2014/05/21

Evolution of dust size distribution and extinction curves in galaxies

Takaya Nozawa

(National Astronomical Observatory of Japan)

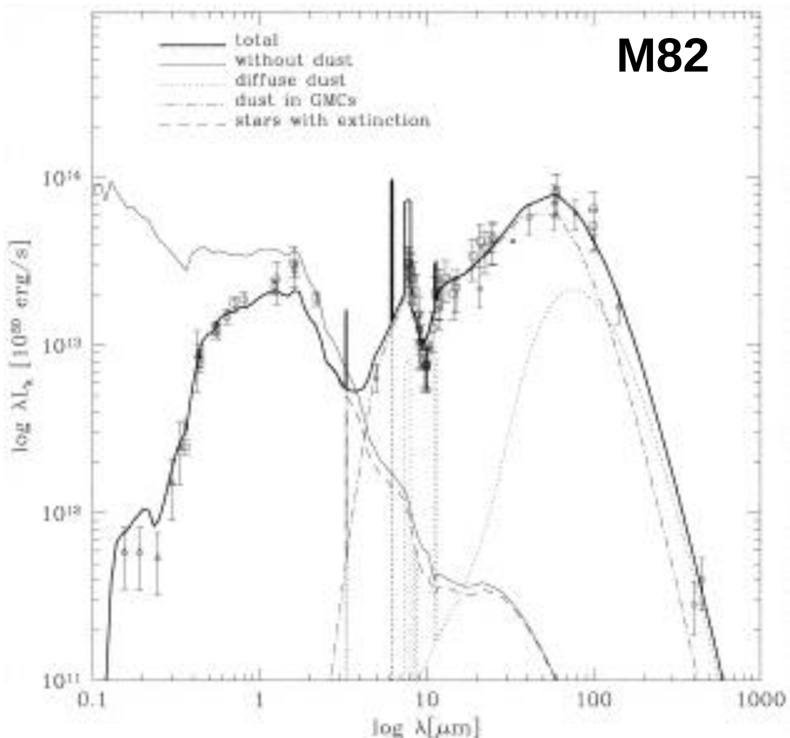
Collaborators:

Asano, S. Ryosuke (Nagoya University)
Takeuchi, T. Tsutomu (Nagoya University)
Hirashita, Hiroyuki (ASIAA)

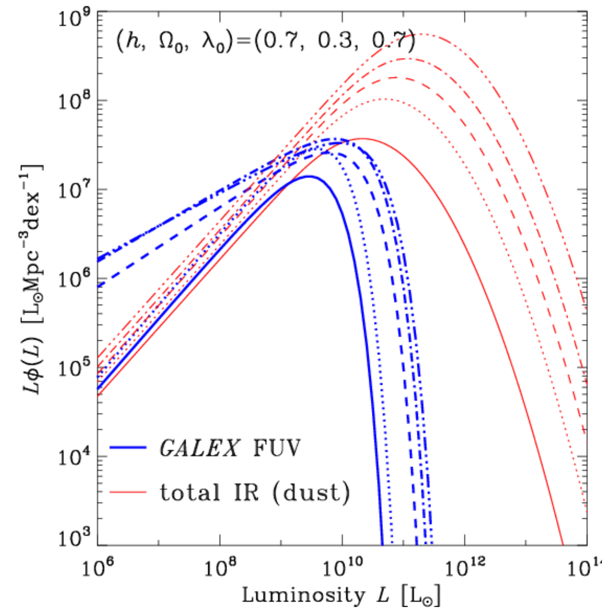
References

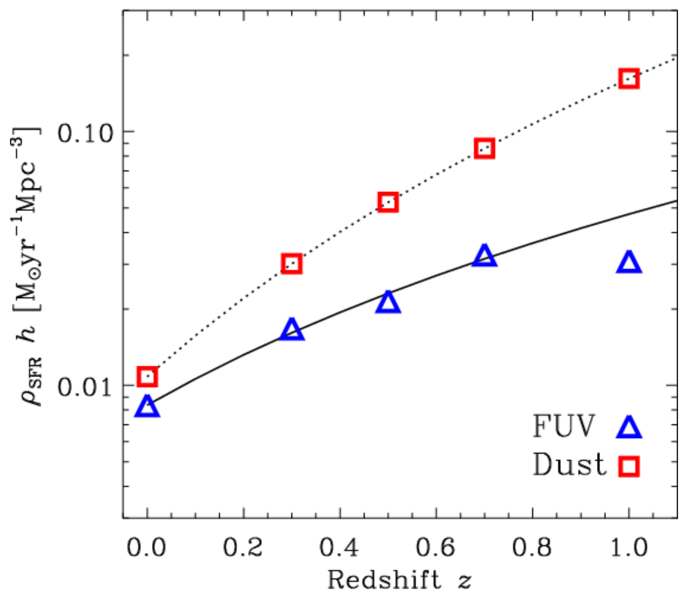
- Asano, Takeuchi, Hirashita, Nozawa (2013, MNRAS, 432, 637)
- Asano Takeuchi, Hirashita, Nozawa (2014, MNRAS, 440, 134)
- Asano, Nozawa, Hirashita, Takeuchi (2014 in prep.)

1-1. Dust alters the SEDs of galaxies



Silva+1998





Takeuchi+2005

Dust absorbs UV/optical lights and re-emits thermal emission in the infrared

70% of the star formation activity at 0.5 <z< 1.2 is obscured by dust

1-2. Aim of our study

to correct the obscuration by dust, many (observational) studies have assumed the MW, SMC, LMC extinction curves or the Calzetti extinction (attenuation) law

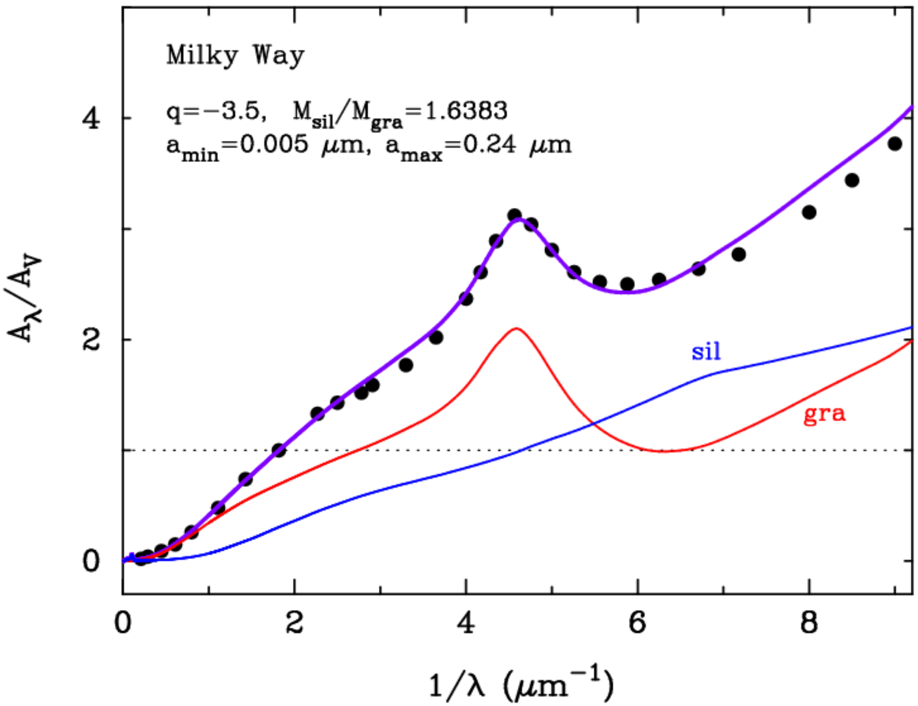
➔ **however, the size distribution of interstellar dust must change as the galaxy evolves**

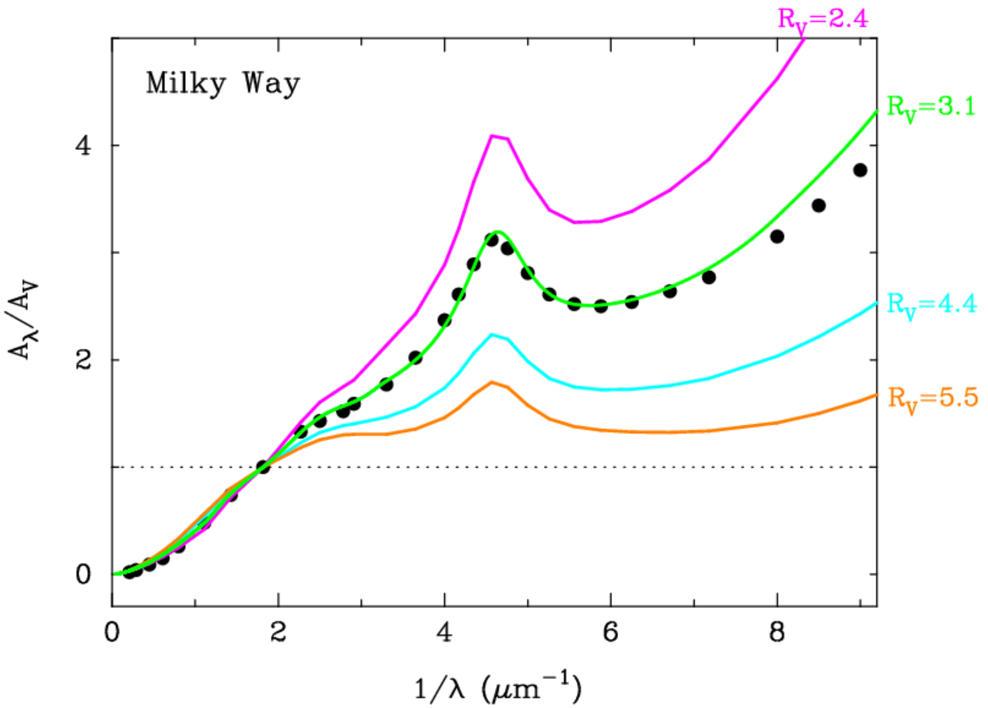
we construct the evolution model of grain size distribution, with the aim at understanding how the extinction curve is modified in the course of galaxy evolution

