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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
Formation of Carbon Dust in Red-supergiant Winds of Very Massive Population III Stars

Nozawa et al. (2014, ApJL, 787, L17)

野沢　貴也（Takaya Nozawa）

NAOJ, Division of theoretical astronomy

Collaborators:

Yoon, S.-C. (SNU), Maeda, K. (Kyoto University.),
Kozasa, T. (Hokkaido University), Nomoto, K. (K-IPMU),
Langer, N. (Bonn University)

0-1. My research interests

- Formation of dust in the ejecta of supernovae
- Dynamics, destruction, and heating of dust grains in high-velocity shock waves
- Evolution of grain size distribution in galaxies and interstellar extinction curves
- Origin of dust grains in the early universe and the roles of dust in star formation
- Formation of dust in stellar winds and mass-loss history at late phases of stellar evolution

1-1. Sources of dust in the early unvierse

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

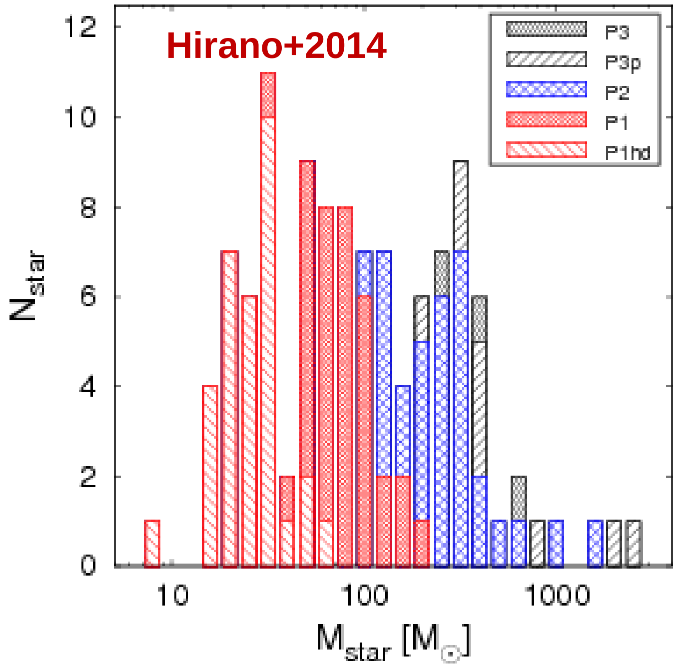
- core-collapse supernovae (CCSNe) may be promising sources of dust grains (e.g., Todini & Ferrara 2001; TN+2003; Dwek+2007)
- the contribution from AGB stars is also invoked to explain the observed dust mass (e.g., Valiante+2009; Dwek & Cherchneff 2011)

➔ what stellar mass range can mainly contribute dust budget in the early universe depends on the 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, Susa+2014)


Hirano+2014

1-2. Very massive Population III stars

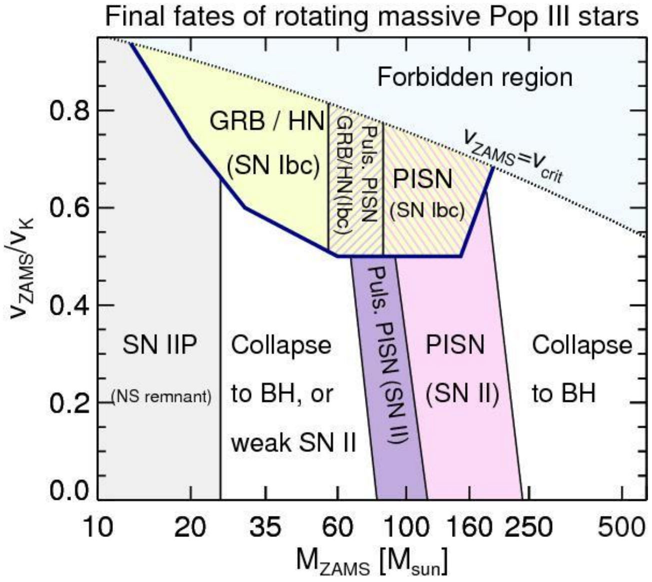
・Role of very massive stars (M_{ZAMS} > ~250 M_{sun})

