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Dust Formation in Stellar Winds of Very Massive Population III Stars

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1-1. Sources of dust in the early unvierse

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

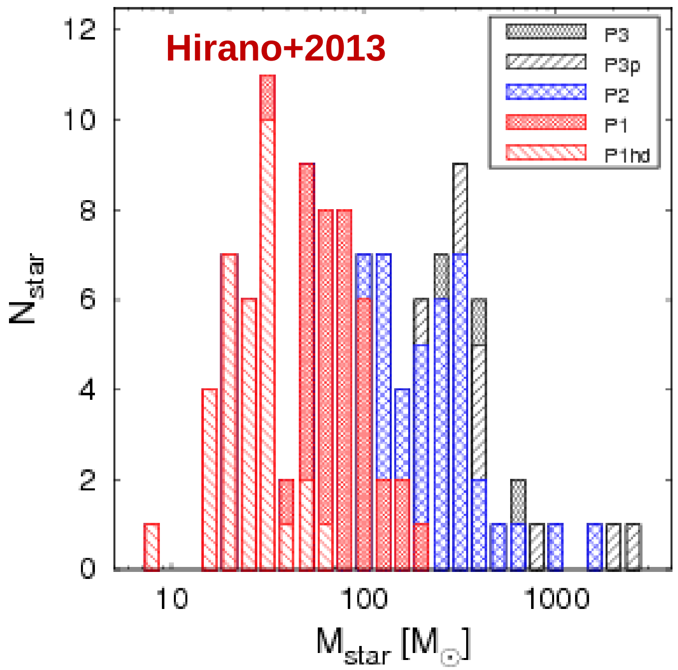
- core-collapse supernovae (CCSNe) may be promising sources of dust grains (e.g., Todini & Ferrara 2001; Nozawa+2003; Dwek+2007)
- the contribution from AGB stars is also invoked to explain the observed dust mass (e.g., Valiante+2009; Dwek & Cherchneff 2011)

➔ 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

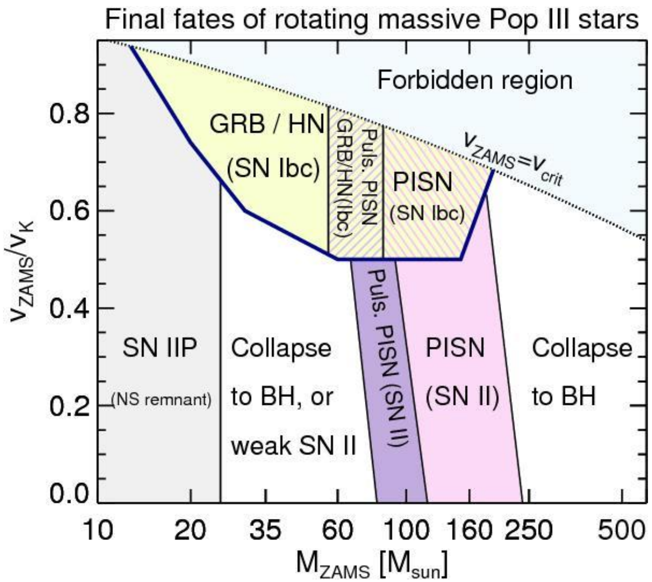
- ~40 Msun (Hosokawa+2011; Susa 2013)
- >300 Msun (Omukai+2003; Ohkubo+2009)
- 10-1000 Msun (Hirano+2013)



1-2. Very massive Population III stars

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

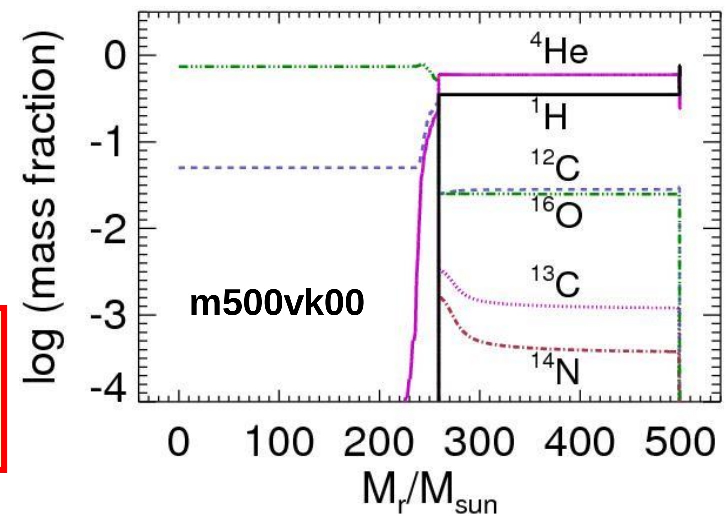
- **emitting numerous ionizing photons**
  ➔ **reionization of the universe**
- **finally collapsing into black holes**
  ➔ **serving as seeds of SMBHs**



