Nature of Dust in the early universe

Takaya Nozawa

IPMU (Institute for the Physics and Mathematics of the Universe, Univ. of Tokyo)

Collaborators

T. Kozasa, A. Habe (Hokkaido Univ.), Eli Dwek（NASA）

H. Umeda（Univ. of Tokyo）, N. Tominaga（NAOJ）

K. Maeda（IPMU）, K. Nomoto（IPMU/Univ. of Tokyo)

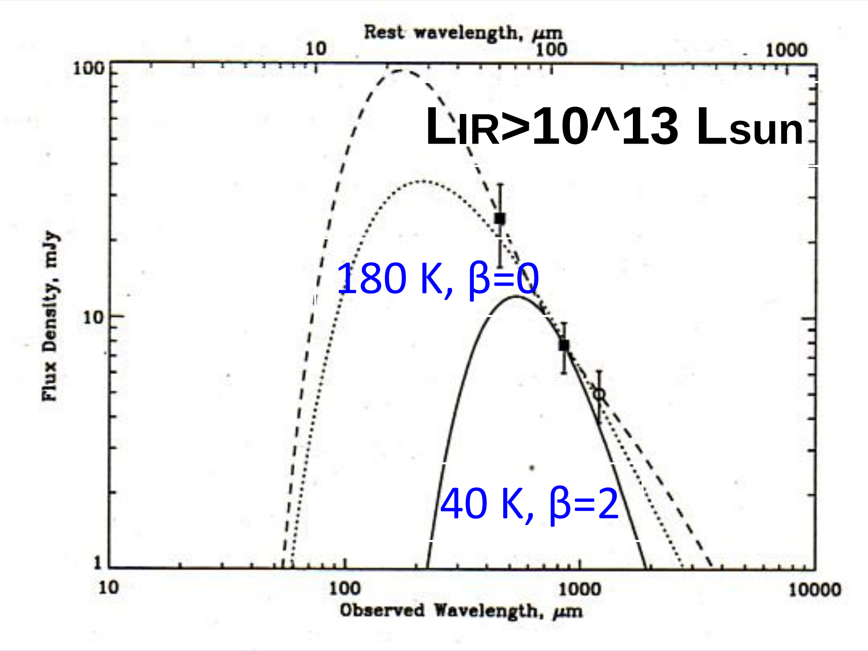
IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Contents

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

- The presence of large amounts of dust grains with mass of **>10^8 Msun** has been confirmed for ~30% of z > 5 quasars
  (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)

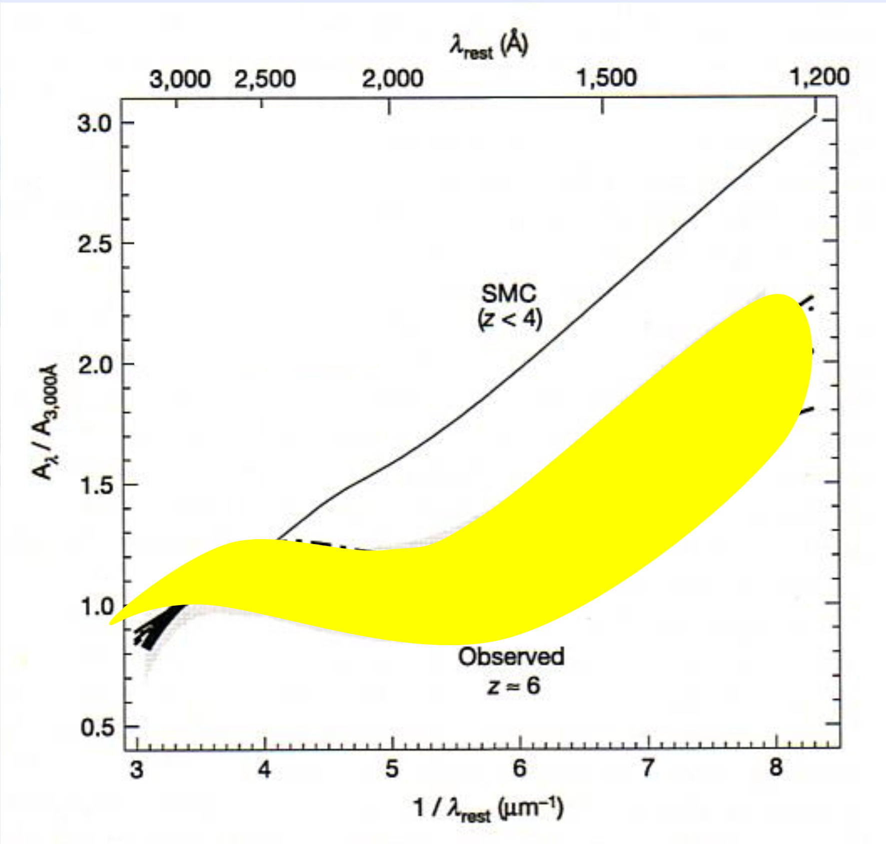
a rapid enrichment with dust formed in the ejecta of SNe

0.1-1 Msun of dust 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)

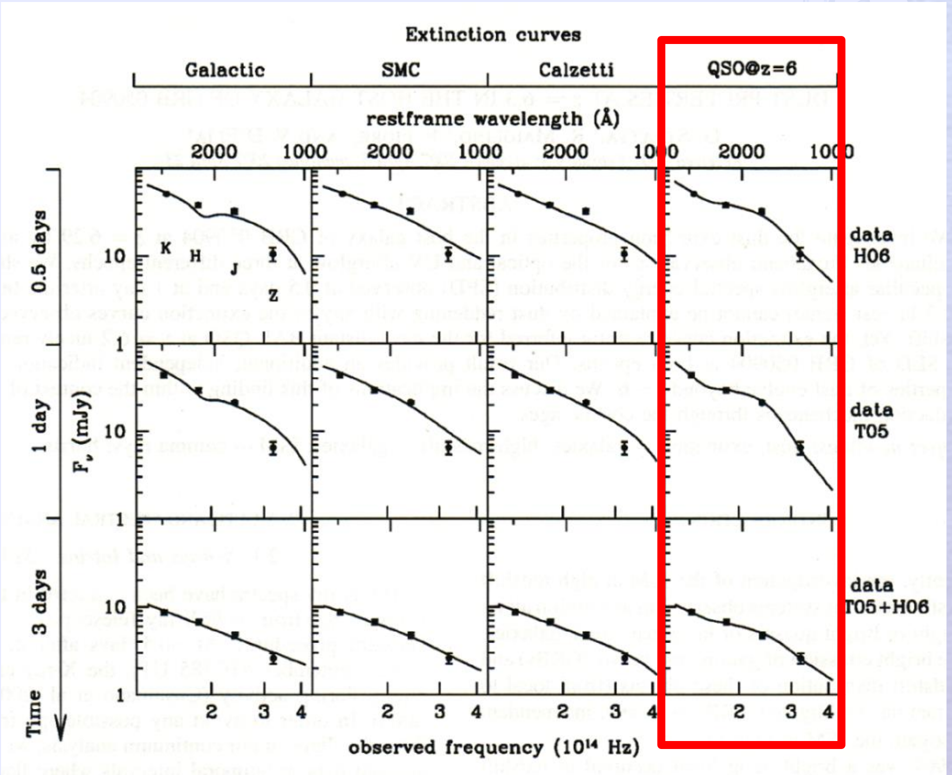
1-2. Extinction curves at high-z

Broad absorption line (BAL) quasars at low-z➔ reddened by dust

SDSS J1048+4637 at z=6.2



GRB 050904 at z=6.3



Maiolino et al. (2004, Nature, 431, 533) Stratta et al. (2007, ApJ, 661, L9)