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

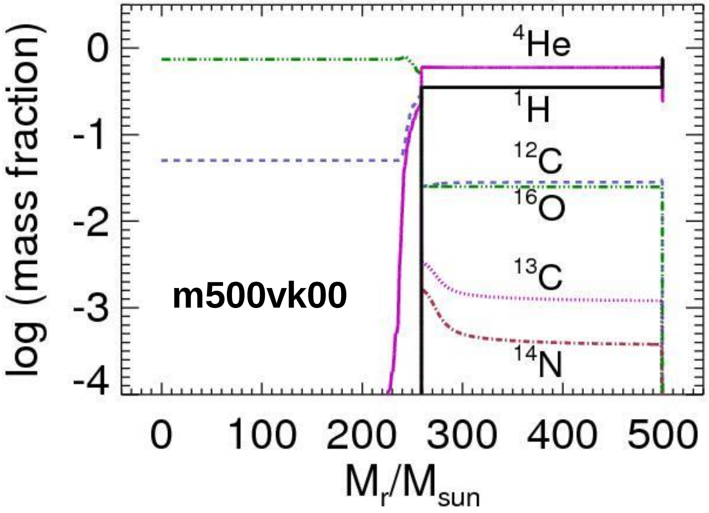
・Evolution of massive Pop III stars

- 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



Yoon+2012



2-1. Model of Pop III red-supergiant winds

・RSG model: m500vk00 (Yoon+2012)

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

・Model of circumstellar envelope

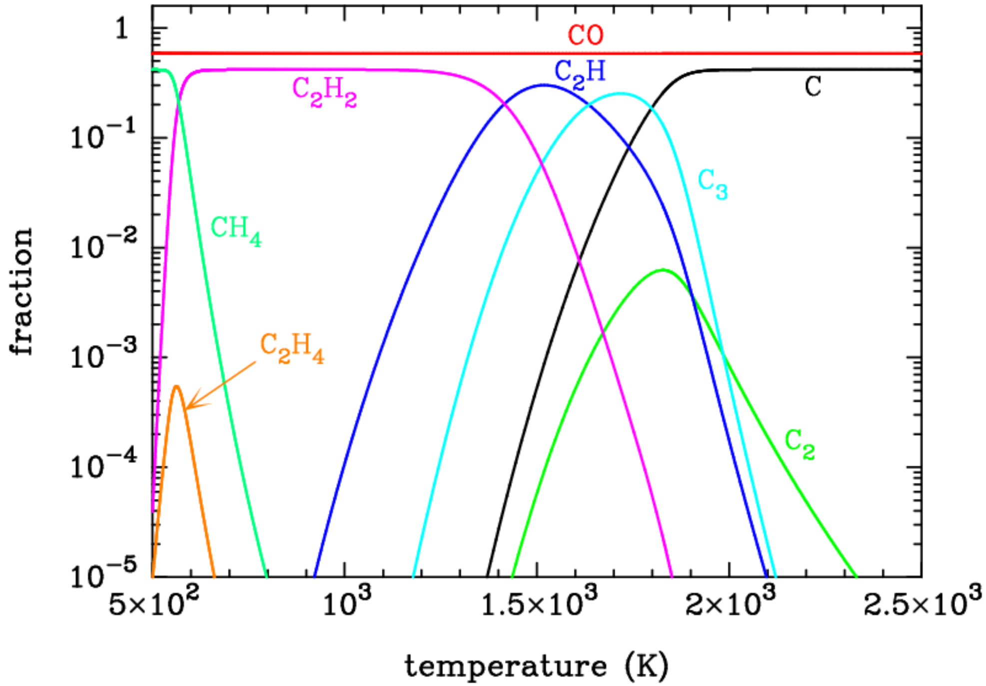
- spherically symmetry, constant wind velocity
- density profile: $$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\rm w}} = \rho_* \left(\frac{r}{R_*}\right)^{-2}$$
- temperature profile: $$T(r) = T_* \left(\frac{r}{R_*}\right)^{-\frac{1}{2}}$$

