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超新星放出ガス中でのダスト形成と衝撃波によるダストの破壊

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wpi World Premier International Research Center Initiative
IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Outline

1. Introduction
   - Properties of interstellar dust in the Galaxy
   - Observations of dust at high redshift

2. Formation and evolution of dust in Pop III Type II-P and pair-instability SNe

3. Formation of dust in various types of SNe

4. Implication and Summary

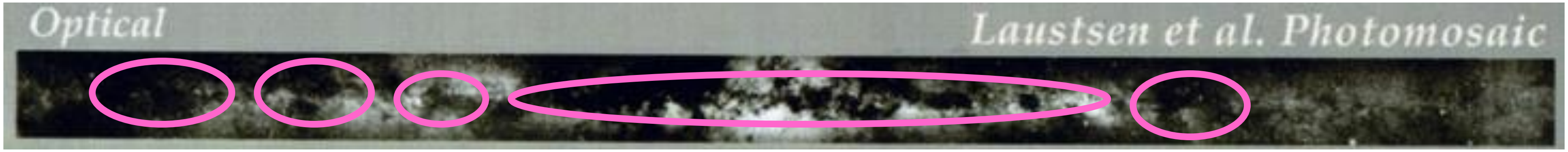
1. Introduction

1-1-1. Cosmic dust

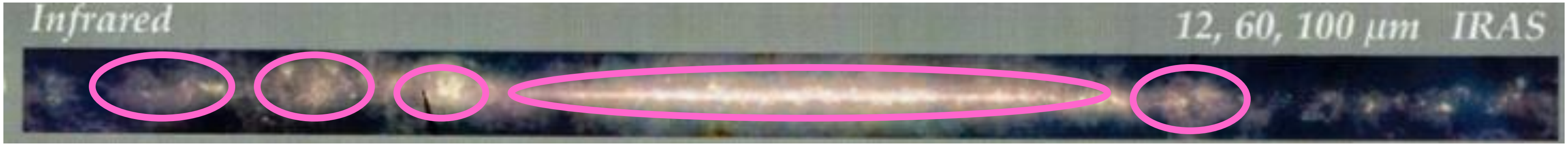
○ **Cosmic dust : solid particles with radii of a few nm to ~0.1 mm in astronomical environments**

interplanetary dust, interstellar dust, intergalactic dust …

Milky Way (optical)



Milky Way (infrared)



Dust grains absorb UV/optical lights and reemit it by their thermal radiation at IR wavelengths!

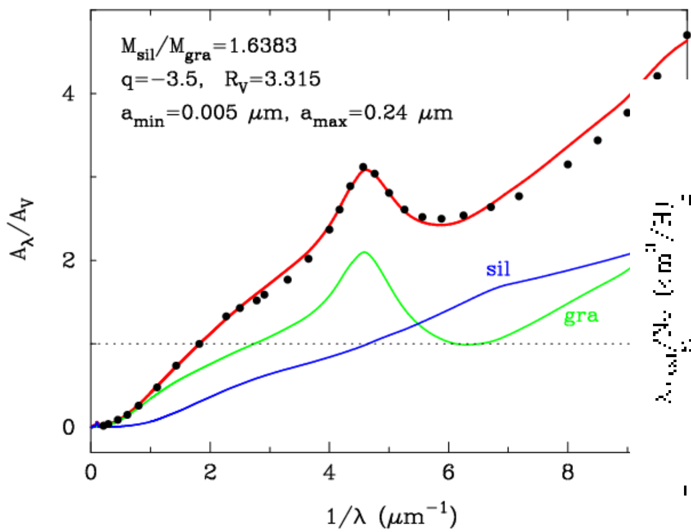
1-1-2. Interstellar dust in our Galaxy

○ **Dust in our Galaxy ➔ when and where is dust formed?**

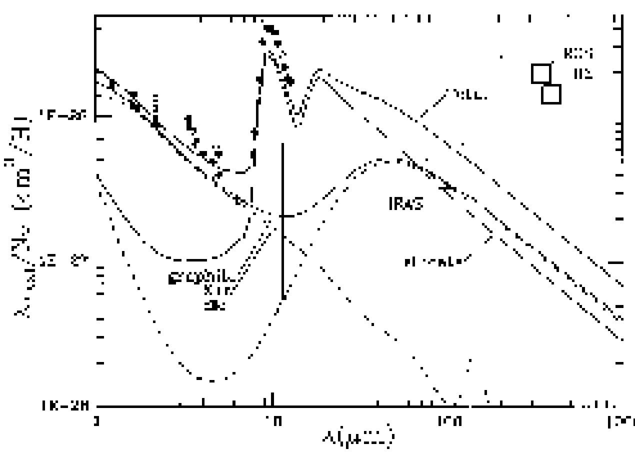
- **composition :** **graphite** (carbonaceous) grains
  silicate (SiO_2, $MgSiO_3$, $MgFeSiO_4$, …) grains
- **size :** $n(a) = f(a)da = a^{-3.5}\,da$ (**0.005~0.25 μm**)
- **amount :** M_{dust} / M_{gas} ~ **1 / 140** (~10^9 Msun)

➔ **MRN dust model (e.g., Mathis+'77; Draine & Lee'84)**

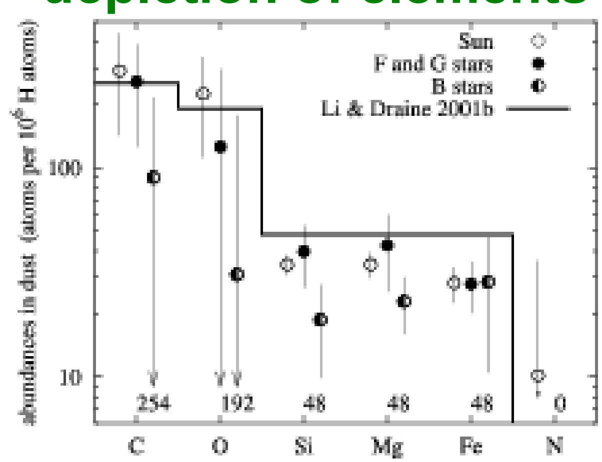
extinction curve



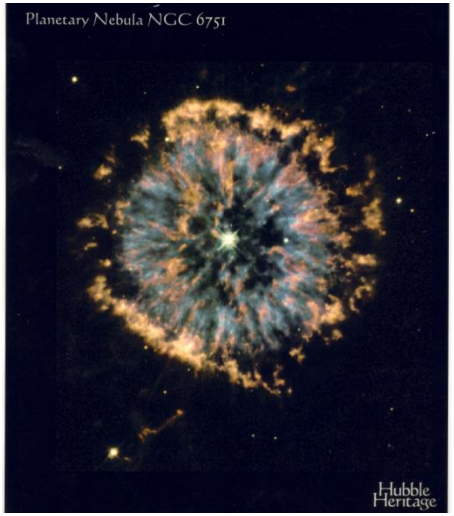
IR spectral feature

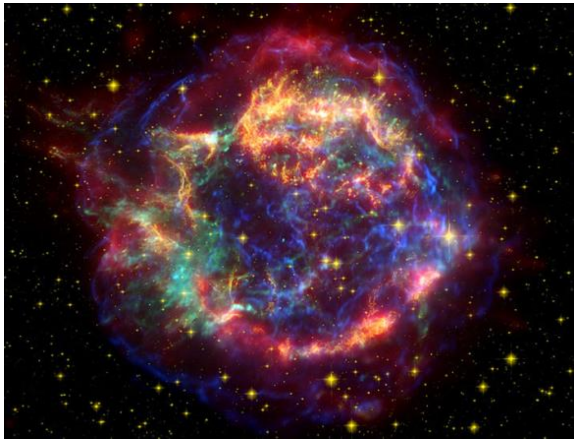


depletion of elements



1-1-3. Formation site of dust





○ Formation sites of dust

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

– **mass-loss winds of AGB stars**

– **expanding ejecta of supernovae**

– molecular clouds (grain growth only)

– red giant, W-R stars, novae, protoplanetary disk …

➔ relative contribution of these sources is unclear!

1-2-1. Discovery of massive dust at z > 5

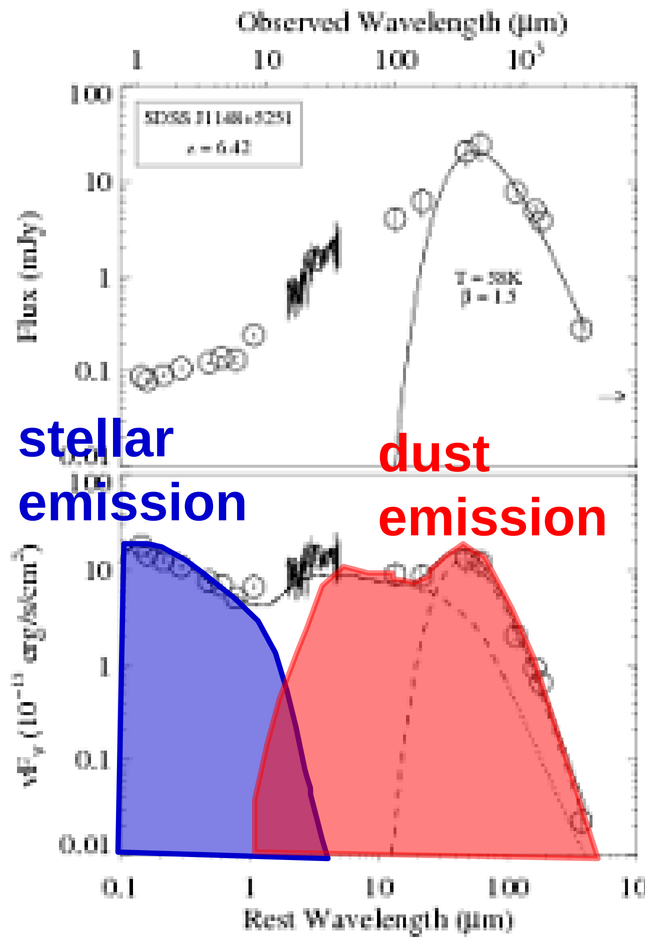
- The submm observations have confirmed the presence of dust in excess of 10^8 Msun in 30% of z > 5 quasars

SDSS J1148+5251 at z=6.4

- age : 890 Myr
- IR luminosity : ~(1-3)x10^{13} Lsun
- dust mass : (2-7)x10^8 Msun
- SFR : ~3000 Msun/yr (Salpeter IMF)
- gas mass : ~3x10^{10} Msun (Walter+'04)
- metallicity : ~solar

***Herschel (3.5m)**

- PACS : 70, 100, 160 μm
- SPIRE 250, 350, 500 μm



Leipski+'10, A&A, 518, L34

1-2-2. What are dust sources in high-z quasar?

・ **Supernovae (Type II SNe)**

➔ ~0.1 Msun per SN is sufficient
(Morgan & Edmunds'03; Maiolino+'06; Li+'08)

➔ > 1 Msun per SN (Dwek+'07)

・ **AGB stars** + SNe

(Valiante+'09; Gall+'11; Dwek & Cherchneff'11)

➔ 0.01-0.05 Msun per AGB (Zhukovska & Gail '08)

➔ 0.01-1 Msun per SN

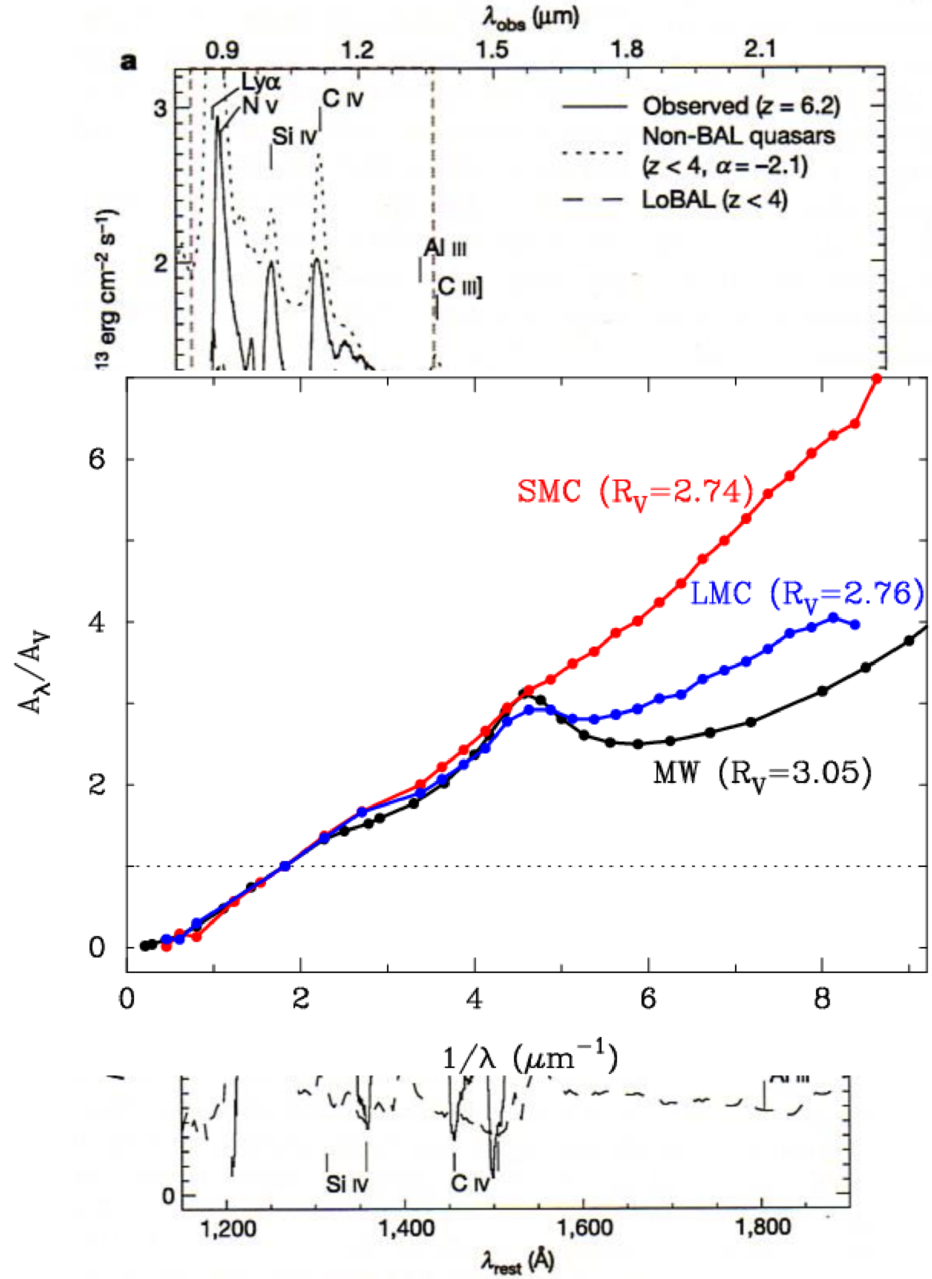
・ **Grain growth in dense clouds** + AGB stars + SNe

(Draine'09; Michalowski+'10; Pipino+'11; Mattsson'11)

➔ $\tau_{growth} \sim 10^7 (Z / Z_{sun})$ yr

・ **Quasar outflows** (Elvis+'02)

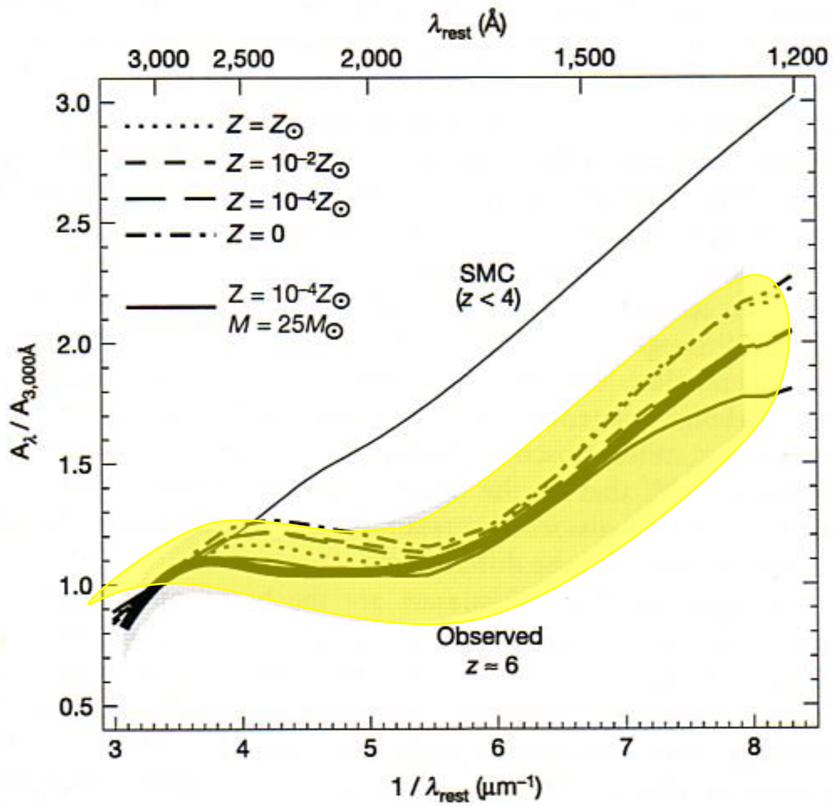
1-3-1. Extinction curves at high-z quasars



