Dust Formation in Various Types of Supernovae

Takaya Nozawa

(IPMU, University of Tokyo)

Collaborators;

T. Kozasa (Hokkaido Univ.)
K. Nomoto (IPMU)
K. Maeda (IPMU)
H. Umeda (Univ. of Tokyo)
N. Tominaga (Konan Univ./IPMU)
M. Tanaka (IPMU)
T. Suzuki (Univ. of Tokyo)
M. Limongi (INAF/IPMU)
H. Hirashita (ASIAA)
I. Sakon (Univ. of Tokyo)
T. Onaka (Univ. of Tokyo)
T. T. Takechi (Nagoya Univ.)
T. T. Ishi (Kyoto Univ.)
A. Habe (Hokkaido Univ.)
E. Dwek (NASA)
O. Krause (MPIA)

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

1-1. Introduction

SNe are important sources of interstellar dust?

- **Theoretical studies : 0.1-1 M_{sun} in Type II-P SNe**
  (Todini & Ferrara 2001; Nozawa et al. 2003)

  ➔ **0.1-1 M_{sun} of dust** per SN is required to form to explain a large content of dust at high-z galaxies
  (Morgan & Edmunds 2003; Dwek et al. 2007)

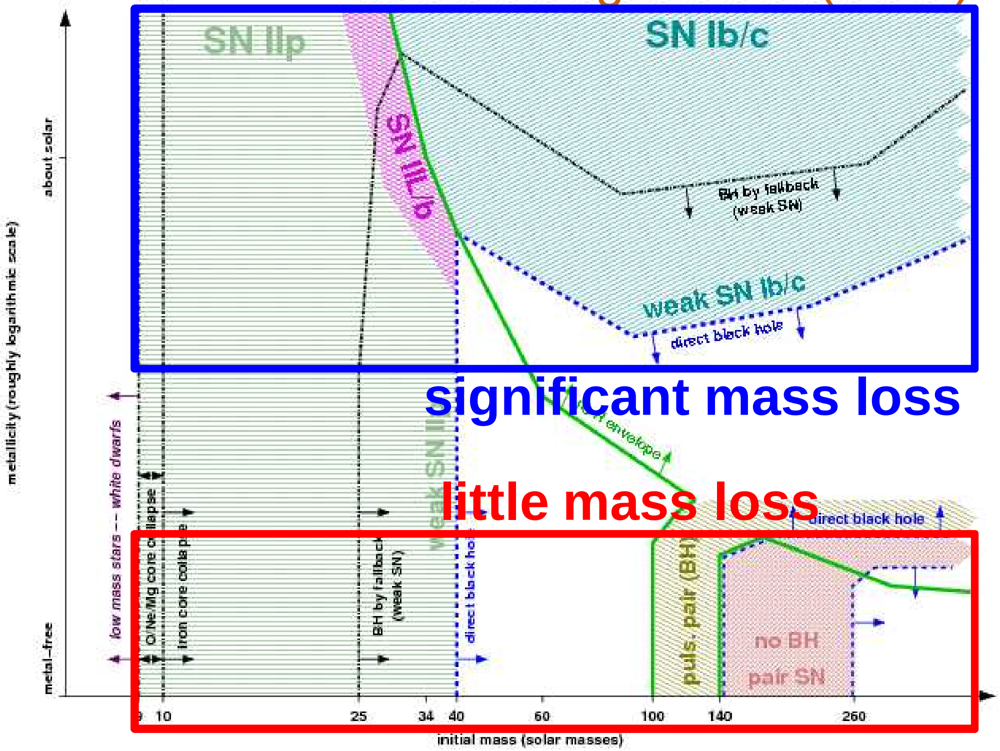
- **Observations of dust-forming SNe : < 10^{-2} M_{sun}**
  (e.g., Meikle et al. 2007, Kotak et al. 2009)

sophisticate radiation transfer model taking account of dust distribution in the ejecta to estimate dust mass
(Sugarmann et al. 2006; Ercolano et al. 2007)

how dust formation process depends on SN type?

1-2. Classification of supernovae

Heger et al. (2003)



At high (solar) metallicity

- **Type II-P SNe:**
  M_{ZAMS}=8-25 M_{sun}?
  massive H envelpe
- **Type IIb SNe:**
  M_{ZAMS} = 25-35 M_{sun}?
  very thin H-envelope
- **Type Ib/Ic SNe :**
  M_{ZAMS} > 35 M_{sun}?
  no H / He envelope

At low metallicity ($Z < 10^{-4} Z_{sun}$)

- **Type II-P SNe:**
  M_{ZAMS}=8-40 M_{sun}
- **pair-instability SNe:**
  M_{ZAMS}=140-260 M_{sun}

- **Type Ia SNe :**

thermonuclear explosion of C+O white dwarfs
$M_{pre\text{-}explosion}$ ~ 1.4 M_{sun}

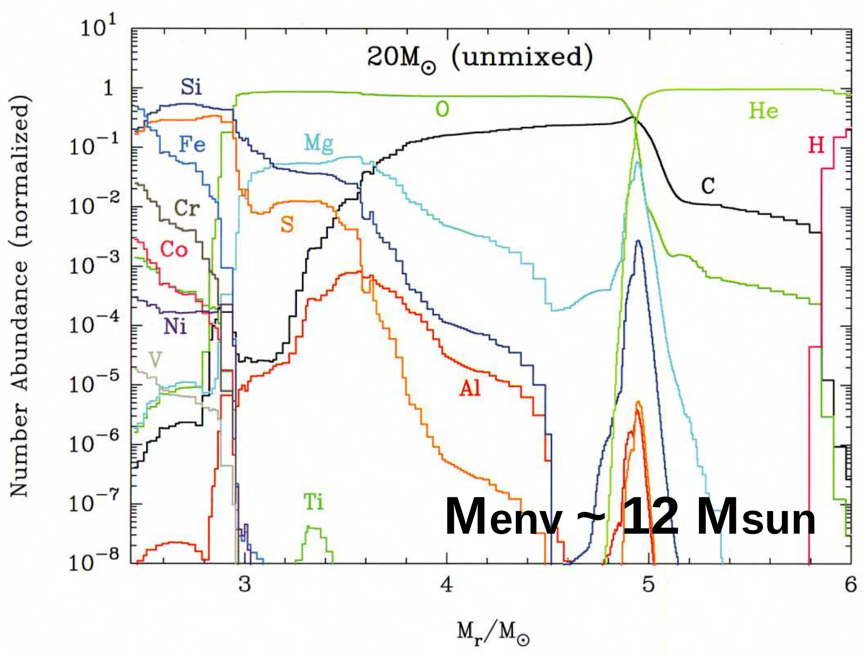
2-1. Dust formation in primordial SNe

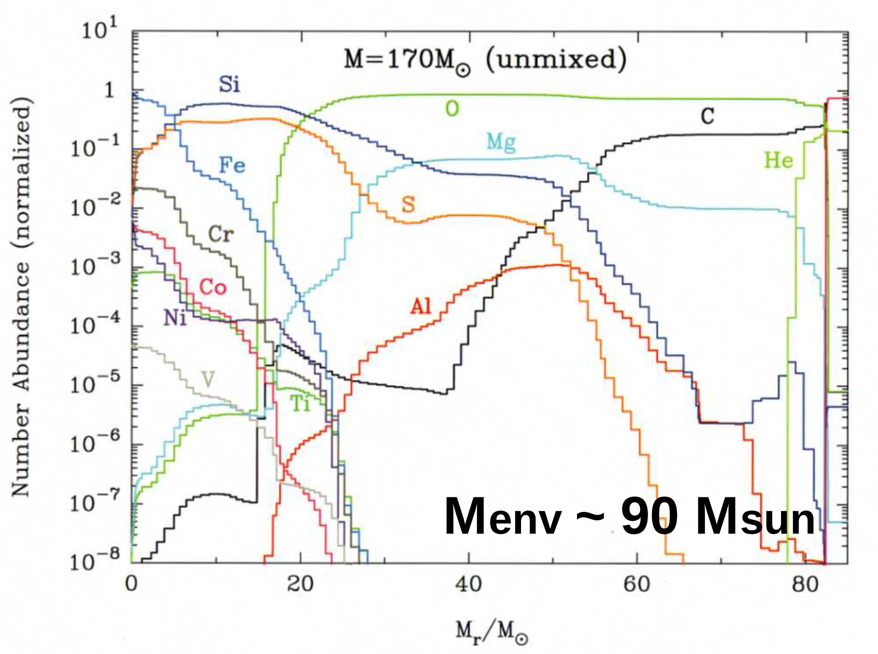
(Nozawa et al. 2003, ApJ, 598, 785)

- nucleation and grain growth theory (Kozasa & Hasegawa 1988)
- no mixing of elements within the He-core
- complete formation of CO and SiO, sticking probability=1