・Fiducial values of $M_{\rm dot}$ and $V_{\rm w}$

- wind velocity: $v_{\rm w}$ = 20 km/s
- mass-loss rate: $M_{\rm dot}$ = 0.003 $M_{\rm sun}$/yr

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

2-2. Chemical equilibrium calculations



major carbon-bearing gas species other than CO:

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

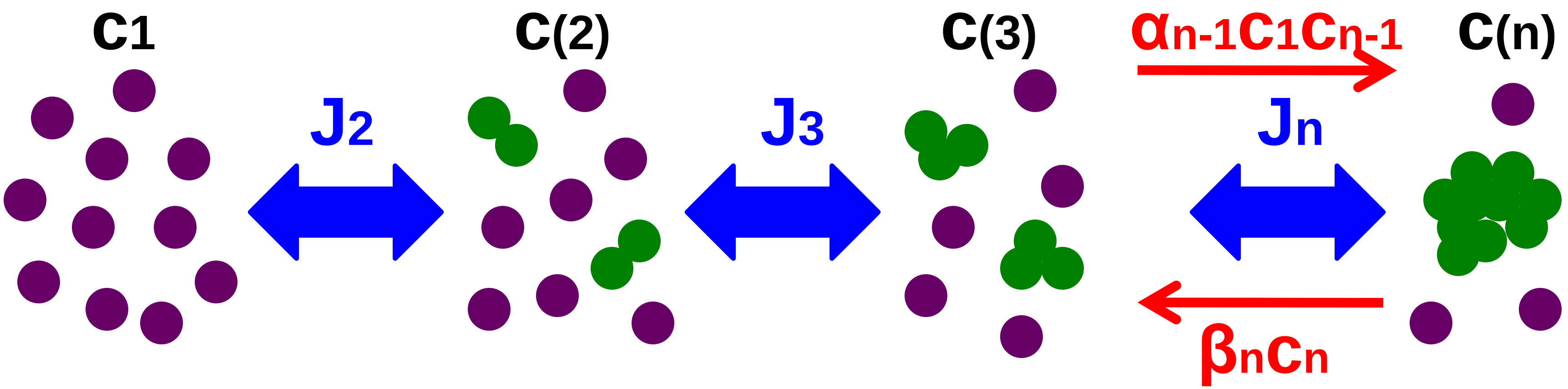
Formation of PAHs would not
be expected

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	$2(C_2H + H) \rightleftharpoons C_{2n} + 2H_2$	$(n = 2)$
		$C_{2(n-1)} + C_2H + H \rightleftharpoons C_{2n} + H_2$	$(n \geq 3)$

- **Dust formation calculations (TN & Kozasa 2013)**
  formulation of non-steady-state dust formation

3-1. Concept of nucleation theory



・ master equations

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

$$J_n(t) = \alpha_{n-1} c_{n-1} c_1 - \beta_n c_n \quad \text{for} \quad 2 \le n \le n_*,$$

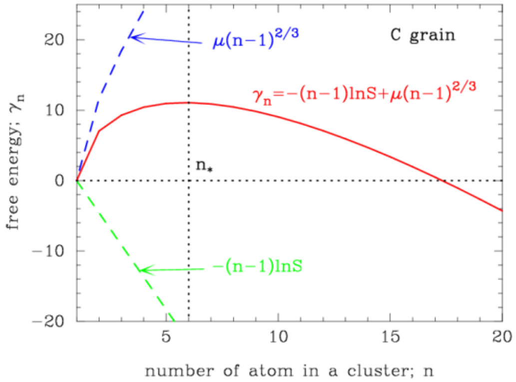
$$\alpha_n = \frac{s_n}{1+\delta_{1n}} 4\pi a_0^2 \, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n} \right)^{\frac{1}{2}},$$

$$\beta_n = \alpha_{n-1} \frac{\mathring{c}_{n-1}}{\mathring{c}_n} \mathring{c}_1,$$

