Formation and Destruction of Dust in Supernovae

（超新星爆発時のダストの形成と破壊）

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Outline

1. Introduction

2. Dust formation in primordial SNe

(Nozawa et al. 2003)

3. Dust evolution in primordial SNRs

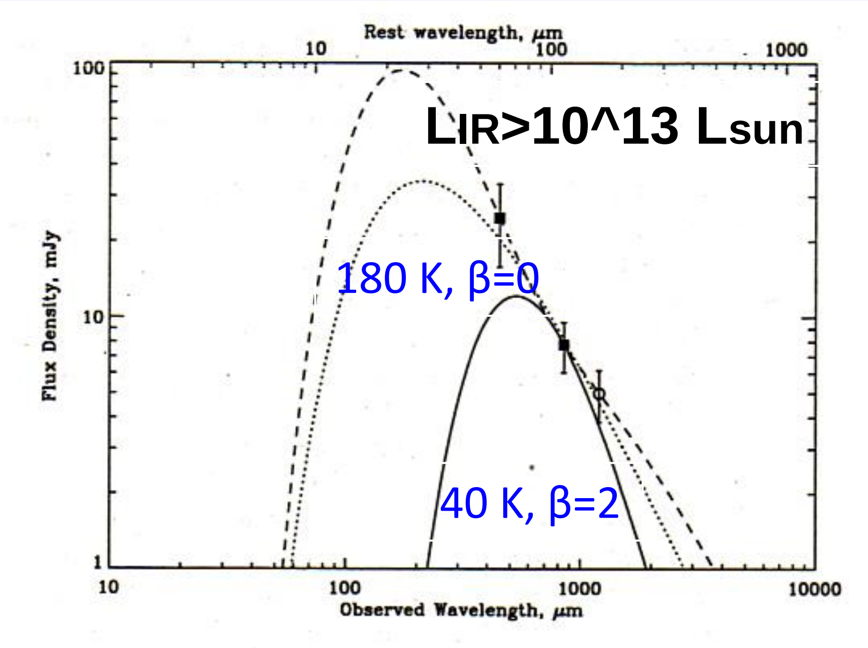
(Nozawa et al. 2007)

4. Summary and ongoing works

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

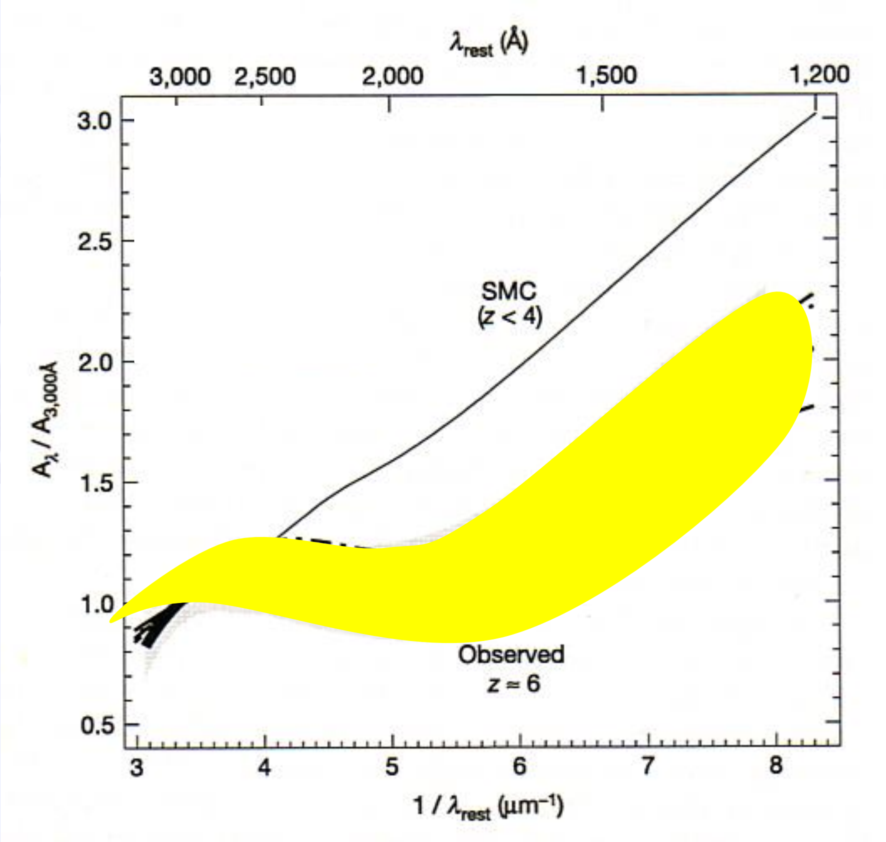
0.1-1 Msun of dust per SN is required to form to explain a large content of dust at high-z galaxies

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

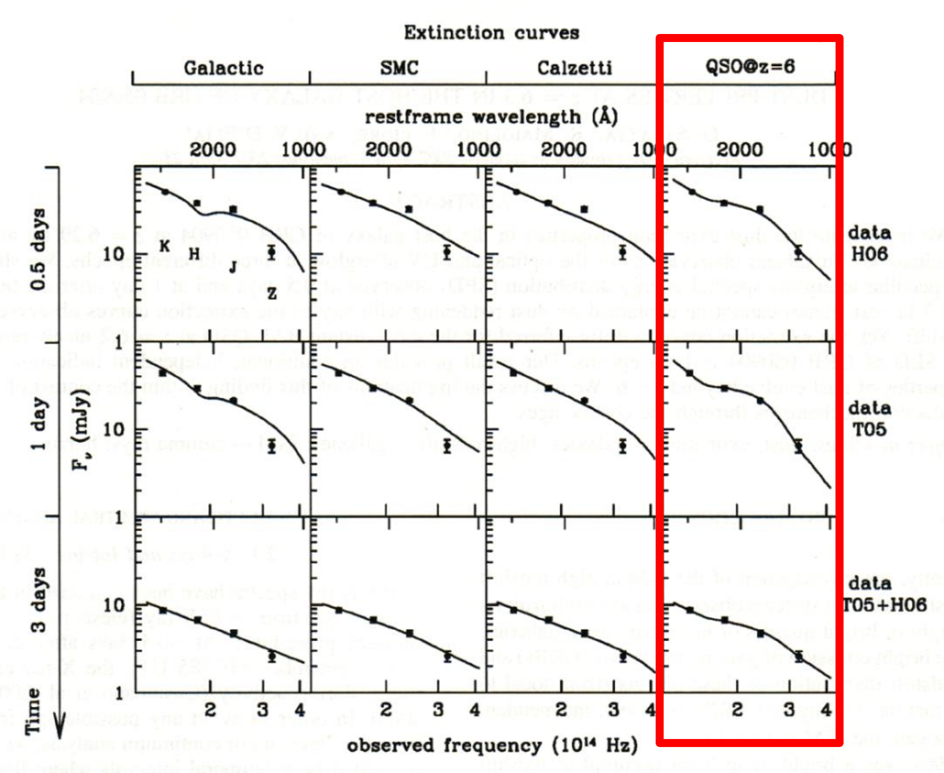
1-2. Extinction curves at high-z

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 galaxies
  - controlling the energy balance in the interstellar space
  - forming molecules (mainly H_2) on the surface
    (e.g., Cazaux & Spaans 2004; Hirashita & Ferrara 2002)
  - providing efficient cooling pathways of gas in metal-poor molecular clouds 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 determining the SFR and the IMF from observations (e.g., Takeuchi-san's talk)

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

1-4. Aim of our study

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

to understand the evolution history of galaxies from both theoretical and observational studies

It is essential to reveal the evolution of dust grains throughout the cosmic age!

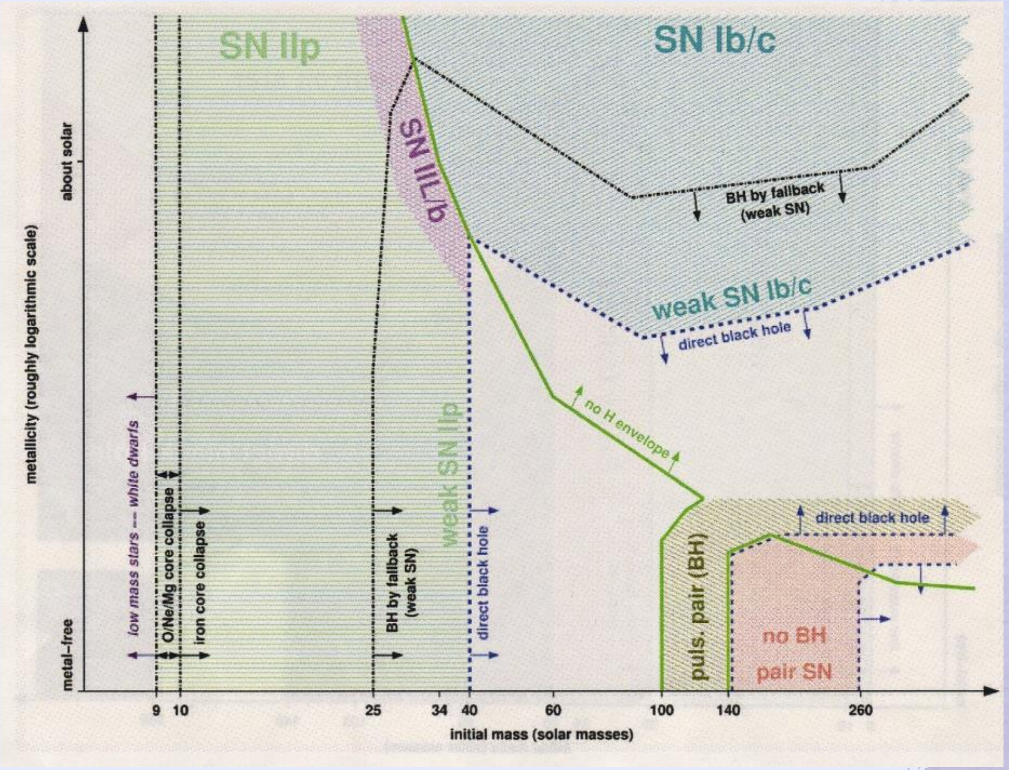
We aim at revealing the composition, size, and amount of dust by treating the formation and destruction processes of dust self-consistently