・ dust processes considered in our works

- **production of dust in SNe II and AGB stars**
- **destruction of dust by interstellar shocks**
- **grain growth due to metal accretion in molecular clouds**
- **shattering and coagulation due to grain-grain collisions**

2-1. Extinction curves in the Milky Way





○ **MRN dust model**

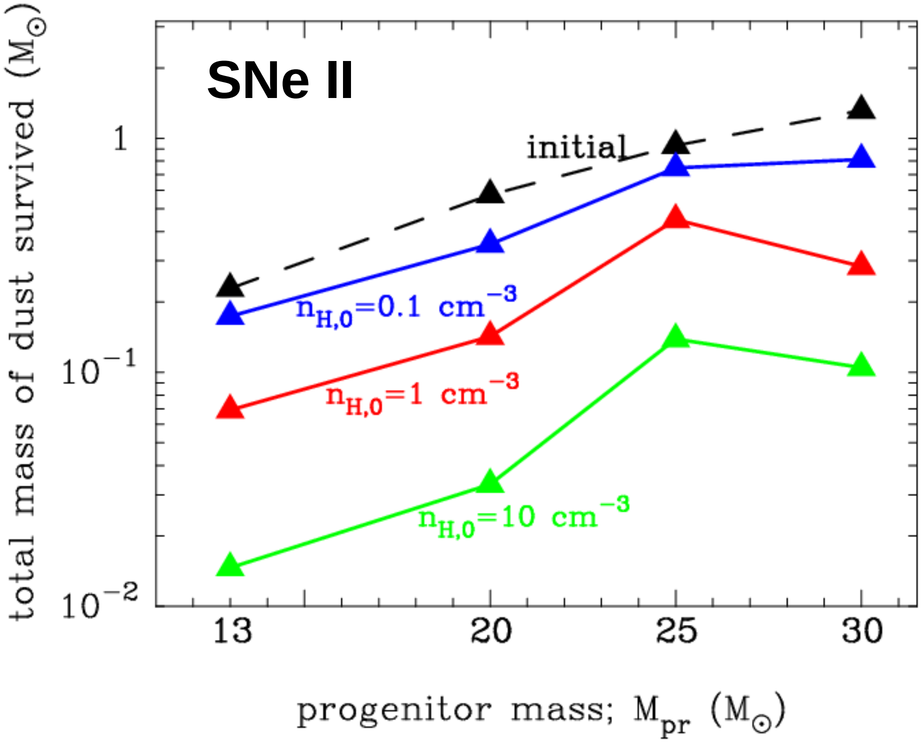
(Mathis, Rumpl, & Nordsieck 1977)

- **composition :**
  silicate and graphite
- **size distribution :**
  n(a) ∝ a^{-q} with q=3.5,
  0.005 μm ≤ a ≤ 0.25 μm

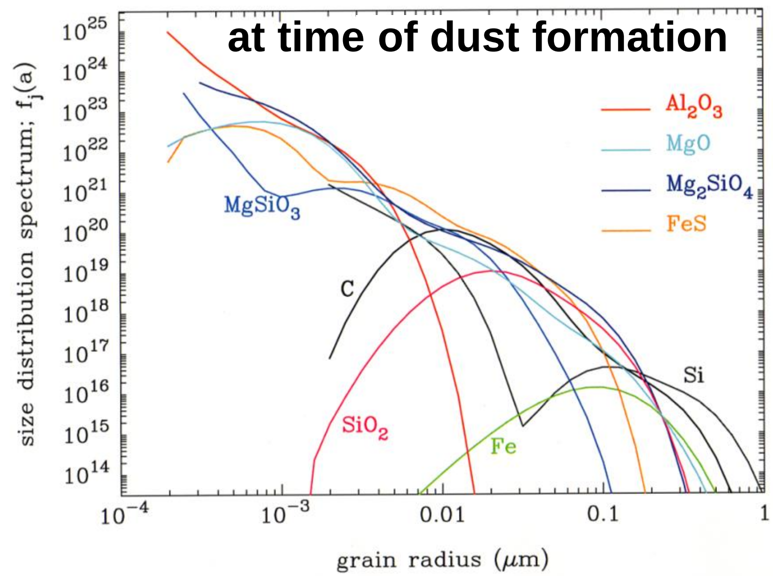
total-to-selective extinction ratio
$R_V = A_V / (A_B - A_V)$

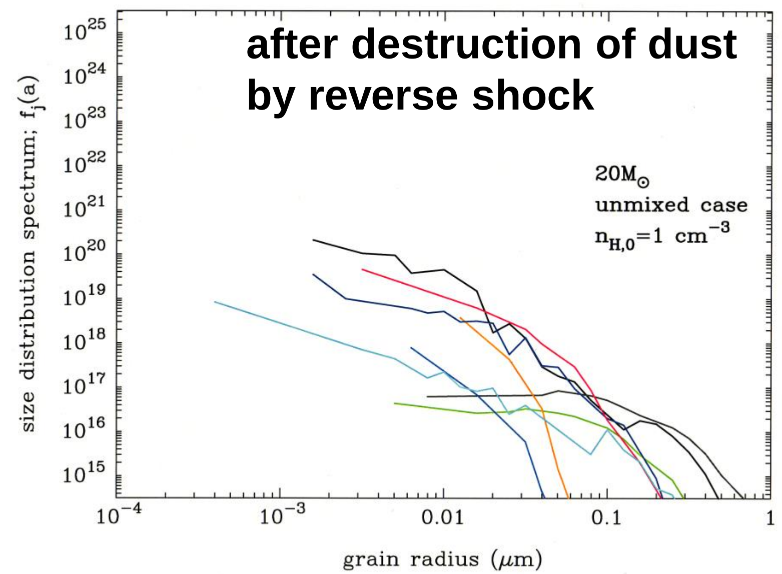
- **small grains (small Rv)**
  ➜ steep extinction curve
- **large grains (large Rv)**
  ➜ flat extinction curve

2-2. Properties of dust ejected from SN II-P



Nozawa+07, ApJ, 666, 955

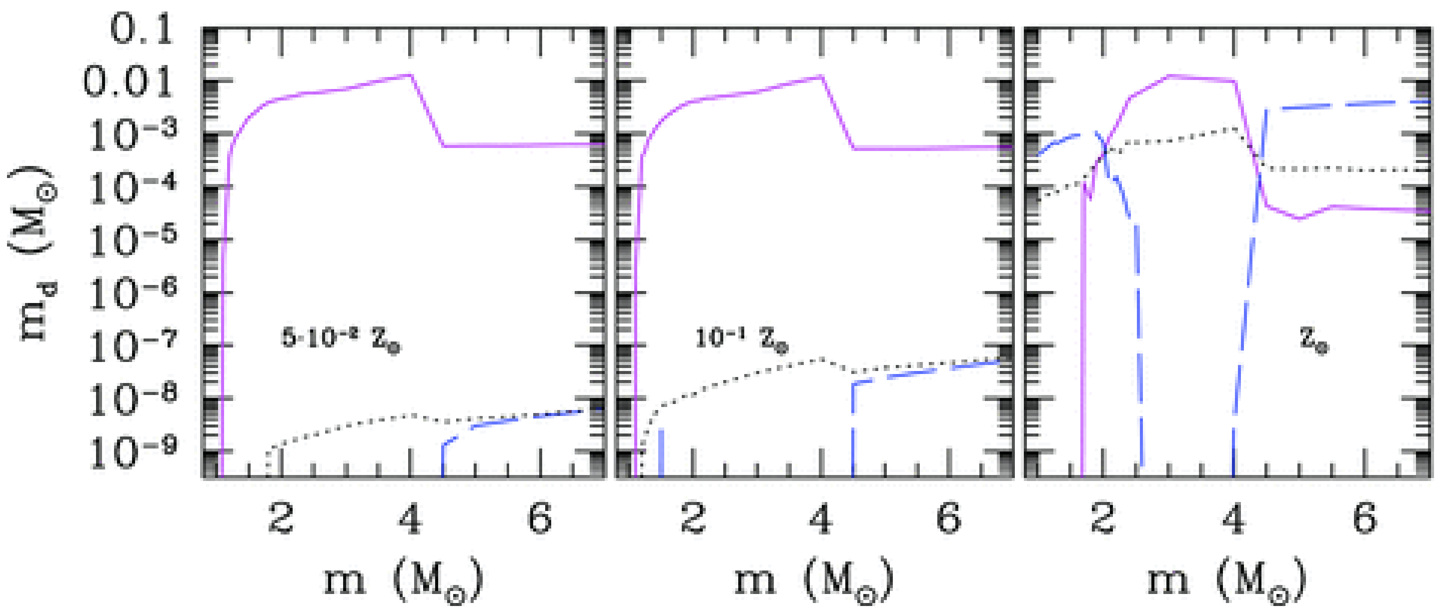




mass of dust grains injected from a SN II into the ISM:
0.07-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

