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星間ダストのサイズ分布の進化と減光曲線
(Evolution of size distribution of interstellar dust and extinction curves)

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References

- Asano, Takeuchi, Hirashita, Nozawa (2013, MNRAS, 432, 637)
- Asano, Takeuchi, Hirashita, Nozawa (2014, MNRAS, 440, 134)
- Nozawa, Asano, Hirashita, Takeuchi (2014, submitted to MNRAS)

Outline

1. Introduction
    - Aim of this study and extinction curves

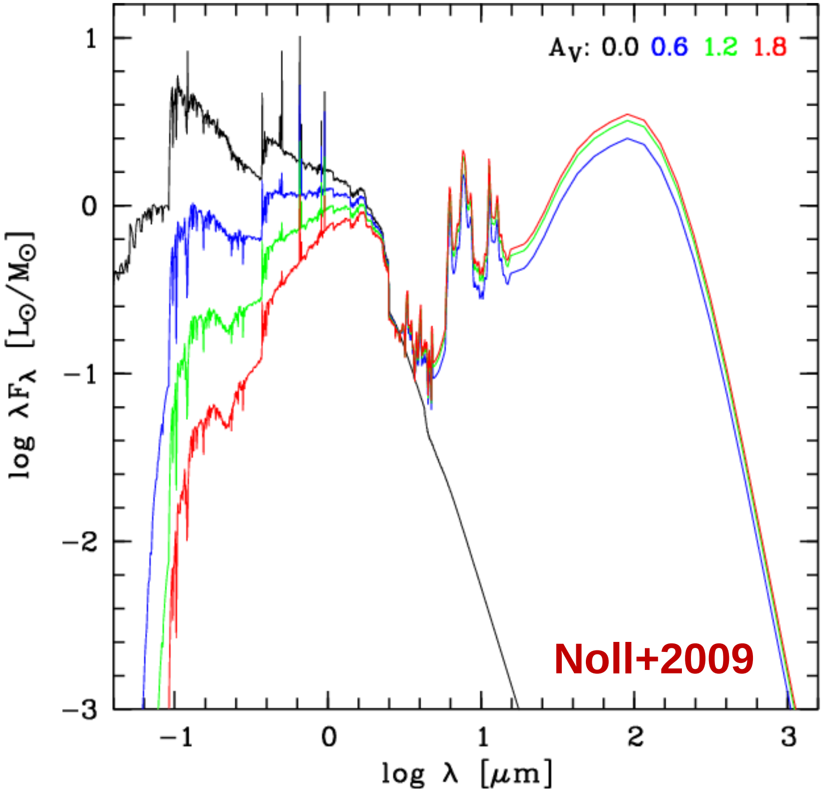
2. Physical processes of dust

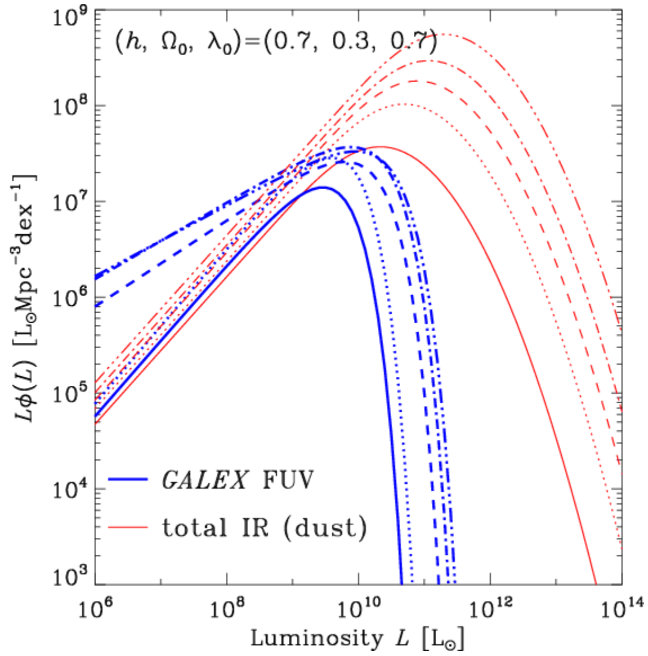
3. Model and Results
    - Evolution of extinction curves in galaxies
    - Extinction curve in the Milky Way

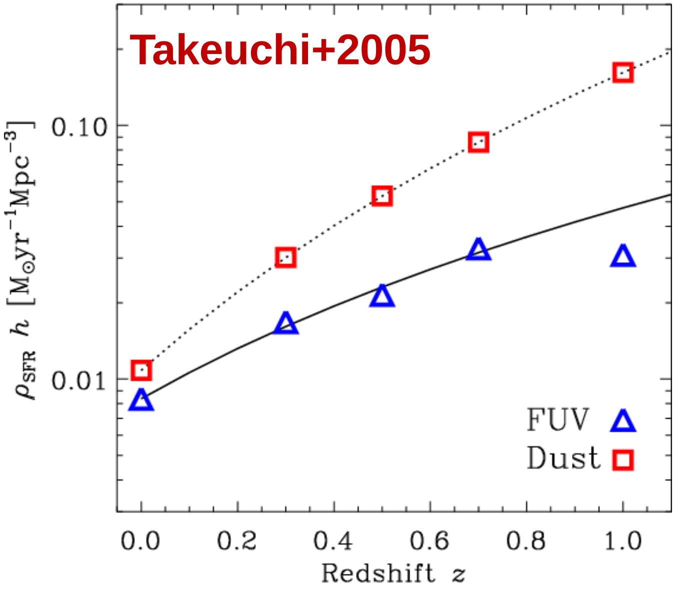
4. Extinction curves at high-z quasars

1. Introduction

1-1. Dust alters the SEDs of galaxies



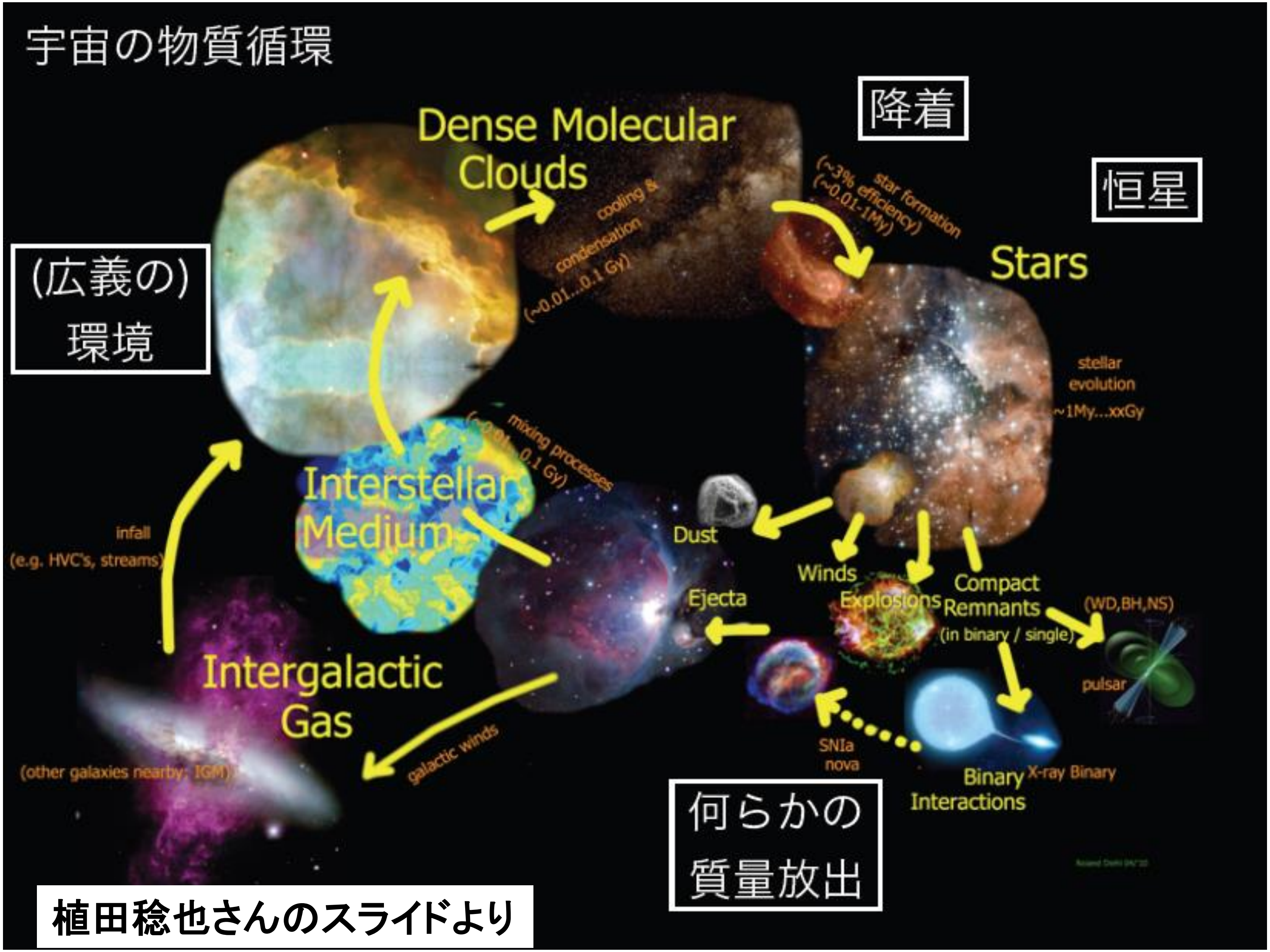




Dust grains absorb UV/optical photons and re-radiate thermal emission at infrared wavelengths