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. Dust formation calculations

Formula of non-steady-state dust formation (Nozawa & Kozasa 2013)

・Master equations of cluster formation

$n_* = 100$

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

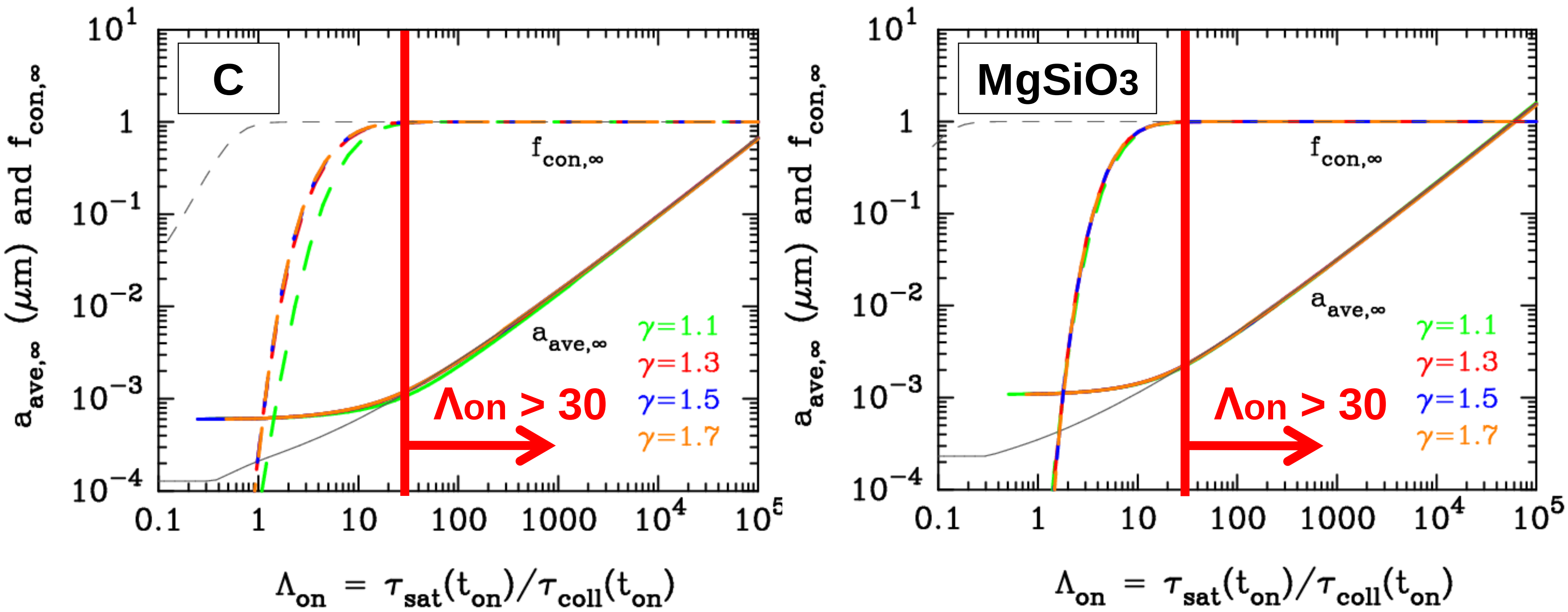
where $J_n(t) = \alpha_{n-1} c_1 \left[c_{n-1} - c_n \exp(\gamma_n) \right].$

$$\alpha_n = \frac{s_n}{1+\delta_{1n}} 4\pi a_0^2 \, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n} \right)^{\frac{1}{2}}, \quad \gamma_n = \mu \left[\left(n - \frac{1}{\omega} \right)^{\frac{2}{3}} - \left(n - 1 - \frac{1}{\omega} \right)^{\frac{2}{3}} \right] - \ln S$$

・Equation of grain growth

$$\frac{da}{dt} = s\Omega_0 \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S} \right),$$

2-2. Scaling relation of average grain radius



$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: 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 = 3.11x10^{-3}, A_O = 1.75x10^{-3} ➔ C/O = 1.78, Z = 0.034

