Injection process of dust from supernovae

（超新星爆発による星間ダストの供給過程）

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Outline

1. Introduction

2. Dust formation in Population III SNe

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

3. Dust evolution in the Population III SNRs

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

4. Formation and evolution of dust in Cas A

(Nozawa et al. 2010, submitted, astro-ph/0909.4145)

1. Introduction

1-1. Sources of dust in the early universe

- At an early epoch of the universe (e.g. $z > 5$), the major sources of dust are considered to be core-collapse SNe

- Population III stars ➔ very massive (M_{pr} =100-500 M_{sun})

(e.g., Nakamura & Umemura 2001; Bromm et al. 2002)

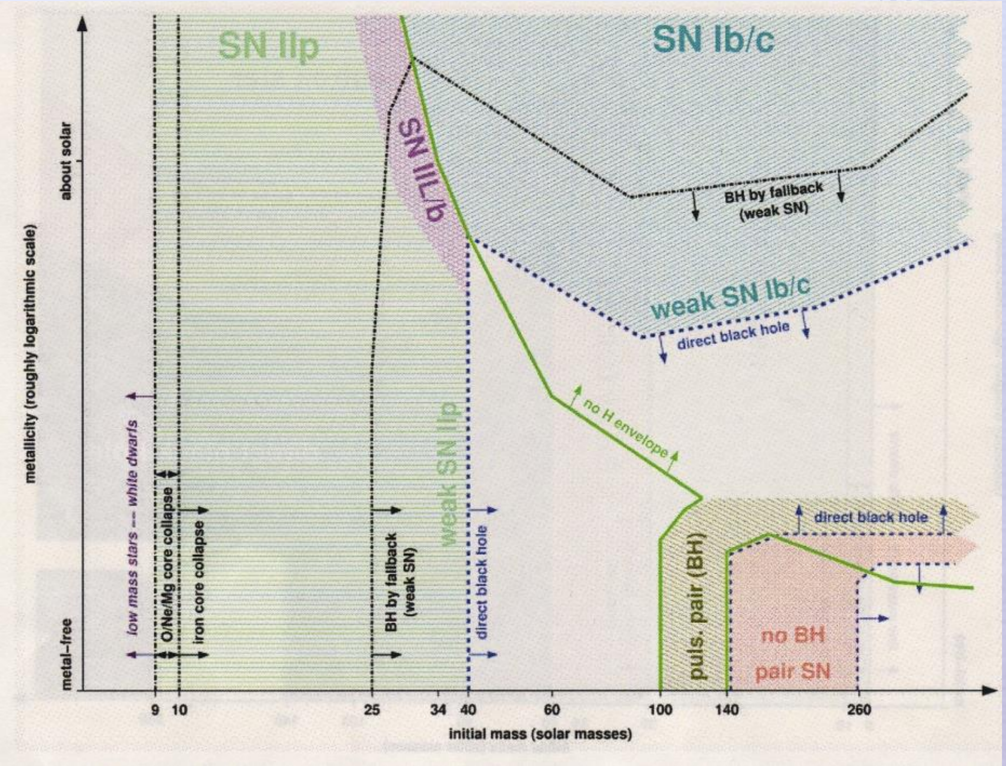
In the early universe

- **Type II SNe (SNe II)**

  ; M_{pr}=8–40 M_{sun}

- **pair-instability SNe**

  ; M_{pr}=140–260 M_{sun}



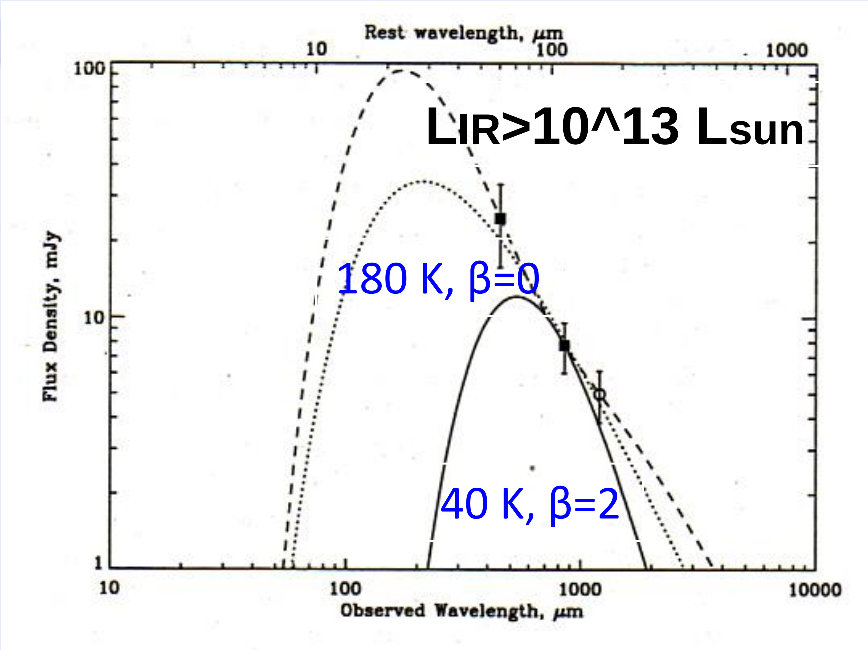
(Heger et al. 2003, ApJ, 591, 288)

1-2. A large amount of dust at z > 5

- The presence of large amounts of dust grains with mass of **$>10^8\,M_{\rm sun}$** 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

(but see Valiante et al. 2009)

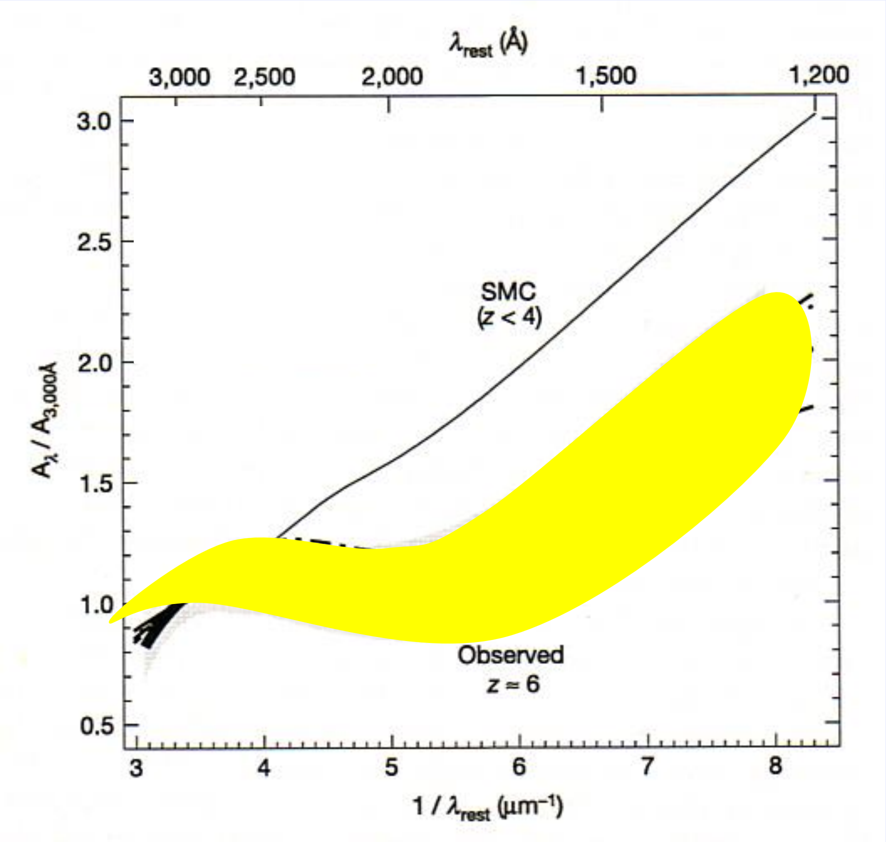
0.1-1 $M_{\rm sun}$ of dust per SN is required to form to explain a large content of dust at high-z galaxies

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

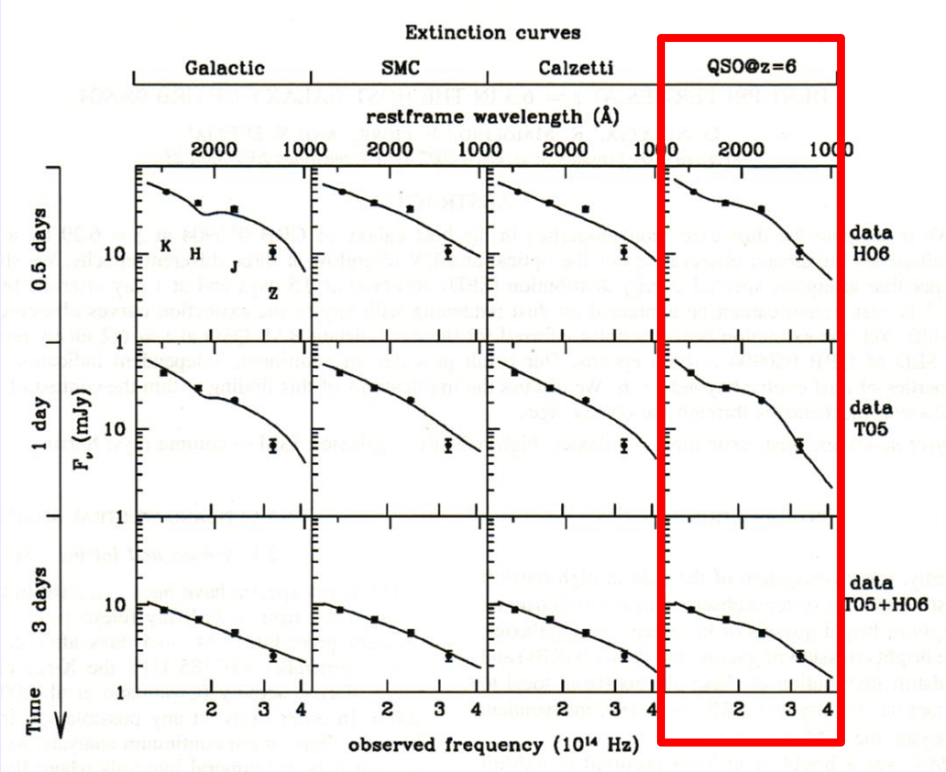
1-3. Extinction curves at high-z

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)

1-4. Role of dust (in the early universe)

- **Dust absorbs starlight and reemits it by thermal radiation**

  ➔ plays a crucial role in determining the SFR and the IMF from observations

- **Dust has great impacts on the formation process of stars**

  – forming molecules (mainly H_2) on the surface

  (e.g., Cazaux & Spaans 2004; Hirashita & Ferrara 2002)

  – controlling the energy balance in the interstellar space

  – providing efficient cooling pathways of gas in metal-poor molecular clouds through thermal emission

  (e.g., Omukai et al. 2005; Schneider et al. 2006)

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

1-5. 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

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

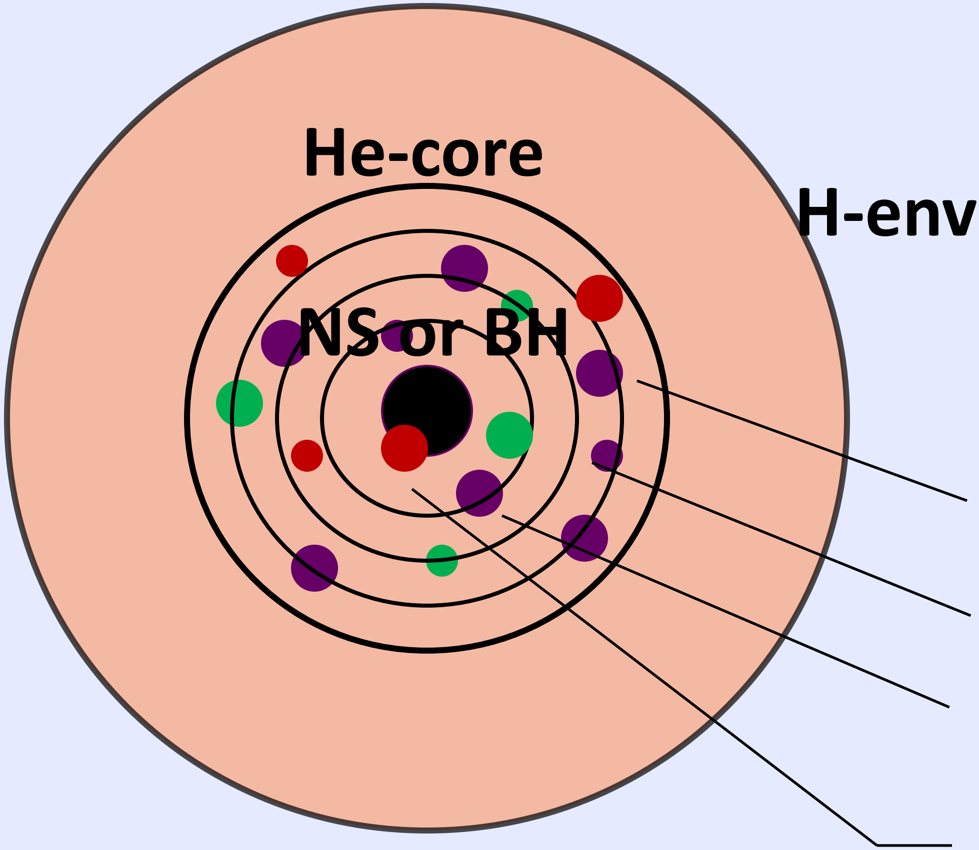
⬇

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

2. Dust Formation in Pop III 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

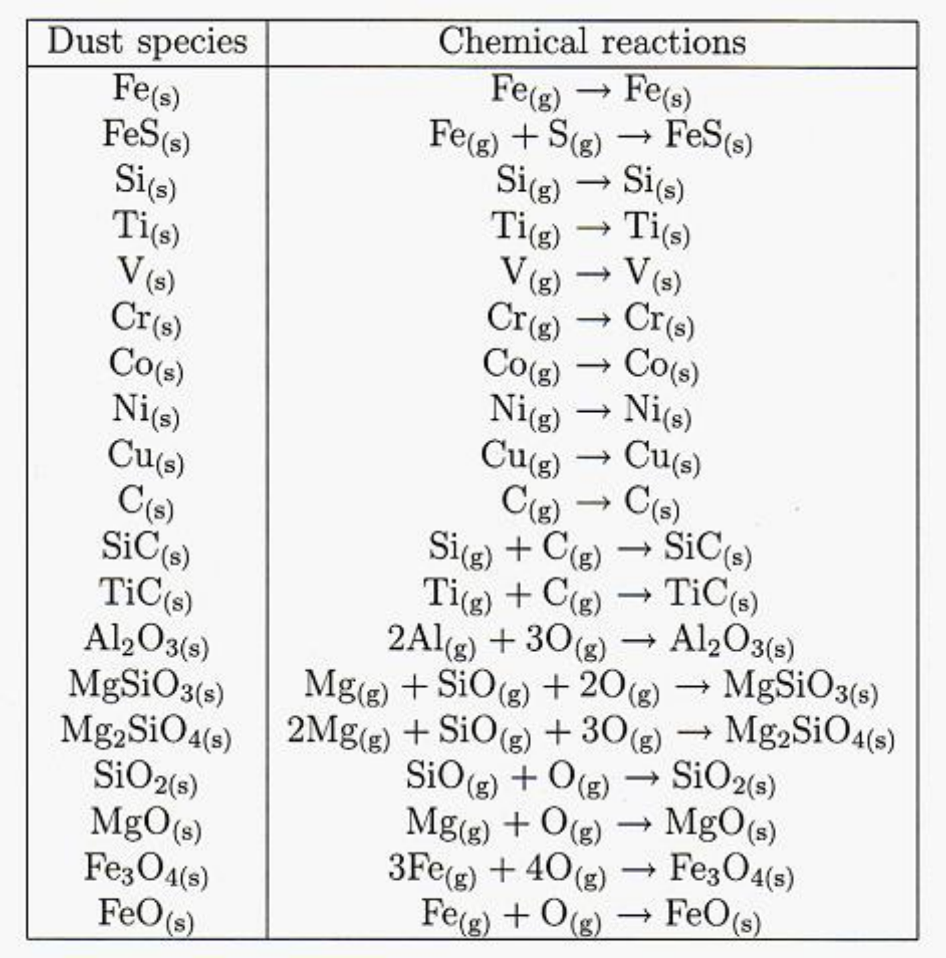
2-1-1. Calculations of dust formation

- 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

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

Supersaturation ratio

$$\ln S = \ln \frac{P_i}{P_{i,\mathrm{eq}}} = -\frac{\Delta G^0}{kT} + \sum_i \nu_i \ln P_i$$

