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Properties of dust ejected from supernovae

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Contents:

- Introduction of dust formation in SNe
- Properties of dust from theoretical works on dust formation and processing in SNe
- Observations of dust composition and size in SNe

1-1. Introduction

○ Supernovae (SNe) are major sources of dust?

- abundant metal (metal : N > 5)
- low temperature (T < ~2000 K)
- high density (n_i > ~10^6 cm^{-3})

➔

- mass-loss winds of AGB stars
- expanding ejecta of SNe

- contribution of dust mass from AGB stars and SNe

N(SNe) / N(AGB stars) ~ 0.05-0.1 (Salpeter IMF)

M_{dust} = 0.01-0.05 M_{sun} per AGB star (e.g., Zhukovska & Gail 2008)

M_{dust} = 0.1-1.0 M_{sun} per SN (e.g., Nozawa+2003, 2007)

- huge amounts of dust grains (>10^8 M_{sun}) at redshift z > 5

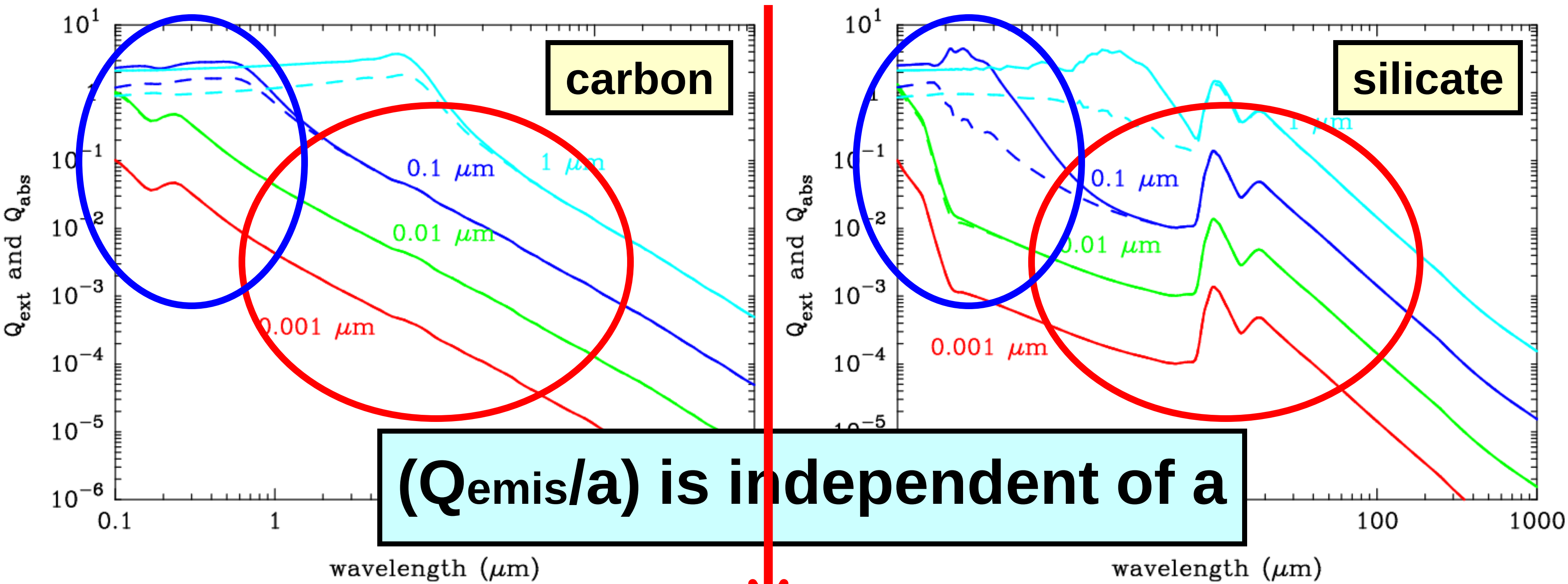
➔ 0.1 M_{sun} of dust per SN is needed to be ejected (Dwek+2007)

what composition, size, and mass of dust are ejected by SNe?

1-2. Emission and absorption efficiency of dust

○ Thermal radiation from a dust grain

$$F_\lambda \propto 4\pi a^2 \, Q_{emis}(a,\lambda) \, \pi B_\lambda(T_{dust})$$ # $Q_{emis} = Q_{abs}$

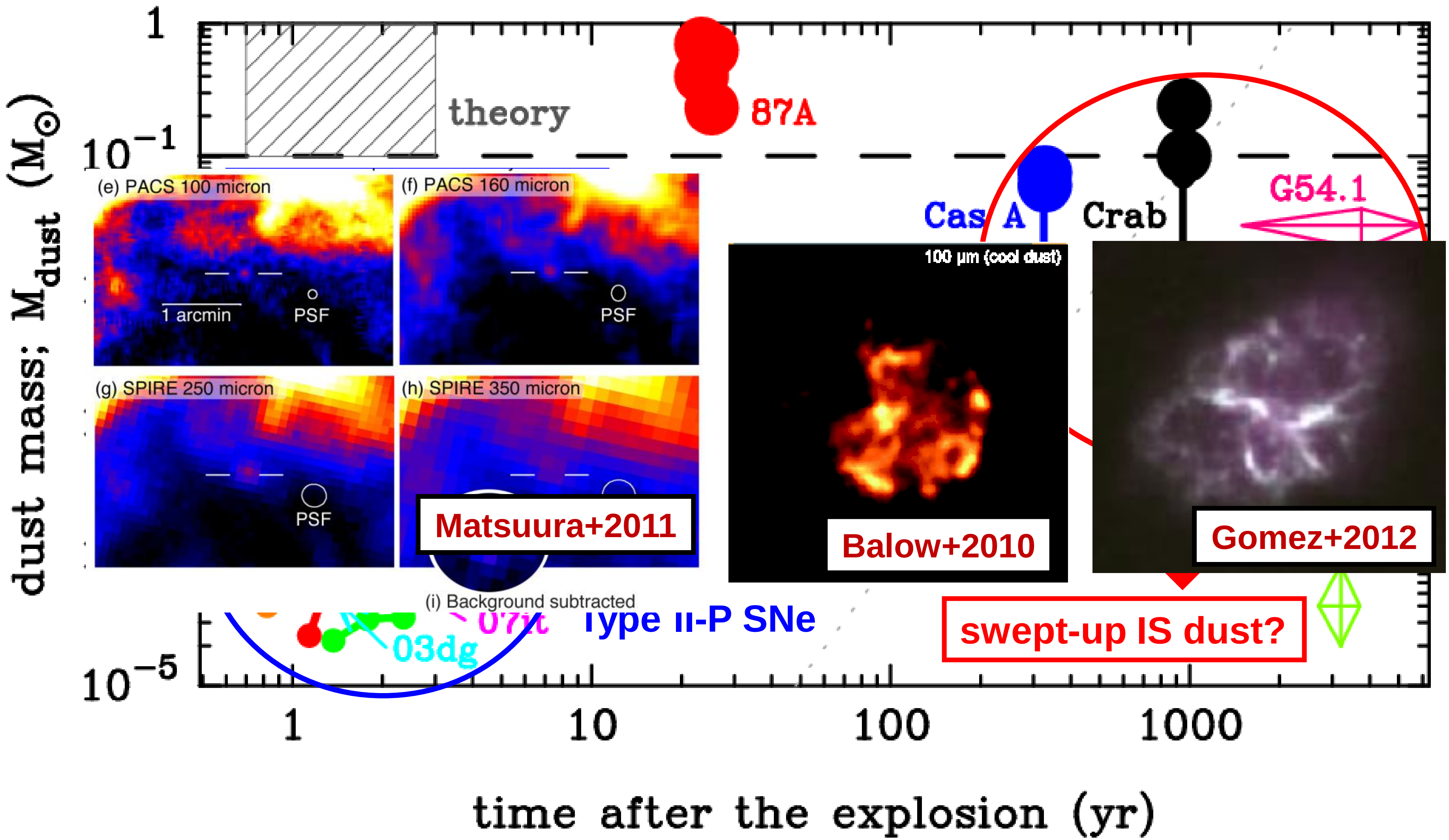


$$F_\lambda \propto 4\pi a^3 \, (Q_{emis}[a,\lambda]/a) \, \pi B_\lambda(T_{dust})$$

$$\propto 4 \, M_{dust} \, \kappa_{emis}(\lambda) \, \pi B_\lambda(T_{dust})$$

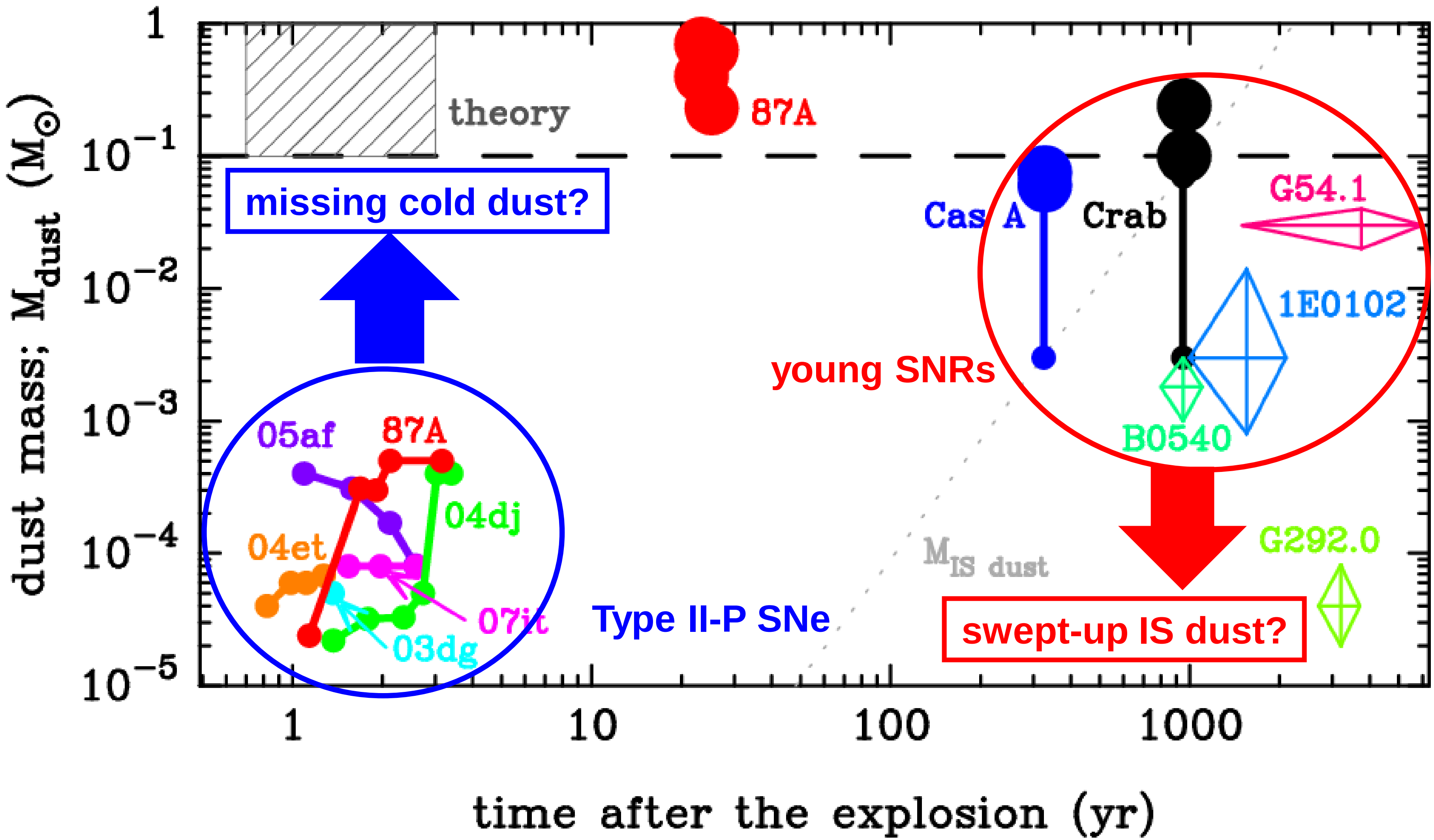
➔ IR emission is derived given M_{dust}, κ_{abs}, and T_{dust}