Source and evolution of dust at high redshift (z > 5) are different from those at low redshift (z < 4)

1-3. Role of dust in the early universe

- Dust has great impacts on the formation processes of stars
  - forming molecules (mainly H_2) on the surface
  - providing additional cooling pathways of gas through thermal emission (e.g., Omukai et al. 2005, Schneider et al. 2006)

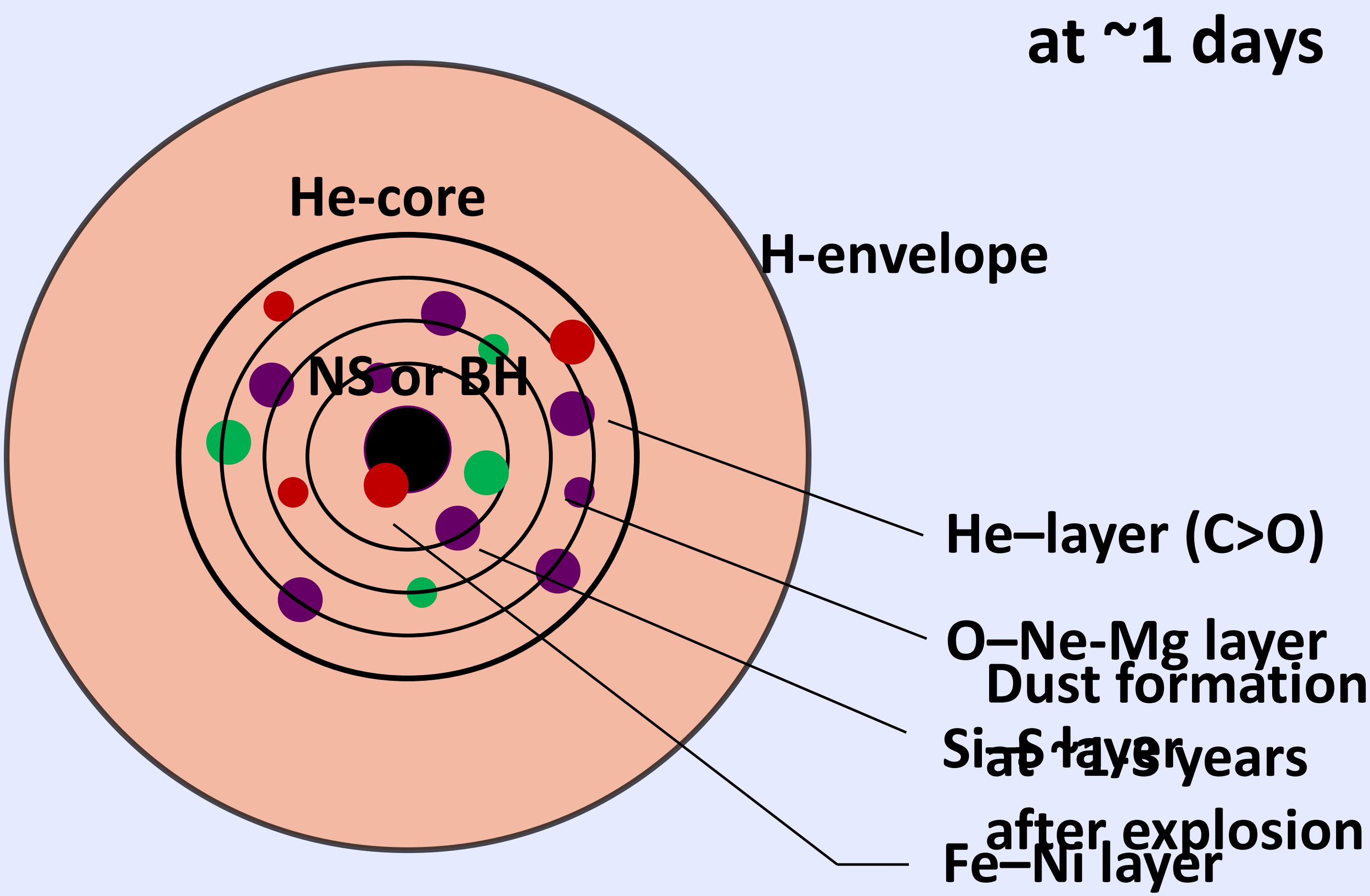
- Dust absorbs stellar light and re-emits it by thermal radiation

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

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

2. Dust Formation in primordial SNe



2-1. Calculations of dust formation

- **nucleation and grain growth theory**
  (Kozasa & Hasegawa 1987)

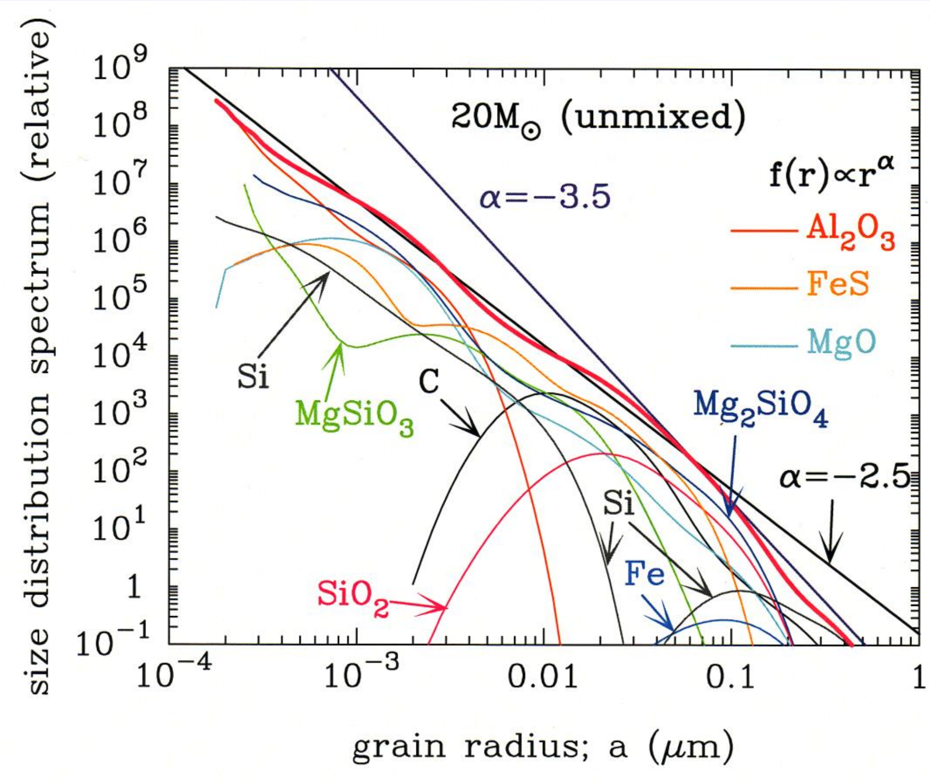
- **models of Pop III SNe** (Umeda & Nomoto 2002)
  - SNe II : M_{pr} = 13, 20, 25, 30 Msun (E_{51}=1)
  - PISNe : M_{pr} = 170 Msun (E_{51}=20), 200 Msun (E_{51}=28)

