Supernovae as sources of dust in the early universe

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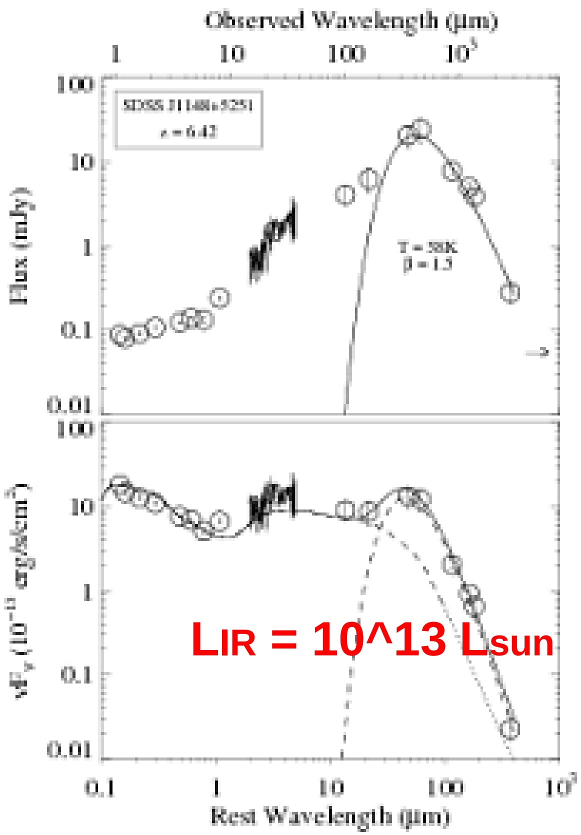
1-1. Discovery of massive dust at high redshift

There has been clear evidence for the presence of a large amount of dust (>10^8 Msun) in QSOs host galaxies at z > 5

SDSS J1148+5251 at z=6.4



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

What is the origin of massive dust?

- **Supernovae (Type II SNe)**

  ➔ ~0.1-1 Msun per SN is needed

  (Morgan & Edmunds'03; Dwek+'07)

- **AGB stars + SNe**

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

  ➔ 0.01-0.05 Msun per AGB stars

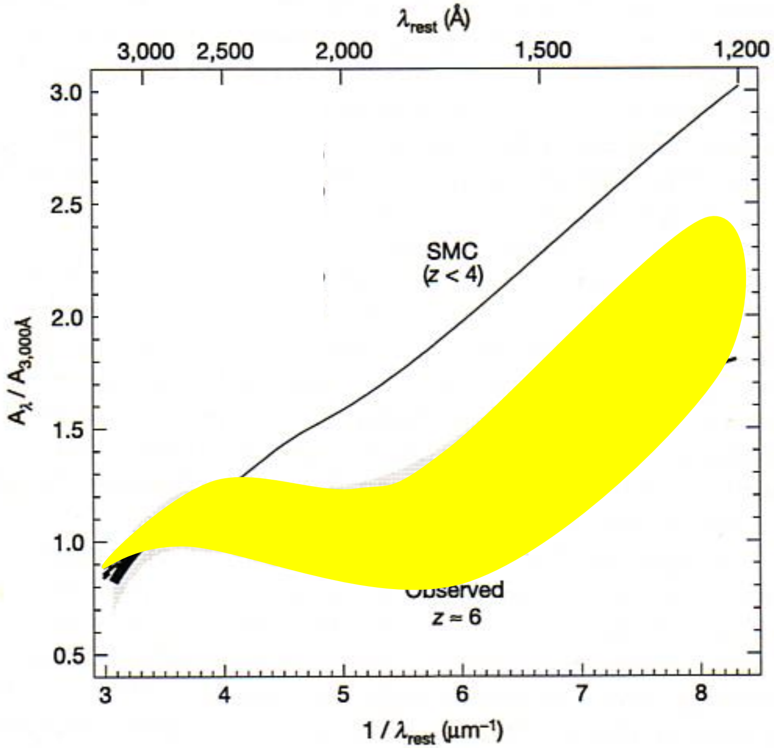
- **Grain growth in ISM + AGB stars + SNe**

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

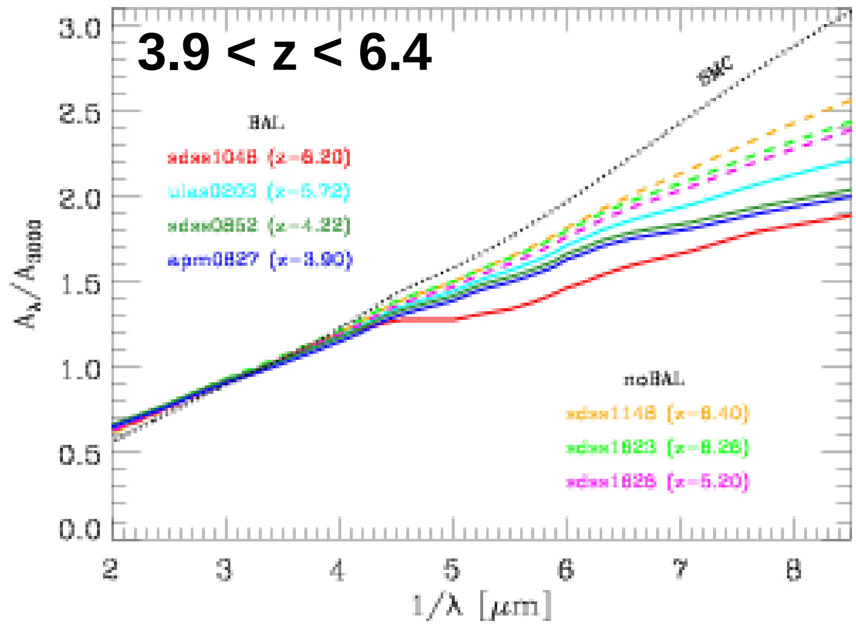
1-2. Extinction curves at high-z quasars