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

Ω : volume of the condensate per key species ($\Omega = 4\pi a_0^3/3$)

σ : surface energy of the condensate

m_1 : mass of key species

$c_1(t)$: number density of key species

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

2-1-3. Basic equations for dust formation

Equation of conservation for key species

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

Equation of grain growth

$$\frac{\partial r}{\partial t} = \alpha_s \frac{4\pi a_0^3}{3} \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1(t) = \frac{1}{3} a_0 \tau_{\rm coll}^{-1}$$

- number density of dust grain, $n_{\rm gr}$

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

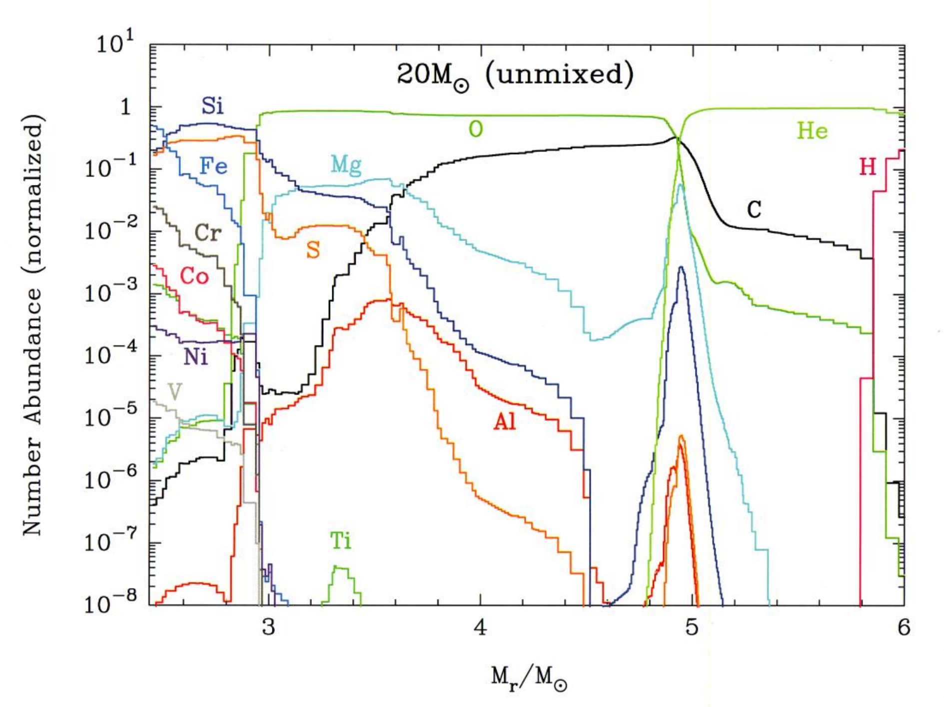
- radius of grain nucleated at t_0 and measured at t, $r(t, t_0)$

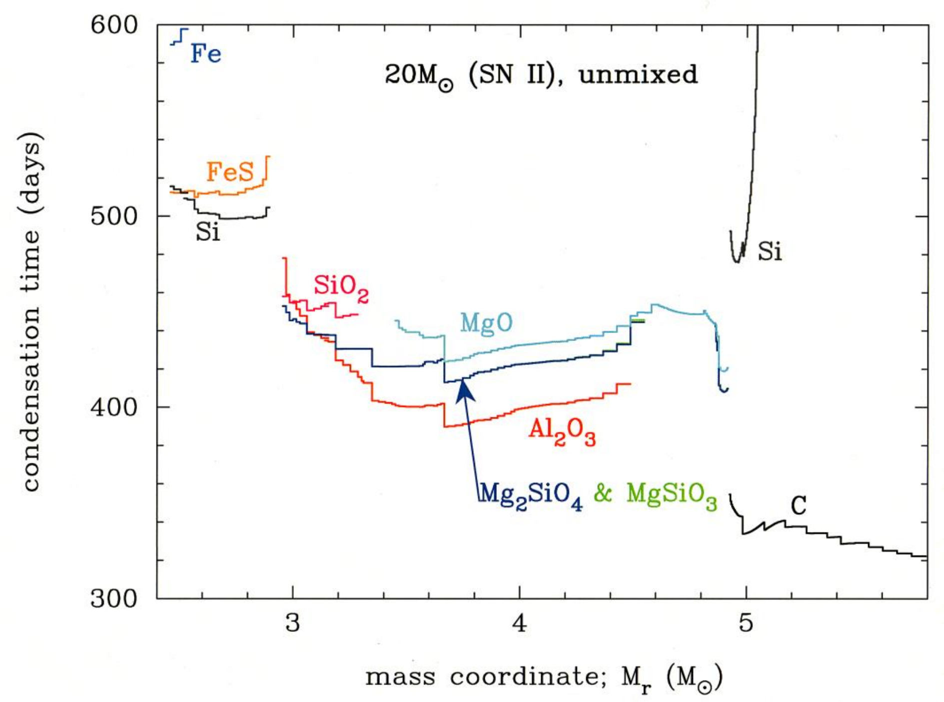
$$r(t, t_0) = r_* + \int_{t_0}^{t} \frac{1}{3} a_0 \tau_{\rm coll}^{-1}(t') dt'$$

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**

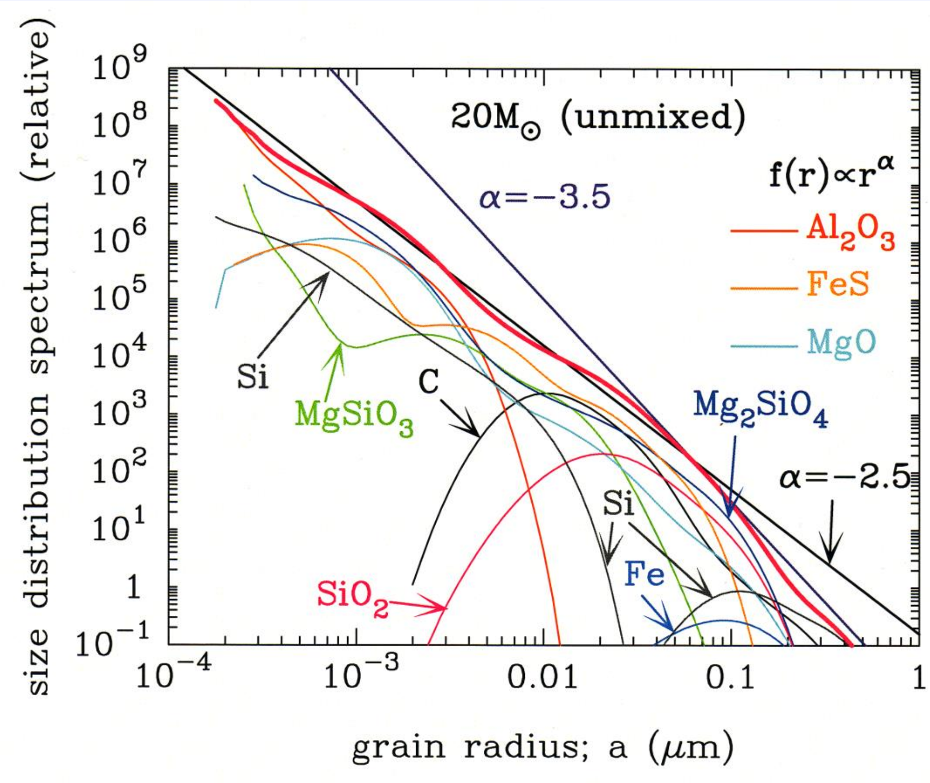
2-3. Dust formation in the unmixed ejecta

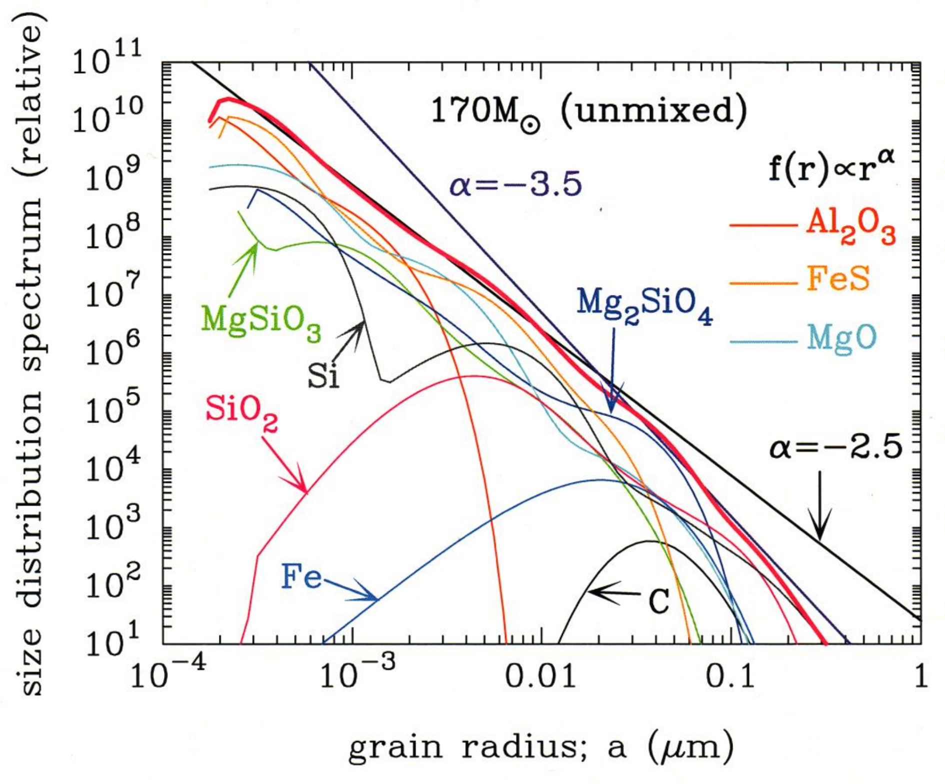




- Various dust species (C, $MgSiO_3$, Mg_2SiO_4, SiO_2, Al_2O_3, MgO, Si, FeS, Fe) form in the unmixed ejecta, reflecting the elemental composition in each layer
- The condensation time; 300-600 days for SNe II
  400-800 days for PISNe

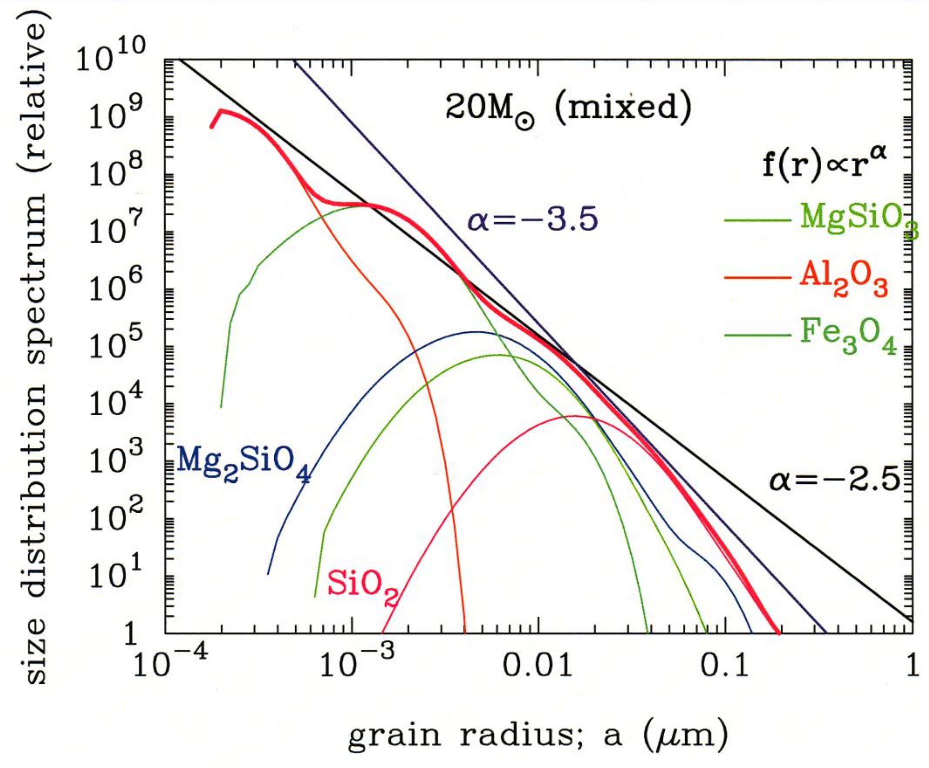
2-4-1. Dust formed in the unmixed ejecta

