Formation and Survival of Dust in Supernovae

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1. Introduction

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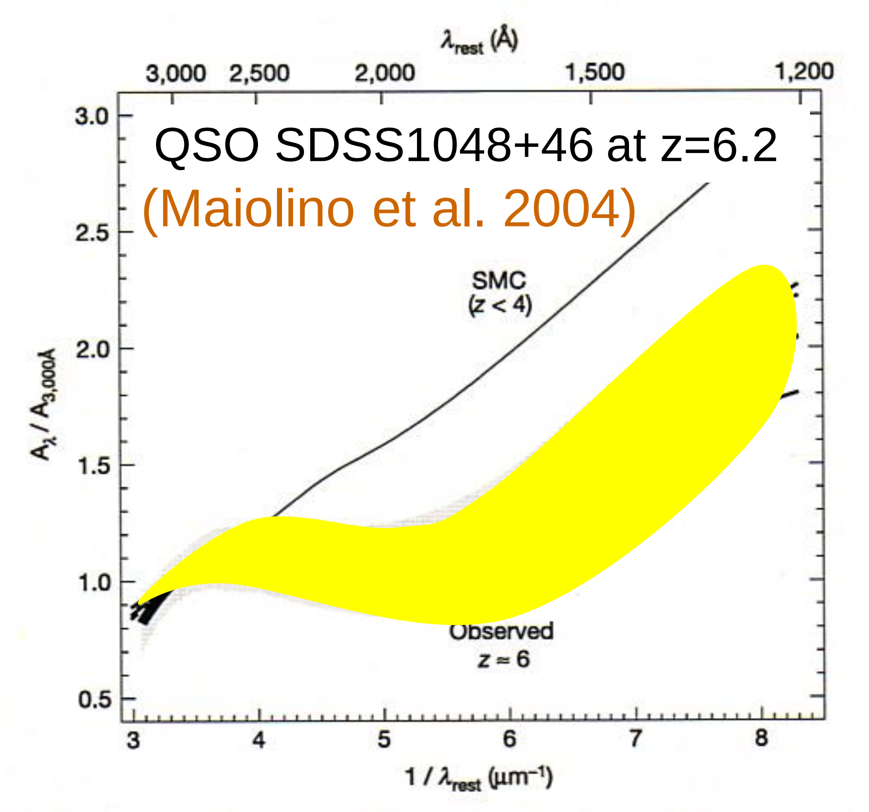
4. Thermal emission of dust in Cas A SNR

1. Introduction

1-1. 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)



dust of 0.1-1 Msun per SN are required to form
(Morgan & Edmunds 2003; Maiolino et al. 2004; Dwek et al. 2007)

properties of dust at high-z (z > 5) are different from those at low-z (z < 4)
(Maiolino et al. 2004; Stratta et al. 2007; Willot et al. 2008)

1-2. 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., Cazaux & Spaans 2004)

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

  (e.g., Schneider et al. 2003, Omukai et al. 2005)

  – controlling the energy balance in the interstellar space

1-3. Aim of our study

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

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

It is essential to clarify the properties of dust in the early epoch of the universe!

Our aim is to estimate the composition, size, and amount of dust by taking account of the formation and destruction processes of dust self-consistently

1-4. 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 ($100\text{-}500\ M_{sun}$)

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

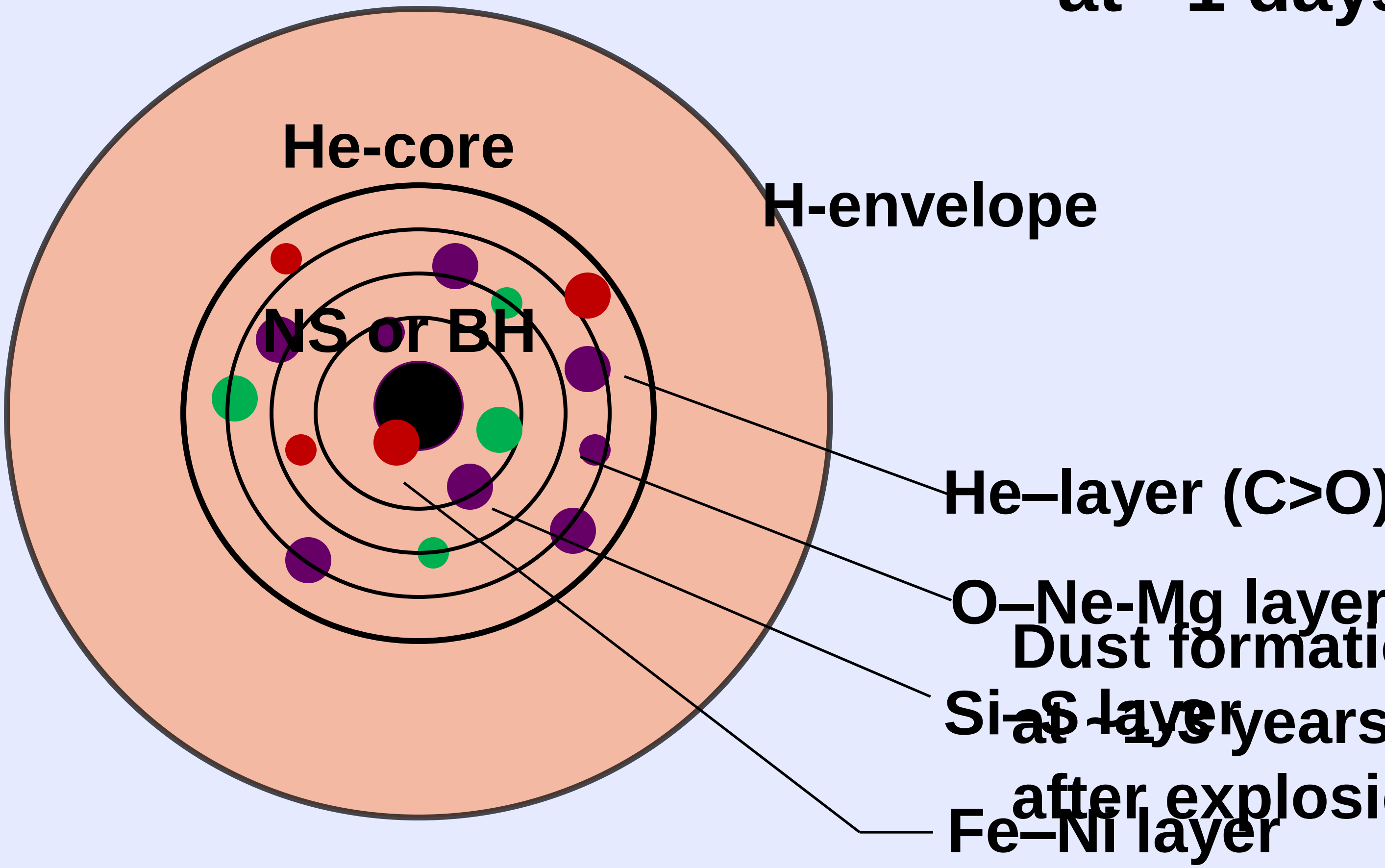
⇓

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

(Fryer et al. 2001; Umeda & Nomoto 2002; Heger et al. 2002)

2. Dust Formation in Primordial SNe

at ~1 days



Dust formation
at ~1-3 years
after explosion

2-1. Calculations of dust formation

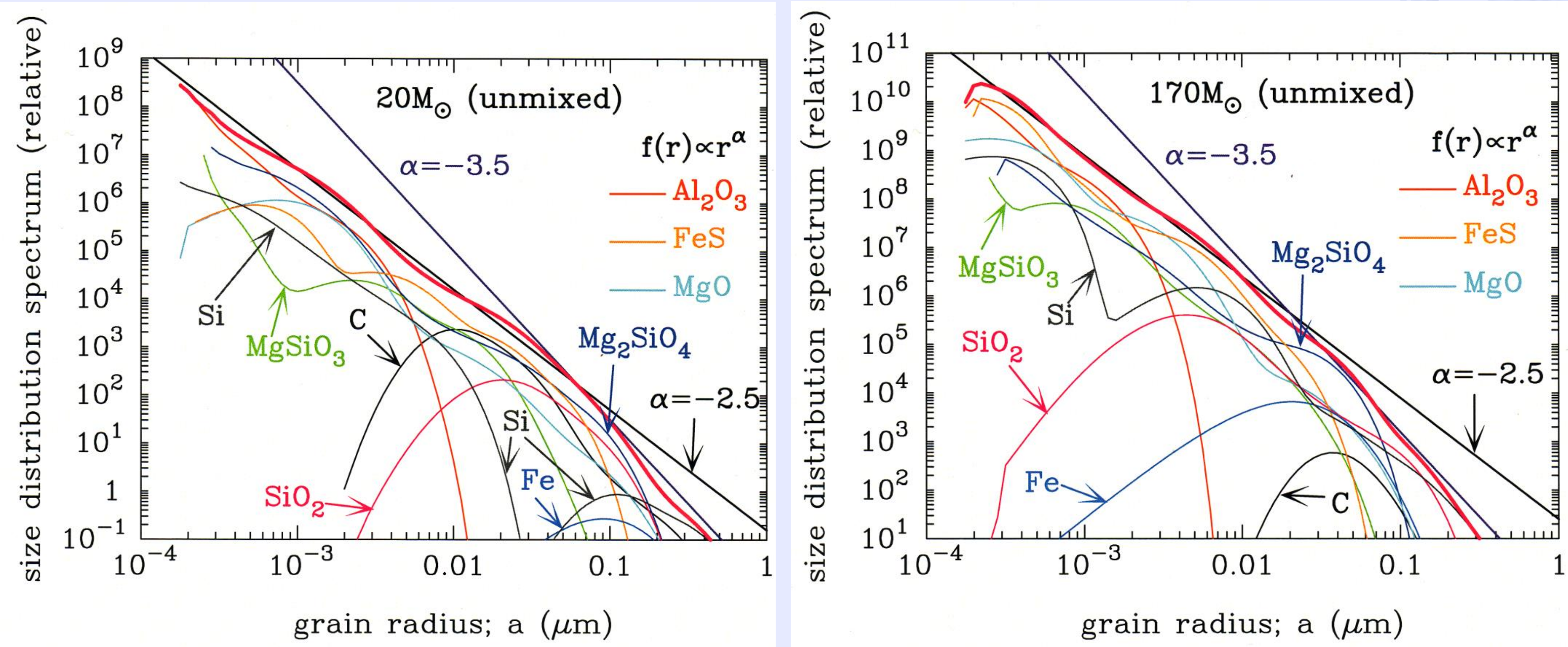
- **nucleation and grain growth theory**
  (Kozasa & Hasegawa 1987)

- **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)

- **time evolution of gas temperature**
  - 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. 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

