Formation of Dust in Supernovae and Its Ejection into the ISM

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1. Introduction

1-1. Background

CCSNe are main sources of interstellar dust?

— **formation of dust in the ejecta of SNe**
— **destruction of dust in the shocked gas of SNRs**

・ Observations of dust-forming SNe

➔ **no information on composition and size of dust**
except for SN 2006jc (Sakon+2009) and SN 2004et (Kotak+2009)

➔ M_{dust} **$<10^{-3}$ M_{sun}**

・ Theoretical studies

➔ M_{form} = **0.1-1 M_{sun}** **for SNe II**
various dust species with 0.001-1 μm
(Todini & Ferrara 2001; Nozawa et al. 2003)

➔ M_{surv} = **0.01-0.8 M_{sun}** for $n_{H,0}$=0.1-10 cm^{-3}
(Bianchi & Schneider 2007; Nozawa et al. 2007)

1-2. Aim of our study

- Comparison of models with IR observations of SNRs
  - erosion by sputtering and collisional heating

  ➔ properties of dust and density structure in CSM

What size and how much amount of dust are injected from CCSNe into the ISM?

- Dust formation and evolution in SN with no envelope
  - 30-40% of CCSNe explode as SNe Ib/c and SN IIb

    (Prieto et al. 2009; Smartt et al. 2008; Boissier & Prantzos 2009)

How do formation and destruction processes of dust depend on the type of CCSNe?

1-3. Outline

・ Formation of dust in the ejecta of Type IIb SN

→ **composition, size, and mass of newly formed dust**

・ Destruction of dust in the hot gas of the SNR

→ **What fraction of dust grains in the SN ejecta can survive and is injected into the ISM?**

・ Thermal emission from shock-heated dust

→ **comparison with IR observations of Cas A SNR**

→ **constraint to gas density in the ambient medium**

1-4. Cassiopeia A SNR

○ Cas A SNR

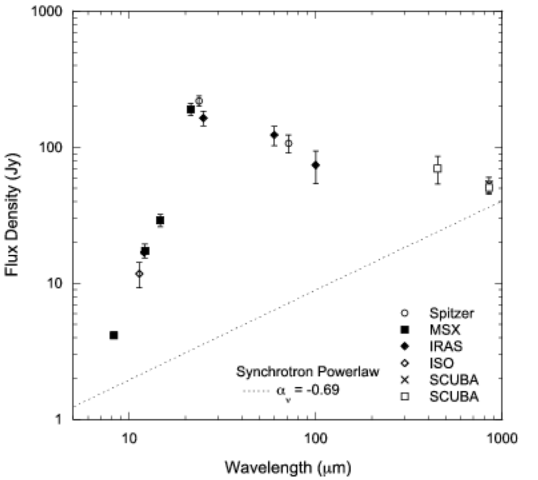
- age: ~330 yr (Thorstensen et al. 2001)
- distance: d=3.4 kpc (Reed et al. 1995)
- shock radius

  forward shock : ~150" (~2.5 pc)

  reverse shock : ~100" (~1.7 pc)

  dM/dt ~ 2×10^{-5} (v_w/10 km/s) M_{sun}/yr

  (Chevalier & Oishi 2003)



- oxygen-rich SNR

  dense O-rich fast-moving knots (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** (Krause et al. 2008)

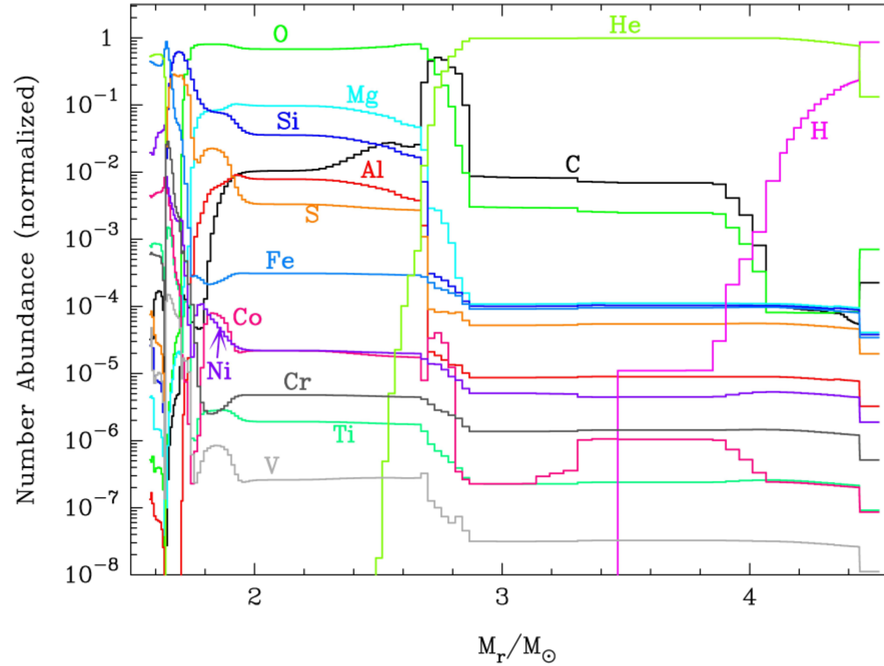
2. Formation of dust in Type IIb SN

2-1. Dust formation calculation

○ Type IIb SN model

(SN1993J-like model)

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

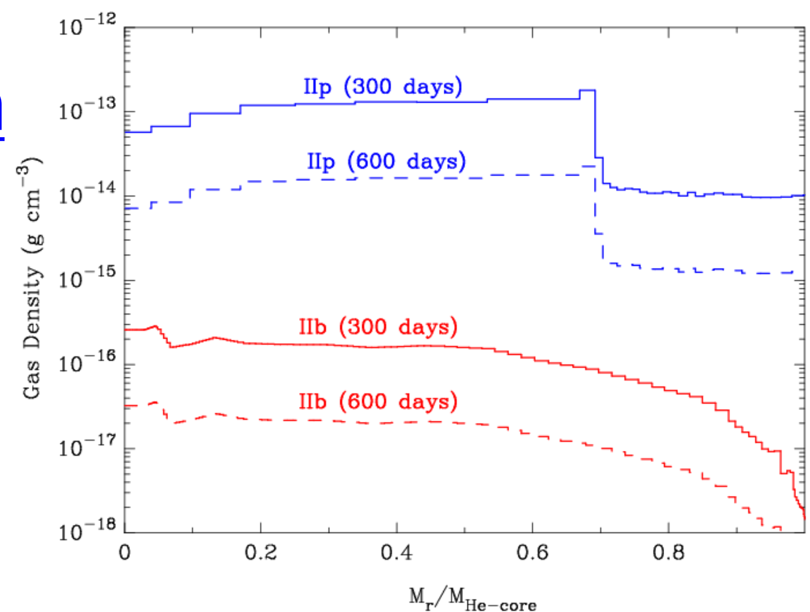


○ Dust formation calculation

- non-steady nucleation and grain growth theory

  (Nozawa et al. 2003)