3-2. Non-steady-state nucleation

・ steady-state nucleation rate: J_s

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



$$(n_c - 1)^{\frac{1}{3}} = \frac{2}{3}\frac{\mu}{\ln S}.$$

where $\mu = 4\pi a_0^2\sigma / kT$

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

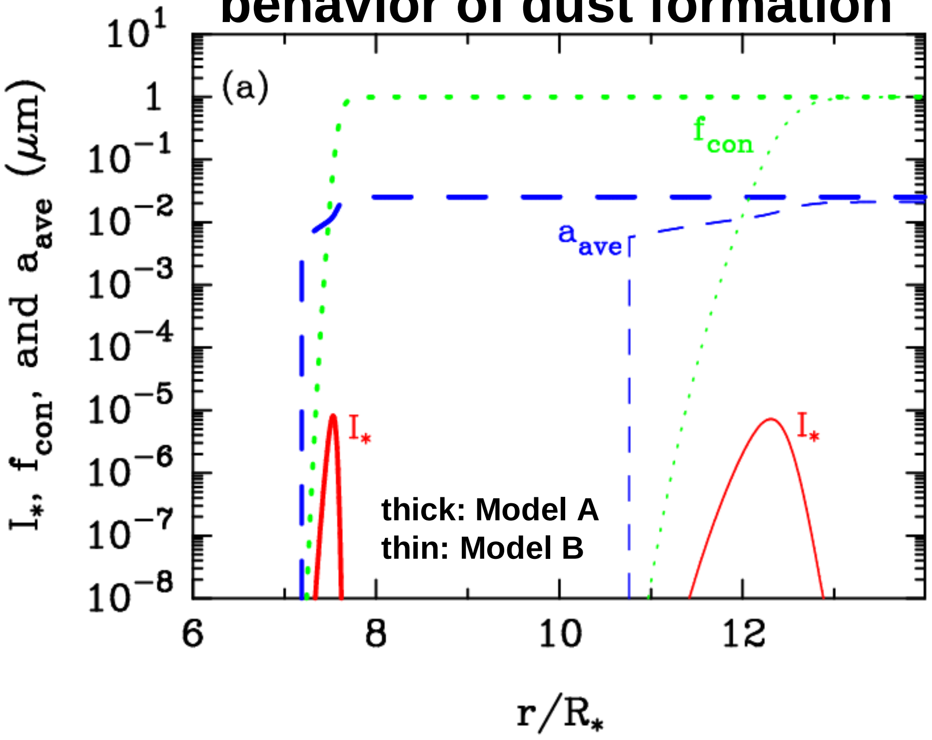
・ non-steady-state dust formation

$n_* = 100$

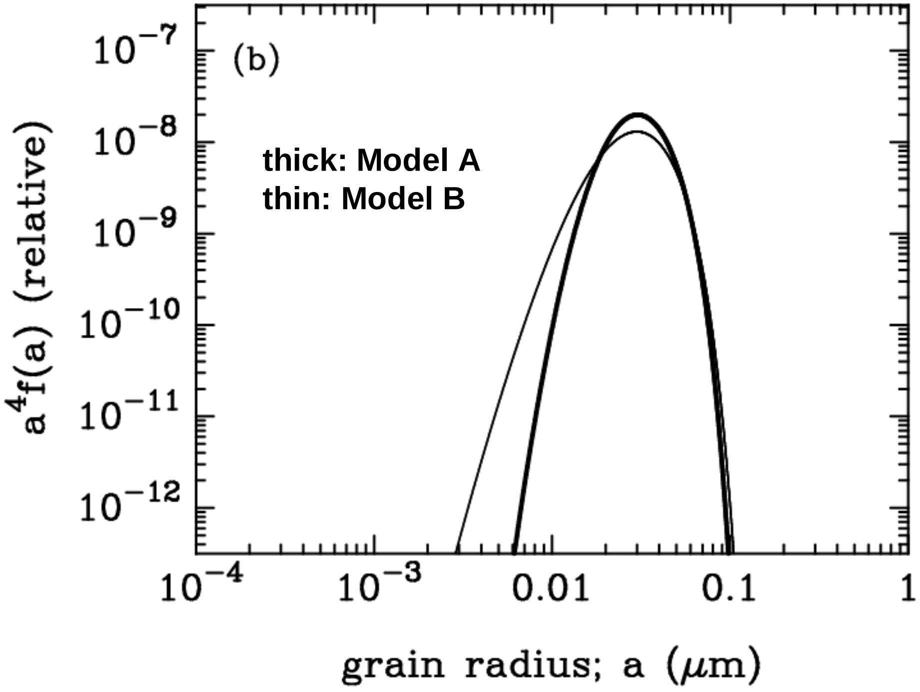
$$\frac{dc_n}{dt} = J_n(t) - J_{n+1}(t) \quad \text{for} \quad 2 \le n \le n_*,$$

