Formation of Dust Grains by Supernova Explosion

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Outline

1. Introduction

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

3. Formation and evolution of dust grains in various types of SNe

4. Missing-dust problem in SNe

5. Conclusion remarks

1. Introduction

1-1. Interstellar dust in our Galaxy

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

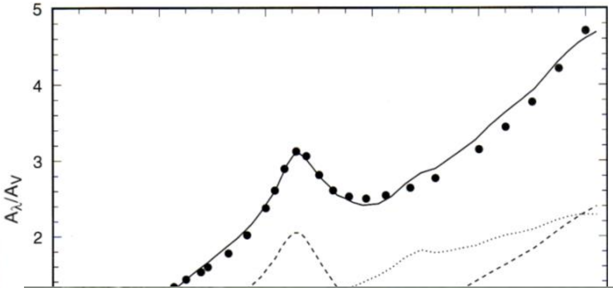
composition : **graphite** (carbonaceous)
silicate (SiO_2, Mg_2SiO_4, $MgFeSiO_4$…)

size : $n(a) = f(a)da = a^{-3.5}\,da$ (0.005~0.25 μm)

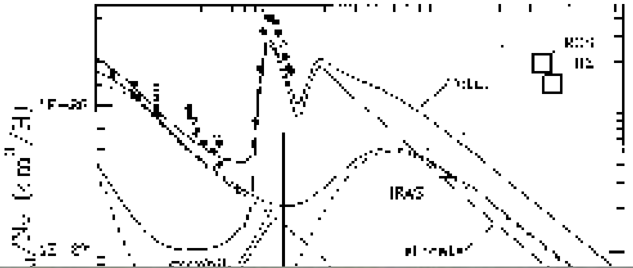
amount : $M_{dust} / M_{gas} \sim 1 / 140$ (~10^9 M_{sun})

(e.g., Mathis+77; Draine & Lee 84)

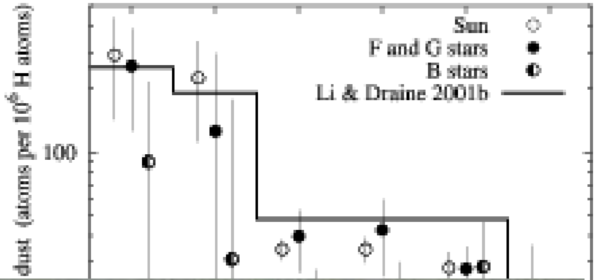
extinction curve



IR spectral feature



depletion of elements

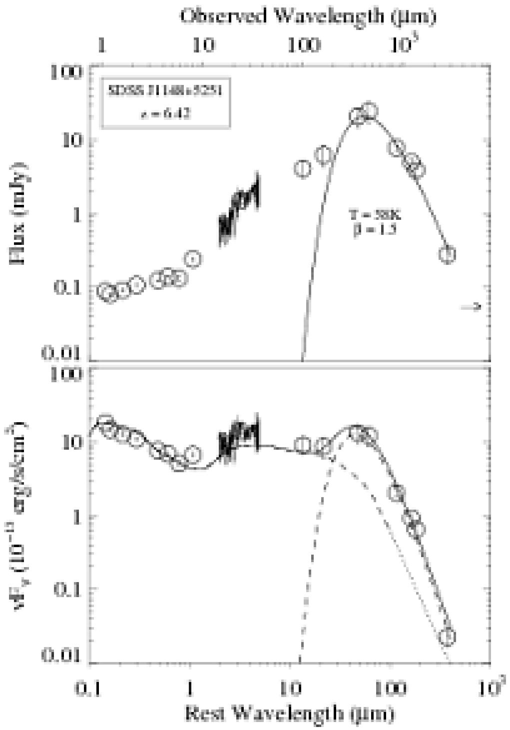


1-2. Discovery of large amounts of dust at z > 5

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

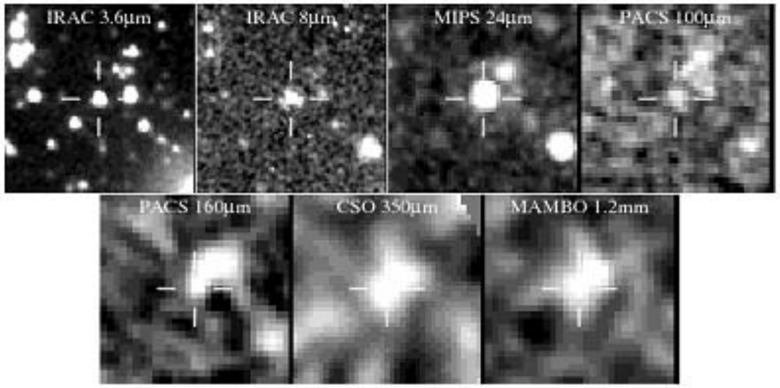
  ➔ **We see warm dust grains heated by absorbing stellar lights in the host galaxies of the quasars**

SDSS J1148+5251 at z=6.4



Leipski+10, A&A, 518, L34

- **age : 840-890 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**



1-3. What are sources of dust in high-z quasar?

- **Supernovae (Type II SNe)**

  ➔ ~0.1 M_{sun} per SN is sufficient
  (Morgan & Edmunds 2003; Maiolino+06; Li+08)

  ➔ > 1 M_{sun} per SN (Dwek+07)

- **AGB stars** + SNe
  (Valiante+09; Gall+10; Dwek & Cherchneff 2011)

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

  ➔ 0.01-1 M_{sun} per SN

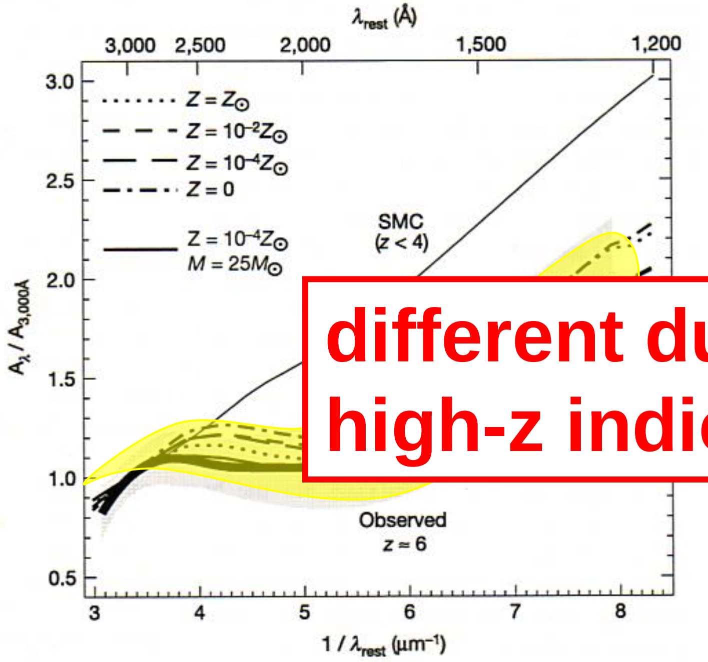
- **Grain growth in the ISM** + AGB stars + SNe
  (Draine 2009; Michalowski+10; Pipino+11)

  ➔ T_{growth} ~ 10^7 (Z / Z_{sun}) yr

- **Quasar outflow** (Elvis+02)

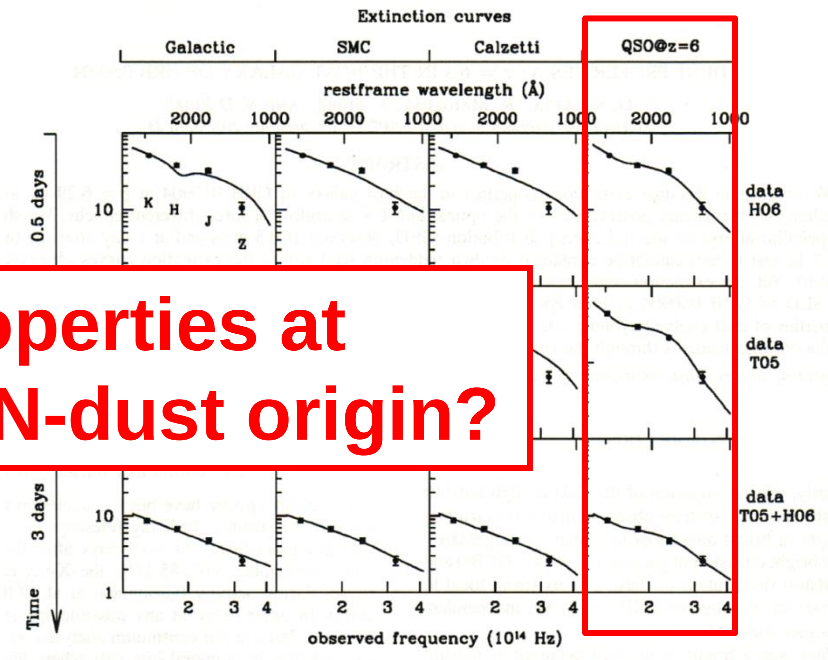
1-4. Extinction curves at high-z quasars

SDSS J1048+4637 at z=6.2



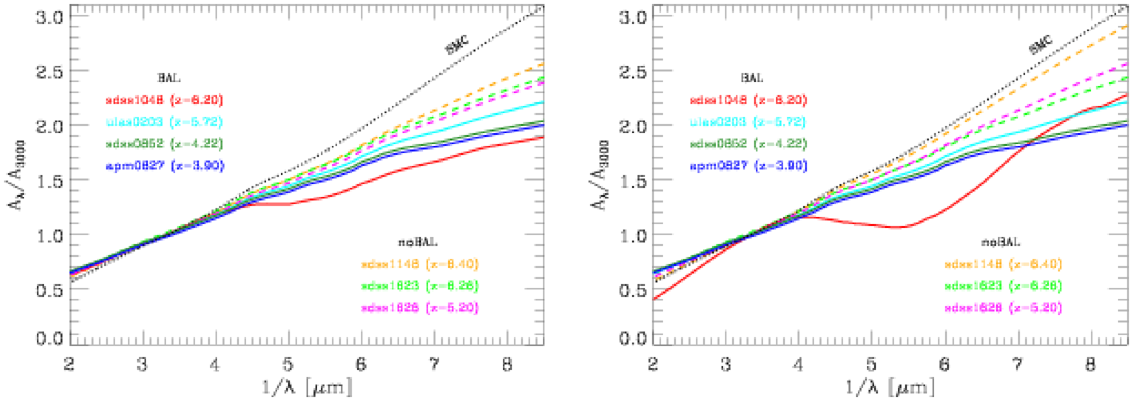
Maiolino+04, Nature, 431, 533

GRB 050904 at z=6.3



Stratta+07, ApJ, 661, L9

different dust properties at high-z indicate SN-dust origin?