1-3. Summary of observed dust mass in CCSNe



Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe

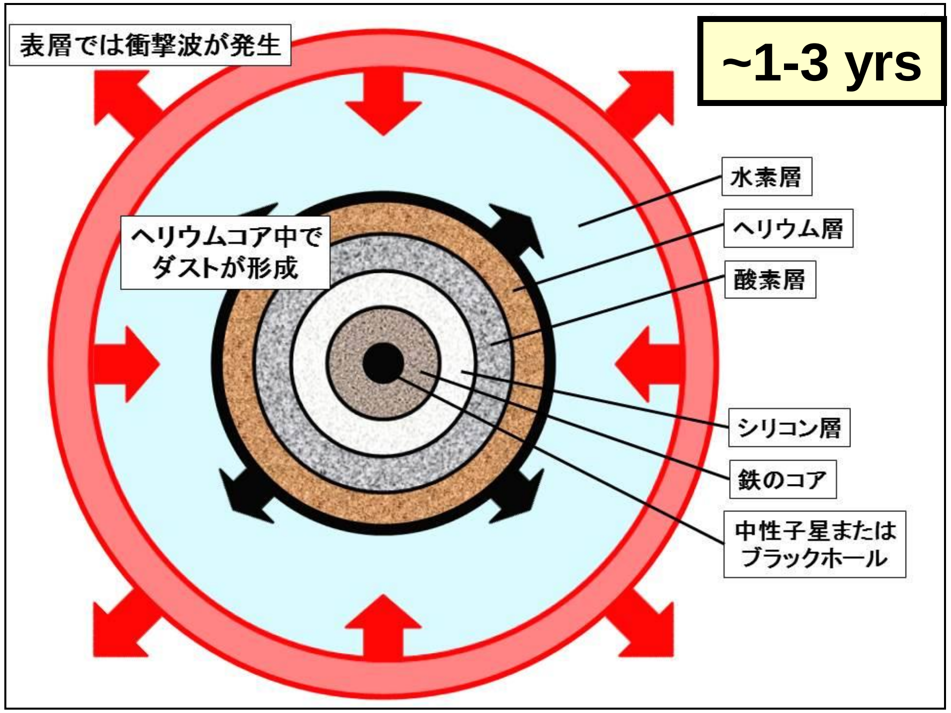
1-3. Summary of observed dust mass in CCSNe

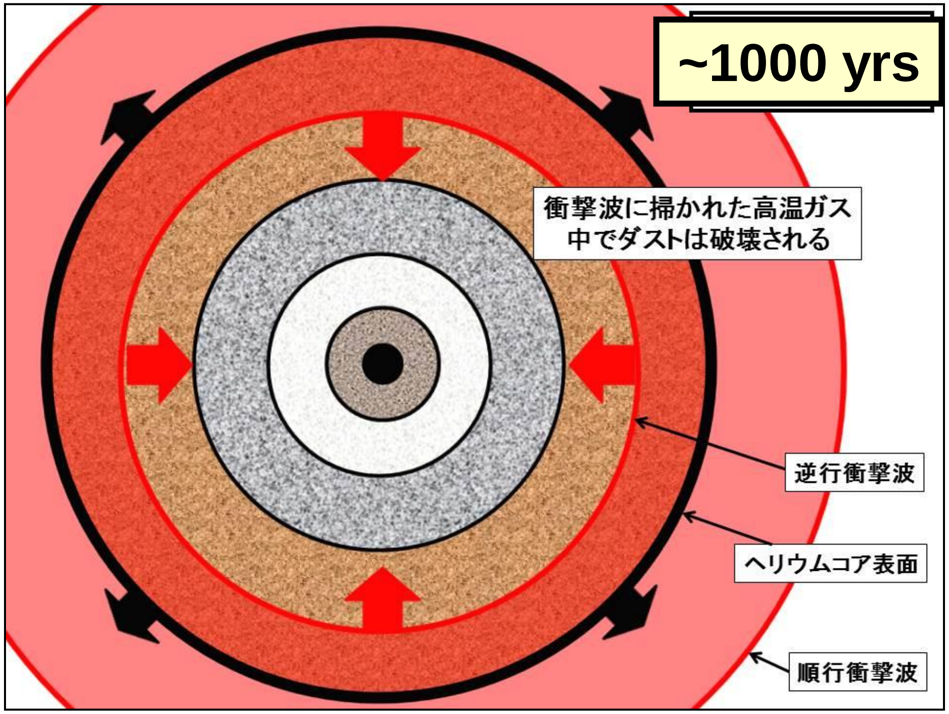


There are increasing pieces of evidence that massive dust in excess of 0.1 Msun is formed in the ejecta of SNe

1-4. Formation and processing of dust in SNe

Nozawa 2014, Astronomical Herald





Destruction efficiency of dust grains by sputtering in the reverse shocks depends on their initial size

The size of newly formed dust is determined by physical condition (gas density and temperature) of SN ejecta

1-5. Achievement and issues on SN dust

○ What we have understood is

Core-collapse supernovae can produce a large amount of dust in excess of ~0.1 M_{sun} in the expanding ejecta

⬇

○ What we have not understood yet is

1) when the observed massive dust was formed?

➜ Cause of difference in dust mass in MIR and FIR

2) What composition and size distribution of dust are?

➜ Critical to the yield of dust finally ejected from SNe

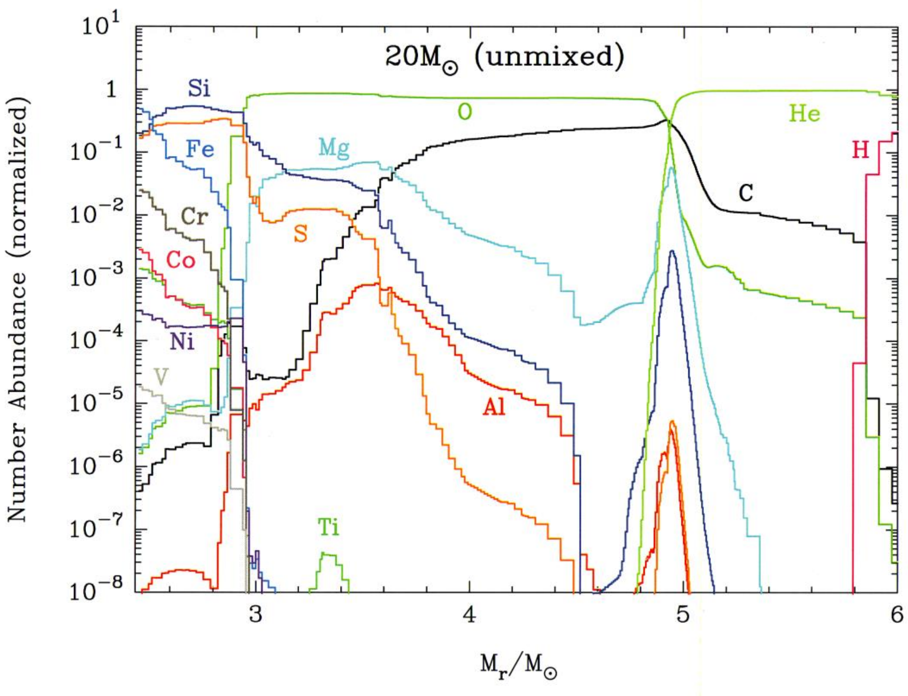
2. Theoretical works on formation and processing of dust in SNe

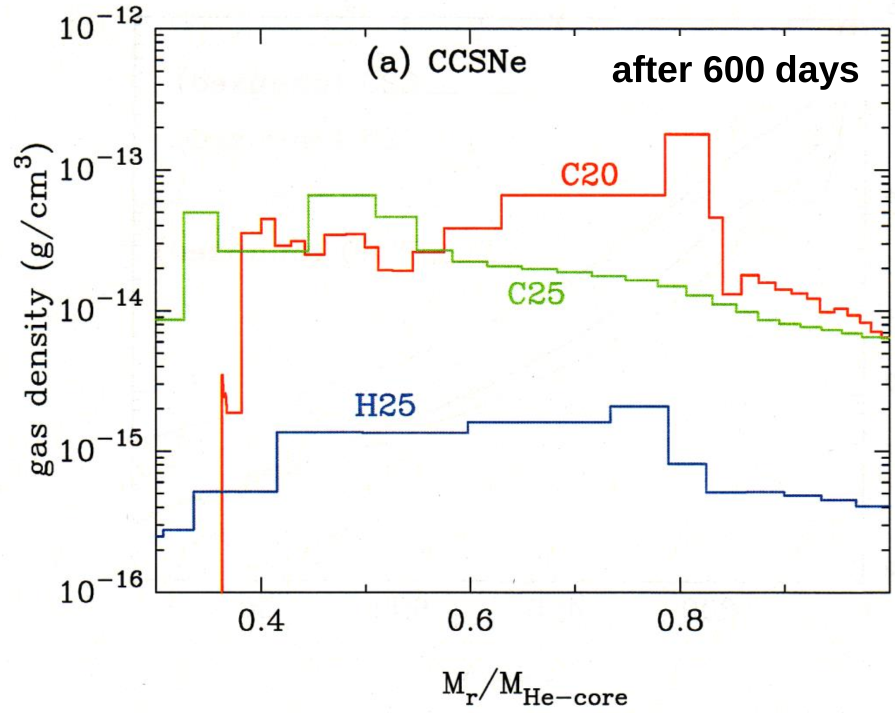
2-1. Dust formation in Type II-P SNe

Nozawa+2003, ApJ, 598, 785

○ SN model (Population III SNe) (Umeda & Nomoto 2002)

- SNe II : M_{ZAMS} = 13, 20, 25, 30 M_{sun} (E_{51}=1)





- layered elemental distribution in the metal-rich He core
- no mixing of elements within the He-core
- gas density: ρ ~ 10^{-14}-10^{-13} g/cm3 ➜ n ~ 10^8-10^{10} /cm3

2-2-1. Grain species considered in this study

○ dust formation theory

- nucleation
- grain growth

taking account of chemical reaction at condensation

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
$Fe_{(s)}$	$Fe_{(g)} \rightarrow Fe_{(s)}$
$FeS_{(s)}$	$Fe_{(g)} + S_{(g)} \rightarrow FeS_{(s)}$
$Si_{(s)}$	$Si_{(g)} \rightarrow Si_{(s)}$
$Ti_{(s)}$	$Ti_{(g)} \rightarrow Ti_{(s)}$
$V_{(s)}$	$V_{(g)} \rightarrow V_{(s)}$
$Cr_{(s)}$	$Cr_{(g)} \rightarrow Cr_{(s)}$
$Co_{(s)}$	$Co_{(g)} \rightarrow Co_{(s)}$
$Ni_{(s)}$	$Ni_{(g)} \rightarrow Ni_{(s)}$
$Cu_{(s)}$	$Cu_{(g)} \rightarrow Cu_{(s)}$
$C_{(s)}$	$C_{(g)} \rightarrow C_{(s)}$
$SiC_{(s)}$	$Si_{(g)} + C_{(g)} \rightarrow SiC_{(s)}$
$TiC_{(s)}$	$Ti_{(g)} + C_{(g)} \rightarrow TiC_{(s)}$
$Al_2O_{3(s)}$	$2Al_{(g)} + 3O_{(g)} \rightarrow Al_2O_{3(s)}$
$MgSiO_{3(s)}$	$Mg_{(g)} + SiO_{(g)} + 2O_{(g)} \rightarrow MgSiO_{3(s)}$
$Mg_2SiO_{4(s)}$	$2Mg_{(g)} + SiO_{(g)} + 3O_{(g)} \rightarrow Mg_2SiO_{4(s)}$
$SiO_{2(s)}$	$SiO_{(g)} + O_{(g)} \rightarrow SiO_{2(s)}$
$MgO_{(s)}$	$Mg_{(g)} + O_{(g)} \rightarrow MgO_{(s)}$
$Fe_3O_{4(s)}$	$3Fe_{(g)} + 4O_{(g)} \rightarrow Fe_3O_{4(s)}$
$FeO_{(s)}$	$Fe_{(g)} + O_{(g)} \rightarrow FeO_{(s)}$

2-2-2. Nucleation rate

Steady-state nucleation rate: Js

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

Supersaturation ratio: S

$$\ln S = \ln \left(\frac{p_1}{\mathring{p}_1} \right) = -\frac{1}{kT} \left(\mathring{g}_s - \mathring{g}_1 \right) + \ln \left(\frac{p_1}{p_0} \right)$$

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

2-2-3. Basic equations for dust formation

- **Equation of mass conservation**

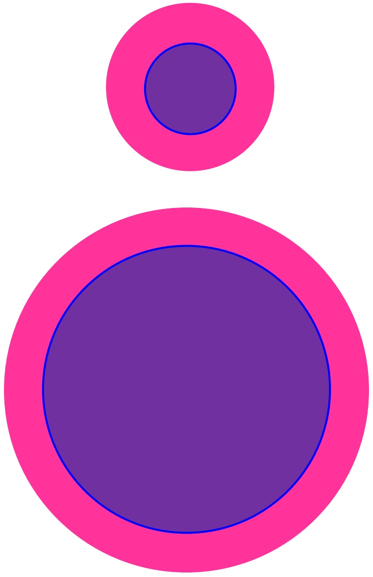
$$c_{10} - c_1 = \int_{t_0}^{t} J_{n_*}(t') \frac{a^3(t,t')}{a_0^3} dt',$$

- **Equation of grain growth**

$$\frac{da}{dt} = s\Omega_0 \left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S}\right),$$

