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超新星放出ガス中でのダスト形成と衝撃波中でのダスト破壊

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TODIAS 東京大学国際高等研究所 TODAI INSTITUTES FOR ADVANCED STUDY
wpi World Premier International Research Center Initiative
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

1. Introduction

・ supernovae (SNe) : explosions of massive (early type) stars with M_{ZAMS} > 8 M_{sun}

・ SNe are important sources of interstellar dust?

— huge amounts of dust grains (>10^8 M_{sun}) are detected in host galaxies of quasars at redshift z > 5

➔ 0.1 M_{sun} of dust per SN is needed to explain such massive dust at high-z (e.g. Dwek et al. 2007)

— contribution of dust mass from AGB stars and SNe

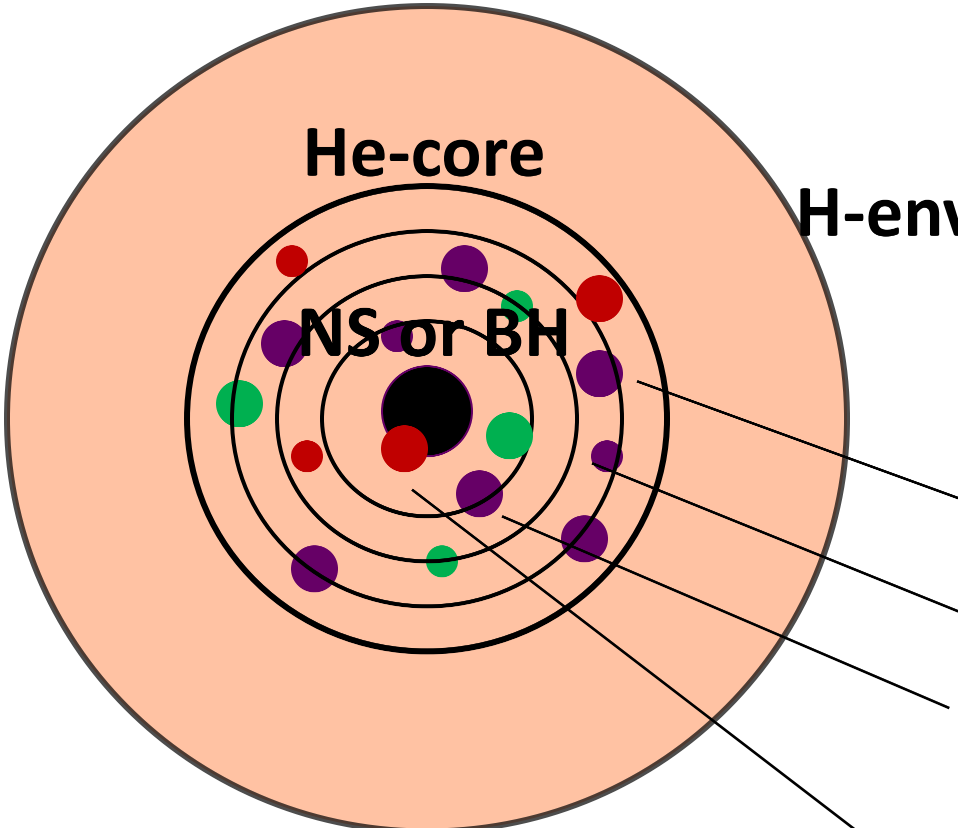
n(AGB stars) / n(SNe) ~ 10-20

M_{dust} = 0.01-0.05 M_{sun} per AGB (Zhukovska & Gail 2008)

M_{dust} = 0.1-1.0 M_{sun} per SN (Nozawa et al. 2003; 2007)

2. Dust Formation in Pop III SNe

at ~1 days



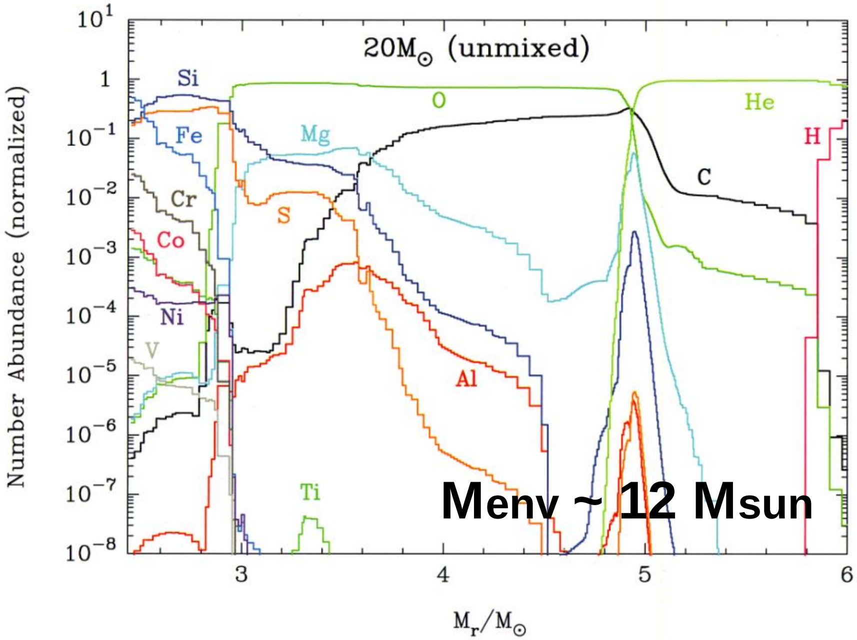
Dust formation
at ~1-3 years
after explosion

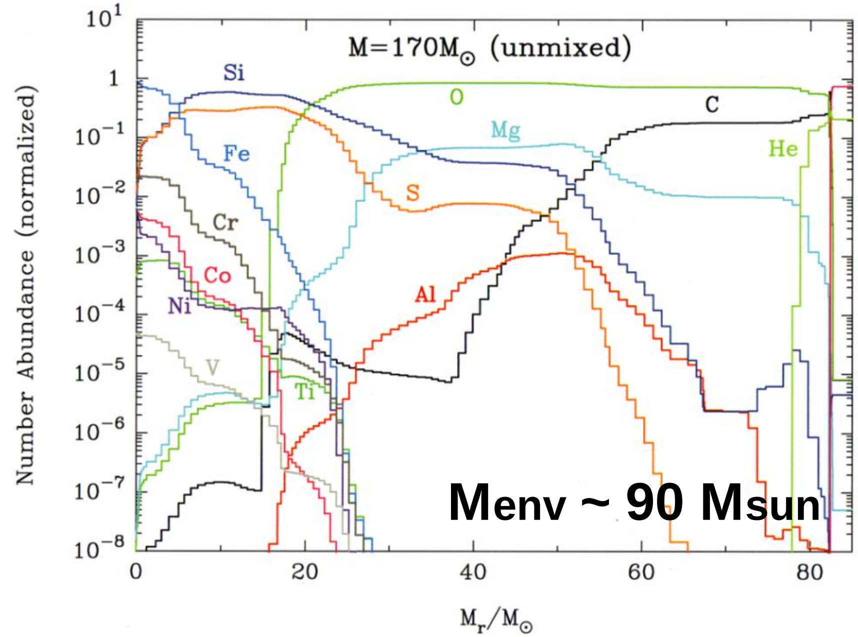
2-1. Dust formation in primordial SNe

Nozawa+'03, ApJ, 598, 785

○ Population III SNe model (Umeda & Nomoto'02)

- **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)**





- **nucleation and grain growth theory** (Kozasa & Hasegawa'88)
- **complete and no mixing of elements within the He-core**
- **complete formation of CO and SiO**

