Supernovae as sources of interstellar dust

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Outline

1. Introduction

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

3. Formation and destruction of dust in Type IIb SNe
   with application to Cassiopeia A SNR

4. Missing-dust problem in core-collapse SNe

5. Formation of dust in the ejecta of Type Ia SNe

6. Summary

1. Introduction

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

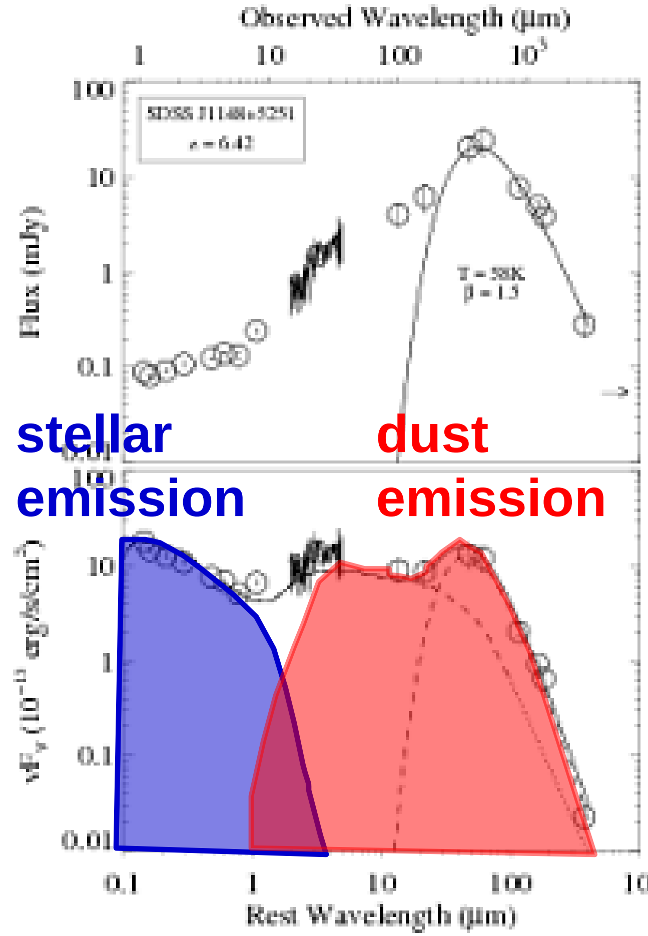
- **The submm observations have confirmed the presence of dust in excess of 10^8 Msun in 30% of z > 5 quasars**

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



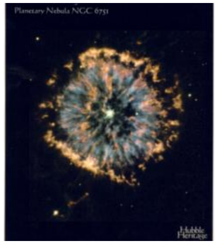
Leipski+'10, A&A, 518, L34

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

・ Supernovae (Type II SNe)

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

➔ > 1 M_{sun} per SN (Dwek+'07)



・ AGB stars + SNe
(Valiante+'09; Gall+'11; Dwek & Cherchneff'11)

➔ 0.01-0.05 M_{sun} per AGB (Zhukovska & Gail '08)

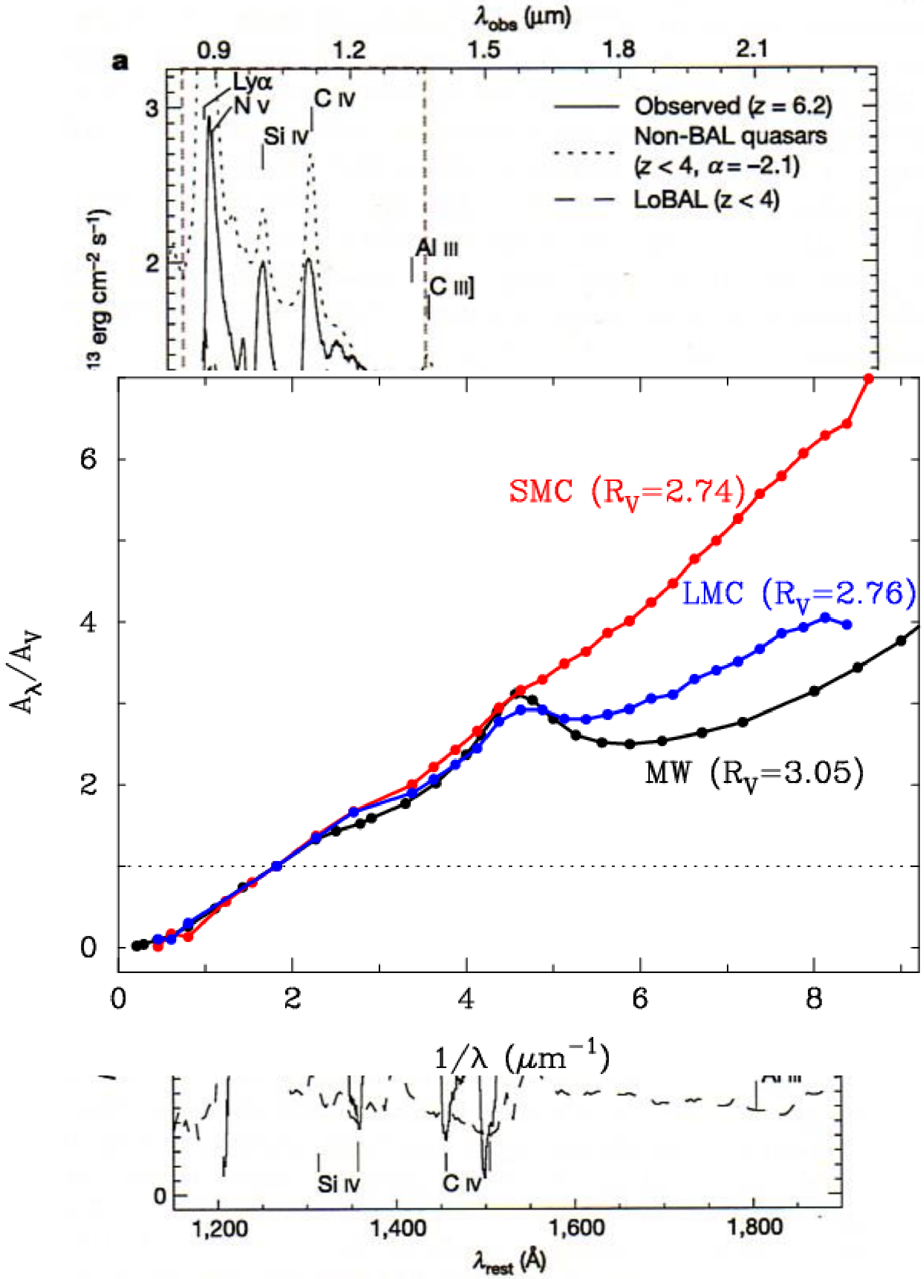
➔ 0.01-1 M_{sun} per SN

・ Grain growth in dense clouds + AGB stars + SNe
(Draine'09; Michalowski+'10; Pipino+'11; Mattsson'11)

➔ T_{growth} ~ 10^7 (Z / Z_{sun}) yr

・ Quasar outflows (Elvis+'02)

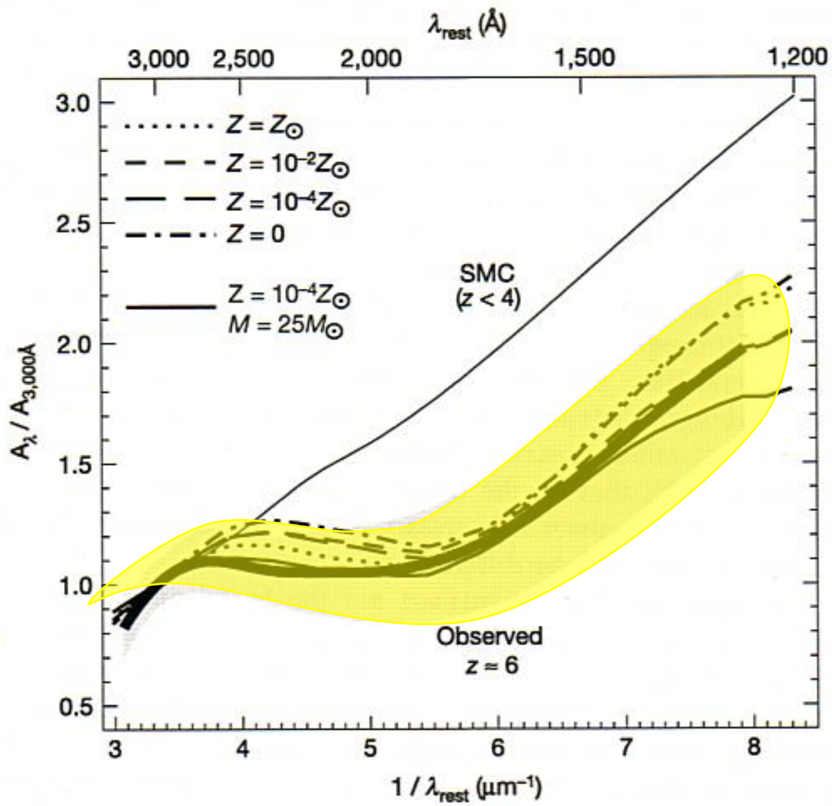
1-3. Extinction curves at high-z quasars



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

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

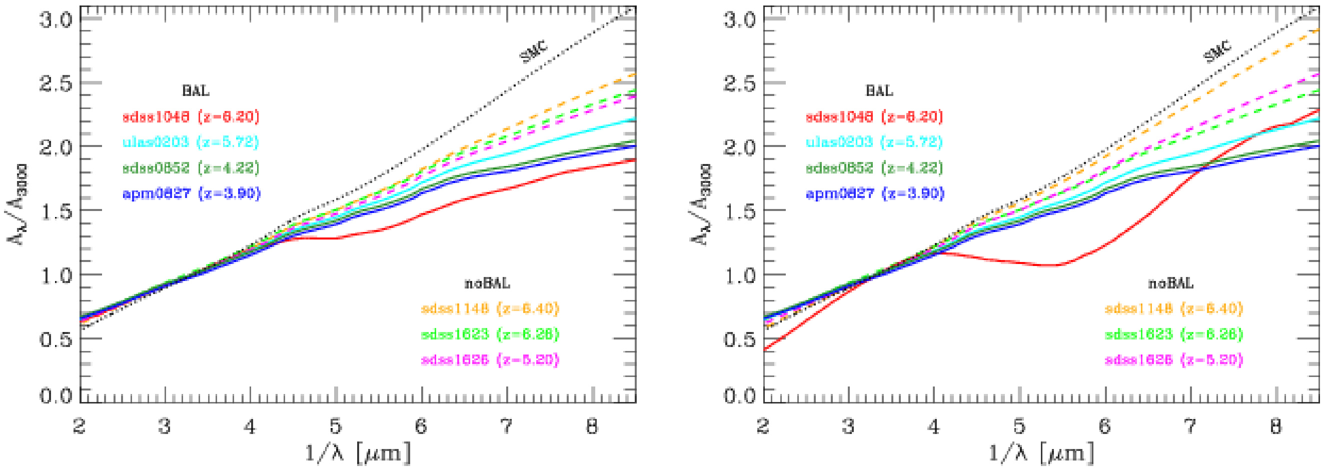
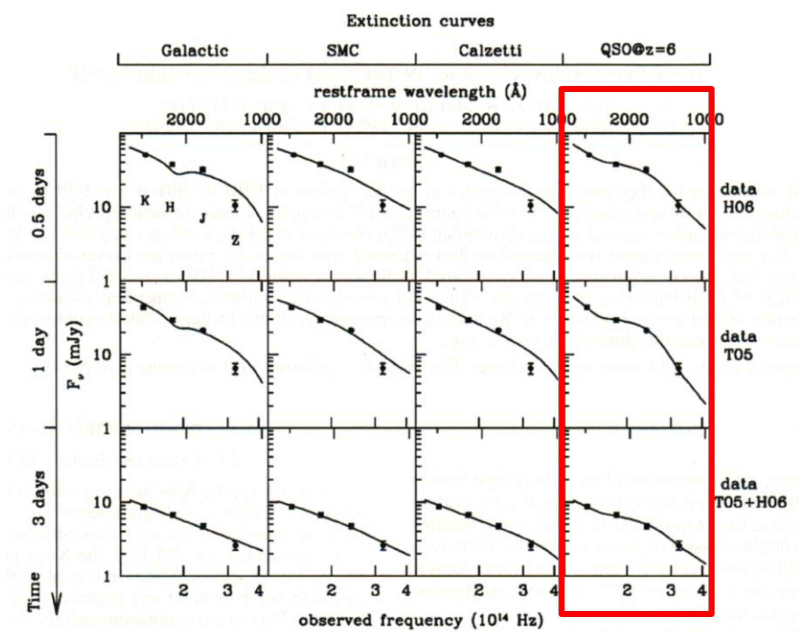