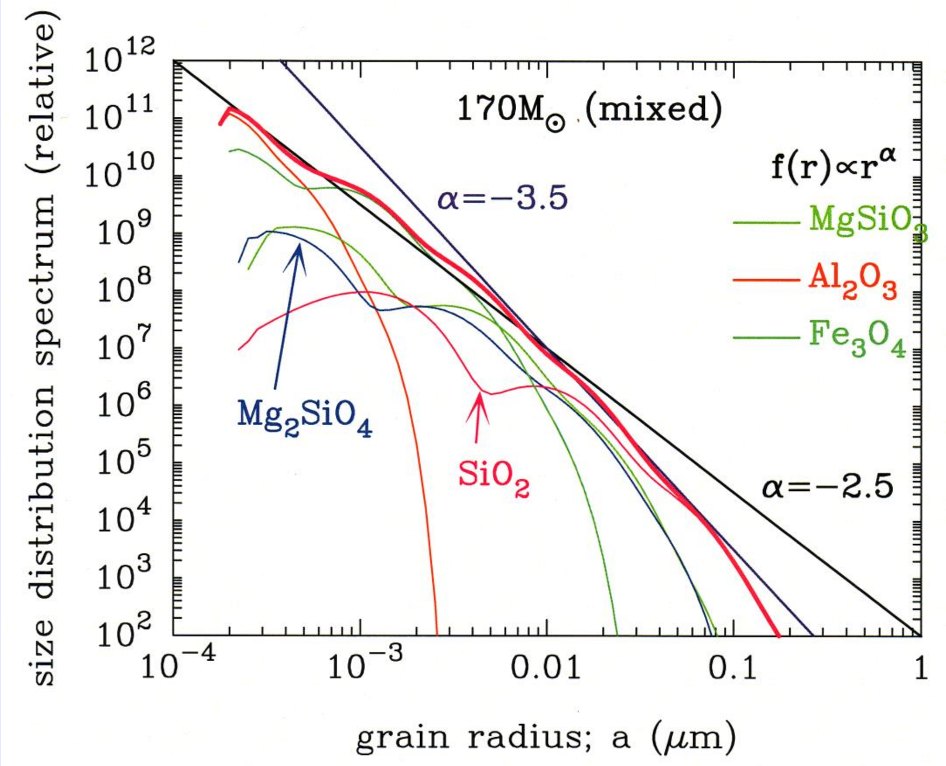




- C, SiO2, and Fe grains have lognormal-like size distribution, while the other grains have power-law-like size distribution
- The composition and size distribution of dust formed are almost independent of types of SNe

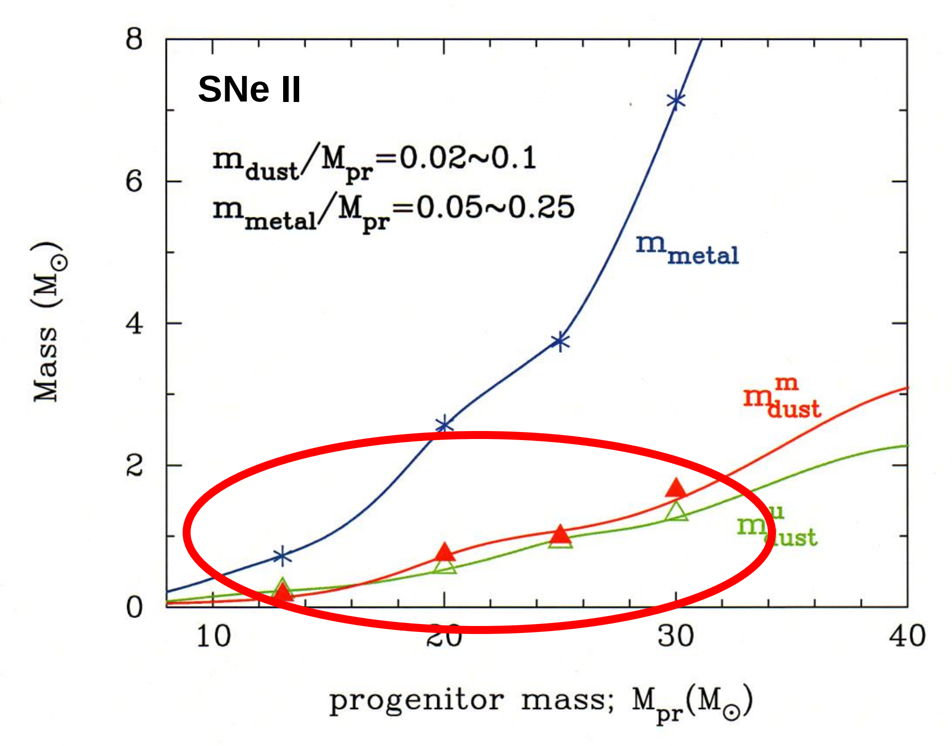
2-4-2. Dust formed in the mixed ejecta

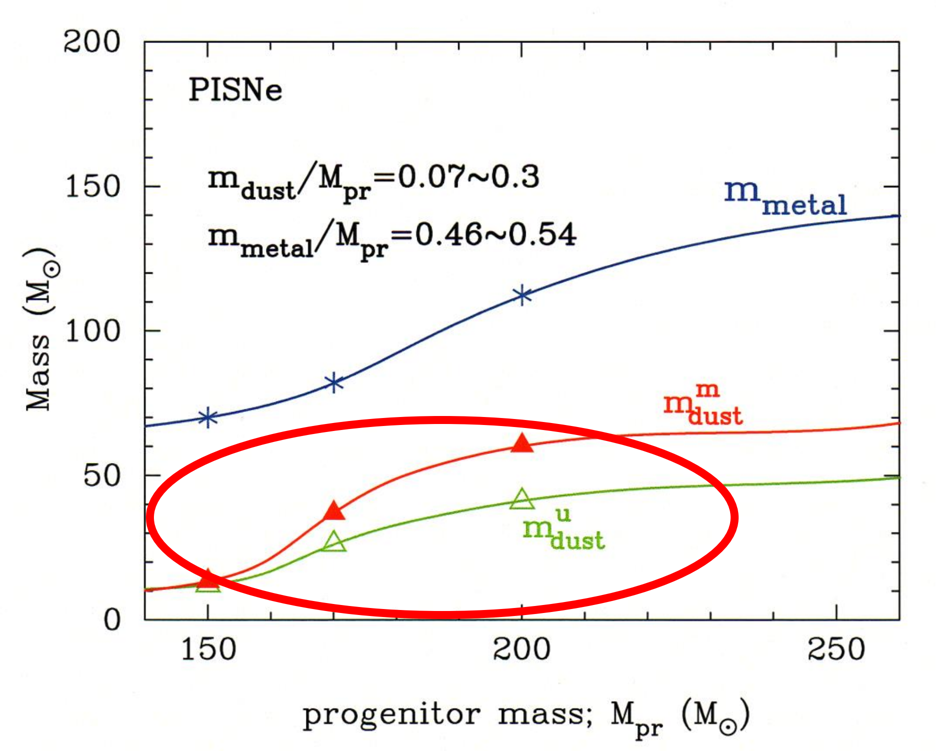




- Because oxygen is rich in the mixed ejecta, only silicates ($MgSiO_3$, Mg_2SiO_4, SiO_2) and oxides (Fe_3O_4, Al_2O_3) form
- The size distribution of each dust species except for Al_2O_3 is lognormal-like

2-5. Total mass of dust formed





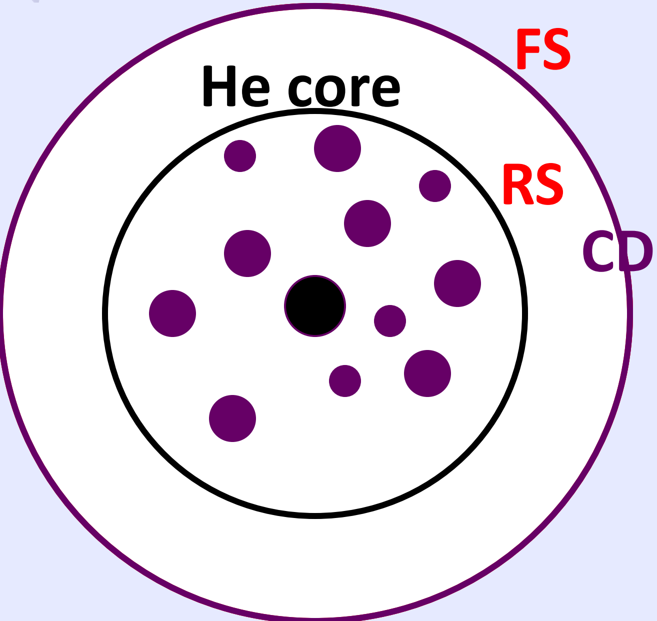
- Total dust mass increases with increasing progenitor mass
  SNe II : M_{dust} = 0.1-2 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.2-0.3
  PISNe : M_{dust} =10-60 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.3-0.5

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

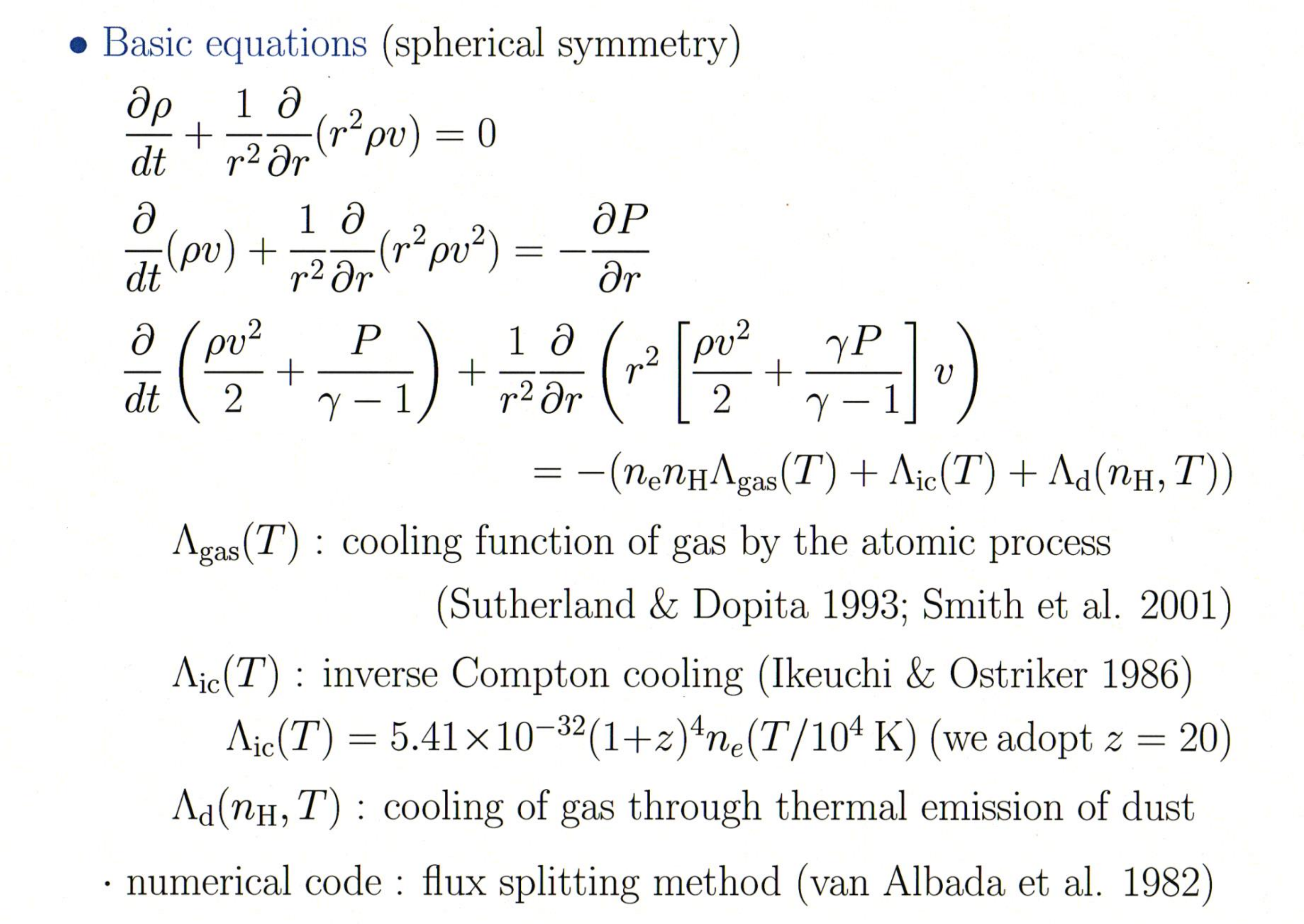
3. Dust Evolution in Pop III SNRs

$T = (1\text{-}2)\text{x}10^4$ K
$n_{H,0} = 0.1\text{-}1\ \text{cm}^{-3}$

(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)

$\Lambda_{\mathrm{ic}}(T) = 5.41\times10^{-32}(1+z)^4 n_e (T/10^4\ \mathrm{K})$ (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)

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}**

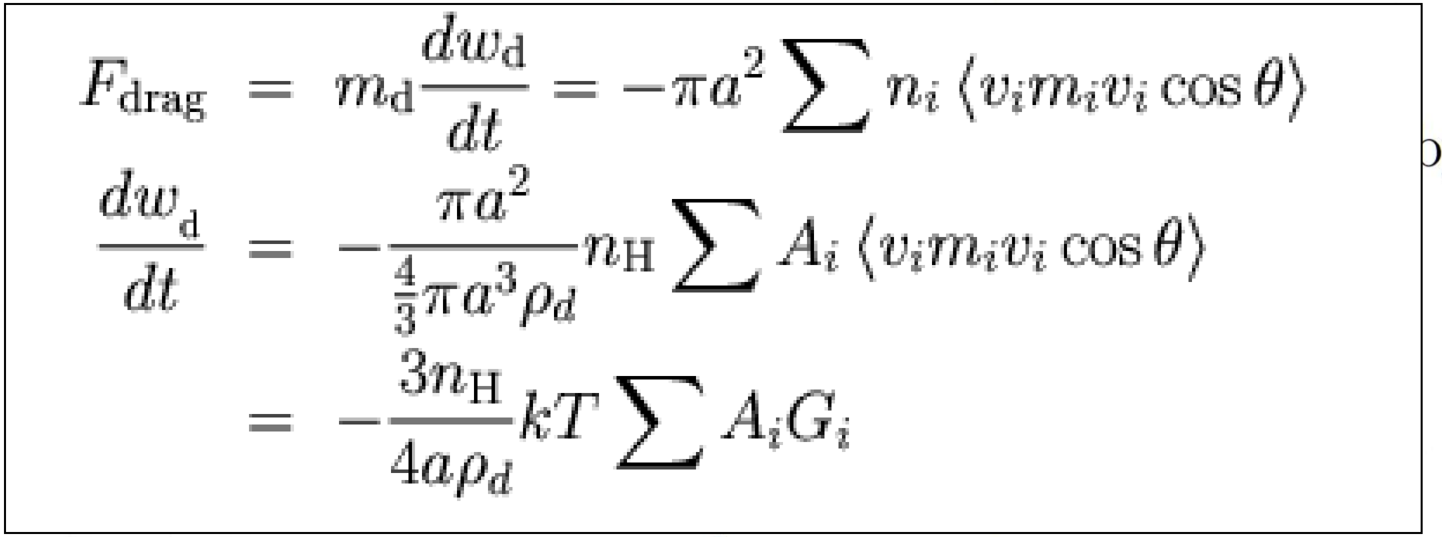
- **Dust Model**
  - initial size distribution and spatial distribution of dust
    ➔ results of dust formation calculations
  - treating as a test particle (neglecting the effects of charge)

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)

