2013/10/29

Formation of Carbon Grains in Red-Supergiant Winds of Very Massive Population III stars

submitted to ApJ Letter

Takaya Nozawa (Kavli IPMU)

collaborators:

Yoon, S.-C. (SNU), Maeda, K. (Kyoto U.),

Kozasa, T. (Hokkaido U.), Nomoto, K. (K-IPMU),

Langer, N. (Bonn U.)

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

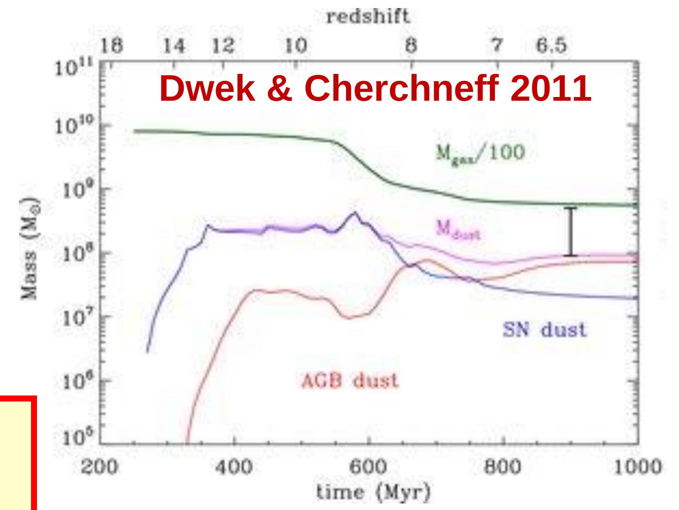
wpi World Premier International Research Center Initiative

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

1-1. Sources of dust in the early unvierse

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

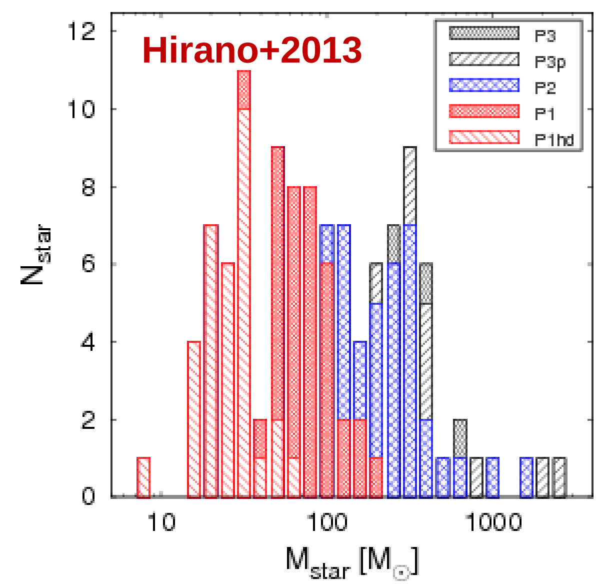
- CCSNe may be promising sources of dust grains (e.g., Dwek+2007)
- the contribution from AGB stars is also invoked to explain observed dust mass (Valiante+2009; Dwek & Cherchneff 2011)



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

・Typical mass scale of Pop III stars

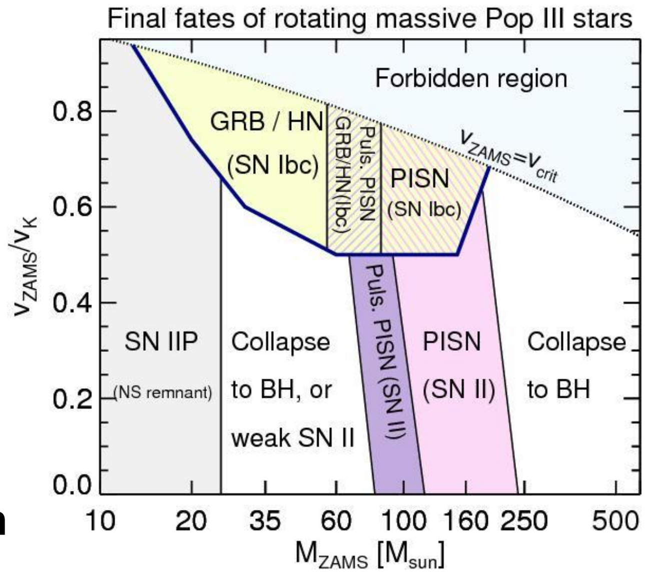
- ~40 Msun (Hosokawa+2011; Susa 2013)
- >300 Msun (Omukai+2003; Ohkubo+2009)
- 10-1000 Msun (Hirano+2013)



