Supernovae as sources of interstellar dust

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Outline

1. Observations of dust at high redshift

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

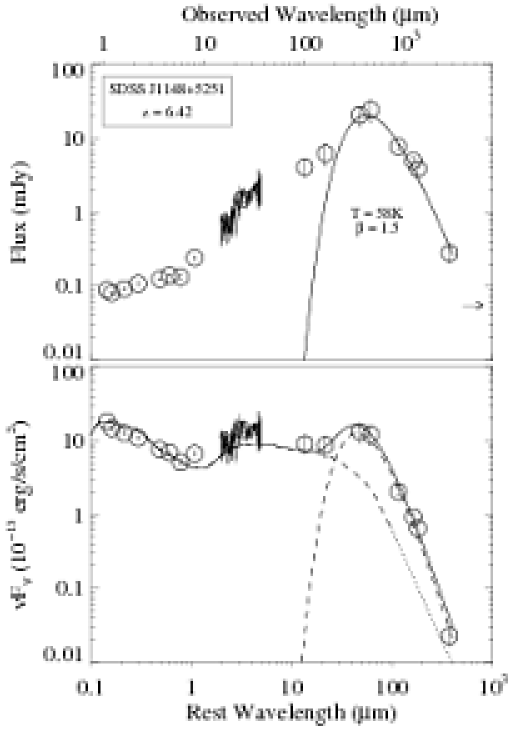
5. Implication on evolution history of dust

1. Observations of dust at high-z

1-1. 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)**
- **dynamical mass :**
  (5±2.5)x10^{10} Msun (Walter+04)
- **BH mass : (1-5)x10^{9} Msun (Willott+03)**
- **stellar mass : ~10^{12} Msun (Li+07)**
- **gas mass : ~3x10^{10} Msun**
  (CO, Walter+04, Bertoldi+03b)
- **metallicity : ~solar**

1-2. What are sources of dust in z =6.4 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)

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

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

1-3. Sources of dust in 5 < z < 6.4

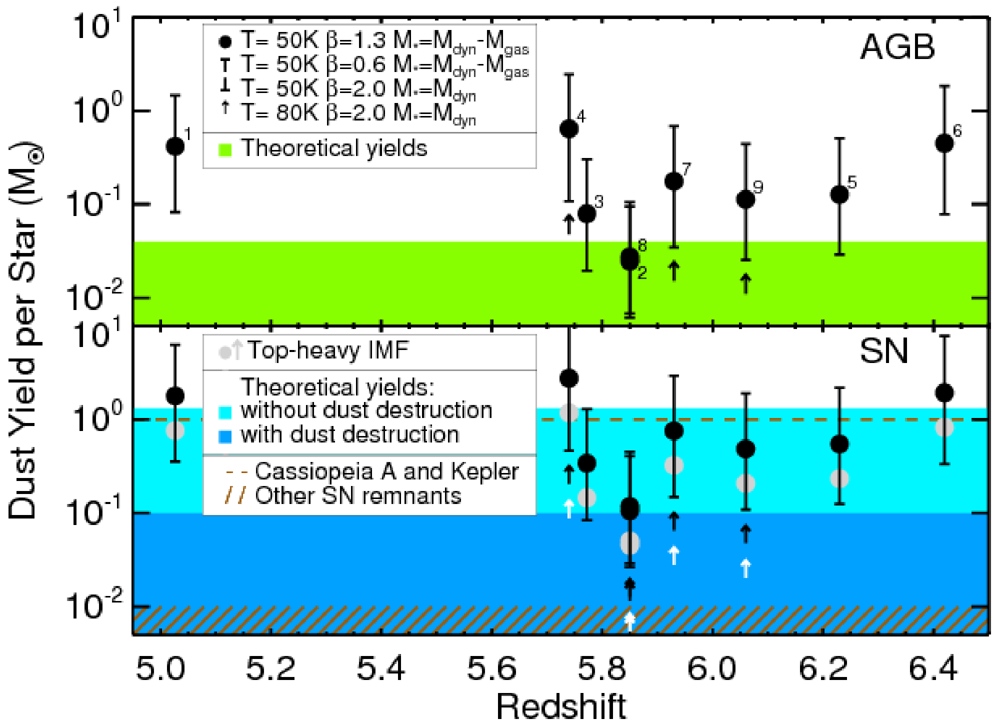


Fig. 1. Dust yields per AGB star (*top*) or per SN (*bottom*) required to explain dust in the $z > 5$ QSOs. For reasonable assumptions on the dust properties, AGB stars are not efficient enough and SNe would need to be unfeasibly efficient to form dust in these sources suggesting rapid grain grown in the ISM is likely to be responsible for the large dust masses. *Circles*: the best estimates of the required dust yields with error bars reflecting the uncertainty of β and M_*. Numbers indicate the QSOs as in Tab. 1. *Arrows*: strict and unlikely lower limits with very high $T_{\rm dust}$ and β shown where data allow it (Tab. 1). *Gray symbols* indicate that a top-heavy IMF was adopted. *Dashed line* and *diagonal lines*: the dust yields derived for Cassiopeia A, Kepler ($\sim 1\,M_\odot$) and other SN remnants ($\sim 10^{-3}$–$10^{-2}\,M_\odot$), respectively. *Green area*: theoretical dust yields for AGB stars ($\lesssim 4 \cdot 10^{-2}\,M_\odot$). *Light blue* and *blue areas*: theoretical SN dust yields without ($\lesssim 1.32\,M_\odot$) and with dust destruction implemented ($\lesssim 0.1\,M_\odot$), respectively.

Michalowski+10, A&A, 522, 15

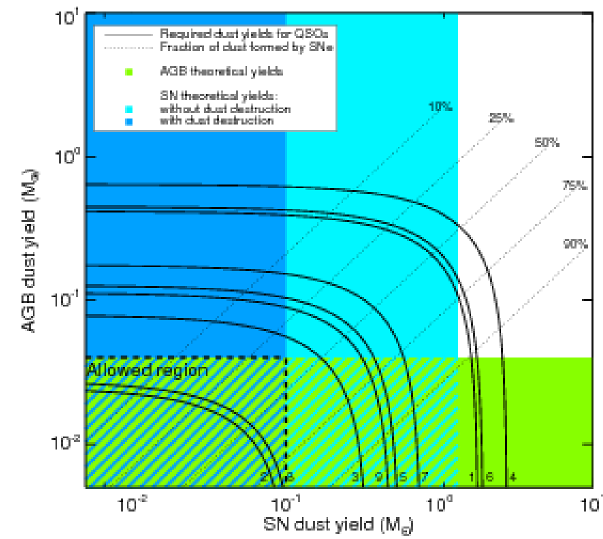
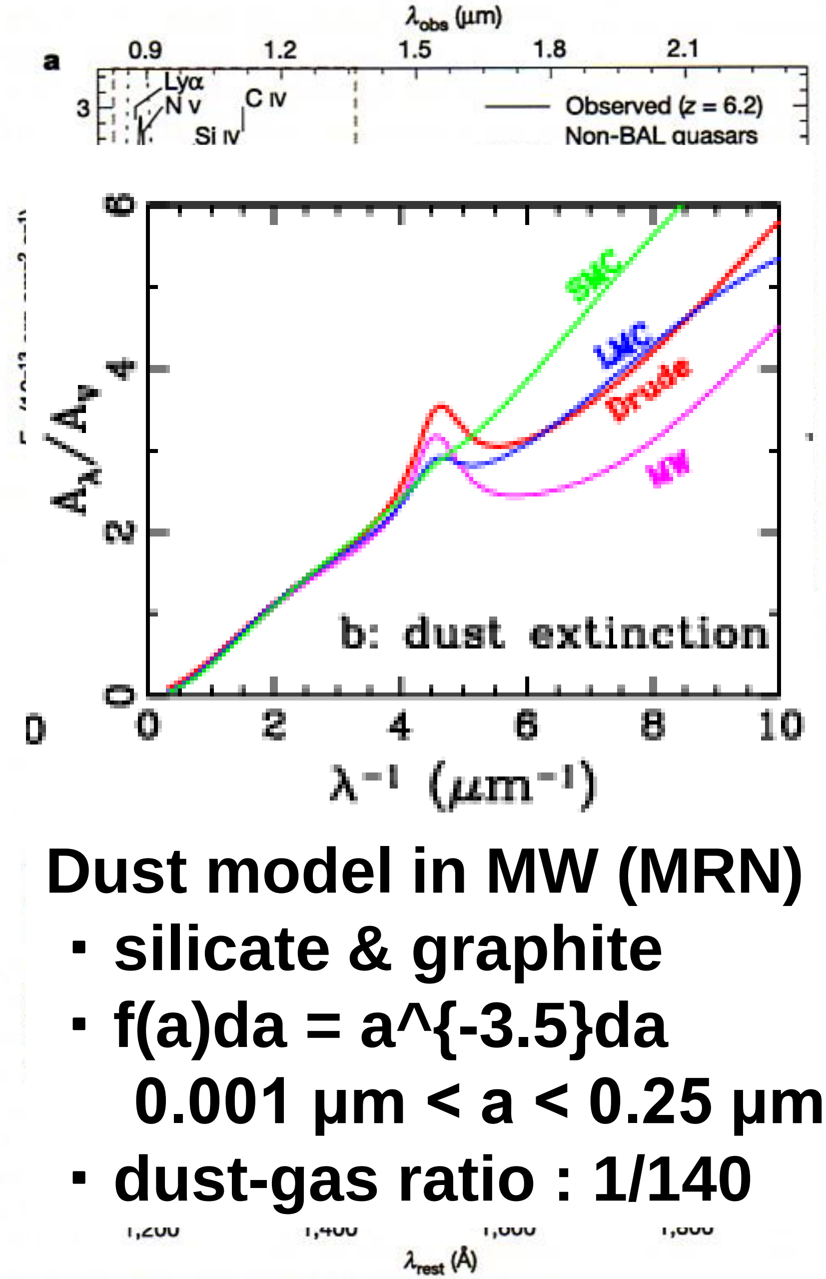


Fig. 2. The relation of the required dust yields per AGB star and per SN for different fractions of dust formed by SNe (shown as *dotted lines*). This is a combination of panels in Fig. 1 relaxing the assumption that only AGB stars or only SNe produced dust in the $z > 5$ QSOs. The theoretically allowed regions of dust yields are shown as in Fig 1. *Hashed region outlined by the dashed line* corresponds to the the allowed region, where the dust yields for both AGB stars and SNe are within theoretical limits (with the dust destruction implemented). The *solid lines* correspond to the $z > 5$ QSOs numbered as in Tab. 1. If higher fraction of dust is attributed to SNe then the QSOs move towards bottom-right corner. The combined effort of AGB stars and SNe can explain dust in QSO 2 and 8, but not in QSO 1, 4 and 6. Dust in QSOs 3, 5, 7 and 9 may have been formed by these stellar sources, but only if little dust is destroyed in SN shocks and that SN account for more than 50–75% of dust in these QSOs.