・Model of circumstellar envelope

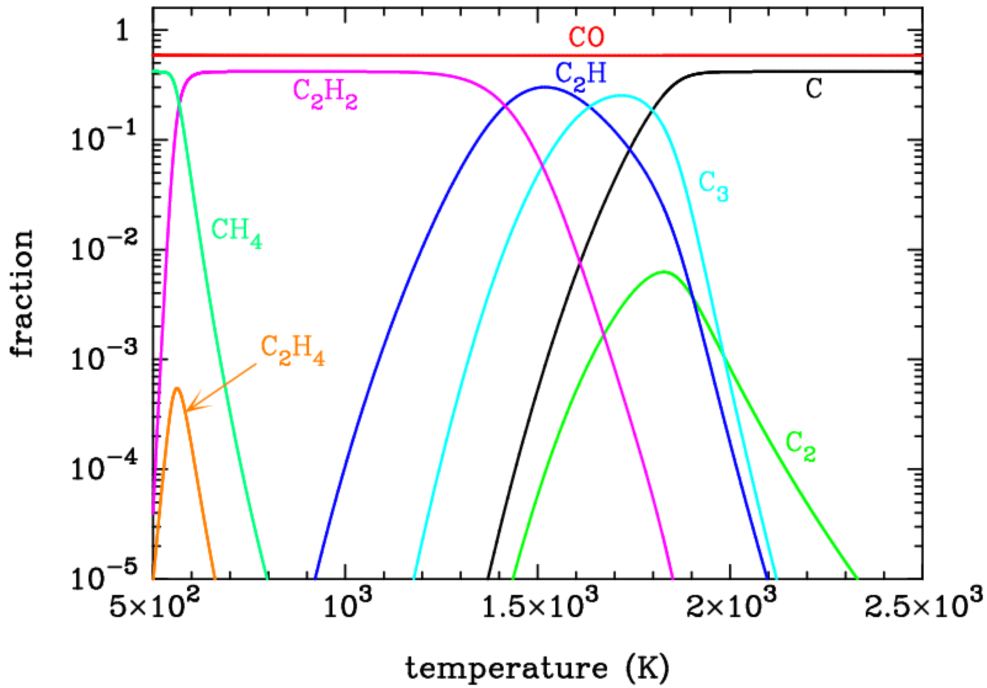
- spherically symmetry, constant wind velocity
- density profile: $$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\rm w}} = \rho_* \left(\frac{r}{R_*}\right)^{-2}$$
- temperature profile: $$T(r) = T_* \left(\frac{r}{R_*}\right)^{-\frac{1}{2}}$$

・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 7x10^4 yr

3-2. Chemical equilibrium calculations



major carbon-bearing gas species other than CO:

- **atomic carbon at T > ~1800K**
- **C_2H molecules at T = 1400-1700 K**

chemical reactions considered in this study

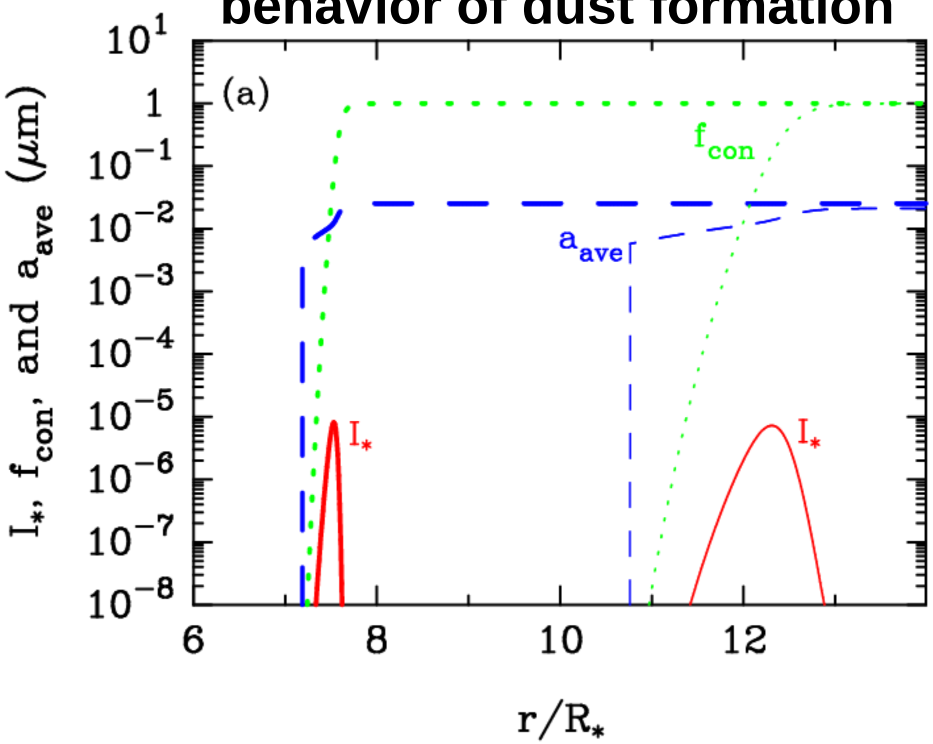
(1) Model A	C	$C_{n-1} + C \rightleftharpoons C_n$	$(n \geq 2)$
(2) Model B	C_2H	$2(C_2H + H) \rightleftharpoons C_{2n} + 2H_2$	$(n = 2)$
		$C_{2(n-1)} + C_2H + H \rightleftharpoons C_{2n} + H_2$	$(n \geq 3)$