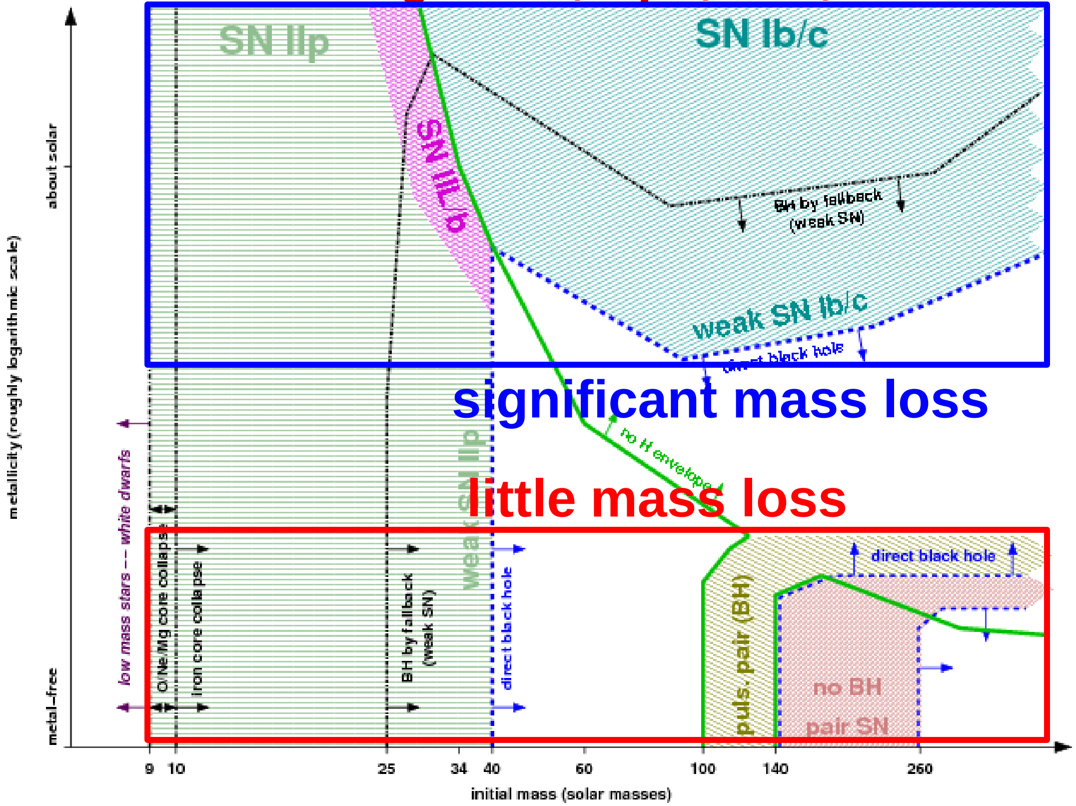


Gallerani+10, A&A, 523, 85

7 among 33 quasars at 3.9 < z < 6.4 requires significant dust extinction, which deviates from those in the SMC

1-5. Death of single massive stars

Heger+03, ApJ, 591, 288



significant mass loss

little mass loss

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$_{sun}$)

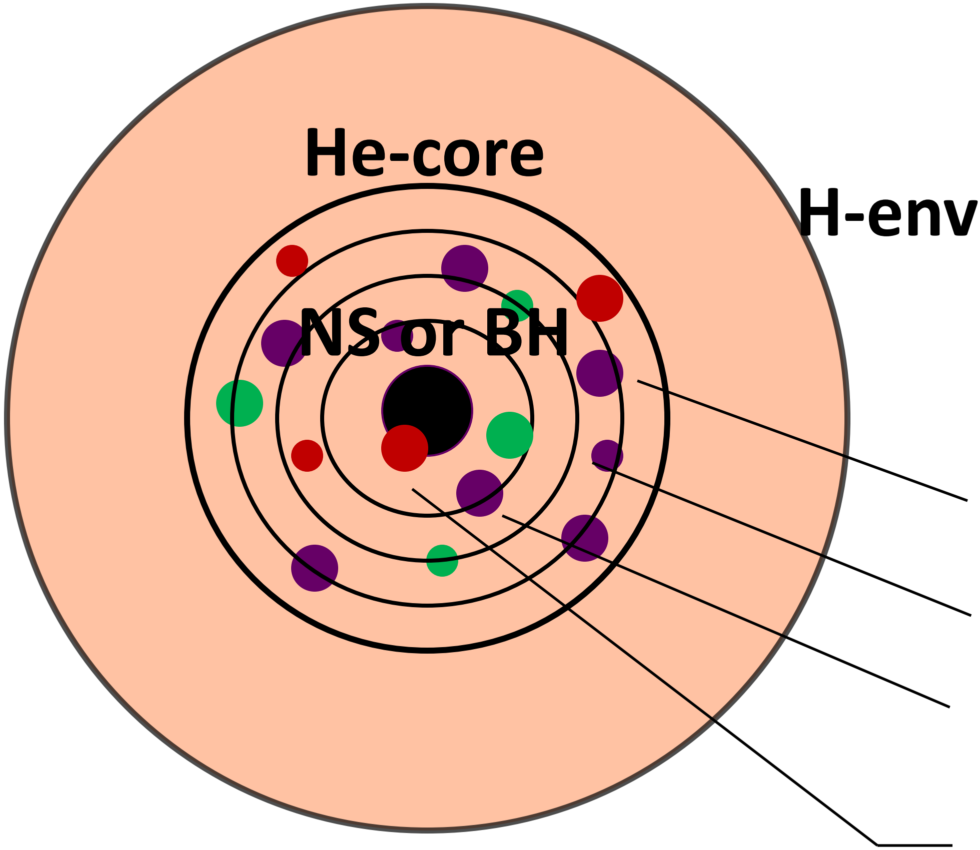
- **Type II-P SNe:**
  M$_{ZAMS}$=8-40 M$_{sun}$
- **pair-instability SNe:**
  M$_{ZAMS}$=140-260 M$_{sun}$

- **Type Ia SNe :**
  thermonuclear explosion of C+O white dwarfs
  M$_{pre-explosion}$ ~ 1.4 M$_{sun}$

2. Formation and evolution of dust in Population III SNe

2-1. Dust Formation in Supernovae

at ~1 days



He–layer (C>O)

O–Ne-Mg layer

Si–S layer

Fe–Ni layer

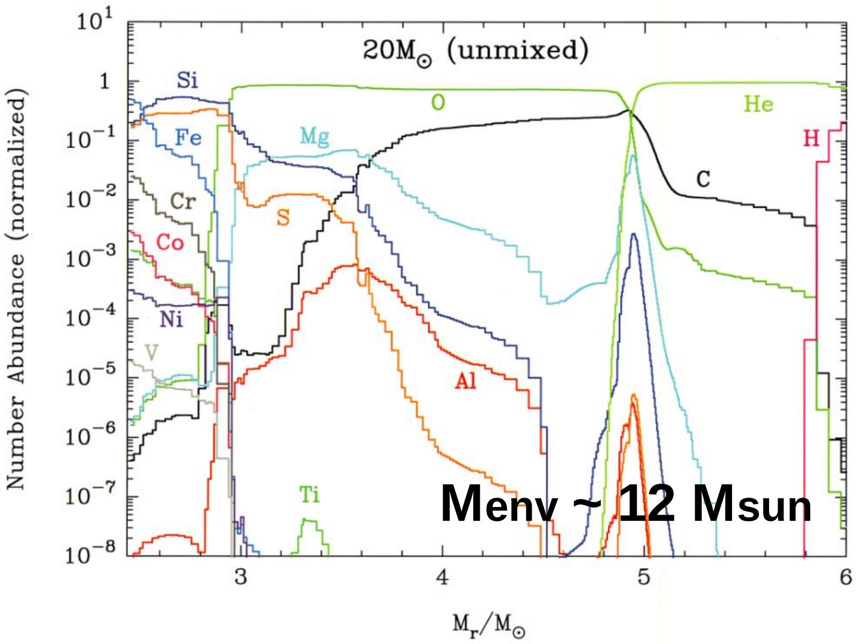
Dust formation
at ~1-3 years
after explosion

2-1-1. Dust formation in primordial SNe

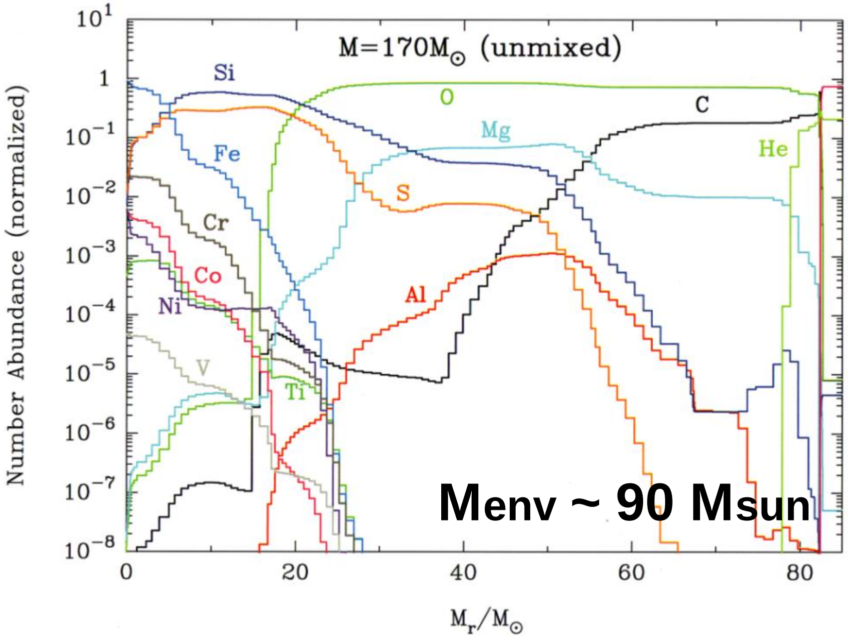
Nozawa+03, ApJ, 598, 785

○ Population III SNe model (Umeda & Nomoto 2002)

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



$M_{\rm env}$ ~ 12 $M_{\rm sun}$



$M_{\rm env}$ ~ 90 $M_{\rm sun}$

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

2-1-2. Nucleation rate of dust

Steady-state classical homogeneous 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

$$\ln S = \ln \frac{P_i}{P_{i,\mathrm{eq}}} = -\frac{\Delta G^0}{kT} + \sum_i \nu_i \ln P_i$$