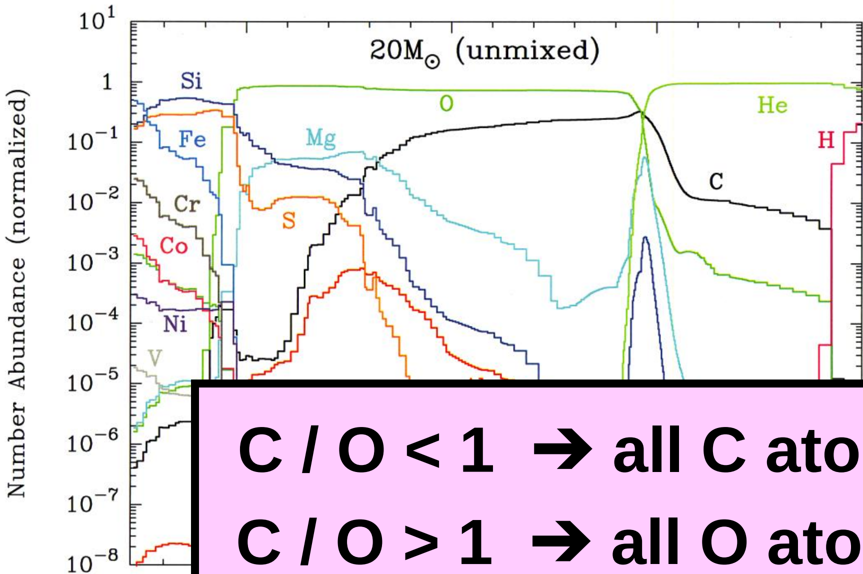
↑

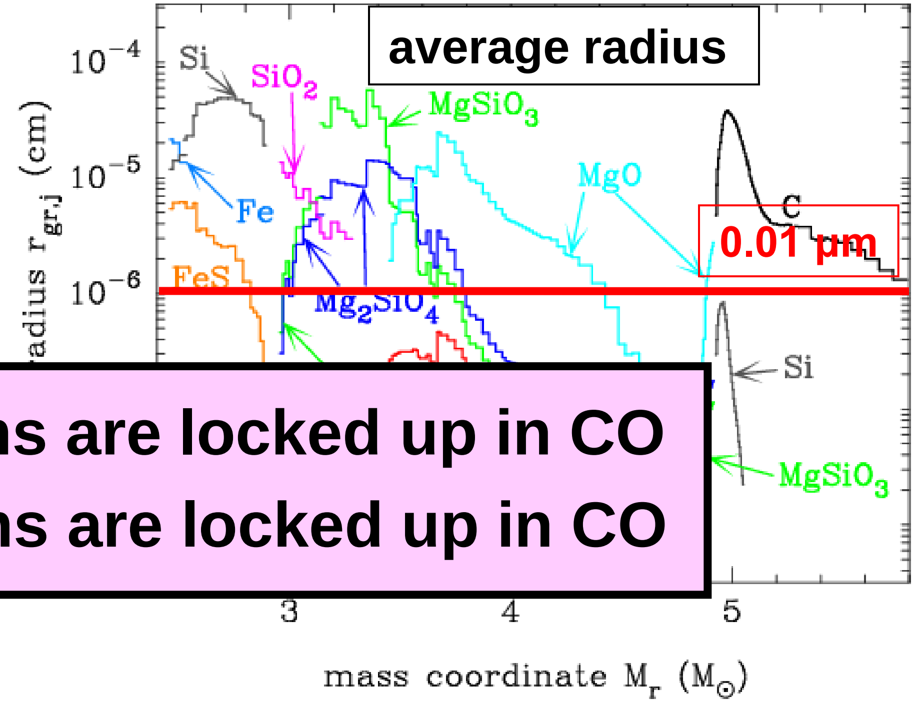
$$\frac{dV}{dt} = s\Omega_0 \, 4\pi a^2 \left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S}\right),$$



Growth rate is independent of grain radius

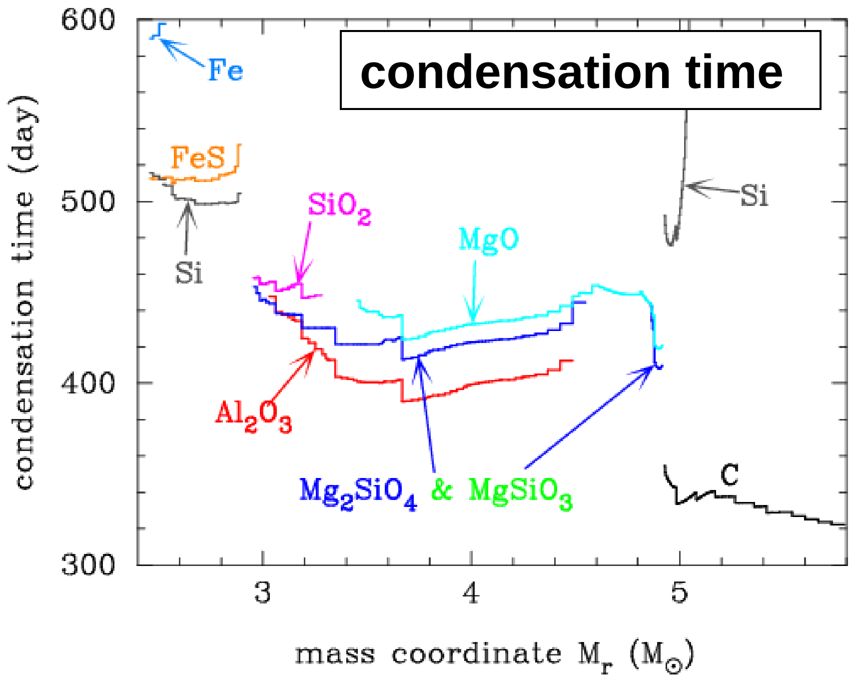
2-3. Dust formed in Type II-P SNe





C / O < 1 ➔ all C atoms are locked up in CO

C / O > 1 ➔ all O atoms are locked up in CO

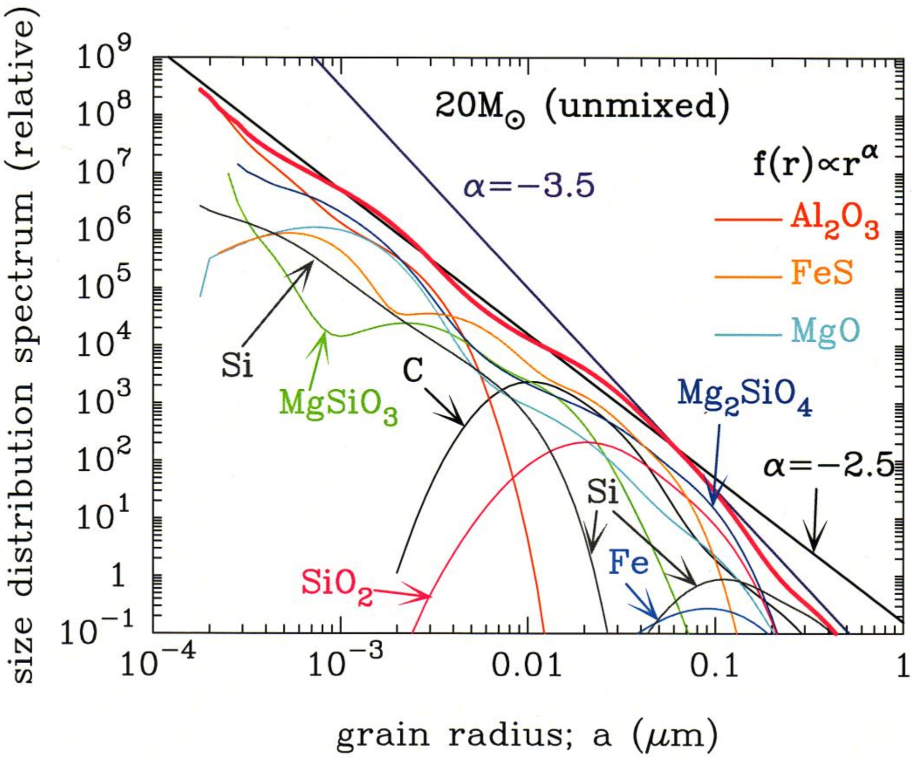


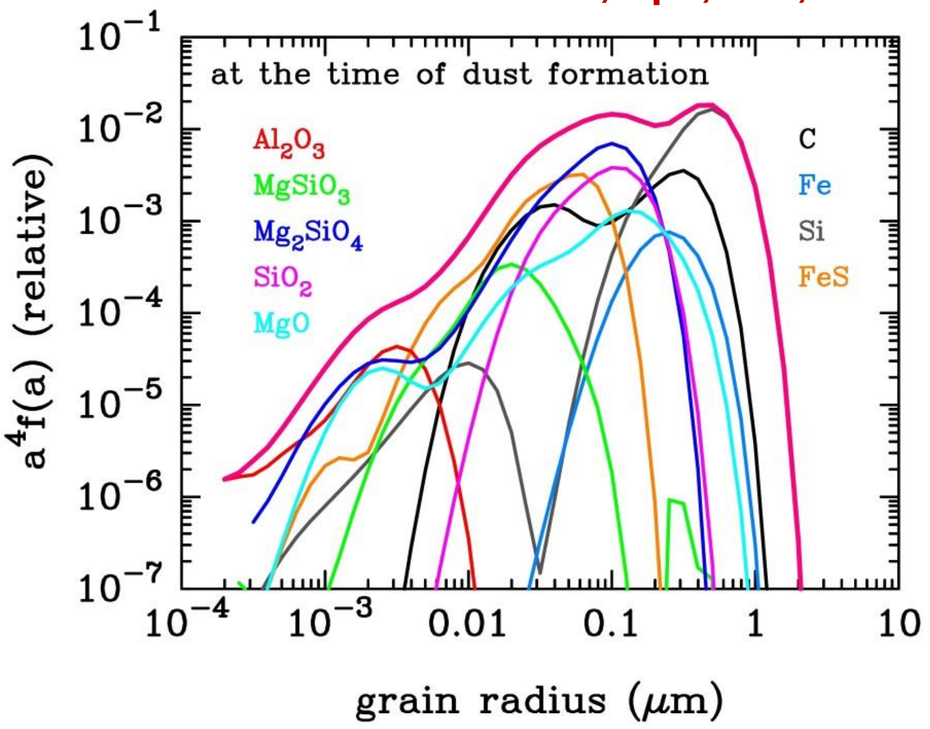
- a variety of grain species can condense according to elemental composition in each layer
- condensation time: 300-600d after explosion
- average grain radii: >~0.01 μm

Nozawa+03, ApJ, 598, 785

2-4. Size distribution of newly formed dust

Nozawa+2003, ApJ, 598, 785

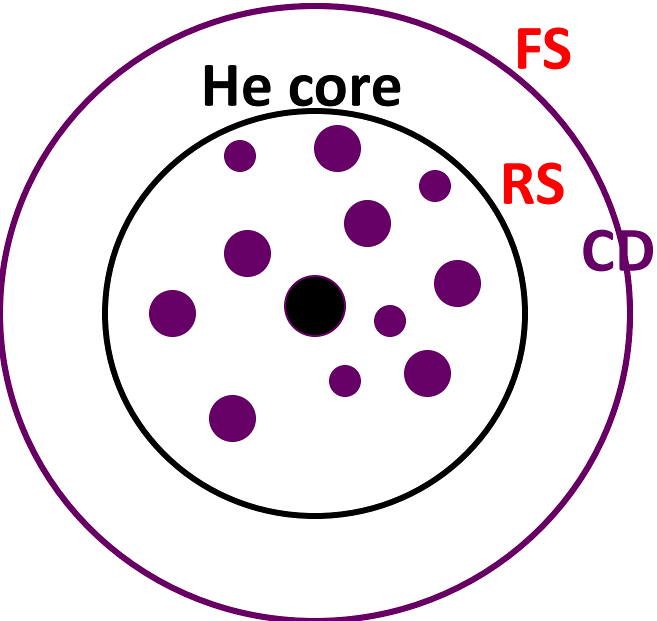




- C, SiO2, and Fe grains have lognormal-like size distribution, while the other grains have power-law size distribution
- Size distribution summed up over all grain species is roughly described by a broken power-law with the index of -2.5 and -3.5
- Size distribution of dust in mass has a peak around 0.1-1 μm

Destruction of dust grains by SN reverse shocks

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



2-5-1. Time evolution of SNRs

- Basic equations (spherical symmetry)

$$\frac{\partial \rho}{dt} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v) = 0$$

$$\frac{\partial}{dt}(\rho v) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v^2) = -\frac{\partial P}{\partial r}$$

$$\frac{\partial}{dt}\left(\frac{\rho v^2}{2} + \frac{P}{\gamma - 1}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left[\frac{\rho v^2}{2} + \frac{\gamma P}{\gamma - 1}\right] v\right)$$

$$= -(n_{\rm e} n_{\rm H} \Lambda_{\rm gas}(T) + \Lambda_{\rm ic}(T) + \Lambda_{\rm d}(n_{\rm H}, T))$$

$\Lambda_{\rm gas}(T)$: cooling function of gas by the atomic process
(Sutherland & Dopita 1993; Smith et al. 2001)

$\Lambda_{\rm ic}(T)$: inverse Compton cooling (Ikeuchi & Ostriker 1986)

$\Lambda_{\rm ic}(T) = 5.41 \times 10^{-32}(1+z)^4 n_e (T/10^4\ {\rm K})$ (we adopt $z = 20$)

$\Lambda_{\rm d}(n_{\rm H}, T)$: cooling of gas through thermal emission of dust

· numerical code : flux splitting method (van Albada et al. 1982)

2-5-2. Dynamics of dust

- deceleration of dust due to drag force (Baines et al. 1965)