2-2-1. Calculations of dust formation

- **nucleation and grain growth theory taking account of chemical reaction at condensation**

(Kozasa & Hasegawa'87)

- **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 of dust

Steady-state nucleation rate

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

Supersaturation ratio

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

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

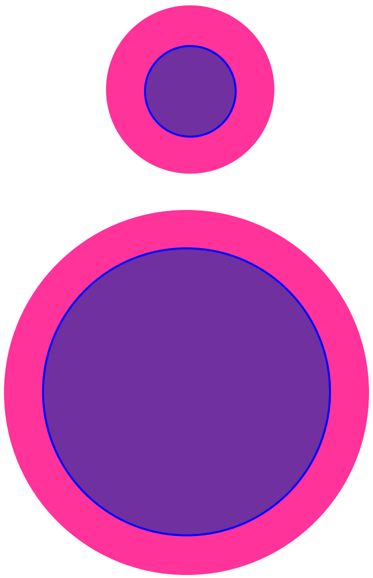
▪ Equation of mass conservation

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

▪ Equation of grain growth

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

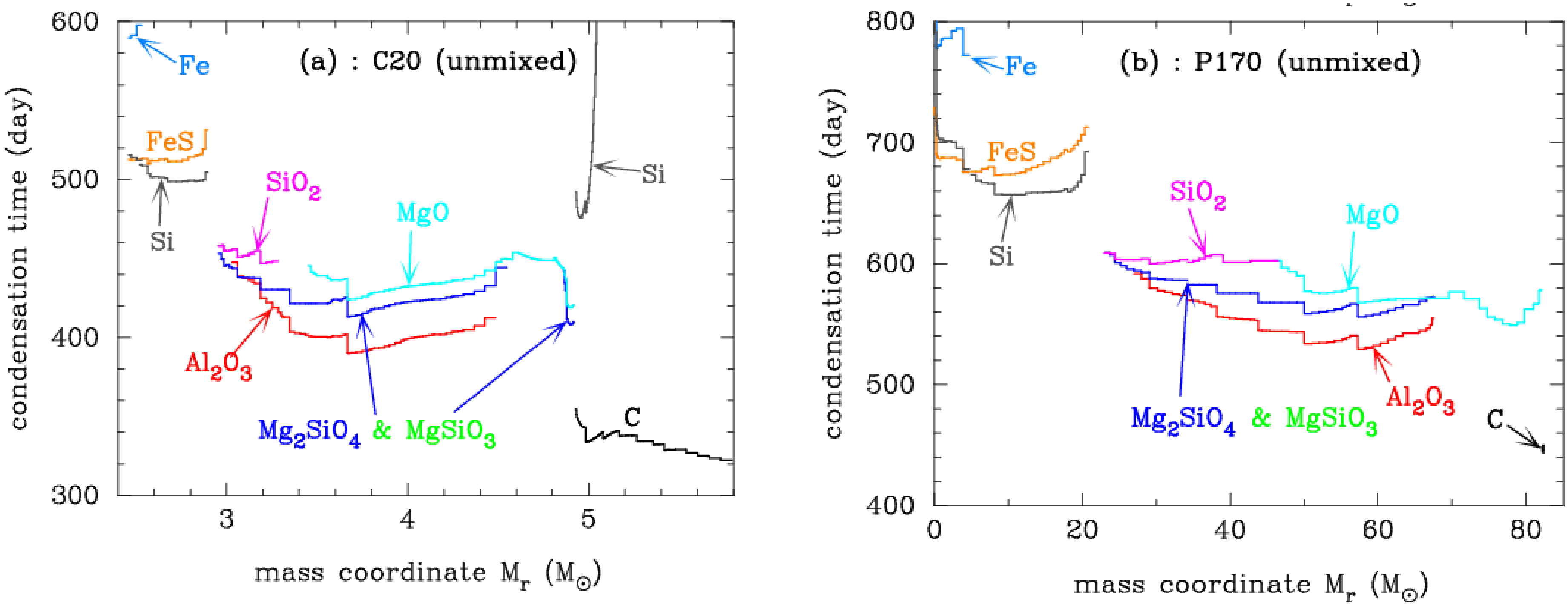
$$\frac{dV}{dt} = s\Omega_0 \, 4\pi a^2 \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S} \right),$$



