

Dust production by various types of supernovae

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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 Ib 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 $10^8 M_{\text{sun}}$ in 30% of $z > 5$ quasars

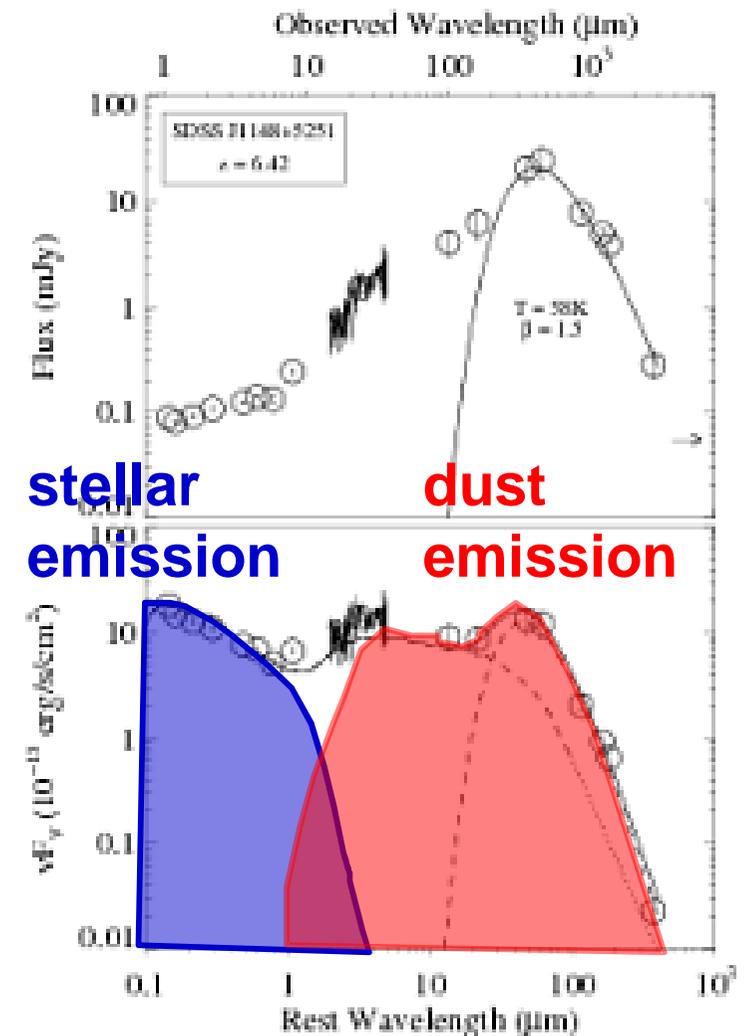
SDSS J1148+5251 at $z=6.4$

- age : 890 Myr
- IR luminosity : $\sim(1-3) \times 10^{13} L_{\text{sun}}$
- dust mass : $(2-7) \times 10^8 M_{\text{sun}}$
- SFR : $\sim 3000 M_{\text{sun/yr}}$ (Salpeter IMF)
- gas mass : $\sim 3 \times 10^{10} M_{\text{sun}}$ (Walter+'04)
- metallicity : \sim solar



** Herschel (3.5m) **

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



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

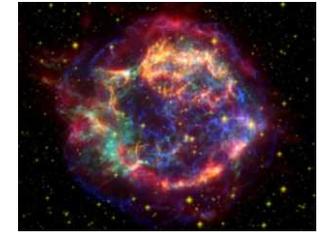
1-2. What are dust sources in high-z quasar?

- 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)

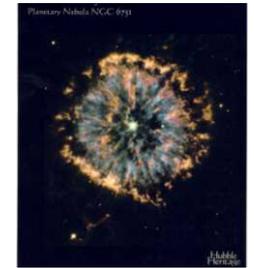


- AGB stars + SNe

- (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

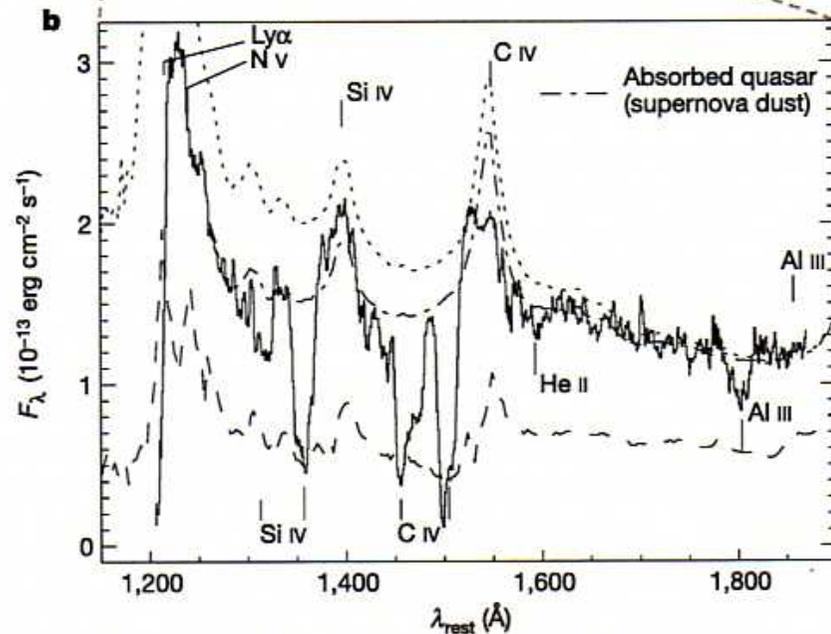
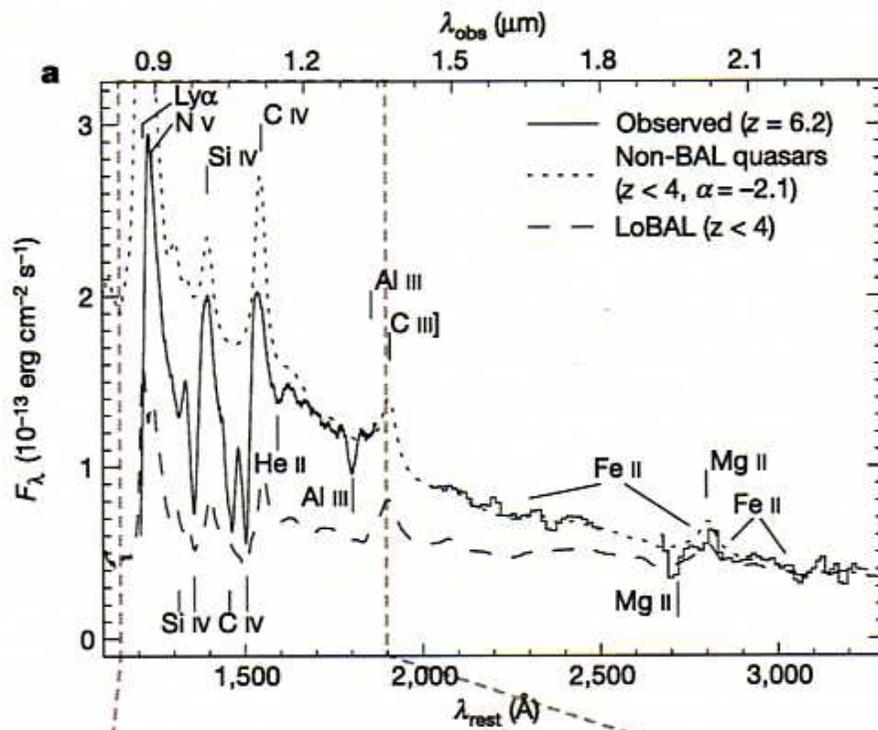
- (Draine'09; Michalowski+'10; Pipino+'11; Mattsson'11)

- $T_{\text{growth}} \sim 10^7 (Z / Z_{\text{sun}}) \text{ yr}$



- Quasar outflows (Elvis+'02)

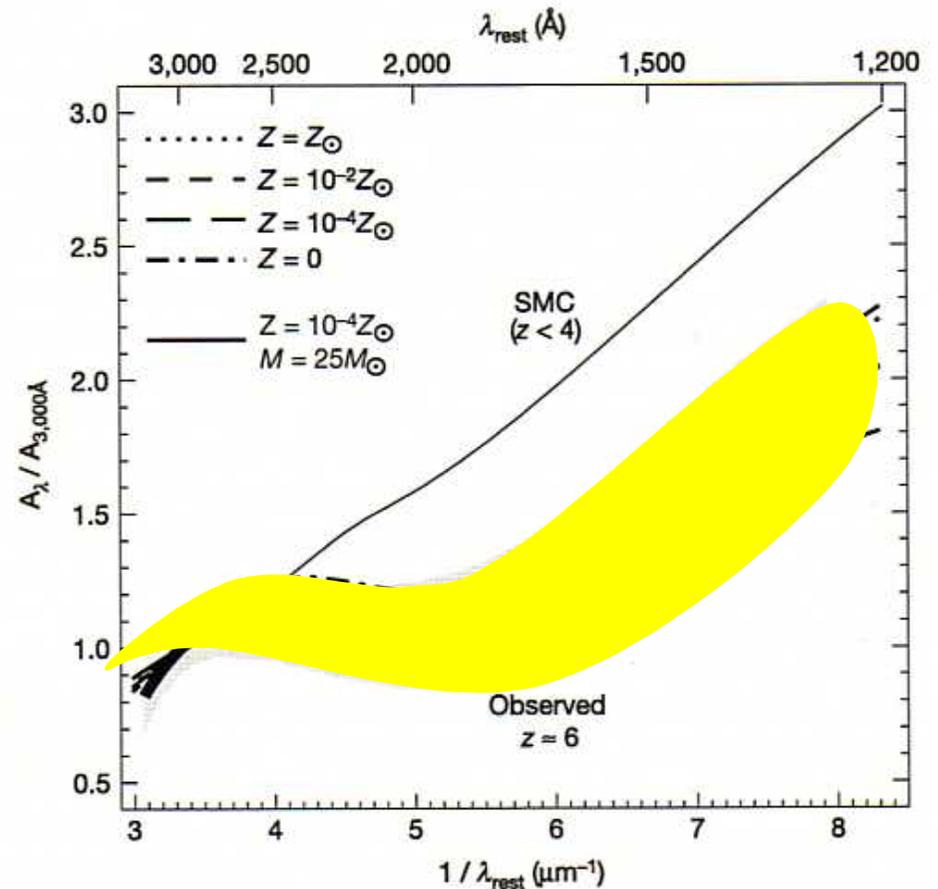
1-3. Extinction curves at high-z quasars



