Formation of Dust in Primordial Supernovae and Its Survival within the Supernova Remnants

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）

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Contents of my talk

1. Introduction

2. Dust formation in the ejecta of Pop III SNe

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

3. Dust evolution within Pop III SN remnants

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

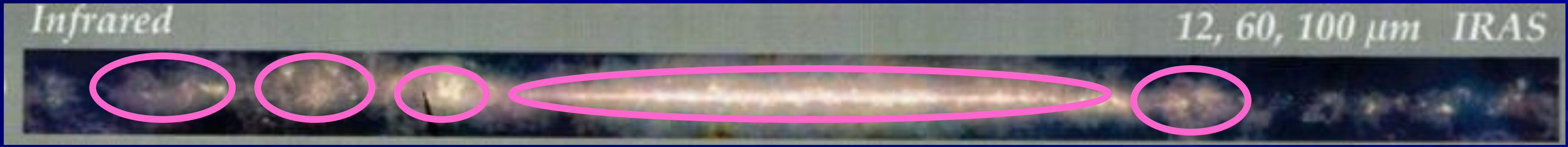
1. Introduction

1-1. Cosmic dust

○ Cosmic dust : solid particle with size of a few Å to 0.1 mm
interplanetary dust, **interstellar dust, intergalactic dust** …

Milky Way (optical)

Milky way (infrared)



Dust grains absorb UV and optical lights and reemit it by their thermal radiation at IR wavelengths!

1-2. Interstellar dust in our Galaxy

○ Dust in our Galaxy ➔ **where and when is dust formed?**

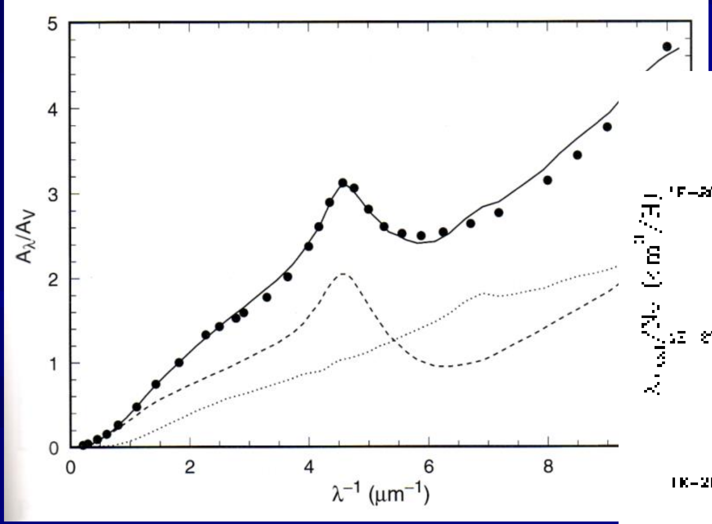
composition; graphite (or carbonacious) grains
silicate (SiO_2, Mg_2SiO_4, $MgFeSiO_4$…) grains

size ; $n(a) = f(a)da = a^{-3.5}\,da$ (0.005~0.25 μm)

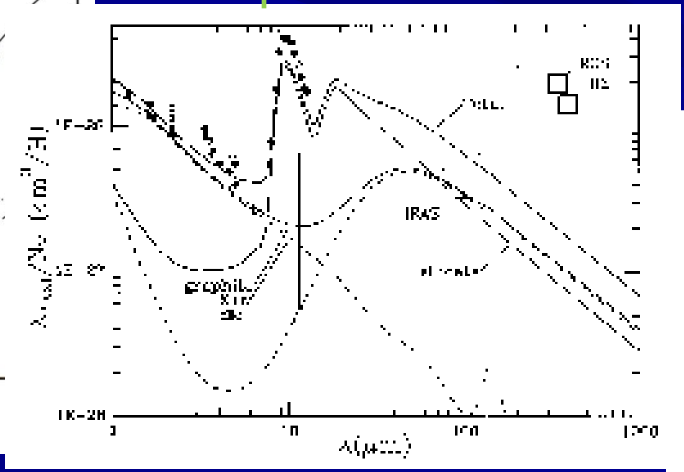
amount ; $M_{dust} / M_{gas} \sim 1 / 140$ (~10^9 Msun)

(e.g., Draine & Lee 1984)

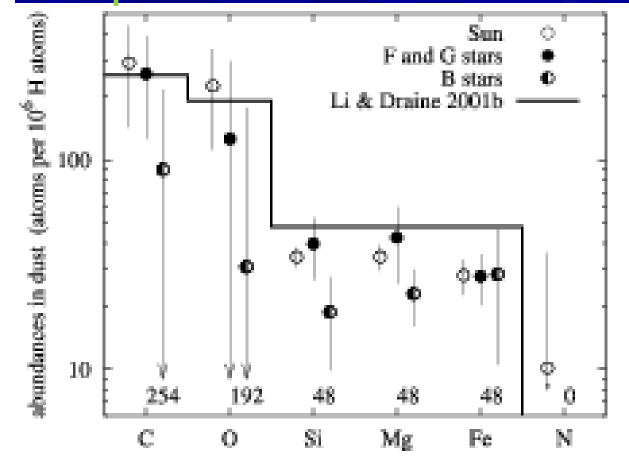
extinction curve



IR spectral feature



depletion of elements



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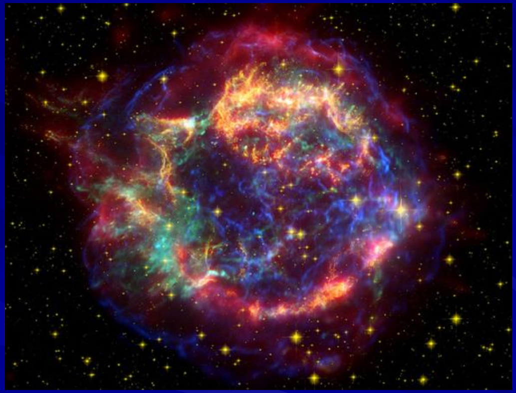
1-3. Formation site of dust

○ Formation site of dust

- abundant metal (metal; N > 5)
- low gas temperature (T < ~2000 K)
- high gas density ($n > 10^8$ cm^{-3})



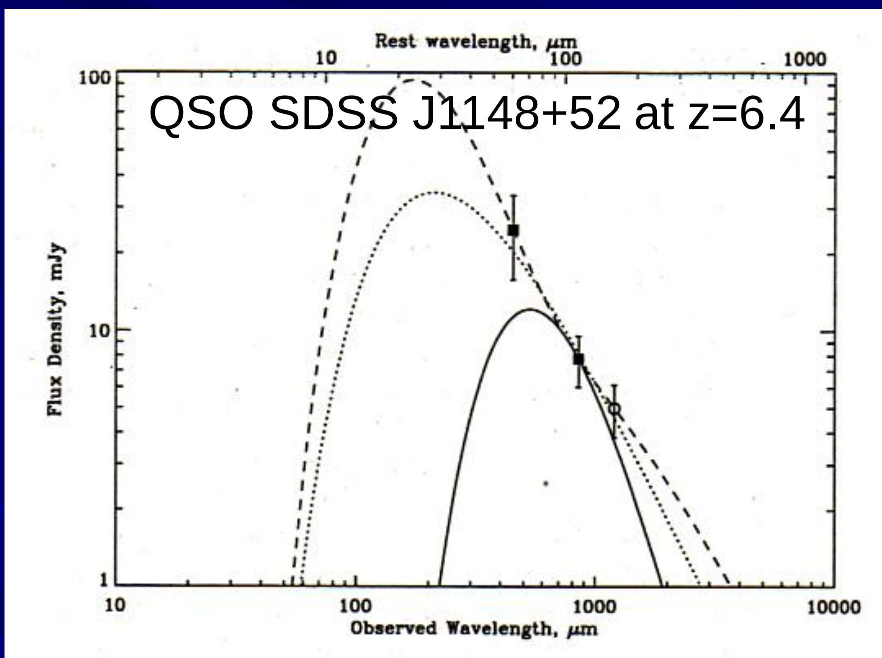
– in the mass-loss winds of AGB stars
– in the expanding ejecta of Type II SNe
– in molecular clouds (growth only)
– novae, red giant, W-R stars, protoplanetary nebulae …