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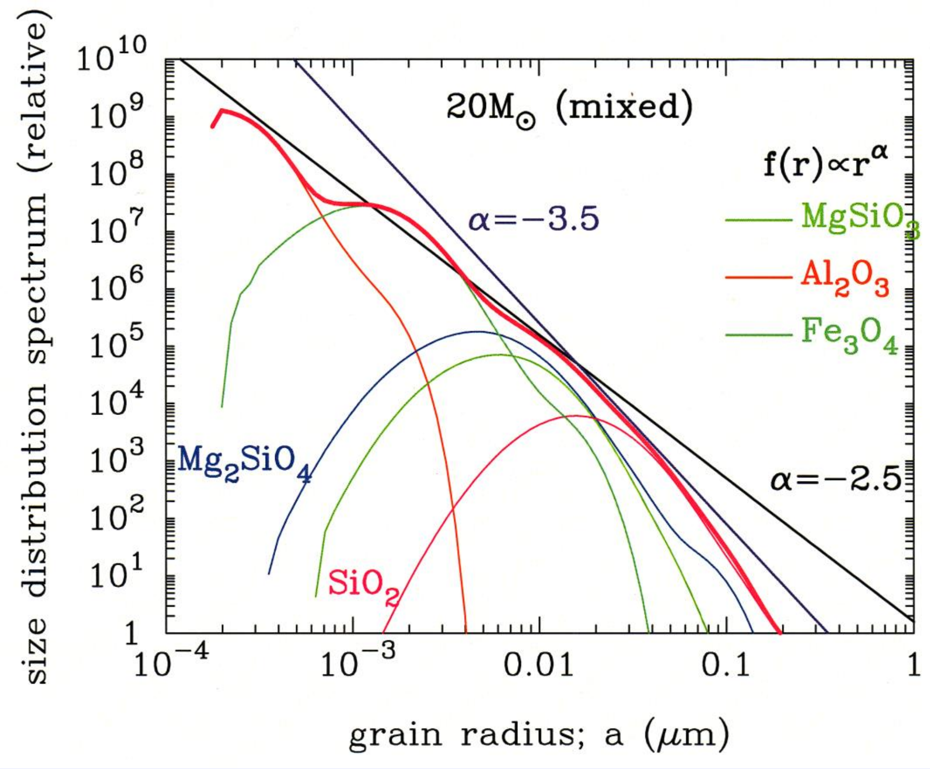
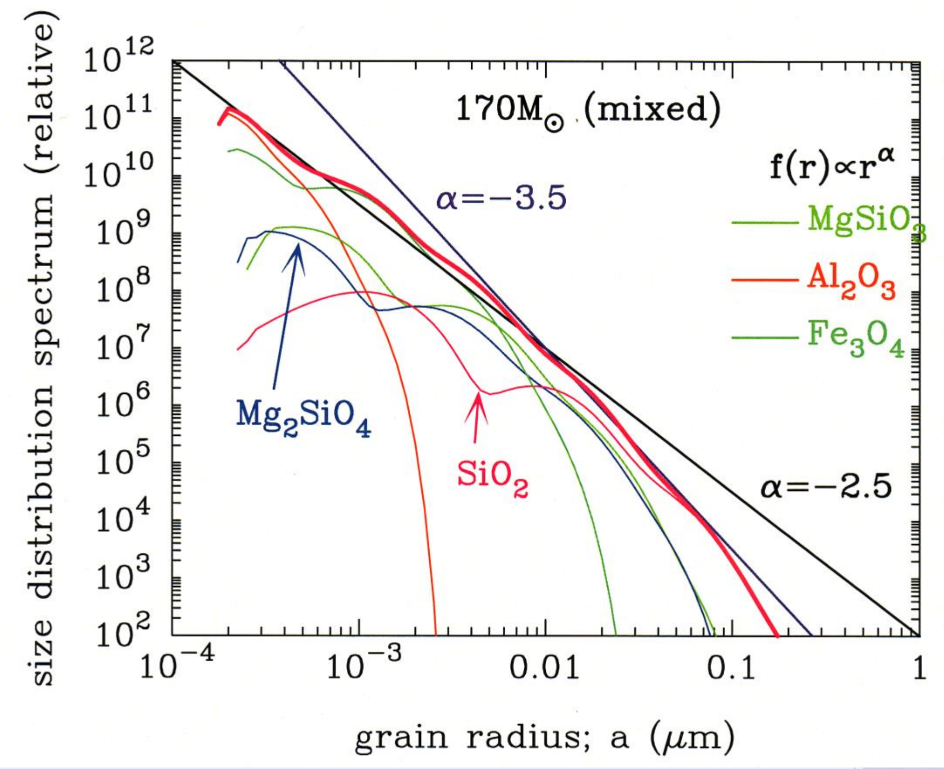
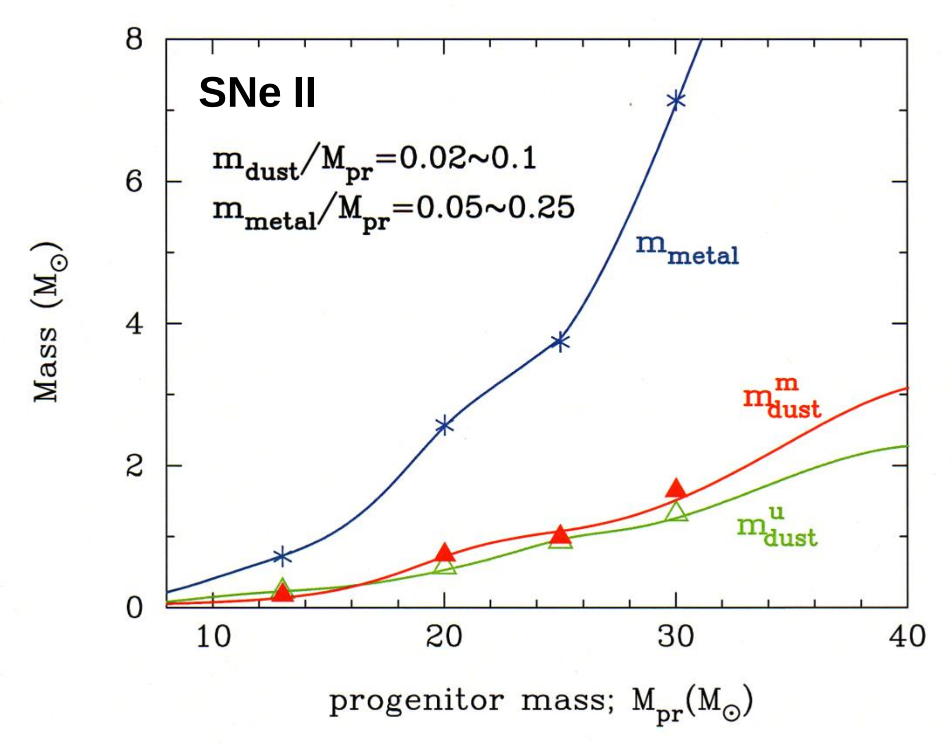
2-3. Dust formed in the mixed ejecta

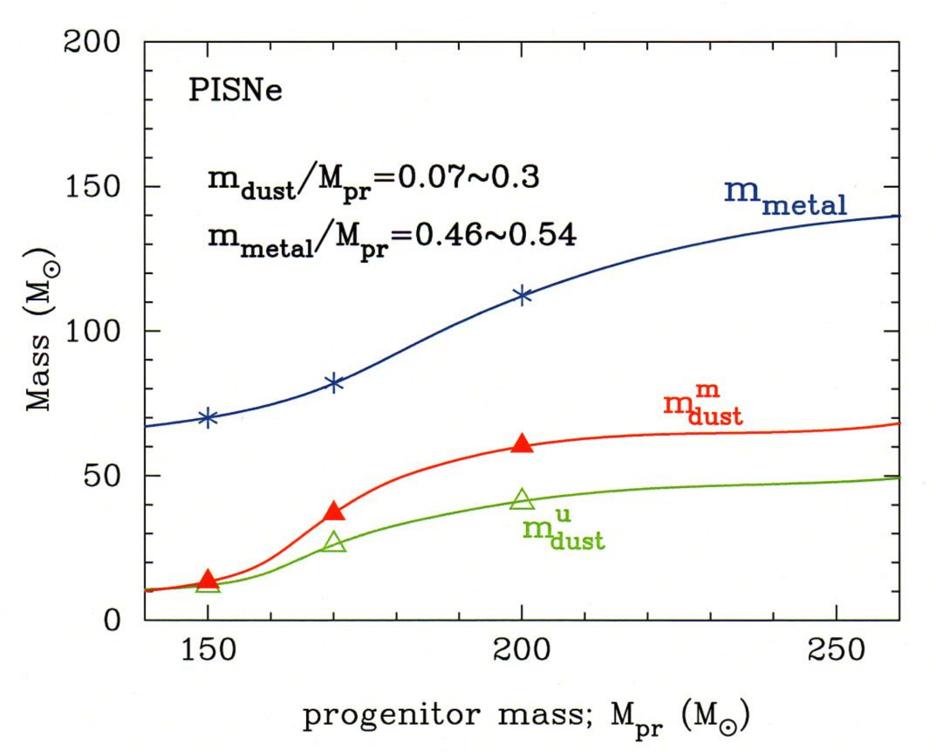




- Because oxygen is rich in the mixed ejecta, only silicates ($MgSiO_3$, Mg_2SiO_4, SiO_2) and oxides (Fe_3O_4, Al_2O_3) form
- The size distribution of each dust species except for Al_2O_3 is lognormal-like

2-4. Total mass of dust formed

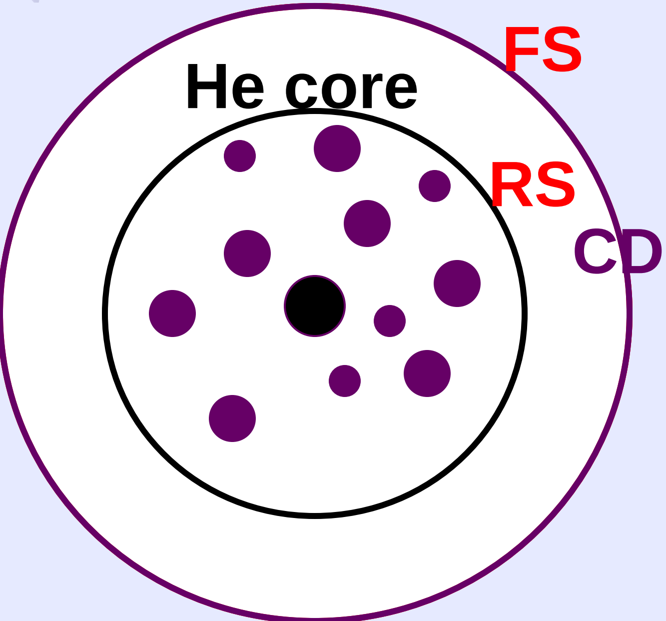




- Total dust mass increases with increasing progenitor mass
  SNe II : M_{dust} = 0.1-2 Msun PISNe : M_{dust} = 10-60 Msun
- Dust mass is generally higher for the mixed case than for the unmixed case

3. Dust Evolution in Primordial SNRs

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



3-1. 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)

3-2. 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

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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. Erosion rate of dust by sputtering

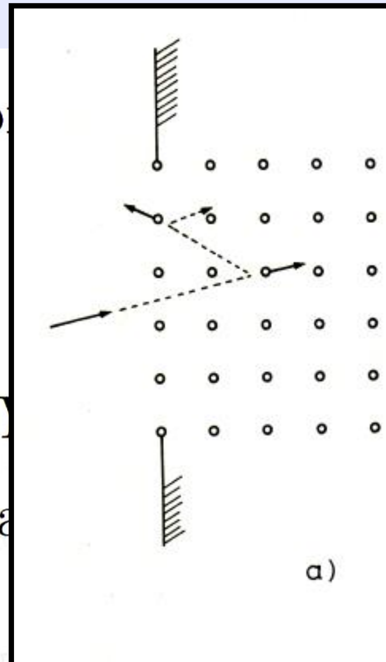
• dust destructio ... 996)

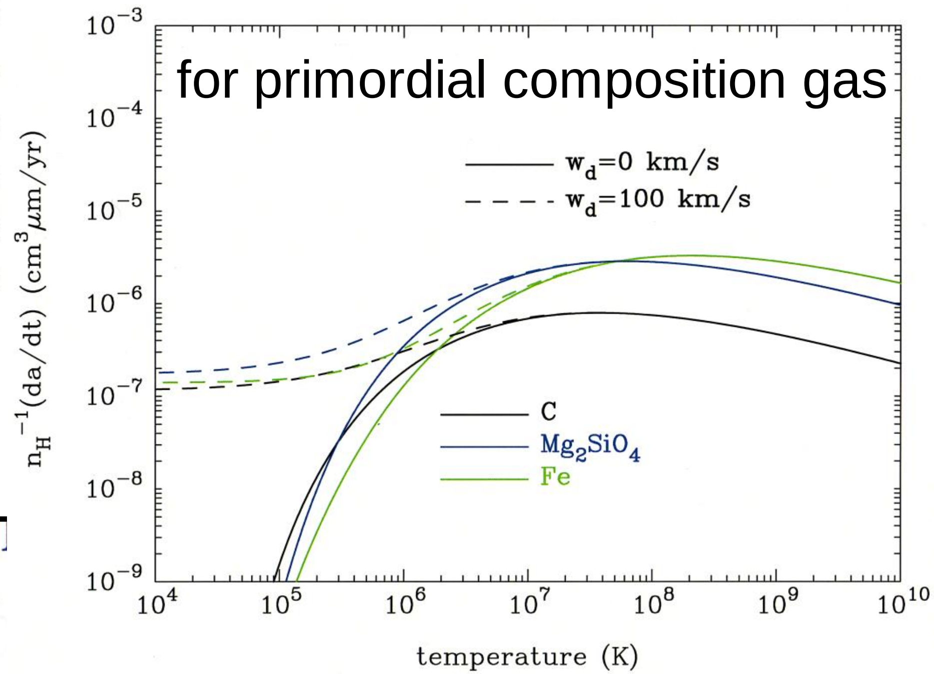
$Y_i(E) = 2Y$ ...

m_{sp} ; avera ...

· rate equation over a modified ...

account of relative velocity of ...





▪ 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

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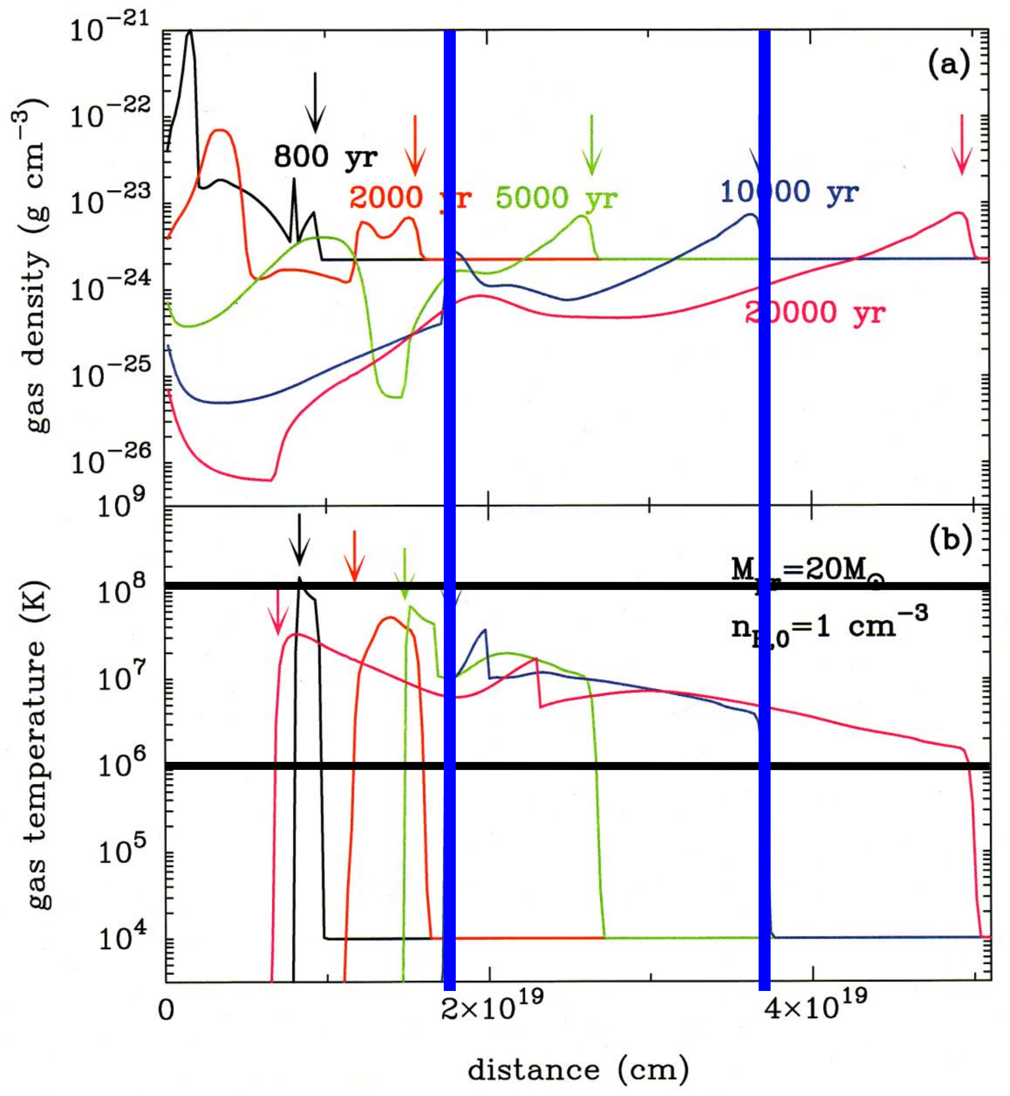
3-5. Temperature and density of gas