Growth rate is independent of grain radius

2-3-1. Dust formed in primordial SNe

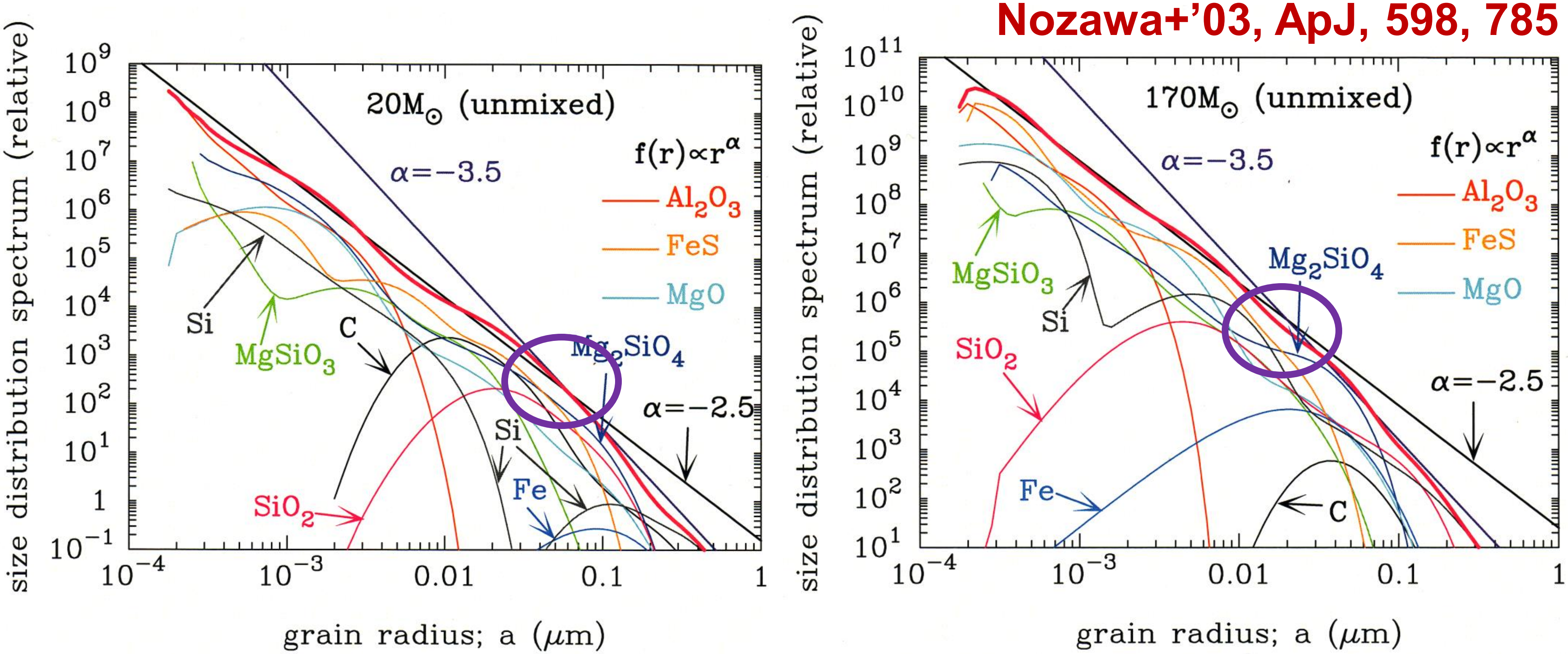
Nozawa+'03, ApJ, 598, 785



- 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

2-3-2. Size distribution of newly formed dust

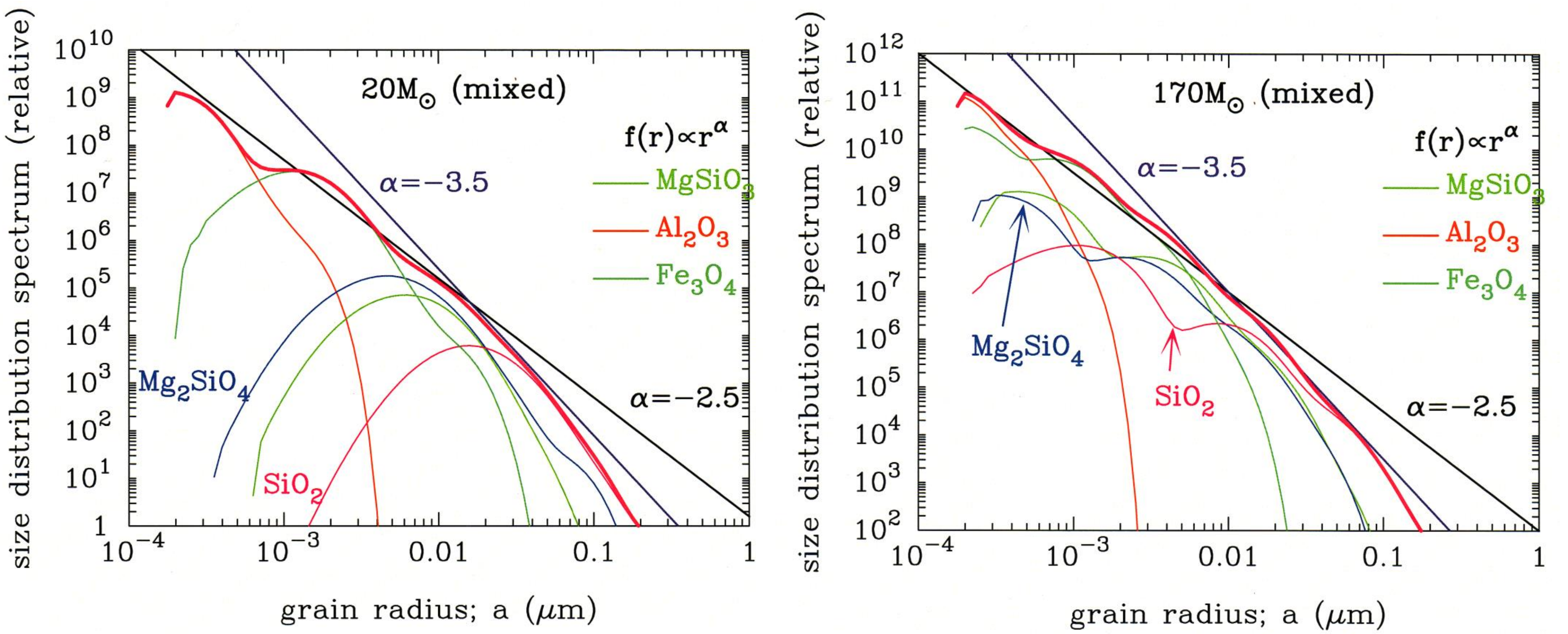
Nozawa+'03, ApJ, 598, 785



- C, SiO2, and Fe grains have lognormal size distribution, while the other grains have power-law size distribution
- The composition and size distribution of dust formed are almost independent of type of supernova

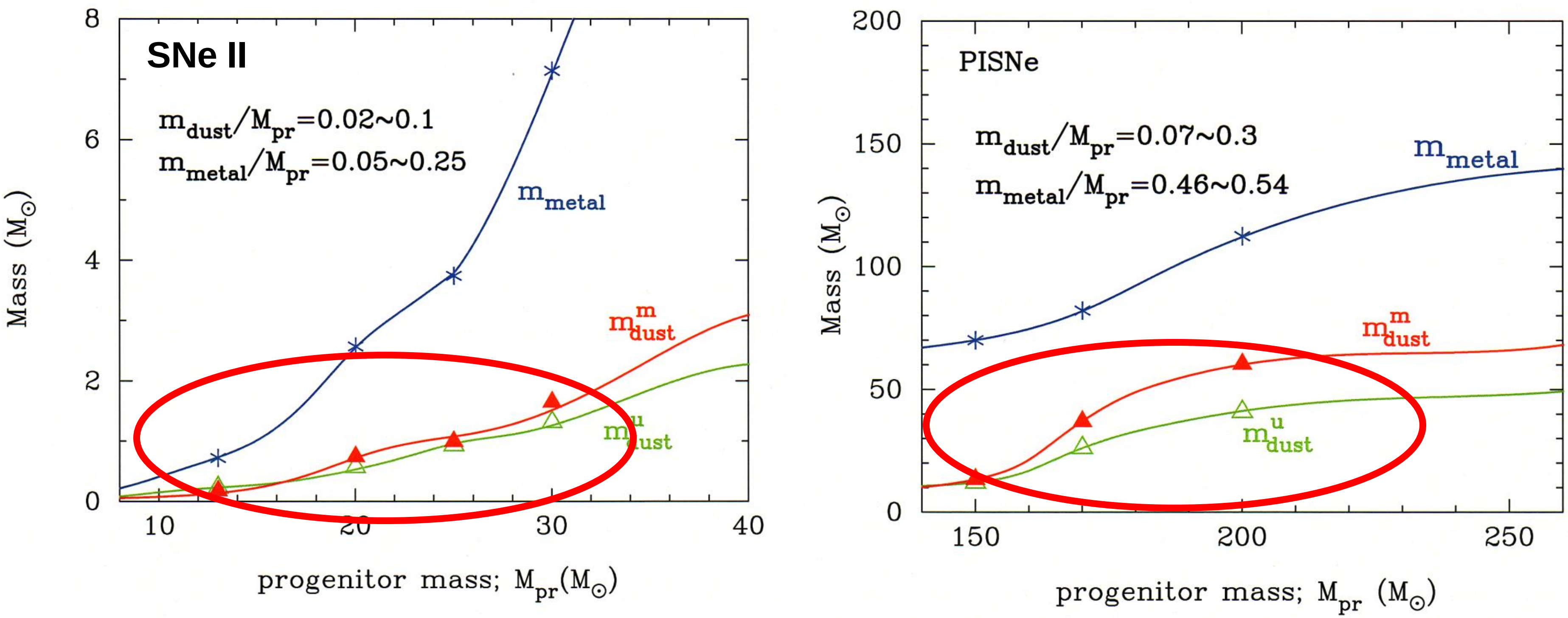
  (average dust radius is smaller for PISNe than SNe II-P)

2-3-3. Size distribution of dust in mixed cases



- **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**

2-3-4. Total mass of dust formed



- **Total dust mass increases with increasing M_{ZAMS}**

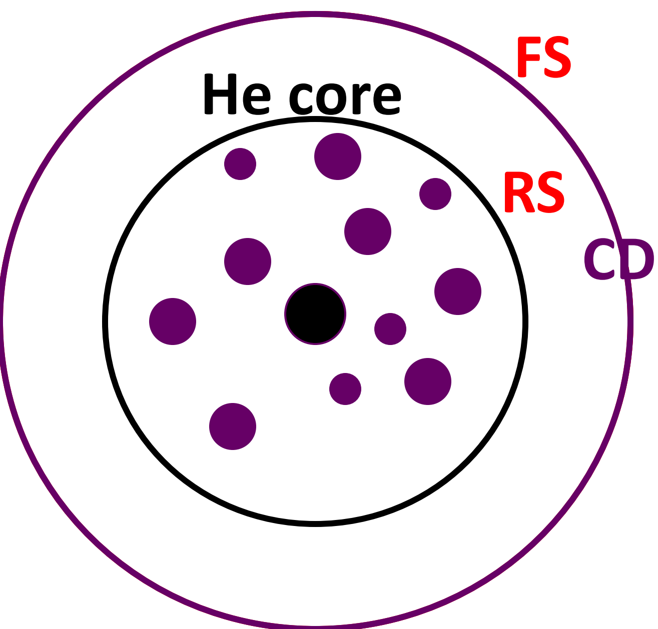
  SNe II : M_{dust} = 0.1-2 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.2-0.3