4-1. Results of dust formation calculations

behavior of dust formation



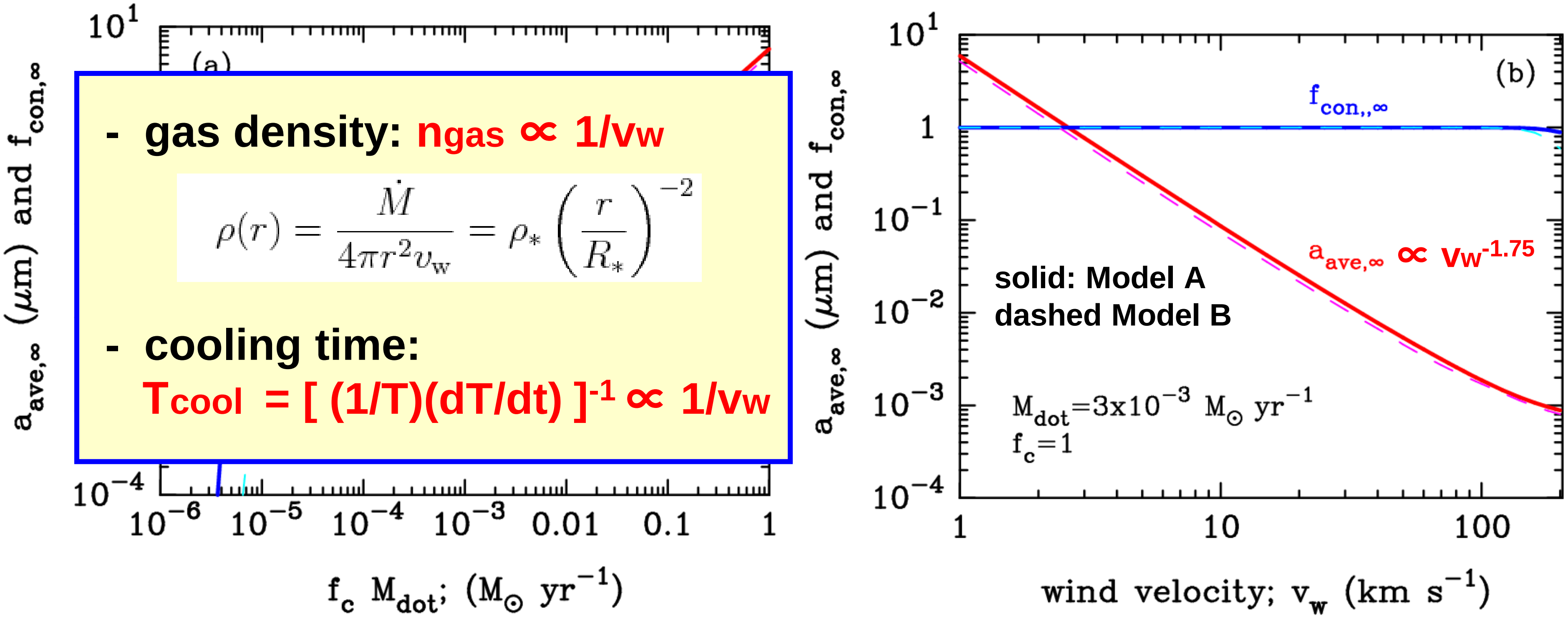
final size distribution of dust



- 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



solid: Model A
dashed Model B

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

- **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} = 3×10^{-3} M_{sun}/yr, v_w=20 km/s, f_c=1)**