Fig. 4. Best fit extinction curves of reddened quasars. The solid lines are for BAL quasars, while dashed lines are for non-BAL quasars. For comparison the SMC extinction curve is also shown and labeled in the Figure (dotted black line). The panel on the left shows the results assuming a minimum intrinsic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



GRB 050904 at z=6.3

additional evidence for different dust properties at high-z

Stratta+'07, ApJ, 661, L9

1-5. Summary of Introduction

- **There is clear evidence for huge amounts of dust at $z > 5$, but the dust sources remain unexplained**

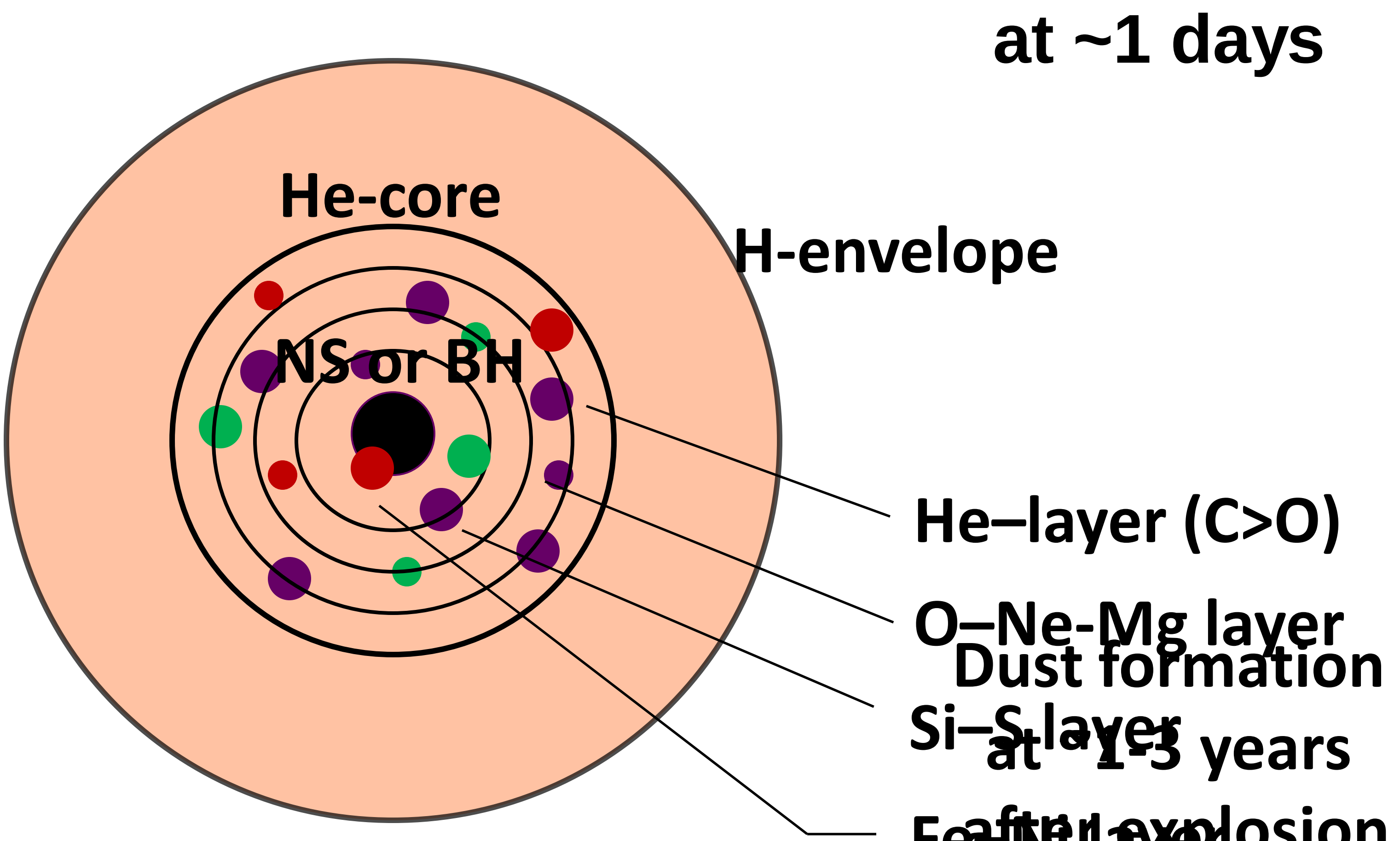
  ➔ **SNe? AGB stars? grain growth in the dense clouds? quasar outflow? any other sources?**

- **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 ($M = 8\text{-}40\ M_{sun}$) dominate the dust production over AGB stars ($M < 8\ M_{sun}$) ??

2-1. Dust Formation in Pop III SNe

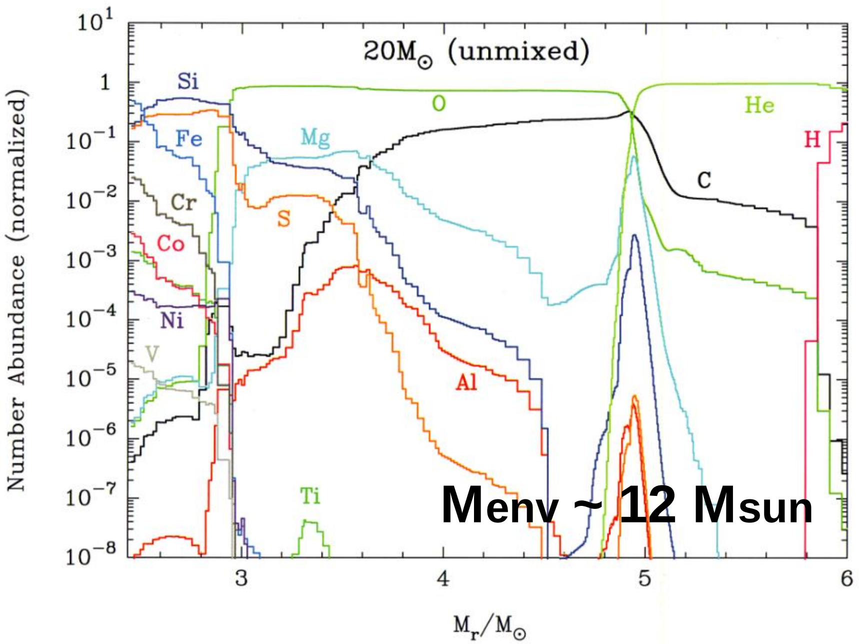


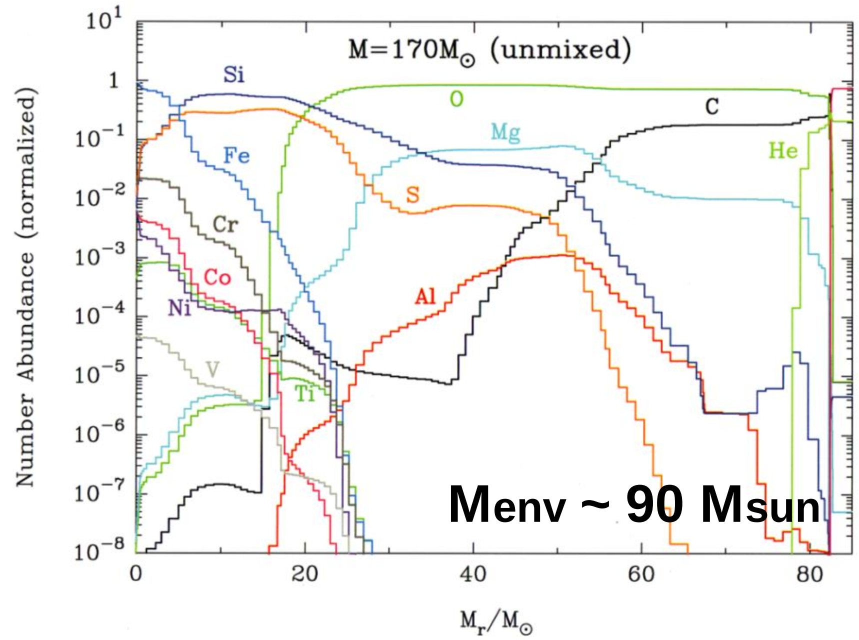
2-1-1. Dust formation in primordial SNe

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)

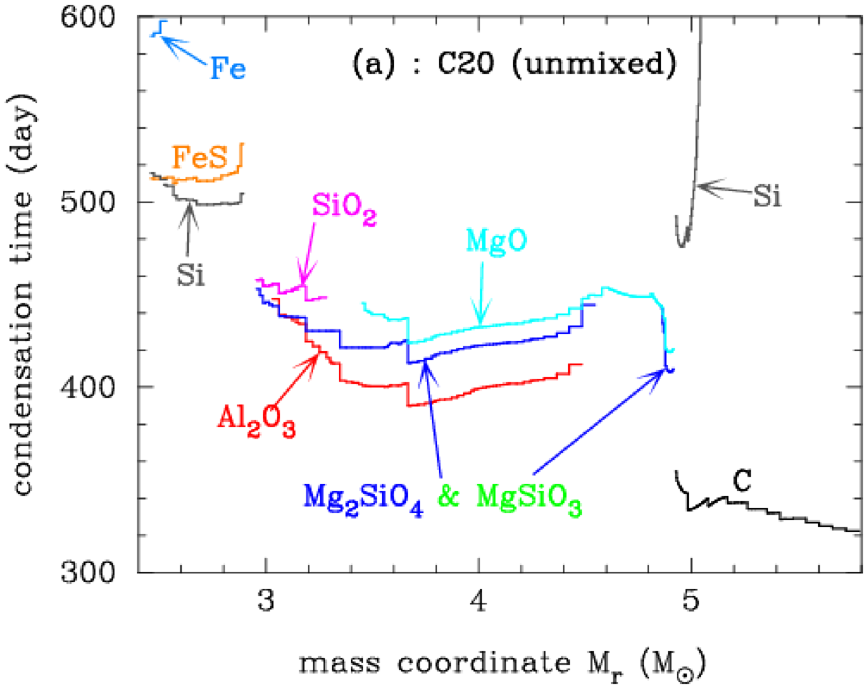


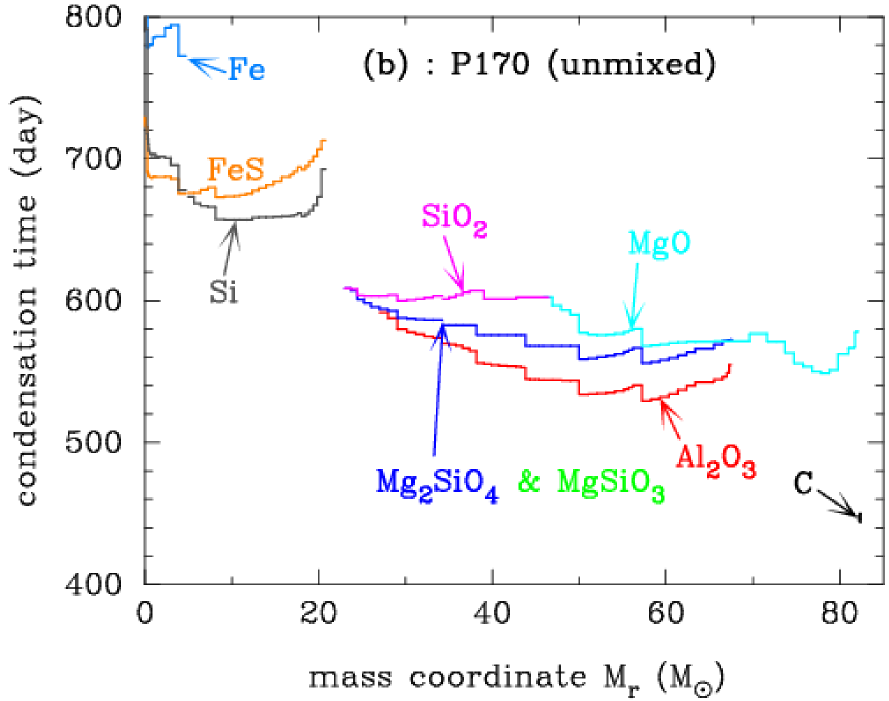


- nucleation and grain growth theory (Kozasa & Hasegawa'88)
- no mixing of elements within the He-core
- complete formation of CO and SiO