1-4. Dust in the high-z universe

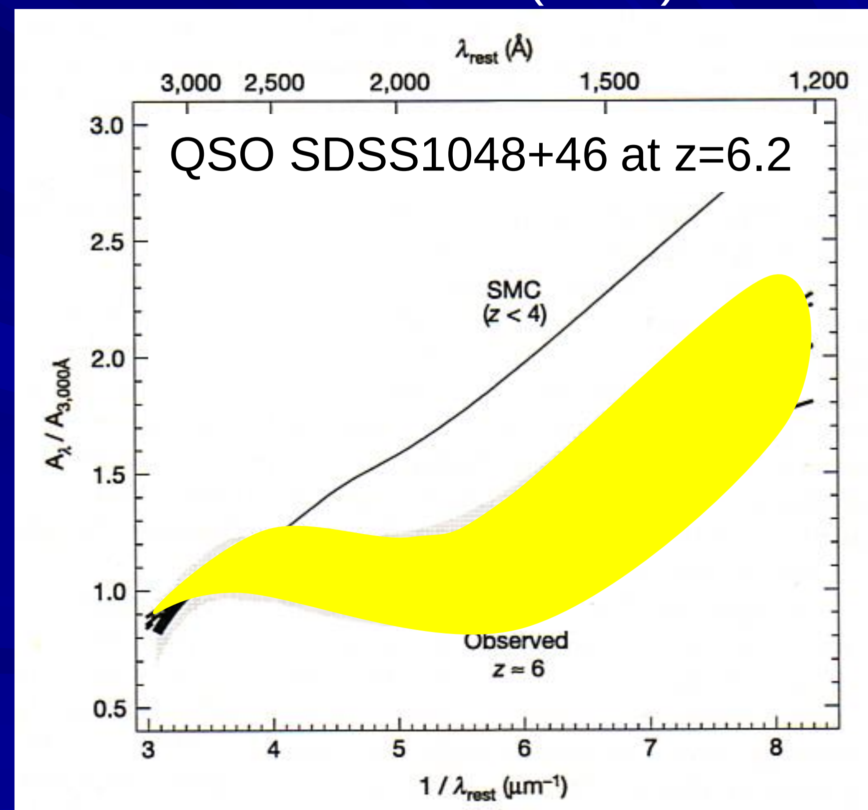
○ Evidence of dust at redshift z > 5 (< 1.2 Gyr)

- estimated dust mass : 10^8 - 10^9 Msun
  (Bertoldi et al. 2003; Robson et al. 2004; Beelen et al. 2006)

- properties of high-z dust is different from those at low-z (z < 4) ?



(Robson et al. 2004)



(Maiolino et al. 2004)

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1-5. 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 underlying physics in the early universe from high-z observations

  (e.g., Loeb & Haiman 1998)

- Dust has great impacts on the formation processes of stars

  – forming molecules (mainly H_2) on the surface

    (e.g., Cozax & Spaans 2004)

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

  – controlling the energy balance in the interstellar space

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1-6. 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 free parameter

Absorption and thermal emission by dust 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, size, and amount of dust by taking account of the formation and destruction processes of dust self-consistently

1-7. Sources of dust in the early universe

- At $z > 5$, AGB stars ($< 8\ M_{sun}$) can not supply a copious amount of dust into the interstellar medium

the main formation sites of dust are considered to be in the ejecta of Type II SNe ($M = 8\text{-}40\ M_{sun}$)

- first stars (Population III stars); very massive ($100\text{-}500\ M_{sun}$)

stars of $M=140\text{-}260\ M_{sun}$ explode as pair-instability SNe

chemical evolution models of dust
→ dust of $0.1\text{-}1\ M_{sun}$ per SN are required to form
(Morgan & Edmunds 2003, Maiolino et al. 2004; Dwek et al. 2007)

2. Dust formation in the ejecta of Population III supernovae

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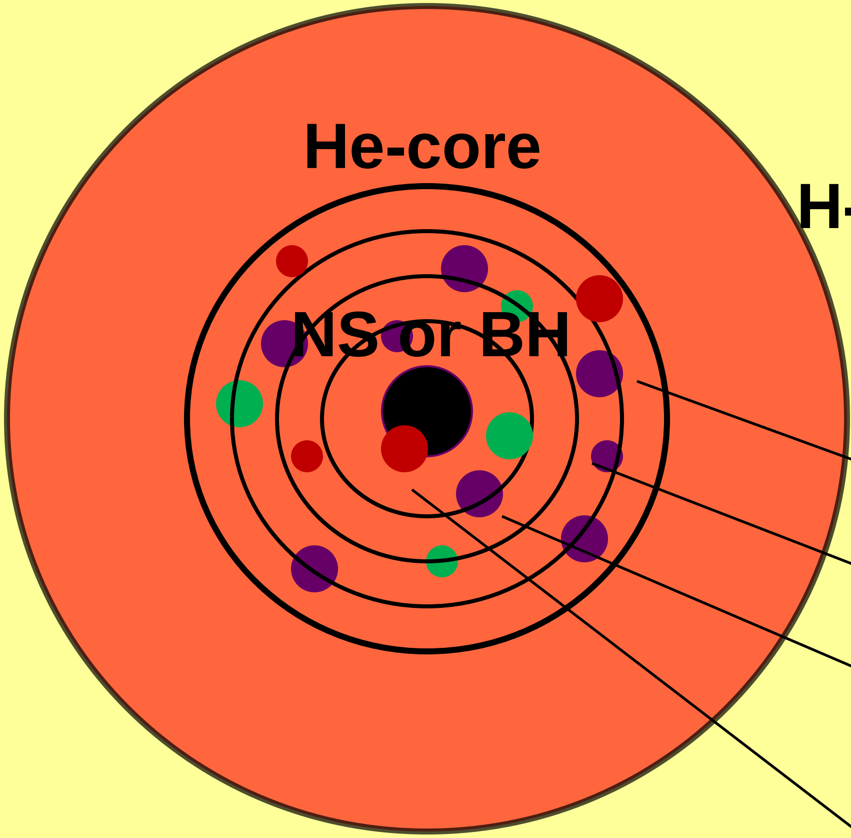
2-1. Dust formation in the ejecta of SNe



2-2-1. Calculations of dust formation

- 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 density and temperature of gas
  - $\rho(t) = \rho_0 (t / t_0)^{-3}$
  - T(t) is calculated 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)

2-2-2. Calculations of dust formation

○ nucleation and grain growth theory

(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

Table 2. Grain species considered in the calculations

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

2-2-3. Calculations of dust formation

Steady-state nucleation rate

$$J_j^s(t) = \alpha_{sj}\Omega_j \left(\frac{2\sigma_j}{\pi m_{1j}}\right)^{1/2} \left(\frac{T}{T_d}\right)^{1/2} \Pi_j c_{1j}^2 \exp\left[-\frac{4}{27}\frac{\mu_j^3}{(\ln S_j)^2}\right],$$

Supersaturation ratio

$$\ln S_j = -\frac{\Delta G_j^0}{kT} + \sum_i \nu_{ij} \ln P_{ij},$$

α_s : sticking probability of key species ($\alpha_s = 1$, in the calculations)

Ω : volume of the condensate per key species

σ : surface energy of the condensate

m_1 : mass of key species

c_1 : number density of key species

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

2-2-4. Calculations of dust formation

Equation of conservation for key species

$$1 - \frac{c_{1j}(t)}{\tilde{c}_{1j}(t)} = 1 - Y_{1j} = \int_{t_e}^{t} \frac{J_j(t')}{\tilde{c}_{1j}(t')} \frac{4\pi}{3\Omega_j} r_j^3(t, t') dt',$$