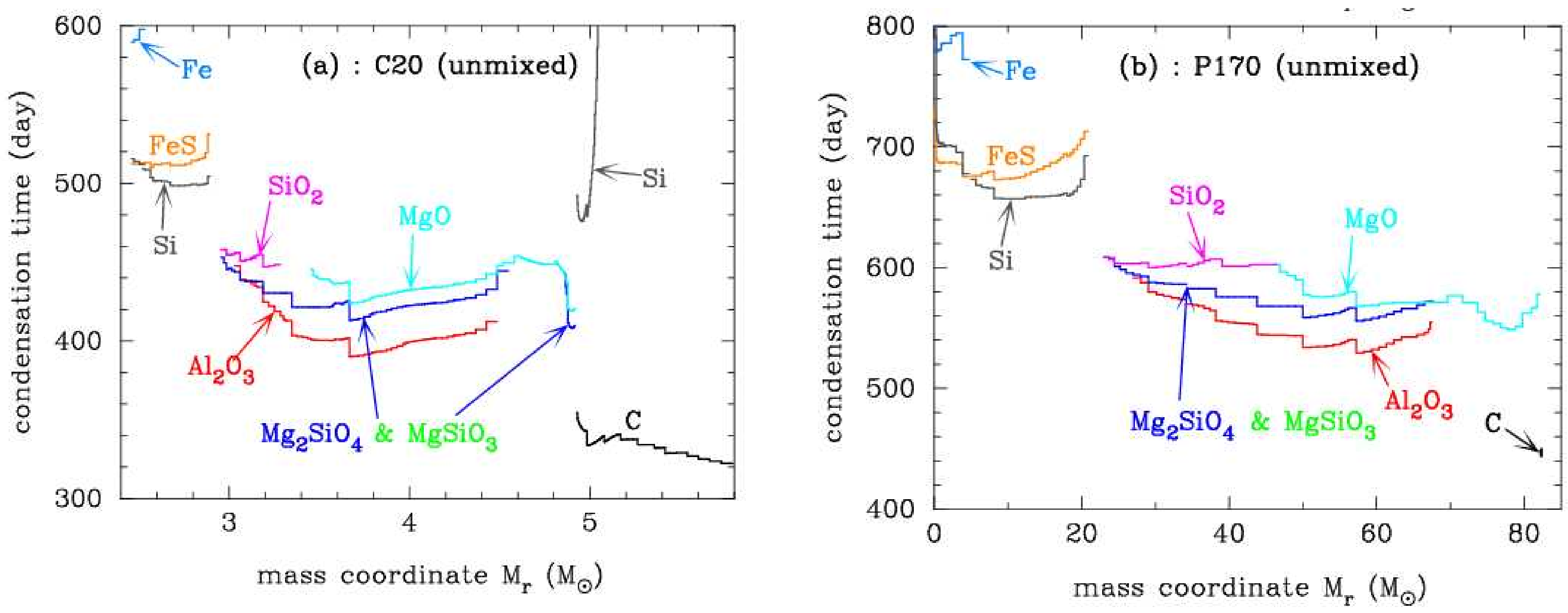
○ Population III SNe model (Umeda & Nomoto 2002)

- SNe II-P : M_{ZAMS} = 13, 20, 25, 30 Msun (E_{51}=1)
- PISNe : M_{ZAMS} = 170 Msun (E_{51}=20), 200 Msun (E_{51}=28)



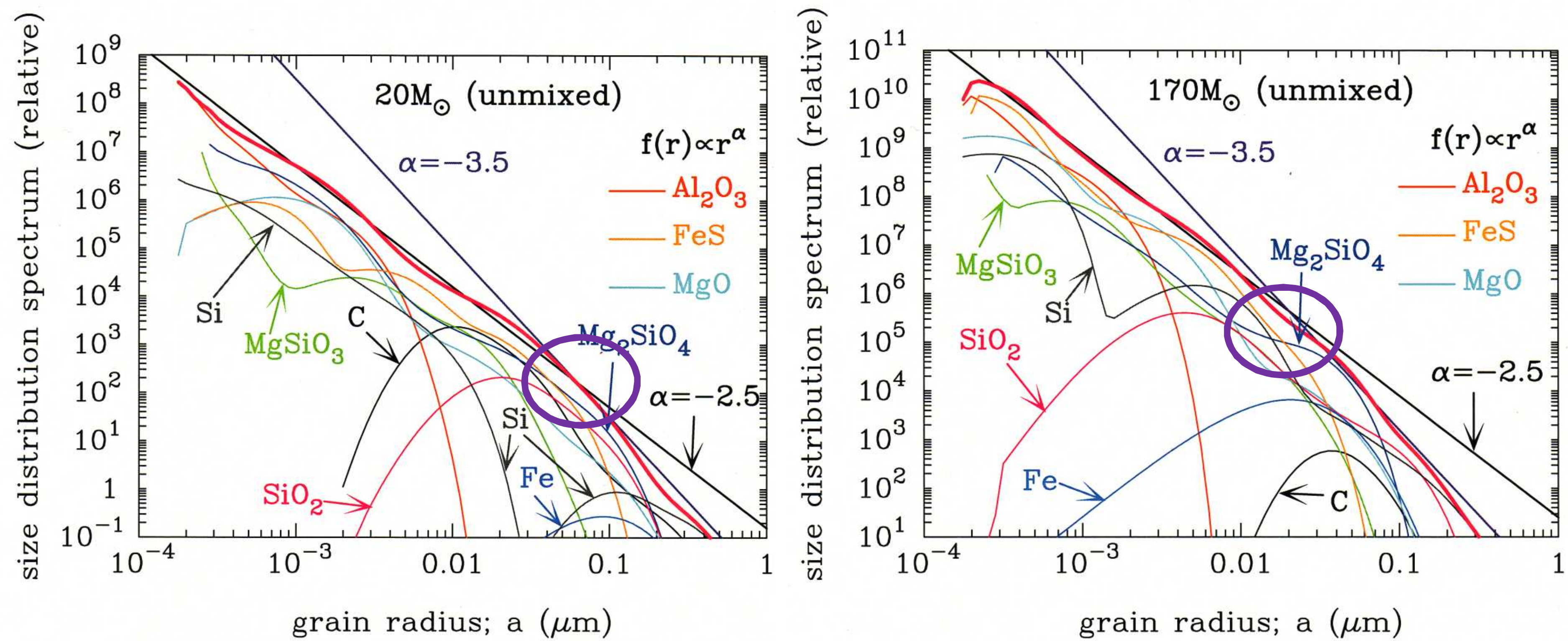


2-2. Dust formed in primordial SNe



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

2-3. Size distribution spectrum of dust



- grain radii range from a few A up to 1 μm
- average dust radius is smaller for PISNe than SNe II-P

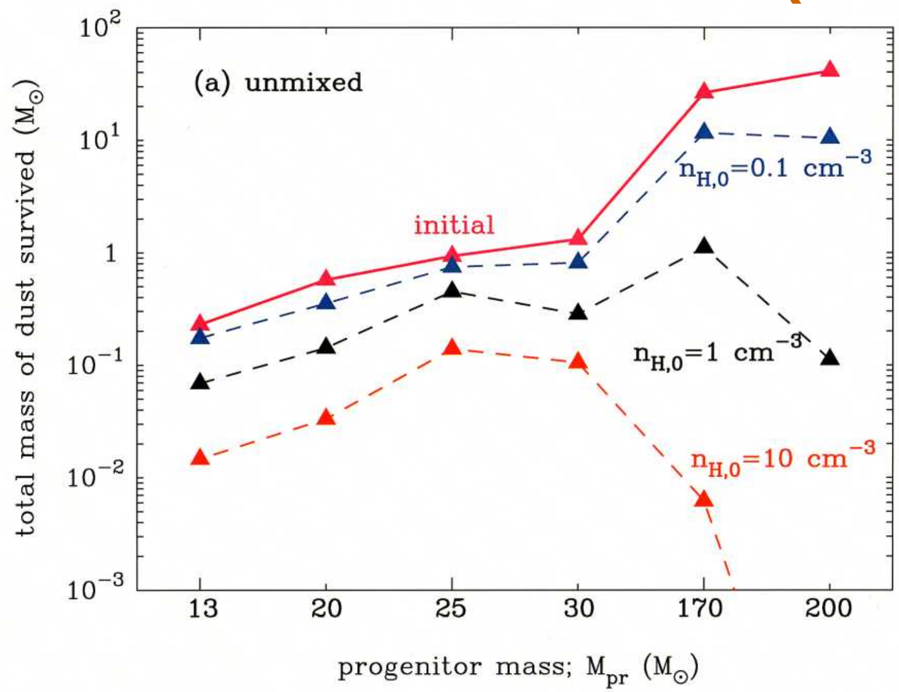
amount of newly formed dust grains

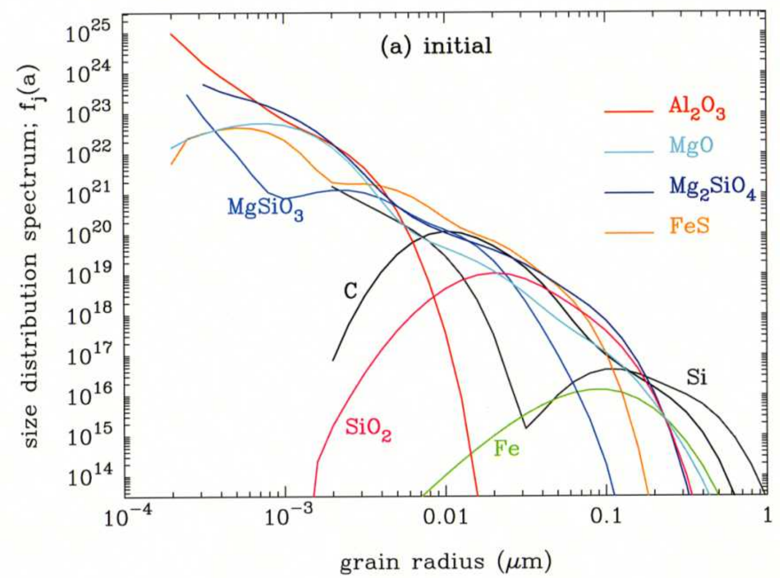
SNe II-P： M_{dust} = 0.1-1 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.2-0.3

