Formation and evolution of dust in Type IIb SN: Application to Cas A

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1. Introduction

1-1. Background

CCSNe are main sources of interstellar dust?

- **formation of dust in metal-rich ejecta of SNe**
- **destruction of dust in shocked gas inside SNRs**

・ Theoretical studies

- **various dust species with 0.001-1 μm**

  M_{form} = 0.1-1 M_{sun} for SNe II-P

  (Todini & Ferrara ’01; Nozawa+’03)

- **M_{surv} = 0.01-0.8 M_{sun}** for $n_{H,0}$=10-0.1 cm^{-3}

  (Bianchi & Schneider ’07; Nozawa+’07)

➔ **0.1-1 Msun of dust per SN II are required to explain a large amount of dust (10^8-10^9 Msun) for QSOs at z > 5**

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

1-2. Dust-forming SNe

・Observations of dust-forming SNe

- few information on composition and size of dust
  - ➔ a limited quantity and quality of observations
- $M_{dust} < 10^{-3}\,M_{sun}$
  - ➔ assuming the ejecta is optically thin
  - ➔ some species of dust grains quickly cool down

derived dust mass can be underestimated

⬇

・sophisticated radiative transport model

・UV/optical to far IR observation data

1-3. Nearby, young SNRs

For nearby, young SNRs

・ Comparison of models with IR observations of SNRs

- erosion by sputtering and stochastic heating
- envelope-poor SNe are more favorable
  (For Type II-P SNe, the reverse shock collides with the He core after a few thousand years)
- ~30% of CCSNe explode as SNe Ib/c and SN IIb
  (Prieto+'09; Smartt+'08; Boissier & Prantzos '09)

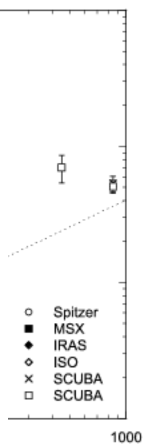
・ Dust formation and evolution in SN with thin envelope

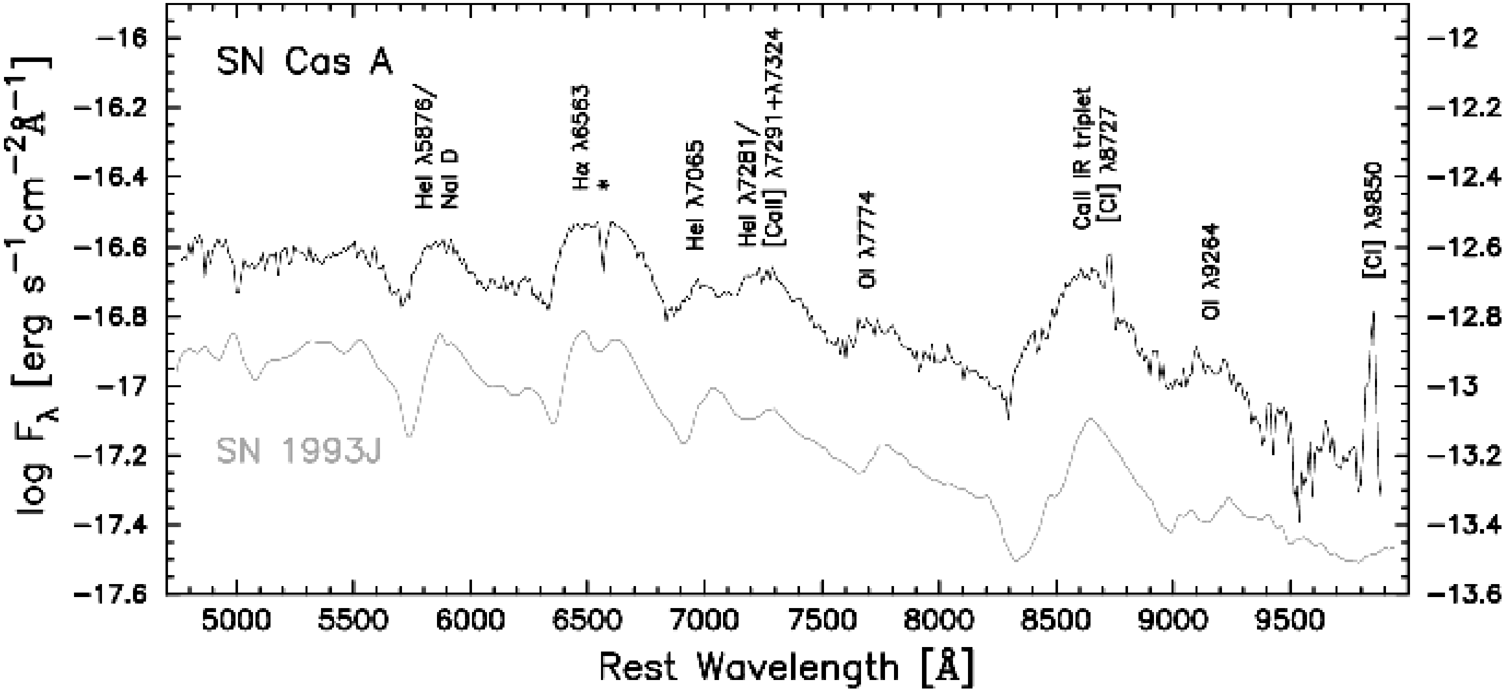
- how formation and destruction processes of dust depend on the thickness of outer envelope?
- apply the results to IR observations of Cas A

1-4. Cassiopeia A SNR

○ Cas A SNR

- **age: ~330 yr** (Thorstensen+'01)
- **distance: d=3.4 kpc** (Reed+'95)





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- **SN type : Type IIb** (Krause+'08)

2. Formation of dust in Type IIb SN

2-1. Calculation of dust formation

○ **nucleation and grain growth theory** (Kozasa & Hasegawa ‘87)

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

nucleation rate

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

grain growth rate

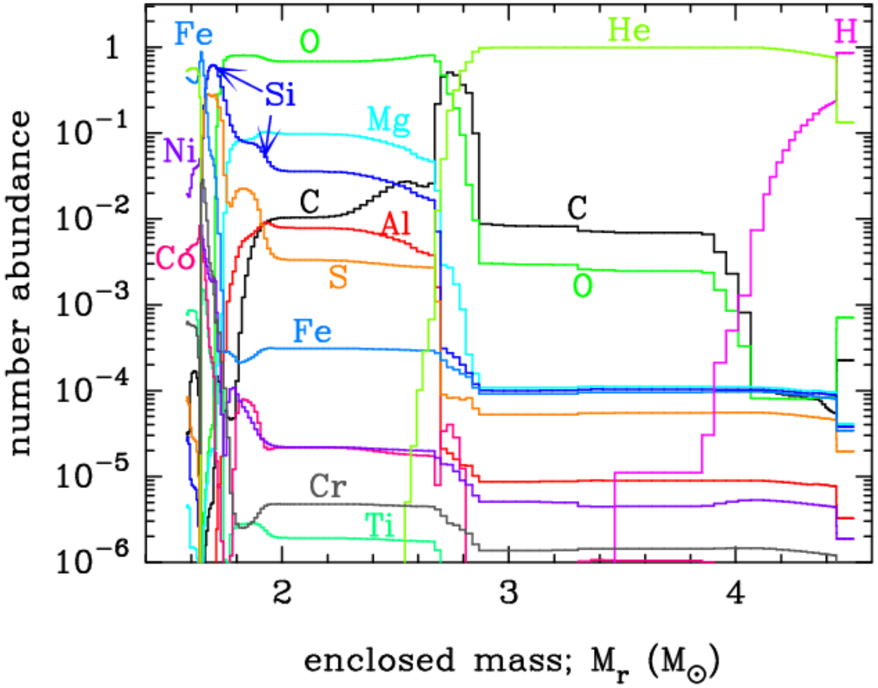
$$\frac{\partial r}{\partial t} = \alpha_s \frac{4\pi a_0^3}{3}\left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}} c_1(t) = \frac{1}{3} a_0 \tau_{\rm coll}^{-1}$$