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

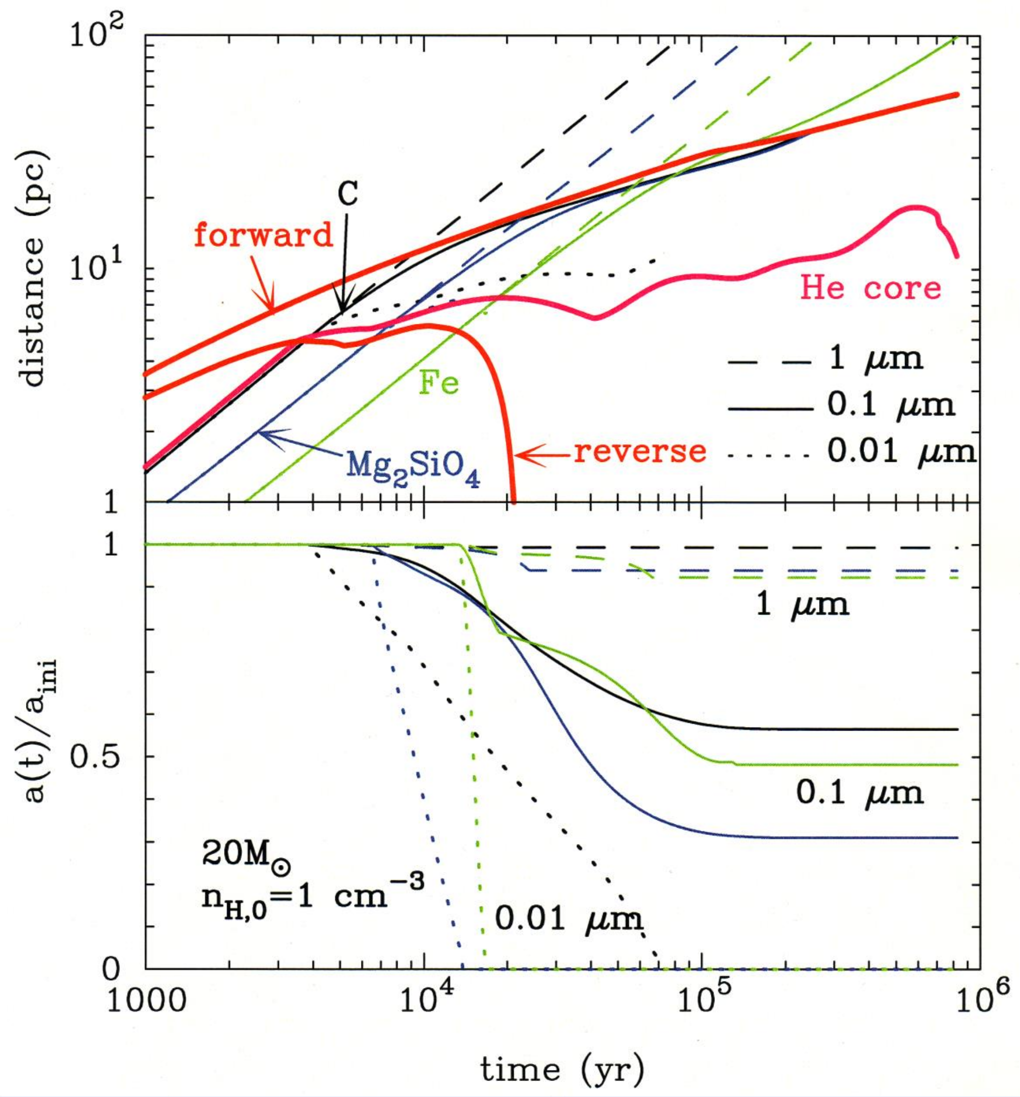
The temperature of the gas swept up by the shocks

➔ 10^6-10^8 K

↓

Dust grains residing in this hot gas are eroded by sputtering

3-6. 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

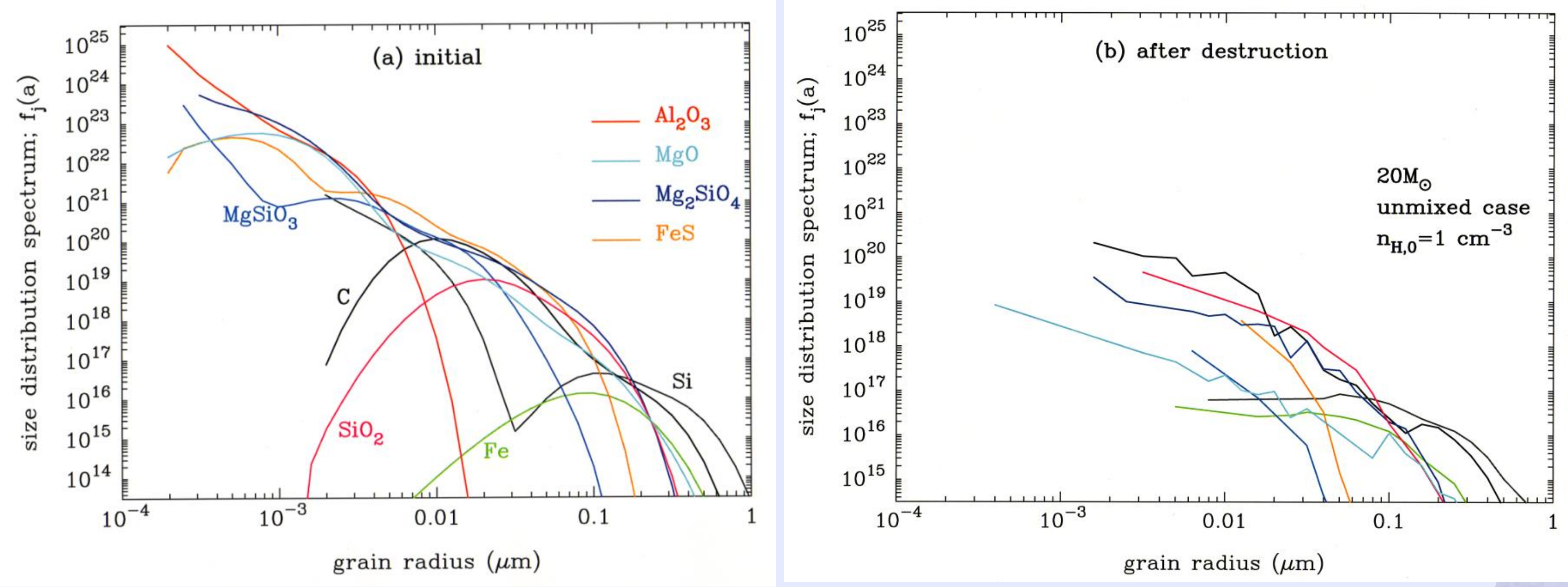
The evolution of dust heavily depends on the initial radius and composition

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

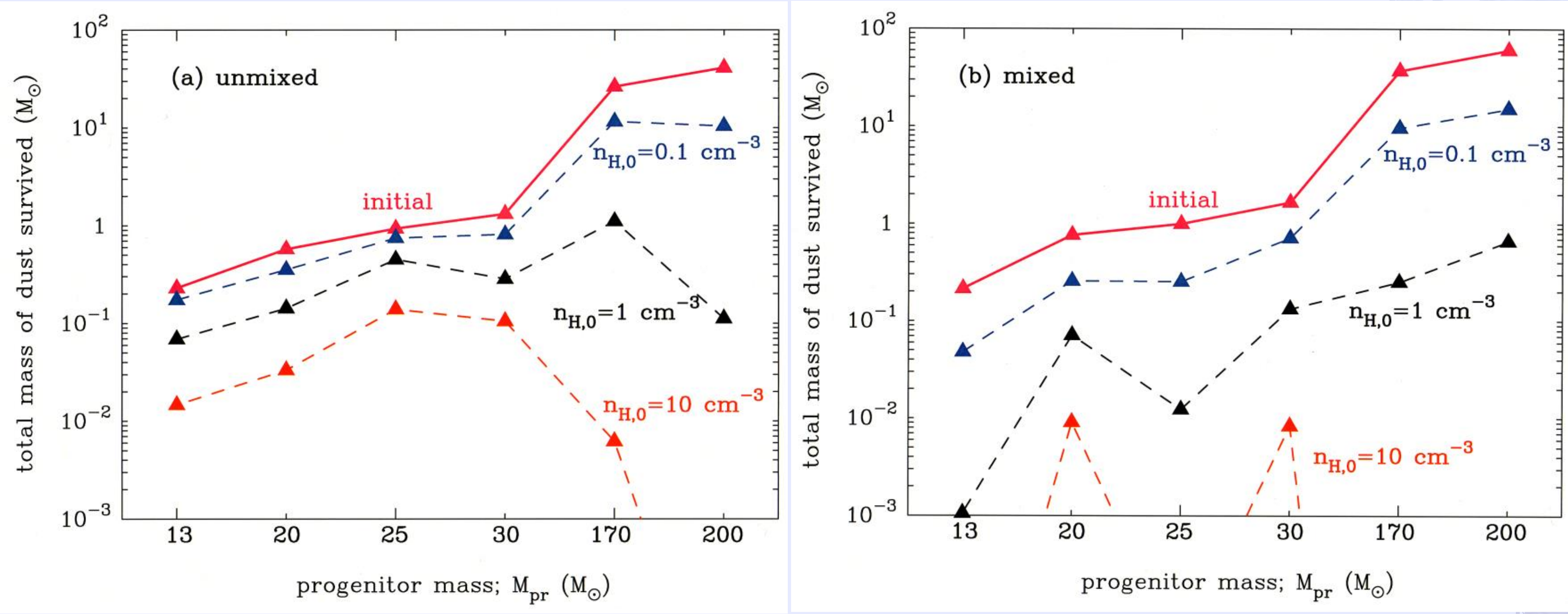
3-7. Size distribution of surviving dust



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 of > 0.01 μm

3-8. Total mass of surviving dust



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

for Type II SNRs;

0.1-0.8 Msun in the unmixed case ($n_{H,0}$ = 0.1-1 cm^{-3})
0.001-0.7 Msun in the mixed case ($n_{H,0}$ = 0.1-1 cm^{-3})

3-9. Summary (1)

- 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

4. Thermal emission of dust in Cas A SNRs

4-1. Introduction

○ Dust in SNe

theoretical studies : M_{dust}=0.1-1 M_{sun}

(Bianchi & Schneider 2007; Nozawa et al. 2007)

observations : $M_{dust}=10^{-4}-10^{-3}$ M_{sun}

(e.g., Hines et al. 2004, Elcolano et al. 2007)

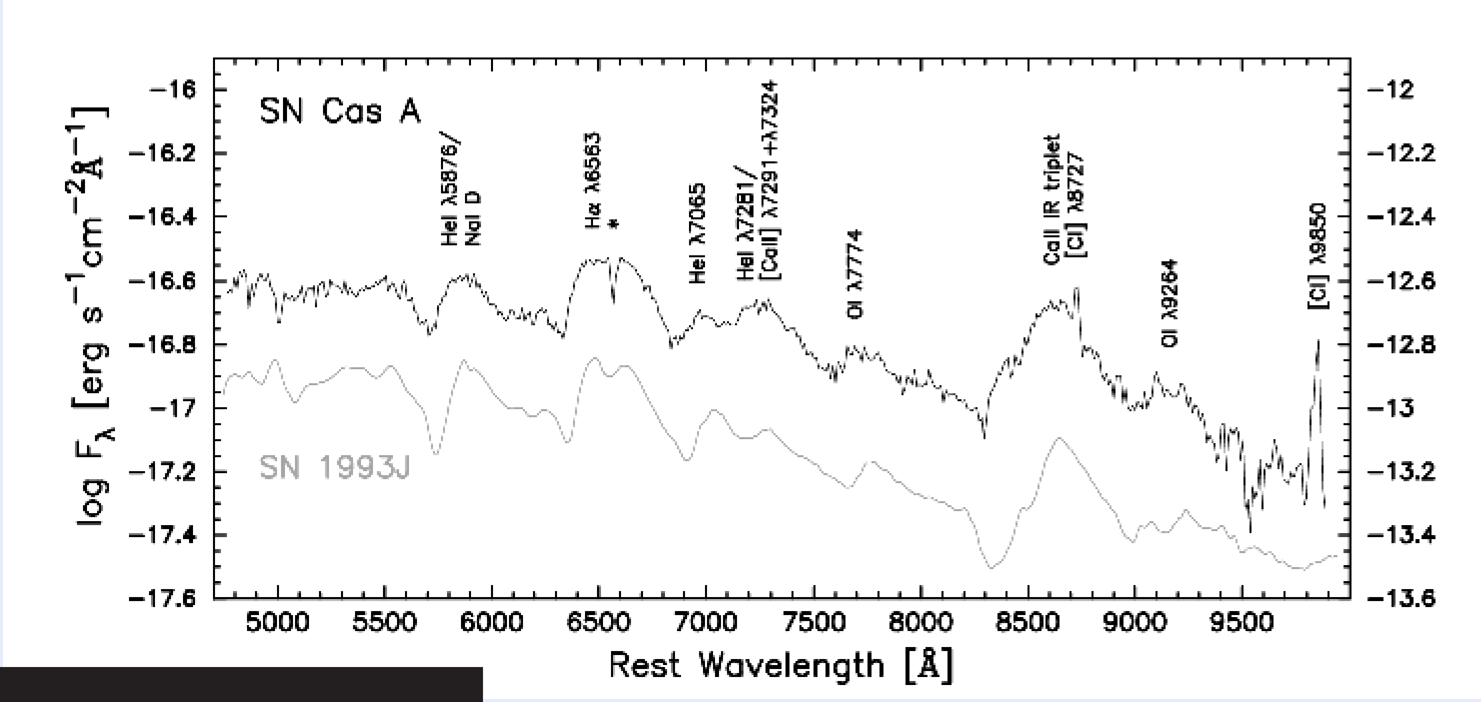
It is still debated whether SNe can be the important sources of the interstellar dust

