Supernovae as resources of interstellar dust

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2011/05/06

Outline

1. Introduction
    - Properties of interstellar dust in the Galaxy
    - Observations of dust at high redshift
2. Formation and evolution of dust in Population III Type II-P and pair-instability SNe
3. Formation of dust grains in various types of SNe
4. Missing-dust problem in core-collapse SNe
5. Implication and Summary

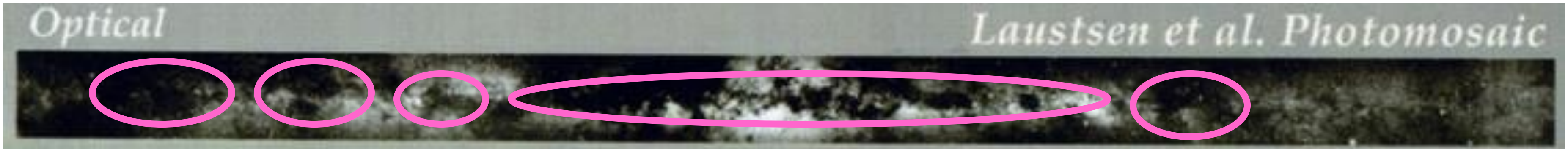
1. Introduction

1-1-1. Cosmic dust

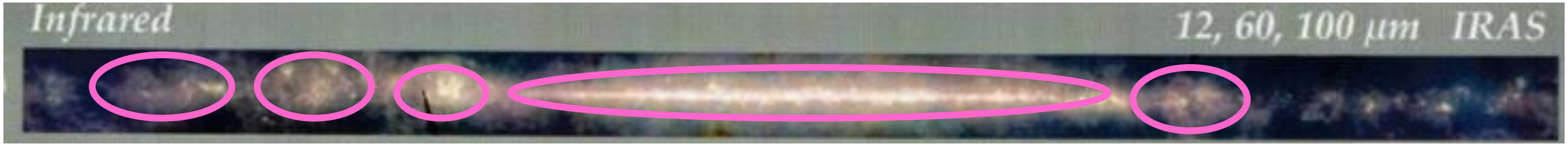
○ **Cosmic dust：solid particles with radii of a few nm to ~0.1 mm in astronomical environments**

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!

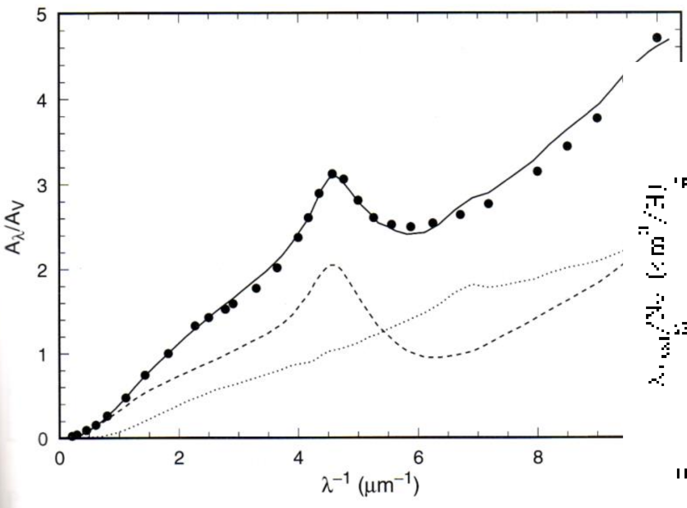
1-1-2. Interstellar dust in our Galaxy

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

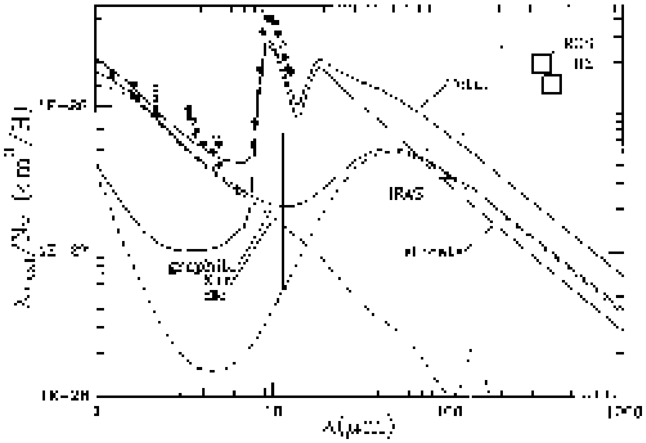
- **composition :** **graphite** (carbonaceous) grains
  silicate (SiO_2, Mg_2SiO_4, $MgFeSiO_4$, …) grains
- **size :** **$n(a) = f(a)da = a^{-3.5}\,da$ ($0.005 \sim 0.25\ \mu m$)**
- **amount :** **$M_{dust} / M_{gas} \sim 1 / 140$ ($\sim 10^9\ M_{sun}$)**

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

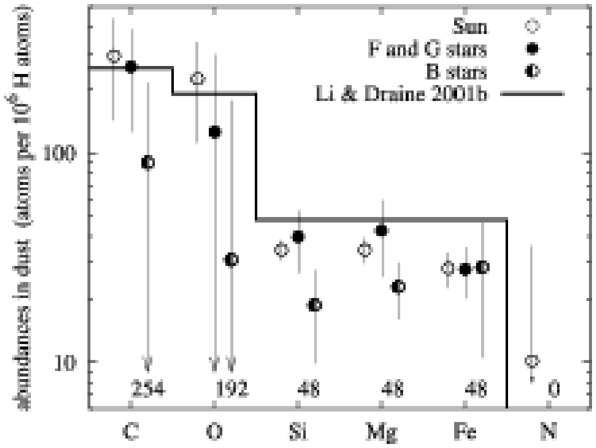
extinction curve



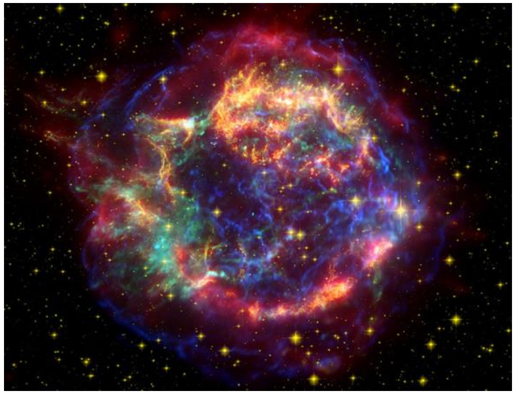
IR spectral feature



depletion of elements



1-1-3. Formation site of dust



○ Formation sites of dust

- abundant metal (metal : N > 5)
- low gas temperature ($T < \sim 2000$ K)
- high gas density ($n > \sim 10^8$ cm^{-3})

- **mass-loss winds of AGB stars**
- **expanding ejecta of supernovae (SNe)**
- molecular clouds (grain growth only)
- red giant, W-R stars, novae, protoplanetary disk …

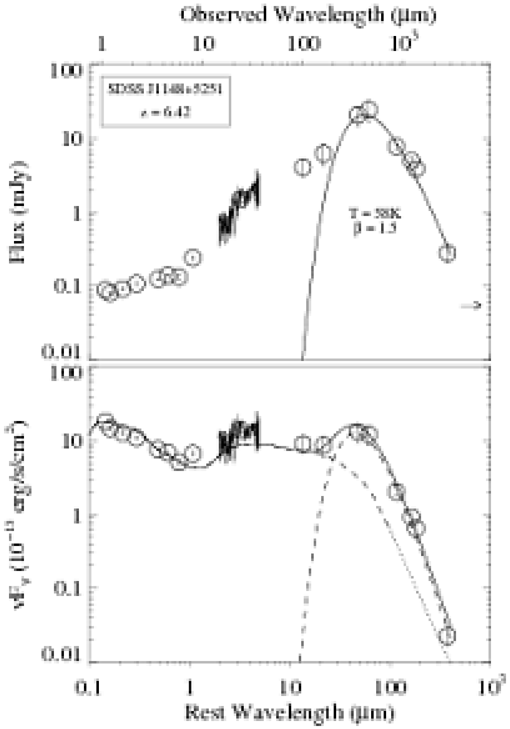
ejected gas : $\langle m_{AGB} \rangle / \langle m_{SN} \rangle \sim 1\text{-}2$
ejected dust : $f_{AGB} \langle m_{AGB} \rangle / f_{SN} \langle m_{SN} \rangle > 1\text{-}2$?

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**

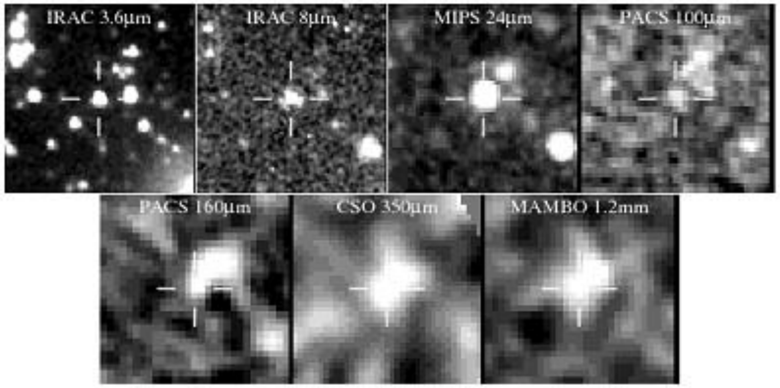
  ➔ **We see warm dust grains heated by absorbing stellar lights in the host galaxies of the quasars**

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**



1-2-2. 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

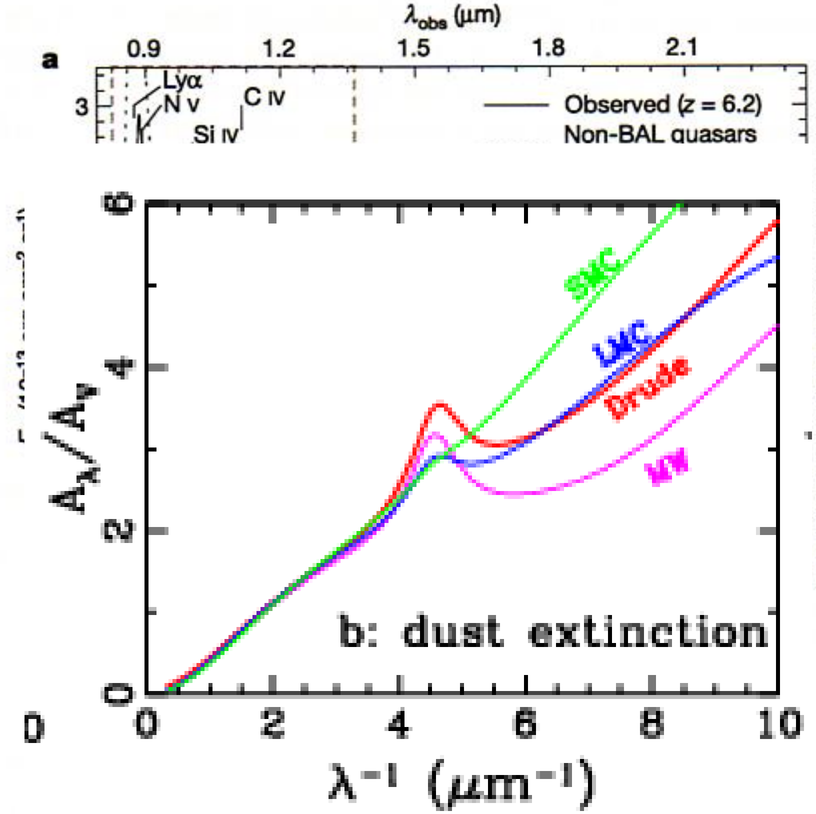
- **Grain growth in dense clouds** + AGB stars + SNe

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

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

- **Quasar outflows** (Elvis+'02)

1-2-3. Extinction curves at high-z quasars



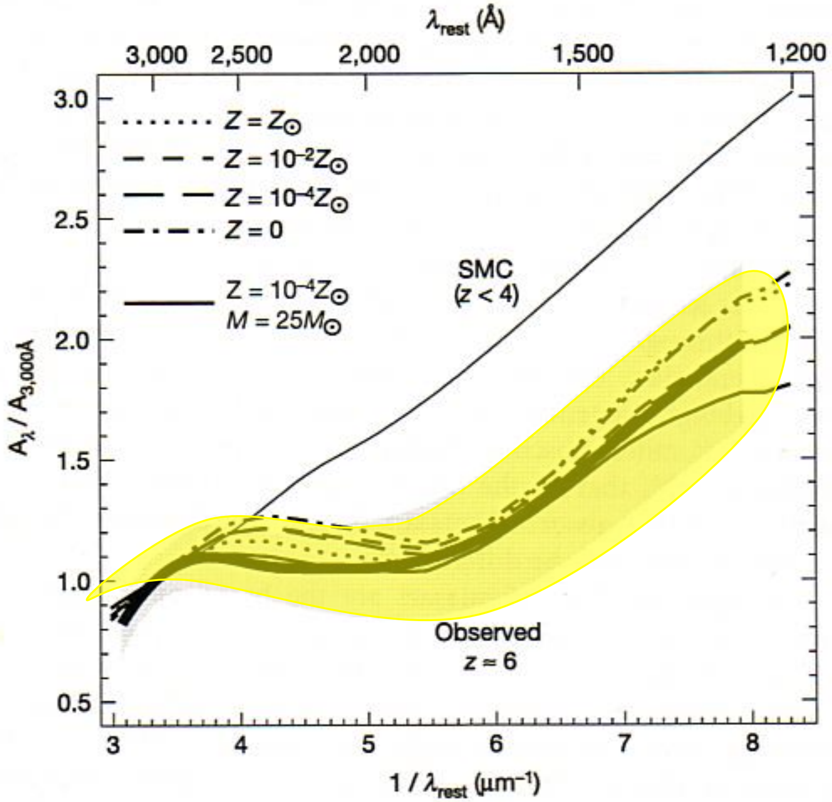
Dust model in MW (MRN)

