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# Origin and Nature of Dust Grains in the Early Universe


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# 1. Introduction

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

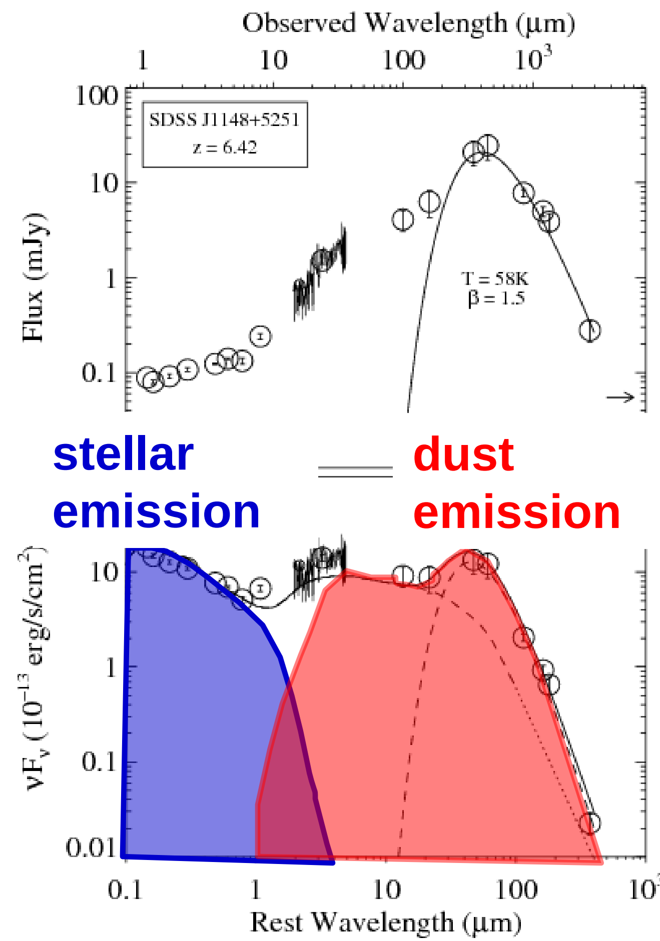
**The far-infrared and submm observations have confirmed the presence of dust in excess of $10^8$ Msun in 30% of z > 5 quasars**

## SDSS J1148+5251 at z=6.4

- cosmic age : 890 Myr
- stellar mass : ~$10^{11}$ Msun
- SFR : ~3000 Msun/yr (Salpeter IMF)
- gas mass : ~$3 \times 10^{10}$ Msun (Walter+2004)

- IR luminosity : $(1\text{-}3) \times 10^{13}$ Lsun
- dust mass : $(2\text{-}7) \times 10^{8}$ Msun
- dust-to-gas mass ratio : ~0.01

- metallicity : ~solar ~ 0.02
- dust-to-metal mass ratio : ~0.5




Leipski+2010, A&A, 518, L34

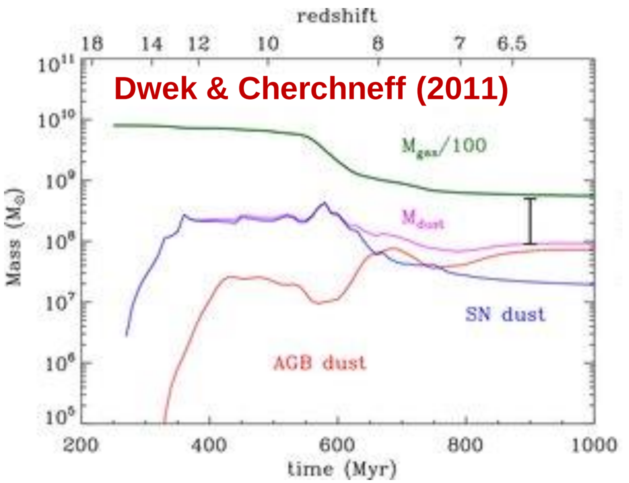
# 1-2. What are dust sources in high-z quasars?

## ・Type II supernovae (SNe II)

- dust evolution model: >0.1-1 Msun per SN
  (Morgan & Edmunds 2003; Maiolino+2006; Dwek+2007)
- theoretical studies of dust formation: ~0.1-1.0 Msun per SN
  (Todini & Ferrara 2001; Nozawa+2003, 2007; Bianchi & Schneider 2007)

## ・AGB stars + SNe

- AGB stars supply more dust grains than SNe II (Valiante+2009; Dwek & Cherchneff 2011)
- dust formation calculation: 0.01-0.05 Msun per AGB star (Zhukovska & Gail 2008)

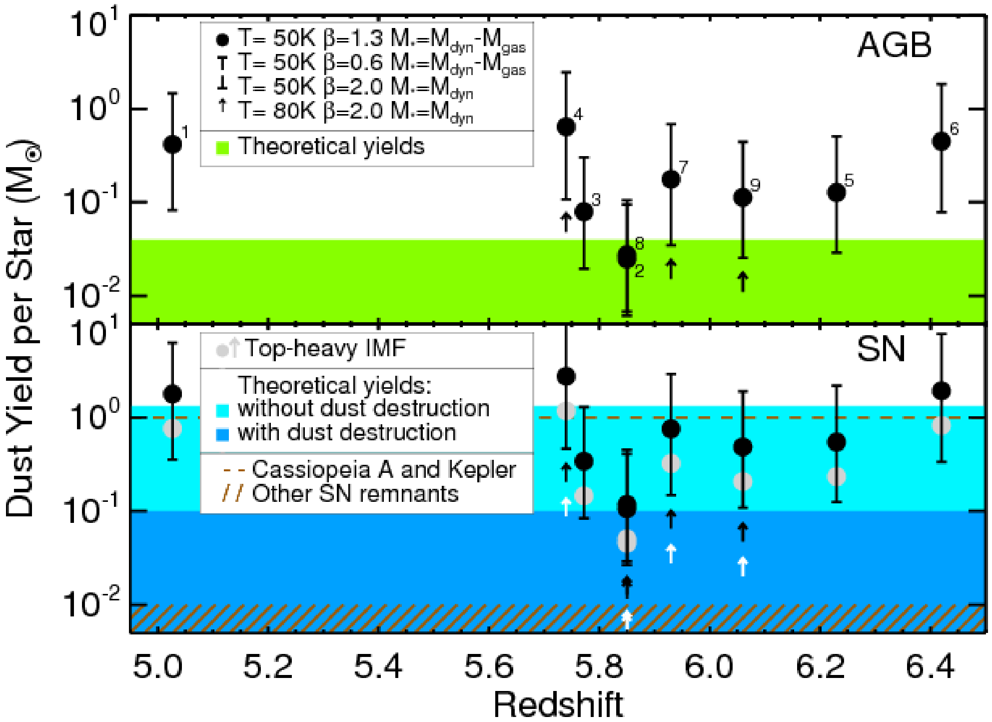



## no efficient dust formation in metal-poor AGB stars (Di Criscienzo+2013)

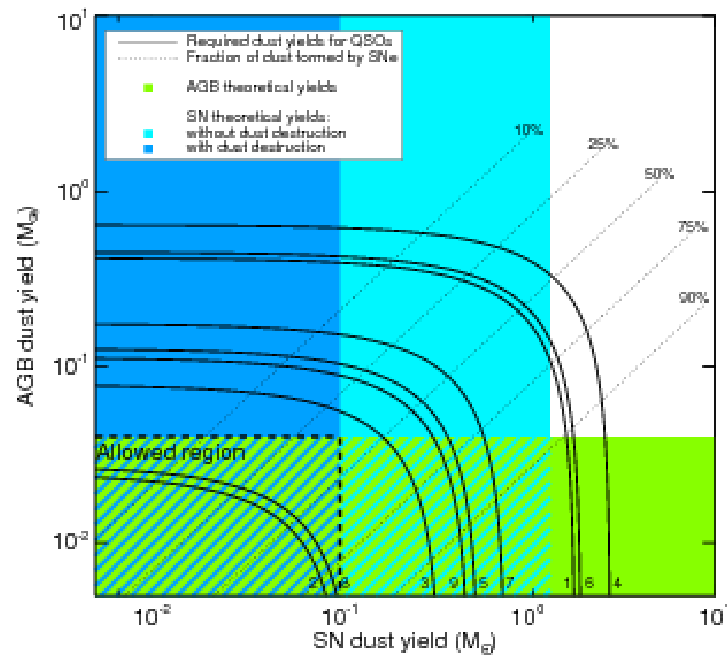
## ・Grain growth in molecular clouds + AGB stars + SNe

(Draine 2009; Michalowski+2010; Gall+2011a, 11b; Pipino+2011; Mattsson+2011; Valiante+2011; Inoue 2011; Kuo & Hirshita 2012)