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**

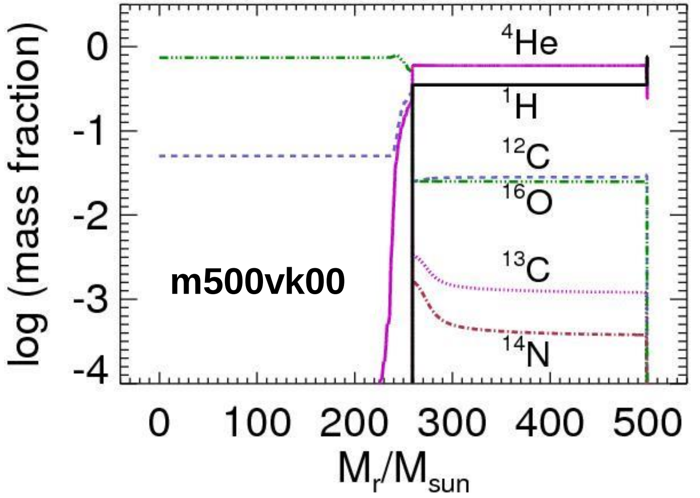


・ Evolution of massive Pop III stars

- **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**

Newly formed grains are not likely to be destroyed by the SN shock

Yoon+2012



2-1. Model of 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: $$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\mathrm{w}}} = \rho_* \left(\frac{r}{R_*}\right)^{-2}$$
- temperature profile: $$T(r) = T_* \left(\frac{r}{R_*}\right)^{-\frac{1}{2}}$$