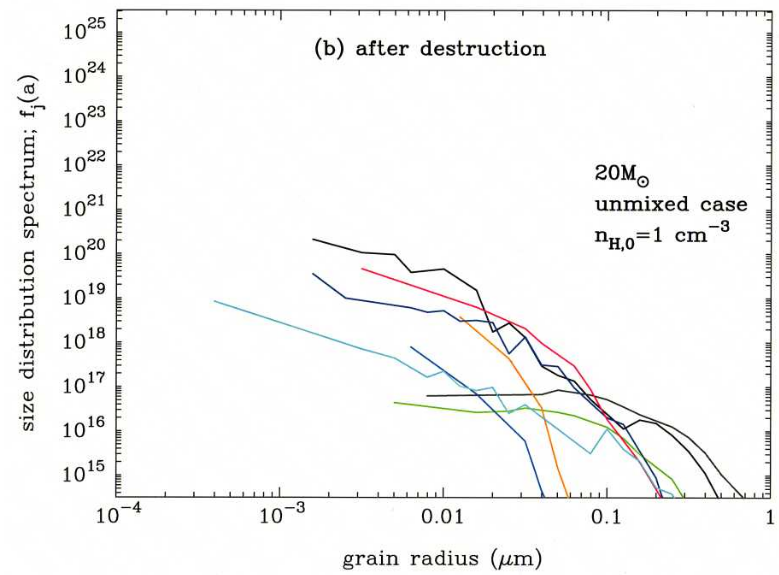
PISNe ： M_{dust} =20-40 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.3-0.4

2-4. Total mass and size of surviving dust

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





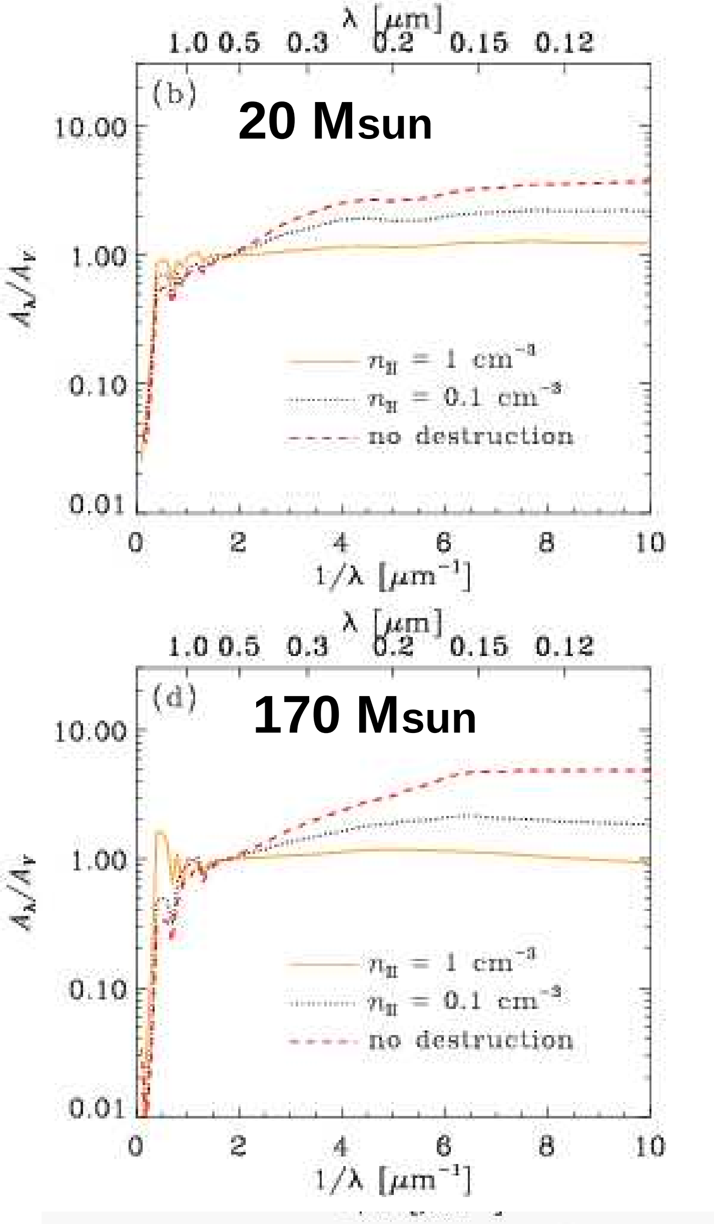


Total dust mass surviving the destruction in Type II-P SNRs; 0.08-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

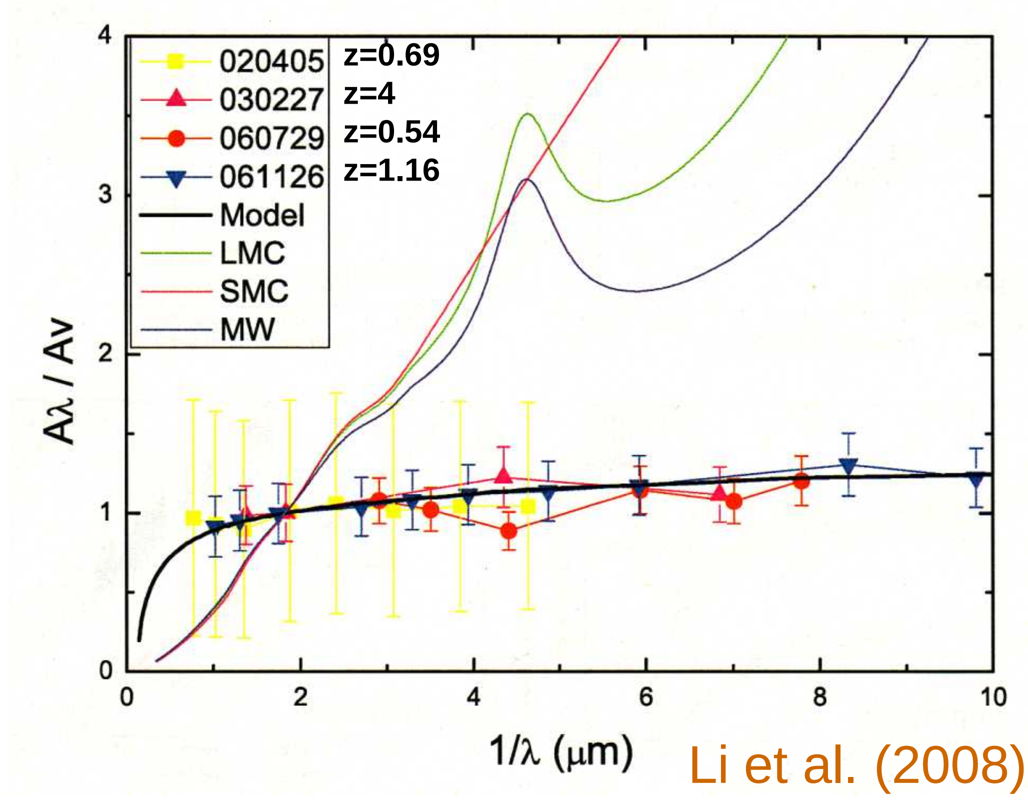
Size distribution of surviving dust is d<u>omimated by large grains (> 0.01 μm)</u>

2-5. Flattened extinction curves

(Hirashita, T. N., et al. 2008, MNRAS, 384, 1725)



flat extinction curve at high-z !