Grain growth in the ISM is required for at least 3 out of 9 QSOs at z > 5

1-4. Extinction curves at high-z quasars



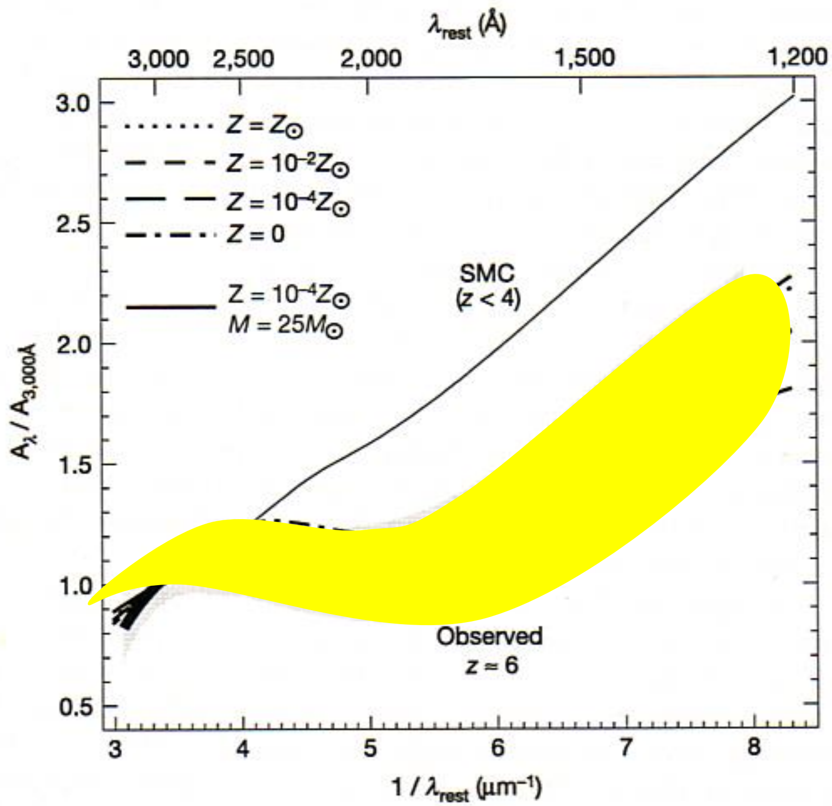
Dust model in MW (MRN)

- **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

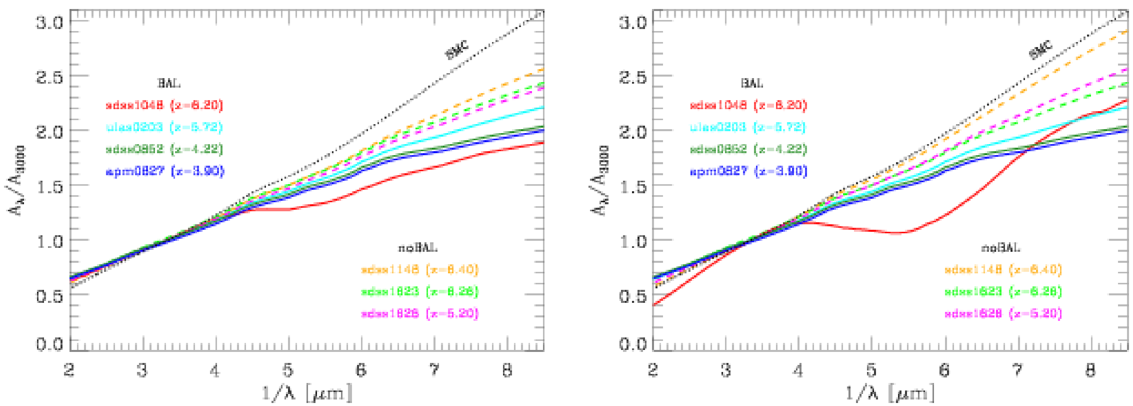
SDSS J1048+4637 at z=6.2

Broad absorption line (BAL) quasars



different dust properties from those at low redshifts

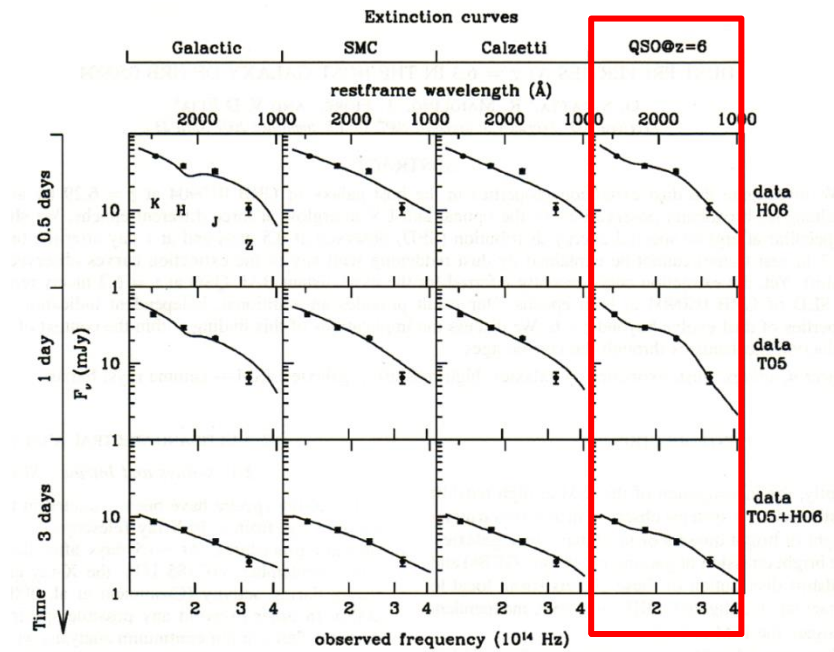
1-5. Other examples of high-z dust extinction



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

GRB 050904 at z=6.3



Stratta+07, ApJ, 661, L9

additional evidence for different dust properties at high-z

but see Liang & Li 2009, ApJ, 690, L56
Zafar+10, A&A, 514, 94
Zafer+11, arXiv/1101.1503

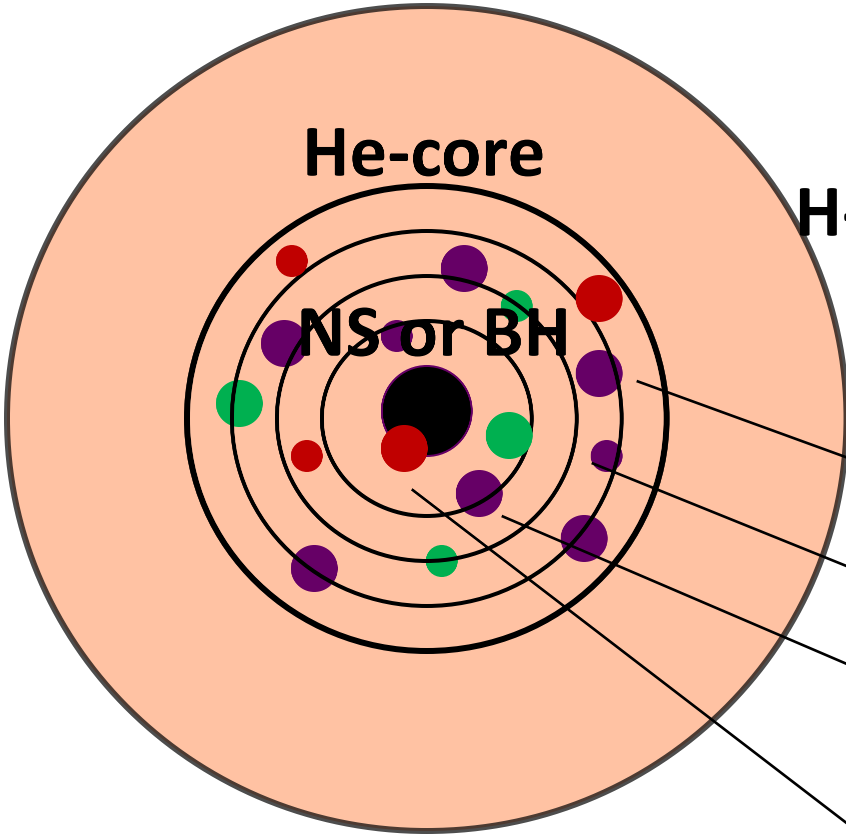
Extinction curves from high-z GRBs

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

2. Formation and evolution of dust in Population III SNe

2-1. Dust Formation in Pop III SNe

at ~1 days

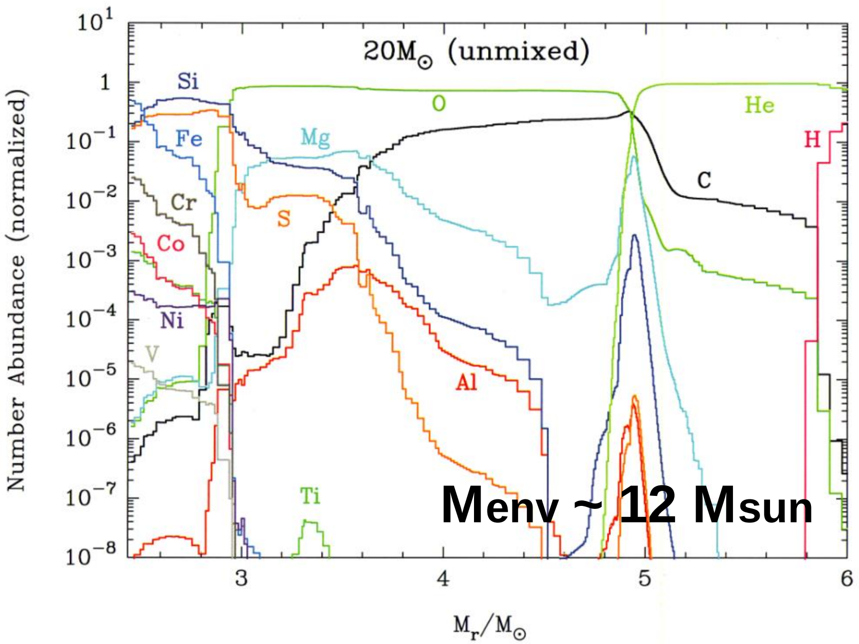


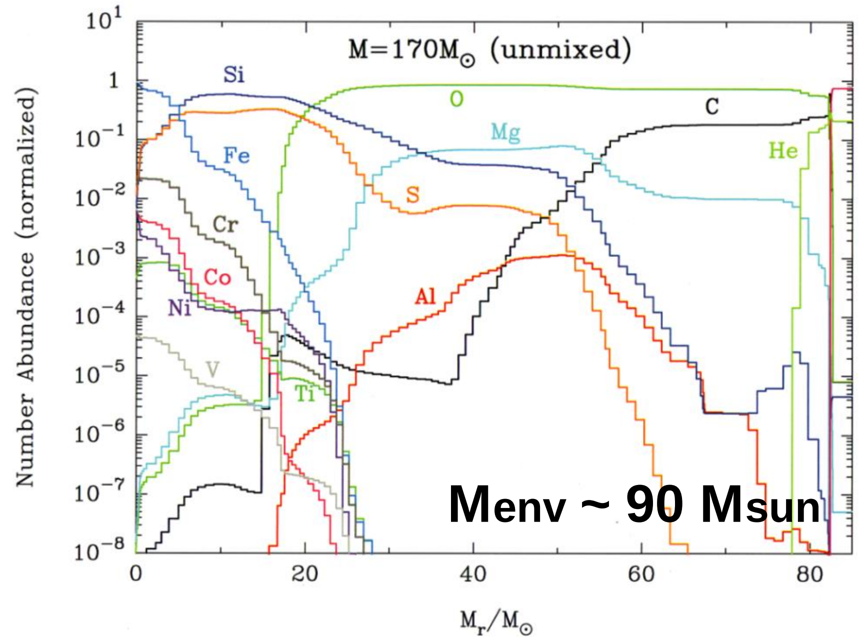
2-1-1. Dust formation in primordial SNe

Nozawa+03, ApJ, 598, 785

○ Population III SNe model (Umeda & Nomoto 2002)