  PISNe : M_{dust} =10-60 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.3-0.5

- **Dust mass for the mixed case is generally larger than for the unmixed case**

3. Dust Evolution in SNRs

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



3-1-1. 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)

3-1-2. Initial condition for hydro calculations

・Hydrodynamical model of SNe (Umeda & Nomoto'02)

- 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 (homogeneous)

- gas temperature : T = 10^4 K
- gas density : $n_{H,0}$ = 0.1, 1, and 10 cm^{-3}

・Dust Model

- initial size distribution and spatial distribution of dust
  ➔ results of dust formation calculations
- treating as a test particle

The calculation is performed from 10 yr up to ~10^6 yr

3-2-1. Dynamics of dust

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

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

$\rho_{\rm d}$; mass density of a grain

A_i ; the number abundance of gas species i normarized by $n_{\rm H}$

$$G_i(s_i) = \left(s_i^2 + 1 - \frac{1}{4s_i^2} \right) erf(s_i) + \left(s_i + \frac{1}{2s_i} \right) \frac{e^{-s_i^2}}{\sqrt{\pi}}$$

$$\Downarrow$$

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

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

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

- dust destruction by sputtering (e.g., Dwek, Foster & Vancura 1996)

$$\frac{da}{dt} = -\frac{m_{\rm sp}}{4\pi a^2 \rho_{\rm d}} \sum_i \mathcal{R}(Y_i(E))$$

$Y_i(E) = 2Y_i^0(E)$; the angle-averaged sputtering yield

$m_{\rm sp}$; average mass of the sputtered atoms

· rate equation over a modified Maxwellian distribution of gas taken account of relative velocity of dust to gas (e.g., Shull 1978)

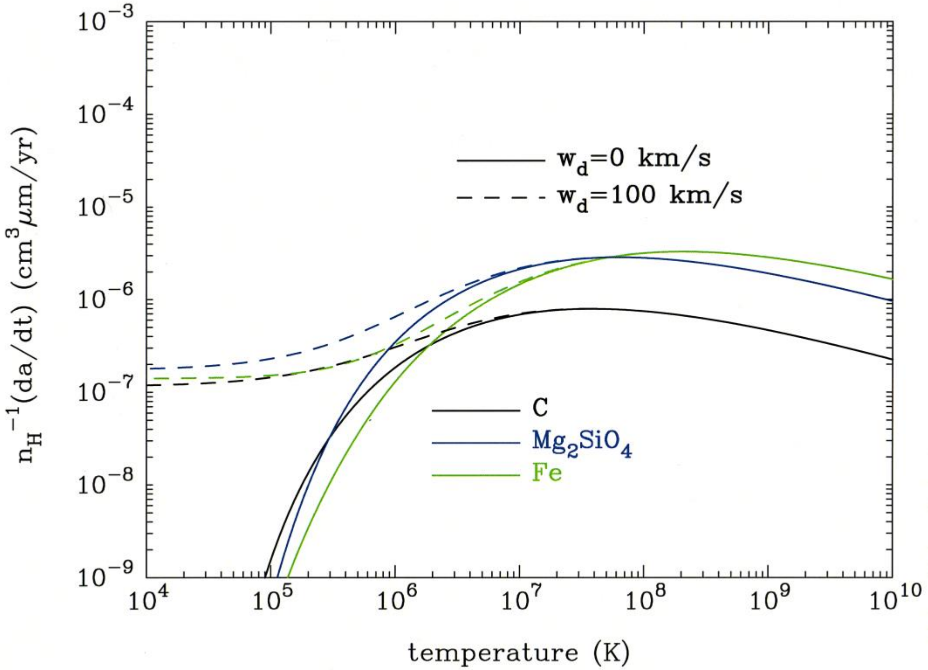
$$\mathcal{R}(X_i(\epsilon)) = n_{\rm H} A_i \pi a^2 \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} \frac{e^{-s_i^2}}{2s_i} \int \sqrt{\epsilon} e^{-\epsilon} \sinh(2s_i\sqrt{\epsilon}) X_i(\epsilon) d\epsilon$$

where $\epsilon = E/kT$

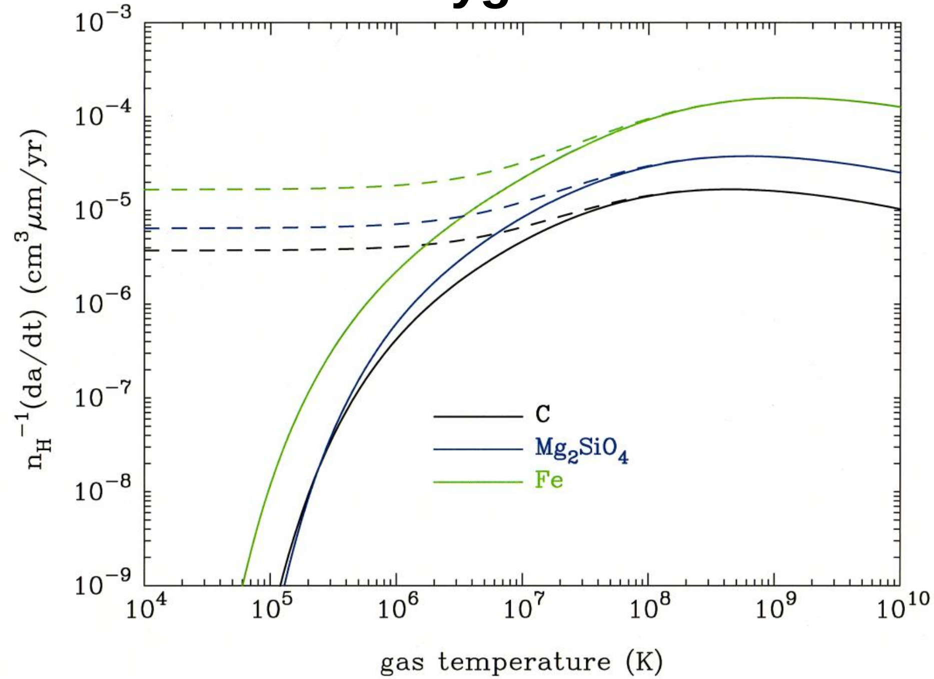
3-2-3. Erosion rate of dust by sputtering