- **silicate & graphite**
- **f(a)da = a^{-3.5}da**
  0.001 μm < a < 0.25 μm
- **dust-gas ratio : 1/140**

Maiolino+'04, Nature, 431, 533

SDSS J1048+4637 at z=6.2

Broad absorption line (BAL) quasars



different dust properties from those at low redshifts

1-2-4. Extinction curves at 3.9 < z < 6.4

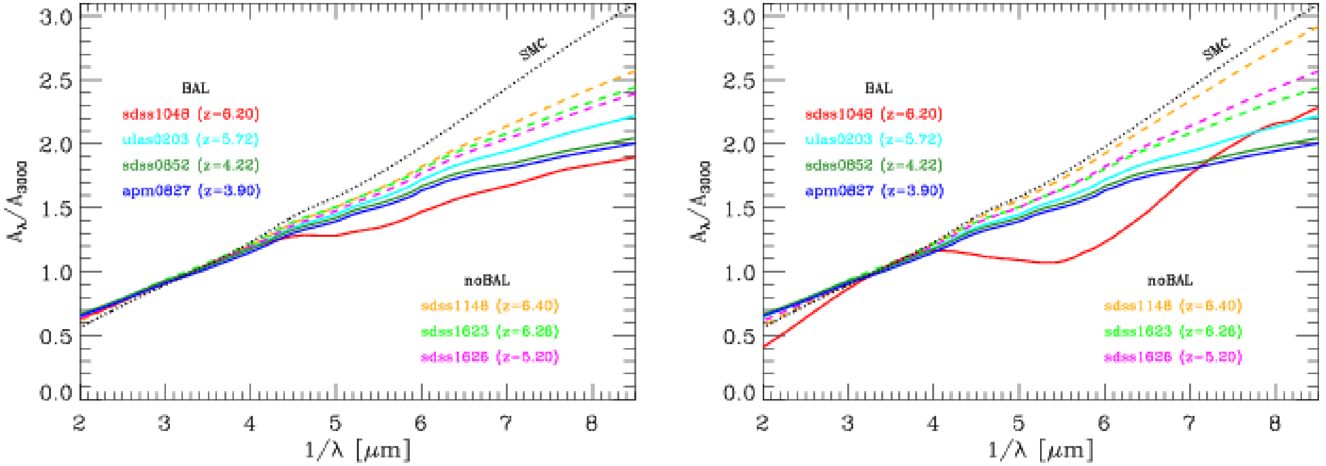


Fig. 4. Best fit extinction curves of reddened quasars. The solid lines are for BAL quasars, while dashed lines are for non-BAL quasars. For comparison the SMC extinction curve is also shown and labeled in the Figure (dotted black line). The panel on the left shows the results assuming a minimum intrinsic 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 %

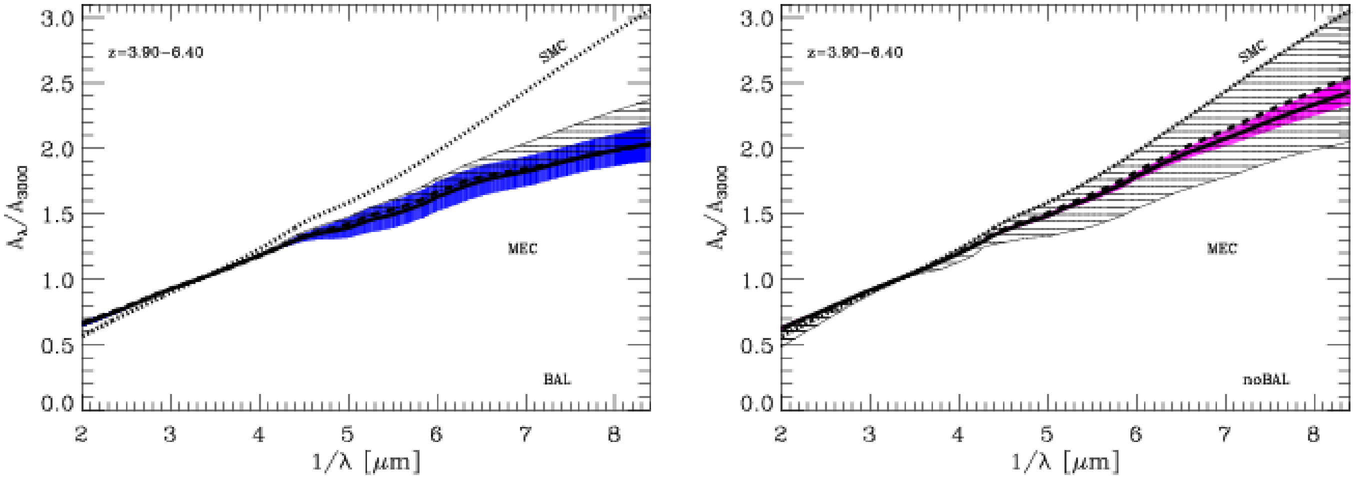
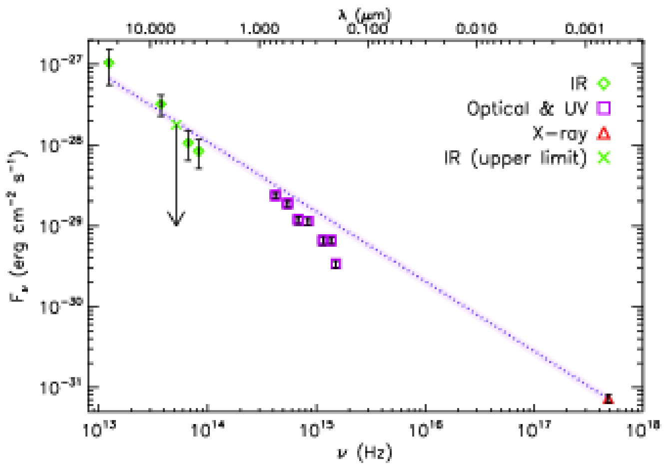
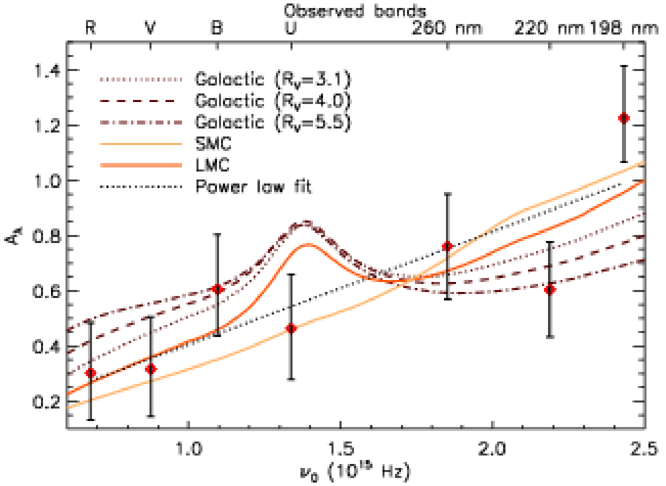


Fig. 6. Mean (MEC) and simultaneous/global (GEC) extinction curve of reddened quasars divided into BAL (left) and non-BAL (right). The coding is the same as in Fig. 5.

1-2-5. Extinction curves from high-z GRBs

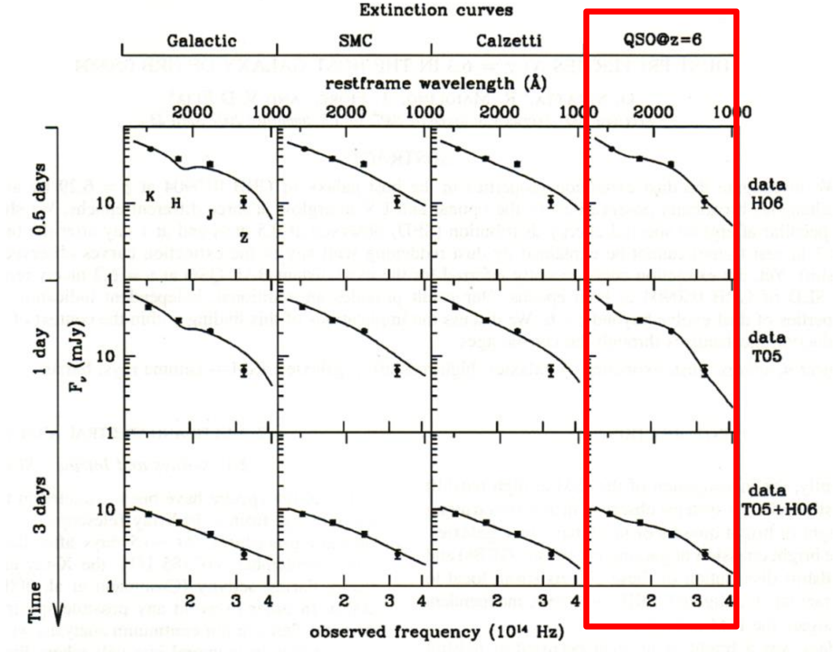




GRB 050525A
at z=0.6

Heng+'08, ApJ, 681, 1116

GRB 050904 at z=6.3



Stratta+'07, ApJ, 661, L9

additional evidence for different dust properties at high-z

but see Liang & Li'09, ApJ, 690, L56
Zafar+'10, A&A, 514, 94
Zafer+'11, arXiv/1101.1503

Extinction curves from high-z GRBs

Li+'08, ApJ, 678, 1136
Perley+'10, MNRAS, 406, 2473
Perley+'11, AJ, 141, 36

1-3. 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 ($M = 8$-$40\ M_{\rm sun}$) dominate the dust production over AGB stars ($M < 8\ M_{\rm sun}$) ??

1-4. 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)

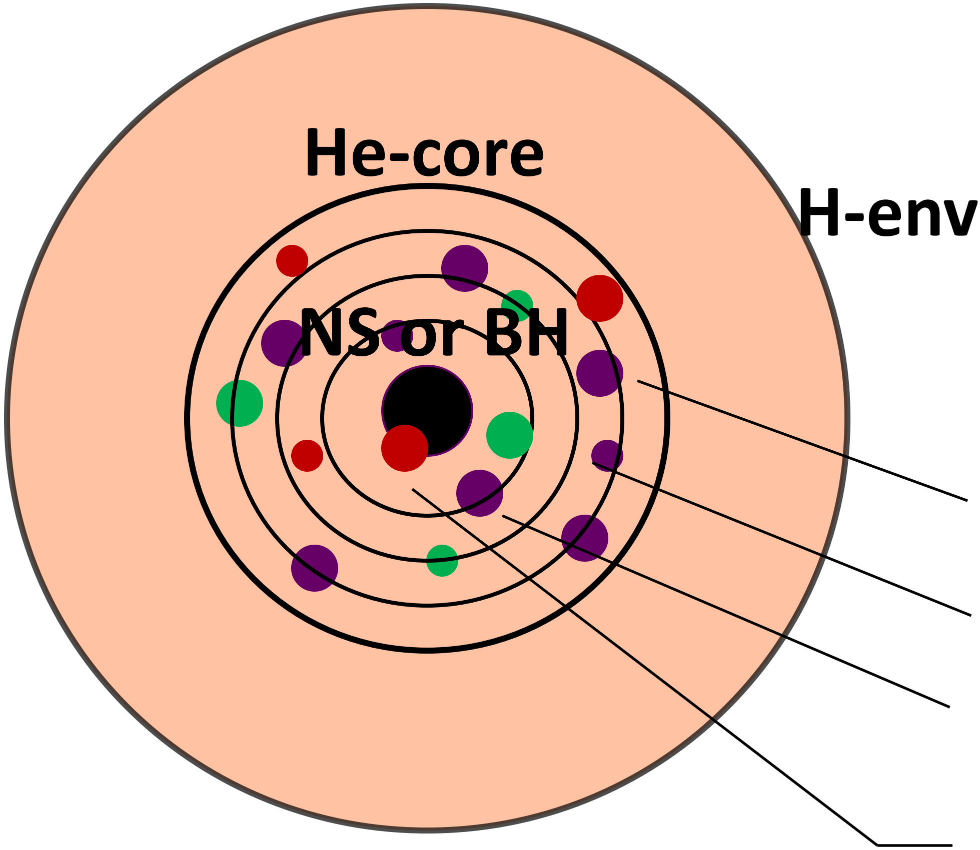
  ― controlling the energy balance in interstellar space

We aim at revealing the evolution of composition, size, and amount of dust by taking account into the formation and destruction processes of dust self-consistently

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

2-1. Dust Formation in Pop III SNe

at ~1 days



He-core

H-envelope

NS or BH

He–layer (C>O)