2-1-2. Dust formed in primordial SNe

Nozawa+'03, ApJ, 598, 785

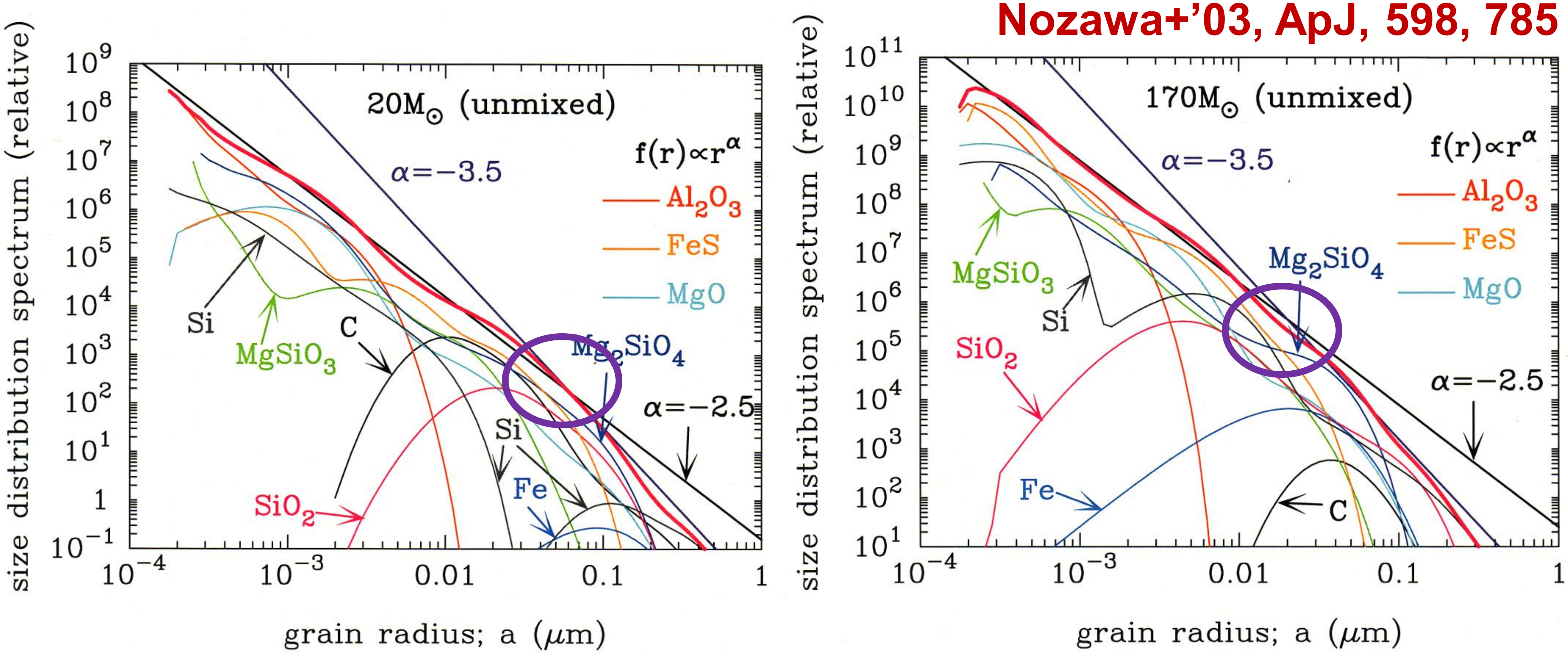




- **Various dust species (C, $MgSiO_3$, Mg_2SiO_4, SiO_2, Al_2O_3, MgO, Si, FeS, Fe) form in the unmixed ejecta, according to the elemental composition of gas in each layer**
- **The condensation time: 300-600 days for SNe II-P**
  400-800 days for PISNe

2-1-3. 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

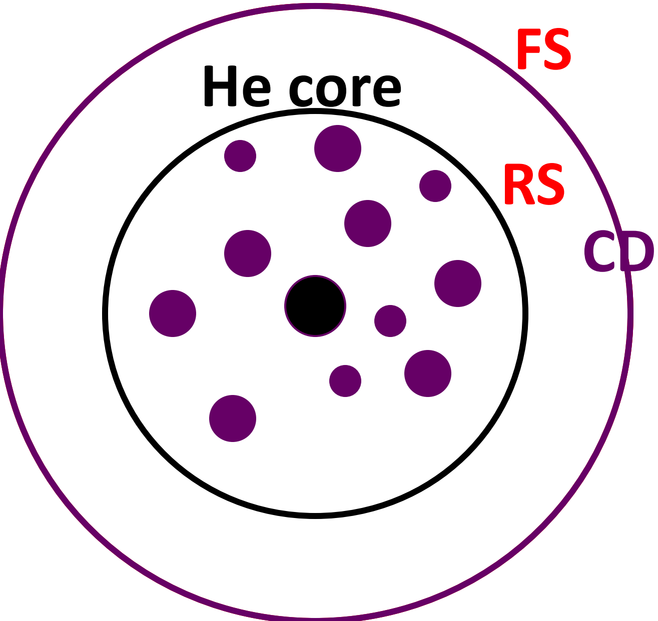
2-2. Dust destruction in supernova remnants

- a part of dust grains formed in SNe are destroyed due to sputtering in the hot gas swept up by the shocks

(e.g., Bianchi & Schneider'07; Nozawa+'07, 10)

➔ destruction efficiency of dust depends on the initial size distribution

- It is necessary to treat formation and destruction of dust self-consistently



2-2-1. 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}

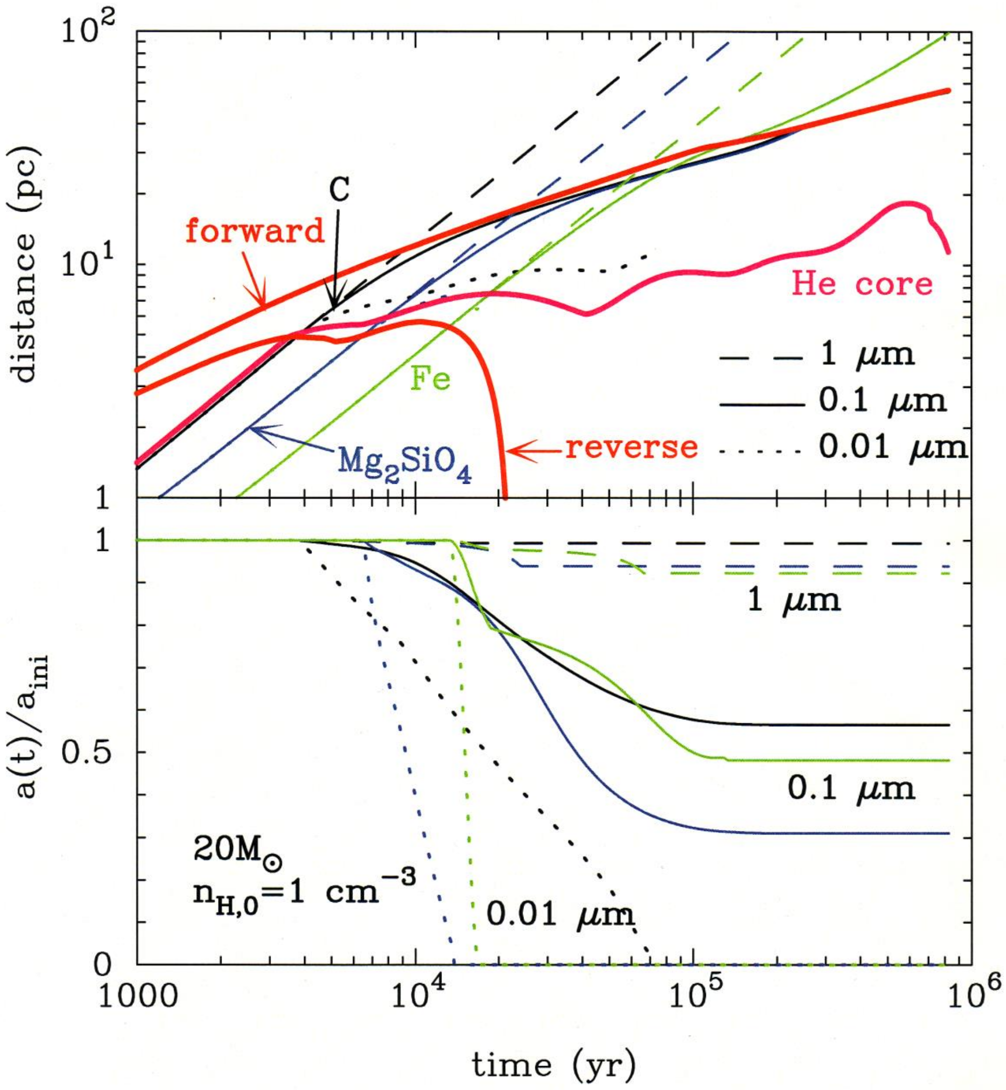
・Dust Model

- 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

2-2-2. Evolution of dust in SNRs

Nozawa+'07, ApJ, 666, 955



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

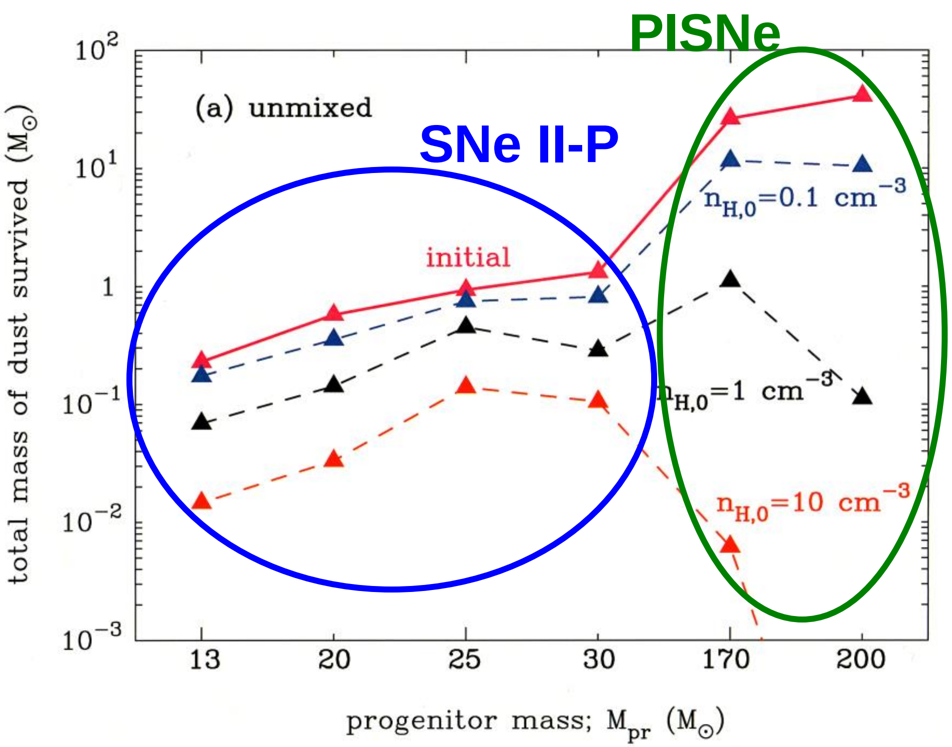
Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