- onion-like composition



2-2. Composition and mass of dust formed

Mass of dust formed

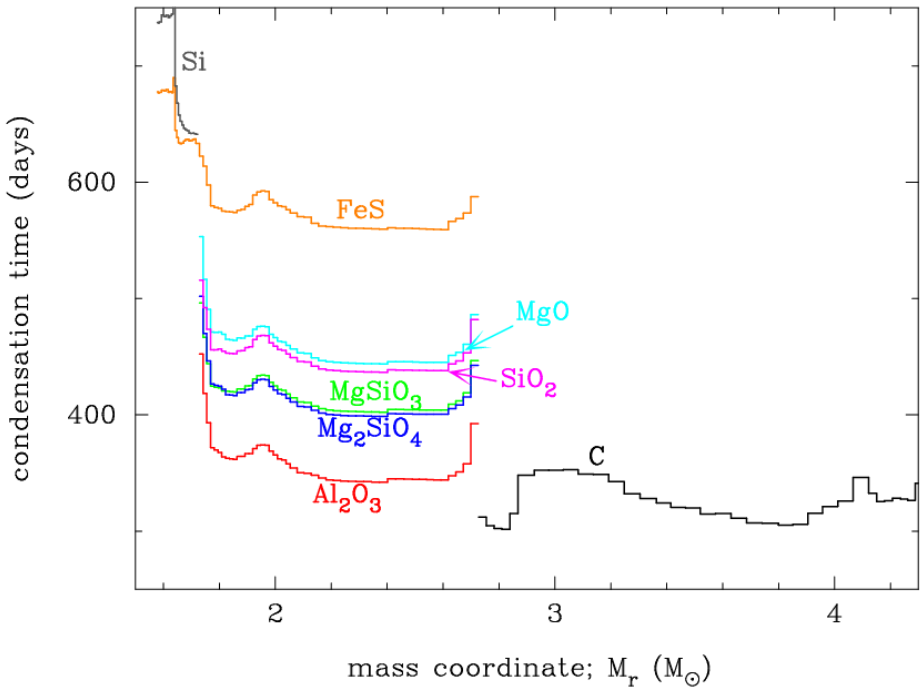
dust species	$M_{d,j}$ ($M_\odot$)	$M_{d,j}/M_{d,total}$
C	7.08×10^{-2}	0.423
Al_2O_3	6.19×10^{-5}	3.7×10^{-4}
Mg_2SiO_4	1.74×10^{-2}	0.104
$MgSiO_3$	5.46×10^{-2}	0.326
SiO_2	1.57×10^{-2}	0.094
MgO	2.36×10^{-3}	0.014
FeS	1.47×10^{-3}	0.009
Si	5.07×10^{-3}	0.030
total	0.167	1

Total mass of dust formed :

0.167 Msun in SN IIb

0.1-1 Msun in SN II-P

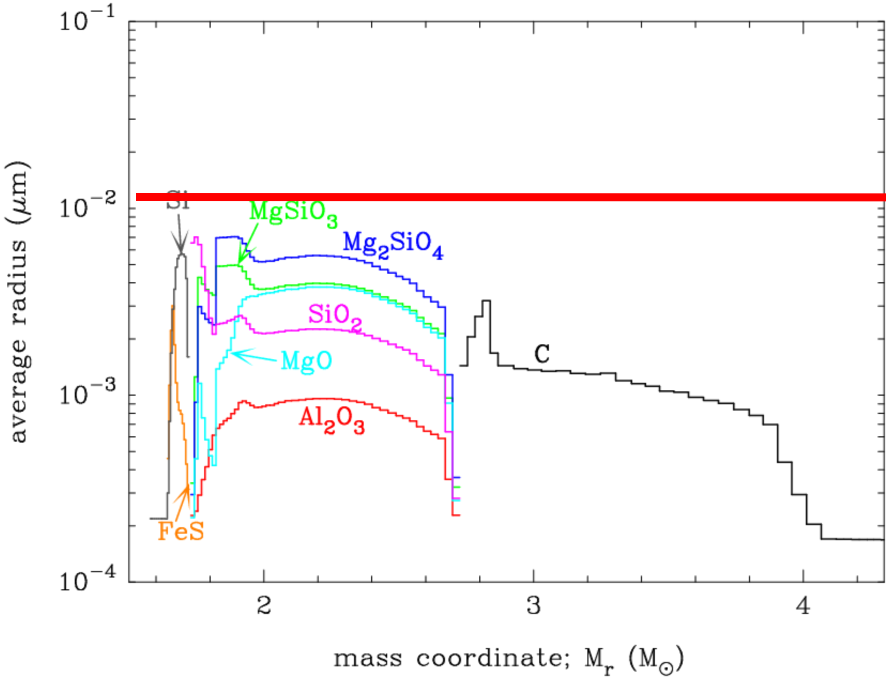
condensation time

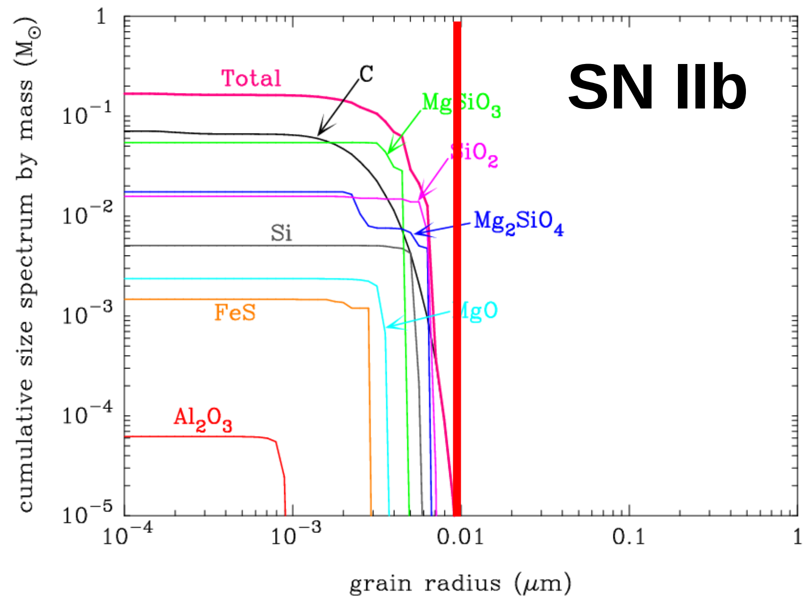


- different species of dust can condense in different layers
- condensation time: 300-700 days