- **time evolution of gas density and temperature**
- **elemental composition of the gas**

2-2. Model of Type IIb SN (1)

○ **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 Msun



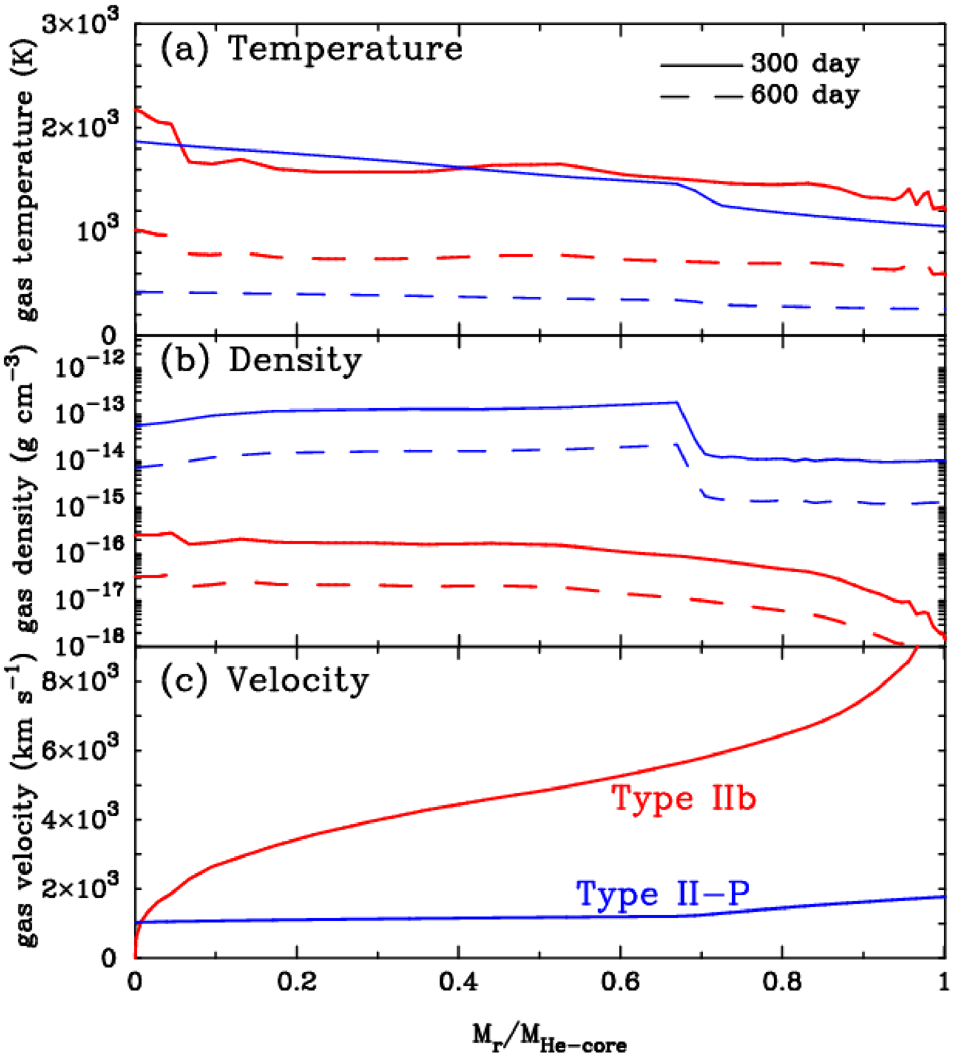
○ **mixing of elements**

- **original onion-like composition**

○ **formation of molecules** ➔ **complete**

C/O < 1 ➔ all C atoms are locked into CO
C/O > 1 ➔ all O atoms are locked in to CO
Si/O < 1 ➔ all Si atoms are locked into SiO

2-3. Model of Type IIb SN (2)



small ejecta mass of Type IIb SN

↓

very high velocity of gas in the He core

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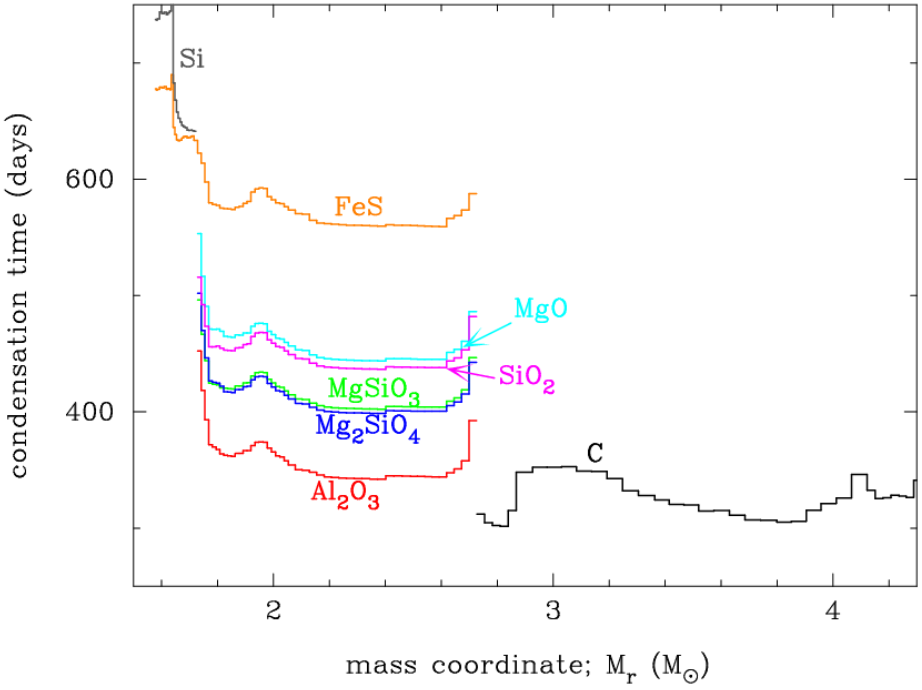
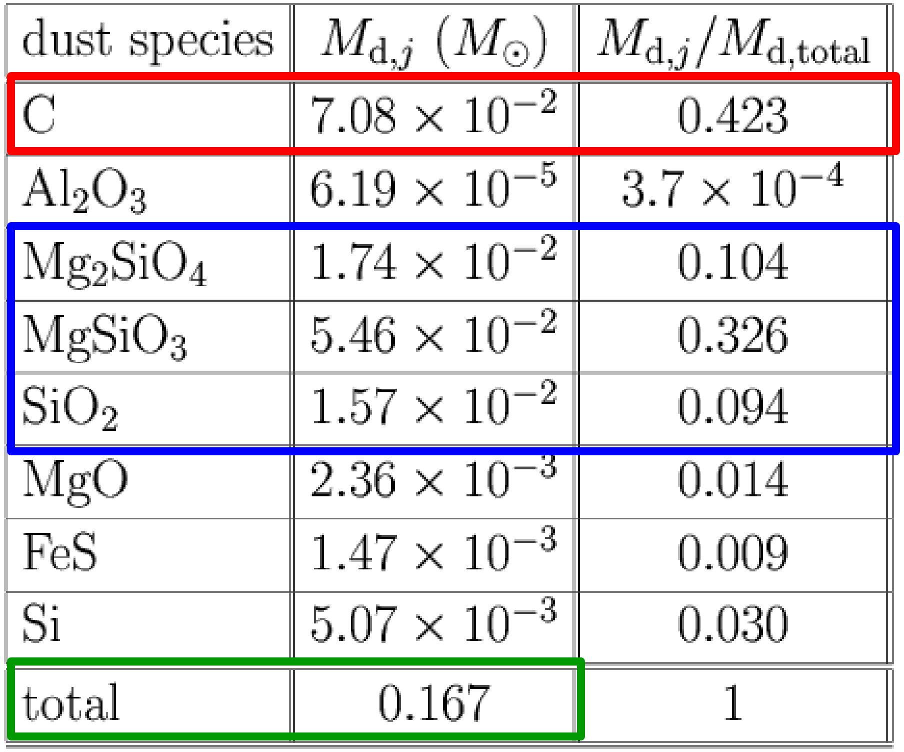
very low gas density in the He core of Type IIb SN

