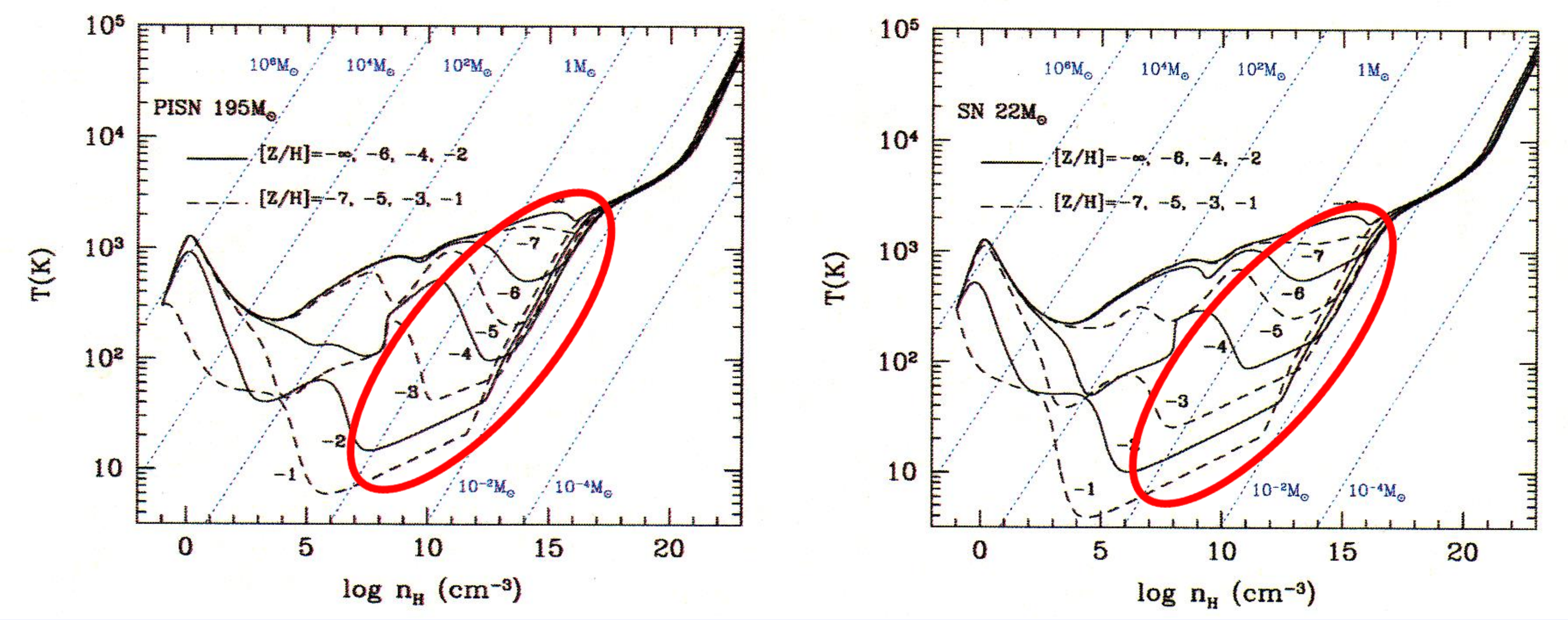
0.06-0.7 Msun for the mixed grain model ($n_{H,0}$ = 0.1 cm^{-3})

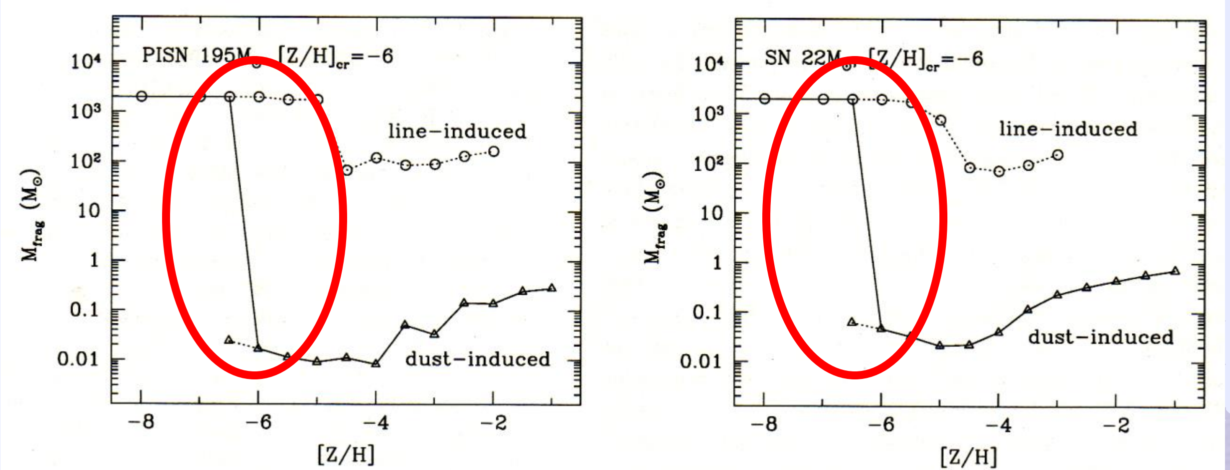
➔ high enough to explain dust content at high-z galaxies