Nozawa+'06, ApJ, 648, 435

for primordial composition gas



for oxygen ions

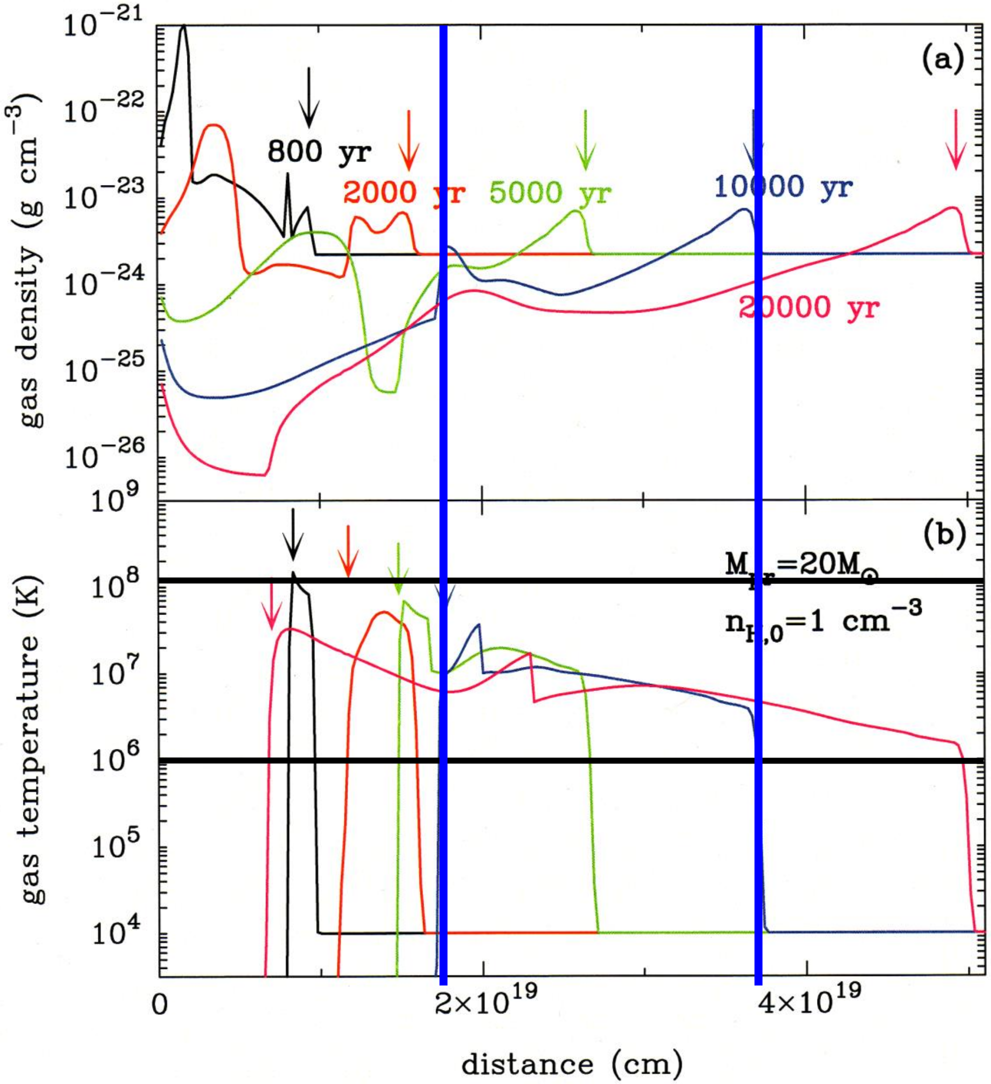


- **erosion rate by sputtering quickly increases above 10^5 K and peaks at 10^7 -10^8 K**

- **erosion rate : $da / dt \sim 10^{-6}\, n_H$ μm yr^{-1} cm^3 for the primordial gas (H and He) at $T > 10^6$ K**

3-3-1. Temperature and density of gas in SNRs

Nozawa+'07, ApJ, 666, 955



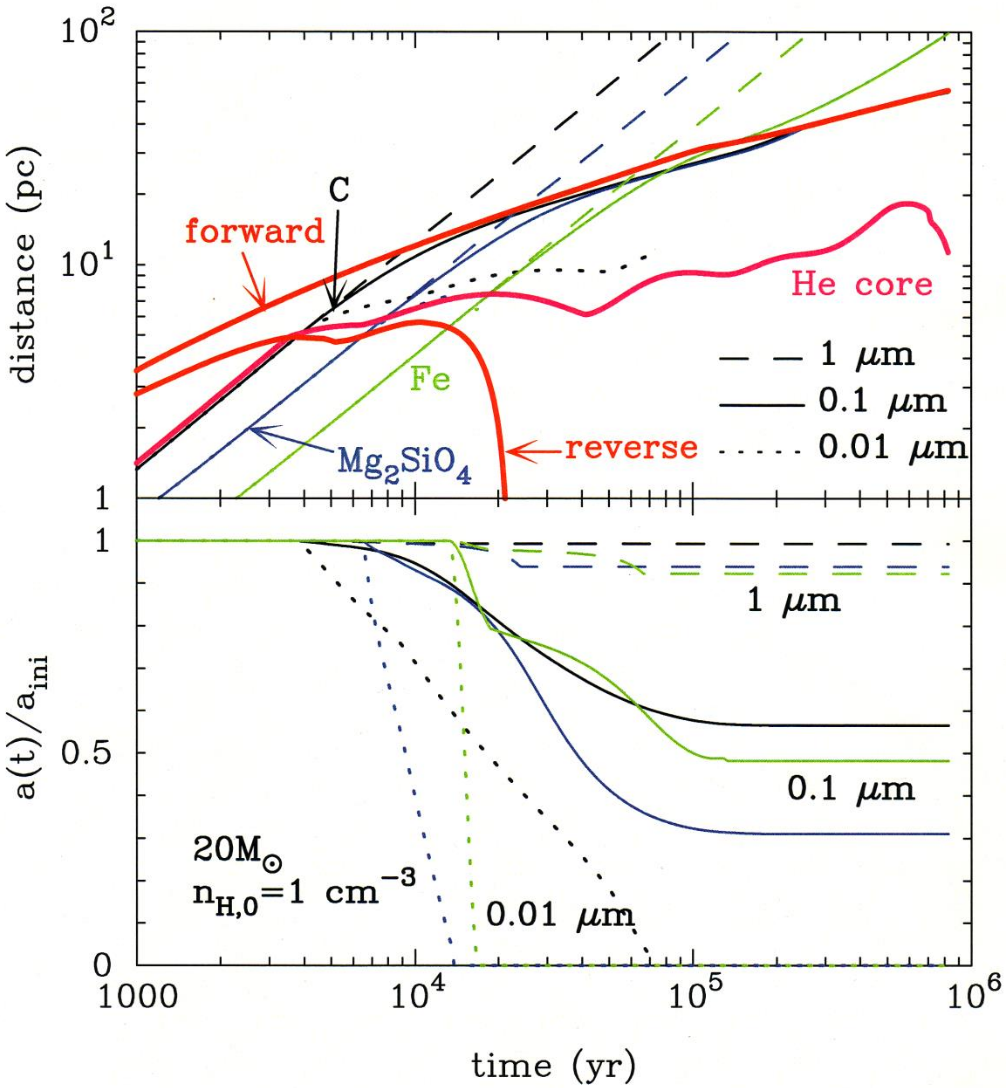
Model : M_{pr}= 20 Msun (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

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 the shocked hot gas are eroded by sputtering

