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種族III巨大質量星の赤色超巨星星風中におけるダスト形成
Dust Formation in Red-supergiant Winds of Very Massive Population III Stars

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東京大学 THE UNIVERSITY OF TOKYO
TODIAS 東京大学国際高等研究所 TODAI INSTITUTES FOR ADVANCED STUDY
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1-1. Sources of dust in the early unvierse

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

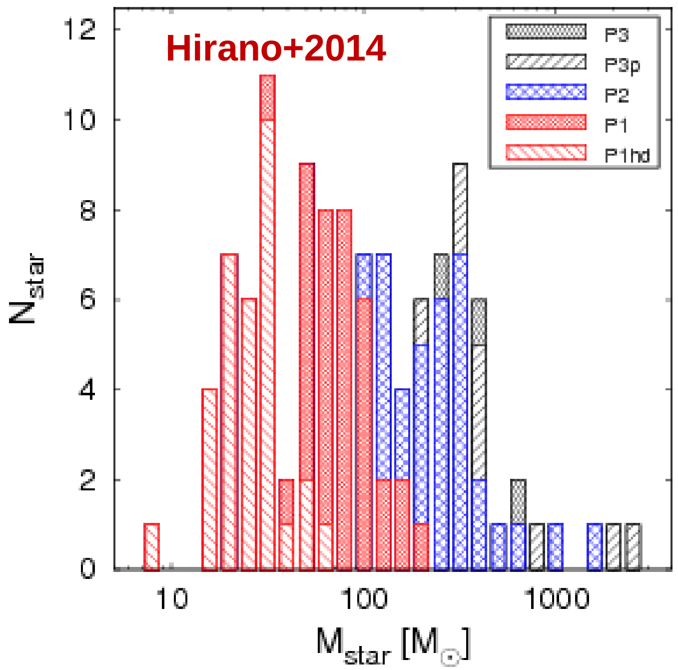
- **core-collapse supernovae (CCSNe)** may be promising sources of dust grains (e.g., Todini & Ferrara 2001; Nozawa+2003; Dwek+2007)
- the contribution from **AGB stars** is also invoked to explain the observed dust mass (e.g., Valiante+2009; Dwek & Cherchneff 2011)

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

・Typical mass of Pop III stars

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

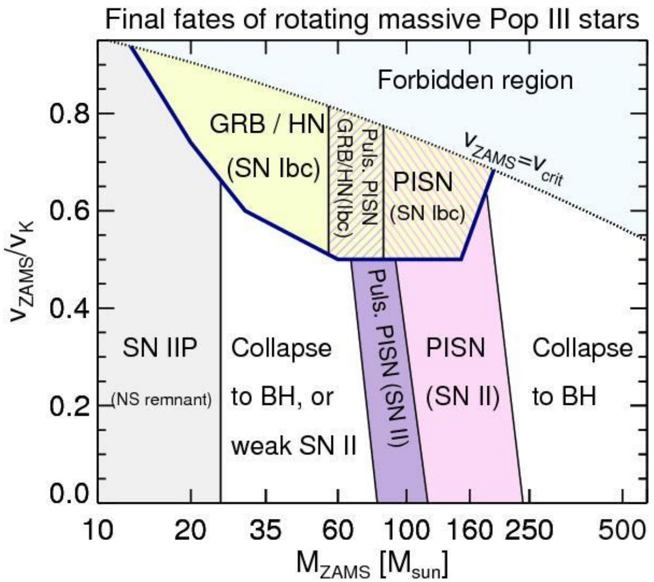
- ~40 Msun (Hosokawa+2011; Susa 2013)
- >300 Msun (Omukai+2003; Ohkubo+2009)
- 10-1000 Msun (Hirano+2014)