2-4. Composition and mass of dust formed

condensation time



mass of dust formed

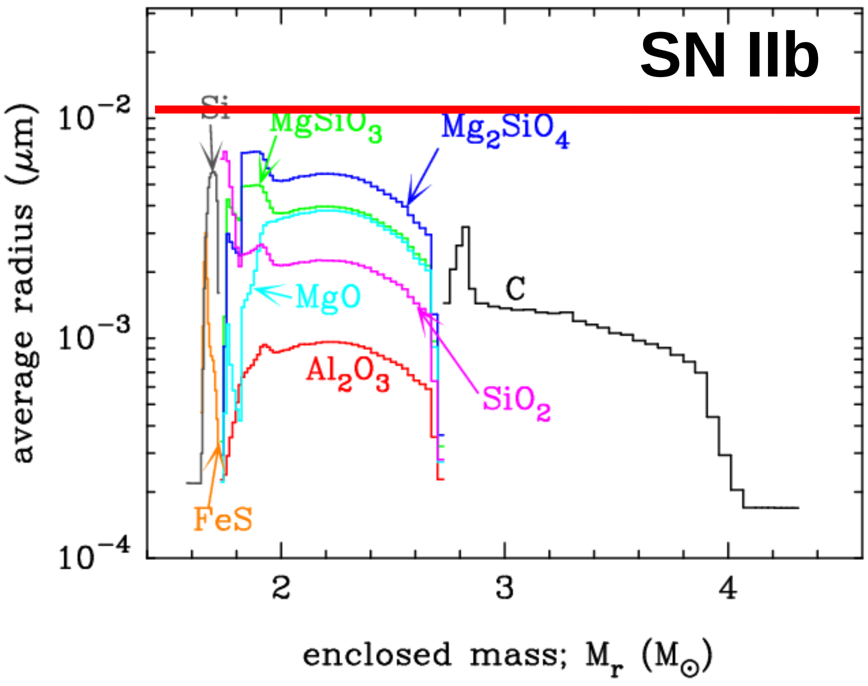


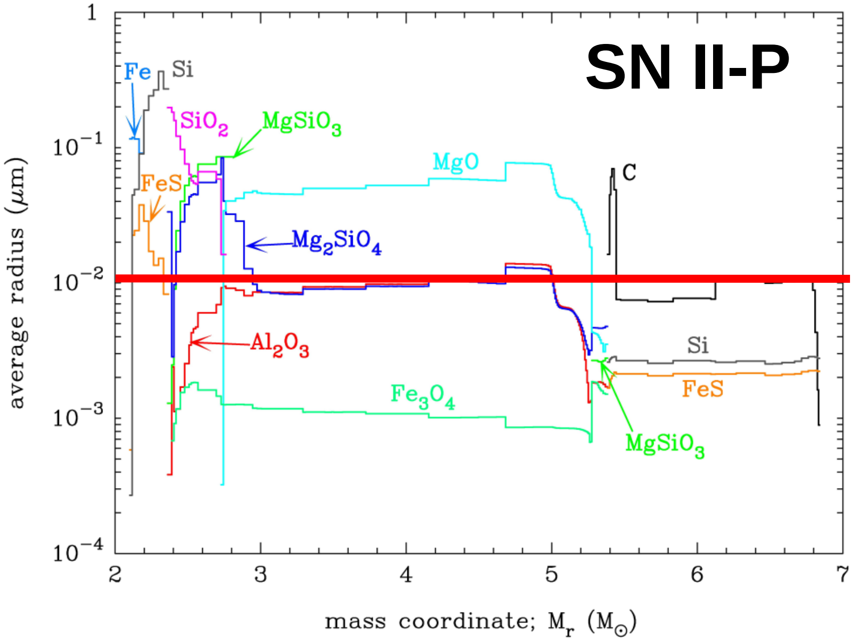
dust species	$M_{d,j}$ ($M_\odot$)	$M_{d,j}/M_{d,total}$
C	7.08×10^{-2}	0.423
Al_2O_3	6.19×10^{-5}	3.7×10^{-4}
Mg_2SiO_4	1.74×10^{-2}	0.104
$MgSiO_3$	5.46×10^{-2}	0.326
SiO_2	1.57×10^{-2}	0.094
MgO	2.36×10^{-3}	0.014
FeS	1.47×10^{-3}	0.009
Si	5.07×10^{-3}	0.030
total	0.167	1

- 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

2-5. Average radii of dust formed in the ejecta



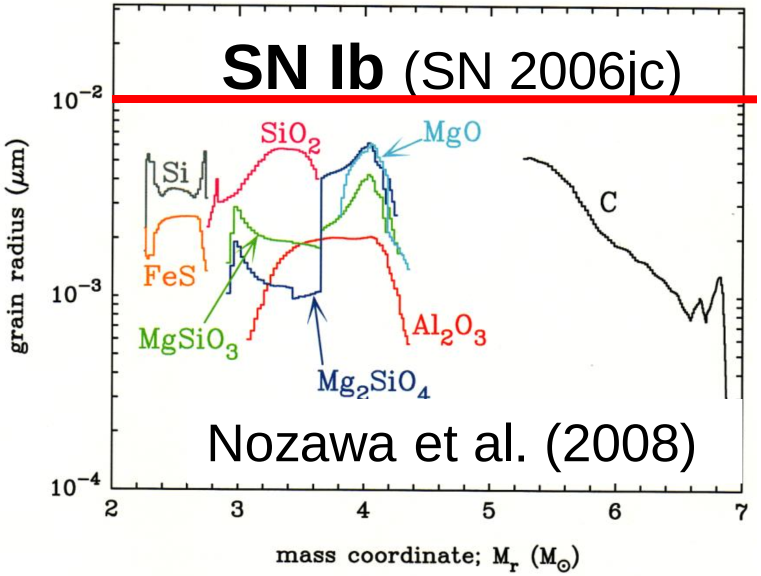


Grain radius

➔ **> 0.01 μm for SN IIP**

➔ **< 0.01 μm for SN IIb**

Dust grains formed in H-deficient SNe are small



Nozawa et al. (2008)

3. Evolution of dust in Type IIb SNR

3-1. Calculation of dust evolution in SNRs

○ time evolution of gas temperature and density in SNR

- ejecta model

  hydrodynamic model for dust formation calculation

- CSM gas density
  - **uniform :** **$n_{H,0}$ = 0.1, 1, 10 cm^{-3}**
  - **stellar wind : $n_{H,1}$ = 30, 120, 200 cm^{-3}**

$$n_H(r) = n_{H,1} (r / r_1)^{-2} \quad r < r_2$$
$$= 1 \text{ cm}^{-3} \quad r \geq r_2$$