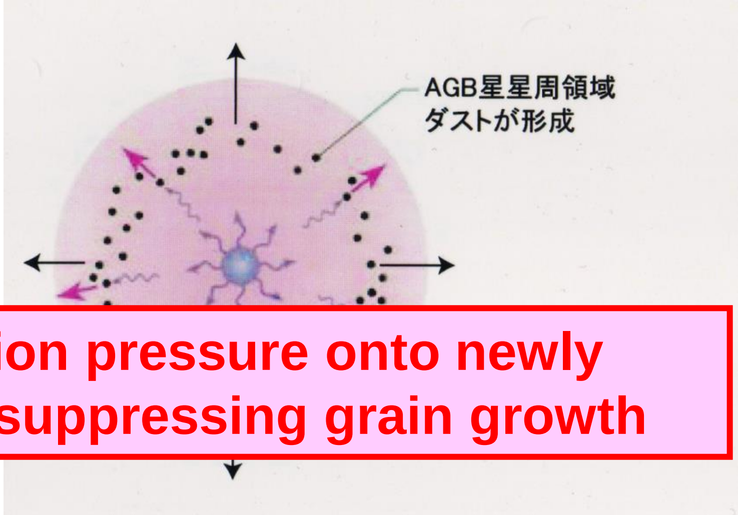
  → 1.7 M_{sun} of C grains is produced over the lifetime of the RSG

4-3. Models of dust-driven winds

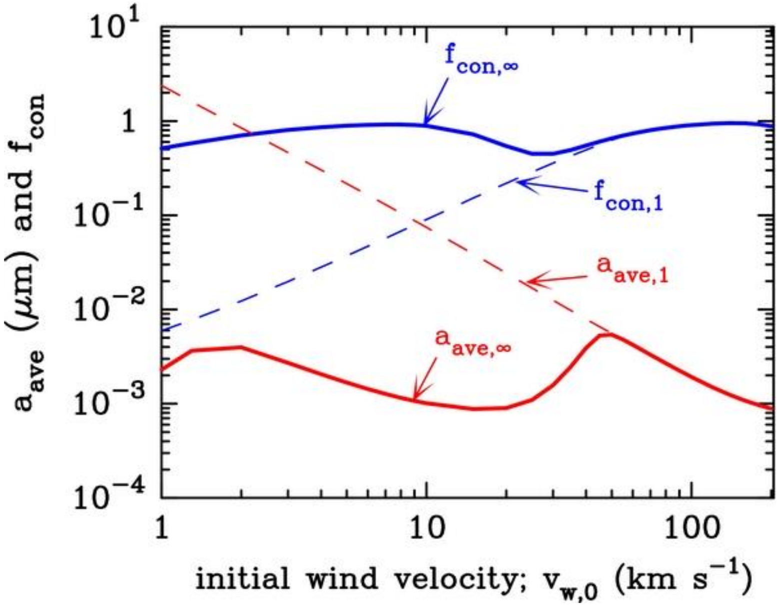
- dust-driven winds

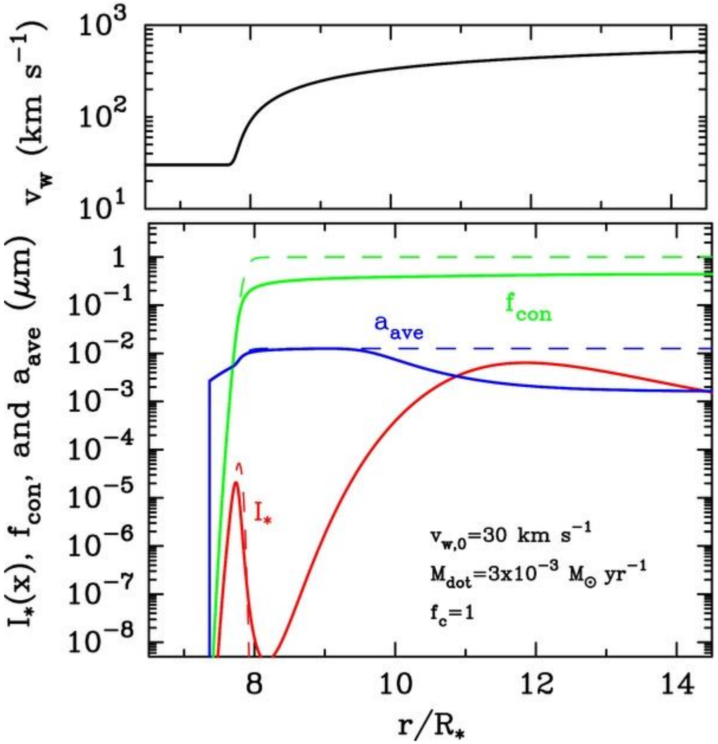
dust formation in the winds
➜ radiation pressure onto dust
➜ acceleration of dust