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



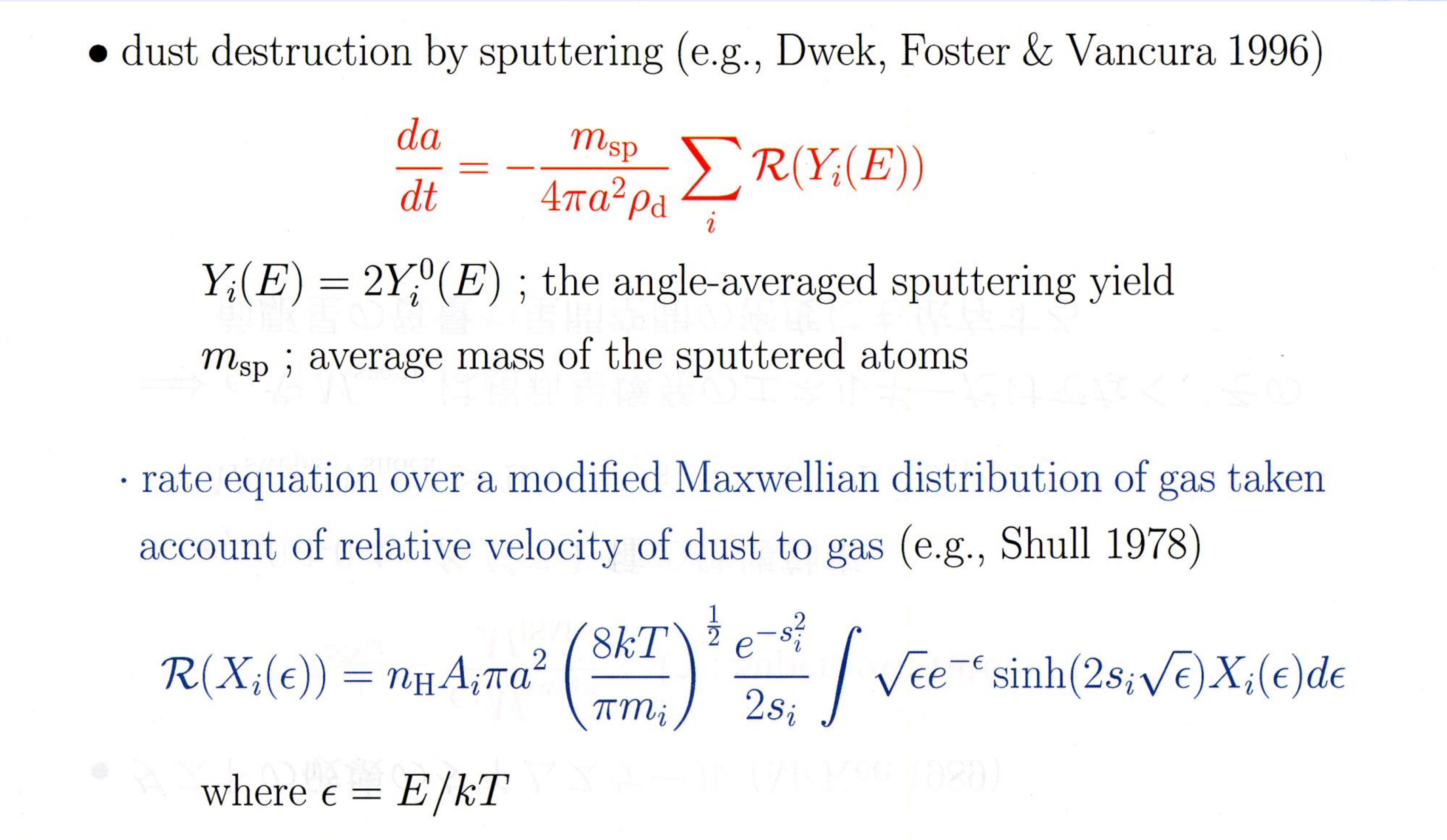
$$\begin{aligned} F_{\mathrm{drag}} &= m_{\mathrm{d}}\frac{dw_{\mathrm{d}}}{dt} = -\pi a^2 \sum n_i \langle v_i m_i v_i \cos\theta\rangle \\ \frac{dw_{\mathrm{d}}}{dt} &= -\frac{\pi a^2}{\frac{4}{3}\pi a^3 \rho_d} n_{\mathrm{H}} \sum A_i \langle v_i m_i v_i \cos\theta\rangle \\ &= -\frac{3n_{\mathrm{H}}}{4a\rho_d}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

y 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

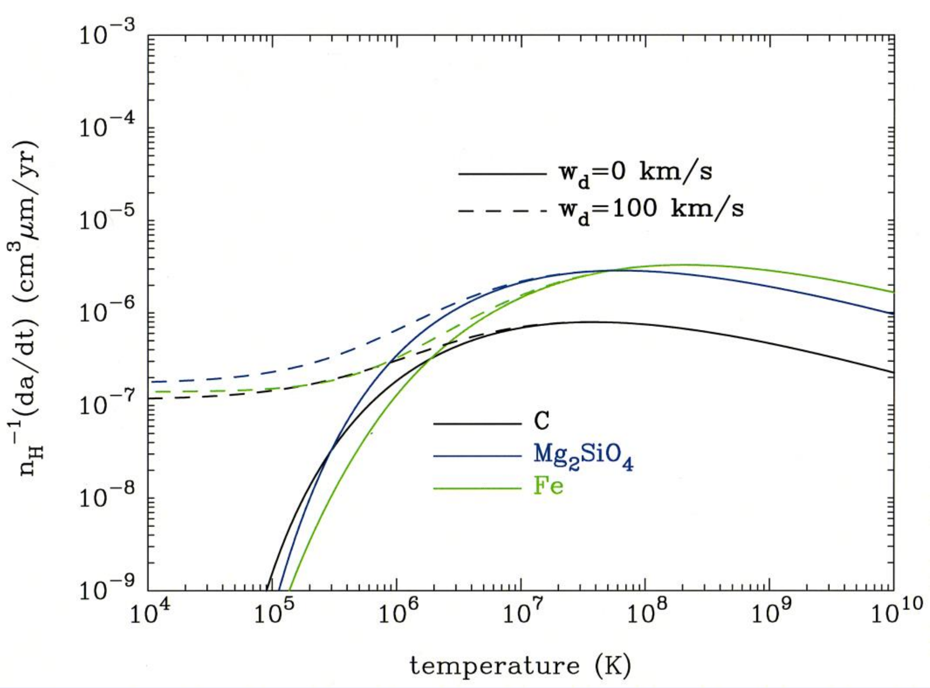
$m_{\rm sp}$; average mass of the sputtered atoms

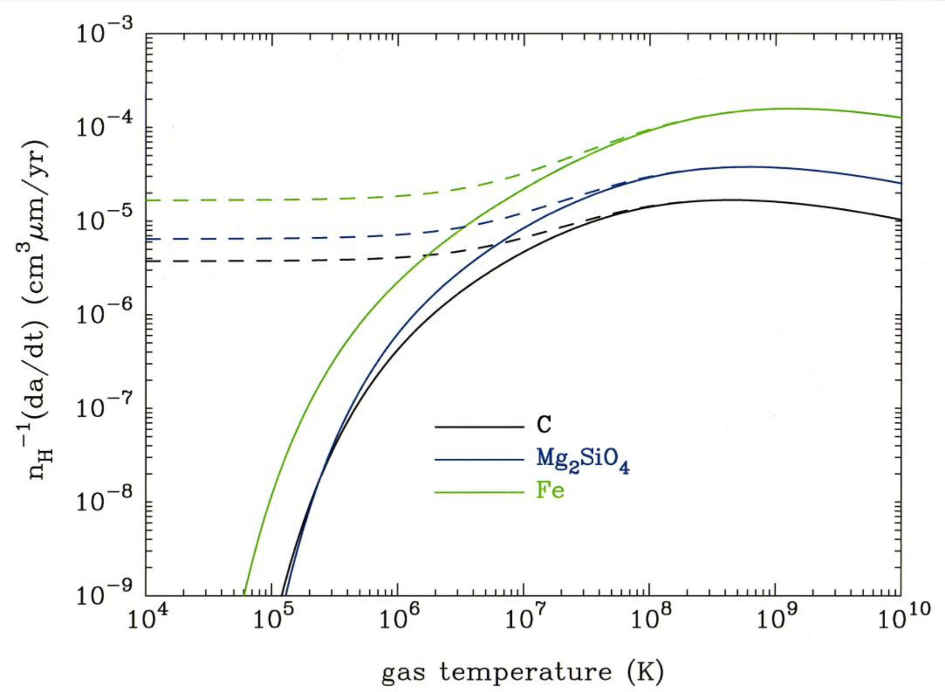
· rate equation over a modified Maxwellian distribution of gas taken account of relative velocity of dust to gas (e.g., Shull 1978)

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

where $\epsilon = E/kT$

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

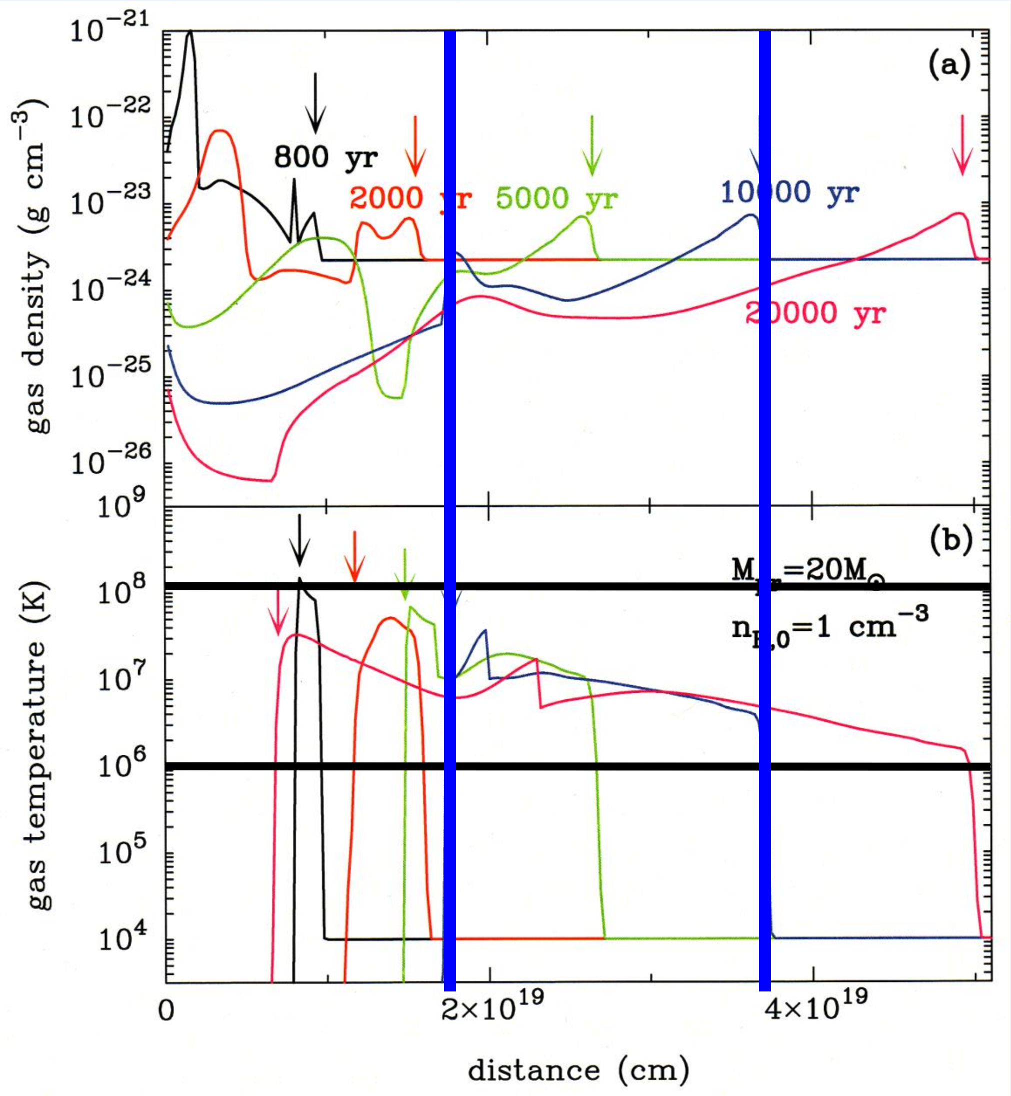

for primordial composition gas


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** (e.g., Nozawa et al. 2006)

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

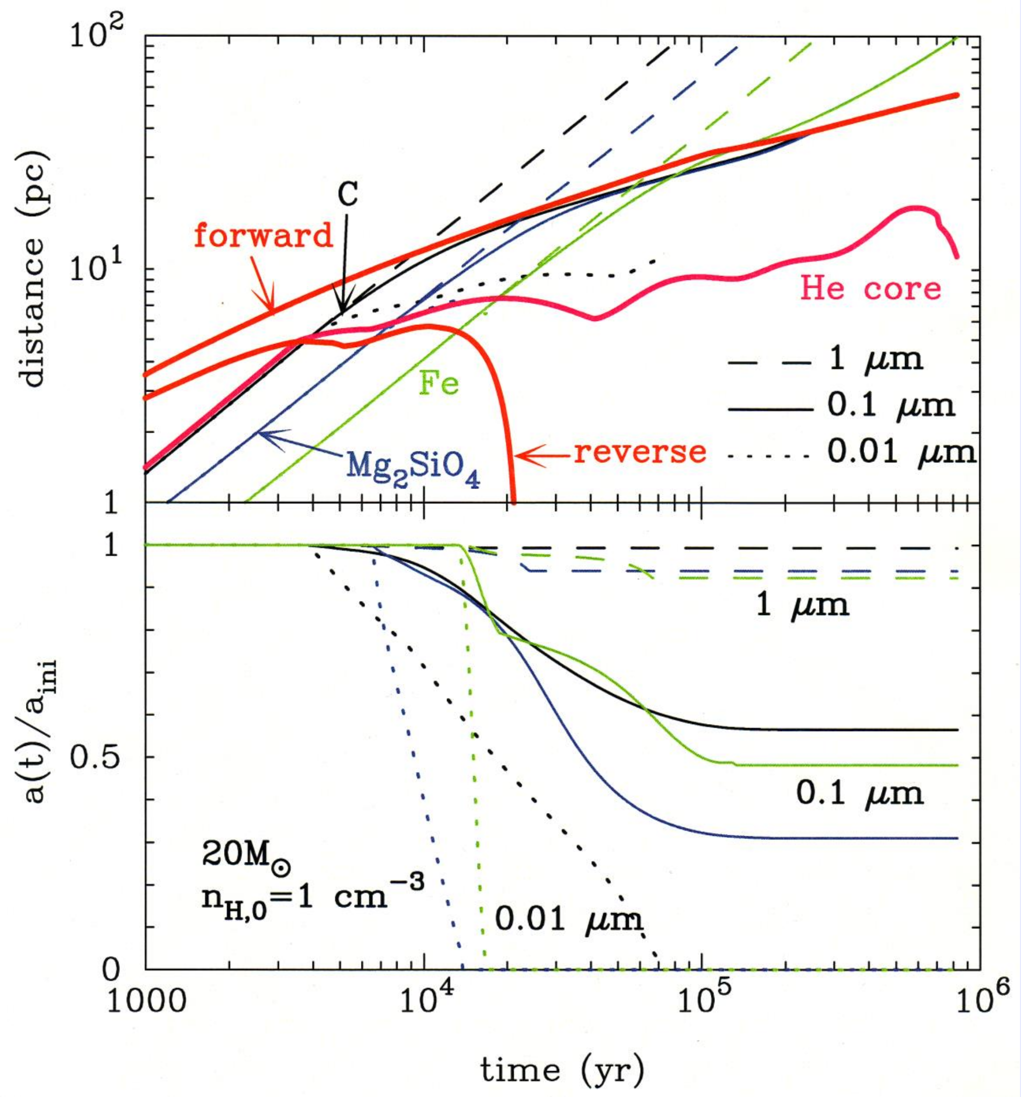
The temperature of the gas swept up by the shocks