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




**Michalowski+2010, A&A, 522, 15**




**Rapid grain growth is required for at least 3 out of 9 quasars at z > 5**

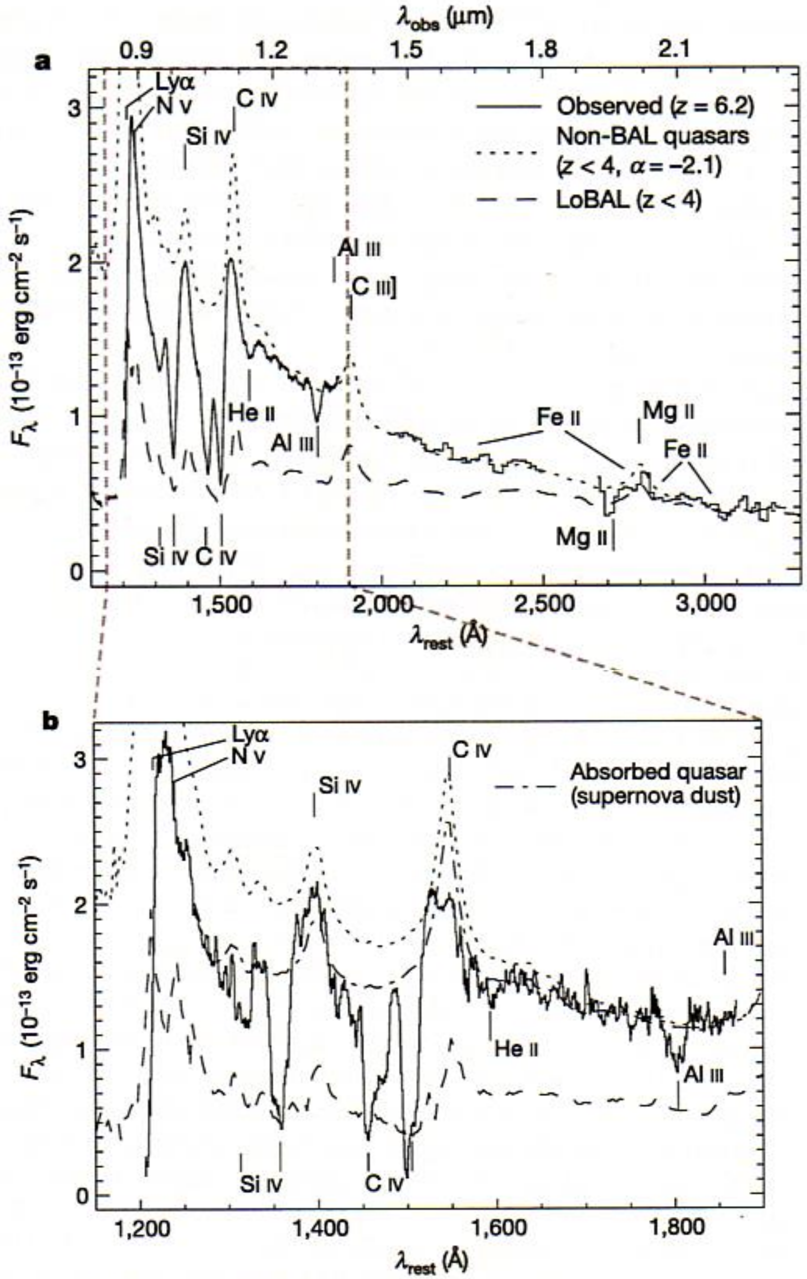
$$M_{dust} = M_{star} \times f_{SN} \times Y_{dust}$$

$$= 1.5\times10^{8}\ M_{sun}\ (M_{star} / 10^{11}\ M_{sun})\ (f_{SN} / 0.3)\ (Y_{dust} / 0.005)$$

$f_{SN} = M_{SN} / M_{star}$ ~ 0.3 for Salpeter IMF

$Y_{dust} = m_{dust} / m_{SN}$ ~ 0.005 for $m_{dust}$=0.1 $M_{sun}$ for $m_{SN}$=20 $M_{sun}$

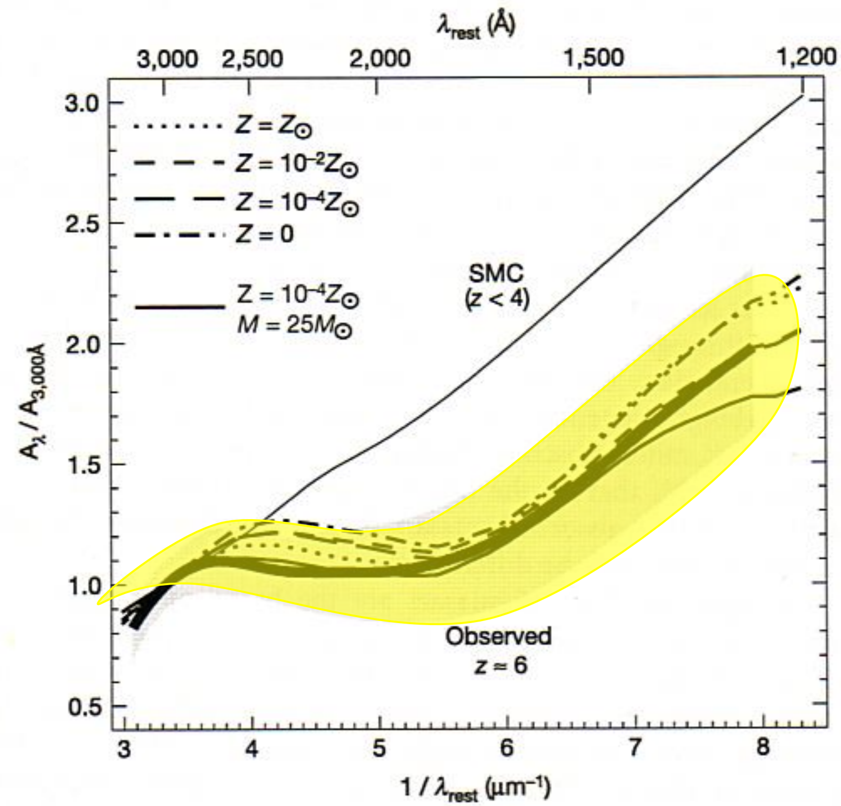
# 1-4. Extinction curves for z=6.4 quasars




Maiolino+2004, Nature, 431, 533

**SDSS J1048+4637 at z=6.2 :**

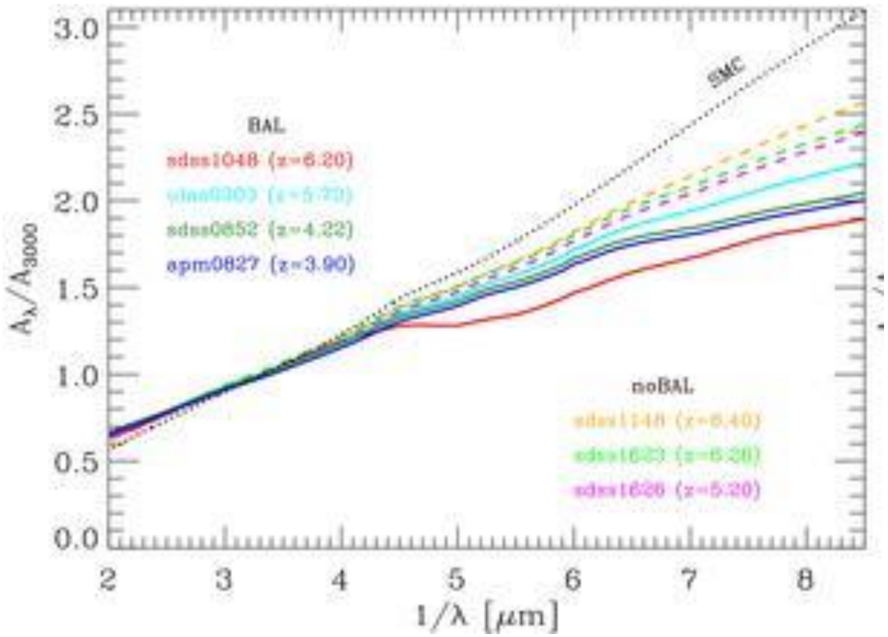
**broad absorption line (BAL) quasars**




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

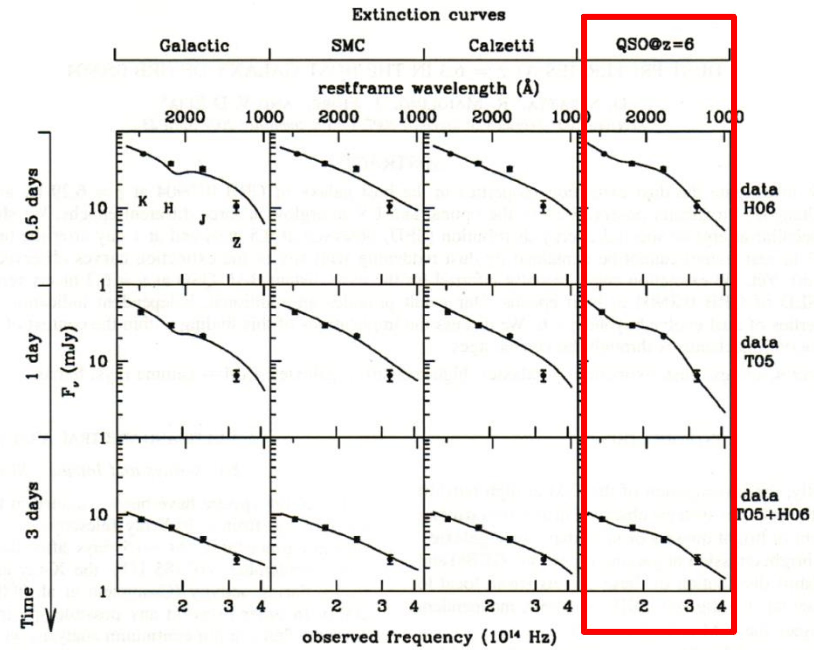
# 1-5. Extinction curves at 3.9 < z < 6.4

