2015/05/25

Dust Production Factories in the Early Universe

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- **Formation of dust in very massive Pop III RSGs**

  Nozawa, T., Yoon, S.-C., Maeda, K., Kozasa, T., et al., (2014), ApJ, 787, L17

- **Evolution of dust in high-redshift dusty quasars**

  Nozawa, T., Asano, R. S., Hirashita, H., Takeuchi, T. T. (2015), 447, L16

1-1. Sources of dust in the early unvierse

・Origin of massive dust at high redshifts (z > 5)

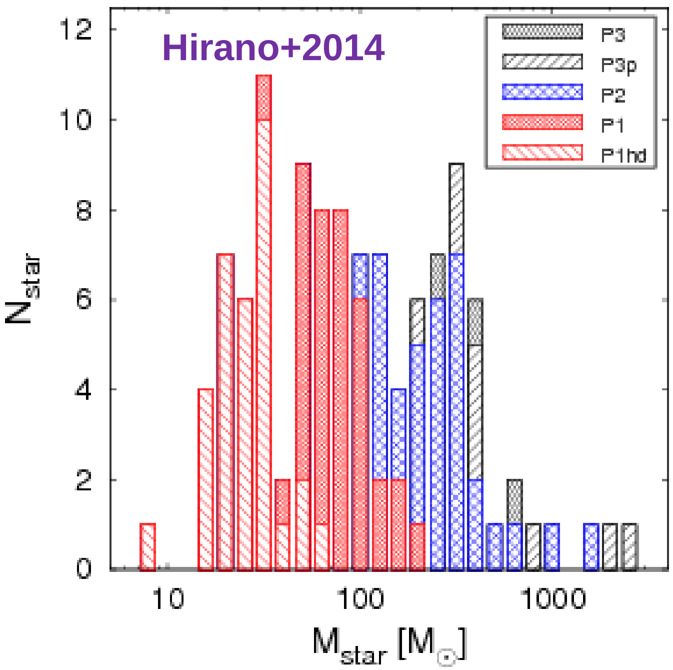
- **core-collapse supernovae (CCSNe) may be promising sources of dust grains** (e.g., Todini & Ferrara 2001; TN+2003; Dwek+2007)
- **the contribution from AGB stars is also invoked to explain the observed dust mass** (e.g., Valiante+2009; Dwek & Cherchneff 2011)

➔ what stellar mass range can mainly contribute dust budget in the early universe depends on the initial mass function

・Typical mass of Pop III stars

➔ Pop III stars may be much more massive than Pop I/II stars

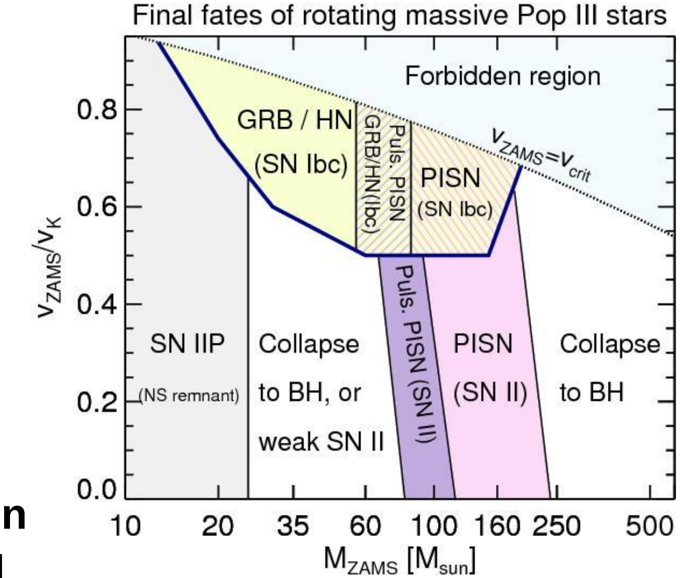
- **~40 Msun** (Hosokawa+2011; Susa 2013)
- **>300 Msun** (Omukai+2003; Ohkubo+2009)
- **10-1000 Msun** (Hirano+2014, Susa+2014)



1-2. Very massive Population III stars

・Role of very massive stars (M_{ZAMS} > ~250 M_{sun})

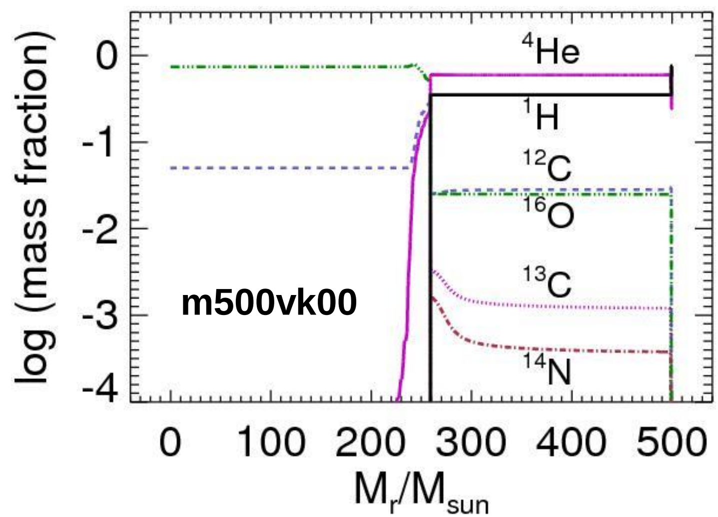
- **emitting numerous ionizing photons**
  ➔ reionization of the universe
- **finally collapsing into black holes**
  ➔ serving as seeds of SMBHs