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

4. Role of Dust in the Early Universe

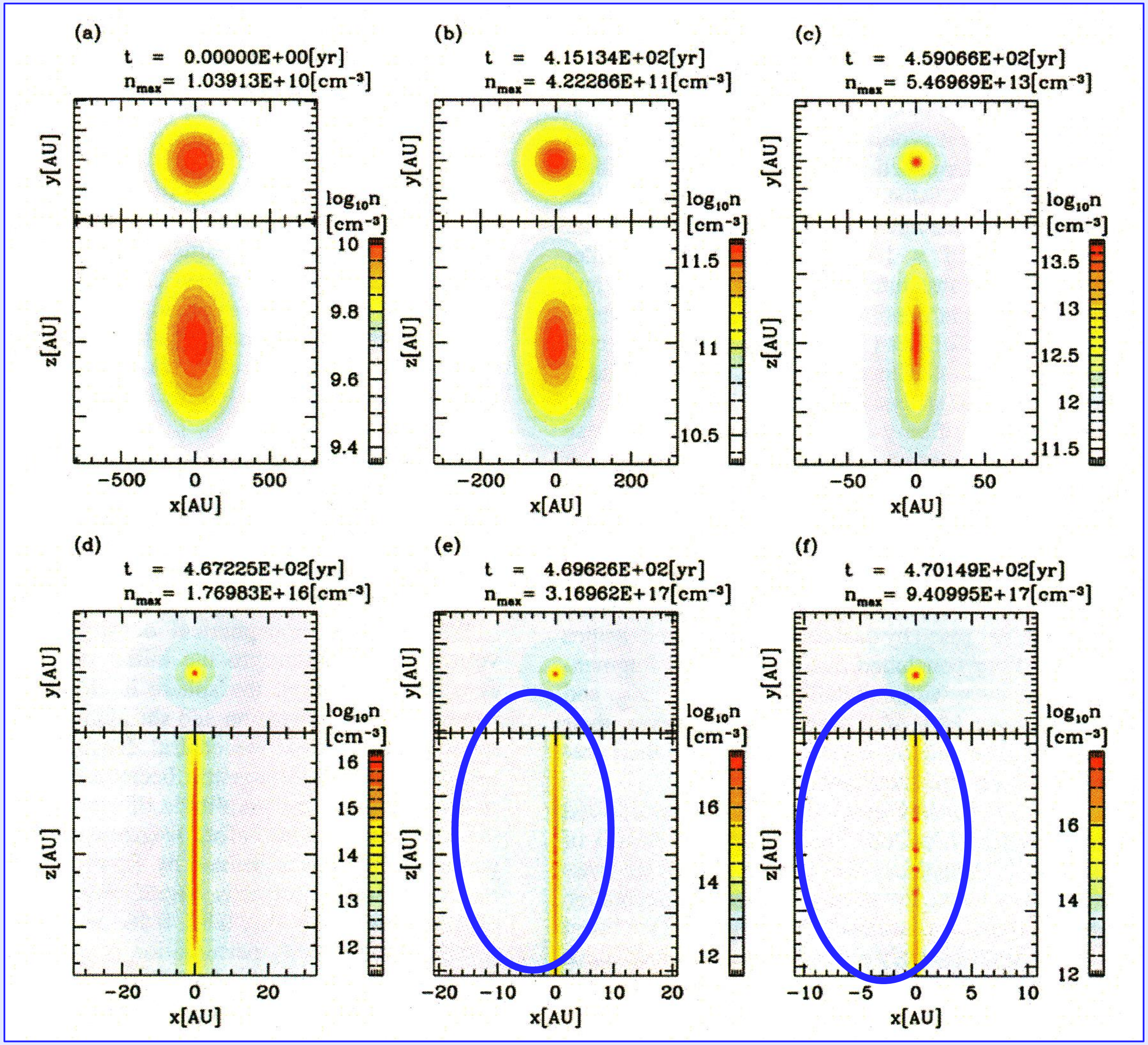
4-1. Critical metallicity





Schneider et al. (2006, MNRAS, 378, 973)

4-2. 3-D simulation of star-forming cloud



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

4-3. 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)

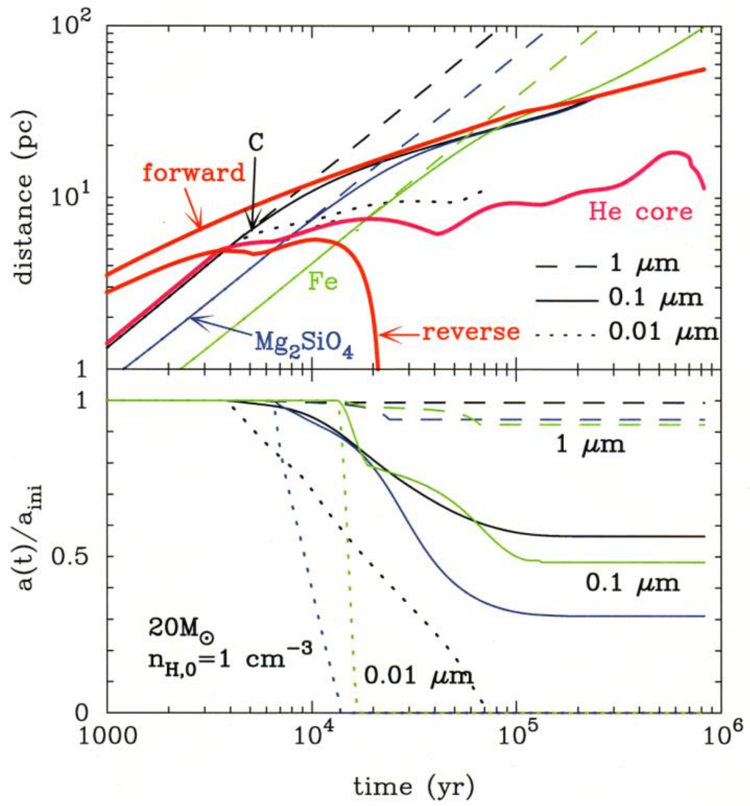
dust grains surviving the destruction but not injected into the ISM are piled up in the dense shell in 10^5-10^6 yr