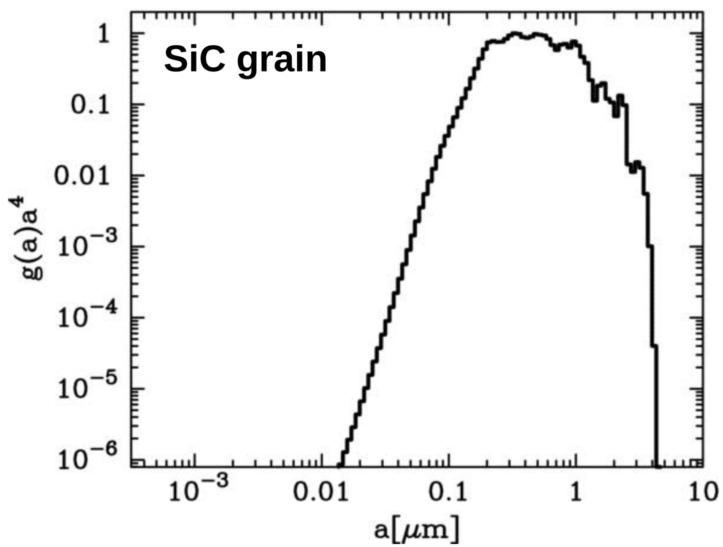
size distribution of dust which is ejected from SNe II is domimated by large grains (> 0.01 μm)

2-3. Properties of dust ejected from AGB stars



solid: carbon
dashed: silicate
dotted: the others

Zhukovska & Gail 2008; Valiante+2009

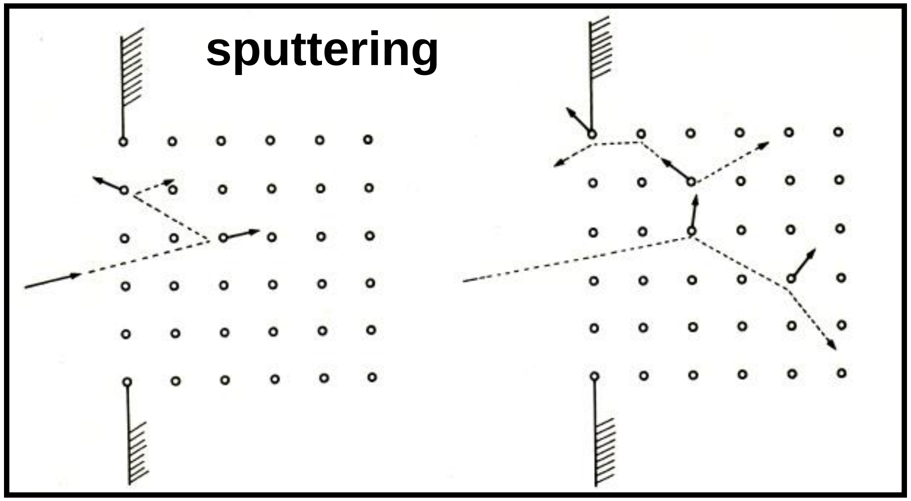


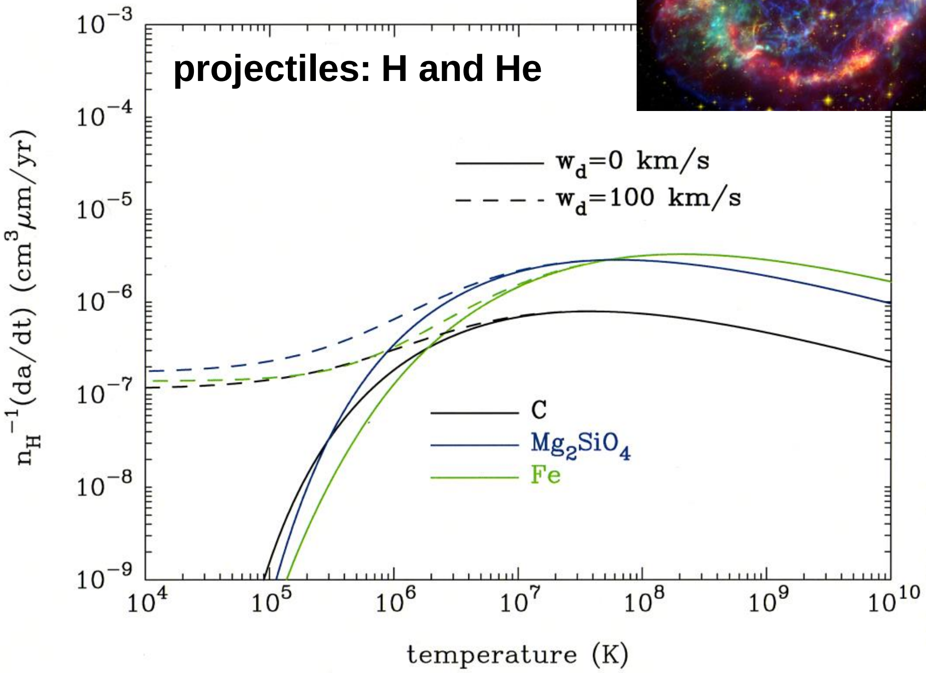
Yasuda & Kozasa 2012

mass of dust grains injected from a AGB star into the ISM:
0.001-0.01 Msun (Mstar > 1 Msun)

average radius of dust ejected from AGB stars is considered to be large (a = 0.1-1.0 μm)

2-4. Destruction of dust in SN shocks





sputtering: ejection of atoms from dust surface

- **erosion rate by sputtering: $da/dt \sim 10^{-6}\ (n_H\ /\ 1.0\ cm^{-3})\ \mu m\ yr^{-1}$**

  (e.g., Nozawa+2006, ApJ, 648, 435)

- **timescale of dust destruction by SN shocks, τ_{dest}**

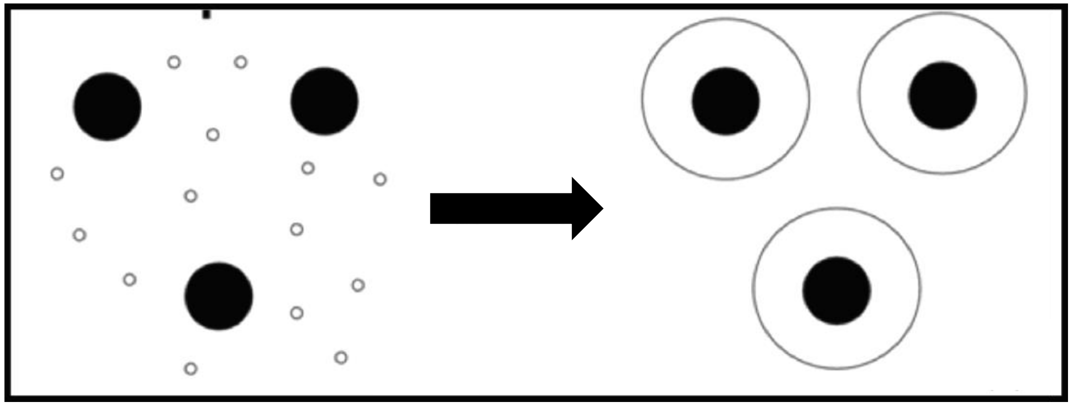
$$\tau_{dest} = [\ (1/M_{dust})(dM_{dust}/dt)\ ]^{-1} = [\ \varepsilon\ M_{swept}\ R_{SN}\ /\ M_{gas}\ ]^{-1}$$

$$\sim 5\times10^8\ yr\ (\varepsilon\ /\ 0.3)^{-1}\ (M_{swept}\ /\ 3000\ M_{sun})^{-1}\ (R_{SN}\ /\ 0.02\ yr^{-1})^{-1}$$

$$\times\ (M_{gas}\ /\ 10^{10}\ M_{sun})$$

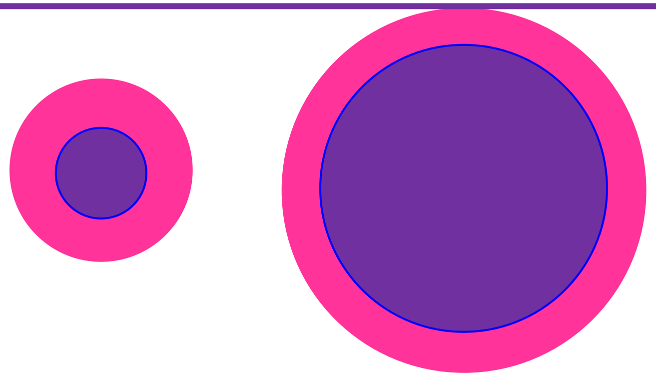
2-5. Growth of dust in molecular clouds

grain growth



Sirono+2013

grain growth:
accretion of gas-phase heavy elements onto pre-existing dust



・ timescale of grain growth, τ_{grow}

$$\tau_{grow} = [\ (1/m_d)(dm_d/dt)\ ]^{-1} = [\ (1/3a)\ \alpha_s\ n_{metal}\ V_0\ \langle v \rangle\ ]^{-1}$$