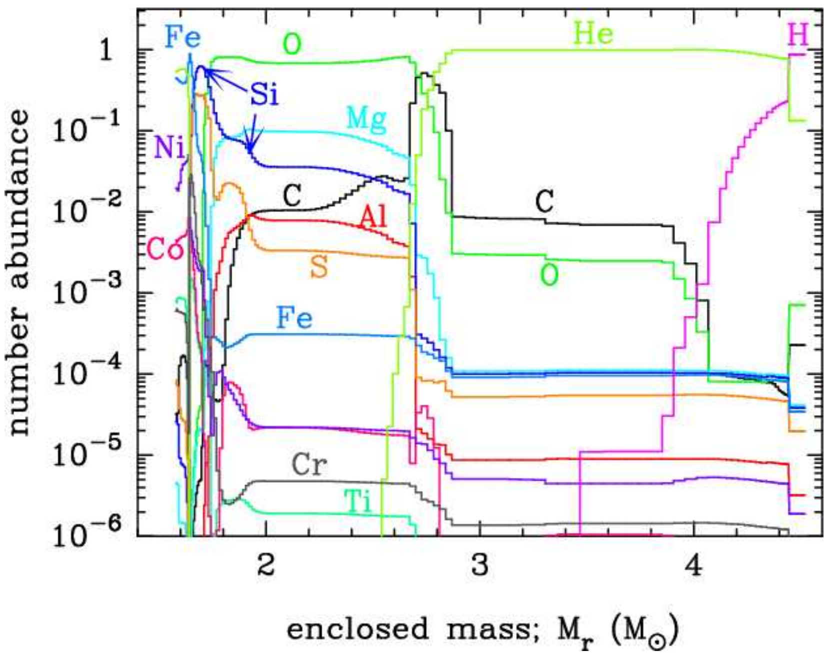
Li et al. (2008)

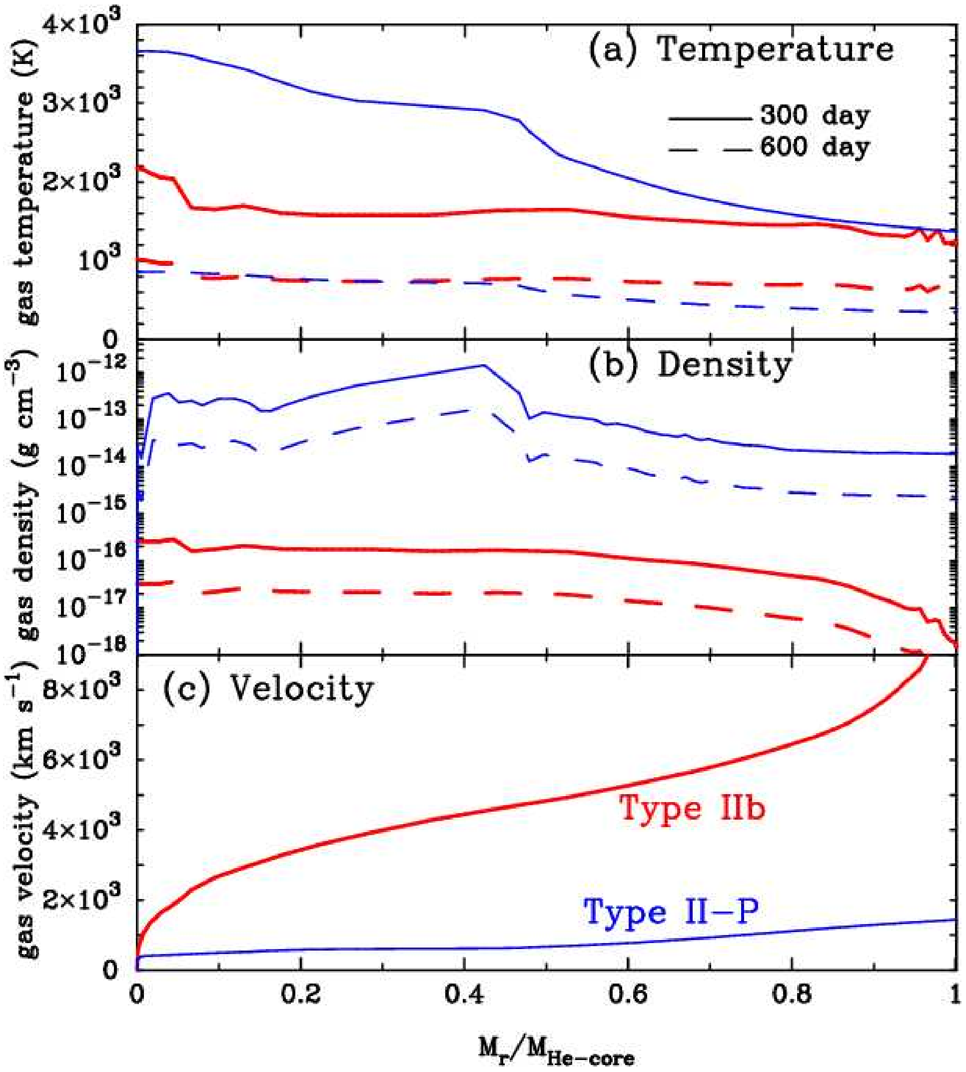
3-1. Dust formation in Type IIb SN

(Nozawa et al. 2010, ApJ, 713, 356)

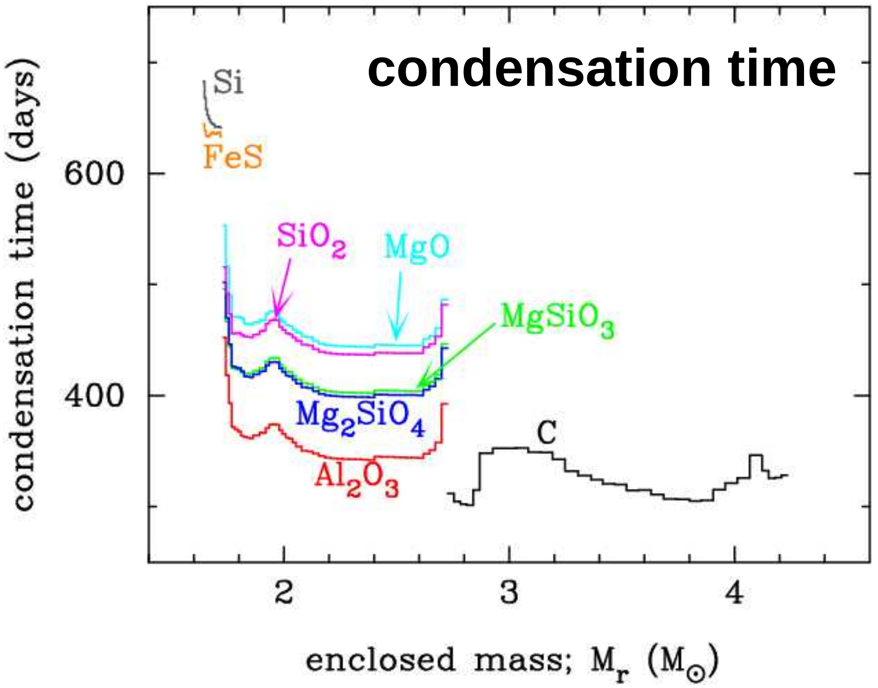
○ SN IIb model (SN1993J-like model)

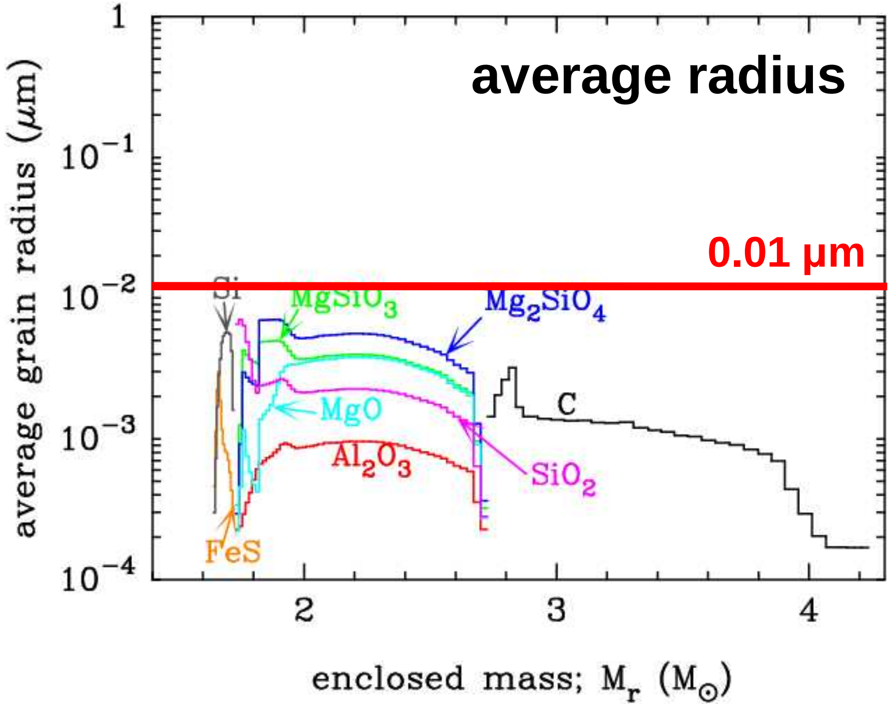
- **$M_{H\text{-env}}$ = 0.08 M_{sun}**
  M_{ZAMS} = 18 M_{sun}
  M_{eje} = 2.94 M_{sun}
- E_{51} = 1
- $M(^{56}Ni)$ = 0.07 M_{sun}