Equation of grain growth

$$\frac{dr_j}{dt} = \alpha_{sj}\Omega_j \left(\frac{kT}{2\pi m_{1j}}\right)^{1/2} c_{1j}(t) = \frac{1}{3} a_{0j} \tau_{\mathrm{coll},j}^{-1}(t).$$

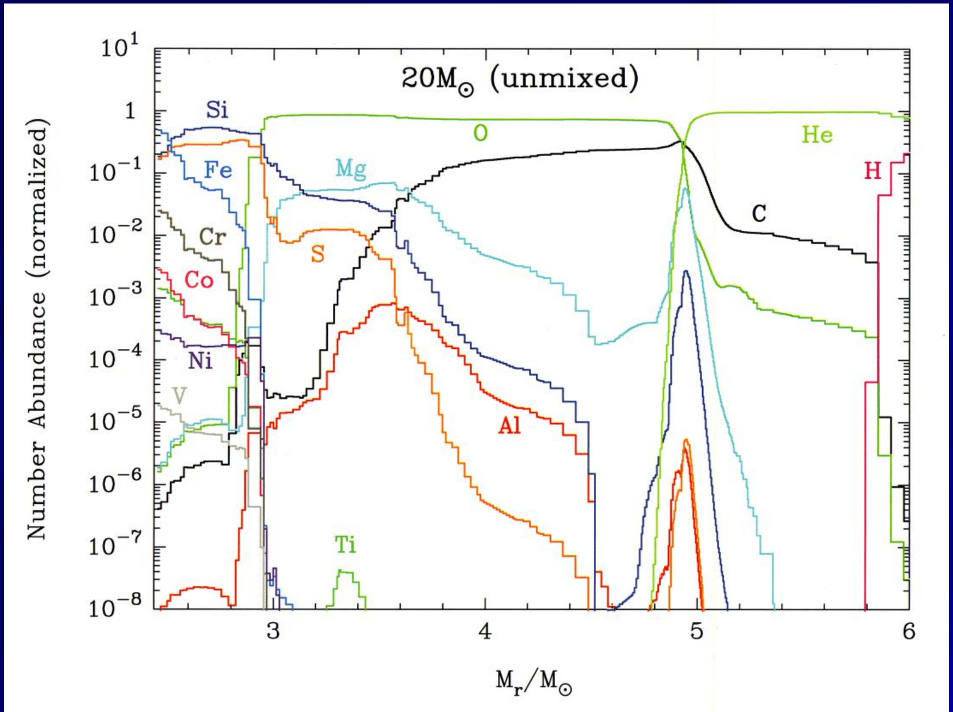
· the number density of dust grains, n_{gr}

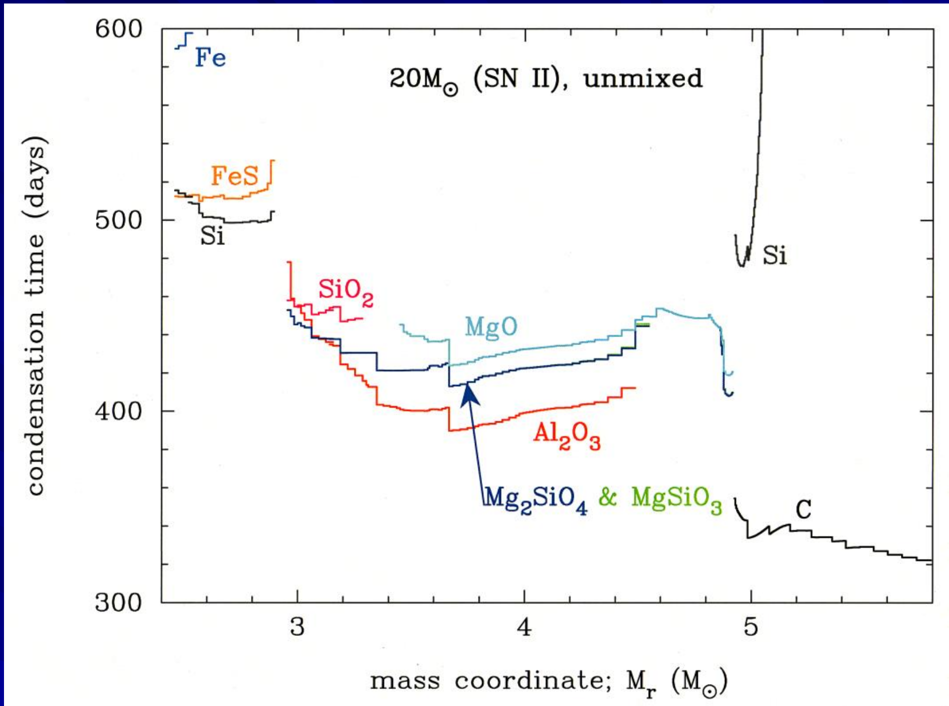
$$\frac{n_{\mathrm{gr}}}{\tilde{c}_1(t)} = \int_{t_0}^{t} \frac{J(t')}{\tilde{c}_1(t')} dt'$$

· the radius of dust grain nucleated at t_0 and measured at t

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

2-3. 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 of dust is 300-600 days