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 core-collapse SNe

- Population III stars ➔ very massive (M_{pr} =100-500 M_{sun})
  (e.g., Nakamura & Umemura 2001; Bromm et al. 2002)

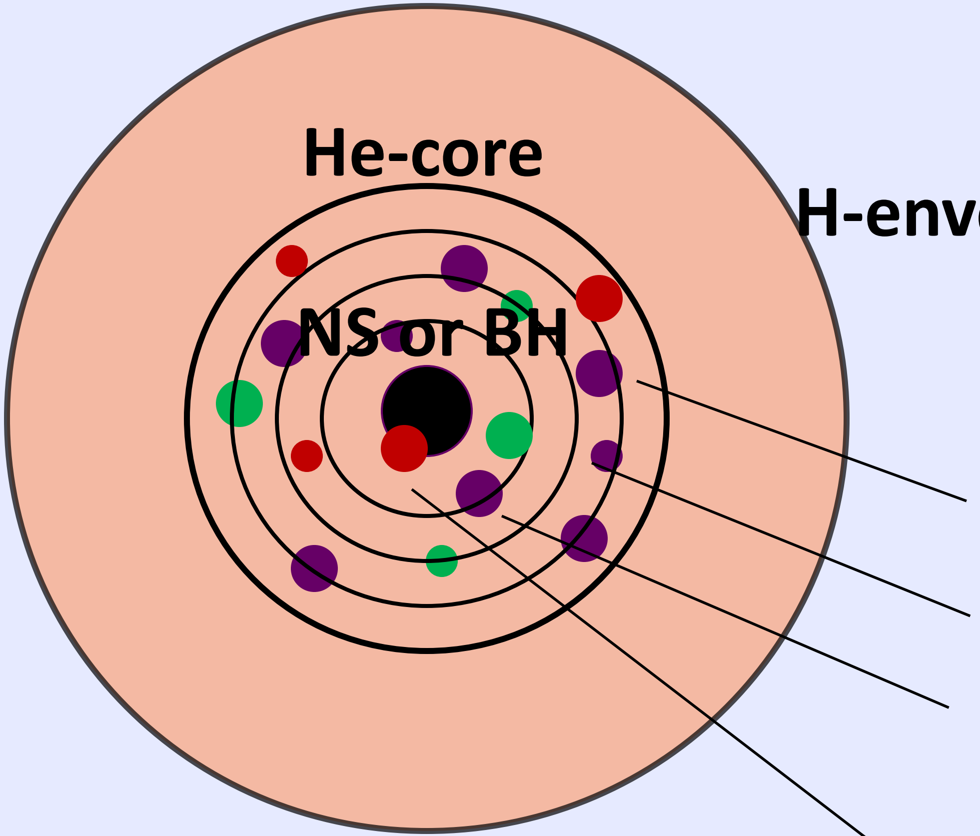
In the early universe
- **Type II SNe (SNe II)**
  ; M_{pr}=8−40 M_{sun}
- **pair-instability SNe**
  ; M_{pr}=140−260 M_{sun}



(Heger et al. 2003, ApJ, 591, 288)

2. Dust Formation in Primordial SNe

at ~1 days



Dust formation
at ~1-3 years
after explosion

2-1-1. Calculations of dust formation

- nucleation and grain growth theory taking account of chemical reaction at condensation

(Kozasa & Hasegawa 1987)

- key species：
  gas species with the least collision frequency among reactants

  key species controls the kinetics of the nucleation and grain growth

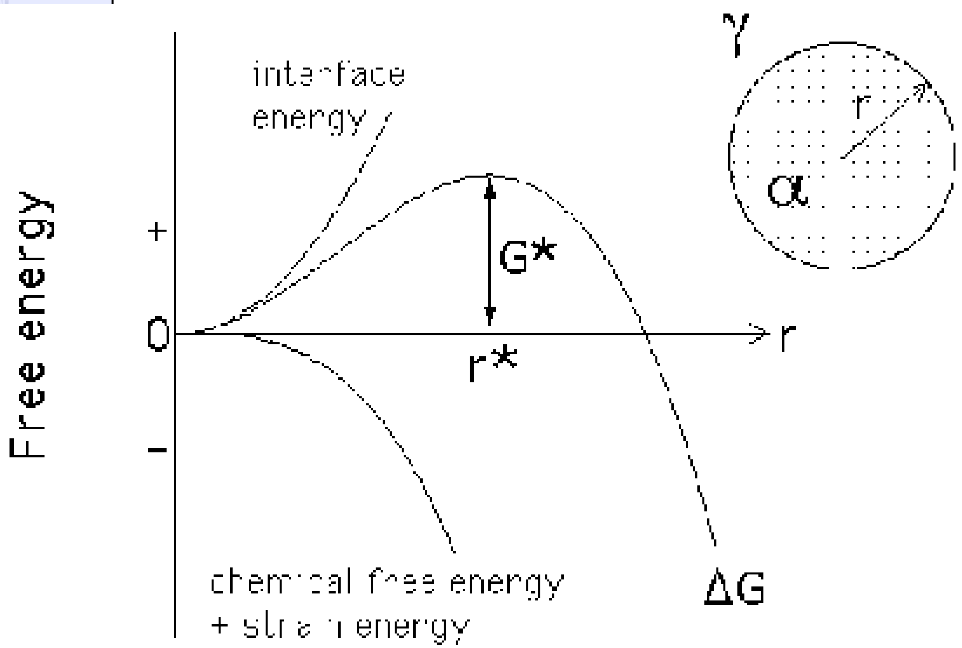
Dust species	Chemical reactions
$Fe_{(s)}$	$Fe_{(g)} \rightarrow Fe_{(s)}$
$FeS_{(s)}$	$Fe_{(g)} + S_{(g)} \rightarrow FeS_{(s)}$
$Si_{(s)}$	$Si_{(g)} \rightarrow Si_{(s)}$
$Ti_{(s)}$	$Ti_{(g)} \rightarrow Ti_{(s)}$
$V_{(s)}$	$V_{(g)} \rightarrow V_{(s)}$
$Cr_{(s)}$	$Cr_{(g)} \rightarrow Cr_{(s)}$
$Co_{(s)}$	$Co_{(g)} \rightarrow Co_{(s)}$
$Ni_{(s)}$	$Ni_{(g)} \rightarrow Ni_{(s)}$
$Cu_{(s)}$	$Cu_{(g)} \rightarrow Cu_{(s)}$
$C_{(s)}$	$C_{(g)} \rightarrow C_{(s)}$
$SiC_{(s)}$	$Si_{(g)} + C_{(g)} \rightarrow SiC_{(s)}$
$TiC_{(s)}$	$Ti_{(g)} + C_{(g)} \rightarrow TiC_{(s)}$
$Al_2O_{3(s)}$	$2Al_{(g)} + 3O_{(g)} \rightarrow Al_2O_{3(s)}$
$MgSiO_{3(s)}$	$Mg_{(g)} + SiO_{(g)} + 2O_{(g)} \rightarrow MgSiO_{3(s)}$
$Mg_2SiO_{4(s)}$	$2Mg_{(g)} + SiO_{(g)} + 3O_{(g)} \rightarrow Mg_2SiO_{4(s)}$
$SiO_{2(s)}$	$SiO_{(g)} + O_{(g)} \rightarrow SiO_{2(s)}$
$MgO_{(s)}$	$Mg_{(g)} + O_{(g)} \rightarrow MgO_{(s)}$
$Fe_3O_{4(s)}$	$3Fe_{(g)} + 4O_{(g)} \rightarrow Fe_3O_{4(s)}$
$FeO_{(s)}$	$Fe_{(g)} + O_{(g)} \rightarrow FeO_{(s)}$