O–Ne-Mg layer

Si–S layer

Fe–Ni layer

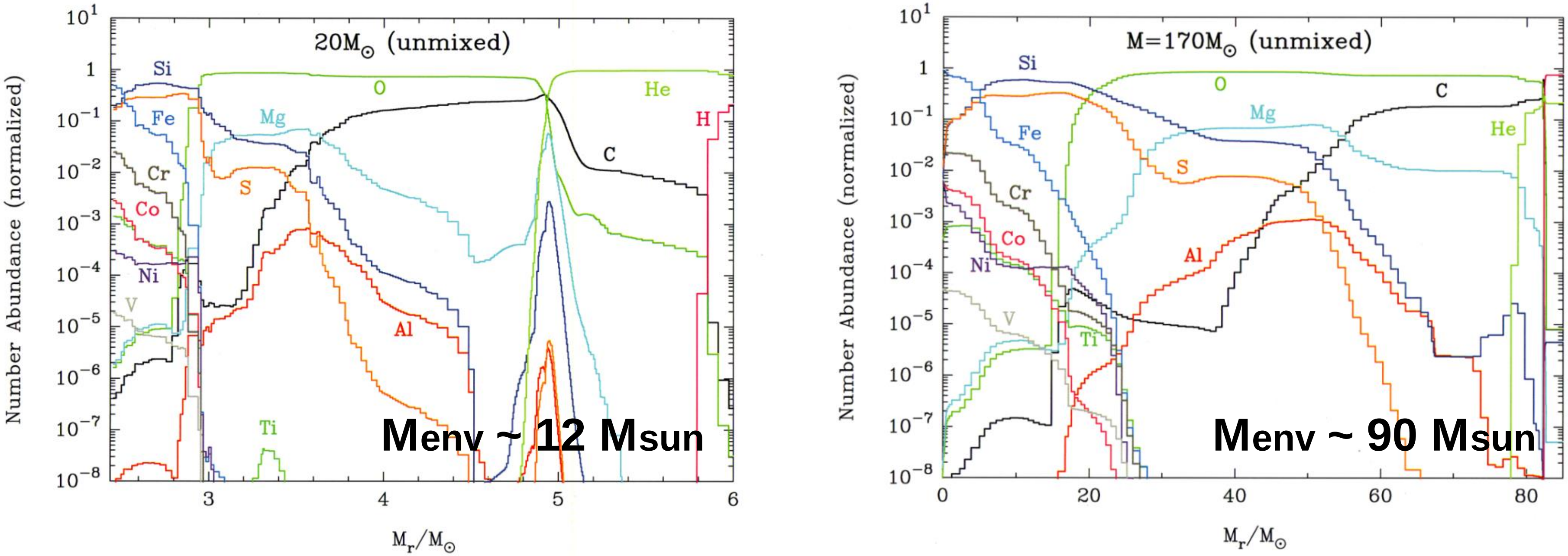
Dust formation
at ~1-3 years
after explosion

2-1-1. Dust formation in primordial SNe

Nozawa+'03, ApJ, 598, 785

○ Population III SNe model (Umeda & Nomoto'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)



Menv ~ 12 Msun

Menv ~ 90 Msun

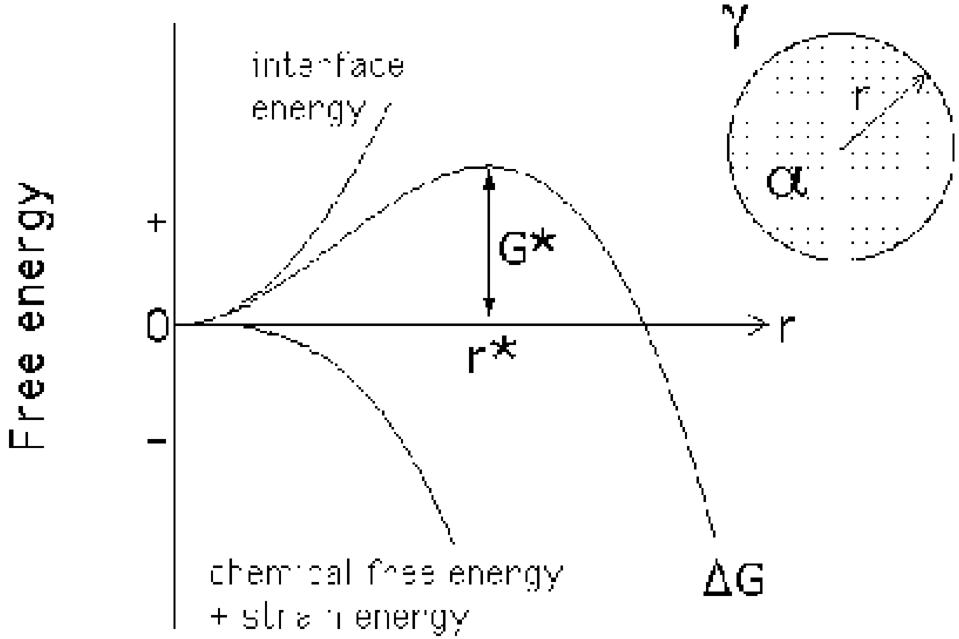
- nucleation and grain growth theory (Kozasa & Hasegawa'88)
- no mixing of elements within the He-core
- complete formation of CO and SiO

2-1-2. Nucleation rate of dust

Steady-state classical nucleation rate

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

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



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

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

$$k_n = 4\pi a^2 \alpha_s \left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}} = 4\pi a_0^2 n^{\frac{2}{3}} \alpha_s \left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}}$$

es

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

2-1-3. Basic equations of dust formation

Equation of conservation for key species

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

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

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

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

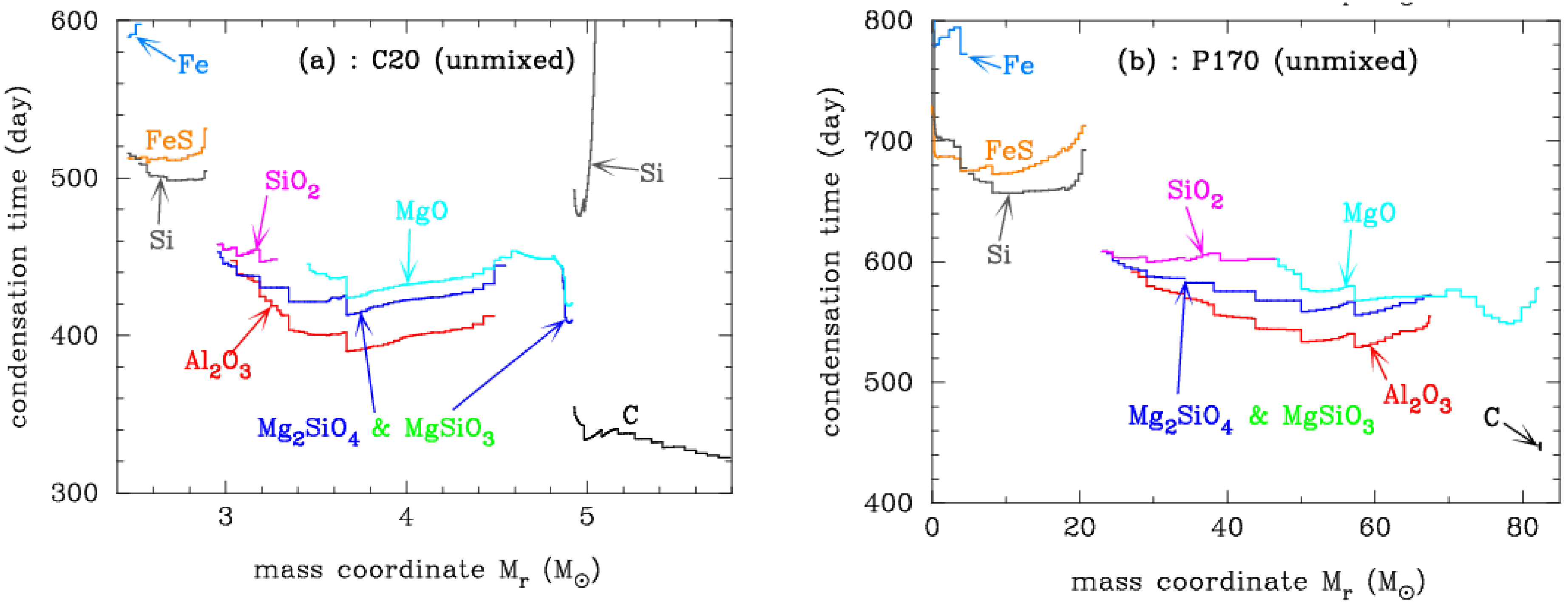
$$\boxed{\tau_{\mathrm{coll}}^{-1}(t) = 4\pi a_0^2 \alpha_s \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1(t)}$$

· ra $t_0)$

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

2-1-4. Dust formed in primordial SNe

Nozawa+'03, ApJ, 598, 785

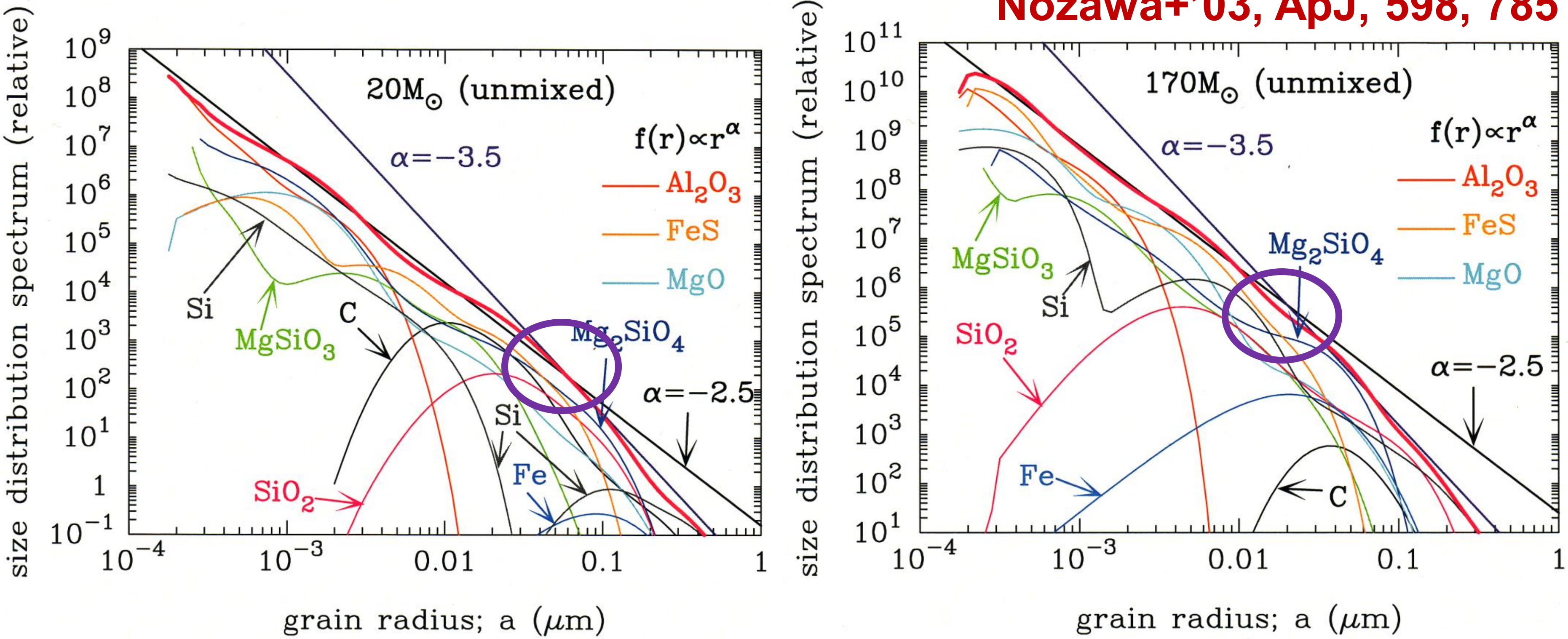


- **Various dust species (C, $MgSiO_3$, Mg_2SiO_4, SiO_2, Al_2O_3, MgO, Si, FeS, Fe) form in the unmixed ejecta, according to the elemental composition of gas in each layer**

- **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

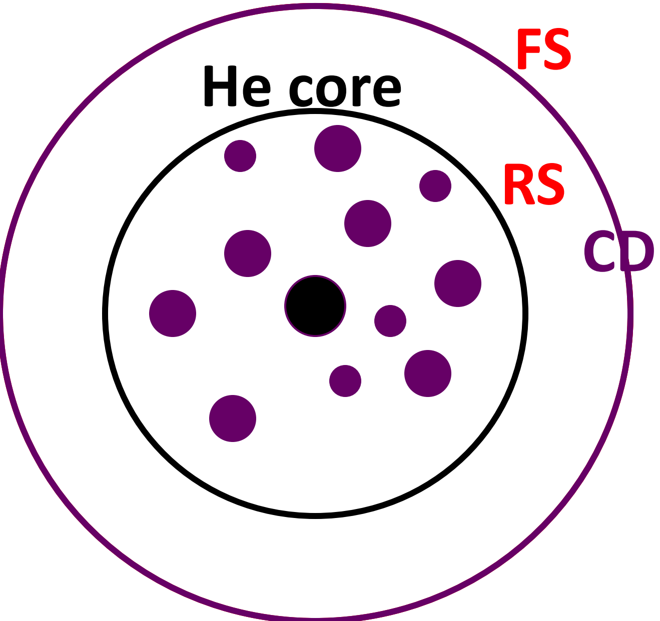
amount of newly formed dust grains

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

2-2. Dust Evolution in SNRs

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



2-2-1. Time evolution of shock wave

- Basic equations (spherical symmetry)

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

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

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

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

$\Lambda_{\mathrm{gas}}(T)$: cooling function of gas by the atomic process

(Sutherland & Dopita 1993; Smith et al. 2001)

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

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

$\Lambda_{\mathrm{d}}(n_{\mathrm{H}}, T)$: 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)

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

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

2-2-4. 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)