↓

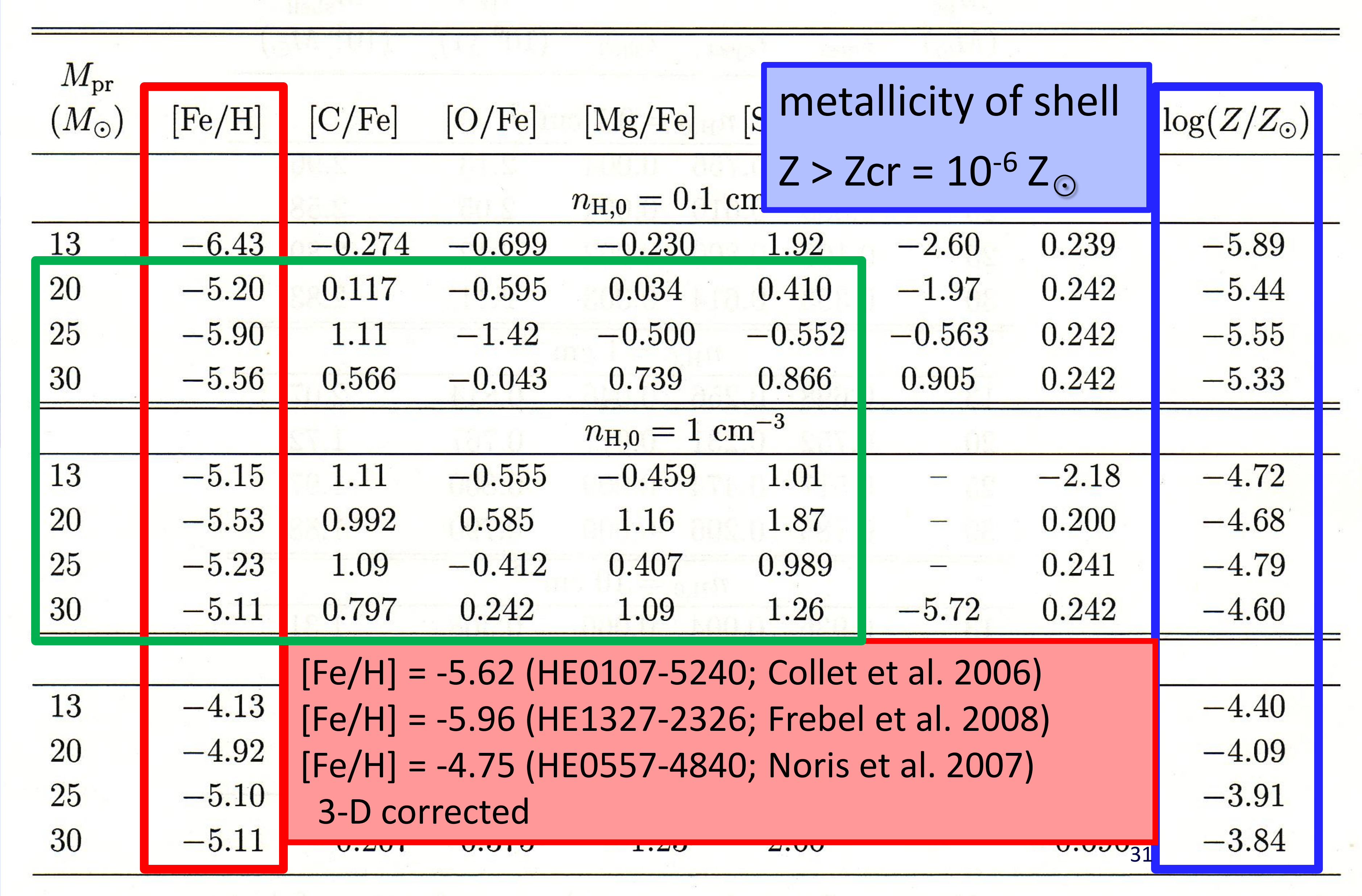
- elemental composition of these piled-up grains

➔ elemental abundance of Population II.5 stars

comparing with observations of HMP and UMP stars



4-4. Elemental abundance in the shell (1)



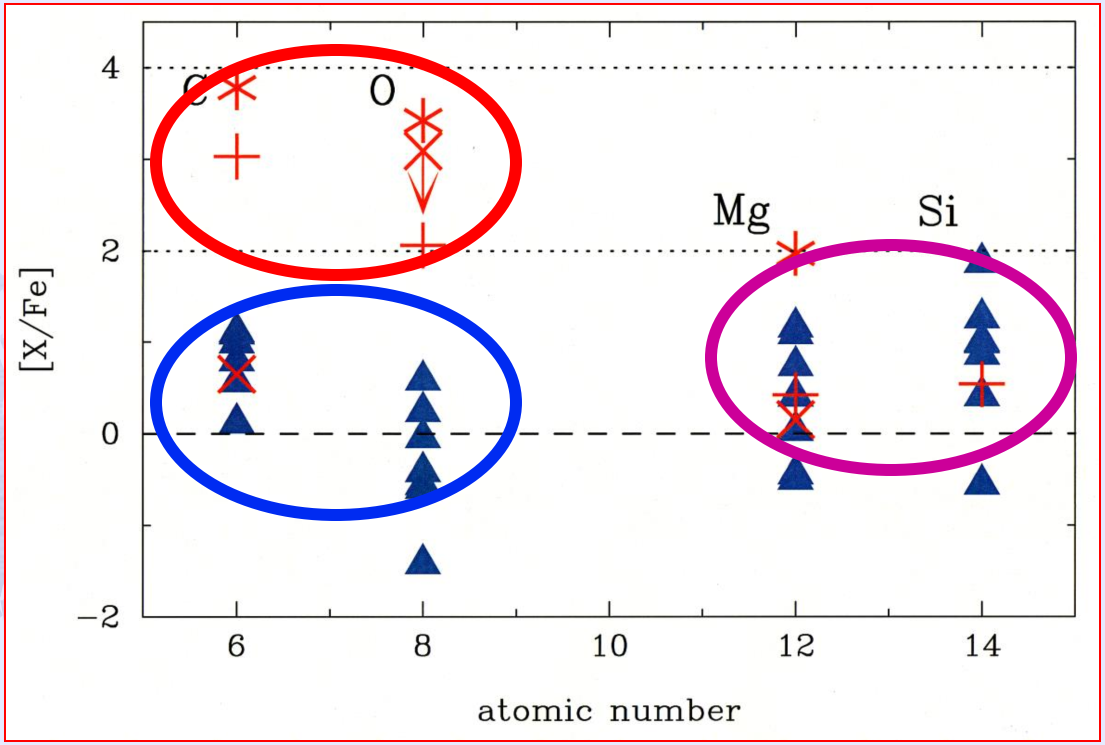
$M_{\rm pr}$ ($M_\odot$)	[Fe/H]	[C/Fe]	[O/Fe]	[Mg/Fe]	[S			$\log(Z/Z_\odot)$
				$n_{\rm H,0} = 0.1$ cm				
13	−6.43	−0.274	−0.699	−0.230	1.92	−2.60	0.239	−5.89
20	−5.20	0.117	−0.595	0.034	0.410	−1.97	0.242	−5.44
25	−5.90	1.11	−1.42	−0.500	−0.552	−0.563	0.242	−5.55
30	−5.56	0.566	−0.043	0.739	0.866	0.905	0.242	−5.33
				$n_{\rm H,0} = 1$ 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							−3.84