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

1-2. Life-cycle of interstellar matter (dust)



植田稔也さんのスライドより

1-3. 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

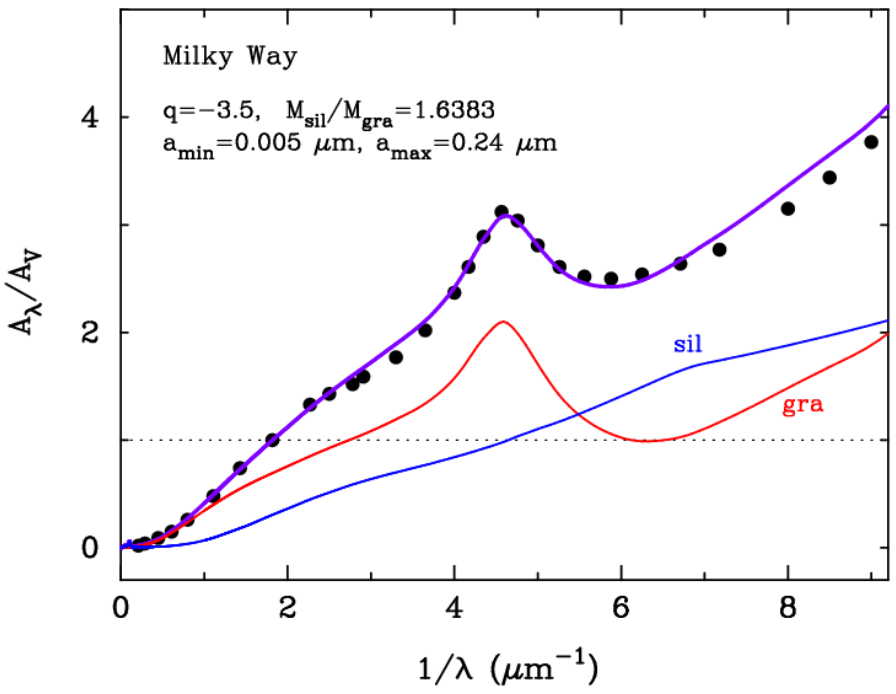
➔ however, the size distribution of interstellar dust must change as the galaxy evolves

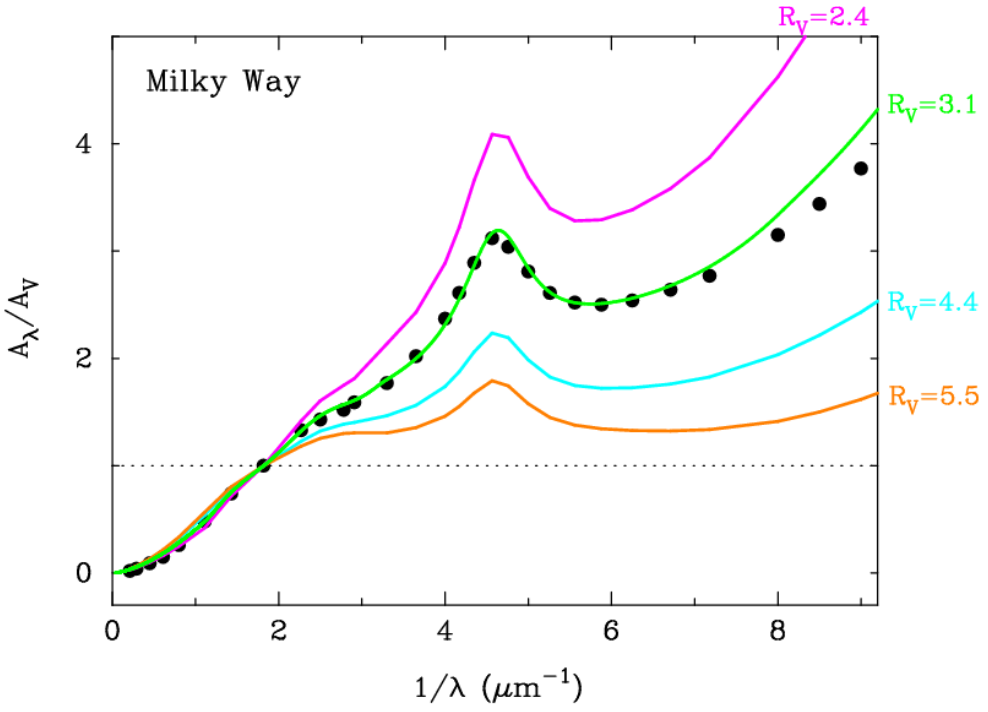
we construct the evolution model of grain size distribution, with the aim at understanding how the extinction curve is modified in the course of galaxy evolution

・ 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**

1-4. Extinction curves in the Milky Way





○ MRN dust model

(Mathis, Rumpl, & Nordsieck 1977)

- **composition :**
  silicate and graphite
- **size distribution :**
  $n(a) \propto a^{-q}$ with $q=3.5$,
  $0.005\ \mu m \le a \le 0.25\ \mu m$

○ CCM relation

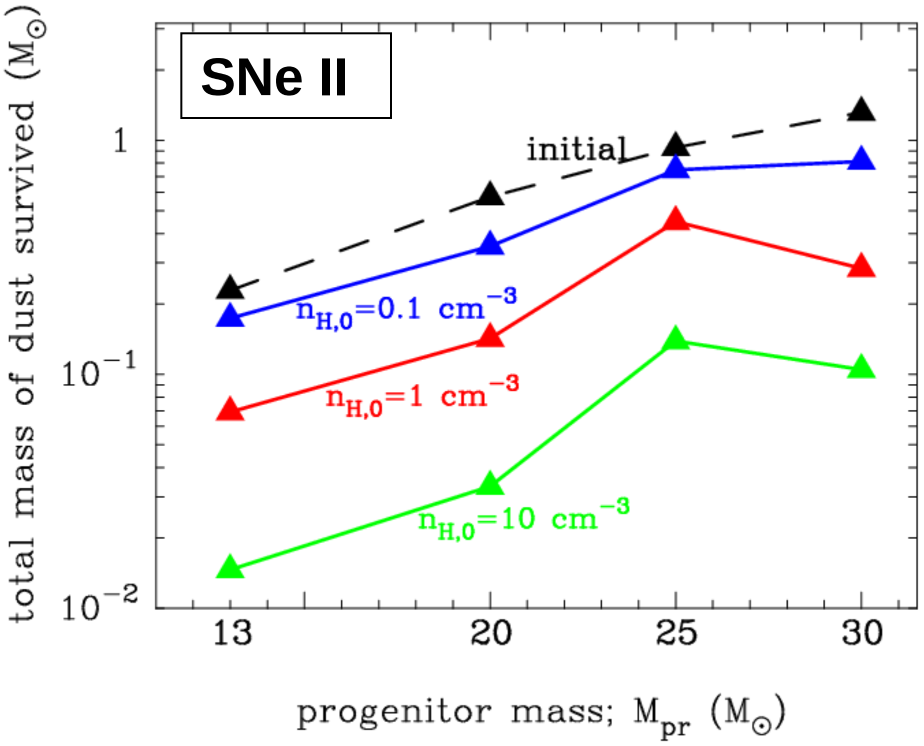
(Cardelli, Clayton, & Mathis 1989)