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

$$F_{\rm drag} = m_{\rm d}\frac{dw_{\rm d}}{dt} = -\pi a^2 \sum n_i \langle v_i m_i v_i \cos\theta \rangle$$

$$\frac{dw_{\rm d}}{dt} = -\frac{\pi a^2}{\frac{4}{3}\pi a^3 \rho_d} n_{\rm H} \sum A_i \langle v_i m_i v_i \cos\theta \rangle$$

$$= -\frac{3n_{\rm H}}{4a\rho_d} kT \sum A_i G_i$$

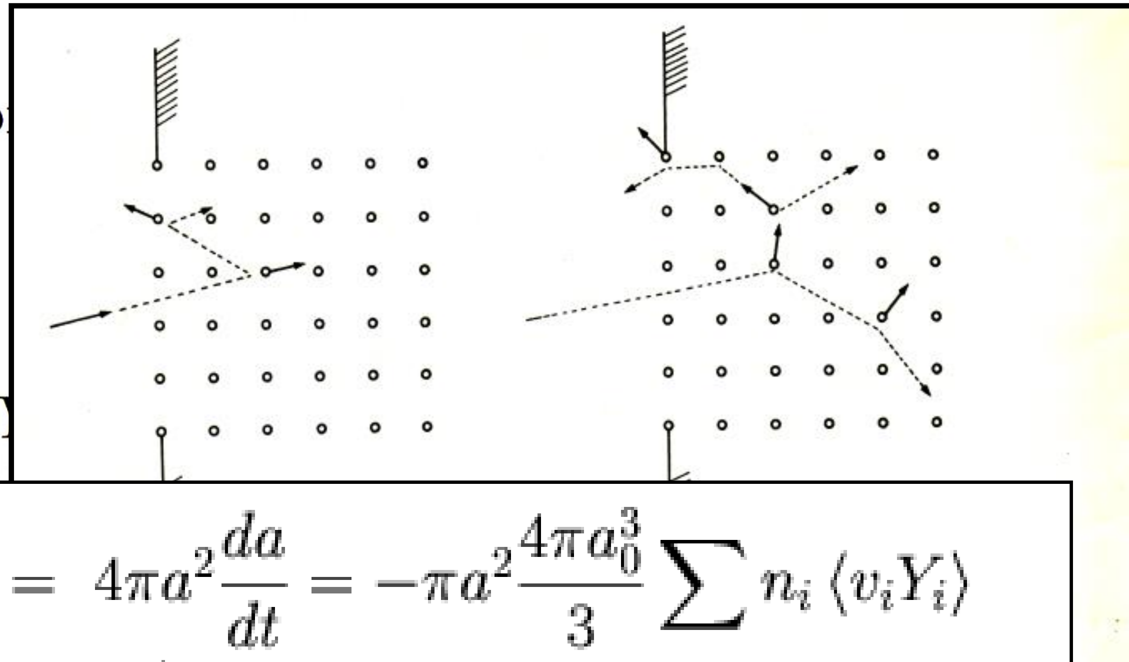
by $n_{\rm H}$

$$G_i(s_i) \approx \frac{8s_i}{3\sqrt{\pi}}\left(1+\frac{9\pi}{64}s_i^2\right)^{\frac{1}{2}}$$ (Draine & Salpeter 1979)

where $s_i^2 = m_i w_{\rm d}^2/2kT$

2-5-3. Erosion rate of dust by sputtering

• dust destructio ... 996)



$Y_i(E) = 2$ ...

r

$$\frac{dV_{\rm d}}{dt} = 4\pi a^2 \frac{da}{dt} = -\pi a^2 \frac{4\pi a_0^3}{3} \sum n_i \langle v_i Y_i \rangle$$

$$\frac{da}{dt} = -\frac{1}{4} \Omega n_{\rm H} \sum A_i \langle v_i Y_i \rangle$$

· rate ... s taken

acco ...)

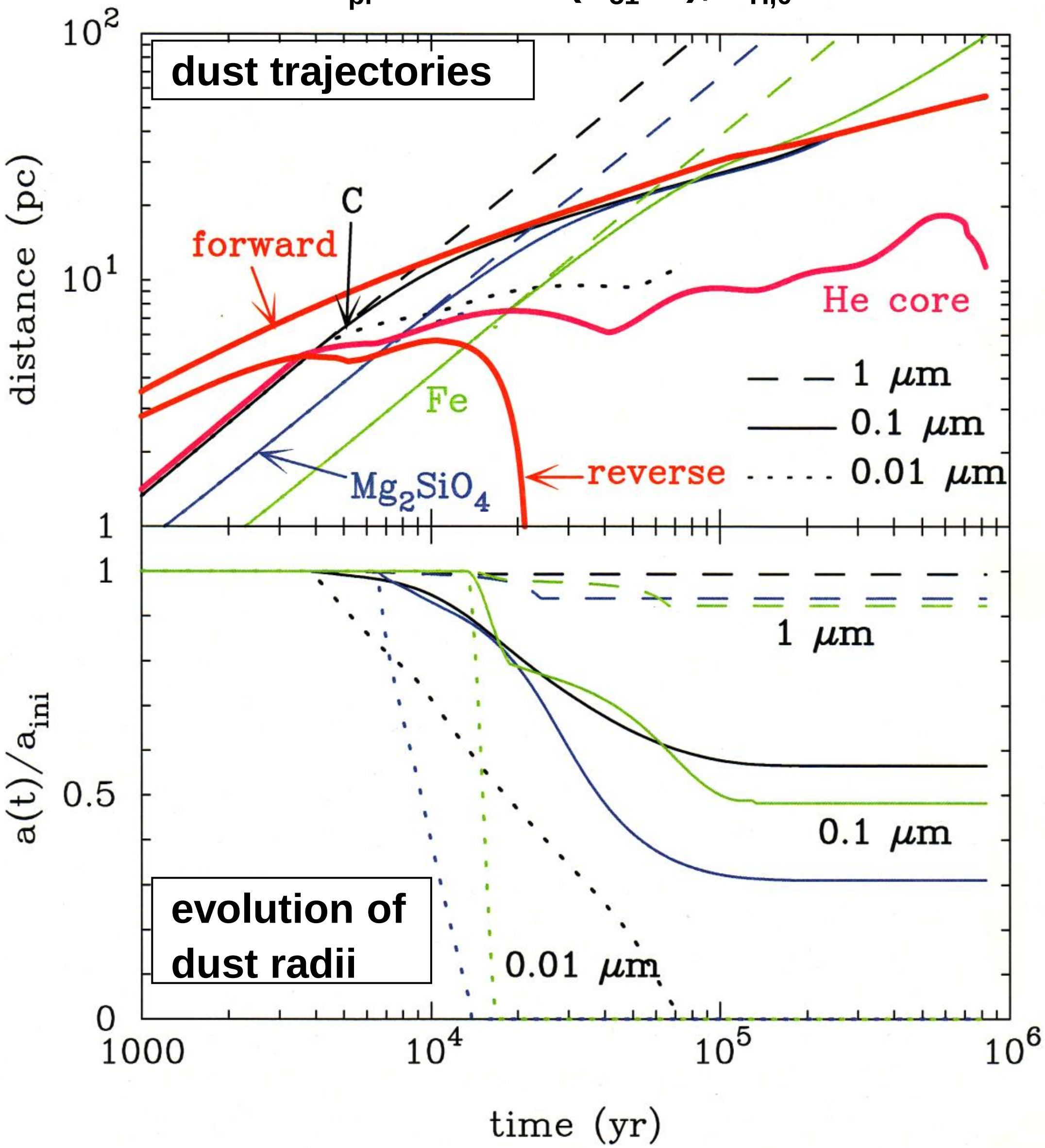
$\mathcal{R}($ ... $)X_i(\epsilon)d\epsilon$

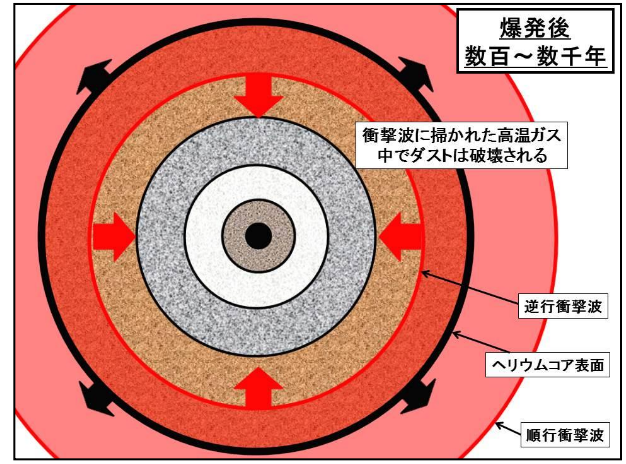
$$\frac{da}{dt} = -\frac{m_{\rm sp}}{2\rho_{\rm d}} n_{\rm H} \sum A_i \left(\frac{8kT}{\pi m_i}\right)^{1/2} \frac{e^{-s_i^2}}{2s_i} \times \int \epsilon^{\frac{1}{2}} e^{-\epsilon_i} \sinh(2 s_i \epsilon_i^{\frac{1}{2}}) Y_i^0(\epsilon_i) d\epsilon_i$$

w

2-6. Evolution of dust in SNRs

Model : M_{pr}= 20 Msun (E_{51}=1), $n_{H,0}$ = 1 cm^{-3}





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

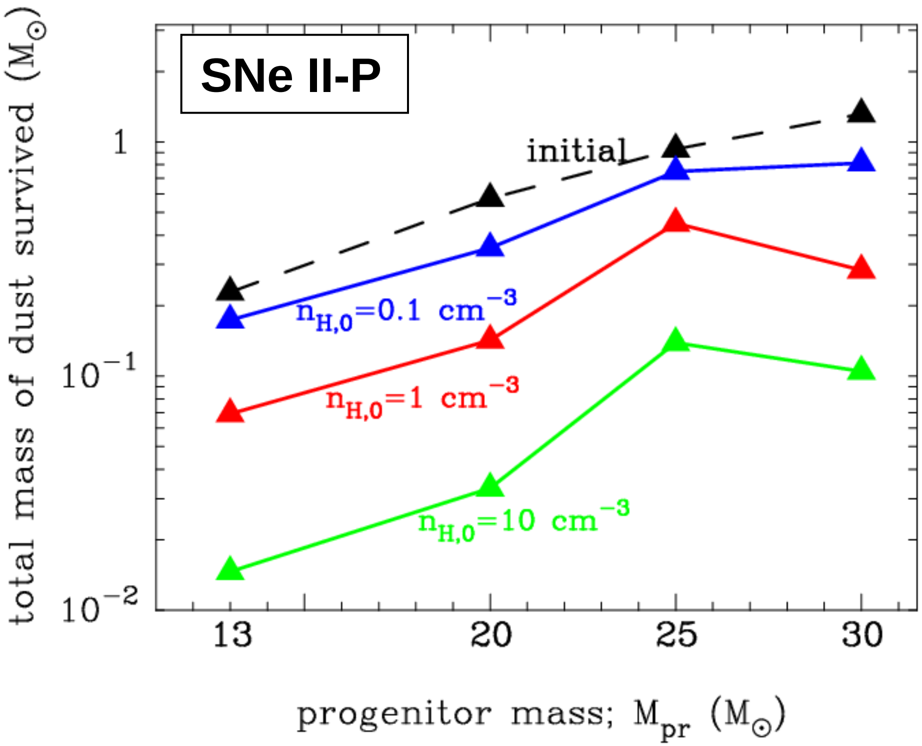
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed

a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell

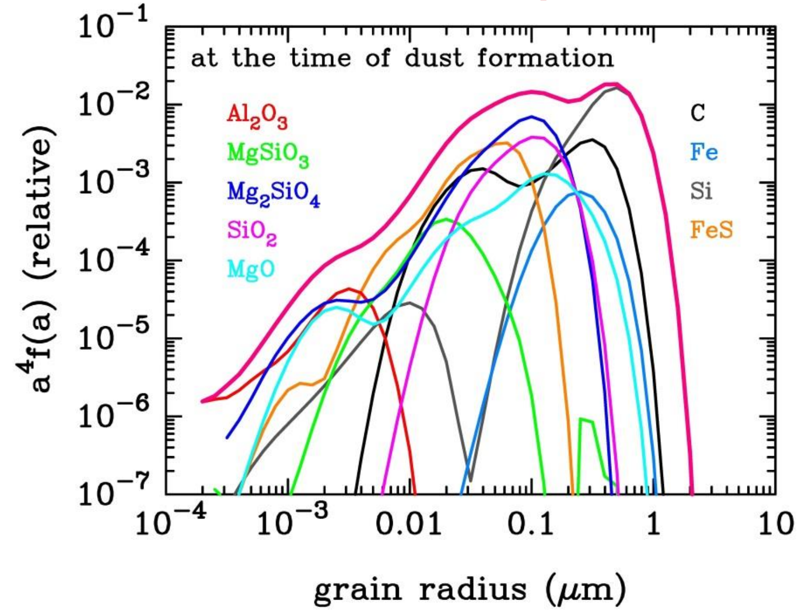
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

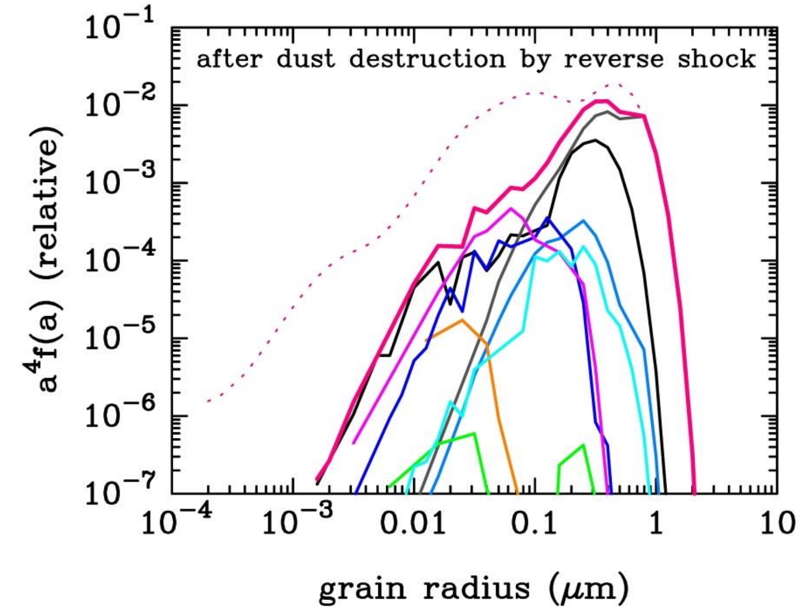
Nozawa+07, ApJ, 666, 955

2-7. Dust mass and size ejected from SNe II



Nozawa+07, ApJ, 666, 955





total mass of dust surviving the destruction in Type II SNRs; 0.07-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

size distribution of dust after the shock-destruction is domimated by large grains (> 0.1 μm)

2-8. Conclusions from theoretical works

1) When the observed massive dust was formed?