metallicity of shell

Z > Zcr = 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

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



$-6 < [\mathrm{Fe/H}] < -5$

$0 < [\mathrm{Mg, Si/Fe}] < 2$

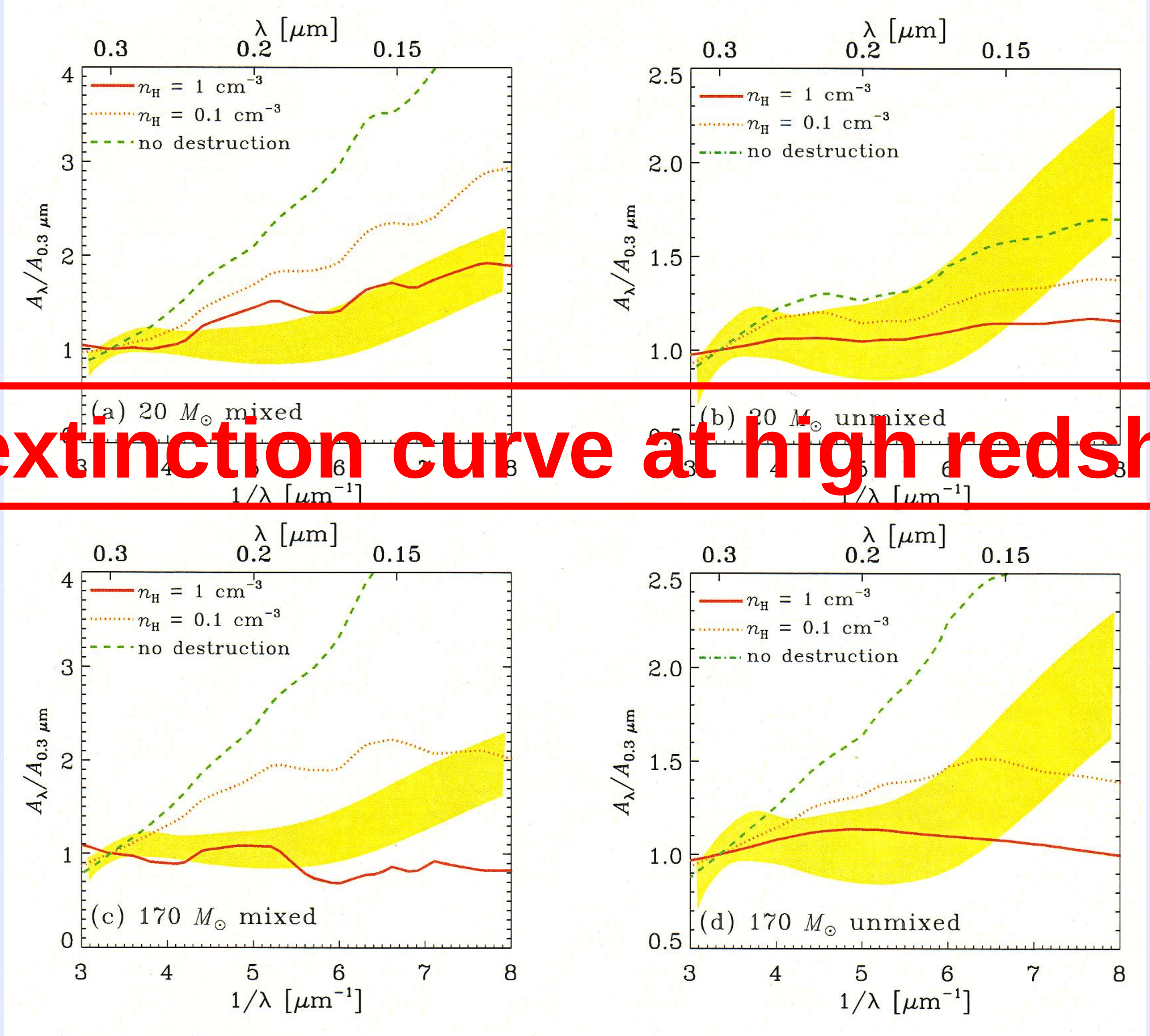
↓

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.