**high-z quasar extinction curves**

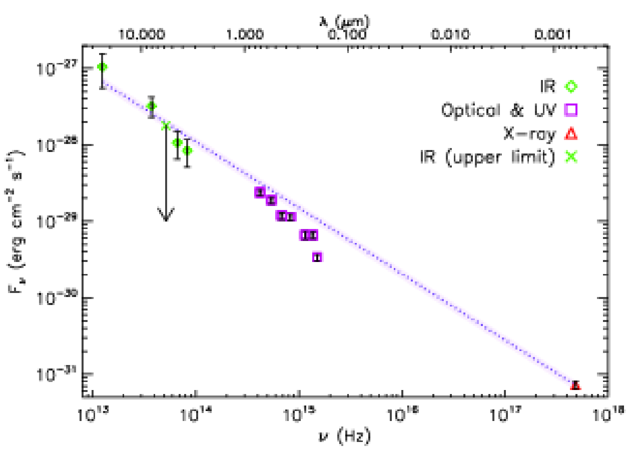


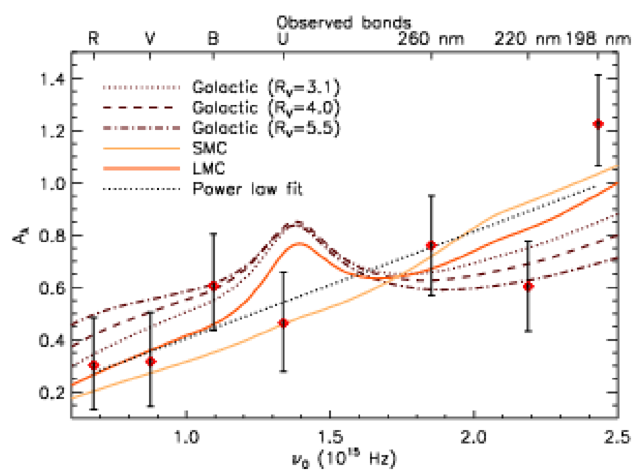

**Gallerani+2010, A&A, 523, 85**

**GRB 050904 at z=6.3**




**Stratta+2007, ApJ, 661, L9**




**GRB 050525A at z=0.6**

**Heng+2008, ApJ, 681, 1116**

# 1-6. Summary of Introduction

- There is clear evidence for a huge amount of dust grains at $z > 5$, but the main sources of such massive dust remain to be specified

➔ SNe II evolving from short-lived massive stars must be sources of dust at the very early times of galaxy evolution

➔ grain growth in molecular clouds seems to be needed to explain the dust content observed for high-z quasars

- Extinction curves at high z are different from those at low z

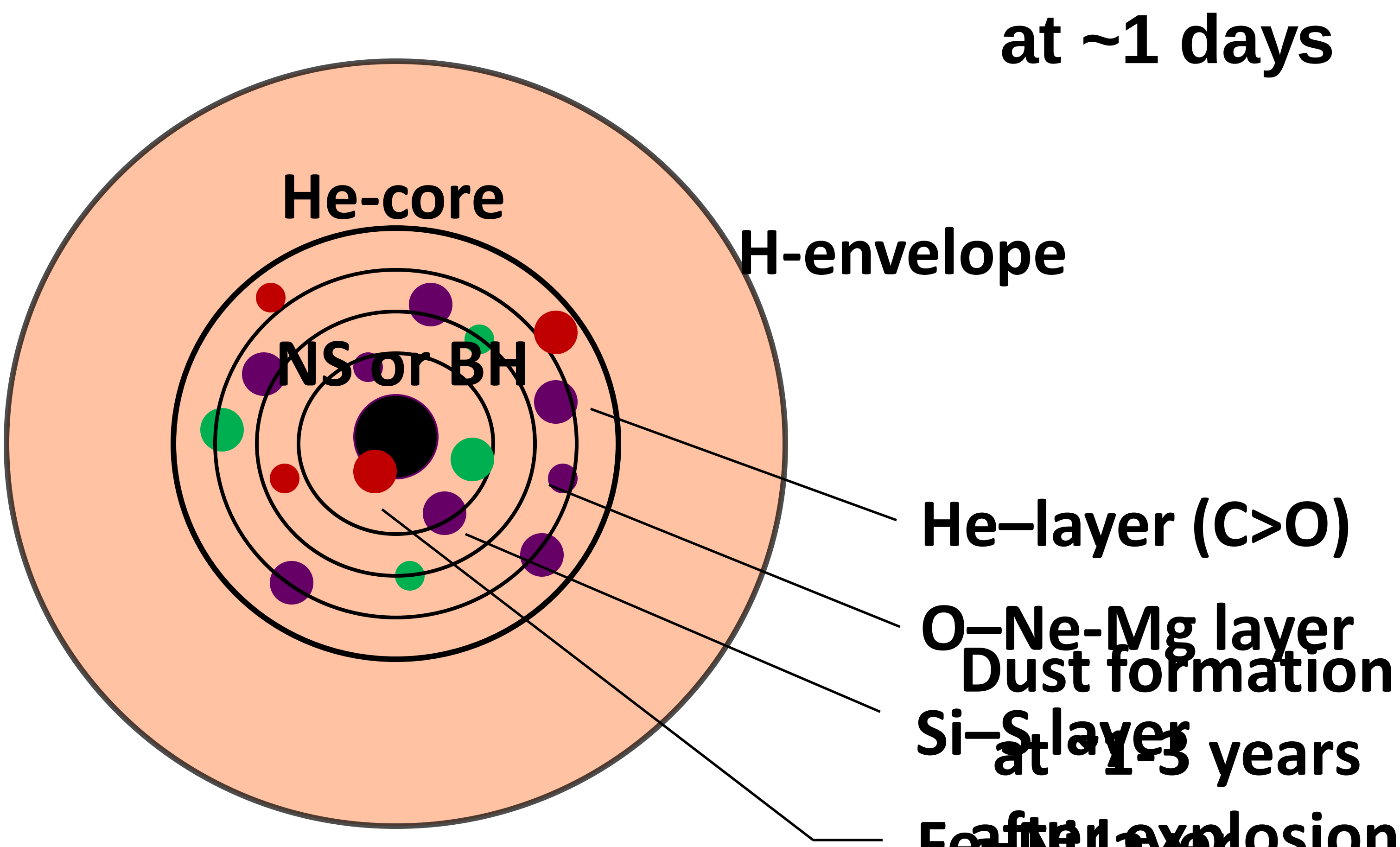
➔ properties (composition & size) of dust at $z > 4$ are likely to be different from those at low z

➔ high-z quasars and GRB afterglows are good targets to probe the extinction curves in their host galaxies

\## there might be possibility that we are seeing the properties of
\## dust in local environments around the quasars and GRBs