- **parameter fc: a fraction of carbon available for dust formation**

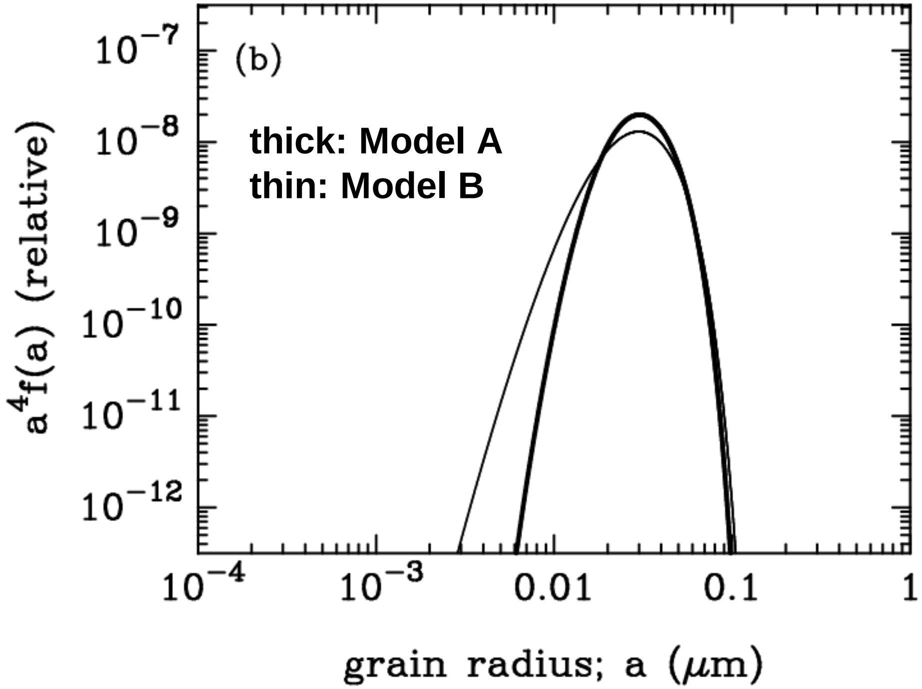
  → fc = 1 as the fiducial case

4-1. Results of dust formation calculations

behavior of dust formation



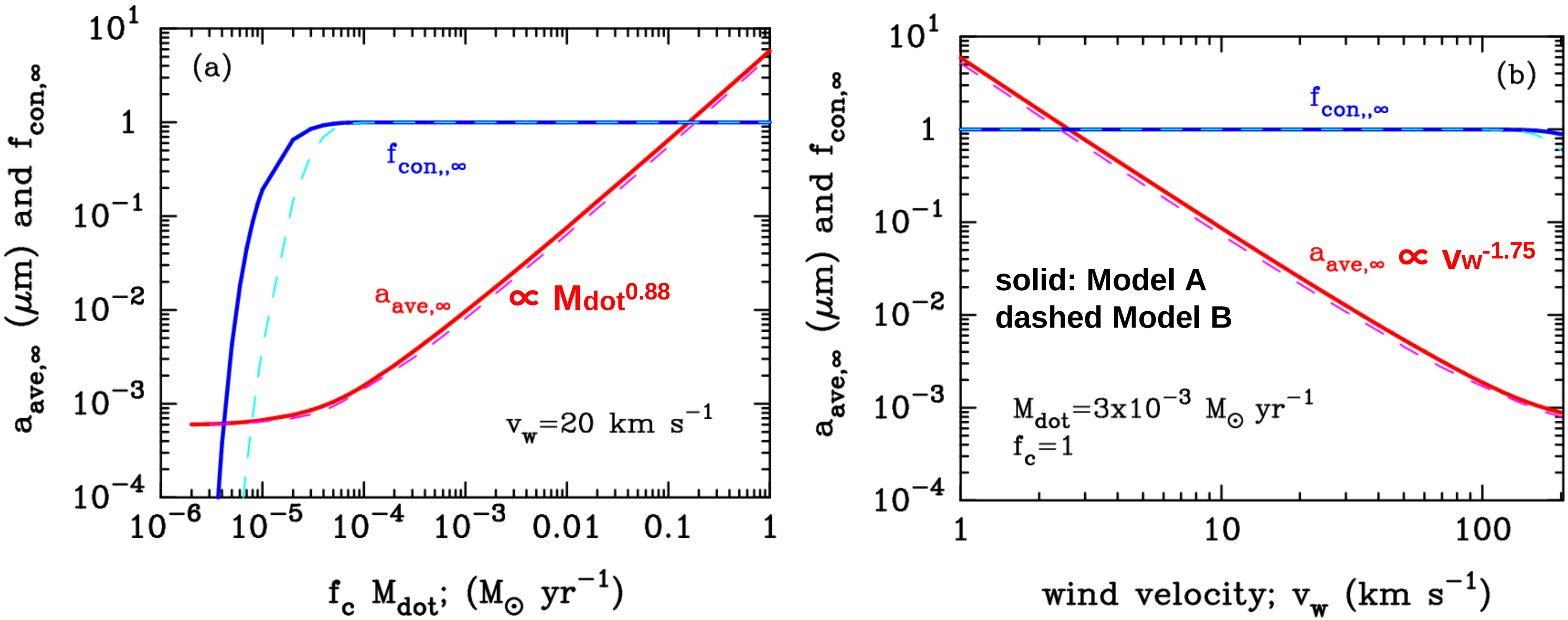
final size distribution of dust



- 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;**

$$\left(\frac{f_c \dot{M}}{3\times10^{-3}\ M_\odot\ \mathrm{yr}^{-1}}\right)\left(\frac{v_w}{20\ \mathrm{km\ s^{-1}}}\right)^{-2} \gtrsim 0.04.$$