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

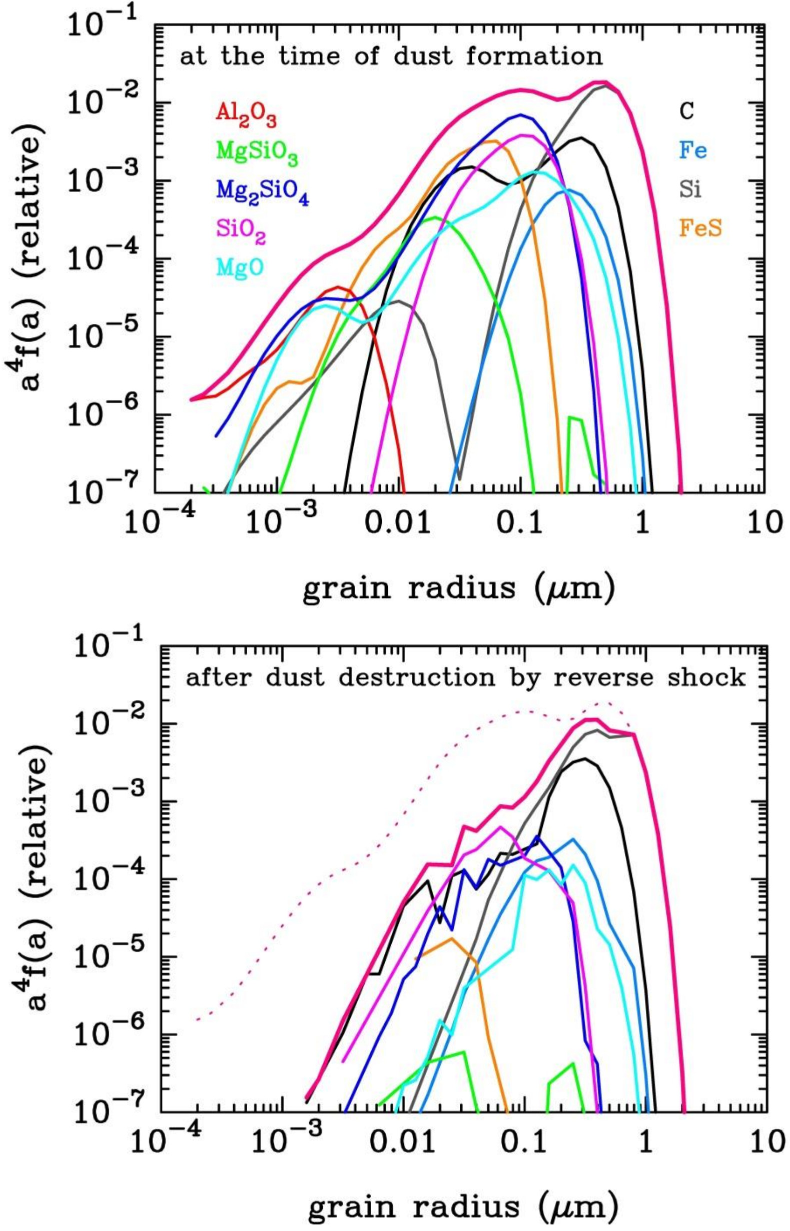
$R_V = A_V / (A_B - A_V)$

2. Physical processes of dust

2-1. Properties of dust ejected from SNe II-P



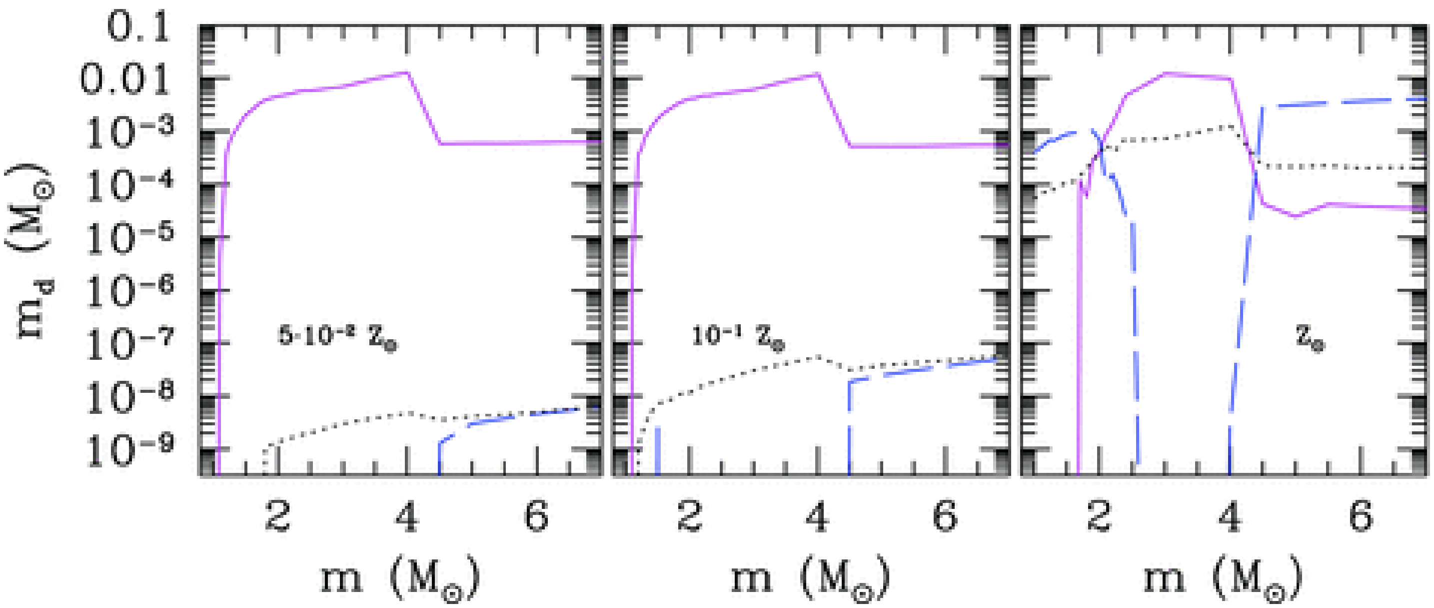
Nozawa+07, ApJ, 666, 955



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

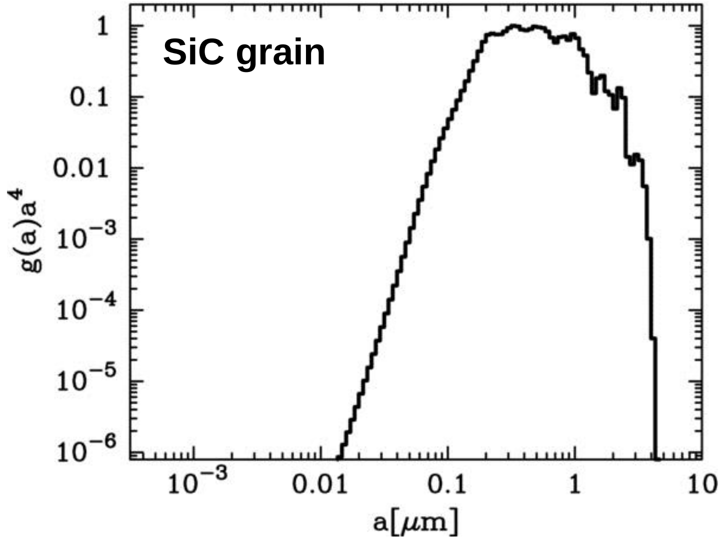
size distribution of dust after the shock-destruction is domimated by large grains **(> 0.1 μm)**

2-2. Properties of dust ejected from AGB stars



solid: carbon
dashed: silicate
dotted: the others

Zhukovska & Gail 2008; Valiante+2009

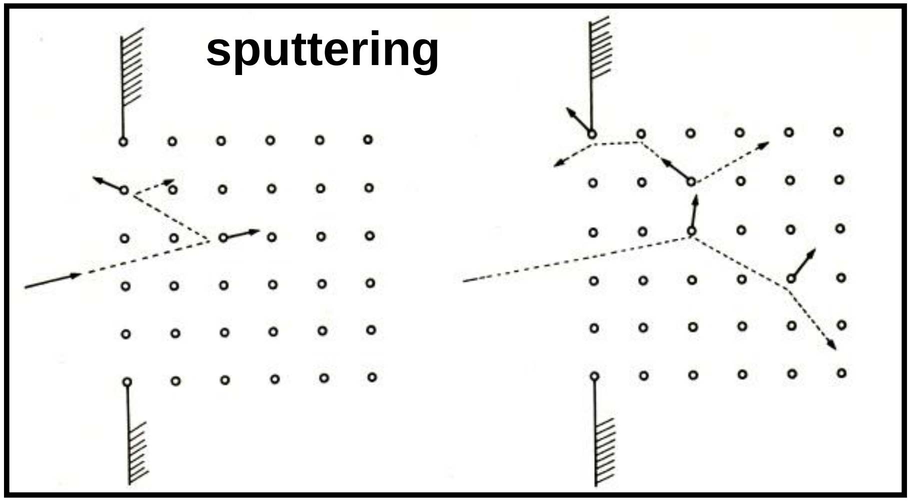


Yasuda & Kozasa 2012

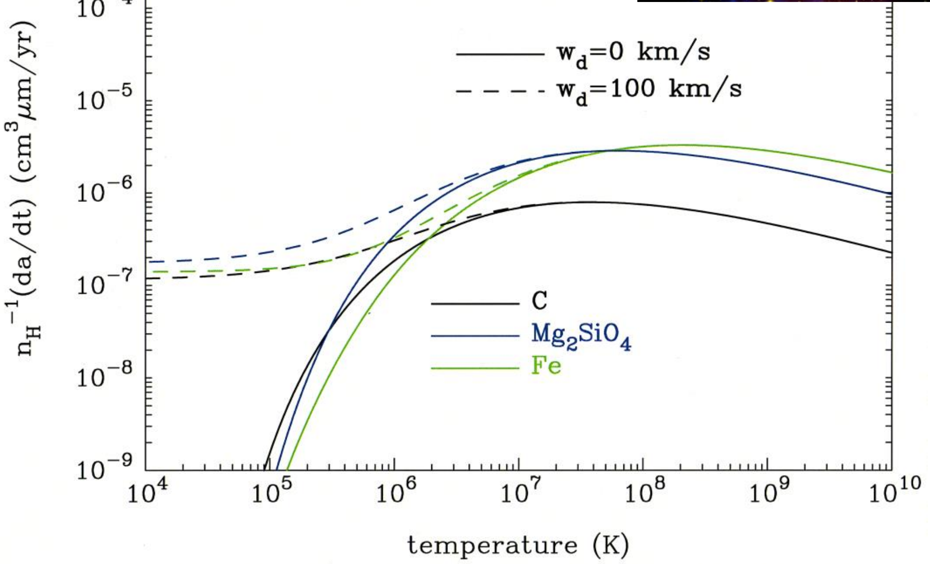
mass of dust grains injected from a AGB star into the ISM:
0.001-0.01 Msun (Mstar > 1 Msun)