# 2. Properties of dust ejected from Population III SNe II and PISNe

# Dust Formation in the ejecta of SNe

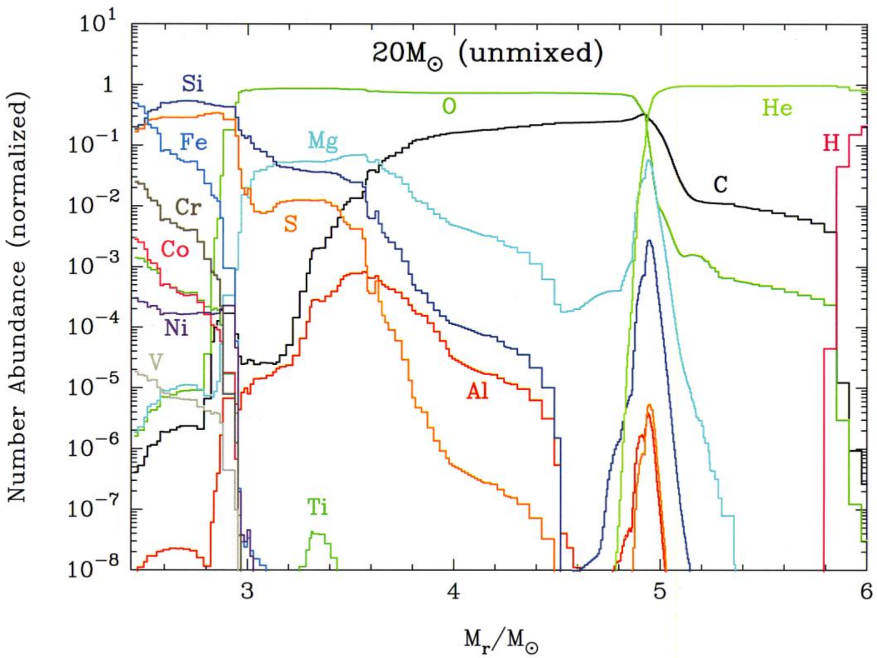


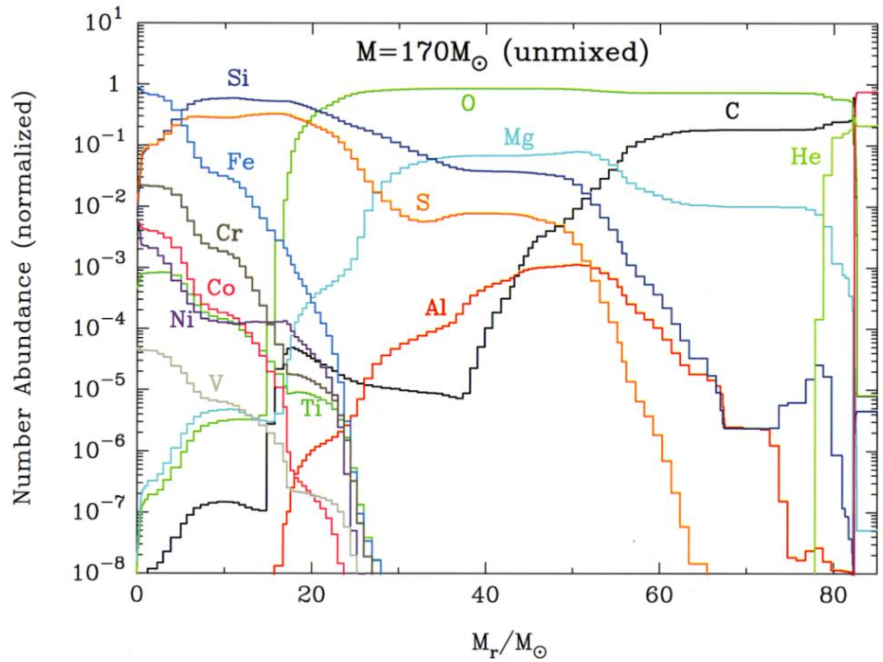
# 2-1. Dust formation in primordial SNe

Nozawa+2003, ApJ, 598, 785

## ○ Population III SNe model (Umeda & Nomoto 2002)

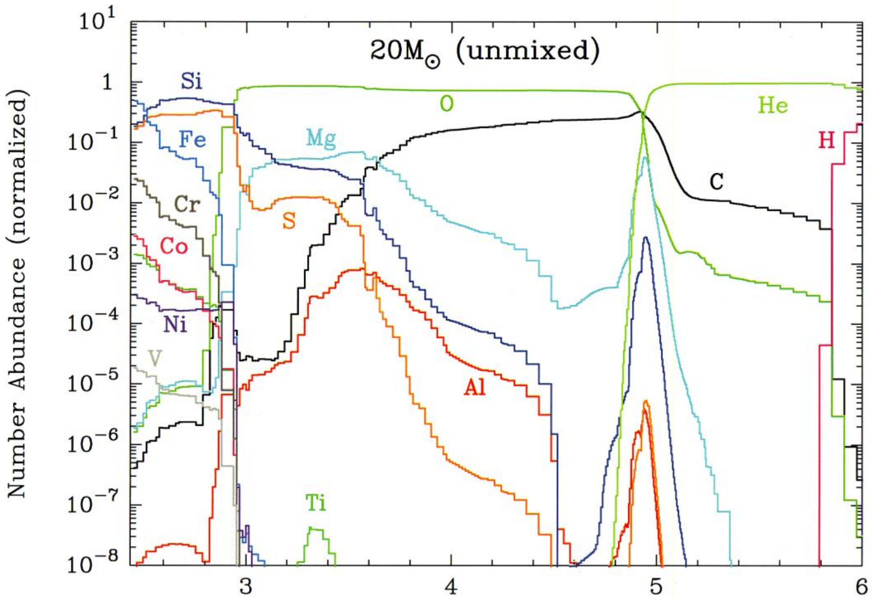
- SNe II : $M_{ZAMS}$ = 13, 20, 25, 30 $M_{sun}$ ($E_{51}$=1)
- PISNe : $M_{ZAMS}$ = 170 $M_{sun}$ ($E_{51}$=20), 200 $M_{sun}$ ($E_{51}$=28)

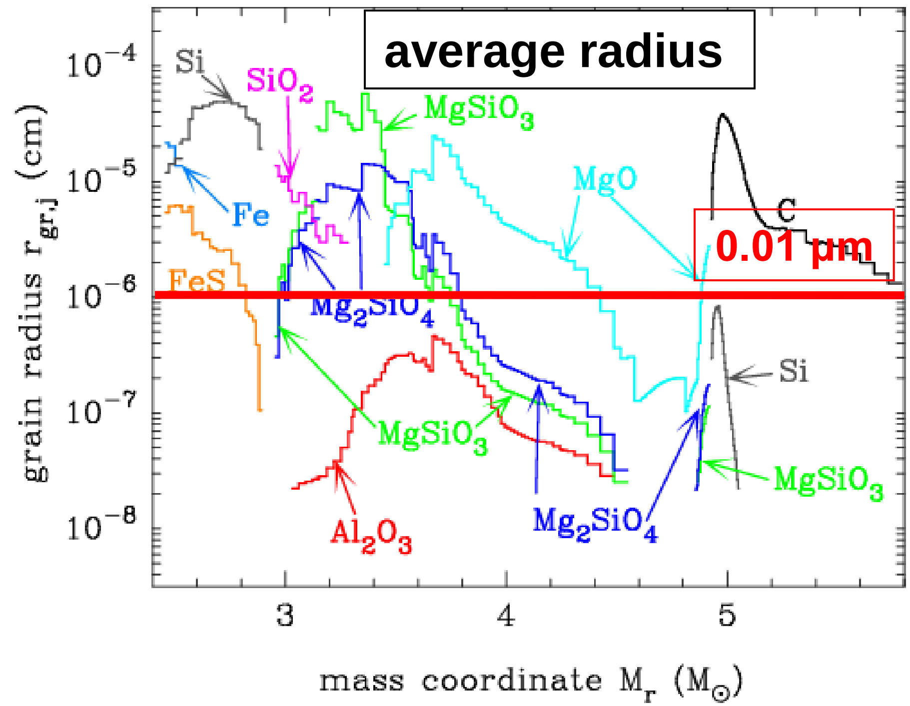


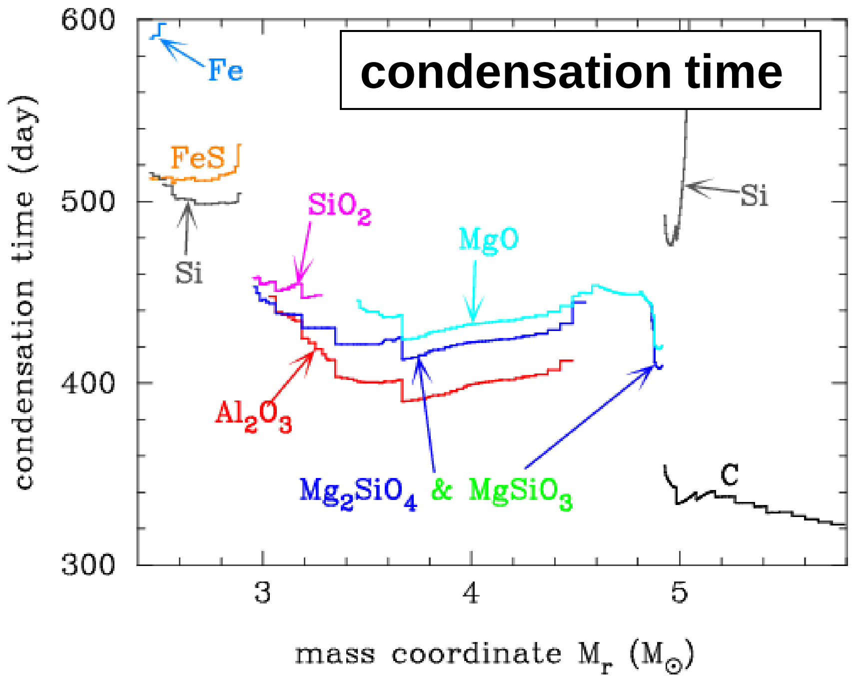




- nucleation and grain growth theory (Kozasa & Hasegawa 1987)
- no mixing of elements within the He-core
- complete formation of CO and SiO

# 2-2. Dust formed in Type II-P SNe



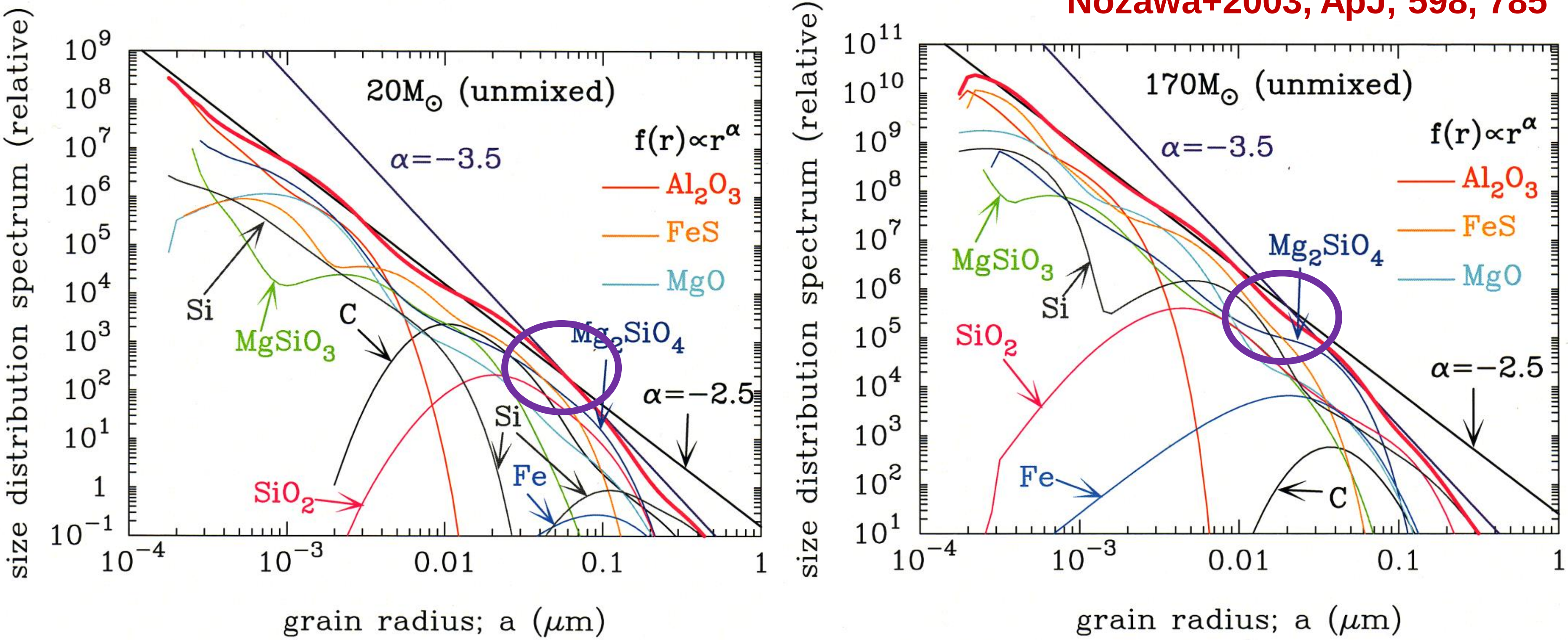




- a variety of grain species can condense according to elemental composition in each layer
- condensation time: **300-600d** after explosion
- average grain radii: **>~0.01 μm**