3-2. Dust formed in Type IIb SN



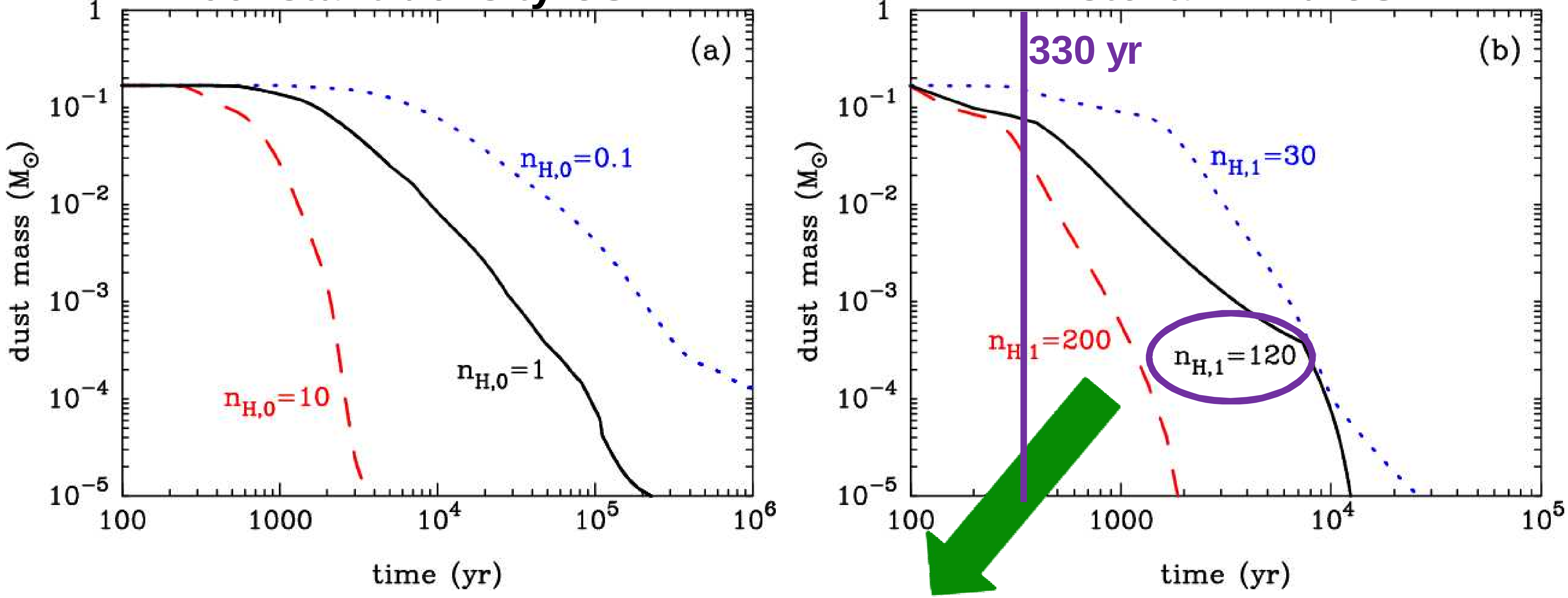


- condensation time of dust 300-700 d after explosion
- total mass of dust formed
  - 0.167 Msun in SN IIb
  - 0.1-1 Msun in SN II-P

- the radius of dust formed in H-stripped SNe is small
  - SN IIb without massive H-env → a_{dust} < 0.01 μm
  - SN II-P with massive H-env → a_{dust} > 0.01 μm

3-3. Destruction of dust in Type IIb SNR

constant-density CSM **stellar-wind CSM**



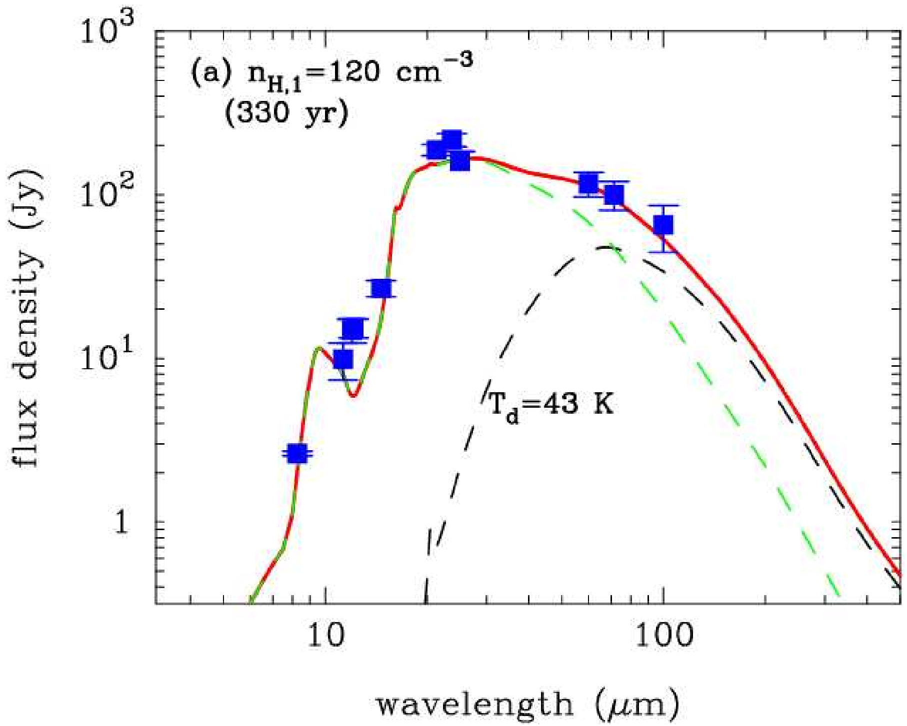
$n_{H,1}$ = 30, 120, 200 /cc
➔ dM/dt = 2.0, 8.0, 13x10^{-5} M_{sun}/yr for v_w=10 km/s

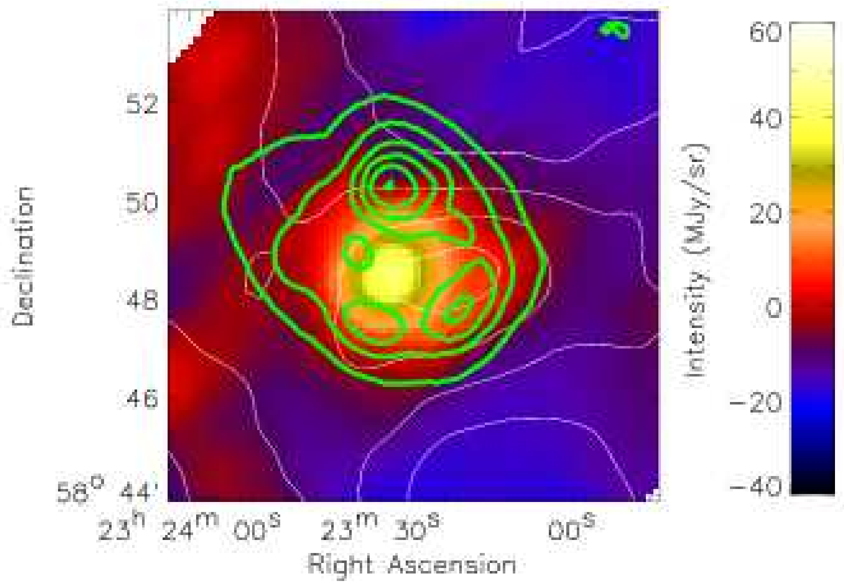
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

➔ small radius of newly formed dust

➔ early arrival of the reverse shock at the He core

3-4. Comparison with observations of Cas A





Sibthorpe et al. 2009

observed IR SED can be well reproduced !