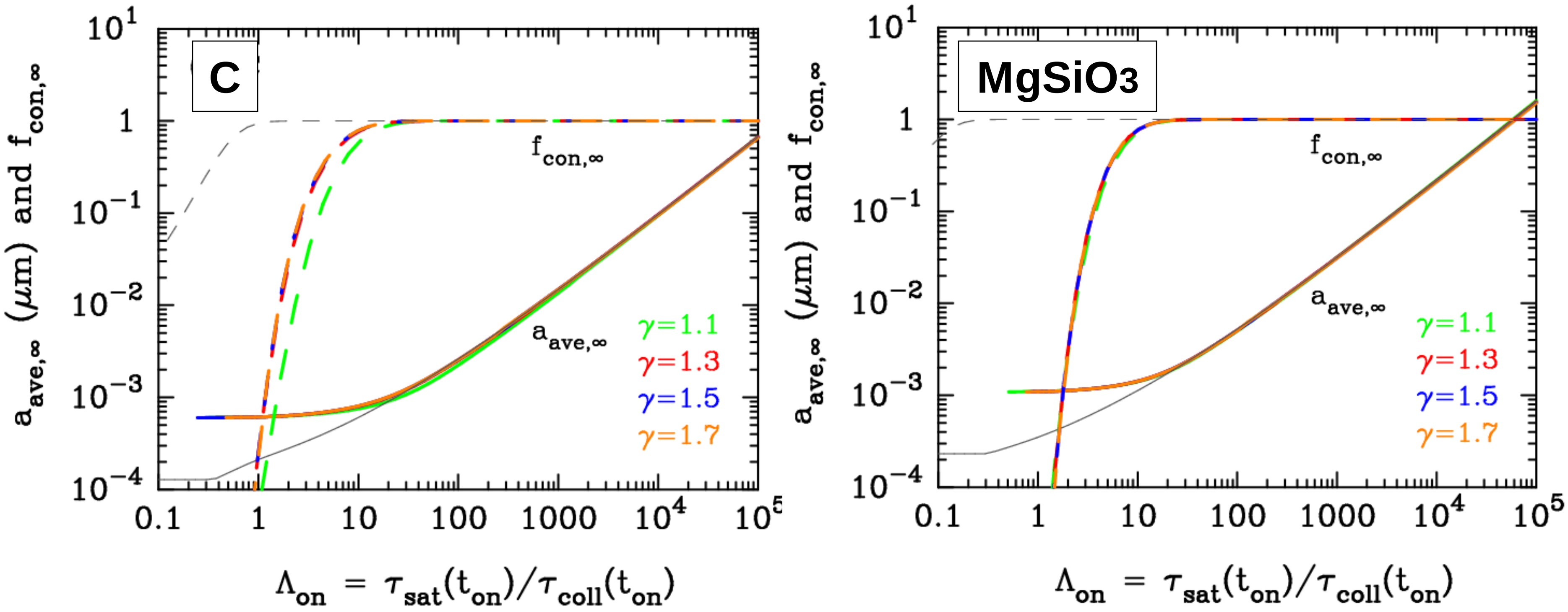
・Free parameters

- average mass-loss rate: M_{dot} = 0.003 M_{sun}/yr
  ➔ losing 90% (208 M_{sun}) of envelope during 7×10^4 yr
- wind velocity: v_w = 20 km/s (also considering v_w= 1-200 km/s)

2-2. Model of dust formation calculations

・**Formula of non-steady-state dust formation**

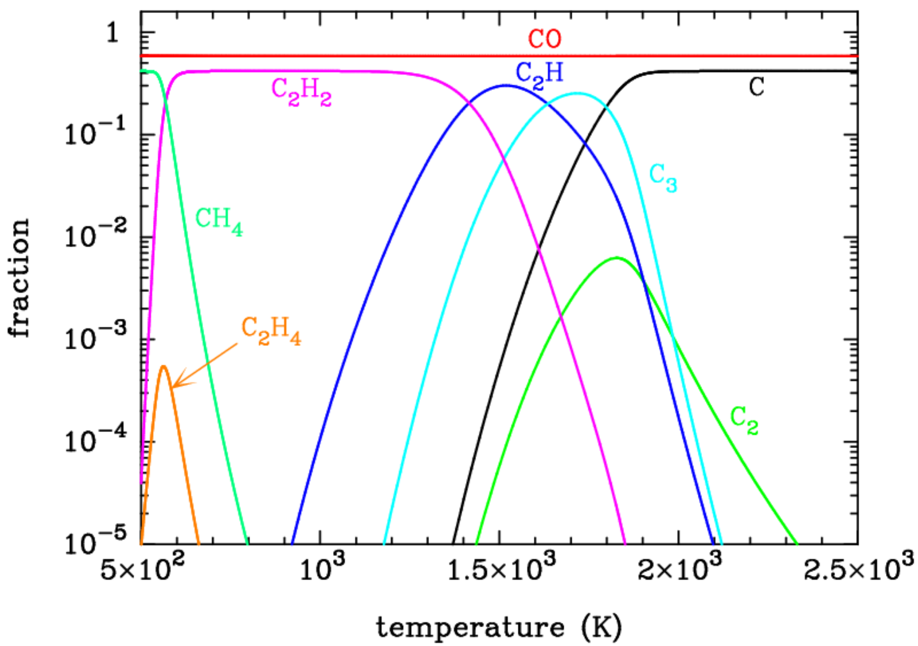
(Nozawa & Kozasa 2013, ApJ, 776, 24)