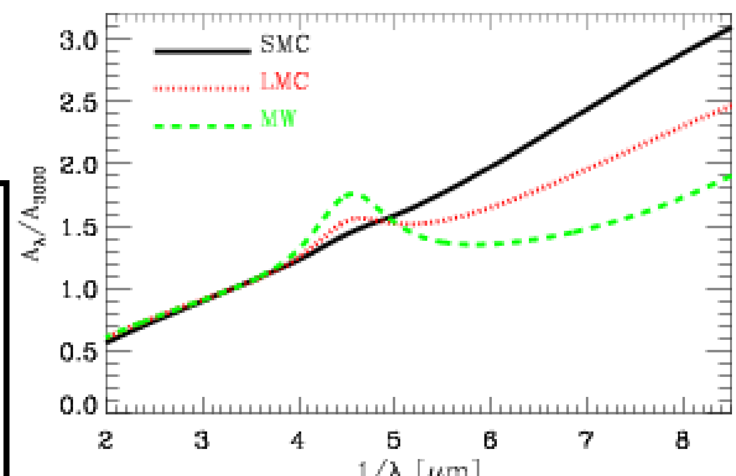
Maiolino+'04, Nature, 431, 533

SDSS J1048+4637 at z=6.2



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





High-z extinction curves do not match those in the MW and SMC

➔ properties of dust at high z may be different from those at low z

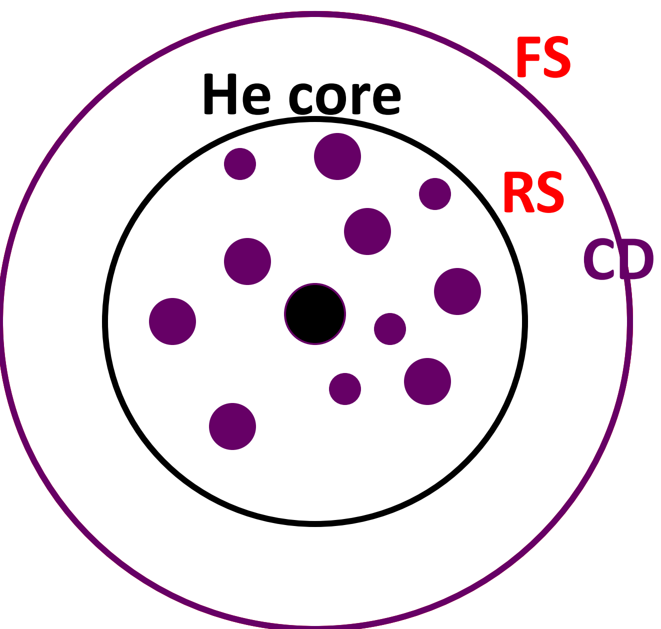
1-3. Dust formation in primordial SNe

・Theoretical studies of dust formation in the SN ejecta

(e.g. Nozawa+'03; Todini & Ferrara'01; Cherchneff & Dwek'10)

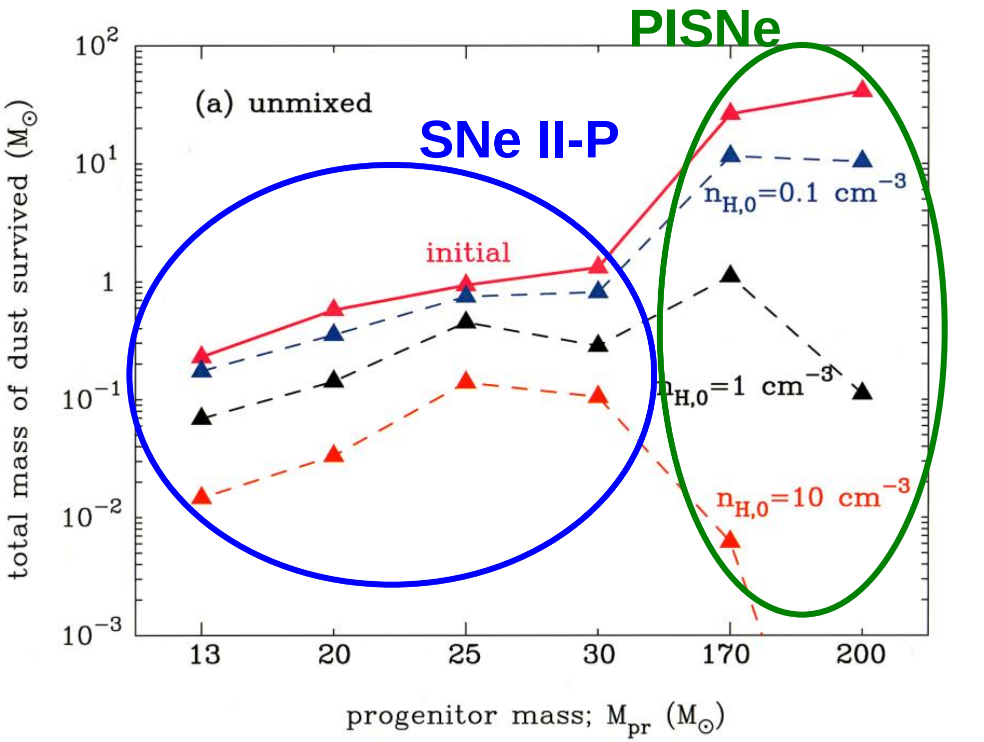
- **M_{dust}=0.1-1 M_{sun} in Type II-P SNe (SNe II-P)**
- **M_{dust}=1[illegible]60 M_{sun} in pair-instability SNe (PISNe)**

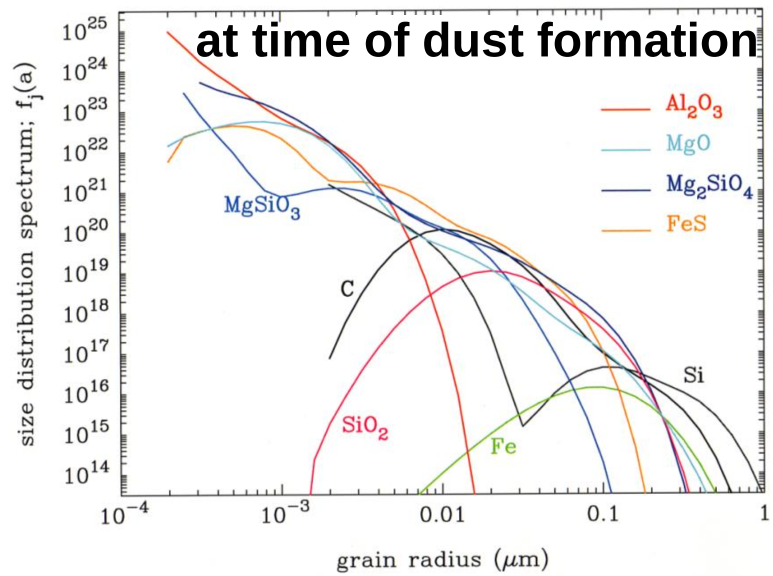
dust amount needed to explain massive dust at high-z