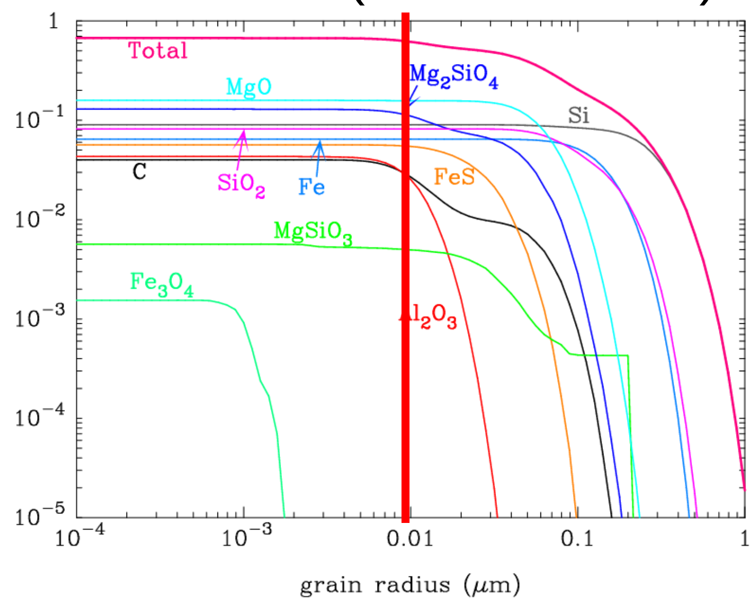
2-3. Radius of dust formed in the ejecta

average radius





SN II-P (Mstar=20 Msun)



Grain radius

- ➔ **> 0.01 μm for SN IIP**
- ➔ **< 0.01 μm for SN IIb**

Dust grains formed in H-deficient SNe are small

3. Evolution of dust in Type IIb SNR

3-1. Calculation of dust evolution in SNRs

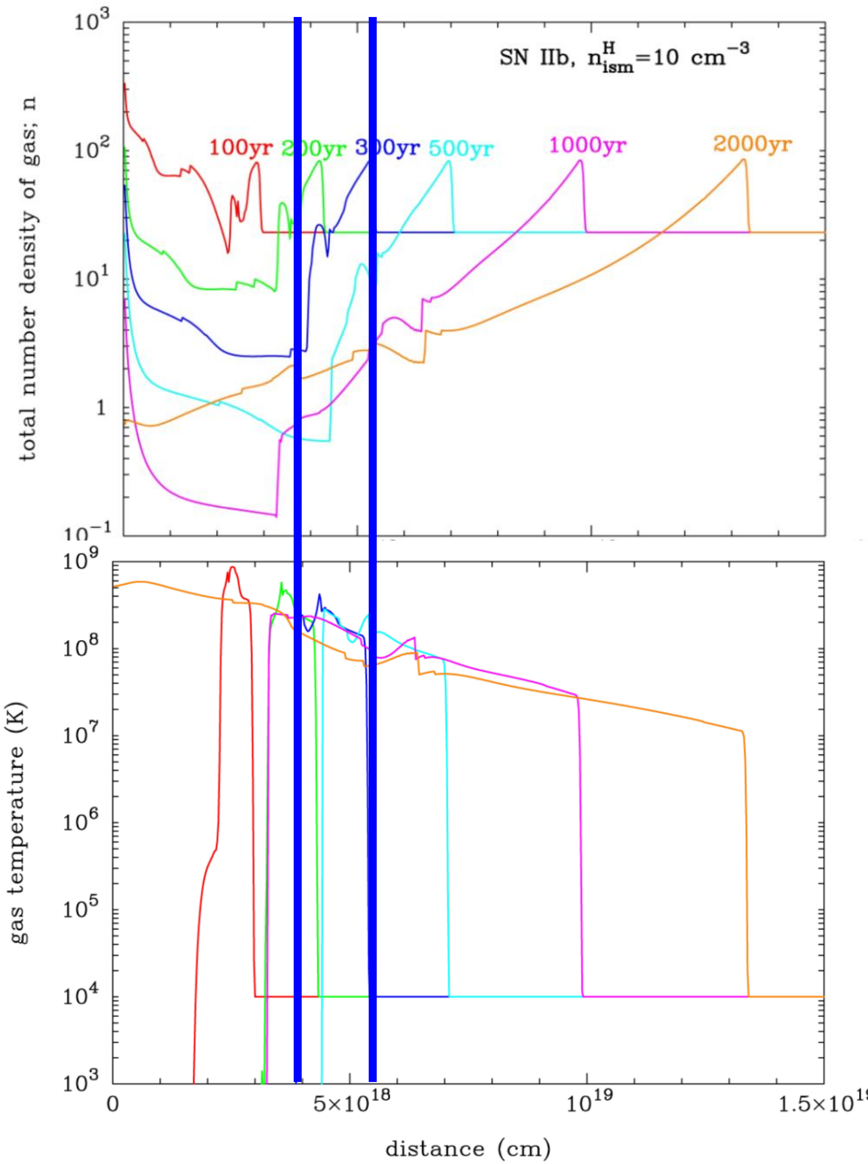
○ Model of calculations

(Nozawa et al. 2006, 2007)