5. Extinction Curves Expected at high redshifts

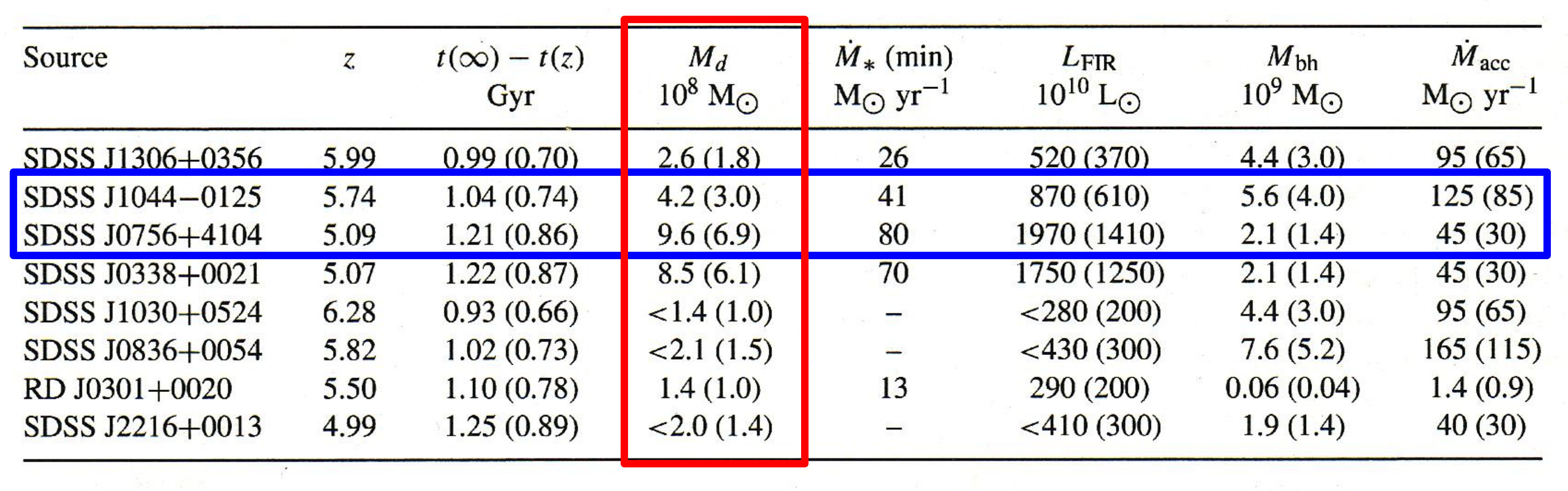
5-1. Flattened extinction curves



flat extinction curve at high redshifts !

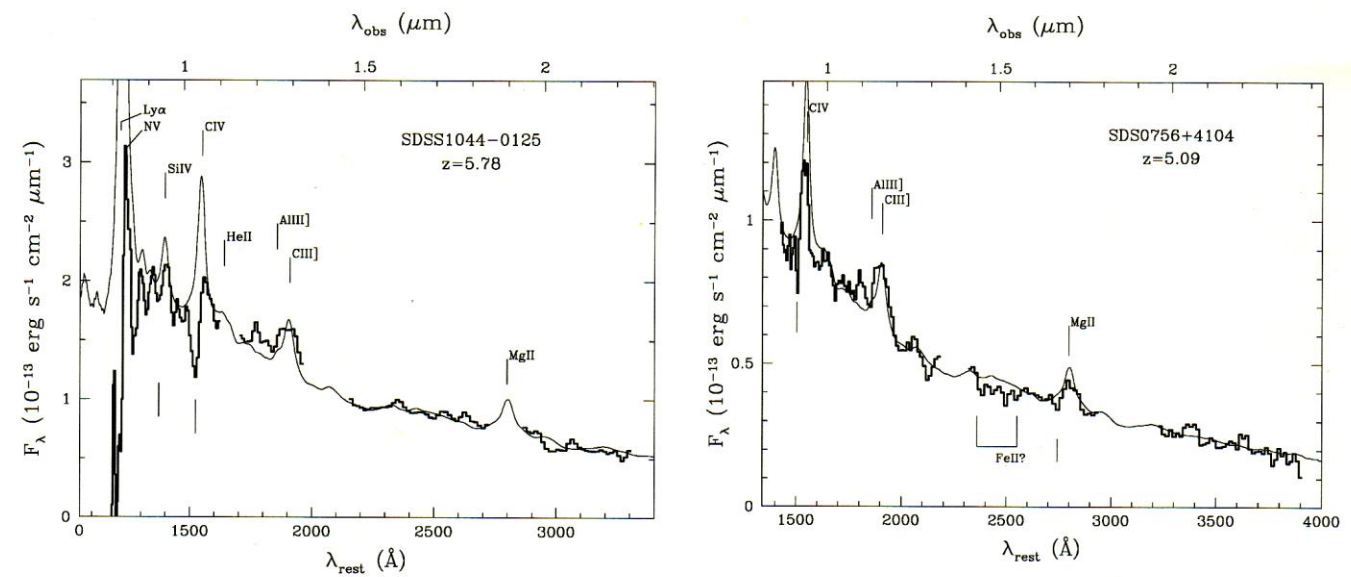
Hitashita et al. (2008, 384, 1725, MNRAS)