Nozawa+03, ApJ, 598, 785

# 2-3. Size distribution of newly formed dust

Nozawa+2003, ApJ, 598, 785

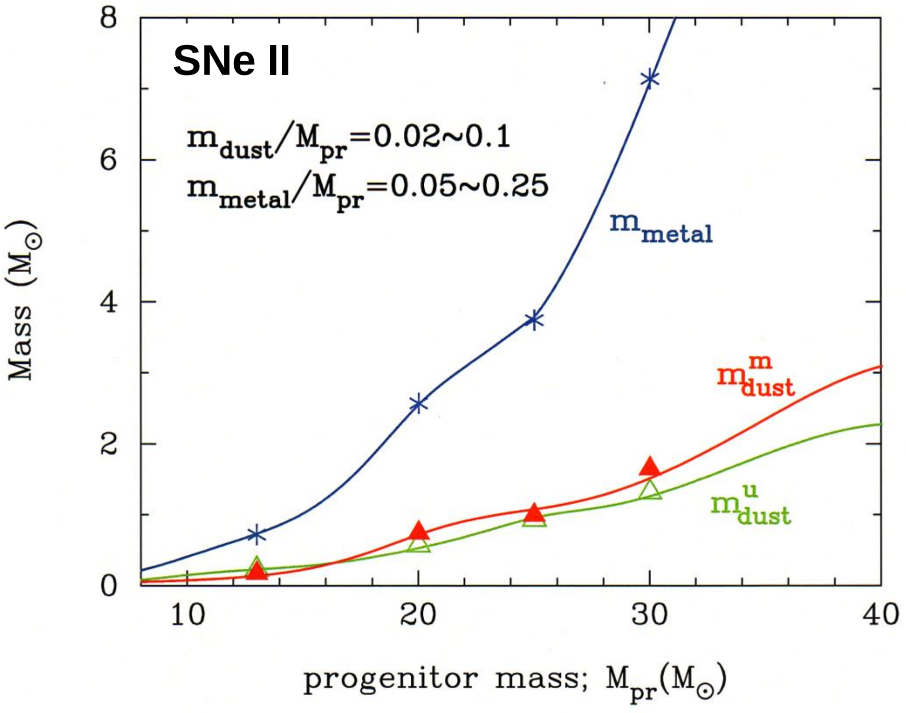


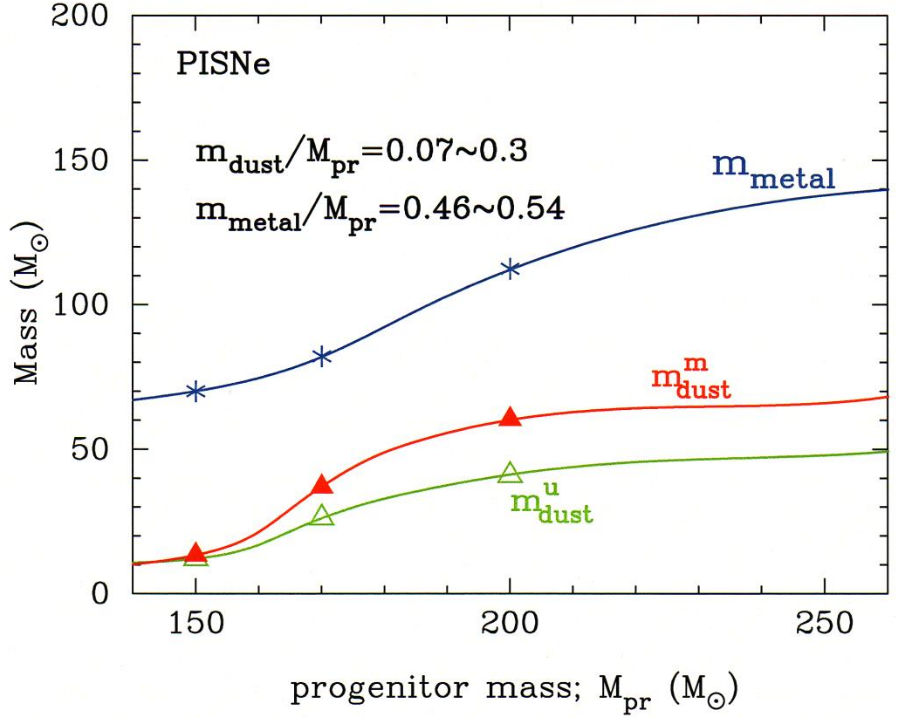

- C, SiO2, and Fe grains have lognormal-like size distribution, while the other grains have power-law size distribution

- The composition and size distribution of dust formed are almost independent of types of supernova

## average grain radius is smaller for PISNe than SNe II-P

# 2-4. Total mass of dust formed in the ejecta



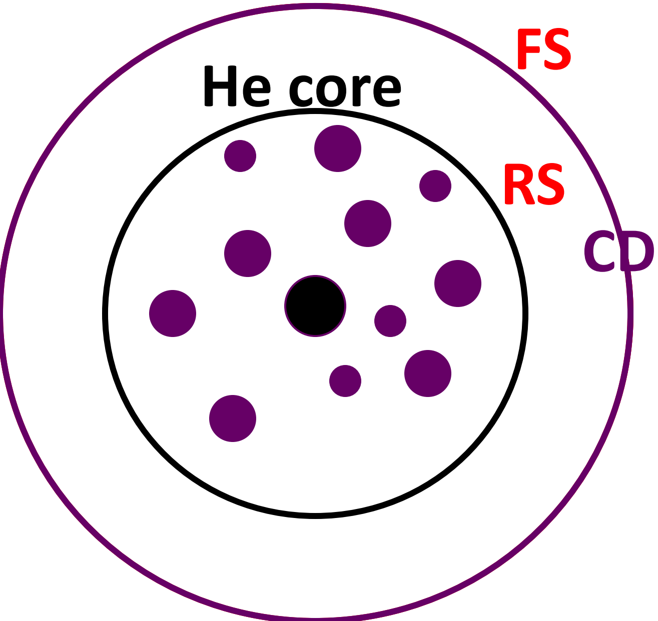




- **Total mass of dust is higher for a higher progenitor mass ($M_{ZAMS}$)**
  **SNe II : $m_{dust}$ = 0.1-1.5 $M_{sun}$, $m_{dust}$ / $m_{metal}$ = 0.2-0.3**
  **PISNe : $m_{dust}$ = 10-30 $M_{sun}$, $m_{dust}$ / $m_{metal}$ = 0.3-0.4**

- **almost all Fe, Mg, and Si are locked up in dust grains, while most of C and O remain in the gas-phase (such as CO)**
  **➔ dust-to-metal mass ratio is not high for SNe II**