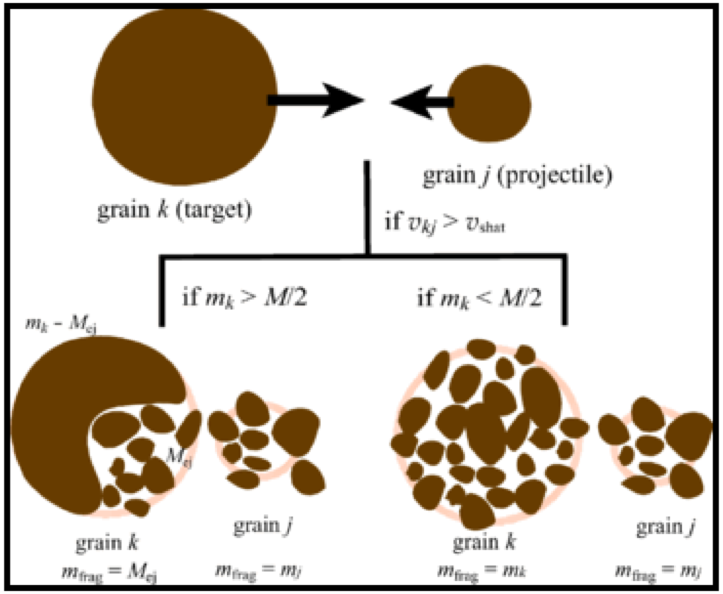
$$\sim 2\times10^{7}\ \mathrm{yr}\ (\alpha_s / 0.2)^{-1}\ (a / 0.01\ \mu m)\ (Z / 0.02)^{-1}\ (n_{gas} / 30\ \mathrm{cm}^{-3})^{-1}$$

➔ **grain growth is more efficient for a higher gas density, a higher metallicity (higher abundance of metals), and a smaller grain**

grain growth is more efficient for a large surface-to-volume ratio of dust grains

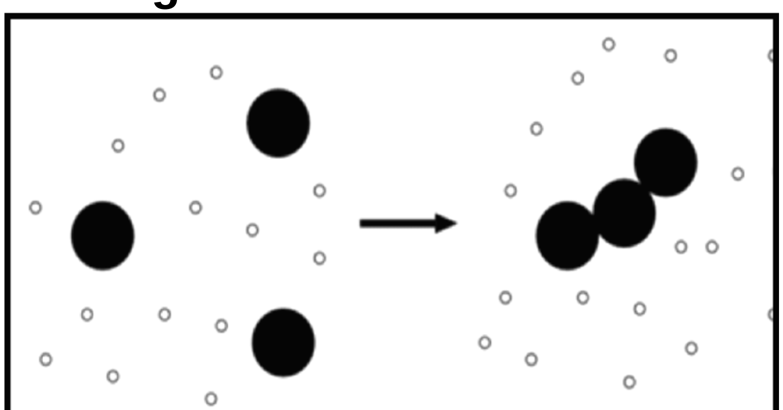
2-6. Shattering and coagulation of dust

shattering



Hirashita & Yan+2009

coagulation



Sirono+2013

- **shattering at $v_{\rm rel} > v_{\rm shat}$**
  where $v_{\rm shat}$ = 1-3 km/s
- **coagulation at $v_{\rm rel} < v_{\rm coag}$**
  where $v_{\rm coag}$ = 0.01-0.1 km/s

in the interstellar turbulence, $v_{\rm rel}$ is higher for a lower gas density and a larger grain radius (Yan+2004)

These processes do not reduce dust mass but change size distribution

- **timescale of shattering, $\tau_{\rm shat}$**

$$\tau_{\rm shat} \sim 1\ (\tau_{\rm SF} / {\rm Gyr})^{1/2}\ {\rm yr}$$

grain-grain collision processes
becomes efficient once dust
grains are enriched sufficiently

2-7. Dust evolution model (1)

- one-zone closed-box galaxy model (no inflow and no outflow)

- star formation rate (SFR)
  Schmidt law with n = 1: $SFR(t) = M_{gas}(t)/\tau_{SF}$ with $\tau_{SF} = 5$ Gyr

- initial mass function (IMF)
  Salpeter IMF: $\varphi(m) = m^{-q}$ with $q=2.35$ for $M_{star} = 0.1\text{-}100\ M_{sun}$

- two dust species
  graphite (carbonaceous grains)
  astronomical silicate (silicate and the other grains species)

- two-phase ISM
  WNM (warm neutral medium): $T = 6000$ K, $n = 0.3$ cm^{-3}
  CNM (cold neutral medium): $T = 100$ K, $n = 30$ cm^{-3}
  ➜ $\eta_{WNM} = \eta_{CNM} = 0.5$

2-8. Dust evolution model (2)

- mass evolution of dust ***ΔM*d*(a,t)*** with radii between ***a*** and ***a+da***

xSFR(t), astration

$$\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t} = -\frac{\Delta M_{\mathrm{d}}(a,t)}{M_{\mathrm{ISM}}(t)} + \Delta Y_{\mathrm{d}}(a,t)$$

dust production by SNe II and AGB stars

$$-\frac{M_{\mathrm{swept}}}{M_{\mathrm{ISM}}(t)}\gamma_{\mathrm{SN}}(t)\left[\Delta M_{\mathrm{d}}(a,t) - m(a)\int_0^{\infty}\xi(a,a')\Delta a f(a',t)\mathrm{d}a'\right]$$

shock destruction

$$+\eta_{\mathrm{CNM}}\left[m(a)\Delta a\frac{\partial[f(a,t)]}{\partial t}\right]$$

grain growth

$$+\eta_{\mathrm{WNM}}\left[\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{shat,WNM}} + \eta_{\mathrm{CNM}}\left[\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{shat,CNM}}$$

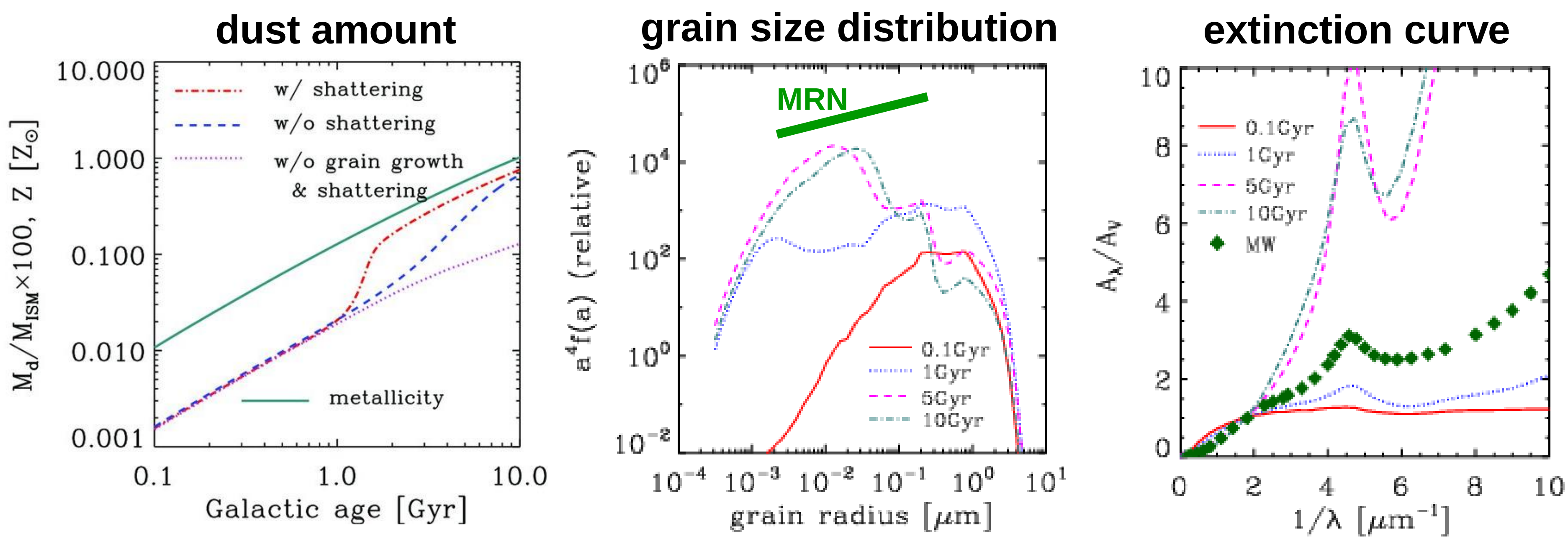
shattering

$$+\eta_{\mathrm{WNM}}\left[\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{coag,WNM}} + \eta_{\mathrm{CNM}}\left[\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{coag,CNM}},$$

coagulation

$$\Delta Y_{\mathrm{d}}(a,t) = \int_{m_{\mathrm{cut}}(t)}^{100\ \mathrm{M}_{\odot}} \Delta m_{\mathrm{d}}(m, Z(t-\tau_m), a)\phi(m)\mathrm{SFR}(t-\tau_m)\mathrm{d}m,$$