In order to examine the causes of this difference, it is important to compare our calculations with observation

4-2. Cassiopeia A SNR

○ Cas A SNR

age : ~340 yr (Thorstensen et al. 2001)
distance : d=3.4kpc (Reed et al. 1995)
dust mass : **M_{dust} = 0.02-0.05 M_{sun}** (Rho et al. 2008)
SN type : **(Type IIb SN)**



Krause et al. (2008)

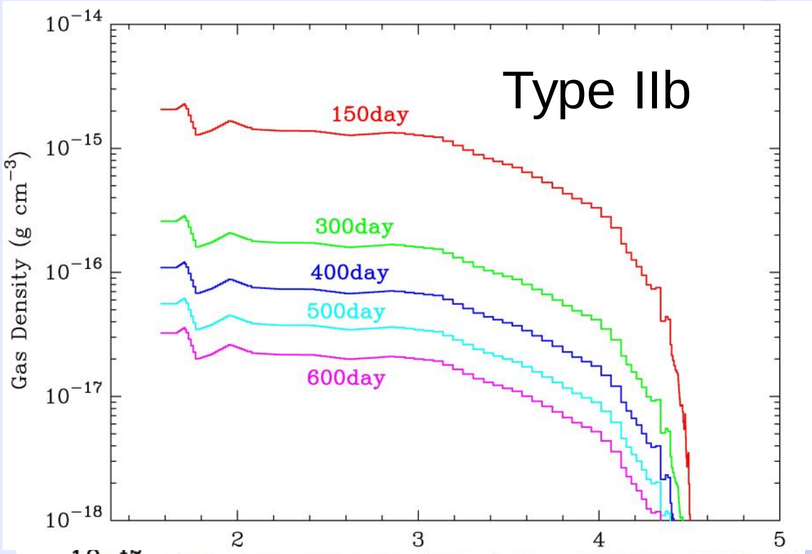
4-3. Dust formation calculation

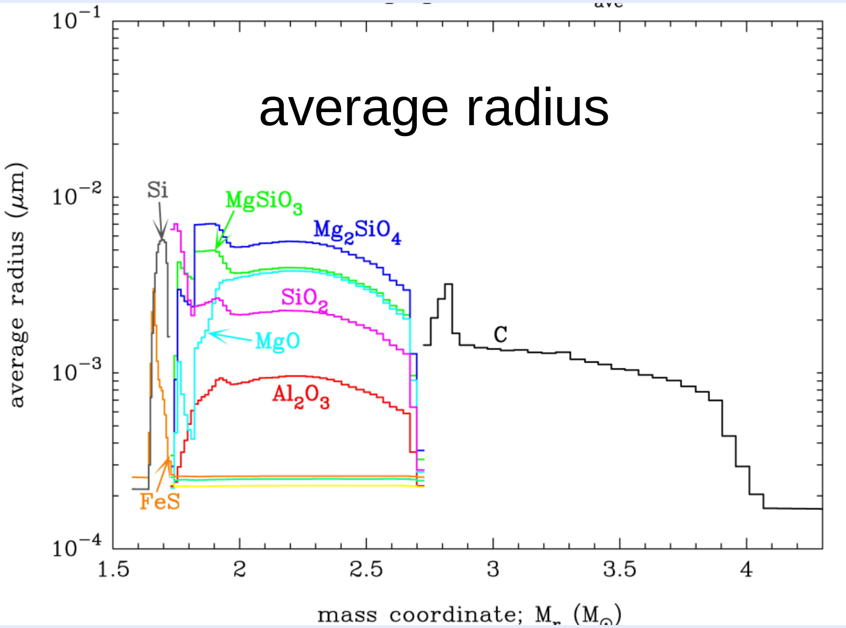
○ Type IIb (1993J-like) model (Tominaga et al. 2005)

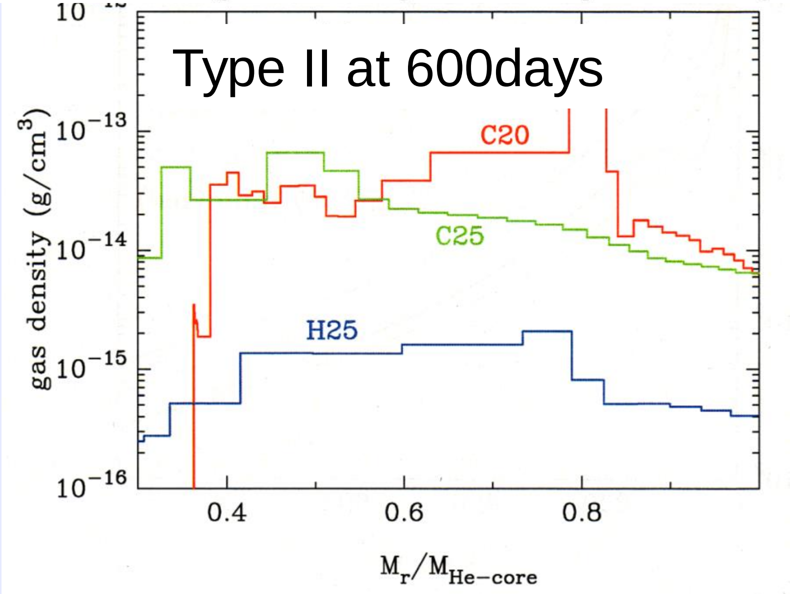
– M_{pr} = 18 M_{sun}
  M_{ej} = 2.94 M_{sun}
  $M_{H\text{-}env}$ = 0.08 M_{sun}

– E_{51} = 1

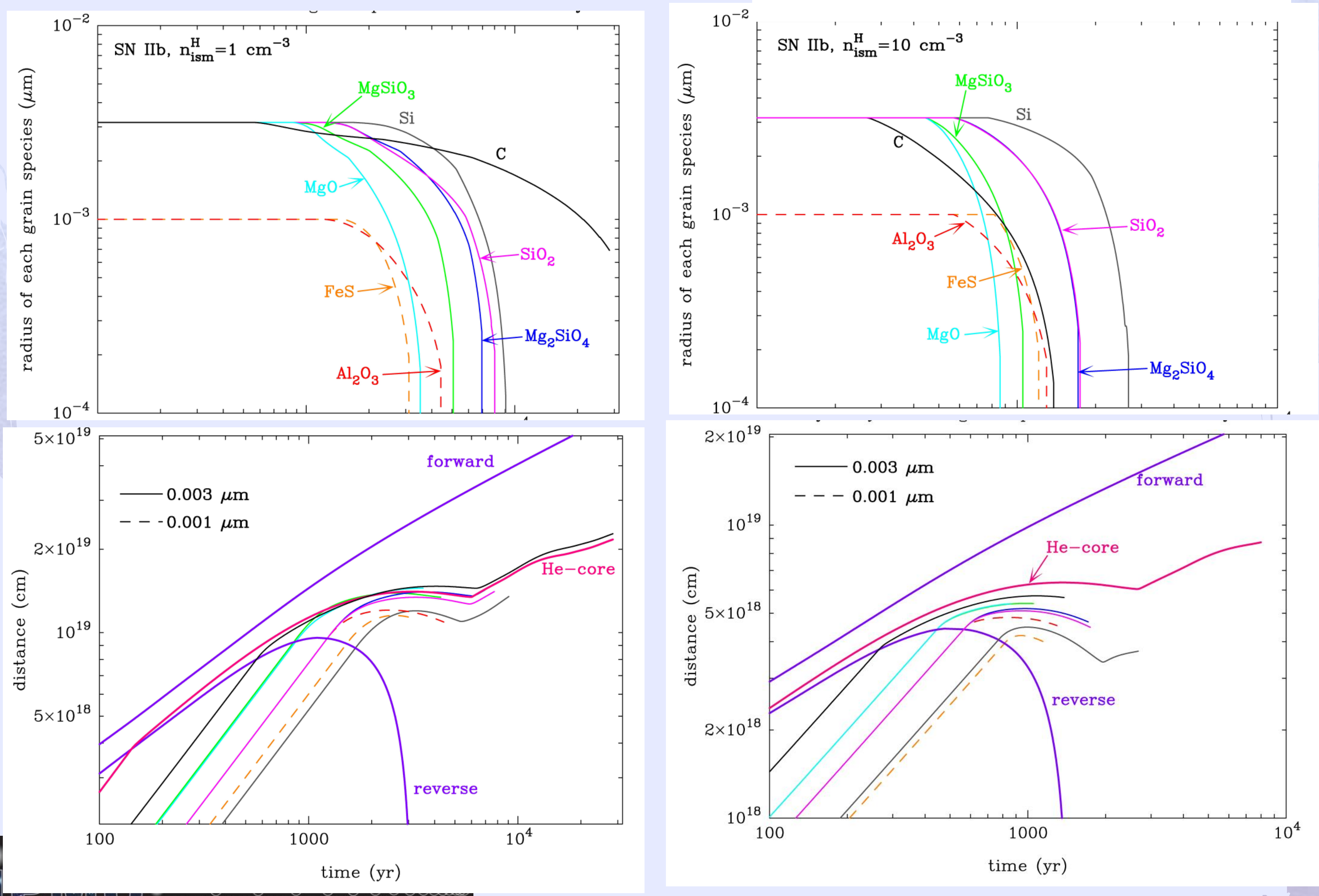
– $M(^{56}Ni) = 0.07\ M_\odot$



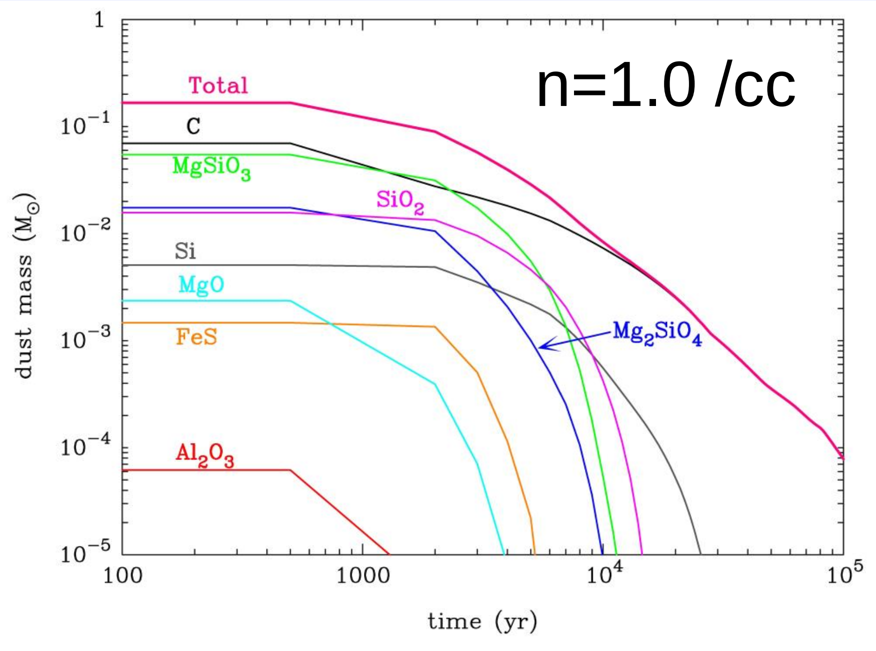


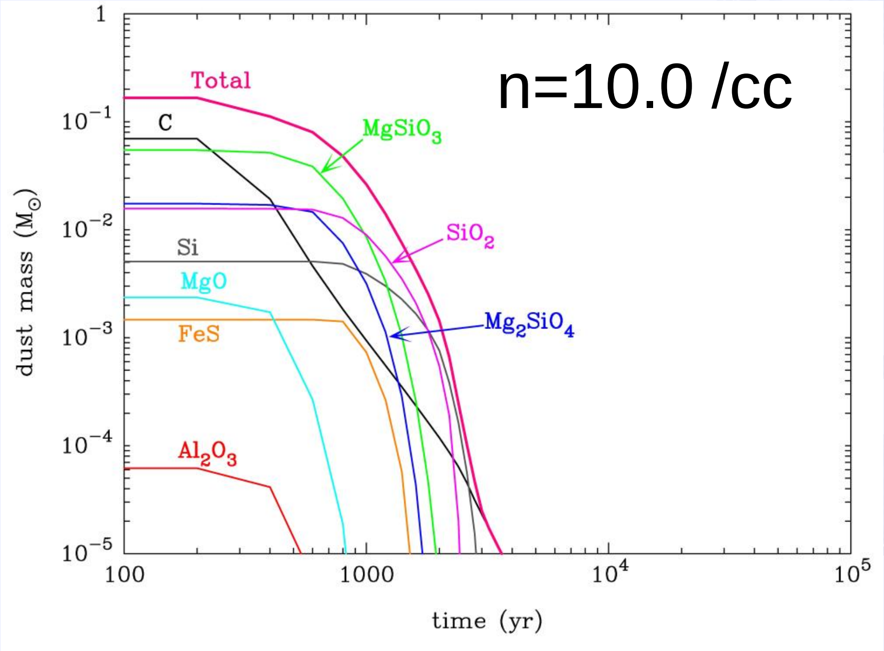


4-4. Evolution of dust in Cas A SNR



4-5. Time evolution of dust mass





M_{dust}~10^{-4} M_{sun} at 10^5 yr

M_{dust}=0 M_{sun} at 10^5 yr

This type of SNe (Type IIb) cannot be the main sources of dust

4-6. Thermal emission from dust in the SNR

- thermal radiation from dust ← temperature of dust
- temperature of dust in SNR is determined by collisional heating with gas and radiative cooling