1-2. Very massive Population III stars

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

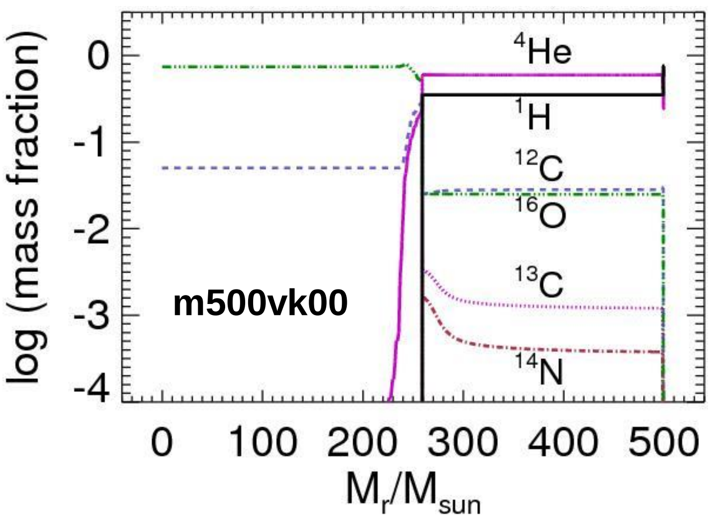
- emitting numerous ionizing photons
  ➔ reionization of the universe
- finally collapsing into black holes
  ➔ serving as seeds of SMBHs



Yoon+2012

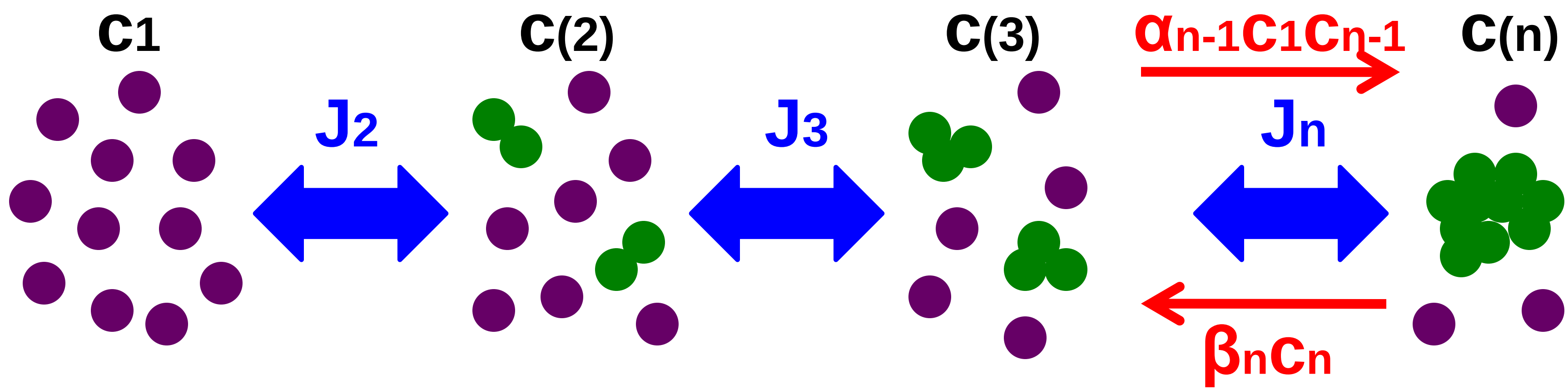
・Evolution of massive Pop III stars

- 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

2-1. Formula of non-steady dust formation



・ steady-state nucleation rate: J_s

➔ assuming $J_s = J_2 = J_3 = \cdots = J_\infty$

$$J_s = s\,\Omega_0 \left(\frac{2\sigma}{\pi m_1} \right)^{\frac{1}{2}} c_1^2 \exp\left[-\frac{4}{27} \frac{\mu^3}{(\ln S)^2} \right].$$