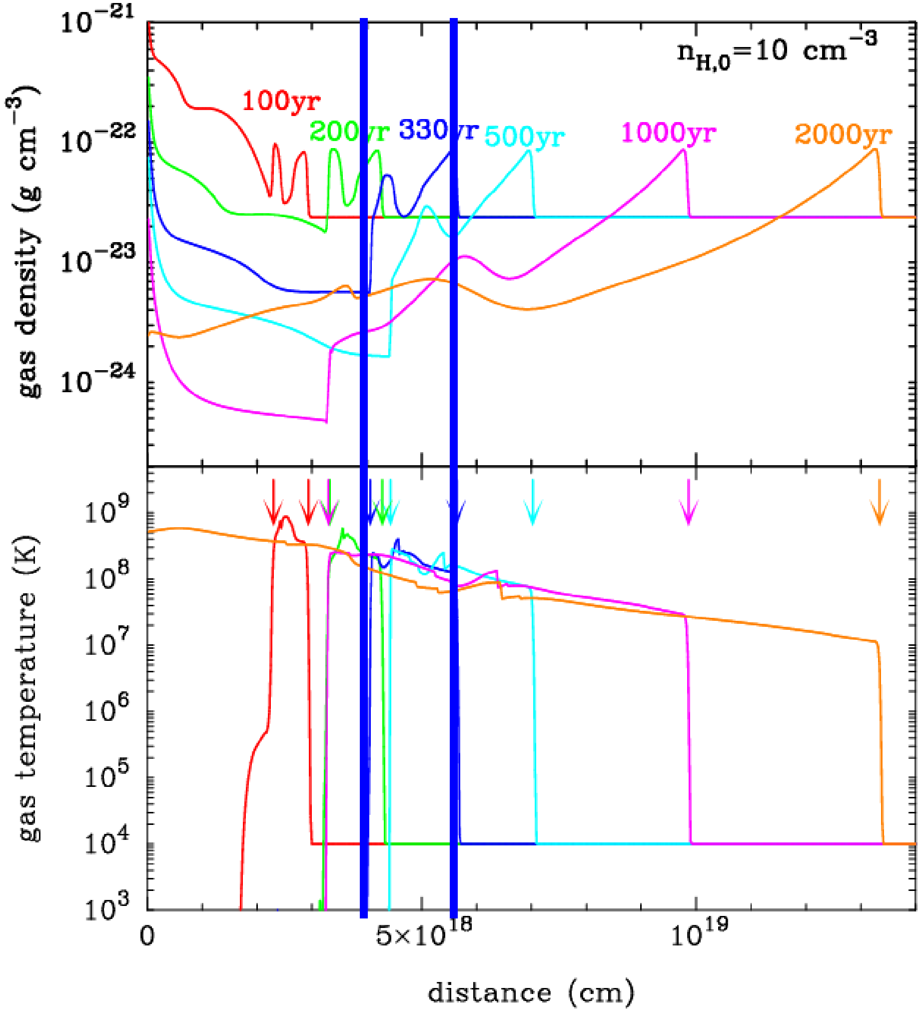
○ time evolution of dust (Nozawa+'06, '07)

- treating dust as a test particle
  - erosion by sputtering and deceleration by gas drag

→ initial size distribution and spatial distribution of dust

- calculations are performed up to ~10^6 yr

3-2. Calculation of dust evolution in SNRs



downward-pointing arrows

→ positions of the forward and reverse shocks

The temperature of the gas swept up by the reverse and reverse shocks is 10^6 -10^8 K.

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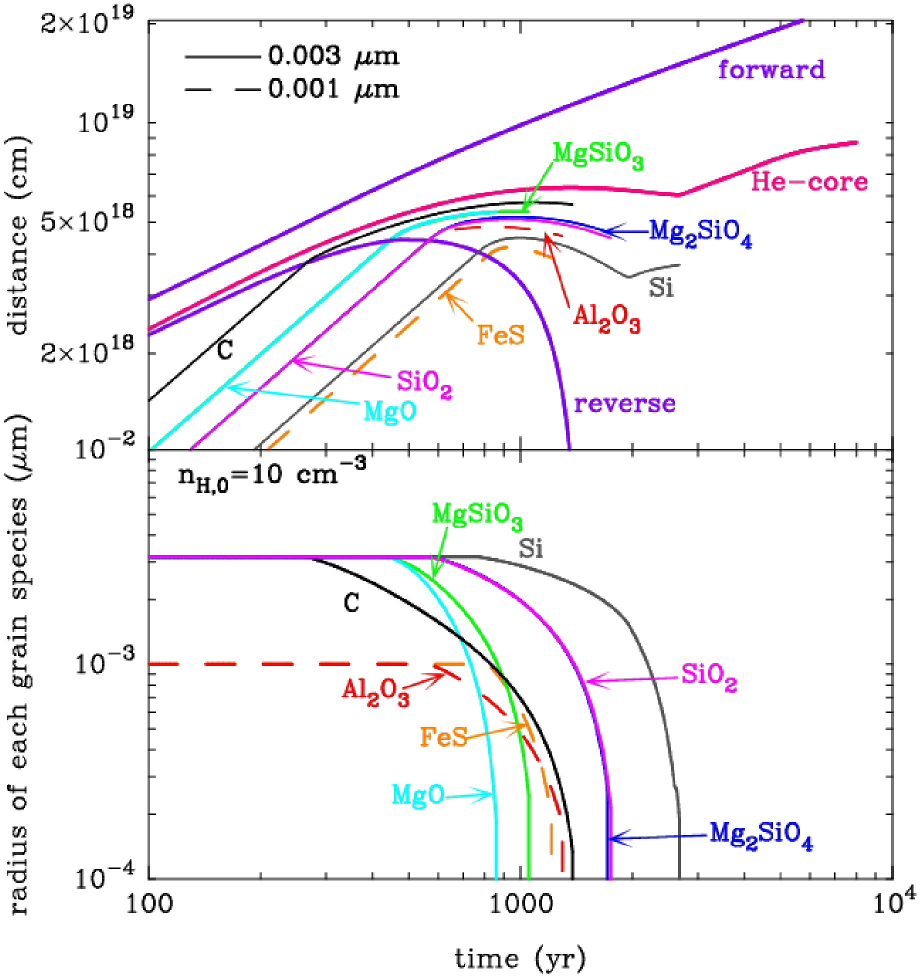
Dust grains residing in this hot gas are eroded by sputtering

3-3. Calculation of dust evolution in SNRs

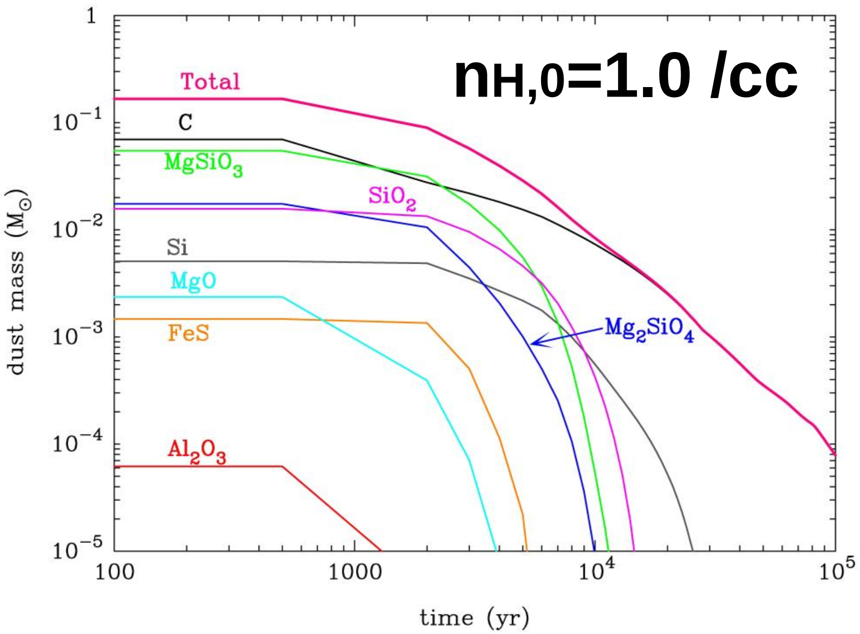


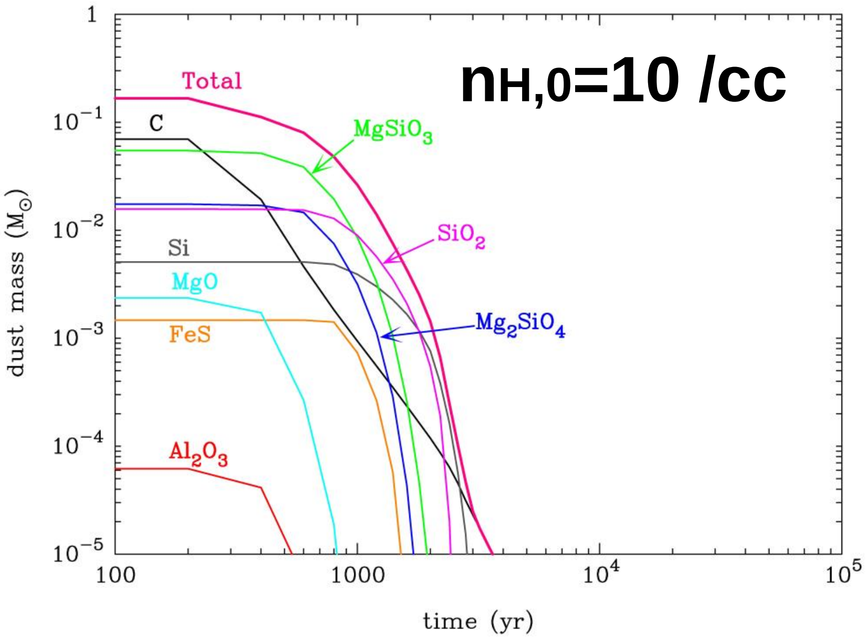
The collision times between the reverse shock and He core is 75 year after the explosion