3-1. Evolution of extinction curves in galaxies

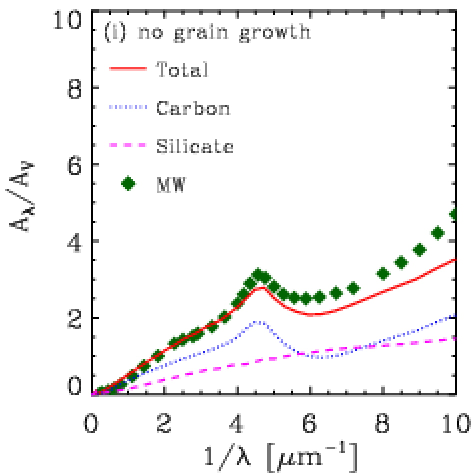


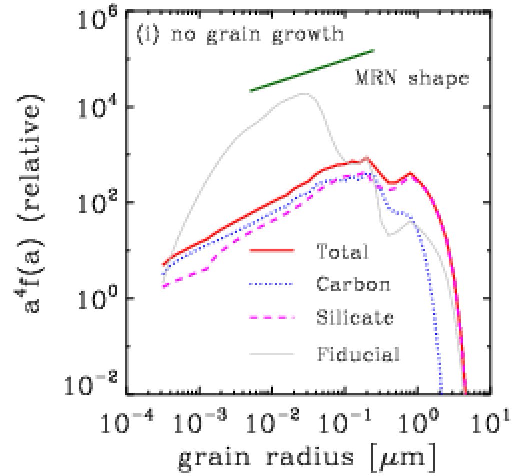
Asano, Takeuchi, Hirashita, TN+13, MNRAS, 432, 637
Asano, Takeuchi, Hirashita, TN+14, MNRAS, 440, 134

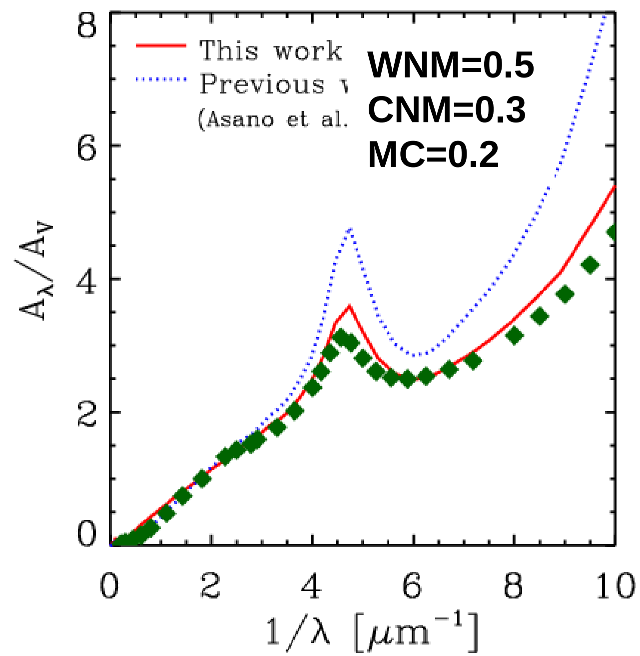
- **early phase** : formation of dust in SNe II and AGB stars
  ➔ large grains (~0.1 μm) are dominant ➔ flat extinction curve
- **middle phase** : shattering, grain growth due to accretion of gas metal
  ➔ small grains (< 0.03 μm) are produced ➔ steep extinction curve
- **late phase** : coagulation of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

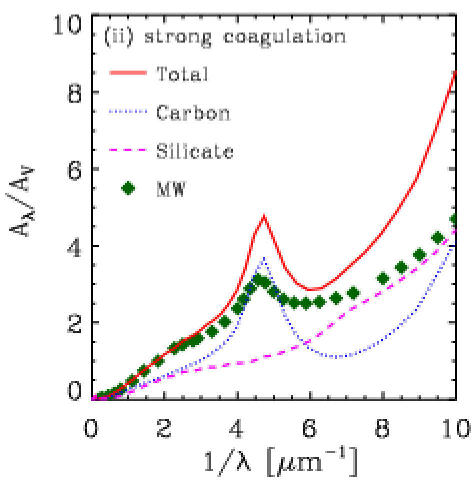
3-2. Reproducing the MW extinction curve

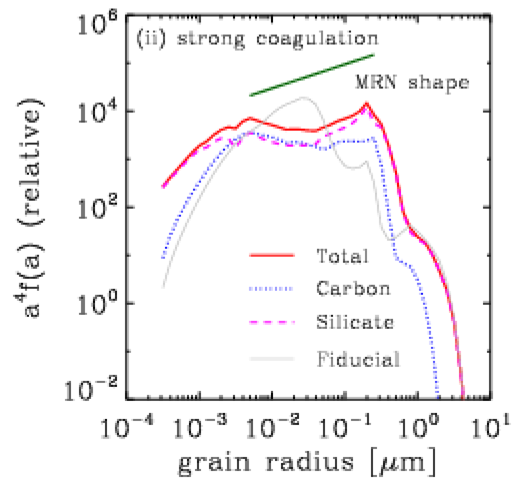
steep extinction curve is due to the presence of too much small grains











- **three-phase ISM**

▪ **WNM**
➜ **T = 6000 K, n = 0.3 cm^{-3}**

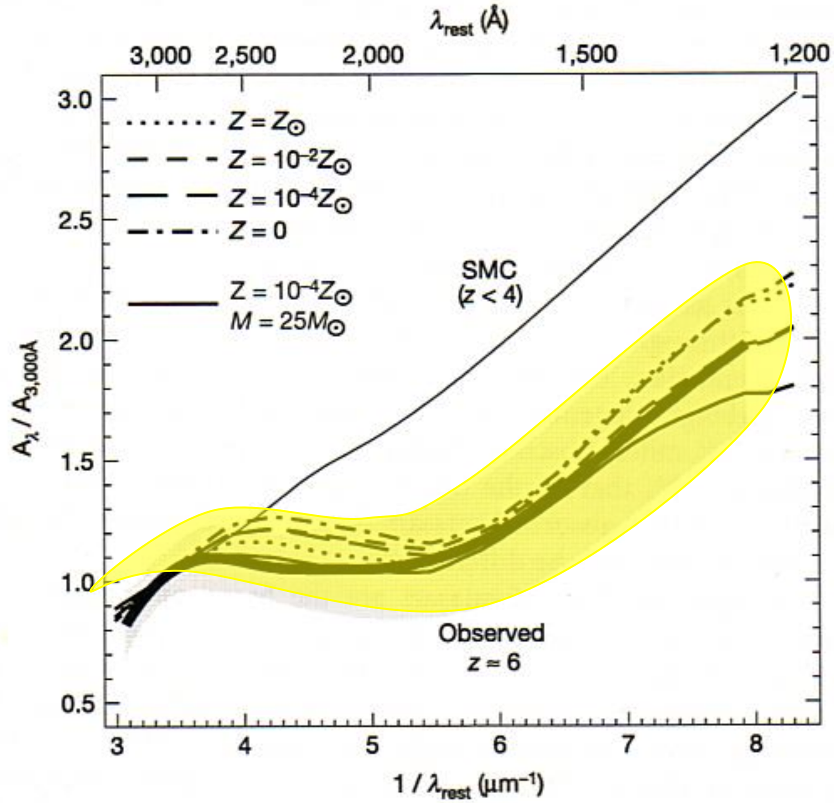
▪ **CNM**
➜ **T = 100 K, n = 30 cm^{-3}**

▪ **MC (molecular clouds)**
➜ **T = 25 K, n = 300 cm^{-3}**

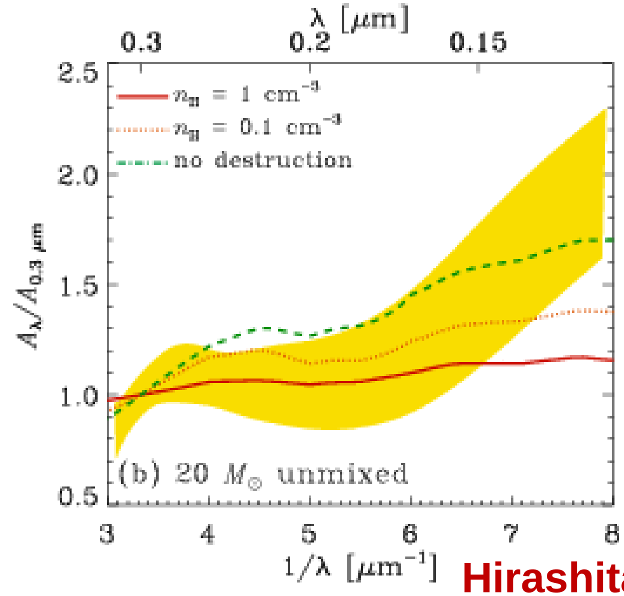
3-3. Extinction curves in high-z quasars

SDSS J1048+4637 at z=6.2 :