➜ within 3 years after SN explosion

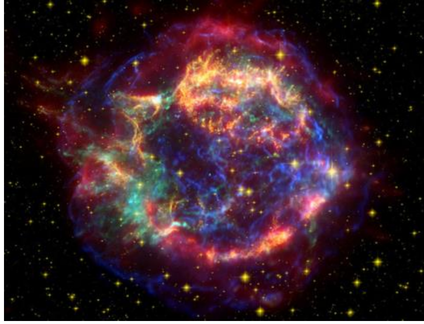
2) What composition and size distribution of dust are?

- composition: carbon, silicate, oxide, pure iron …

- size (distribution)
  - at the formation ➜ a few A to ~1 μm (broken power-law)
  - after destruction ➜ biased to larger than ~0.1 μm

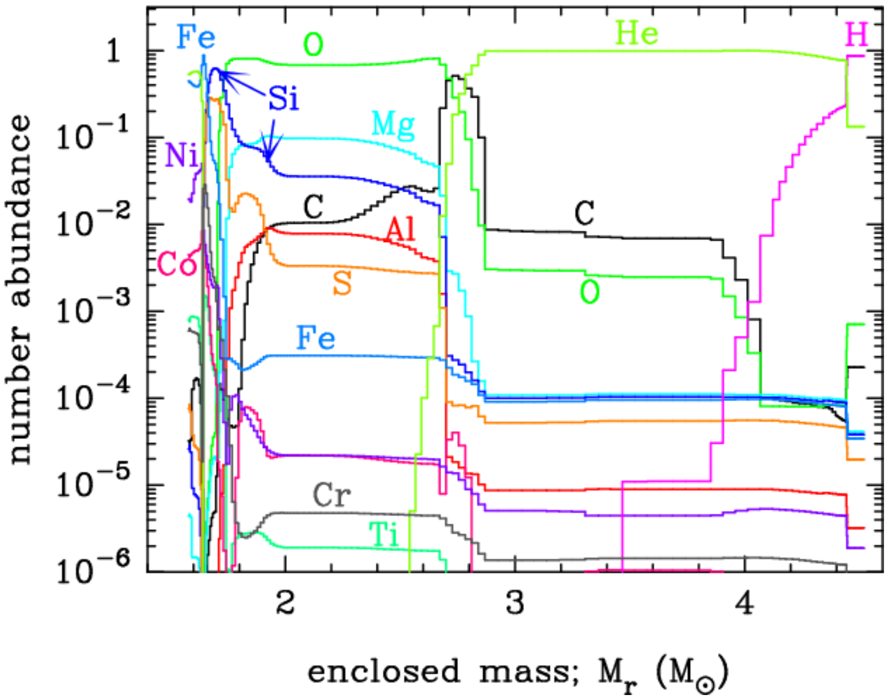
- dust mass
  - at the formation: 0.1-1.3 Msun
  - after destruction: 0.07-0.8 Msun

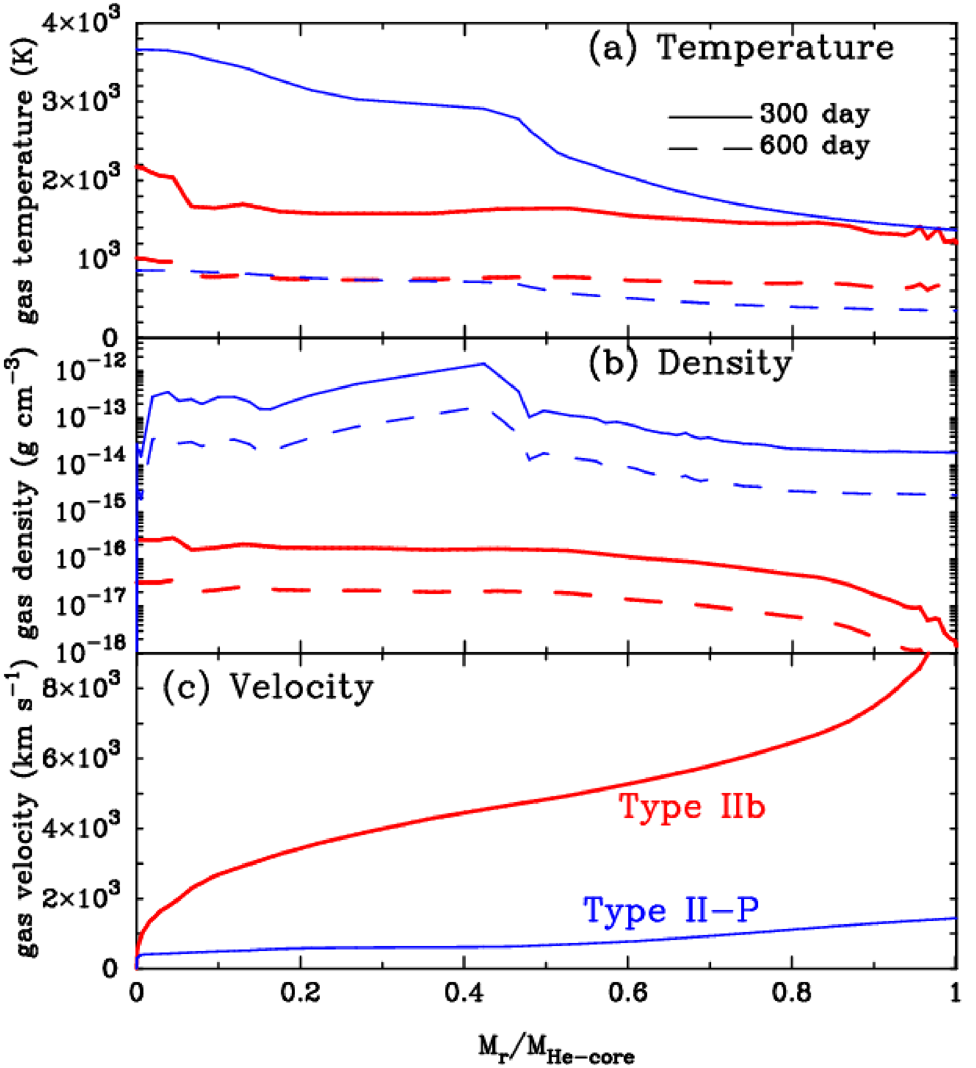
A-1. Dust formation in Type IIb SN



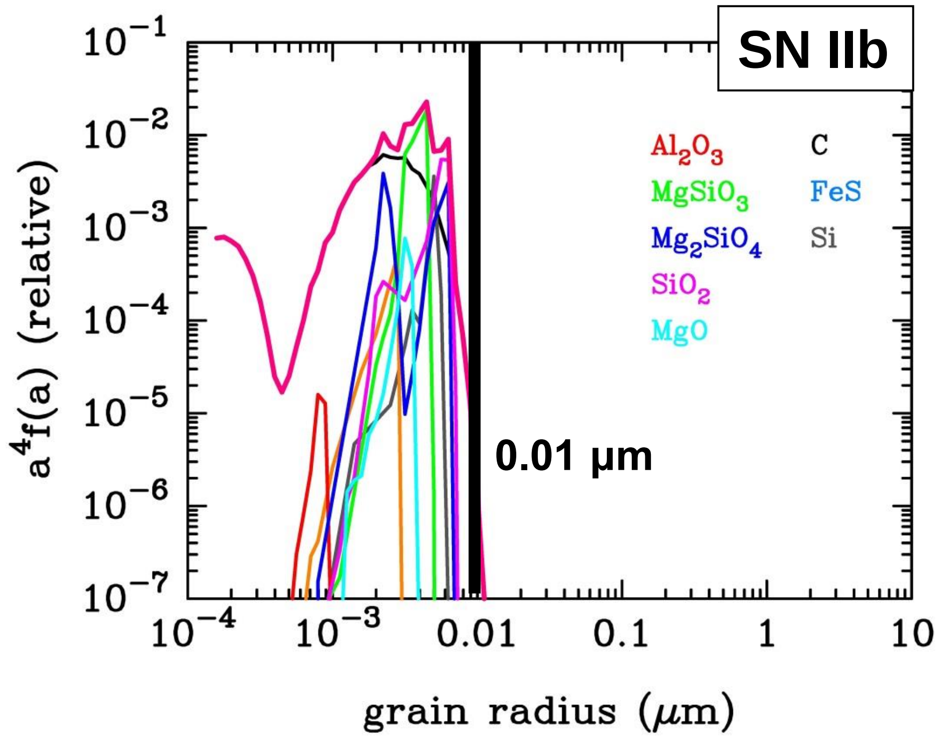
○ SN IIb model (SN1993J-like model)

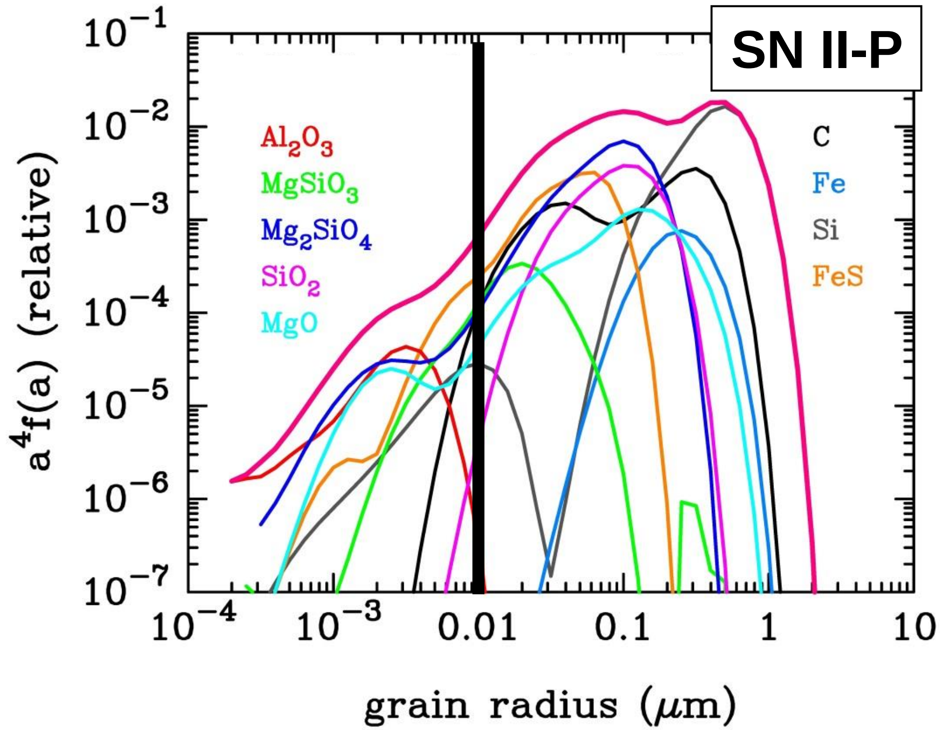
- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1
- $M(^{56}Ni)$ = 0.07 Msun