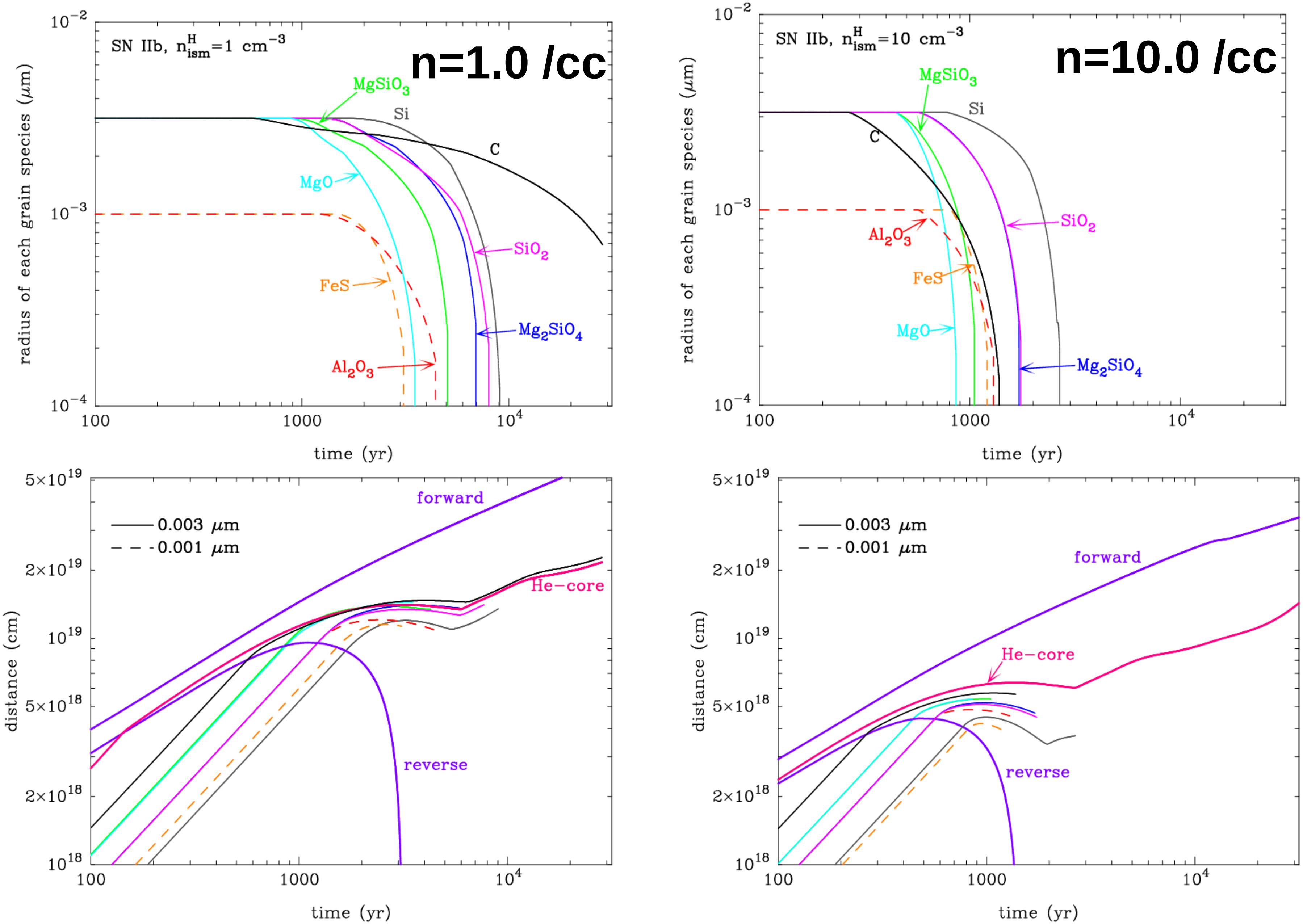
- ejecta model
  - hydrodynamic model for dust formation calculation

- CSM gas density
  - **n_H = 1.0 and 10.0 cm^{-3}**
  - **$n_H(r) \propto M / (4\pi r^2 v_w)$ g/cm^{-3}**
    ($M = 2 \times 10^{-5}$ M_{sun}/yr)

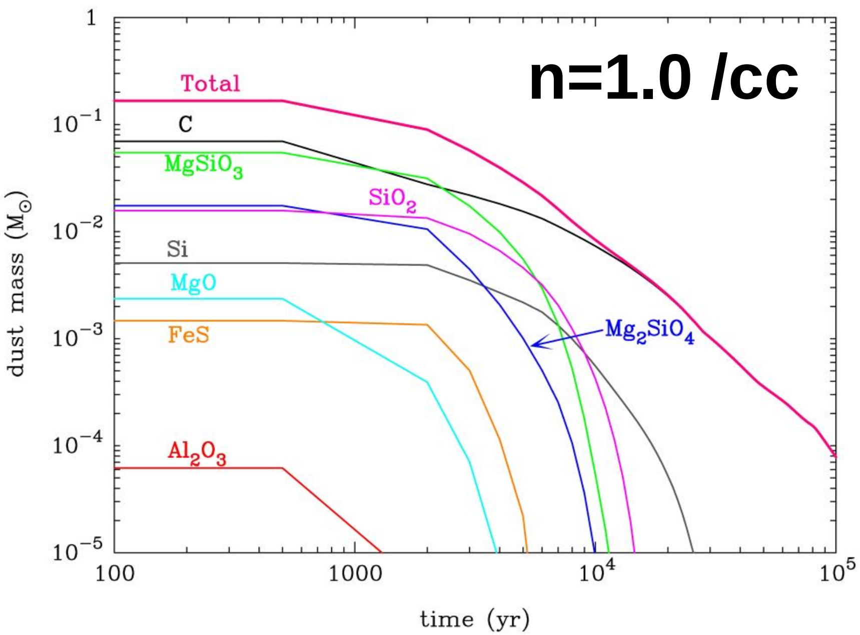
- treating dust as a test particle
  - erosion by sputtering
  - deceleration by gas drag
  - collsional heating
    ➔ stochastic heating

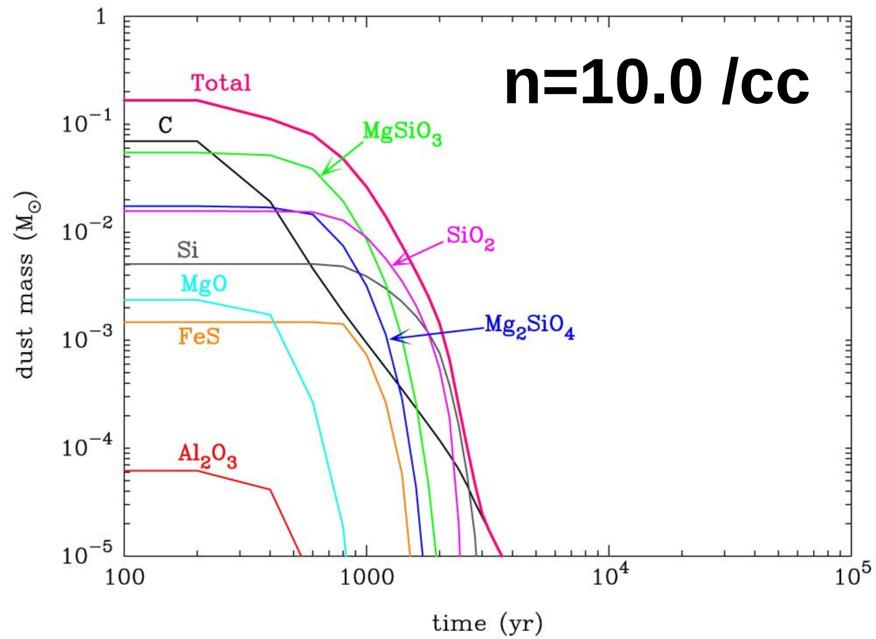


3-2. Evolution of dust in Type IIb SNR



3-3. Time evolution of dust mass





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

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

Newly formed dust grains in the ejecta are completely destroyed in the shocked gas within the SNR