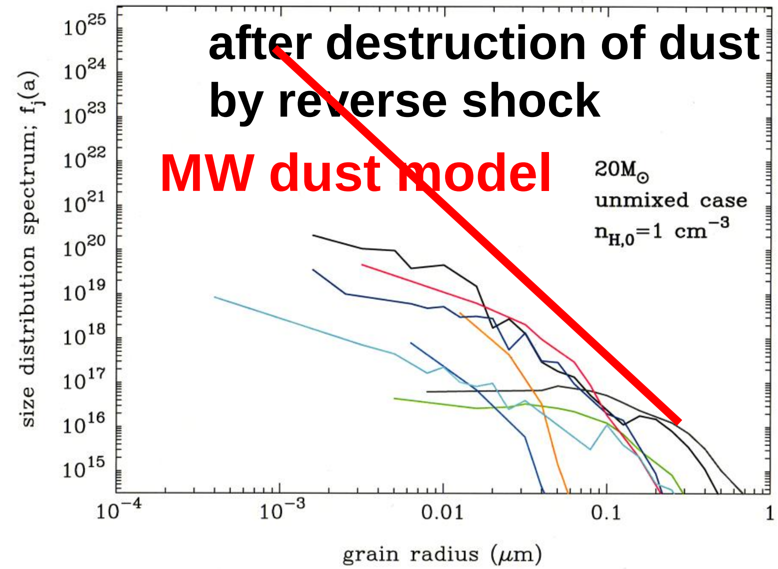


2-1. Mass and size of dust ejected from SN II-P

Nozawa+'07, ApJ, 666, 955





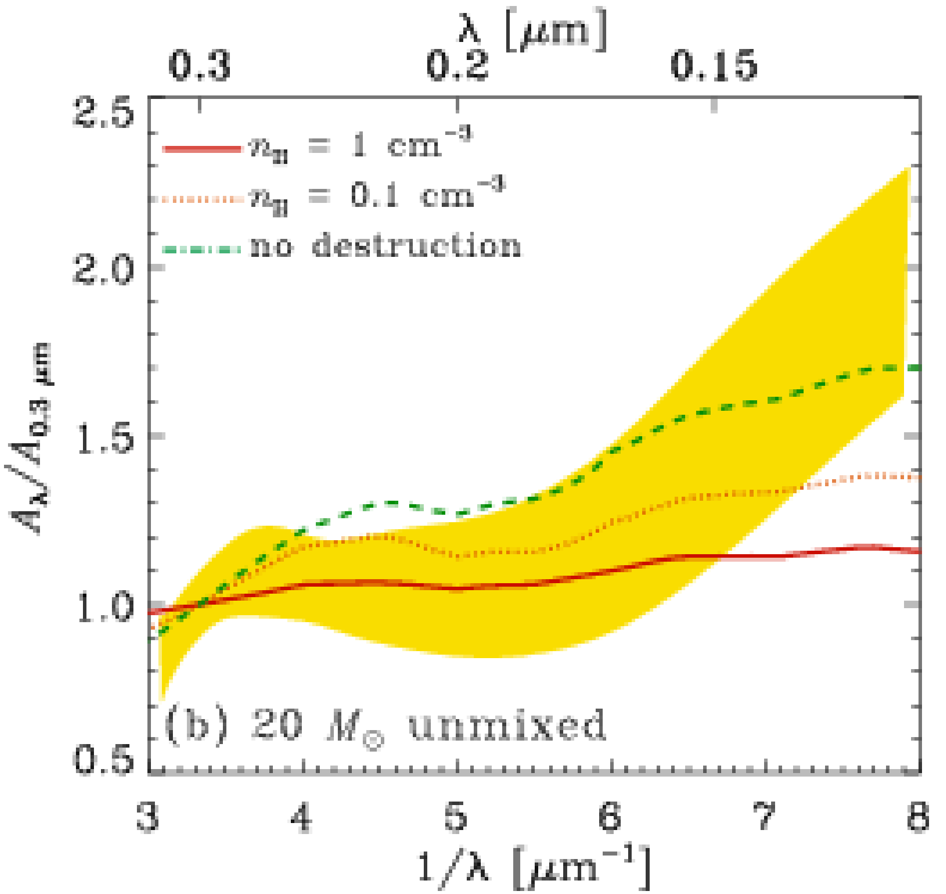


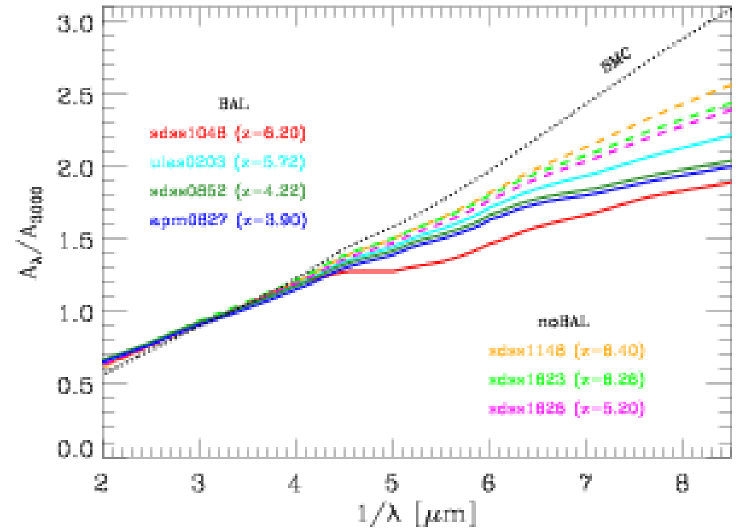
total dust mass surviving the destruction in Type II-P SNRs; 0.07-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

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

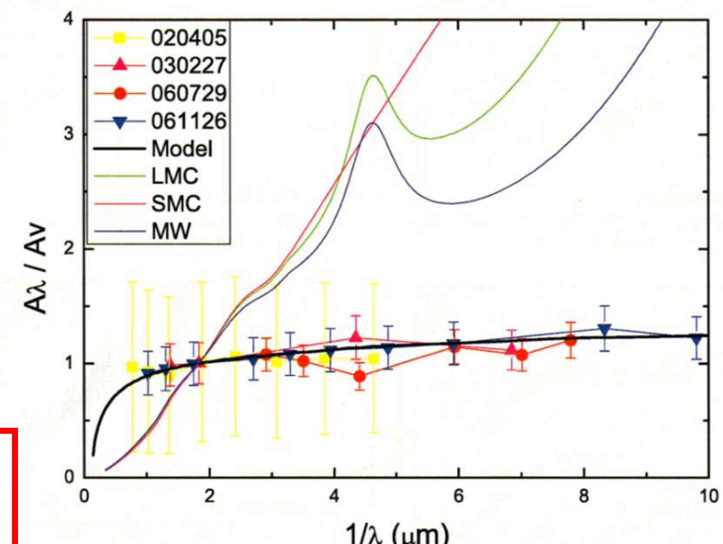
2-2. Flattened extinction curves at high-z