Maiolino+'04, Nature, 431, 533

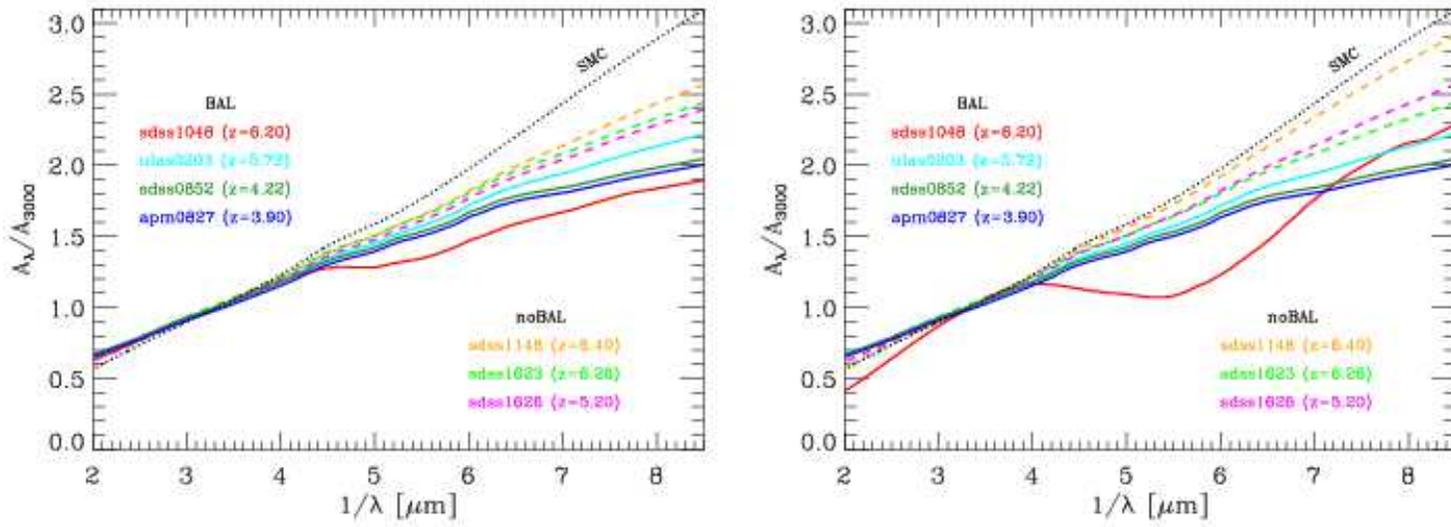
SDSS J1048+4637 at $z=6.2$

Broad absorption line (BAL) quasars



**different dust properties
from those at low redshift**

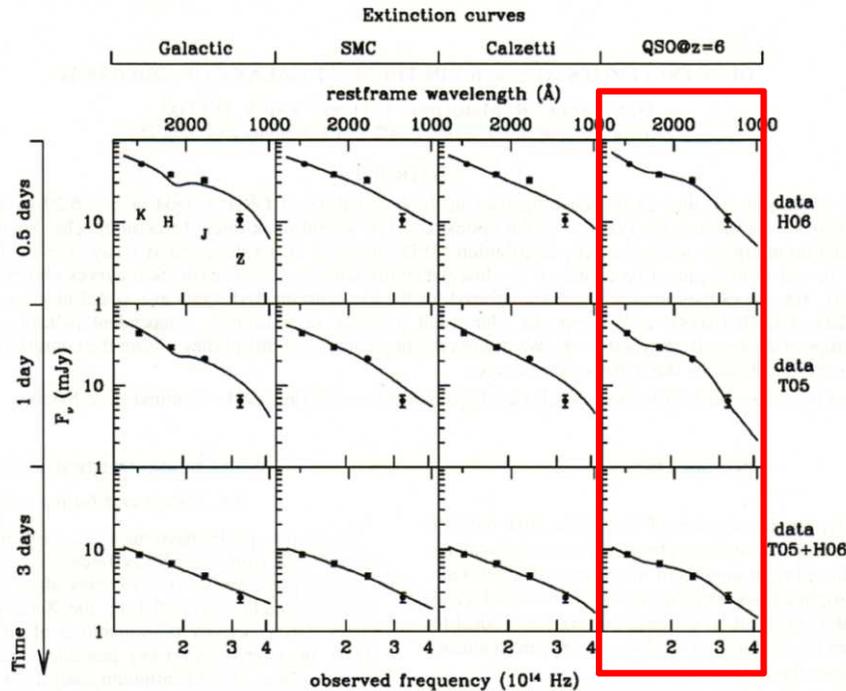
1-4. Extinction curves at $3.9 < z < 6.4$



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

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

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 $\alpha_{\lambda, \text{min}} = -2.9$, while the panel on the right is obtained with $\alpha_{\lambda, \text{min}} = -2.6$.



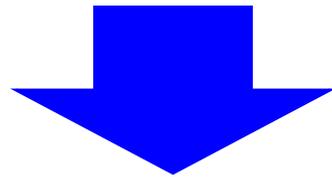
GRB 050904 at $z=6.3$

additional evidence for different dust properties at high-z

Stratta+'07, ApJ, 661, L9

1-5. Summary of Introduction

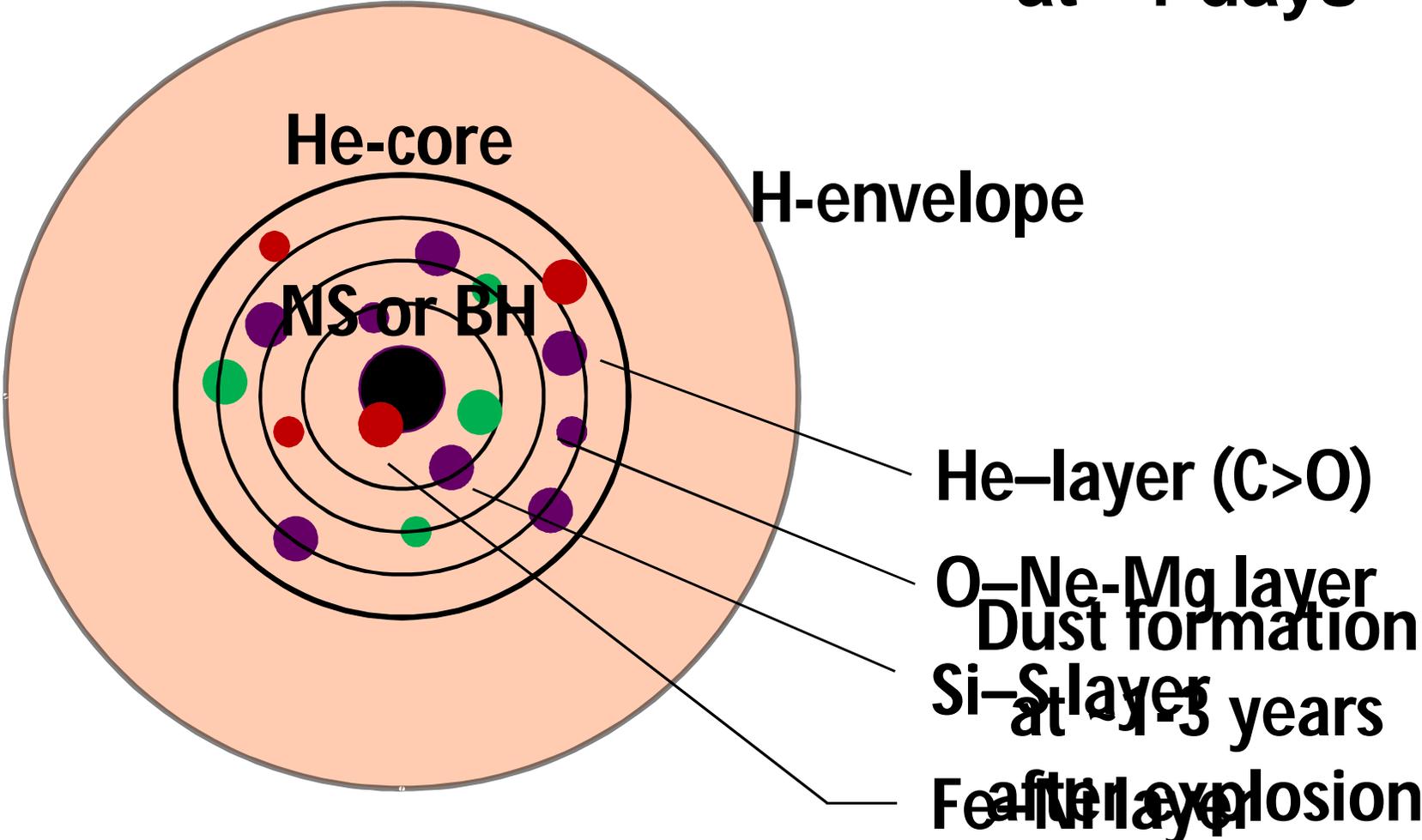
- **There is clear evidence for huge amounts of dust at $z > 5$, but the dust sources remain unexplained**
 - SNe? AGB stars? grain growth in the dense clouds? quasar outflow? any other sources?
- **Properties (composition & size) of dust at high z are likely to be different from those at low z**
 - high- z quasars and GRBs are good targets to probe the extinction curves in their host galaxies



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

2-1. Dust Formation in Pop III SNe

at ~1 days

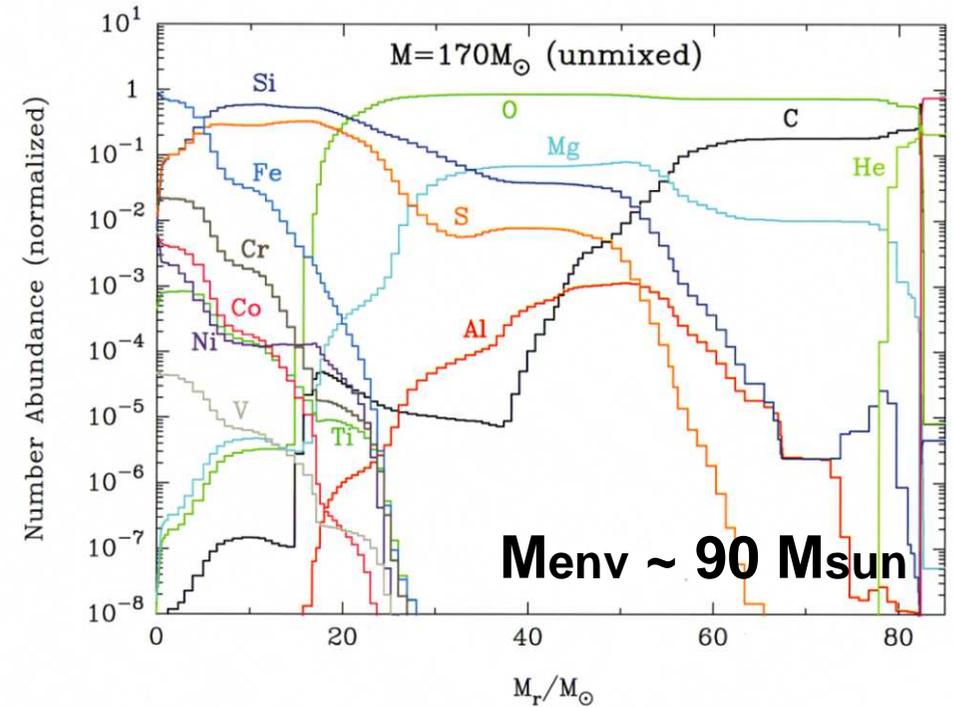
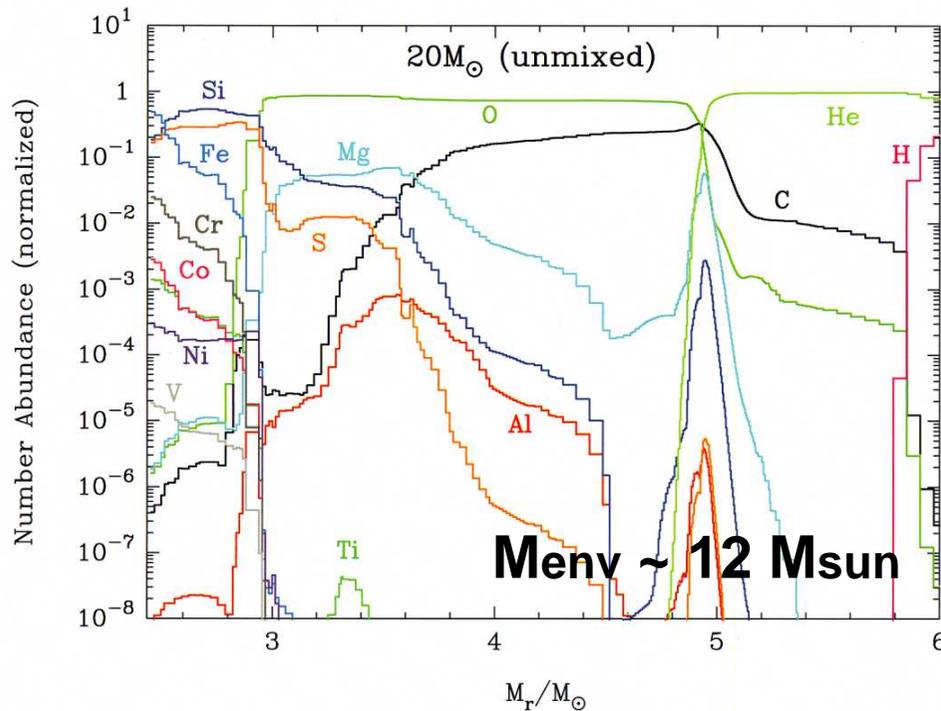