The acceleration of the wind by radiation pressure onto newly formed dust reduces the gas density, suppressing grain growth



$$v_{\rm w}\frac{dv_{\rm w}}{dr} = -\frac{GM_*}{r^2}\left[1-\frac{L_*\langle\kappa_{\rm ext}(T)\rangle}{4\pi cGM_*}D\right],$$





5-1. How efficient is dust formation?

· Dust ejection efficiency by very massive Pop III RSGs

- $X_{VMS} = M_{dust} / M_{ZAMS} < 3.4\text{x}10^{-3} = \sim 0.3\ \%$
- $M_{dust} / M_{metal} < 0.24$

· Dust ejection efficiency by CCSNe

- $X_{CCSN} = (0.1\text{-}30)\text{x}10^{-3} = 0.1\text{-}3.0\ \%$
- $M_{dust} / M_{metal} = 0.01\text{-}0.25$ ($M_{dust} / M_{metal} < 0.15$)

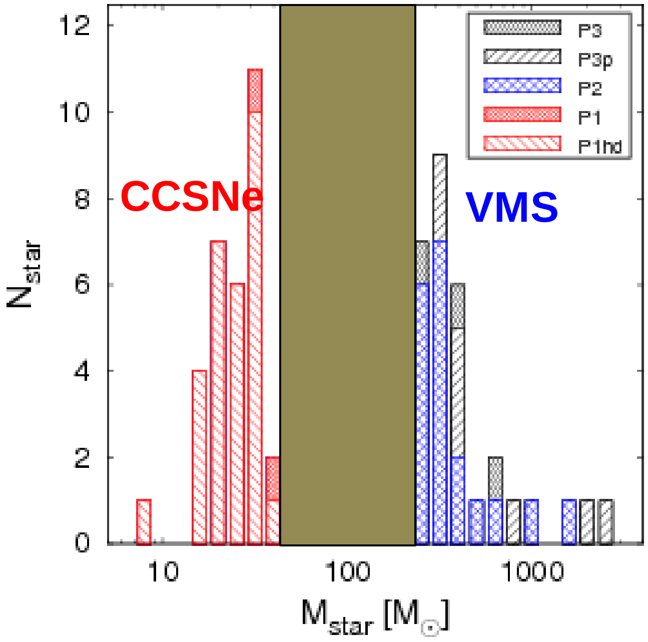
The ranges above reflects the destruction
efficiency of dust by the reverse shock