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

  → producing 1.7 Msun of C grains over the lifetime of the RSG

5-1. How efficient is dust formation?

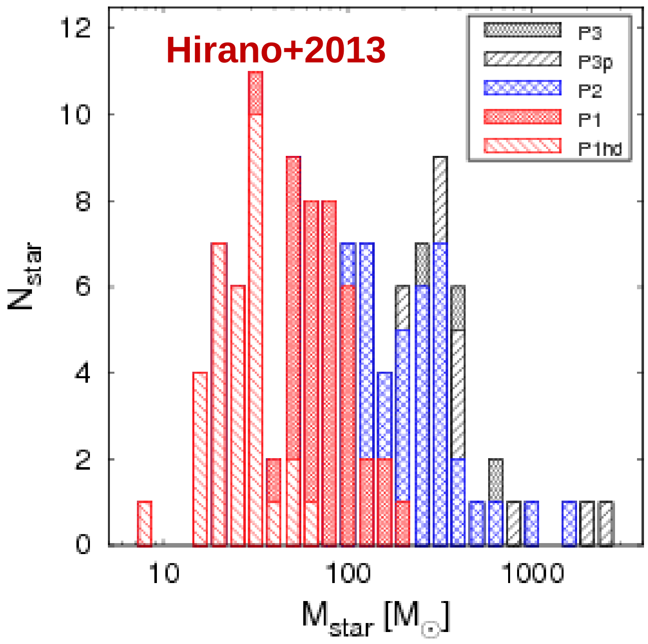
・Dust ejection efficiency by very massive Pop III RSGs

- $X_{VMS} = M_{dust} / M_{ZAMS} < 3.4 \times 10^{-3}$
- $M_{dust} / M_{metal} < 0.24$

・Dust ejection efficiency by CCSNe (PISNe)