2-1-2. Nucleation rate of dust

Steady-state nucleation rate

$$J_s(t) = \alpha_s \Omega \left(\frac{2\sigma}{\pi m_1} \right)^{\frac{1}{2}} \Pi c_1^2(t) \exp \left[-\frac{4}{27} \frac{\mu^3}{(\ln S)^2} \right]$$

$$J_s(t) = 4\pi a_0^2 \alpha_s \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1^2(t) \frac{1}{3} \left(\frac{\mu}{\pi} \right)^{\frac{1}{2}} \exp \left[-\frac{4}{27} \frac{\mu^3}{(\ln S)^2} \right]$$



$$g(n) = -(n-1) \ln S + \mu (n-1)^{\frac{2}{3}}$$

$$\boxed{(n_* - 1)^{\frac{1}{3}} = \frac{2\mu}{3 \ln S}}$$

$$k_n = 4\pi a^2 \alpha_s \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} = 4\pi a_0^2 n^{\frac{2}{3}} \alpha_s \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}}$$

es

μ : $\mu = 4\pi a_0^2 \sigma / kT$; energy barrier for nucleation

2-1-3. Basic equations of dust formation

Equation of conservation for key species

$$1-\frac{c_1(t)}{\tilde{c}_1(t)}=\int_{t_0}^{t}\frac{J(t')}{\tilde{c}_1(t')}\frac{4\pi}{3\Omega}r^3(t,t')dt'$$

$$V(t)\tilde{c}_1(t)-V(t)c_1(t)=\int_{t_0}^{t}V(t')J(t')n[r(t,t')]dt'$$

$$\frac{\partial V_{\rm d}}{\partial t}=4\pi r^2\frac{\partial r}{\partial t}=\alpha_s\Omega 4\pi r^2\left\langle v\right\rangle c_1(t)$$

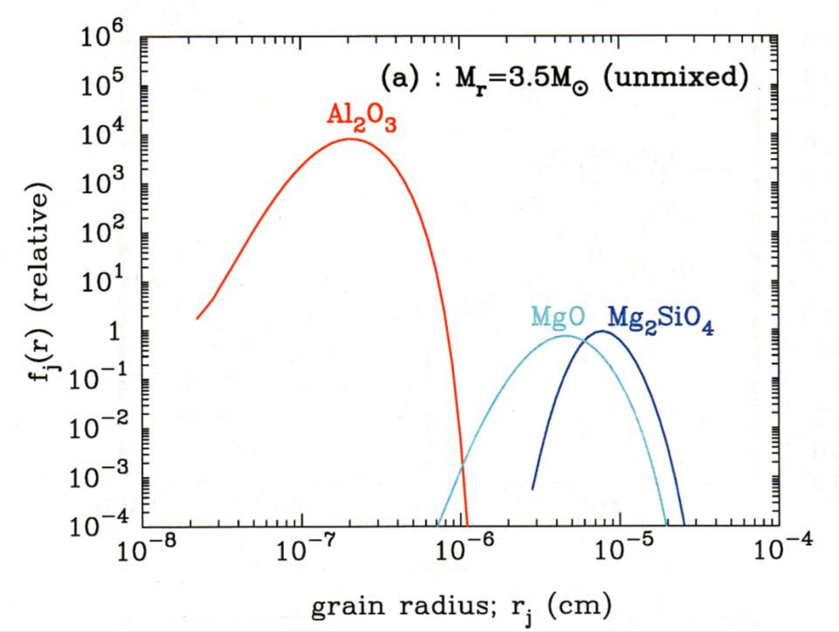
$$\tau_{\rm coll}^{-1}(t)=4\pi a_0^2\alpha_s\left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}}c_1(t)$$

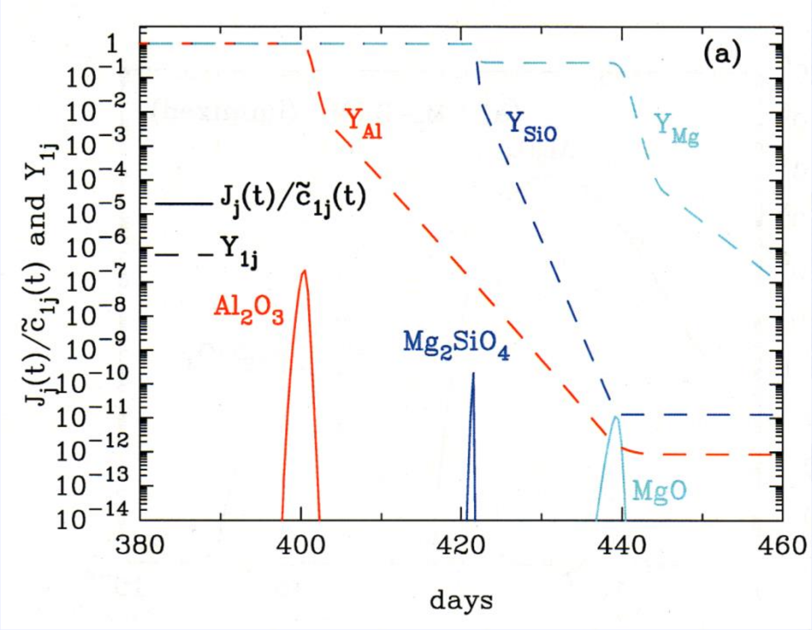
$$r(t,t_0)=r_*+\int_{t_0}^{t}\frac{1}{3}a_0\tau_{\rm coll}^{-1}(t')dt'$$

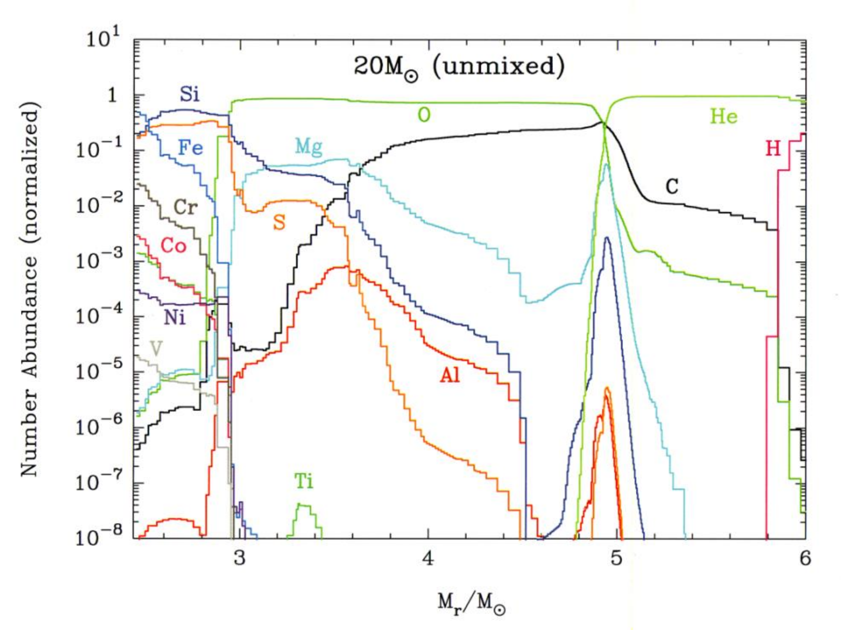
2-2. Models of dust formation calculation

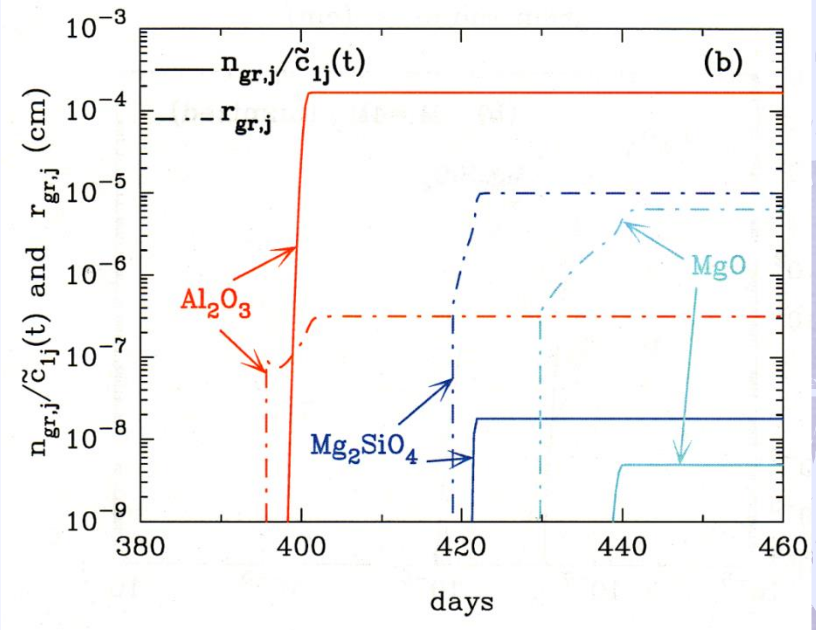
- **models of Pop III SNe** (Umeda & Nomoto 2002)
  - SNe II : M_{pr} = 13, 20, 25, 30 Msun (E_{51}=1)
  - PISNe : M_{pr} = 170 Msun (E_{51}=20), 200 Msun (E_{51}=28)
- **time evolution of gas temperature**
  - $\rho(t) = \rho_0 (t / t_0)^{-3}$
  - T(t) is calculated by solving the radiative transfer 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)
- **formation of CO and SiO molecules ➔ complete**