2-1-1. Dust formation in primordial SNe

Nozawa+'03, ApJ, 598, 785

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

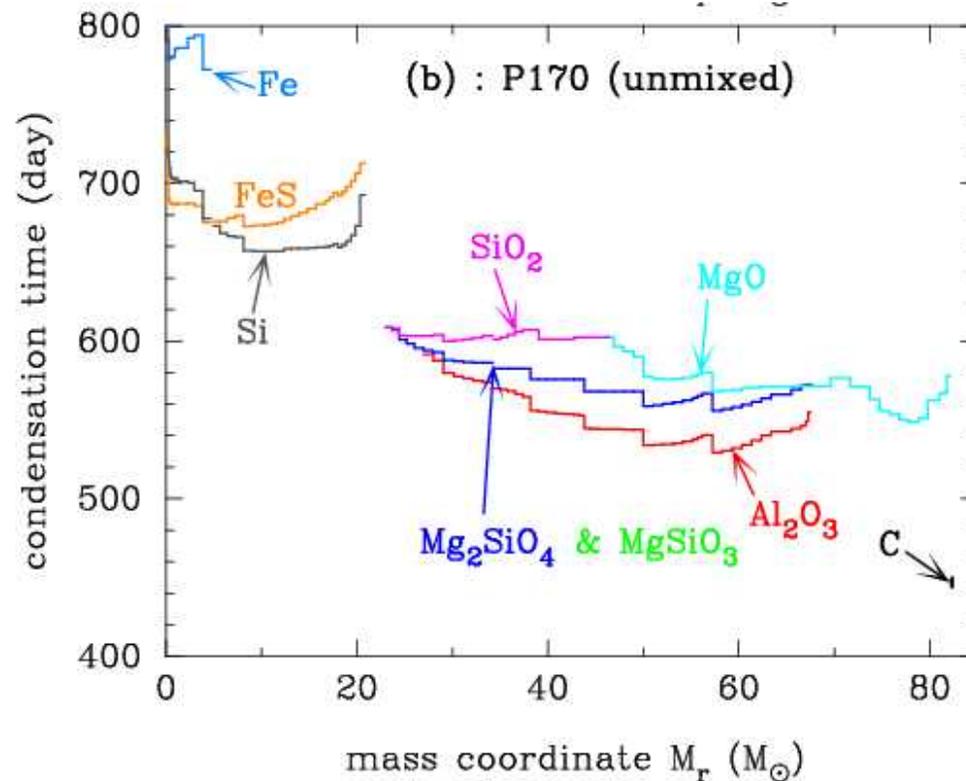
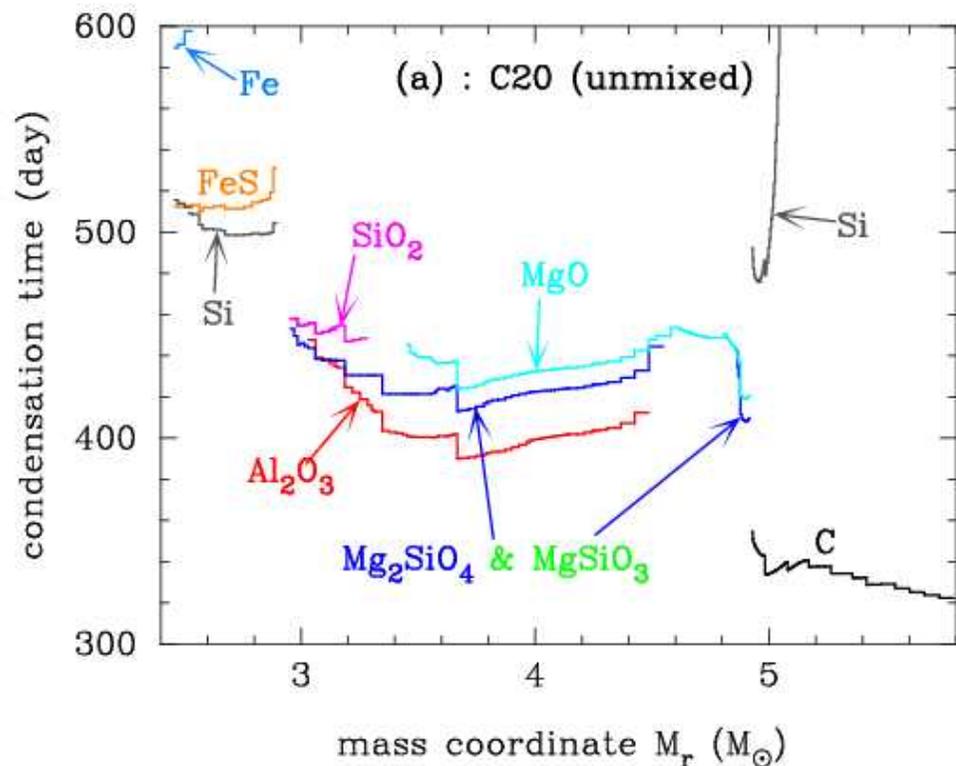
- SNe II-P : $M_{\text{ZAMS}} = 13, 20, 25, 30 M_{\text{sun}}$ ($E_{51}=1$)
- PISNe : $M_{\text{ZAMS}} = 170 M_{\text{sun}}$ ($E_{51}=20$), $200 M_{\text{sun}}$ ($E_{51}=28$)



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

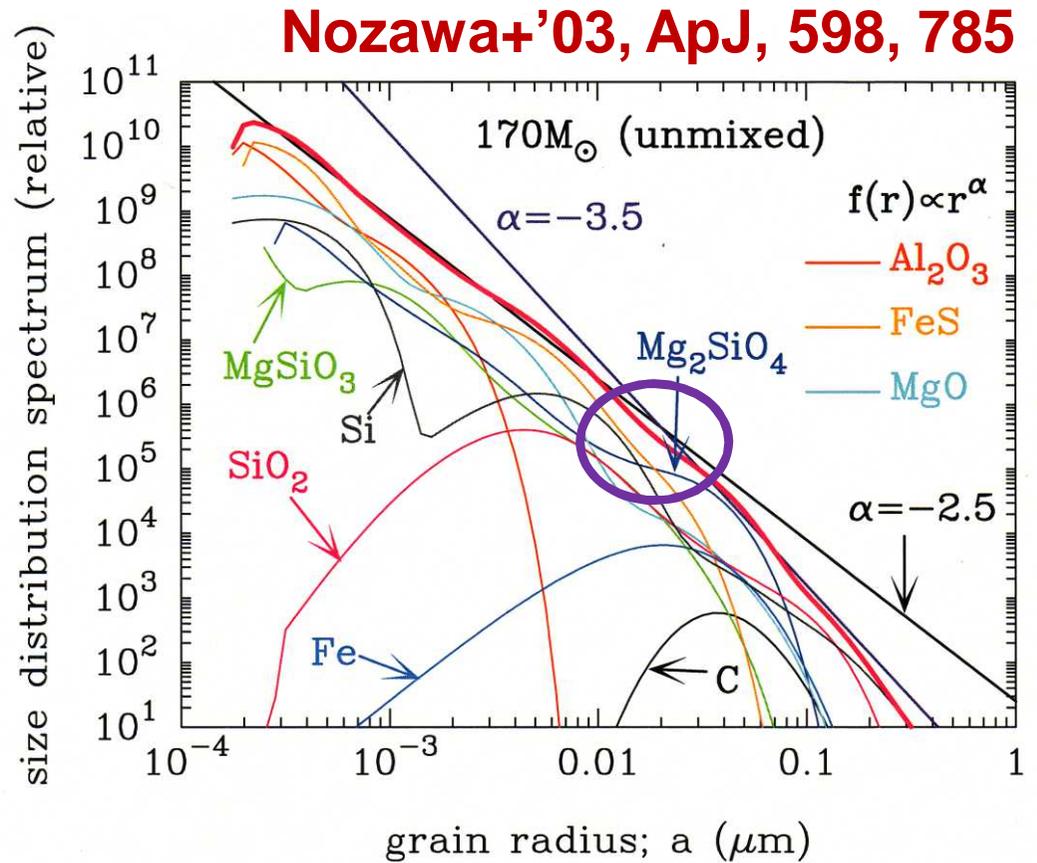
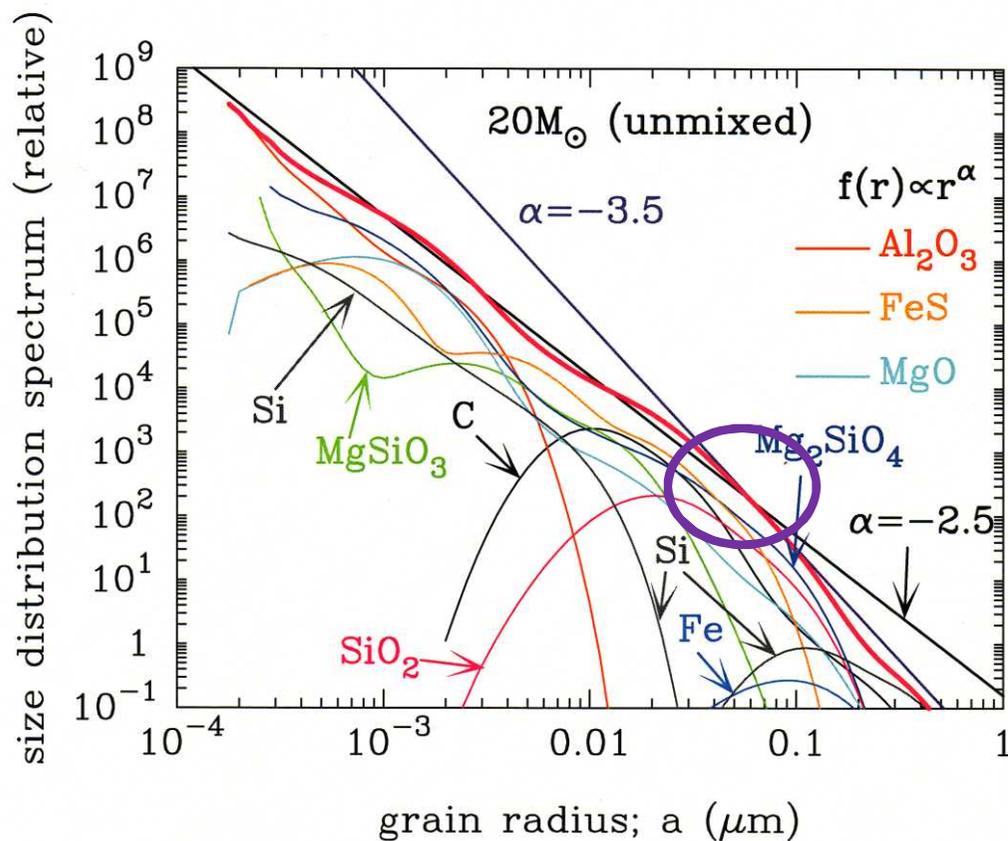
2-1-2. Dust formed in primordial SNe

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 Å up to 1 μm
- average dust radius is smaller for PISNe than SNe II-P

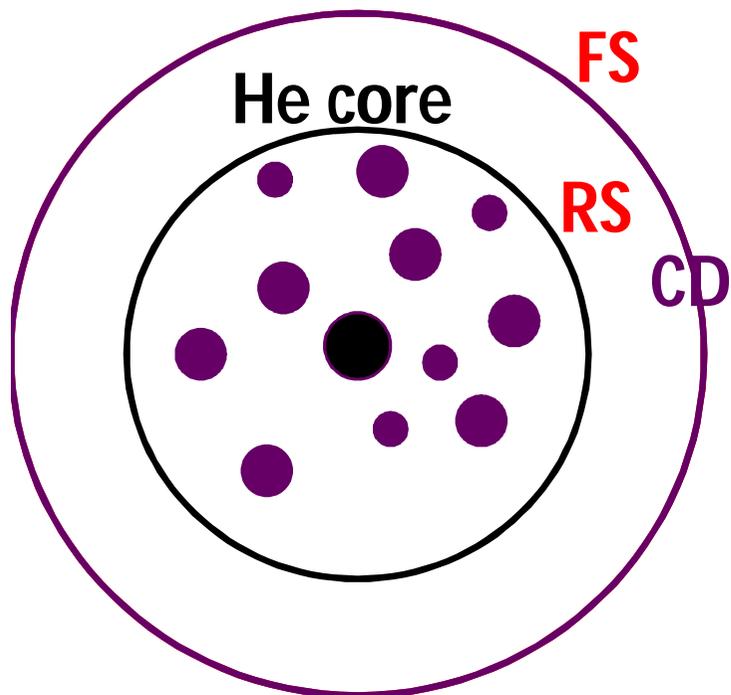
amount of newly formed dust grains

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

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

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 : $M_{\text{pr}}=13, 20, 25, 30 \text{ Msun}$ ($E_{51}=1$)
- PISNe : $M_{\text{pr}}=170$ ($E_{51}=20$), 200 Msun ($E_{51}=28$)

- The ambient medium (homogeneous)