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

2-1-3. Basic equations of dust formation

Equation of conservation for key species

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

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

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

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

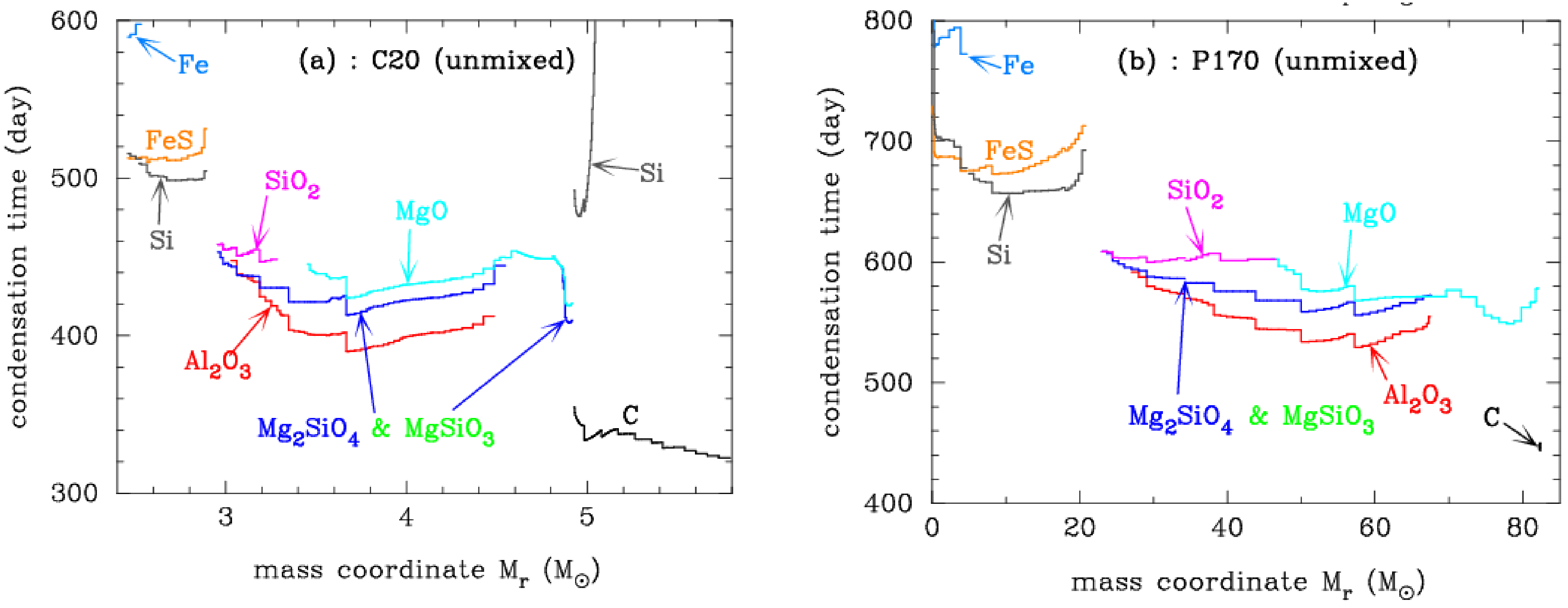
$$\tau_{\rm coll}^{-1}(t) = 4\pi a_0^2 \alpha_s \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1(t)$$

· 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

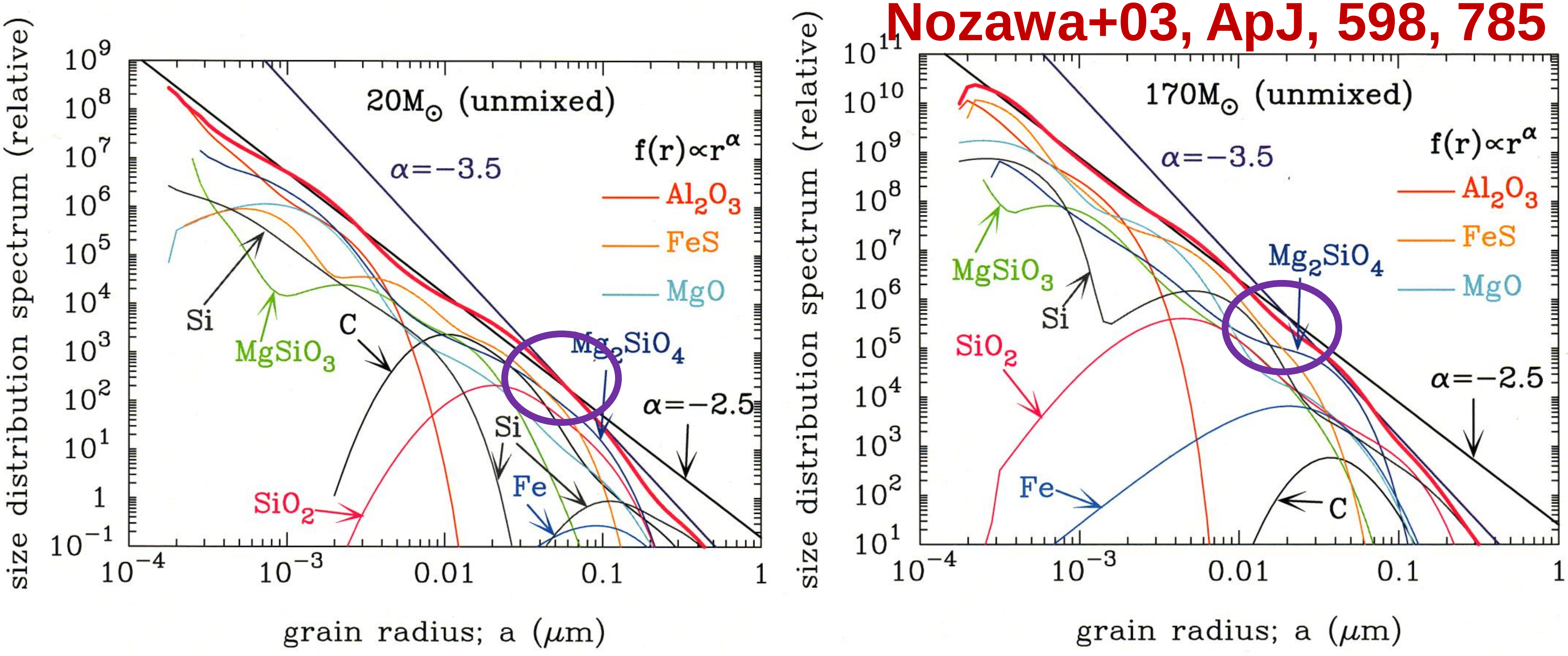
Nozawa+03, ApJ, 598, 785



- 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

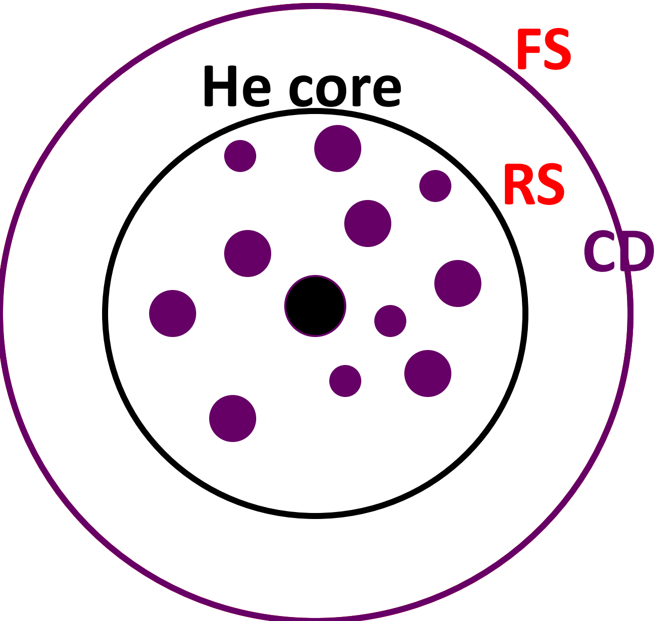
SNe II-P : M_{dust} = 0.1-1 M_{sun}, f_{dep} = M_{dust} / M_{metal} = 0.2-0.3