↑

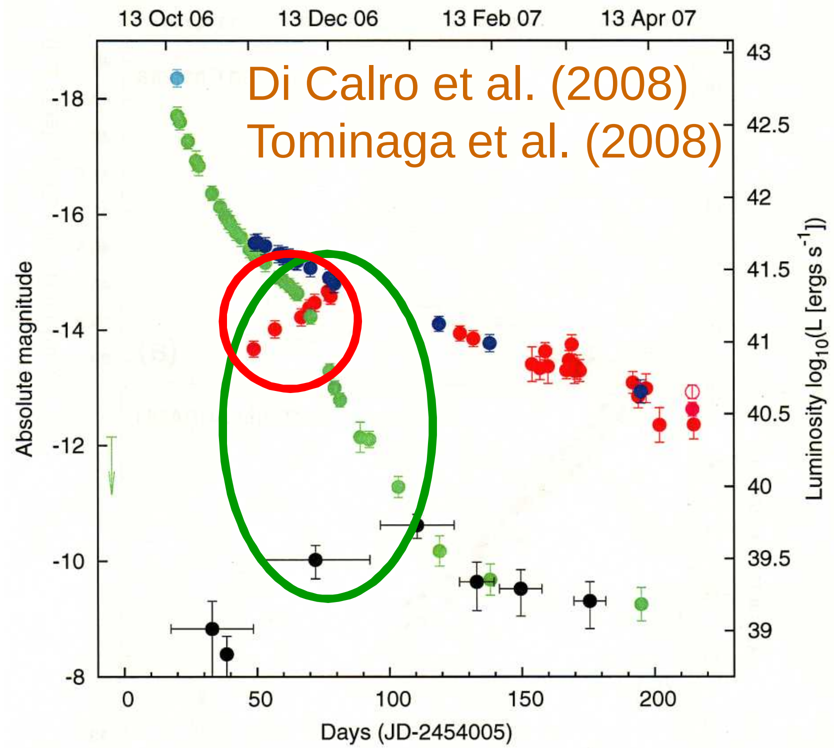
- $M_{d,warm}$ ~ 0.008 M_{sun}
- $M_{d,cool}$ ~ 0.07 M_{sun} with T_{dust} ~ 40 K

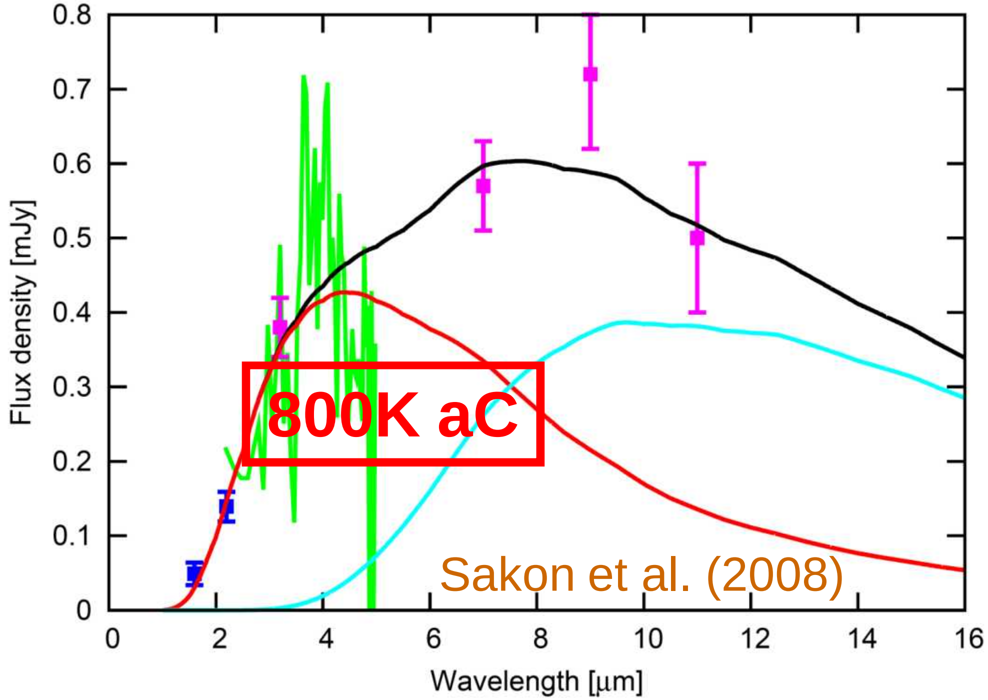
AKARI reduced 90μm image
➔ centrally peaked cool dust component

↓

$M_{d,cool}$ = 0.03-0.06 M_{sun} with T_{dust} = 33-41 K

4-1. Peculiar dust-forming SN : 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

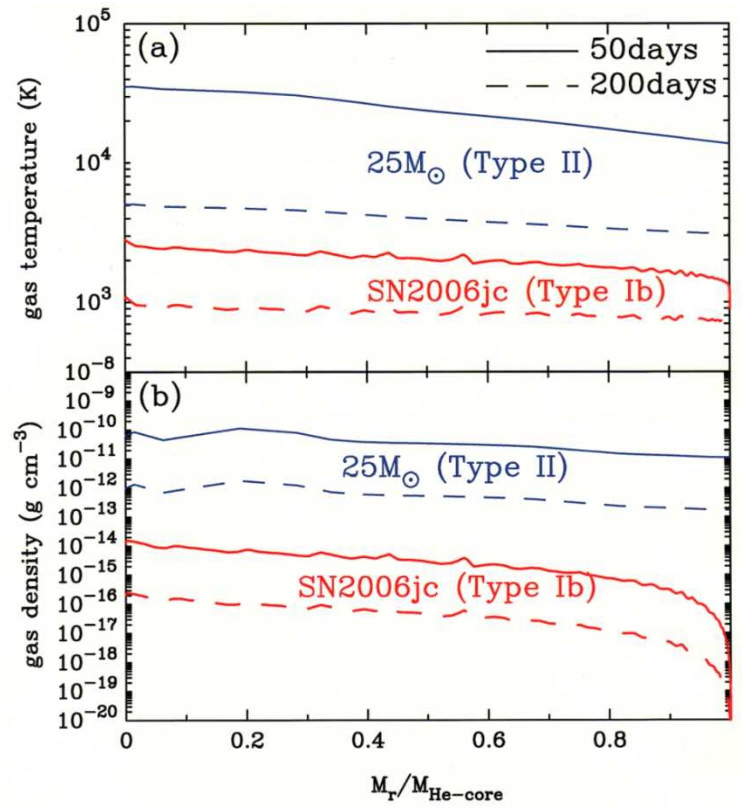
- at 75-102 days
  ➔ C grains of ~1600 K
- at 220 days
  ➔ C grains of 800 K

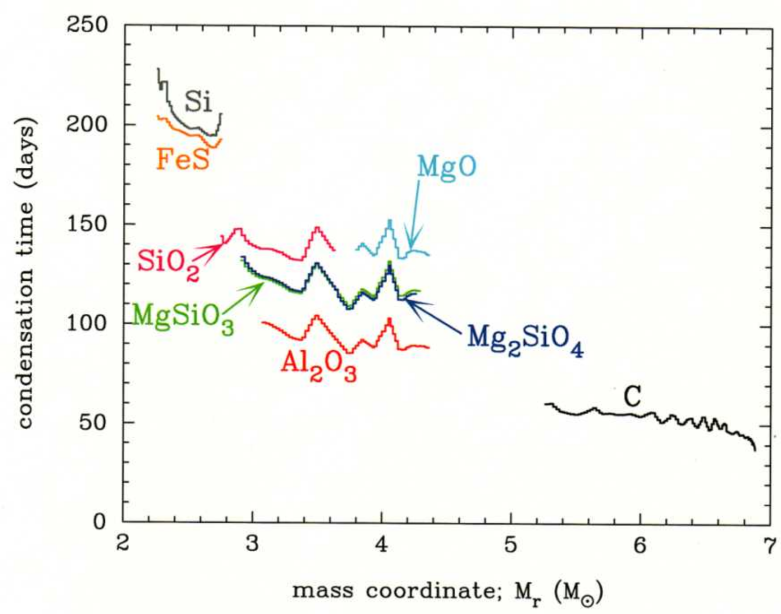
4-2. Dust formation in Type Ib SN : SN 2006jc

(Nozawa et al. 2008, ApJ, 684, 1343)

○ SN 2006jc model (Tominaga et al. 2008)

- **M_{eje} = 4.9 M_{sun}** (M_{ZAMS} = 40 M_{sun})
- **E_{51} = 10** (hypernova-like)
- M(^{56}Ni) = 0.22 M_{sun}