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

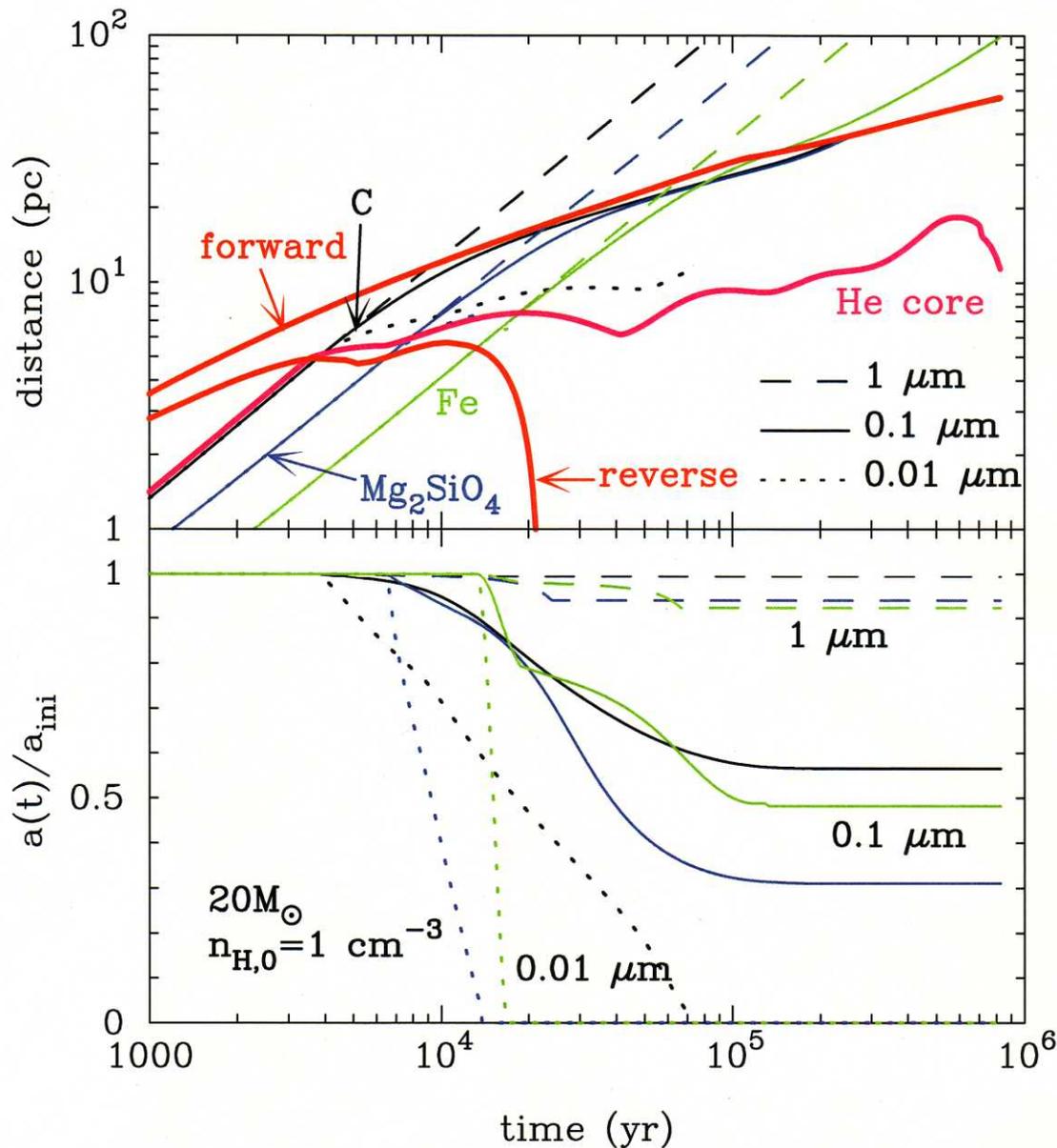
- Dust Model

- 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 $\sim 10^6$ yr

2-2-2. Evolution of dust in SNRs

Nozawa+'07, ApJ, 666, 955



Model : $M_{pr} = 20 M_{sun}$ ($E_{51}=1$)

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

Dust grains in the He core collide with reverse shock at $(3-13) \times 10^3 \text{ yr}$

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

$a_{ini} = 0.01 \mu\text{m}$ (dotted lines)

→ completely destroyed

$a_{ini} = 0.1 \mu\text{m}$ (solid lines)

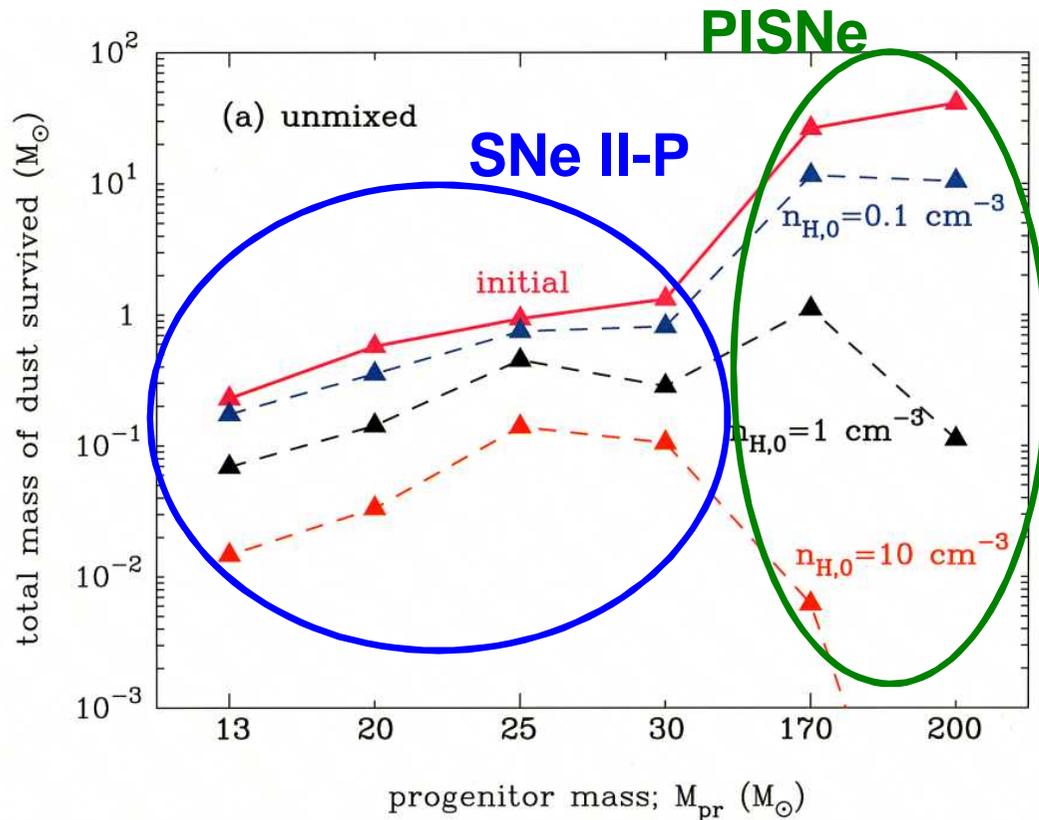
→ trapped in the shell

$a_{ini} = 1 \mu\text{m}$ (dashed lines)

→ injected into the ISM

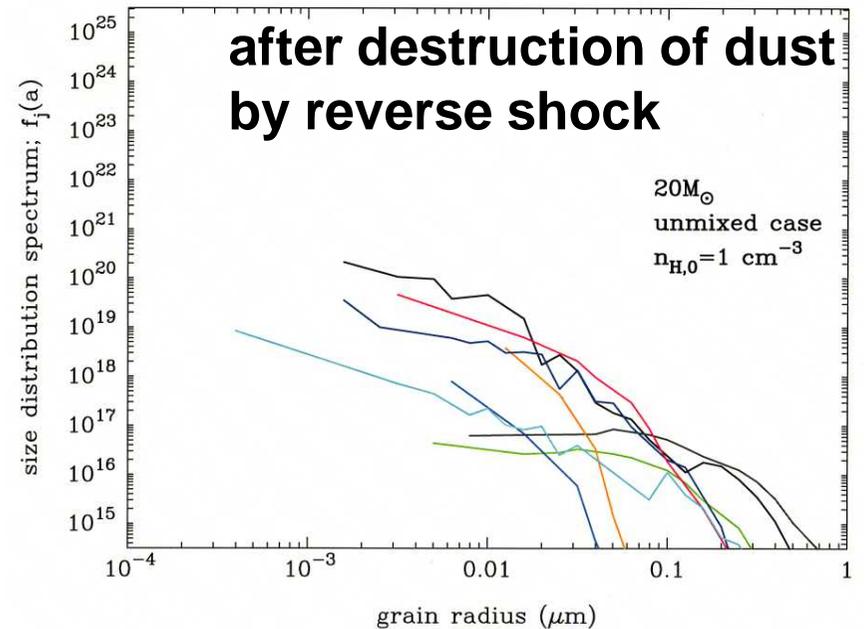
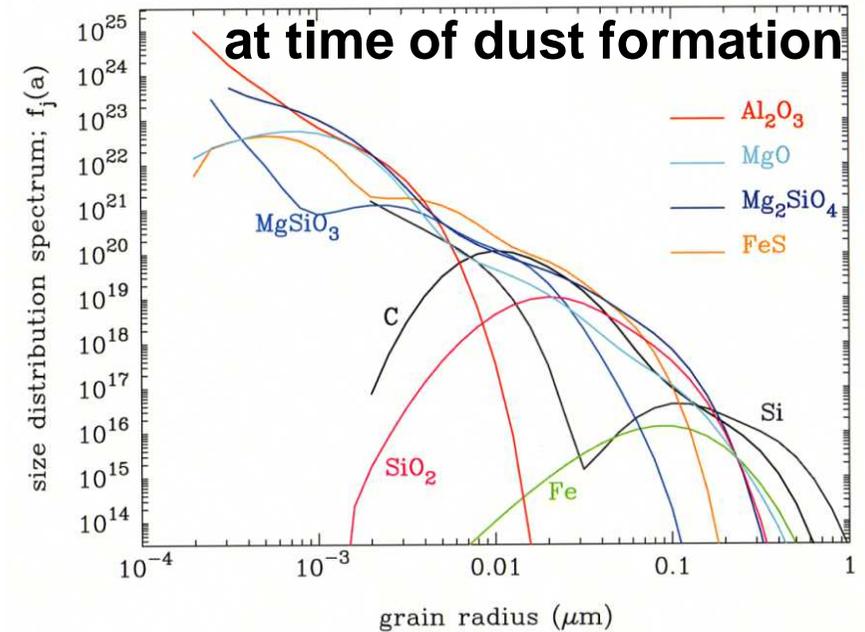
2-2-3. Dust mass and size ejected from SN II-P

Nozawa+'07, ApJ, 666, 955



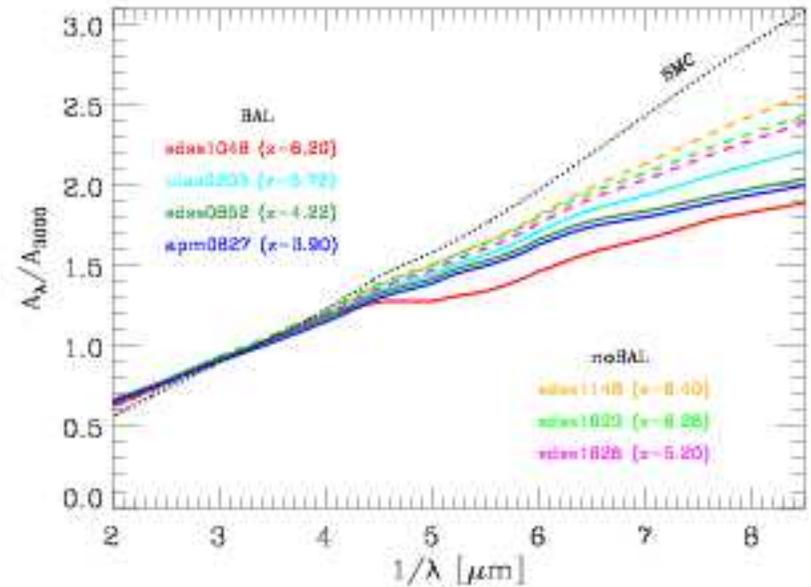
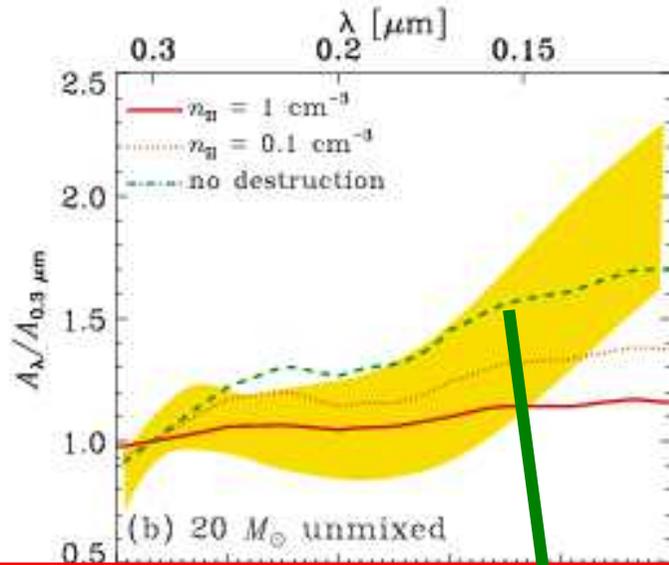
total dust mass surviving the destruction in Type II-P SNRs;
0.07-0.8 M_{sun} ($n_{\text{H},0} = 0.1-1 \text{ cm}^{-3}$)

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



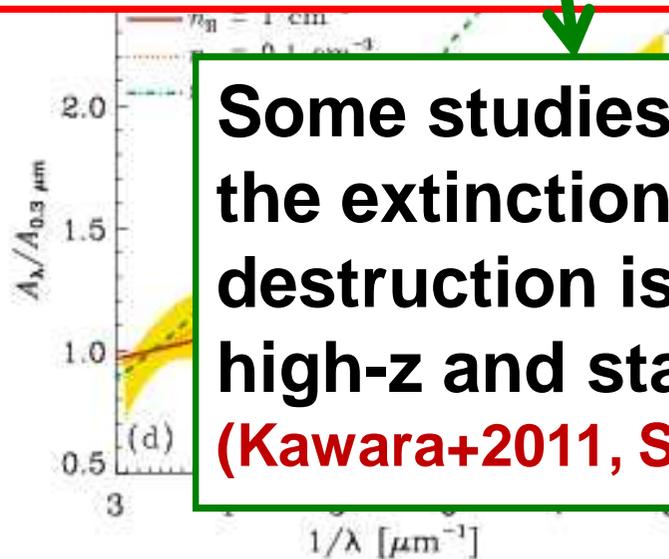
2-3. Flattened extinction curves at high-z