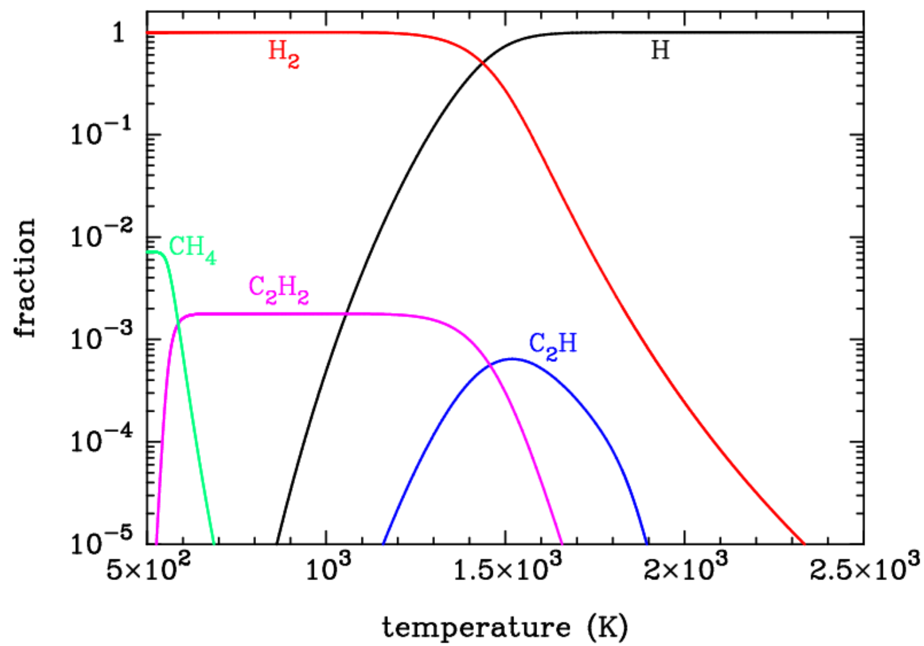


$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: ratio of supersaturation timescale to gas collision timescale at the onset time (t_{on}) of dust formation

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

2-3. Chemical equilibrium calculations





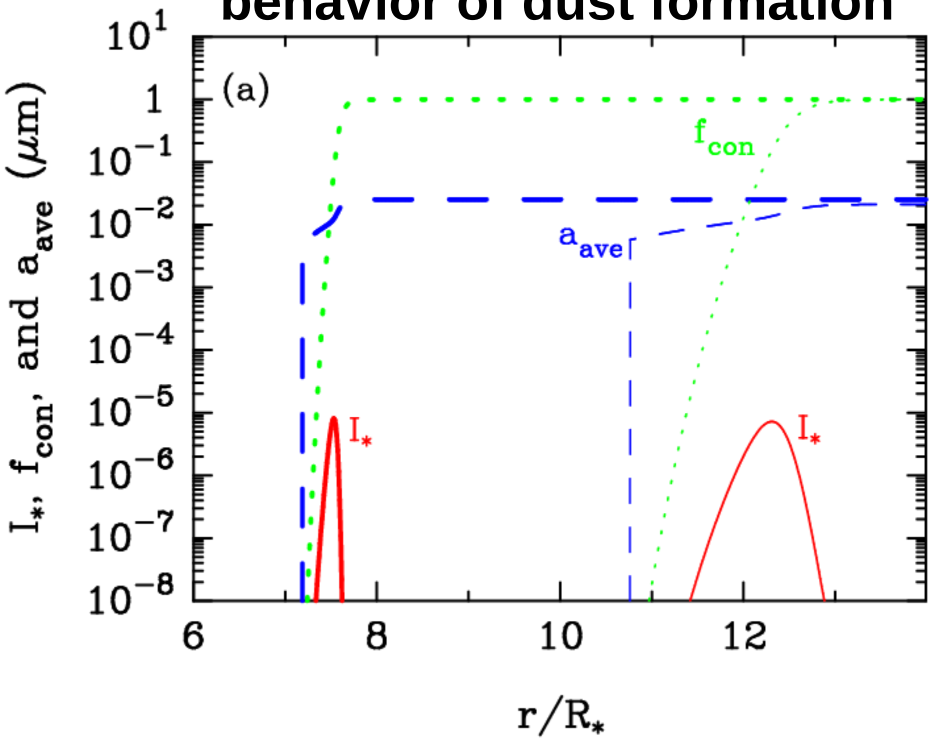
- **Major carbon-bearing gas species other than CO**
  - **carbon atoms at T > ~1700K**
  - **C2H molecules at T = 1400-1700 K**