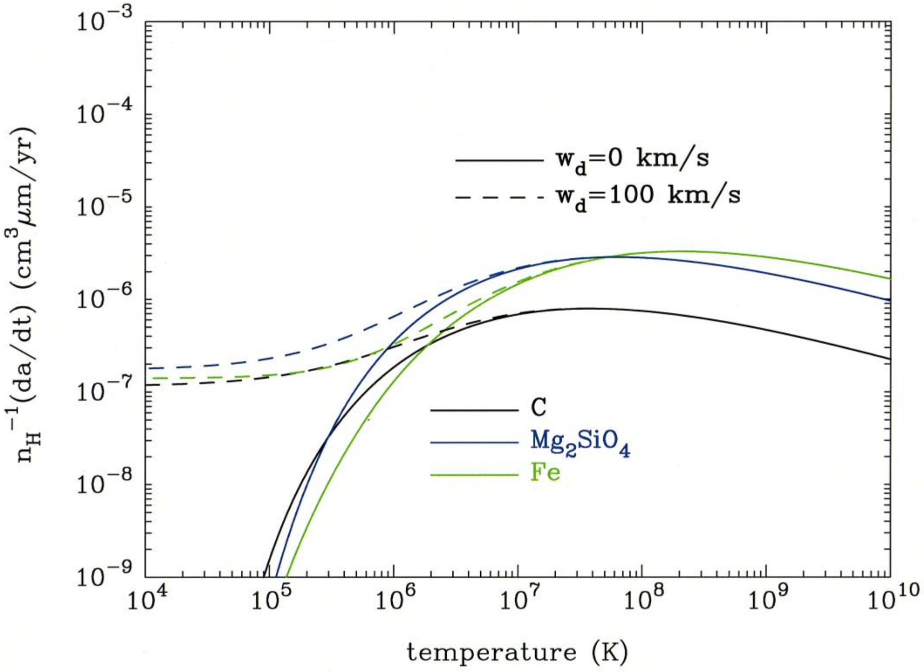
$$\mathcal{R}(X_i(\epsilon)) = n_{\rm H} A_i \pi a^2 \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} \frac{e^{-s_i^2}}{2s_i} \int \sqrt{\epsilon} e^{-\epsilon} \sinh(2s_i\sqrt{\epsilon}) X_i(\epsilon) d\epsilon$$

where $\epsilon = E/kT$

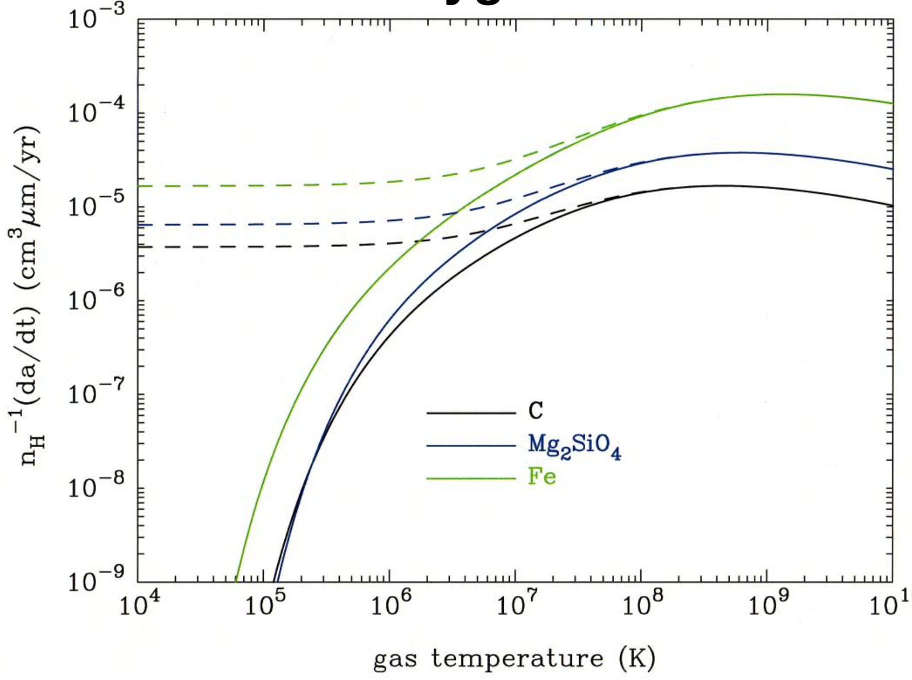
2-2-5. Erosion rate of dust by sputtering

Nozawa+’06, ApJ, 648, 435

for primordial composition gas



for oxygen ions

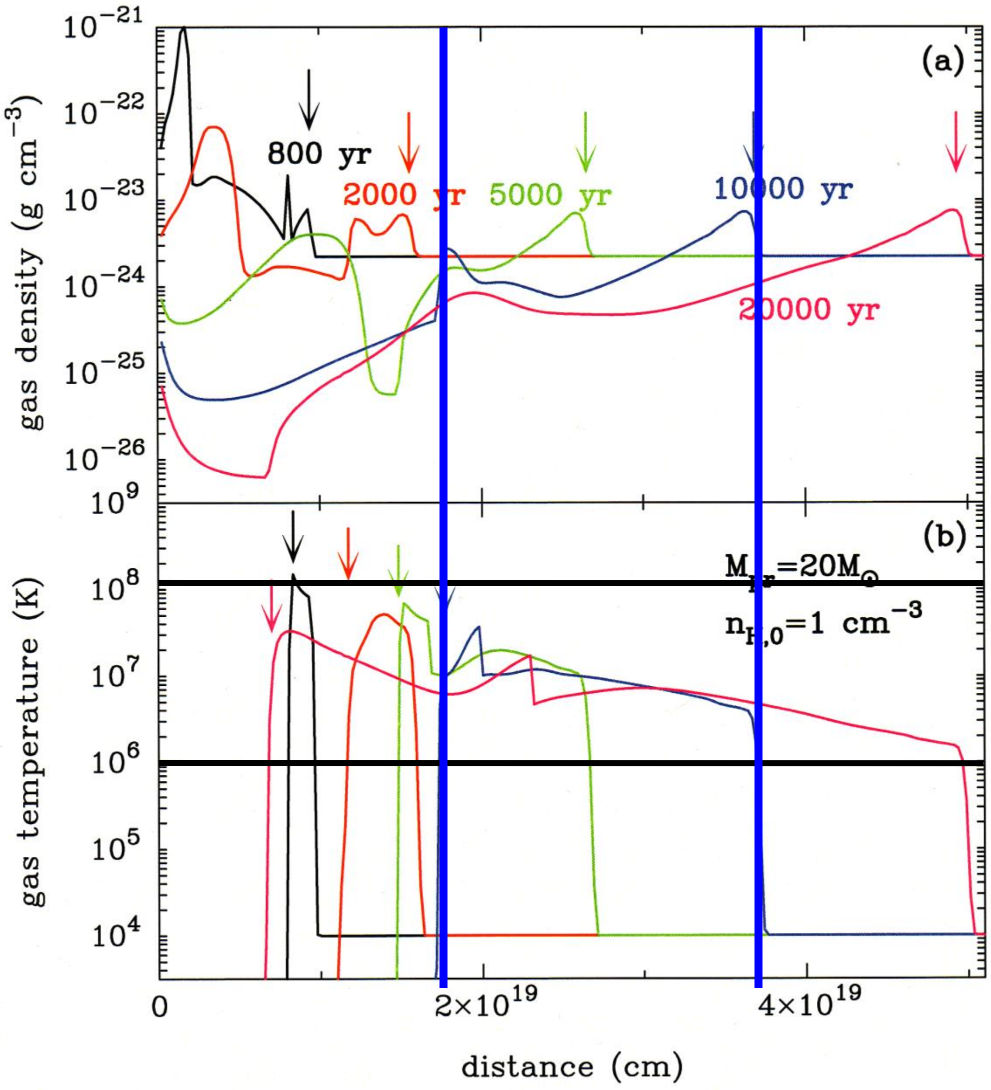


- erosion rate by sputtering quickly increases above 10^5 K and peaks at 10^7 -10^8 K

- 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

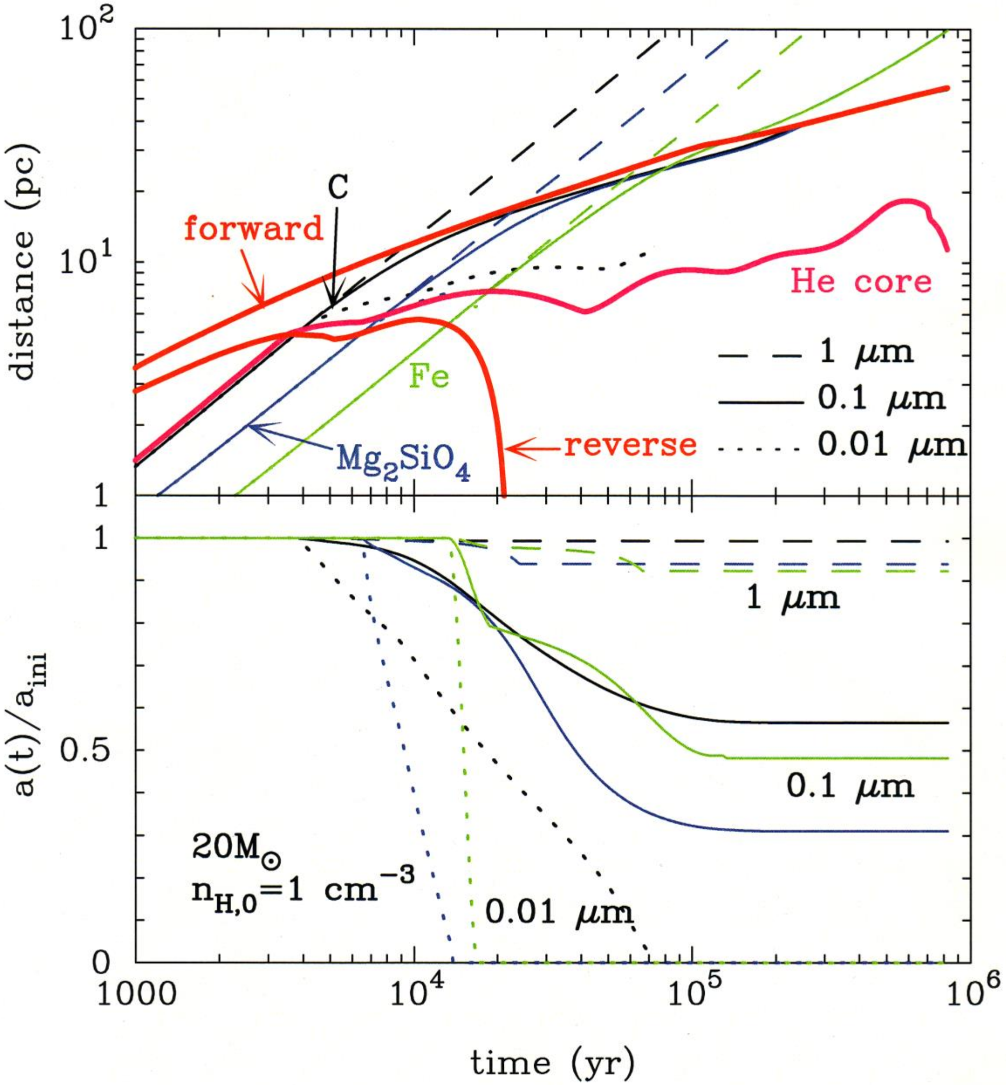
The temperature of the gas swept up by the shocks
➔ 10^6-10^8 K

↓

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}

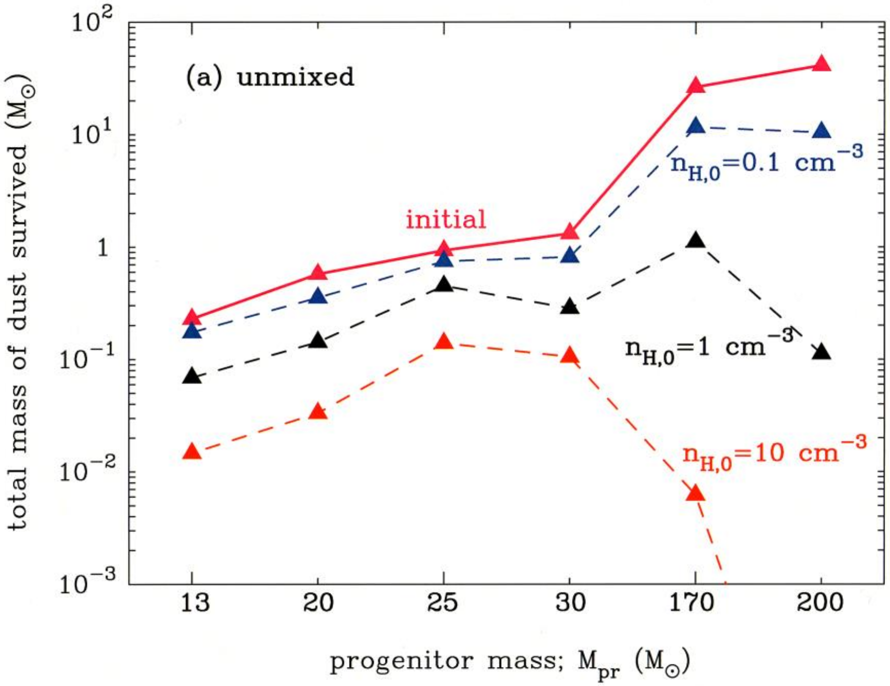
Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

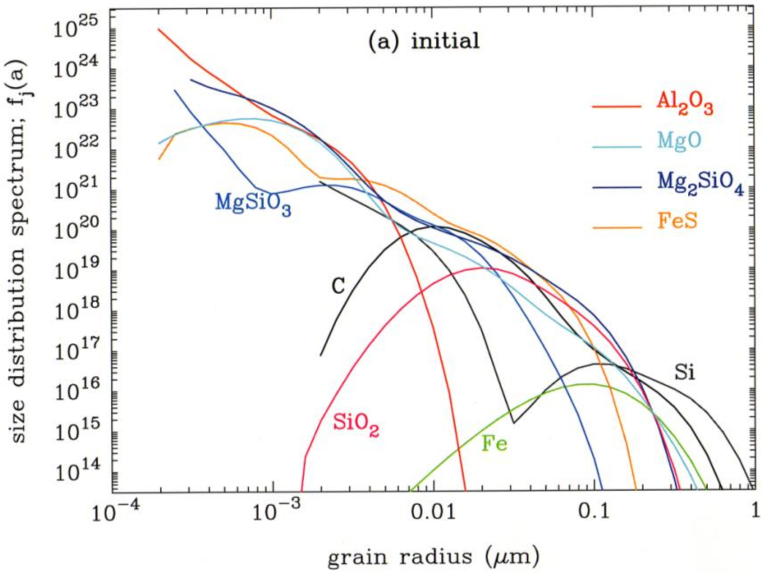
The evolution of dust heavily depends on the initial radius and composition