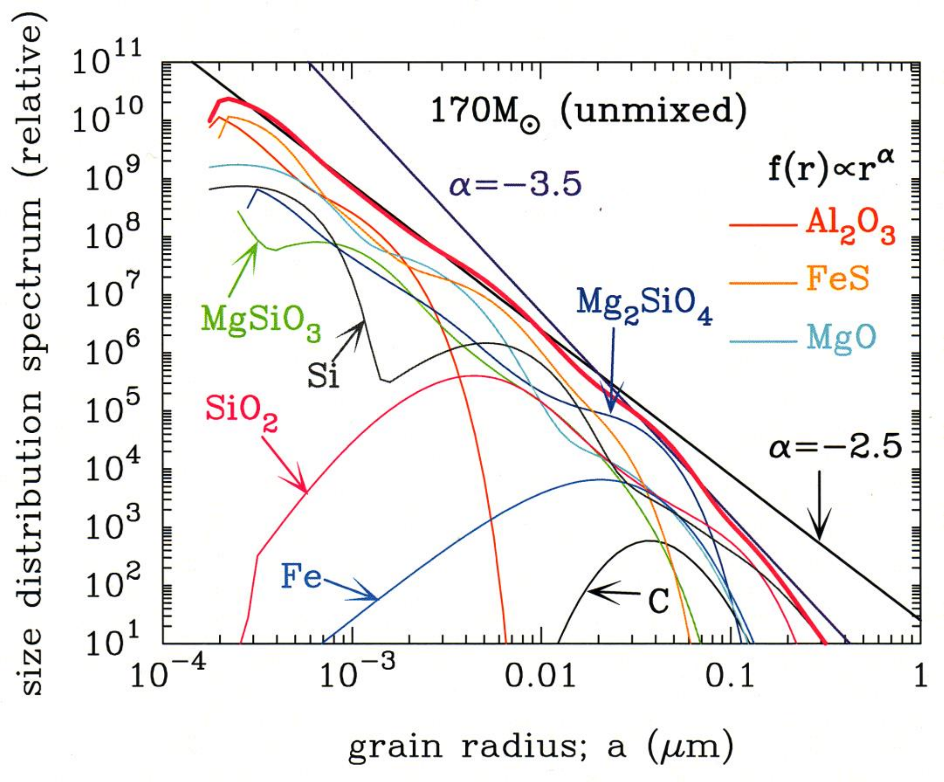
- **formation of CO and SiO molecules ➔ complete**

- **time evolution of gas temperature**
  - derived by the radiative transport calculations taking account of energy deposition from ^{56}Ni and ^{56}Co

- **mixing of elements within the He-core**
  - **unmixed case (onion-like composition)**
  - uniformly mixed case (retaining the density profile)

2-2. Dust formed in the unmixed ejecta

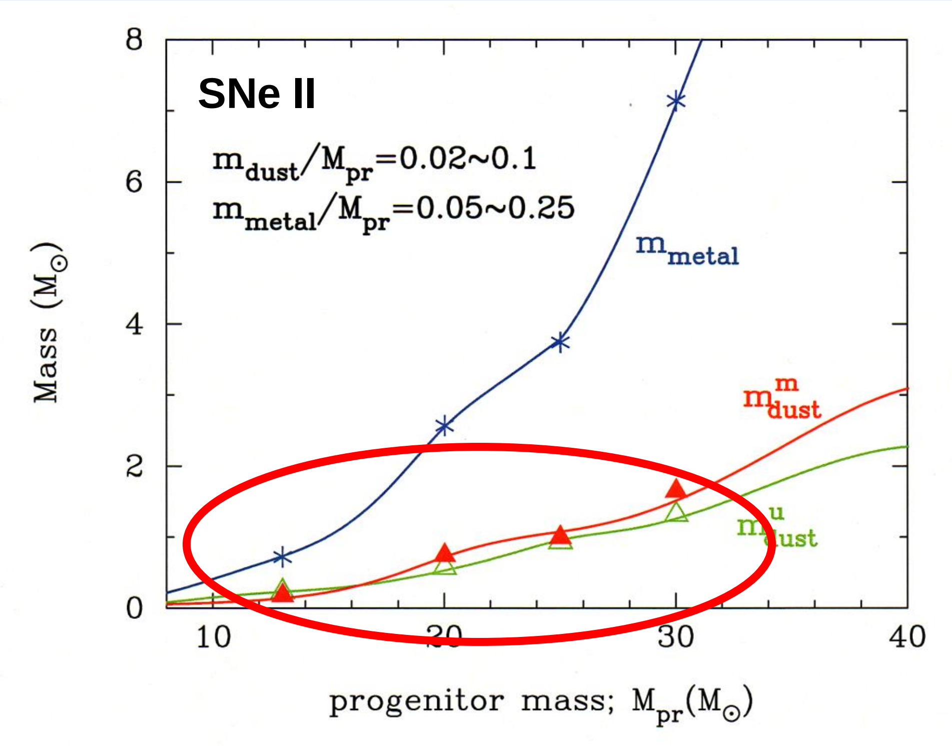


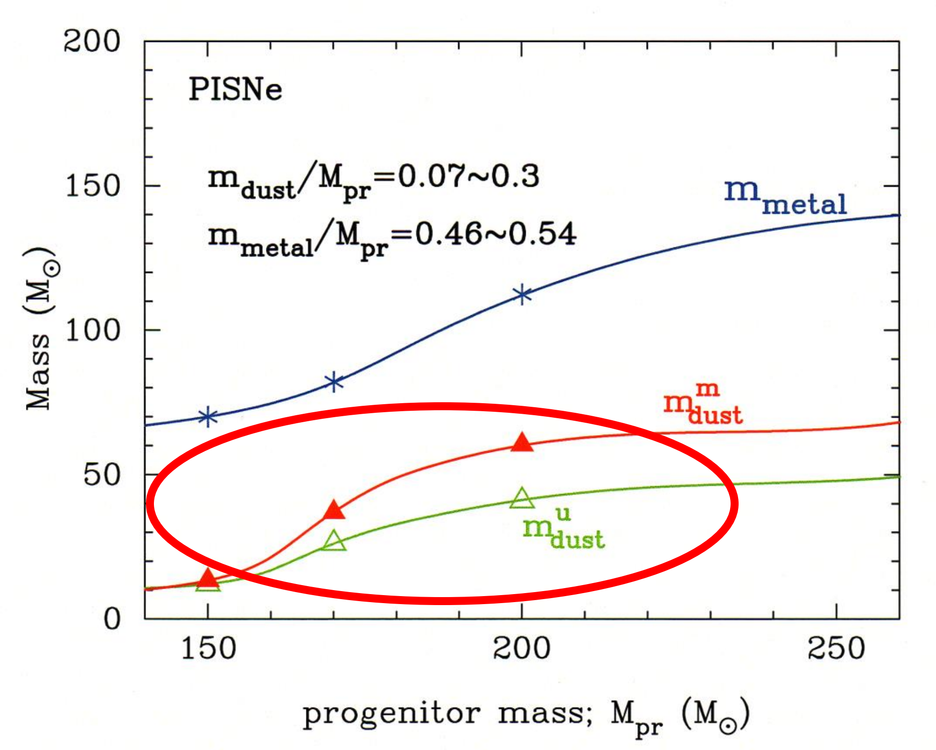


- In the unmixed ejecta, various dust species form, reflecting the difference of elemental composition in each layer
- C, SiO2, and Fe grains have lognormal-like size distribution, while the other grains have power-law-like size distribution