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

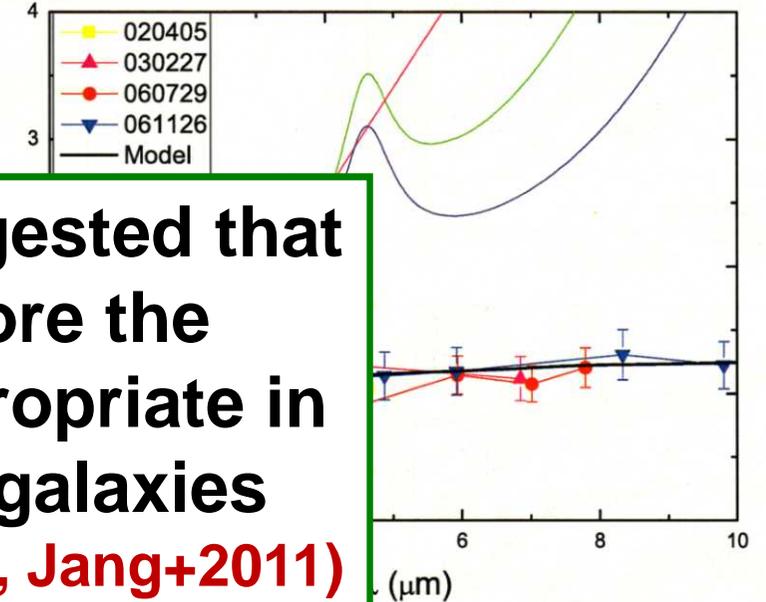


Gallerani+'10, A&A, 523, 85

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



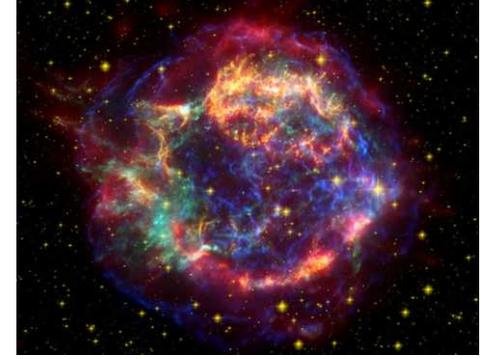
Some studies have suggested that the extinction curve before the destruction is more appropriate in high-z and star-forming galaxies (Kawara+2011, Shimizu+2011, Jang+2011)



Li+'08, ApJ, 678, 1136

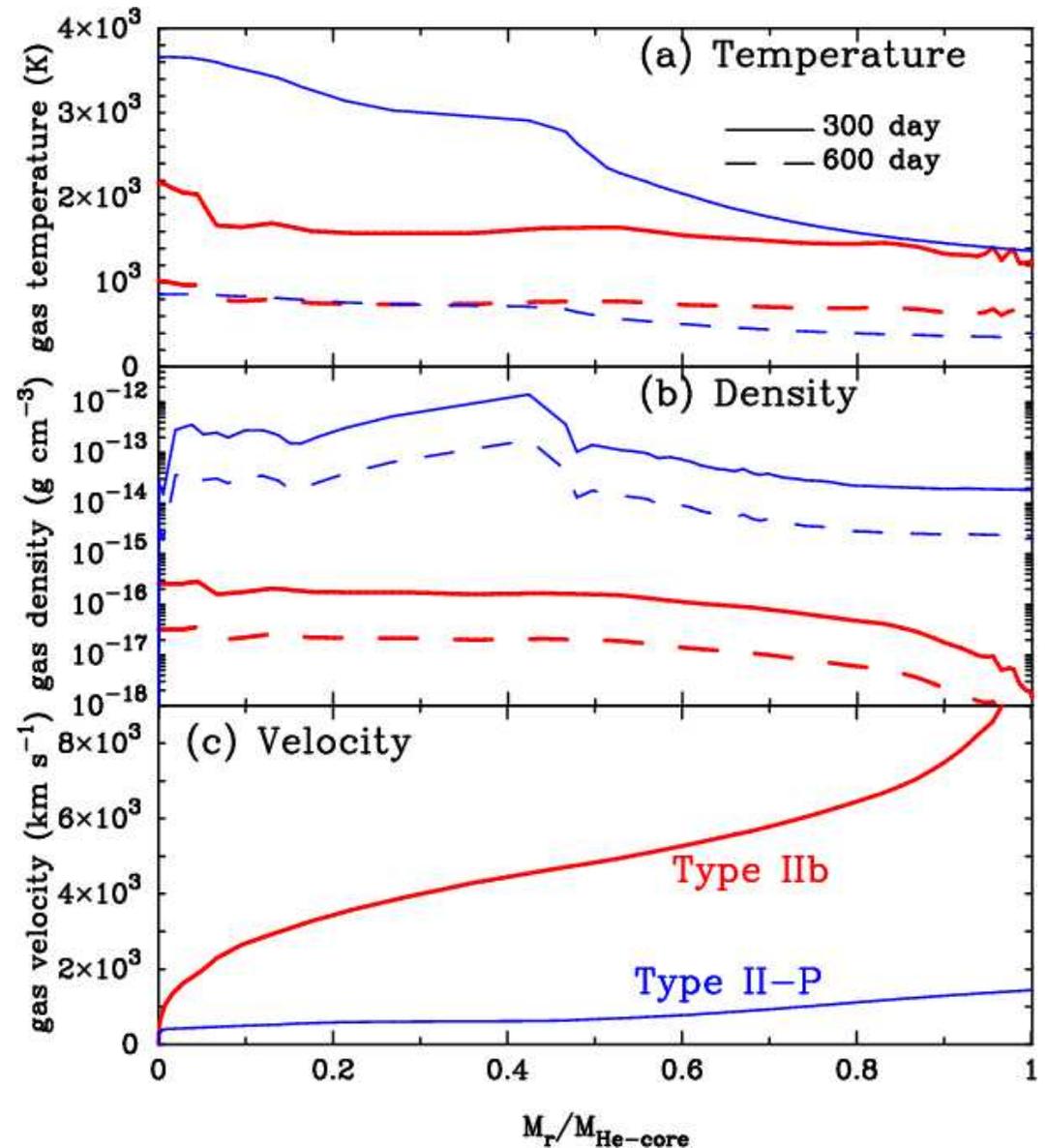
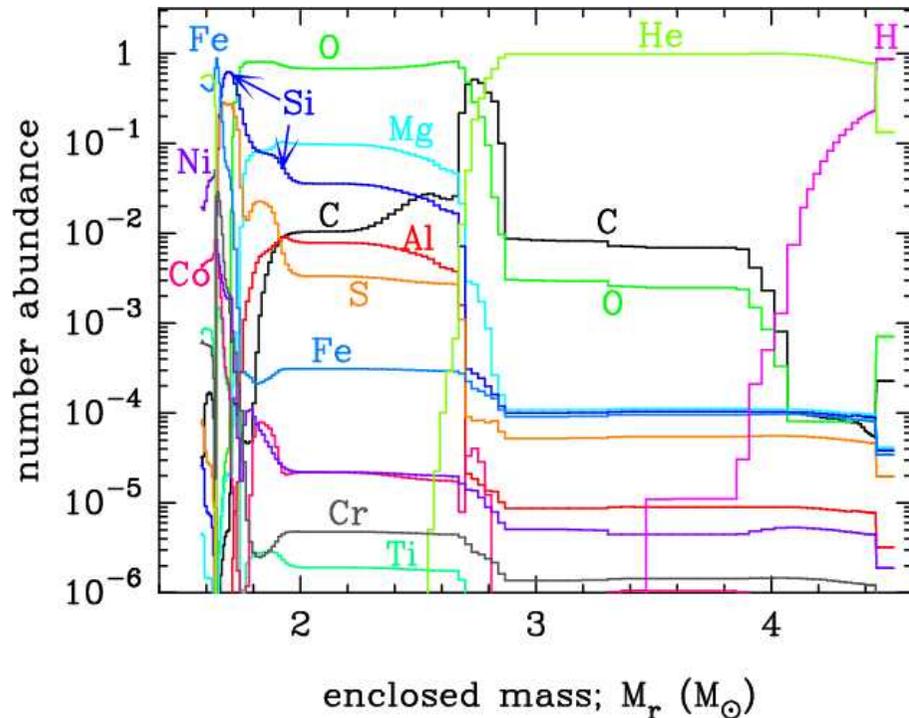
3. Formation and evolution of dust in SNe IIb: Application to Cas A

3-1. Dust formation in Type IIb SN

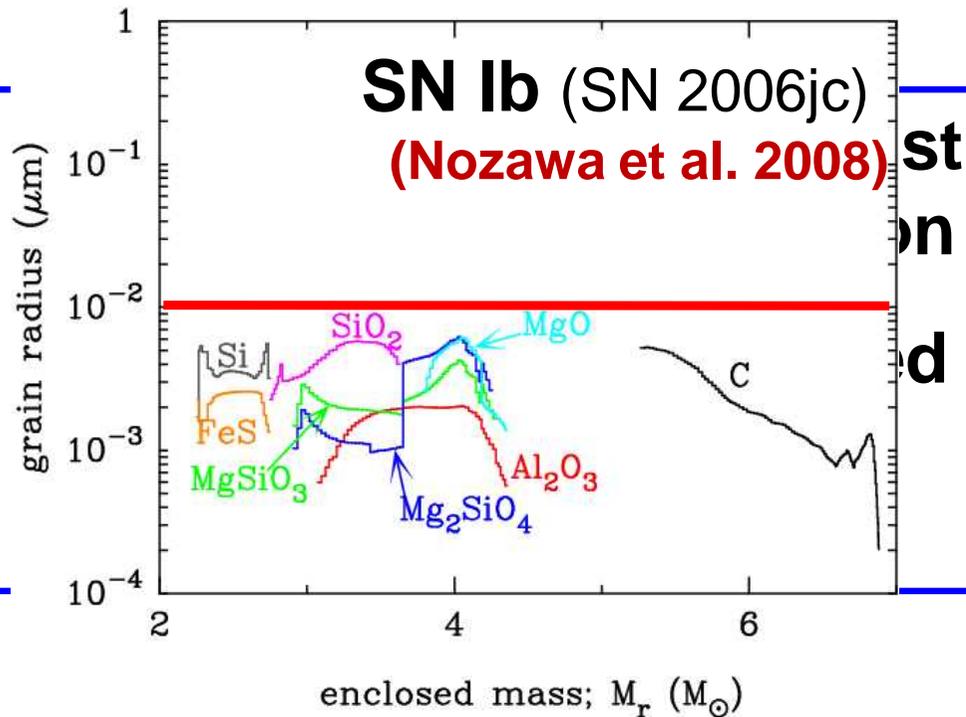
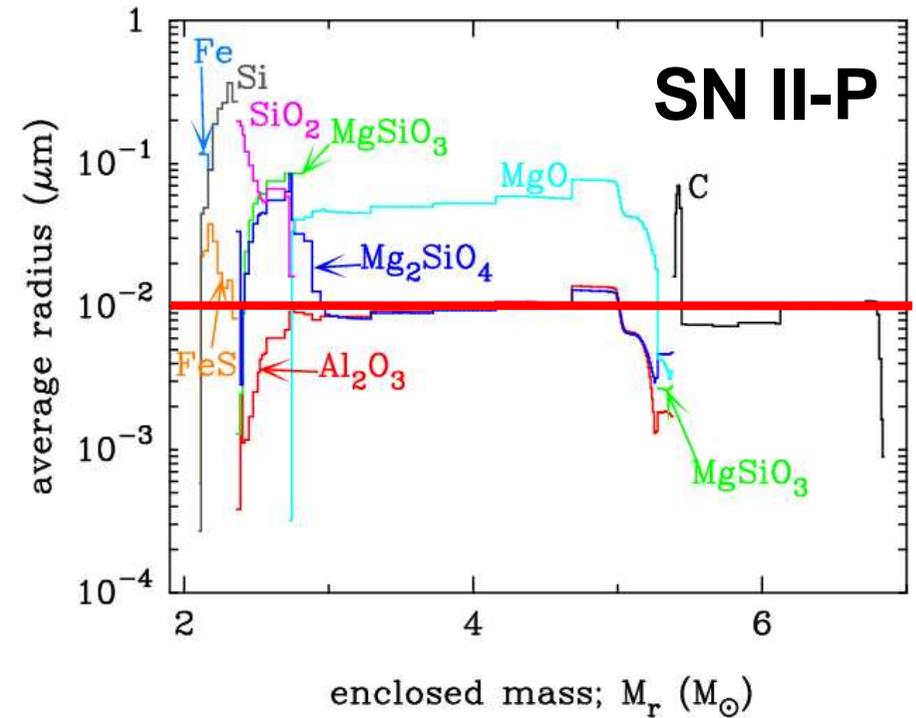
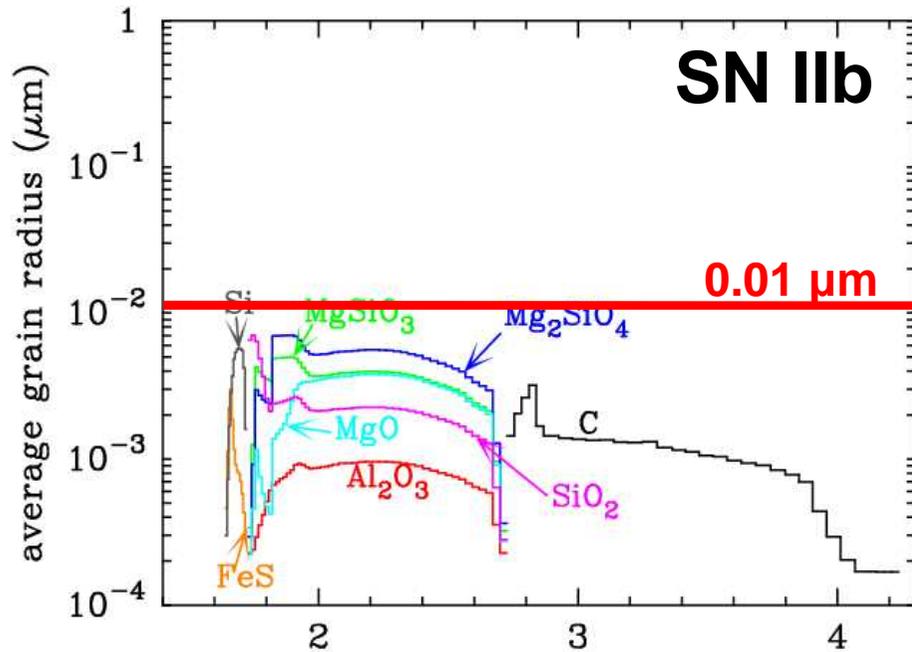