- $X_{CCSN} = (0.1\text{-}30) \times 10^{-3}$ ($X_{PISN} < 0.05$)
- $M_{dust} / M_{metal} = 0.01\text{-}0.25$ ($M_{dust} / M_{metal} < 0.15$)

depending on the destruction efficiency
of dust by the reverse shock

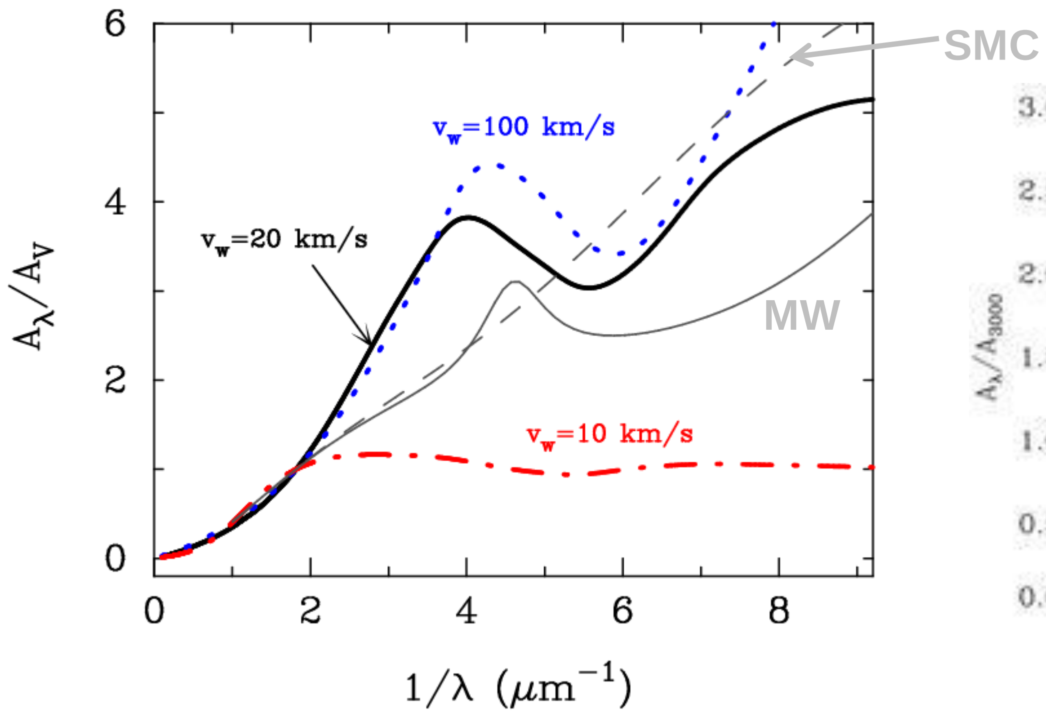


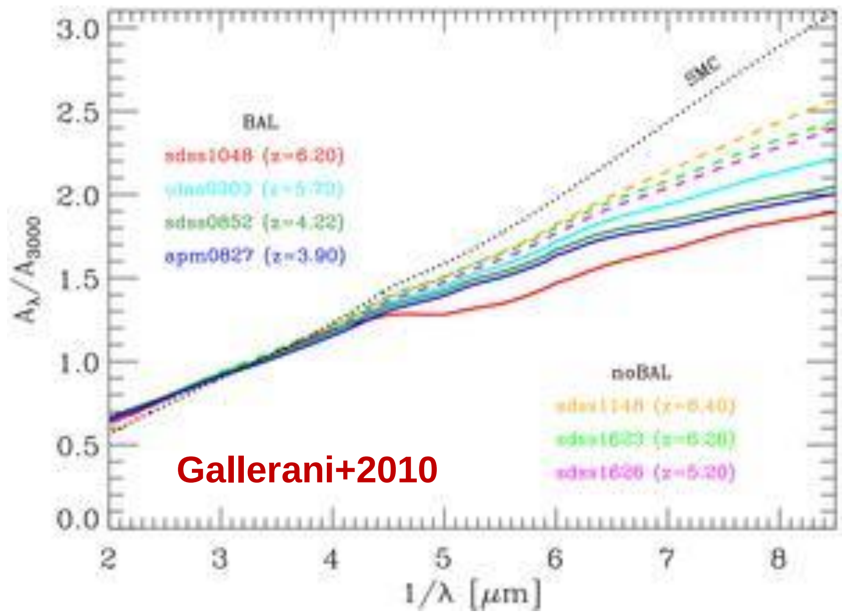
If $N_{VMS} \sim N_{CCSN}$ in the Pop III IMF …

➔ 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 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
  ➔ **These 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 stars with [Fe/H] < -4 record chemical imprint 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+2013)

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

6. Summary

We examine the formation of dust grains 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**

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

- **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**