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

2-2. Dust Evolution in SNRs

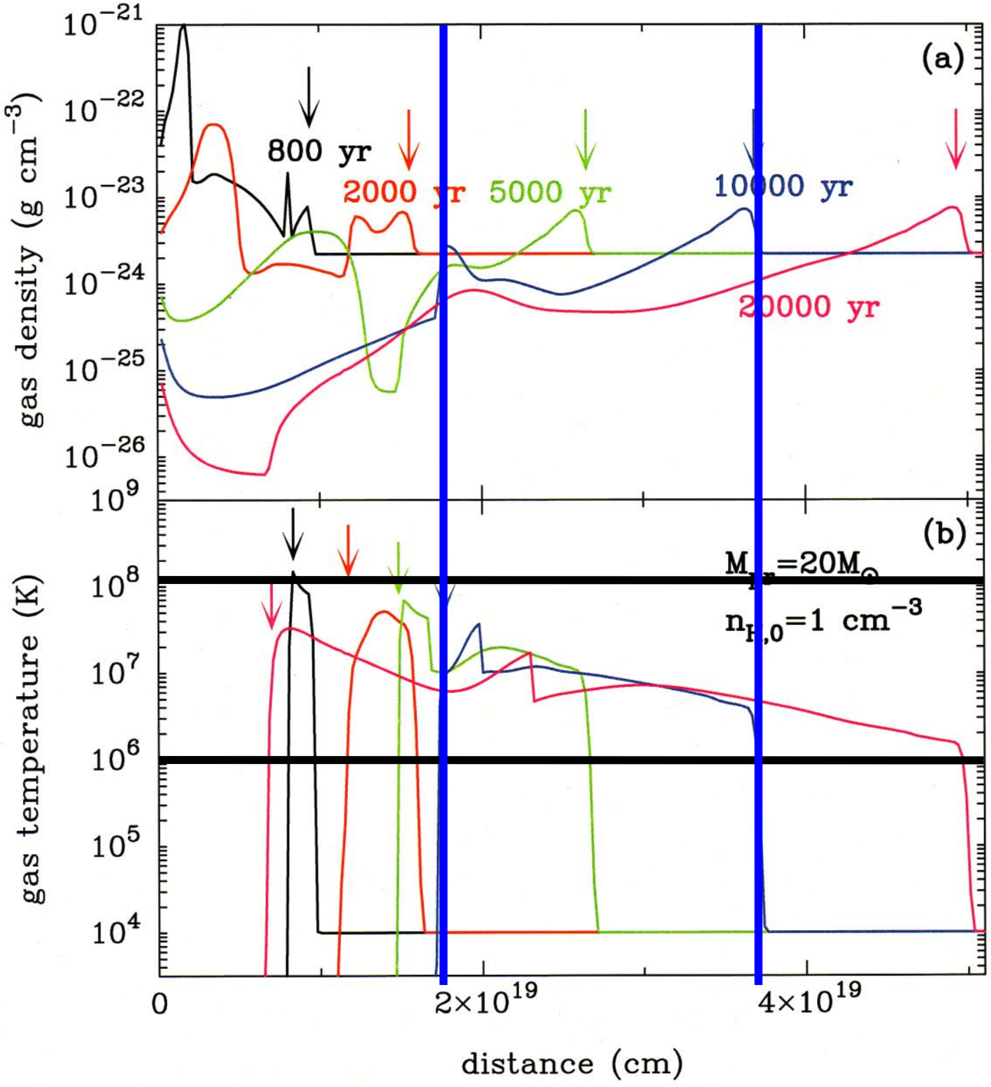
$T = (1\text{-}2)\times10^4$ K

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



2-2-1. Temperature and density of gas in SNRs

Nozawa+07, ApJ, 666, 955



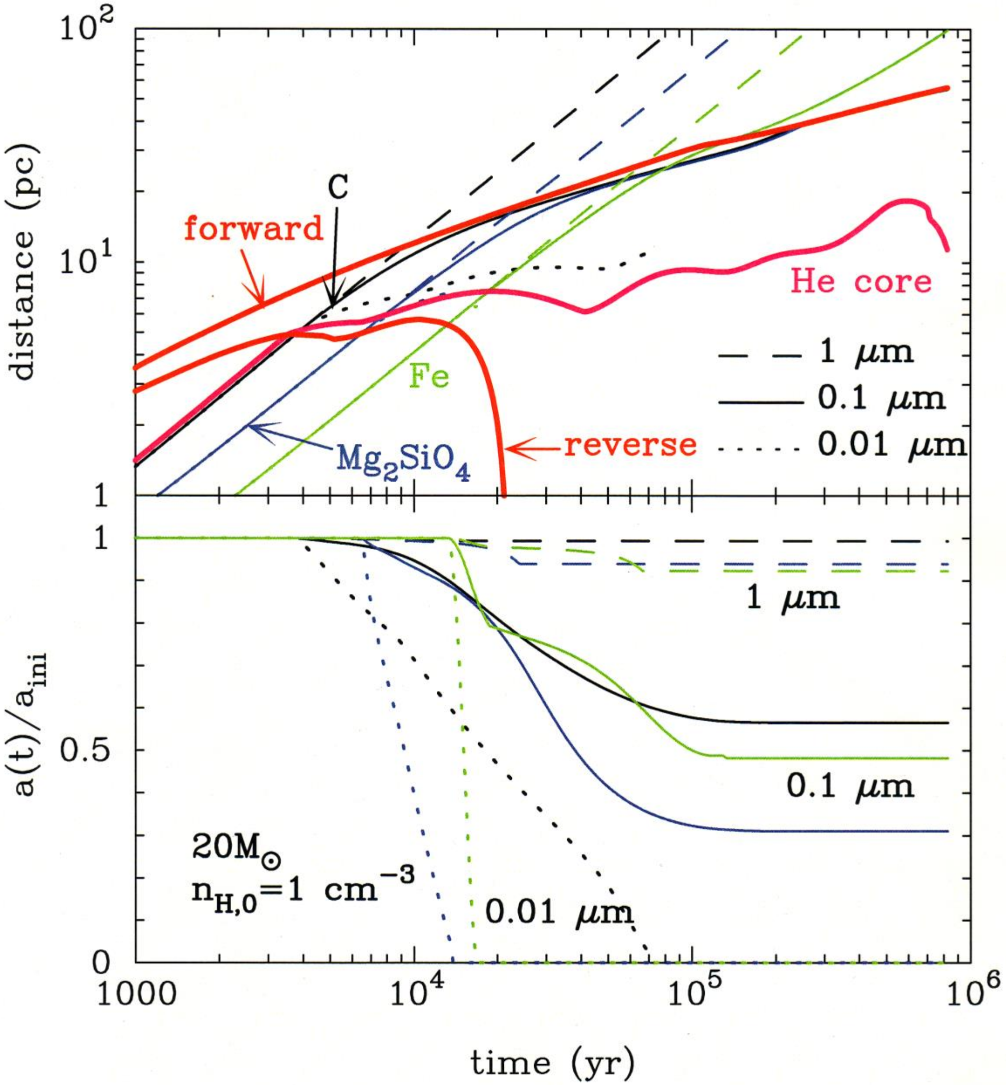
Model : M_{pr}= 20 Msun (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

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

2-2-2. Evolution of dust in SNRs

Nozawa+07, ApJ, 666, 955



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

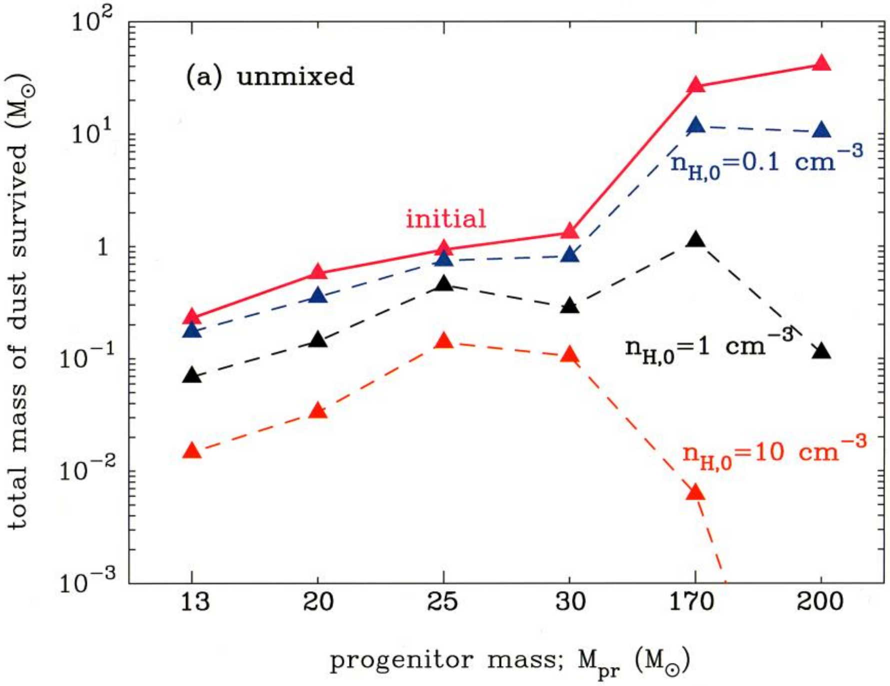
Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

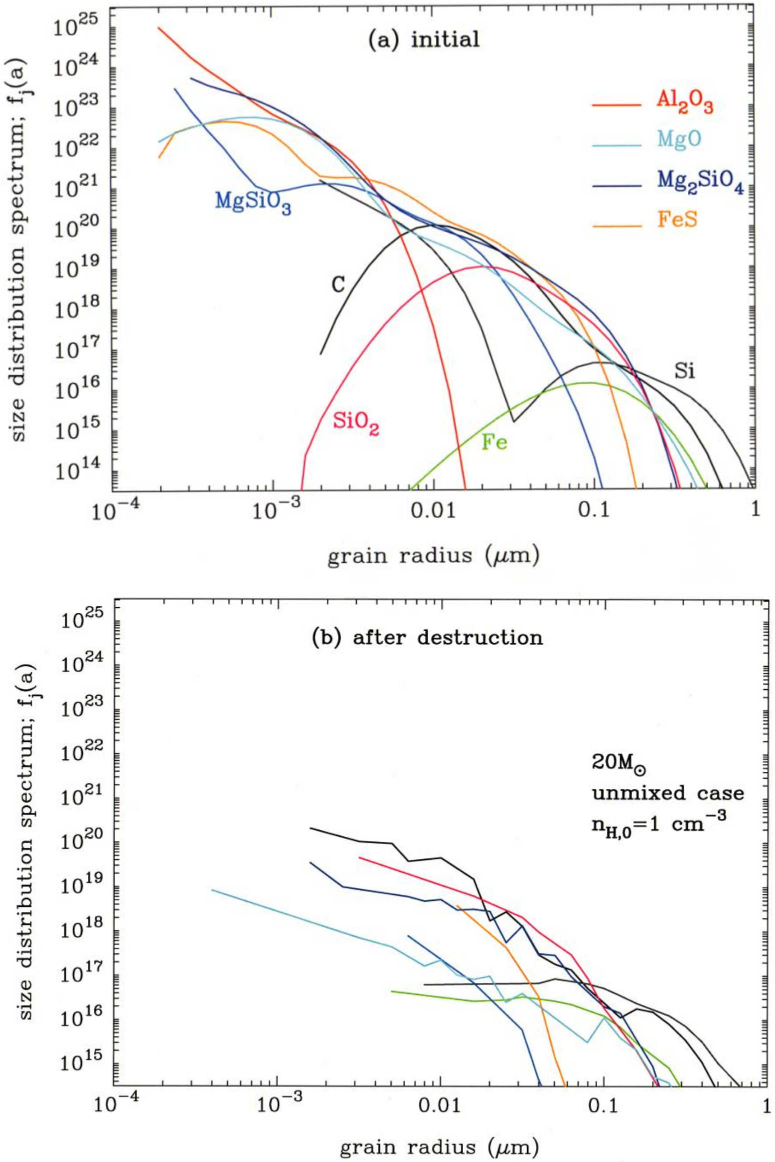
The evolution of dust heavily depends on the initial radius and composition

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

2-2-3. 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 M_{sun} ($n_{H,0}$ = 0.1-1 cm^{-3})

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

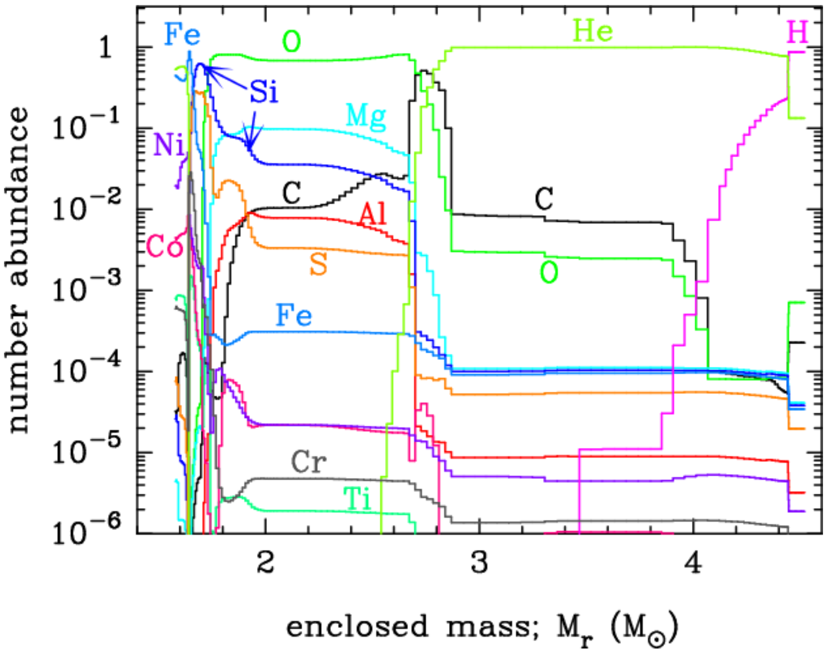
3. Formation and evolution of dust in various types of SNe