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

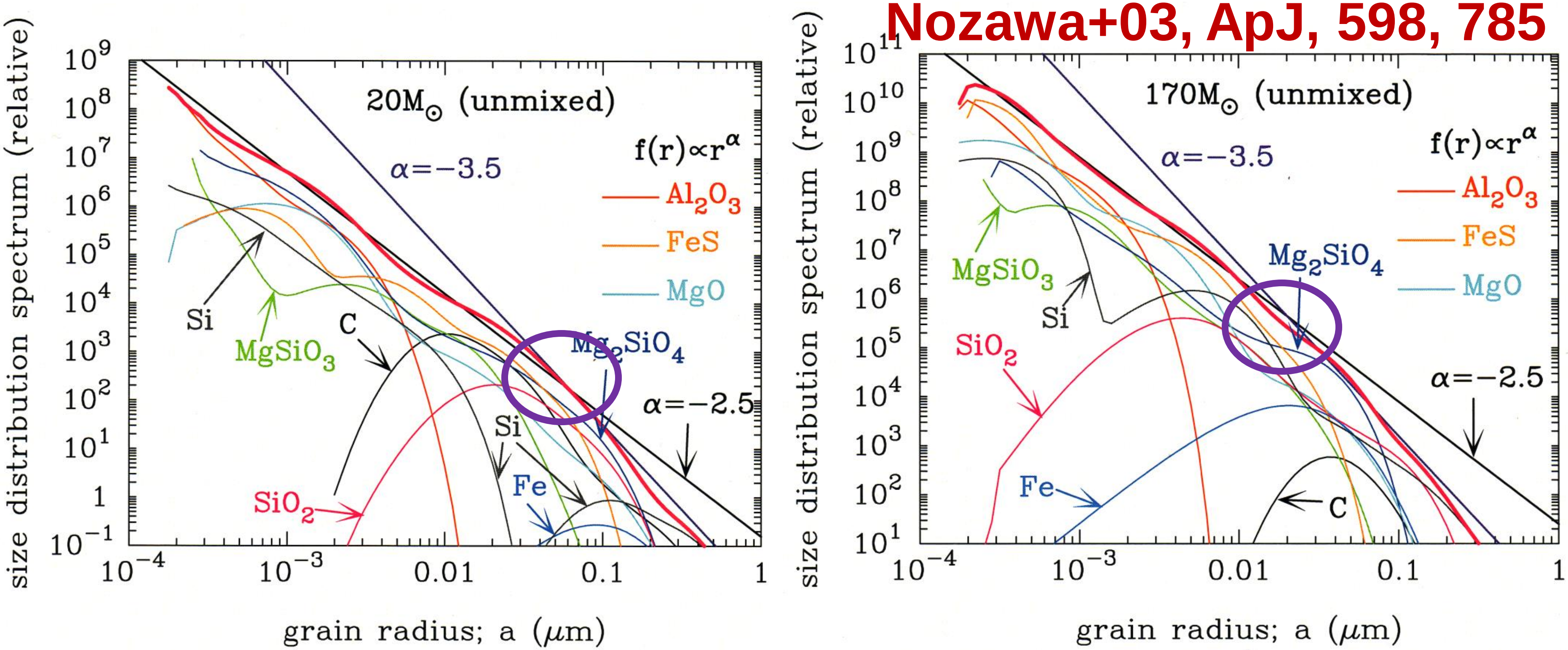




- **nucleation and grain growth theory** (Kozasa & Hasegawa 1988)
- **no mixing of elements within the He-core**
- **complete formation of CO and SiO, sticking probability=1**

2-1-2. 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

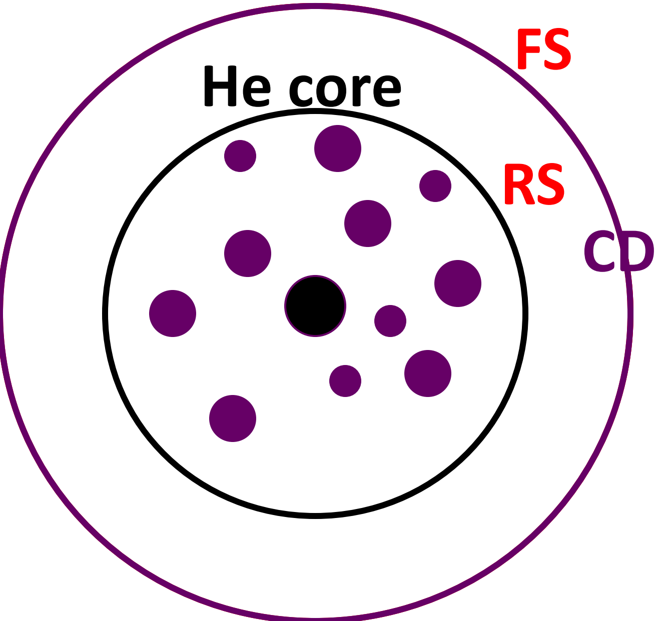
amount of newly formed dust grains

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

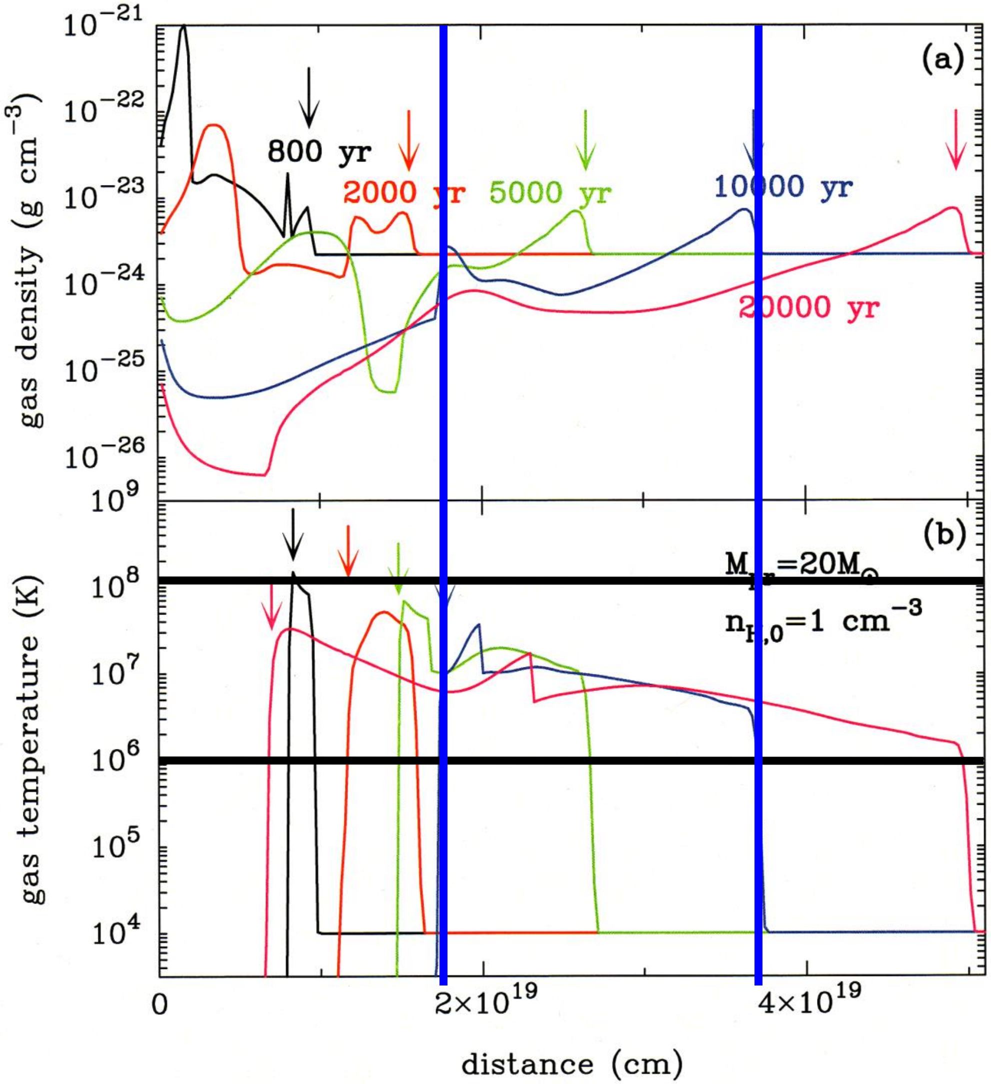
2-2. Dust Evolution in SNRs

$T = (1\text{-}2) \times 10^4$ 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



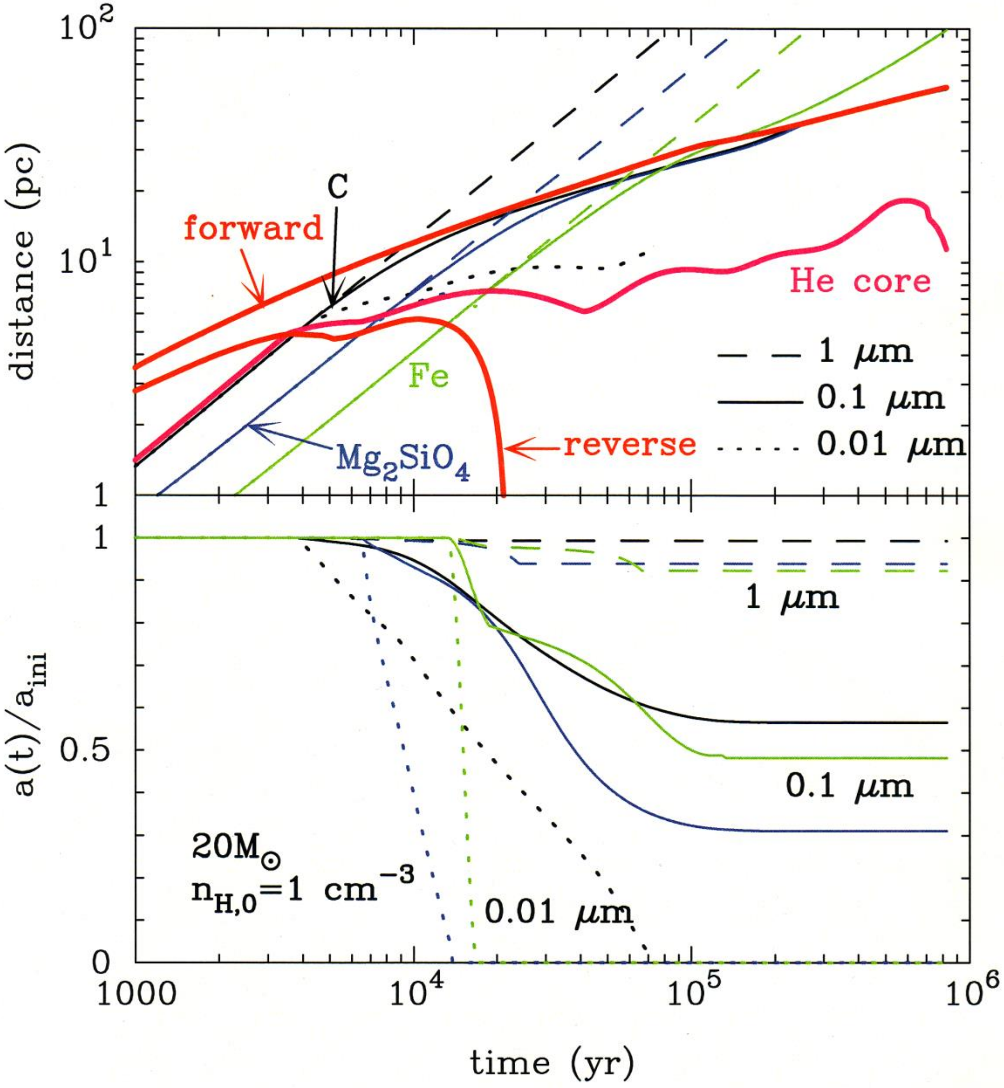
Model : M_{pr}= 20 Msun (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