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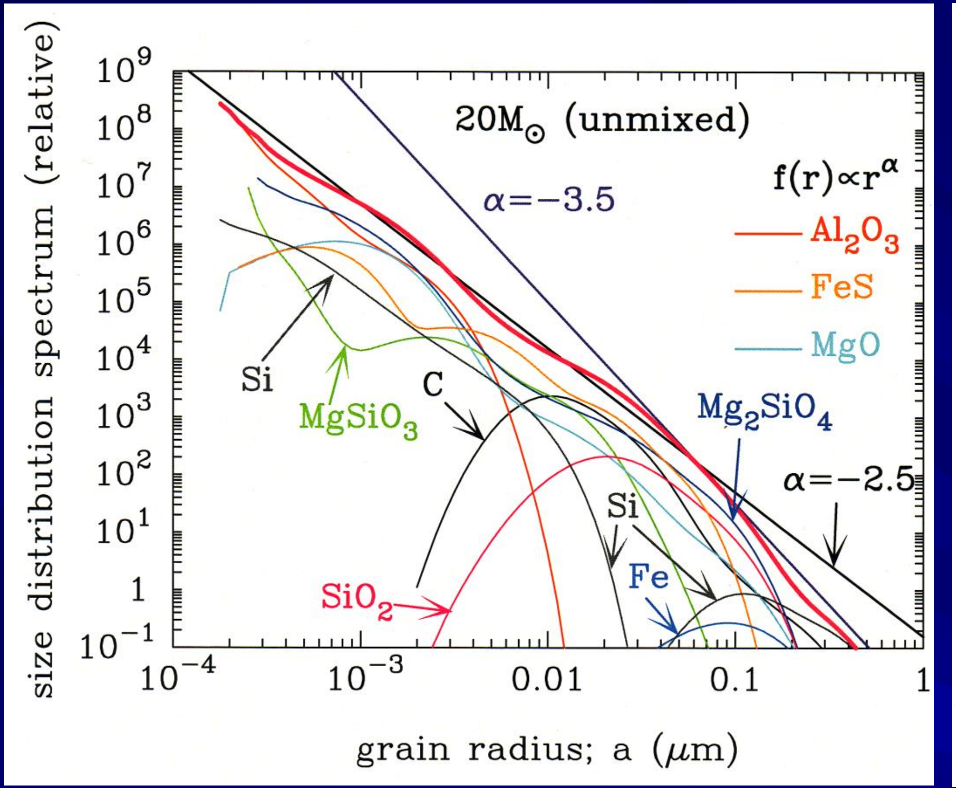
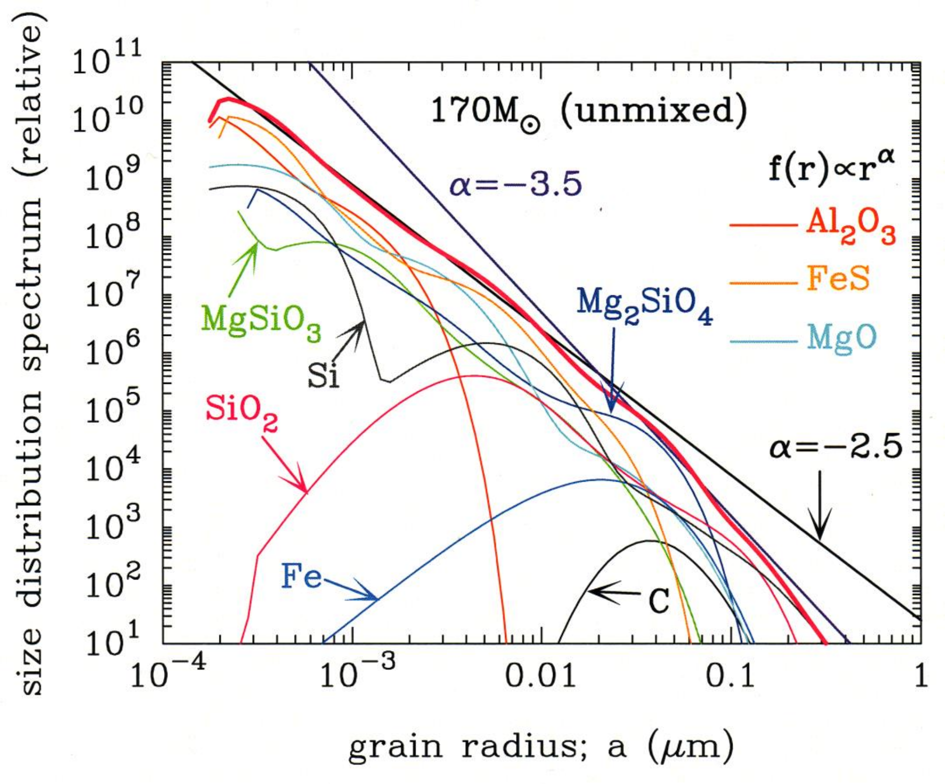
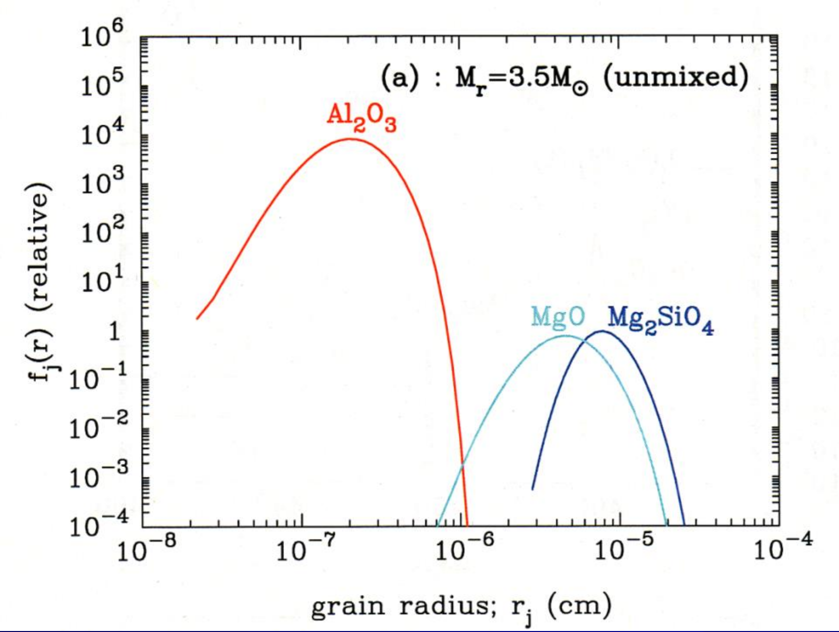
2-4. Dust formed in the unmixed ejecta

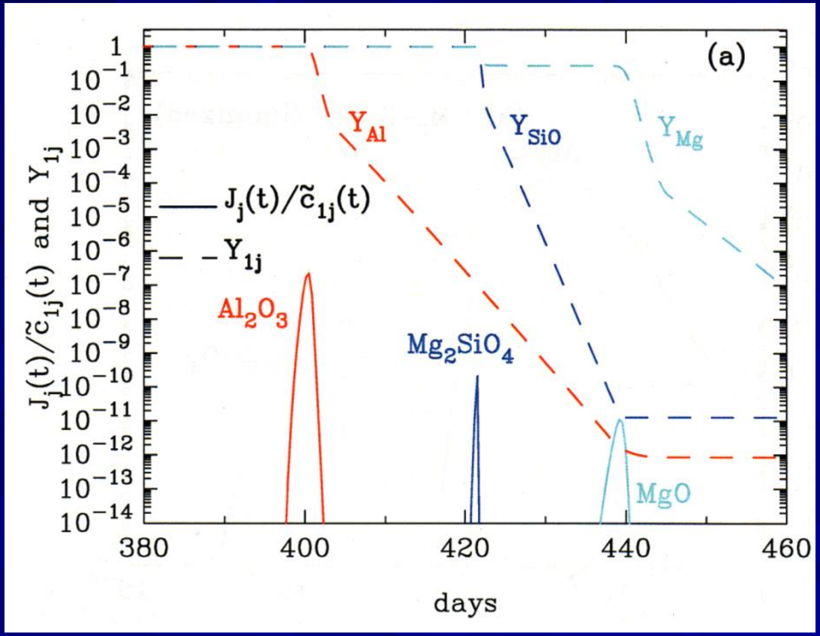


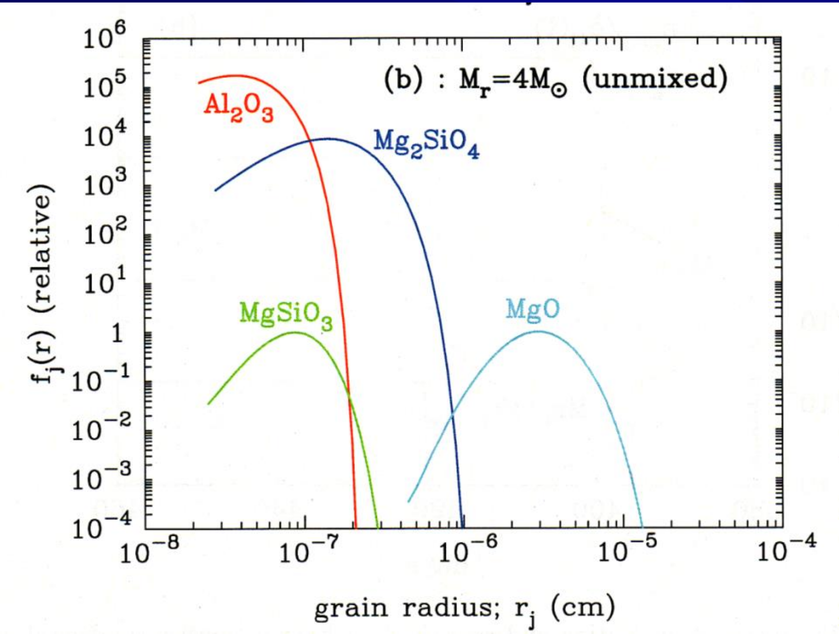


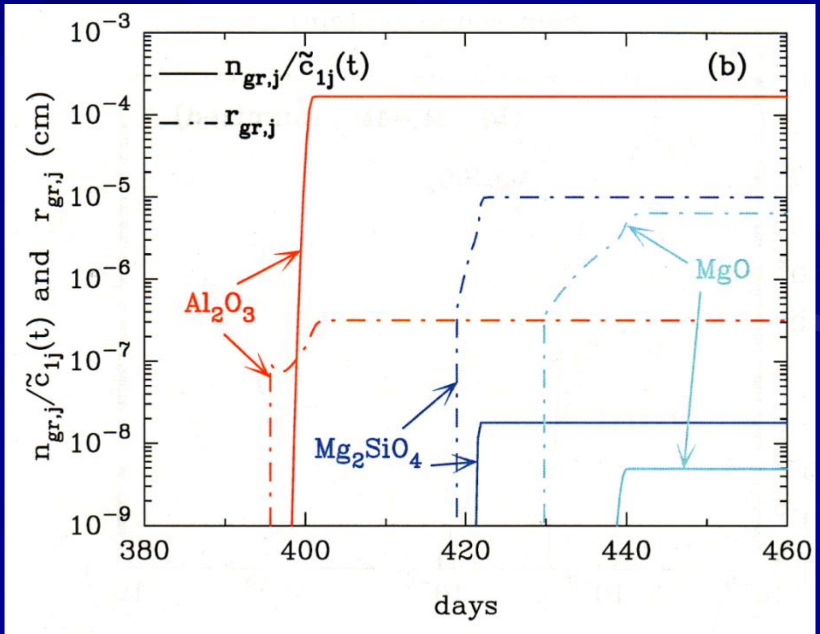
- C, SiO2, and Fe grains have lognormal-like size distribution, while the other grains have power-law-like size distribution
- The composition and size distribution of dust formed are almost independent of type of supernova