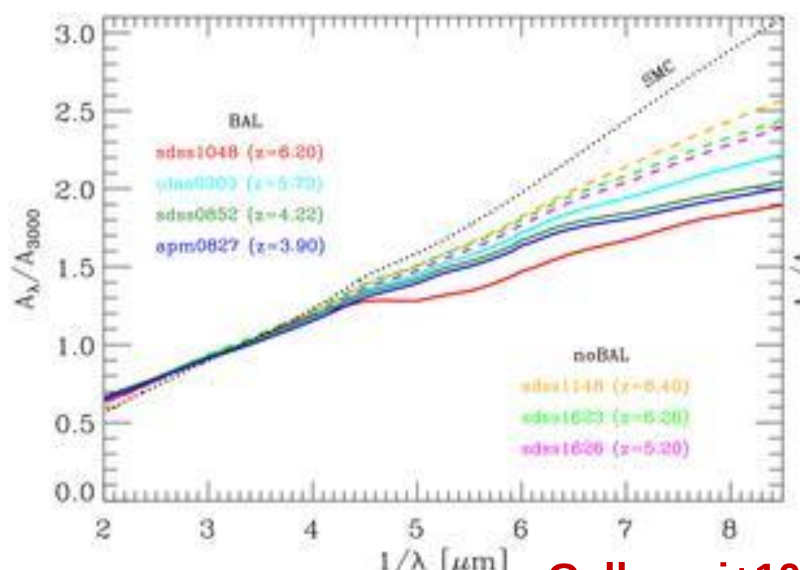
broad absorption line (BAL) quasars



Maiolino+2004, Nature, 431, 533



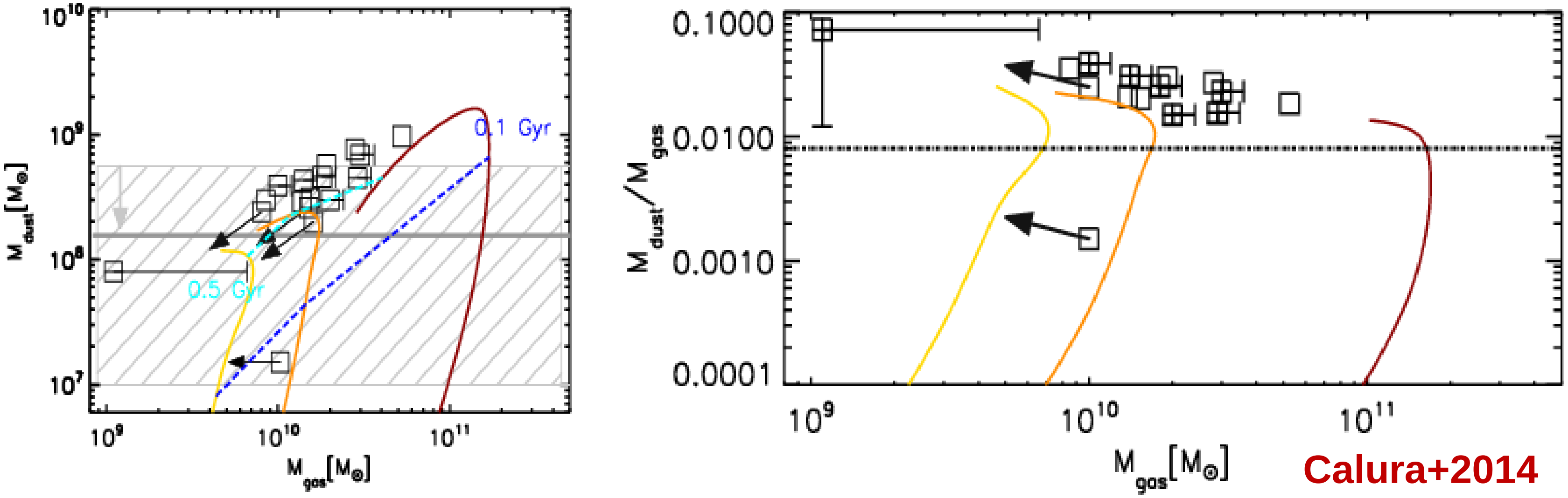
Hirashita+2008



Gallerani+10

➔ interstellar dust in the early universe is SN origin?

3-4. A large amount of dust in high-z quasars



Calura+2014

- **Huge amounts of dust grains are observed for the host galaxies of quasars at z < 5**

➜ it is suggested that the grain growth is needed to account for such massive dust contents

it seems only the contribution of dust from SNe II cannot explain

the observed amount of dust grains in high-z quasars

How can we explain the dust mass and unusual extinction curves observed for high-z quasars in a consistent way?

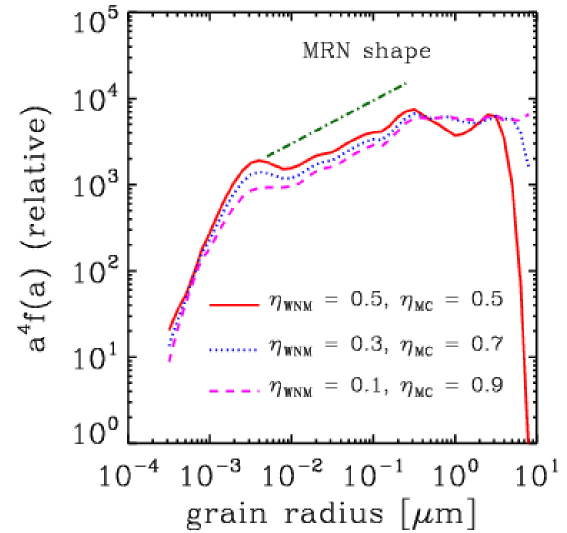
3-5. Explaining the high-z extinction curves

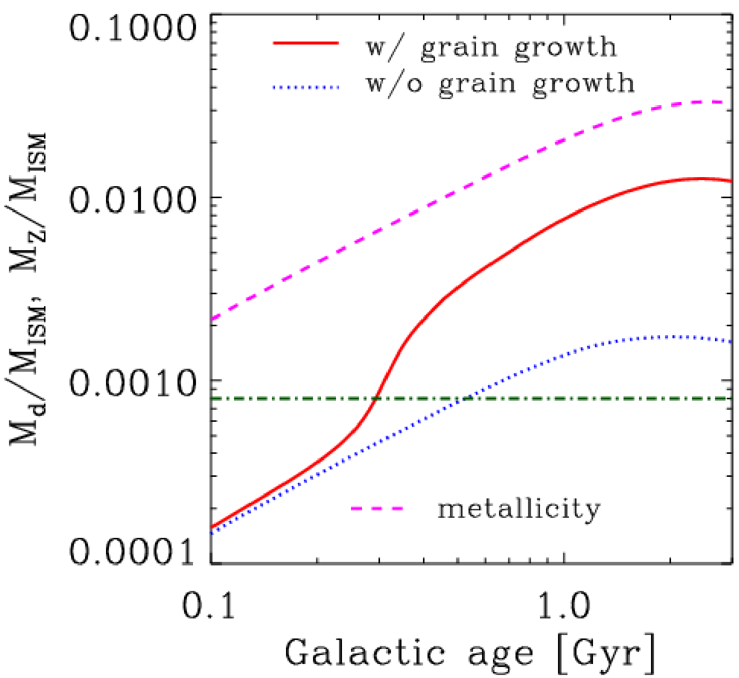
high-z quasar host: starburst galaxies

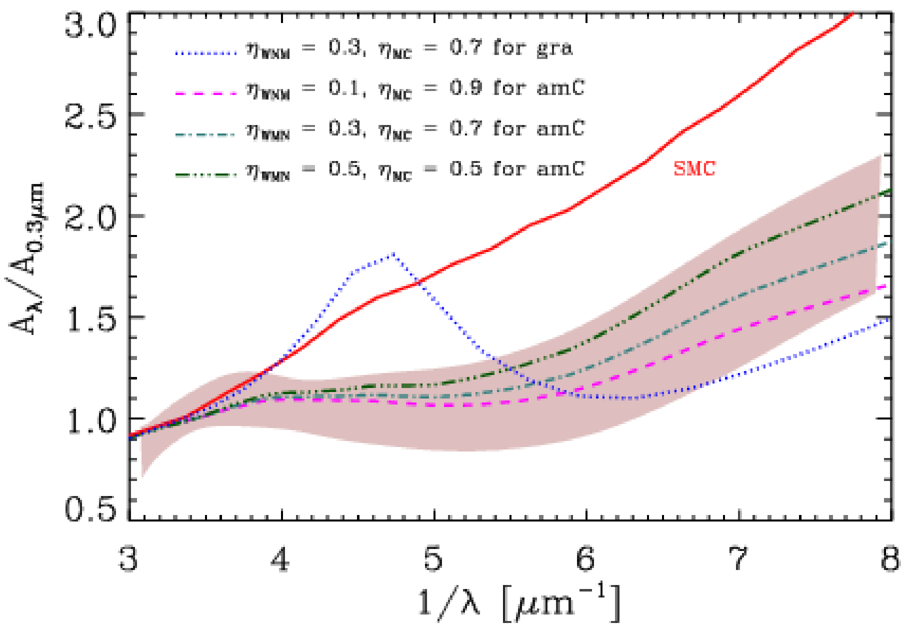
➜ indicating a high fraction of MC

cf. M_{H2}/M_H ~ 5 from observations

- **two-phase ISM: WNM and MC**
- **τ_{SF} = 0.5 Gyr**
- **amorphous carbon & silicate**