  $H\ (a, n, T_g) = \mathbf{\Lambda}(a, Q_{abs}, T_d)$ → equilibrium temperature T_d

  → thermal emission

- small-sized dust grains (<0.01 μm) undergo stochastic heating

  → not equilibrium

⇩

the time evolution of thermal radiation including stochastic heating, based on the dust evolution model

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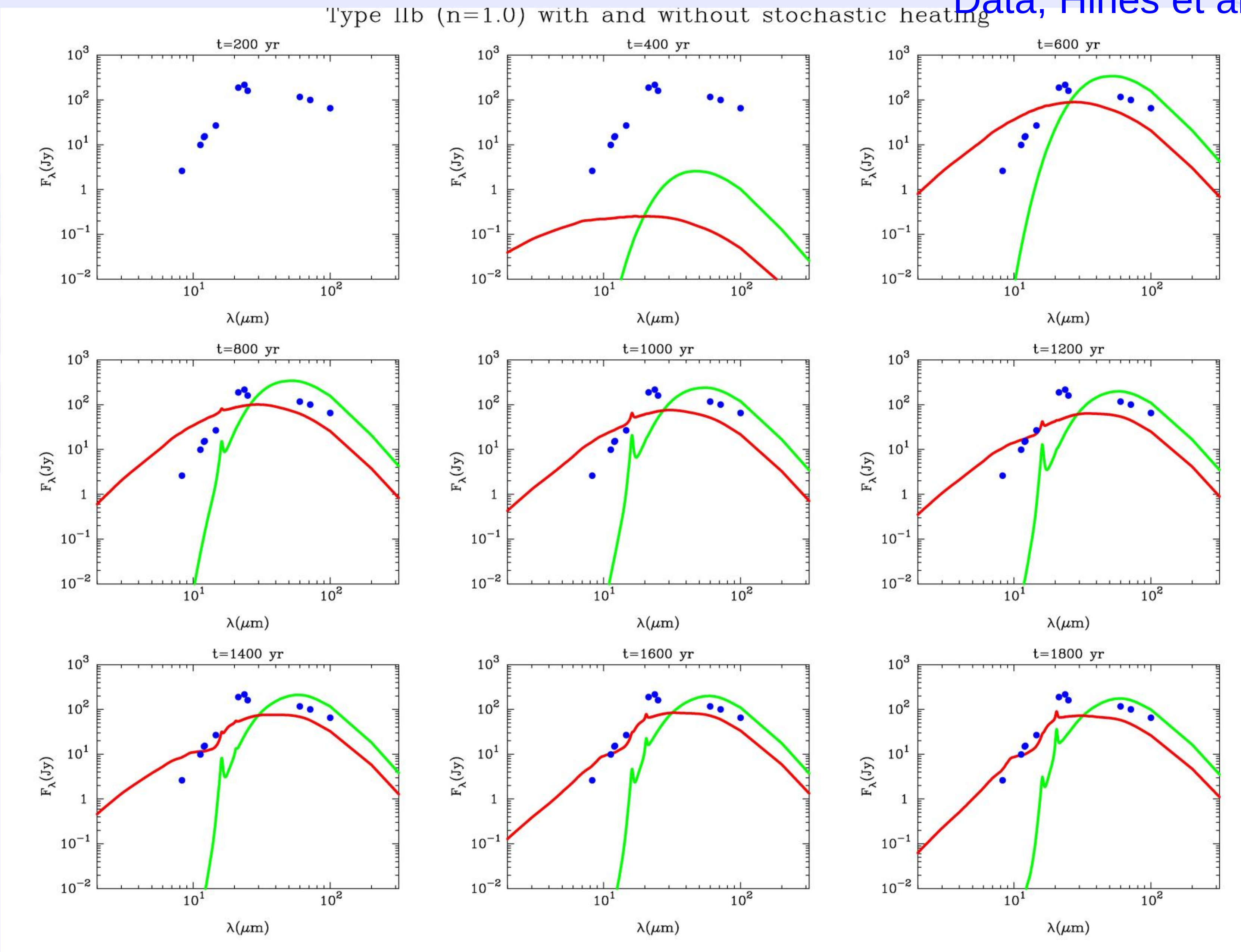
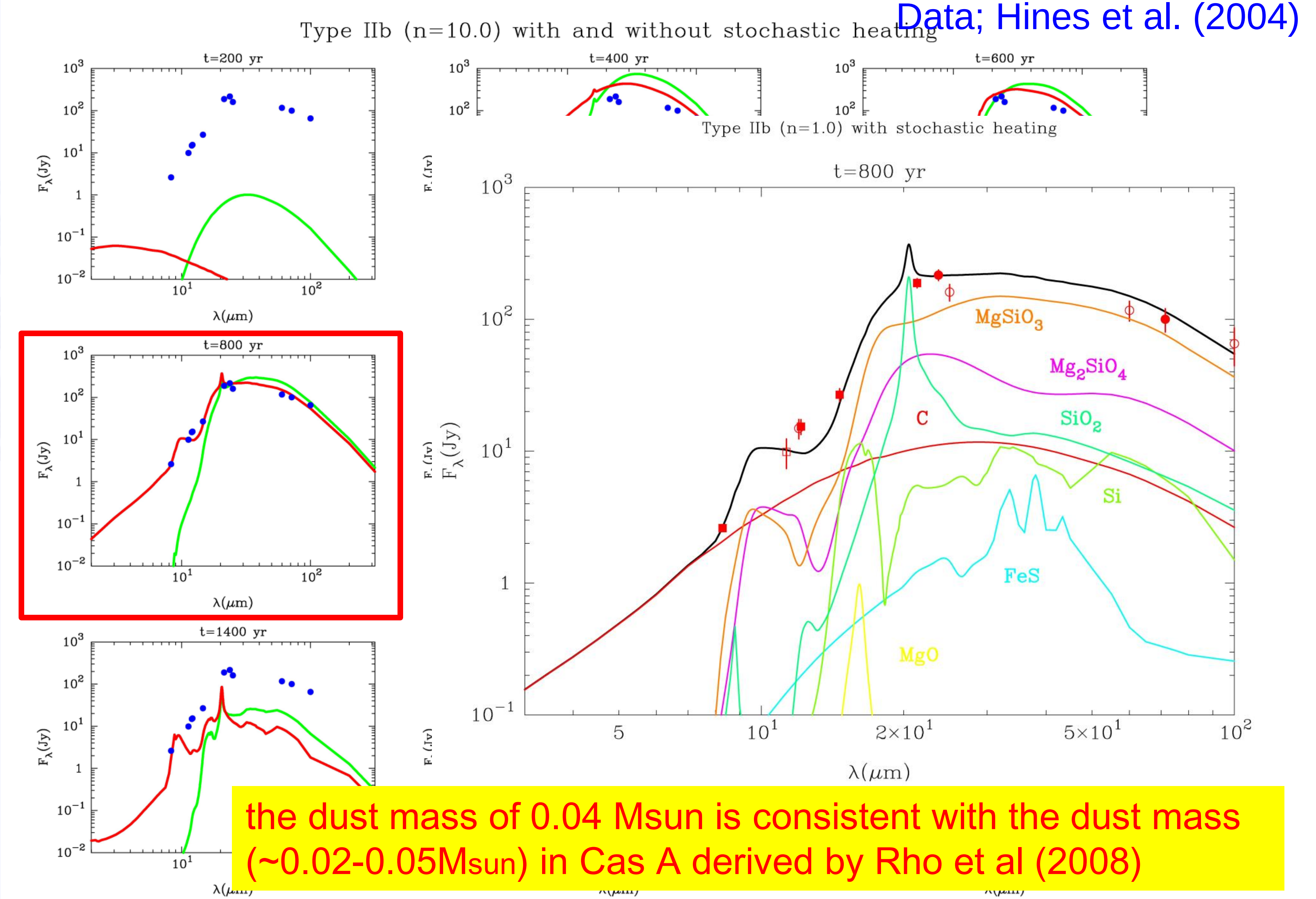
4-7. Comparison with Cas A observation (1)

Data; Hines et al. (2004)



4-8. Comparison with Cas A observation (2)

Data; Hines et al. (2004)



the dust mass of 0.04 Msun is consistent with the dust mass (~0.02-0.05Msun) in Cas A derived by Rho et al (2008)

4-9. Summary(2)

1) The size of dust formed in the ejecta of H-deficient Type IIb is relatively small because of low gas density of the ejecta.

2) Newly formed dust grains cannot survive the reverse shock owing to their small size.

3) Thermal radiation from dust well reflects the size of dust in SNR through the effect of stochastic heating.

4) Model of dust formation and destruction of Type IIb SN for n_H=10.0 cm^{-3} fairly reproduces the observed SED of Cas A.

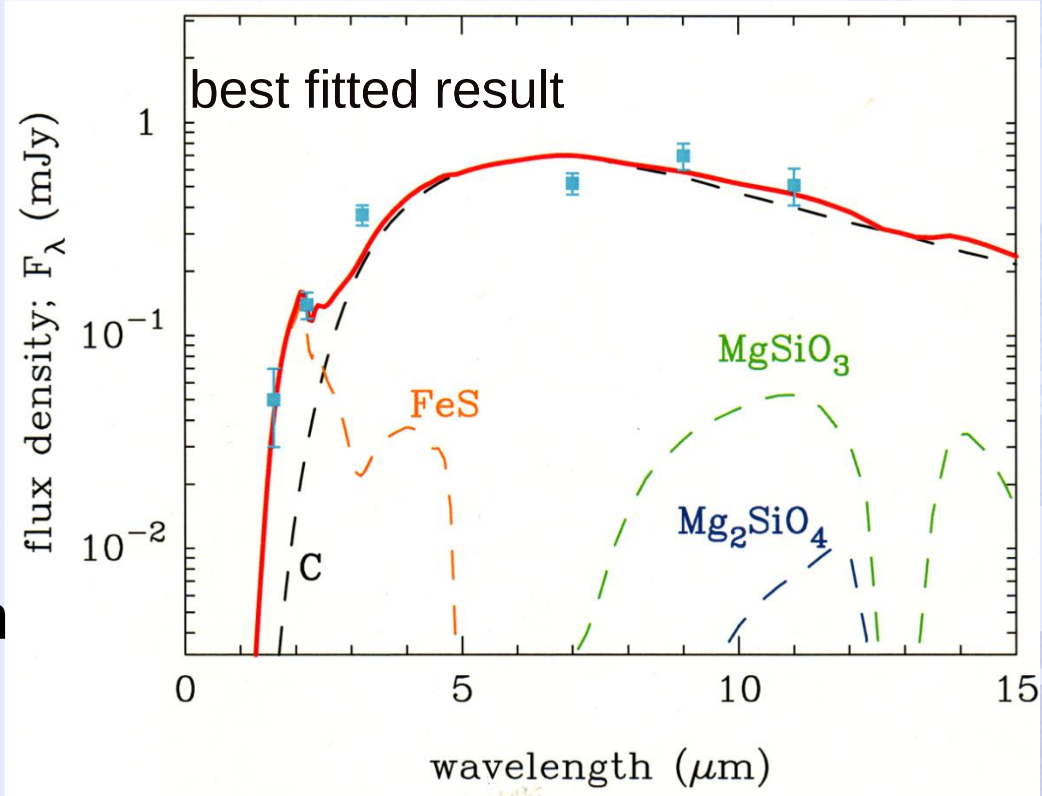
5) Dust grains in and around SNe can be powerful probes for understanding the properties and evolution history of the progenitor stars.