2-4. Dust formed in the unmixed ejecta

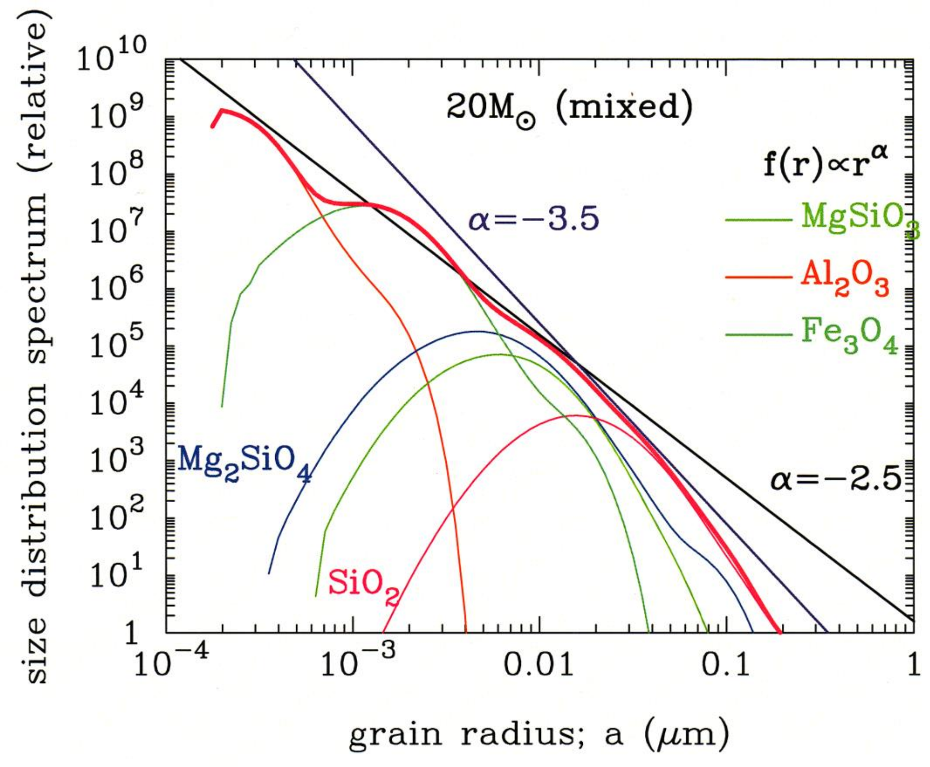


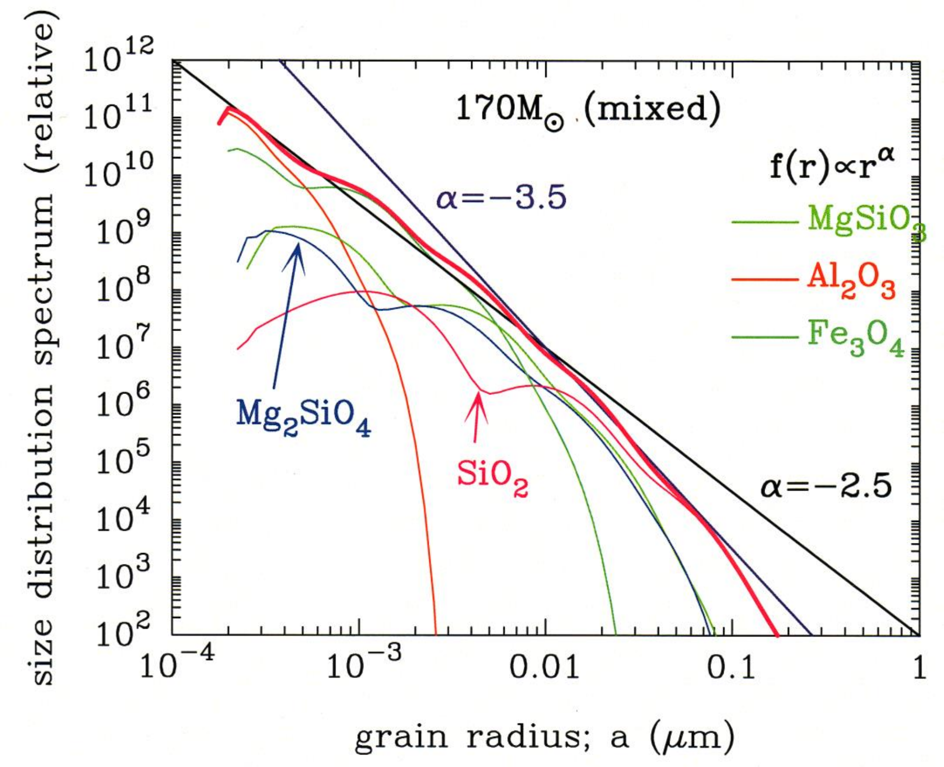






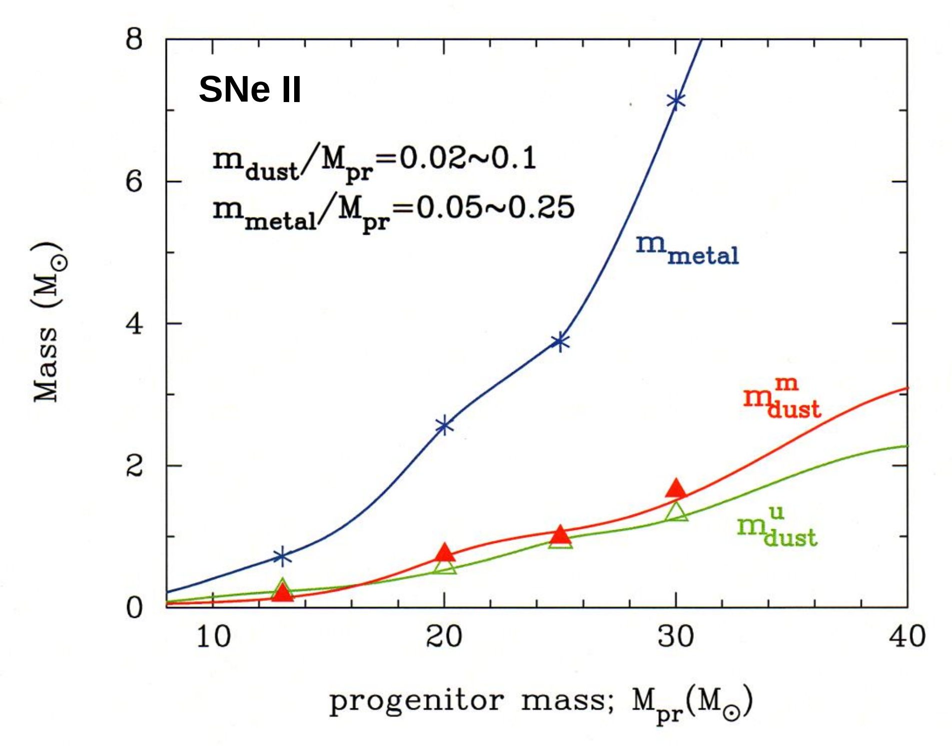
2-5. Dust formed in the mixed ejecta

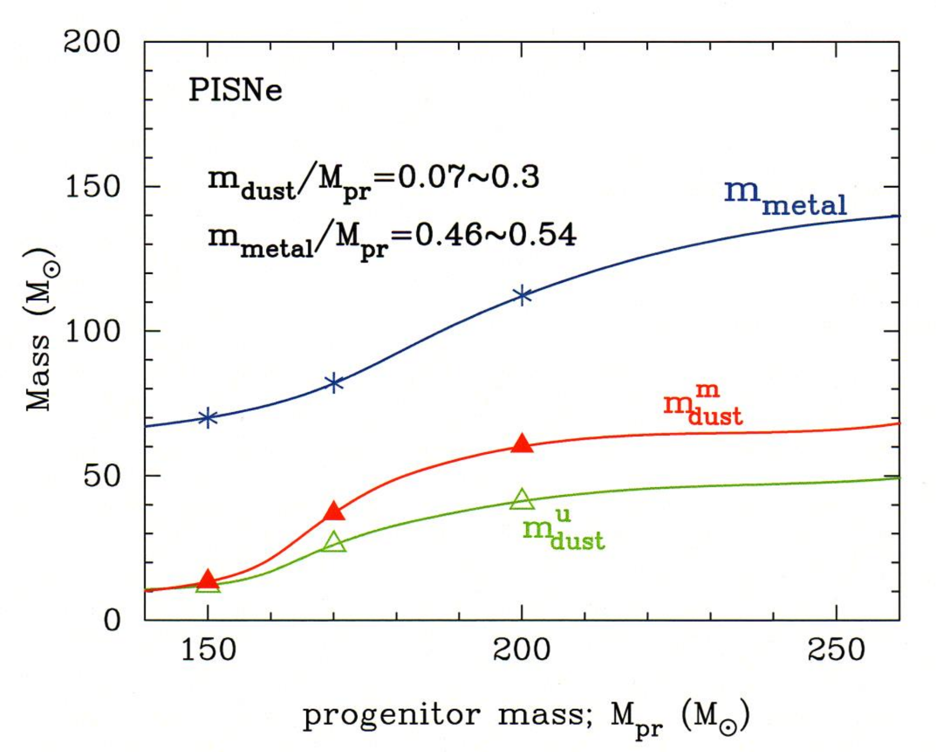




- Because oxygen is rich in the mixed ejecta, only silicates ($MgSiO_3$, Mg_2SiO_4, SiO_2) and oxides (Fe_3O_4, Al_2O_3) form
- The size distribution of each dust species except for Al_2O_3 is lognormal-like

2-6. Total mass of dust formed





- 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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2-7. Summary of dust formation

○ composition of dust

- unmixed case

  C, Si, Fe, FeS, Al_2O_3, $MgSiO_3$, Mg_2SiO_4, SiO_2, MgO

- mixed case

  $MgSiO_3$, Mg_2SiO_4, SiO_2, Fe_3O_4, Al_2O_3

○ size distribution of dust

- for each dust species ; lognormal-like or power-law-like
- over all dust grains ; broken power-law

○ total mass of dust

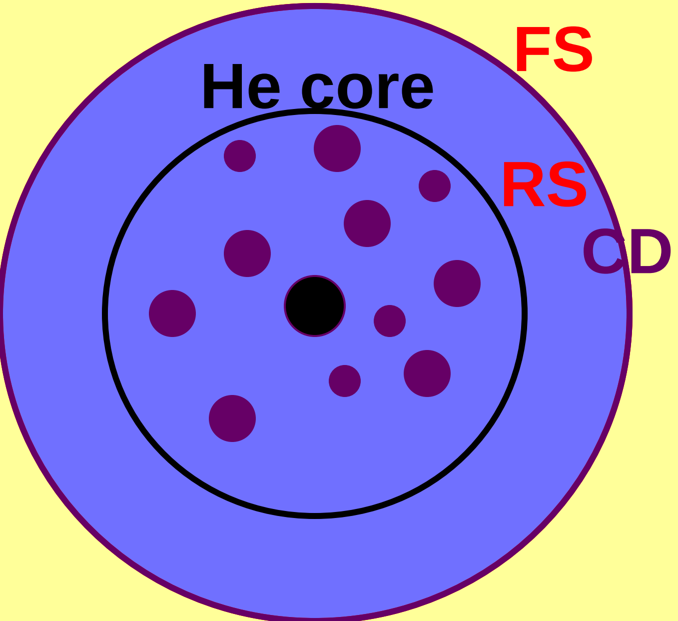
SNe II (8-40 M_{sun}) : M_{dust} = 0.1-2 M_{sun}

PISNe (140-260 M_{sun}) : M_{dust} = 10-60 M_{sun}

3. Dust evolution within Pop III supernova remnants

3-1. Dust evolution in a SN remnant

T = (1-2) x10^4 K