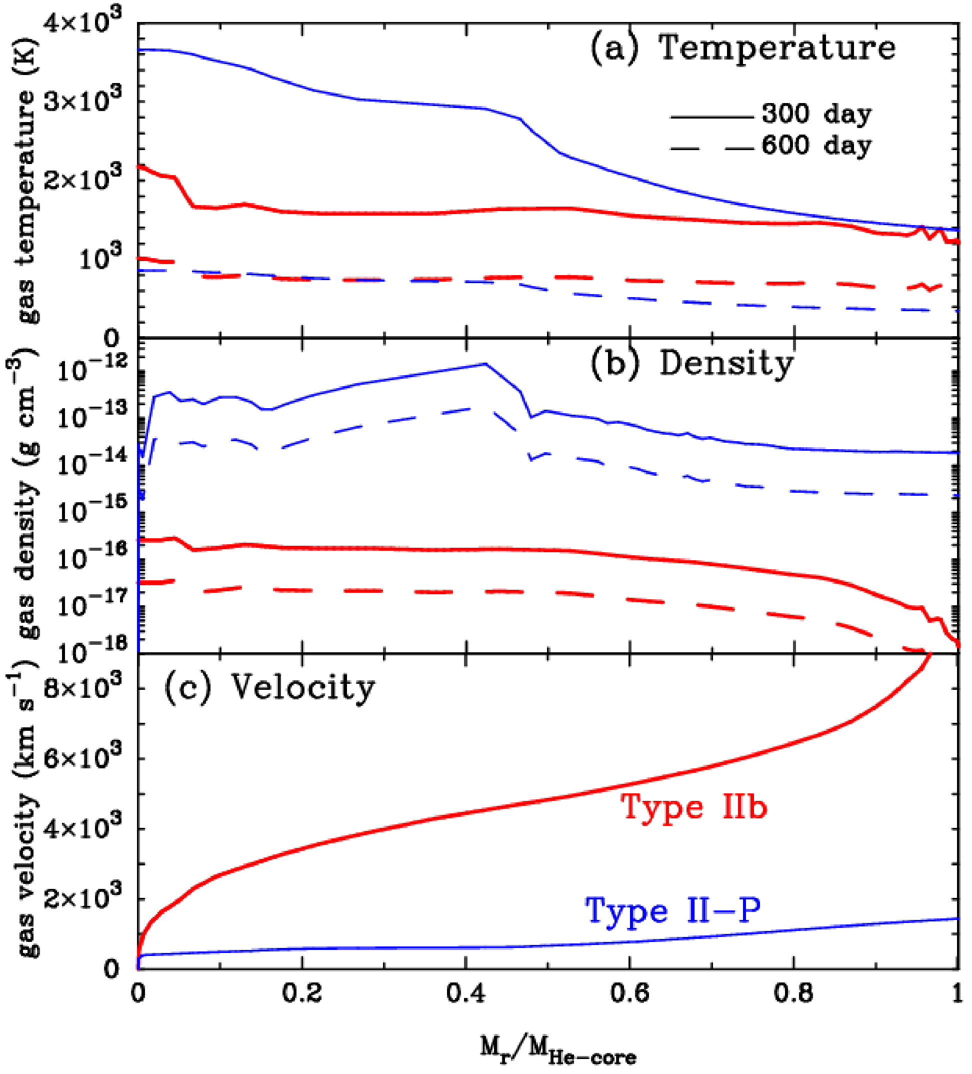
3-1-1. Dust formation in Type IIb SN

Nozawa+10, ApJ, 713, 356

○ SN IIb model (SN1993J-like model)

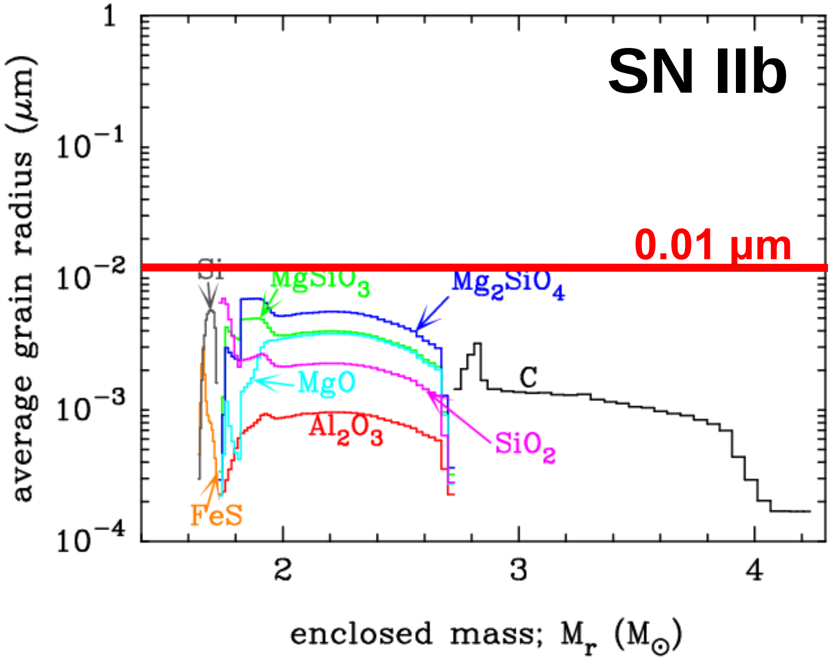
- **$M_{H\text{-}env}$ = 0.08 Msun**
  M_{ZAMS} = 18 Msun
  M_{eje} = 2.94 Msun
- $E_{51} = 1$
- $M(^{56}Ni) = 0.07$ Msun

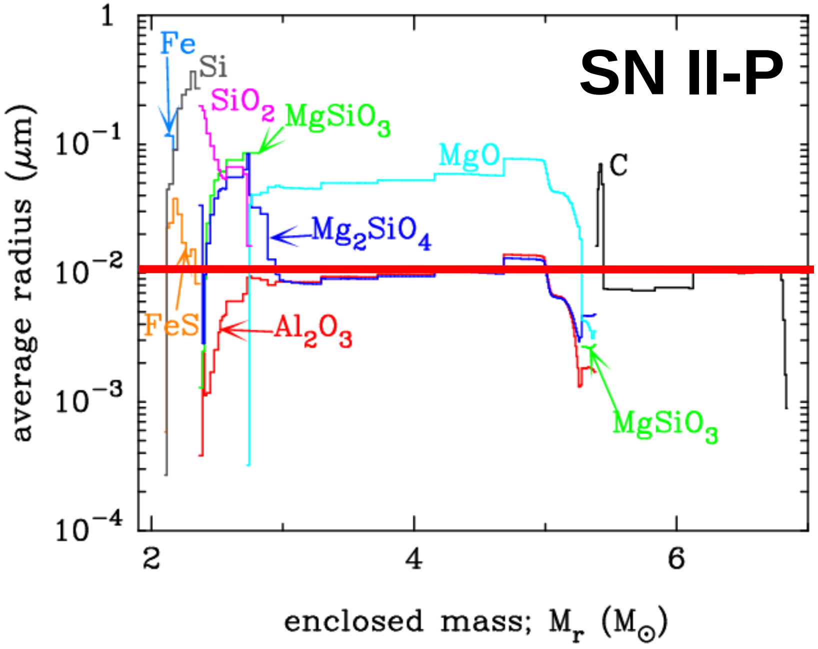




3-1-2. Dependence of dust radii on SN type

Nozawa+10, ApJ, 713, 356

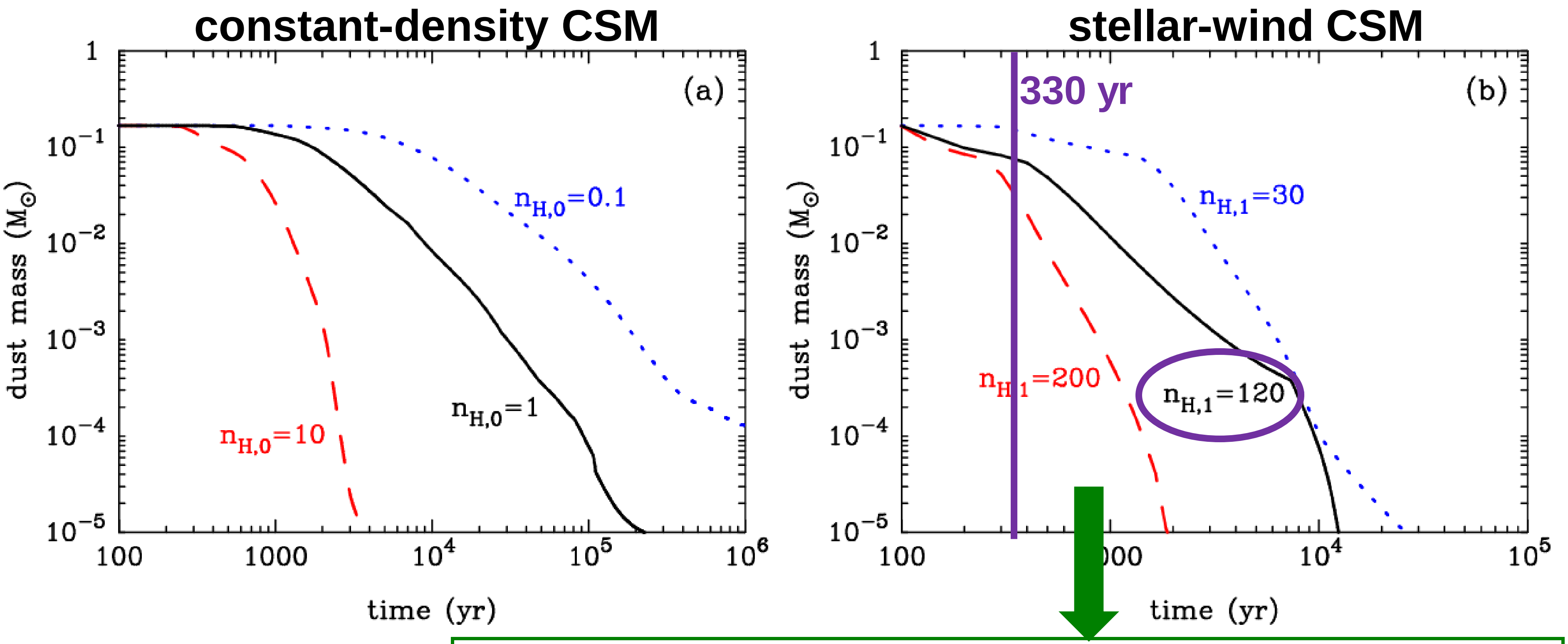




- condensation time of dust **300-700 d** after explosion
- total mass of dust formed
  - **0.167 Msun in SN IIb**
  - **0.1-1 Msun in SN II-P**

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

3-1-3. Destruction of dust in Type IIb SNR



Nozawa+10, ApJ, 713, 356

$n_{H,1}$ = 30, 120, 200 /cc

➔ dM/dt = 2.0, 8.0, 13x10^{-5} M_{sun}/yr for v_w=10 km/s

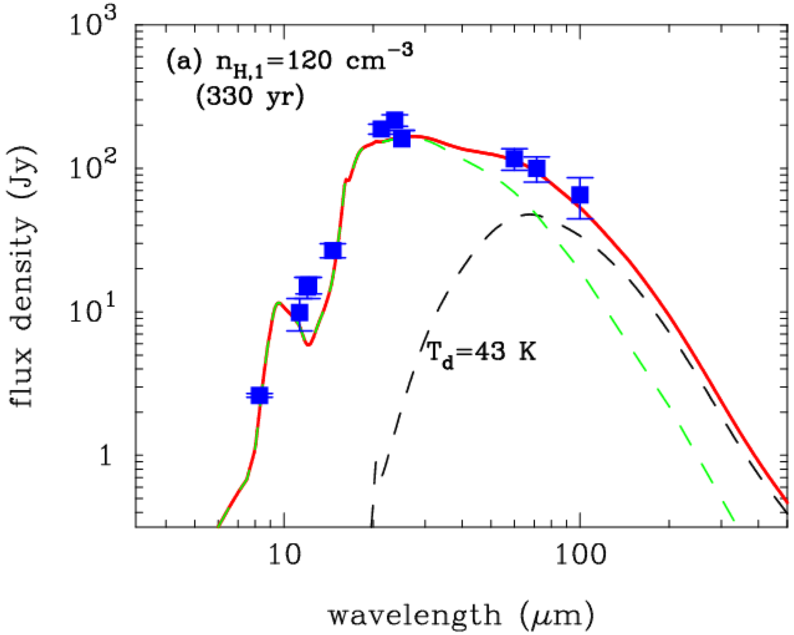
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