➔ 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)

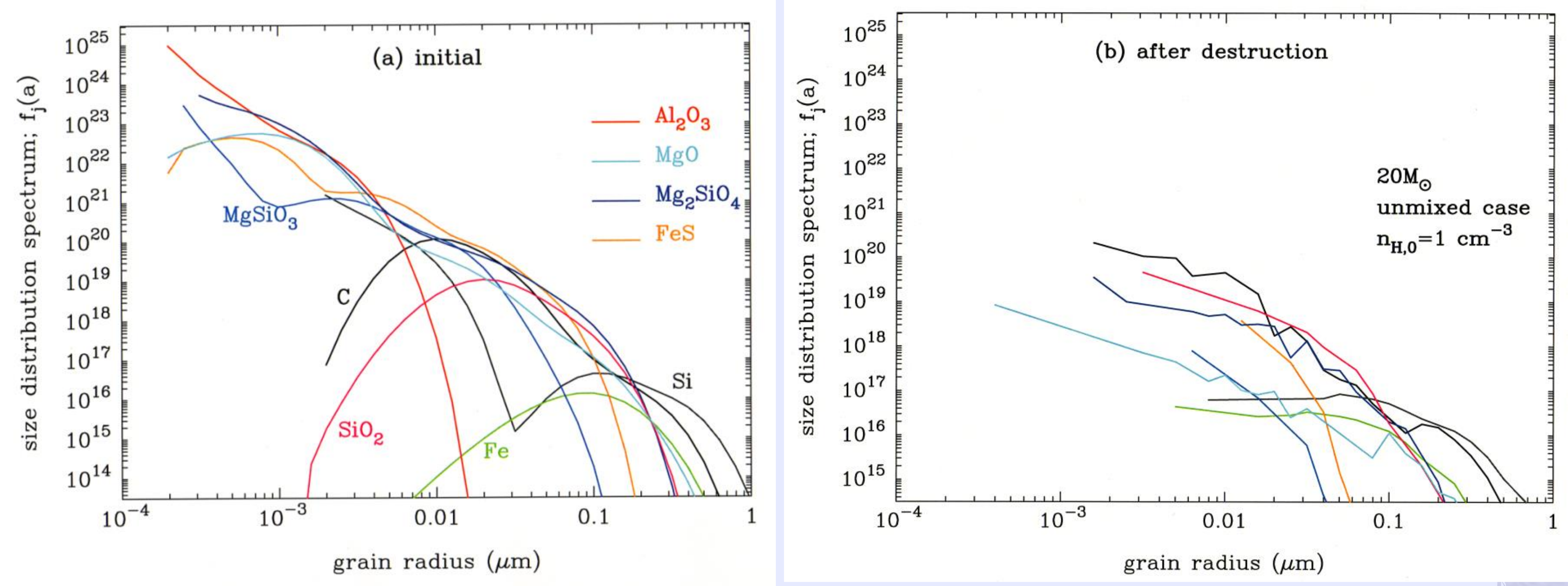
$n_{H,0}$ = 1 cm^{-3}

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

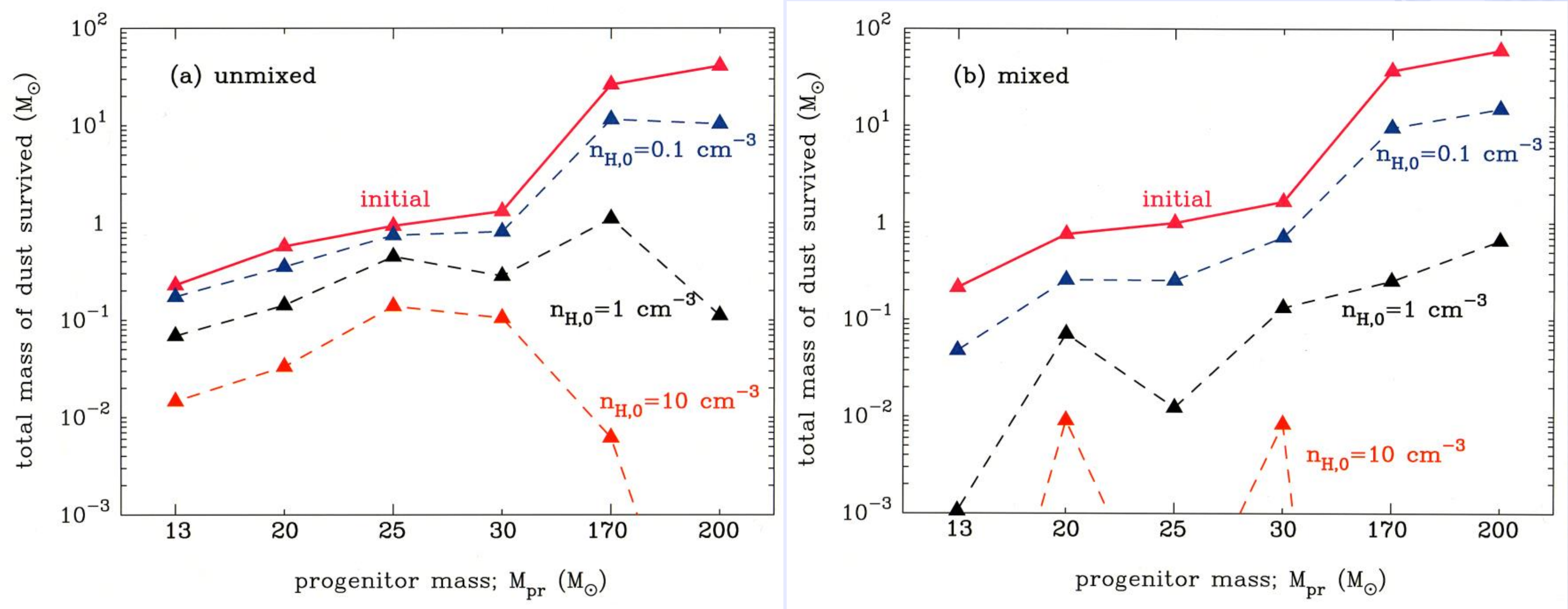
3-5. Size distribution of surviving dust



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 of surviving dust

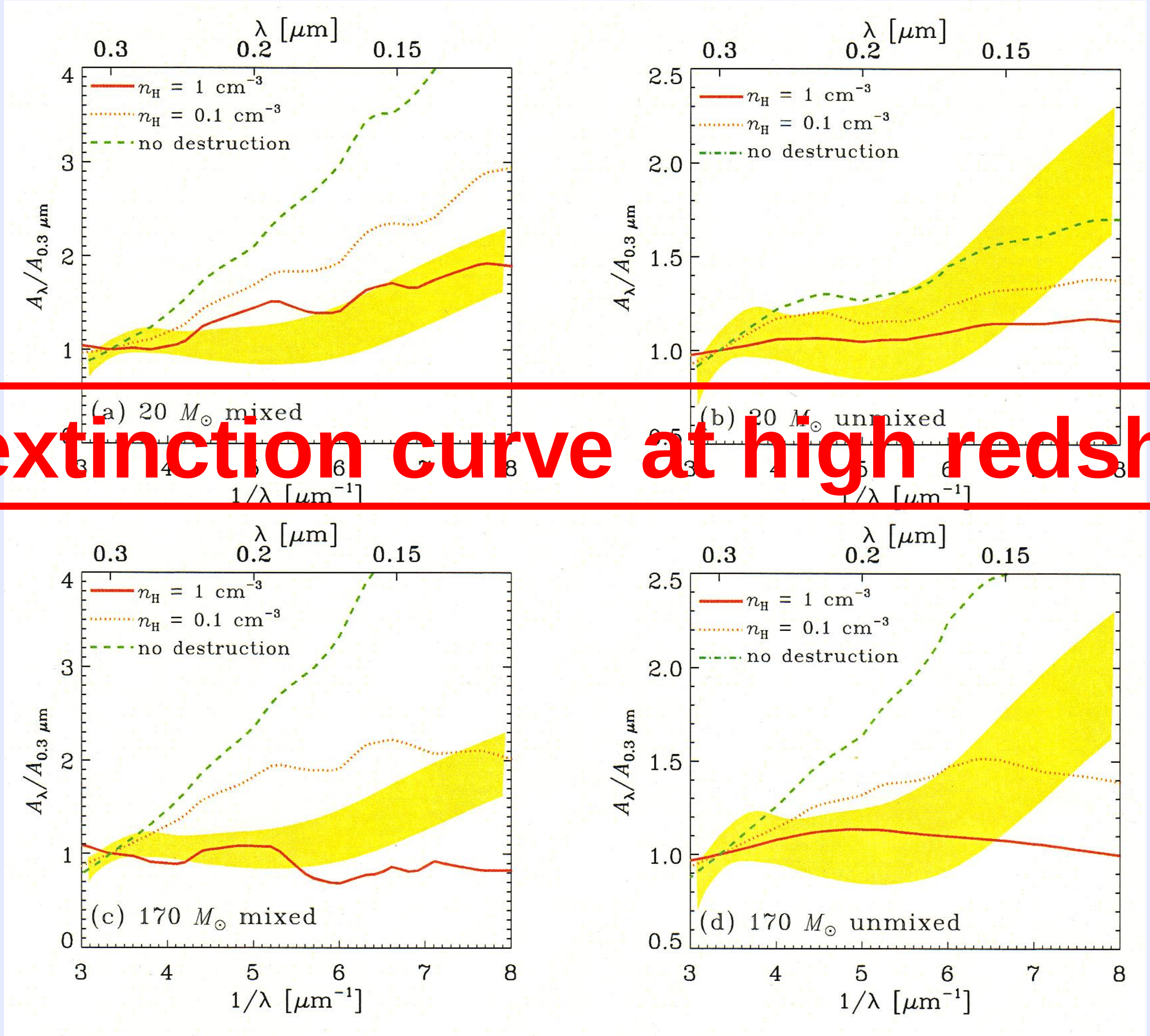


Total mass of dust surviving the destruction for Type II SNRs;
0.1-0.8 Msun for the unmixed grain model ($n_{H,0}$ = 0.1-1 cm^{-3})
0.06-0.7 Msun for the mixed grain model ($n_{H,0}$ = 0.1 cm^{-3})

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

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

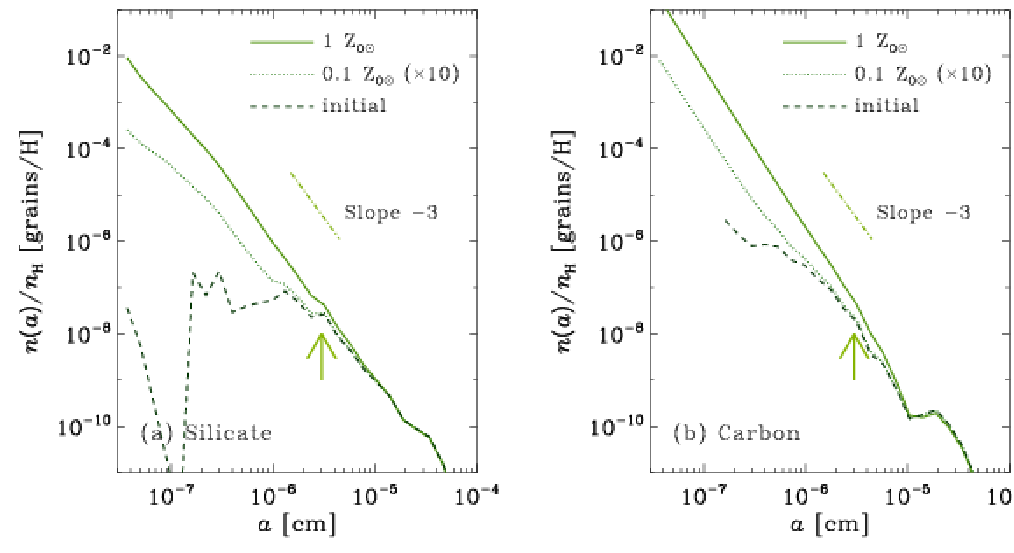
3-7-1. Flattened extinction curves

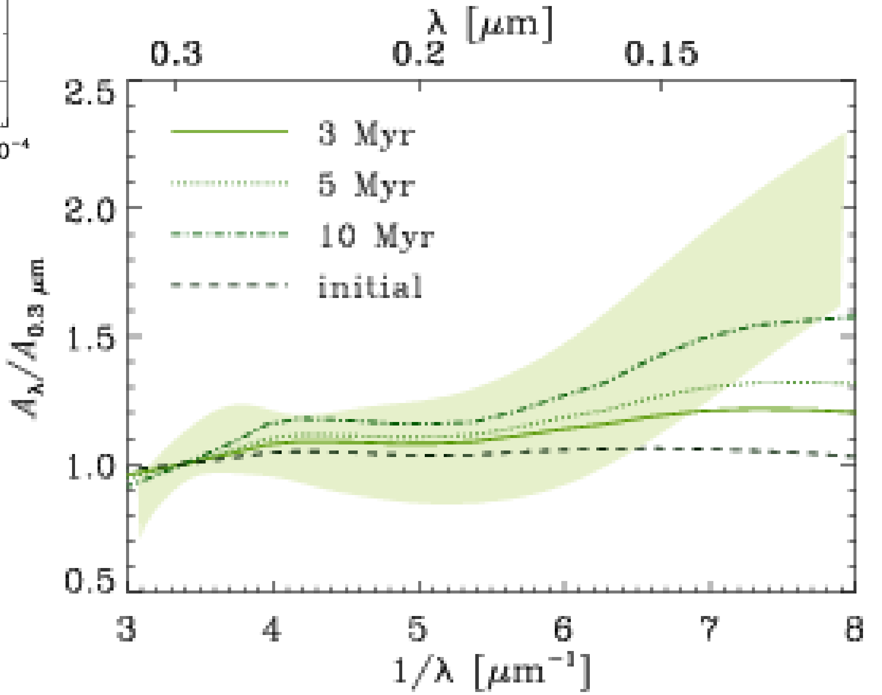


flat extinction curve at high redshifts !