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





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

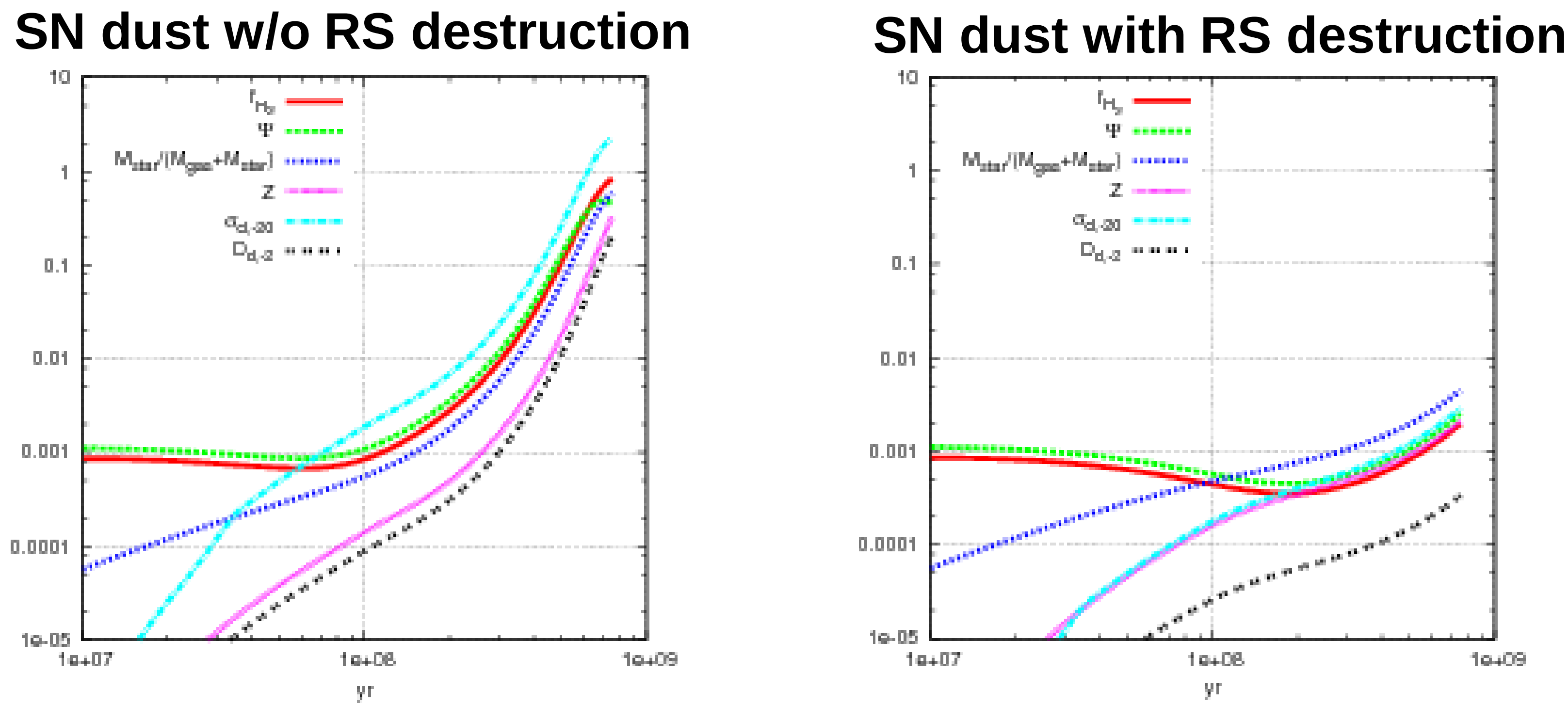


Li+'08, ApJ, 678, 1136

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

2-3. Effect of dust on star formation history

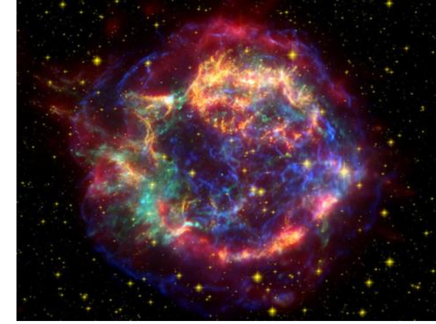
efficient formation of H_2 molecules on the surface
(e.g., Cozaux & Spaans'04)
➔ promoting formation of stars (Hirashita & Ferrara'02)



Yamasawa, …, TN,+'11, accepted (arXiv/1104.0728)

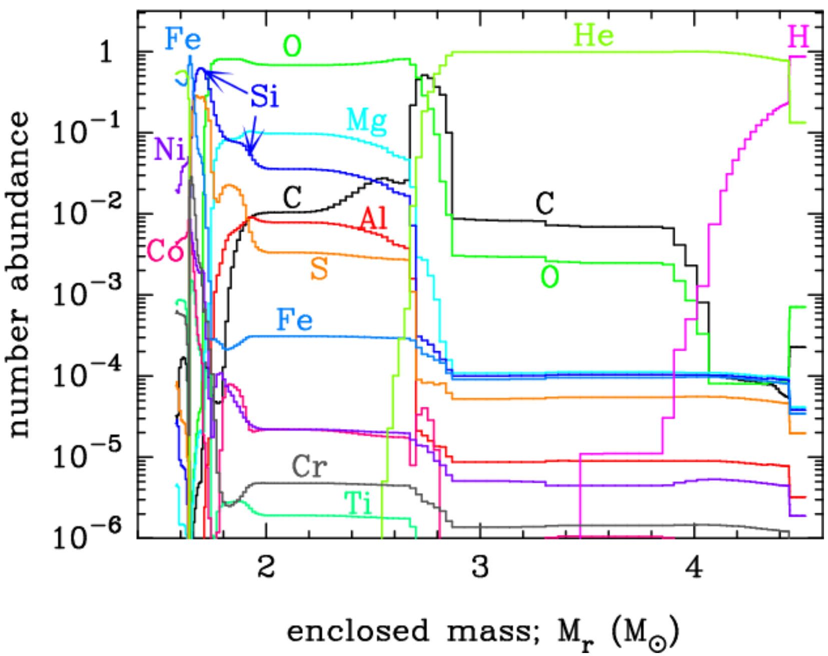
Larger size of dust suppresses the formation rate of H_2 and thus does not activate star formation significantly