Yoon+2012

・Evolution of massive Pop III stars

- **non-rotating stars with M_{ZAMS} > 250M_{sun} undergo convective dredge-up of C and O during the RSG phase** (Yoon+2012)
- **enriching the surrounding medium with CNO through the RSG winds**
  ➔ serving as formation sites of dust



Dust grains formed in the winds are not likely to be destroyed by the SN shocks

1-3. Model of Pop III red-supergiant winds

・Formula of non-steady-state dust formation

(Nozawa & Kozasa 2013)

・RSG model: m500vk00 (Yoon+2012)

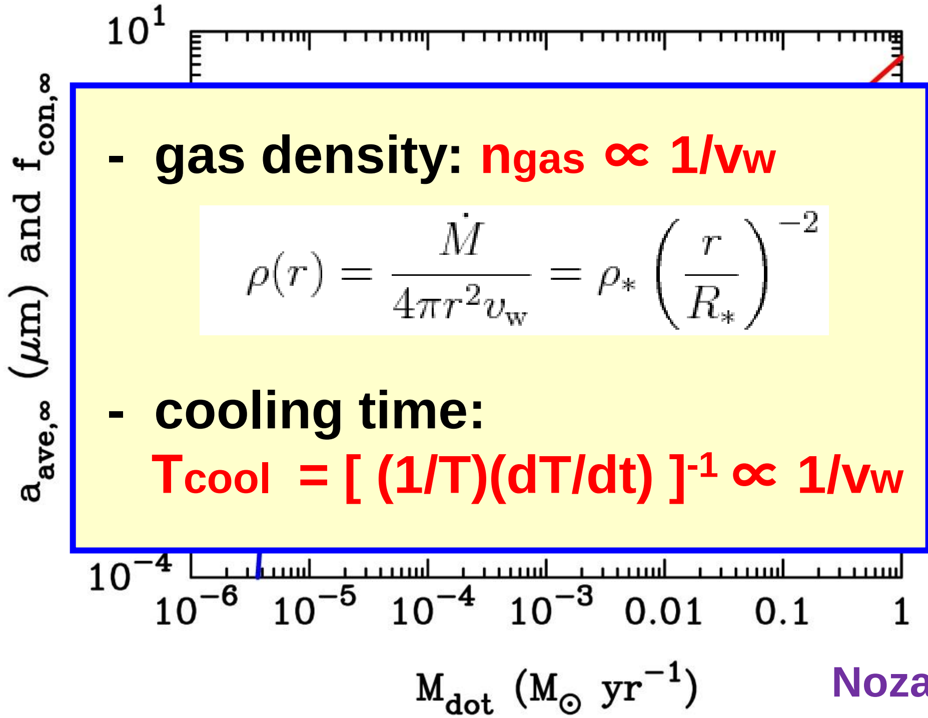
- M_{ZAMS} = 500 M_{sun} (no rotation)
- L = $10^{7.2}$ L_{sun}, T_{star} = 4440 K, R_{star} = 6750 R_{sun}
- A_C = 3.11×10^{-3}, A_O = 1.75×10^{-3} ➔ C/O = 1.78, Z = 0.034

・Model of circumstellar envelope

- spherically symmetry, constant wind velocity
- density profile: $$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\rm w}} = \rho_* \left(\frac{r}{R_*} \right)^{-2}$$
- temperature profile: $$T(r) = T_* \left(\frac{r}{R_*} \right)^{-\frac{1}{2}}$$
- wind velocity: v_w = 20 km/s
- mass-loss rate: M_{dot} = 0.003 M_{sun}/yr