2-3. Total mass of dust formed

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





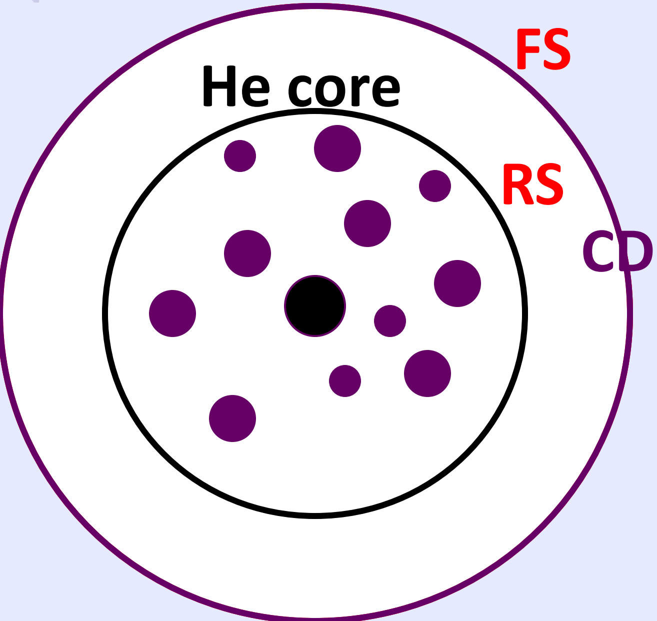
- Total dust mass increases with increasing progenitor mass

SNe II : M_{dust} = 0.1-2 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.2-0.3

PISNe : M_{dust} = 10-60 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.4-0.5

3. Dust Evolution in Primordial SNRs

$T = (1\text{-}2) \times 10^4$ K
$n_H = 0.1\text{-}1$ cm^{-3}

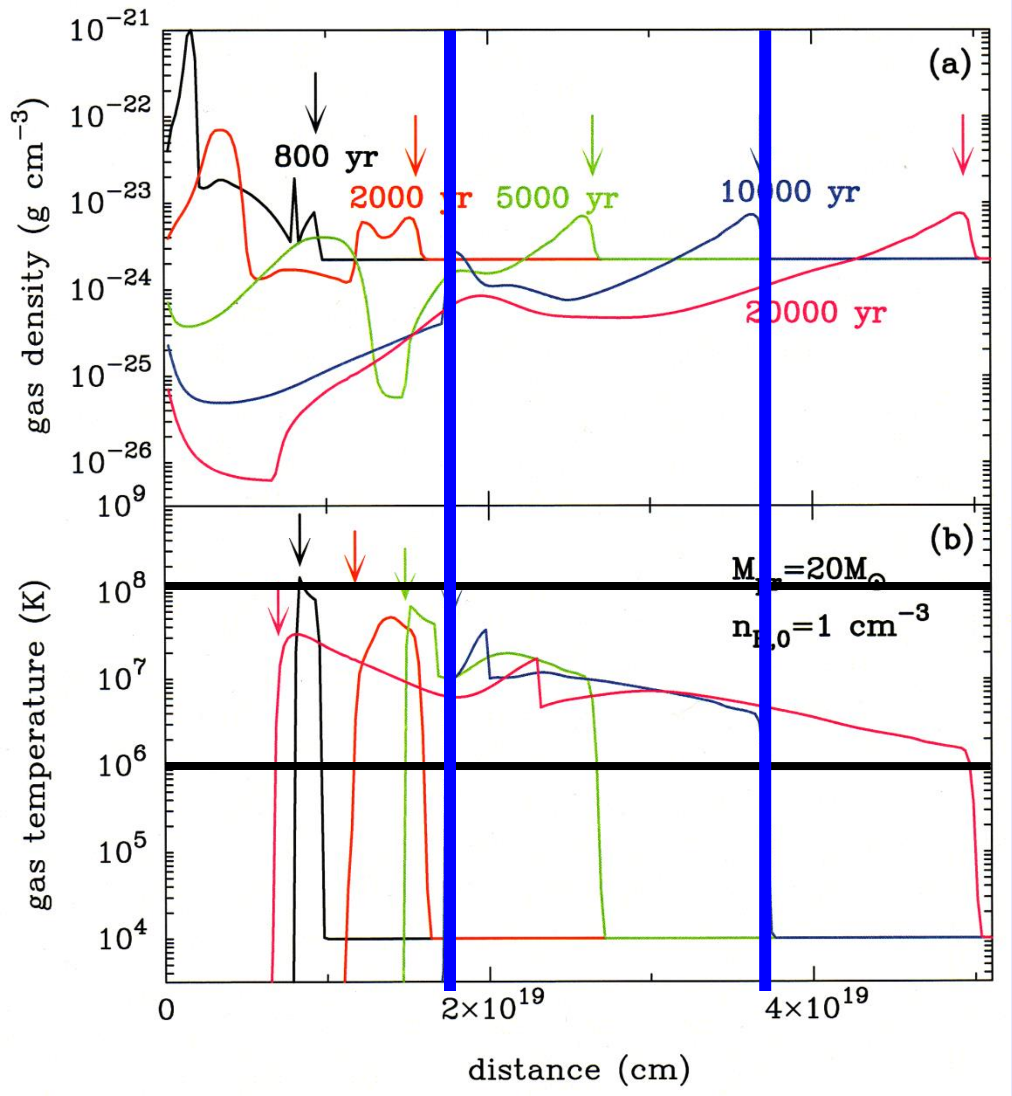


3-1. Calculation of dust destruction

- **SN ejecta models** (Umeda & Nomoto 2002)
  - SNe II : M_{pr}=13, 20, 25, 30 Msun (E_{51}=1)
  - PISNe : M_{pr}=170 (E_{51}=20), 200 Msun (E_{51}=28)
- **The ambient medium** (homogenious)
  - gas temperature ; $T = 10^4$ K
  - gas density ; **$n_{H,0}$ = 0.1, 1, and 10 cm^{-3}**
- **Dust** (test particle)
  - deceleration by the gas drag, erosion by sputtering
    ← initial size distribution and spatial distribution of dust