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}

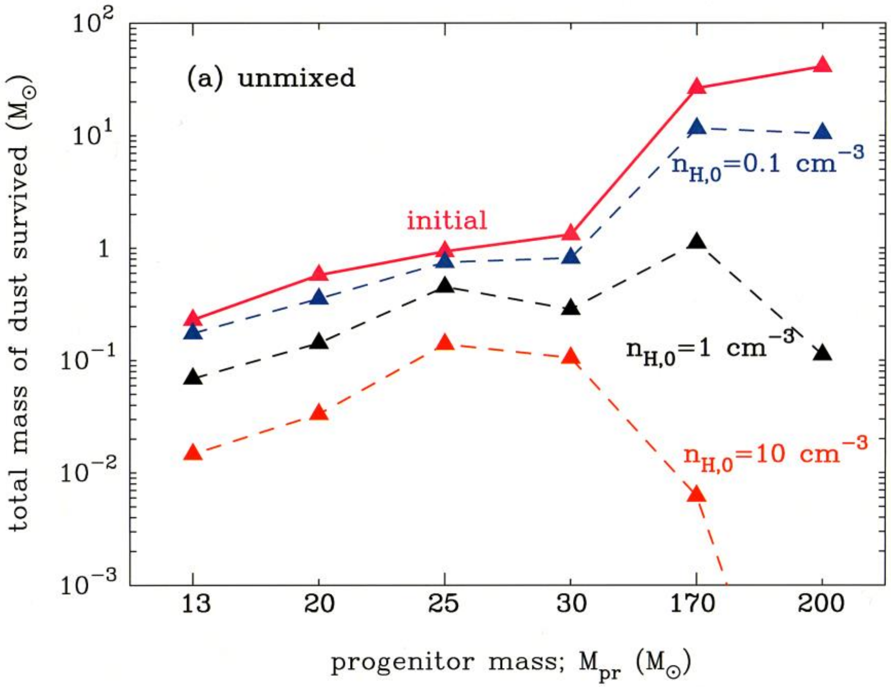
Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

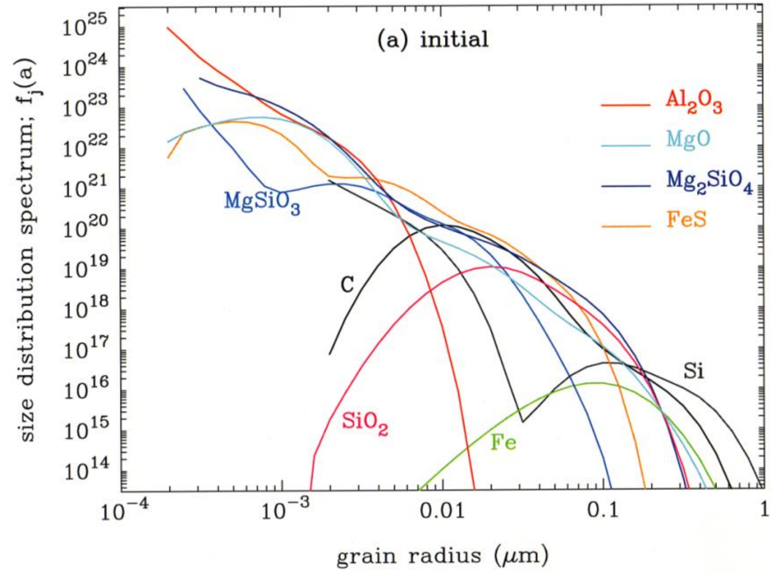
The evolution of dust heavily depends on the initial radius and composition

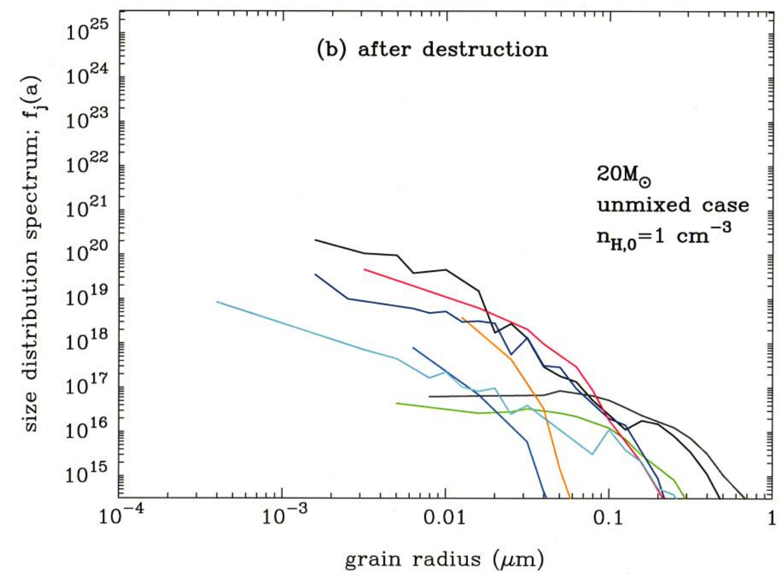
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

2-2-3. Total mass and size of surviving dust

Nozawa+07, ApJ, 666, 955





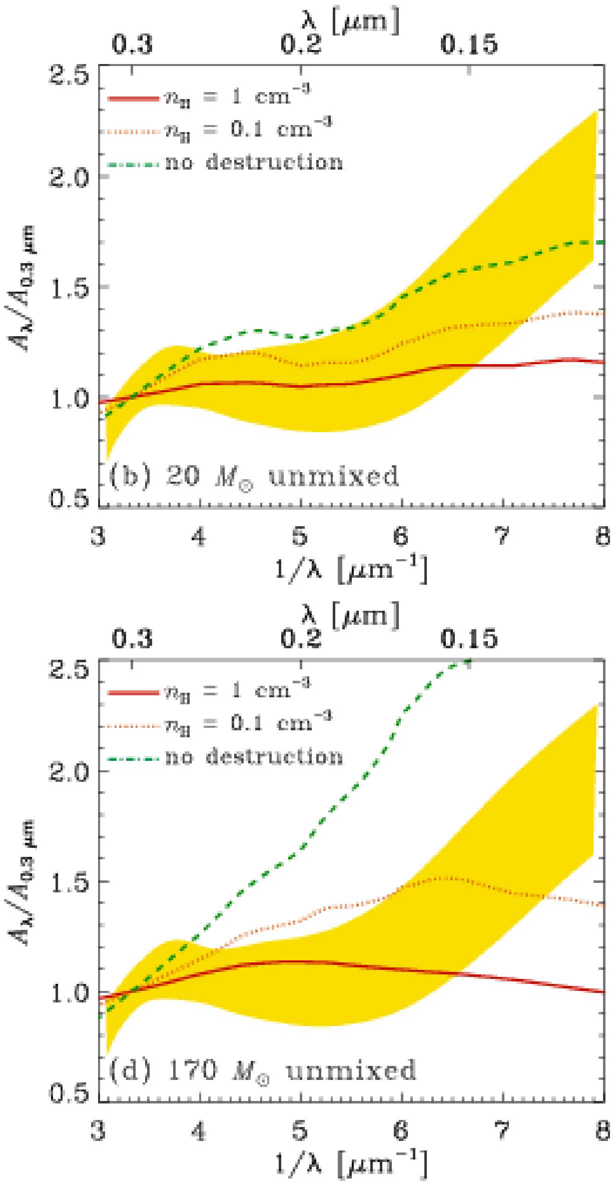


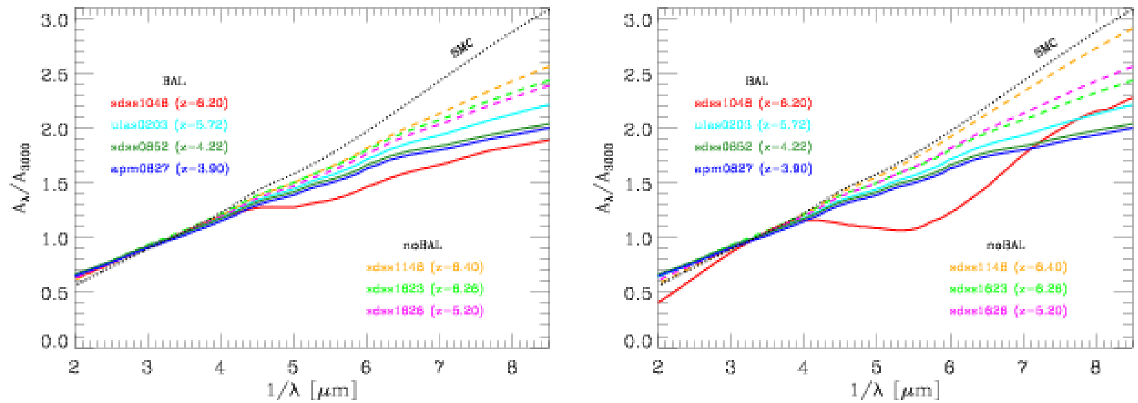
total dust mass surviving the destruction in Type II-P SNRs; 0.08-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