n_H = 0.1-1 cm^{-3}



3-2-1. Time evolution of shock wave

- Basic equations (spherical symmetry)

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

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

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

$\Lambda_{\mathrm{gas}}(T)$: 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)

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

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

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

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3-2-2. Initial condition for shock wave

○ 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

- 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)

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

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

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

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

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

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

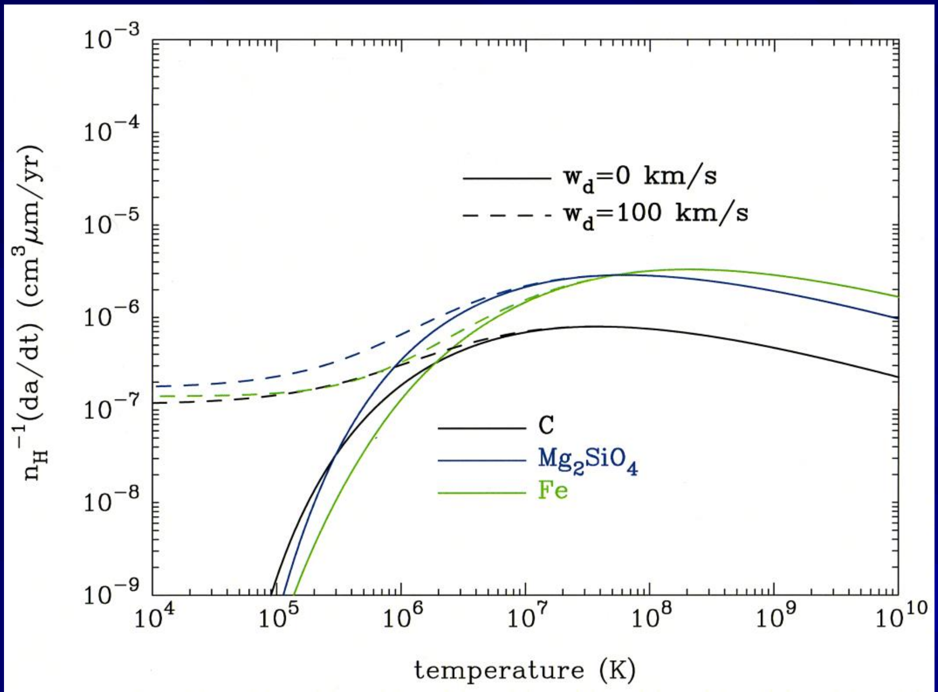
· rate equation over a modified Maxwellian distribution of gas taken account of relative velocity of dust to gas (e.g., Shull 1978)