  ➔ losing 90% (208 M_{sun}) of envelope during 7×10^4 yr of the RSG

1-4. Dependence on Mdot and vw

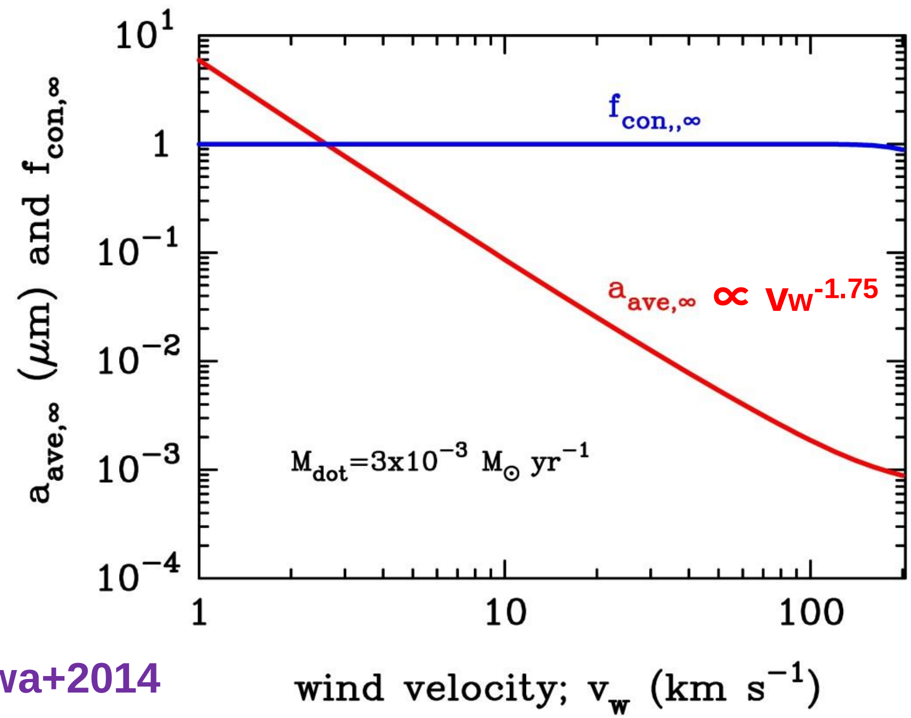


- **gas density:** **$n_{gas} \propto 1/v_w$**

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\rm w}} = \rho_* \left(\frac{r}{R_*}\right)^{-2}$$

- **cooling time:**
  $T_{cool} = [\,(1/T)(dT/dt)\,]^{-1} \propto 1/v_w$

Nozawa+2014



- **The condensation efficiency of dust is unity for the condition;**

$$\left(\frac{f_{\rm c}\dot{M}}{3\times10^{-3}\ M_\odot\ {\rm yr}^{-1}}\right)\left(\frac{v_{\rm w}}{20\ {\rm km\ s}^{-1}}\right)^{-2} \gtrsim 0.04.$$

- **for the fiducial case (M_{dot} = 3x10^{-3} M_{sun}/yr, v_w=20 km/s, f_c=1)**

  → 1.7 M_{sun} of C grains is produced over the lifetime of the RSG

1-5. How efficient is dust formation?

・Dust ejection efficiency by very massive Pop III RSGs

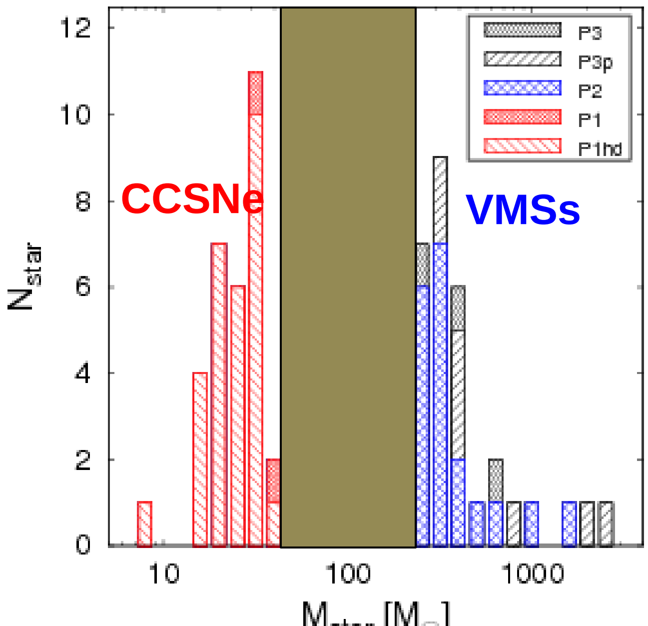
- $X_{VMS} = M_{dust} / M_{ZAMS} < 3.4\times10^{-3}$ = ~0.3 %
- $M_{dust} / M_{metal} < 0.24$

・Dust ejection efficiency by CCSNe

- $X_{CCSN} = (0.1\text{-}30)\times10^{-3}$ = 0.1-3.0 %
- M_{dust} / M_{metal} = 0.01-0.25 ($M_{dust} / M_{metal} < 0.15$)

The ranges above reflects the destruction
efficiency of dust by the reverse shock

Hirano+2014



If $N_{VMS} \sim N_{CCSN}$ in the Pop III IMF …

➔ The contribution of dust from very massive RSGs is comparable with, or even higher than that from CCSNe

$(X_{VMS}\, N_{VMS}) / (X_{CCSN}\, N_{CCSN}) \sim 1$

1-6. Summary and discussion

We examine the possibility of dust formation in a mass-loss wind of a Pop III RSG with M_{ZAMS} = 500 M_{sun}

- **The condensation efficiency is unity for**

$$\left(\frac{f_c \dot{M}}{3 \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}}\right)\left(\frac{v_\mathrm{w}}{20\ \mathrm{km\ s}^{-1}}\right)^{-2} \gtrsim 0.04.$$