5-2. Extinction in high-z BAL quasars



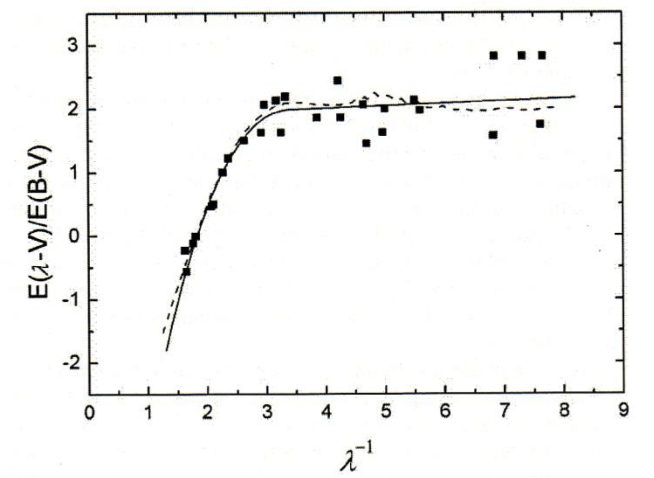
Source	z	$t(\infty) - t(z)$ Gyr	M_d 10^8 $M_\odot$	$\dot{M}_*$ (min) $M_\odot$ yr^{-1}	L_{FIR} 10^{10} $L_\odot$	M_{bh} 10^9 $M_\odot$	$\dot{M}_{acc}$ $M_\odot$ yr^{-1}
SDSS J1306+0356	5.99	0.99 (0.70)	2.6 (1.8)	26	520 (370)	4.4 (3.0)	95 (65)
SDSS J1044−0125	5.74	1.04 (0.74)	4.2 (3.0)	41	870 (610)	5.6 (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)

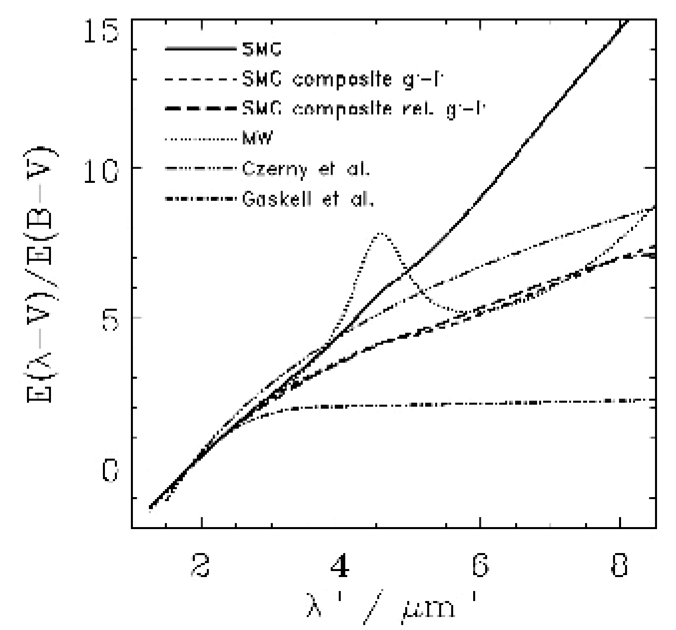


Maiolino et al. (2004, A&A, 420, 889)