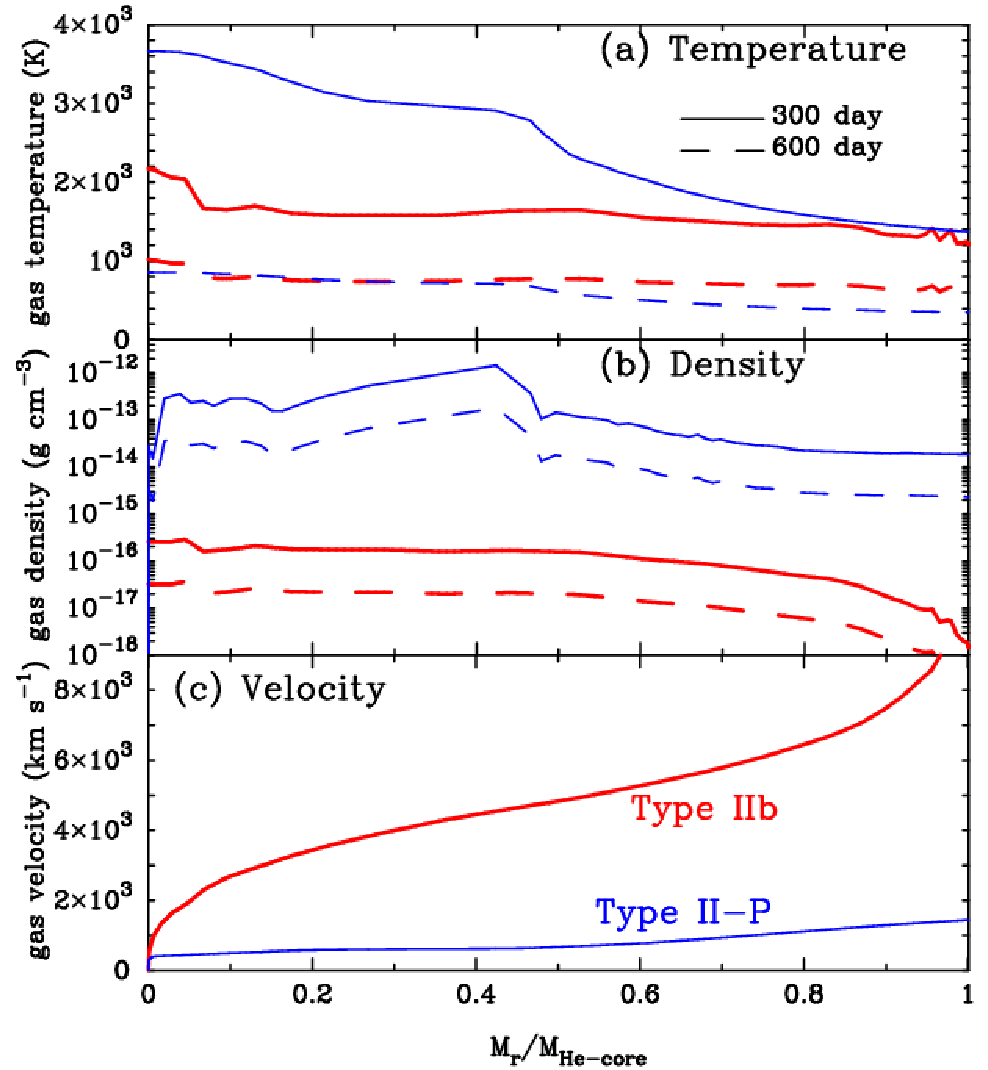
3-1. Dust formation in Type IIb SN



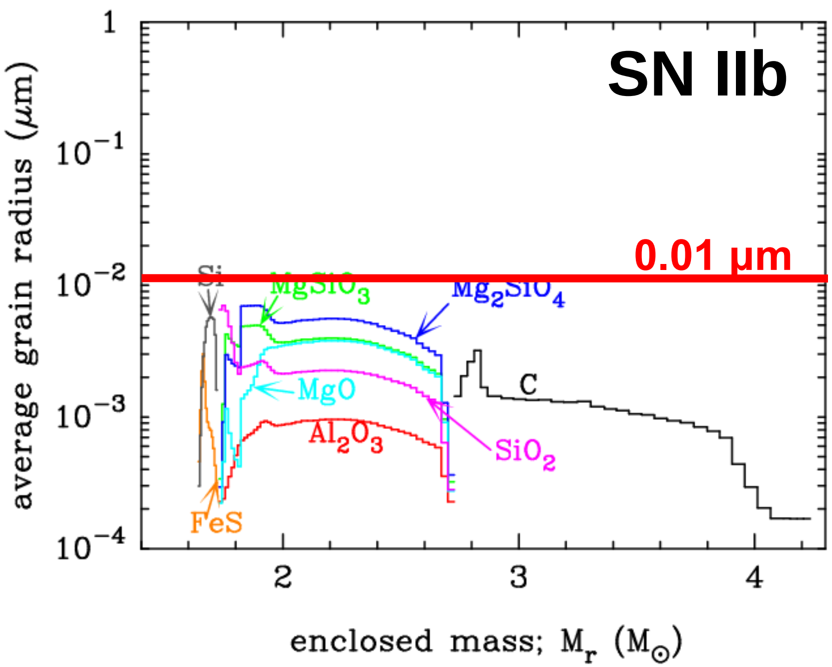
○ SN IIb model (SN1993J-like model)

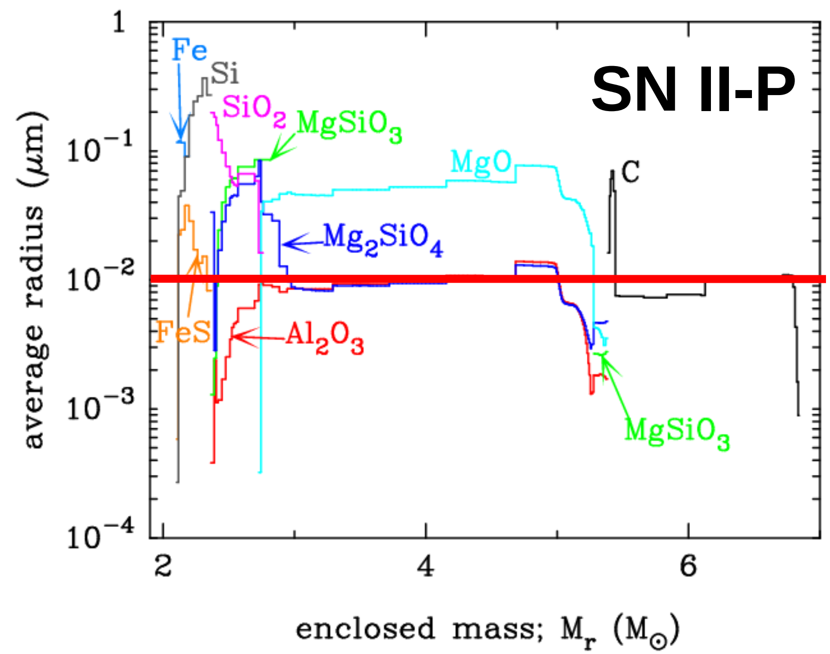
- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1.0
- $M(^{56}Ni)$ = 0.07 Msun