Maiolino+'04, Nature, 431, 533

SDSS J1048+4637 at z=6.2

Broad absorption line (BAL) quasars



different dust properties from those at low redshift

1-3-2. Extinction curves at 3.9 < z < 6.4

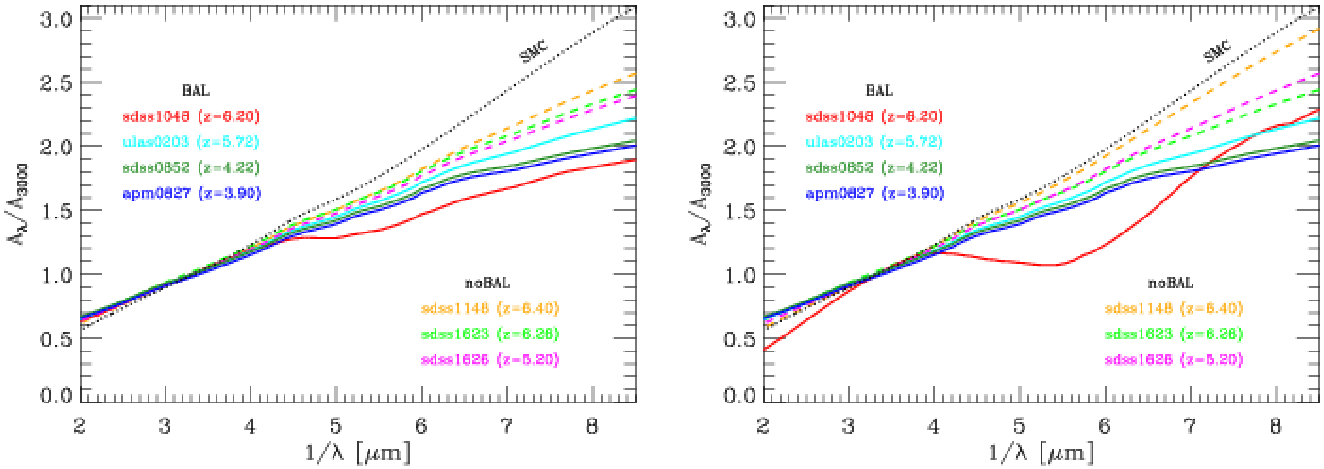


Fig. 4. Best fit extinction curves of reddened quasars. The solid lines are for BAL quasars, while dashed lines are for non-BAL quasars. For comparison the SMC extinction curve is also shown and labeled in the Figure (dotted black line). The panel on the left shows the results assuming a minimum intrinsic slope $\alpha_{\lambda,min} = -2.9$, while the panel on the right is obtained with $\alpha_{\lambda,min} = -2.6$.

Gallerani+'10, A&A, 523, 85

7 of 33 requires substantial dust extinction, which deviates from the SMC

The mean Extinction curves for BAL quasars deviates from the SMC with level > 95 %

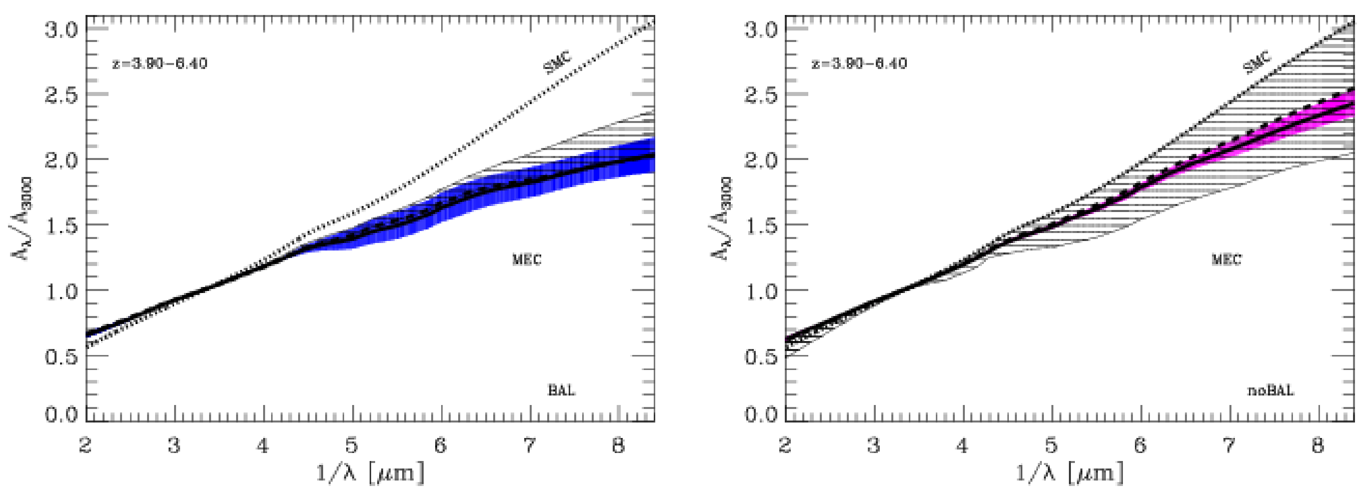


Fig. 6. Mean (MEC) and simultaneous/global (GEC) extinction curve of reddened quasars divided into BAL (left) and non-BAL (right). The coding is the same as in Fig. 5.

1-4. Summary of Introduction

- There is clear evidence for huge amounts of dust at z > 4, but the dust sources remain unexplained

  ➔ SNe? AGB stars? grain growth in the dense clouds? quasar outflow? any other sources?

- Properties (composition & size) of dust at high z are likely to be different from those at low z

  ➔ high-z quasars and GRBs are good targets to probe the extinction curves in their host galaxies

At z > 4, short-lived SNe II (M = 8-40 M_{sun}) dominate the dust production over AGB stars (M < 8 M_{sun}) ??

1-5. Aim of our study

- Dust absorbs stellar light and emits it by thermal radiation

  ➔ plays a crucial role in interpreting the evolution history of the universe from high-z observations

- Dust has great impacts on formation processes of stars

  – forming molecules (mainly H_2) on the surface (e.g., Cozaux & Spaans'04)

  – providing additional cooling pathways of gas through thermal emission (e.g., Omukai+'05; Schneider+'06)

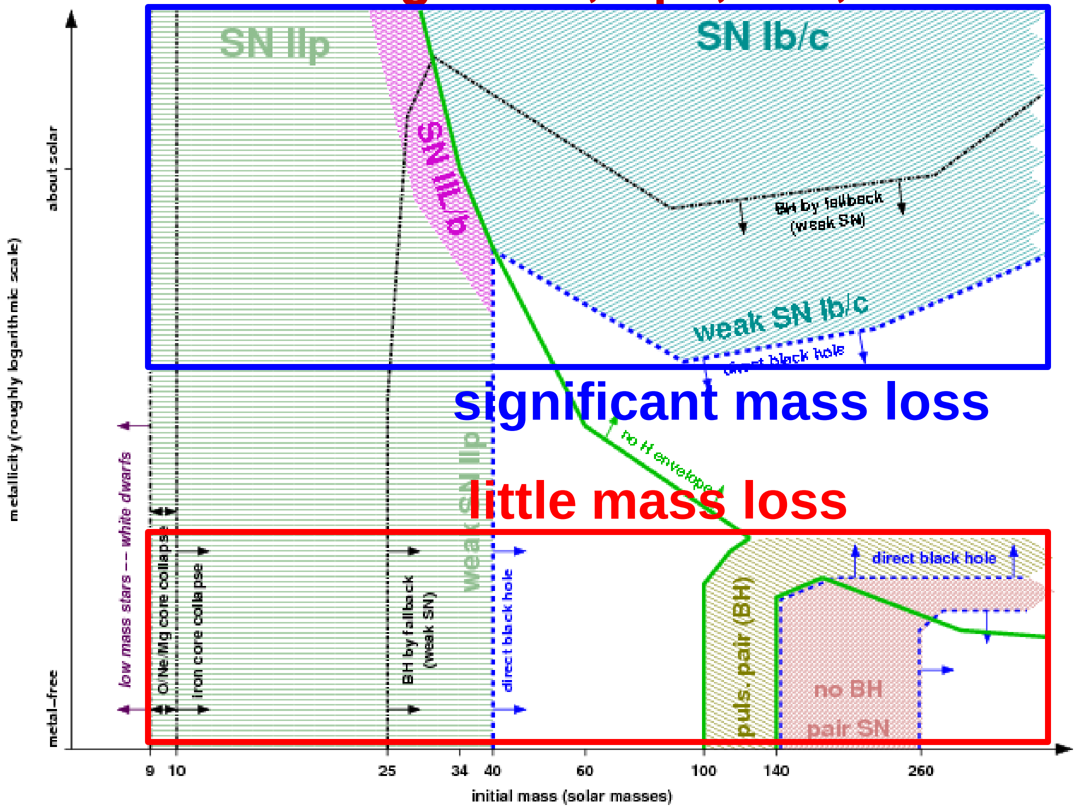
  – controlling the energy balance in interstellar space

We aim at revealing the evolution of composition, size, and amount of dust, considering formation and destruction processes of dust consistently!!

2. Formation and evolution of dust in Pop III SNe II-P and PISNe

2-0. Death of single massive stars

Heger+'03, ApJ, 591, 288



At high metallicity

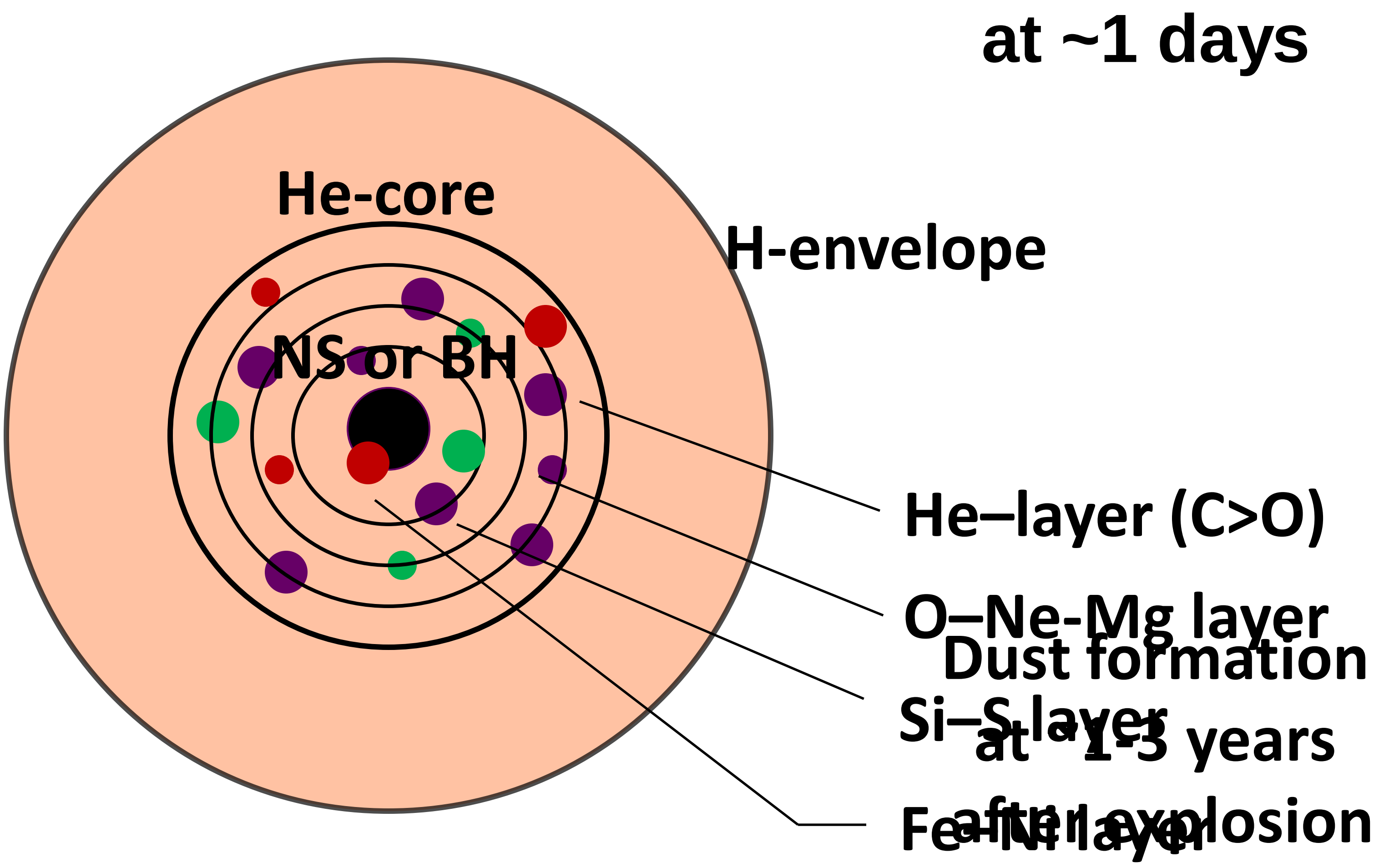
- **Type II-P SNe:**
  - M_{ZAMS}=8-25 M_{sun}?
  - massive H envelope
- **Type IIb SNe:**
  - M_{ZAMS} = 25-35 M_{sun}?
  - very thin H-envelope
- **Type Ib/Ic SNe :**
  - M_{ZAMS} > 35 M_{sun}?
  - no H / He envelope

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 Pop III SNe

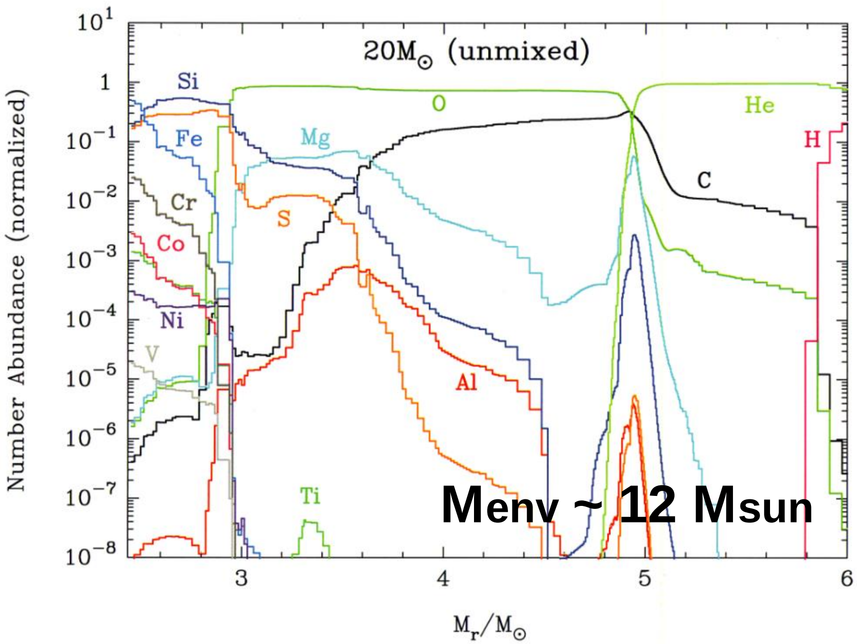


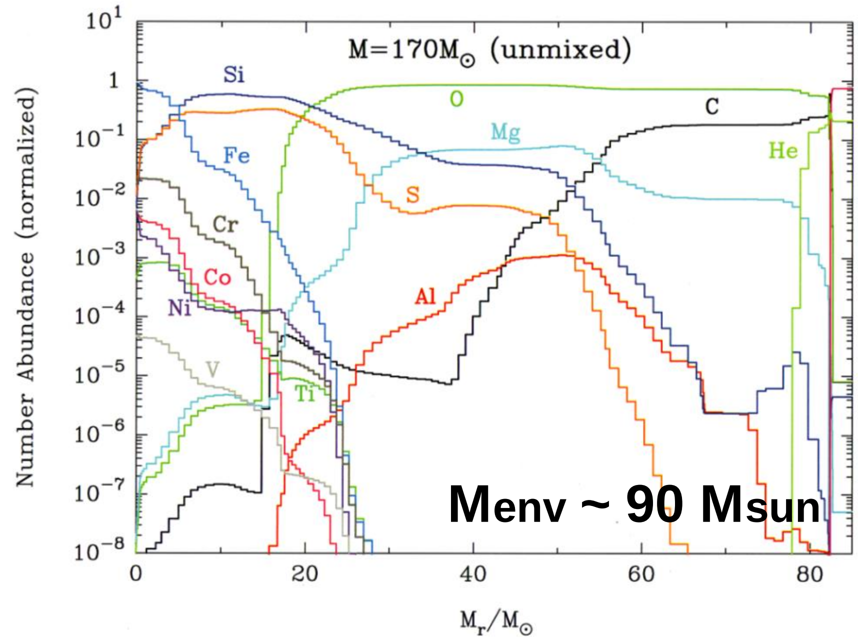
2-1-1. Dust formation in primordial SNe

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)
- no mixing of elements within the He-core
- complete formation of CO and SiO