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

2-3. 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, τdest**

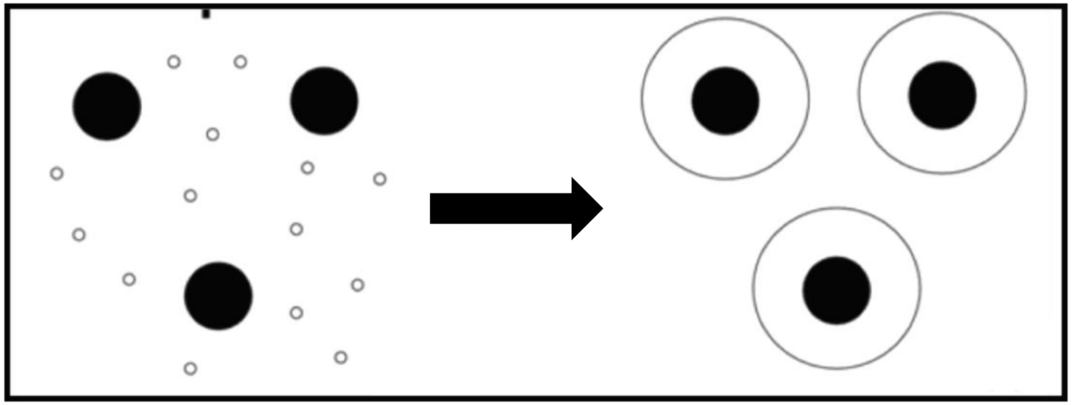
$$\tau_{dest} = [\ (1/M_{dust})(dM_{dust}/dt)\ ]^{-1} = [\ \varepsilon\ M_{swept}\ R_{SN} / M_{gas}\ ]^{-1}$$

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

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

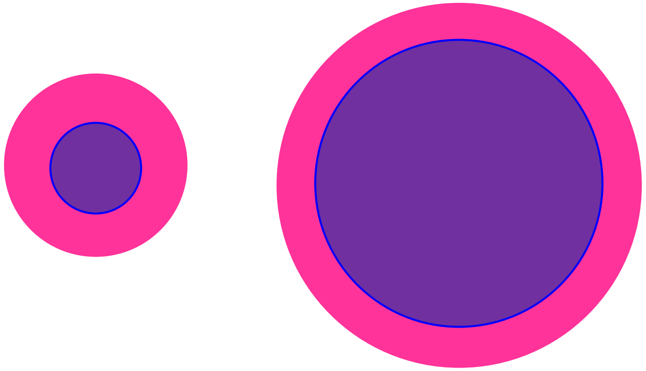
2-4. Growth of dust in molecular clouds

grain growth



Sirono+2013

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



・ timescale of grain growth, $\tau_{\rm grow}$

$$\tau_{\rm grow} = [\,(1/m_{\rm dust})(dm_{\rm dust}/dt)\,]^{-1} = [\,(1/3a)\,\alpha_s\, n_{\rm metal}\, V_0\, \langle v \rangle\,]^{-1}$$

$$\sim 2\text{x}10^{7}\ \text{yr}\ (\alpha_s / 0.2)^{-1}\ (a / 0.01\ \mu\text{m})\ (Z / 0.02)^{-1}\ (n_{\rm gas} / 30\ \text{cm}^{-3})^{-1}$$

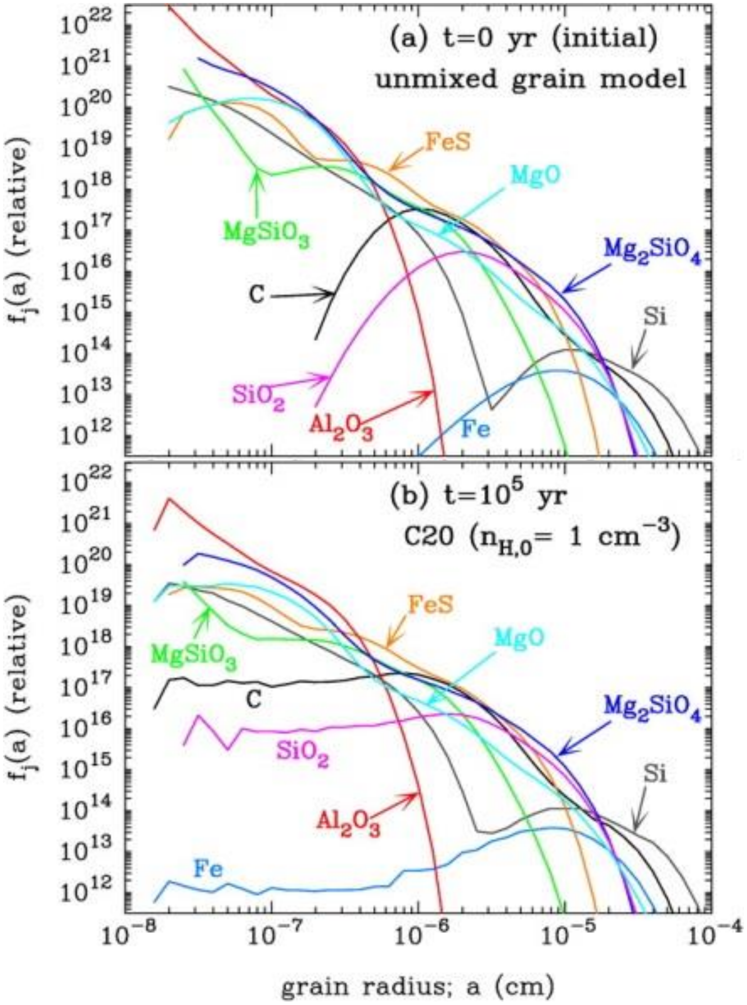
➔ grain growth is more efficient for a higher gas density, a higher metallicity (higher abundance of metals), and a smaller grain

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

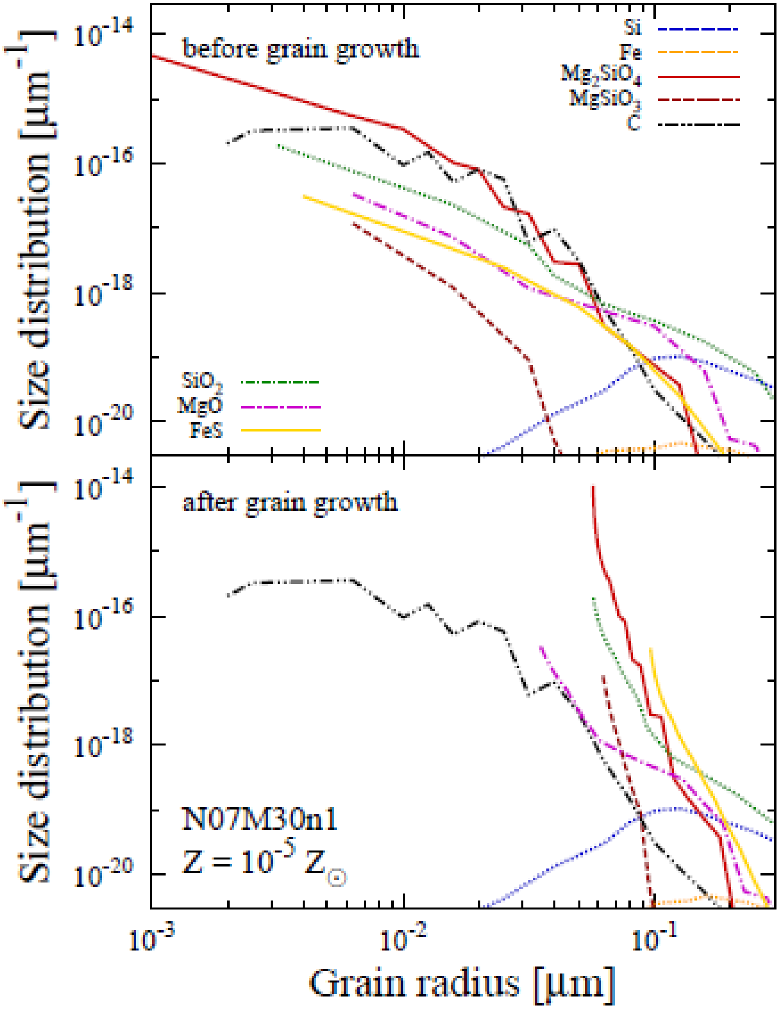
2-5. Examples of change of size distribution (1)