chemical reactions considered in this study

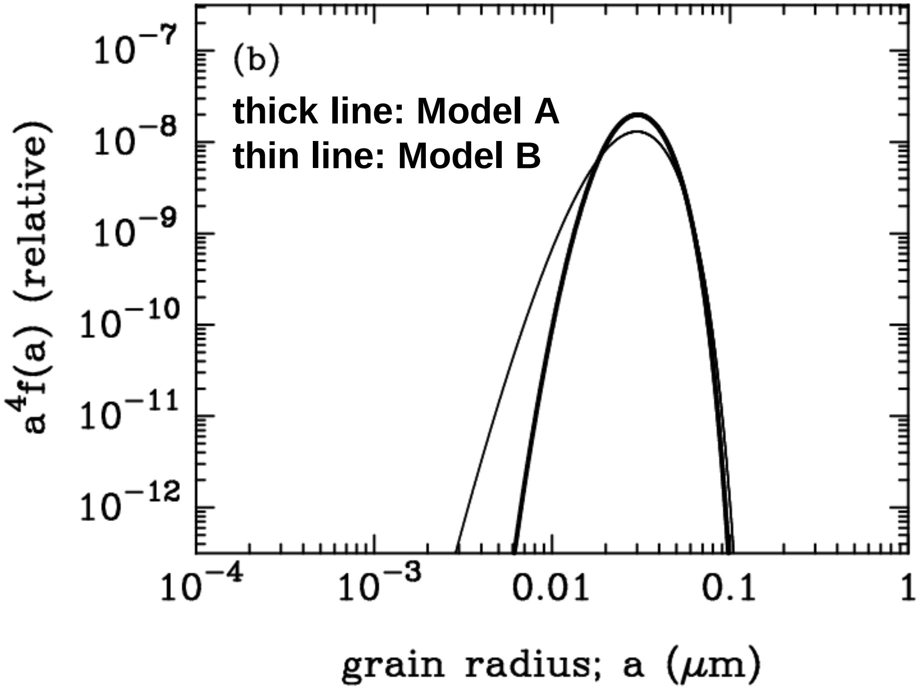
(1) Model A	C	$C_{n-1} + C \rightleftharpoons C_n$	$(n \geq 2)$
(2) Model B	C_2H	$2(C_2H + H) \rightleftharpoons C_{2n} + 2H_2$	$(n = 2)$
		$C_{2(n-1)} + C_2H + H \rightleftharpoons C_{2n} + H_2$	$(n \geq 3)$