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

3-7-2. Effect of grain shattering





Hitashita et al. (2010, accepted , astro-ph/1001.2606)

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 grains decreases with increasing the ambient gas density

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

  SNe II ➔ $M_{dust} = 0.1\text{-}0.8\ M_{sun}$ for the unmixed case

  PISNe ➔ $M_{dust} = 0.1\text{-}15\ M_{sun}$

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

4. Formation and evolution of dust in Cassiopeia A SNR

4-1-1. Introduction

○ Dust in SNRs

- CCSNe are important sources of dust?
  - Theoretical studies : 0.01-0.8 M_{sun}

    (Bianchi & Schneider 2007; Nozawa et al. 2007)
  - Observations : < 10^{-3} M_{sun}

  ➔ What kind and how much amount of dust are supplied by CCSNe?

- physical processes of dust in shocked gas
  - erosion by sputtering and collisional heating

- IR thermal emission from shock-heated dust

  ➔ structure of circumstellar medium and mass-loss history of progenitor star

4-1-2. Cassiopeia A SNR

○ Cas A SNR

- **age: ~330 yr** (Thorstensen et al. 2001)
- **distance: d=3.4 kpc** (Reed et al. 1995)
- **ejecta mass = 2-4 M_{sun}**
- **shock radius** (Gotthelf et al. 2001)

  R_{forw} = ~153" (~2.52 pc), R_{rev} = ~95" (~1.57 pc)

  ➔ **$dM/dt \sim 2\times10^{-5}$ (v_w/10 km/s) M_{sun}/yr**

  (Chevalier & Oishi 2003)
- **oxygen-rich SNR**

  detection of metal lines such as O, Ar, S, Si, Fe …

  thermal emission from ejecta-dust

  ➔ **M_{dust} = 0.02-0.054 M_{sun}** (Rho et al. 2008)
- **SN type : Type IIb (M_{star}=15-20 M_{sun})** (Krause et al. 2008)

4-1-3. Aim of our study

- Formation of dust in the ejecta of Type IIb SN

  ➔ composition, size, and mass of newly formed dust
  ➔ dependence of dust formation process on types of SNe (on the mass of H envelope)

- Evolution of dust in shocked gas within the SNR

  ➔ What fraction of newly formed dust can survive and is injected into the ISM?

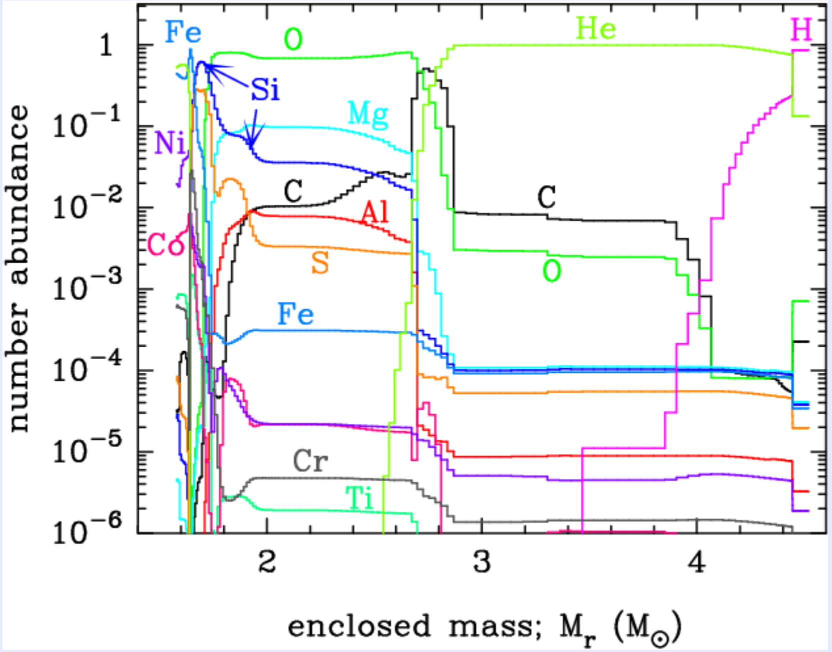
- Thermal emission from shock-heated dust

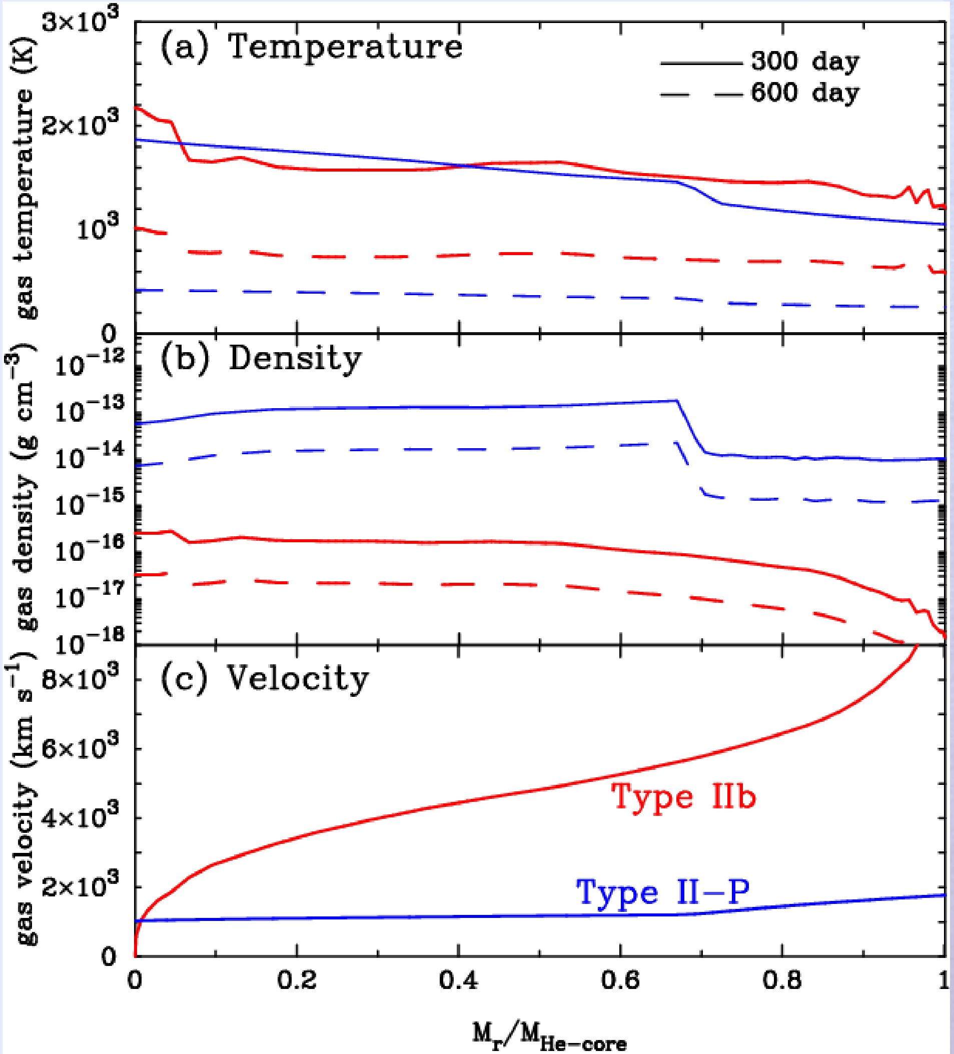
  ➔ comparison with IR observations of Cas A
  ➔ constraint to gas density in the ambient medium

4-2. Model of Type IIb SN

○ SN IIb model (SN1993J-like model)

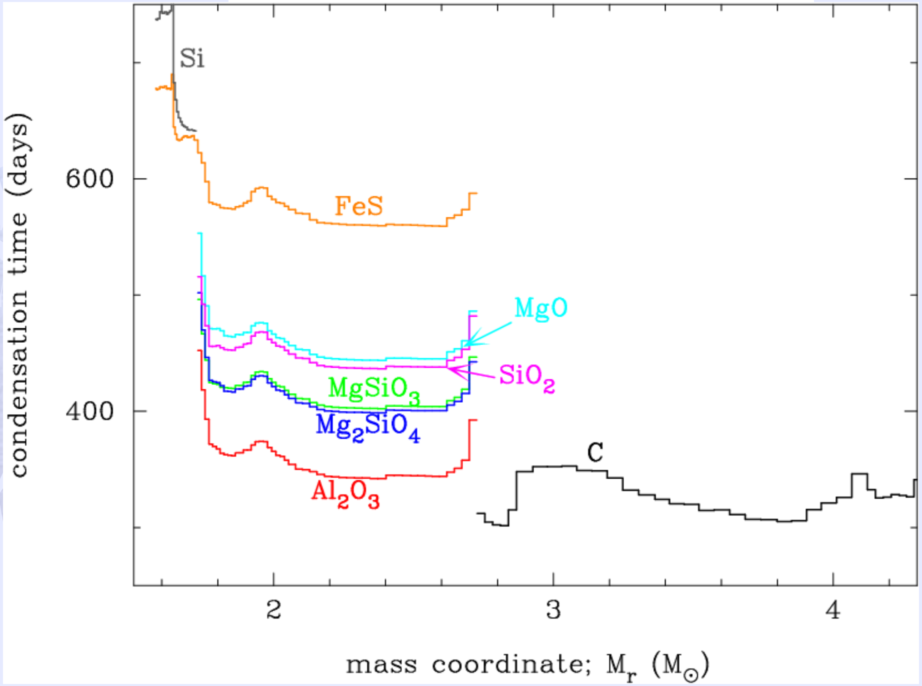
- M_{eje} = 2.94 M_{sun}
  $M_{H\text{-}env}$ = 0.08 M_{sun}
  M_{star} = 18 M_{sun}
- E_{51} = 1
- $M(^{56}Ni)$ = 0.07 M_{sun}



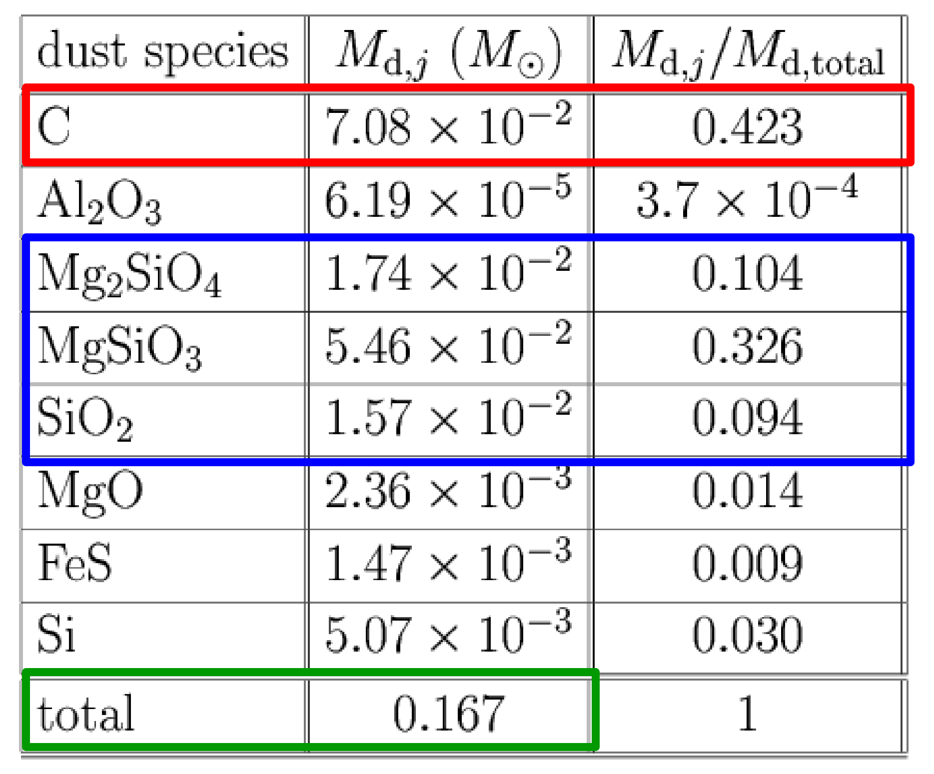


4-3-1. Composition and mass of dust

condensation time



mass of dust formed



dust species	$M_{d,j}$ ($M_\odot$)	$M_{d,j}/M_{d,\mathrm{total}}$
C	7.08×10^{-2}	0.423
Al_2O_3	6.19×10^{-5}	3.7×10^{-4}
Mg_2SiO_4	1.74×10^{-2}	0.104
$MgSiO_3$	5.46×10^{-2}	0.326
SiO_2	1.57×10^{-2}	0.094
MgO	2.36×10^{-3}	0.014
FeS	1.47×10^{-3}	0.009
Si	5.07×10^{-3}	0.030
total	0.167	1

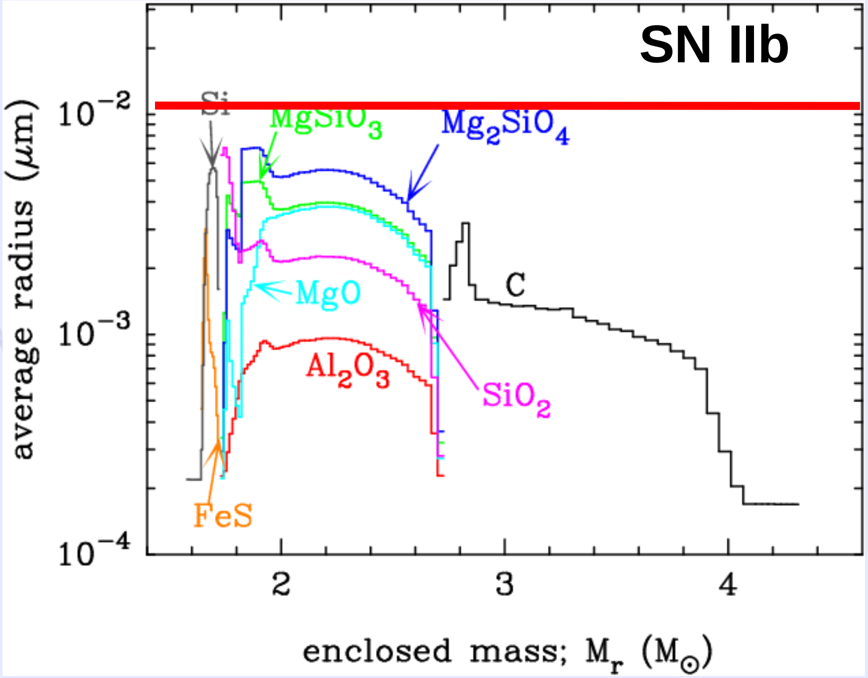
- different species of dust can condense in different layers
- condensation time:
  300-700 days