3-2. 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**

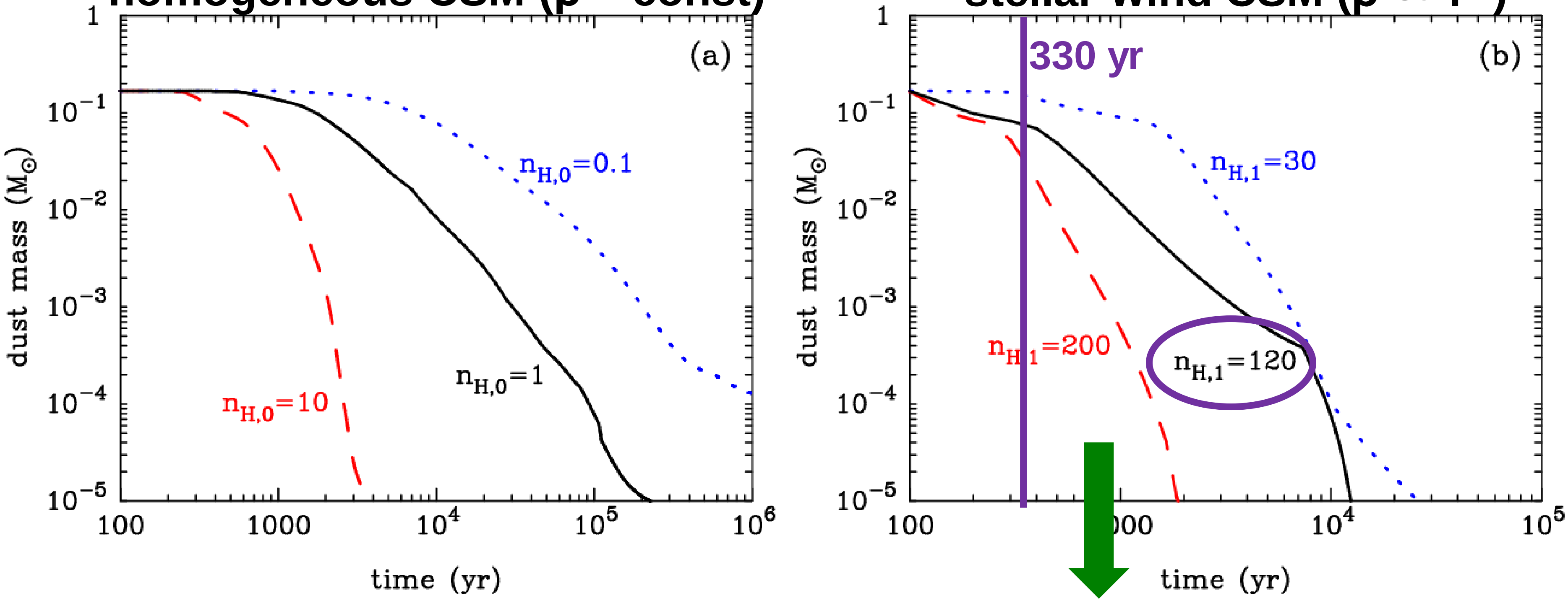
Nozawa+'10, ApJ, 713, 356

— 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**

3-3. Destruction of dust in Type IIb SNR

homogeneous CSM (ρ = const) **stellar-wind CSM (ρ ∝ 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

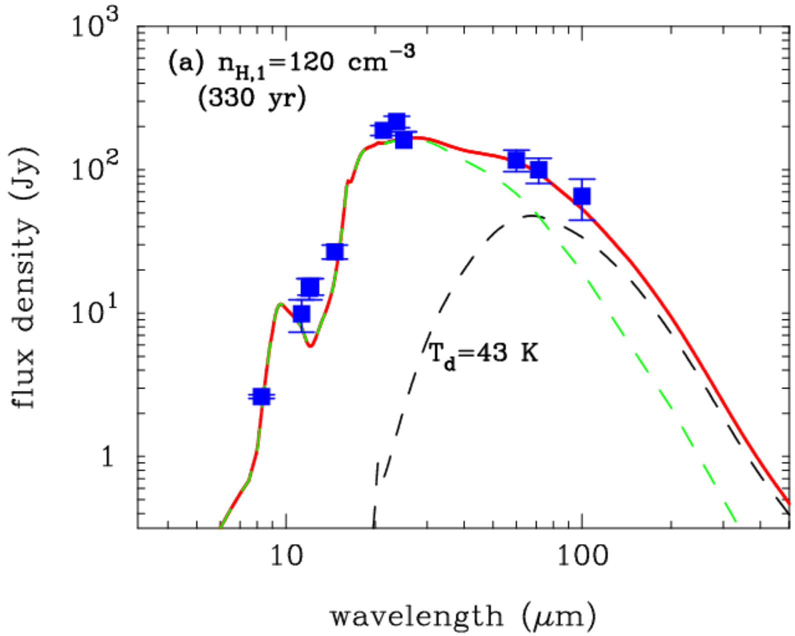
➔ **small radius of newly formed dust**

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

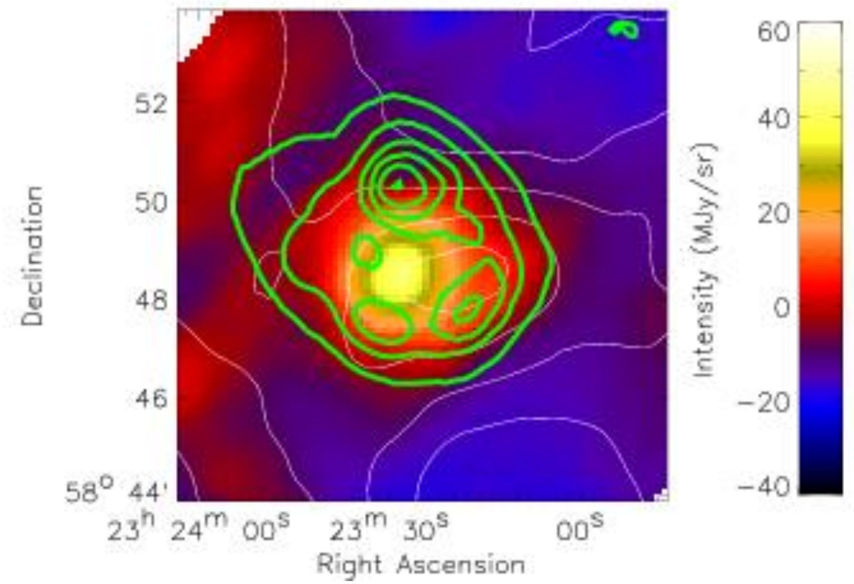
Nozawa+'10, ApJ, 713, 356

3-4. 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

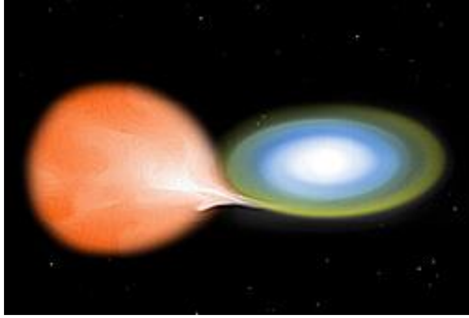
(Sibthorpe+10)