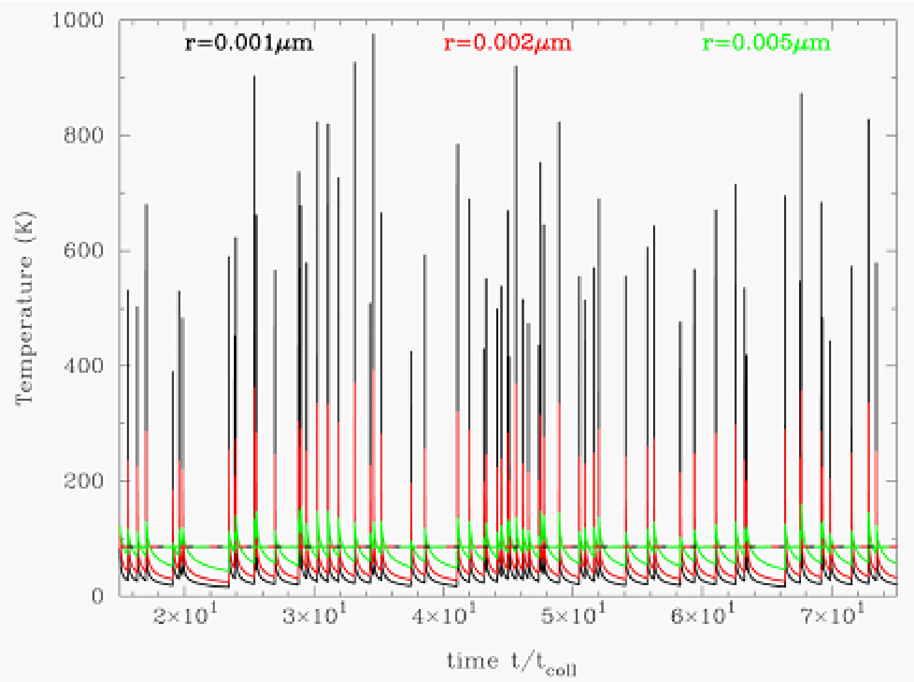
Core-collapse SNe with the thin outer envelope cannot be main sources of dust

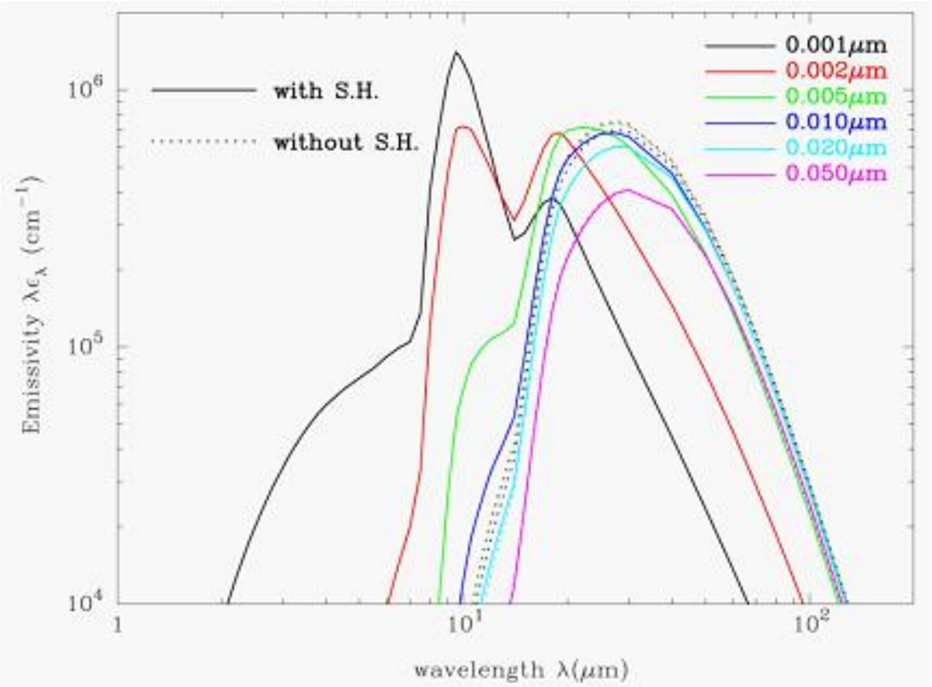
4. Thermal emission of dust in SNRs

4-1. Thermal emission from dust in the SNR

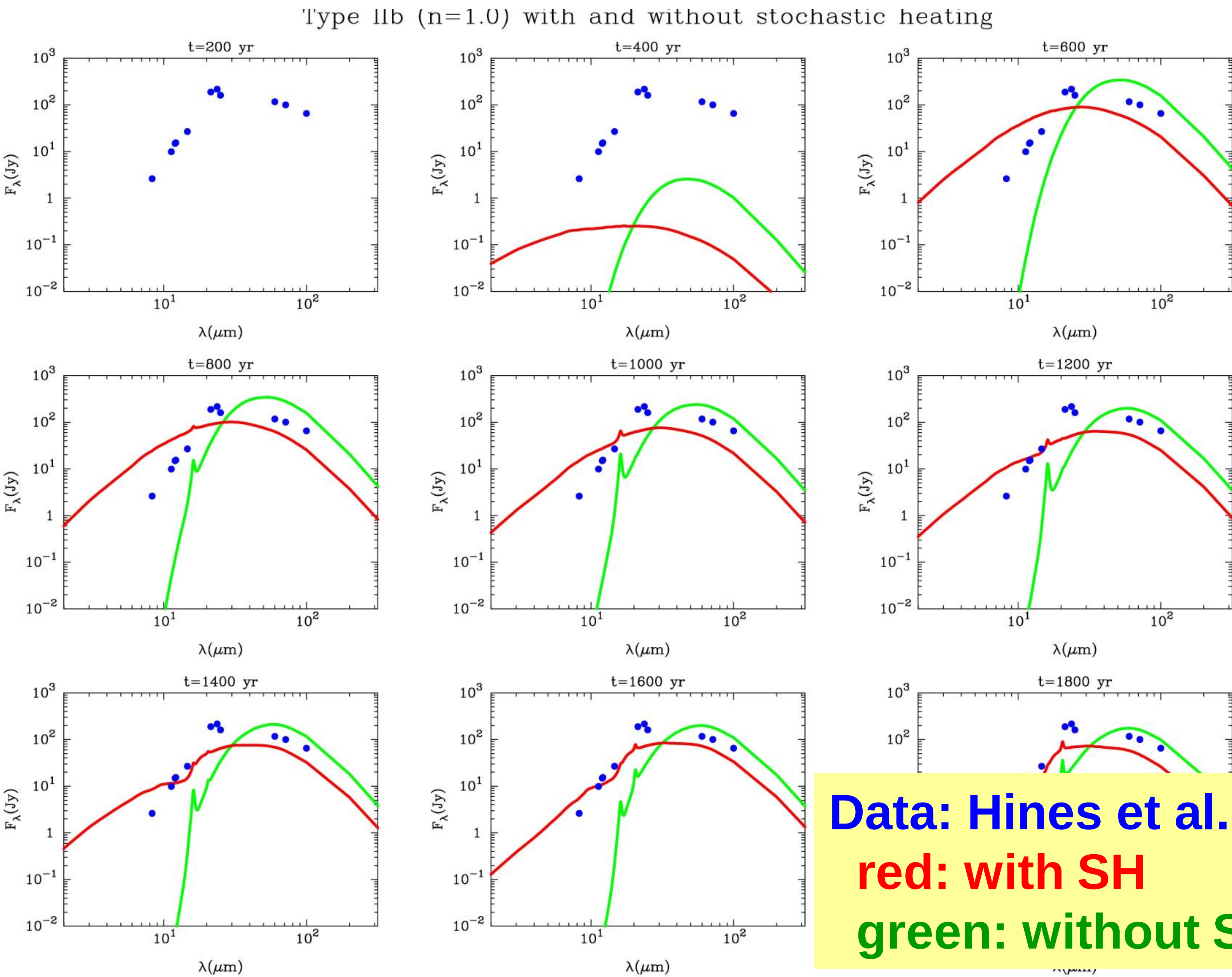
- thermal radiation from dust ← temperature of dust
- equilibrium temperature of dust in SNR is determined by collisional heating with gas and radiative cooling