➔ 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

3-4. Time evolution of dust mass


$n_{H,0}$=1.0 /cc


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

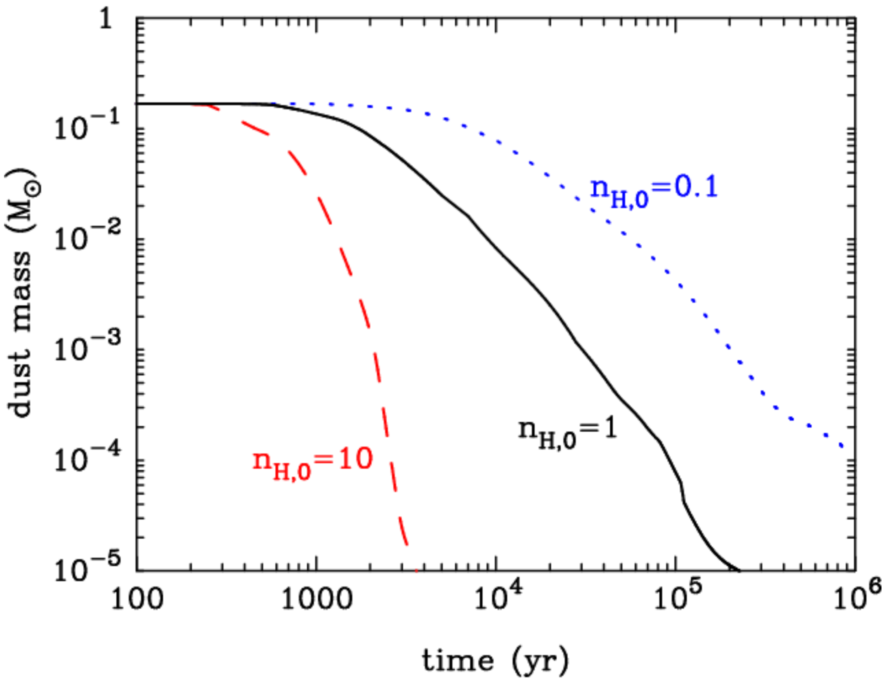
M_{dust} ~ **10^{-4} M_{sun}** at 10^5 yr

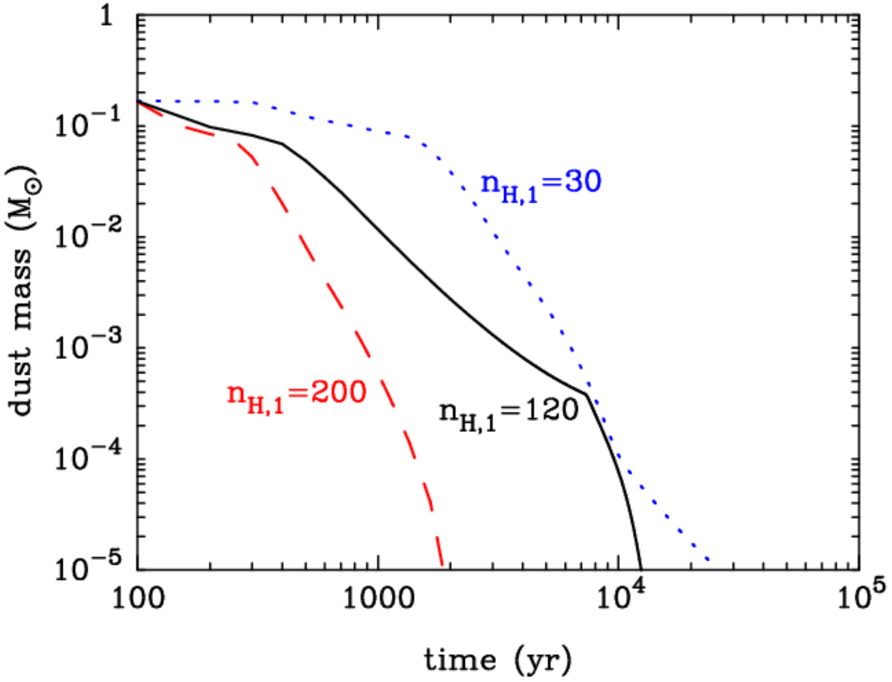
M_{dust} = **0 M_{sun}** at 10^5 yr

higher ambient density leads to the earlier arrival of the reverse shock at the dust-forming region

higher gas density causes more efficient deceleration and destruction of dust

3-5. 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

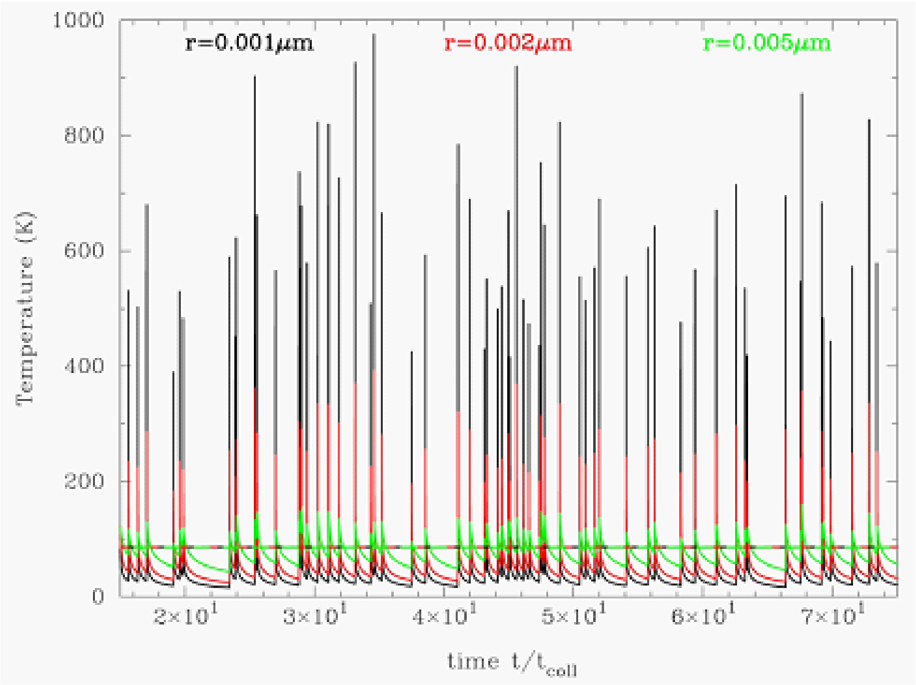
➔ early arrival of the reverse shock at the He core