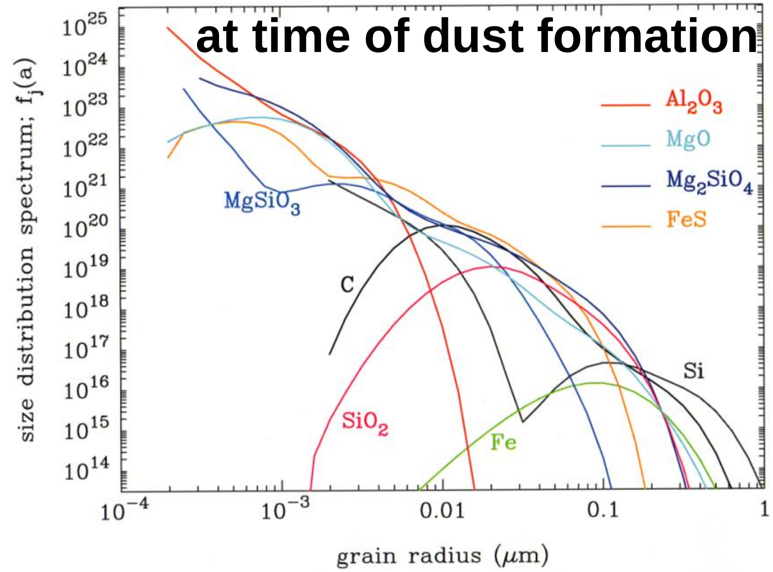
The evolution of dust heavily depends on the initial radius and composition

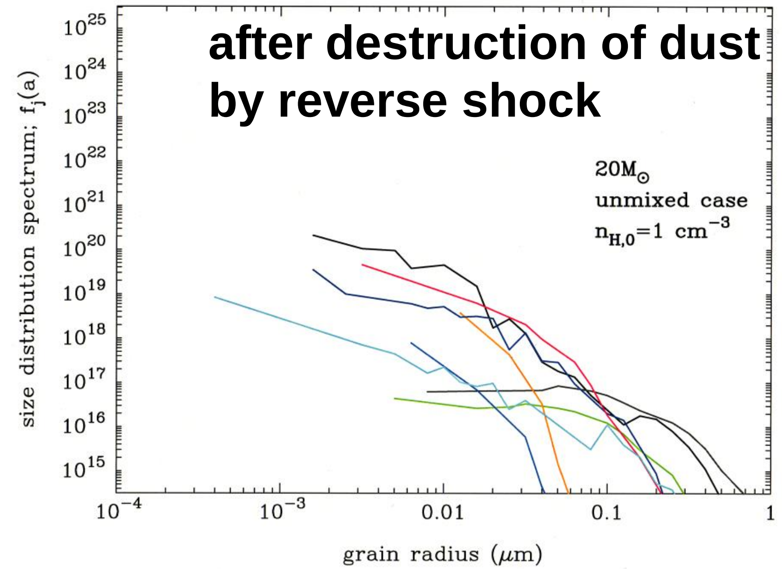
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

2-2-3. Dust mass and size ejected from SN II-P

Nozawa+'07, ApJ, 666, 955





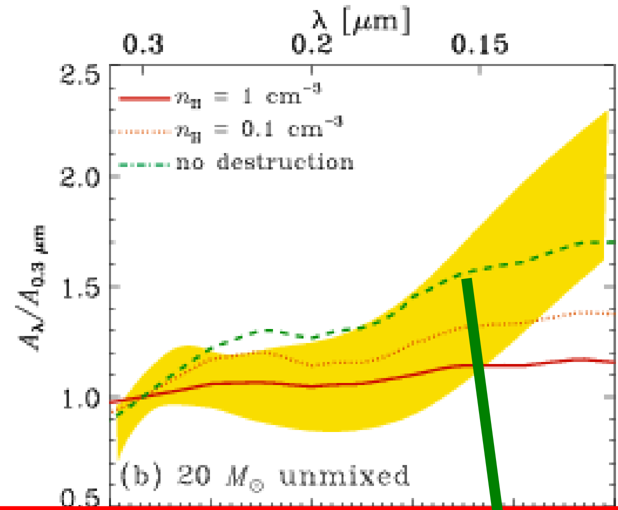


total dust mass surviving the destruction in Type II-P SNRs; 0.07-0.8 M_{sun} ($n_{H,0}$ = 0.1-1 cm^{-3})

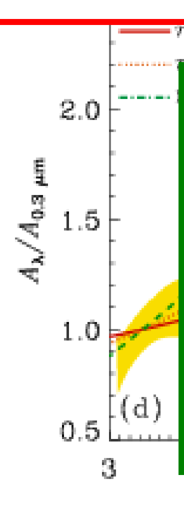
size distribution of dust after RS destruction is domimated by large grains (> 0.01 μm)

2-3. Flattened extinction curves at high-z

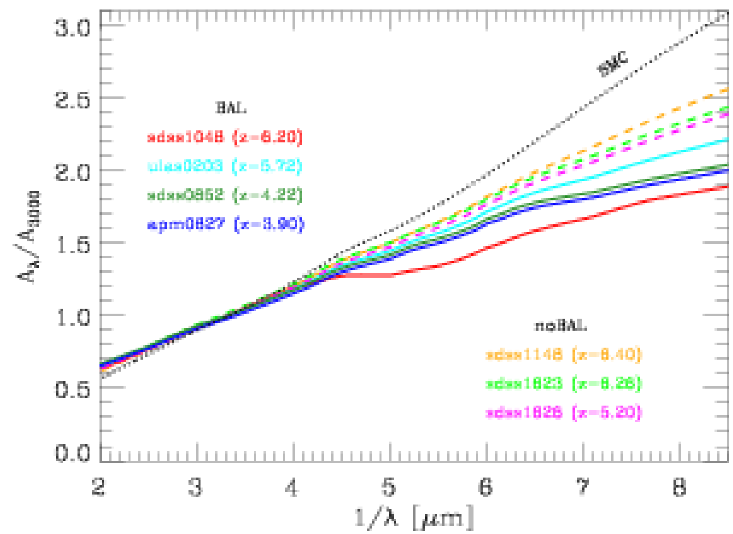
Hirashita, TN, et al. 2008, MNRAS, 384, 1725



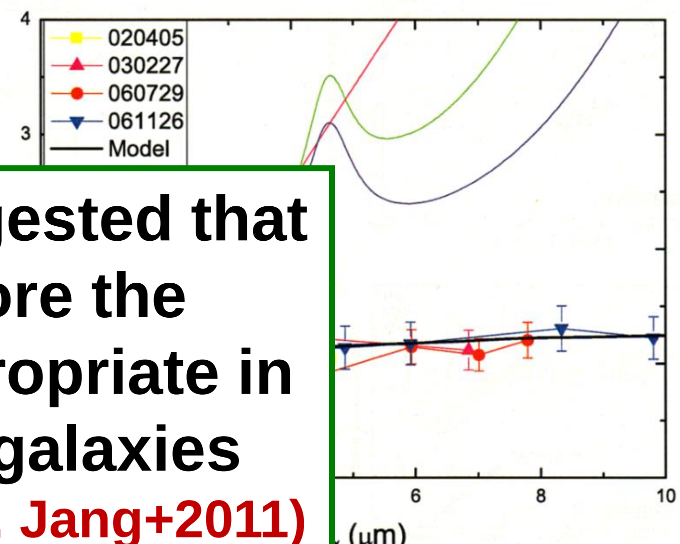
Dust extinction curves in the early universe are expected to be flat



Some studies have suggested that the extinction curve before the destruction is more appropriate in high-z and star-forming galaxies
(Kawara+2011, Shimizu+2011, Jang+2011)



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

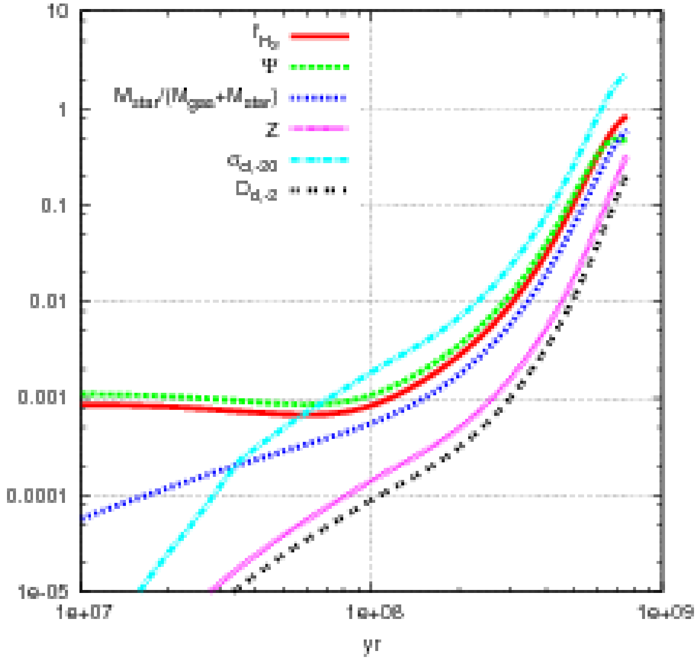


Li+'08, ApJ, 678, 1136

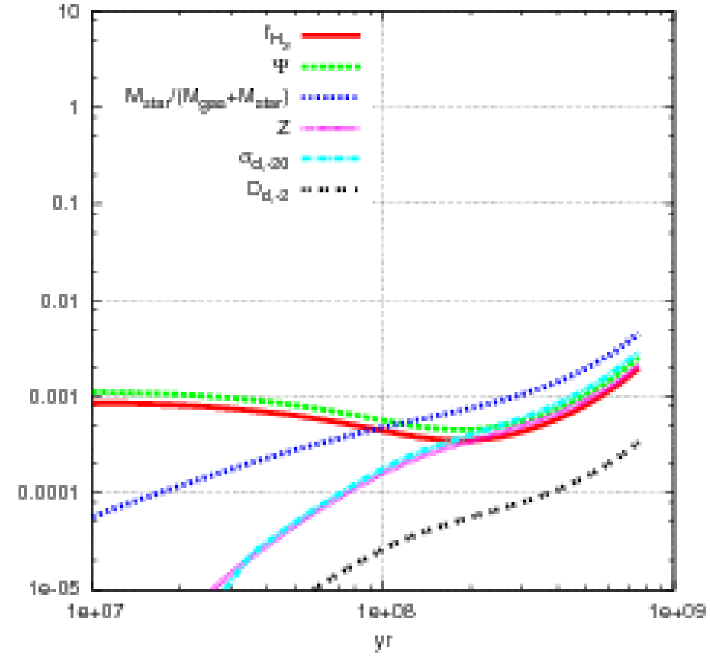
2-4. Effect of dust on star formation history

efficient formation of H_2 molecules on the surface
(e.g., Cozaux & Spaans'04)
➔ promoting formation of stars (Hirashita & Ferrara'02)

SN dust w/o RS destruction



SN dust with RS destruction

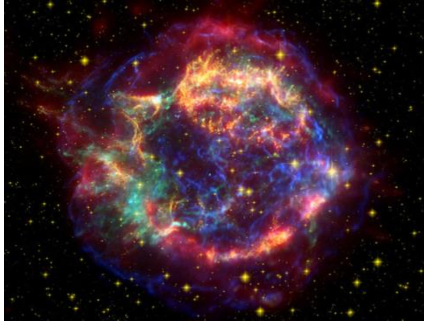


Yamasawa, …, TN, et al. 2011, ApJ, 735, 44

Larger size of dust suppresses the formation rate of H_2 and thus does not activate star formation significantly