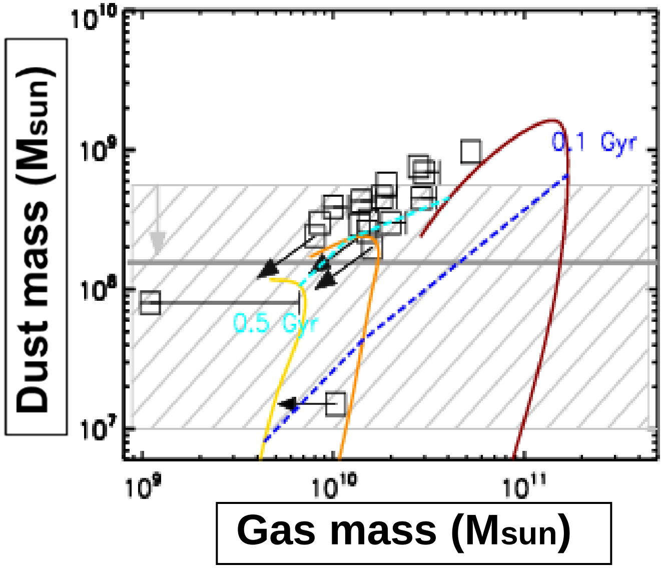
➔ the first dust grains in the universe ??

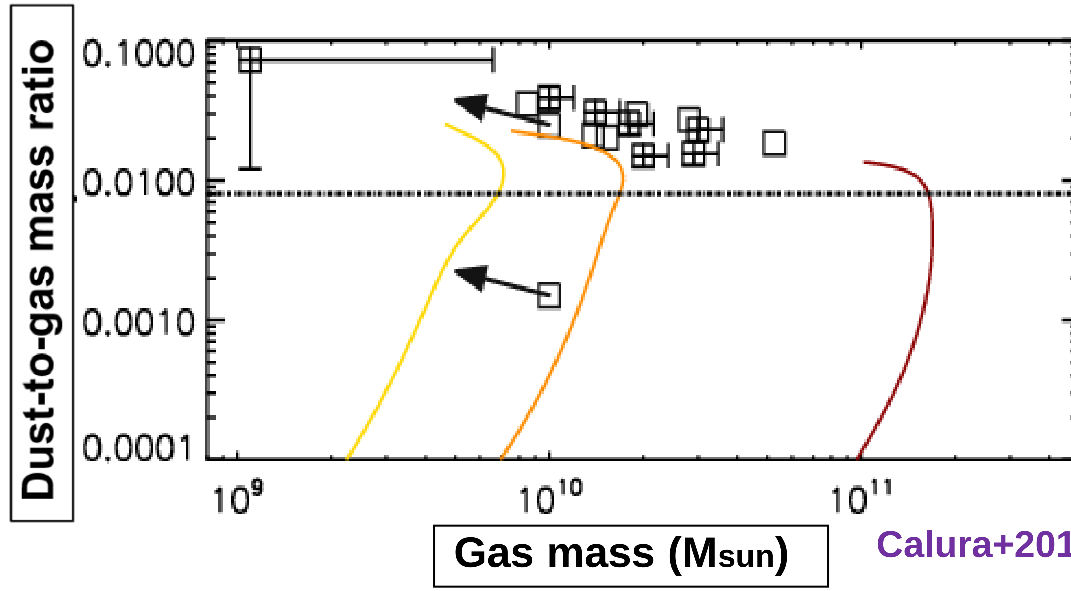
- **The mass of C grains is <1.7 M_{sun} (M_{dust}/M_{ZAMS} < 3.4×10^{-3}), which would be high enough to have impacts on dust enrichment history in the early universe, if the IMF of Pop III stars were top-heavy**

- **Very massive Pop III stars might supply dust grains only at the very early phase of the universe**

- **Our study proposes a new scenario of dust formation in Pop III stars as possible sources of dust in the early universe**

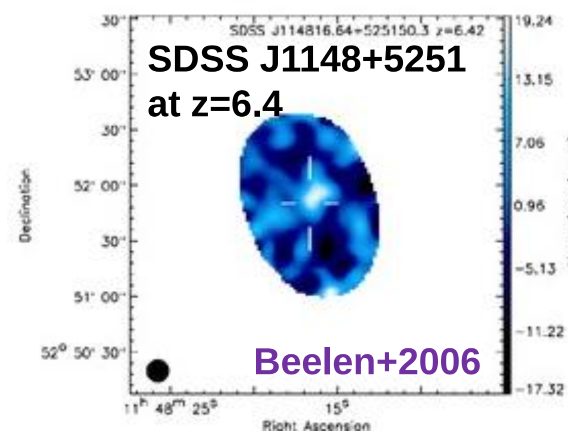
2-1. What are dust sources in quasars at z > 5?