2-3. Behavior of dust formation

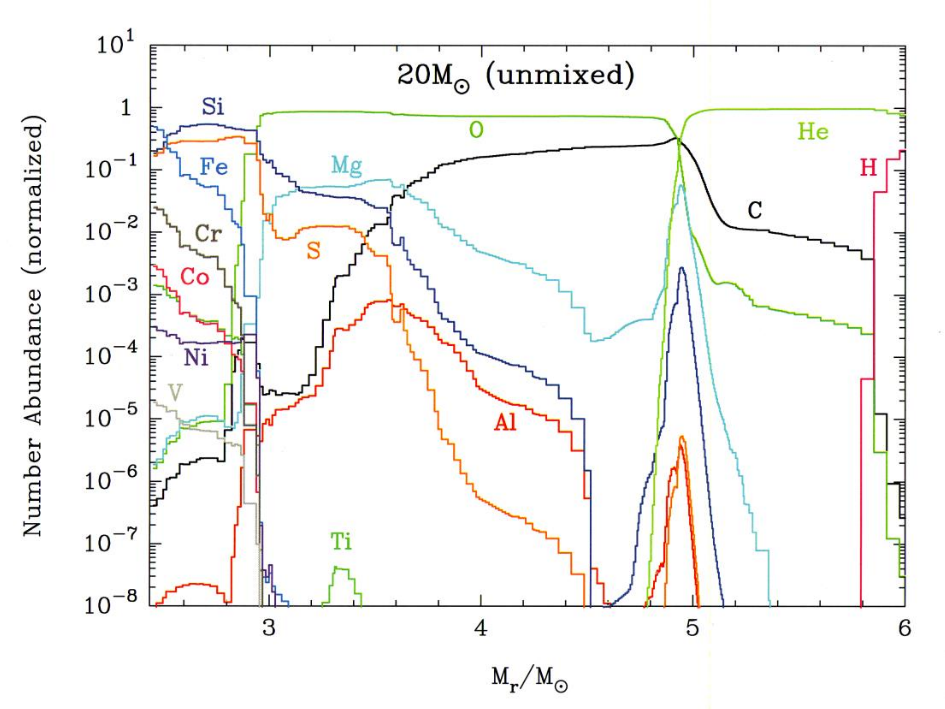


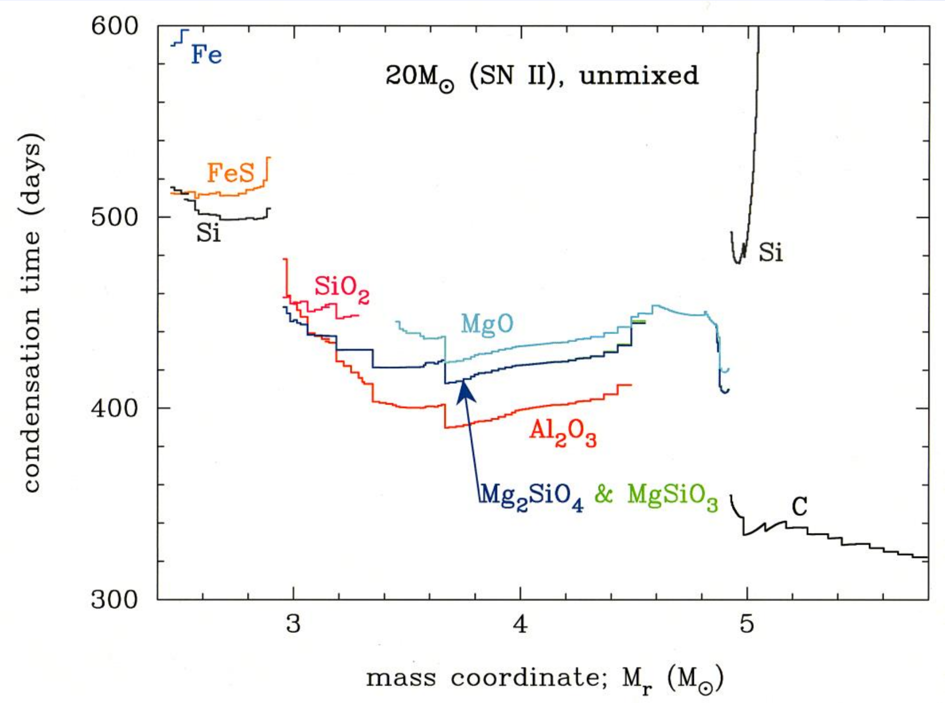






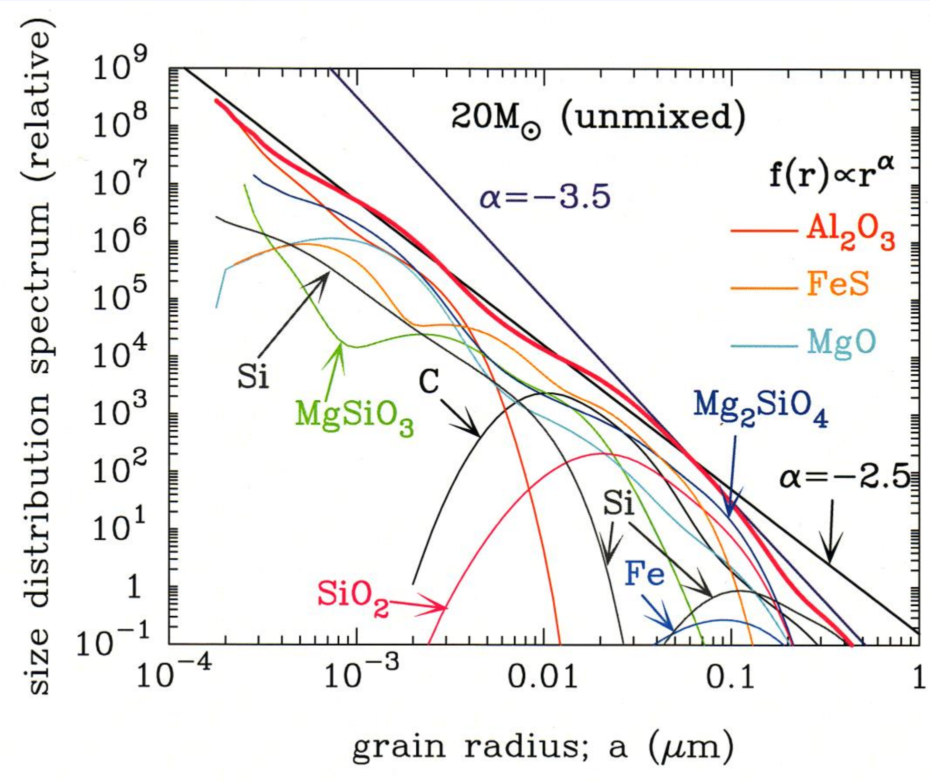
2-4. Dust formation in the unmixed ejecta

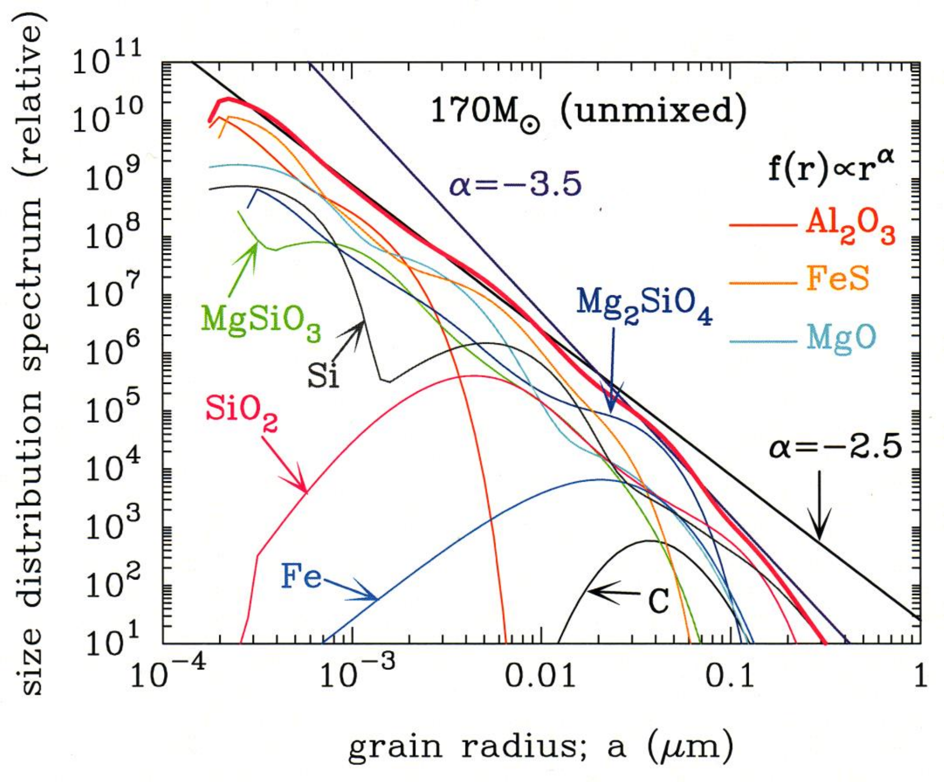




- Various dust species (C, $MgSiO_3$, Mg_2SiO_4, SiO_2, Al_2O_3, MgO, Si, FeS, Fe) form in the unmixed ejecta, reflecting the elemental composition in each layer
- The condensation time; 300-600 days for SNe II
  400-800 days for PISNe