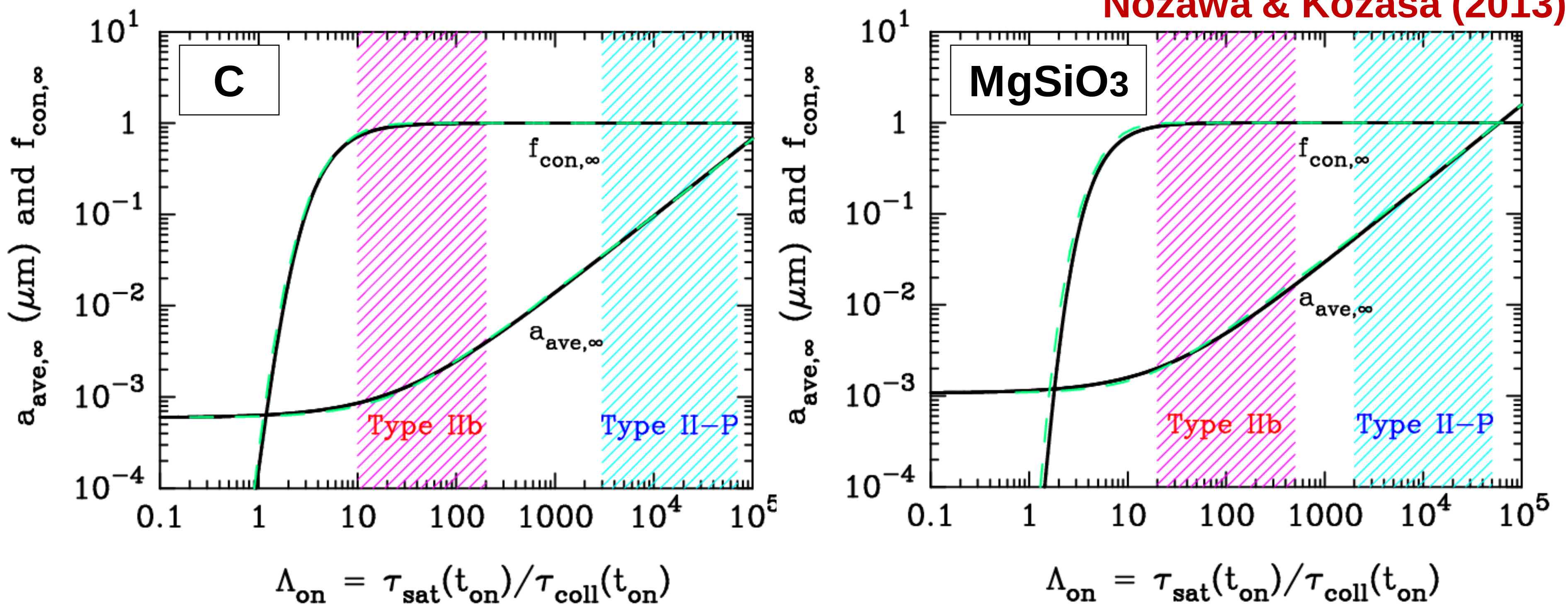
・ master equations (Nozawa & Kozasa 2013)

$n_* = 100$

$$\frac{dc_n}{dt} = J_n(t) - J_{n+1}(t) \quad \text{for} \quad 2 \le n \le n_*,$$

2-2. Scaling relation of average grain radius

Nozawa & Kozasa (2013)



$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: ratio of supersaturation timescale to gas collision timescale at the onset time (t_{on}) of dust formation

$\Lambda_{on} = \tau_{sat}/\tau_{coll} \propto \tau_{cool}\, n_{gas}$

- $f_{con,\infty}$ and $a_{ave,\infty}$ are uniquely determined by Λ_{on}
- steady-state nucleation rate is applicable for $\Lambda_{on} > 30$

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

・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}
- $A_C = 3.11 \times 10^{-3}$, $A_O = 1.75 \times 10^{-3}$ ➔ C/O = 1.78, Z = 0.034