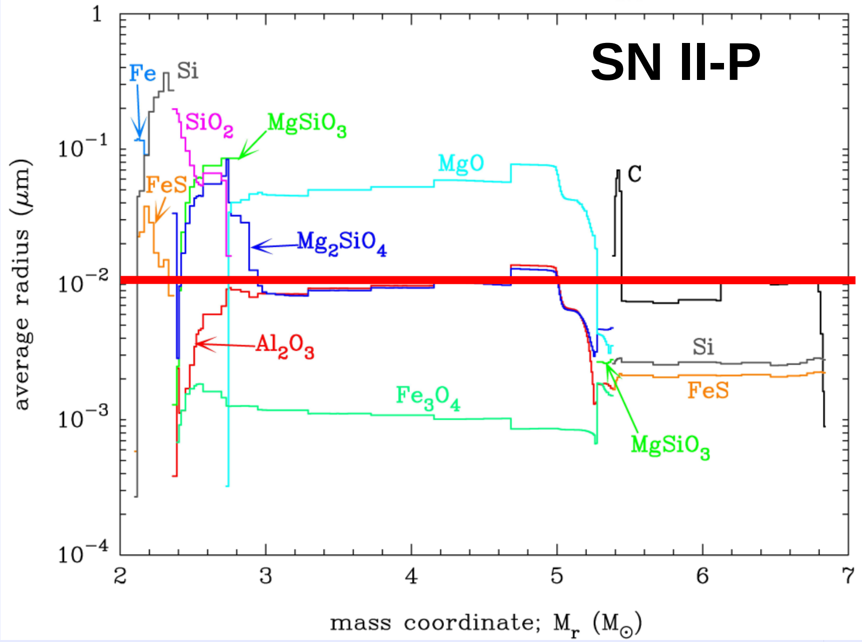
Total mass of dust formed :

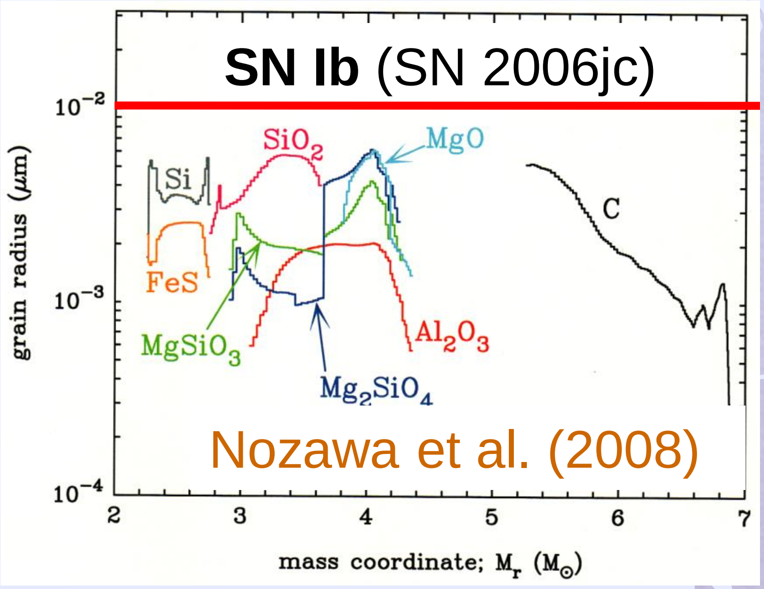
0.167 Msun in SN IIb

0.1-1 Msun in SN II-P

4-3-2. Average radii of dust formed







Nozawa et al. (2008)

Grain radius

➔ **> 0.01 μm for SN IIP**

➔ **< 0.01 μm for SN IIb**

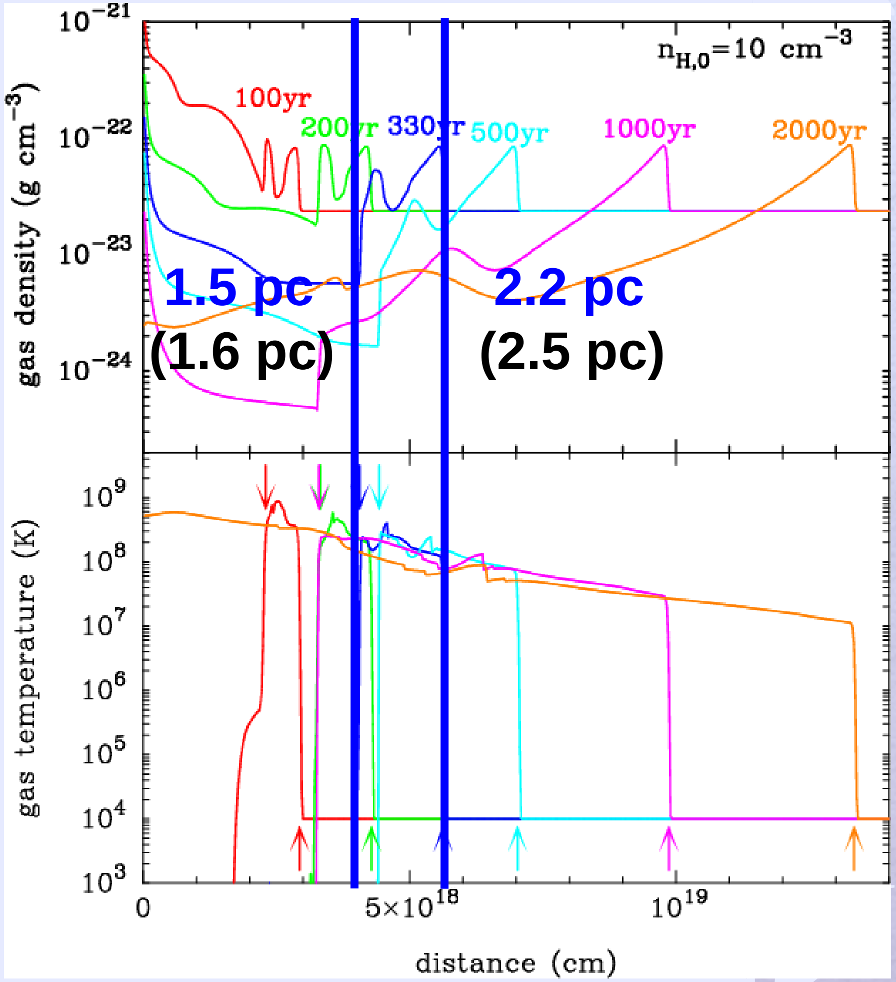
Dust grains formed in H-deficient SNe are small

4-4. Calculation of dust evolution in SNR

○ Model of calculations

(Nozawa et al. 2006, 2007)

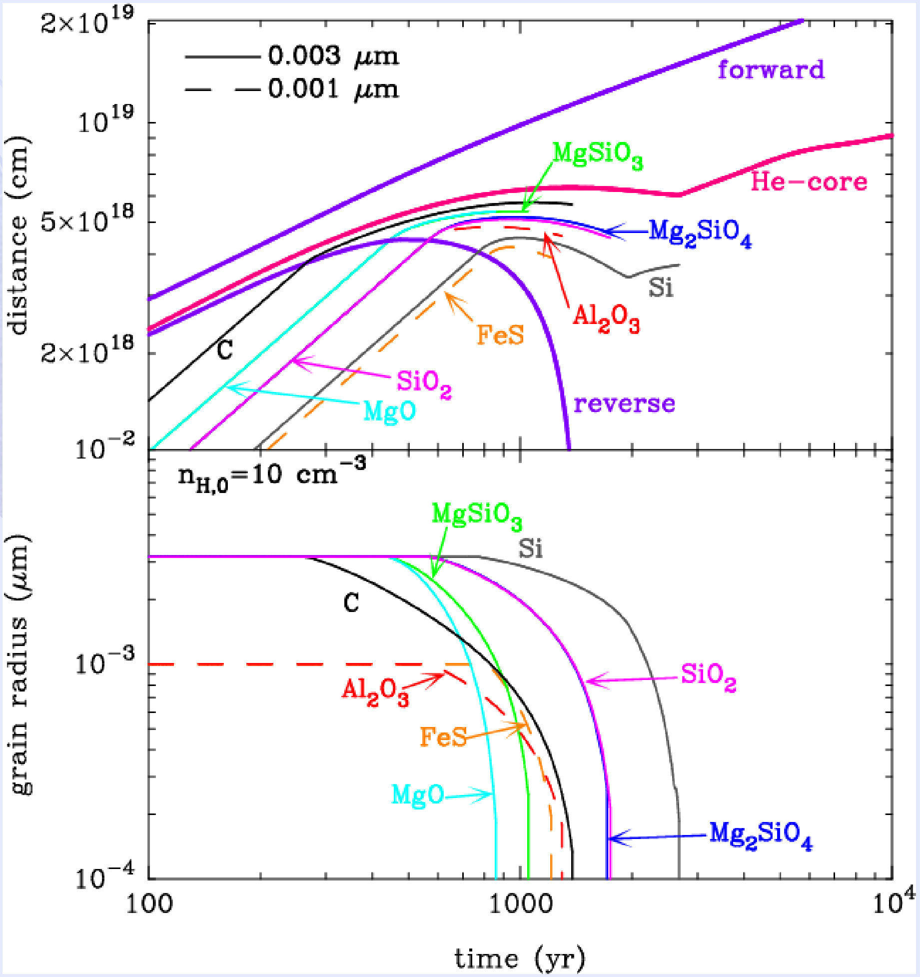
- ejecta model
  - hydrodynamic model for dust formation calculation
- CSM gas density
  - $n_{H,0}$ = 0.1, 1.0, 10.0 cm^{-3}
  - $n_H(r) = n_{H,1} (r / r_1)^{-2}$
    $n_{H,1}$ = 30, 120, 200 cm^{-3}
- treating dust as a test particle
  - erosion by sputtering
  - deceleration by gas drag



1.5 pc (1.6 pc)

2.2 pc (2.5 pc)

4-5-1. Evolution of dust in SNRs

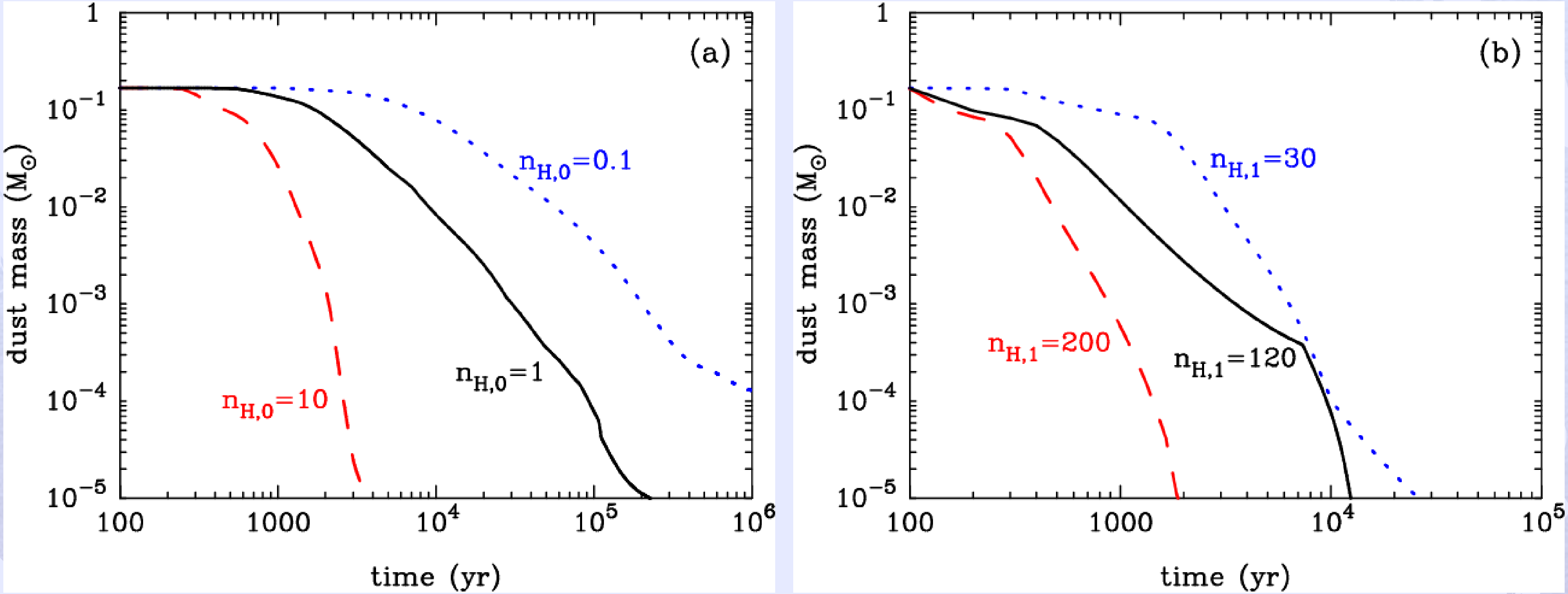


The collision times between the reverse shock and He core is 75 year after the explosion

➔ much earlier than those (> 1000 yr) for Type II-P

small grains formed in the ejecta are quickly trapped in the hot gas and are completely destroyed

4-5-2. Time evolution of total dust mass

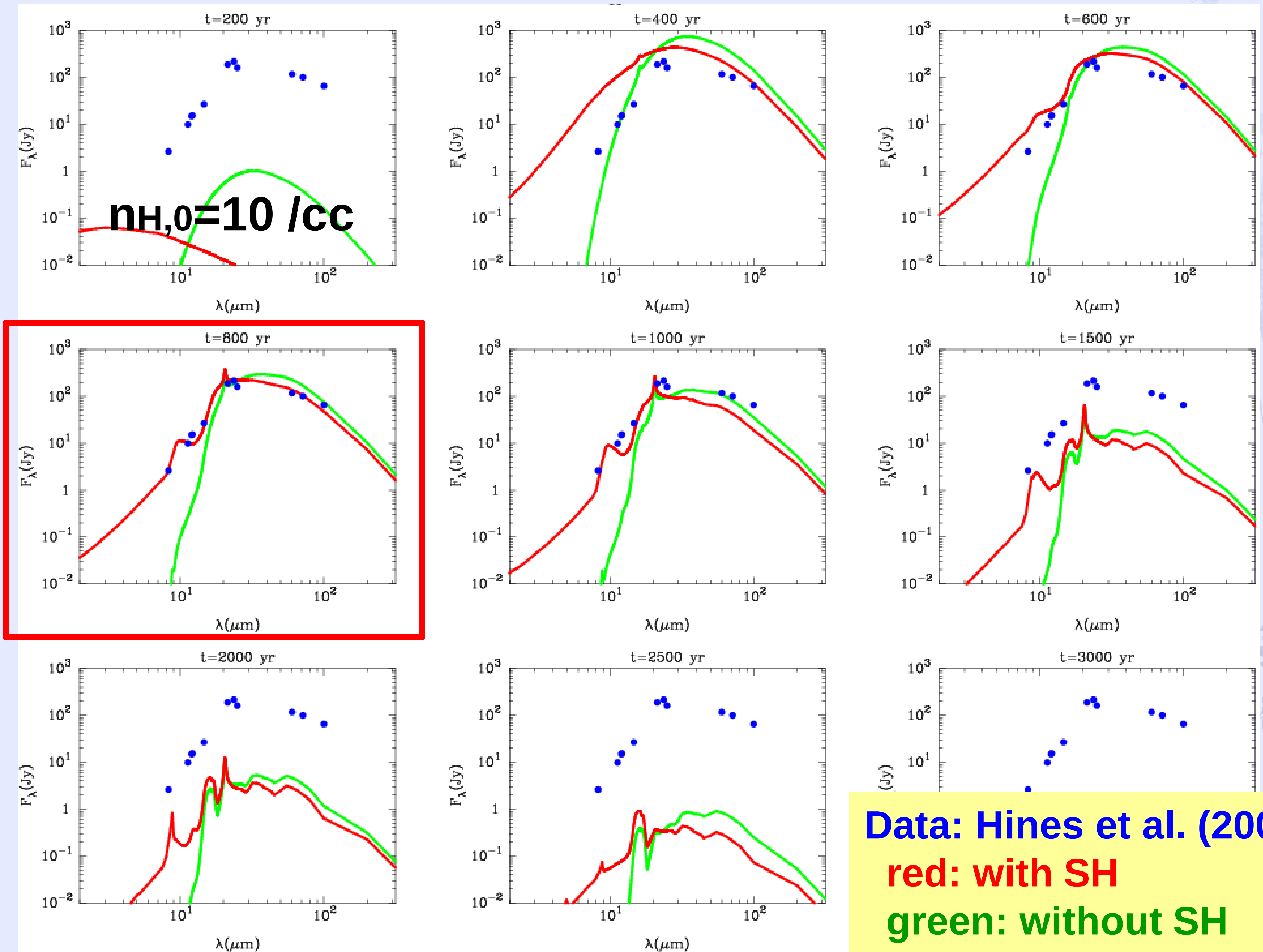


Almost all newly formed dust grains are destroyed in the shocked gas within the SNR