3-1. Results of dust formation calculations

behavior of dust formation



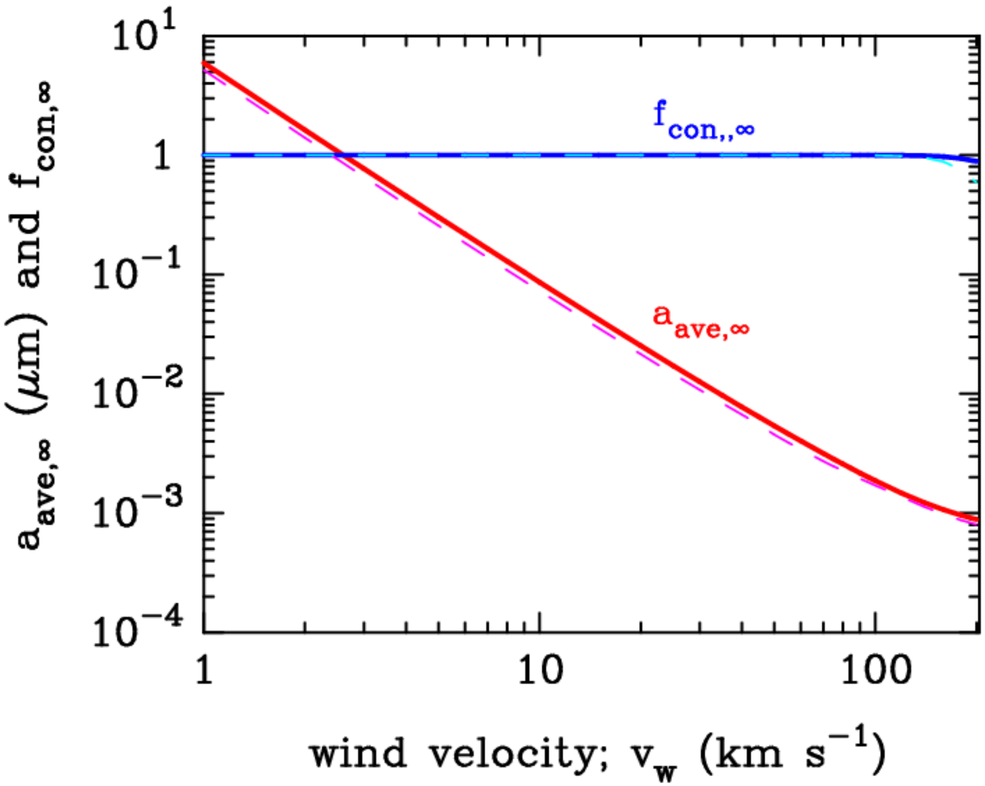
final size distribution of dust



- carbon grains start to form at r = 7.2 Rstar (r = 11.5 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

3-2. Dependence on wind velocity



$\Lambda_{on} \propto \tau_{cool}\, n_{gas}$

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

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

- **cooling time:**

$\tau_{cool} = [\,(1/T)(dT/dt)\,]^{-1} \propto 1/v_w$

$$T(r) = T_* \left(\frac{r}{R_*}\right)^{-\frac{1}{2}}, \quad r = v_w\, t$$

- **The average grain radius is larger for a smaller v_w, and scales as $a_{ave} \propto v_w^{-1.75}$ for v_w = 1-100 km/s**
- **The condensation efficiency is unity for v_w = 1-100 km/s**
  → producing 1.7 M_{sun} of C grains in total over the lifetime of the RSG

4-1. Discussion

· Dust ejection efficiency by very massive Pop III RSGs

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

· Dust ejection efficiency by CCSNe (PISNe)

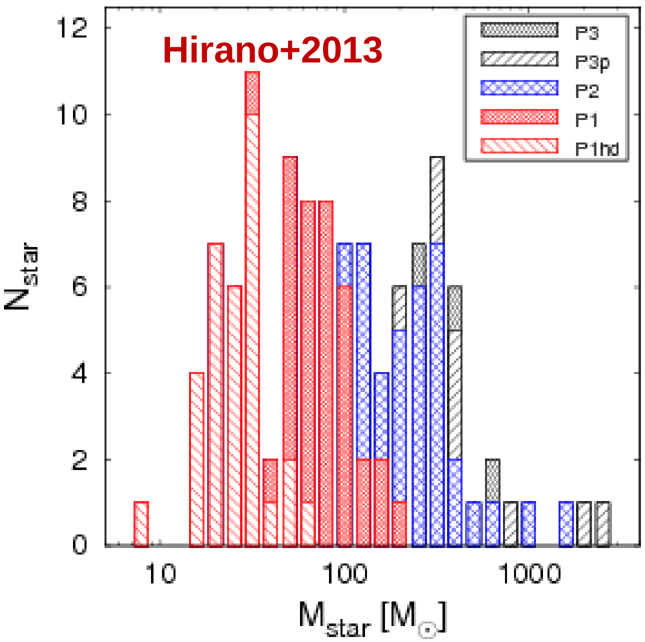
- $X_{CCSN} = (0.1\text{-}30) \times 10^{-3}\ M_{sun}$ ($X_{PISN} < 0.05$)
- $M_{dust} / M_{metal} = 0.01\text{-}0.25$ ($M_{dust} / M_{metal} < 0.15$)