➔ **small radius of newly formed dust**

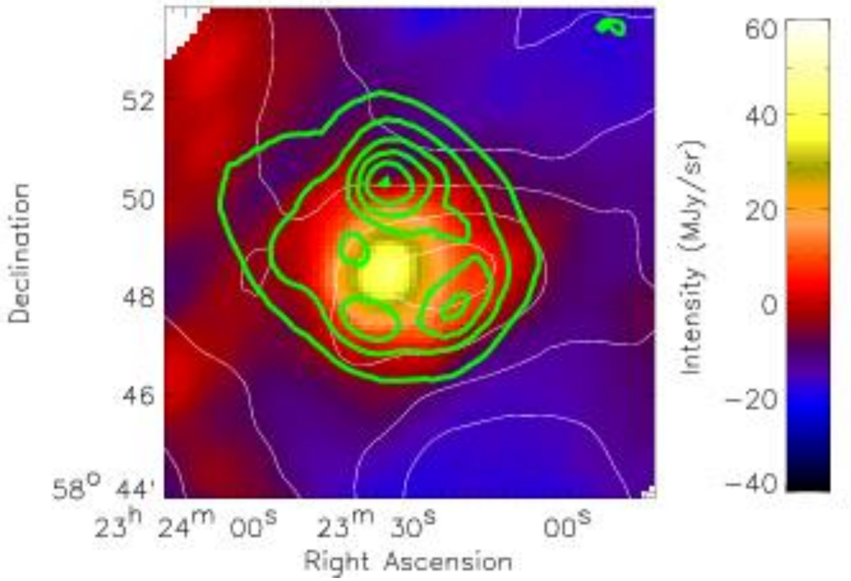
➔ **early arrival of the reverse shock at the He core**

3-1-4. Dust in Cassiopeia A

Nozawa+10, ApJ, 713, 356



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

AKARI observation

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

T_{dust} = 33-41 K

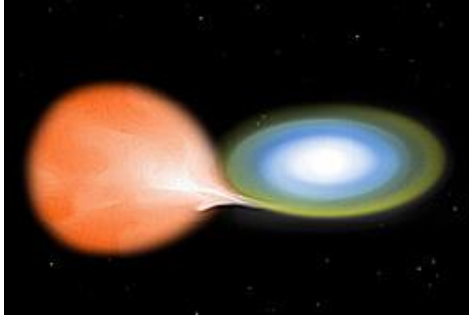
(Sibthorpe+10)

Herschel observation

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

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

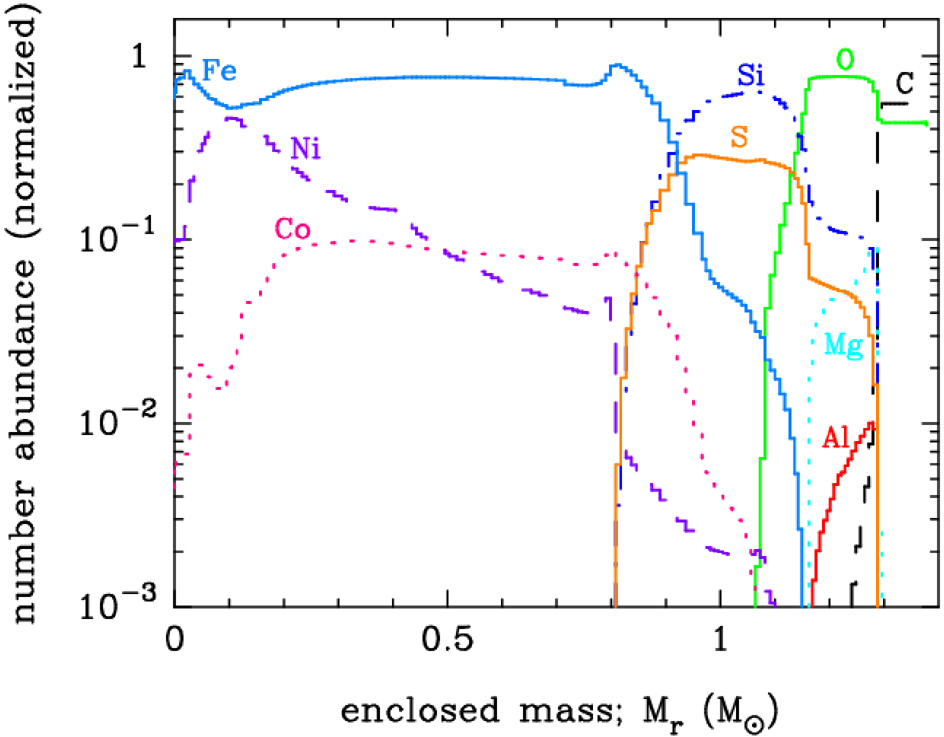
3-2-1. Dust formation in Type Ia SN

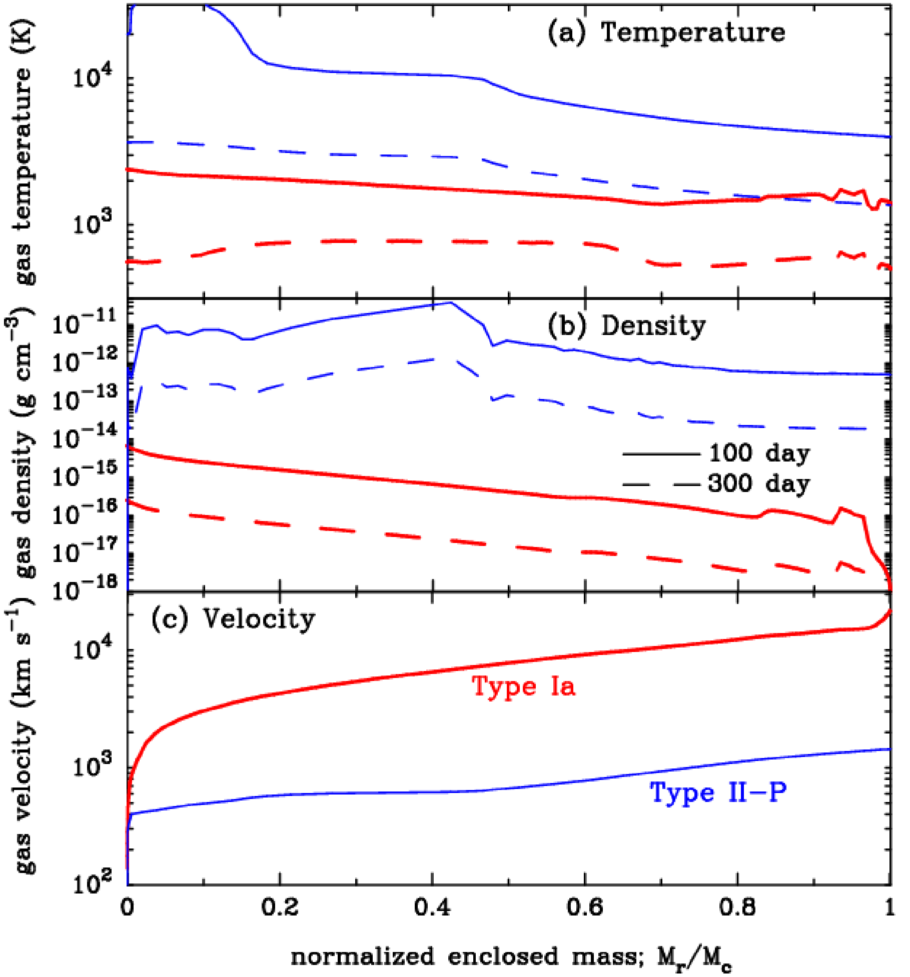


○ Type Ia SN model

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

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

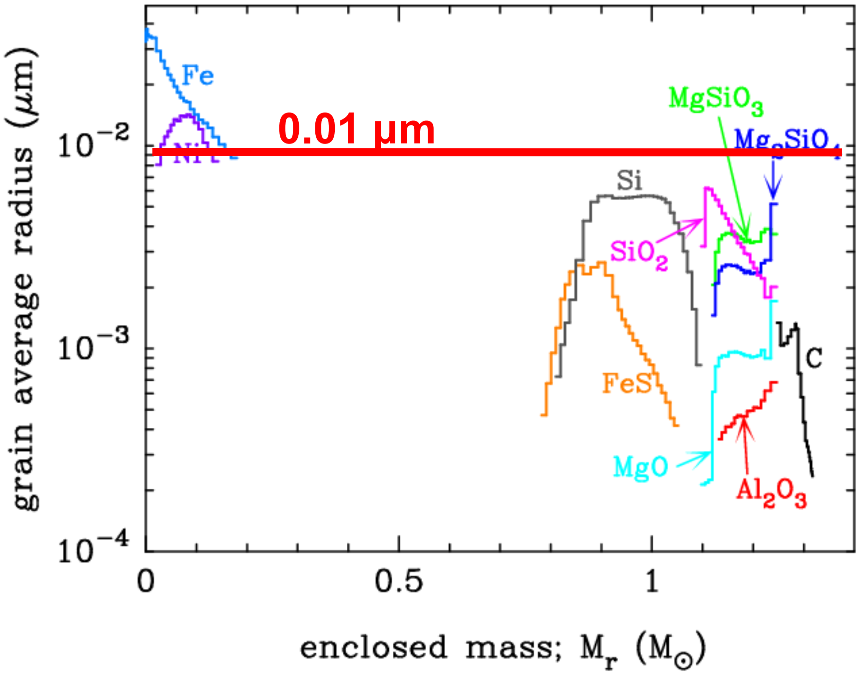




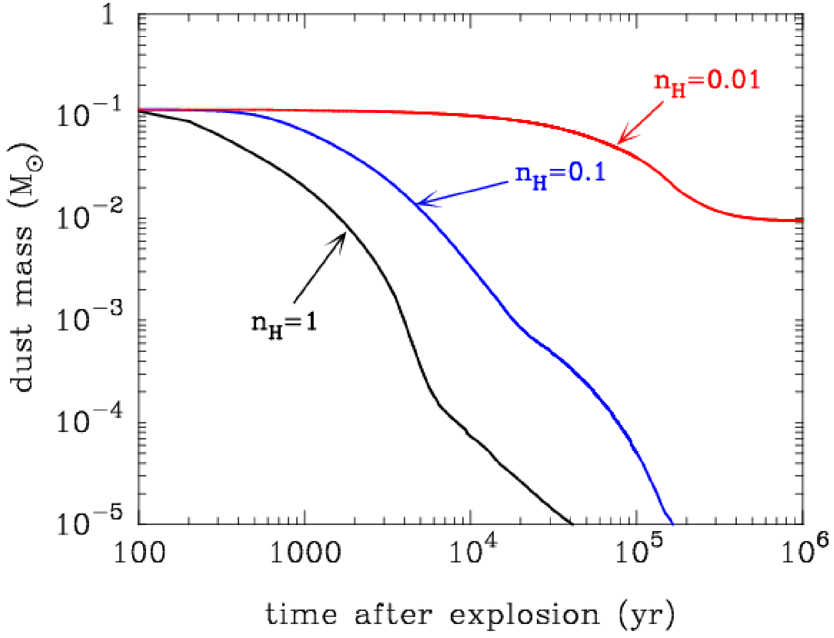
3-2-2. Dust formation and evolution in SNe Ia

Nozawa+11, submitted

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

4. Missing-dust problem in SNe

4-1. SNe are important sources of dust?