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

3-2.Temperature and density of gas



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

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

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

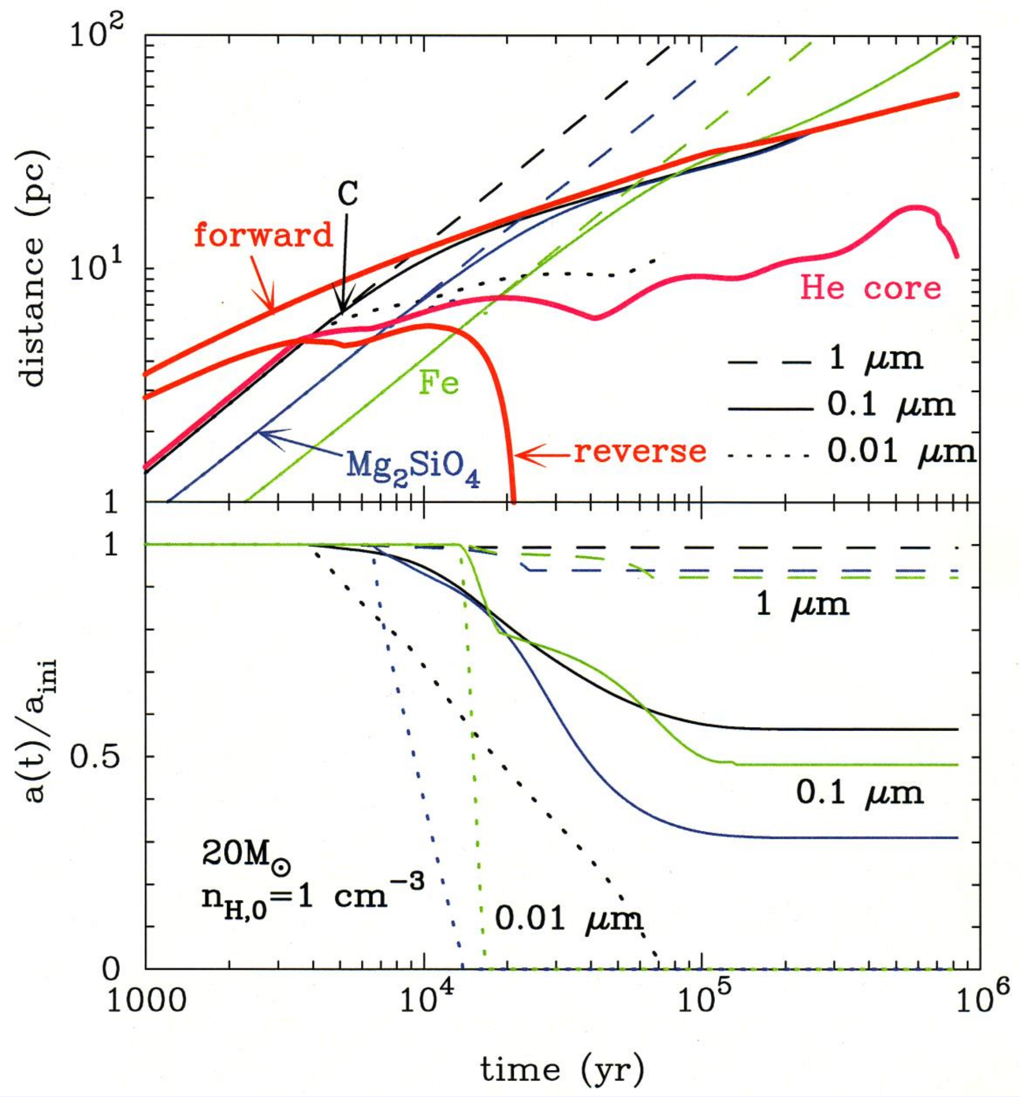
The temperature of the gas swept up by the shocks