Modification of grain size distribution due to sputtering in SN shocks

Modification of grain size distribution due to grain growth



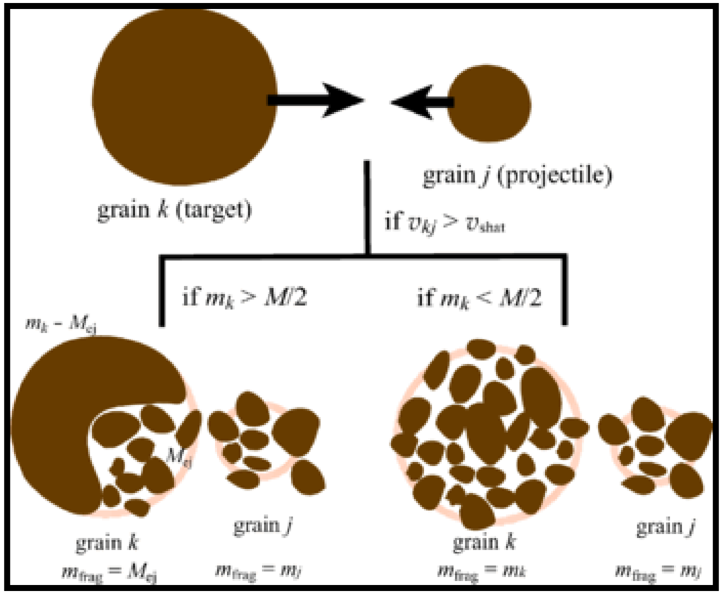
Nozawa+2006



Chiaki. Marrasi, TN+2014, submitted

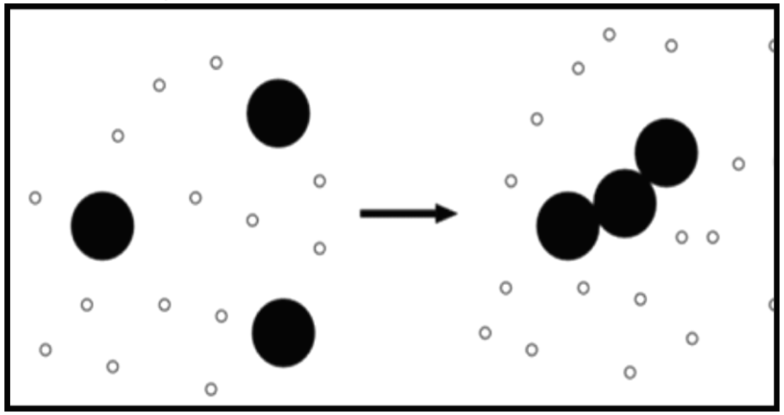
2-6. Shattering and coagulation of dust

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 $v_{\rm coag}$ = 0.001-0.1 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

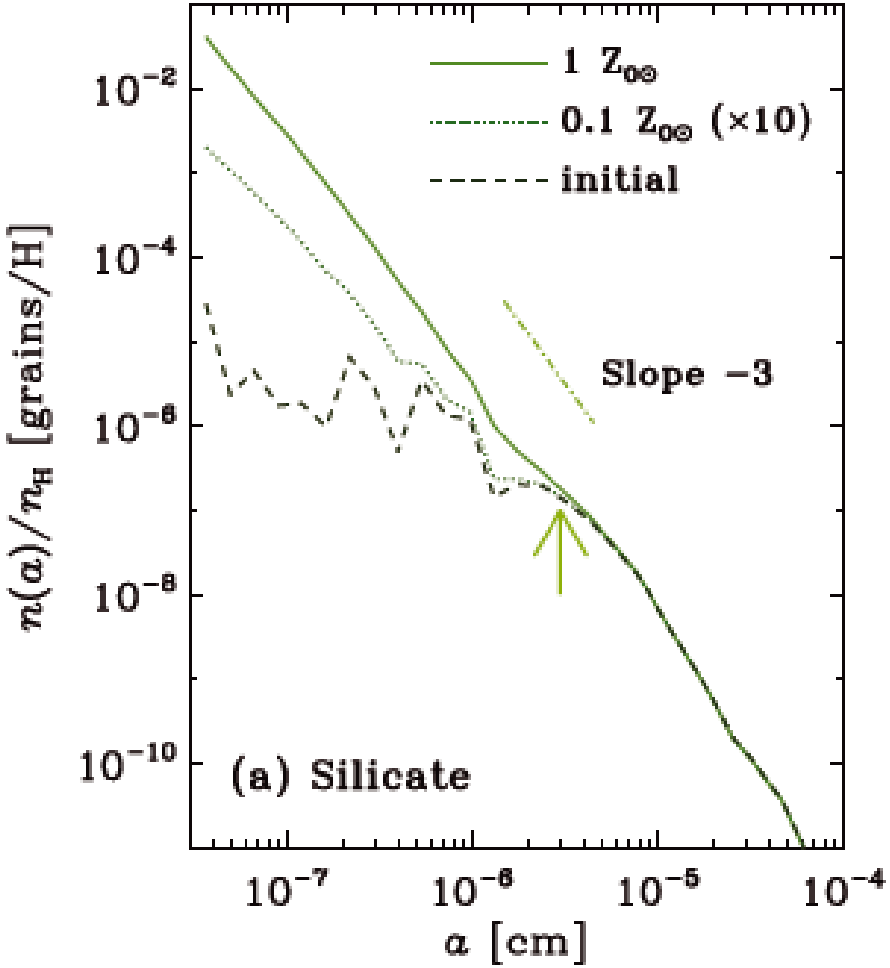
- timescale of shattering, $\tau_{\rm shat}$

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

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

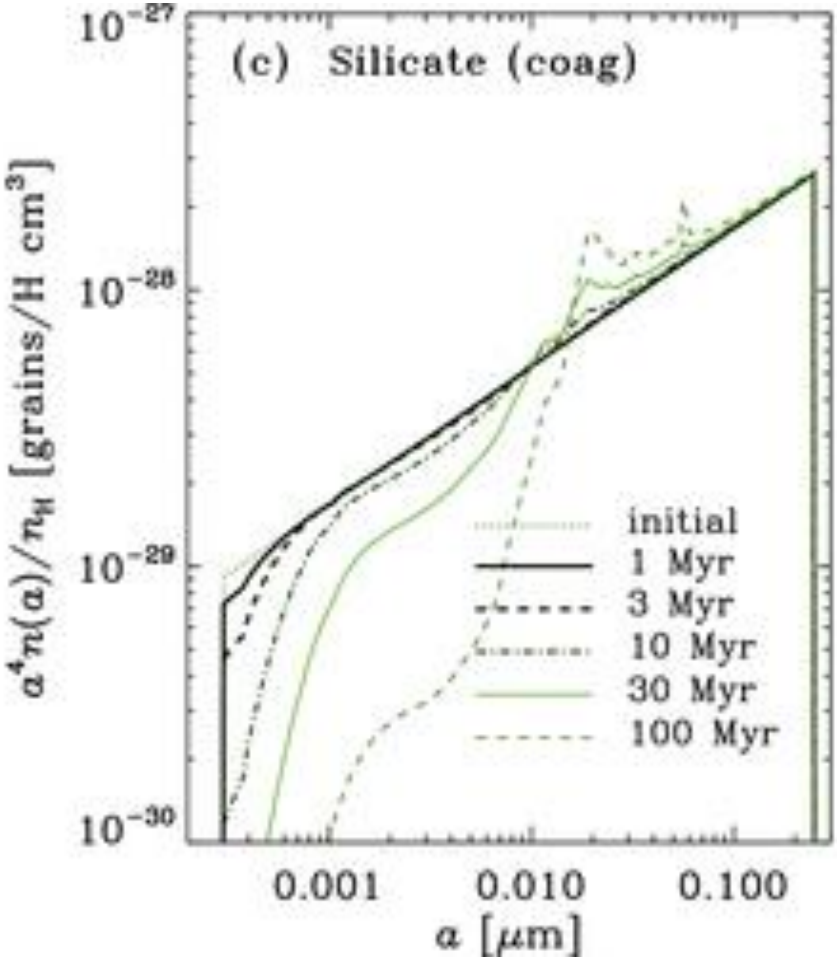
2-7. Examples of change of size distribution (2)

Modification of grain size distribution due to shattering



Hirashita, TN+2010

Modification of grain size distribution due to coagulation



Hirashita, 2012

3. Model and results

3-1. Dust evolution model in a galaxy (1)

- one-zone closed-box 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: $\phi(m) = m^{-q}$ 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}

  ➜ $\eta_{WNM} = \eta_{CNM} = 0.5$

3-2. Dust evolution model in a galaxy (2)