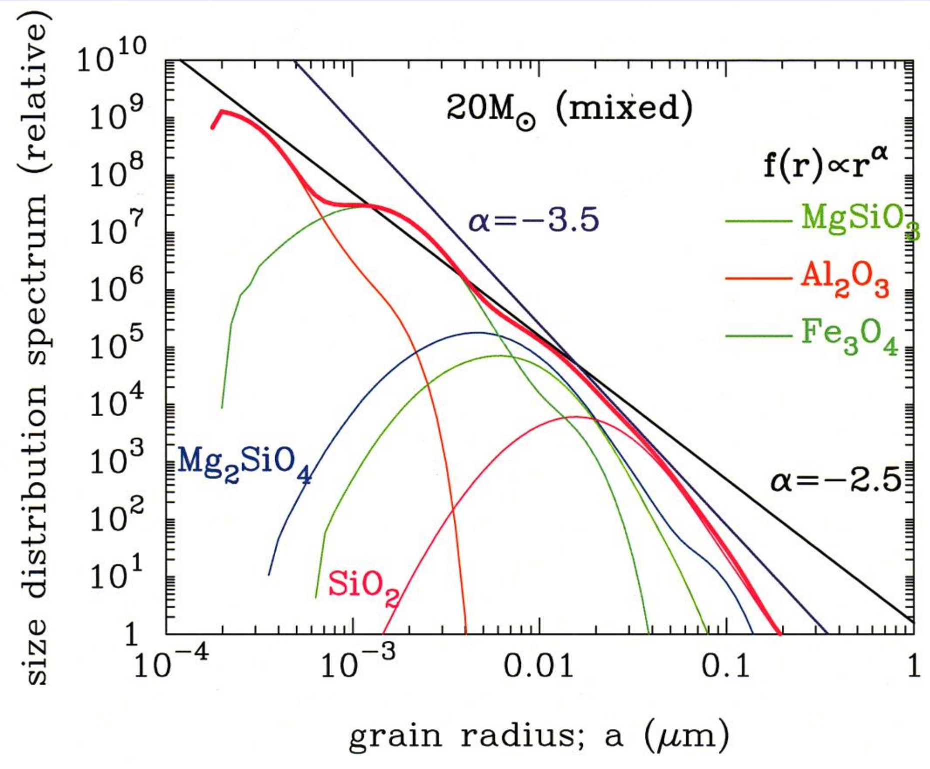
2-5. Dust formed in the unmixed ejecta

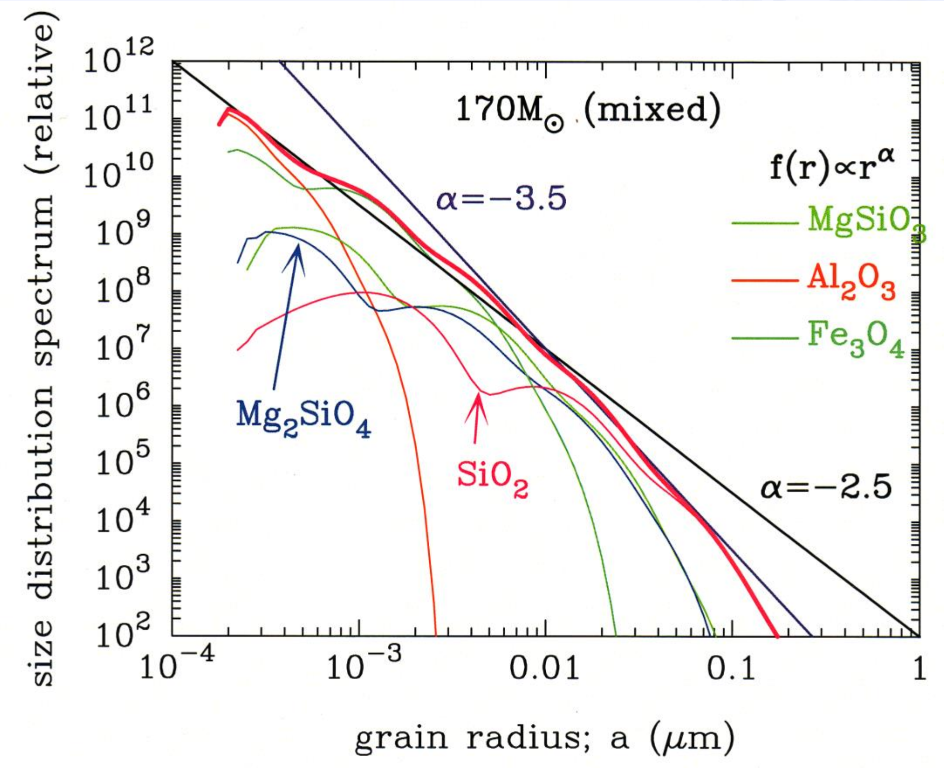




- C, SiO2, and Fe grains have lognormal-like size distribution, while the other grains have power-law-like size distribution
- The composition and size distribution of dust formed are almost independent of type of supernova