Calura+2014

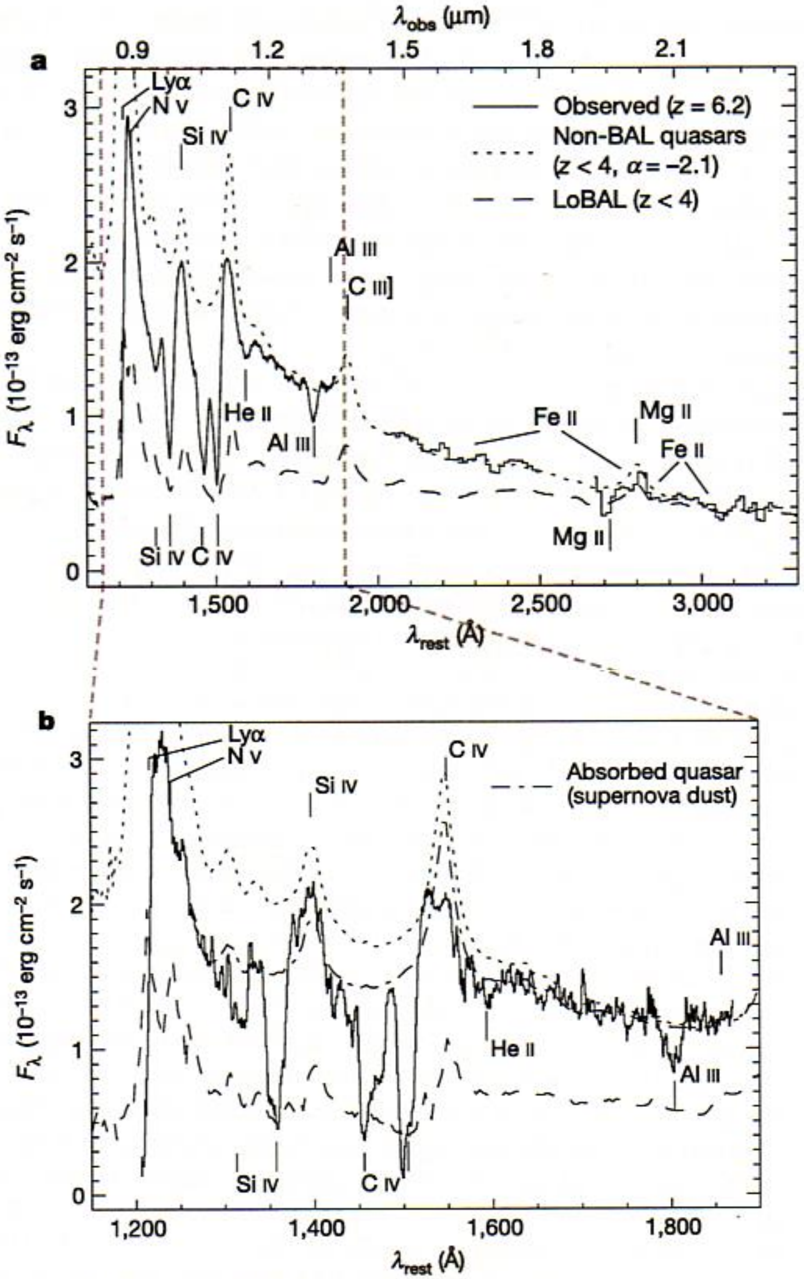
What is the sources of massive dust grains?



- ○ only SNe
  - 0.1-1.0 Msun per SN (e.g., Nozawa+2003, 2007)
- ○ AGB stars + SNe
  - 0.01-0.05 Msun per AGB star (Zhukovska & Gail 2008)
- ○ Grain growth in molecular clouds + AGB stars + SNe

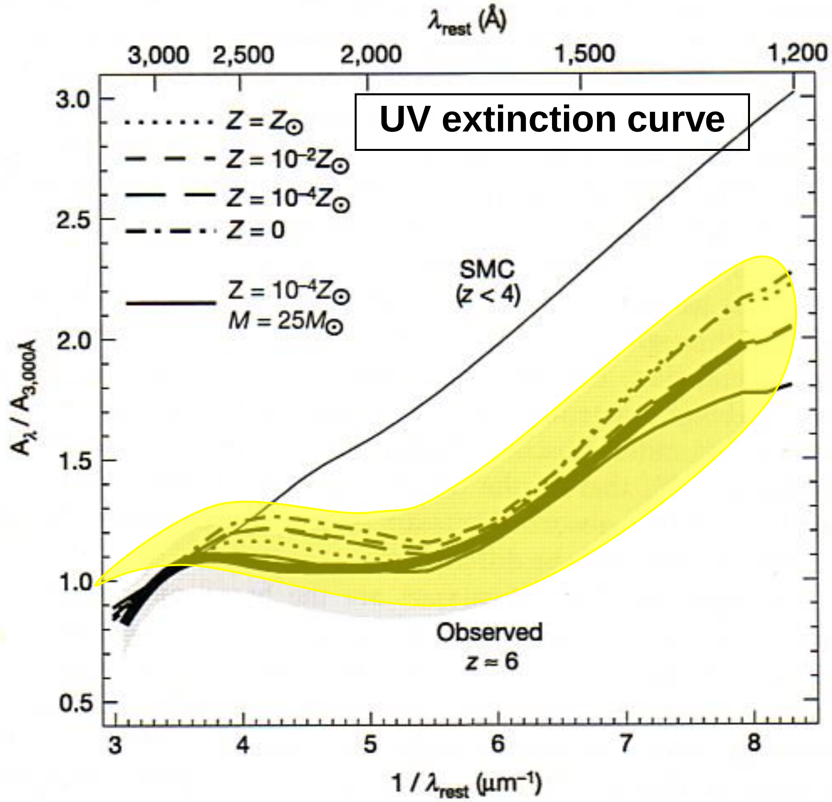
(Draine 2009; Michalowski+2010; Gall+2011a, 11b; Pipino+2011; Mattsson+2011; Valiante+2011; Inoue 2011; Kuo & Hirshita 2012; Calura+2014; Michalowski 2015)