・Model of circumstellar envelope

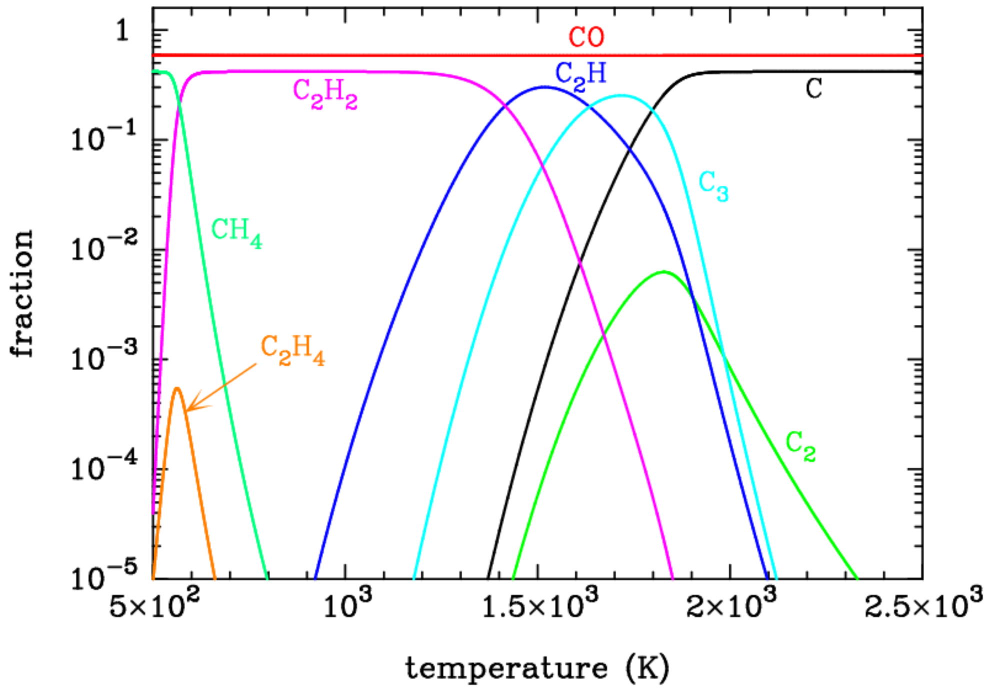
- spherically symmetry, constant wind velocity
- density profile: $$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\rm w}} = \rho_* \left(\frac{r}{R_*}\right)^{-2}$$
- temperature profile: $$T(r) = T_* \left(\frac{r}{R_*}\right)^{-\frac{1}{2}}$$

・Fiducial values of M_{dot} and V_w

- 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

3-2. Chemical equilibrium calculations



major carbon-bearing gas species other than CO:

- atomic carbon
  at T > ~1800K
- C2H molecules
  at T = 1400-1700 K

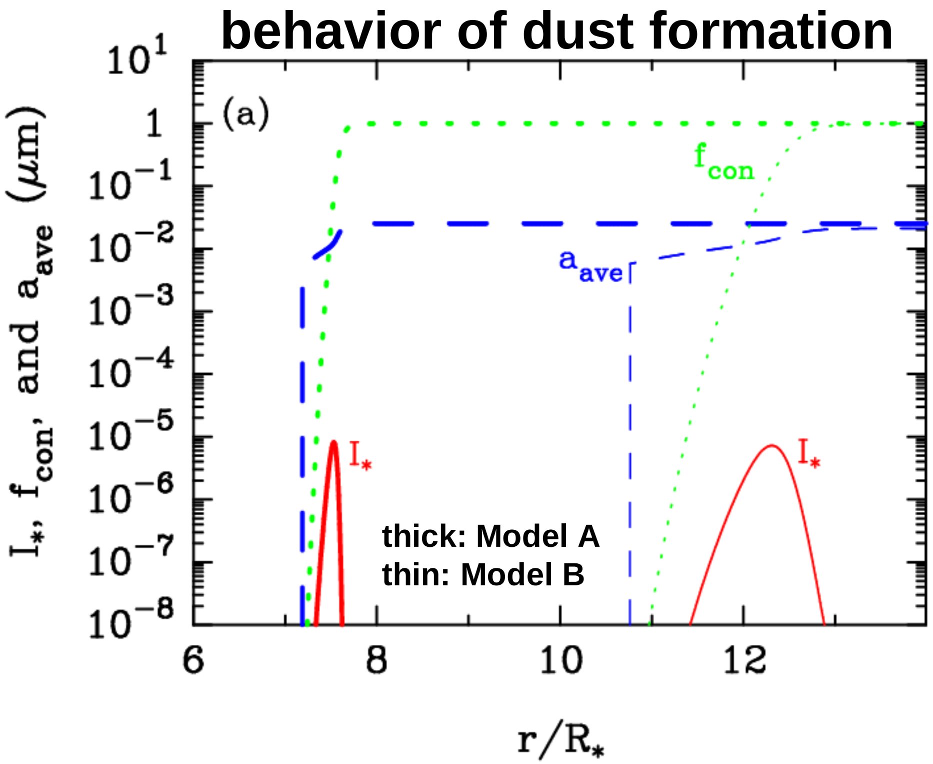
Formation of PAHs would not
be expected

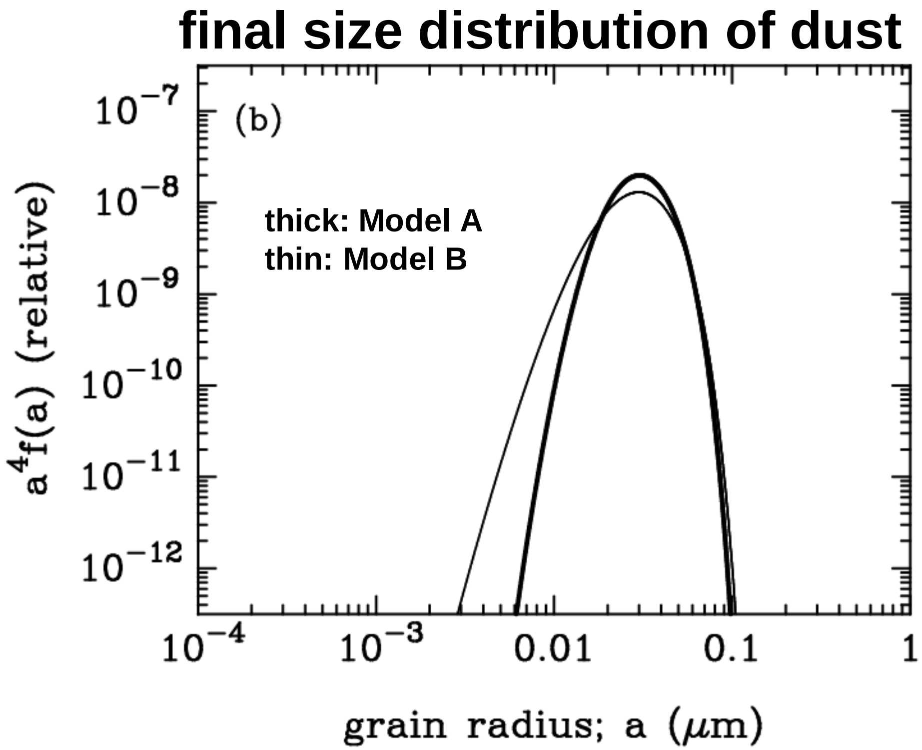
chemical reactions considered in this study

(1) Model A	C	$C_{n-1} + C \rightleftharpoons C_n$	$(n \geq 2)$
(2) Model B	C_2H	$2(C_2H + H) \rightleftharpoons C_{2n} + 2H_2$	$(n = 2)$
		$C_{2(n-1)} + C_2H + H \rightleftharpoons C_{2n} + H_2$	$(n \geq 3)$