2-1-1.5. 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
$Fe_{(s)}$	$Fe_{(g)} \rightarrow Fe_{(s)}$
$FeS_{(s)}$	$Fe_{(g)} + S_{(g)} \rightarrow FeS_{(s)}$
$Si_{(s)}$	$Si_{(g)} \rightarrow Si_{(s)}$
$Ti_{(s)}$	$Ti_{(g)} \rightarrow Ti_{(s)}$
$V_{(s)}$	$V_{(g)} \rightarrow V_{(s)}$
$Cr_{(s)}$	$Cr_{(g)} \rightarrow Cr_{(s)}$
$Co_{(s)}$	$Co_{(g)} \rightarrow Co_{(s)}$
$Ni_{(s)}$	$Ni_{(g)} \rightarrow Ni_{(s)}$
$Cu_{(s)}$	$Cu_{(g)} \rightarrow Cu_{(s)}$
$C_{(s)}$	$C_{(g)} \rightarrow C_{(s)}$
$SiC_{(s)}$	$Si_{(g)} + C_{(g)} \rightarrow SiC_{(s)}$
$TiC_{(s)}$	$Ti_{(g)} + C_{(g)} \rightarrow TiC_{(s)}$
$Al_2O_{3(s)}$	$2Al_{(g)} + 3O_{(g)} \rightarrow Al_2O_{3(s)}$
$MgSiO_{3(s)}$	$Mg_{(g)} + SiO_{(g)} + 2O_{(g)} \rightarrow MgSiO_{3(s)}$
$Mg_2SiO_{4(s)}$	$2Mg_{(g)} + SiO_{(g)} + 3O_{(g)} \rightarrow Mg_2SiO_{4(s)}$
$SiO_{2(s)}$	$SiO_{(g)} + O_{(g)} \rightarrow SiO_{2(s)}$
$MgO_{(s)}$	$Mg_{(g)} + O_{(g)} \rightarrow MgO_{(s)}$
$Fe_3O_{4(s)}$	$3Fe_{(g)} + 4O_{(g)} \rightarrow Fe_3O_{4(s)}$
$FeO_{(s)}$	$Fe_{(g)} + O_{(g)} \rightarrow FeO_{(s)}$

2-1-2. Nucleation rate of dust

Steady-state classical nucleation rate

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

$$J_s(t) = 4\pi a_0^2 \alpha_s \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1^2(t) \frac{1}{3} \left(\frac{\mu}{\pi} \right)^{\frac{1}{2}} \exp\left[-\frac{4}{27} \frac{\mu^3}{(\ln S)^2} \right]$$

α_s : sticking probability of key species ($\alpha_s = 1$, in the calculations)

Ω : volume of the condensate per key species ($\Omega = 4\pi a_0^3/3$)

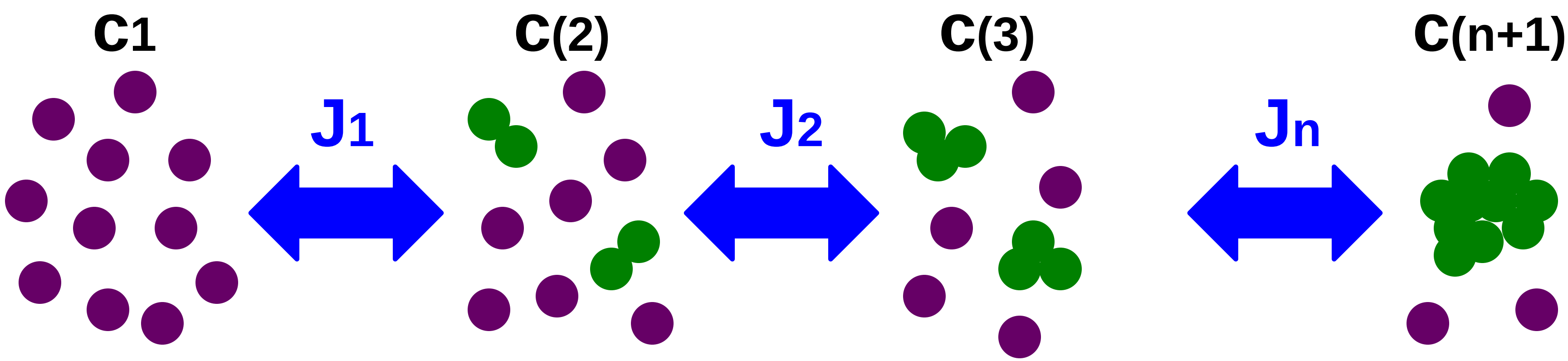
σ : surface energy of the condensate

m_1 : mass of key species

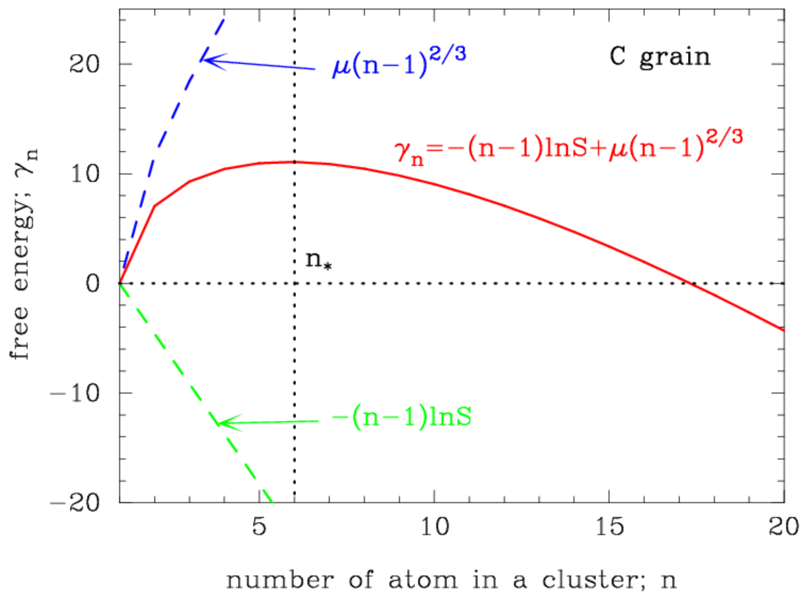
$c_1(t)$: number density of key species

μ : $\mu \equiv 4\pi a_0^2 \sigma / kT$; energy barrier for nucleation

2-1-2.5. Steady-state nucleation rate



$$J_s = J_1 = J_2 = \cdots = J_n$$
$$= \{ 1/(\alpha_1 c_1) + \sum 1/(\alpha_n c_1^2) \exp[g(n)] \}^{-1}$$



$$g(n) = -(n-1)\ln S + \mu(n-1)^{\frac{2}{3}}$$

$$(n_* - 1)^{\frac{1}{3}} = \frac{2\mu}{3\ln S}$$

2-1-3. Basic equations of dust formation

Equation of conservation for key species

$$1 - \frac{c_1(t)}{\tilde{c}_1(t)} = \int_{t_0}^{t} \frac{J(t')}{\tilde{c}_1(t')} \frac{4\pi}{3\Omega} r^3(t, t') dt'$$

$$V(t)\tilde{c}_1(t) - V(t)c_1(t) = \int_{t_0}^{t} V(t')J(t')n[r(t, t')]dt'$$

$$\frac{\quad}{\partial t} = \alpha_s \frac{\quad}{3} \left(\frac{\quad}{2\pi m_1} \right) c_1(t) = \frac{\quad}{3} a_0 \tau_{\rm coll}$$

$$\frac{\partial V_{\rm d}}{\partial t} = 4\pi r^2 \frac{\partial r}{\partial t} = \alpha_s \Omega 4\pi r^2 \langle v \rangle c_1(t)$$

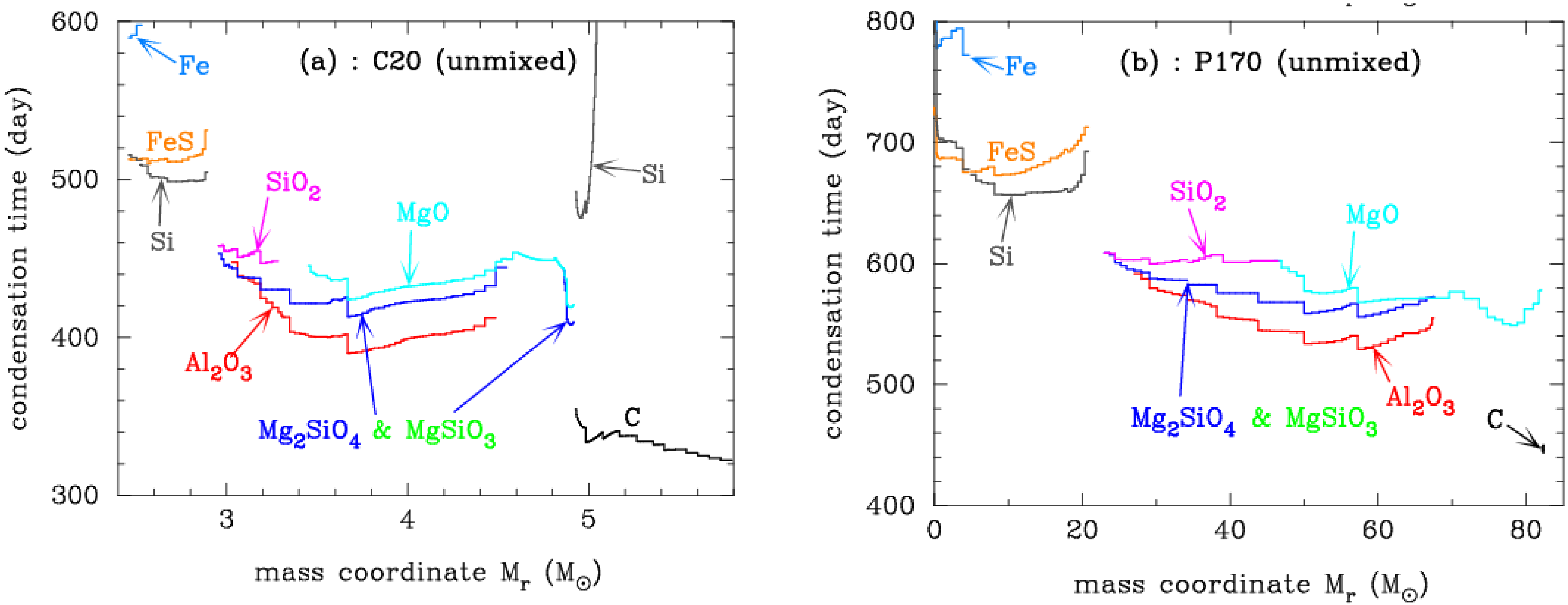
$$\tau_{\rm coll}^{-1}(t) = 4\pi a_0^2 \alpha_s \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1(t)$$

· ra ... $t_0)$

$$r(t, t_0) = r_* + \int_{t_0}^{t} \frac{1}{3} a_0 \tau_{\rm coll}^{-1}(t') dt'$$

2-1-4. Dust formed in primordial SNe

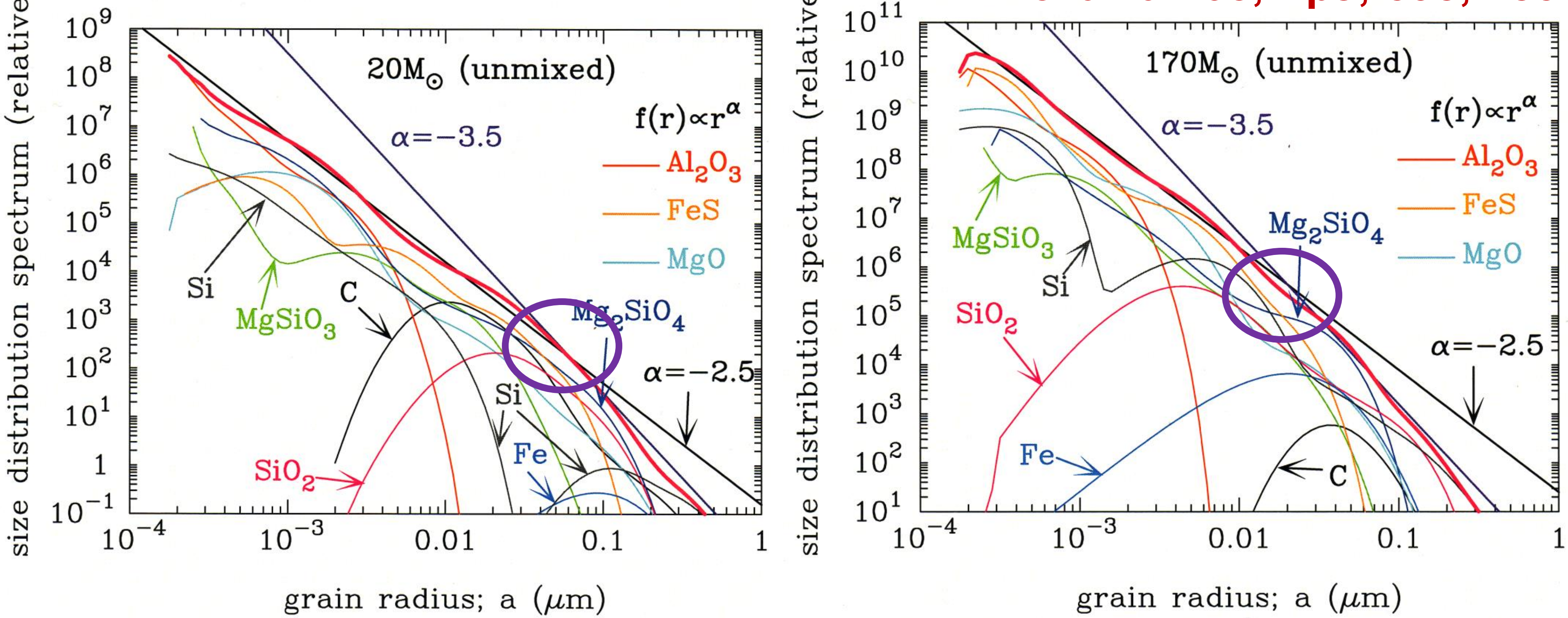
Nozawa+'03, ApJ, 598, 785



- 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

2-1-5. Size distribution of newly formed dust

Nozawa+'03, ApJ, 598, 785



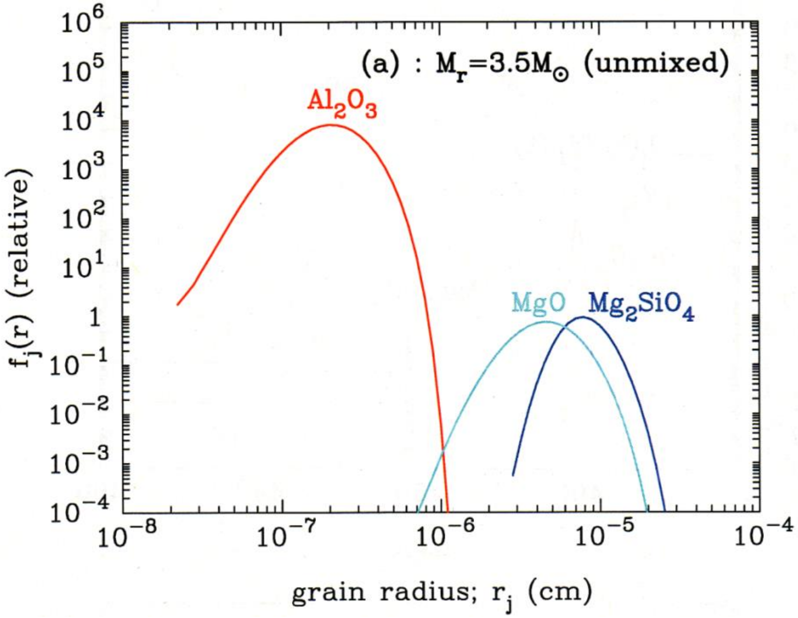
- grain radii range from a few A up to 1 μm
- average dust radius is smaller for PISNe than SNe II-P