2-2. Extinction curves in high-z quasars



SDSS J1048+4637 at z=6.2 :

broad absorption line (BAL) quasars

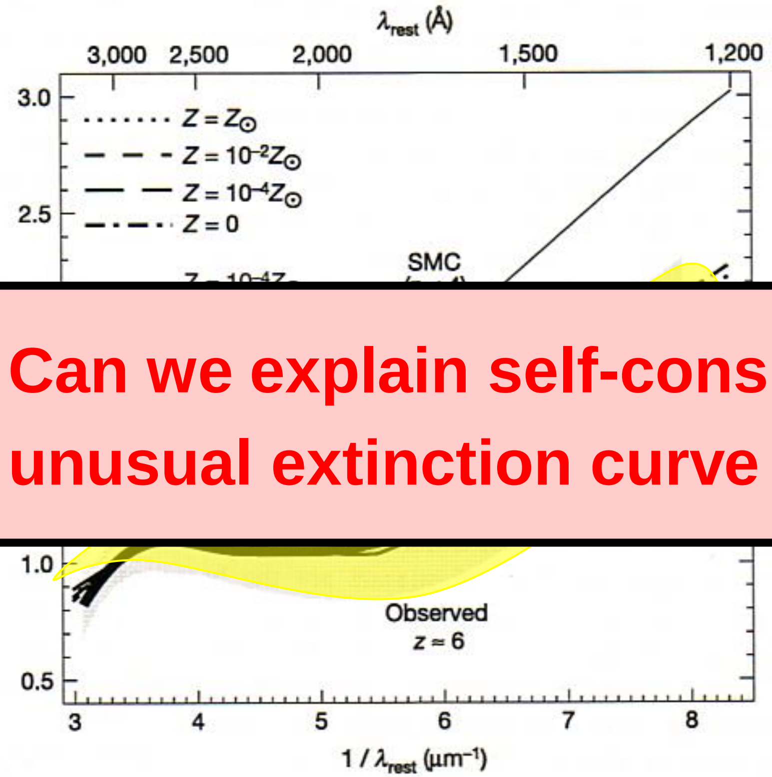


Maiolino+2004, Nature, 431, 533

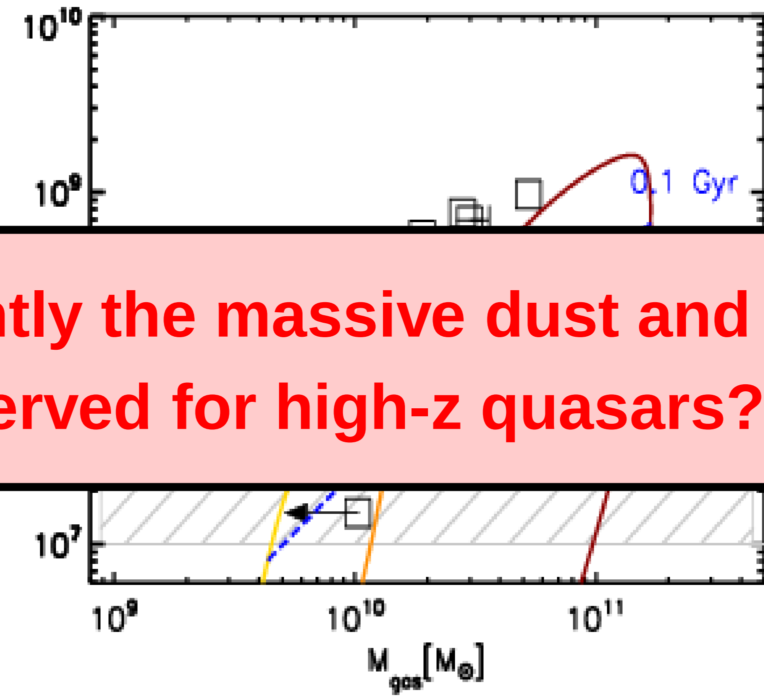
The interstellar dust in the epoch as early as z=5 was predominantly supplied by CCSNe?

2-3. Inconsistency in the origin of high-z dust

unusual extinction curve



huge amounts of dust grains



Can we explain self-consistently the massive dust and unusual extinction curve observed for high-z quasars?

SN dust only !

???