➔ **10^6-10^8 K**

↓

Dust grains residing in this hot gas are eroded by sputtering

3-3. Evolution of dust in SNRs



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

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

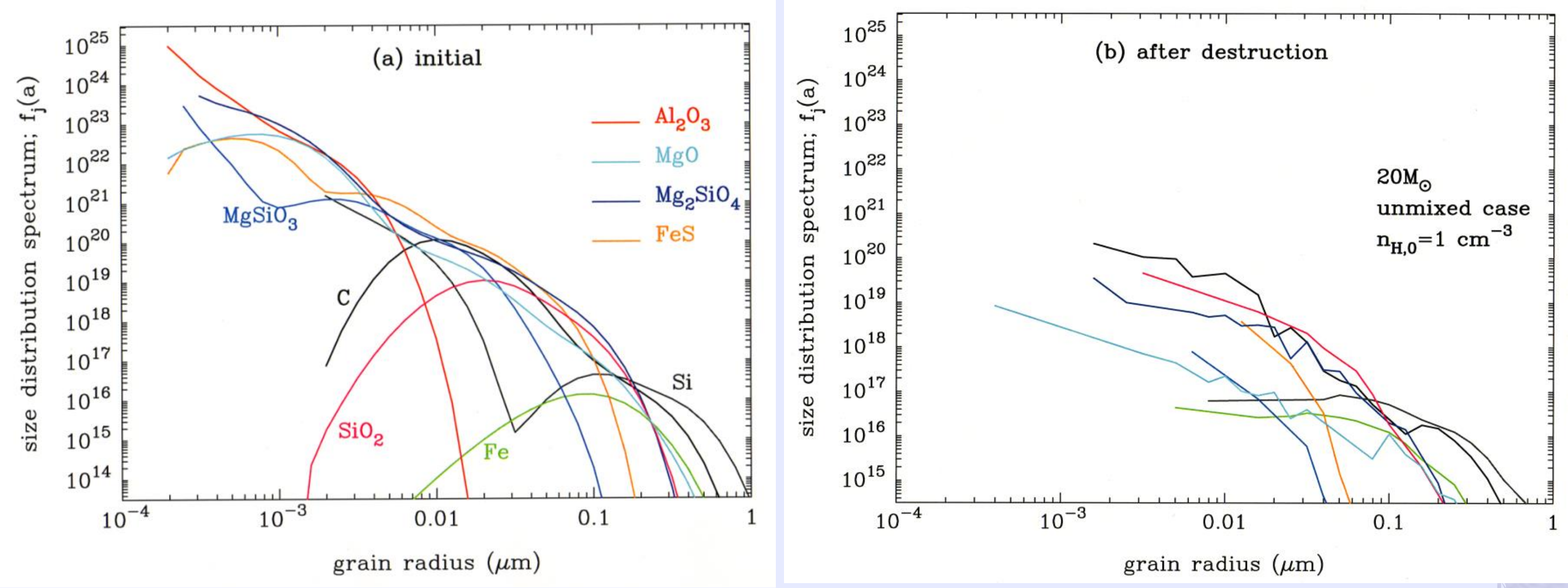
$n_{H,0}$ = 1 cm^{-3}

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

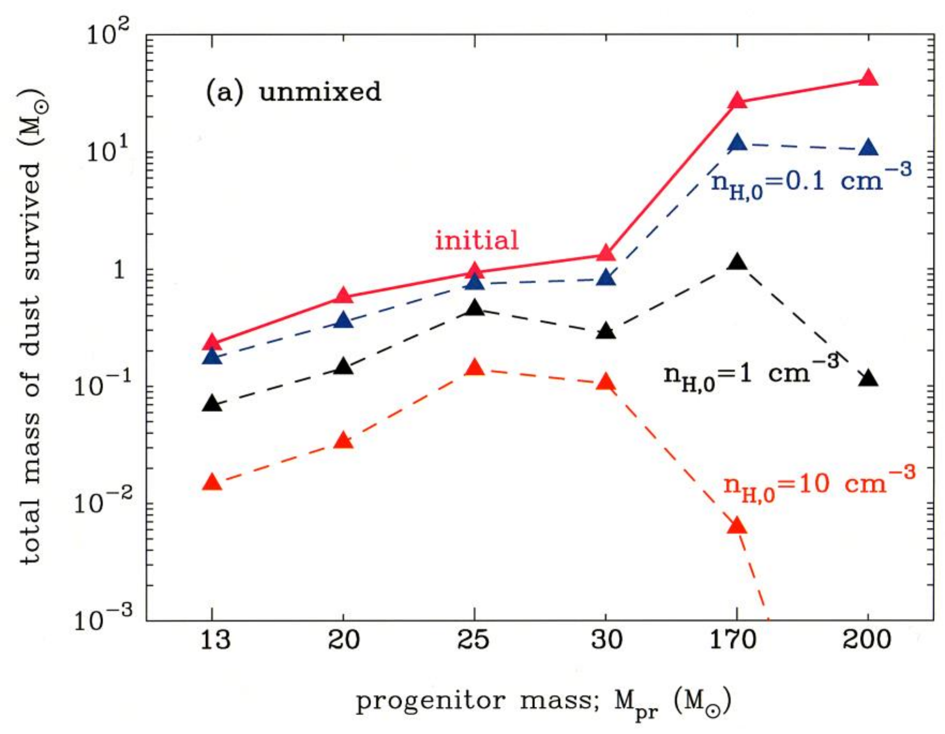
3-4. Size distribution of surviving dust

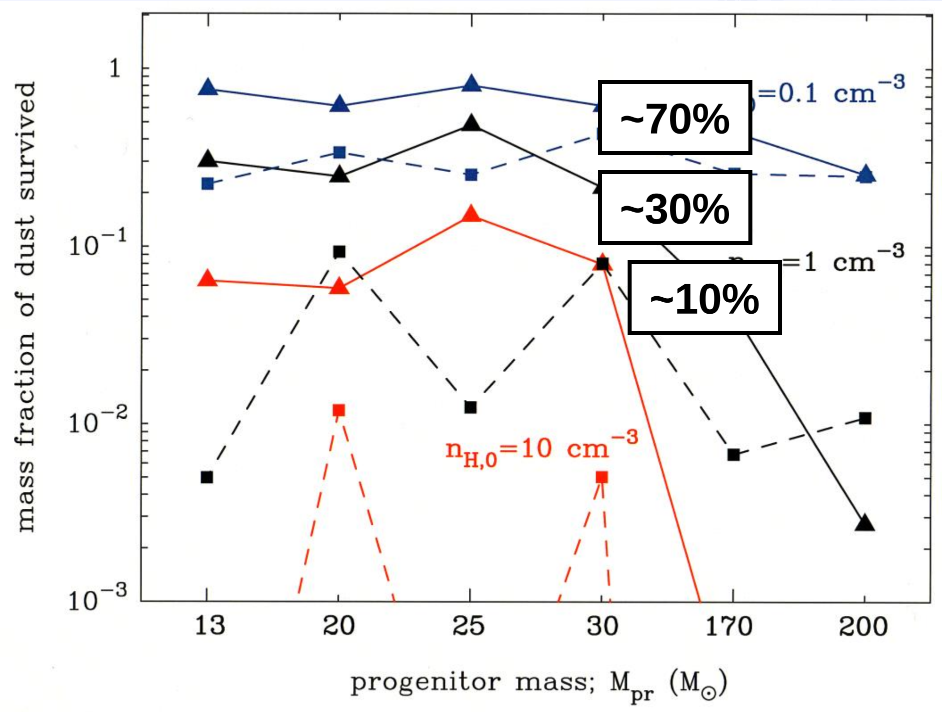


The size distribution of surviving dust is greatly deficient in small-sized grains, compared with that at its formation

➔ **Dust grains in the early universe are dominated by large-sized grains of > 0.01 μm**

3-5. Total mass of surviving dust





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

0.01-0.8 Msun for SNe II ($n_{H,0}$ = 0.1-1 cm^{-3})

0.001-15 Msun for PISNe ($n_{H,0}$ = 0.1 cm^{-3})

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

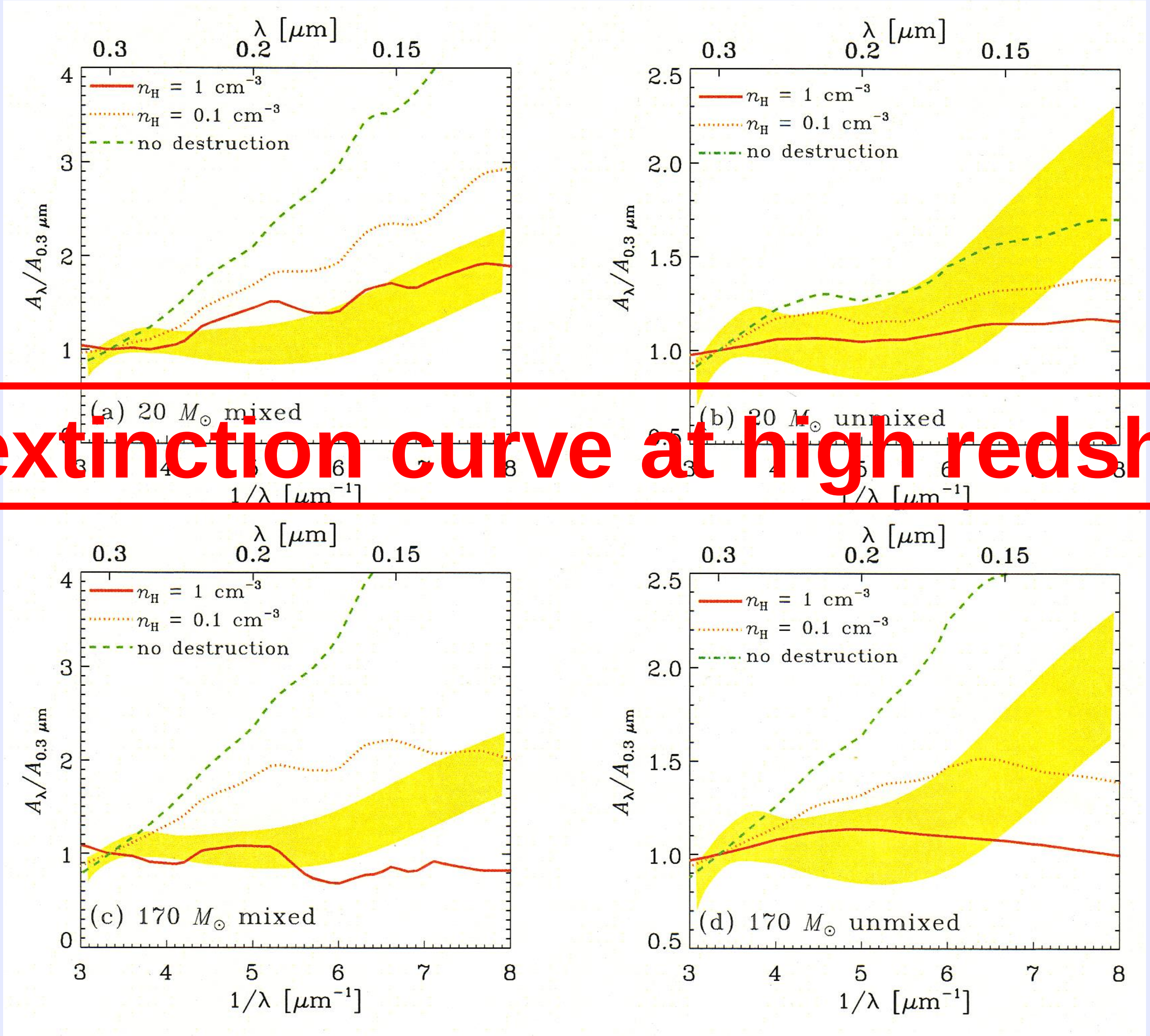
(Morgan & Edmunds 2003, Maiolino et al. 2006; Dwek et al. 2007)