・Theoretical studies

— **at dust formation : ~0.1-1 M_{sun} in CCSNe (SNe II-P)**
(Nozawa+03; Todini & Ferr ra 2001; Cherchneff & Dwek 2010)

— **after destruction of dust y reverse shock :**
~0.01-0.5 M_{sun} (Nozawa 7; Bianchi & Schneider 2007)

dust amount needed to explain massive dust at high-z!

・Observational works

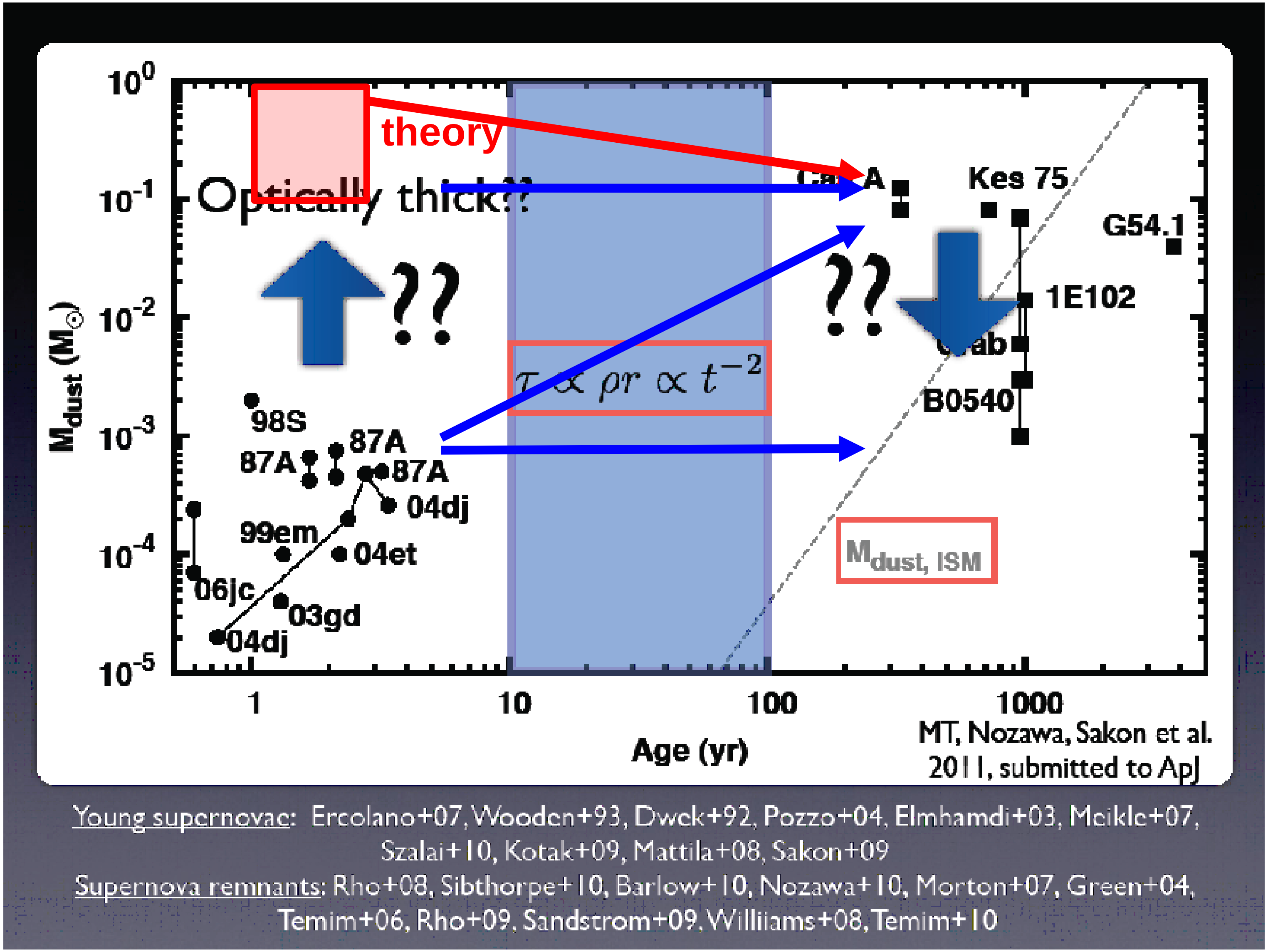
— **MIR observations of dust-forming SNe : $< 10^{-3}$ M_{sun}**
(e.g., Ercolano+07; Sakon+09; Kotak+09)

— **submm observations of SNRs : >1 M_{sun}**
(Dunne+03; Morgan+03; Dunne+09; Krause+05)

— **MIR-FIR observation of Cas A SNR : 0.02-0.075 M_{sun}**
(Rho+08; Sibthorpe+09; Barlow+10)

4-2. Missing-dust problem in CCSNe

Tanaka, TN, +11, submitted



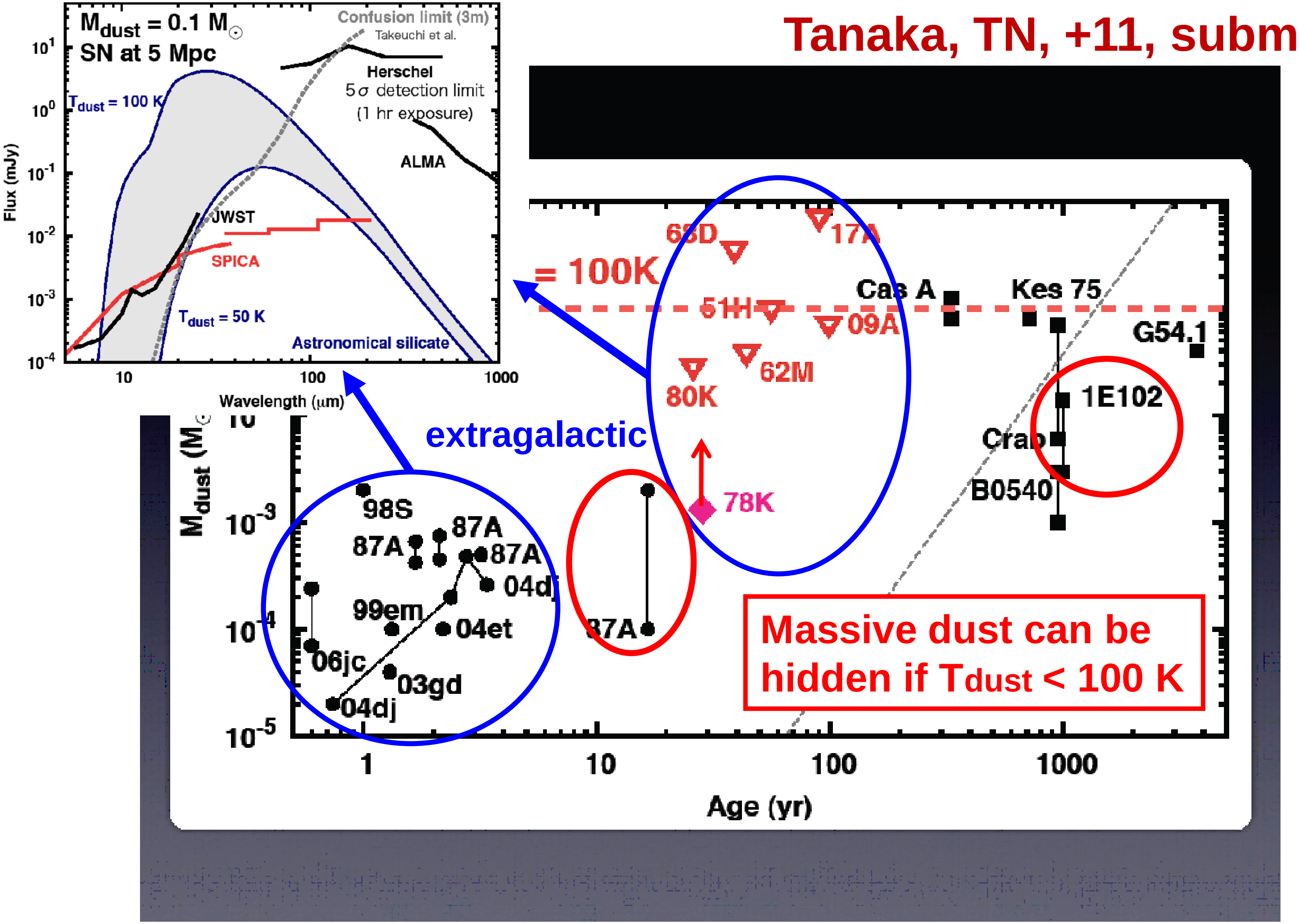
MT, Nozawa, Sakon et al.
2011, submitted to ApJ

Young supernovae: Ercolano+07, Wooden+93, Dwek+92, Pozzo+04, Elmhamdi+03, Meikle+07, Szalai+10, Kotak+09, Mattila+08, Sakon+09

Supernova remnants: Rho+08, Sibthorpe+10, Barlow+10, Nozawa+10, Morton+07, Green+04, Temim+06, Rho+09, Sandstrom+09, Williams+08, Temim+10