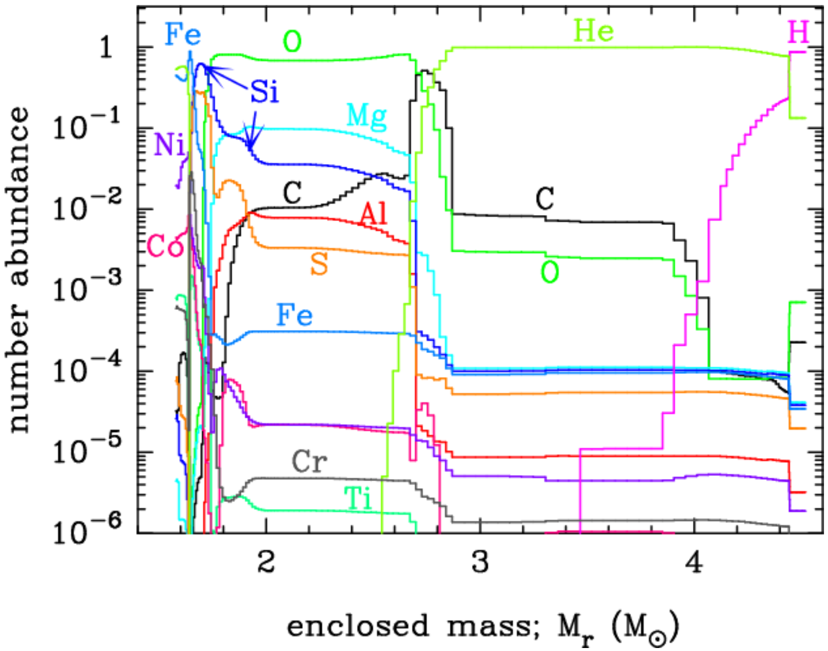
3. Formation and evolution of dust in SNe IIb: Application to Cas A

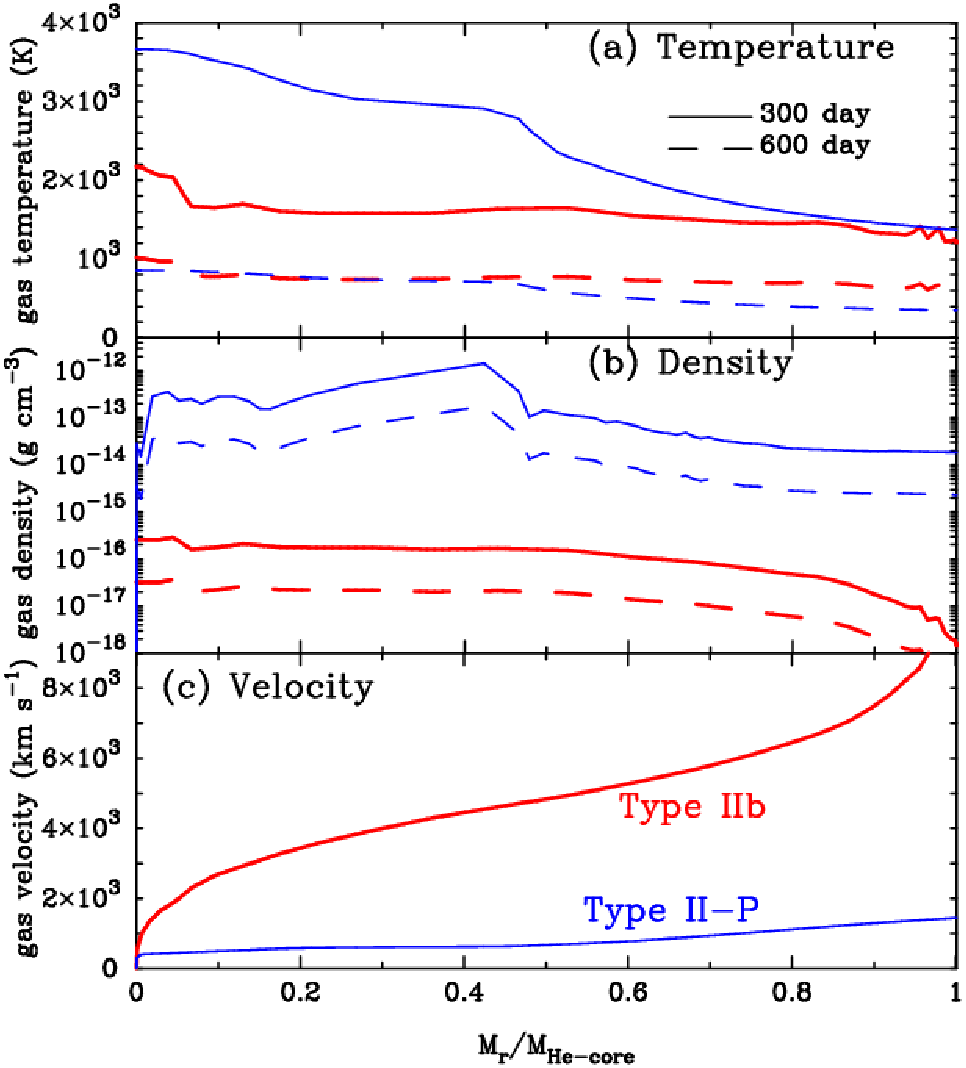
3-1. Dust formation in Type IIb SN



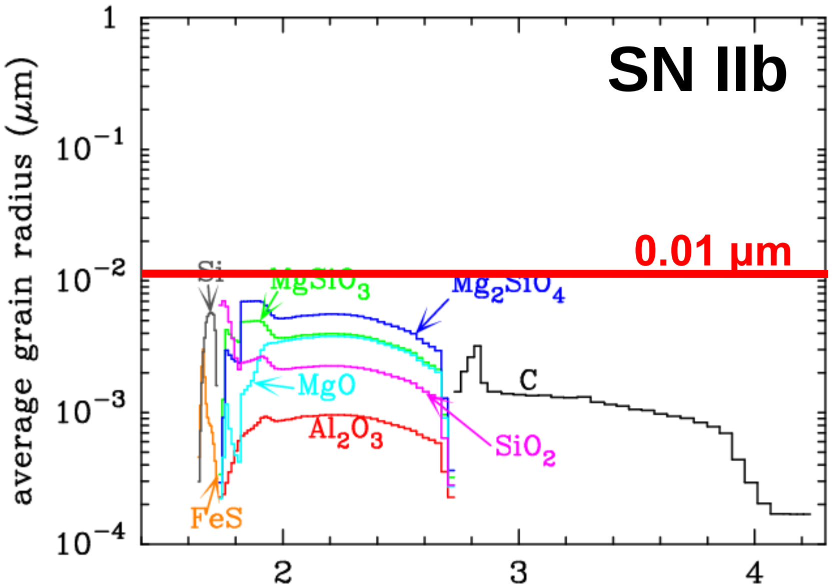
○ SN IIb model (SN1993J-like model)

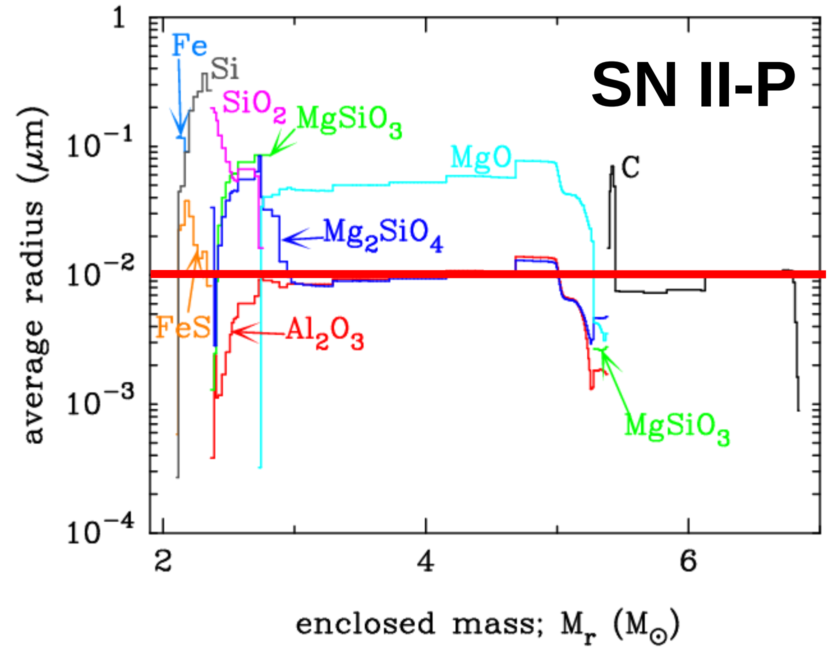
- M_{eje} = 2.94 M_{sun}
  M_{ZAMS} = 18 M_{sun}
  $M_{H\text{-}env}$ = 0.08 M_{sun}
- E_{51} = 1.0
- $M(^{56}Ni)$ = 0.07 M_{sun}

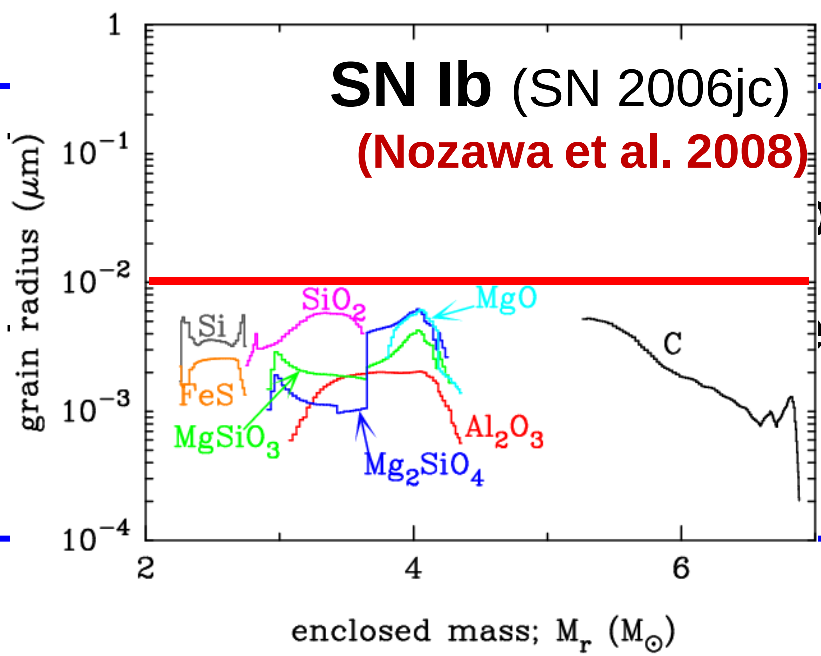




3-2. Dependence of dust radii on SN type







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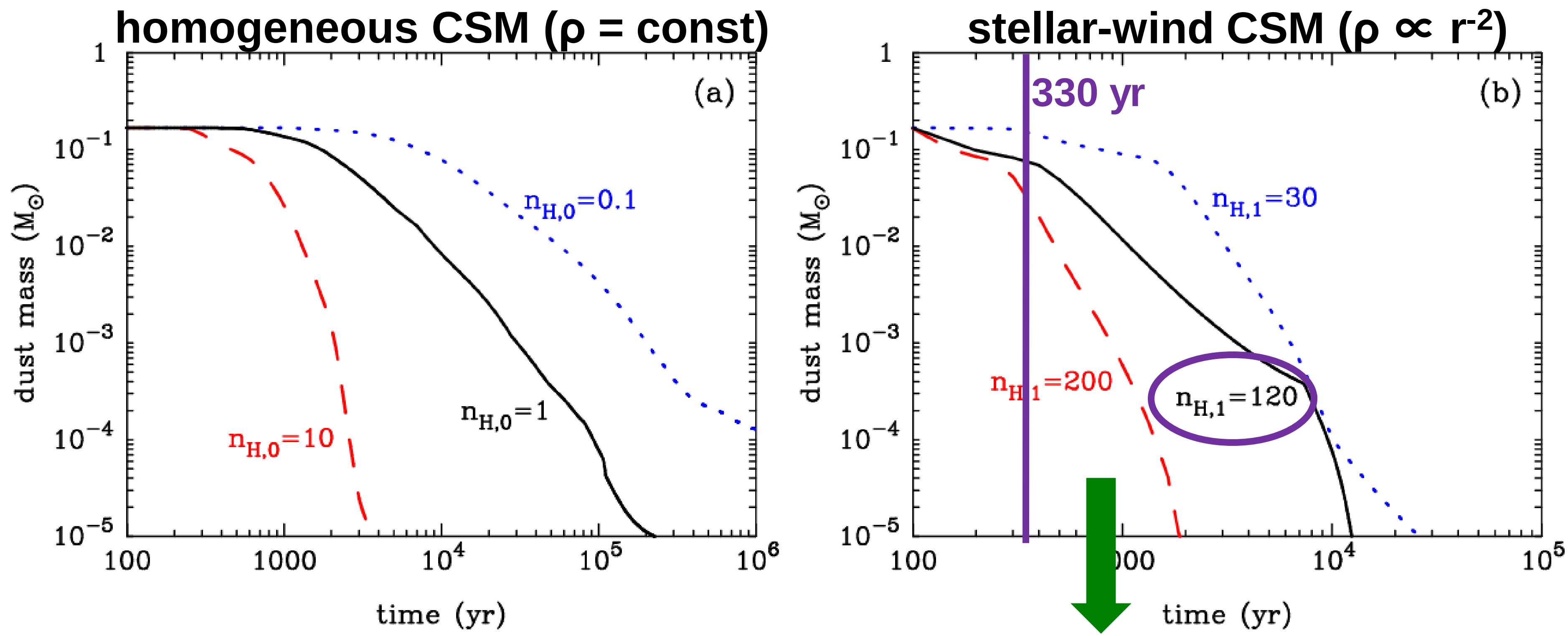
— the radius of dust formed in H-stripped SNe is small