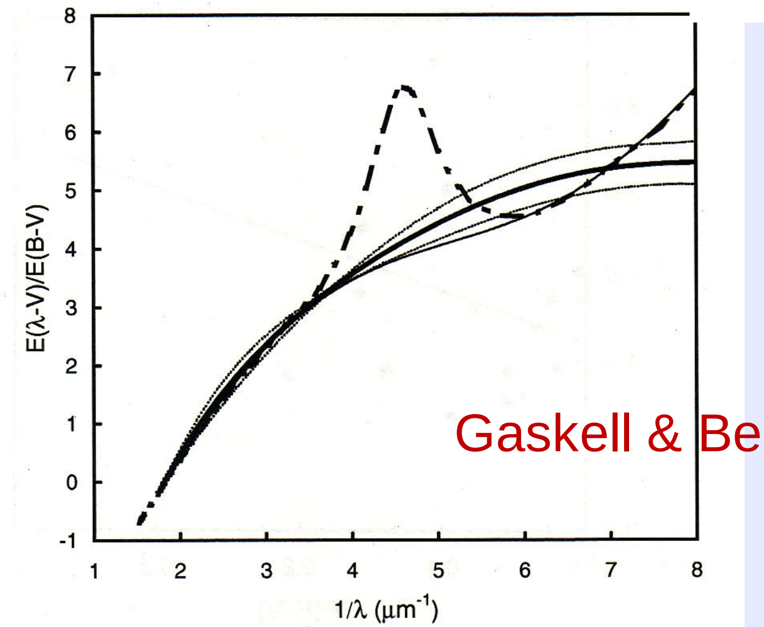
5-3. Extinction curves of low-z AGNs



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

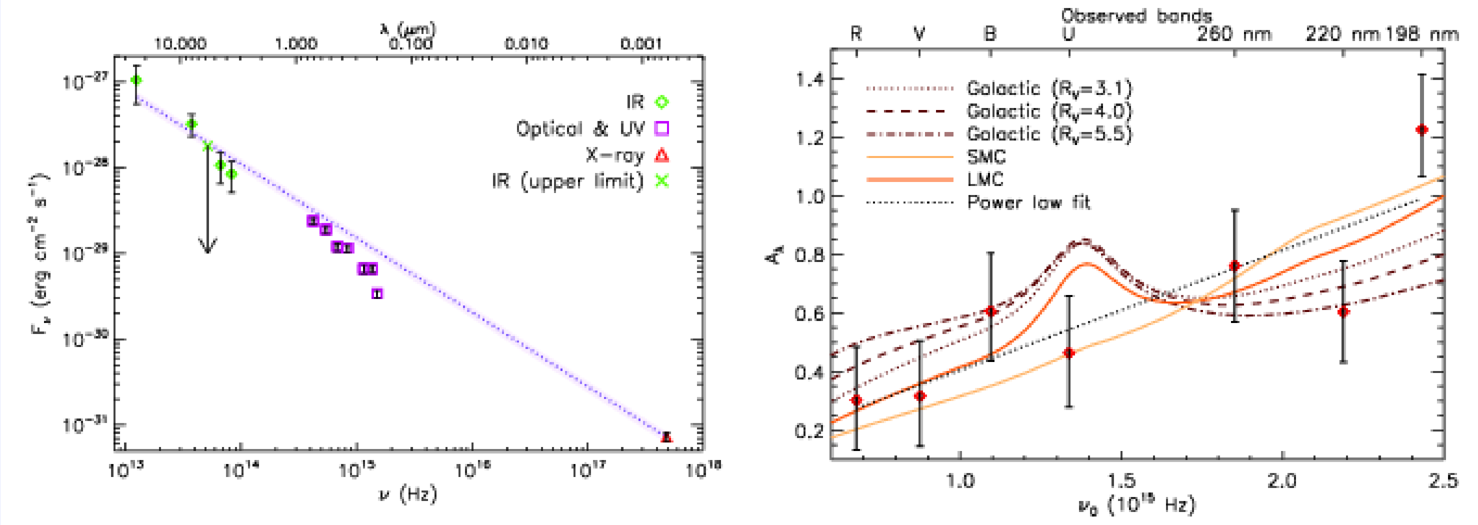


Willot (2005, ApJ, 627, L201)

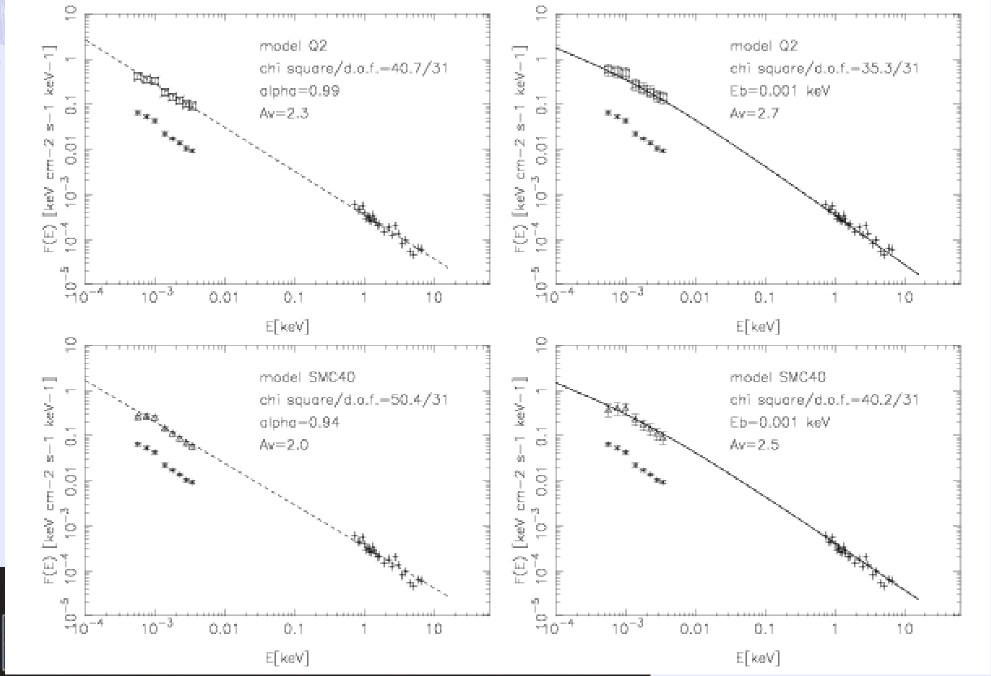


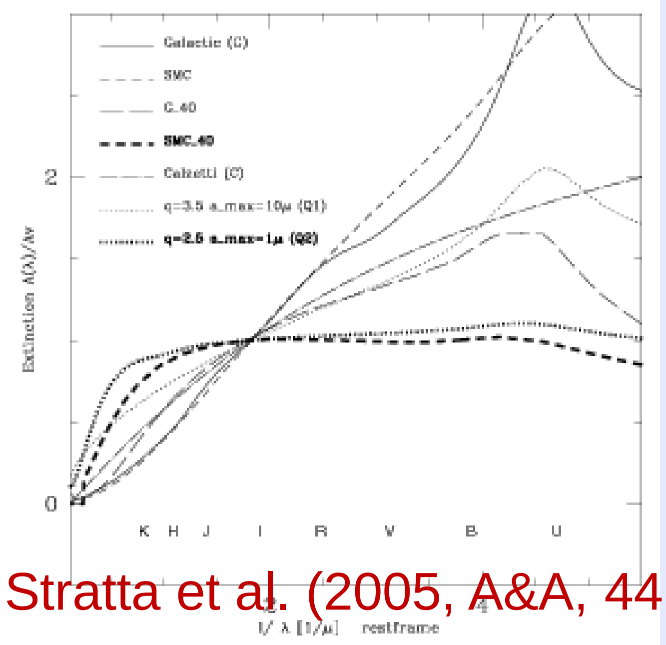
Gaskell & Benker (2008, astro-ph/0711.1013)