A-2. Dependence of grain radii on SN type



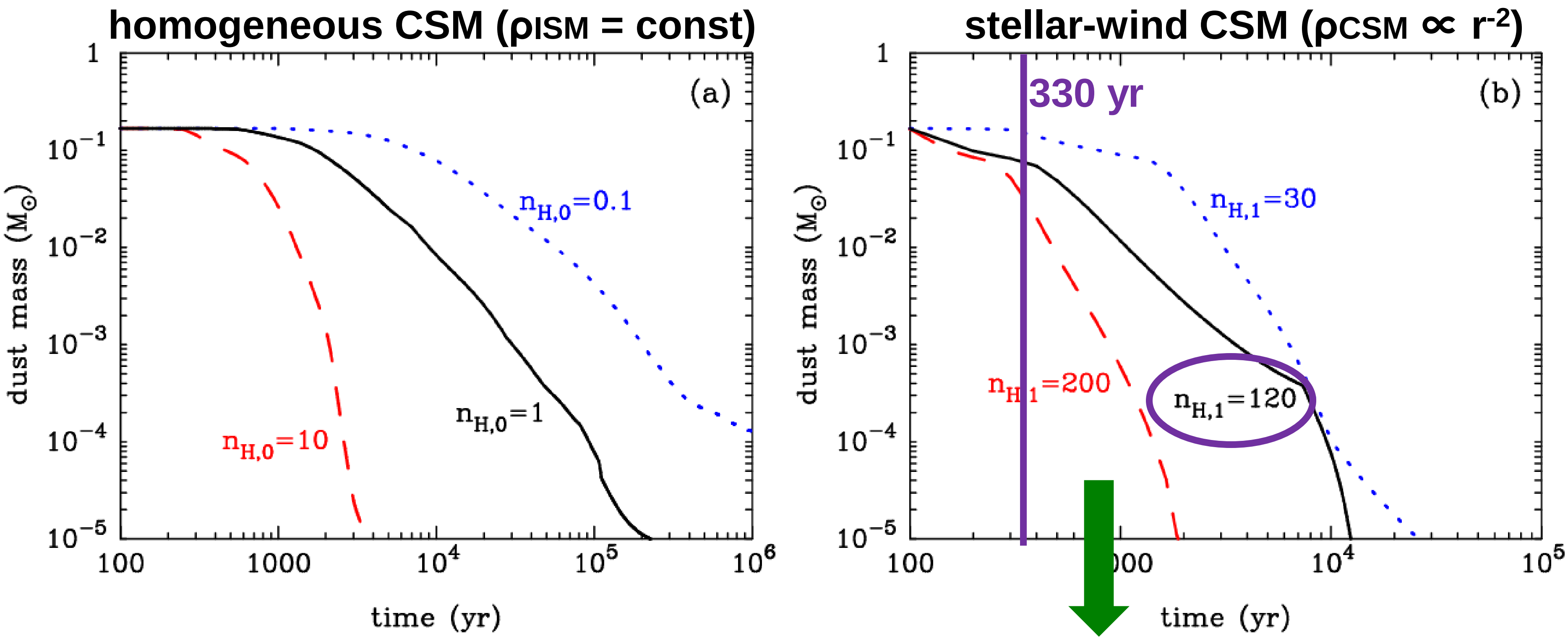


- condensation time of dust 300-700 days after explosion
- total mass of dust formed
  - 0.167 Msun in SN IIb
  - 0.1-1 Msun in SN II-P

- 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

Nozawa+10, ApJ, 713, 356

A-3. Destruction of dust in Type IIb SNR



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

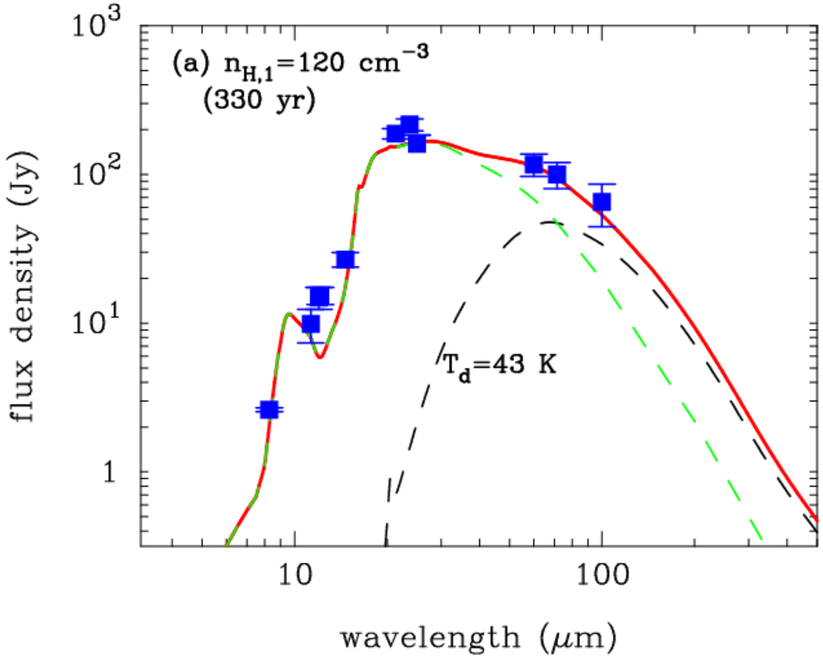
Almost all newly formed grains are destroyed in the hot gas that was swept up by the reverse shocks

➔ small radius of newly formed grains

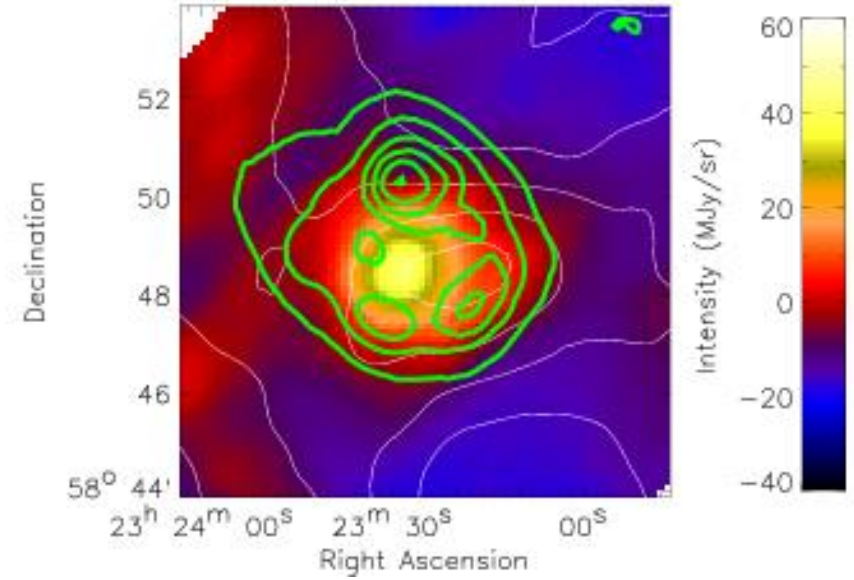
➔ early arrival of reverse shock at dust-forming region

Nozawa+10, ApJ, 713, 356

A-4. IR emission from dust in Cas A SNR



AKARI 90 μm image (color)



- total mass of dust formed
  M_{dust} = 0.167 M_{sun}
- shocked dust : 0.095 M_{sun}
  $M_{d,warm}$ = 0.008 M_{sun}
- unshocked dust :
  $M_{d,cool}$ = 0.072 M_{sun}
  with T_{dust} ~ 40 K

Nozawa+10, ApJ, 713, 356

AKARI observation

$M_{d,cool}$ = 0.03-0.06 M_{sun}

T_{dust} = 33-41 K

(Sibthorpe+10)

Herschel observation

$M_{d,cool}$ = 0.075 M_{sun}

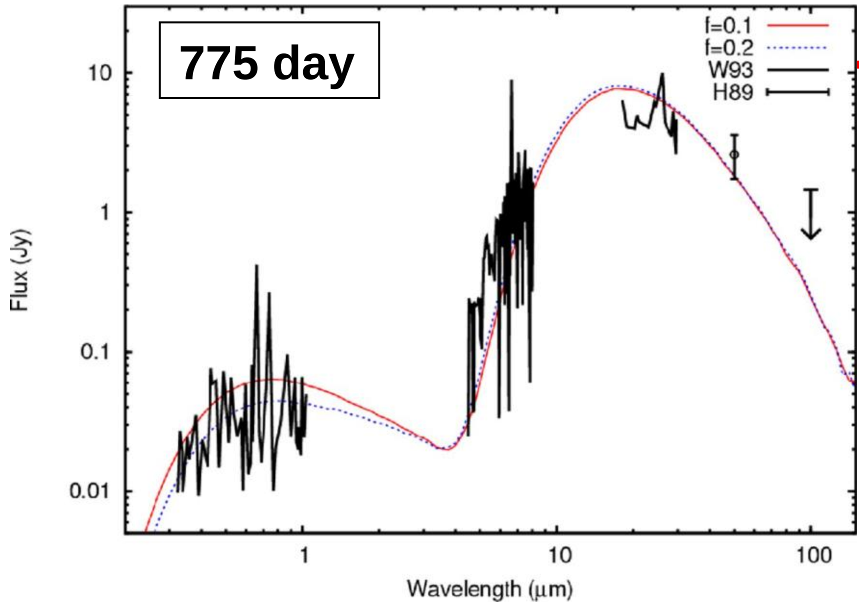
T_{dust} ~ 35 K (Barlow+10)

3. Observations of composition and size of dust in SNe

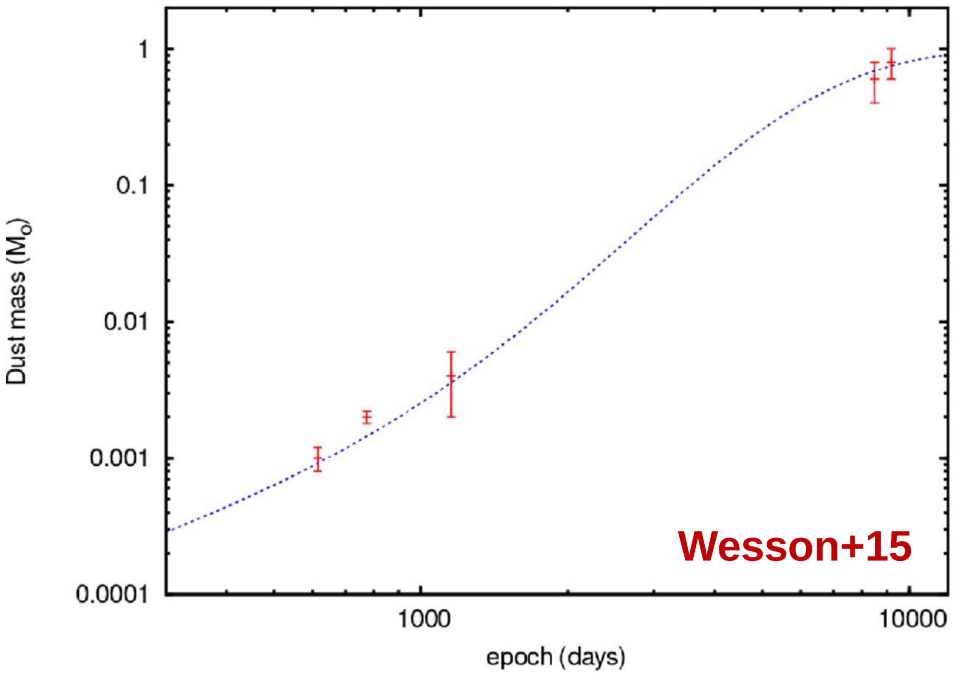
1) When the observed massive dust was formed?

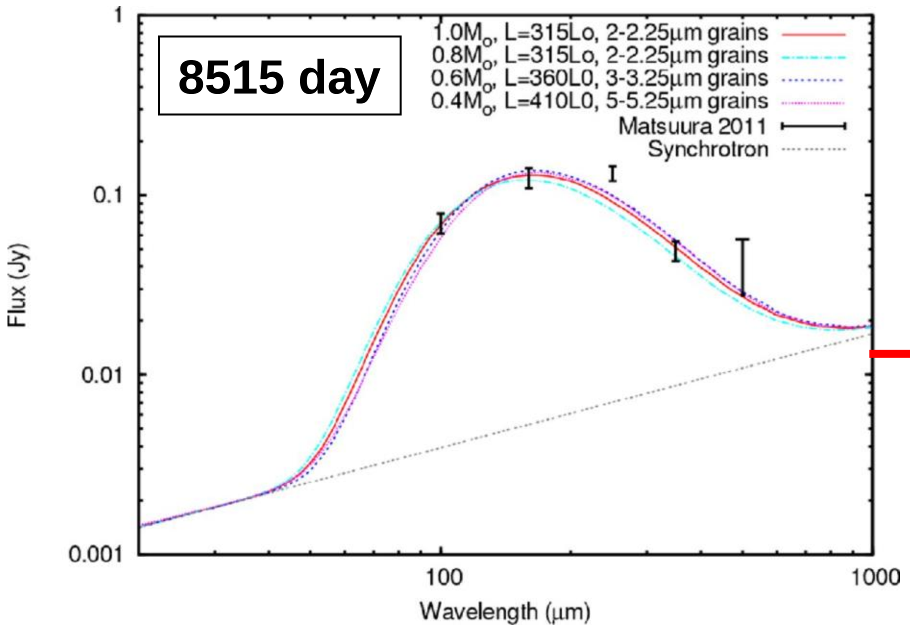
2) What composition and size distribution of dust?