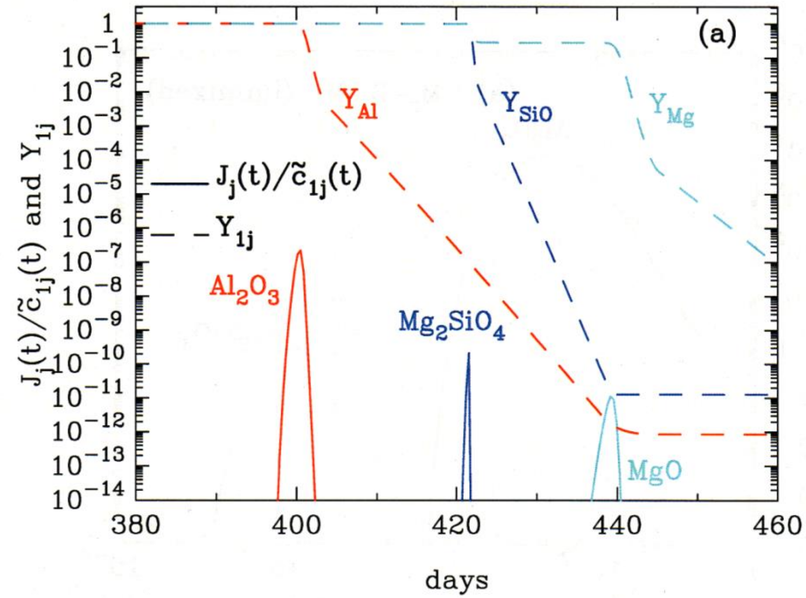
amount of newly formed dust grains

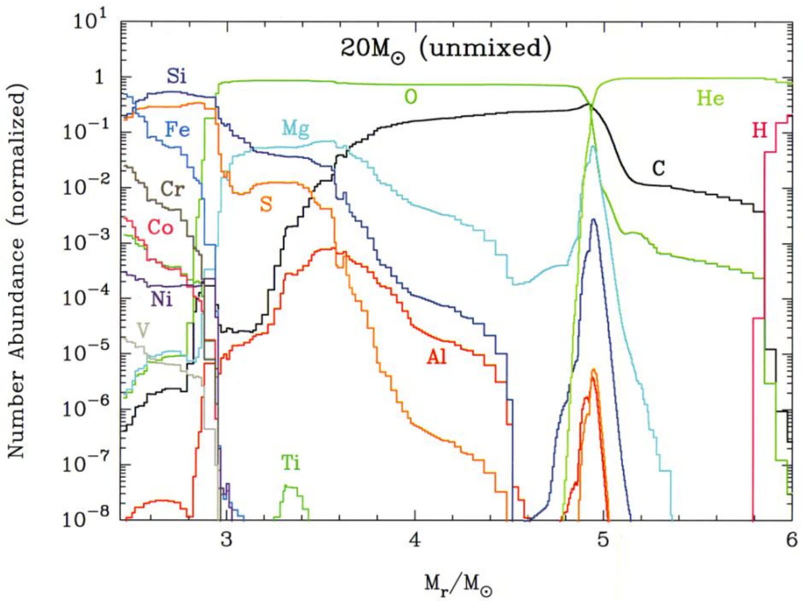
SNe II-P : M_{dust} = 0.1-1 M_{sun}, M_{dust} / M_{metal} = 0.2-0.3

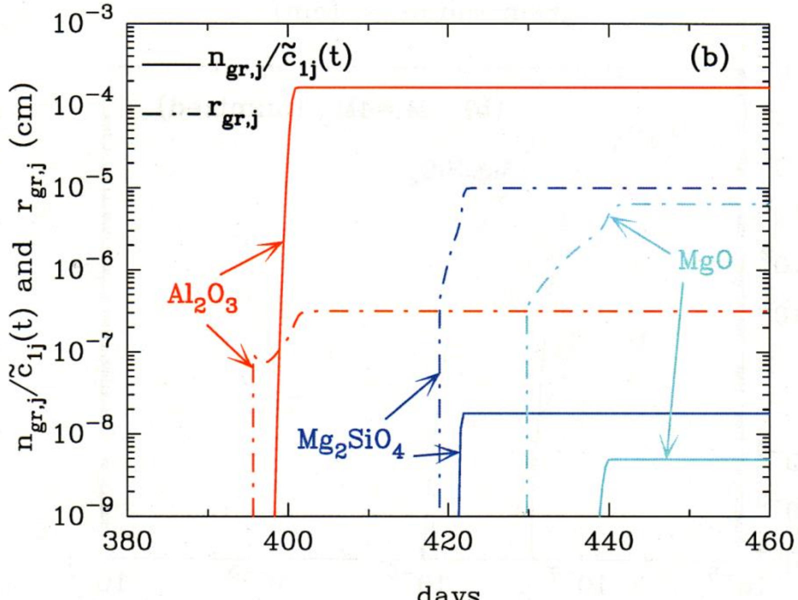
PISNe : M_{dust} =20-40 M_{sun}, M_{dust} / M_{metal} = 0.3-0.4

2-1-6. Behavior of dust formation



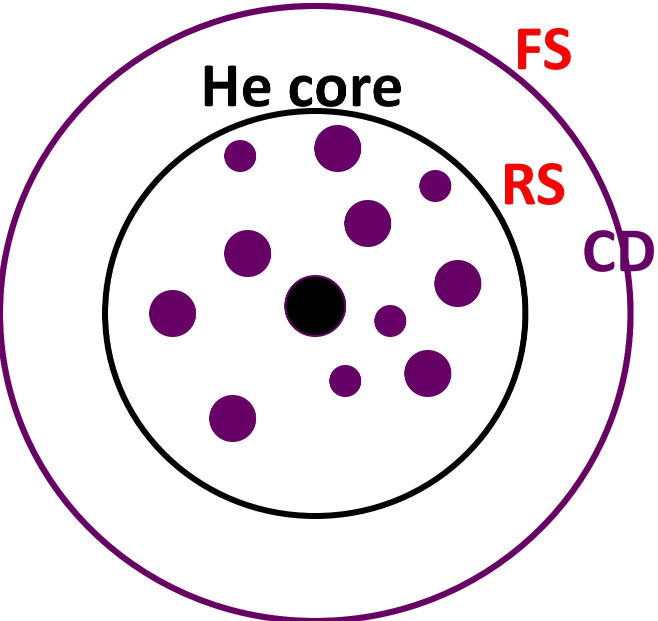






2-2. Dust Evolution in SNRs

$T = (1\text{-}2)\times10^4$ K
$n_{H,0} = 0.1\text{-}1\ cm^{-3}$



2-2-1. Time evolution of shock wave

- 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)

2-2-2. Initial condition for shock waves

・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

2-2-3. Dynamics of dust

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

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

$$\begin{aligned} F_{\rm drag} &= m_{\rm d}\frac{dw_{\rm d}}{dt} = -\pi a^2 \sum n_i \langle v_i m_i v_i \cos\theta \rangle \\ \frac{dw_{\rm d}}{dt} &= -\frac{\pi a^2}{\frac{4}{3}\pi a^3 \rho_d} n_{\rm H} \sum A_i \langle v_i m_i v_i \cos\theta \rangle \\ &= -\frac{3n_{\rm H}}{4a\rho_d} kT \sum A_i G_i \end{aligned}$$

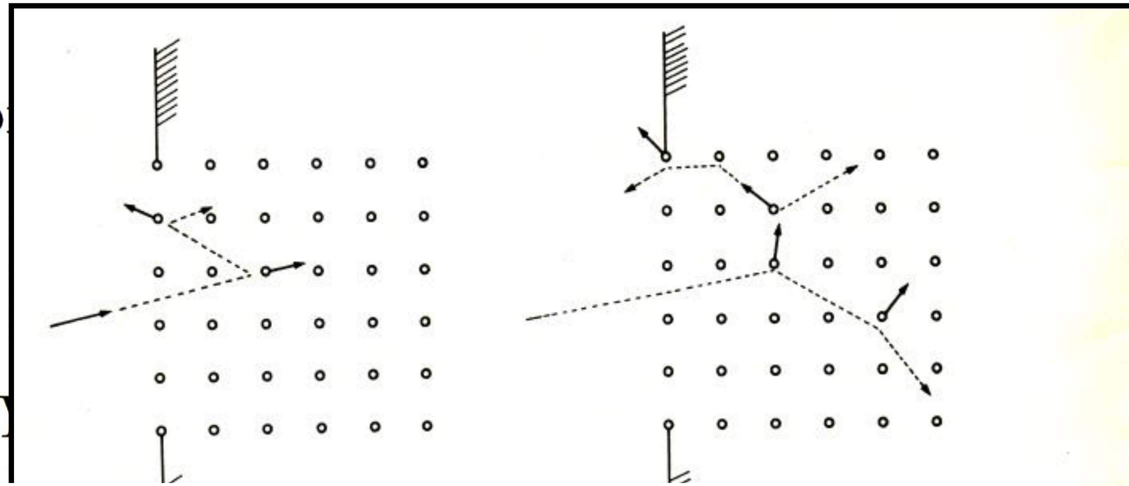
by $n_{\rm H}$

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

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

2-2-4. Erosion rate of dust by sputtering

• dust destructio 996)



$Y_i(E) = 2Y$

n

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

· rate s taken

acco)

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

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

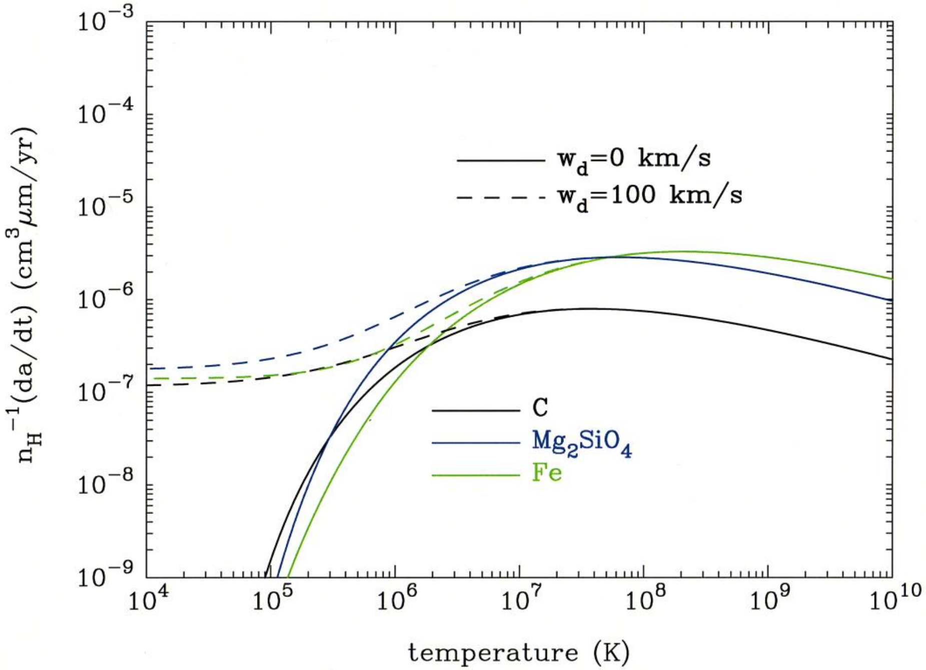
$$\frac{da}{dt} = -\frac{m_{\rm sp}}{2\rho_{\rm d}} n_{\rm H} \sum A_i \left(\frac{8kT}{\pi m_i}\right)^{1/2} \frac{e^{-s_i^2}}{2s_i} \times \int \epsilon^{\frac{1}{2}} e^{-\epsilon_i} \sinh(2 s_i \epsilon_i^{\frac{1}{2}}) Y_i^0(\epsilon_i) d\epsilon_i$$

w

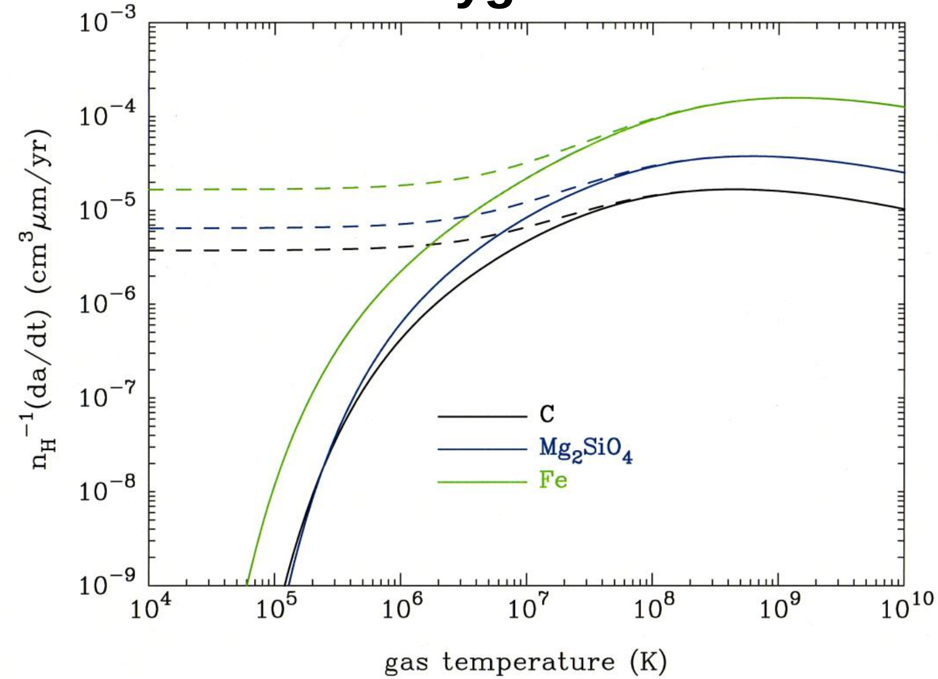
2-2-5. Erosion rate of dust by sputtering

Nozawa+'06, ApJ, 648, 435

for primordial composition gas



for oxygen ions

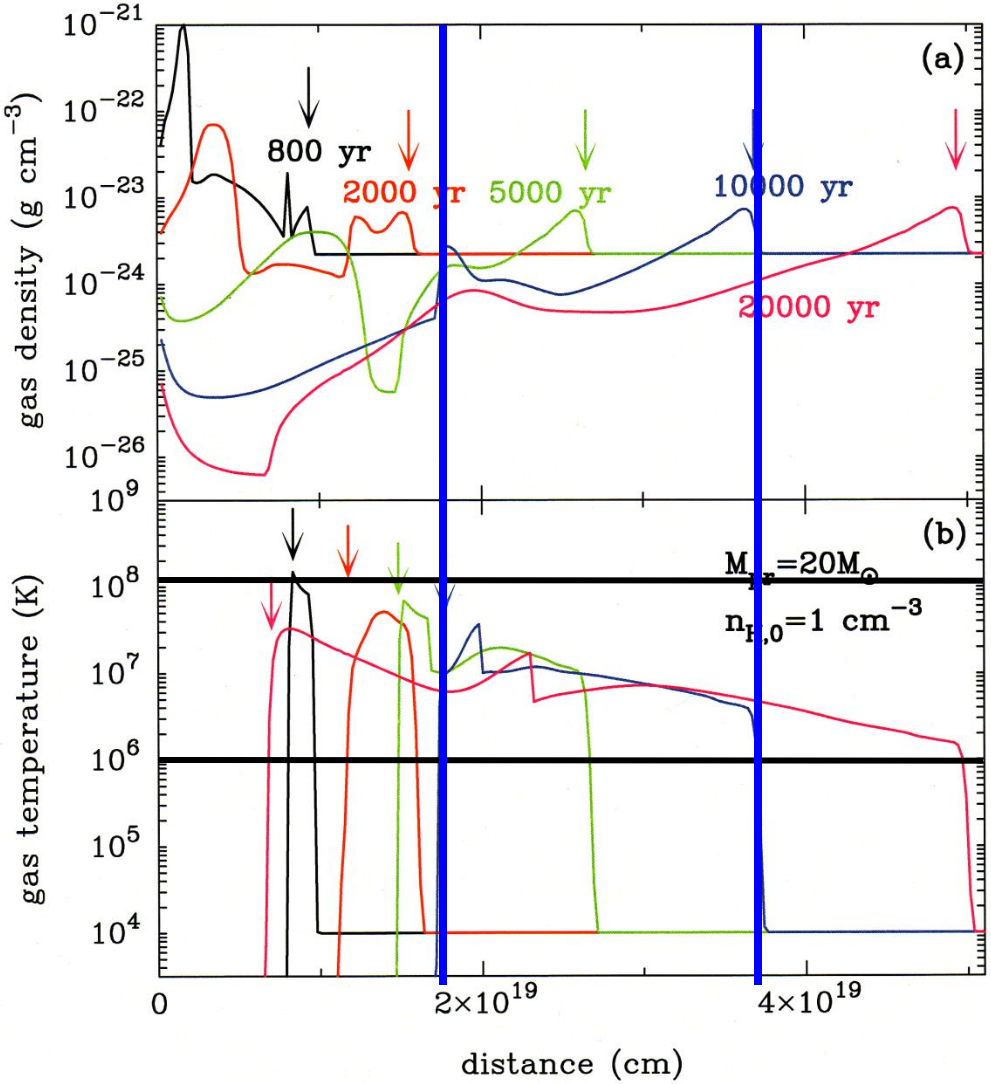


- **erosion rate by sputtering quickly increases above 10^5 K and peaks at 10^7 -10^8 K**