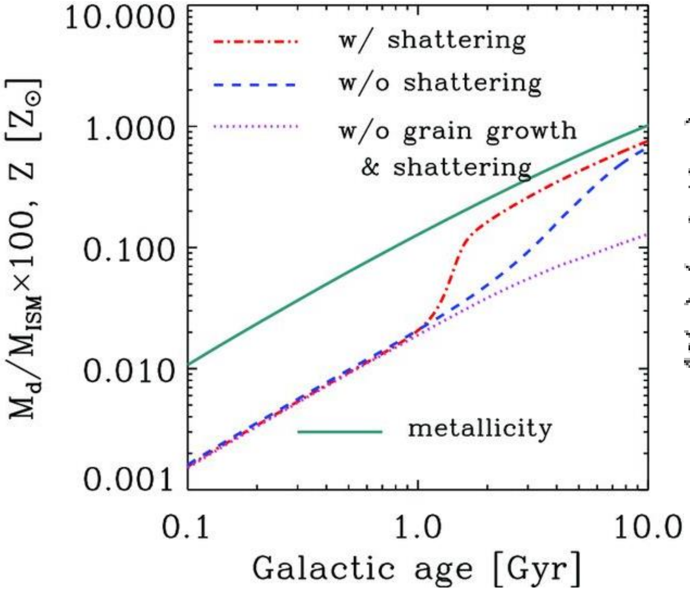
- mass evolution of dust *ΔMd(a,t)* with radii between *a* and *a+da*

$$
\begin{aligned}
\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t} = & \overset{\text{xSFR(t), astration}}{\underline{-\frac{\Delta M_{\mathrm{d}}(a,t)}{M_{\mathrm{ISM}}(t)}}} + \underline{\Delta Y_{\mathrm{d}}(a,t)} \; \text{dust production by SNe II and AGB stars}\\
& \underline{-\frac{M_{\mathrm{swept}}}{M_{\mathrm{ISM}}(t)}\gamma_{\mathrm{SN}}(t)\left[\Delta M_{\mathrm{d}}(a,t) - m(a)\int_0^{\infty}\xi(a,a^{'})\Delta a f(a^{'},t)\mathrm{d}a'\right]}\\
& \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{shock destruction}\\
& \underline{+\eta_{\mathrm{CNM}}\left[m(a)\Delta a\frac{\partial[f(a,t)]}{\partial t}\right]} \; \text{grain growth}\\
& \underline{+\eta_{\mathrm{WNM}}\left[\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{shat,WNM}}} + \cancel{\eta_{\mathrm{CNM}}\left[\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{shat,CNM}}}\\
& \qquad\qquad\qquad\qquad \text{shattering}\\
& \cancel{+\eta_{\mathrm{WNM}}\left[\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{coag,WNM}}} \underline{+\eta_{\mathrm{CNM}}\left[\frac{\mathrm{d}\Delta M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{coag,CNM}}},\\
& \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{coagulation}
\end{aligned}
$$

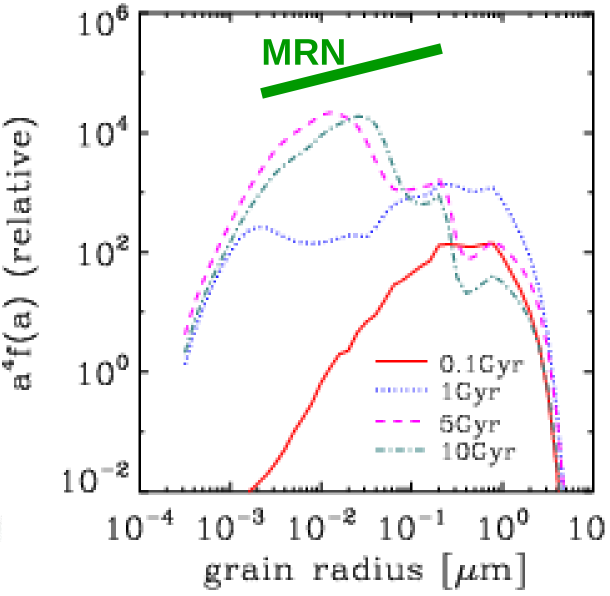
$$\boxed{\Delta Y_{\mathrm{d}}(a,t) = \int_{m_{\mathrm{cut}}(t)}^{100\ \mathrm{M}_{\odot}} \Delta m_{\mathrm{d}}(m, Z(t-\tau_m), a)\phi(m)\mathrm{SFR}(t-\tau_m)\mathrm{d}m,}$$

3-3. Evolution of extinction curves in galaxies

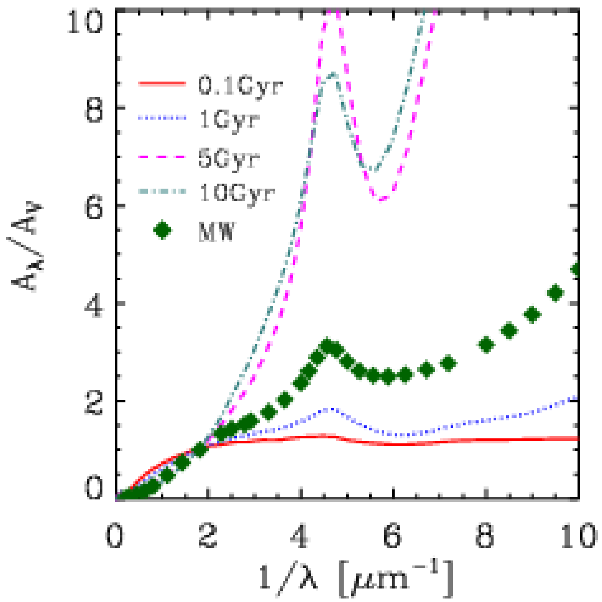
dust amount



grain size distribution



extinction curve



Asano, Takeuchi, Hirashita, TN+2013, 2014

- **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

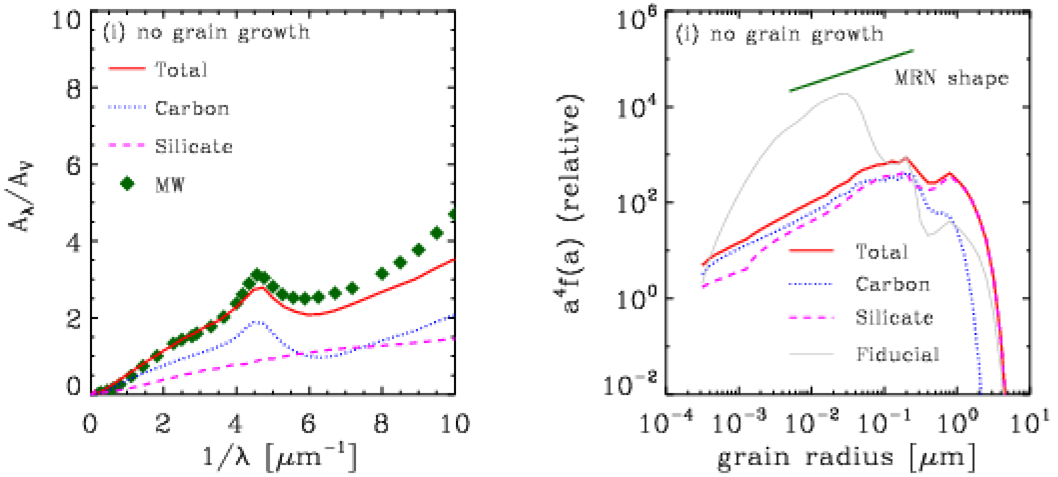
3-4. Reproducing the MW extinction curve