3-3-2. Evolution of dust in SNRs

Nozawa+'07, ApJ, 666, 955



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

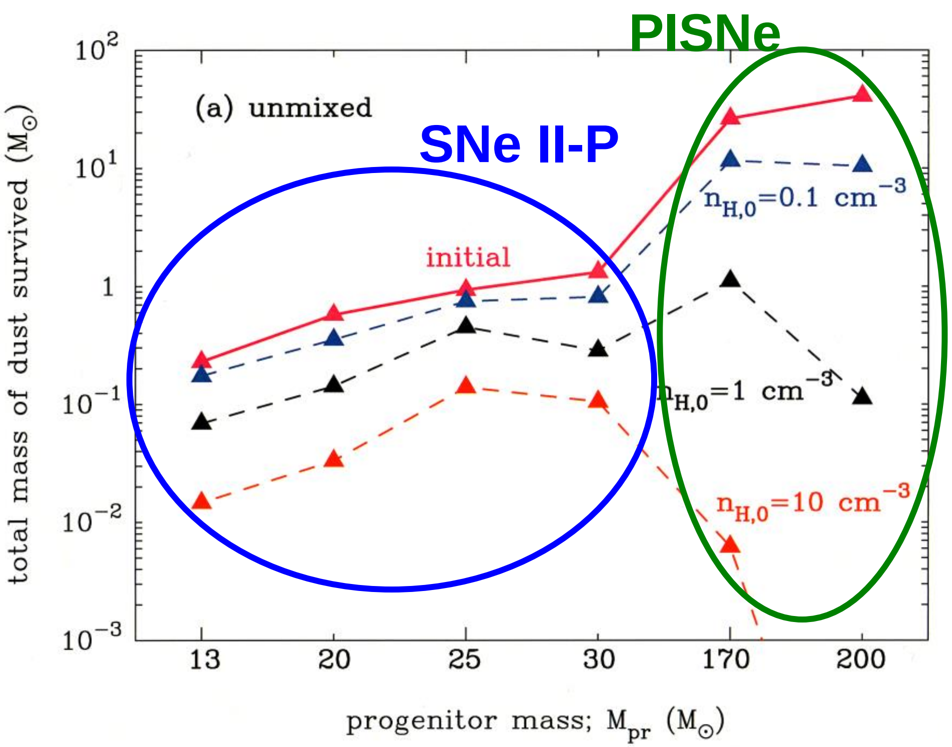
Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

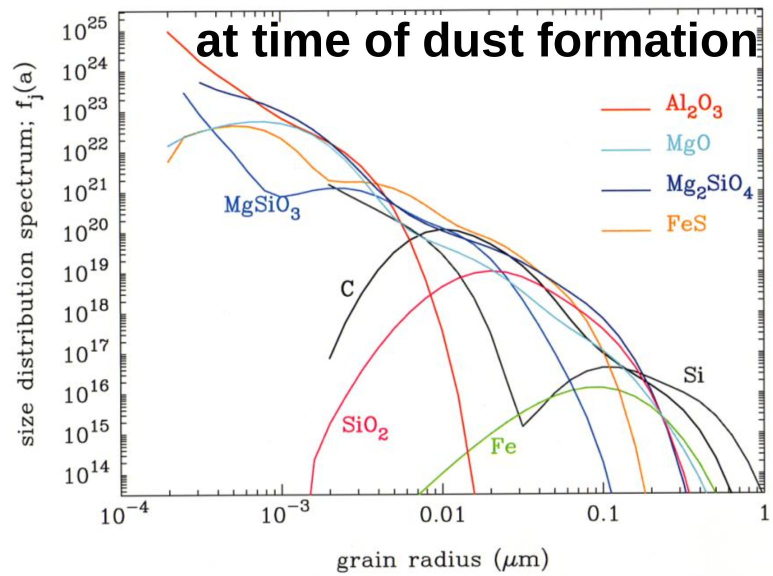
The evolution of dust heavily depends on the initial radius and composition

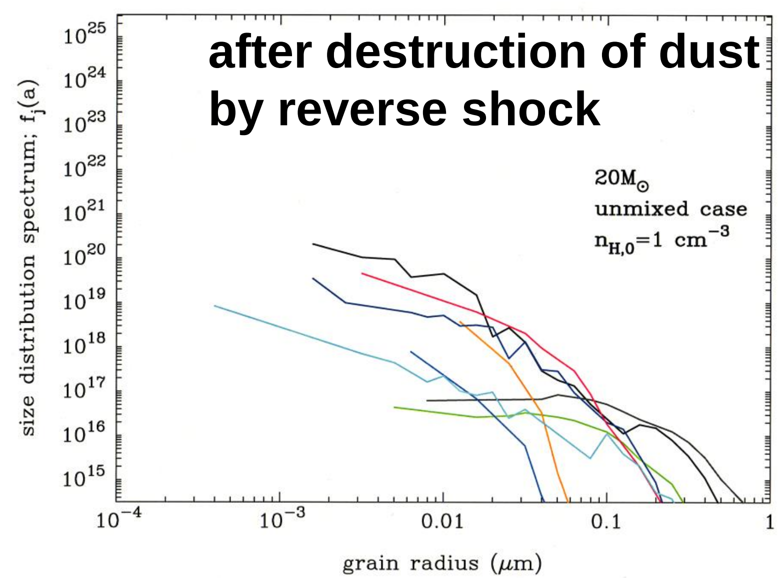
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

3-3-3. Dust mass and size ejected from SN II-P

Nozawa+'07, ApJ, 666, 955







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

size distribution of dust after RS destruction is domimated by large grains (> 0.01 μm)

3-4. Summary of dust production in Pop III SNe

- **Various species of dust form in the unmixed ejecta**
  (almost all Fe, Mg, and Si atoms are locked in dust)

- **The fate of newly formed dust within primordial SNRs strongly depends on the initial radii and compositions.**

- **The size distribution of dust surviving the destruction in SNRs is weighted to relatively large size (> 0.01 μm).**

- **The total mass of dust injected into the ISM decreases with increasing the ambient gas density**

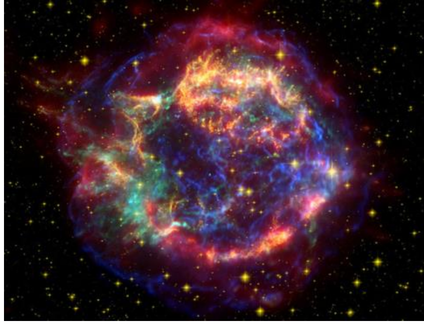
  for $n_{H,0}$ = 0.1-1 cm^{-3}

  SNe II-P ➔ M_{dust} = 0.1-0.8 M_{sun}

  PISNe ➔ M_{dust} = 0.1-15 M_{sun}

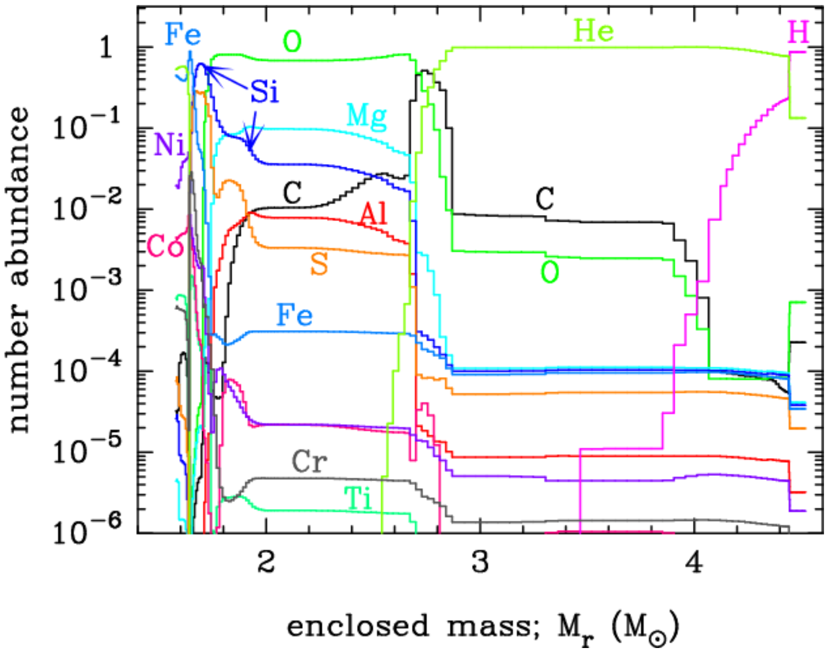
3. Formation of dust grains in various types of SNe