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



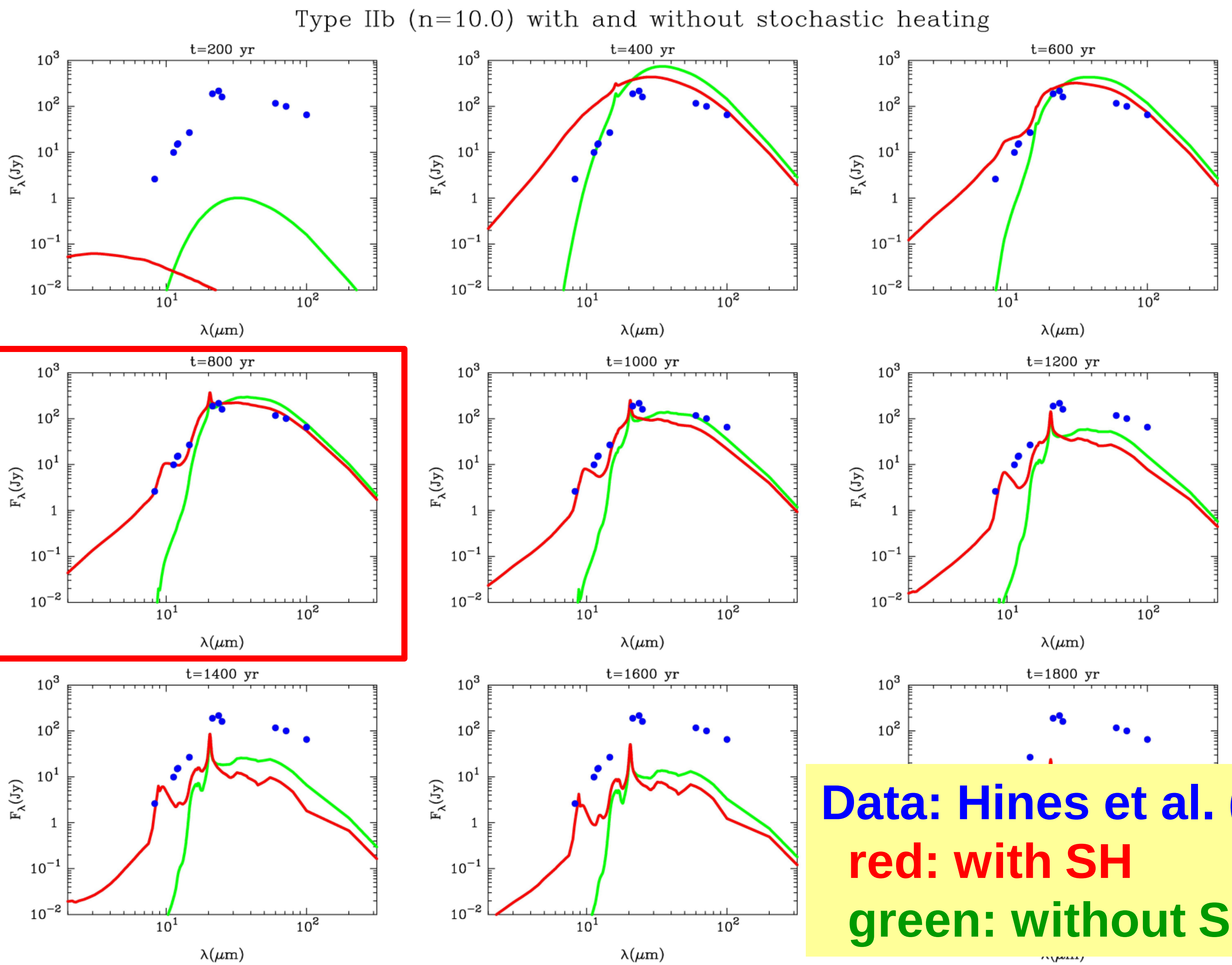


4-2. Time evolution of IR thermal emission (1)