4. Extinction curve expected at high-z

- **Evolution of dust within SNRs**
  ➔ small-sized grains are destroyed more efficiently
  ➔ for the higher ambient gas density, the average radius of surviving dust shifts toward larger size

- **$2 \pi a / \lambda > 1$ ➔ Q_{ext} ~ const**

4-1. Flattened extinction curves



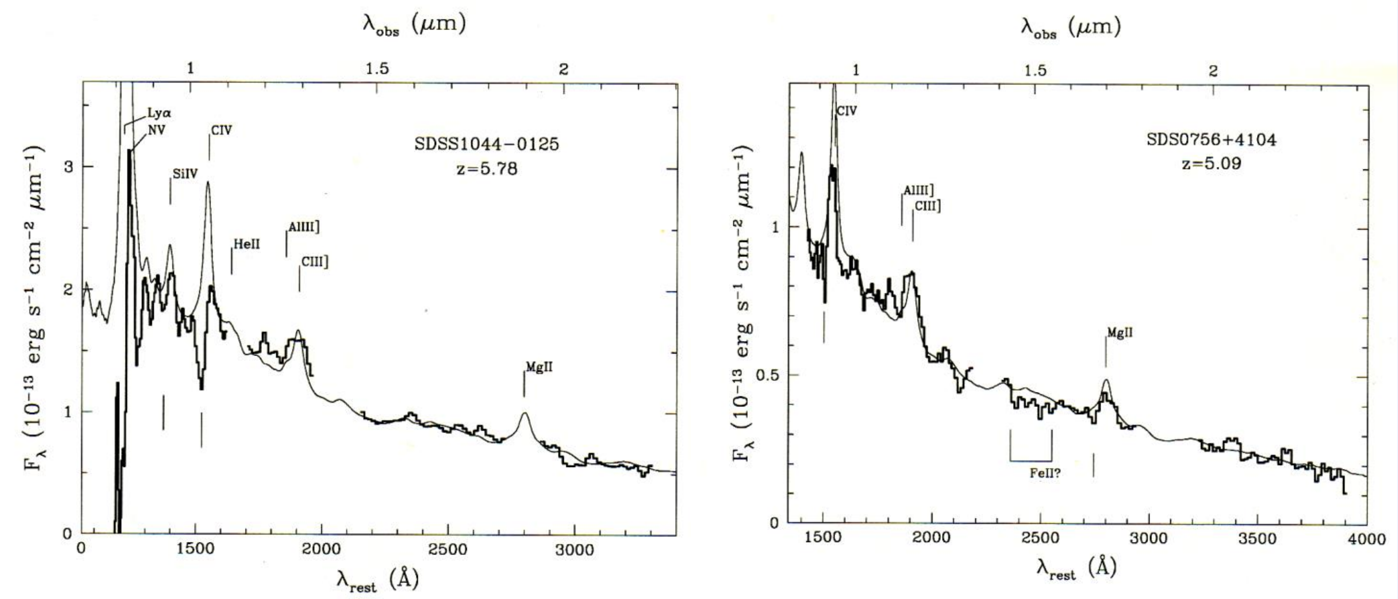
flat extinction curve at high redshifts !

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

4-2. Extinction in high-z BAL quasars

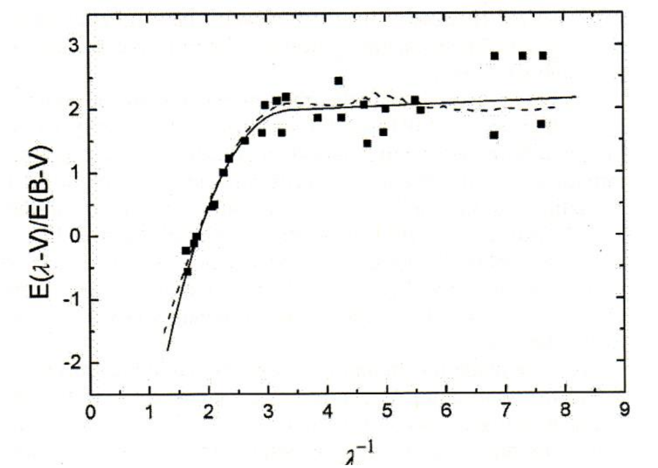
Source	z	$t(\infty) - t(z)$ Gyr	M_d 10^8 $M_\odot$	$\dot{M}_*$ (min) $M_\odot$ yr^{-1}	L_{FIR} 10^{10} $L_\odot$	M_{bh} 10^9 $M_\odot$	$\dot{M}_{acc}$ $M_\odot$ yr^{-1}
SDSS J1306+0356	5.99	0.99 (0.70)	2.6 (1.8)	26	520 (370)	4.4 (3.0)	95 (65)
SDSS J1044−0125	5.74	1.04 (0.74)	4.2 (3.0)	41	870 (610)	5.6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



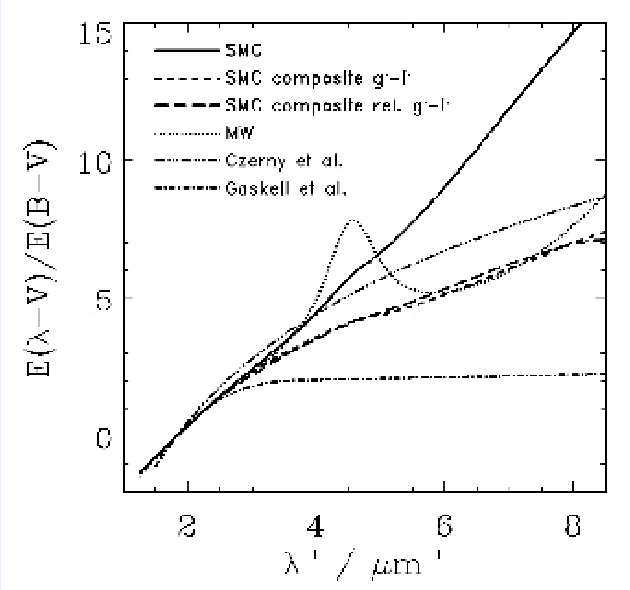
Maiolino et al. (2004, A&A, 420, 889)