SN IIb model (SN1993J-like model)

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

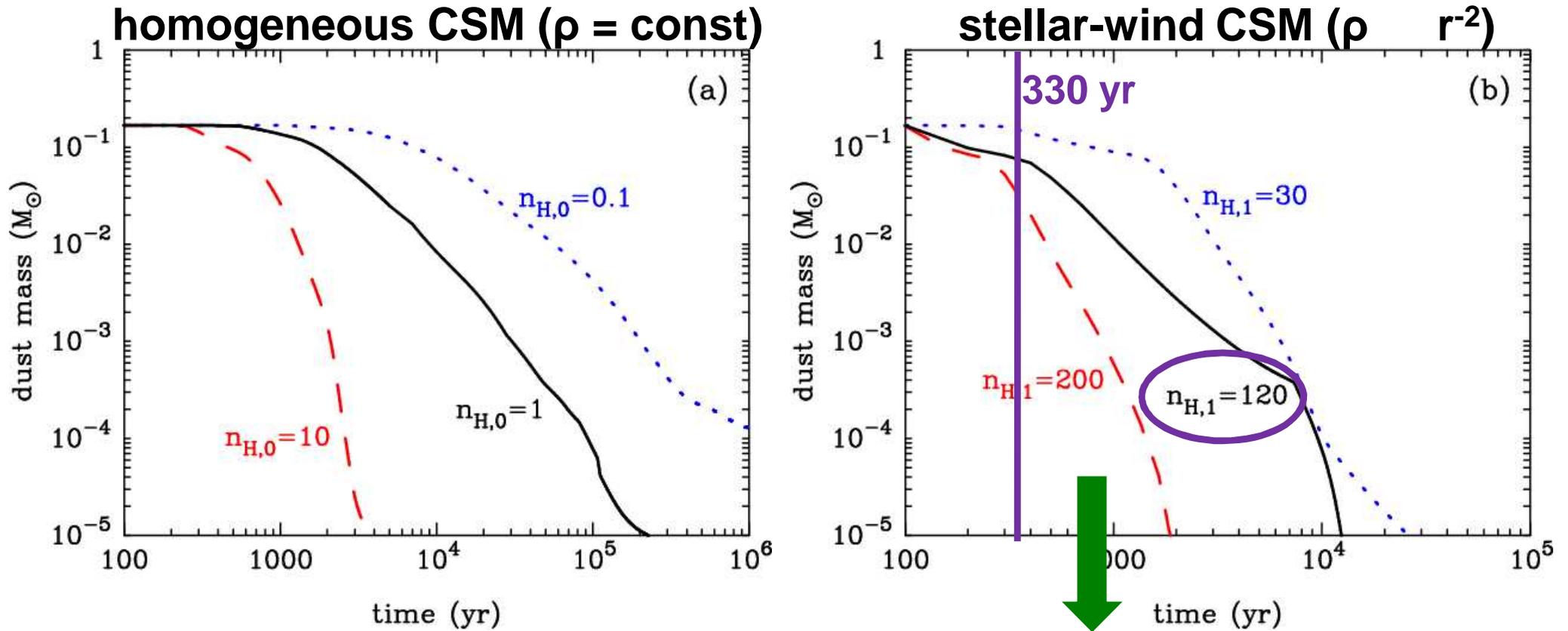


3-2. Dependence of dust radii on SN type



- the radius of dust formed in H-stripped SNe is small
- SN IIb without massive H-env $\rightarrow a_{\text{dust}} < 0.01 \mu\text{m}$
- SN II-P with massive H-env $\rightarrow a_{\text{dust}} > 0.01 \mu\text{m}$

3-3. Destruction of dust in Type IIb SNR



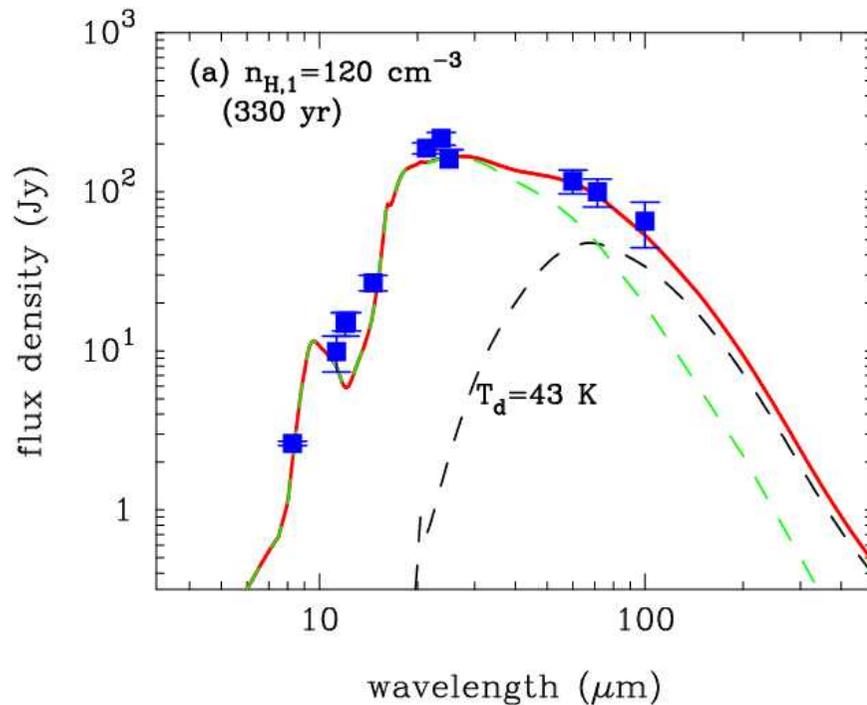
$n_{H,1} = 30, 120, 200 / \text{cc} \rightarrow dM/dt = 2.0, 8.0, 13 \times 10^{-5} M_{\text{sun}}/\text{yr}$ for $v_w = 10 \text{ km/s}$

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

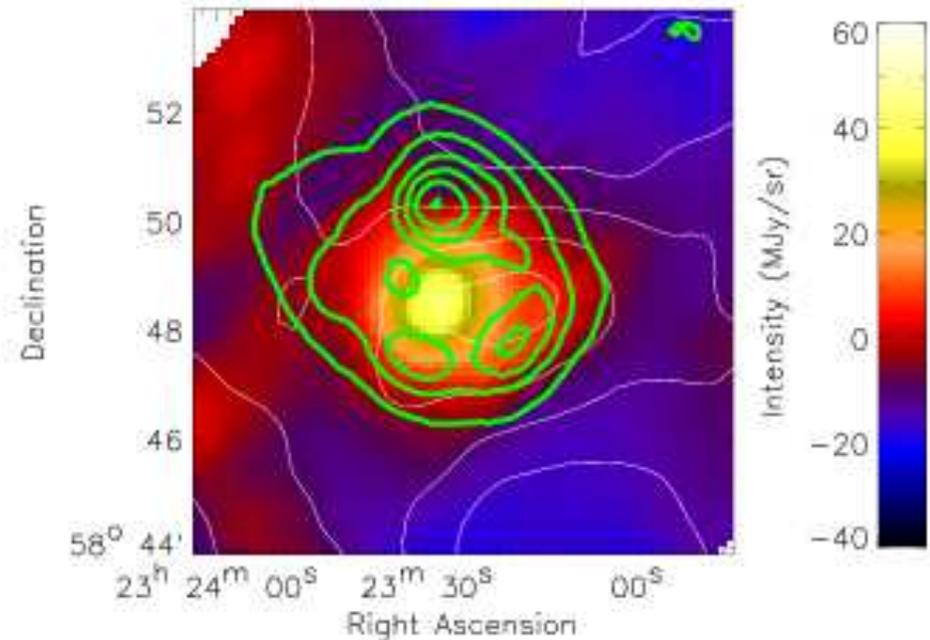
→ small radius of newly formed dust

→ early arrival of reverse shock at dust-forming region

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



AKARI corrected 90 μm image



- total mass of dust formed
 $M_{\text{dust}} = 0.167 M_{\text{sun}}$
- shocked dust : $0.095 M_{\text{sun}}$
 $M_{\text{d,warm}} = 0.008 M_{\text{sun}}$
- unshocked dust :
 $M_{\text{d,cool}} = 0.072 M_{\text{sun}}$
with $T_{\text{dust}} \sim 40 \text{ K}$

Nozawa+'10, ApJ, 713, 356

AKARI observation

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

$T_{\text{dust}} = 33\text{-}41 \text{ K}$

(Sibthorpe+10)

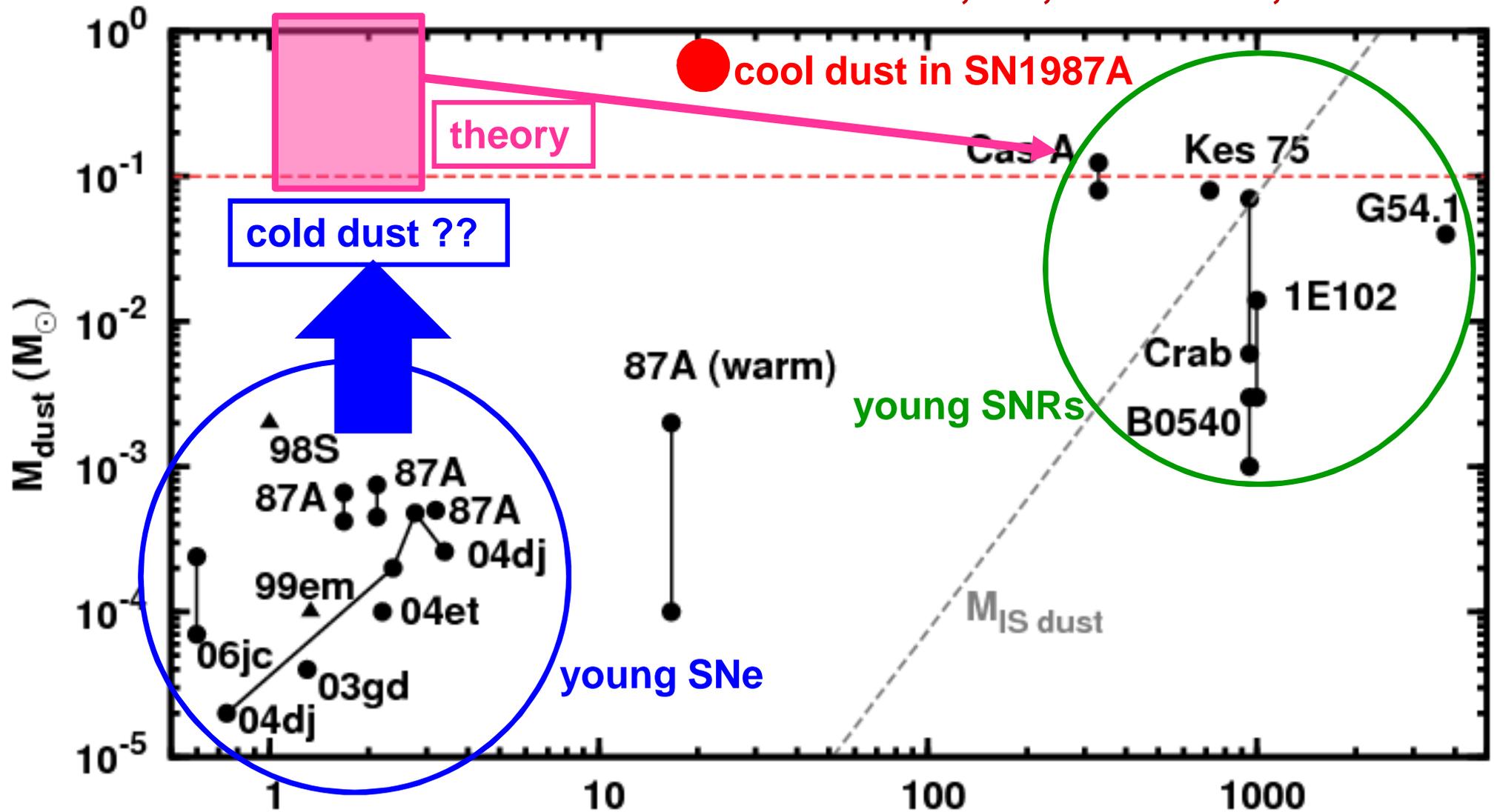
Herschel observation

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

$T_{\text{dust}} \sim 35 \text{ K}$ (Barlow+10)