- parameter fc: a fraction of carbon available for dust formation
  → fc = 1 as the fiducial case

4-1. Results of dust formation calculations

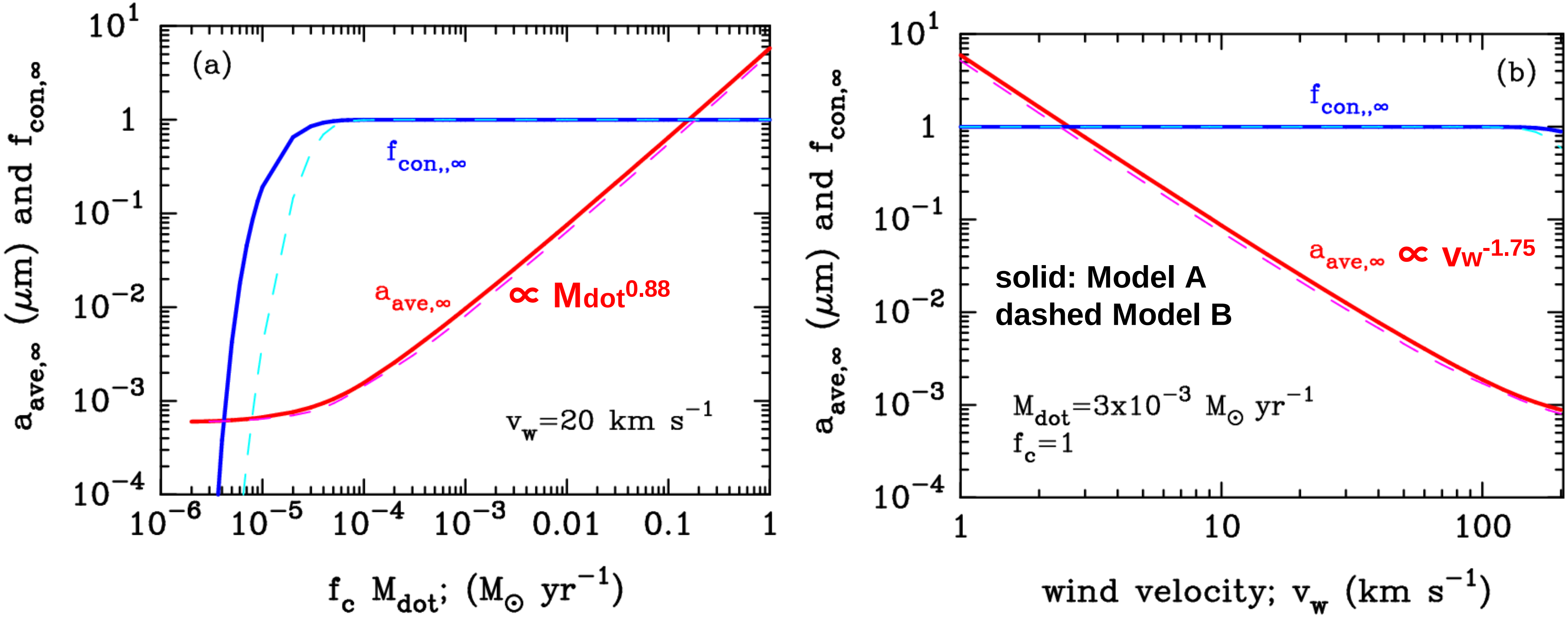




- carbon grains form around r = 7.5 Rstar (r = 12 Rstar) for Model A (Model B)
- final condensation efficiency is unity for both of the models
- final average radius is similar in both Model A and Model B

→ the results are almost independent of chemical reactions

4-2. Dependence on Mdot and vw



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

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

- for the fiducial case (Mdot = 3x10^{-3} Msun/yr, vw=20 km/s, fc=1)

  → 1.7 Msun of C grains is produced over the lifetime of the RSG

5-1. How efficient is dust formation?