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

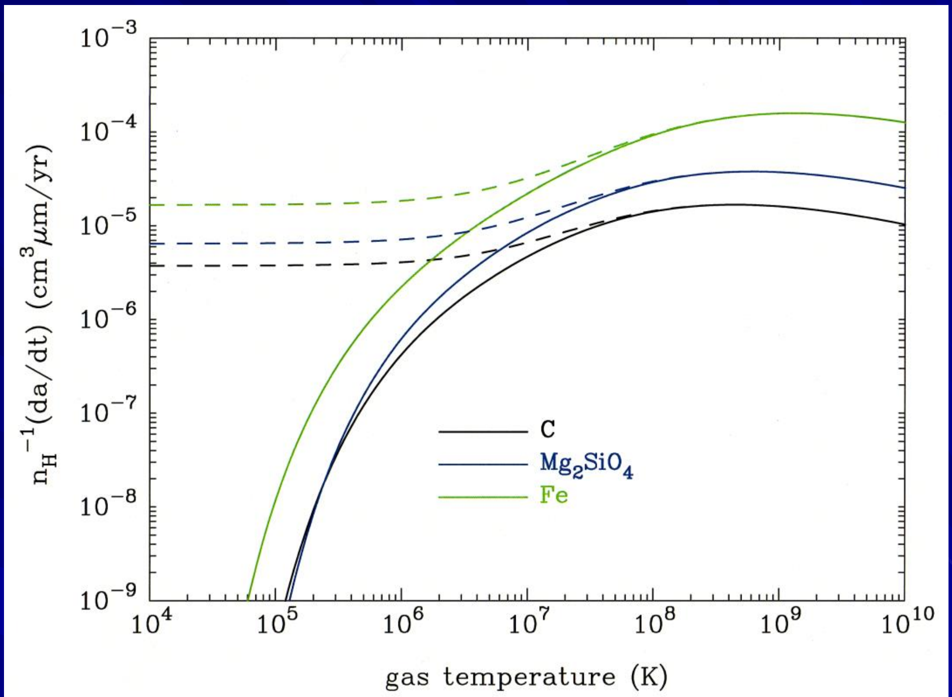
where $\epsilon = E/kT$

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

for primordial composition gas



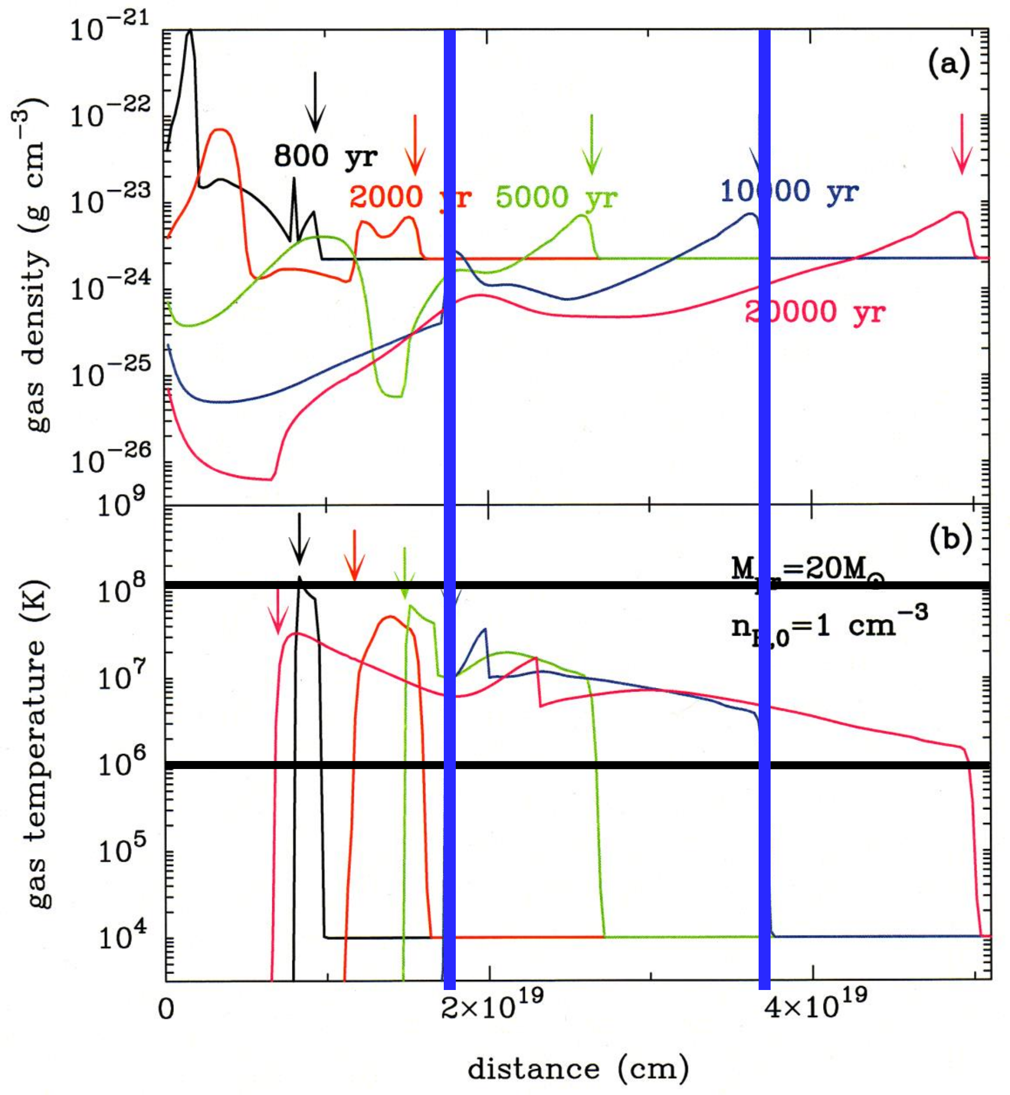
for oxygen ions



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

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

3-5. Temperature and density of gas

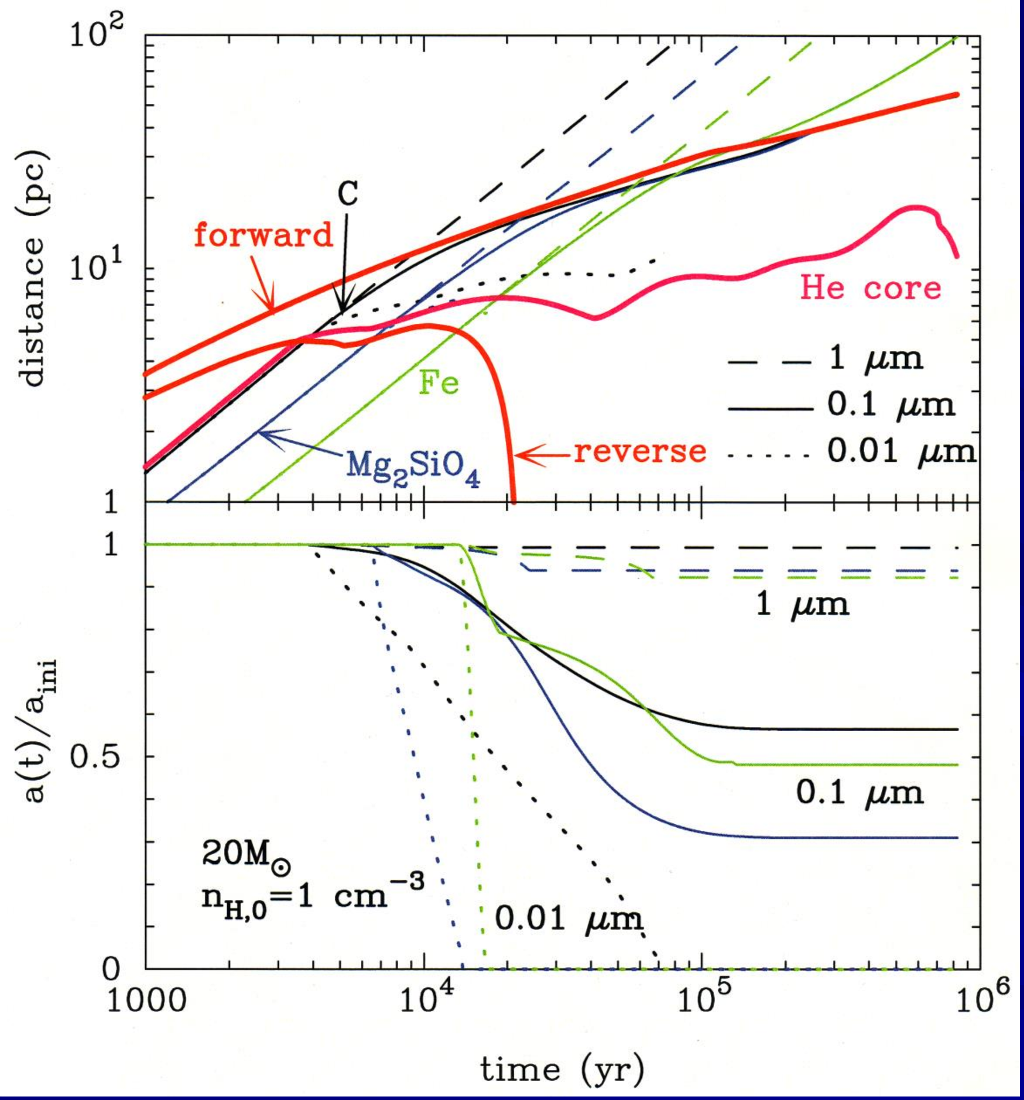


Model : M_{pr}=20 $M_\odot$ (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

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

3-6. Evolution of dust in SNRs



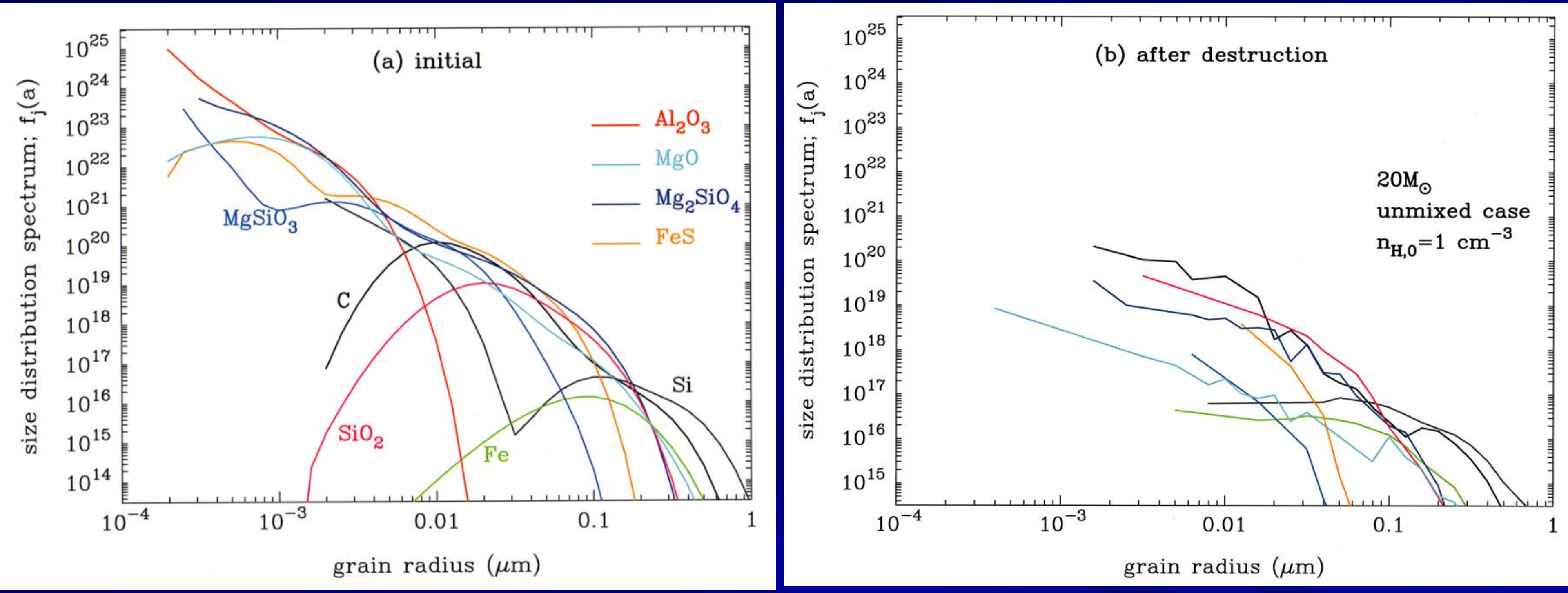
Model : M_{pr}=20 $M_\odot$ (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