4-3. Extinction curves of low-z AGNs

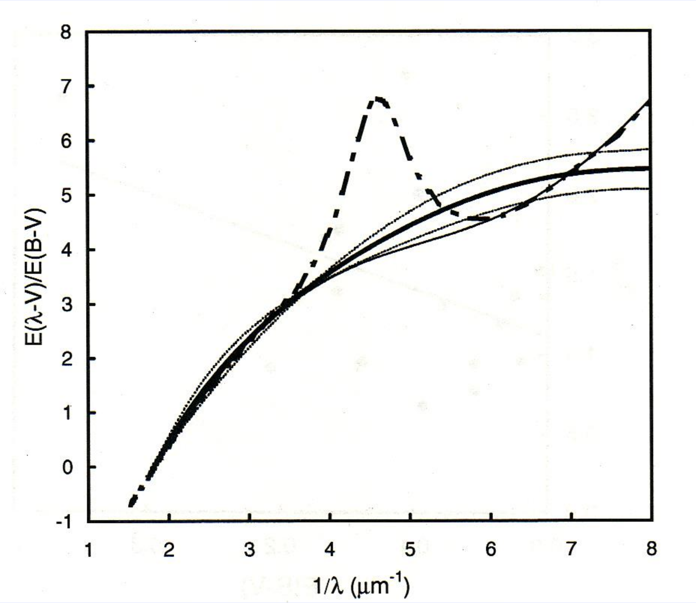


Gaskell et al.
(2004, ApJ, 616, 147)

coagulation of grains?
sublimation of small grains?
(Maiolino et al. 2001)



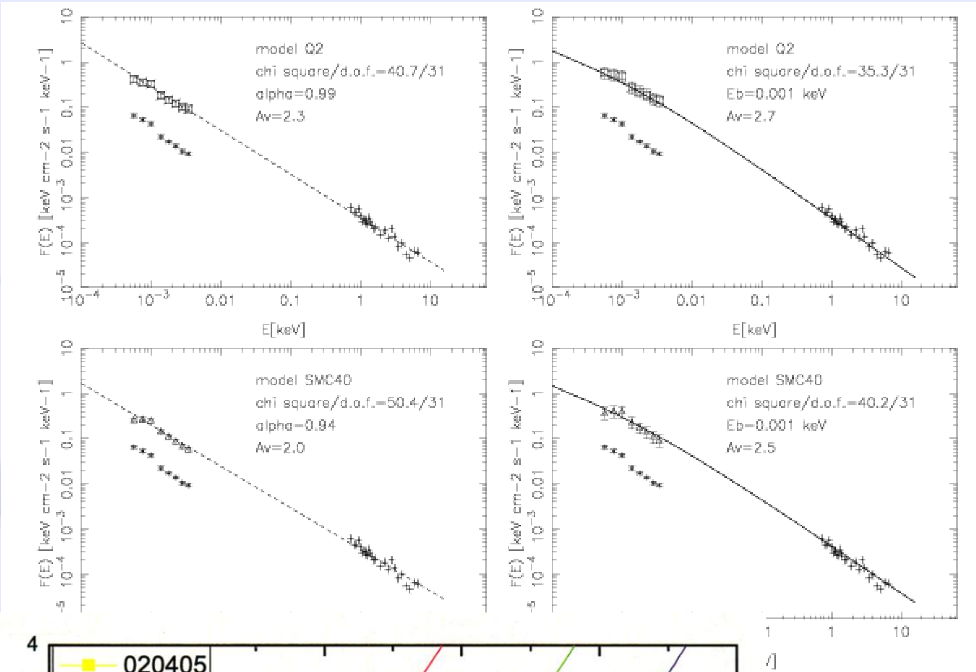
Willot (2005, ApJ, 627, L201)

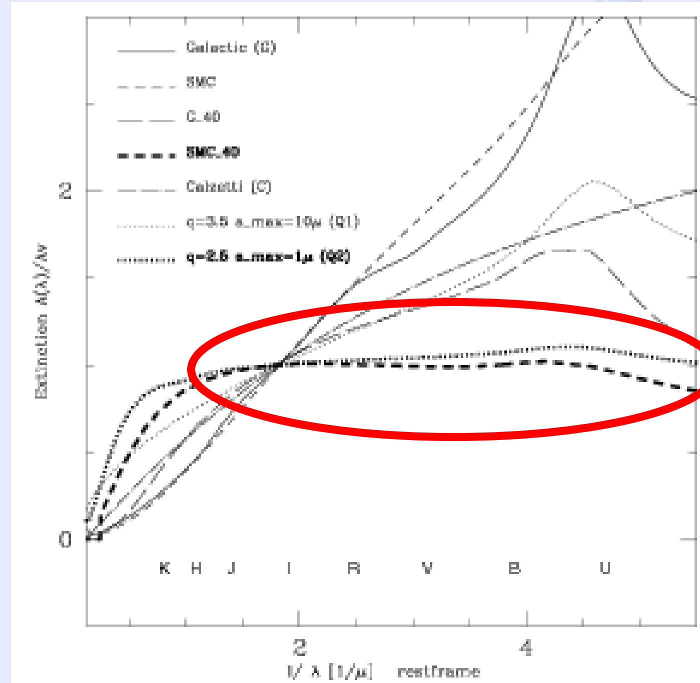


Gaskell & Benker (2008, astro-ph/0711.1013)

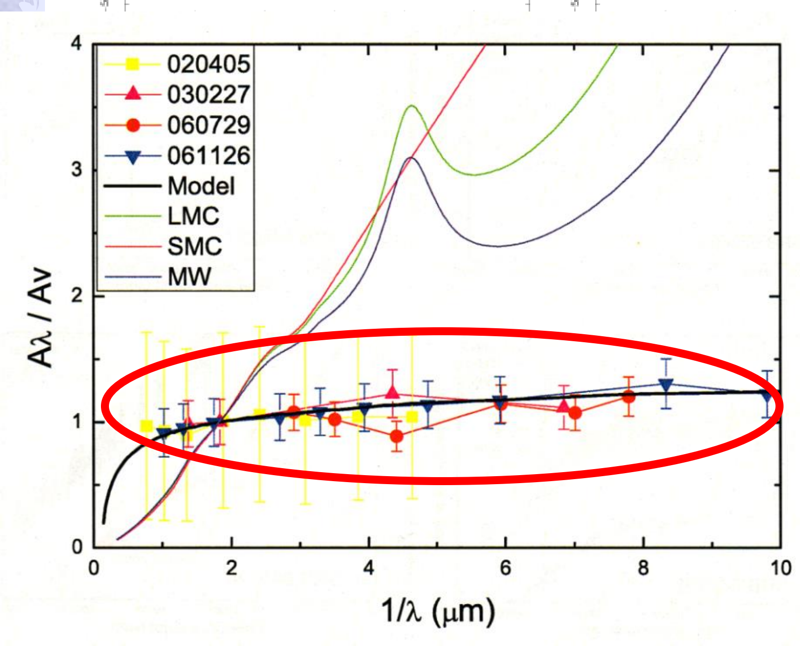
4-4. Extinction curves from GRBs

GRB 020405 at z=0.69





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



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

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

Summary

- The fates of dust grains within SN remnants depend on their initial radii and compositions

- The size distribution of dust surviving the destruction is weighted to relatively large size (> 0.01 μm)

- The mass of surviving dust decreases with increasing the ambient gas density (and explosion energy of SNe)

  for $n_{H,0}$ = 0.1-1 cm^{-3}

  SNe II ➔ M_{dust} = 0.1-0.8 M_{sun}

  PISNe ➔ M_{dust} = 0.1-15 M_{sun}

- Extinction curves in the early universe are expected to be flat.