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

2-2-6. Temperature and density of gas in SNRs

Nozawa+'07, ApJ, 666, 955



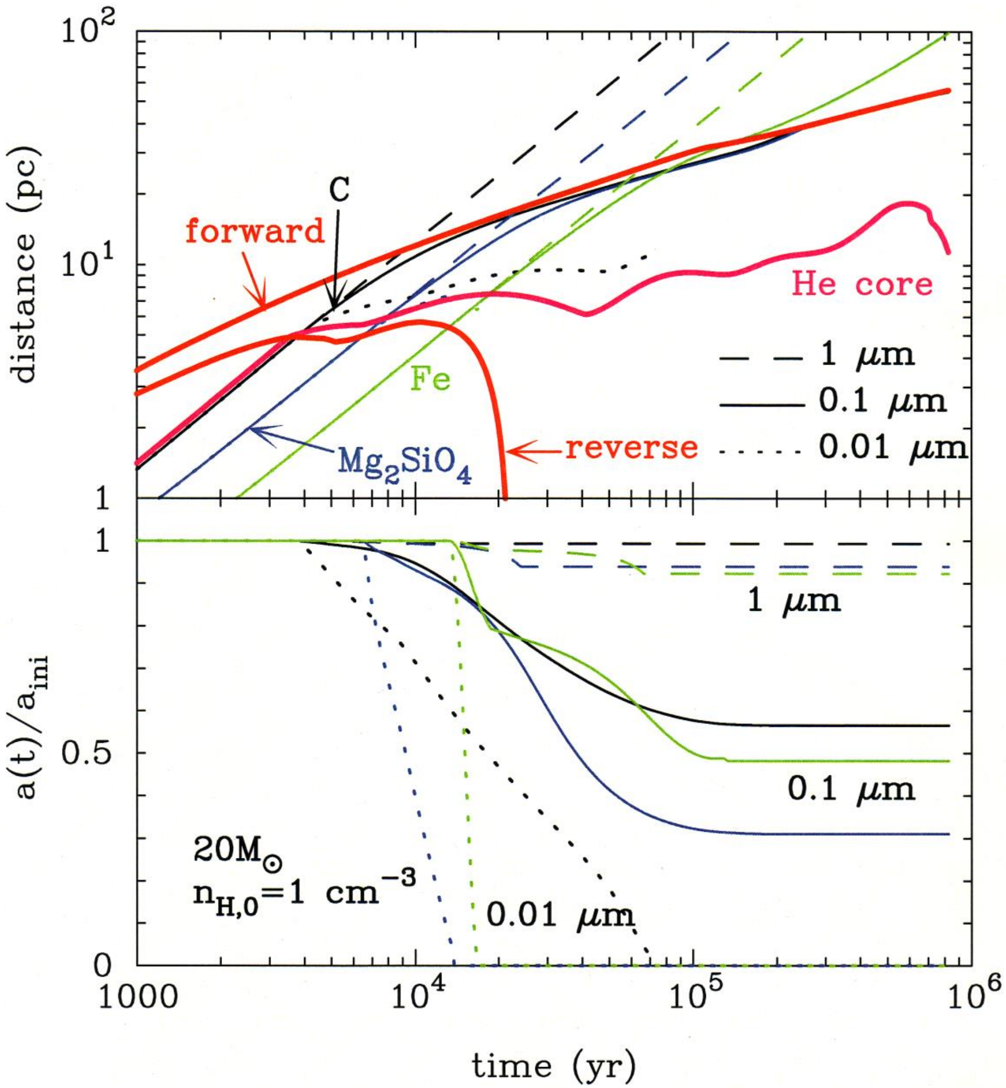
Model : M_{pr}= 20 Msun (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

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

2-2-7. Evolution of dust in SNRs

Nozawa+'07, ApJ, 666, 955



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

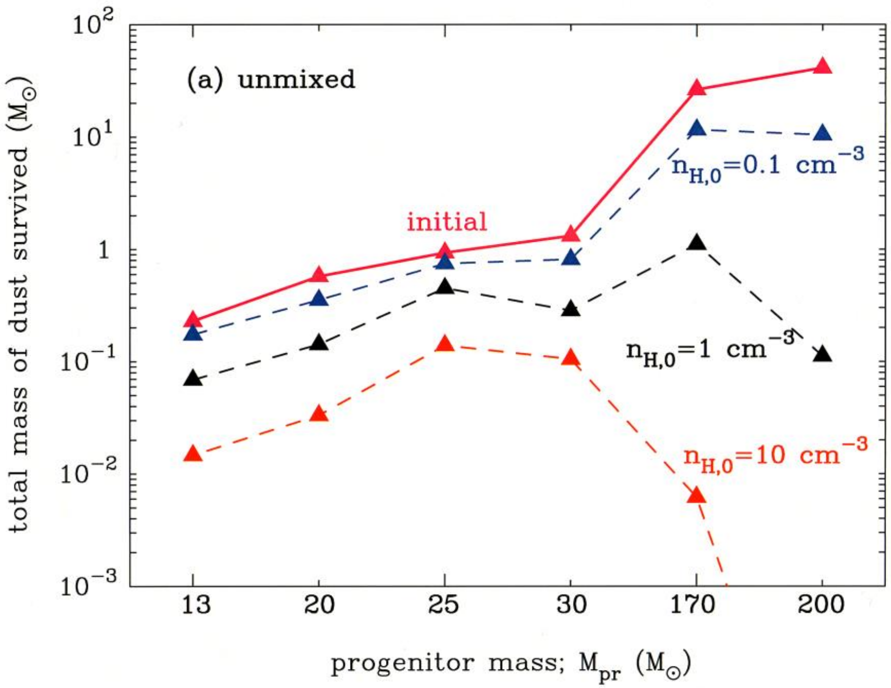
Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

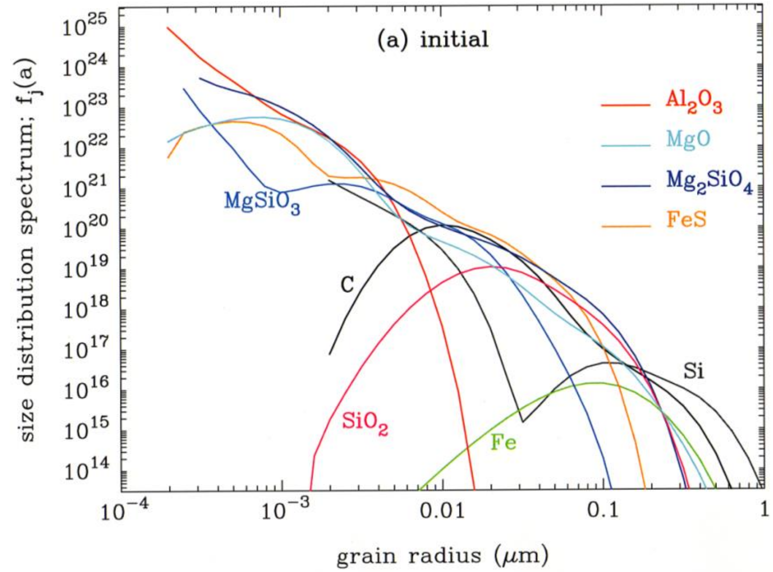
The evolution of dust heavily depends on the initial radius and composition

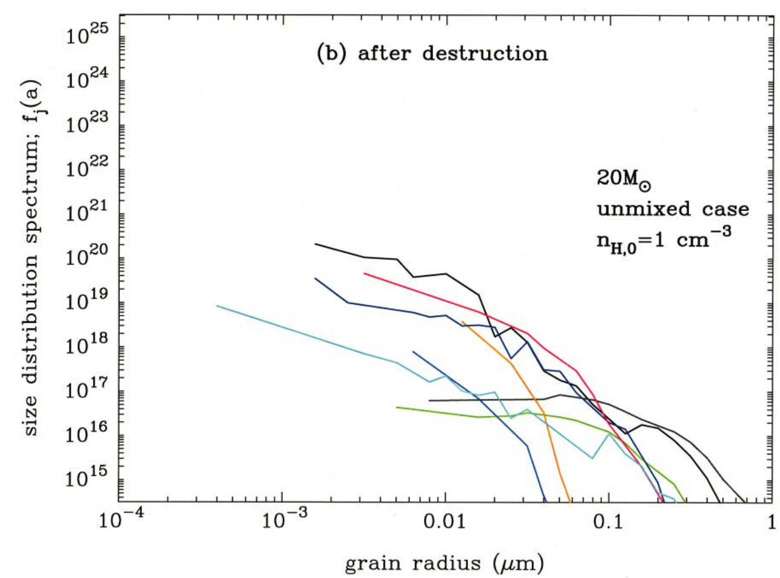
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

2-2-8. Total mass and size of surviving dust

Nozawa+'07, ApJ, 666, 955





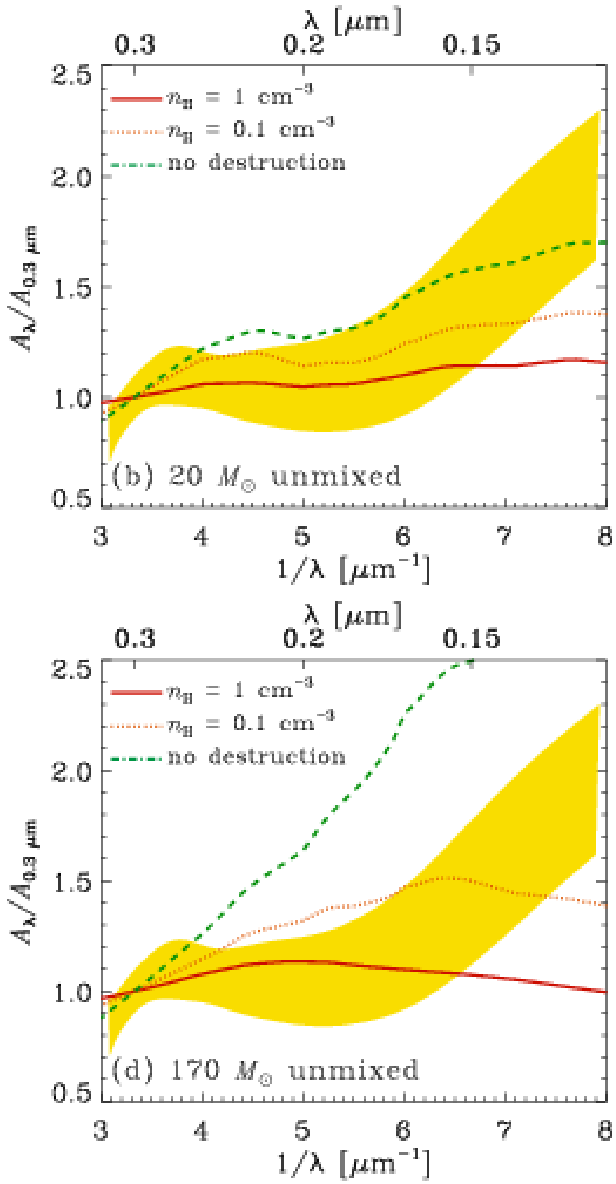


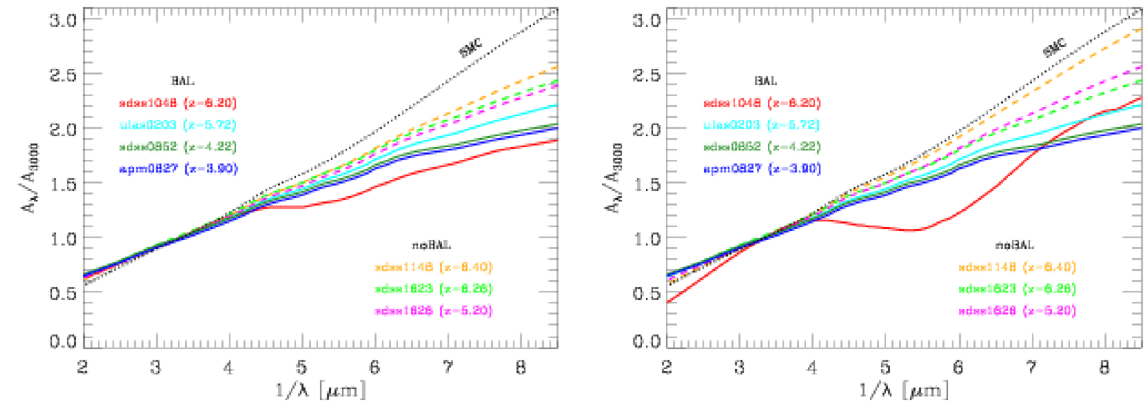
total dust mass surviving the destruction in Type II-P SNRs; 0.08-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

size distribution of surviving dust is domimated by large grains (> 0.01 μm)

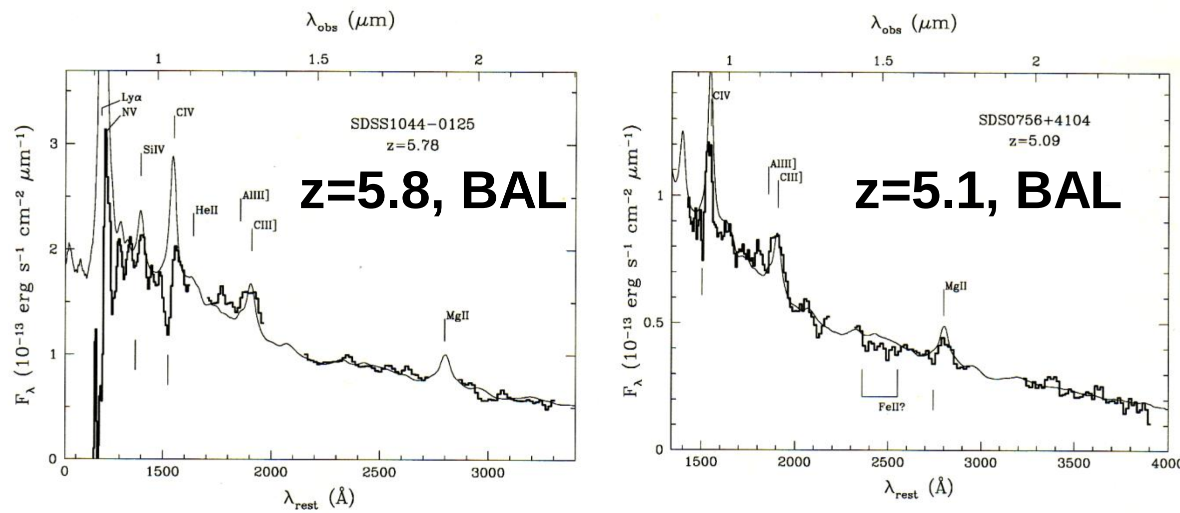
2-2-9. Flattened extinction curves at high-z

Hirashita, TN,+'08, MNRAS, 384, 1725





Gallerani+'10, A&A, 523, 85



Maiolino+'04, A&A, 420, 889

2-3. Summary of dust production in Pop III SNe

- 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 surviving dust grains decreases with increasing the ambient gas density

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

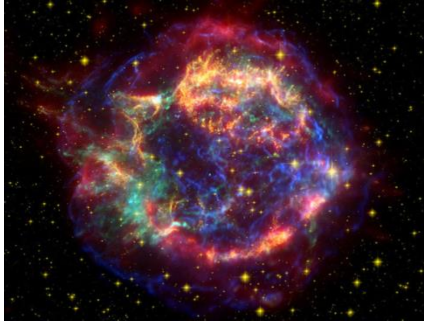
  SNe II-P ➔ M_{dust} = 0.1-0.8 M_{sun}

  PISNe ➔ M_{dust} = 0.1-15 M_{sun}

- Extinction curves in the early universe are expected to be flat if SNe II-P are main sources of dust at high z.