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

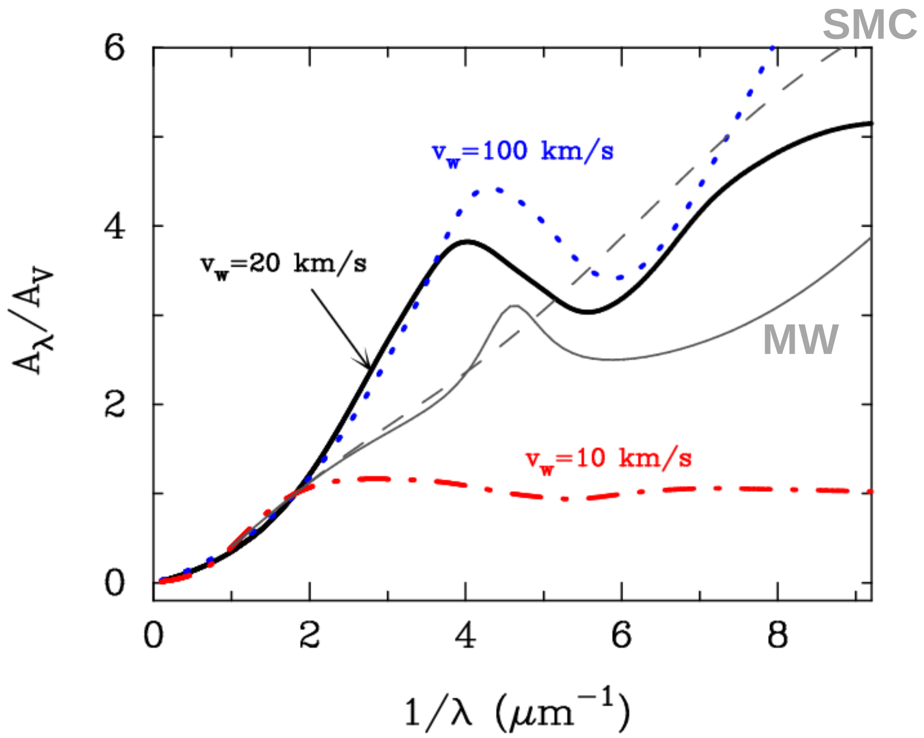
➔ **The contribution of dust from very massive RSGs is comparable with, or even higher than that from CCSNe**

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

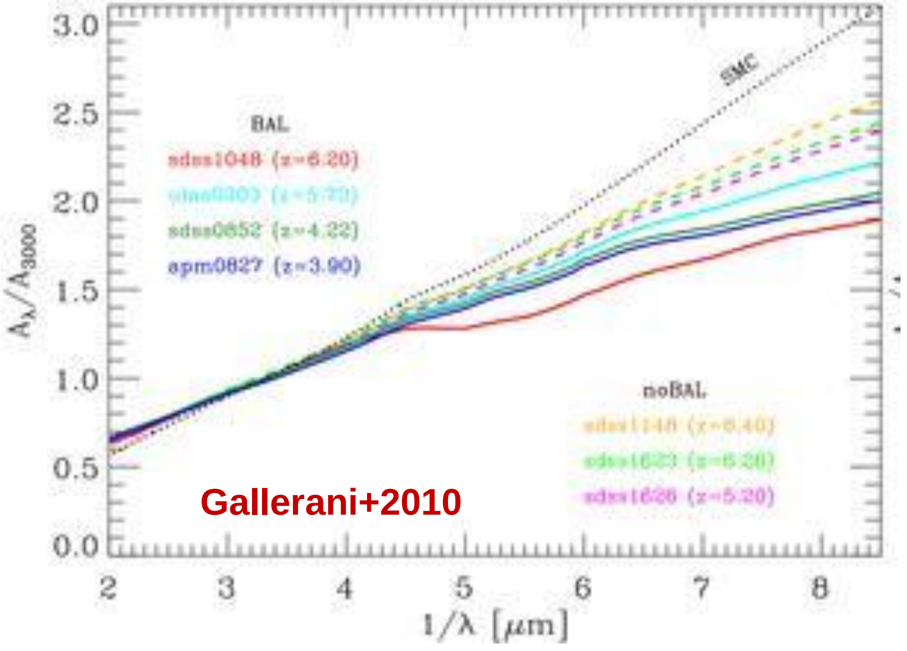
Hirano+2014



5-2. Expected extinction curves



extinction curves for high-z QSOs



Gallerani+2010

- 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 CNO-rich low-mass stars

- We do not predict the presence of heavier elements (Mg, Si, Fe)
  ➔ Further observations and more quantitative theoretical studies are needed to show whether UMP stars formed through our scenario

SMSS J0313-6708: [C/H] = -2.6, [Fe/H] < -7 (Keller+2014)

6. Summary

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

- **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**

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

➔ the first dust grains in the universe ??

- **The mass of C grains is <1.7 $M_{\rm sun}$ ($M_{\rm dust}/M_{\rm ZAMS} < 3.4\mathrm{x}10^{-3}$), 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**

 # 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