· Dust ejection efficiency by very massive Pop III RSGs

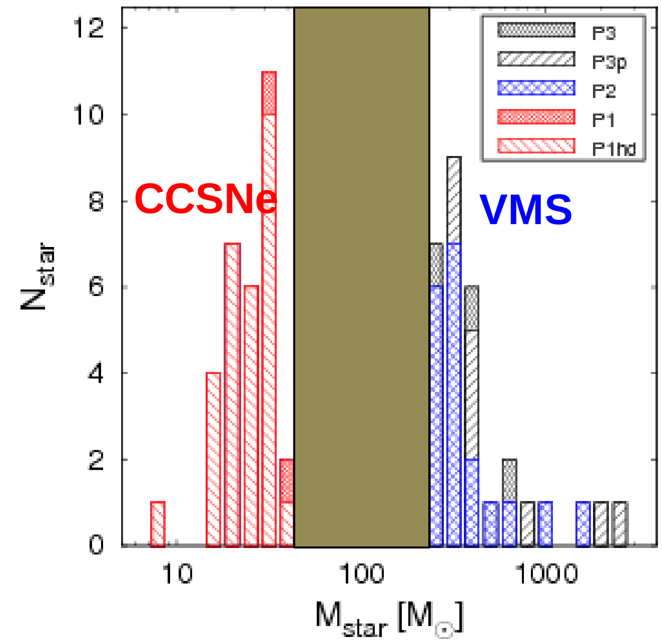
- $X_{VMS} = M_{dust} / M_{ZAMS} < 3.4\times10^{-3}$
- $M_{dust} / M_{metal} < 0.24$

· Dust ejection efficiency by CCSNe (PISNe)

- $X_{CCSN} = (0.1\text{-}30)\times10^{-3}$ ($X_{PISN} < 0.05$)
- $M_{dust} / M_{metal} = 0.01\text{-}0.25$ ($M_{dust} / M_{metal} < 0.15$)