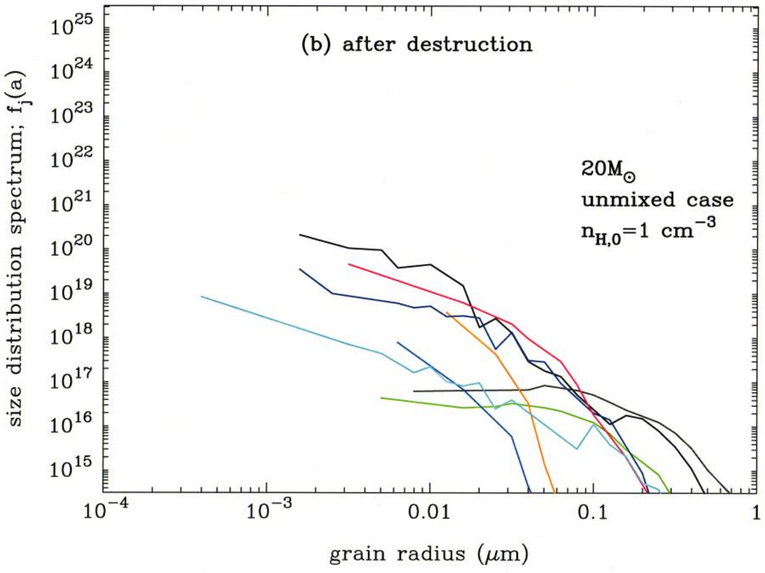
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

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

Nozawa+'07, ApJ, 666, 955





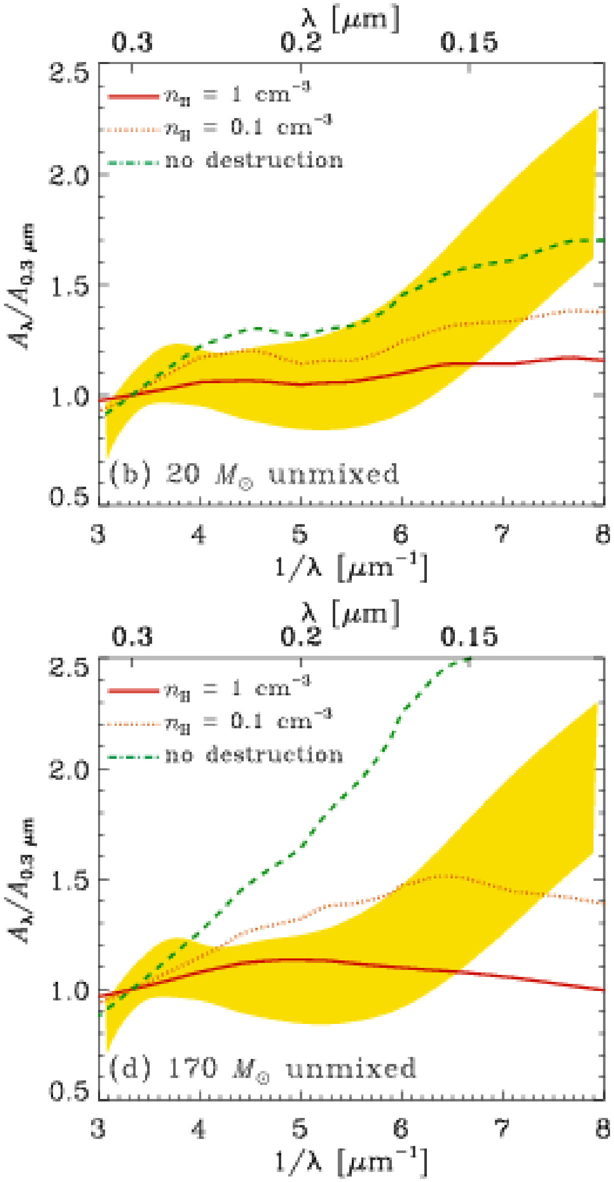


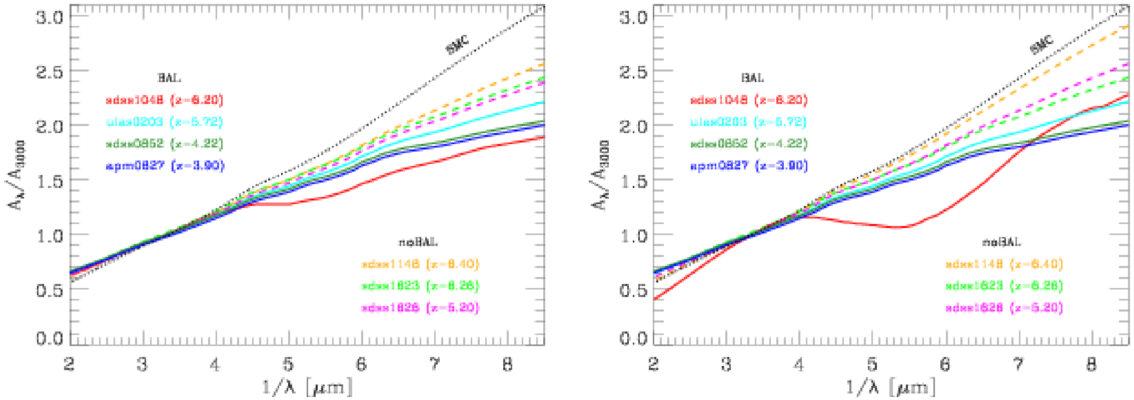
total dust mass surviving the destruction in Type II-P SNRs; 0.08-0.8 M_{sun} ($n_{H,0} = 0.1\text{-}1\ \mathrm{cm}^{-3}$)

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

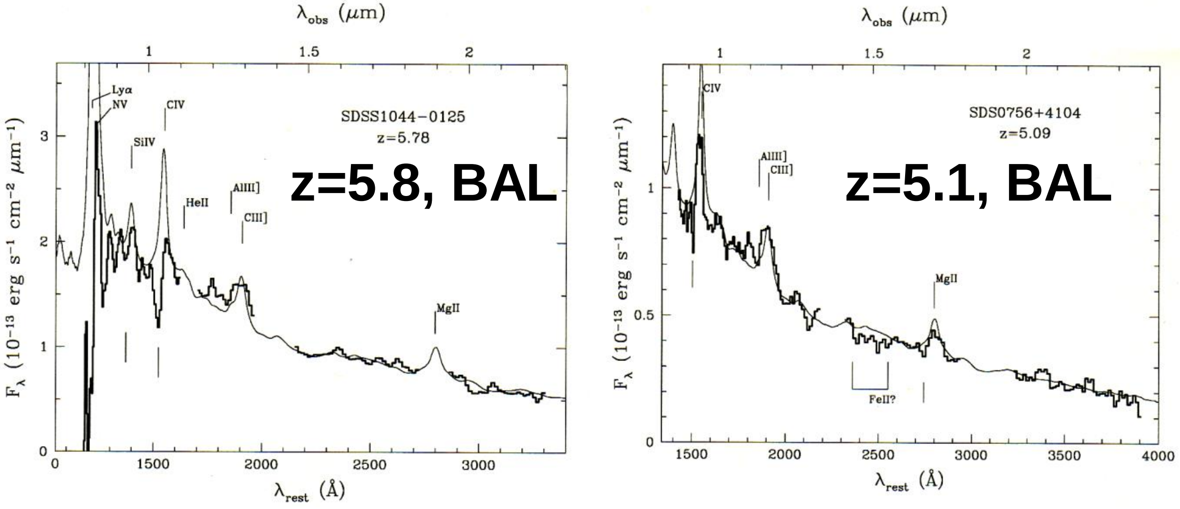
2-2-9. Flattened extinction curves at high-z

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}

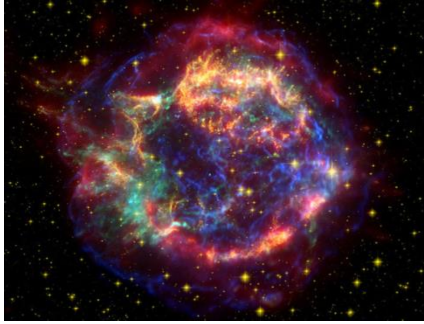
  SNe II-P ➔ M_{dust} = 0.1-0.8 M_{sun}

  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.

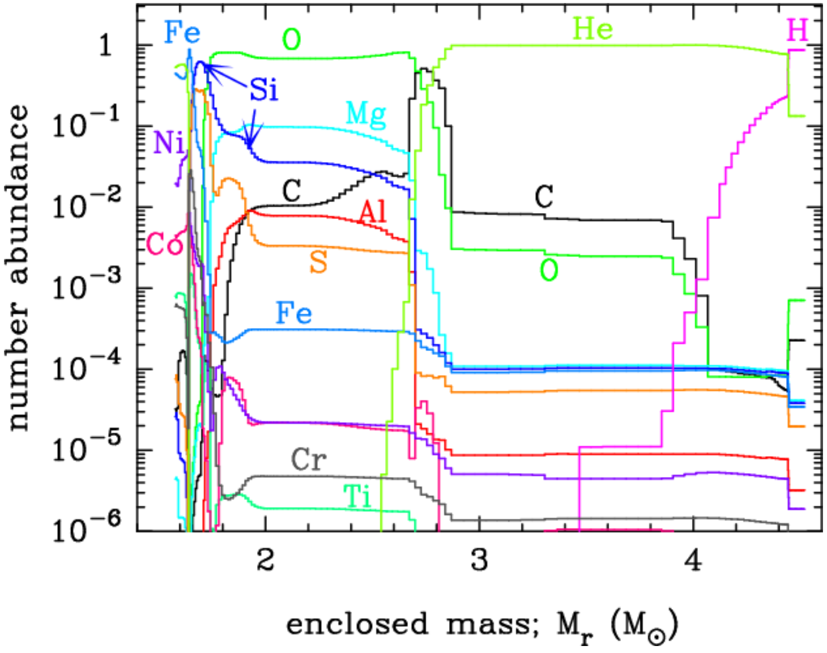
3. Formation of dust grains in various types of SNe