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

3-7. 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-sized grains

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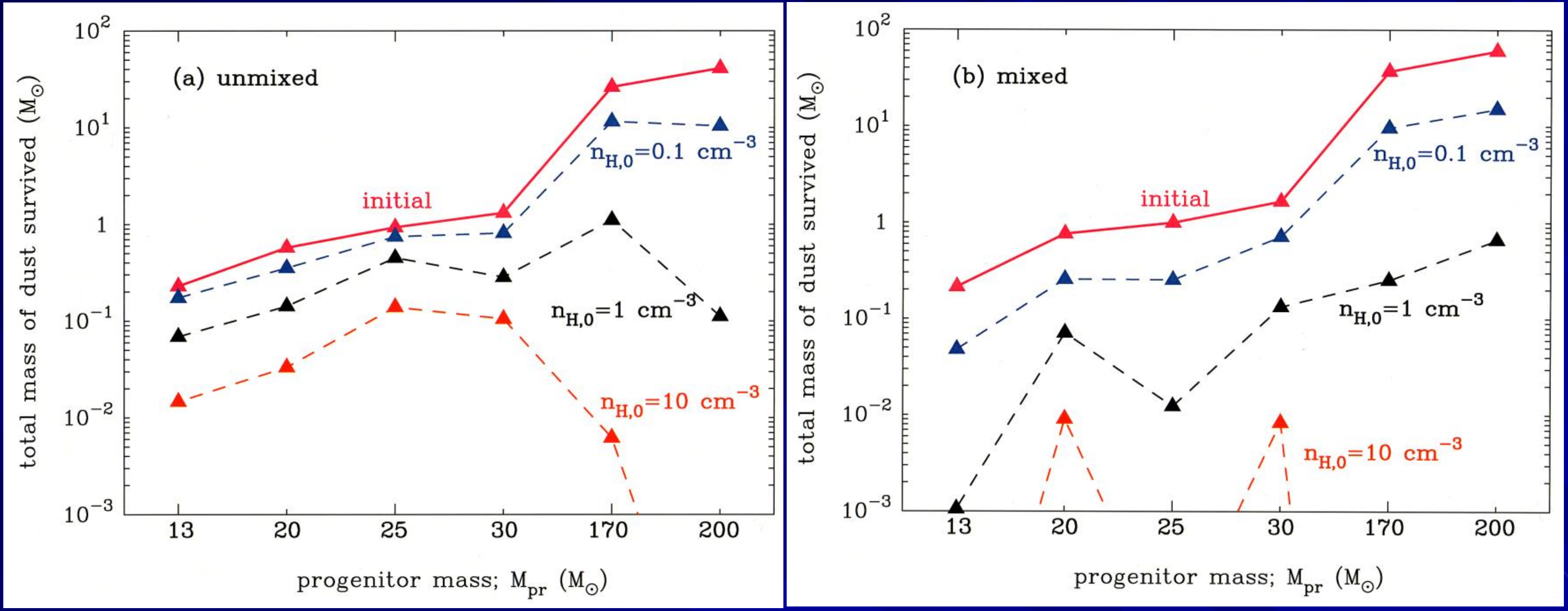
3-8. Total mass of surviving dust



Total mass of surviving dust decreases with increasing the ambient gas density

for Type II SNRs;

0.01-0.8 Msun in the unmixed case ($n_{H,0}$ = 0.1-10 cm^{-3})

0.001-0.7 Msun in the mixed case ($n_{H,0}$ = 0.1-1 cm^{-3})

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3-9. Summary of dust evolution in SNRs

- 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

- 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