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

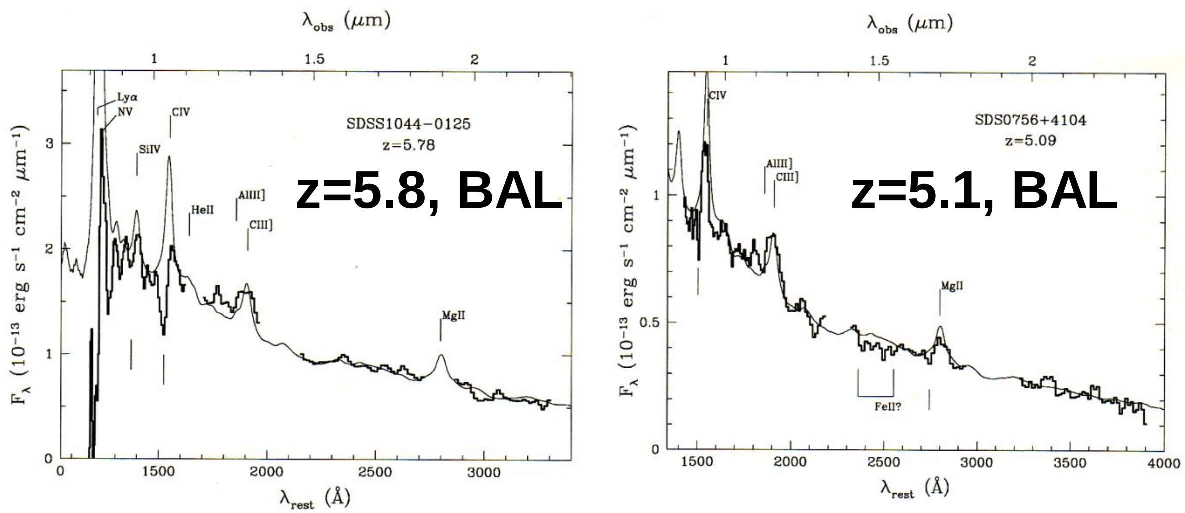
2-3. Flattened extinction curves at high-z

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





Gallerani+10, A&A, 523, 85



Maiolino+04, A&A, 420, 889

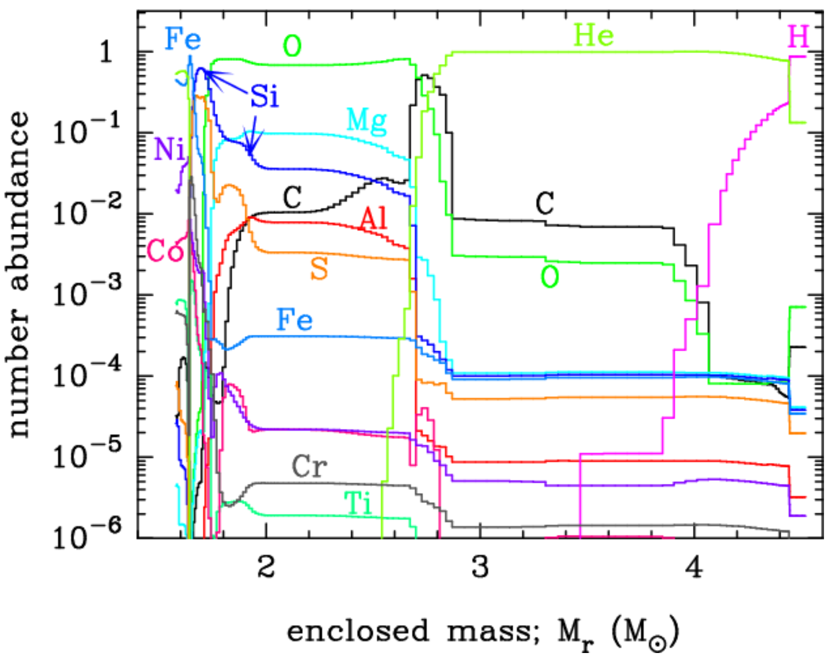
3. Formation and evolution of dust in various types of SNe

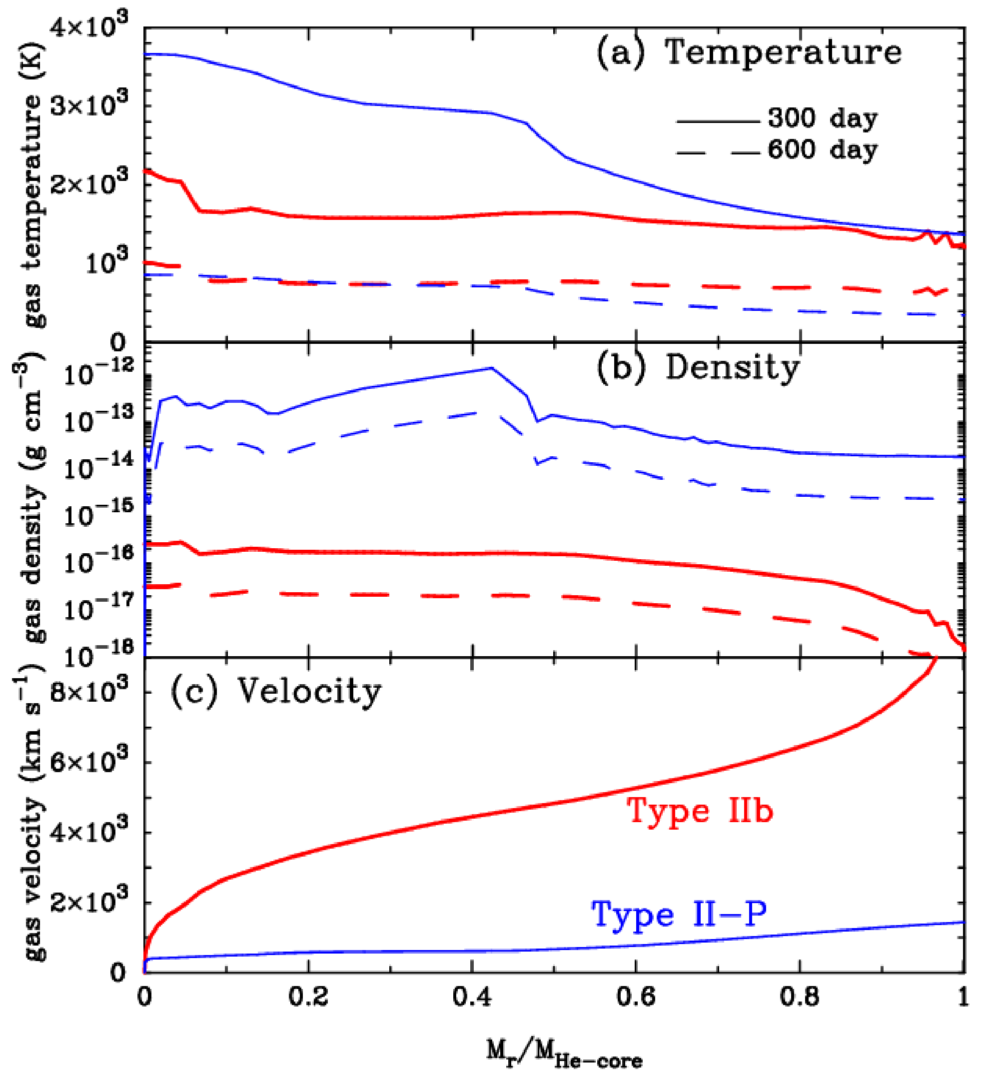
3-1-1. Dust formation in Type IIb SN

Nozawa+10, ApJ, 713, 356

○ SN IIb model (SN1993J-like model)

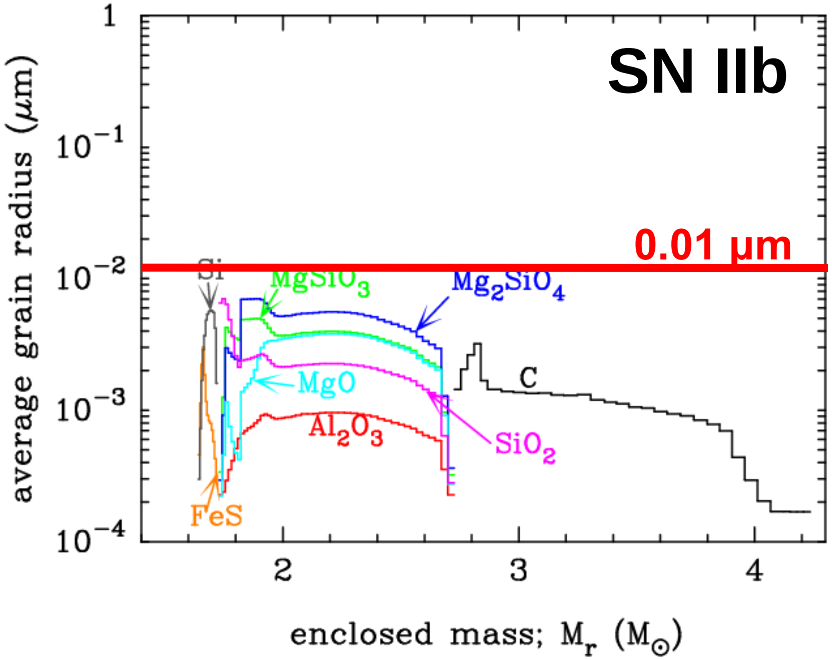
- $M_{H\text{-}env} = 0.08\ M_{sun}$
  $M_{ZAMS} = 18\ M_{sun}$
  $M_{eje} = 2.94\ M_{sun}$
- $E_{51} = 1$
- $M(^{56}Ni) = 0.07\ M_{sun}$