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

- no grain growth in CNM

➜ producing the MW-like extinction curve

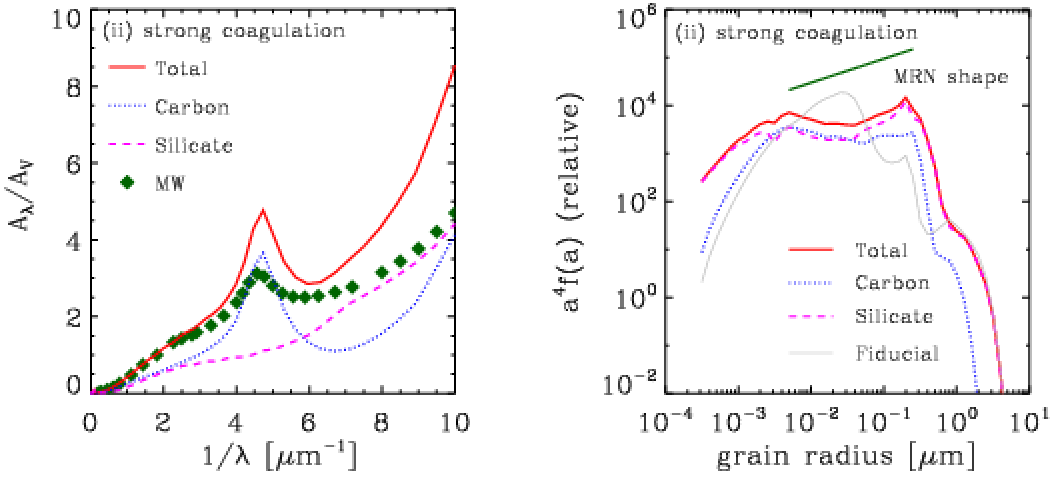
➜ not explaining the total mass of dust



- efficient coagulation

➜ producing flatter extinction curve than original

➜ still too steep to be consistent with MW curve

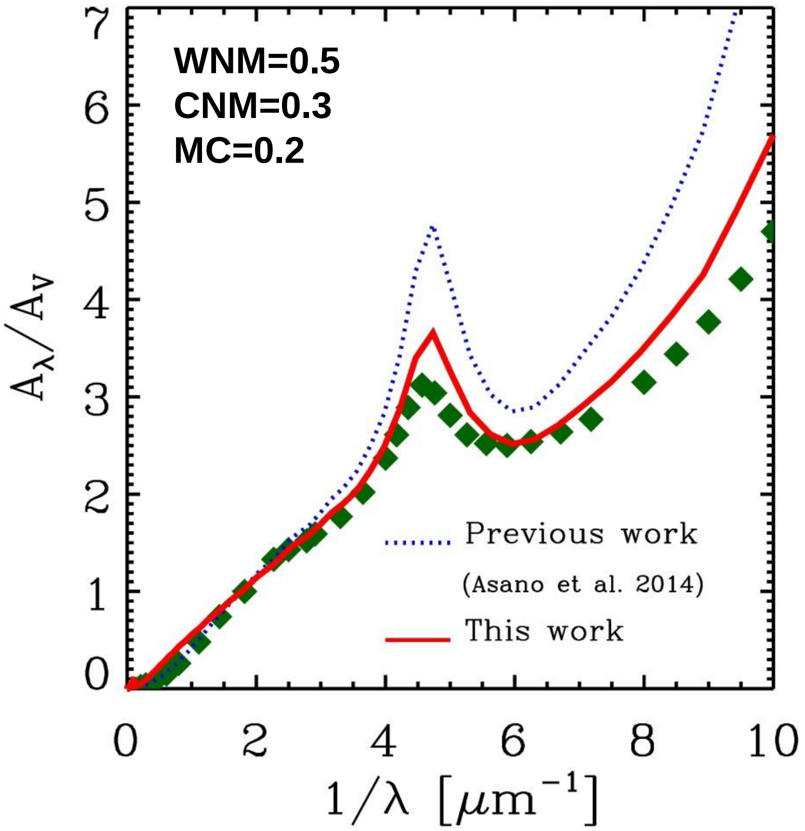


Asano, Takeuchi, Hirashita, TN+14, MNRAS, 440, 134

3-5. Reproducing the MW extinction curve

- two-phase ISM
  - WNM (T = 6000 K, n = 0.3 cm^{-3})
  - CNM (T = 100 K, n = 30 cm^{-3})

- 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}



Nozawa+2014, submitted

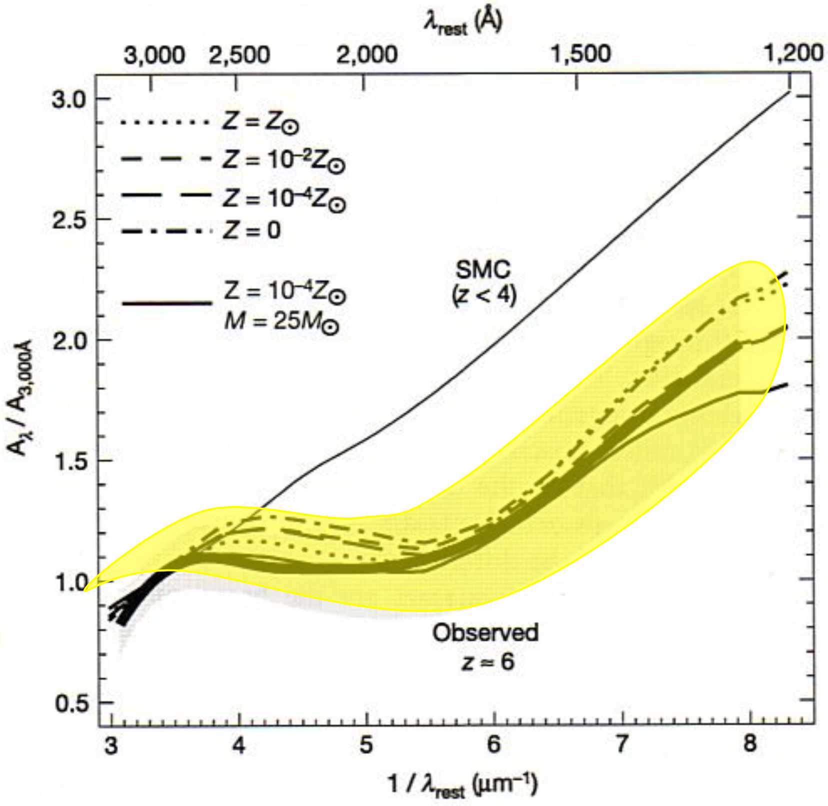
- three-phase ISM model including the MC phase can reproduce the average extinction curve in the MW
- ISM phase is one of the important quantities in constructing the evolution model of interstellar dust

4. Extinction curve at high-z QSOs

4-1. Extinction curves in high-z quasars

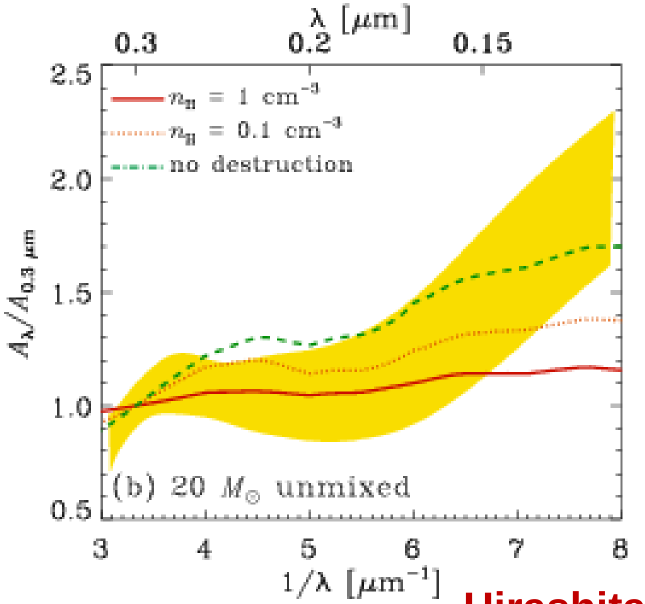
SDSS J1048+4637 at z=6.2 :

broad absorption line (BAL) quasars

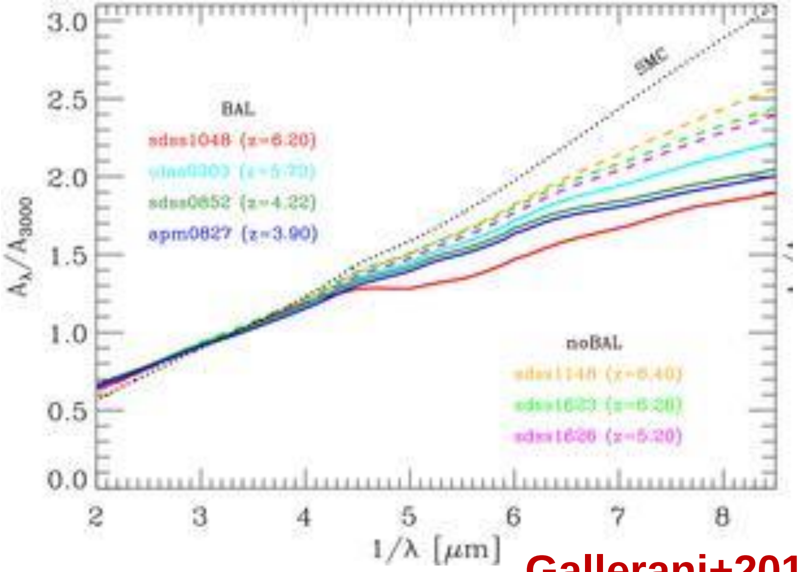


Maiolino+2004, Nature, 431, 533

➔ interstellar dust in the early universe is SN origin?