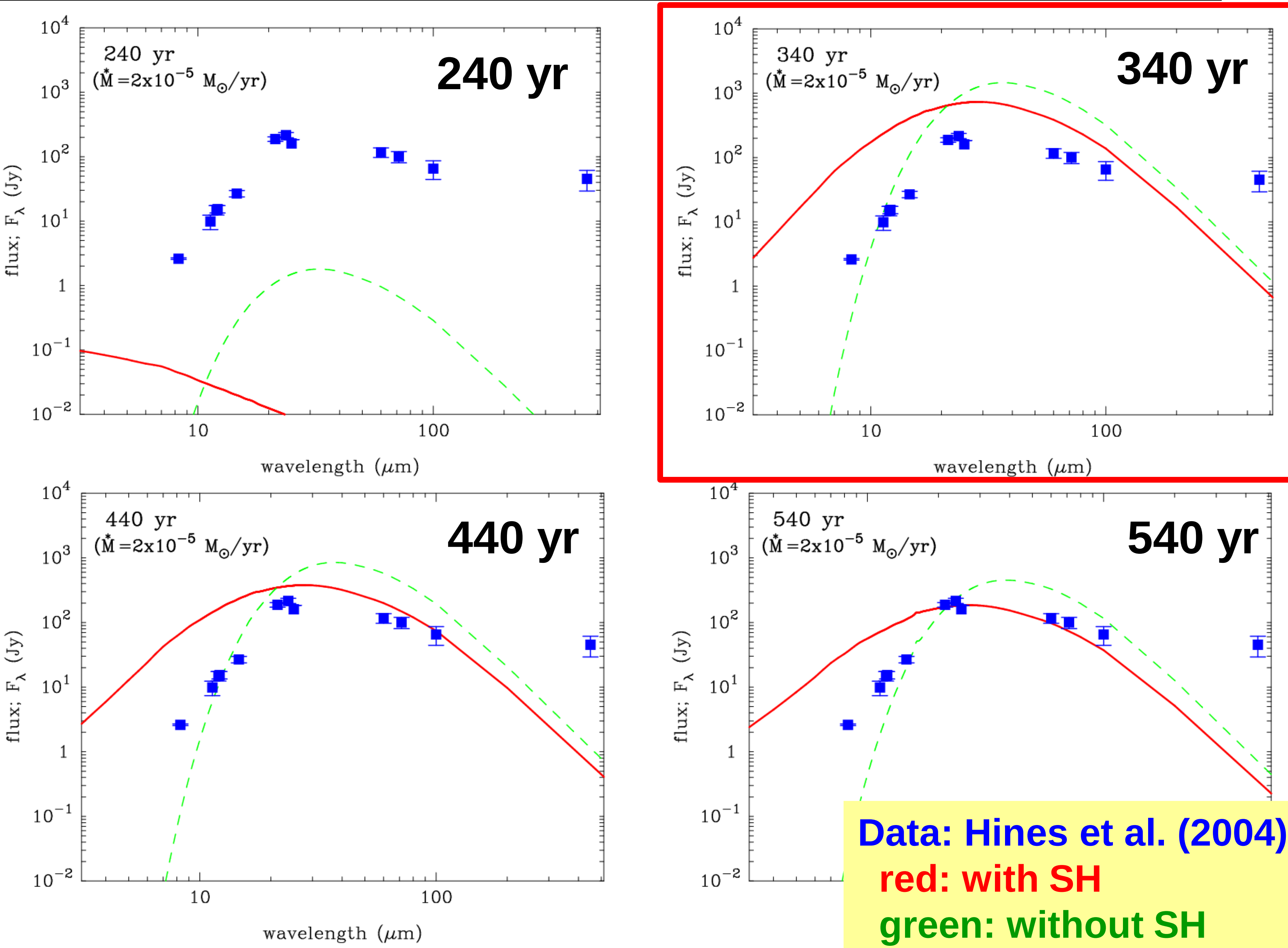
Data: Hines et al. (2004)
red: with SH
green: without SH

4-3. Time evolution of IR thermal emission (2)



Data: Hines et al. (2004)
red: with SH
green: without SH

4-4. Time evolution of IR SEDs for Cas A SNR

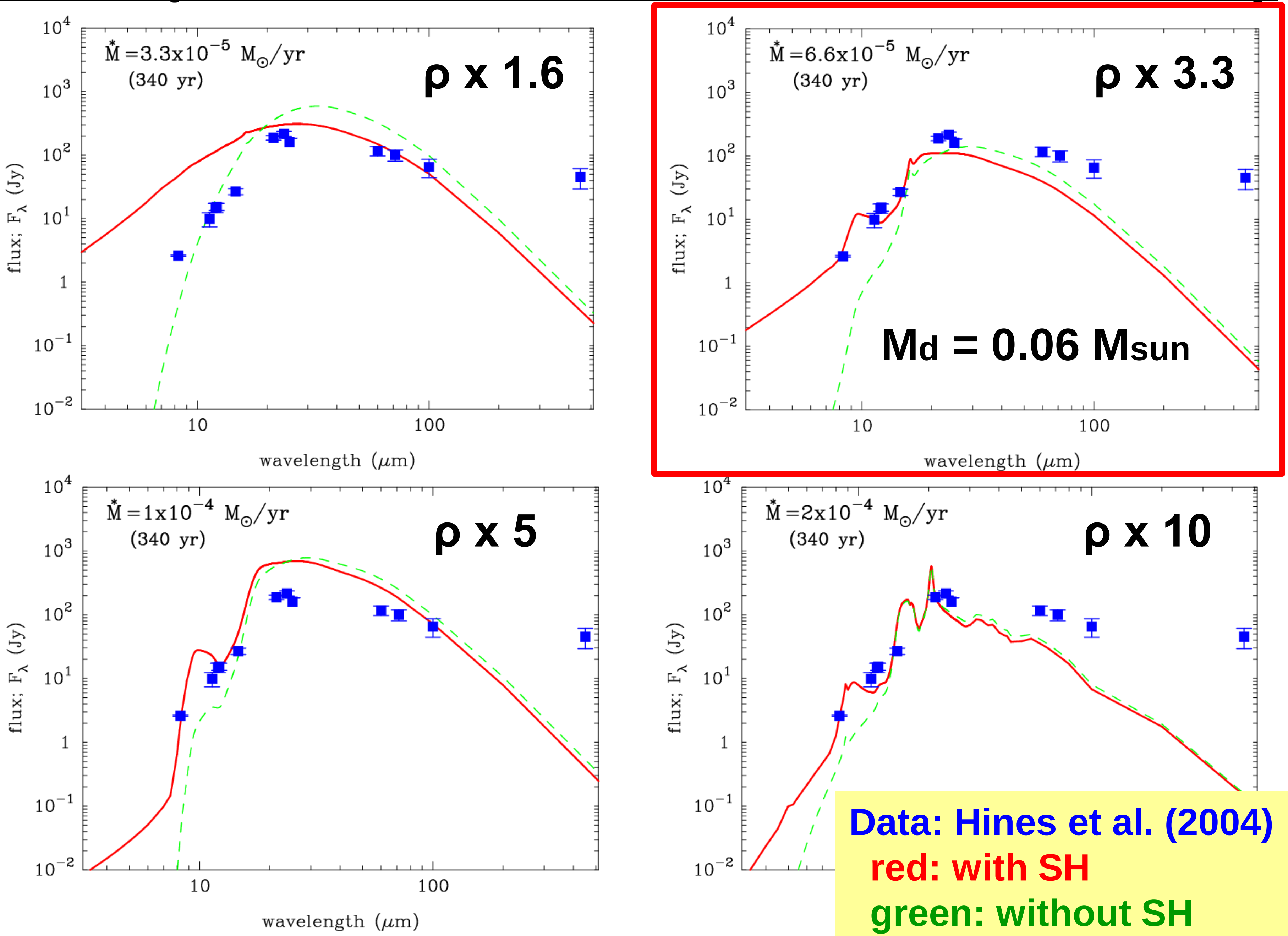


Data: Hines et al. (2004)