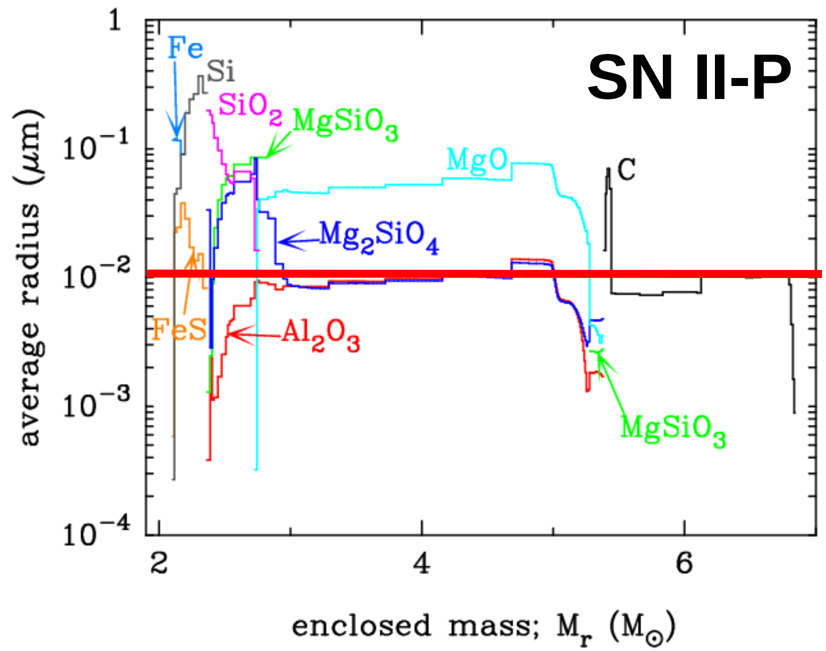




3-1-2. Dependence of dust radii on SN type

Nozawa+10, ApJ, 713, 356



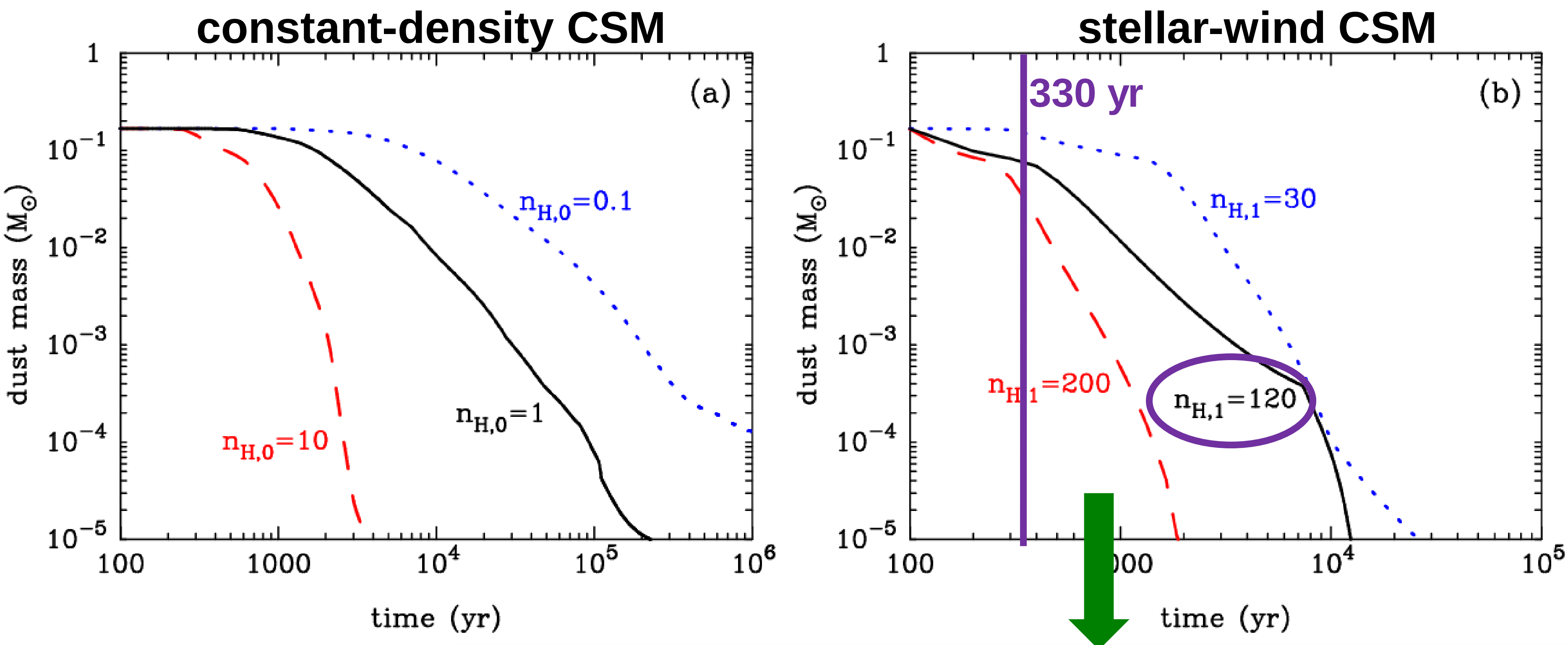


— condensation time of dust **300-700 d** after explosion

— 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 → a_{dust} < 0.01 μm**
- **SN II-P with massive H-env → a_{dust} > 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

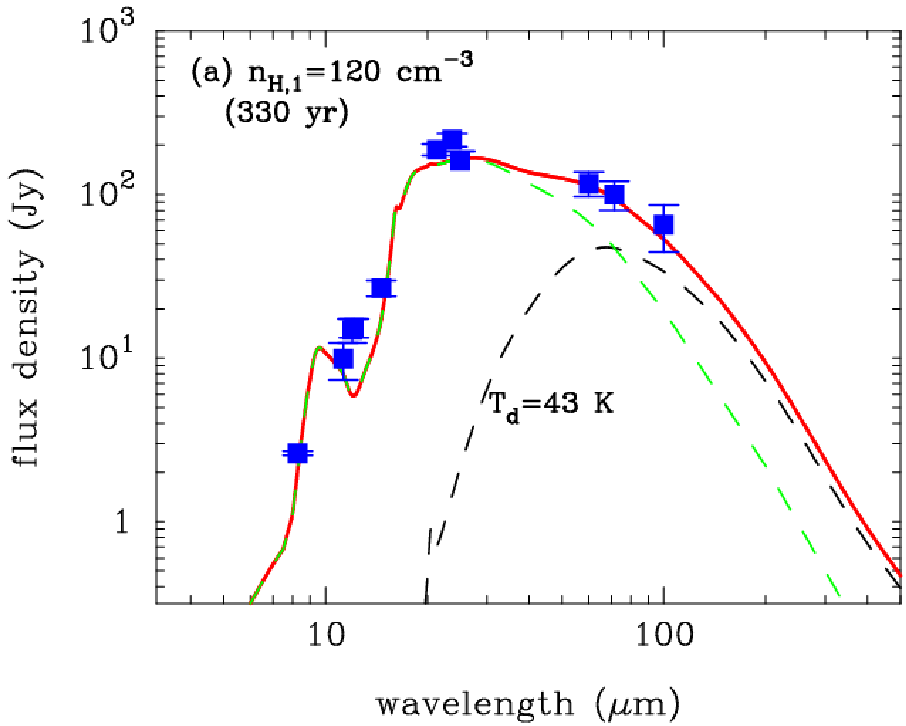
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

➔ small radius of newly formed dust

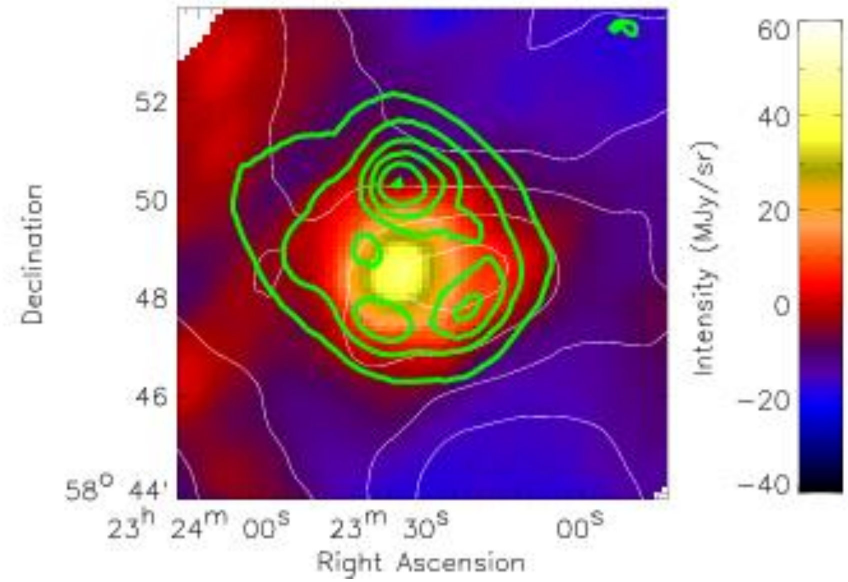
➔ early arrival of the reverse shock at the He core

3-1-4. Dust in Cassiopeia A

Nozawa+10, ApJ, 713, 356



AKARI corrected 90 μm image



- $M_{d,warm}$ ~ 0.008 M_{sun}
- $M_{d,cool}$ ~ 0.072 M_{sun} with T_{dust} ~ 40 K
- mass-loss rate
  dM/dt = 8x10^{-5} M_{sun}/yr

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)

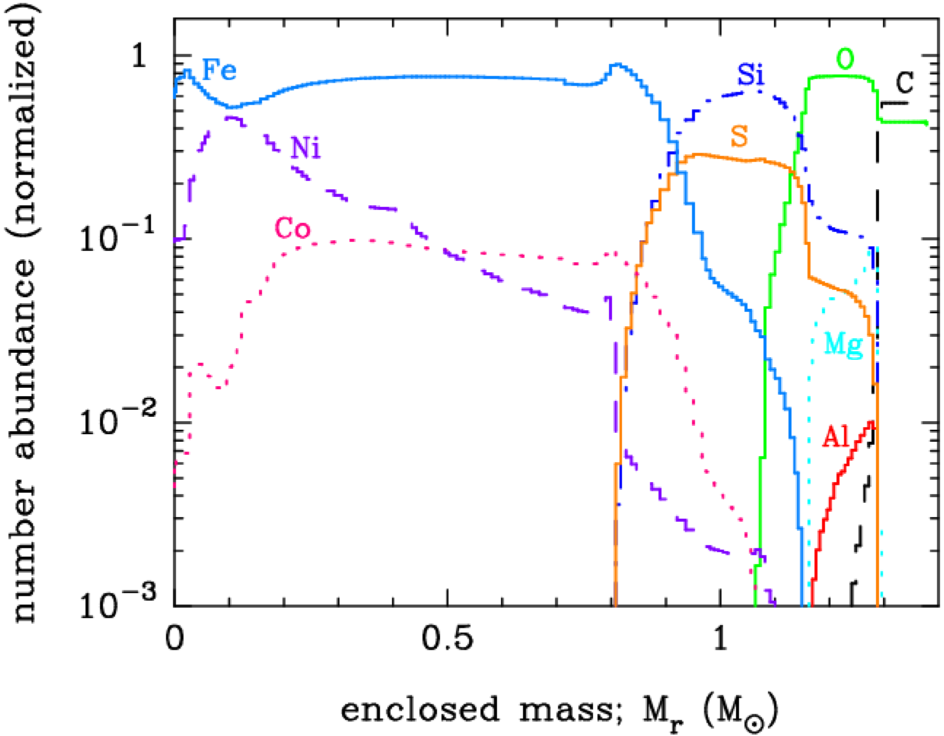
3-2-1. Dust formation in Type Ia SN : W7 model