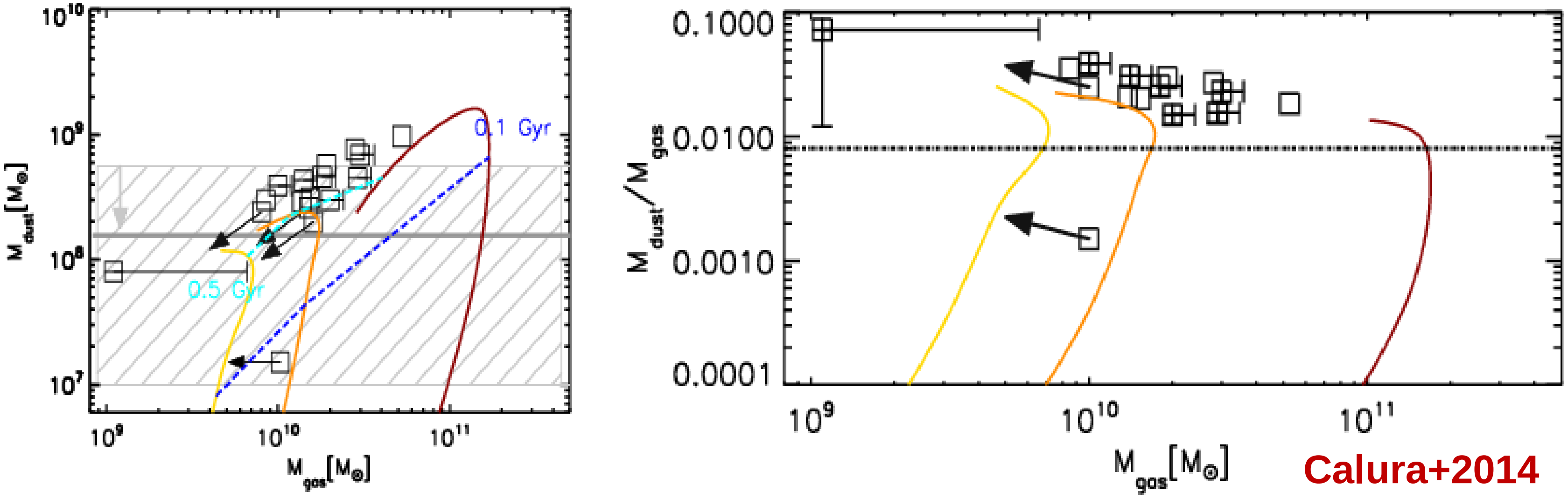


Hirashita+2008



Gallerani+2010

4-2. 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?

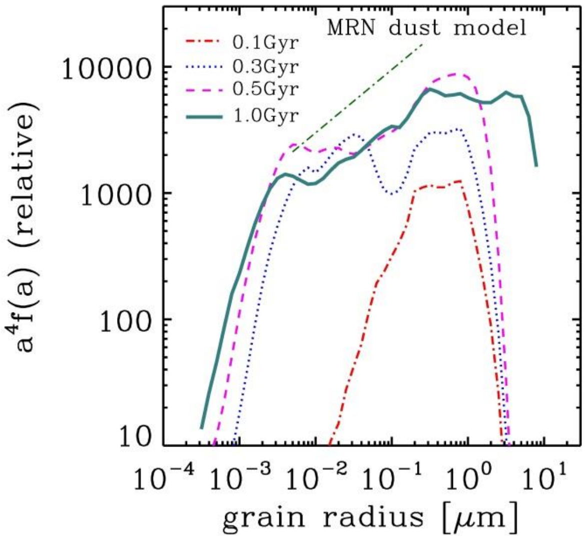
4-3. Explaining massive dust in high-z quasars

high-z quasar host: starburst galaxies

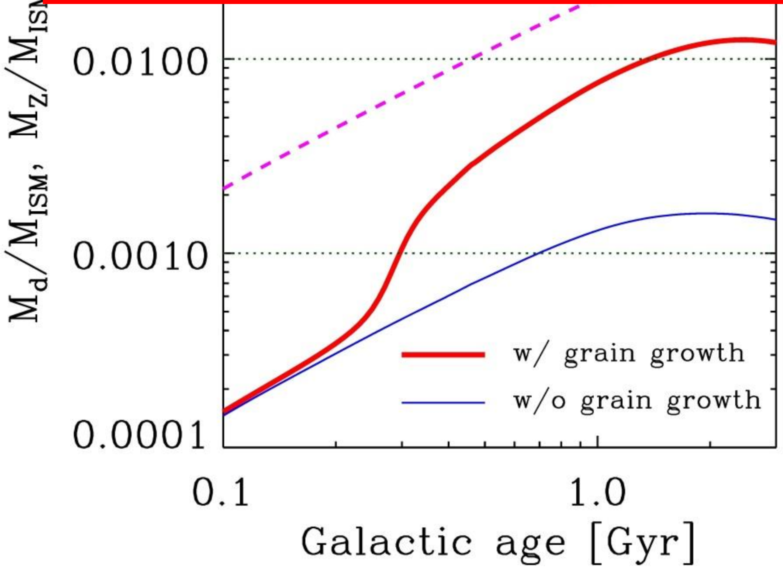
➜ indicating a high fraction of MC

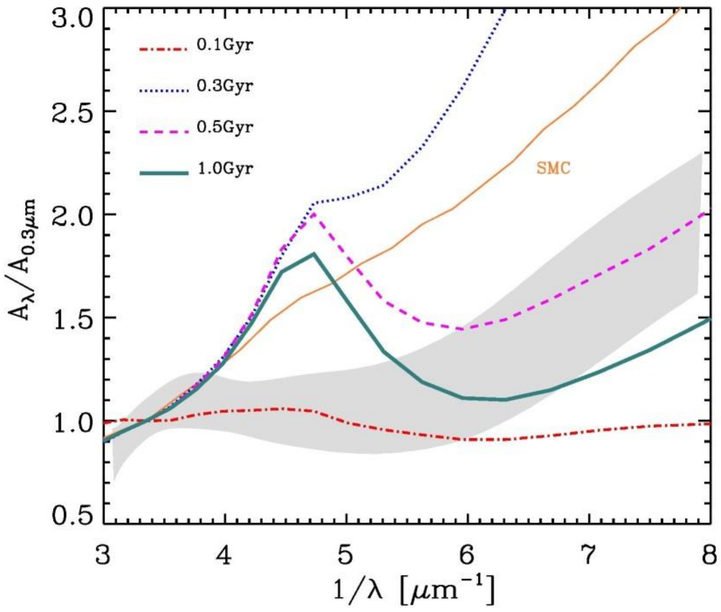
$M_{H2}/M_{H,total}$ ~ 0.7-0.97 (Calura+2014)

- **two-phase ISM:**
  WNM=0.3 and MC=0.7
- **τ_{SF} = 0.5 Gyr**



Grain growth is necessary to achieve the observed high D/G





Nozawa+2014 submitted

4-4. Explaining the high-z extinction curves

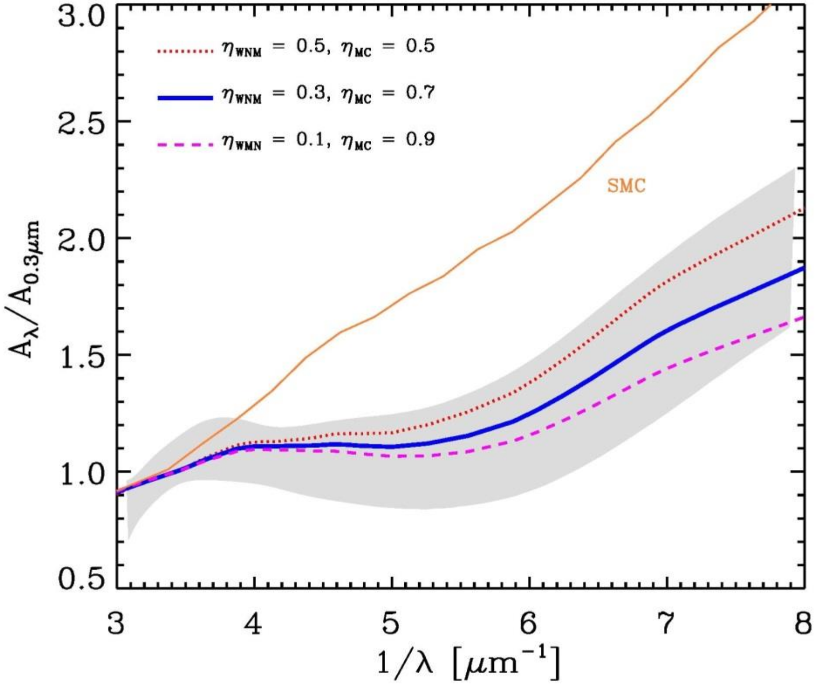
The presence/absence of 2175 A bump may be related to the dust composition of dust rather than the dust evolution model

- **graphite and silicate**

⬇

- **amorphous carbon & silicate**

➜ the derived extinction curve well match the observed high-z extinction curve



Nozawa+2014 submitted

The origin of the 2175 A bump is still unclear

➜ small size (<0.02 μm) of graphite? (e.g., Draine & Lee 1984)

➜ PAHs (polycyclic aromatic hydrocarbon?) (e.g., Joblin+1992)

・ formation site of PAHs

- **AGB stars? (bottom-up scenario) (e.g., Cherchneff+1993)**
- **shattering of C grains? (up-down scenario) (e.g., Seok+2014)**

5. Summary of this talk

We investigate the evolutions of grain size distribution and the extinction curves 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

▪ **the average extinction curve in the MW can be reproduced by our three-phase (WNM, CNM, MC phases) ISM model**

▪ **our model can explain the unusual extinction curves and large amounts of dust grains observed for high-z quasars**
➜ a large fraction of MCs (>0.5), silicate & amorphous carbon