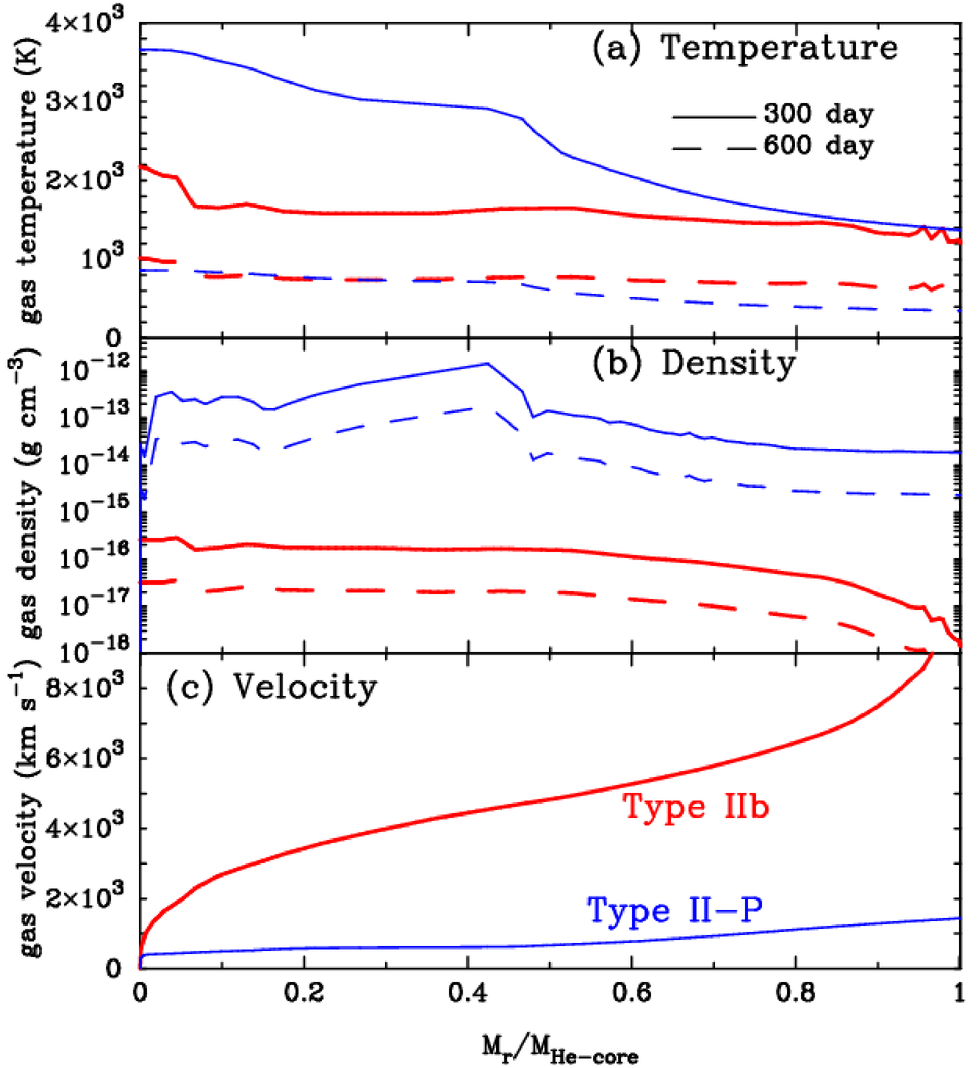
5-1. Dust formation in Type IIb SN



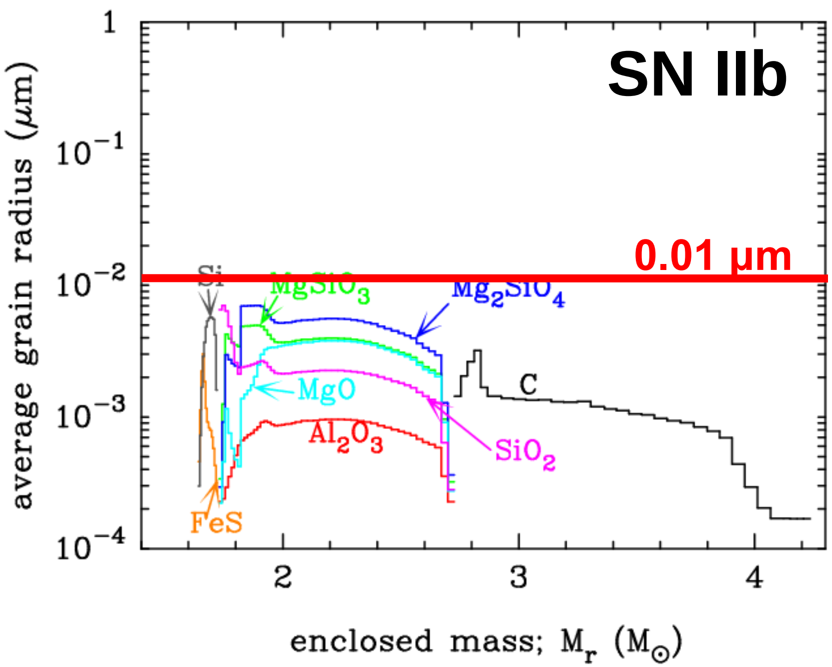
○ SN IIb model (SN1993J-like model)

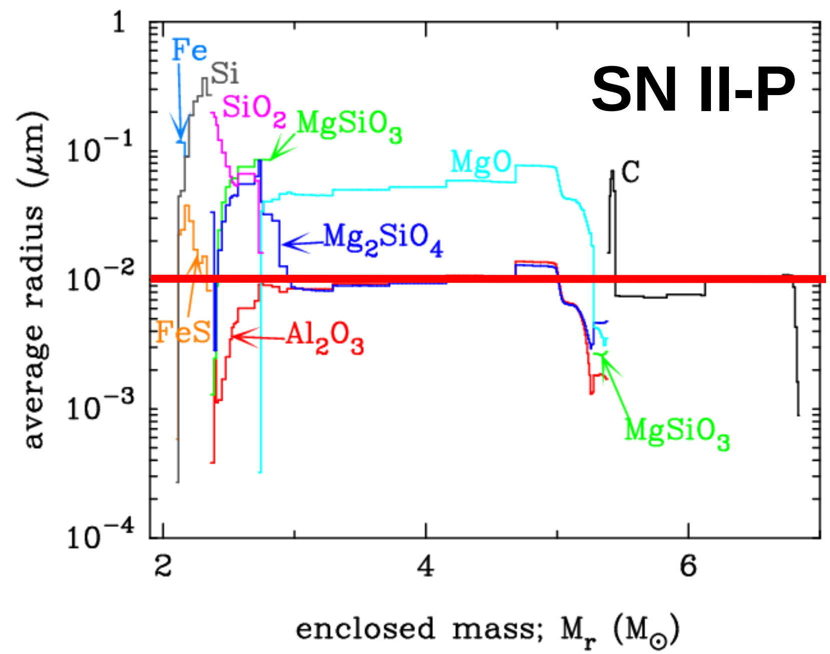
- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1
- $M(^{56}Ni)$ = 0.07 Msun