5-4. Extinction curves from GRBs



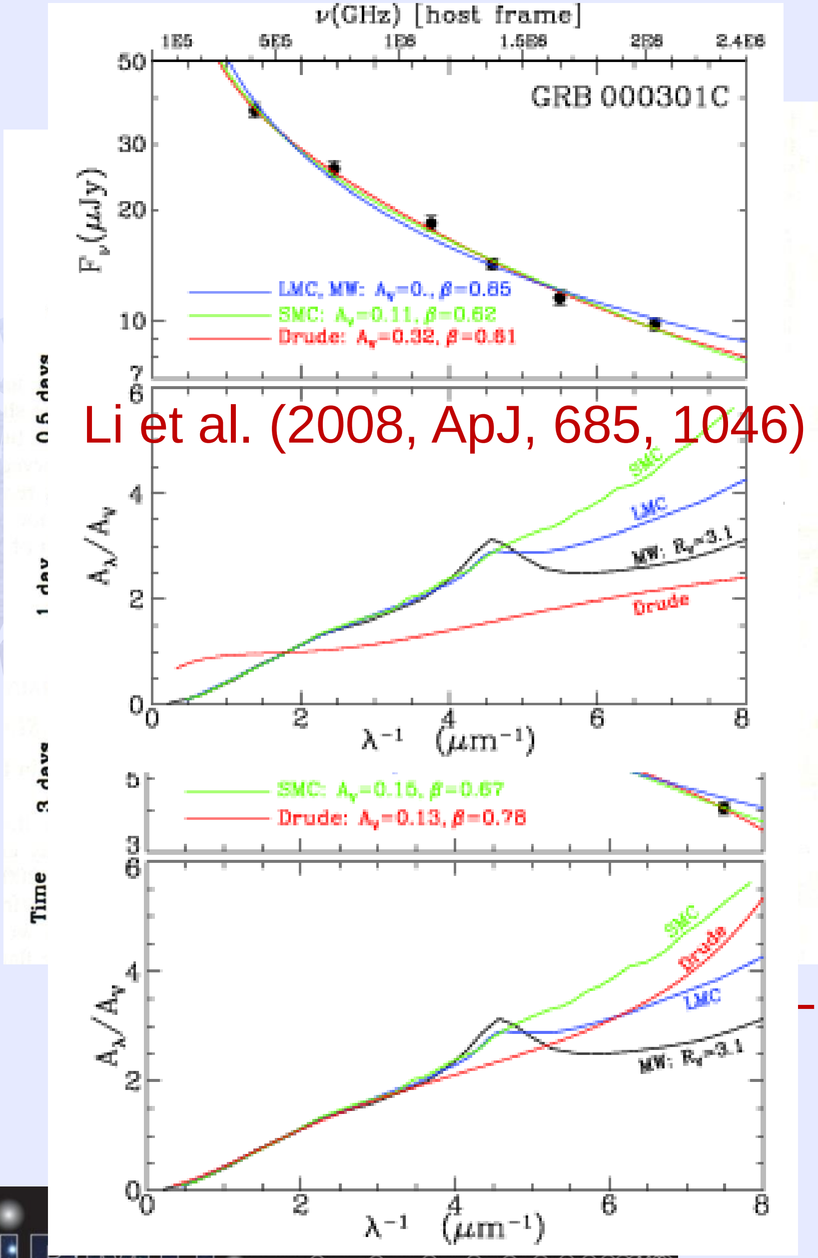
Heng et al. (2004, ApJ, 681, 1116)





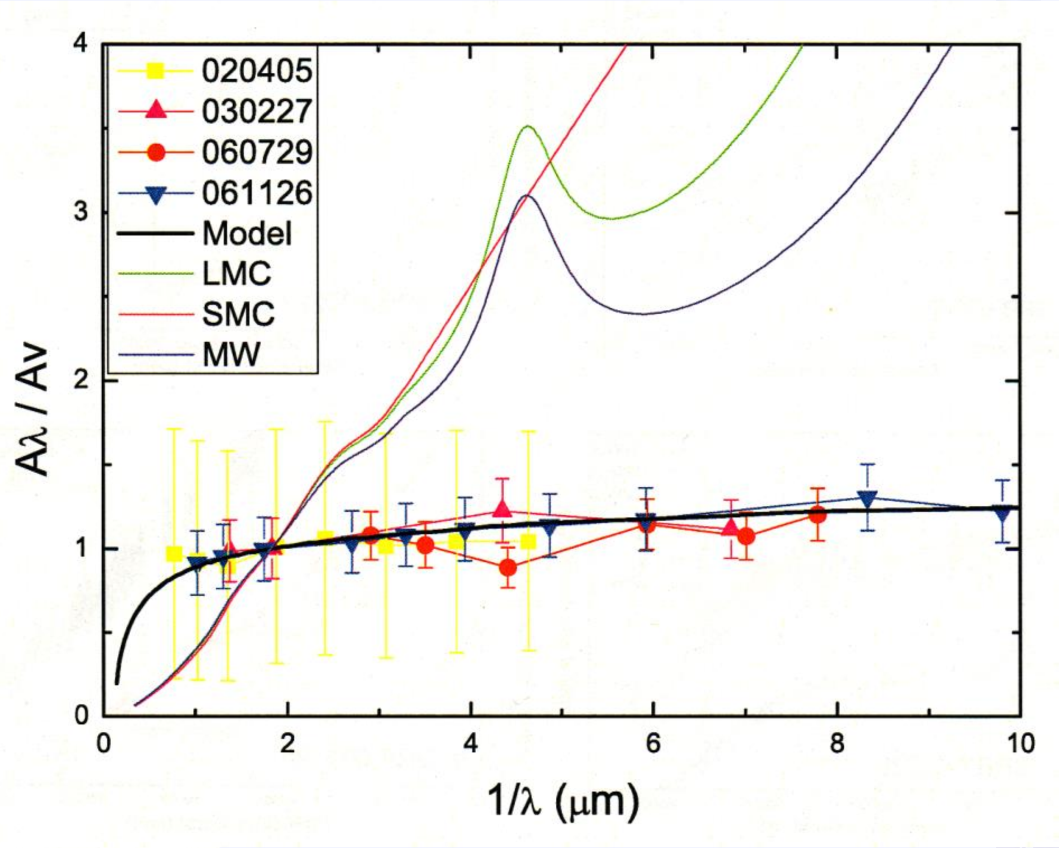
Stratta et al. (2005, A&A, 441, 83)

5-5. Extinction curves from GRBs



Li et al. (2008, ApJ, 685, 1046)

9)



Li et al. (2008, ApJ, 678, 1136)

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

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. **Dust grains in the early universe play crucial roles in the formation of metal-deficient low-mass stars.**
4. **Dust formed in Population III stars has great impacts on the composition and formation of Population II.5 stars.**
5. **Extinction curves in the early universe are expected to be flat.**