4-3. Detectability of dust with SPICA

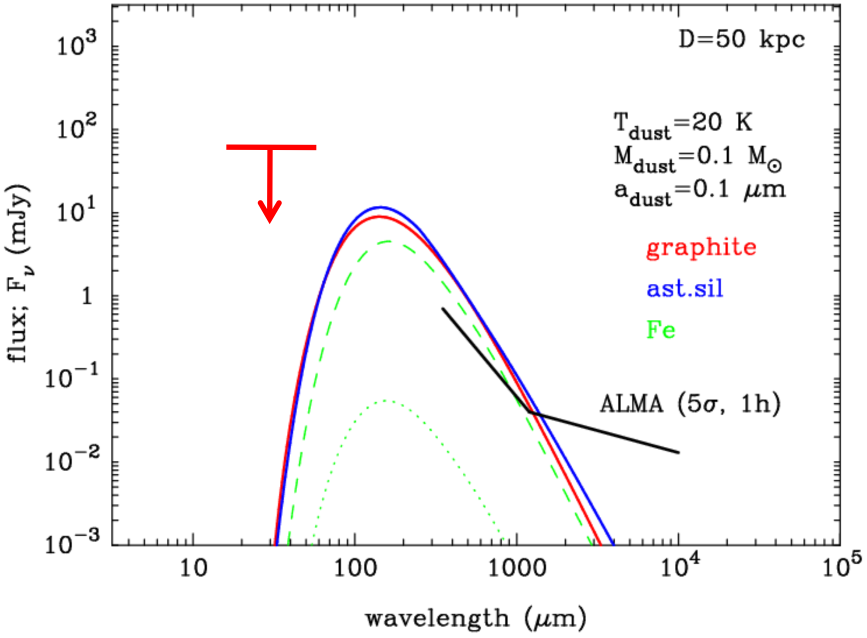
Tanaka, TN, +11, submitted

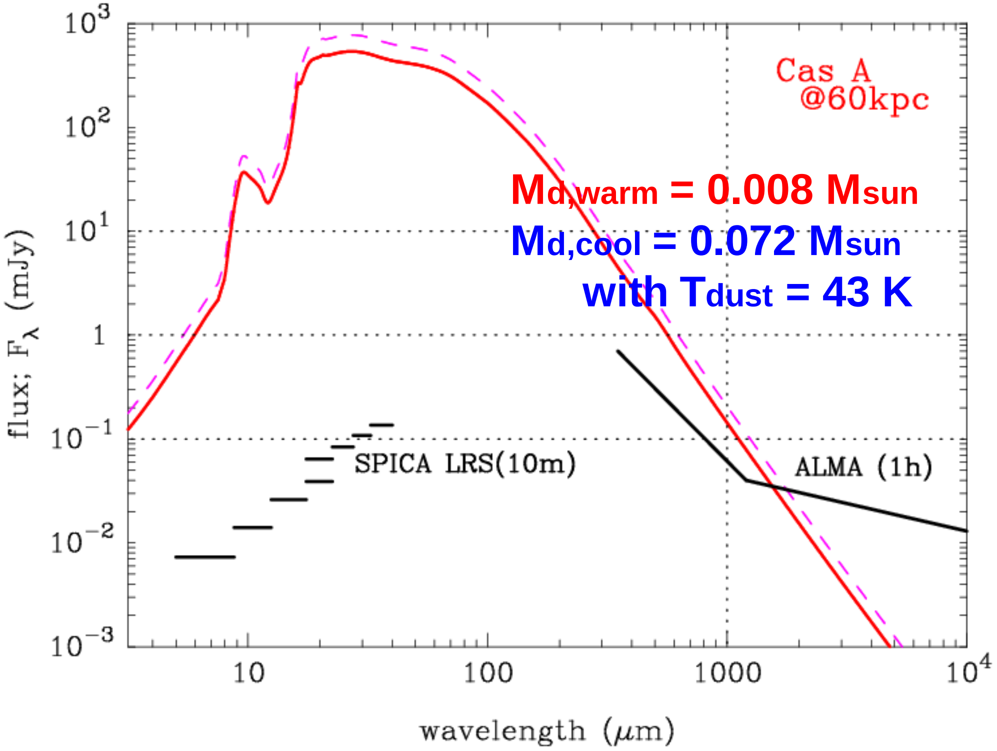


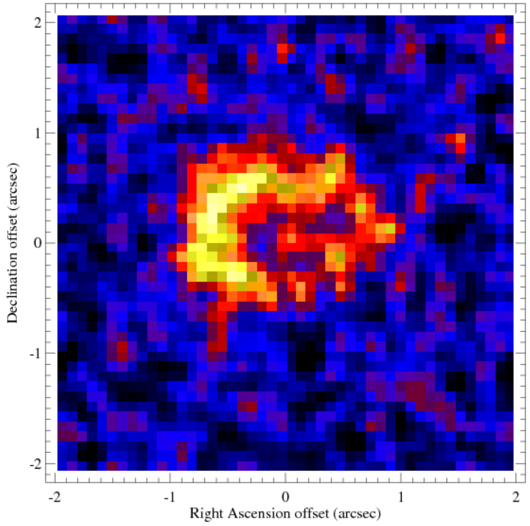
extragalactic

Massive dust can be hidden if Tdust < 100 K

4-4. Detectability of cold dust with ALMA







(Bouchet+04)

— **SN 1987A in LMC**
diameter : 2", most feasible

— **1E0102.2-7219 in SMC**
diameter : 40"
too extended to be detected

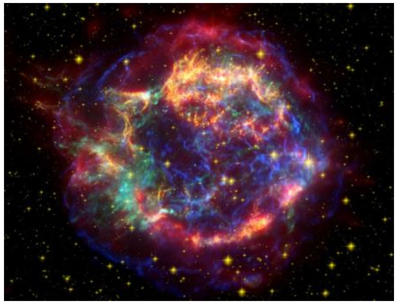
5. Conclusion remarks

5-1. Implication on evolution history of dust (1)

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

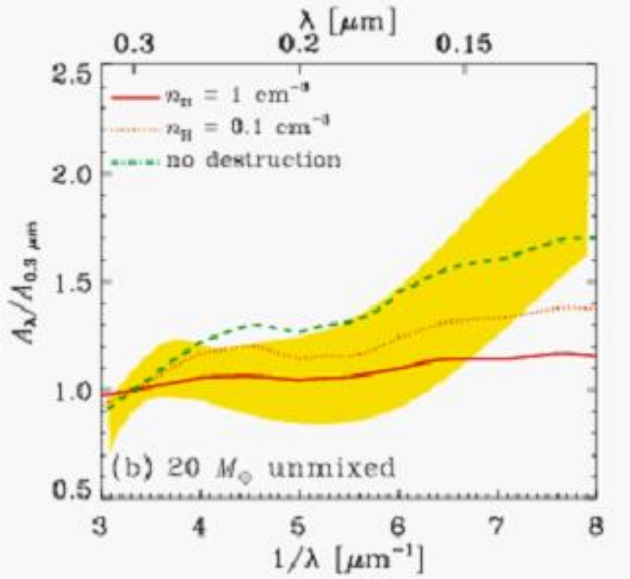
- massive stars (SNe) are dominate
- mass loss of massive stars would be less efficient

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

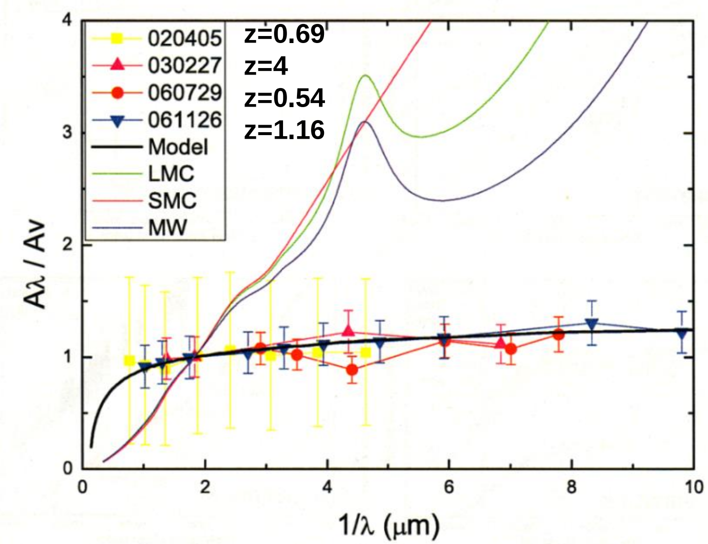


- a_{ave} is relatively large (> 0.01 μm)
- grain growth makes grain size larger

➔ dust extinction curve might be gray



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



Li+08, ApJ, 678, 1136

5-2. Implication on evolution history of dust (2)

○ metal-rich (low-z or Milky Way) galaxies

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

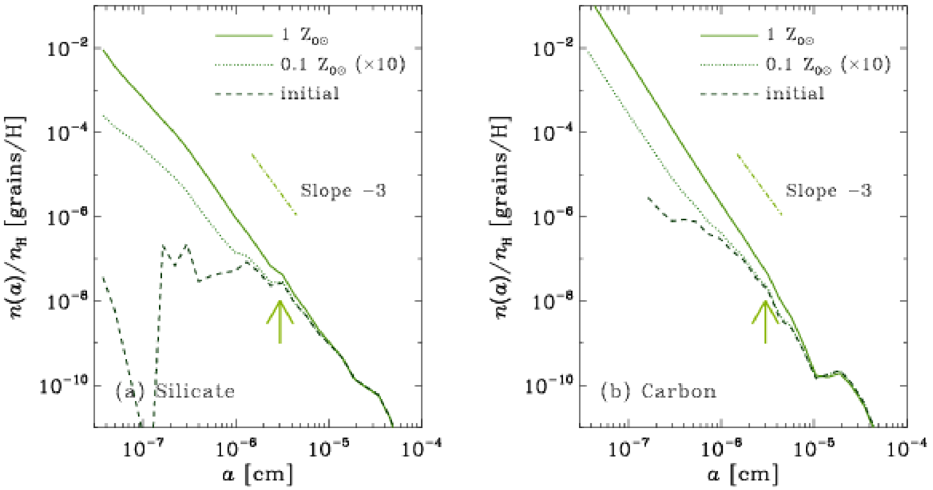
➔ SNe (IIb, Ib/c, Ia) might be minor sources of dust

- dust from AGB stars may also be large (0.01-0.1 μm)

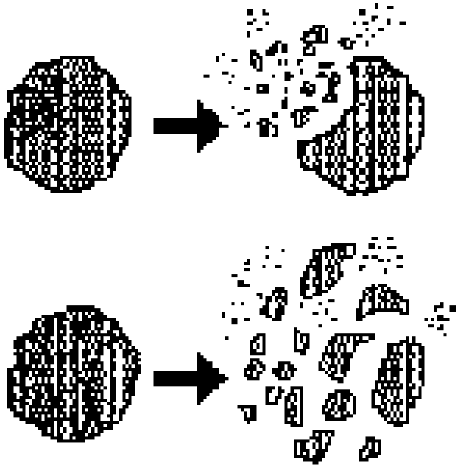
➔ How are small dust grains produced?

shattering process?

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



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



5-3. Future prospects

➔ SNe are important sources of dust?

- maybe, Yes in the early universe
- at least, to serve the seeds for grain growth in the ISM

➔ composition, size, and mass of dust?

- SPICA will make great advances on this issue

➔ theoretical and experimental approach is essential!

- nucleation process, crystalization
- dust temperature, optical properties

➔ application to other dust formation site

- novae, mass-loss wind of AGB and massive stars
- grain growth and processing in the molecular clouds

evolution history of dust throughout the cosmic age!