SN dust
+
AGB dust and dust growth

2-4. Dust evolution model in a galaxy

Asano, Takeuchi, Hirashita, TN (2014a, 2014b)

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

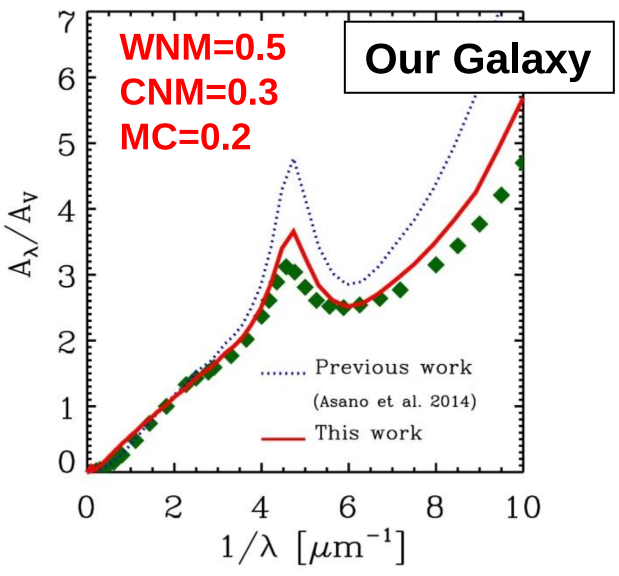
- SFR(t) = $M_{gas}(t)/\tau_{SF}$ (Schmidt law with n = 1)

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

- dust processes
  - 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

- two dust species:
  - graphite and silicate

- multi-phase ISM
  - WNM (warm neutral medium)
  - CNM (cold neutral medium)
  - MC (molecular cloud)

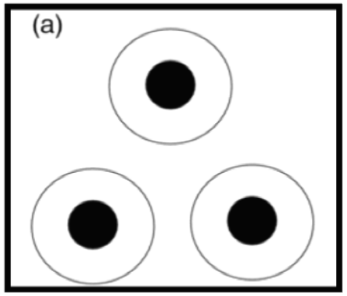


2-5. Explaining massive dust in high-z quasars

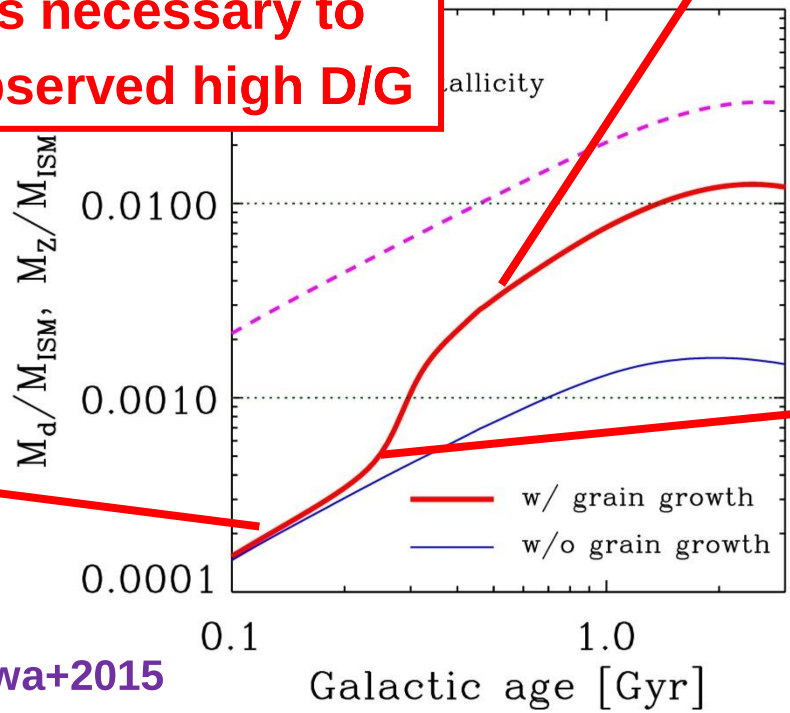
high-z quasar host: starburst galaxies
➜ indicating a high fraction of MC
$M_{H2}/M_{H,total}$ ~ 0.7-0.97 (Calura+2014)

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

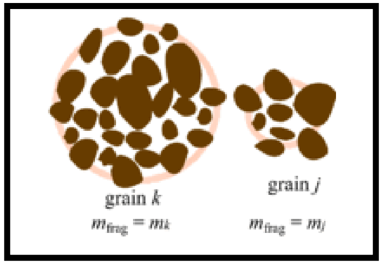
Growth of small grains via accretion of gas in the MCs



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



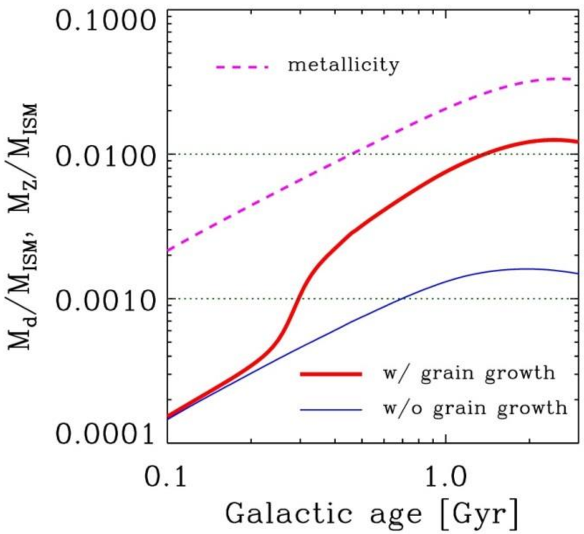
Production of small grains via shattering in the ISM