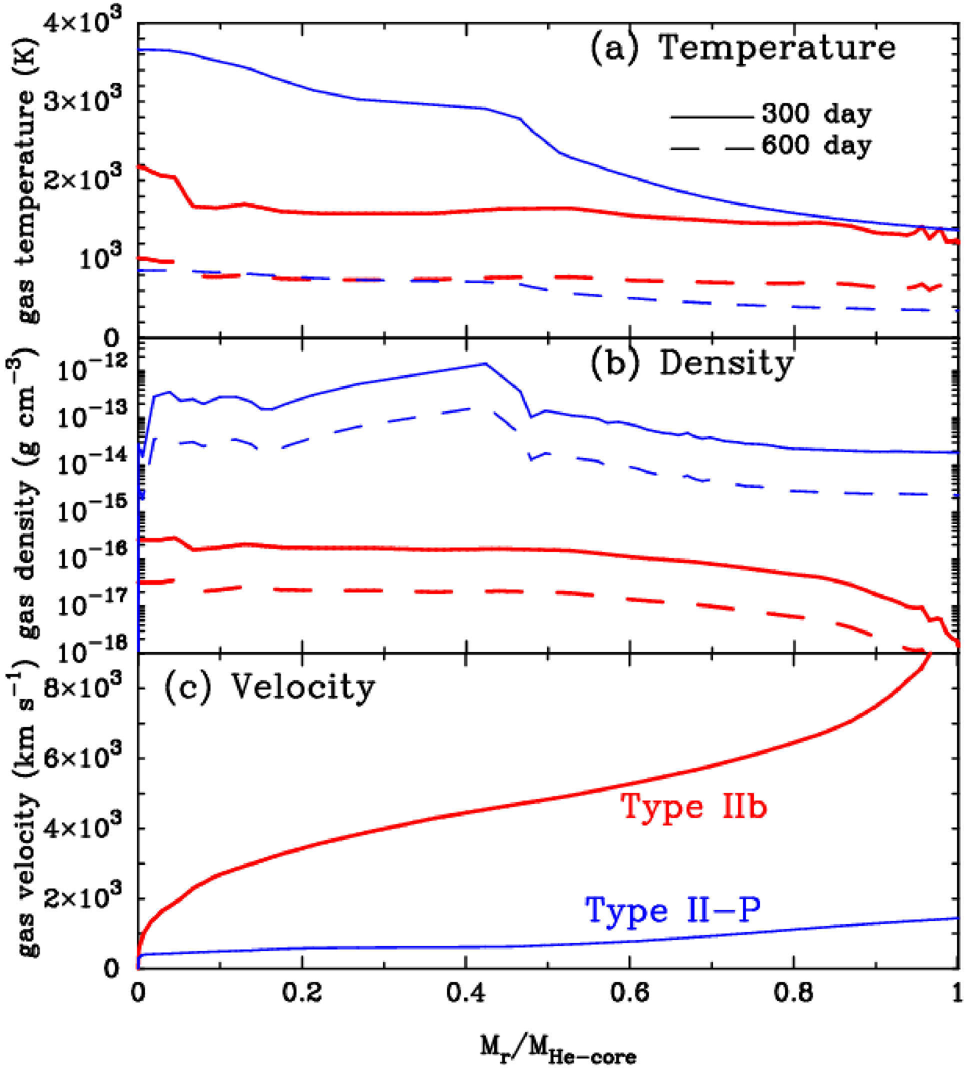
3-1-1. Dust formation in Type IIb SN



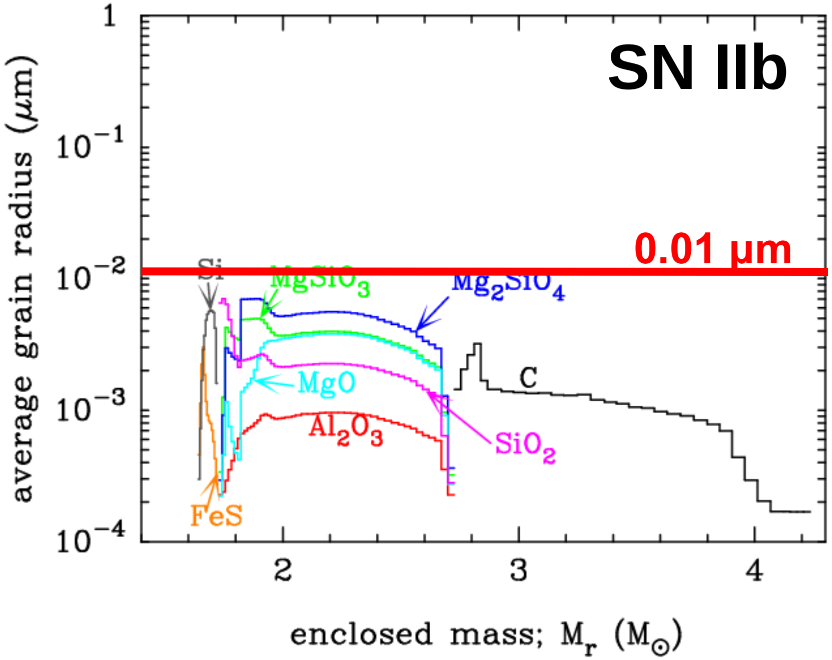
○ SN IIb model (SN1993J-like model)

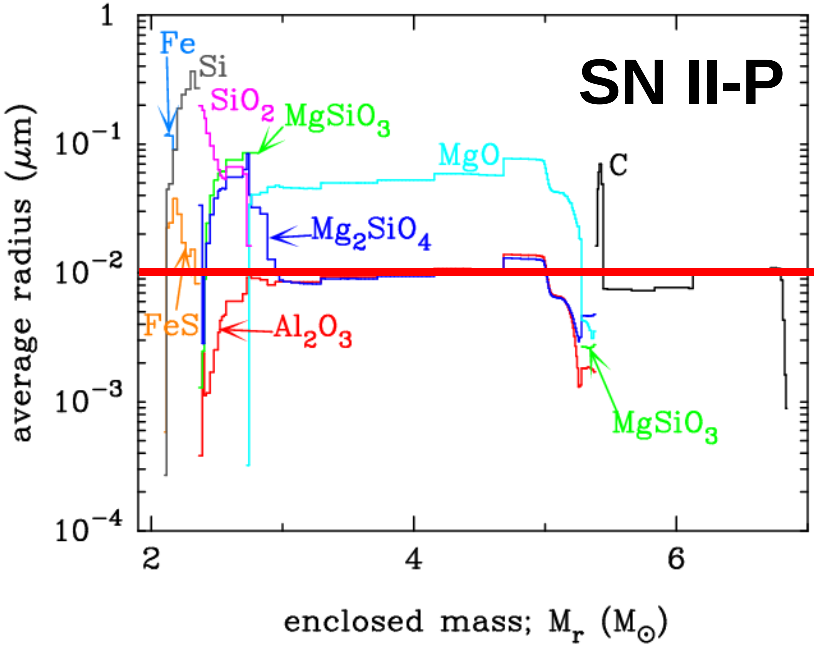
- **$M_{\rm eje} = 2.94\ M_{\rm sun}$**
  $M_{\rm ZAMS} = 18\ M_{\rm sun}$
  $M_{\rm H\text{-}env} = 0.08\ M_{\rm sun}$
- **$E_{51} = 1$**
- **$M(^{56}{\rm Ni}) = 0.07\ M_{\rm sun}$**





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





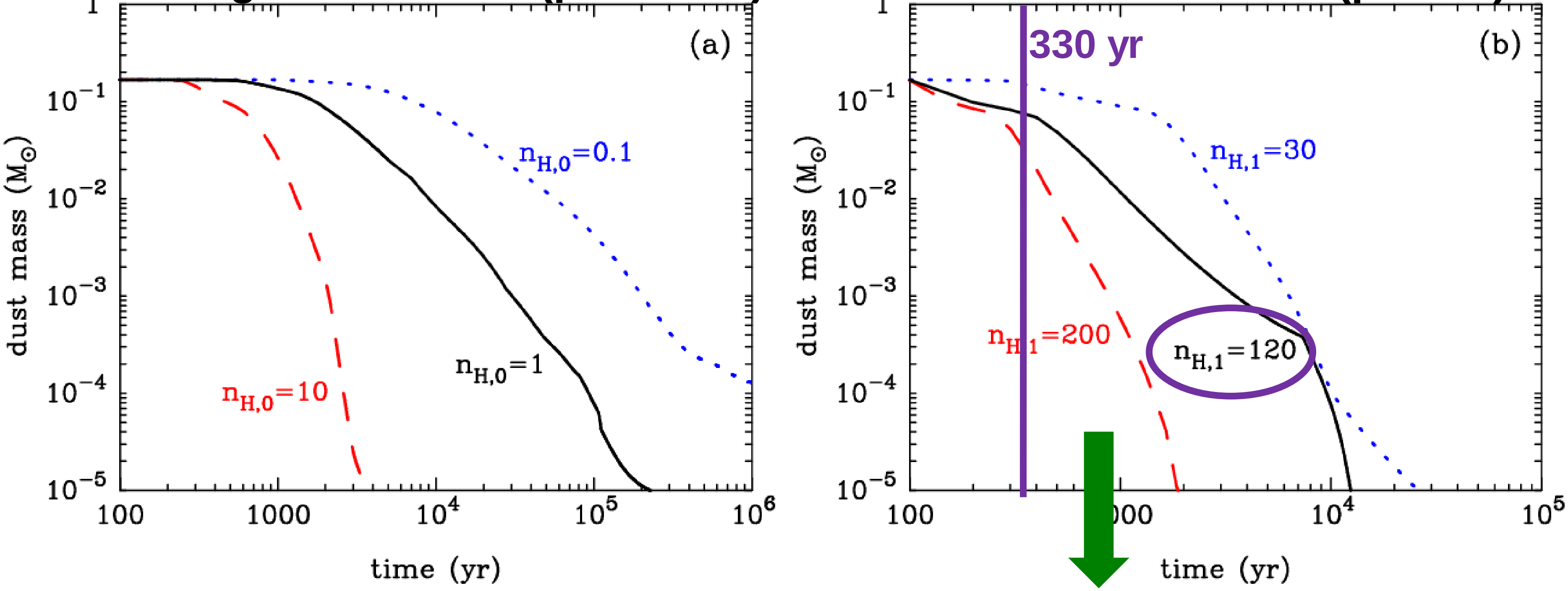
- condensation time of dust **300-700 d** after explosion

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

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**

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



homogeneous CSM (ρ = const) stellar-wind CSM ($\rho \propto r^{-2}$)

$n_{H,1}$ = 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

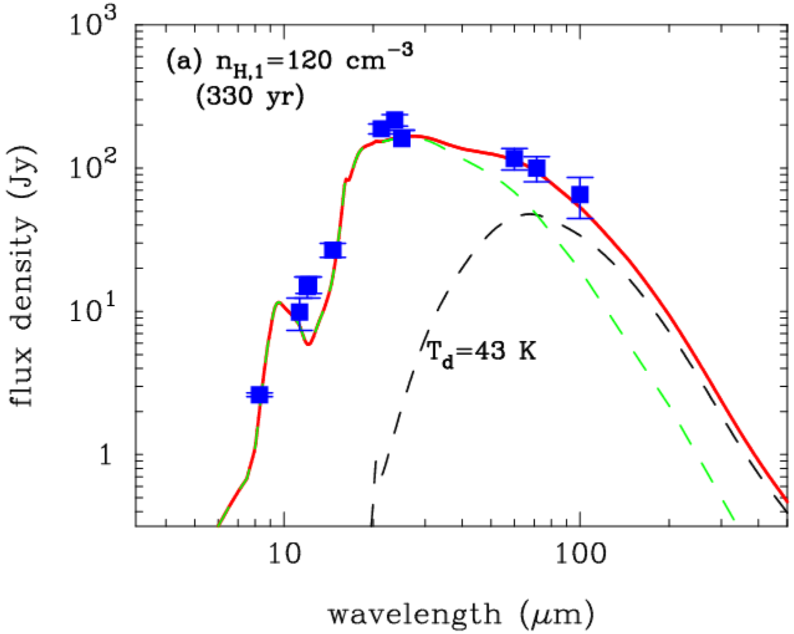
➔ small radius of newly formed dust

➔ early arrival of reverse shock at dust-forming region

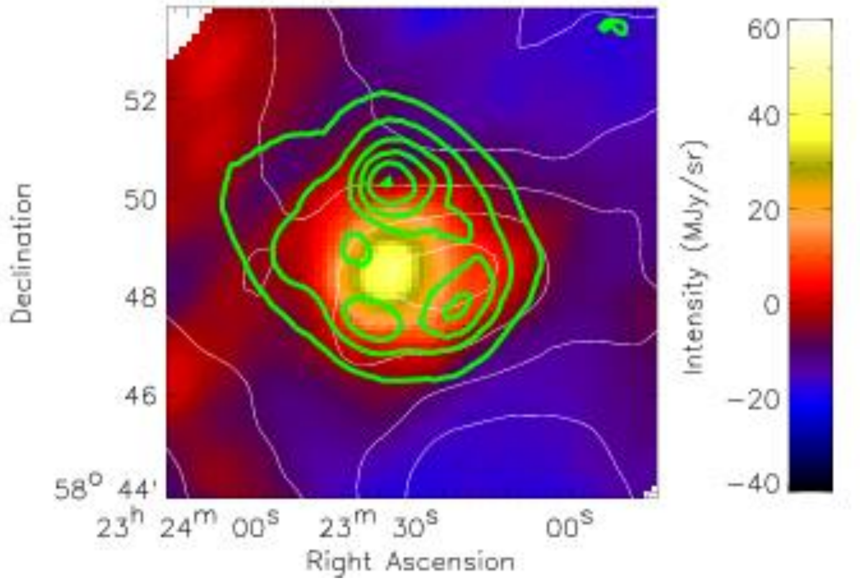
Nozawa+'10, ApJ, 713, 356

3-1-4. IR emission from dust in Cas A SNR

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

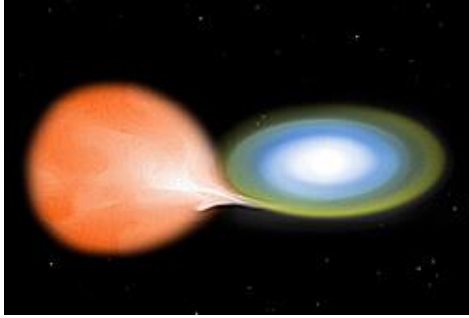
(Sibthorpe+10)