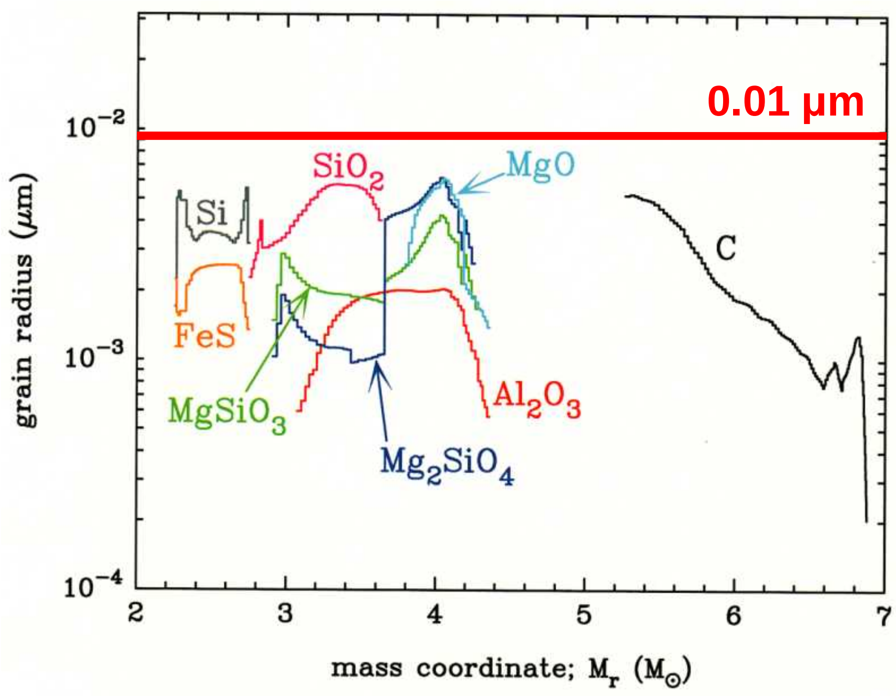


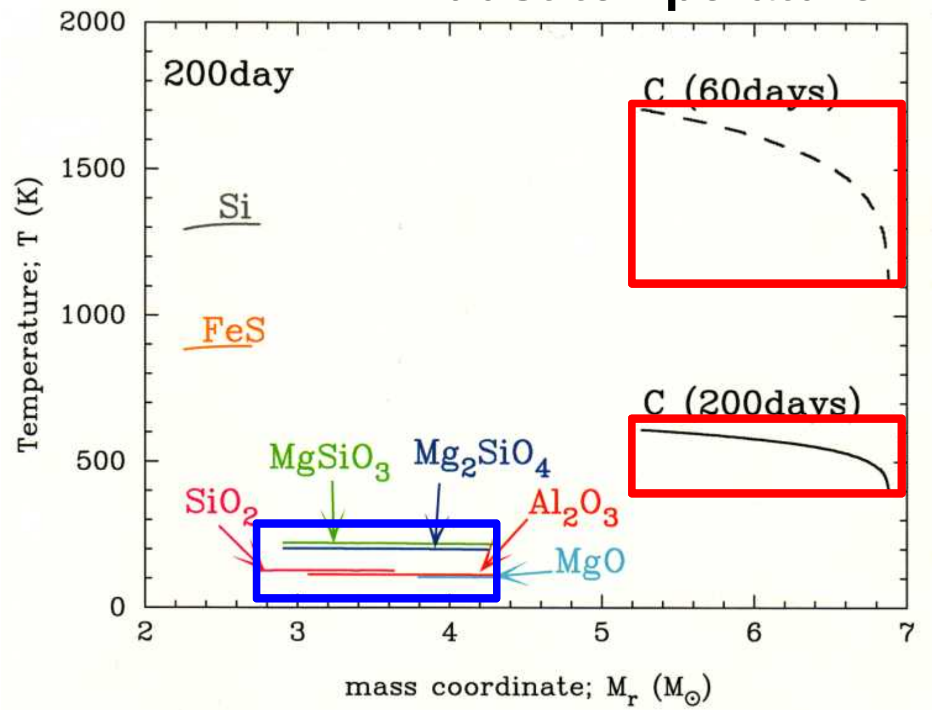


The quick decrease of gas temperature

➔ C grains can form at 40-60 days in outermost ejecta

4-3. Average radius and temperature of dust

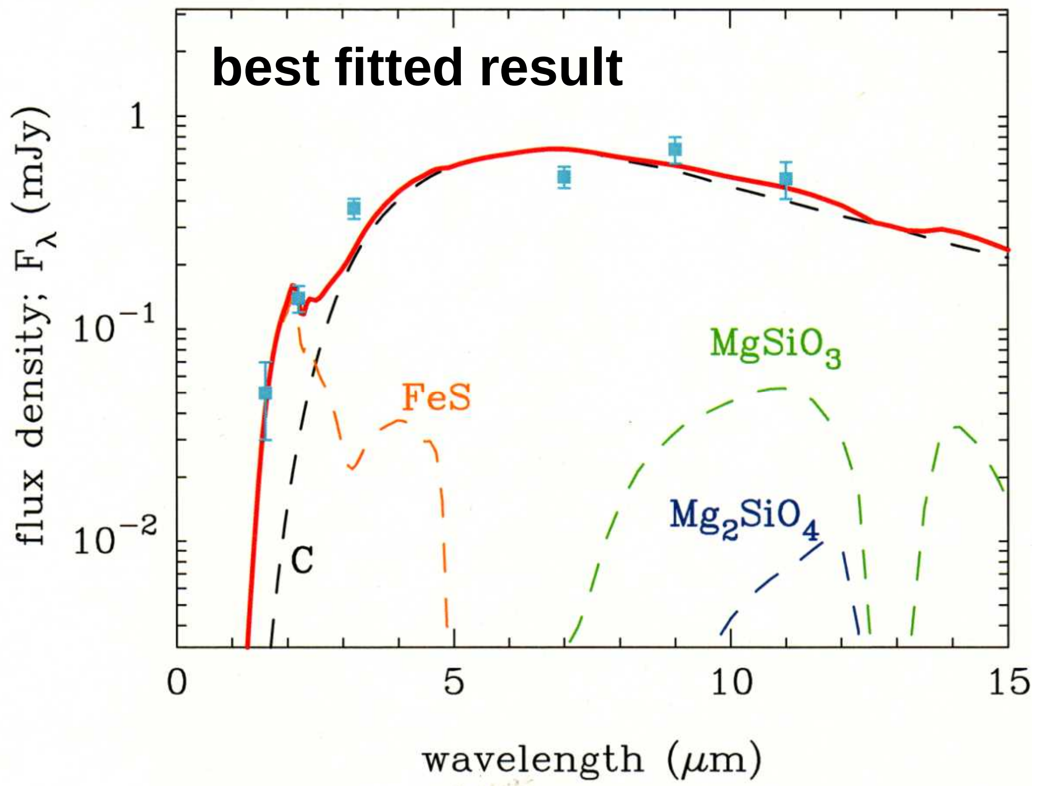




– Average radius of dust is **smaller than 0.01 μm** because of the low gas density at dust formation

– Temperature of C grains
- at 60 days → 1200-1700 K
- at 200 days → 500-600 K

4-4. IR spectral energy distribution



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

- **fitting of IR SED**

  C grains ➔ 5.6×10^{-4} Msun   FeS grains ➔ 2×10^{-3} Msun

- **mass of cold silicates and oxides cannot be constrained**

  optical thin case can underestimate dust mass

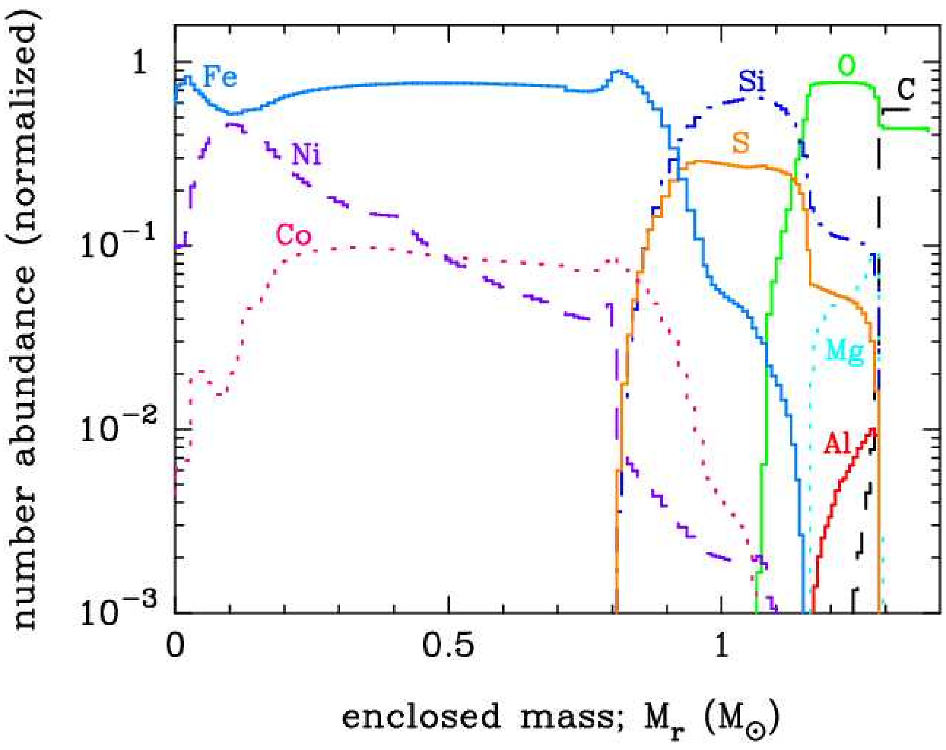
5-1. Dust formation in Type Ia SN : W7 model