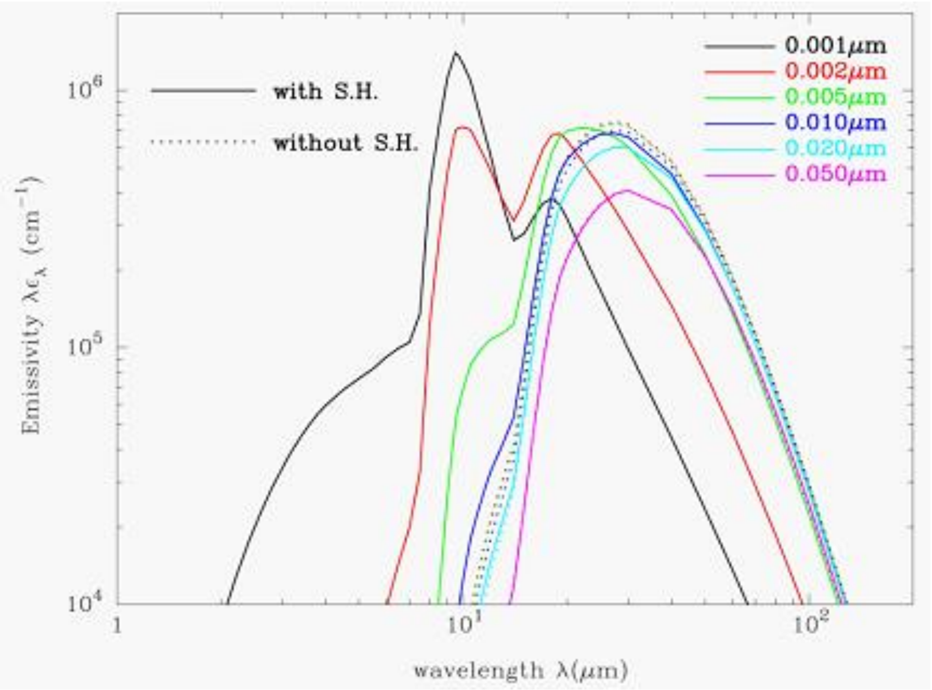
4. Thermal emission of dust in SNRs

4-1. Thermal emission from dust in the SNR

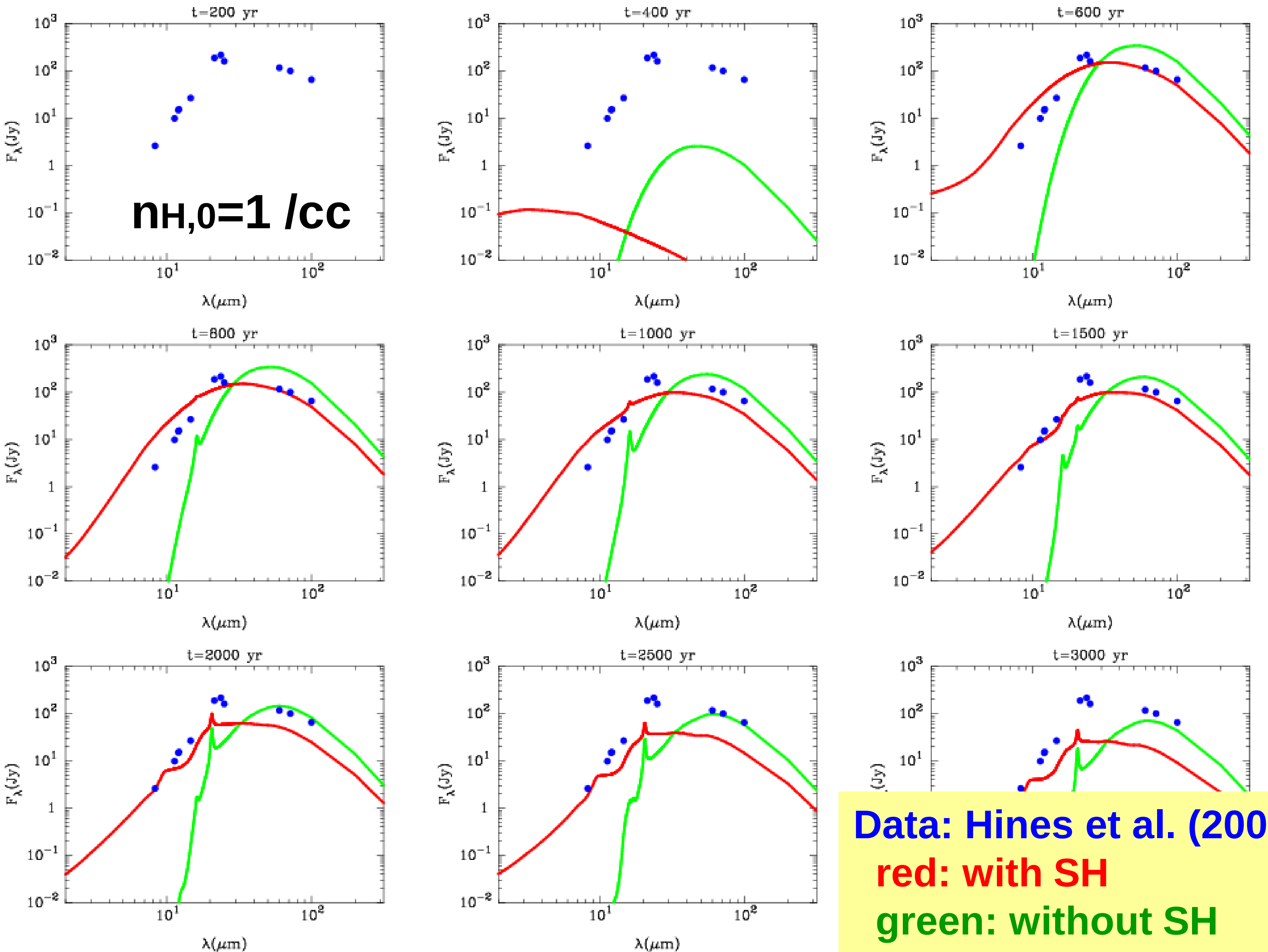
- thermal radiation from dust ← temperature of dust
- equilibrium temperature of dust in SNR is determined by collisional heating with gas and radiative cooling

  $H\ (a, n, T_g) = \Lambda(a, Q_{abs}, T_d)$ ➔ thermal emission
- small-sized dust grains (＜0.01 μm) ➔ stochastic heating





4-2. Time evolution of IR thermal emission (1)