- SN IIb without massive H-env ➔ a_{dust} < 0.01 μm
- SN II-P with massive H-env ➔ a_{dust} > 0.01 μm

3-3. 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

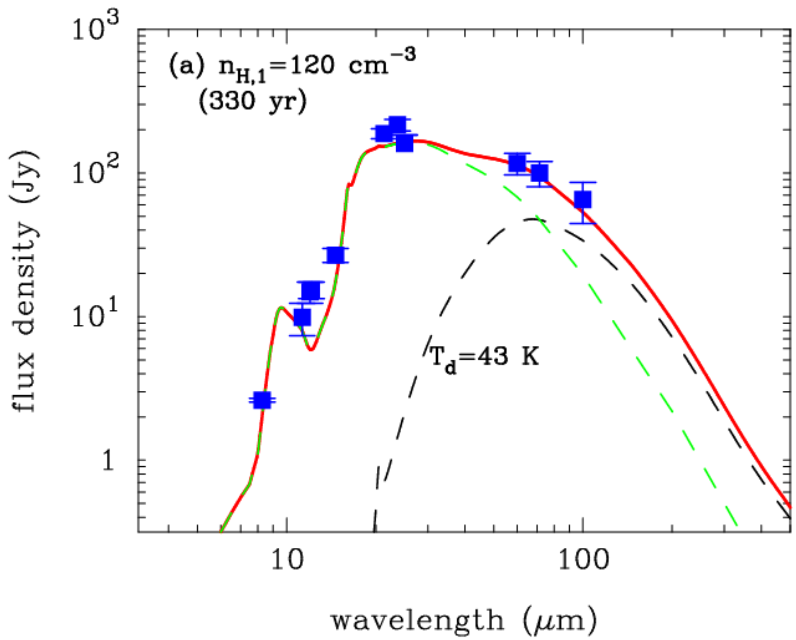
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

➔ **small radius of newly formed dust**

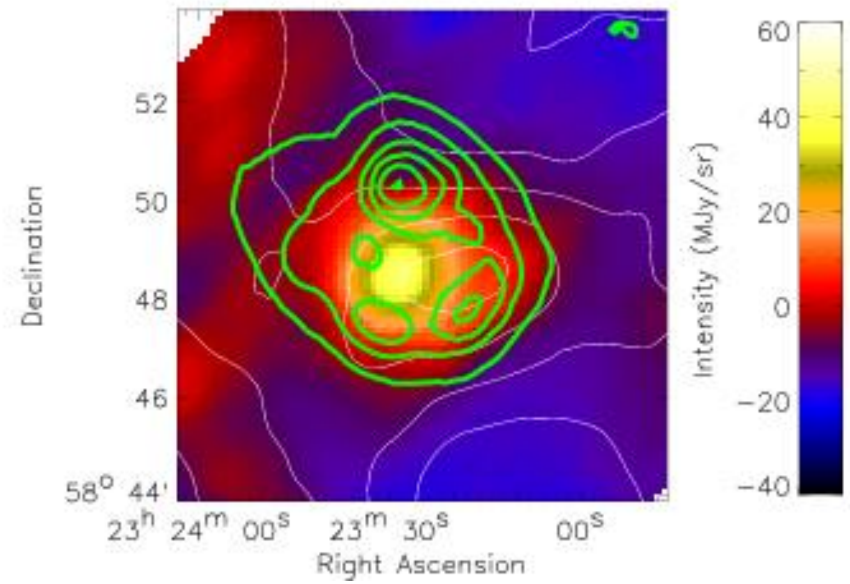
➔ **early arrival of reverse shock at dust-forming region**

Nozawa+'10, ApJ, 713, 356

3-4. 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+'10, ApJ, 713, 356

AKARI observation

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

T_{dust} = 33-41 K

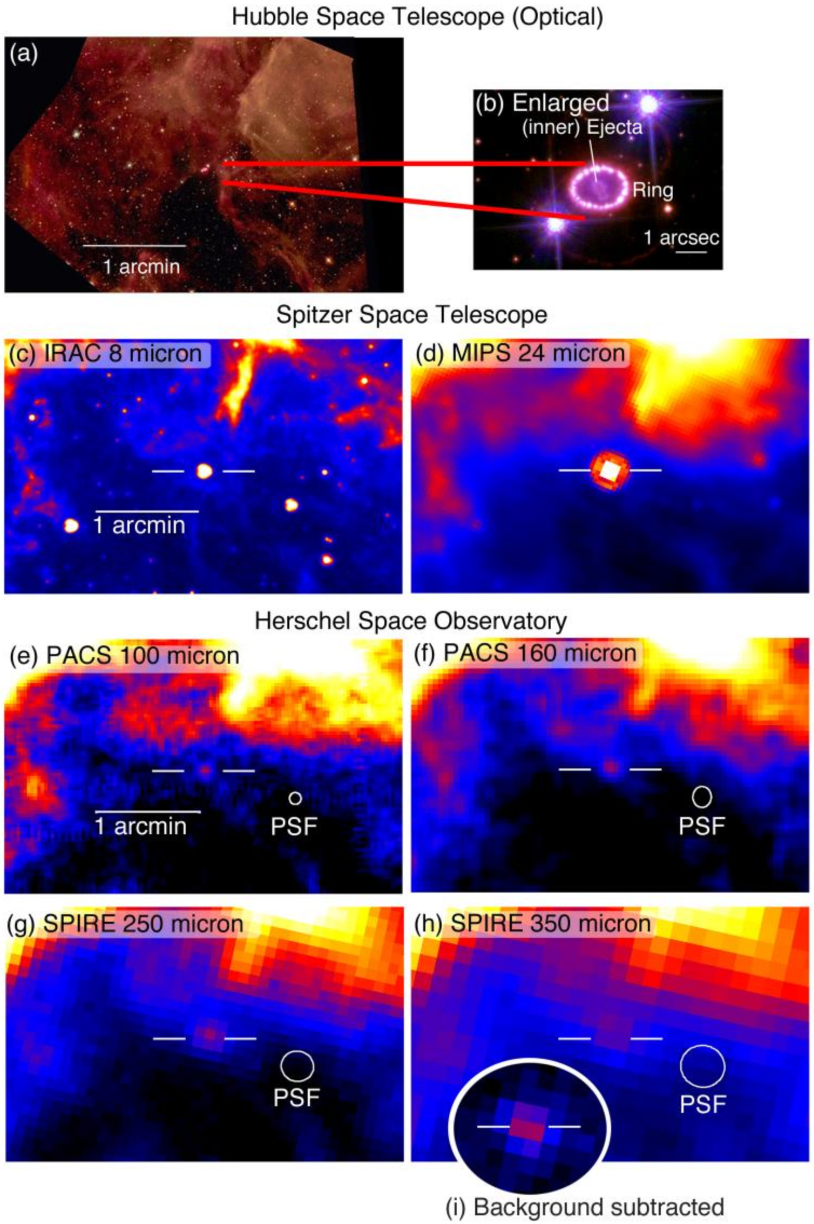
(Sibthorpe+10)

Herschel observation

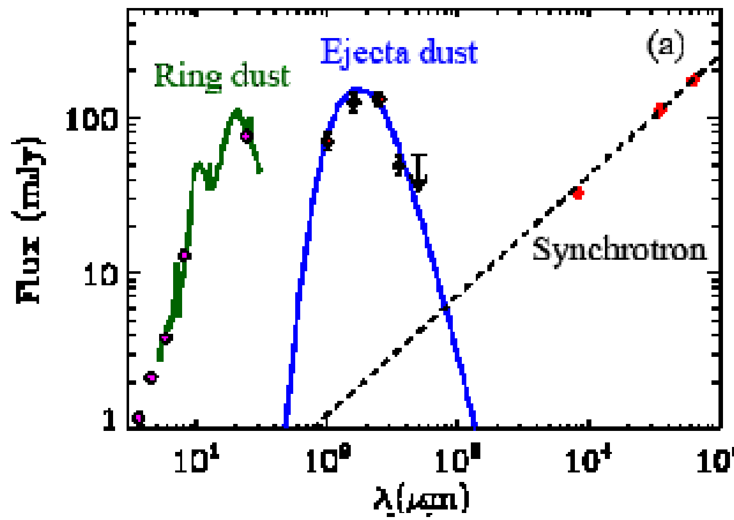
$M_{d,cool}$ = 0.075 M_{sun}

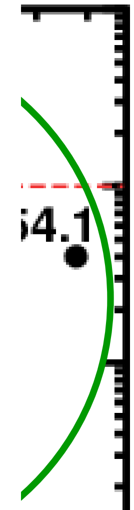
T_{dust} ~ 35 K (Barlow+10)