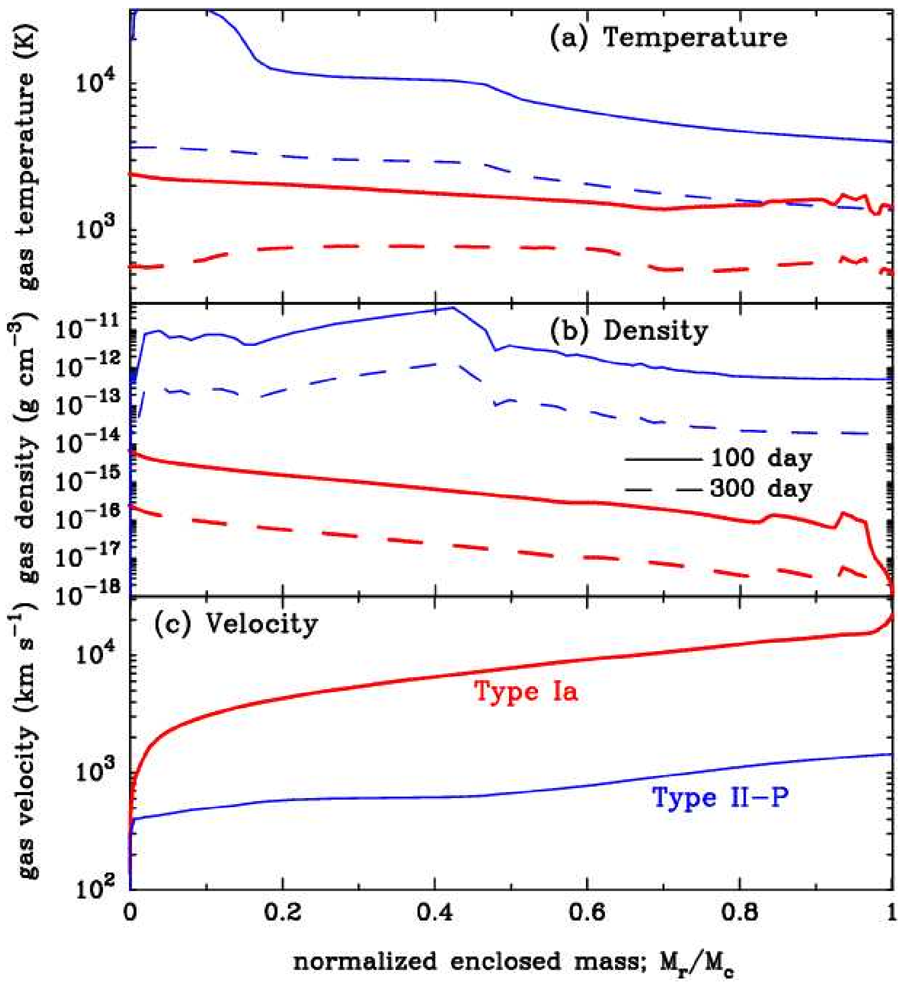
(Nozawa et al. in preparation)

○ Type Ia SN model

W7 model (C-deflagration) (Nomoto et al. 1984)

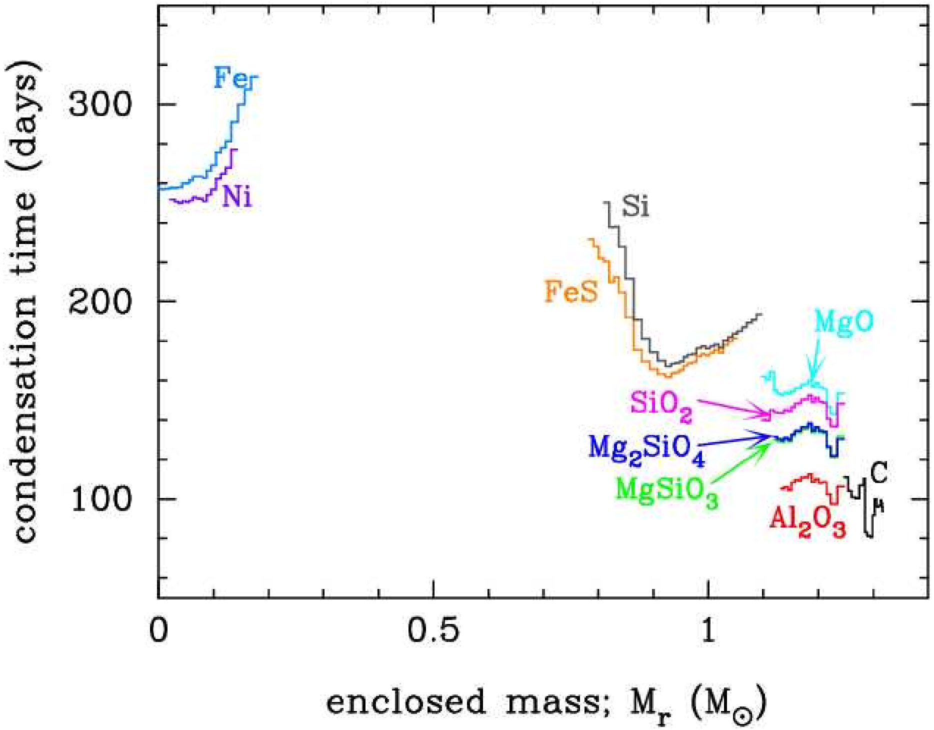
- **M_{eje} = 1.38 Msun**
- E_{51} = 1.3
- **$M(^{56}Ni)$ = 0.56 Msun**



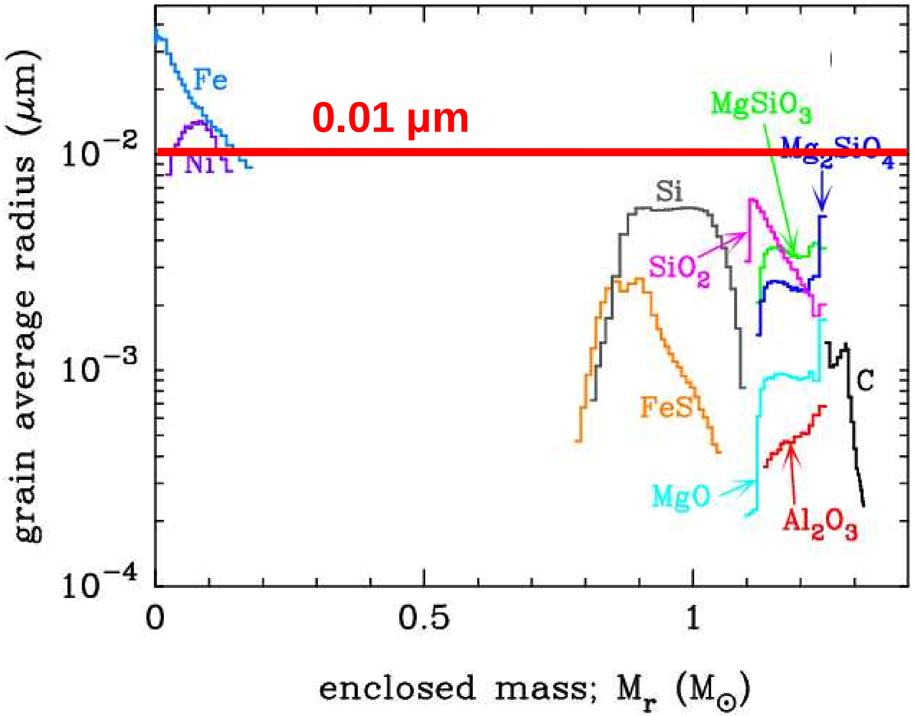


5-2. Dust formation in Type Ia SN

condensation time



average radius



- **condensation time: 100-300 days**
- **average radius of other dust species : < 0.01 μm**
  because of low density of gas in the expanding ejecta
- **Fe grains cannot condense significantly < 10^{-4} Msun**

5-3. Mass of dust formed in Type Ia SN

Mass of major dust

~~C~~	~~: 0.03 M_{sun}~~
Silicate	: 0.03 M_{sun}
~~FeS~~	~~: 0.02 M_{sun}~~
~~Si~~	~~: 0.06 M_{sun}~~
Total	: 0.14 M_{sun}

- early formation of dust at 100-300 days
- high M(56Ni) of ~0.6 M_{sun}

➔ dust formation can be affected by strong radiation field in the ejecta

➔ Si and FeS are inhibited

There is no evidence that C are detected in SN Ia

If we ignore C grains in SN Ia

M_{dust} ~ 0.03 M_{sun}, consisting of silicate in Type Ia

Summary of this talk

- **Type II SNe and PISNe**

  Average grain radii are larger than 0.01 μm

  ➔ primordial SNe may be important sources of dust

- **Type IIb, Type Ib/Ic, and Type Ia SNe**

  Average grain radii are smaller than 0.01 μm

  ➔ envelope-stripped SNe may not be major sources of dust

in future work

mixing of elements, formation of molecules such as CO and SiO, sticking probability of atom, effects of radiation field in the ejcta, non-spherical and/or clumpy structure …