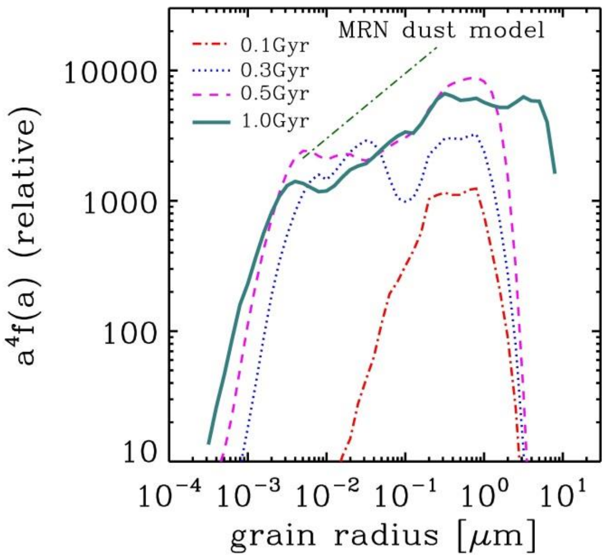


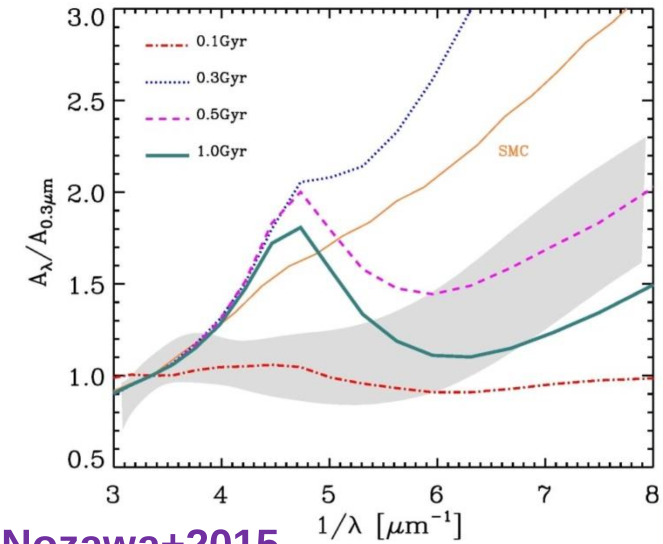
Ejection of large grains from SNe and AGB stars

Nozawa+2015

2-6. Explaining the high-z extinction curves





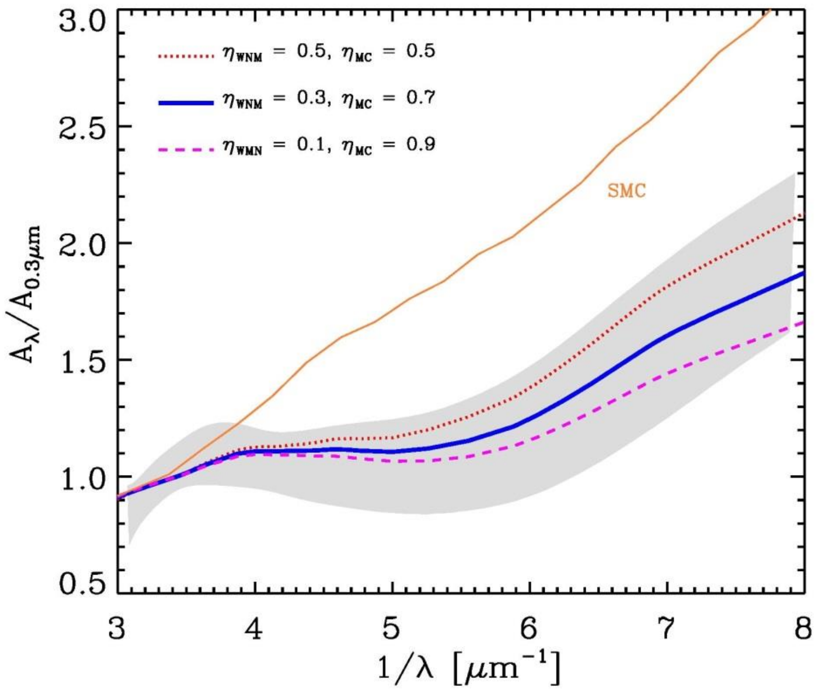


Nozawa+2015

The presence/absence of 2175 A bump may be related to the dust composition of dust

- graphite and silicate

- amorphous carbon & silicate
  ➜ the derived extinction curve well match the observed high-z extinction curve



2-7. Summary

We investigate the evolutions of grain size distribution and the extinction curves in high-z dusty galaxies

- **a large amount of dust grains and the unusual extinction curve observed for high-z quasars can be explained by considering**
  - **a large mass fraction of MC (>0.5) in the ISM**
    ➜ efficient growth/coagulation of dust grains
  - **amorphous carbon & silicate (instead of graphite & silicate)**
    ➜ different properties of carbonaceous dust