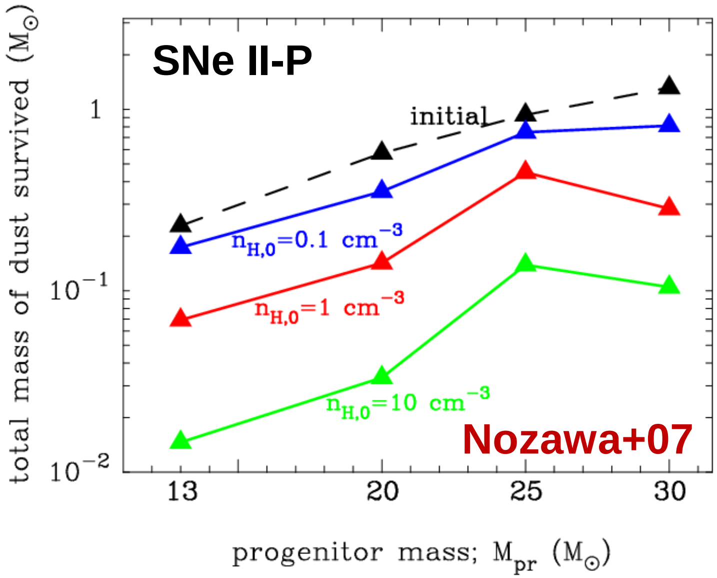




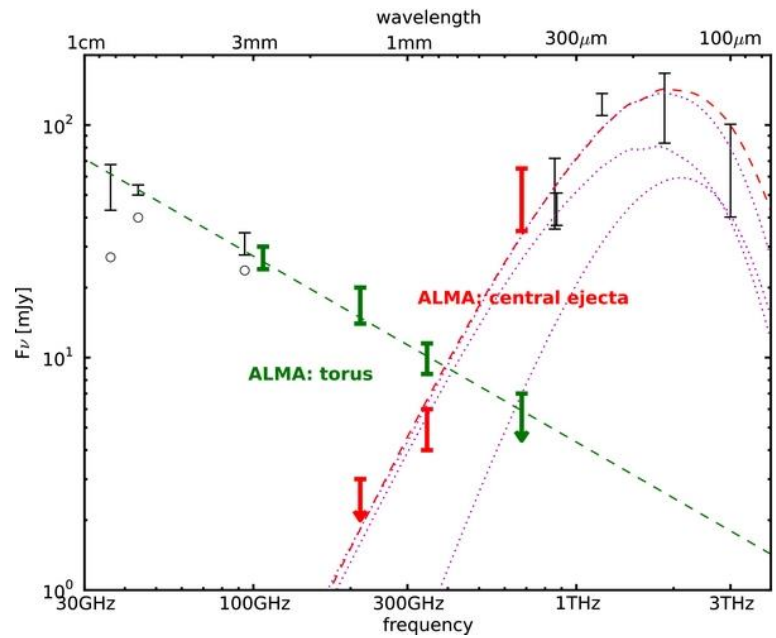


Asano, TN, Hirashita, Takeuchi, 2014 in prep.

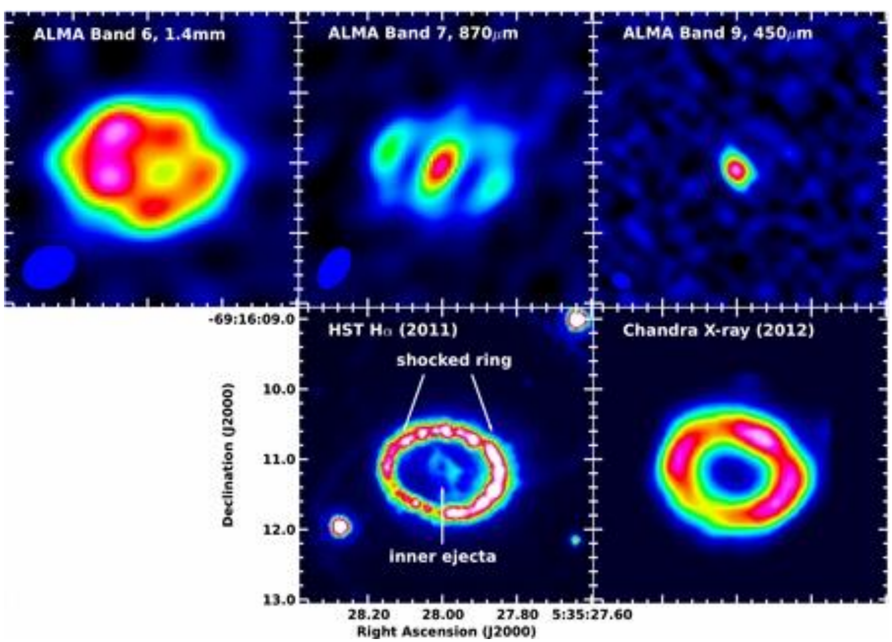
4-1. ALMA reveals dust formed in SN 1987A



SED of 25-years old SN 1987A



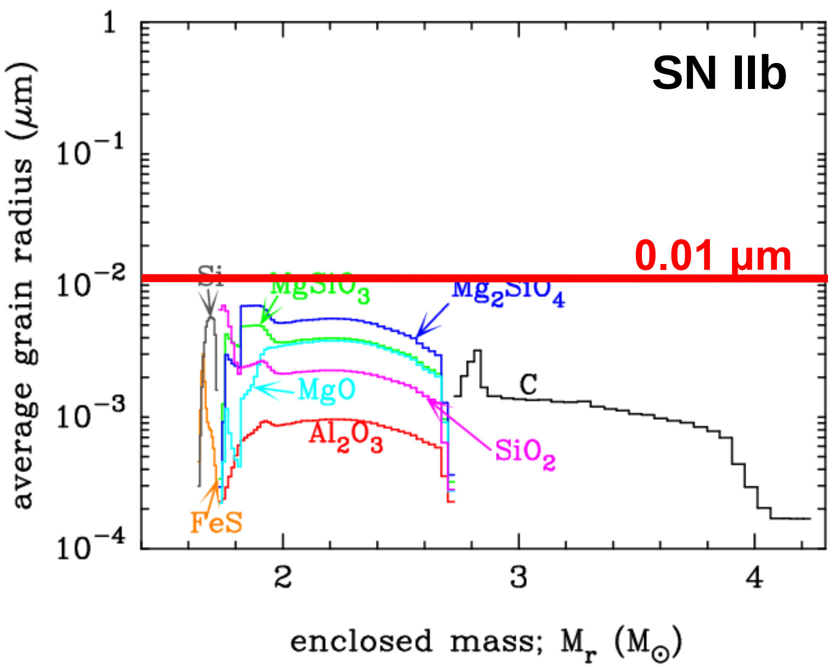
Indebetouw+2014

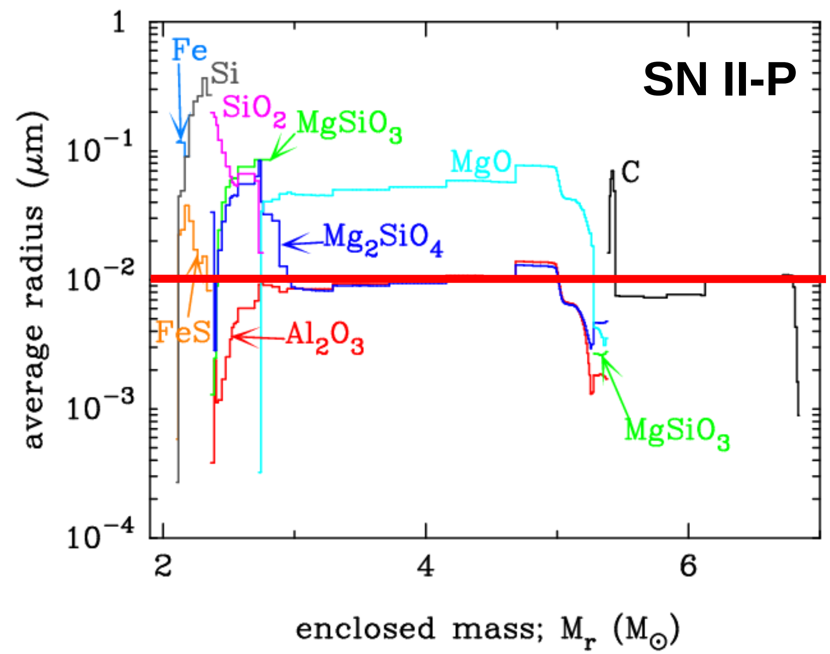


ALMA spatially resolves cool (~20K) dust of ~0.5 Msun formed in the ejecta of SN 1987A