3-1. Revisiting dust mass formed in SN 1987A



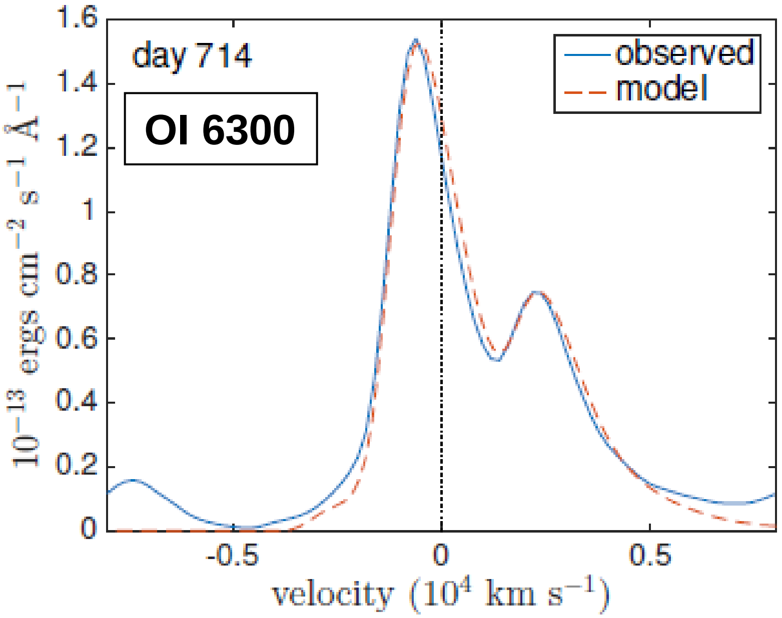
- dust mass ~ 0.002 Msun

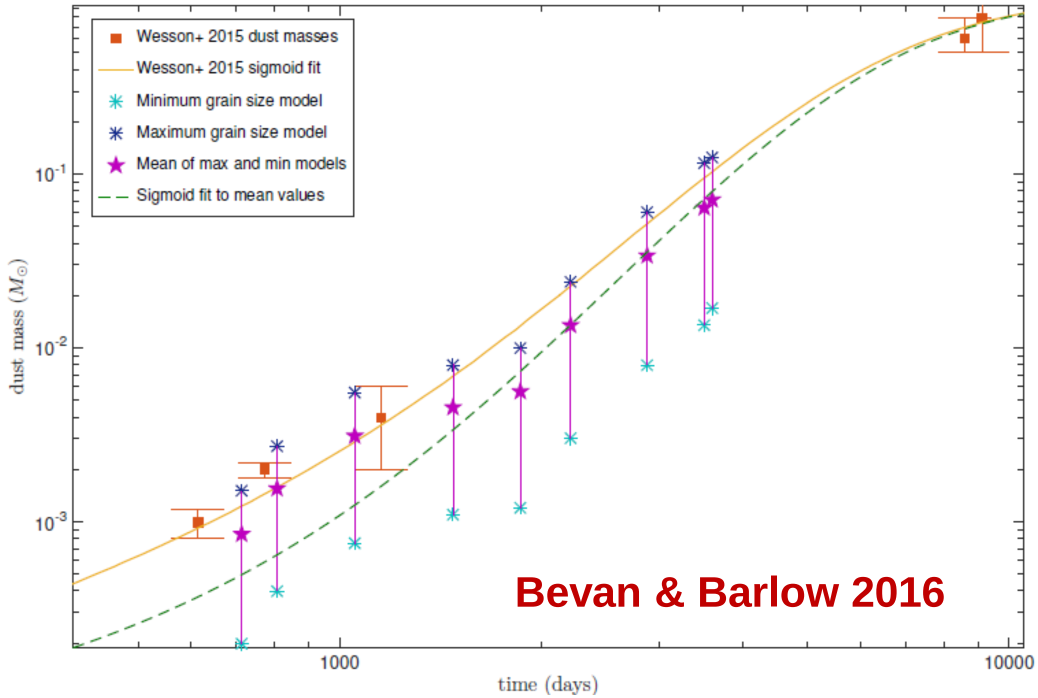


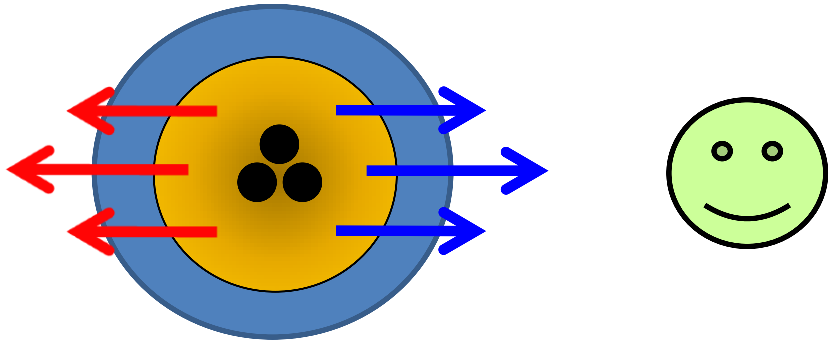


- dust mass ~ 0.7 Msun
- dust radius ~ 0.2 μm
  large radius is required to have Tdust ~ 20 K in LMC

3-2. Dust mass from line profiles in SN 1987A



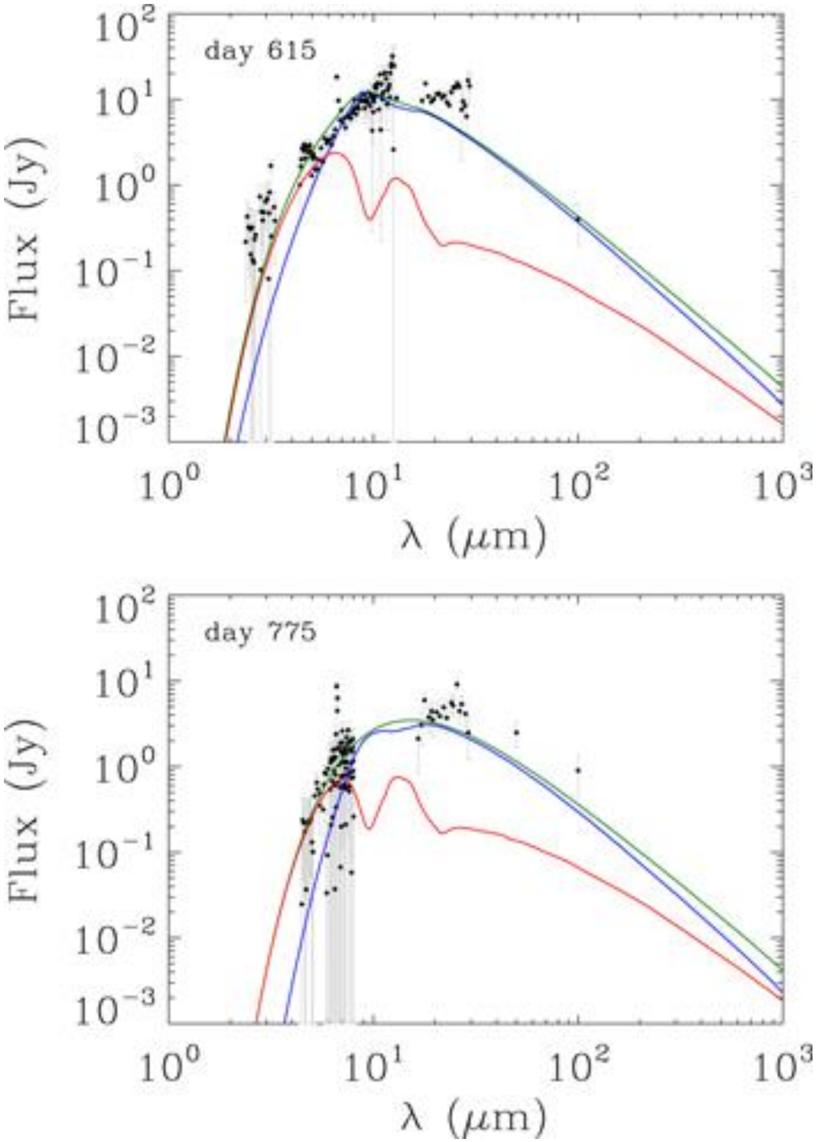




At 714 day

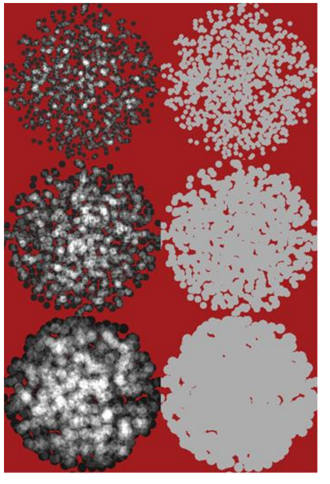
- **dust mass < 3x10^{-3} Msun (< 0.07 Msun if silicate)**
- **grain radius > ~0.6 μm**

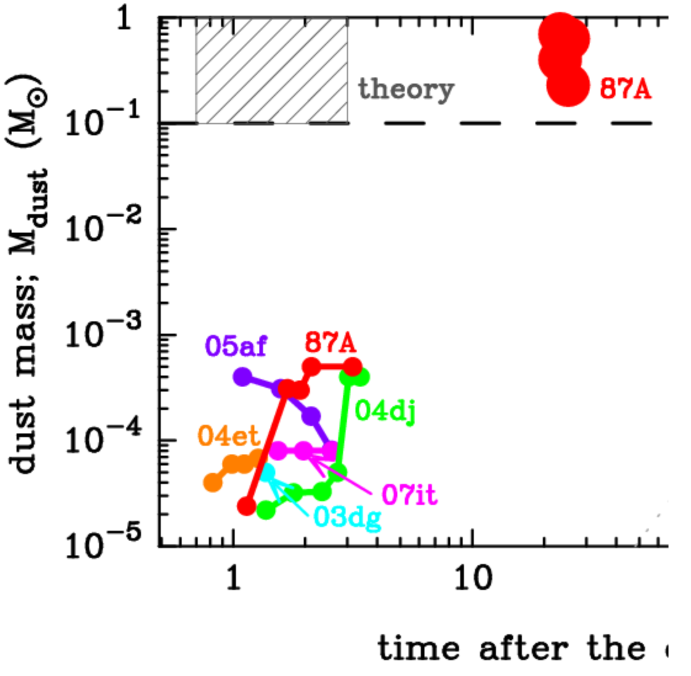
3-3. Evolution of dust mass in SN 1987A



Dwek & Arendt 2015, ApJ, 810, 75

It seems to be difficult that dust continues to form in later epochs at which gas density is low



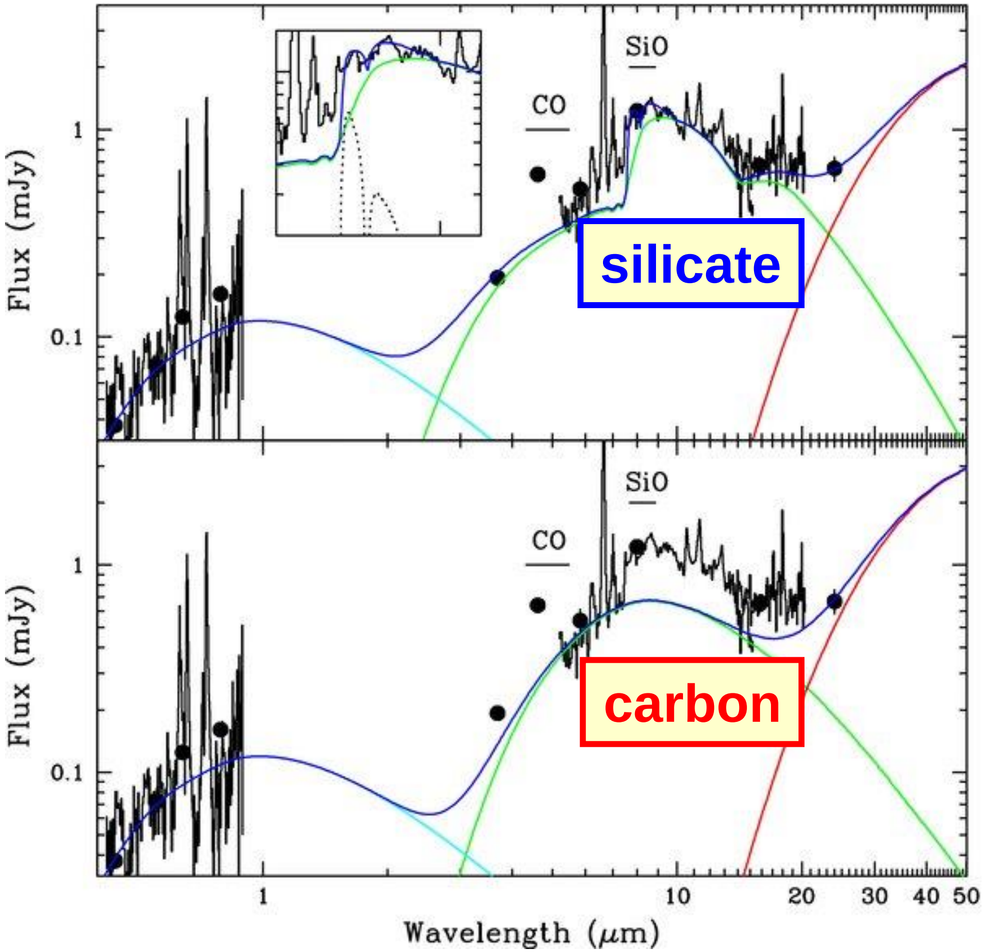


At 615 and 714 day

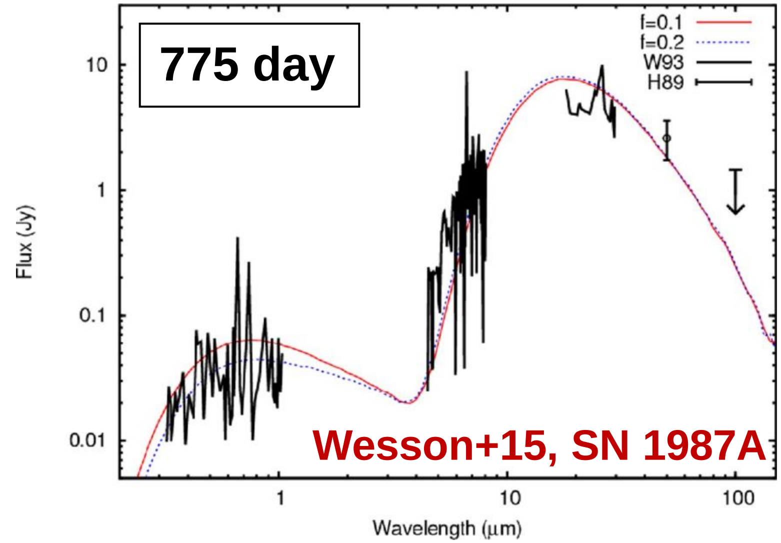
- **dust mass: ~0.4 Msun**
- **silicate-dominated**