Herschel observation

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

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

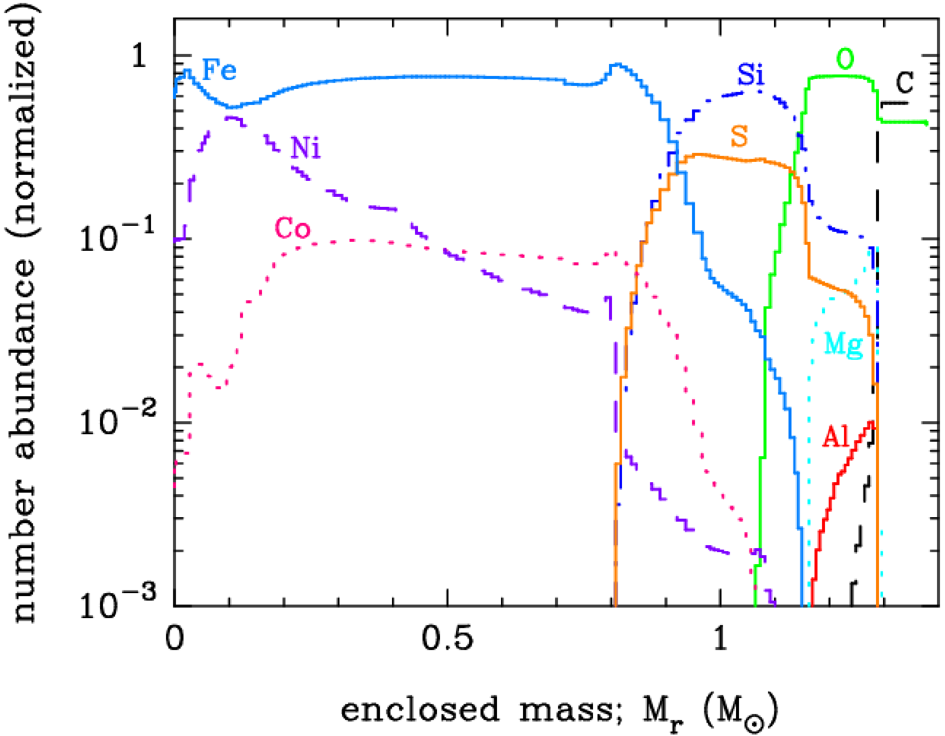
4-1. Dust formation in Type Ia SNe

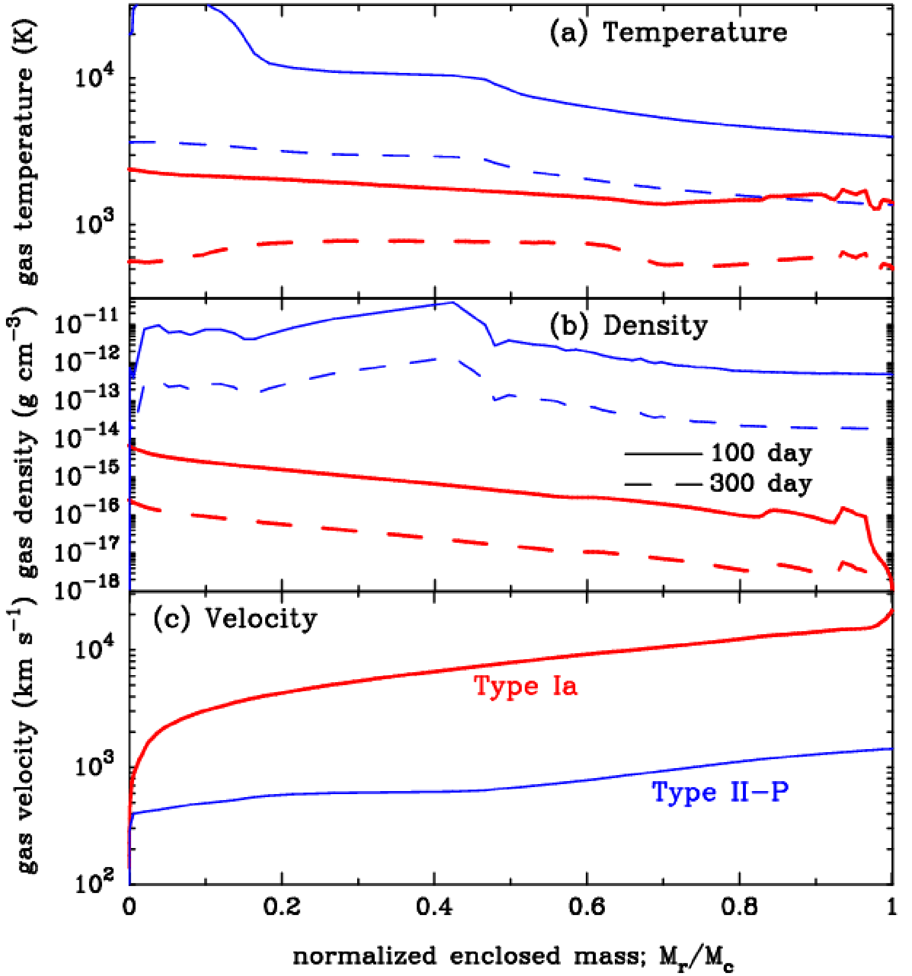


○ Type Ia SN model

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

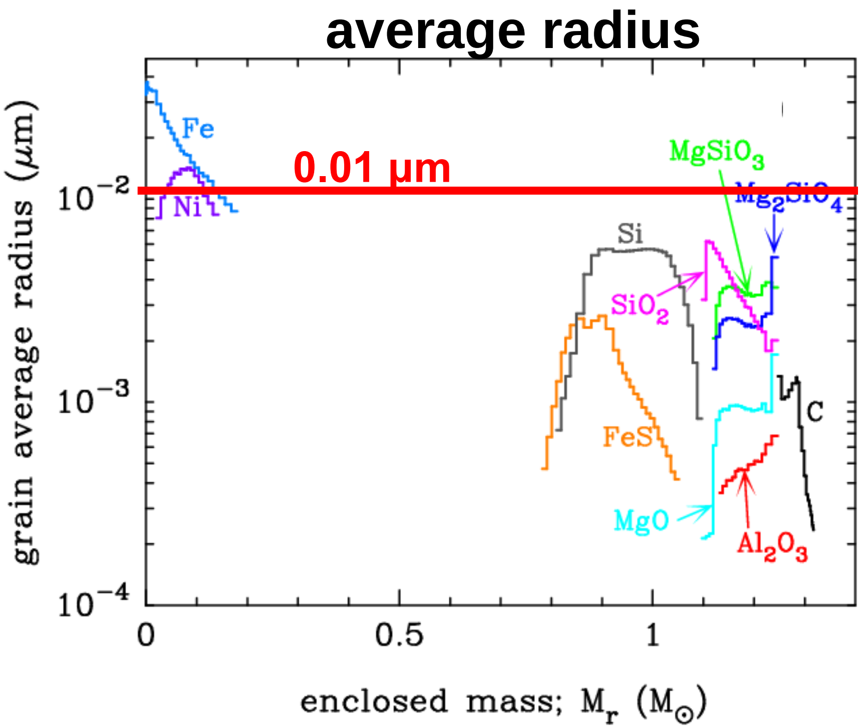
- M_{eje} = 1.38 Msun
- E_{51} = 1.3
- M(^{56}Ni) = 0.6 Msun

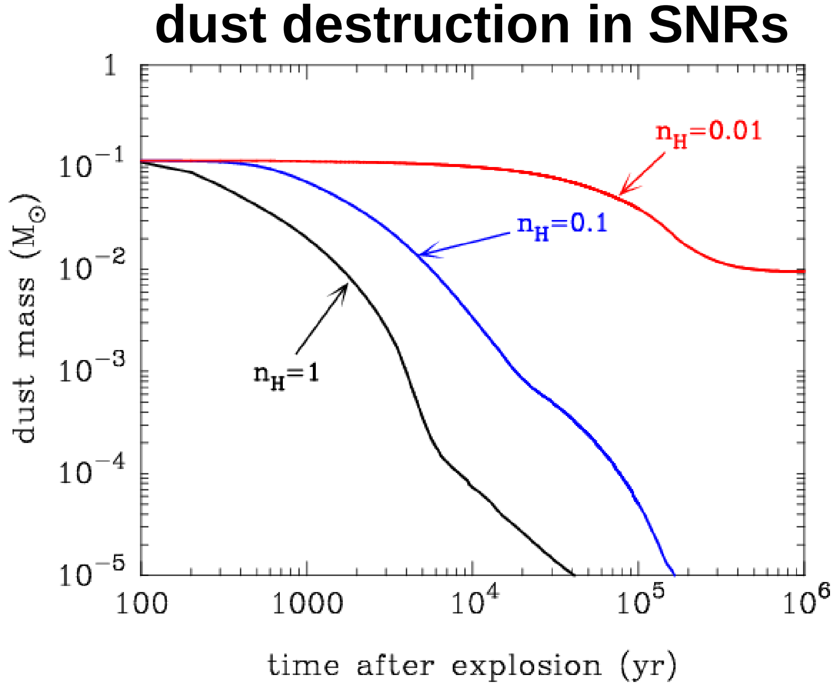




4-2. Dust formation and evolution in SNe Ia

Nozawa+'11, accepted (arXiv/1105.0973)





- **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

5-1. Implication on evolution history of dust