Herschel observation

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

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

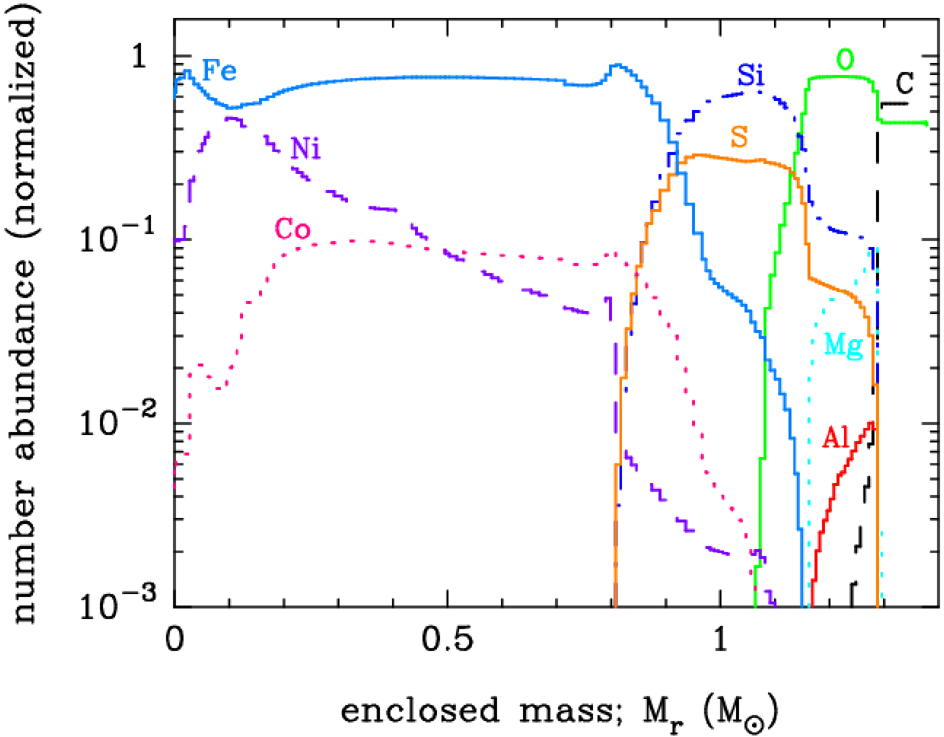
3-2-1. Dust formation in Type Ia SN

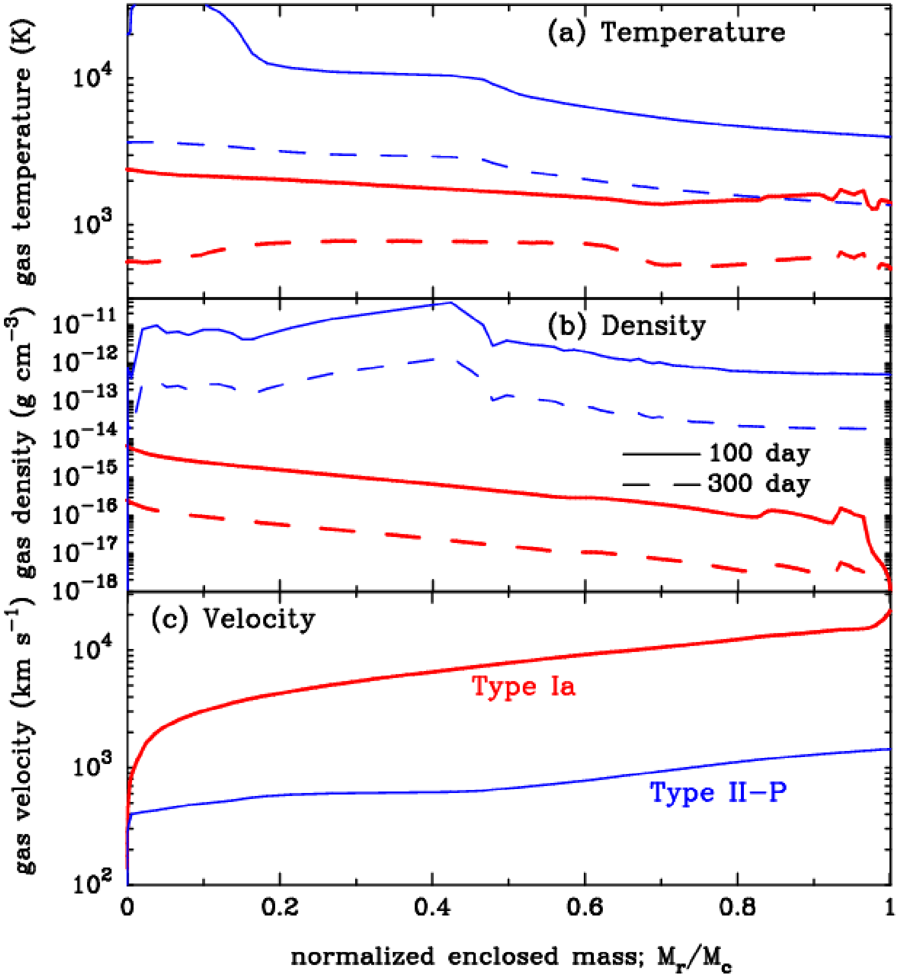


○ Type Ia SN model

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

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

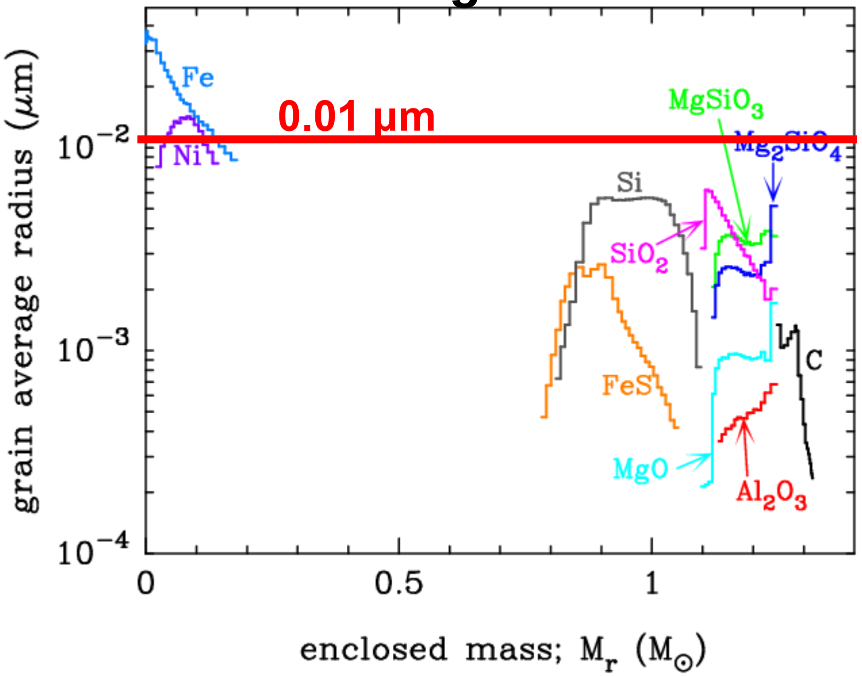




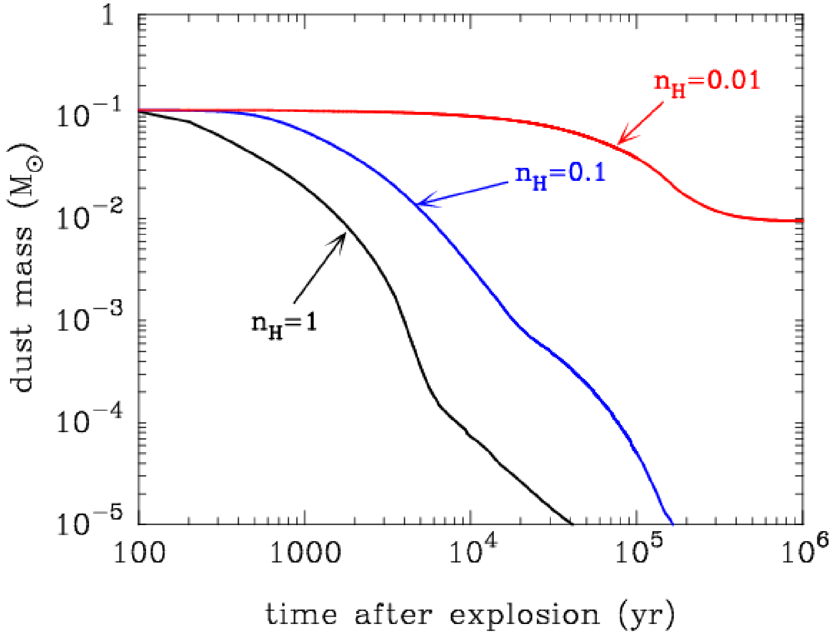
3-2-2. Dust formation and evolution in SNe Ia

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}

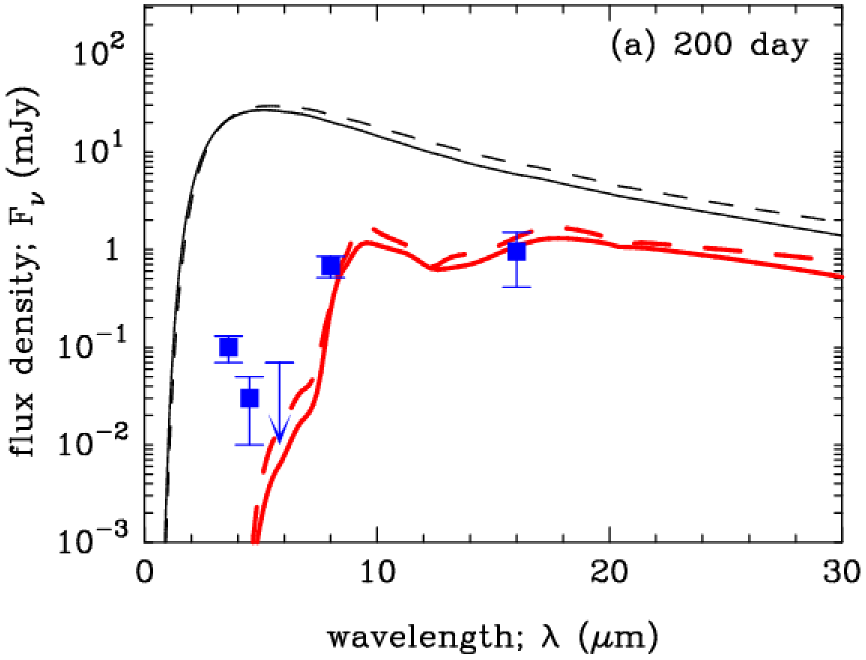
newly formed grains are completely destroyed for ISM density of n_H > 0.1 cm^{-3}

➔ SNe Ia are unlikely to be major sources of dust

3-2-3. 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 Msun) in deflagration**

➔ change of composition of WD by He-shell flash

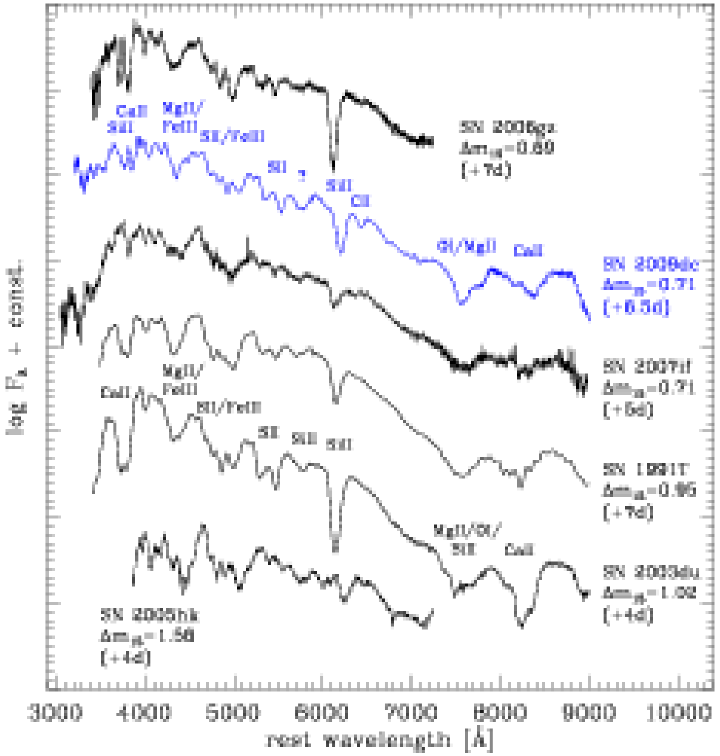
➔ burning of carbon by a delayed detonation

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

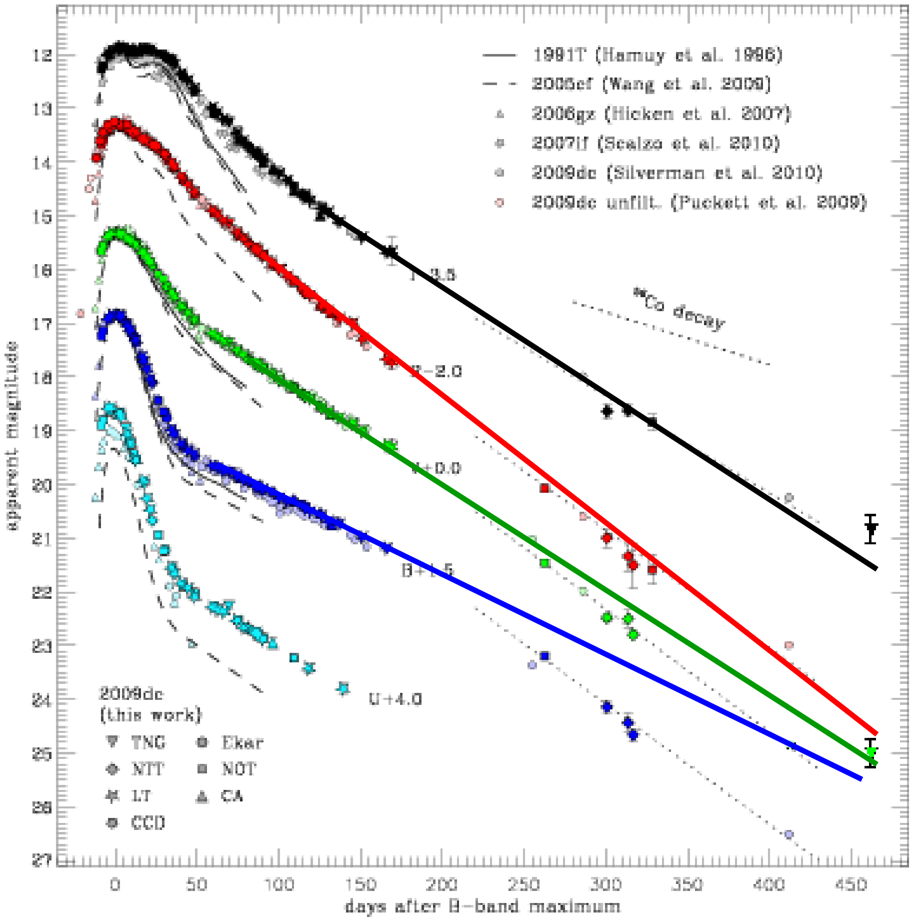
3-2-4. Dust formation in super-Chandra SNe?