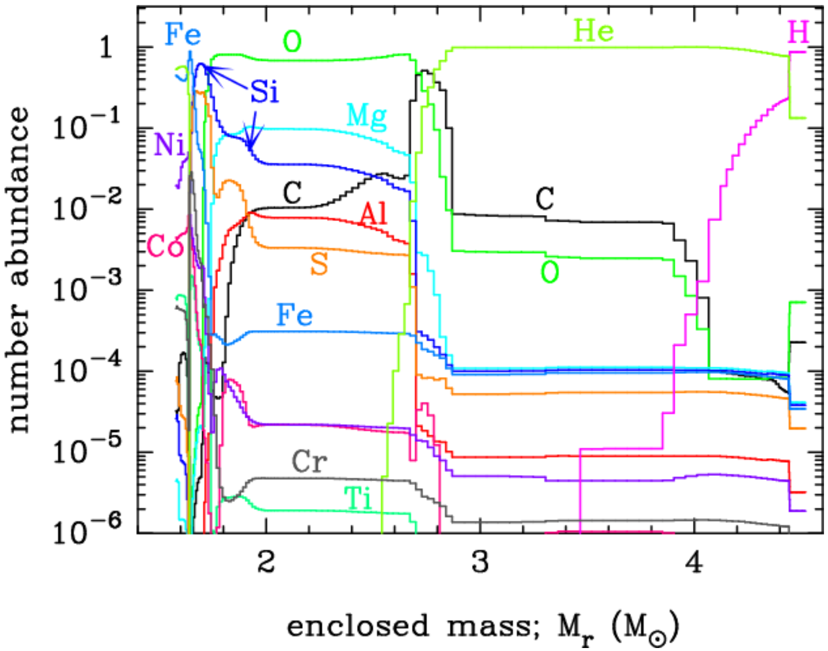
3. Formation of dust grains in various types of SNe

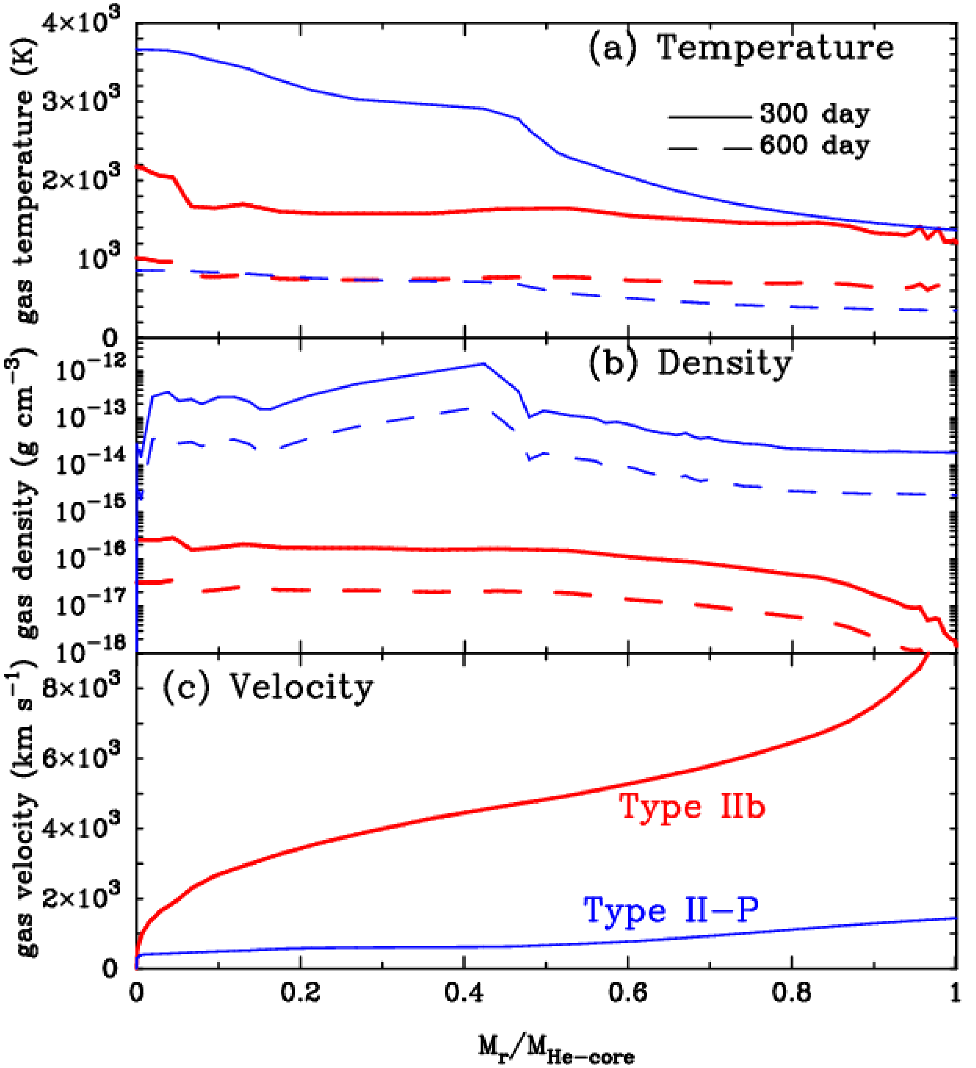
3-1-1. Dust formation in Type IIb SN



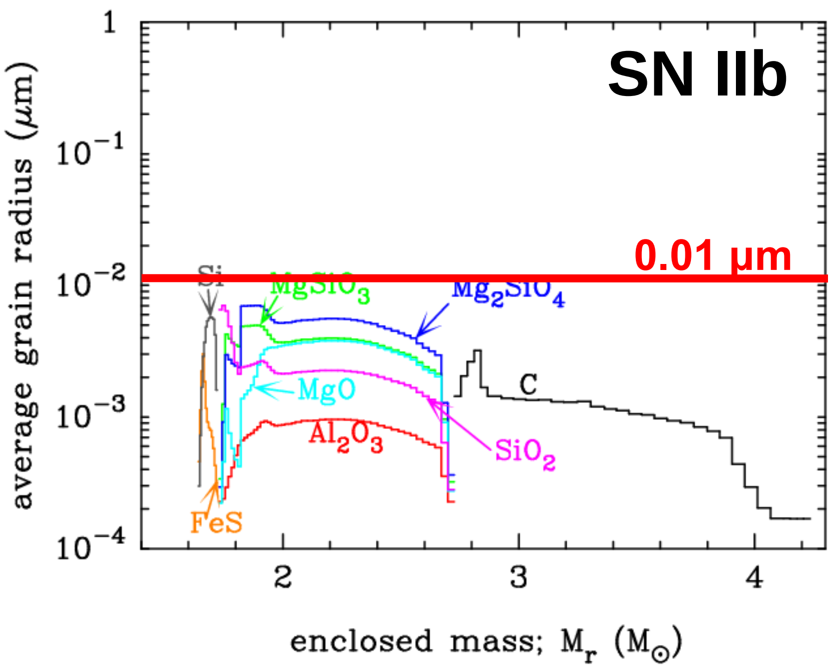
○ SN IIb model (SN1993J-like model)

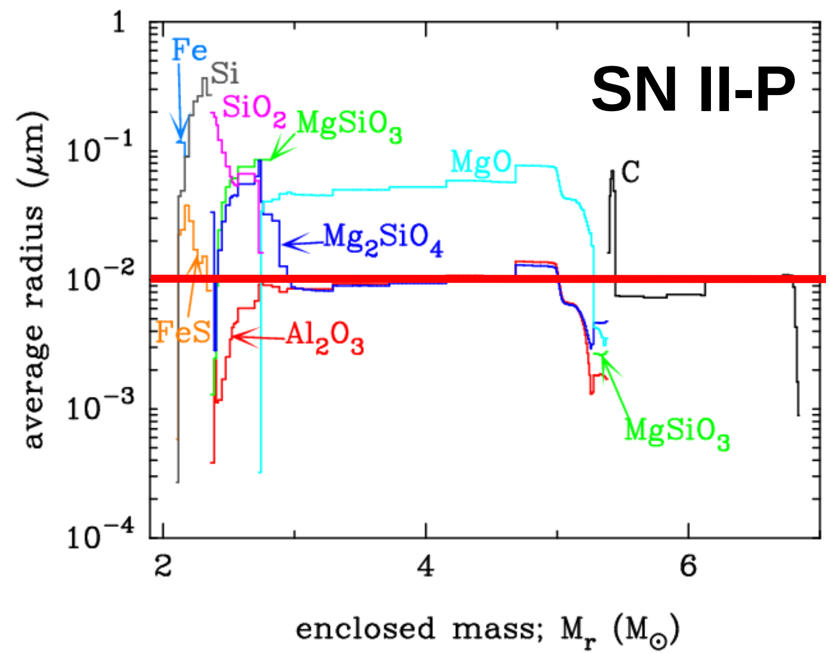
- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1
- $M(^{56}Ni)$ = 0.07 Msun





3-1-2. Dependence of dust radii on SN type





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

— total mass of dust formed

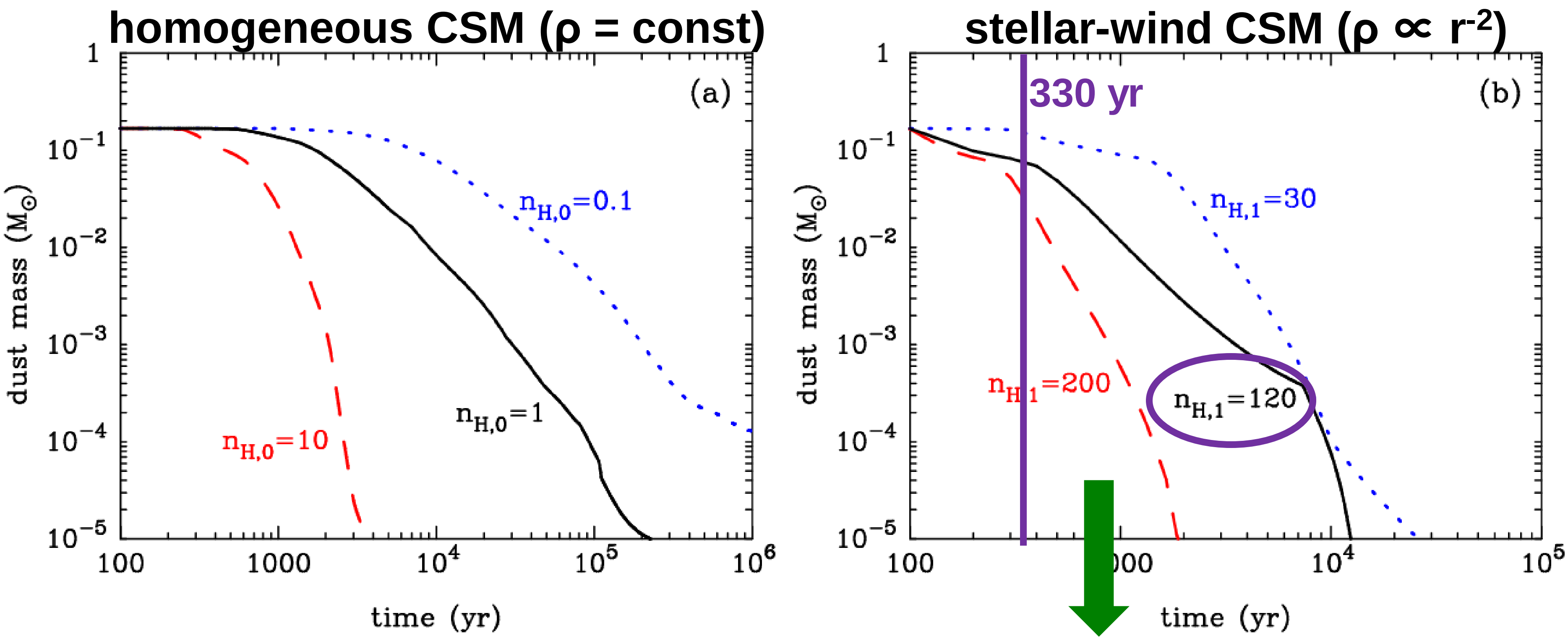
- **0.167 Msun in SN IIb**
- **0.1-1 Msun in SN II-P**

— 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

3-1-3. 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

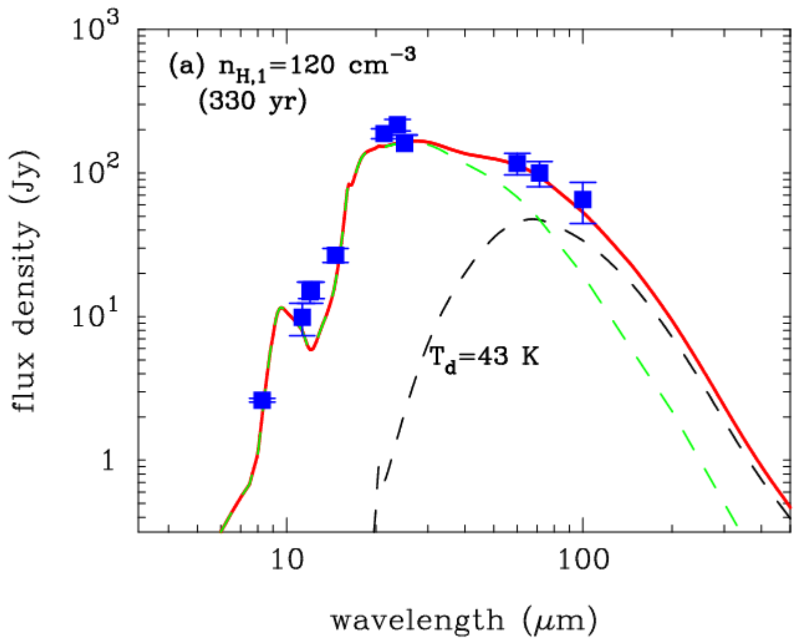
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

➔ small radius of newly formed dust

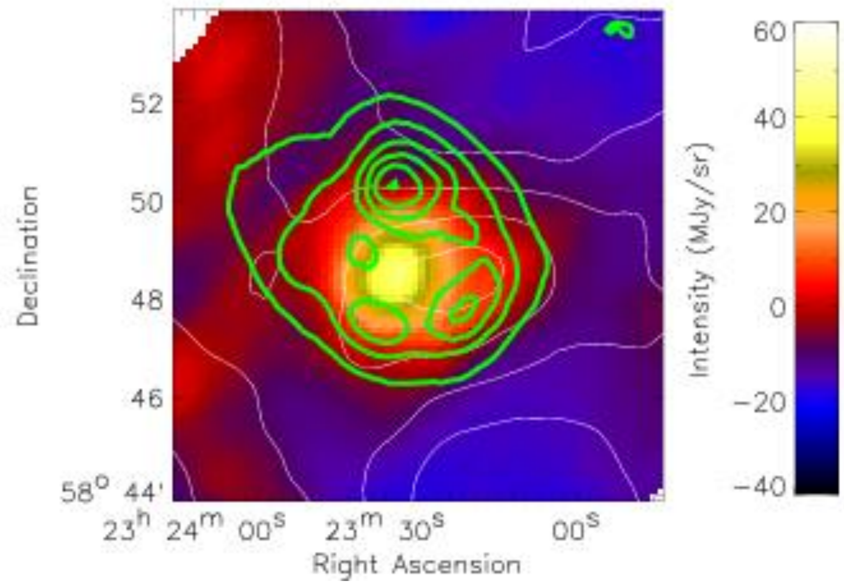
➔ early arrival of reverse shock at dust-forming region

Nozawa+'10, ApJ, 713, 356

3-1-4. 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)