4-10. Case of SN 2006jc

small grains in SN 2006jc
(Type Ib)

early formation of C dust
at 50 days
(Nozawa et al. 2008)

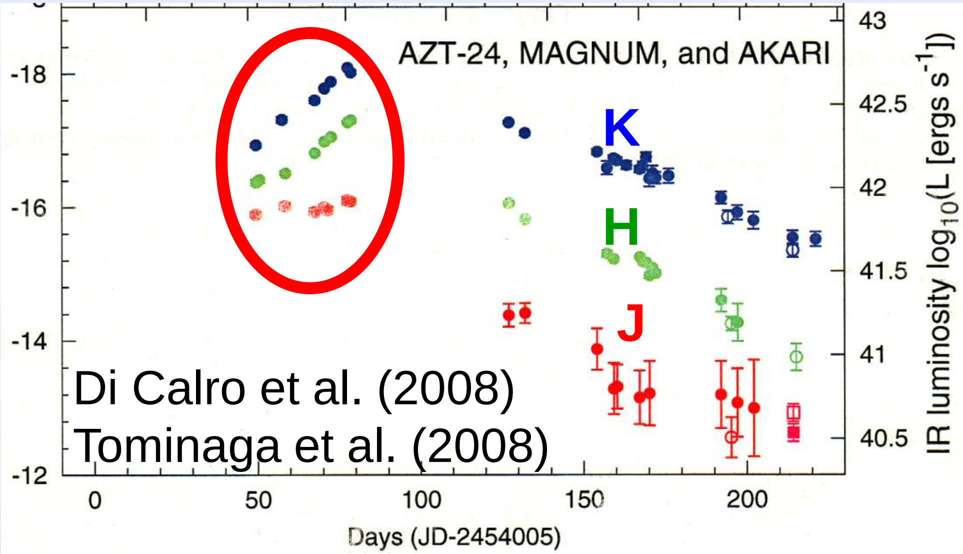
NIR-MIR observations with
AKARI and MAGNUM
(Sakon et al. 2008)

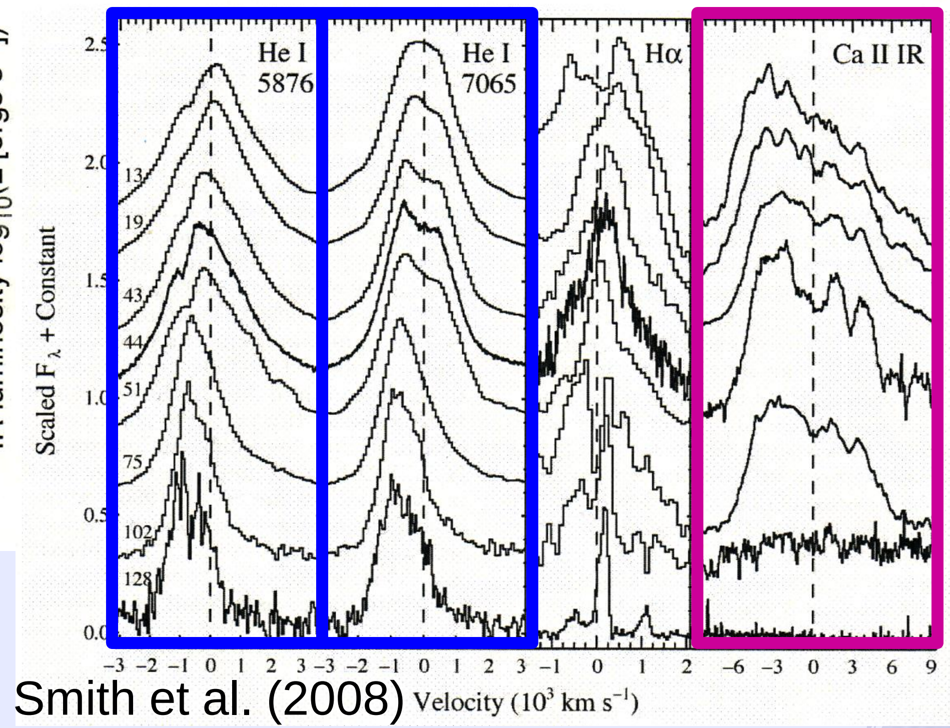


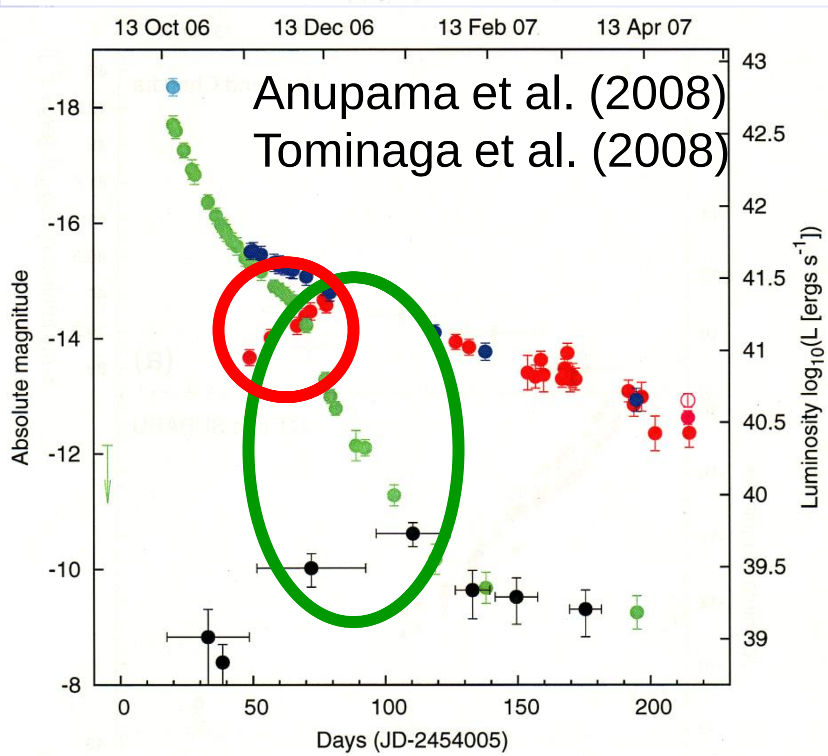
theory of stellar evolution and calculation of light curve
(Tominaga et al. 2008)
➔ properties of SN 2006jc (E51, stellar mass at explosion),
evolution history of the progenitor star

5. Formation of dust in SN 2006jc

5-1. Evidence for dust formation in SN 2006jc



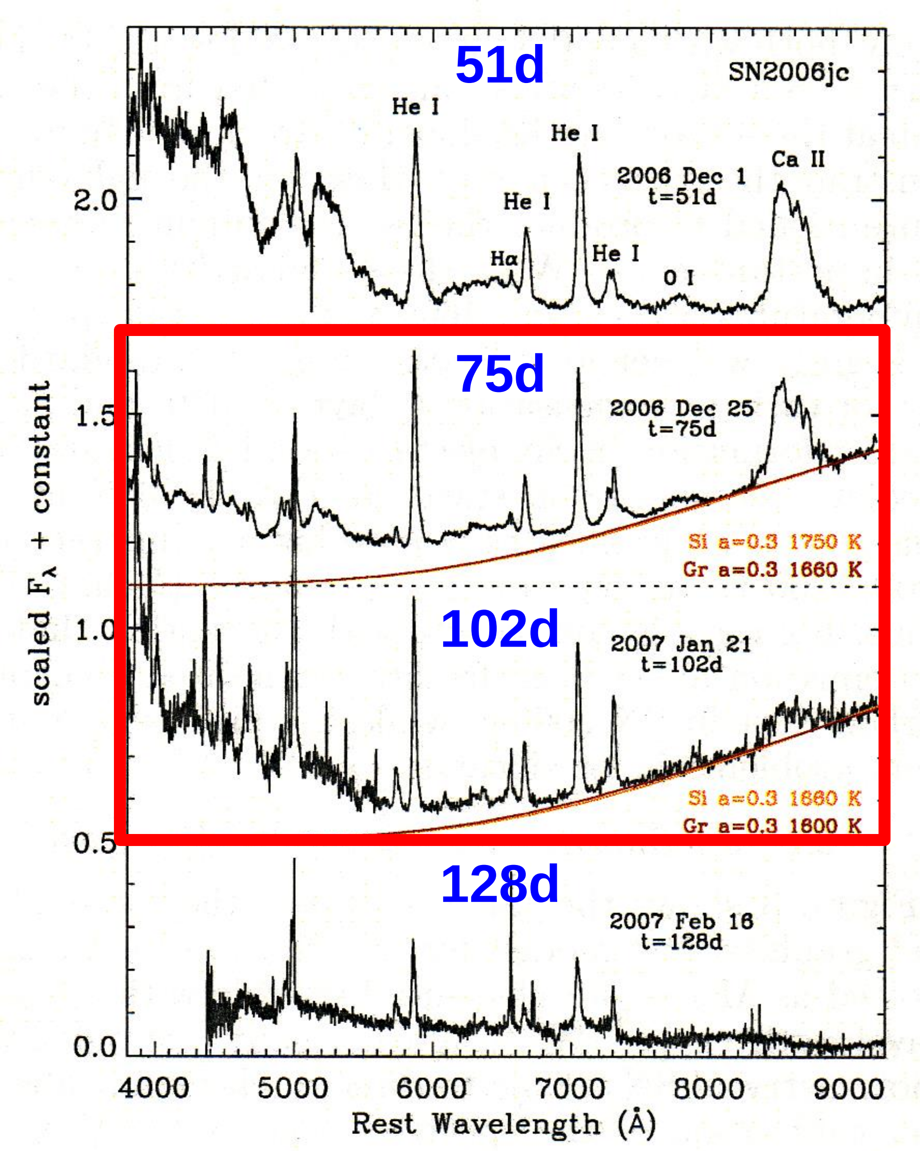




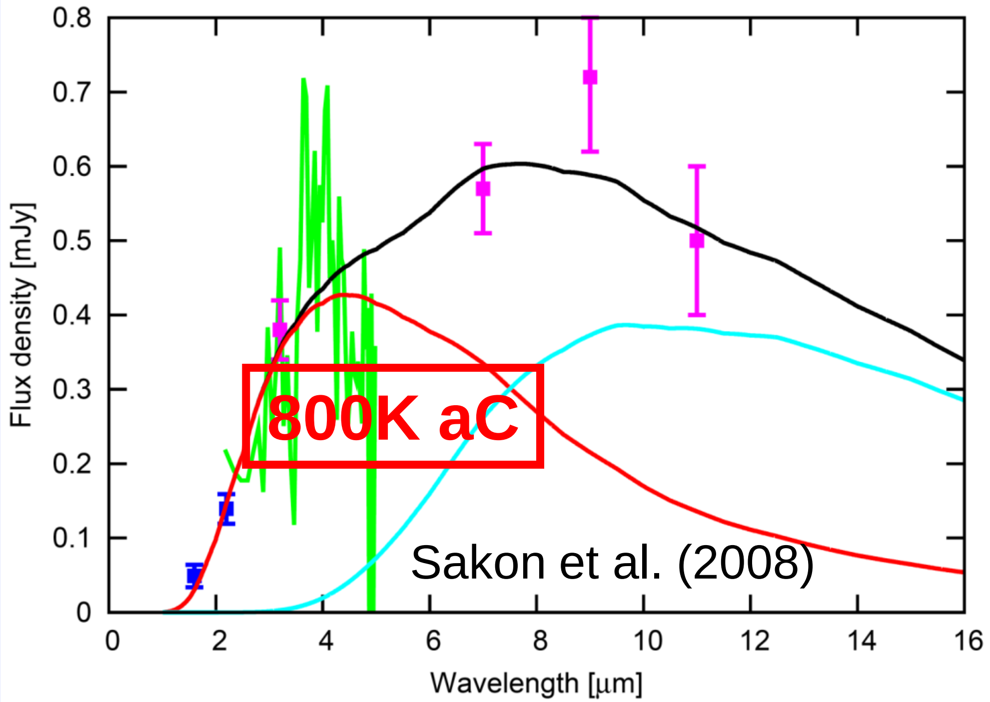
- re-brightning of NIR
- rapid decline of optical light
- blueshift of He I narrow lines

ongoing formation of dust from ~50 days in SN2006jc

5-2. Composition of newly formed dust



Smith et al. (2008)



- fitting to red/NIR continum
  at 75-102 days
  ➔ graphite of ~1600 K

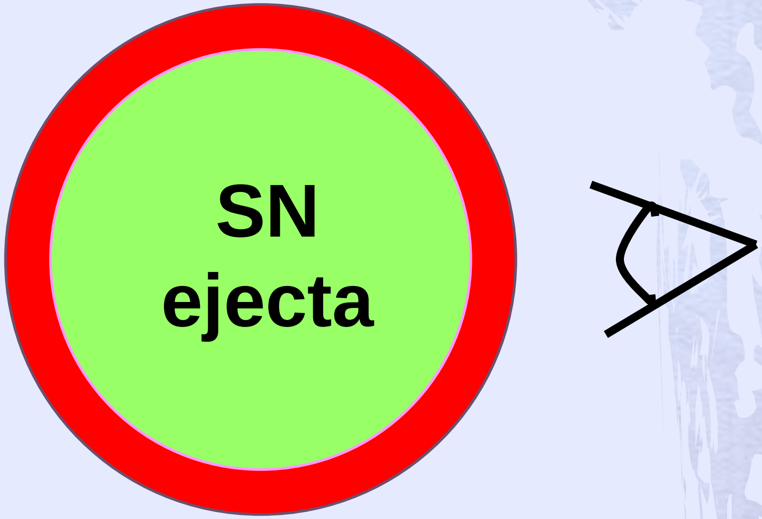
- fitting to NIR/MIR continuum
  at 200 days
  ➔ amorphous C of 800 K

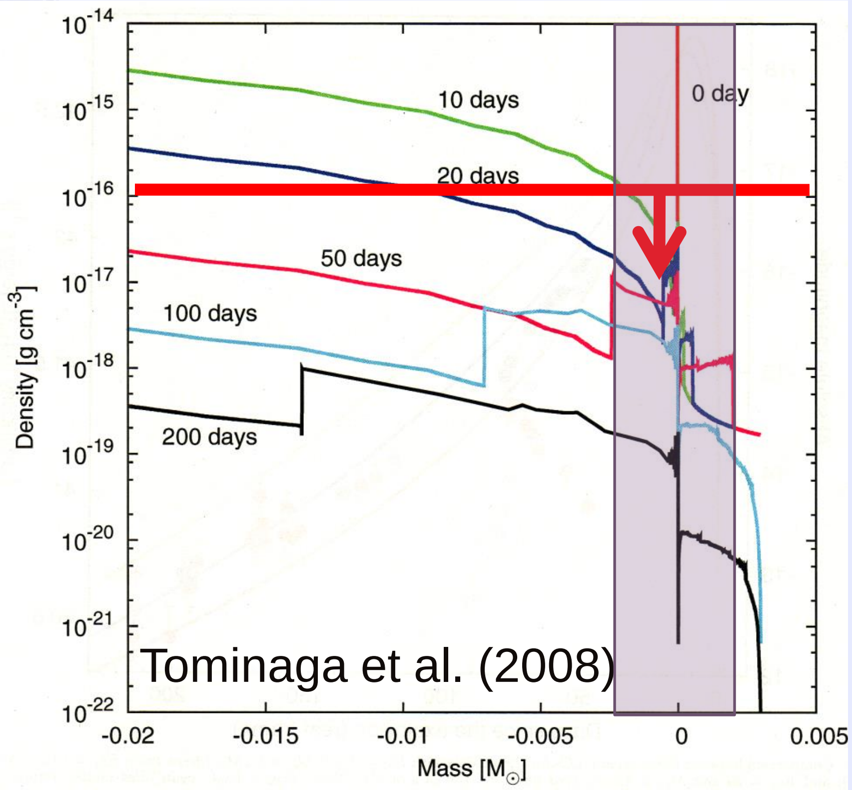
5-3. Dust formation in dense cooling shell?