- ➔ **small grain size of newly formed dust**
- ➔ **early arrival of the reverse shock at the He core**

SNe IIb (as well as SNe Ib/c) with low-mass outer envelope could not be important sources of dust

4-6. Time evolution of IR emission (2)



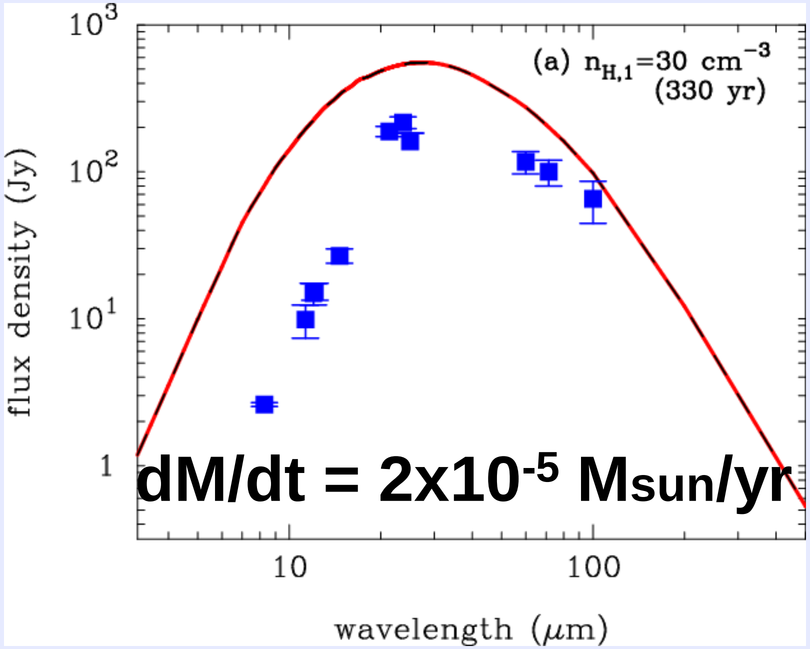
$n_{H,0}$=10 /cc

Data: Hines et al. (2004)

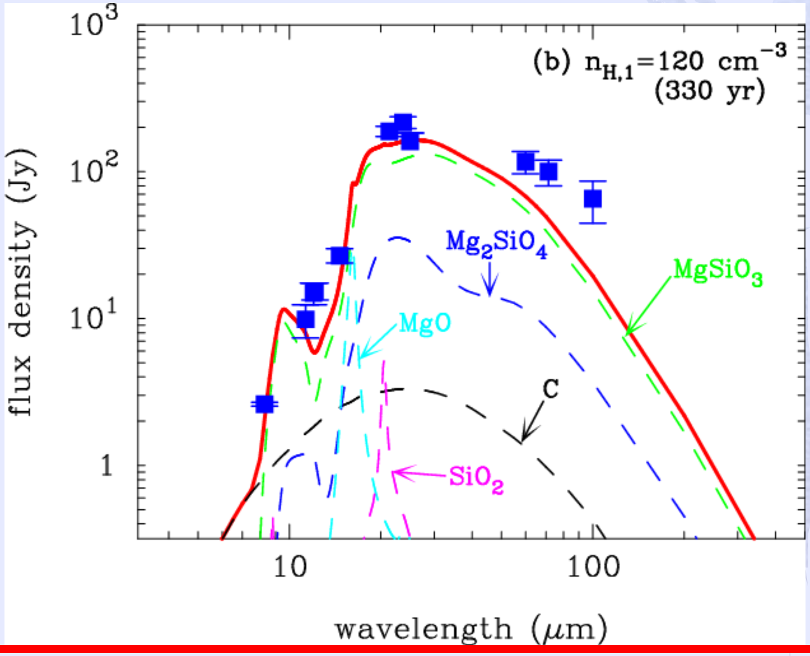
red: with SH

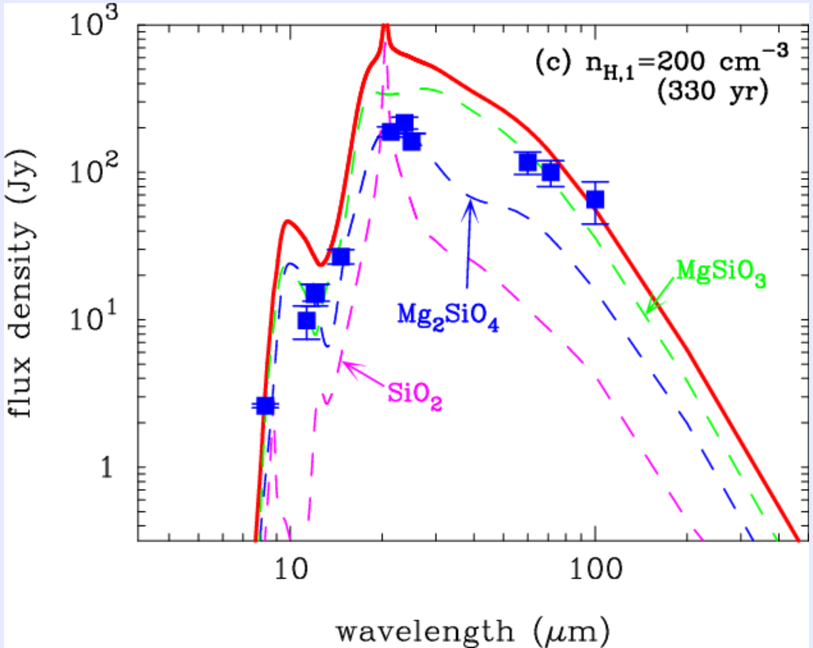
green: without SH

4-7-1. IR SED for various ambient density



dM/dt = 2x10^{-5} Msun/yr





M_d = 0.008 Msun
dM/dt = 8x10^{-5} Msun/yr

4-7-2. Contribution from CS dust

- **dust species**

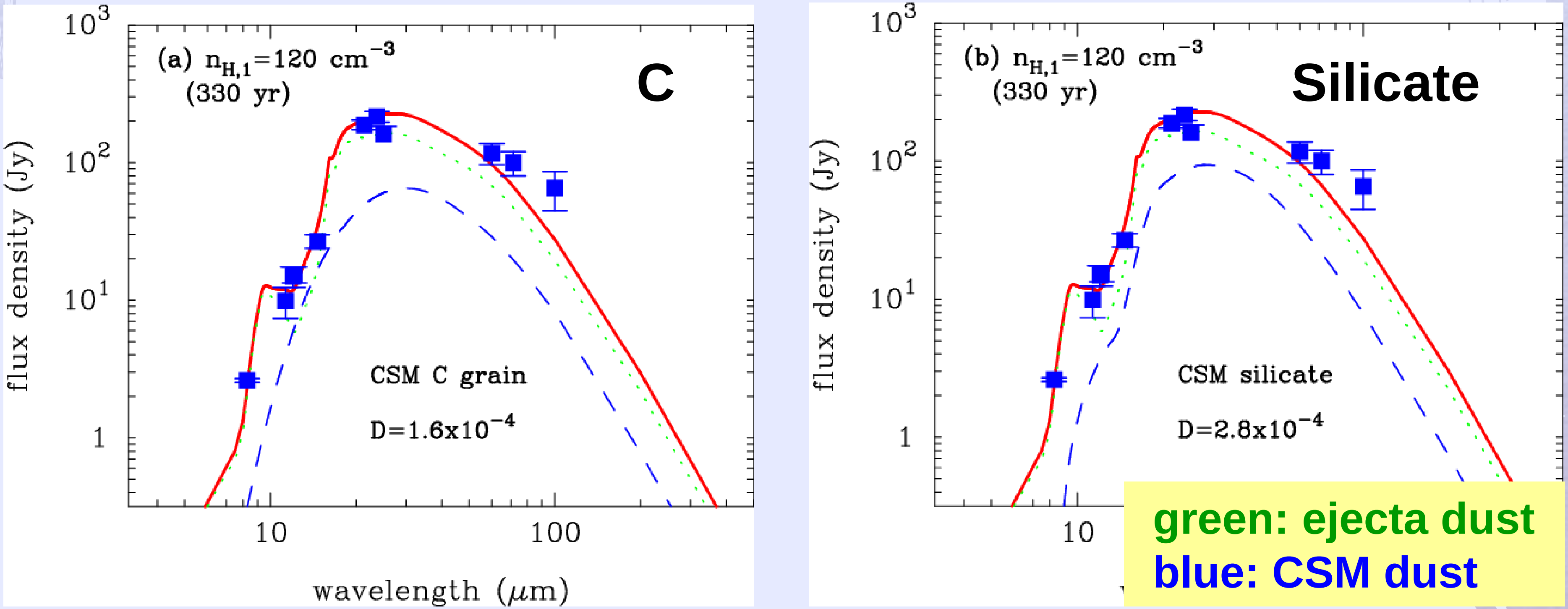
  C and silicate
- **dust size distribution**

  f(a) ∝ a^-3.5

  a_{min} = 0.001 μm

  a_{max} = 0.5 μm
- **dust-gas ratio: parameter**

- **thermal emission from both CS grains has a peak at λ~30 μm**

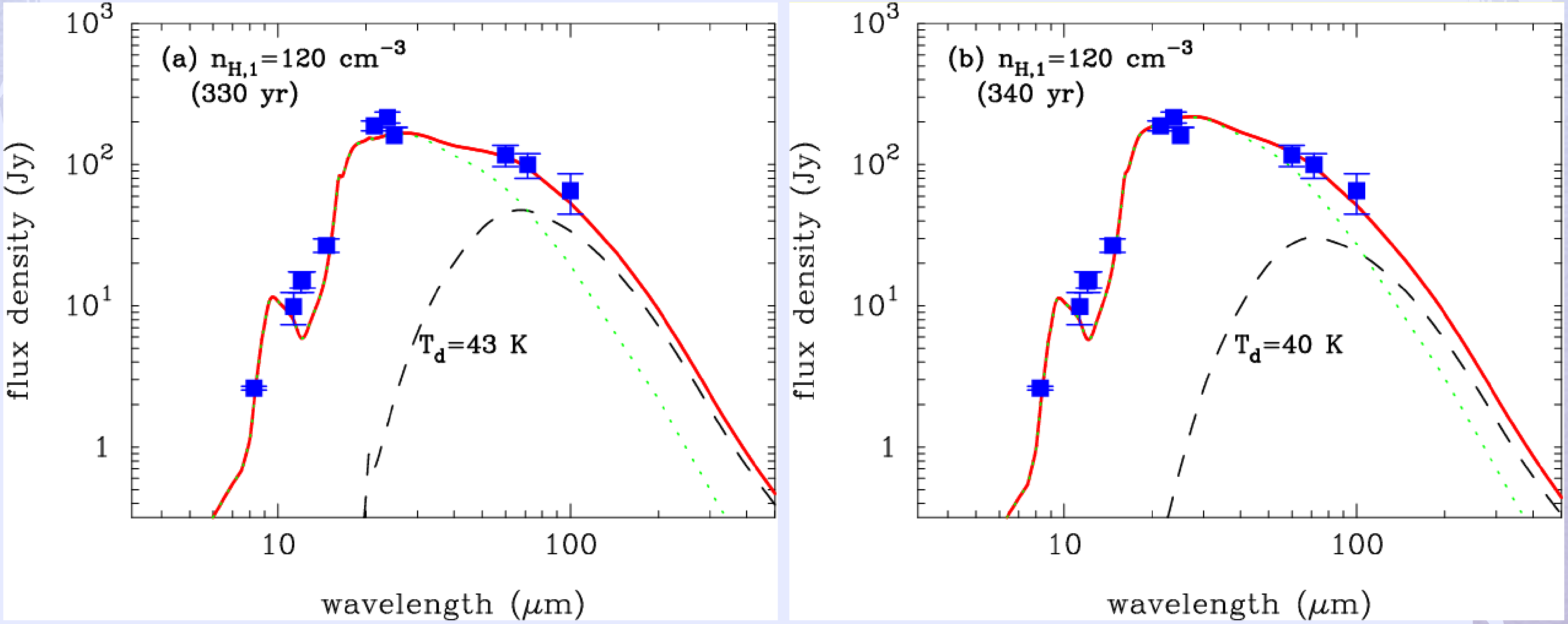


green: ejecta dust
blue: CSM dust

4-7-3. Contribution from unshocked dust

$M_{d,warm}$ ~ 0.008 M_{sun}
$M_{d,cool}$ ~ 0.072 M_{sun}
$dM/dt = 8 \times 10^{-5}$ M_{sun}/yr

- **observed SED can be well reproduced If the temperature of unshocked cold dust is around 40 K**



Summary

1) The radius of dust formed in the ejecta of Type IIb SN is quite small (< 0.01 μm) because of low ejecta density

2) Small dust grains formed in Type IIb SN cannot survive destruction in the shocked gas within the SNR

3) IR SED reflects the destruction and stochastic heating
   ➔ properties (size and composition) of dust
   ➔ density structure of circumstellar medium

4) Model of dust destruction and heating in Type IIb SNR can reasonably reproduce the observed SED of Cas A;
   $M_{d,warm} = 0.008\ M_{sun}$, $M_{d,cool} = 0.072\ M_{sun}$
   $dM/dt = \sim 8\times10^{-5}\ M_{sun}/yr$