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

- **massive stars (SNe) are likely to dominate**
- **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 dominate

▪ mass loss of massive stars would be more efficient

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

but, our model treating formation and evolution of dust self-consistently can reproduce IR emission from Cas A

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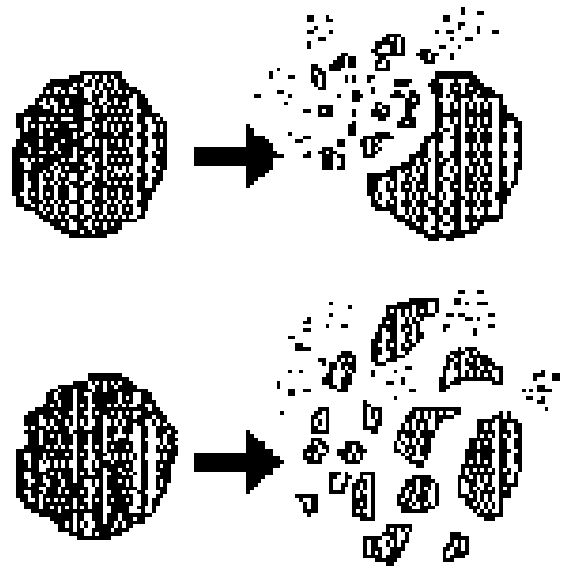
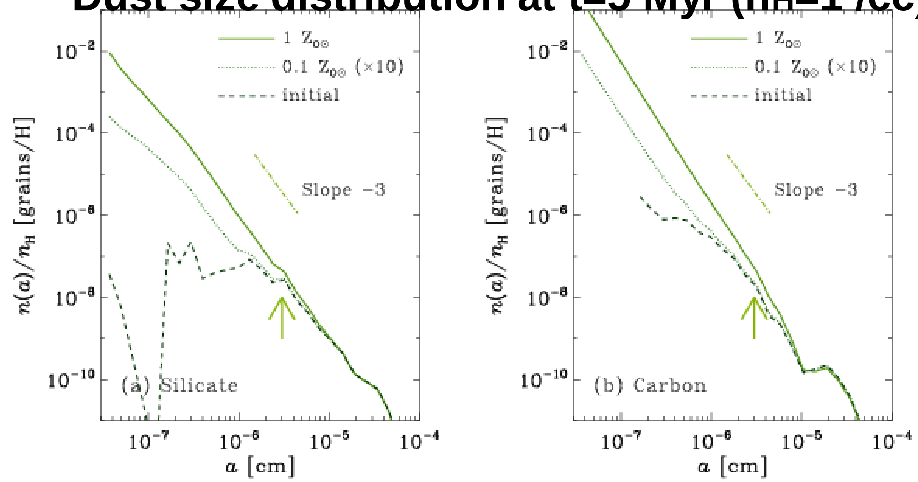


Dust size distribution at t=5 Myr (n_H=1 /cc)



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