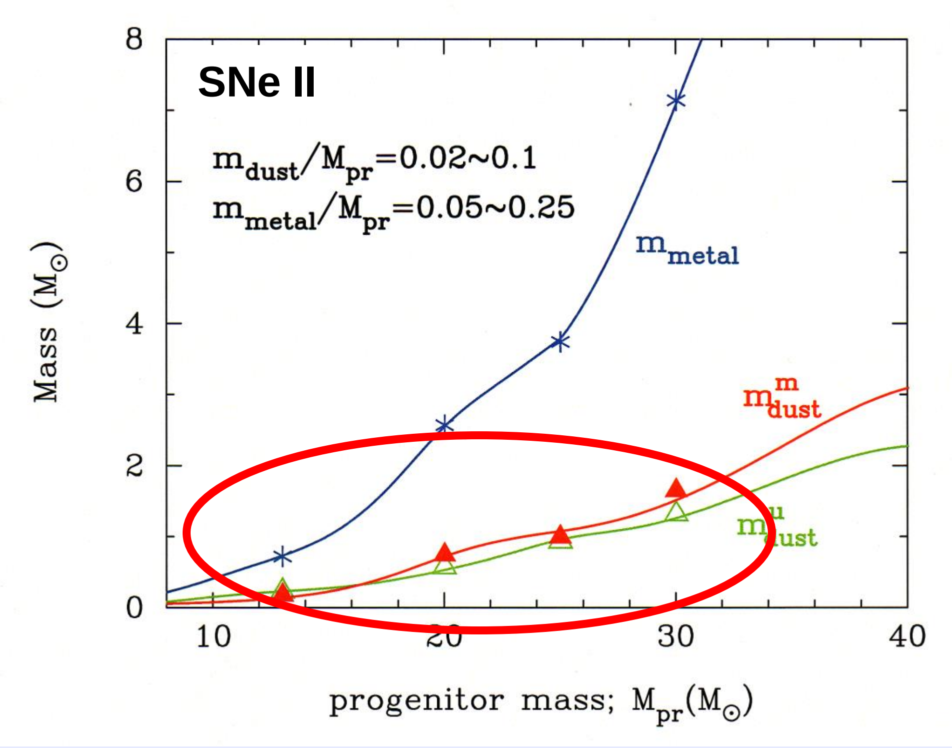
2-6. Dust formed in the mixed ejecta

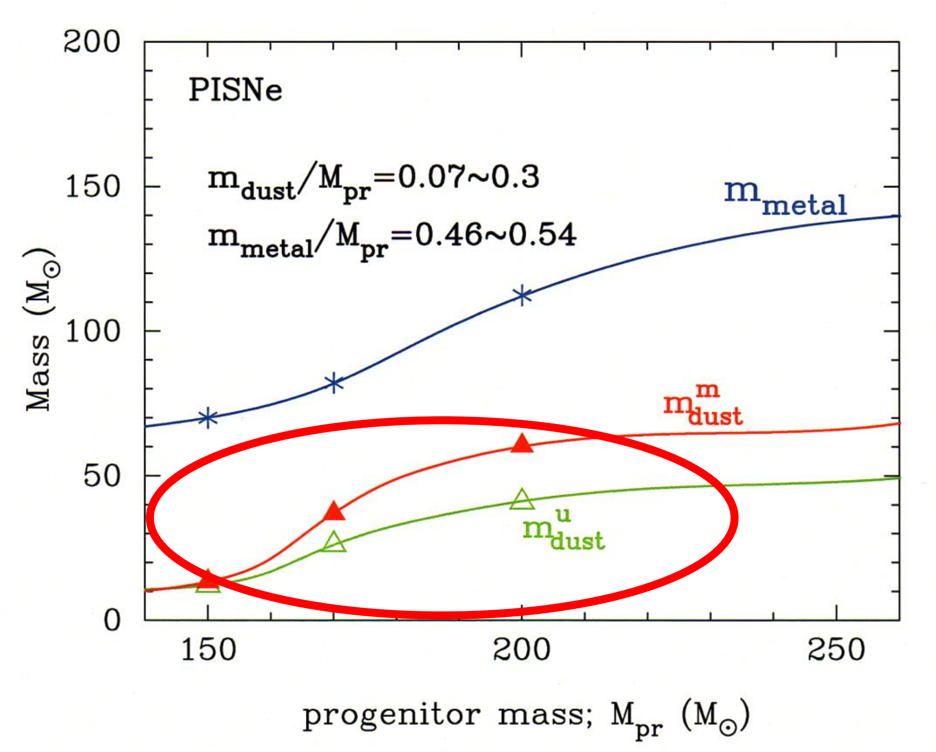




- Because oxygen is rich in the mixed ejecta, only silicates ($MgSiO_3$, Mg_2SiO_4, SiO_2) and oxides (Fe_3O_4, Al_2O_3) form
- The size distribution of each dust species except for Al_2O_3 is lognormal-like

2-7. Total mass of dust formed





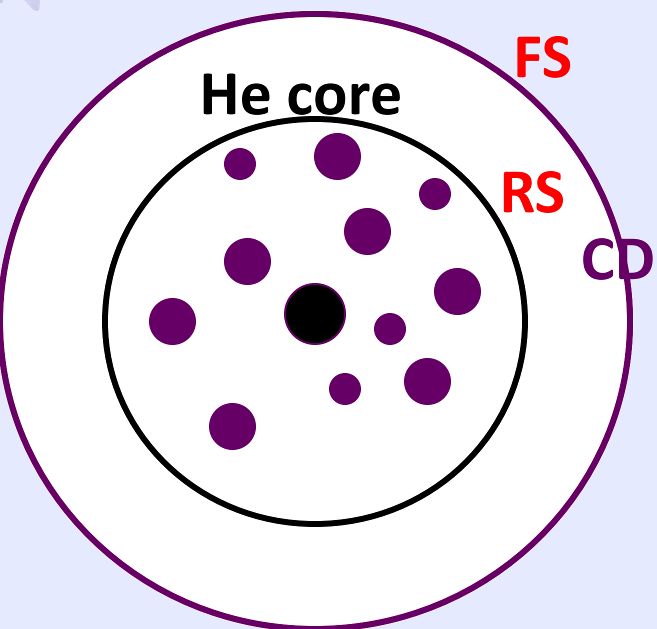
- Total dust mass increases with increasing progenitor mass
  SNe II : M_{dust} = 0.1-2 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.2-0.3
  PISNe : M_{dust} =10-60 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.3-0.5

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

3. Dust Evolution in Primordial SNRs

$T = (1\text{-}2)\ x10^4$ K
$n_{H,0} = 0.1\text{-}1\ cm^{-3}$

(Kitayama et al. 2004;
Machida et al. 2005)



3-1-1. Time evolution of shock wave

- Basic equations (spherical symmetry)

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

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

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

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

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

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

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

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

3-1-2. Initial condition for shock wave

- **Hydrodynamical model of SNe** (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** (homogeneous)
  - gas temperature ; $T = 10^4$ K
  - gas density ; **$n_{H,0}$ = 0.1, 1, and 10 cm^{-3}**

- **Model of Dust**
  - initial size distribution and spatial distribution of dust
    ➔ results of dust formation calculations
  - treating as a test particle (neglecting the effects of charge)

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

3-2-1. Dynamics of dust

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

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

$$\boxed{\begin{aligned} F_\mathrm{drag} &= m_\mathrm{d}\frac{dw_\mathrm{d}}{dt} = -\pi a^2 \sum n_i \langle v_i m_i v_i \cos\theta \rangle \\ \frac{dw_\mathrm{d}}{dt} &= -\frac{\pi a^2}{\frac{4}{3}\pi a^3 \rho_d} n_\mathrm{H} \sum A_i \langle v_i m_i v_i \cos\theta \rangle \\ &= -\frac{3n_\mathrm{H}}{4a\rho_d} kT \sum A_i G_i \end{aligned}}$$

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

3-2-2. 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

$$\frac{dV_{\rm d}}{dt} = 4\pi a^2 \frac{da}{dt} = -\pi a^2 \frac{4\pi a_0^3}{3} \sum n_i \langle v_i Y_i \rangle$$

$$\frac{da}{dt} = -\frac{1}{4}\Omega n_{\rm H} \sum A_i \langle v_i Y_i \rangle$$

· rate ... s taken

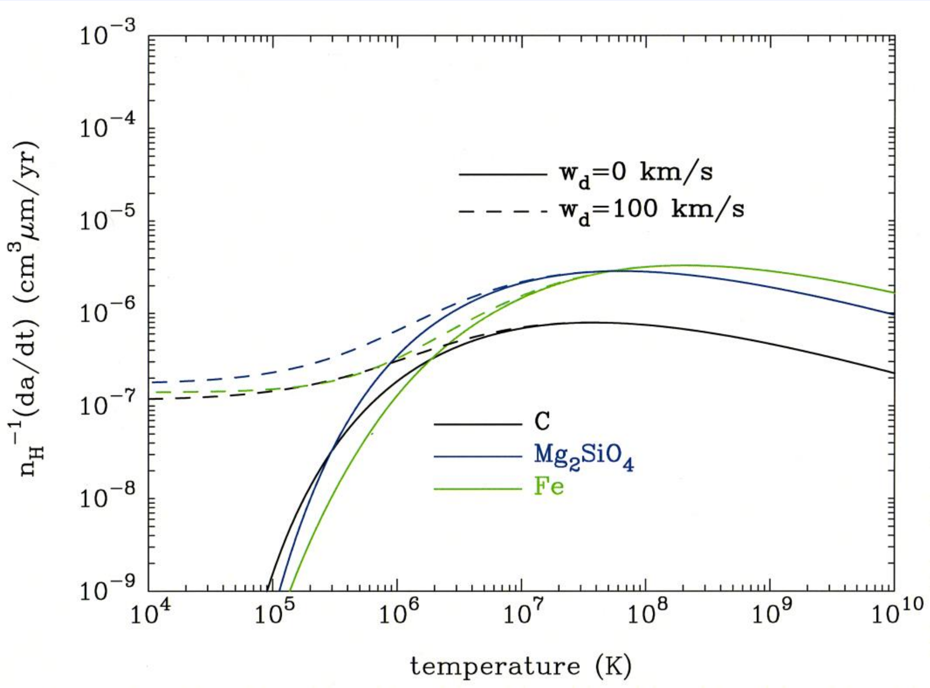
acco ...)

$\mathcal{R}($ ... $)X_i(\epsilon)d\epsilon$

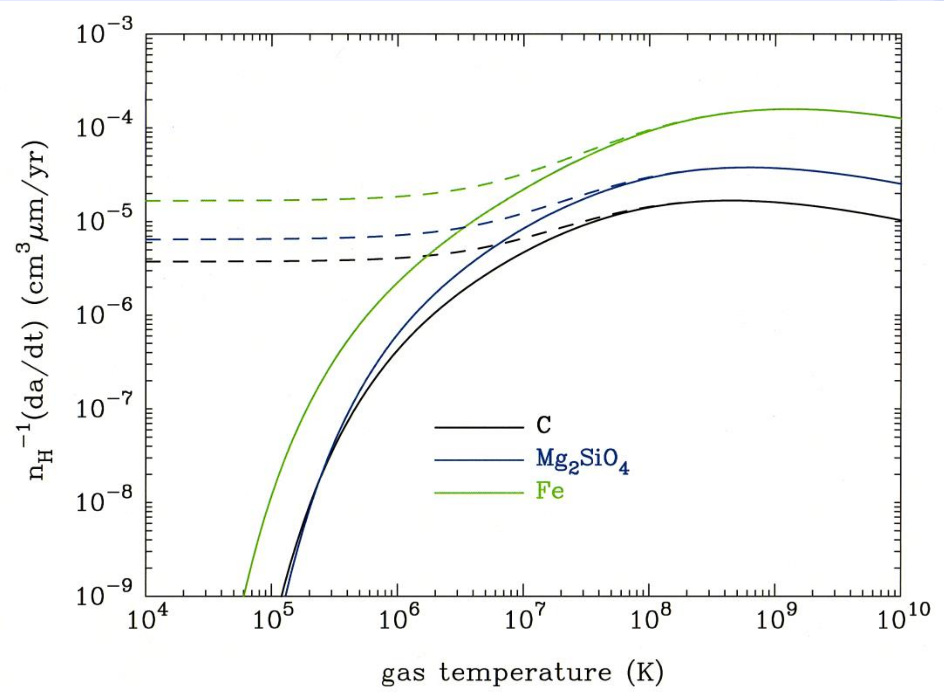
$$\frac{da}{dt} = -\frac{m_{\rm sp}}{2\rho_{\rm d}} n_{\rm H} \sum A_i \left(\frac{8kT}{\pi m_i}\right)^{1/2} \frac{e^{-s_i^2}}{2s_i} \times \int \epsilon^{\frac{1}{2}} e^{-\epsilon_i} \sinh(2 s_i \epsilon_i^{\frac{1}{2}}) Y_i^0(\epsilon_i) d\epsilon_i$$