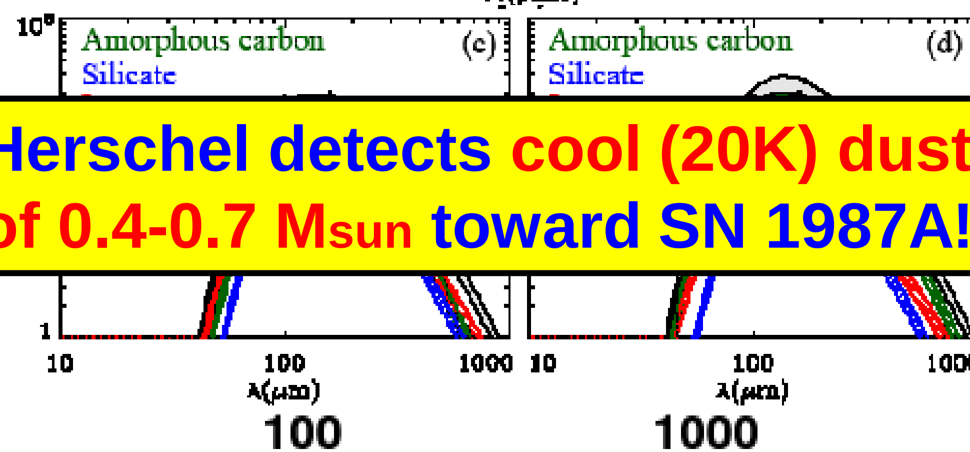
4-1. Missing-dust problem in CCSNe



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



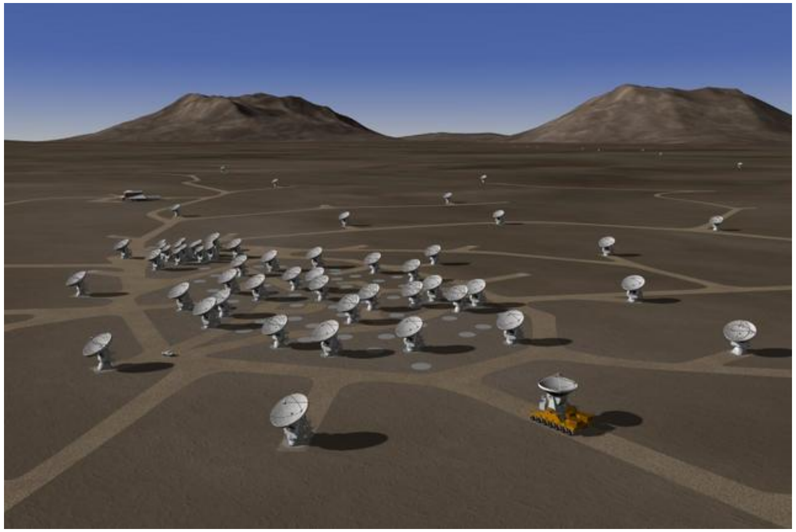


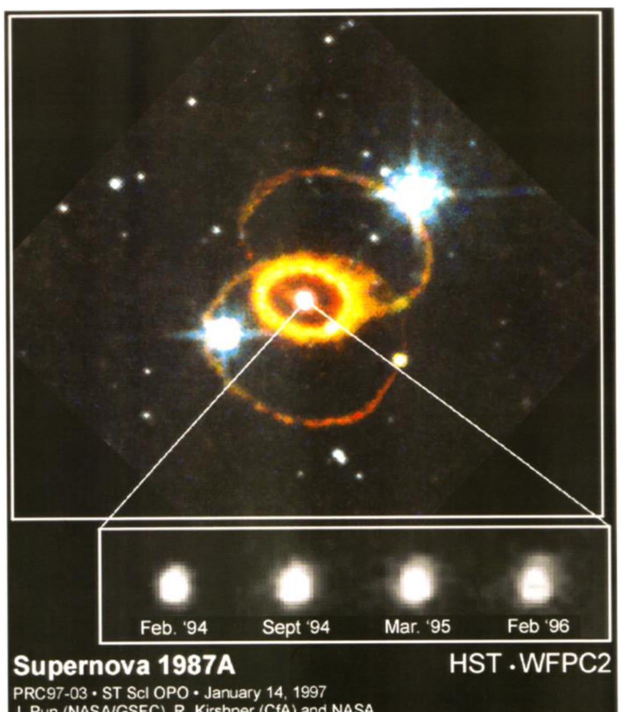


Herschel detects cool (20K) dust of 0.4-0.7 Msun toward SN 1987A!

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

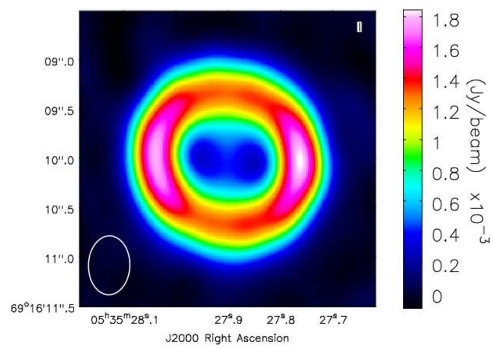
4-2. Resolving cold dust in SN87A with ALMA



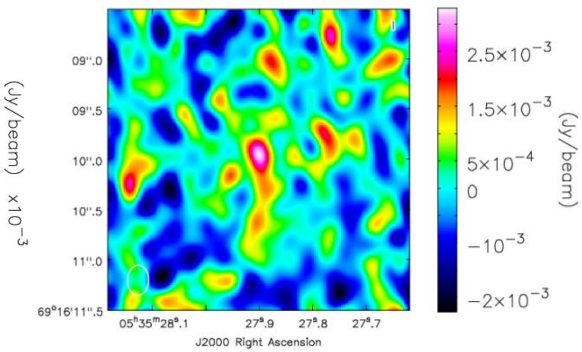


ALMA Cycle 0 Proposal
'Detecting cool dust in SN1987A'
(PI: Nozawa)

Band 7 (850 μm)



Band 9 (450 μm)

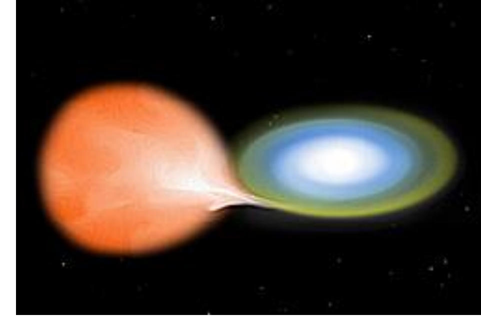


0.1 Msun of silicate ➔ 5σ detection

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

4. Formation of dust in SNe Ia

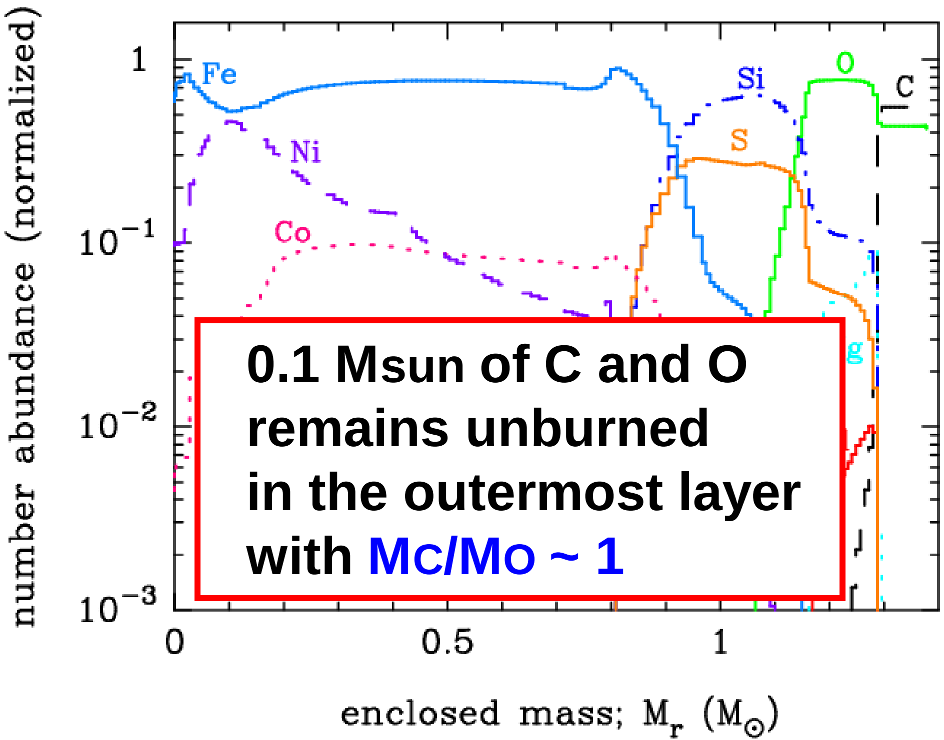
4-1. Dust formation in Type Ia SNe



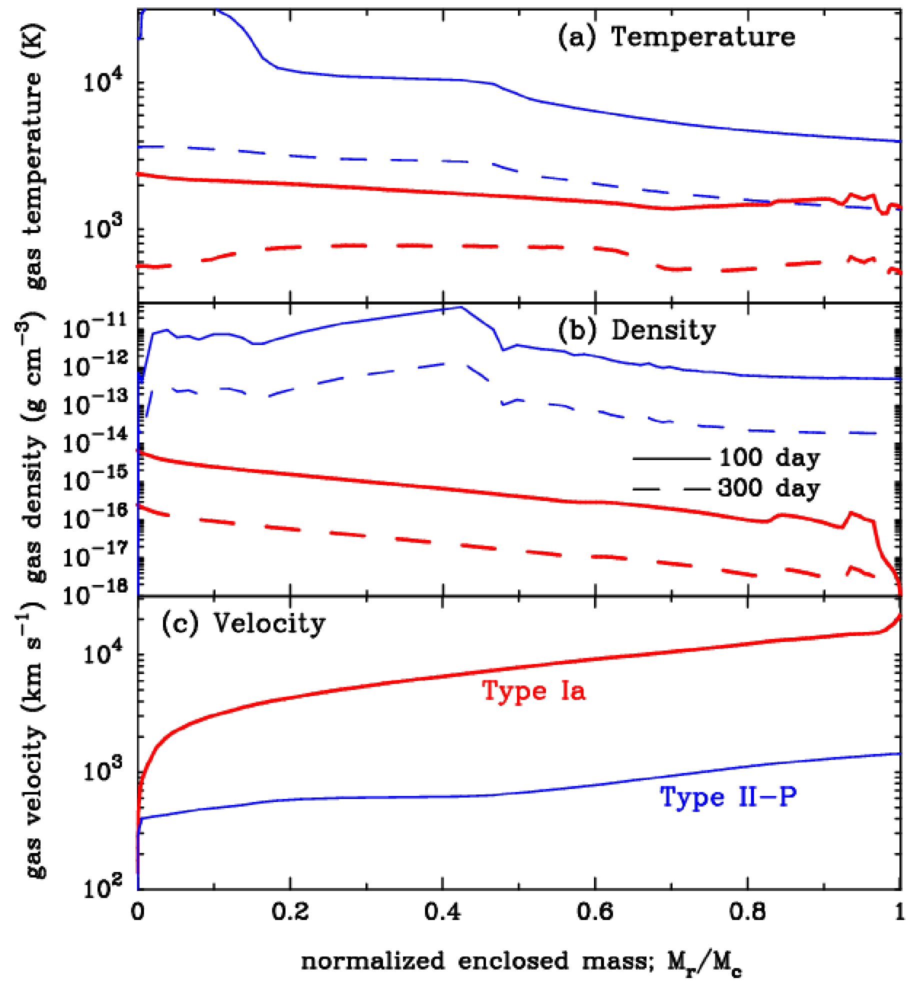
○ Type Ia SN model

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

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



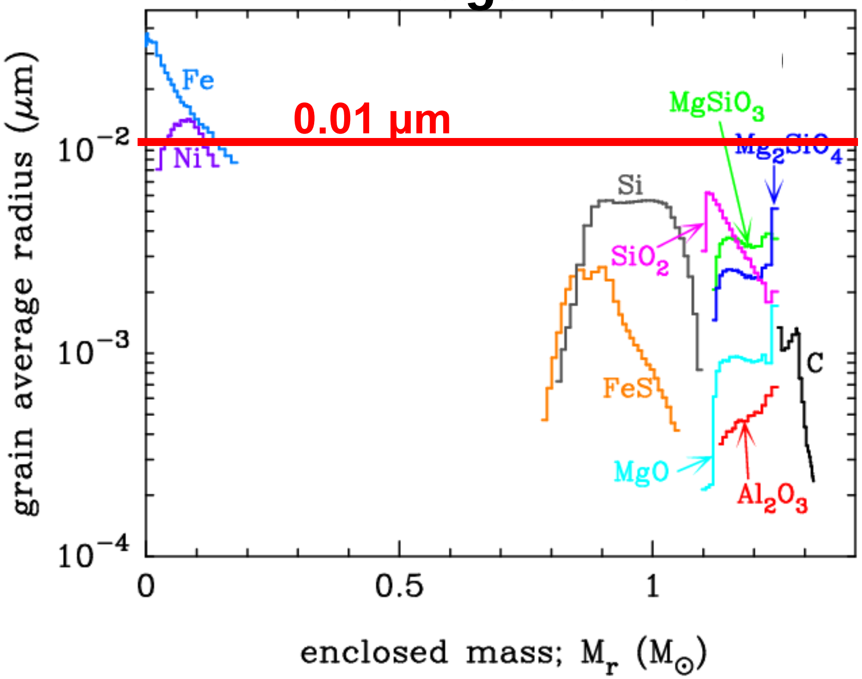
0.1 Msun of C and O remains unburned in the outermost layer with Mc/Mo ~ 1



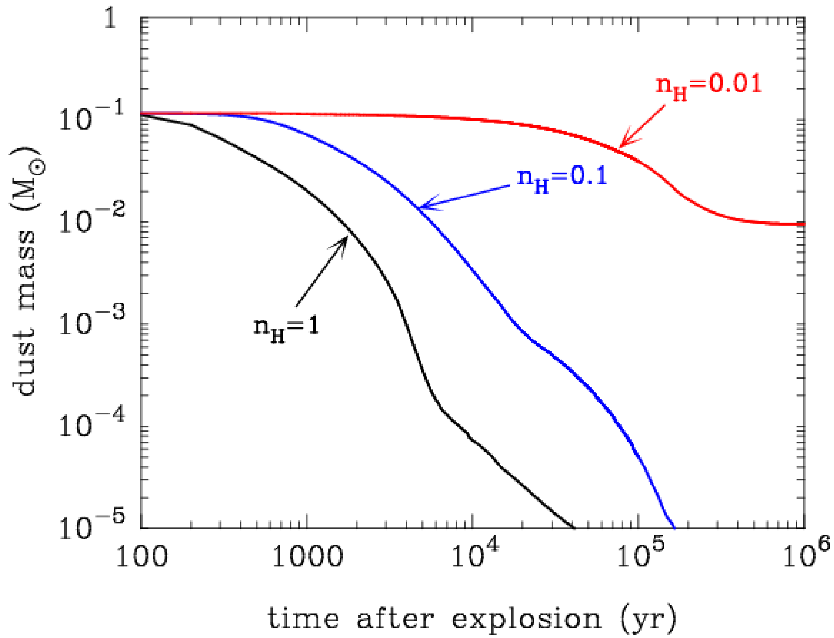
4-2. Dust formation and evolution in SNe Ia