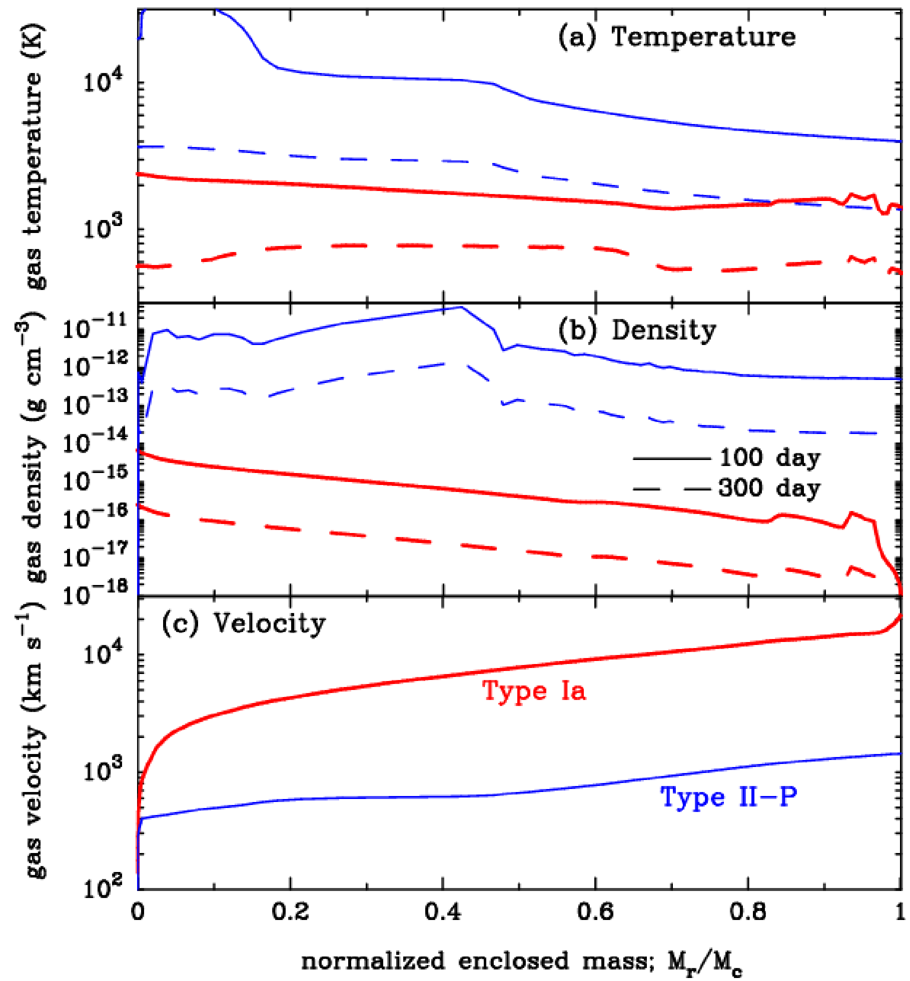
Nozawa+11, to be submitted

○ Type Ia SN model

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

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

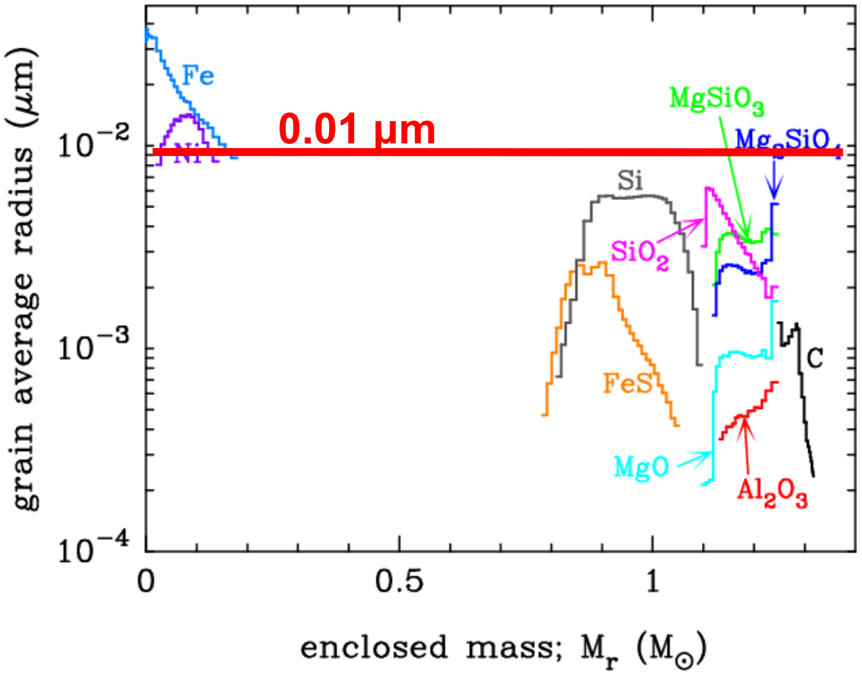




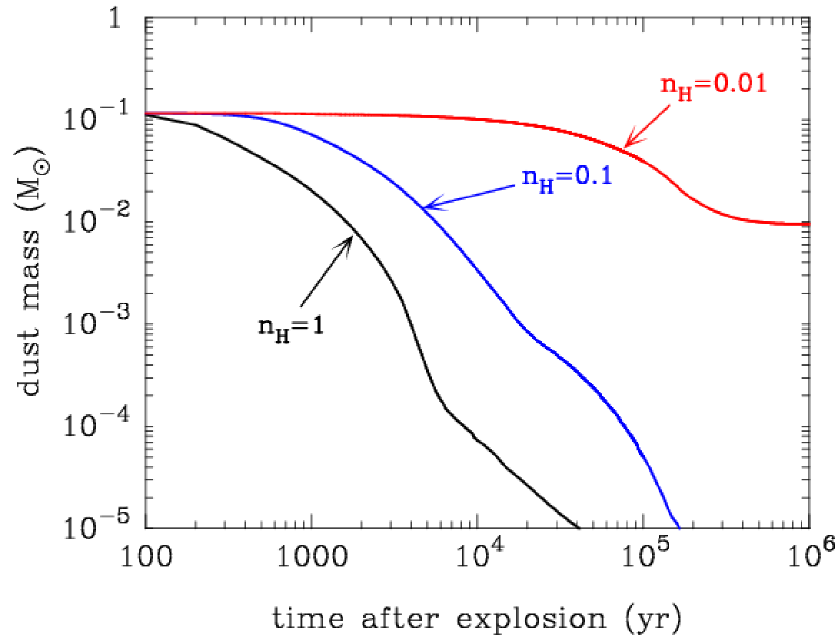
3-2-2. Dust formation and evolution in SNe Ia

Nozawa+11, to be 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

— before destruction : ~0.1-1 M_{sun} in Type II-P SNe
(Nozawa+03; Todini & Ferrara 2001; Cherchneff & Dwek 2010)

— after destruction by reverse shock
0.08-0.8 M_{sun} (Nozawa+07)
0.01-0.1 M_{sun} (Bianchi & Schneider 2007)

・Observational works

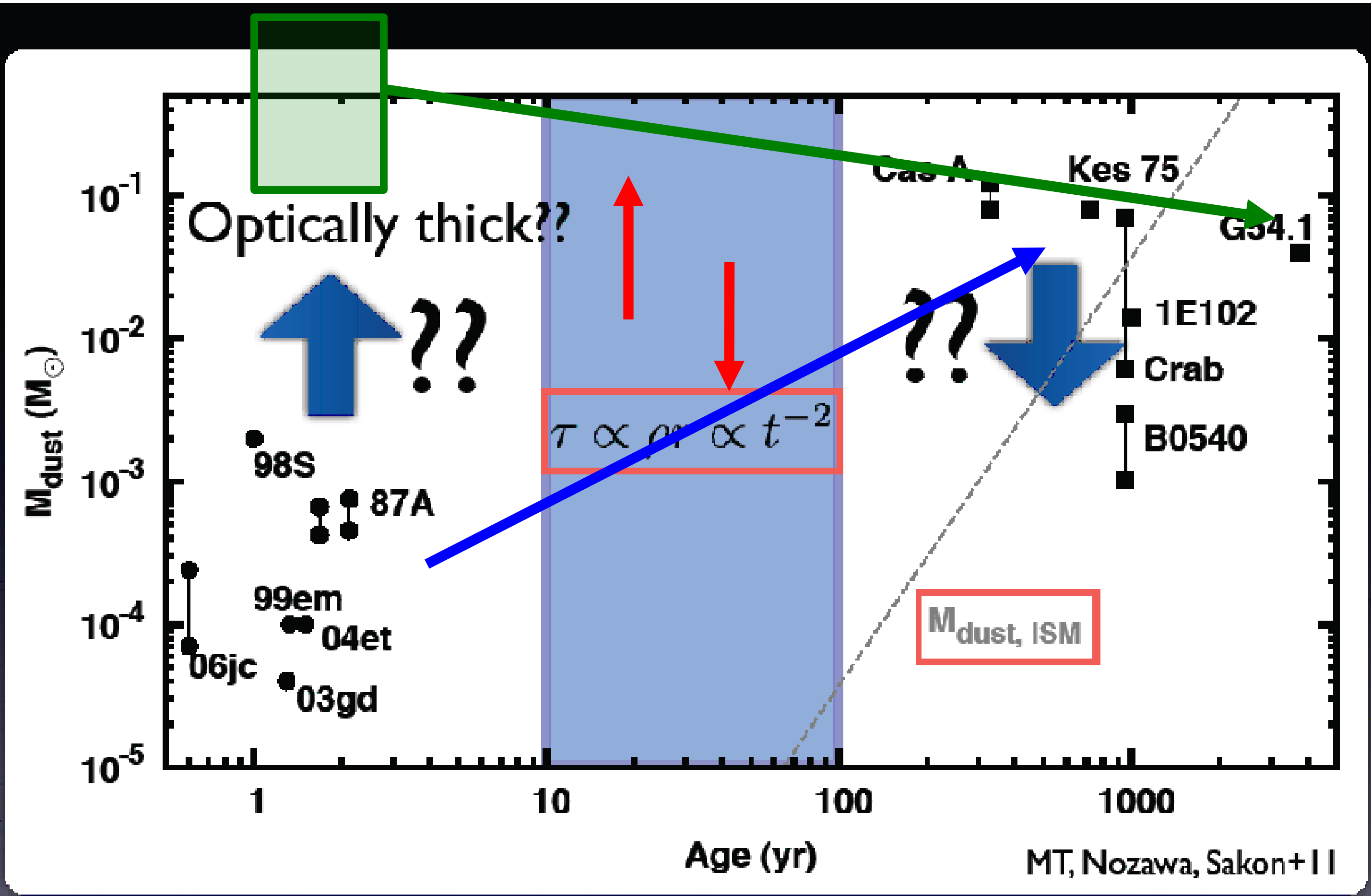
— IR observations of dust-forming SNe : < 10^{-3} M_{sun}
(e.g., Meikle+07; Sakon+09; Kotak+09)

— submm observations of SNRs : ~1 M_{sun}
(Dunne+03; Morgan+03; Dunne+09)