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

for primordial composition gas



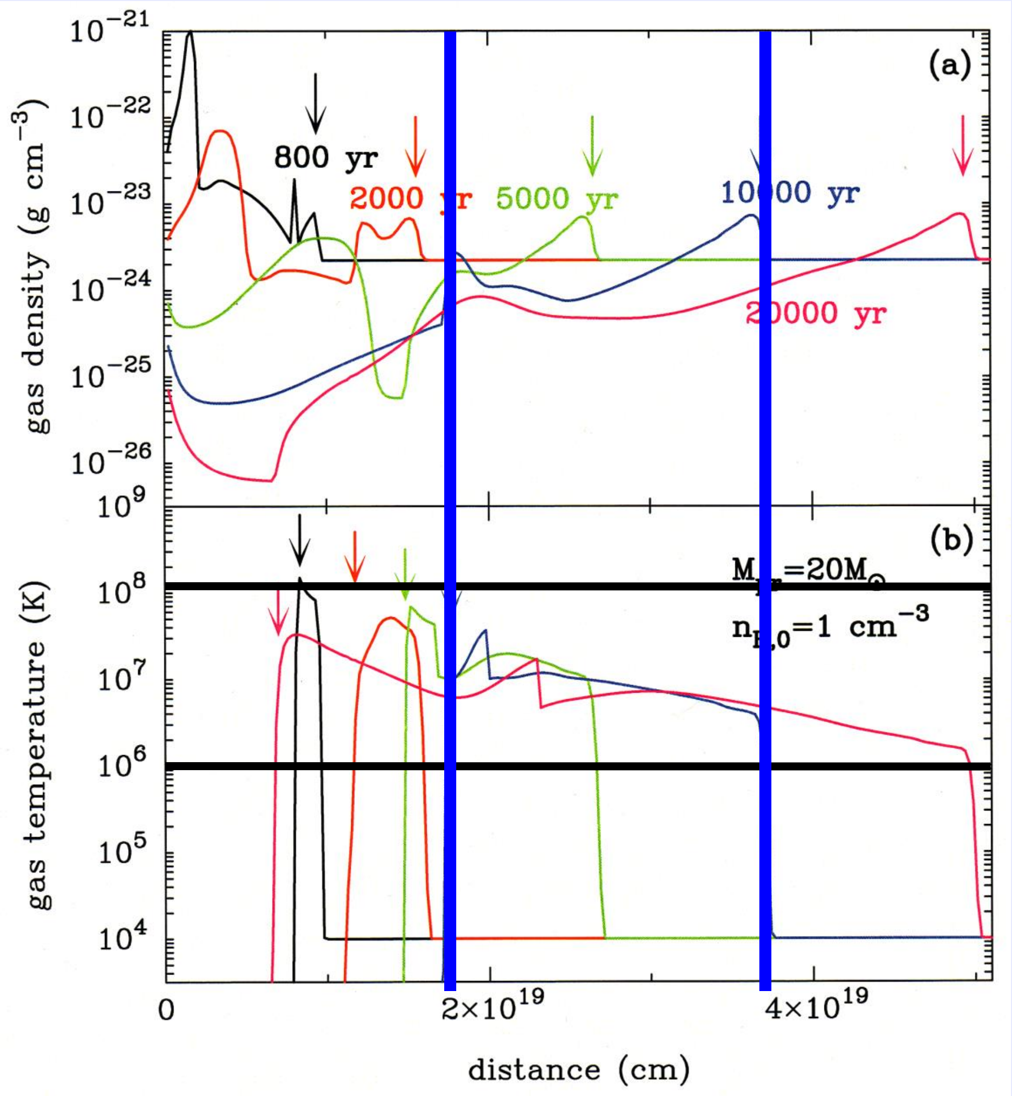
for oxygen ions



- 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 the primordial gas with T > 10^6 K**

3-3.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

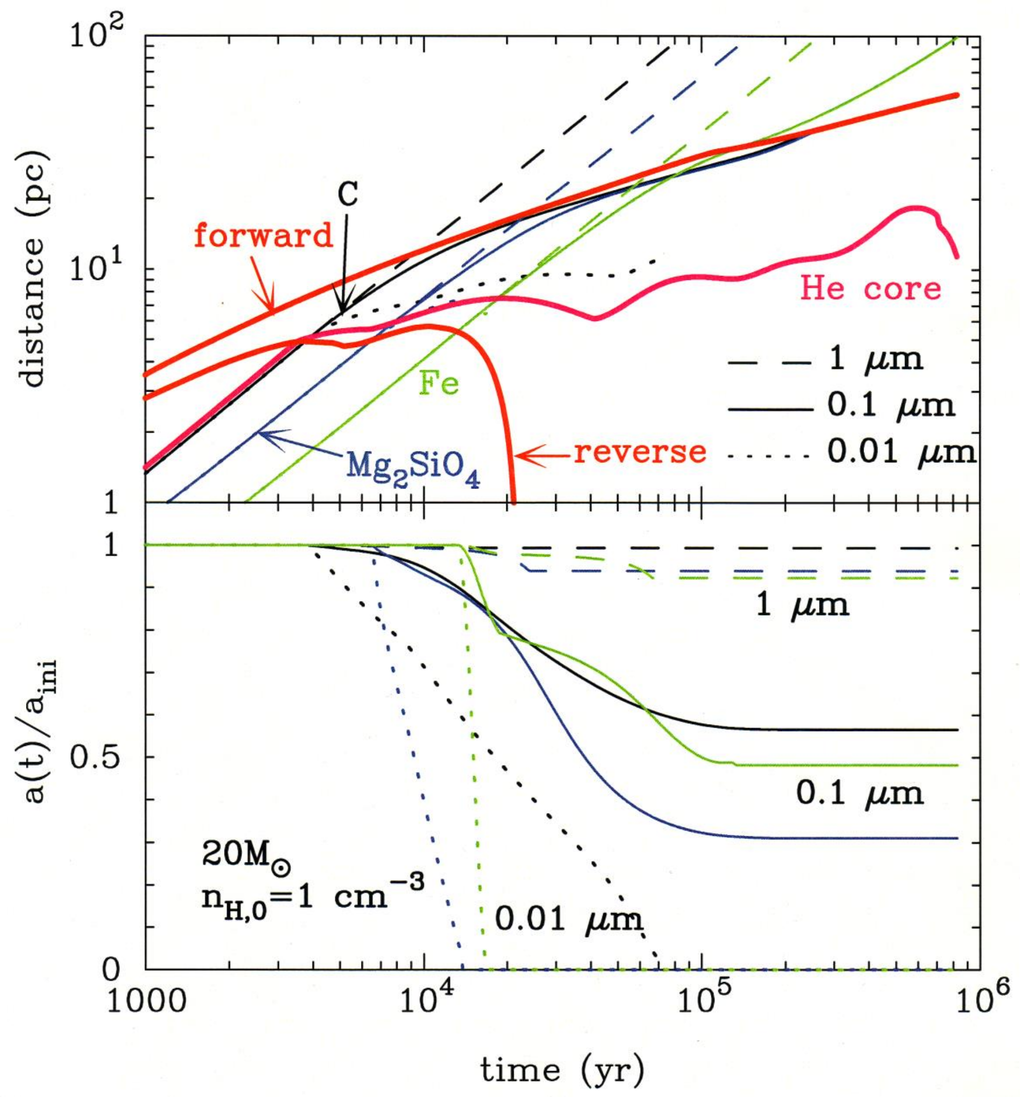
The temperature of the gas swept up by the shocks