➔ SNe could be production factories of dust grains

4-2. Dependence of dust radii on SN type





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

— total mass of dust formed

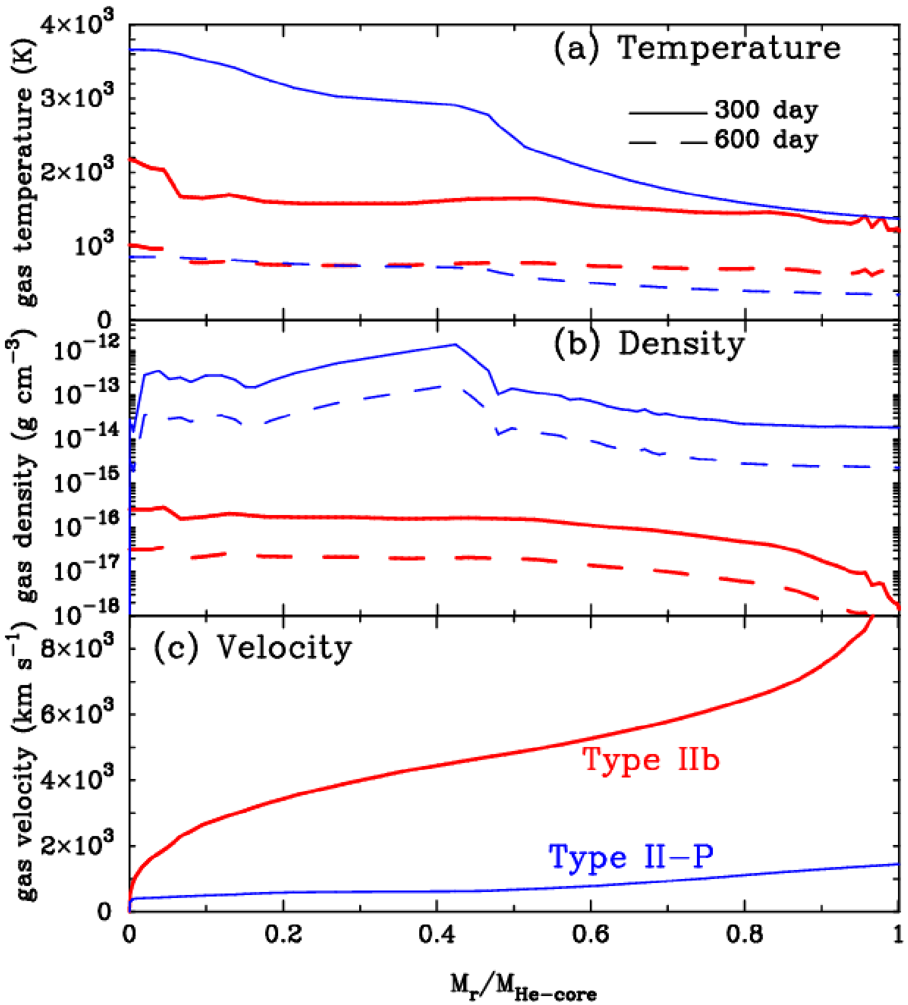
- 0.167 Msun in SN IIb
- 0.1-1 Msun in SN II-P

— 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

Nozawa+10, ApJ, 713, 356

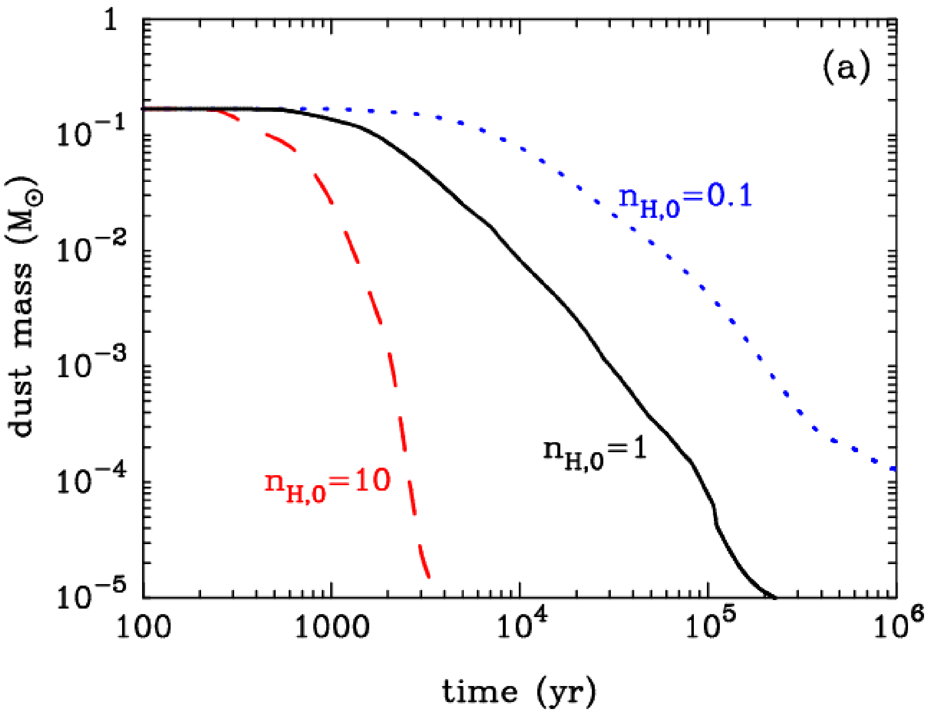
4-3. Destruction of dust in Type IIb SNR



gas density in SN IIb is much smaller than in SNe II-P

Nozawa+10, ApJ, 713, 356

dust destruction in SNRs



Almost all of the newly formed grains are finally destroyed in shocked gas

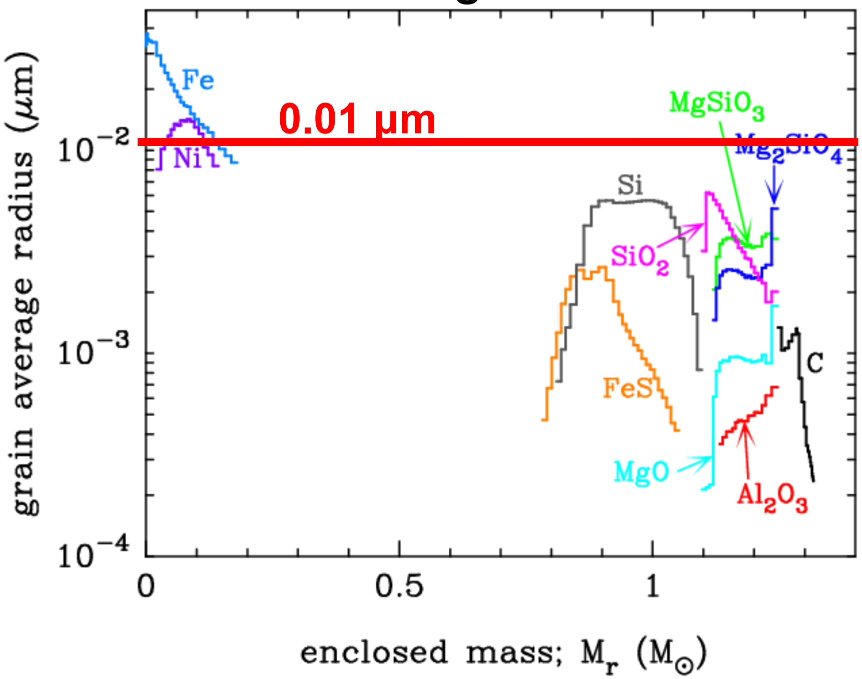
➔ small radius of newly formed dust

➔ early arrival of reverse shock at the ejecta

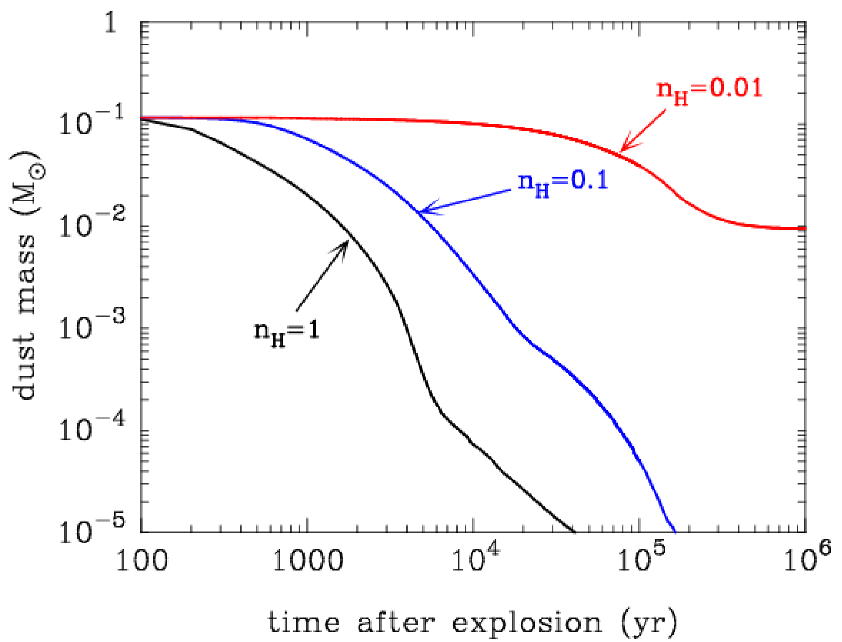
4-4. Dust formation and evolution in SNe Ia

Nozawa+11, 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 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. Summary of this talk

We investigate the evolutions of grain size distribution the extinction curve in galaxies

- **early phase : large grains (~0.1 μm) from SNe II and AGB stars**
  ➔ flat extinction curve

- **mid phase : small grains (<0.03 μm) via shattering/grain growth**
  ➔ steep extinction curve

- **late phase : shift of peak of size distribution due to coagulation**
  ➔ making extinction curve flatter

▪ **our model can explain the unusual extinction curve and large amounts of dust grains observed for high-z quasars**
  ➜ a large fraction of molecular clouds, silicate and am.C

▪ **envelope-stripped SNe (Type IIb, Ib Ia SNe) are not likely to be main sources of dust**