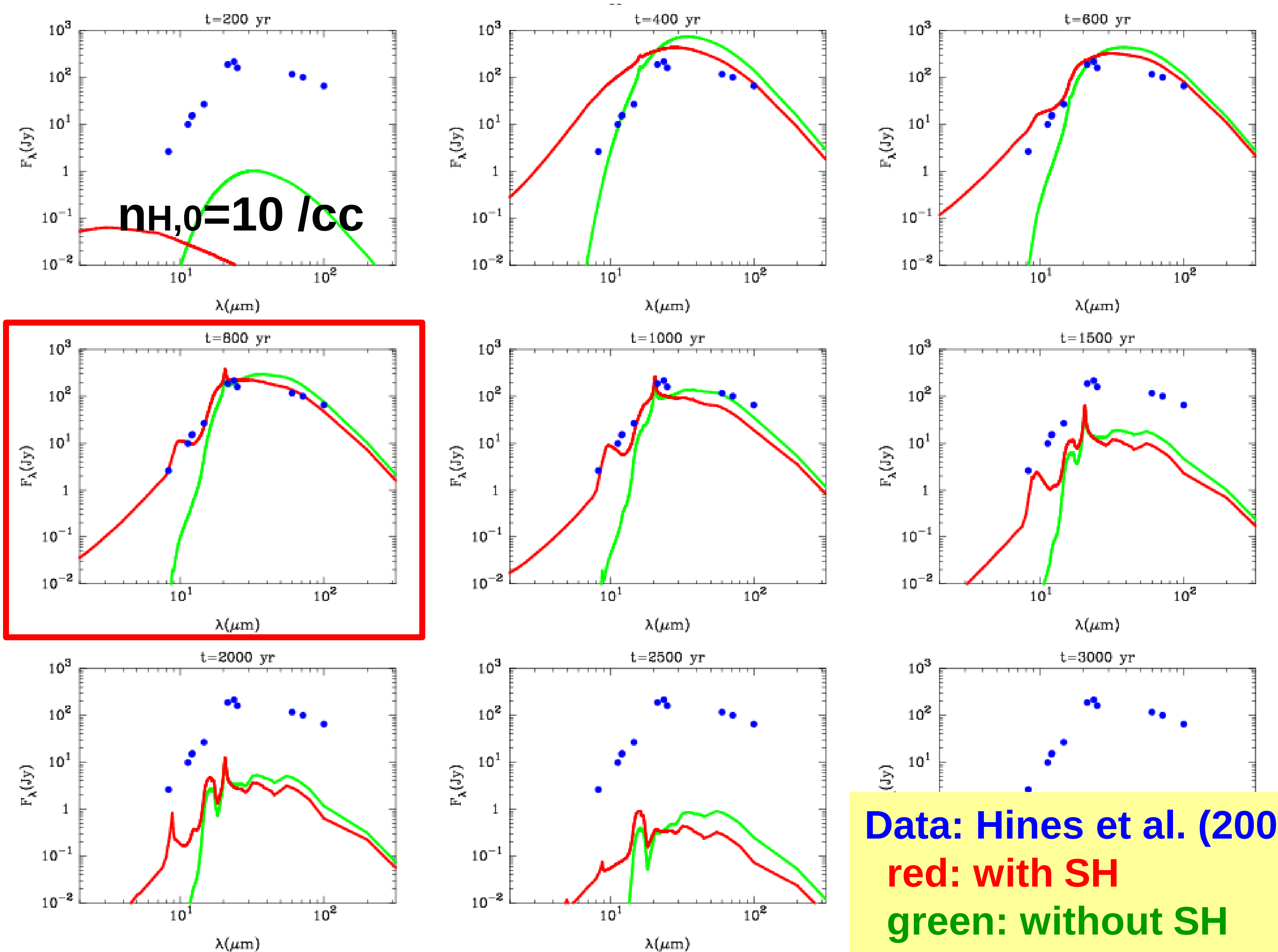
$n_{H,0}$=1 /cc

Data: Hines et al. (2004)

red: with SH

green: without SH

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



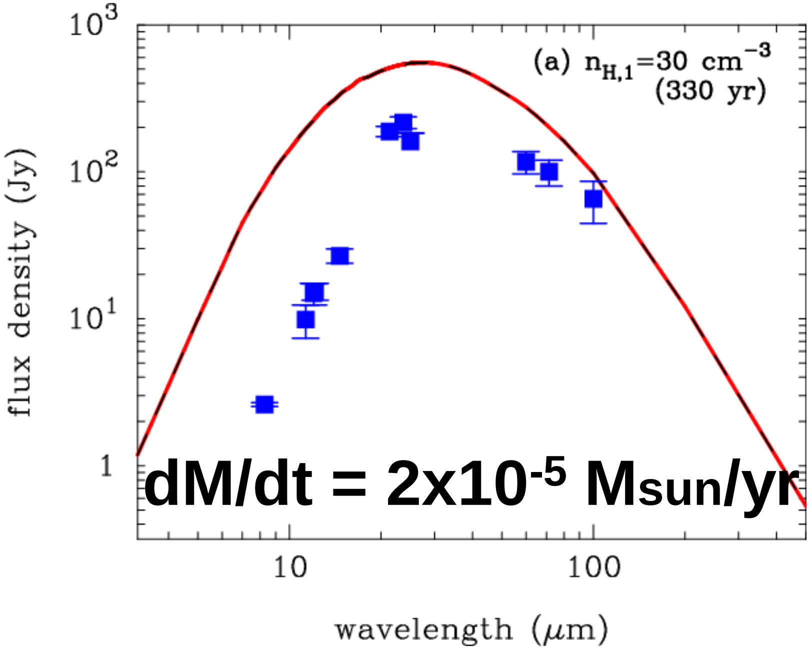
$n_{H,0}$=10 /cc

Data: Hines et al. (2004)