red: with SH

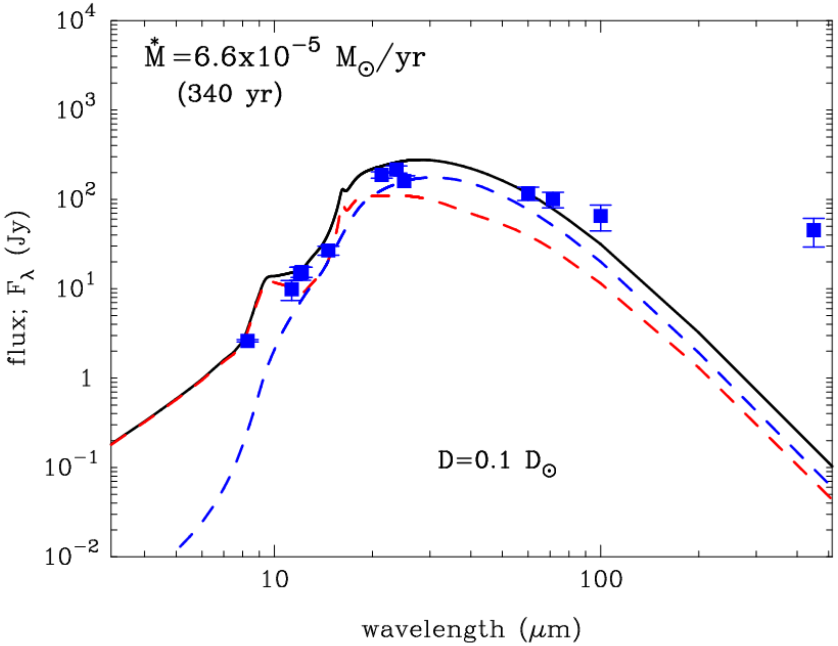
green: without SH

4-5. Dependence of IR SED on ambient density

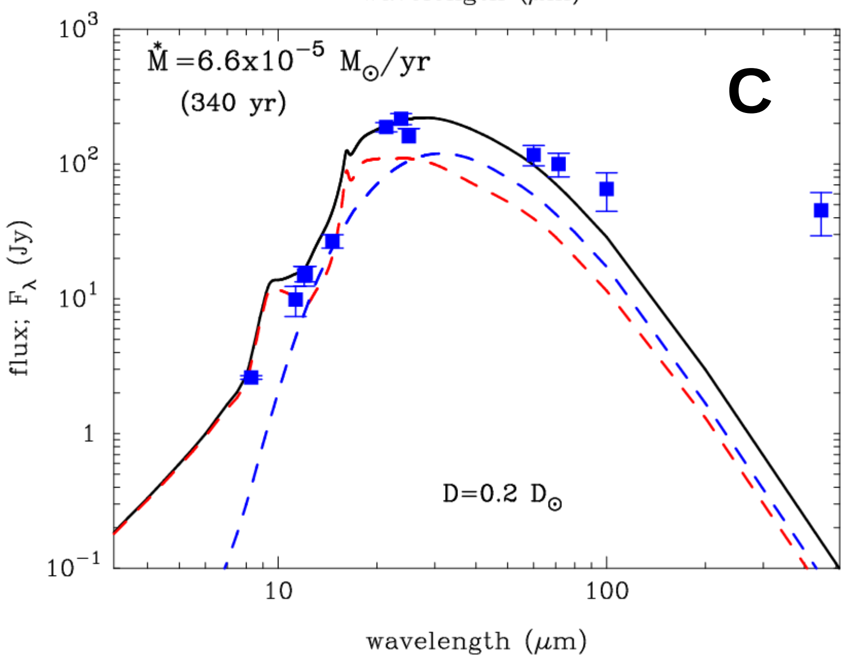


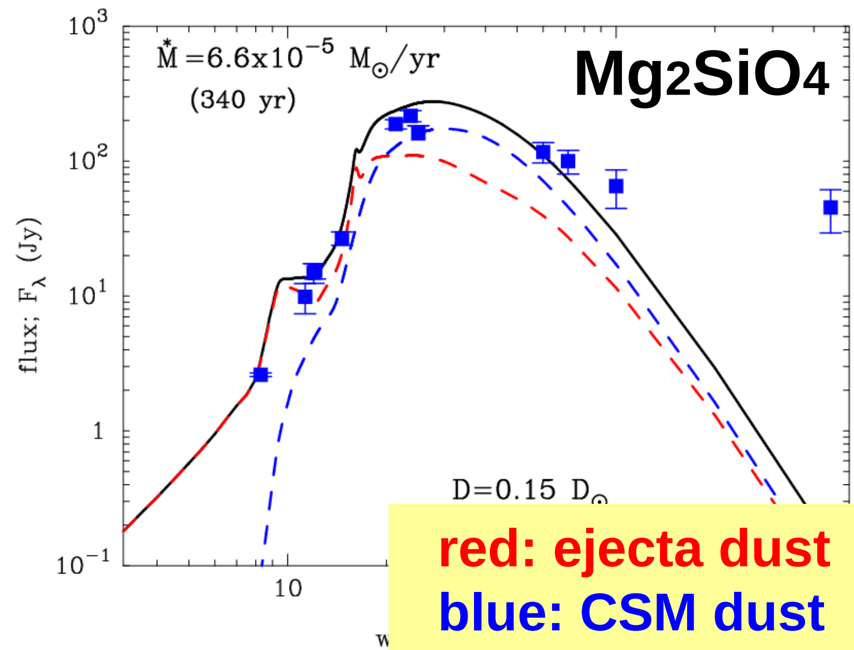
Data: Hines et al. (2004)
red: with SH
green: without SH

4-6. Contribution from circumstellar dust



- dust species
  - C and Mg_2SiO_4
- dust size distribution
  - f(a) ∝ a^-3.5
  - a_{min} = 0.001 μm
  - a_{max} = 0.5 μm
- M_C : M_{sil} = 3 : 7





red: ejecta dust
blue: CSM dust

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) Model of dust destruction and heating in Type IIb SNR to reproduce the observed SED of Cas A is

   $M_{d,eje}$ = 0.06 M_{sun}, $M_{d,ism}$ = 0.03-0.07 M_{sun}

   $dM/dt = 6.6 \times 10^{-5}$ Msun/yr

4) IR SED reflects the destruction and stochastic heating

   ➔ properties (size and composition) of dust

   ➔ density structure of circumstellar medium