5-2. Dependence of dust radii on SN type





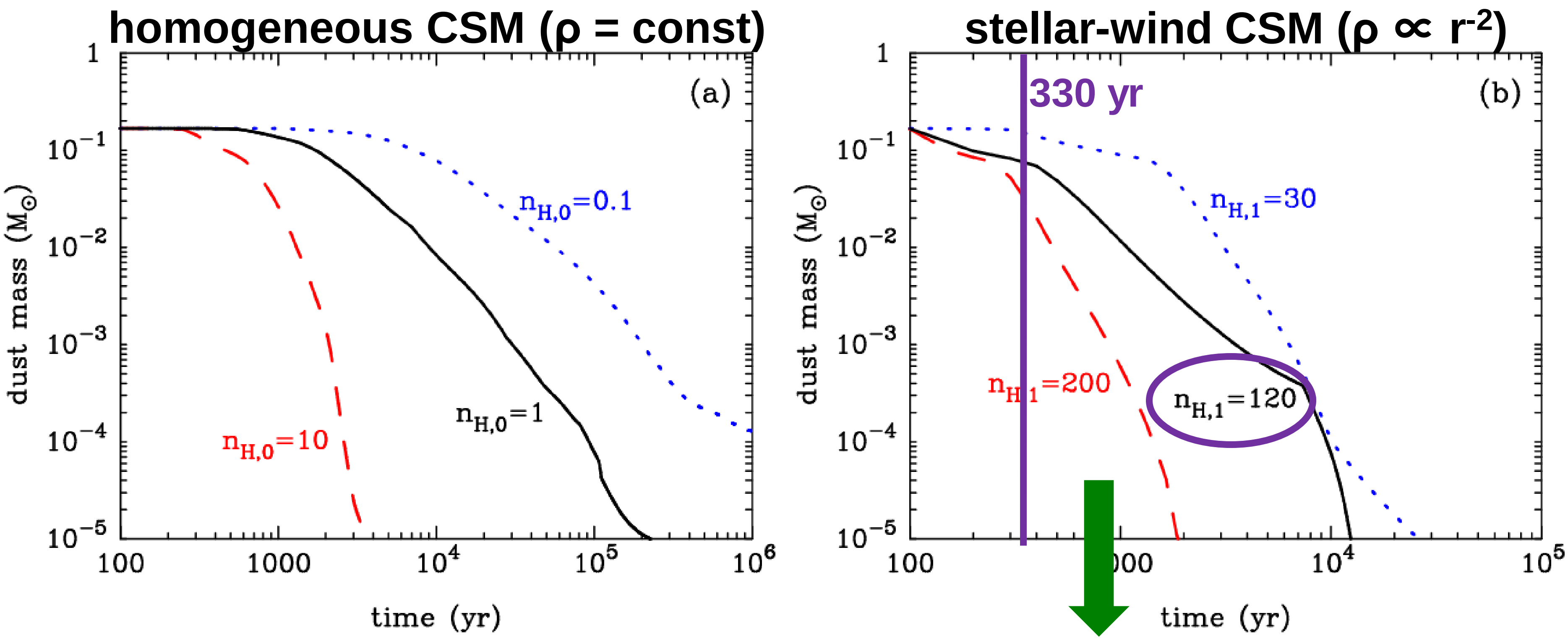
— condensation time of dust **300-700 d** after explosion

— total mass of dust formed
- **0.167 Msun in SN IIb**
- **0.1-1 Msun in SN II-P**

Nozawa+'10, ApJ, 713, 356

— the radius of dust formed in H-stripped SNe is small
- **SN IIb without massive H-env ➔ adust < 0.01 μm**
- **SN II-P with massive H-env ➔ adust > 0.01 μm**

5-3. 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

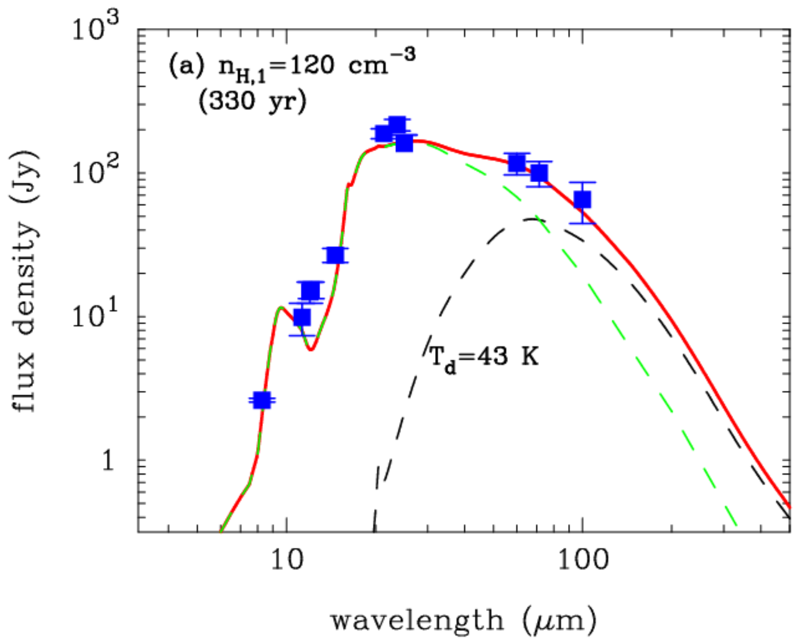
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

➔ small radius of newly formed dust

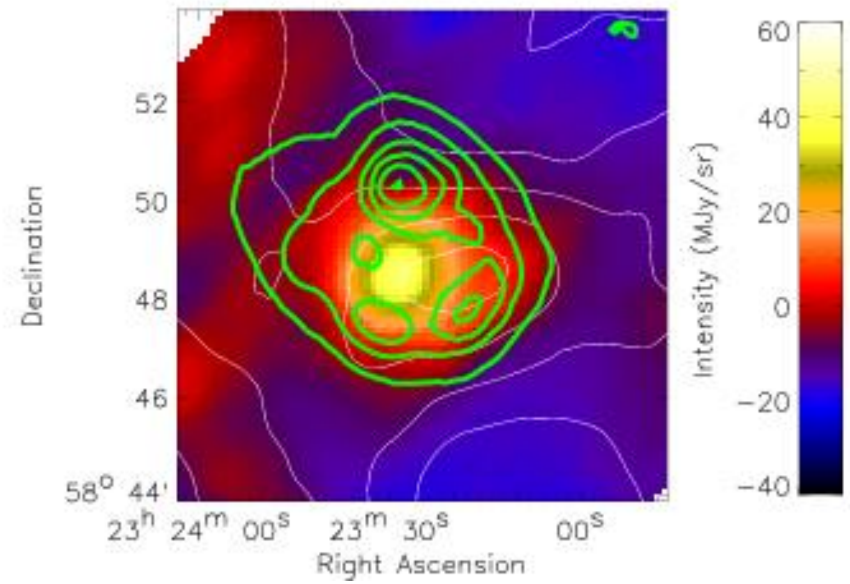
➔ early arrival of reverse shock at dust-forming region

Nozawa+'10, ApJ, 713, 356

5-4. IR emission from dust in Cas A SNR



AKARI corrected 90 μm image



- 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 et al. 2010, 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)

6. Summary of this talk

・ SNe are important sources of dust?

— maybe, Yes in the early universe

(at least, to serve the seeds for grain growth in the ISM)

・ Size of newly formed dust depends on types of Sne

— H-retaining SNe (Type II-P) : a_{ave} > 0.01 μm

— H-stripped SNe (Type IIb/Ib/Ic and Ia) : a_{ave} < 0.01 μm

➔ dust is almost completely destroyed in the SNRs

➔ H-stripped SNe may be poor producers of dust

・ Our model treating dust formation and evolution self-consistently can reproduce IR emission from Cas A

・ Mass of dust in SNe must be dominated by cool dust

➔ FIR and submm observations of SNe are essential