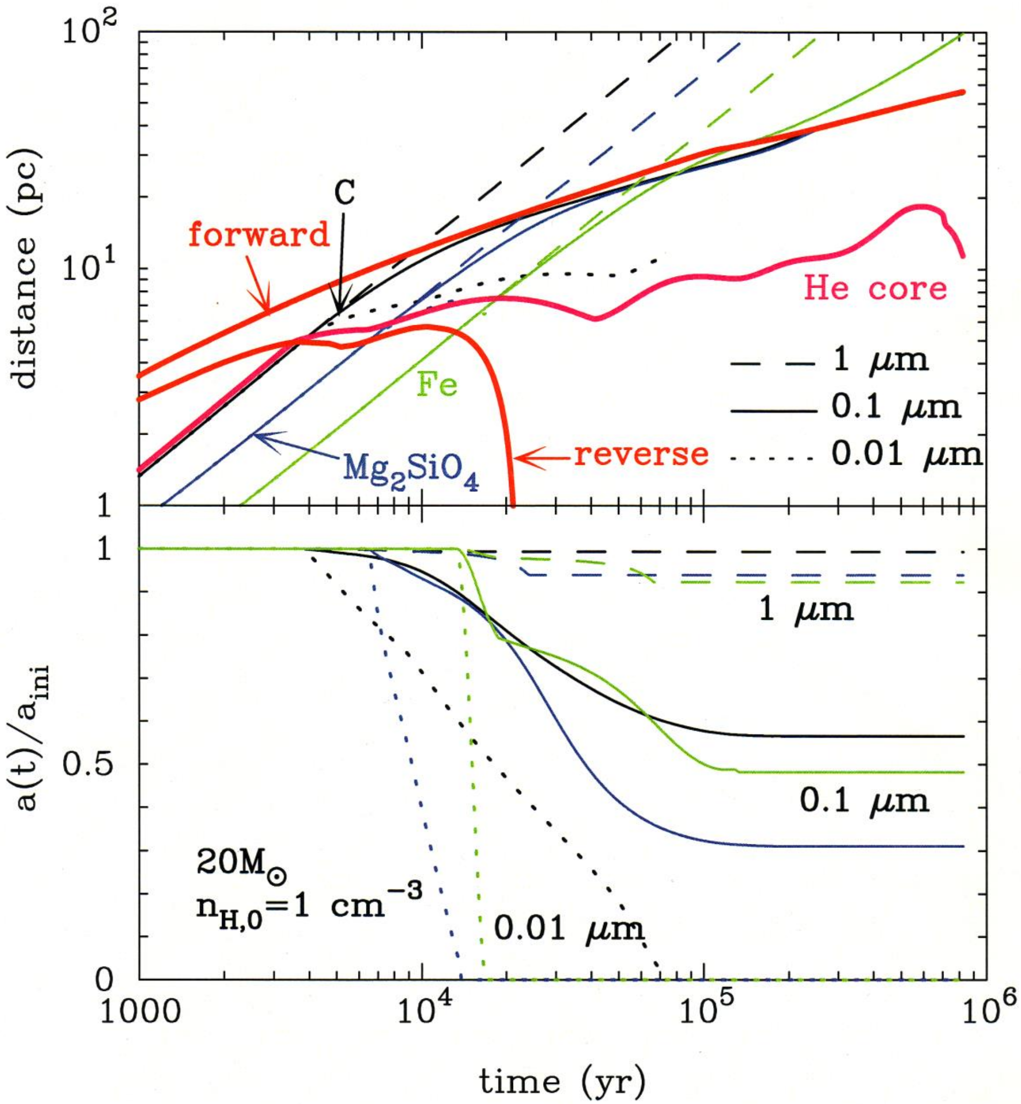
# Evolution of dust in SN remnants

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



# 2-5. 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)x$10^3$ yr**

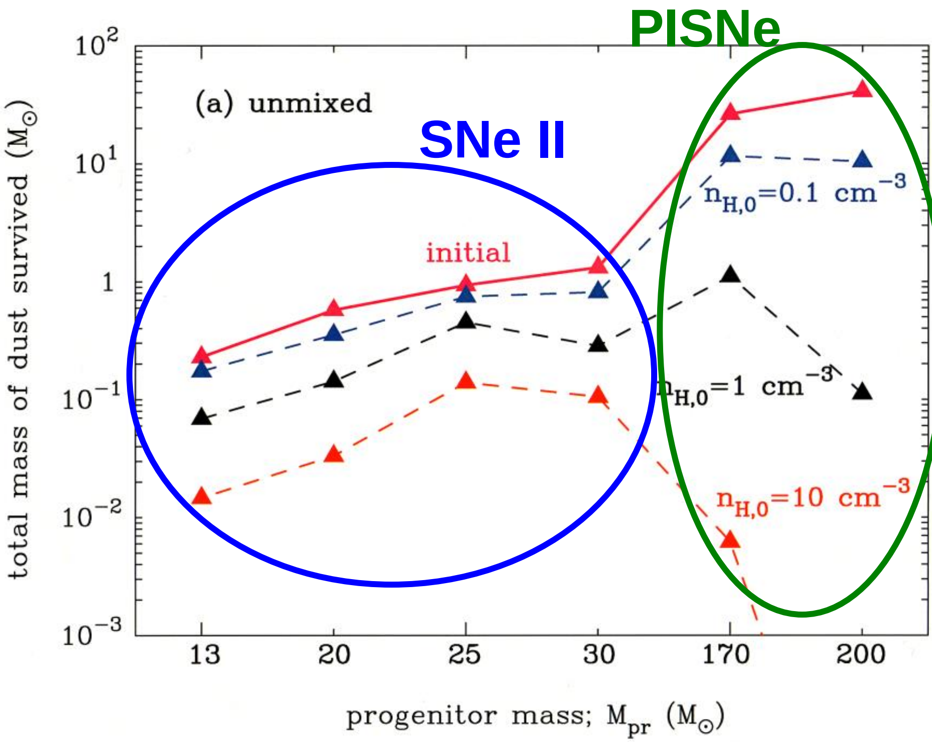
**The evolution of dust heavily depends on the initial radius and composition**

**$a_{ini}$ = 0.01 μm (dotted lines)**
**➔ completely destroyed**

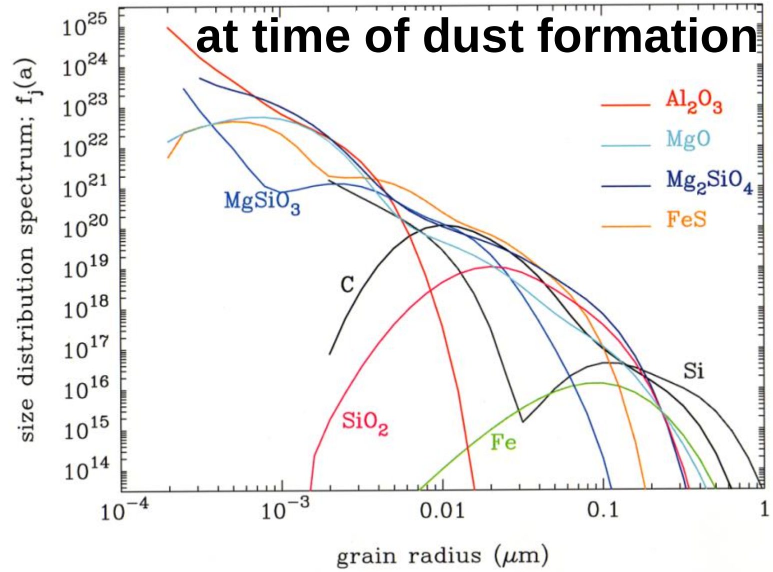
**$a_{ini}$ = 0.1 μm (solid lines)**
**➔ trapped in the shell**

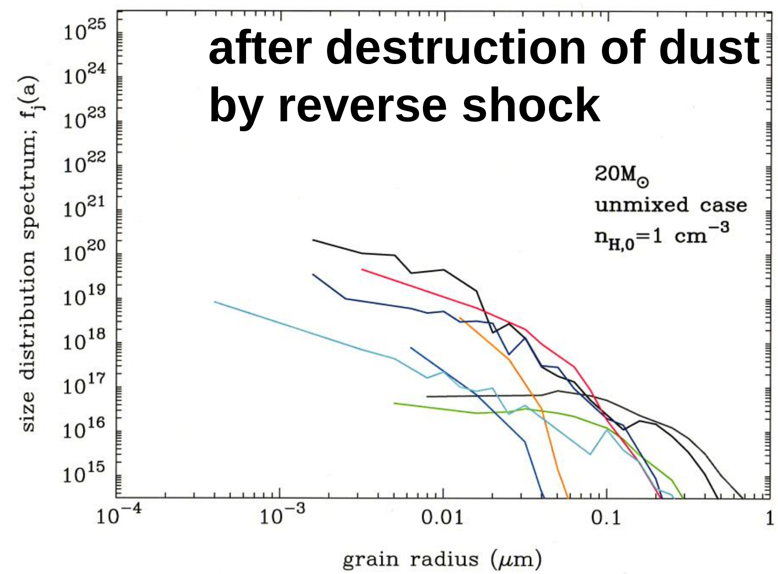
**$a_{ini}$ = 1 μm (dashed lines)**
**➔ injected into the ISM**

# 2-6. Dust mass and size ejected from SN II-P




**Nozawa+07, ApJ, 666, 955**




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

**size distribution of dust after the shock-destruction is domimated by large grains (> 0.01 μm)**

# 2-7. Summary of dust production in Pop III SNe

- Various grain species can condense in the ejecta
  ➔ almost all Fe, Mg, and Si are locked up in grains

- The fate of newly formed dust within 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 dust injected into the ISM decreases with increasing the ambient gas density

  for $n_{H,0}$ = 0.1-1 $cm^{-3}$

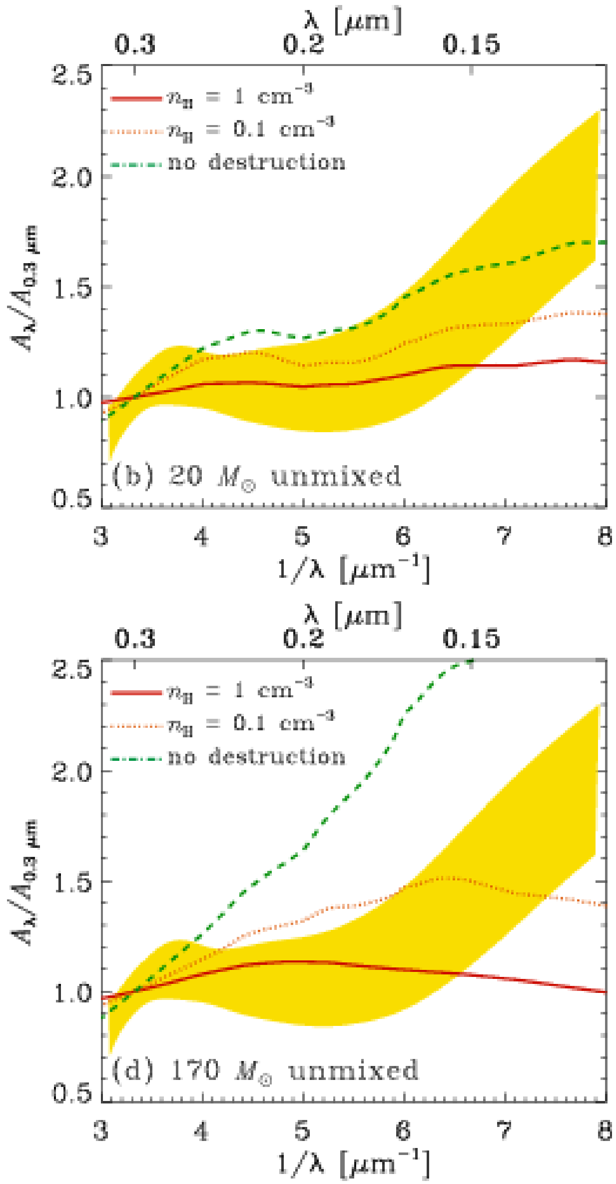
  SNe II-P ➔ $M_{dust}$ = 0.1-0.8 $M_{sun}$

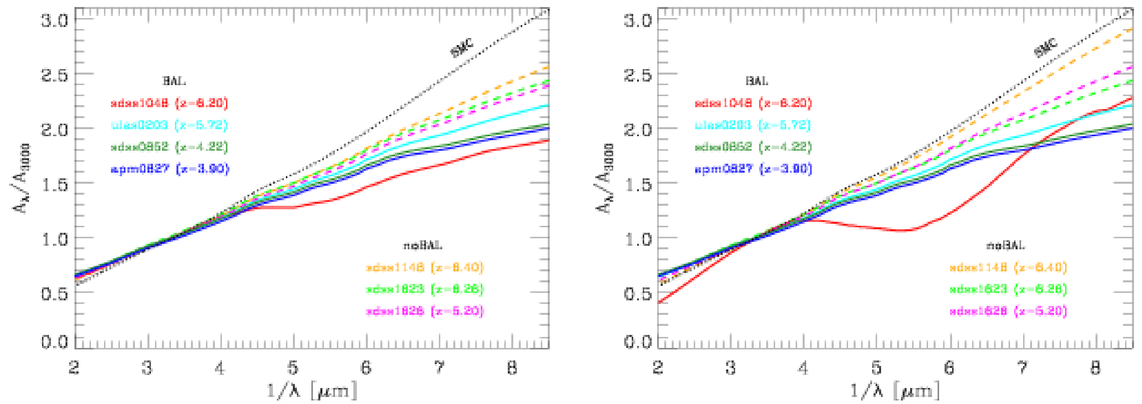
  ➔ significant contribution to dust budget at high z