- Dust grains are newly formed in dense cooling post-shock shell?

  (Smith et al. 2008; Mattila et al. 2008)

- Dense shell was created by the outburst 2 yr before explosion





hydrodynamic calculations for the ejecta-CSM interaction

➔ estimated CS density profile;

$\rho = 10^{-13} (r / 3 \times 10^{10})^{-1}$ g/cm^3

(Tominaga et al. 2008)

density of shocked region

＜critical density for dust formation

$\sim 10^{-16}$–10^{-14} g cm^{-3}

5-4. Aim of this study

We investigate the possibility of an early formation of dust grains in the expanding ejecta of SN 2006jc

– very earlier dust formation?
– high temperature of newly formed dust?
– time evolution of line profiles?

Dust-forming SNe

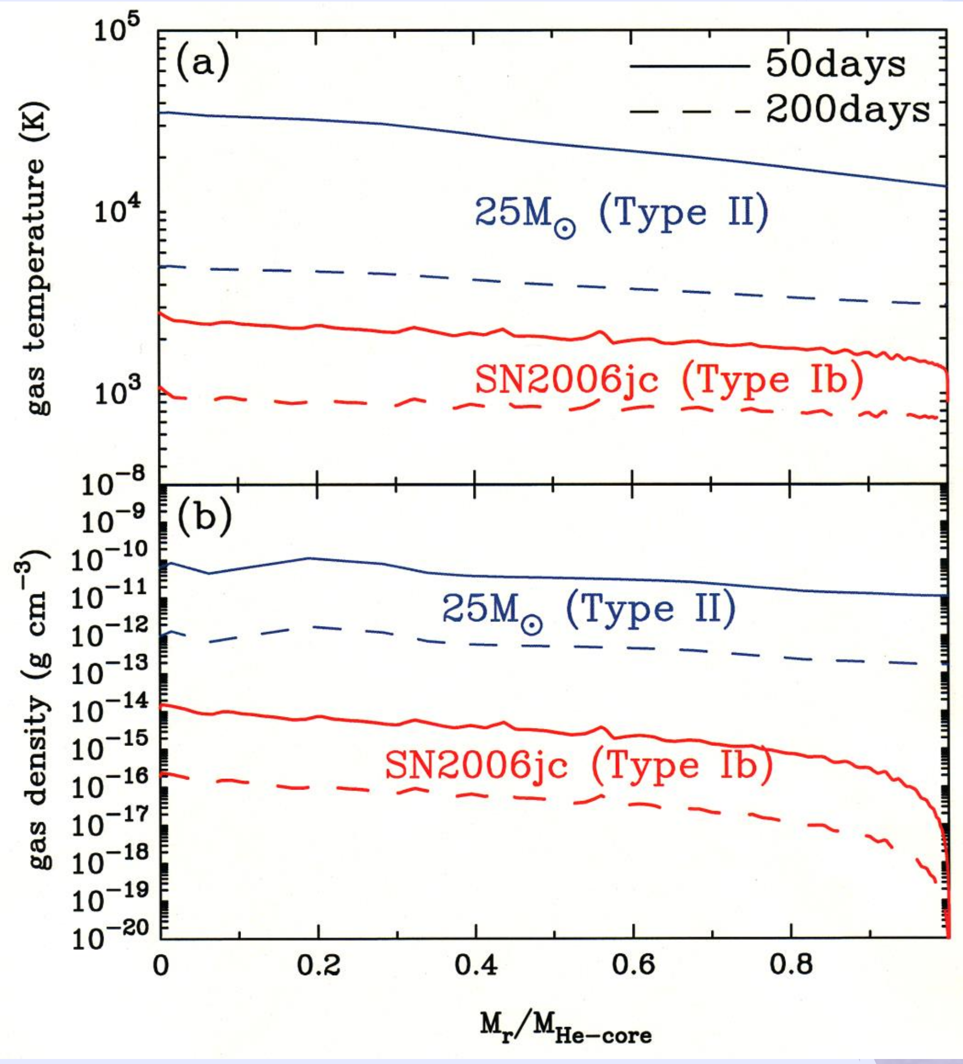
- Type II (SN1987A, SN1999em, SN 2003gd)
  ➔ 400-500 days
- Type IIn (SN1998S) ➔ ~230 days
- Type Ib (SN1990I) ➔ ~230 days
- Type Ic ➔ not observed

Formation process of dust in the ejecta depends on the type of SNe?

5-5. Dust formation calculation

○ supernova model (Tominaga et al. 2008)

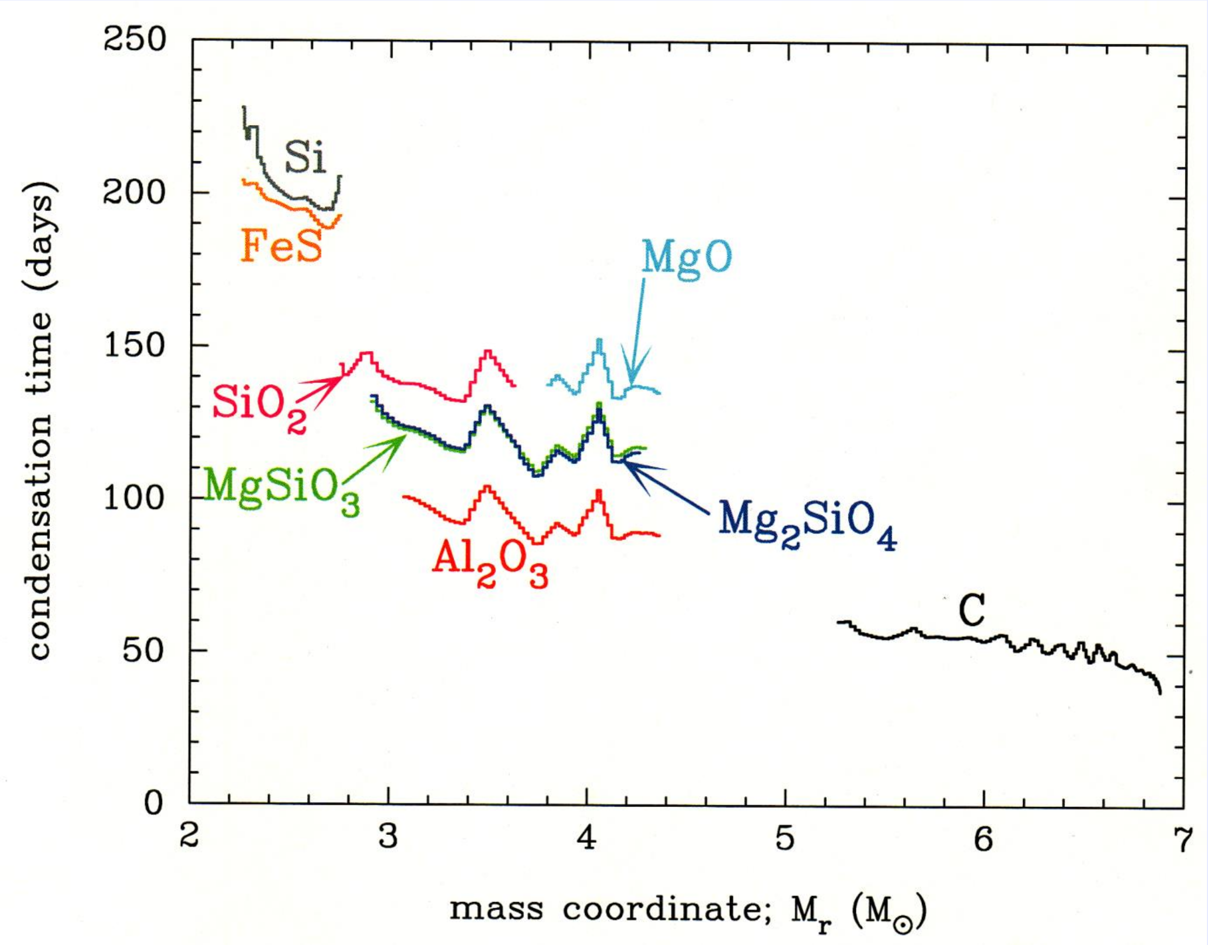
– **$M_{ej} = 4.9\ M_\odot$**
  ($M_{MS} = 40\ M_\odot$, $M_{preSN} = 6.9\ M_\odot$)
– **$E_{51} = 10$**
  (hypernova-like)
– $M(^{56}Ni) = 0.22\ M_\odot$



○ dust formation theory

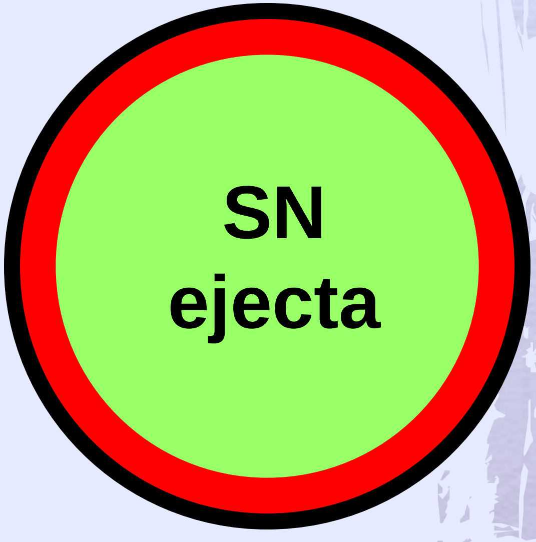
- non-steady nucleation and grain growth theory
  (Nozawa et al. 2003)
- onion-like composition
- sticking probability; $\alpha_s = 1$

5-6. Condensation time of dust



The quick decrease of gas temperature

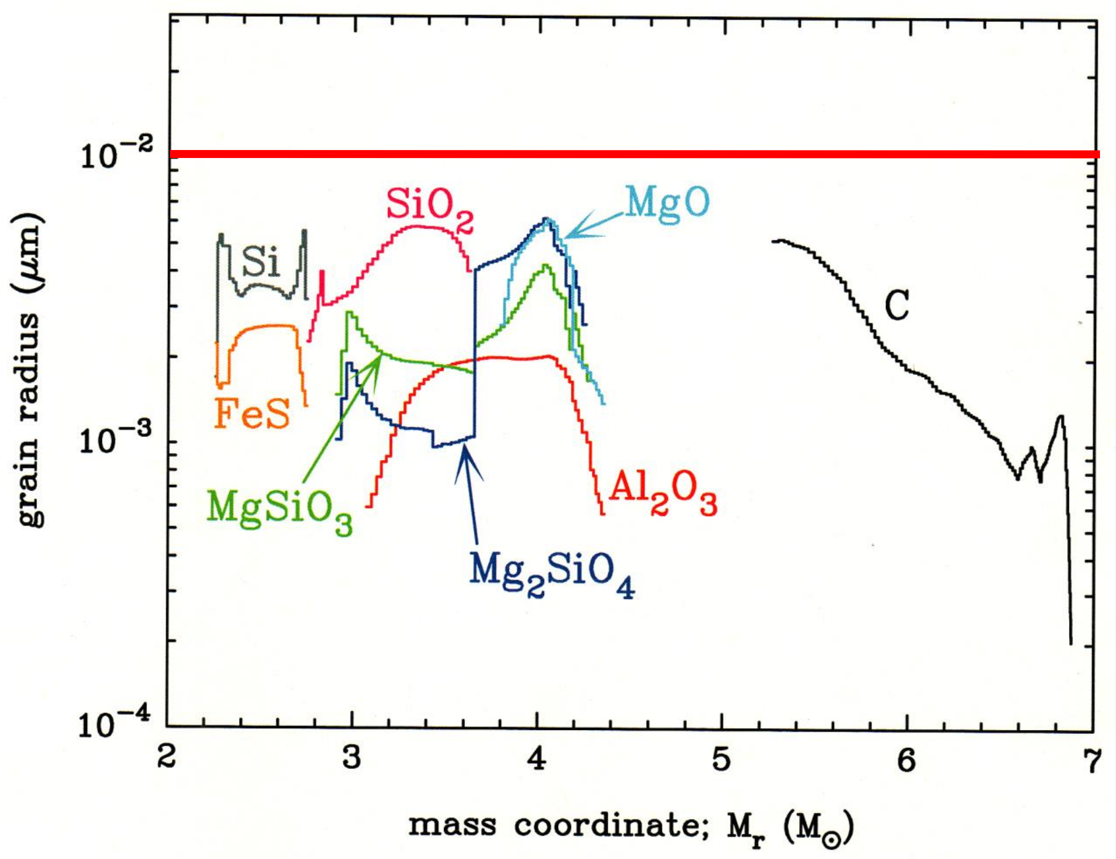
C grains are formed at 40-60 days in the outermost ejecta