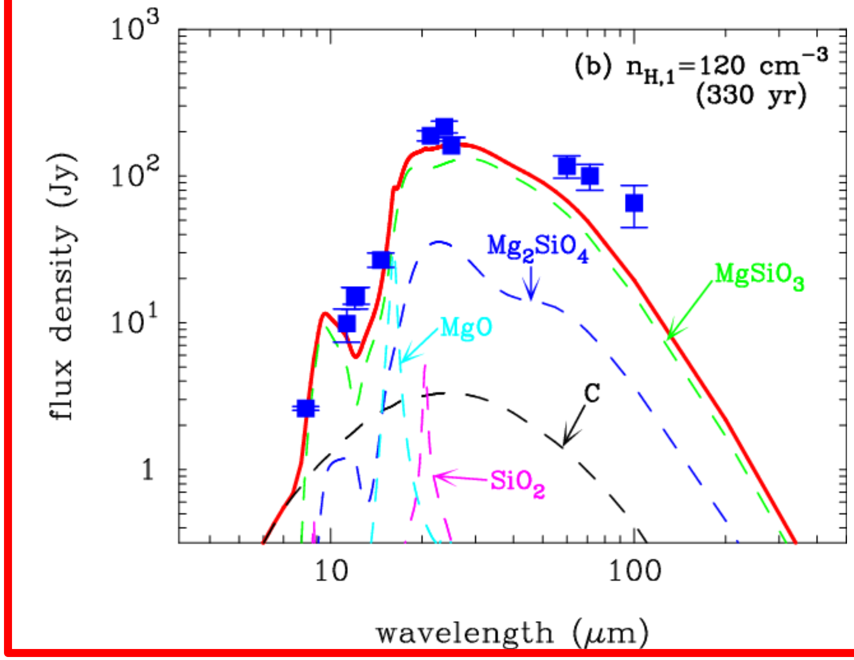
red: with SH

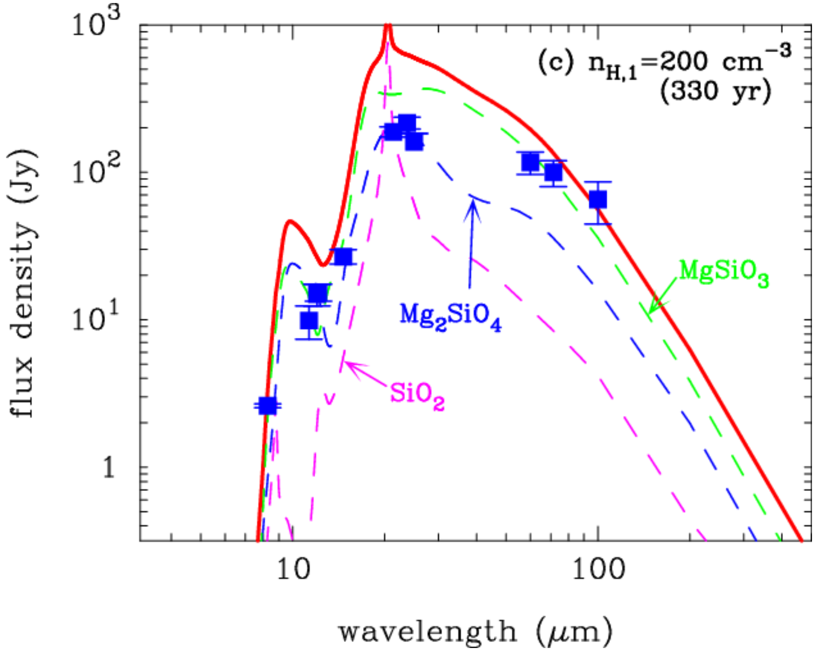
green: without SH

4-3. Dependence of IR SED on ambient density



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



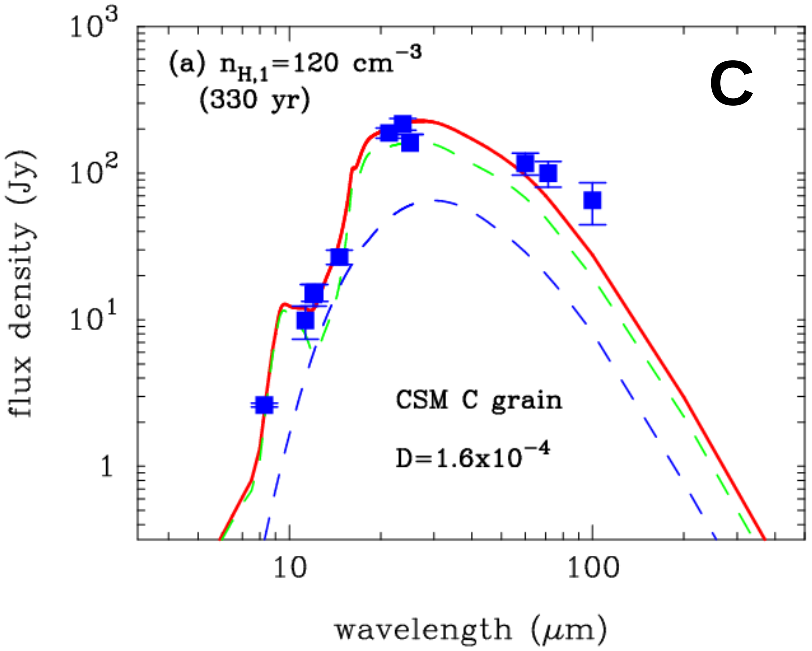


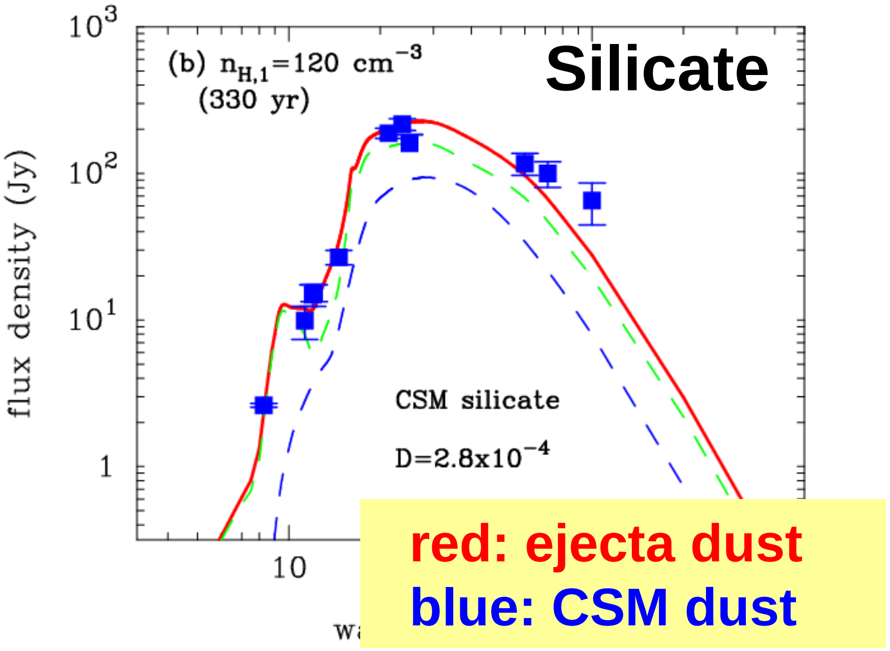
Md = 0.008 Msun
dM/dt = 8x10^{-5} Msun/yr

4-4. Contribution from circumstellar 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**



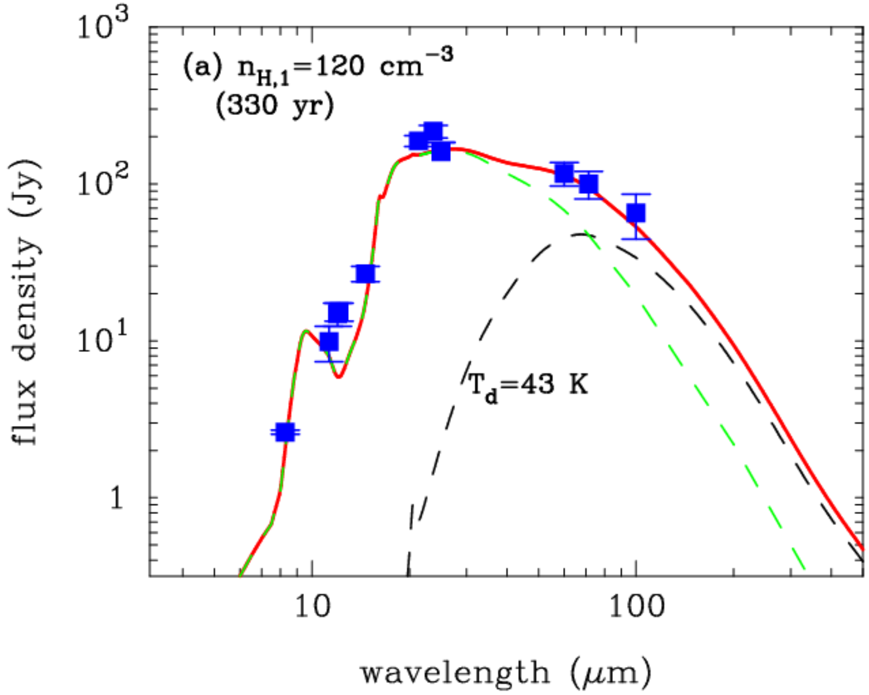


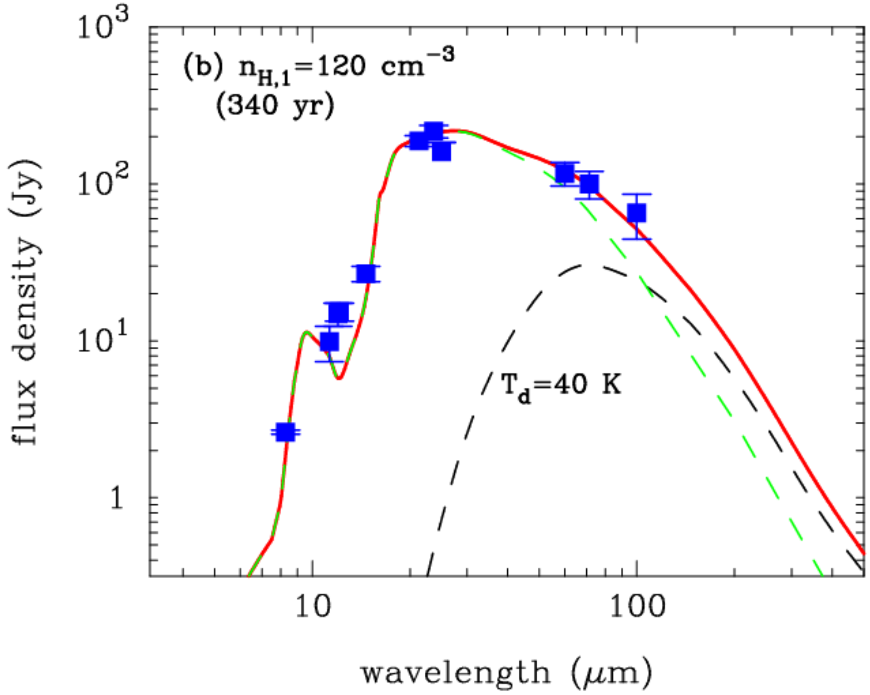
red: ejecta dust
blue: CSM dust

4-5. Contribution from unshocked dust

$M_{d,warm}$ ~ 0.008 M_{sun},
$M_{d,cool}$ ~ 0.07 M_{sun}
$dM/dt = 8\times10^{-5}$ Msun/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;
   $M_{d,warm} = 0.008\ M_{sun}$, $M_{d,cool} = 0.07\ M_{sun}$
   $dM/dt = \sim 8\times10^{-5}\ M_{sun}/yr$