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

4-2. Dust mass estimated from observations

Tanaka, TN, +11, submitted

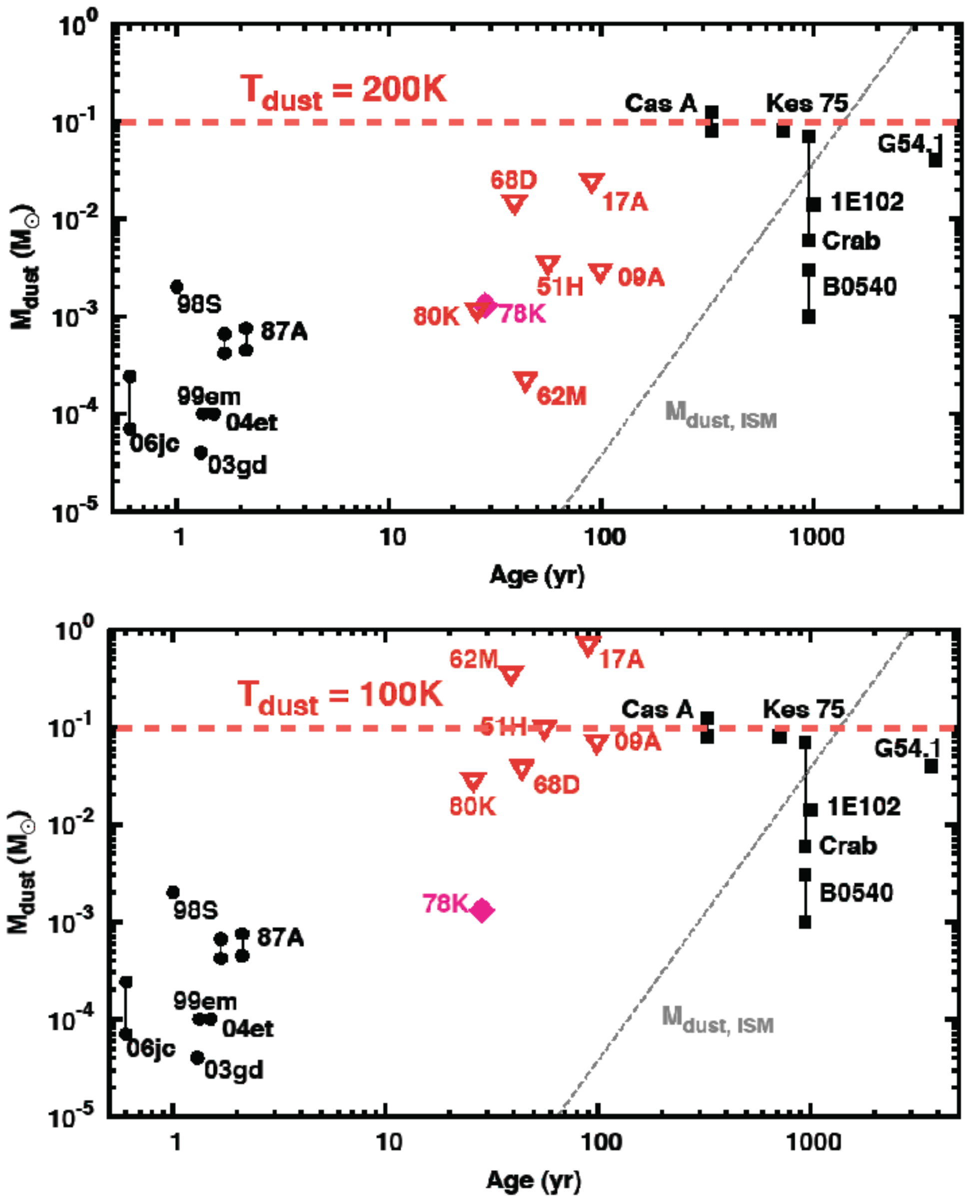


Young supernovae: Ercolano+07, Wooden+93, Pozzo+04, Elmhamdi+03, Meikle+07, Kotak+09, Mattila+08, Sakon+09

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. Dust in middle-aged core-collapse SNe

Tanaka, TN, +11, submitted



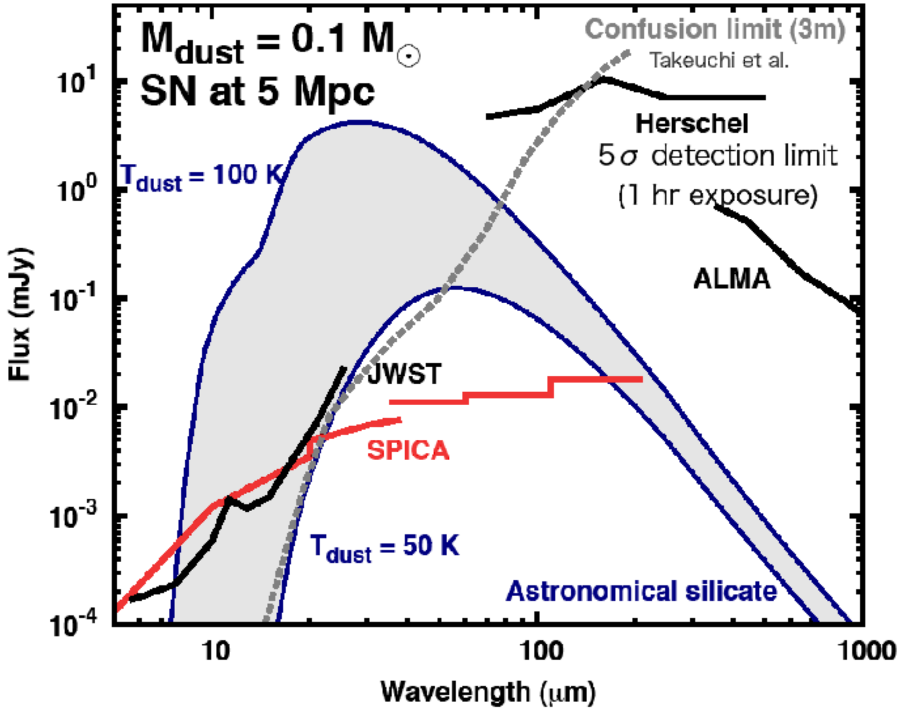
- The IR emissions from SN 1978K are detected
  → silicate dust
  T_{dust} = 230 K
  M_{dust} = 1.3×10^{-3} M_{sun}

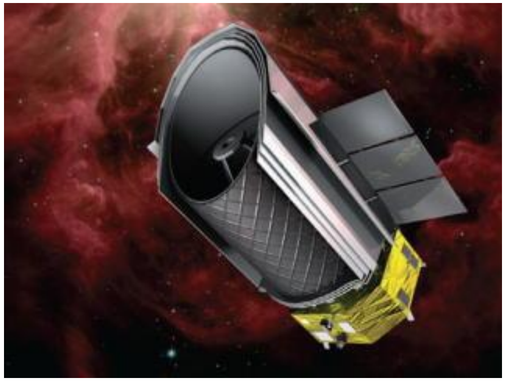
- If T_{dust} > 200 K, M_{dust} < 0.1 M_{sun} for 6 non-detected SNe

- If T_{dust} < 80-100 K, as much as 0.1 M_{sun} of dust can be allowed

4-4. Promising targets for SPICA

Tanaka, TN, +11, submitted





SPICA will give the answer to the question whether SNe can produce dust in the early universe

- **Imaging observations of nearby galaxies**
- **Coverage from MIR and FIR is essential**
- **~10 targets at <~ 5 Mpc**

5. Conclusion remarks

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

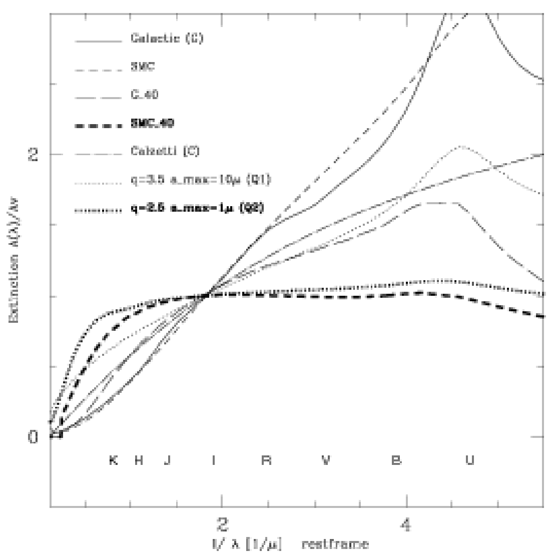
○ metal-poor (high-z or starbust) galaxies

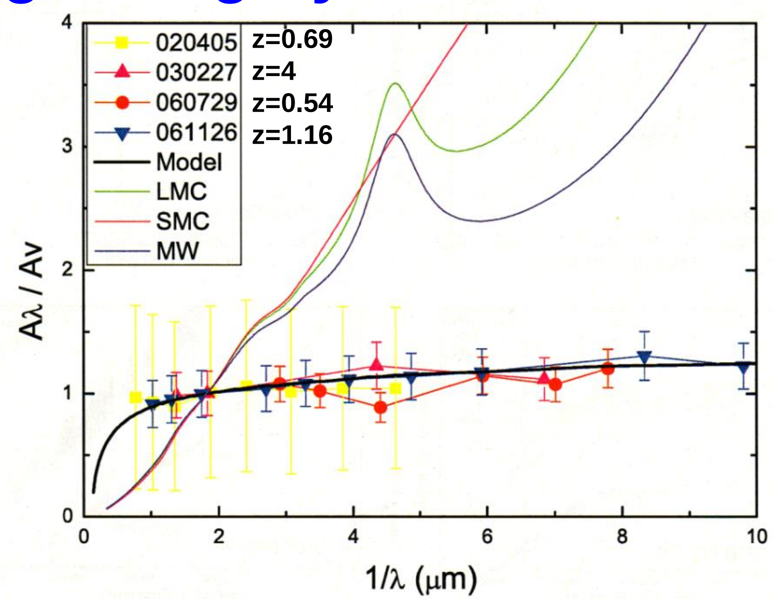
- massive stars (SNe) are dominate
- mass loss of massive stars would be less efficient

➔ **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)

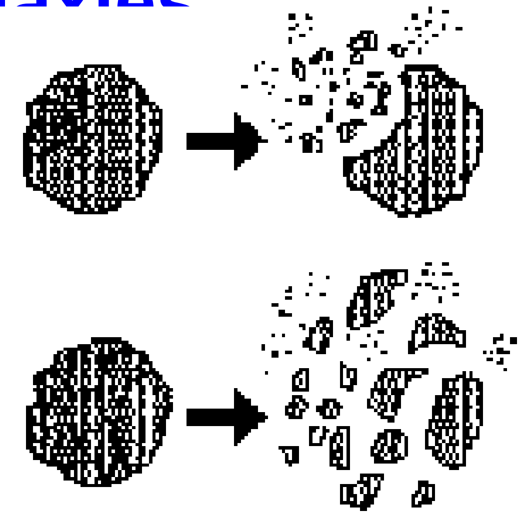
○ metal-rich (low-z or Milky Way) gal

- 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?



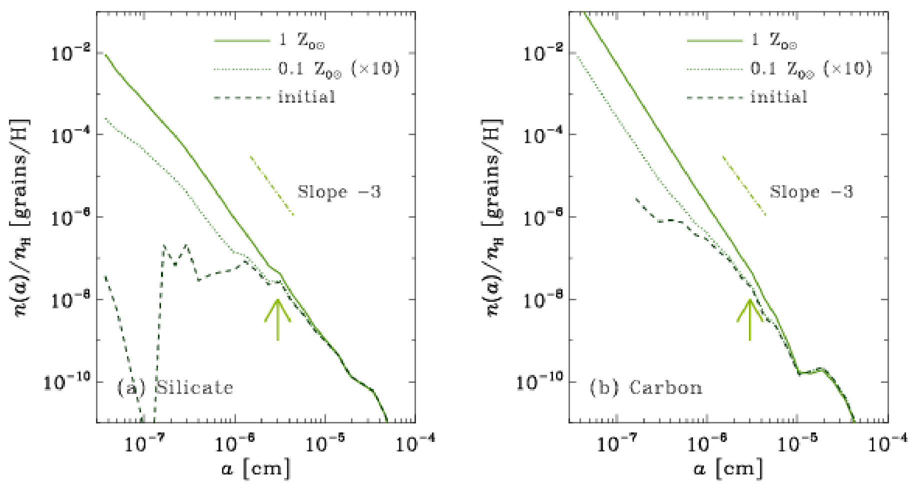
grain shattering

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

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

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

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



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