➔ **10^6-10^8 K**

↓

Dust grains residing in this hot gas are eroded by sputtering

3-4. Evolution of dust in SNRs



Model : M_{pr}=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

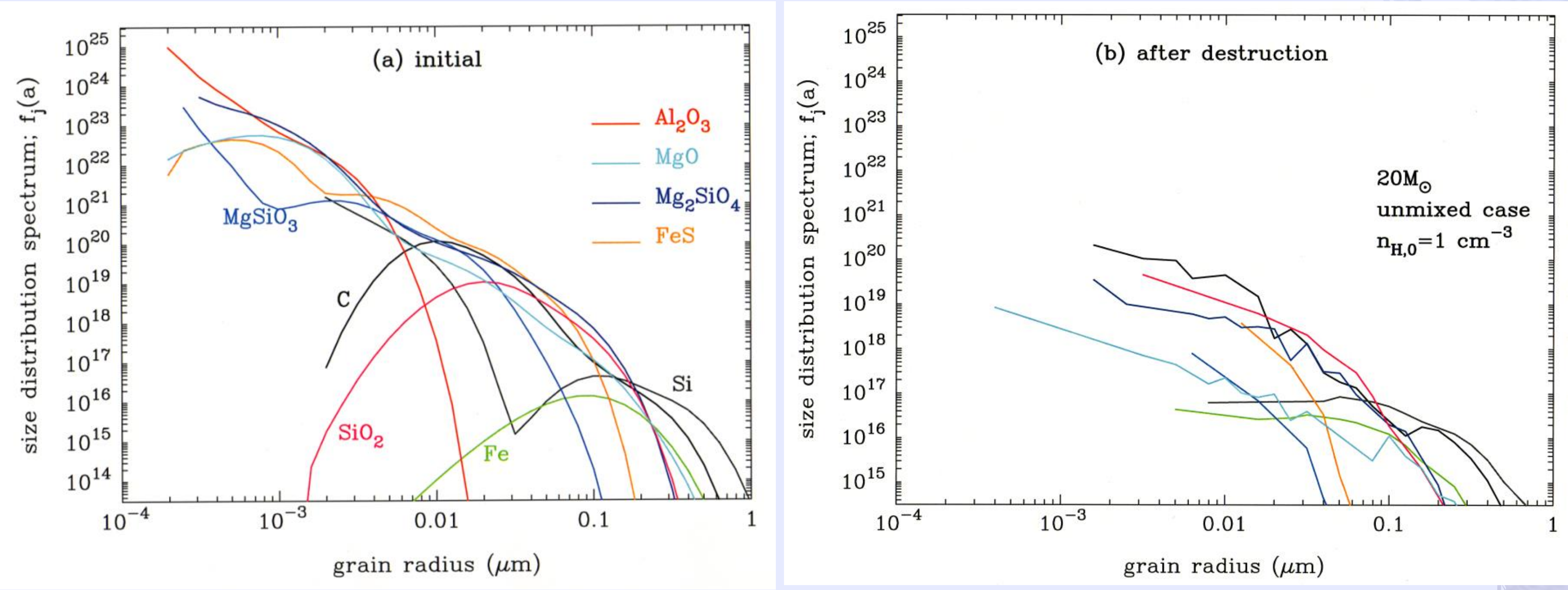
The evolution of dust heavily depends on the initial radius and composition

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

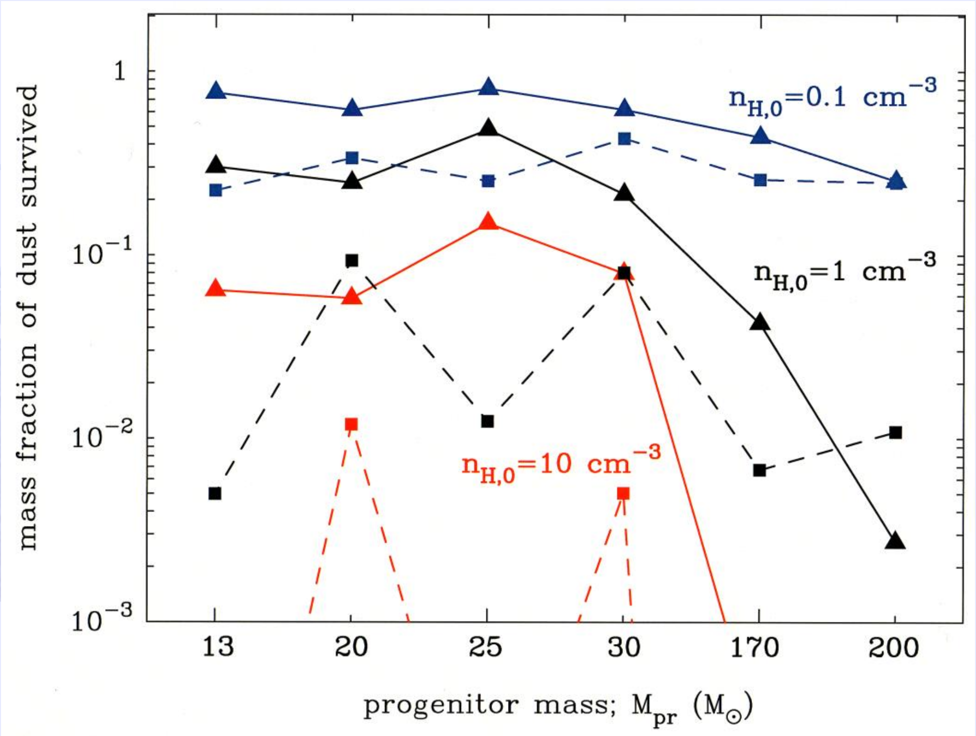
3-5. Size distribution of surviving dust



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 (> 0.01 μm)**

3-6. Total mass fraction of surviving dust



星間空間中の密度が大きいほど、
生き残るダストの質量は小さい

完全に破壊されるダストの初期サイズ

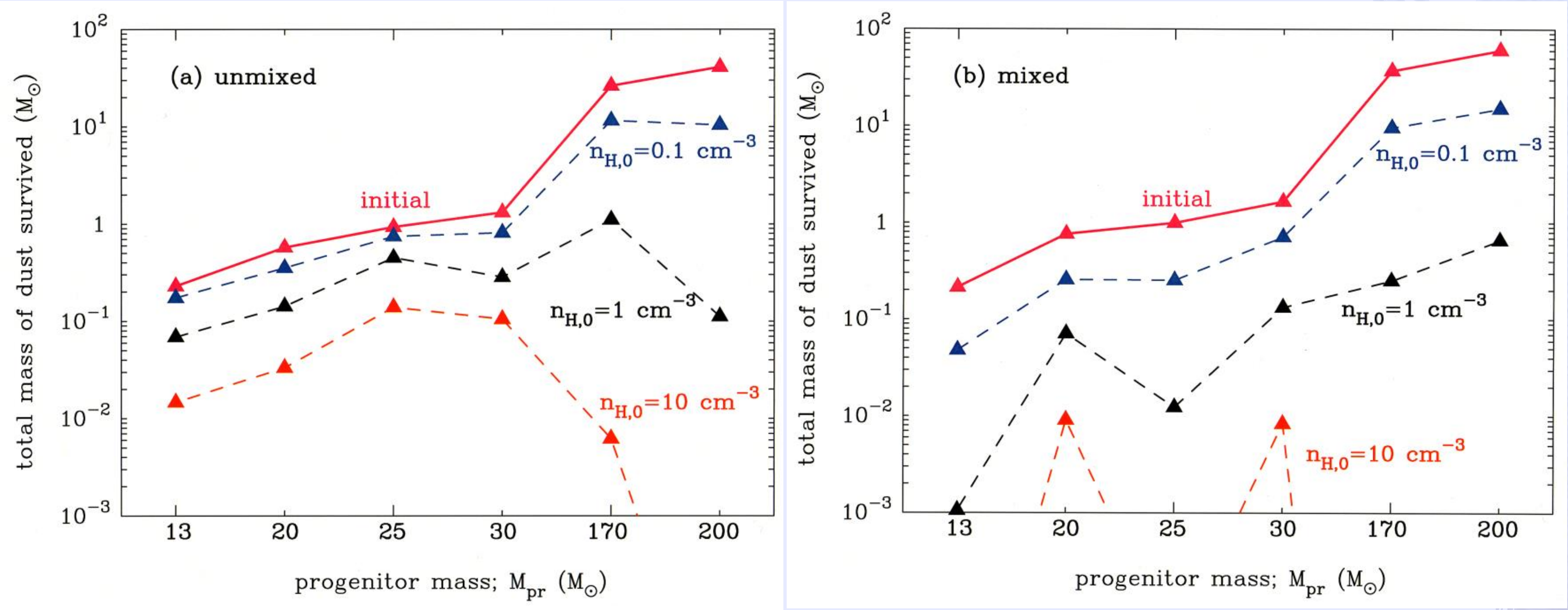
a_{ini} ＜～0.01μm for $n_{H,0}$ = 0.1 cm^{-3}

a_{ini} ＜～0.05μm for $n_{H,0}$ = 1 cm^{-3}

a_{ini} ＜～0.2μm for $n_{H,0}$ = 10 cm^{-3}

- mixed caseで形成されたダストはunmixed caseで形成されたダストよりも破壊されやすい
- PISNeで形成されたダストはSNe IIよりも破壊されやすい

3-7. 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)

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} for the unmixed case

PISNe ➔ M_{dust} = 0.1-15 M_{sun}

➔ high enough to explain the content of dust in high-redshift galaxies

Ongoing work

- **dependence of dust formation on the initial metallicity (Z) of progenitor star and type of SNe**
- **comparison with observations**

➔ insights into the fundamental processes of formation and destruction of dust

– formation of dust in SN Ib (peculiar SN 2006jc)

(Nozawa et al. 2008)

– formation of dust in SNe IIb and its evolution

➔ Cas A SNR

– formation of dust in SNe Ia, in mass-loss winds of AGB stars and massive stars? and quasar winds?

– destruction of ISM-dust by SN shock (Nozawa et al. 2006)

➔ including grain-grain collision