# 3. Extinction curves expected in high-z galaxies

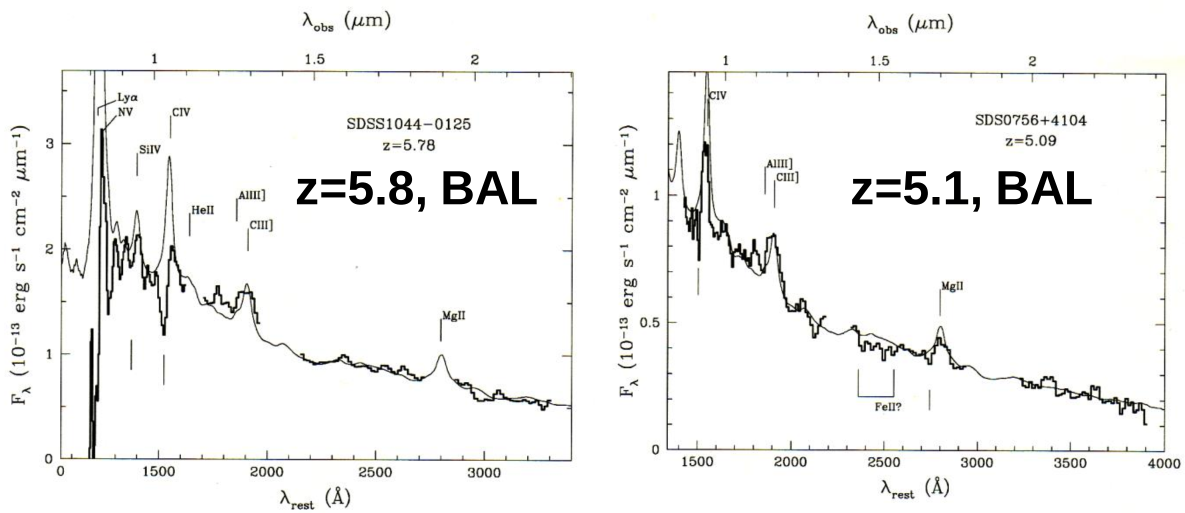
# 3-1. Flattened extinction curves at high-z

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




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




**Maiolino+04, A&A, 420, 889**

# 3-2. Discussion on high-z extinction curves

average radii of dust grains ejected from SNe are large (~0.1 μm)

- extinction curve expected from SN dust is flat
- consistent with a tendency that the extinction curves observed for high-z objects are flat

➔ these seem to support the idea that SNe II are the main dust sources in the early universe

## ○ concerns and questions

- too flat extinction curves, compared with the observations?
- only SN dust can explain a massive amount of dust observed at high redshifts?
- grain growth is needed? (which enhances the size of grains)

➔ extinction curves become much flatter?
➔ grain growth can take place efficiently in such an early epoch?

# 3-3. Rapid grain growth at high-z objects?

## grain growth : accretion of gas-phase metals onto pre-existing dust,
## which works more efficiently in denser molecular clouds

○ timescale of grain growth (gas accretion timescale onto dust)

$\tau_{acc} = [\ (1/a)(da/dt)\ ]^{-1} = [\ (1/a)\ \alpha_s\ n_{metal}\ V_0 \langle v \rangle\ ]^{-1}$

$\sim 5 \times 10^7$ yr $(\alpha_s / 0.2)^{-1}\ (a / 0.01\mu m)\ (Z / 0.02)^{-1}\ (n_{gas} / 30 cm^{-3})^{-1}$

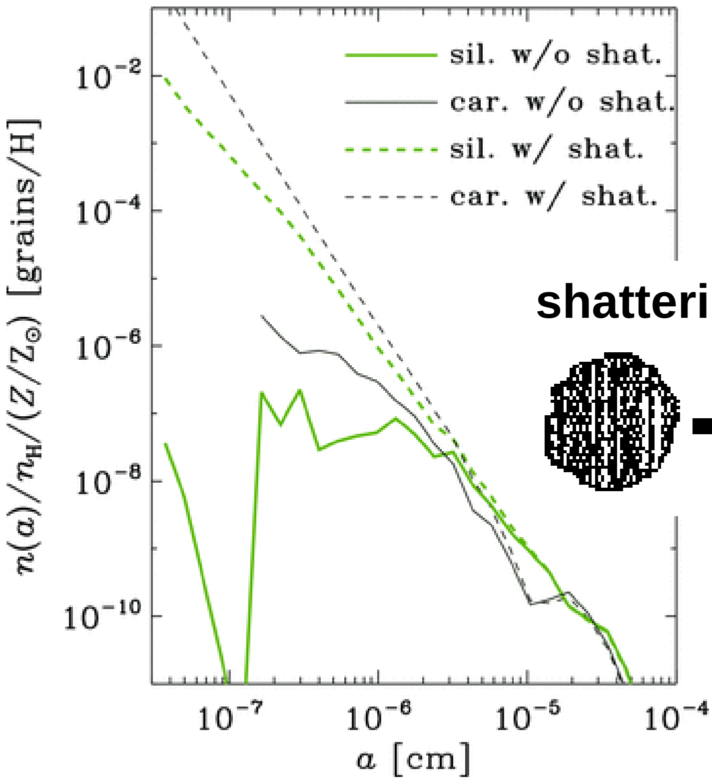
➔ grain growth is more efficient for higher metallicity and smaller grains

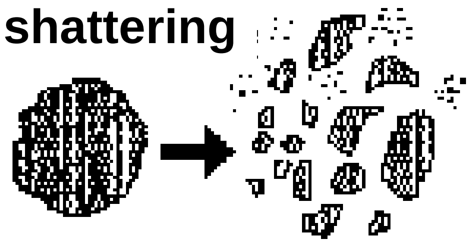
○ high-z quasars (age: ~0.5 Gyr)

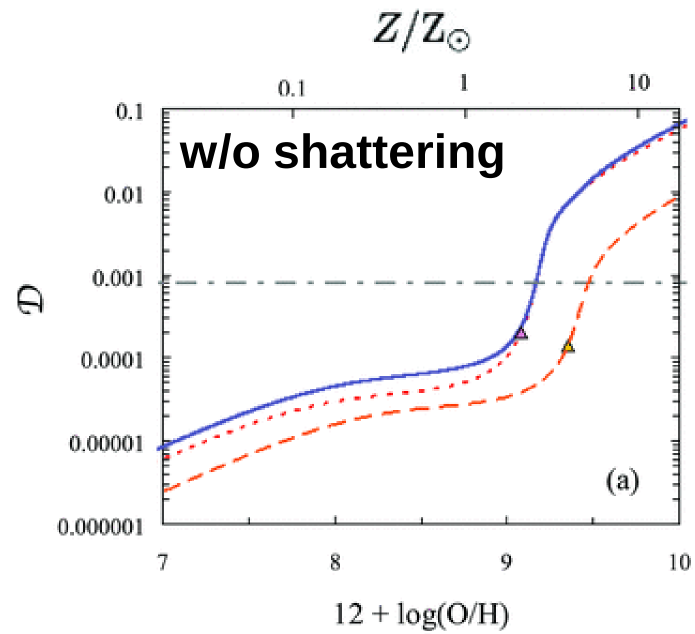
- metallicity ~ solar
- average radius of SN dust ~ 0.1 μm

$\tau_{acc} \sim 5 \times 10^8$ yr ➔ grain growth is not effective??

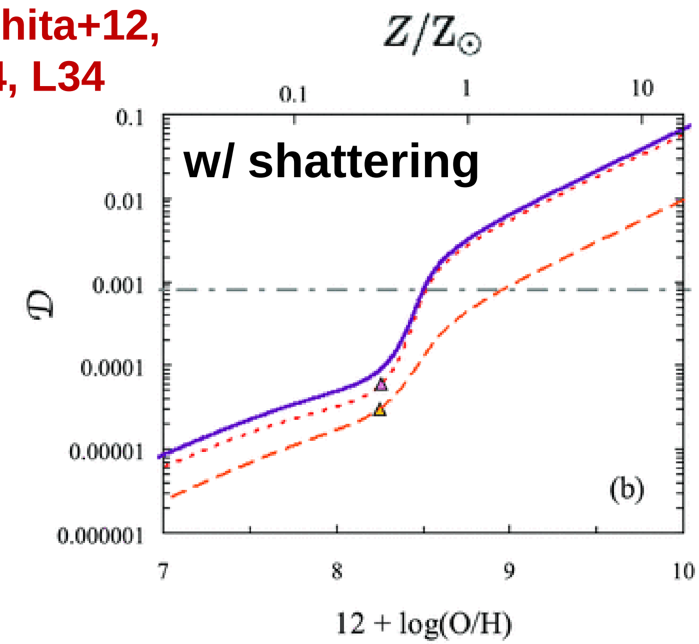
# 3-4. Effect of size distribution on grain growth