- 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. Missing-dust problem in CCSNe

4-1. Difference in estimate of dust mass in SNe

・Theoretical studies

– at time of dust formation : $M_{dust}=0.1\text{-}1\ M_{sun}$ in CCSNe
(Nozawa+'03; Todini & Ferrara'01; Cherchneff & Dwek'10)

– after destruction of dust by reverse shock (SNe II-P) :
$M_{surv}\sim 0.01\text{-}0.8\ M_{sun}$ (Nozawa+'07; ianchi & Schneider'07)

dust amount needed to explain massive dust at high-z

・Observational works

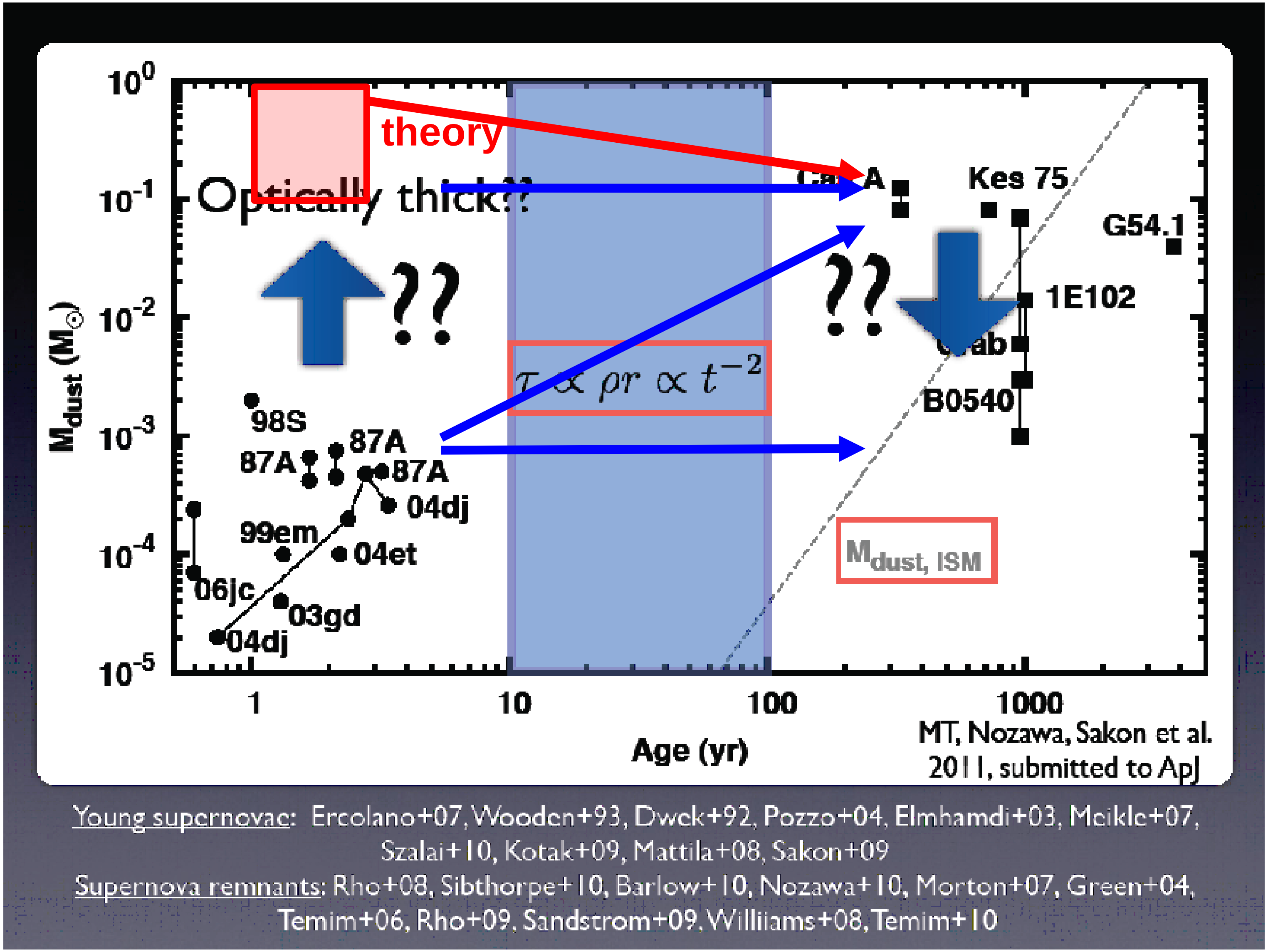
– MIR observations of SNe : $M_{dust} < 10^{-3}\ M_{sun}$
(e.g., Ercolano+'07; Sakon+'09; Kotak+'09)

– submm observations of SNRs : $M_{dust} > 1\ M_{sun}$
(Dunne+'03; Morgan+'03; Dunne+'09)

– MIR/FIR observation of Cas A : $M_{dust}=0.02\text{-}0.075\ M_{sun}$
(Rho+'08; Sibthorpe+'09; Barlow+'10)

4-2. Missing-dust problem in CCSNe

Tanaka, TN,+’11, submitted



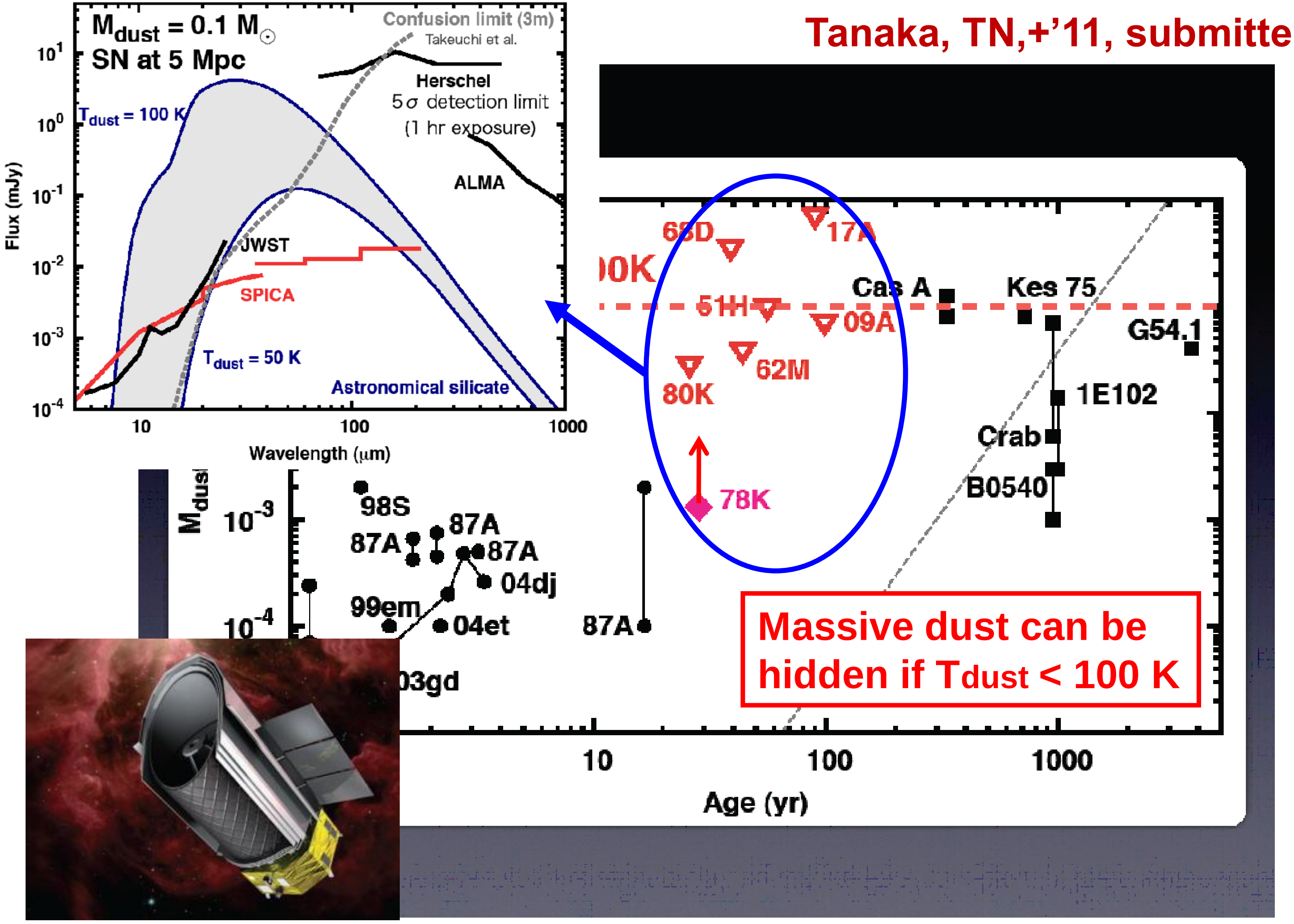
MT, Nozawa, Sakon et al. 2011, submitted to ApJ

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 SNe-dust with SPICA

Tanaka, TN,+'11, submitted



Massive dust can be hidden if Tdust < 100 K

5. Conclusion remarks

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

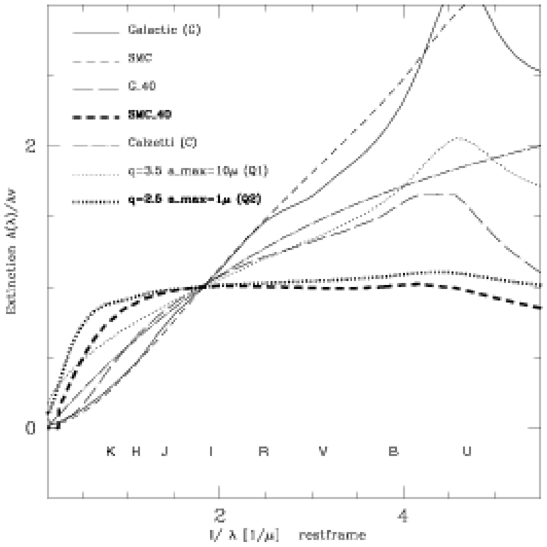
○ metal-poor (high-z or starbust) galaxies

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

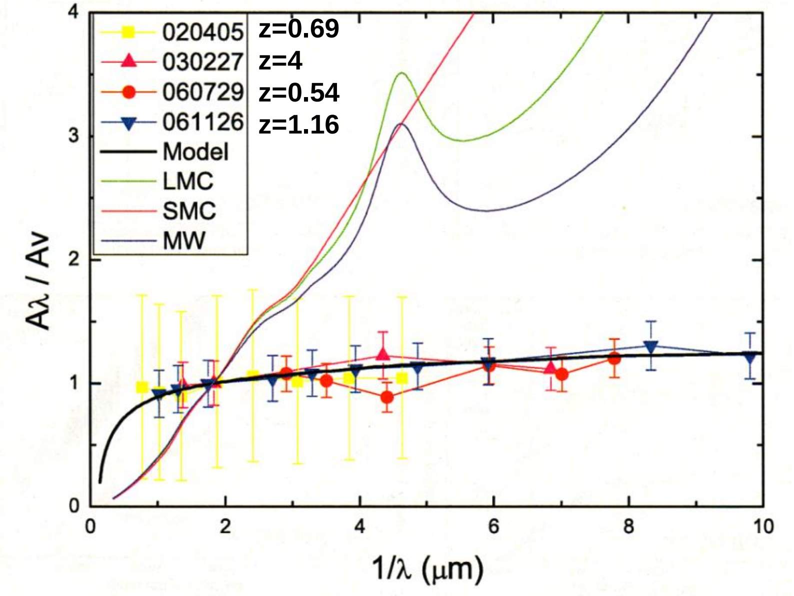
➔ Type II-P SNe might be major sources of dust

- 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

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

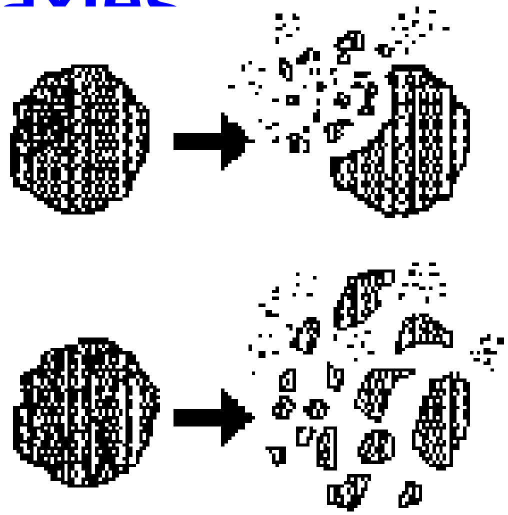
○ metal-rich (low-z or Milky Way) gal

- 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?



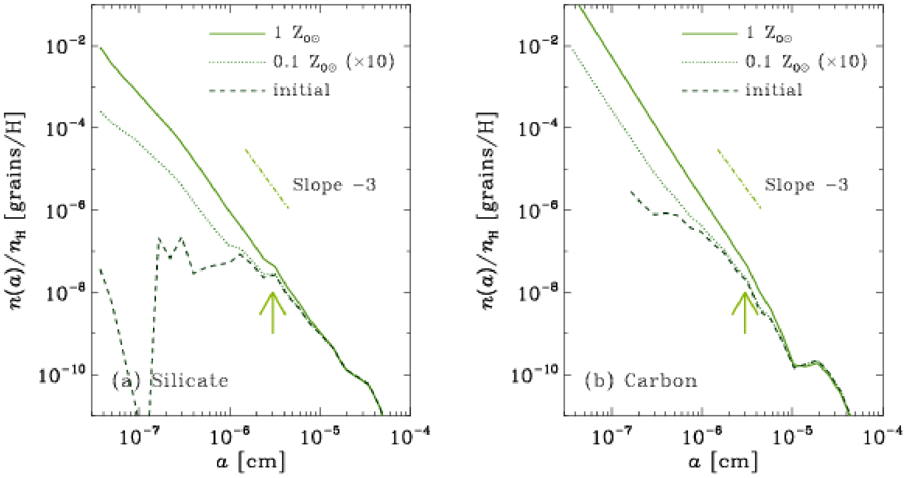
grain shattering

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

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

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

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



Hirashita, TN, +’10, MNRAS, 404, 1437

5-3. 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