3-4. Composition of dust formed in SNe

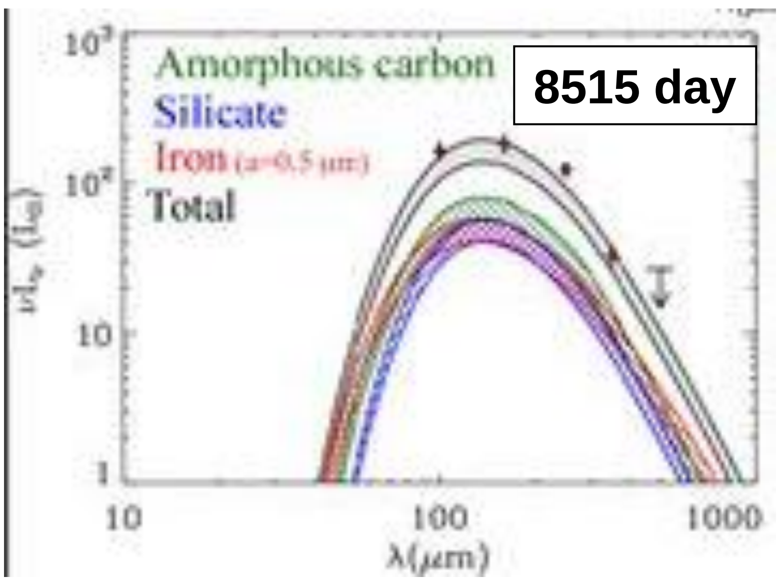
first detection of silicate in SN



Kotak+09, SN 2004et

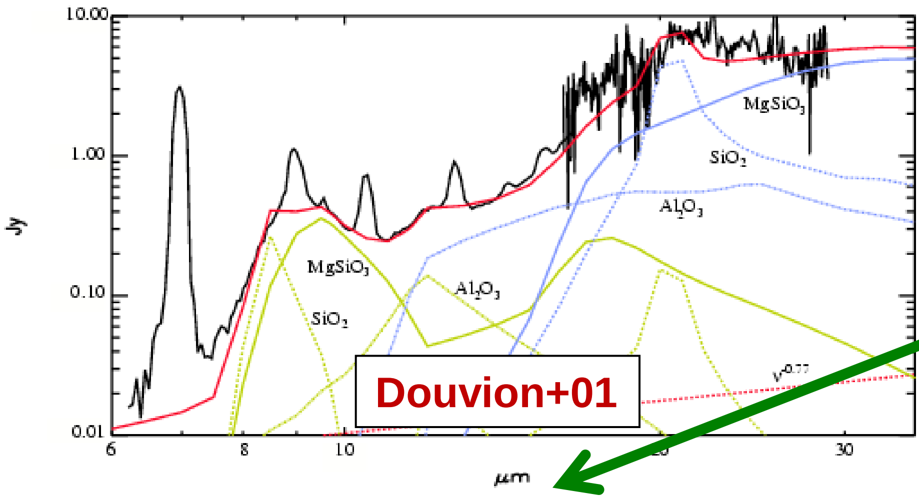


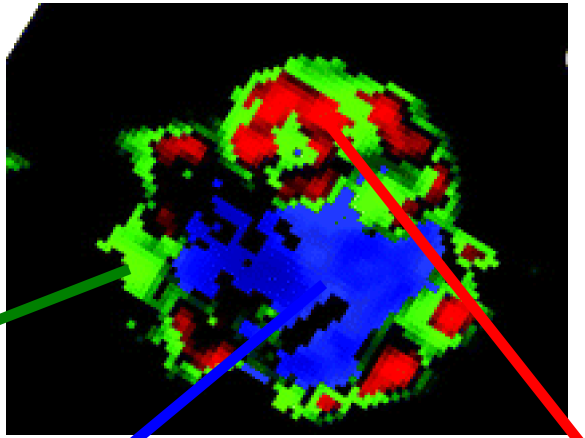
Wesson+15, SN 1987A

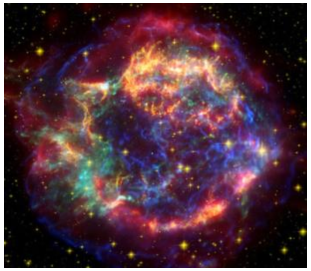


Matuura+2011, SN 1987A

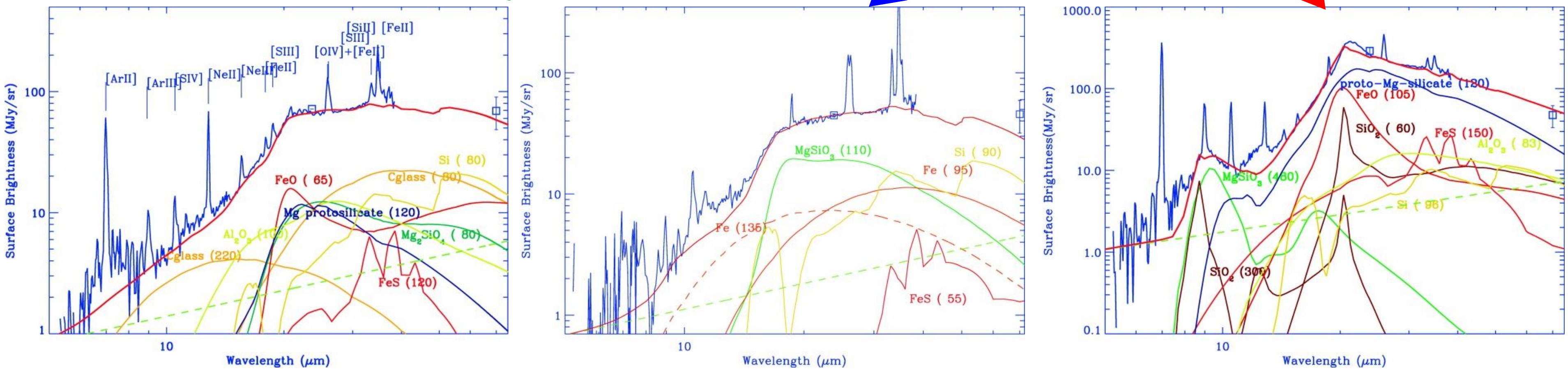
3-5. Composition of dust in Cas A SNR







Rho+08



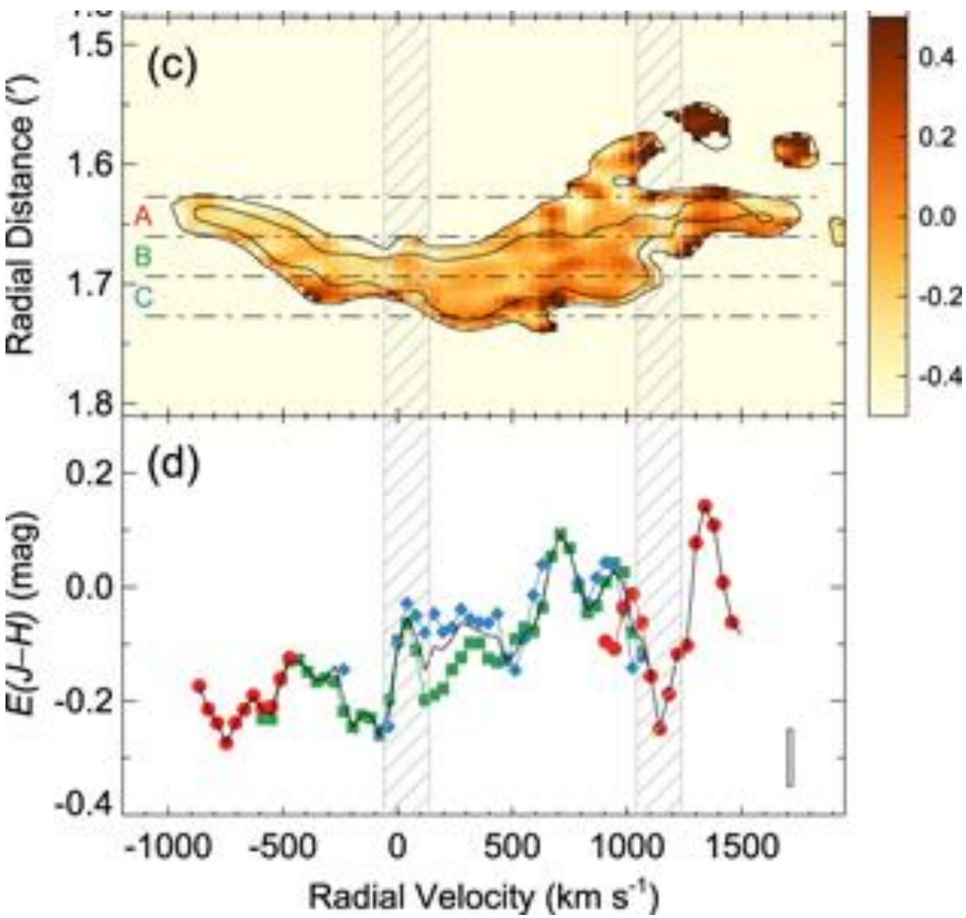
- glassy carbon
- FeO, Al2O3

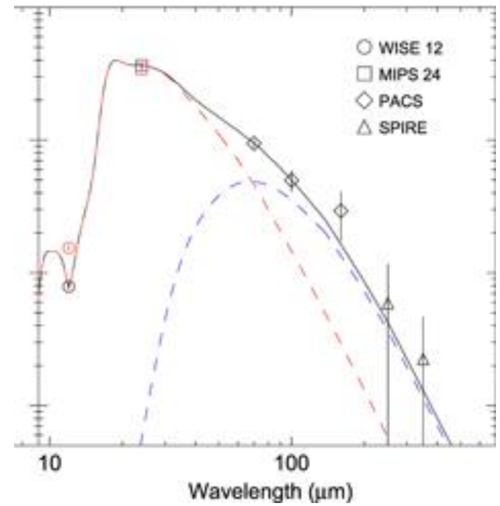
- MgSiO3
- Fe, FeS, Si

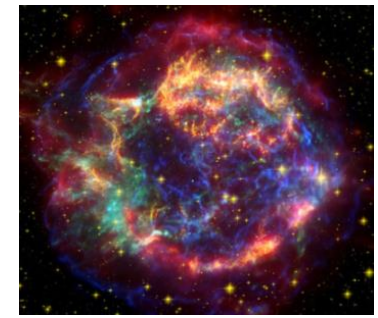
- Mg-silicate
- FeO, SiO2

various grain species exist in each place (layer)

3-6. Dust properties in one knot of Cas A SNR







Lee, Koo et al. 2015, ApJ, 808, 98

Far-side is more obscured than near-side E(J-H) = 0.23

to cause large extinction, large dust mass is needed

cool dust component

➜ Fe with a < 0.01 μm
(or large Si dust)

$$F_\lambda \propto 4\, M_{dust}\, \kappa_{emis}(\lambda)\, \pi B_\lambda(T_{dust})$$

3-7. Conclusions from observational works

1) When the observed massive dust was formed?

➜ under debate

- dust mass gradually increases throughout 25 years
- dust formation must be finished within a few years

2) What composition and size distribution of dust are?

- composition: carbon, silicate, oxide, pure iron …
  ➜ consistent with the theoretical prediction

- size (distribution)
  - SN 1987A ➜ relatively large above 0.1 μm?
  - Cas A ➜ small Fe (< 0.01 μm) or large silicon?
    not well constrained for the other species