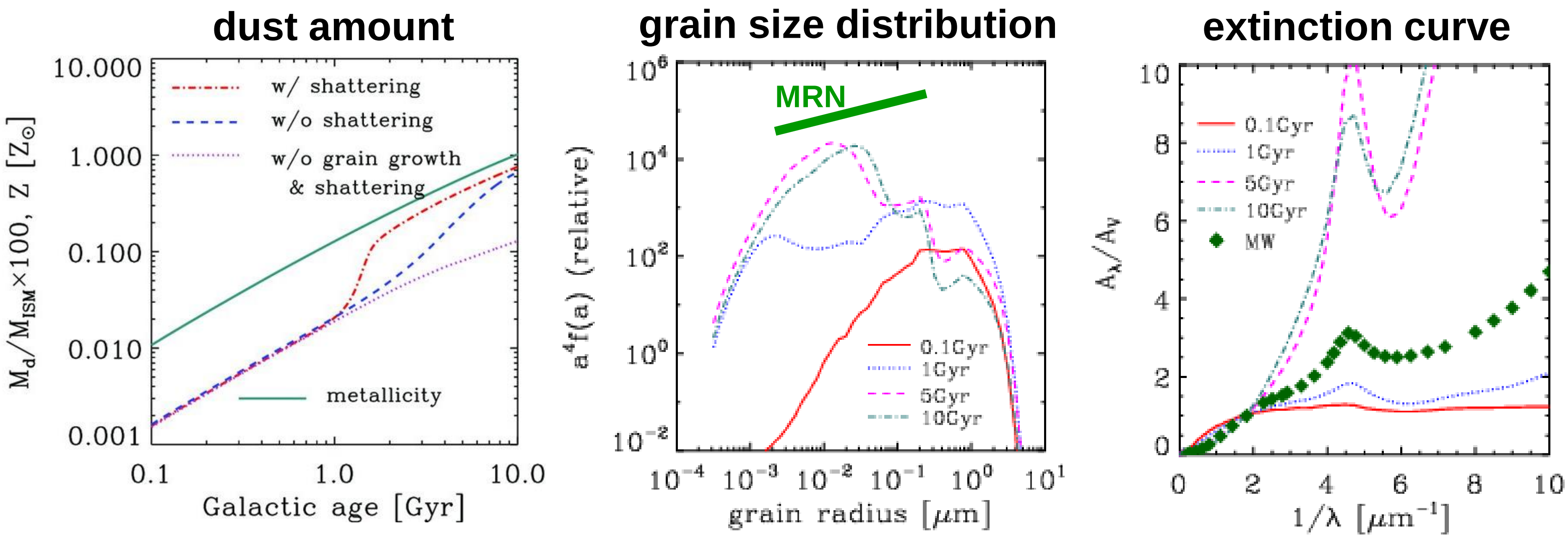

Kuo & Hirashita+12, MNRAS, 424, L34




- **w/o shattering :** grain growth becomes efficient at **super-solar** metallicity
- **w/ shattering :** grain growth becomes efficient at **sub-solar** metallicity

➔ **production of small grains due to shattering is needed for grain growth**

# 3-5. Evolution of extinction curves in galaxies

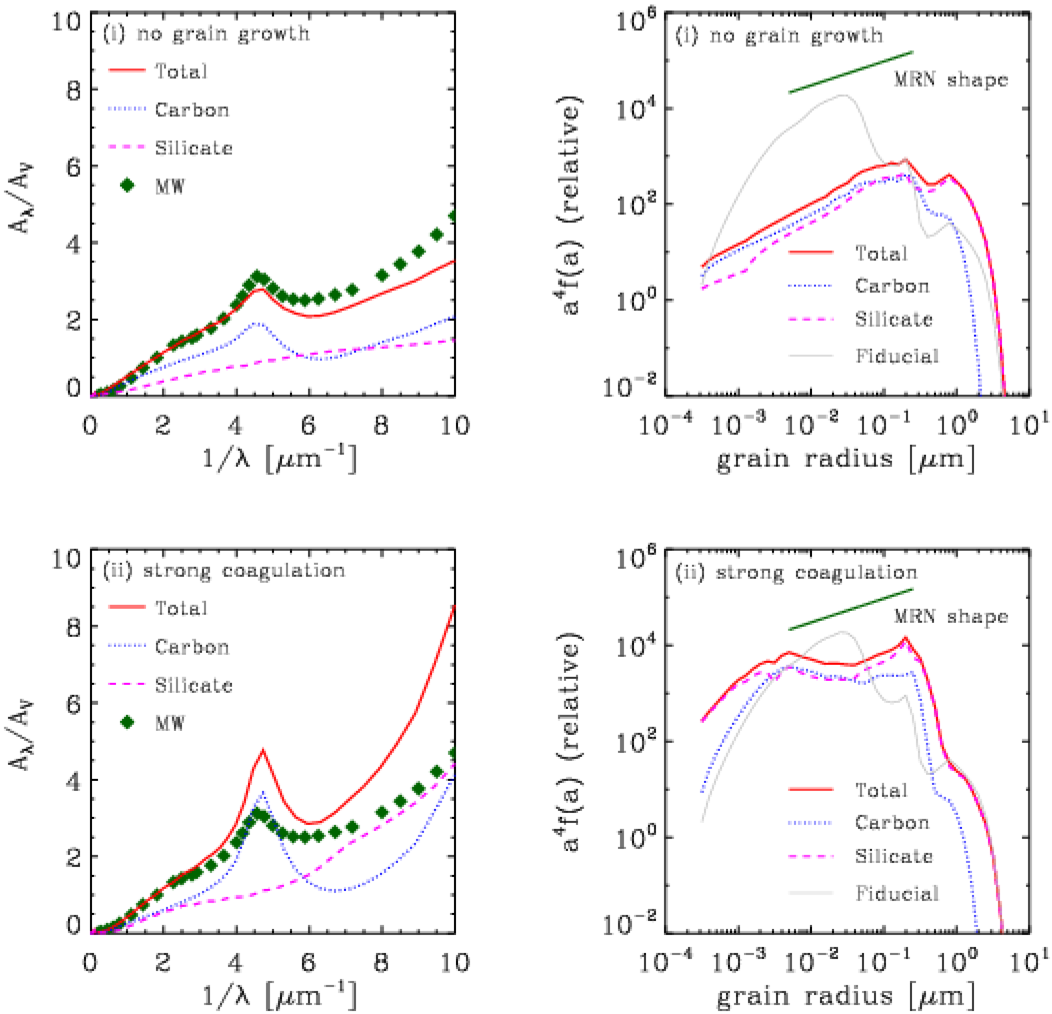


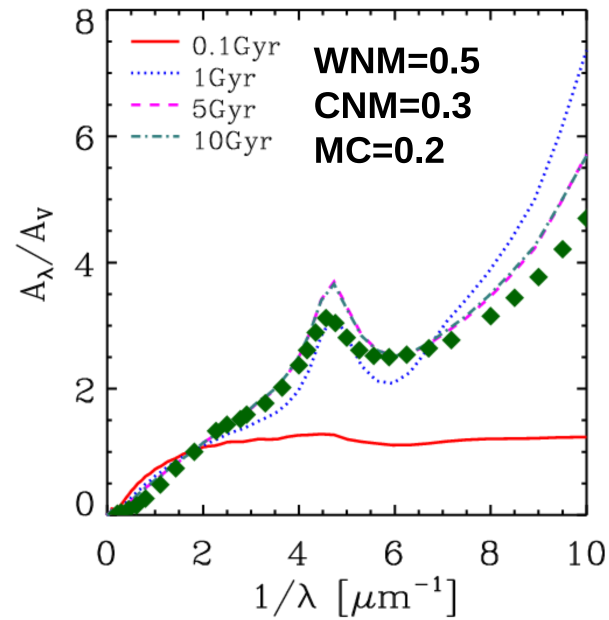

Asano, Takeuchi, Hirashita, TN+13, MNRAS, 432, 637
Asano, Takeuchi, Hirashita, TN+14, accepted for MNRAS, arXiv/1401.7121

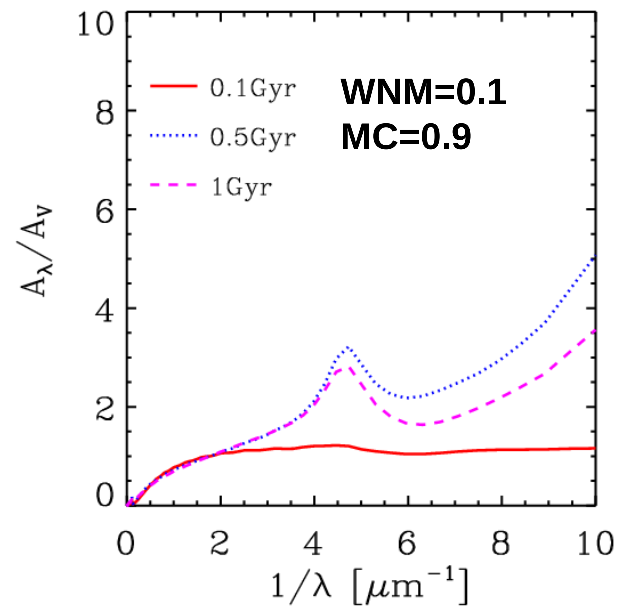
- **early phase** : formation of dust in SNe II and AGB stars
  ➔ large grains (~0.1 μm) are dominant ➔ flat extinction curve
- **middle phase** : shattering, grain growth due to accretion of gas metal
  ➔ small grains (< 0.03 μm) are produced ➔ steep extinction curve
- **late phase** : coagulation of small grains
  ➔ shift of peak of size distribution ➔ making extinction curve flatter

# 3-6. Reproducing the MW extinction curve

**Steep extinction curve is due to the presence of too much small grains**




**Asano, Takeuchi, Hirashita, TN+14**

# 3-7. Summary of dust properties at high z

- Large grains (~0.1 μm) that are supplied by SNe II can produce flat extinction curves as observed for high-z quasars
  ➔ but, it seems only the contribution from SNe II cannot explain a large amount of dust grains observed for high-z quasars
  ➔ growth of large grains is inefficient

- Shattering + grain growth can produce the dust mass as high as observed for high-z quasars
  ➔ but, the expected extinction curves are too steep

- The dust model which can explain the dust mass and extinction curve simultaneously is necessary

If coagulation of dust works very efficiently, it is likely that the extinction curves in both MW and high-z can be explained