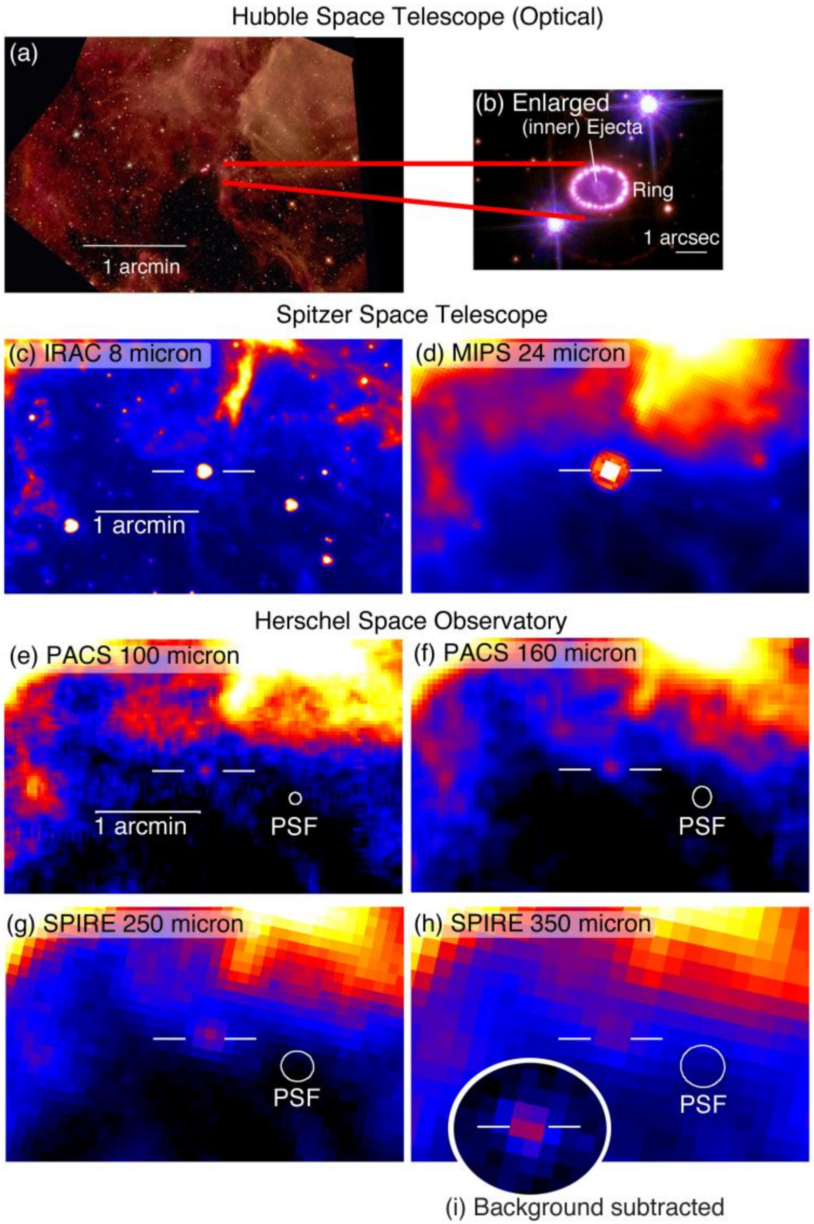
Herschel observation

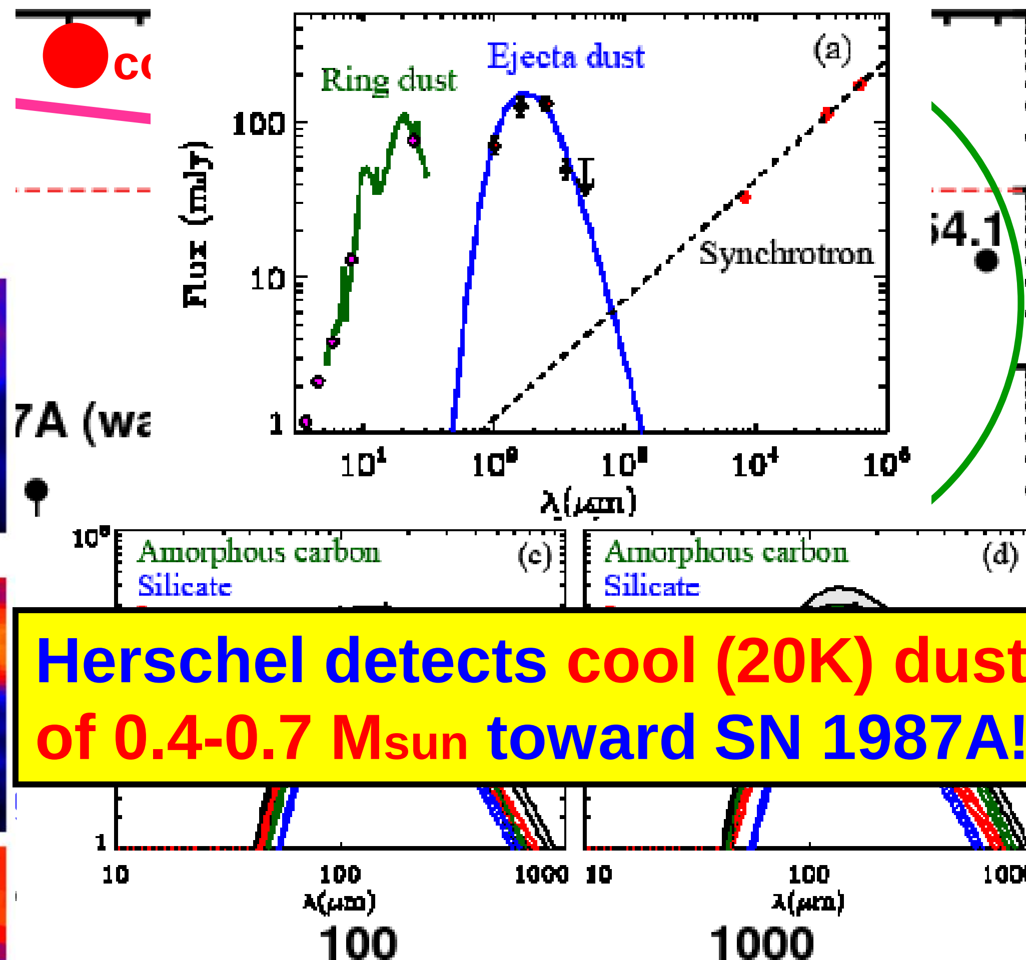
$M_{d,cool}$ = 0.075 M_{sun}

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

3-2-1. Missing-dust problem in CCSNe

Matsuura, ..., TN, et al. 2011, Science

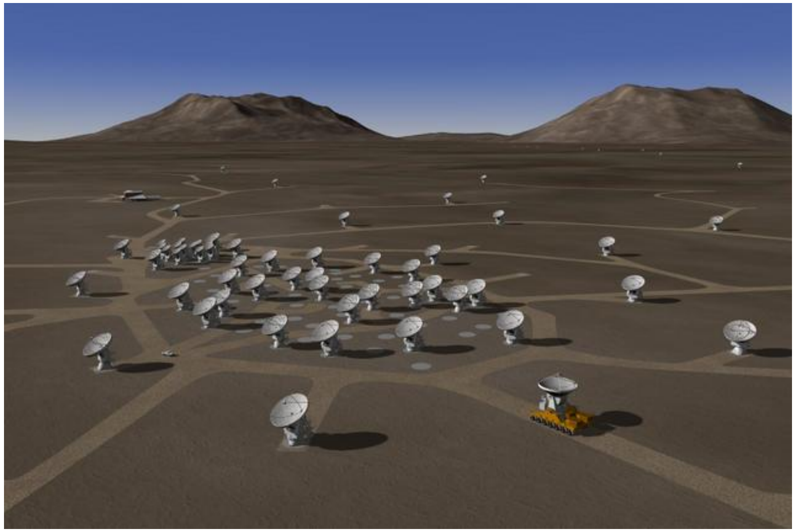




Herschel detects cool (20K) dust of 0.4-0.7 M_{sun} toward SN 1987A!

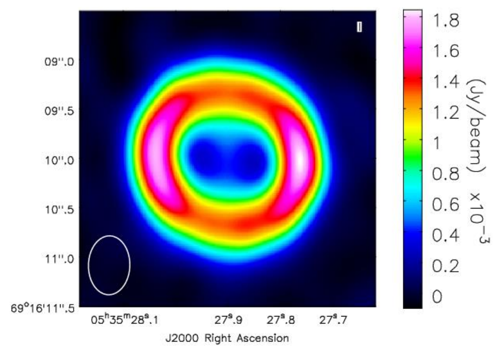
...nce in the mass of dust between ...tes and theoretical predictions!!

3-2-2. Resolving cold dust in SN87A with ALMA

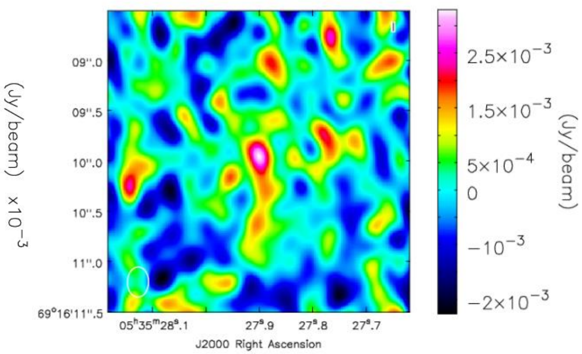


ALMA Cycle 0 Proposal
‘Detecting cool dust in SN1987A’
（PI：Nozawa）

Band 7 (850 μm)

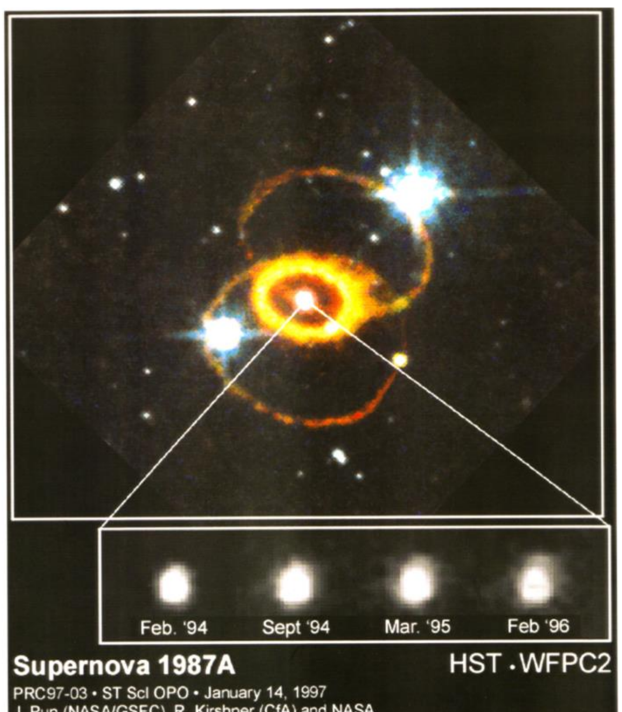


Band 9 (450 μm)

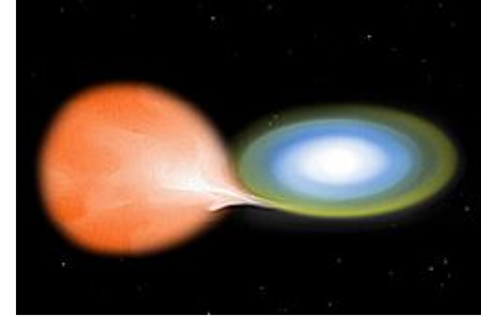


0.1 Msun of silicate ➔ 5σ detection

This proposal is ranked in the highest priority to be observed !



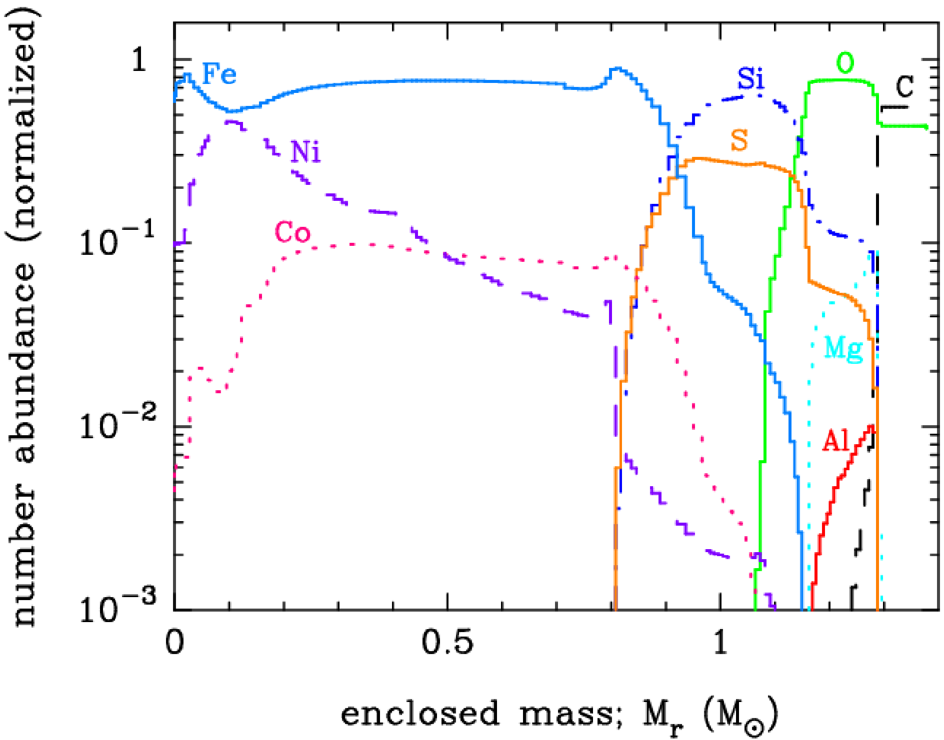
3-3-1. Dust formation in Type Ia SN

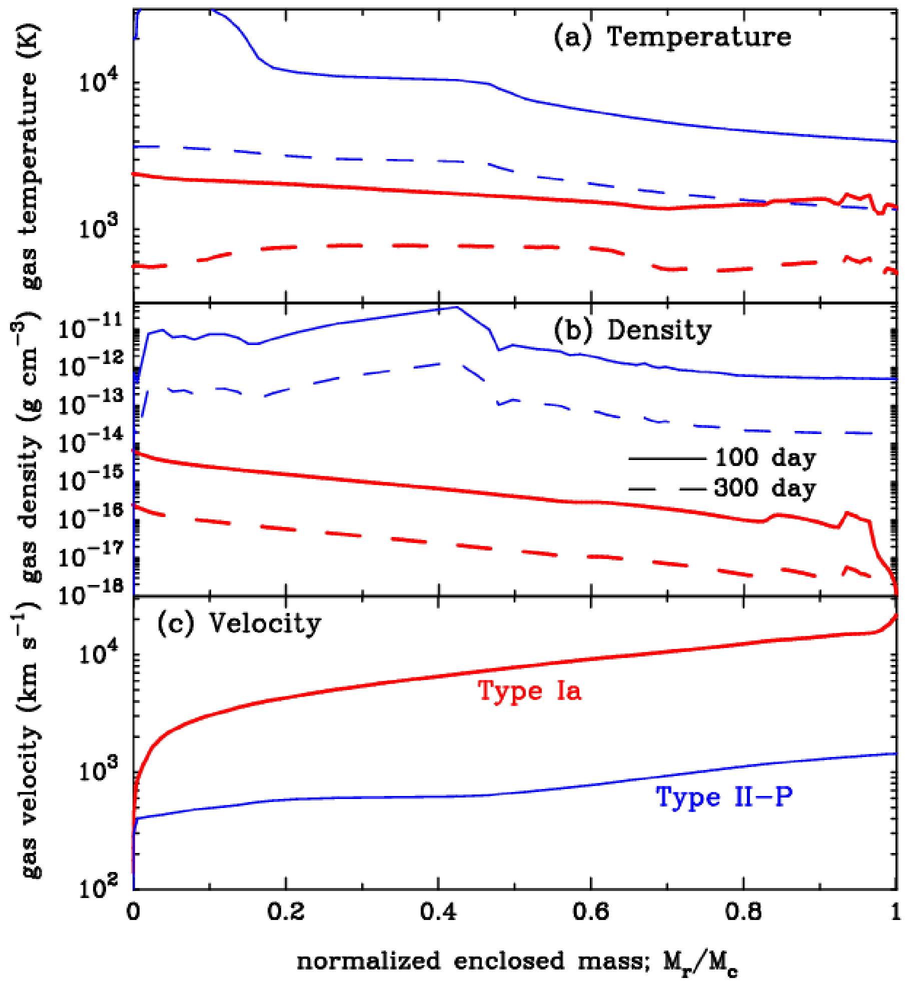


○ Type Ia SN model

W7 model (C-deflagration) (Nomoto+'84; Thielemann+'86)