4-1. Missing-dust problem in CCSNe

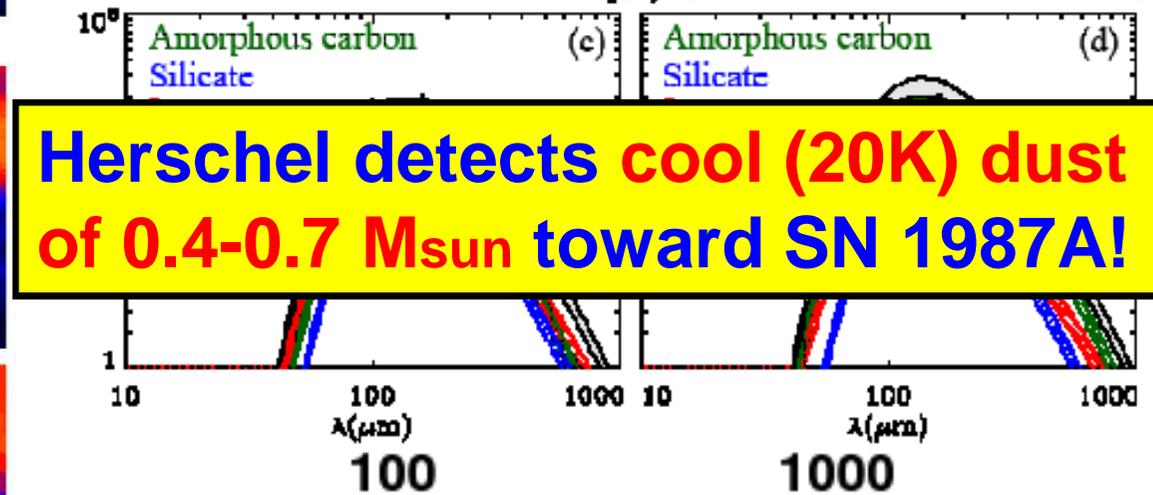
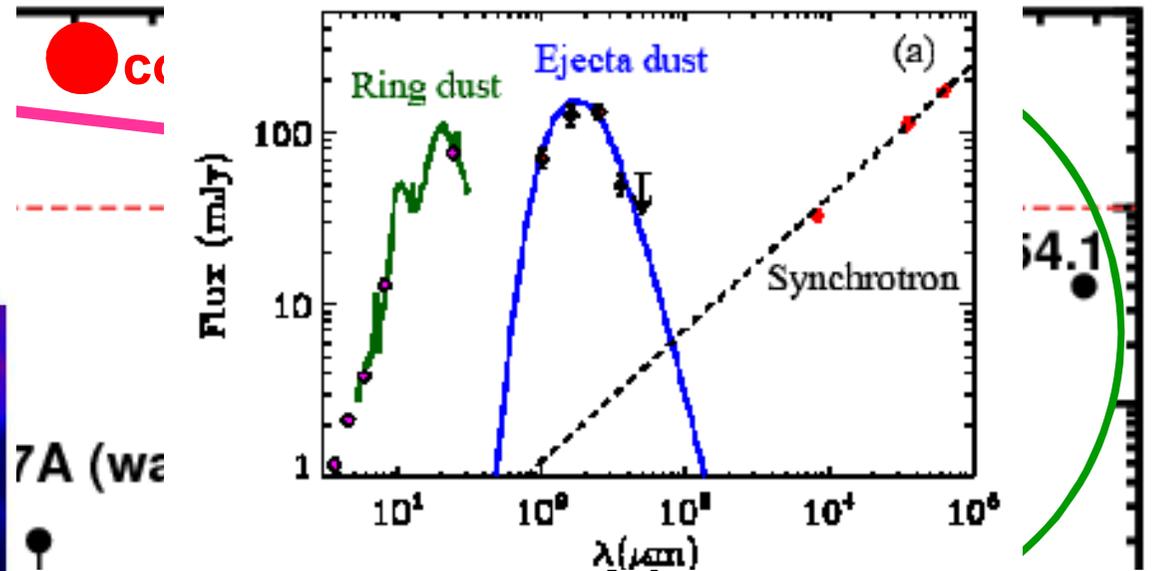
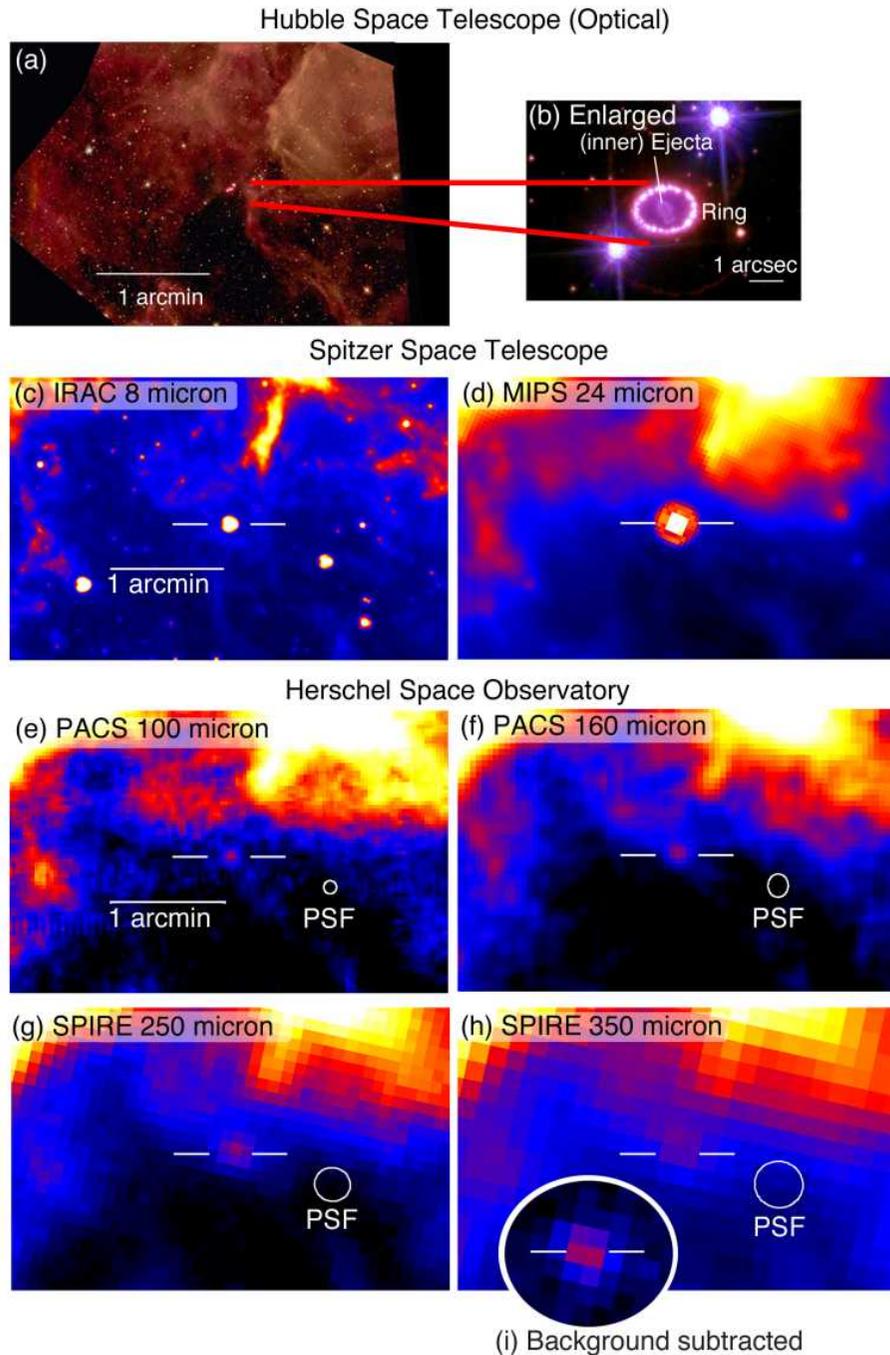
Tanaka, TN, et al. 2011, submitted



There is a big difference in the mass of dust between observational estimates and theoretical predictions!!

4-2. Missing-dust problem in CCSNe

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

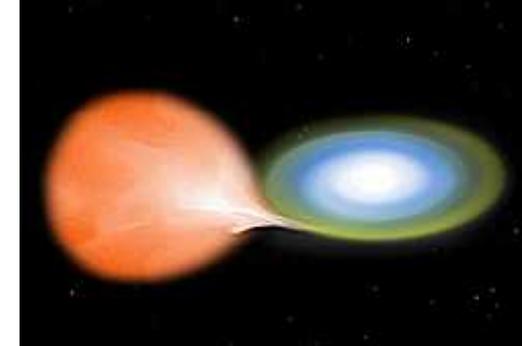


Herschel detects cool (20K) dust of 0.4-0.7 M_{sun} toward SN 1987A!

Discrepancy in the mass of dust between observations and theoretical predictions!!