Nozawa+2011, ApJ, 736, 45

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

4-3. Optical depths by newly formed dust

V band (0.55 μm) opacity at 300 days for γ = 1

M_C = 0.006 M_{sun} → τ_C = 22

$M_{silicate}$ = 0.030 M_{sun} → $\tau_{silicate}$ = 0.01

~~M_{FeS} = 0.018 M_{sun} → τ_{FeS} = 14~~

~~M_{Si} = 0.063 M_{sun} → τ_{Si} = 78~~

M_{total} = 0.116 M_{sun} → τ_{total} = 114

V band (0.55 μm) opacity at 300 days for γ = 0.1

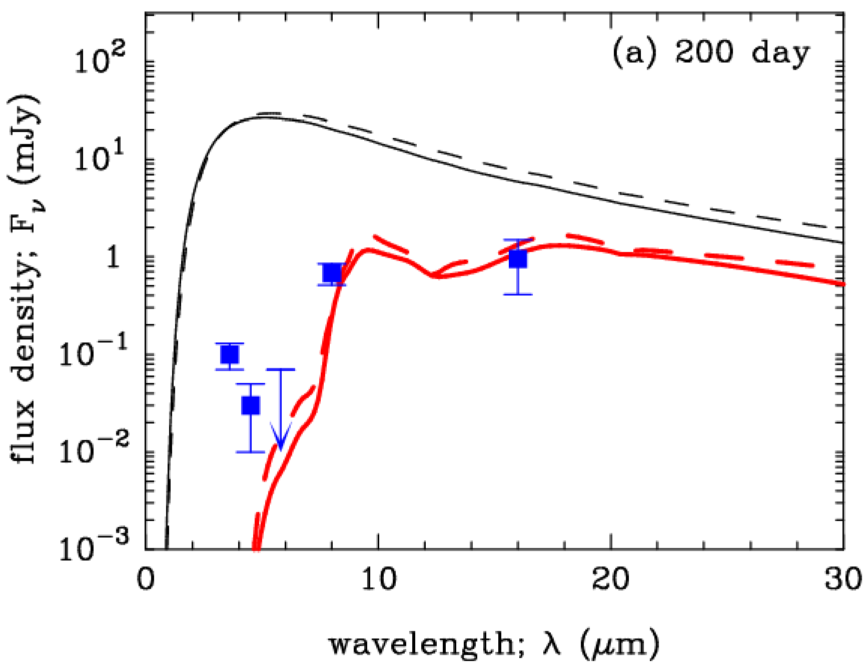
M_{total} ~ 3×10^{-4} M_{sun} → τ_{total} = 1

Formation of dust grains (C, Si, and Fe) should be suppressed to be consistent with the observations

4-4. Carbon dust and outermost layer of SNe Ia

- **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+2011, ApJ, 736, 45

― massive unburned carbon (~0.05 Msun) in deflagration

➔ change of composition of WD by He-shell flash

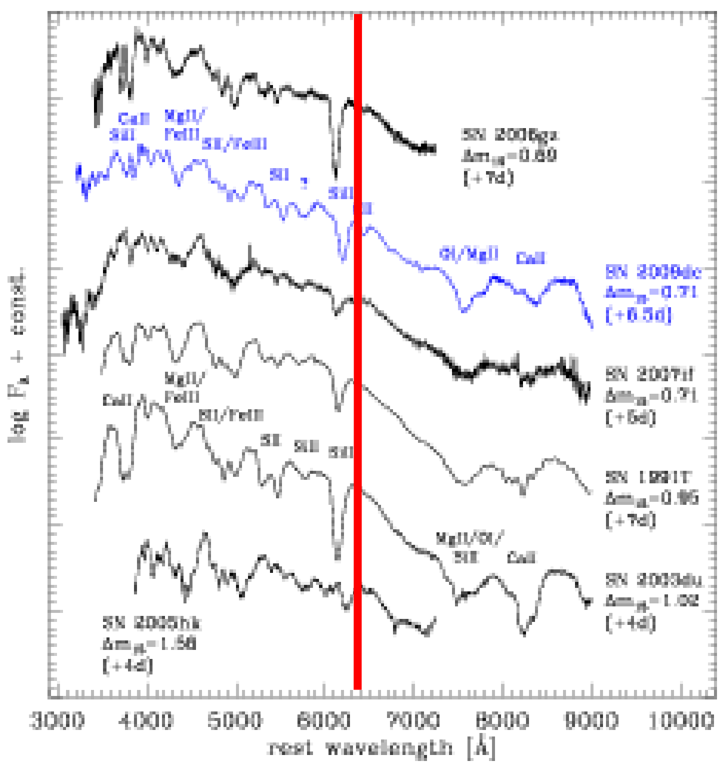
➔ burning of carbon by a delayed detonation

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

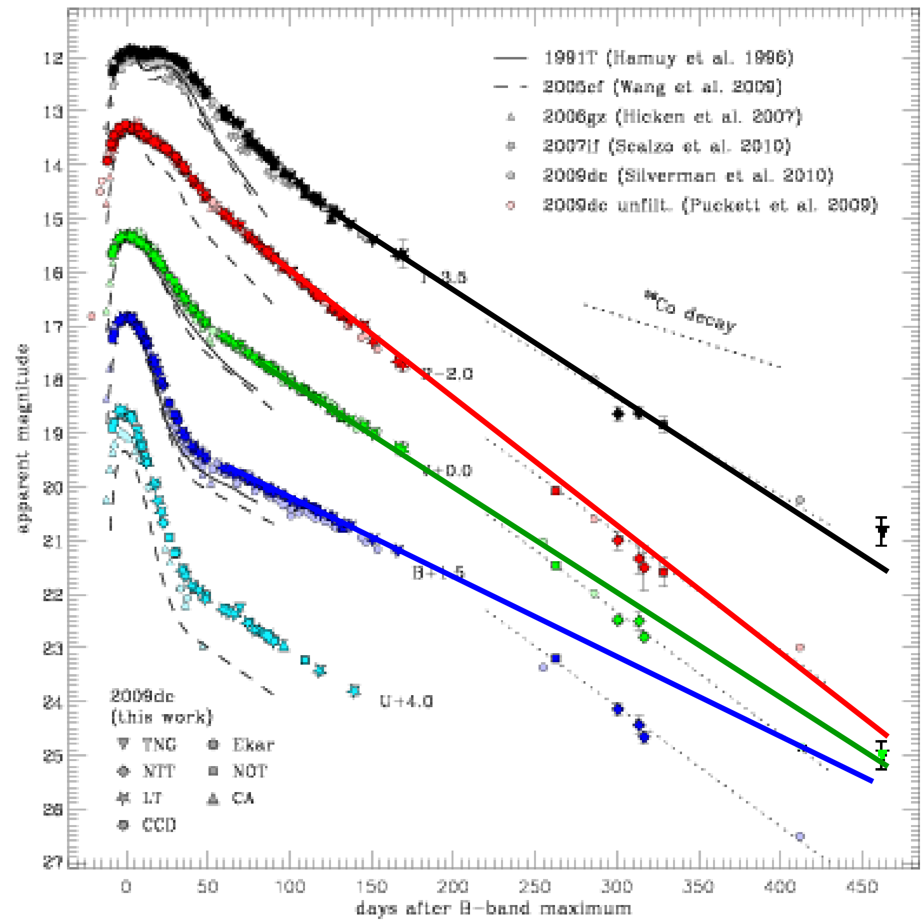
4-5. Dust formation in super-Chandra SNe?

– 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?

5. Summary of this talk

・ Type II SNe with massive H envelopes

— radius of dust formed : a_{ave} > 0.01 μm

➔ H-retaining SNe may be important sources of dust, supplying 0.1-1.0 M_{sun} of dust to the ISM

・ Type IIb/Ib/Ia SNe without massive H envelopes

— grain radius formed : a_{ave} < 0.01 μm

➔ dust is almost completely destroyed in the SNRs

➔ H-stripped SNe are not likely to be sources of dust

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

・ Mass of dust in young SNRs are dominated by cool dust

— FIR and submm observations of SNRs are essential

➔ Herschel detected massive cool dust in SN 1987A

5-1. Implication on evolution history of dust

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

- **massive stars (SNe) are likely to be dominant**
- **mass loss of massive stars would be less efficient**

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

necessary for serving the seeds for grain growth in the ISM

— **dust mass per SN II-P after the RS destruction**
M_{dust} = 0.1-0.8 M_{sun} for $n_{H,0}$ = 0.1-1 cm^{-3}
— **average radius of dust is quite large (> 0.01 μm)**

- **grain growth in the ISM makes grain size larger**

➔ **dust extinction curve in the early universe might be gray (wavelength-independent) if SNe II-P (and grain growth) are main sources of dust at high redshift**

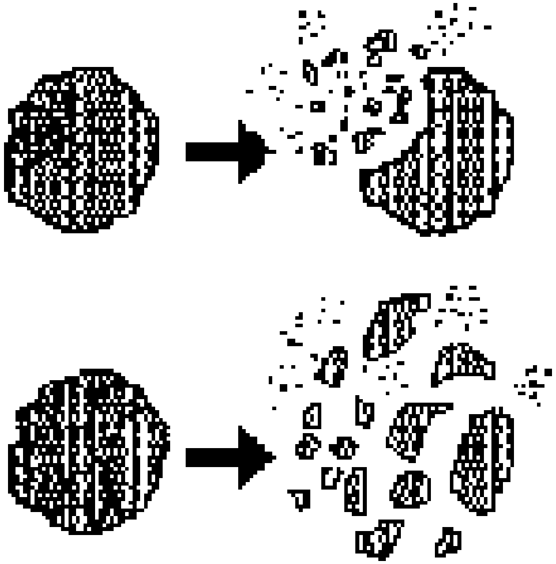
5-2. Implication on evolution history of dust

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

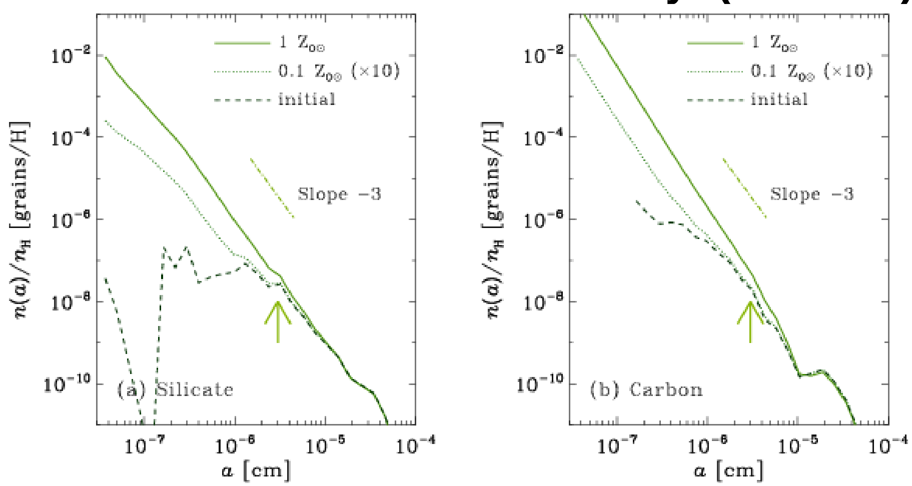
- low-mass stars are dominant
- mass loss of massive stars would be more efficient

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

— dust is almost completely destroyed in the SNRs since size of newly formed dust is small (< 0.01 μm)



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



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