- M_{eje} = 1.38 Msun
- E_{51} = 1.3
- $M(^{56}Ni)$ = 0.6 Msun

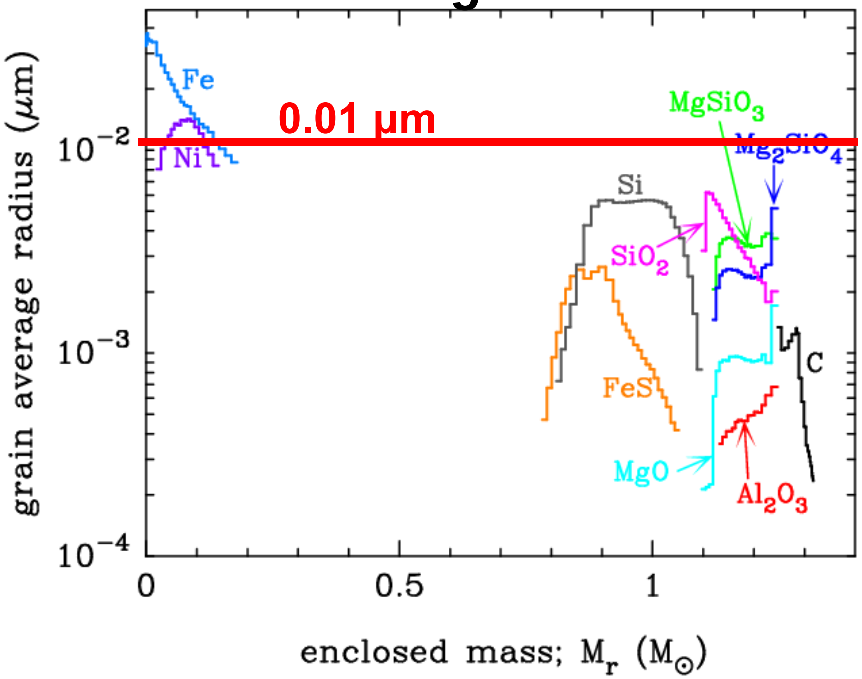




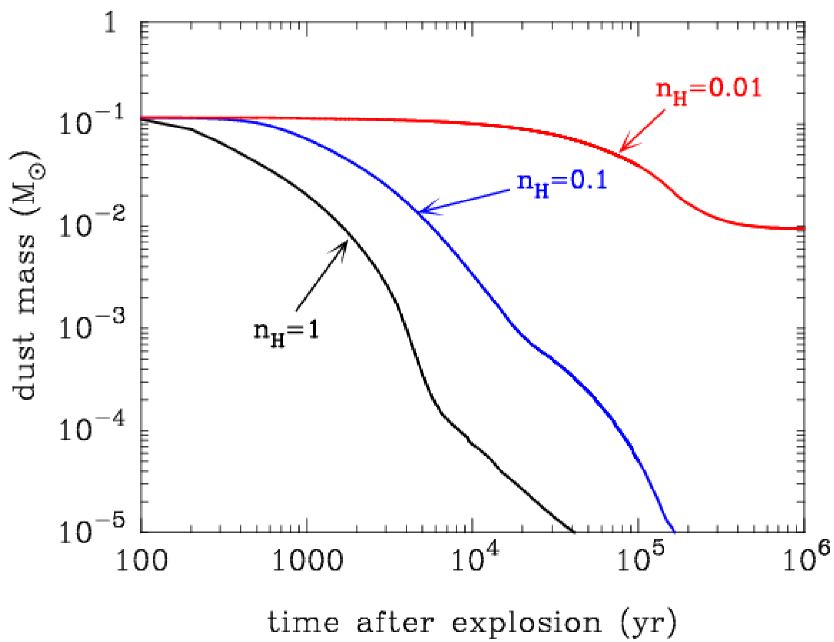
3-3-2. Dust formation and evolution in SNe Ia

Nozawa+'11, arXiv/1105.0973

average radius



dust destruction in SNRs



- condensation time :
  100-300 days
- average radius of dust :
  a_{ave} <~ 0.01 μm
- total dust mass :
  M_{dust} = 0.1-0.2 M_{sun}

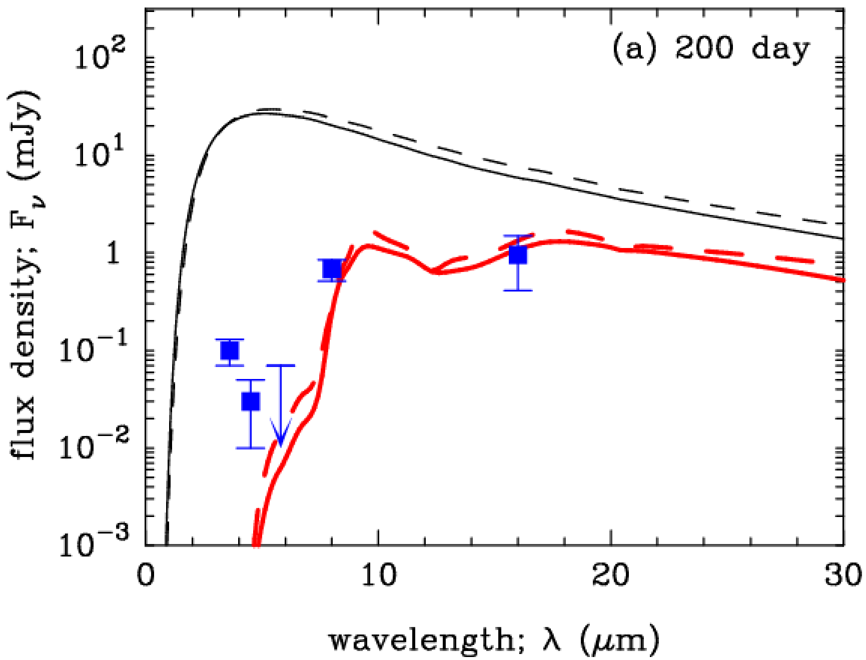
newly formed grains are completely destroyed for ISM density of n_H > 0.1 cm^{-3}

➔ SNe Ia are unlikely to be major sources of dust

3-3-3. Carbon dust and outermost layer

- **There has been no evidence for dust formation in SNe Ia**
  - **➔ Formation of massive carbon dust does not match the observations**

Observational data : SN 2005df at day 200 and 400 (Gerardy+'07)



Nozawa+'11, accepted

— massive unburned carbon (~0.05 M_{sun}) in deflagration

➔ change of composition of WD by He-shell flash

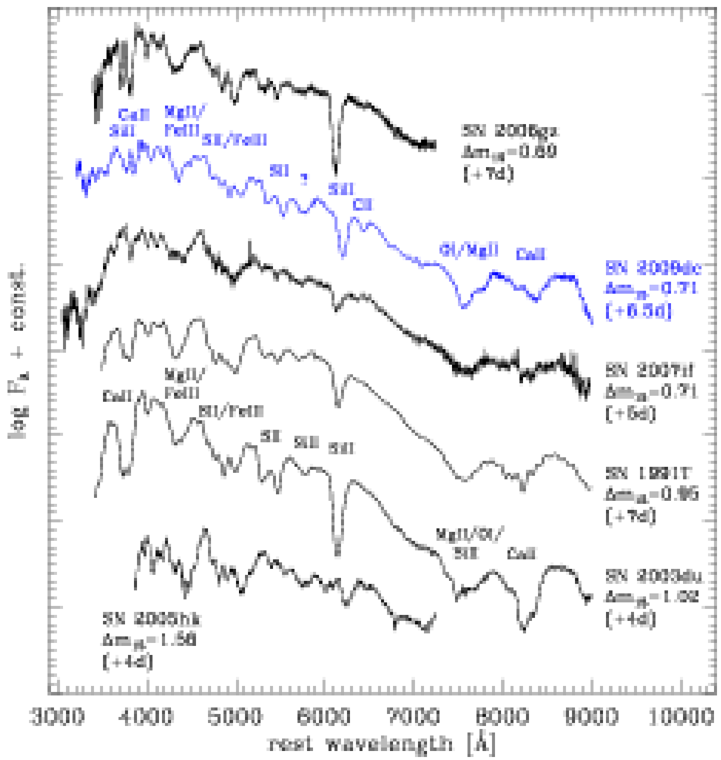
➔ burning of carbon by a delayed detonation

observationally estimated carbon mass in SNe Ia :
Mc < 0.01 M_{sun}
(Marion+'06; Tanaka+'08)

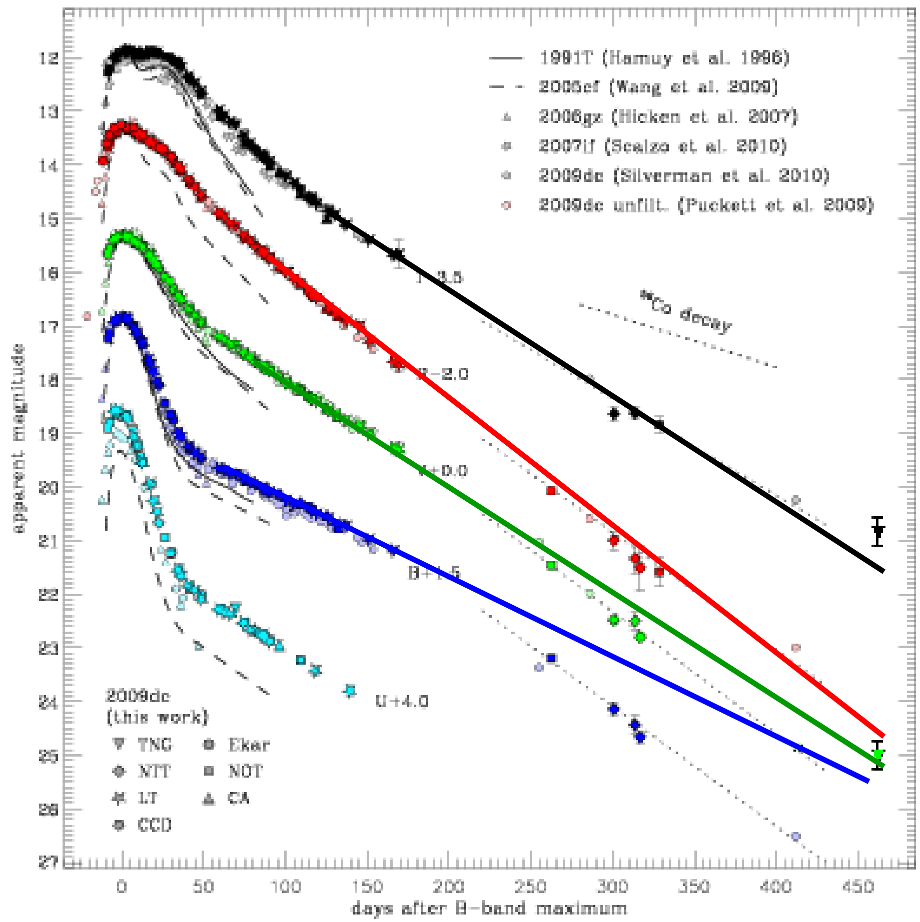
3-3-4. Dust formation in super-Chandra SNe?

– super-Chandra SNe :
M(56Ni) ~ 1.0 Msun

detection of CII line
➔ presence of massive unburned carbon



SN 2009dc, Tarbenberger+'10



enhanced fading at ~200 day
➔ formation of carbon dust?

4. Implication and Summary

4-1. Implication on evolution history of dust (1)

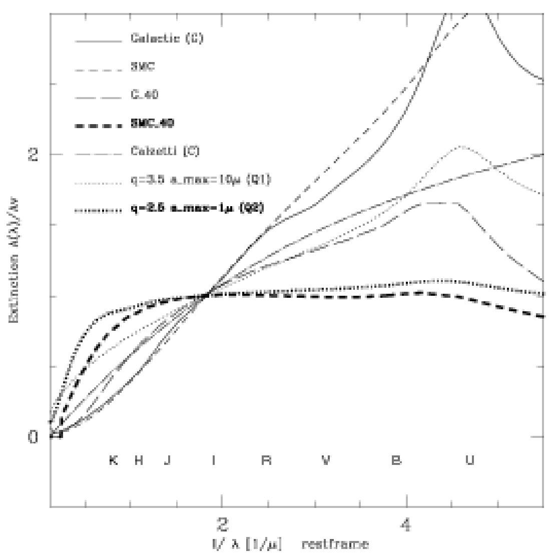
○ **metal-poor (high-z or starbust) galaxies**

- **massive stars (SNe) are dominate**
- **mass loss of massive stars would be less efficient**

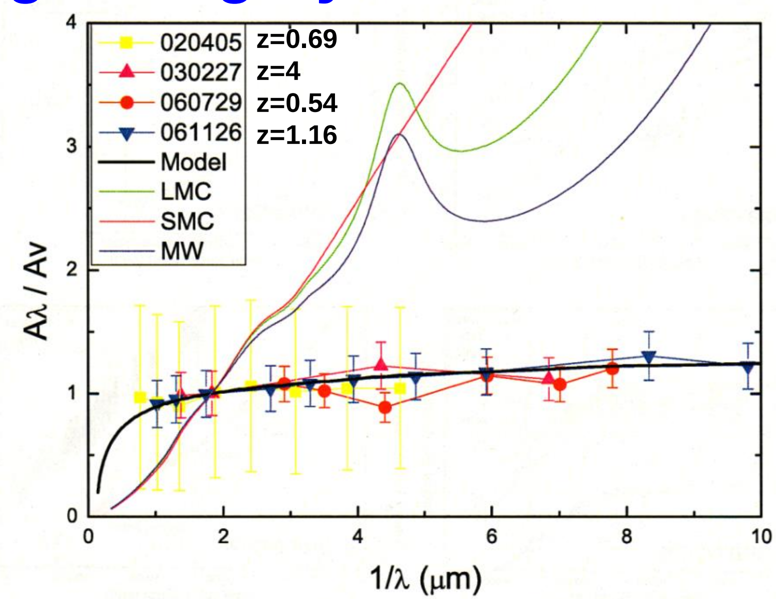
➔ **Type II-P SNe might be major sources of dust**

- **average radius of dust is relatively large (> 0.01 μm)**
- **grain growth makes grain size larger**

➔ **dust extinction curve might be gray**



Stratta+'05, A&A, 441, 83



Li+'08, ApJ, 678, 1136

4-2. Implication on evolution history of dust (2)

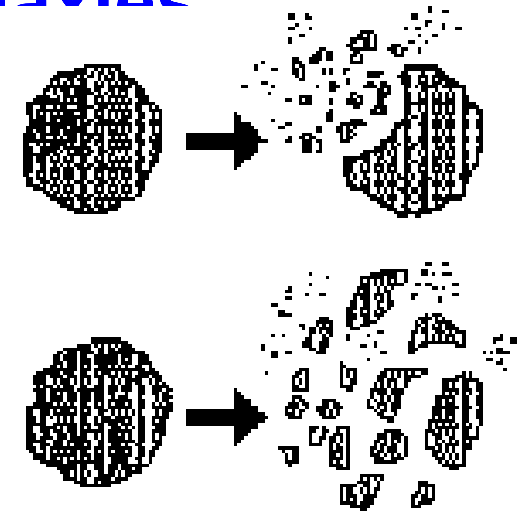
○ metal-rich (low-z or Milky Way) gal...

- low-mass stars are dominate
- mass loss of massive stars would be

➔ SNe (IIb, Ib/c, Ia) might be minor sour...

- dust from AGB stars may also be larg...

➔ How are small dust grains produced?



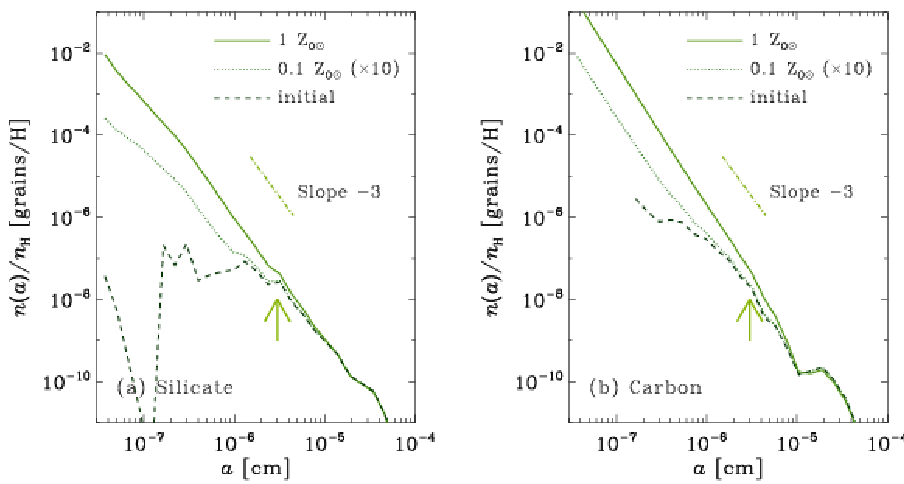
grain shattering

— warm ionized medium (WIM) relative velocity of dust in turbulence : 1-20 km/s

— grain shattering is efficient in WIM at t=5 Myr if metallicity is solar and more

— the production of small grains by shattering steepens the extinction curve

Dust size distribution at t=5 Myr (n_H=1 /cc)



Hirashita, TN, +'10, MNRAS, 404, 1437

4-3. 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