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

Hirano+2014

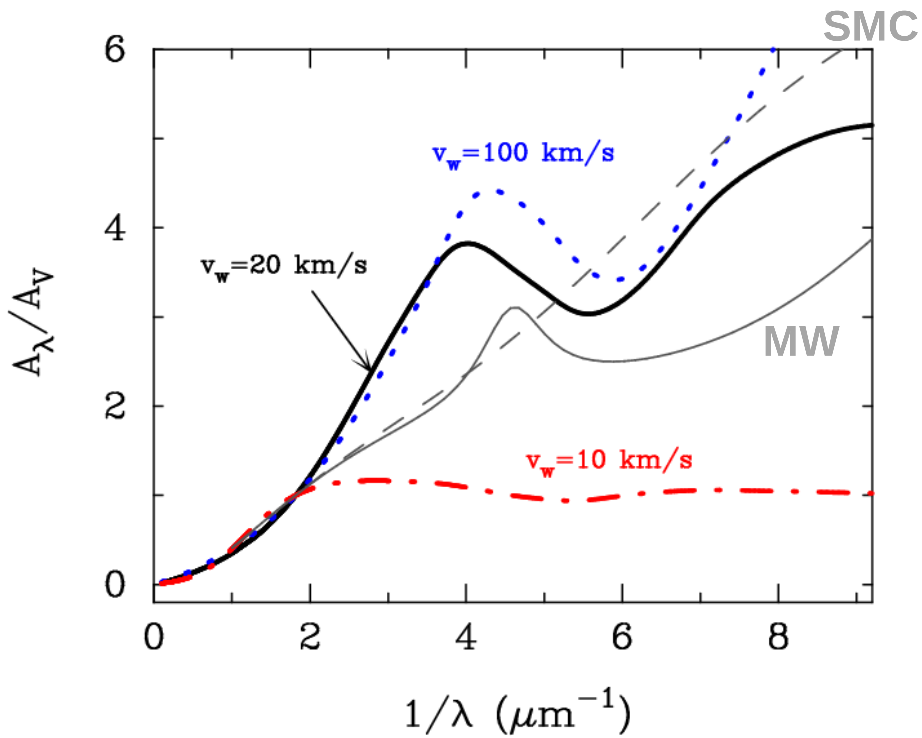


If $N_{VMS} \sim N_{CCSN}$ in the Pop III IMF …

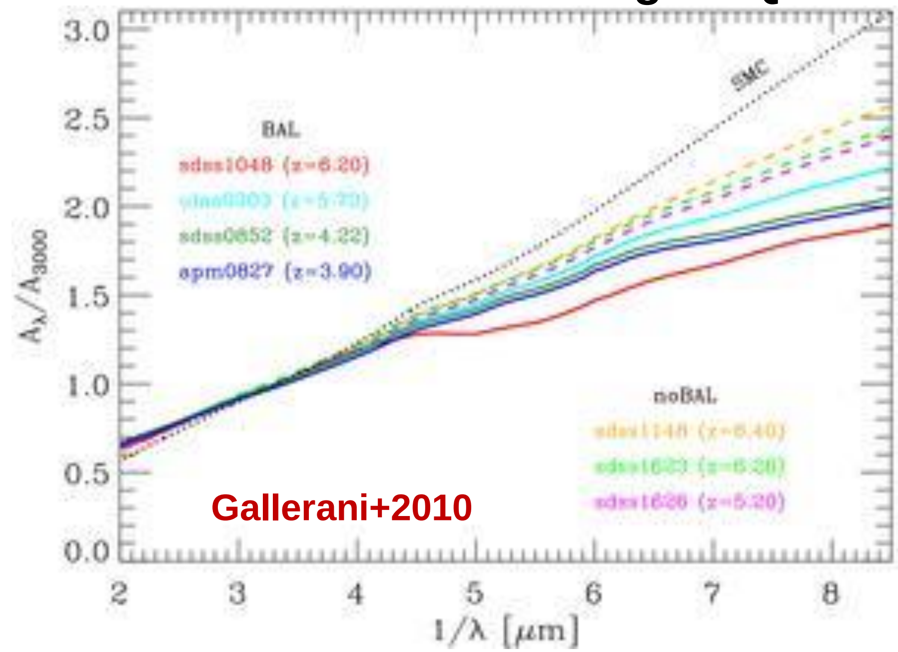
➔ The contribution of dust from very massive RSGs is comparable with, or even higher than that from CCSNe

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

5-2. Expected extinction curves



extinction curves for high-z QSOs



- **Extinction curves derived in this study do not resemble any of the known extinction law such as those in the MW and SMC**
- **The extinction curves observed for high-z quasars do not show a bump structure, being inconsistent with those given here**

  ➔ The derived extinction curves can be powerful tools to probe the formation of C grains in very massive Pop III stars

5-3. Composition of low-mass UMP stars

- The ultra-metal-poor (UMP) stars with [Fe/H] < -4 would record chemical imprints of Population III stars

- The formation of such low-mass metal-poor stars is triggered through the cooling of gas by dust produced by Pop III SNe

(e.g., Schneider+2012a, 2012b; Chiaki+2014)

・Possible channel for C-rich UMP star formation

- Very massive Pop III RSGs are sources of carbon grains as well as CNO elements

  ➔ In the gas clouds enriched by Pop III RSGs, carbon grains enable the formation of low-mass stars whose chemical compositions are highly enriched with CNO

- We do not predict the presence of heavier elements (Mg, Si, Fe)

  ➔ Further observations and more quantitative theoretical studies are needed to show whether any UMP stars have formed through our scenario

6. Summary

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

- **For a steady stellar wind, C grains can form with a lognormal-like size distribution whose average radius is sensitive to wind velocity**

- **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} < 3.4x10^{-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**

 # The extinction curves expected from ejected C grains are different from any known ones

 # The chemical feedback by PopIII VMSs predicts a new type of UMP stars