4. Formation of dust in SNe Ia

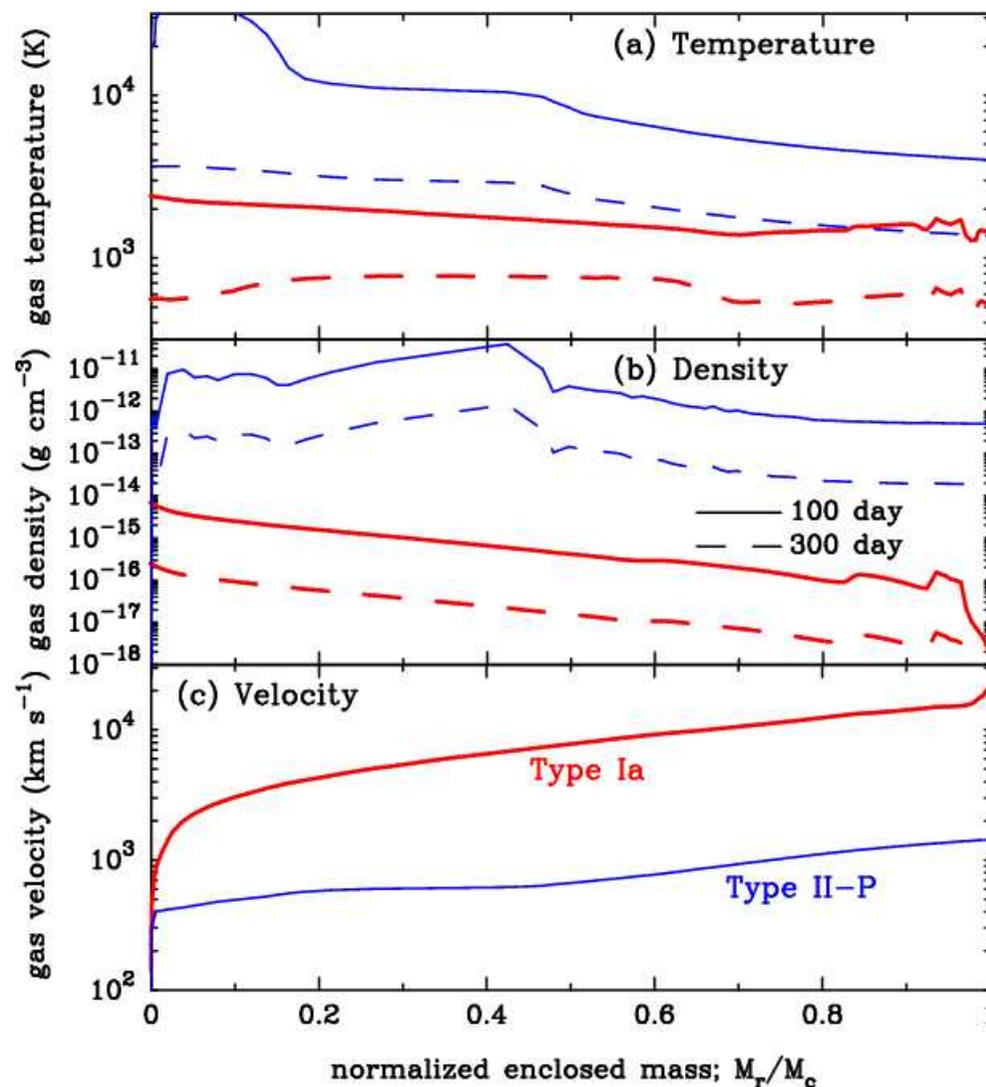
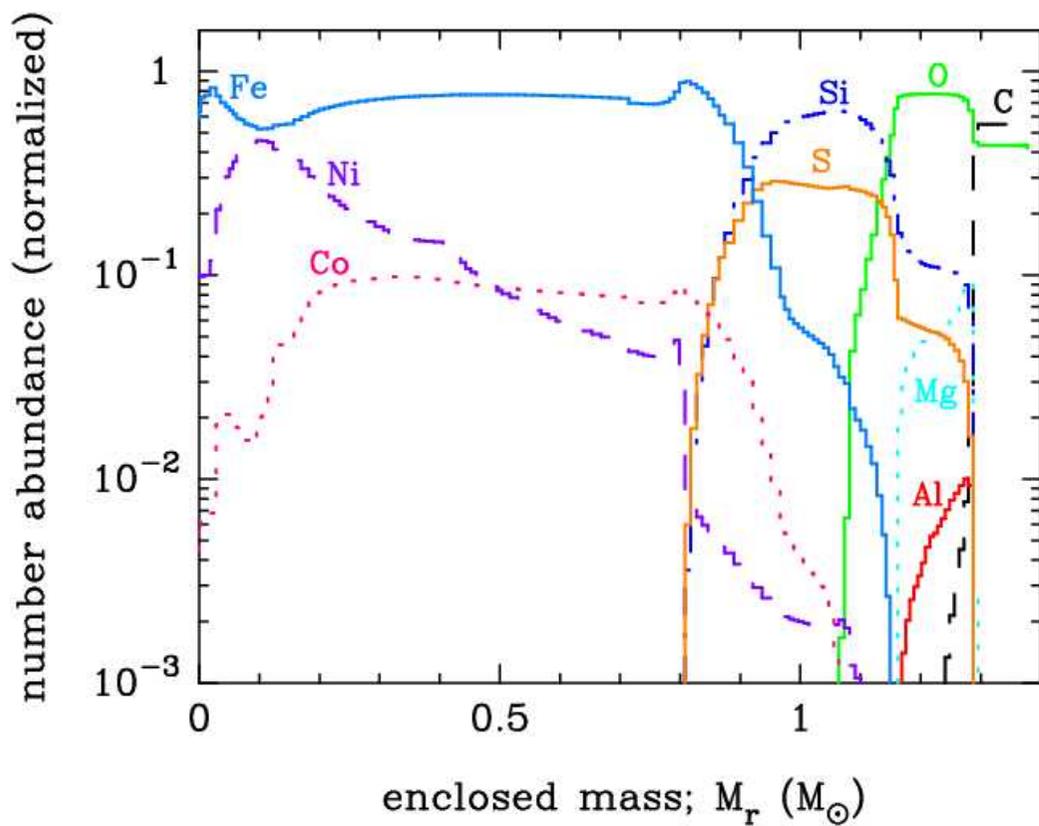
4-1. Dust formation in Type Ia SNe



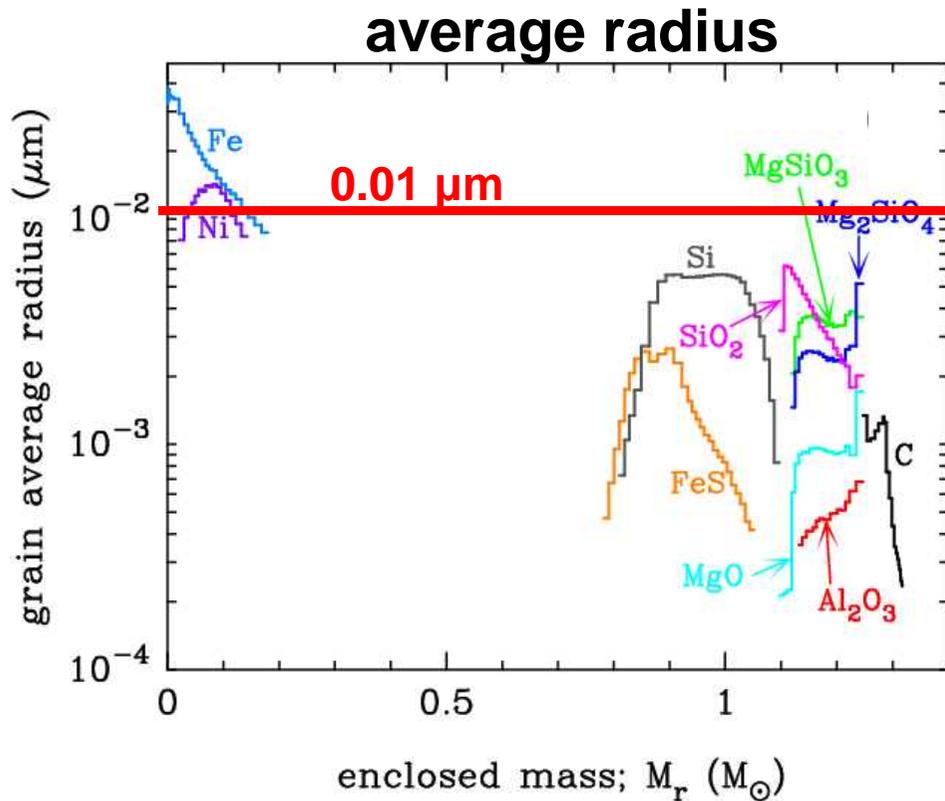
Type Ia SN model

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

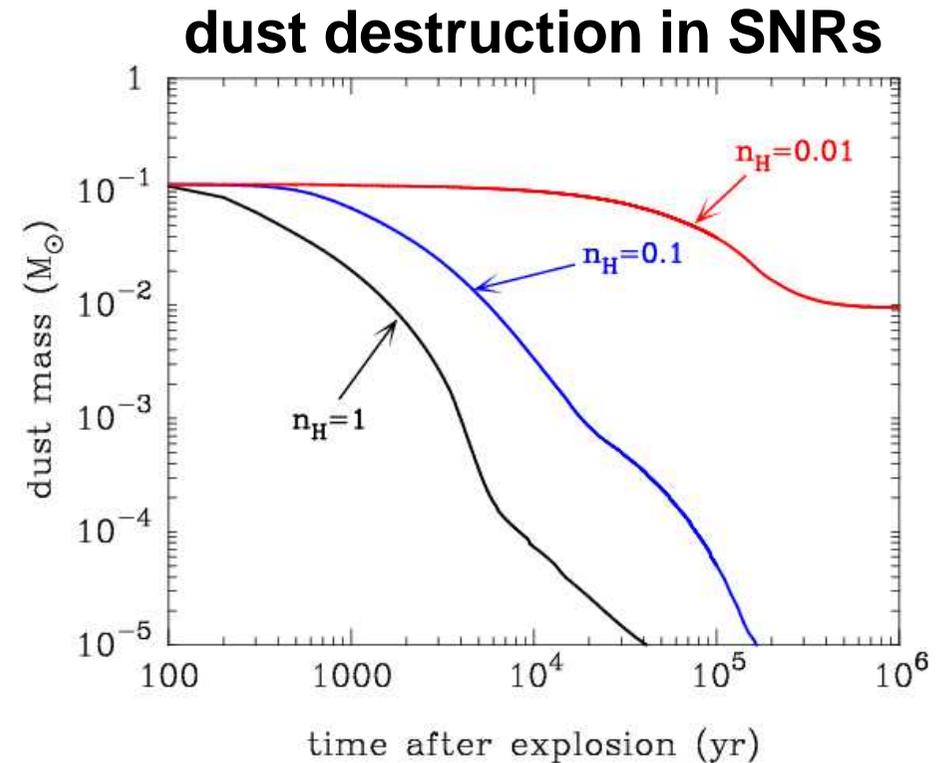
- $M_{\text{eje}} = 1.38 M_{\text{sun}}$
- $E_{51} = 1.3$
- $M(^{56}\text{Ni}) = 0.6 M_{\text{sun}}$



4-2. Dust formation and evolution in SNe Ia



Nozawa+2011, ApJ, 736, 45



- condensation time :
100-300 days
- average radius of dust :
 $a_{\text{ave}} \sim 0.01 \mu\text{m}$
- total dust mass :
 $M_{\text{dust}} = 0.1-0.2 M_{\text{sun}}$

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

\rightarrow SNe Ia are unlikely to be major sources of dust

5. Summary of this talk

- Type II SNe with massive H envelopes
 - radius of dust formed : $a_{ave} > 0.01 \mu\text{m}$
 - 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 : $a_{ave} < 0.01 \mu\text{m}$
 - 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 starburst) 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

$$M_{\text{dust}} = 0.1\text{-}0.8 M_{\text{sun}} \text{ for } n_{\text{H},0} = 0.1\text{-}1 \text{ cm}^{-3}$$

- average radius of dust is quite large ($> 0.01 \mu\text{m}$)

- 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

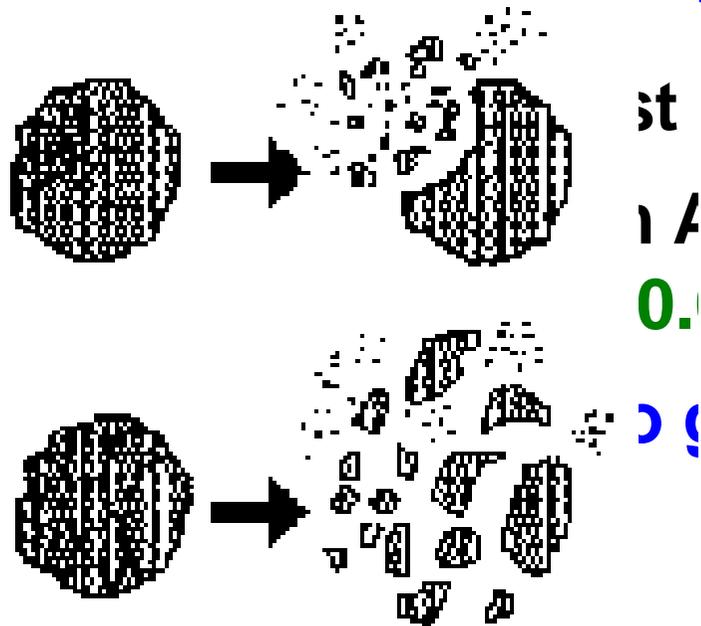
5-2. Implication on evolution history of dust

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

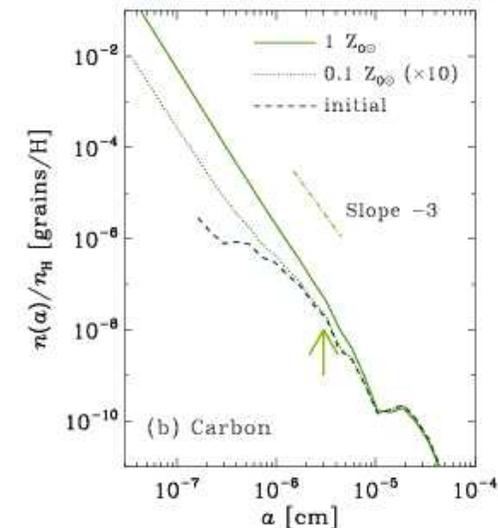
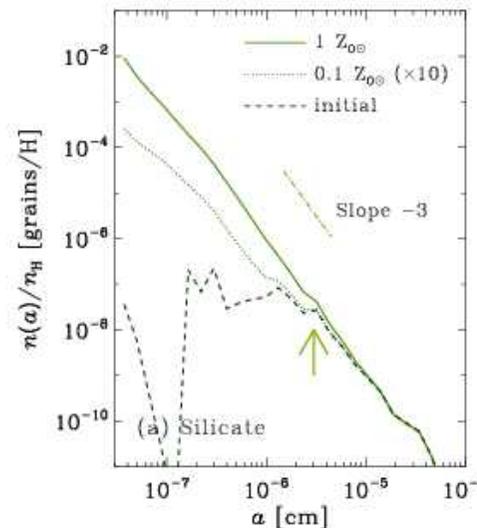
- low-mass stars are dominant
- mass loss of massive stars would be more efficient

→ 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 ($< 0.01 \mu\text{m}$)



Dust size distribution at $t=5 \text{ Myr}$ ($n_{\text{H}}=1 / \text{cc}$)



(11)