- Silicates and oxide grains can condense at 90-150 days
- FeS and Si grains are formed at ~200 days

5-7. Average radius and mass of dust

average radius



dust mass

dust species	$M_{d,j}$ ($M_\odot$)
C	0.701
Al_2O_3	0.008
Mg_2SiO_4	0.082
$MgSiO_3$	0.157
MgO	0.010
SiO_2	0.229
FeS	0.067
Si	0.196
total	1.450

- Average radius of each dust species is confined to be less than 0.01 μm because of the low gas density
- The total dust mass : 1.45 $M_\odot$ (C grains : 0.7 $M_\odot$)

5-8. Temperature of newly formed dust

$$4\pi a^2 \sigma_{\mathrm{B}} T_{\mathrm{d}}(r)^4 \langle Q_\lambda(a, T_{\mathrm{d}})\rangle = \frac{F(r)}{\sigma_{\mathrm{B}} T_{\mathrm{BB}}^4} \int \pi a^2 Q_\lambda(a) B_\lambda(T_{\mathrm{BB}}) d\lambda$$
$$+4\pi a^2 n_{\mathrm{gas}} \frac{3}{2} k T_{\mathrm{gas}} \left(\frac{kT_{\mathrm{gas}}}{2\pi\mu m_{\mathrm{H}}}\right)^{\frac{1}{2}} - 4\pi a^2 n_{\mathrm{gas}} \frac{3}{2} k T_{\mathrm{d}} \left(\frac{kT_{\mathrm{gas}}}{2\pi\mu m_{\mathrm{H}}}\right)^{\frac{1}{2}}$$

$T_{\mathrm{d}}(r)$: equilibrium temperature of dust at a position r

$F(r)$: flux at a position r

(radiating as a blackbody with $T_{\mathrm{BB}} = 5000\mathrm{K}$)

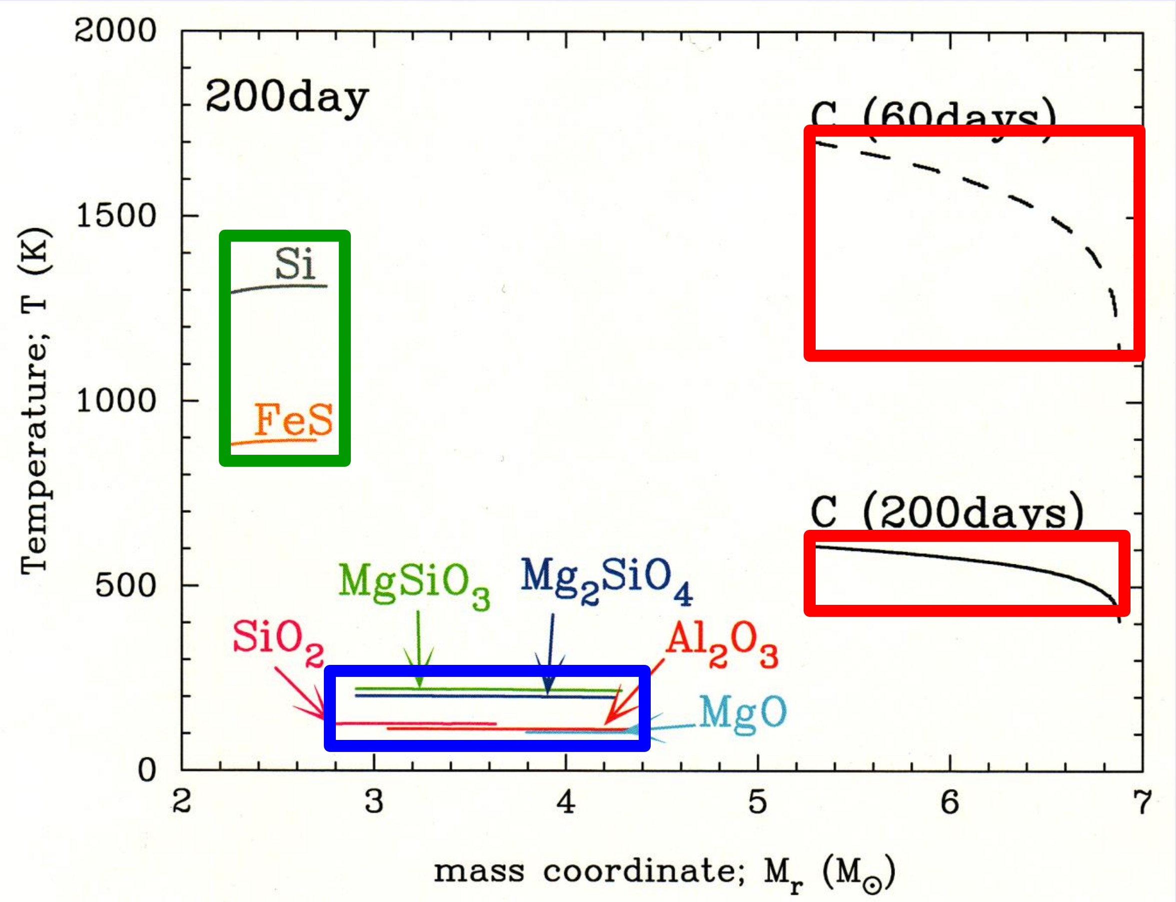
$\langle Q_\lambda(a, T_{\mathrm{d}})\rangle$: Plank-averaged value of $Q_\lambda(a)$

Dust size of 0.01 μm is adopted.

$T_{\mathrm{gas}}(r)$: gas temperature at a position r

$n_{\mathrm{gas}}(r)$: number density of gas at a position r

5-9. Dust temperature at 60 and 200 days



- Temperature of C grains

  at 60 days ➔ 1200-1700 K

  at 200 days ➔ 500-600 K

- Temperature of silicates and oxides is 100-200 K at 200 days
- FeS grains ➔ ~900 K at 200 days
  Si gains ➔ ~1300 K at 200 days

5-10. IR spectral energy distribution

$$F_{\lambda,j}(obs) = \frac{1}{4\pi D^2}\int_0^R 4\pi r^2 m_{\mathrm{d},j}(r)\kappa_{\lambda,j}B_\lambda(T_\mathrm{d}(r))\exp[-(\tau_\lambda(R)-\tau_\lambda(r))]dr$$

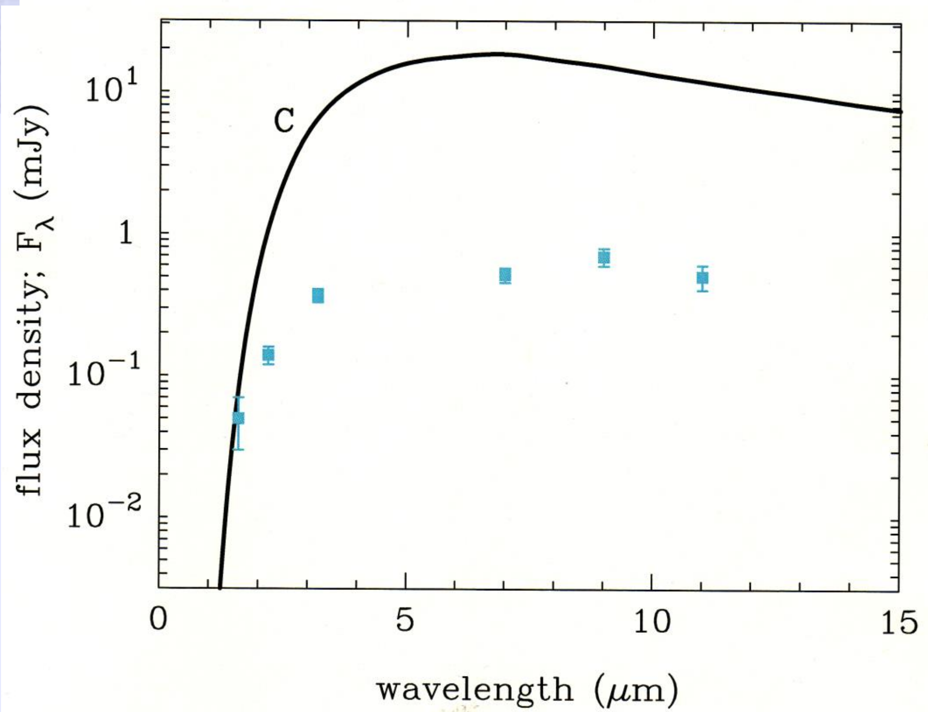
$$\tau_\lambda(R) = \int_0^R \sum_j m_{\mathrm{d},j}(r)\kappa_{\lambda,j}dr$$

$m_{\mathrm{d},j}(r)$: mass of dust species j per volume at a position r

ass absorption coefficient

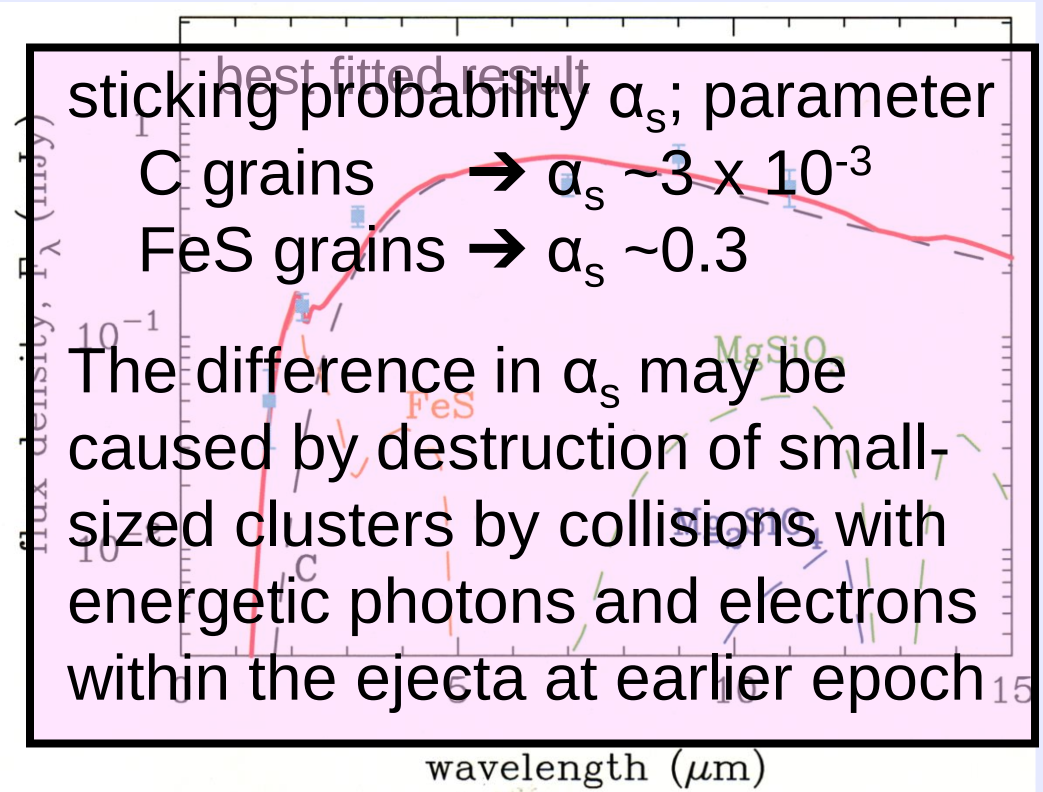
lust-forming region in the ejecta

n the observer



The IR spectrum obtained by adopting the results of dust formation calculation cannot reproduce the observed SED

5-11. IR spectral energy distribution fitting



sticking probability α_s; parameter

C grains ➔ α_s ~3 x 10^{-3}

FeS grains ➔ α_s ~0.3

The difference in α_s may be caused by destruction of small-sized clusters by collisions with energetic photons and electrons within the ejecta at earlier epoch

dust species	$M_{1,j}$ ($M_\odot$)	$M_{2,j}$ ($M_\odot$)
C	0.701	5.6×10^{-4}
Al_2O_3	0.008	≤ 0.008
Mg_2SiO_4	0.082	≤ 0.082
$MgSiO_3$	0.157	≤ 0.157
MgO	0.010	≤ 0.010
SiO_2	0.229	≤ 0.229
FeS	0.067	0.002
Si	0.196	—
total	1.450	≤ 0.489

- C grains ➔ 5.6 x 10^{-4} $M_\odot$ FeS grains ➔ 2 x 10^{-3} $M_\odot$
- the mass of cold silicates and oxides cannot be constrained

The process affecting dust formation is the energy deposition on small-sized clusters through the latent heat deposition and the collisions with energetic photons and electrons

5-12. Summary

1. The very early formation of dust at ~50 days in SN 2006jc can be realized by the condensation in the expanding ejecta, thanks to the rapid decrease of gas temperature in the ejecta.

2. Average radius of newly formed dust is smaller than 0.01 μm, because of the low gas density at the time of formation.

3. The calculated temperature of C grains can explain the time evolution of dust temperature suggested by the observations.

4. The temperature of silicates and oxides at 200 days is too cold to explain the MIR spectrum observed by AKARI.

5. The difference between calculated and evaluated masses of C and FeS grains may be explained by the destruction of small-sized clusters due to energetic photons and electrons.