depending on the destruction efficiency
of dust by the reverse shock

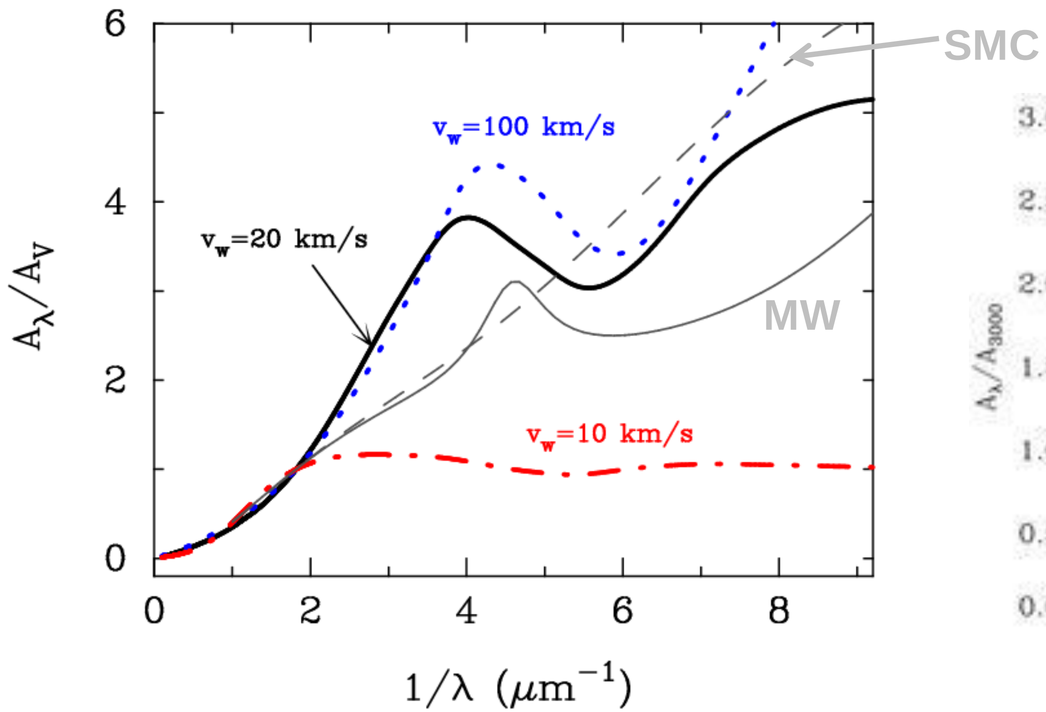
If $N_{VMS} \sim N_{CCSN}$ in the Pop III IMF …

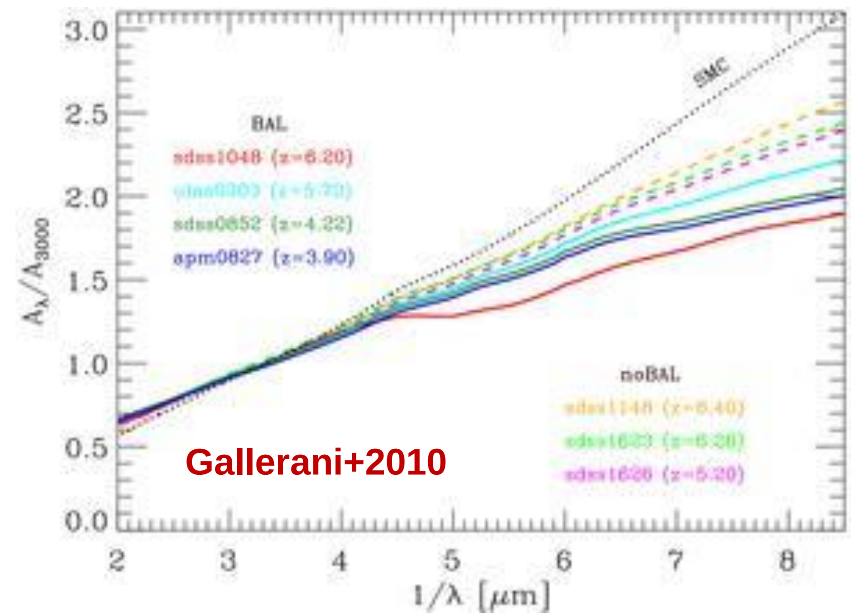
➔ The contribution of very massive RSGs is comparable with, or even higher than that from CCSNe

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



4-2. 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

4-3. Formation and composition of UMP stars

- The ultra-metal-poor (UMP) stars with [Fe/H] < -4 show the large excess of CNO

- The formation of such low-mass metal-poor stars is believed to be triggered through the cooling of gas by dust

(e.g., Schneider+2012; Chiaki+2013)

・possible channel for 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

5. 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, carbon grains can form with a lognormal-like size distribution whose average radius is sensitive to the wind velocity**

- **As long as the mass-loss rate is as high as 10^{-3} M_{sun}/yr, the condensation efficiency is unity for v_w = 1-100 km/s**

- **The total mass of dust is 1.7 M_{sun}, which would be high enough to have an impact on dust enrichment history in the very early universe, especially if the IMF of Pop III stars were top-heavy**