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Dust Formation in Extreme Astronomical Objects

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(➔ moving to the theory group of NAOJ from this April)

Contents

- Formulation of non-steady-state nucleation
- Dust formation in very massive Pop III stars
- Dust formation in macronovae (or kilonovae)

1. Formulation of non-steady-state Nucleation

1-1. Uncertainty in classical nucleation theory

・Application of classical nucleation theory

- sticking coefficient? ➔ usually $s = 1$

- surface energy of small clusters? ➔ same as the bulk material

- cluster temperature? ➔ $T_{clus} = T_{gas}$

- shape of small clusters? ➔ sphere

- cluster-cluster reactions? ➔ no

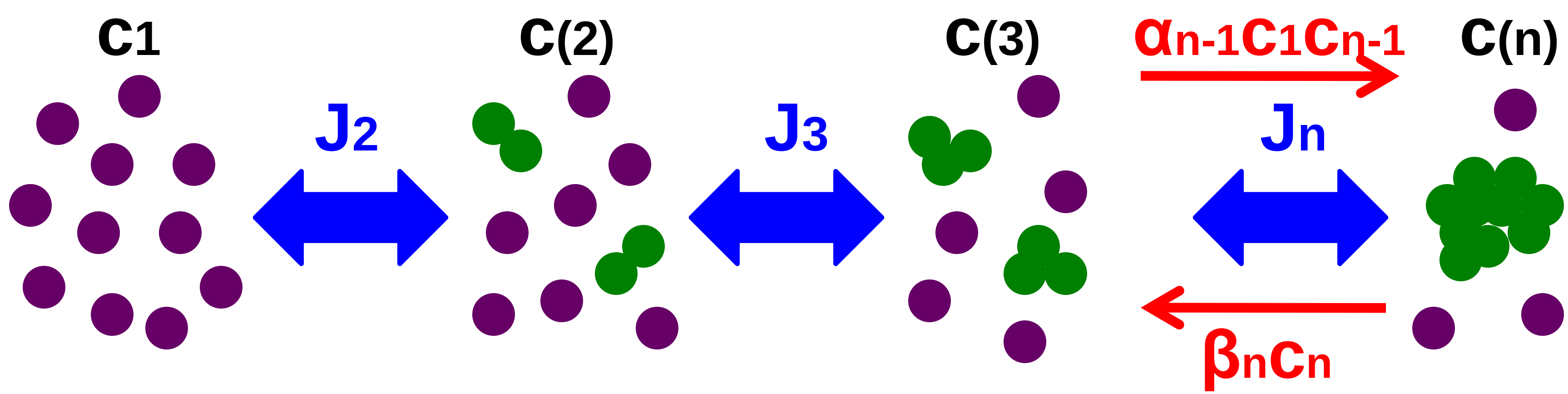
- steady-state nucleation, which cannot be applied in rarefied astrophysical environments

(e.g., Donn & Nuth 1985, but see also Paquette & Nuth 2011)

molecular formation?

➔ complete formation of CO and SiO molecules

1-2. Concept of nucleation theory



・ master equations

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

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

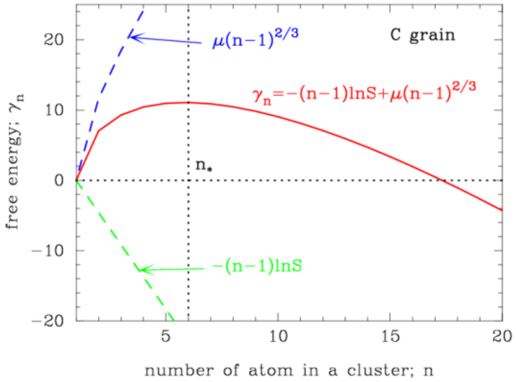
$$\alpha_n = \frac{s_n}{1+\delta_{1n}} 4\pi a_0^2\, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n}\right)^{\frac{1}{2}},$$

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

1-3. 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 $\mu = 4\pi a_0^2\sigma / kT$

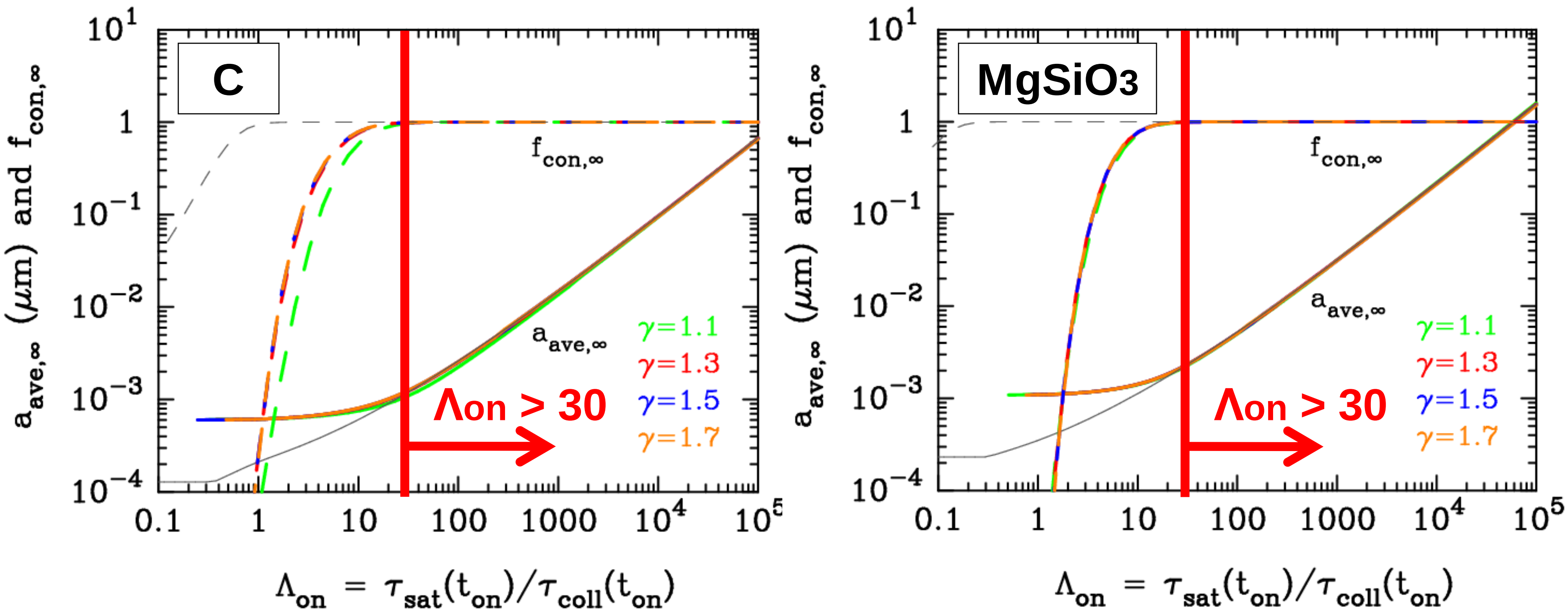
$$J_s = s\,\Omega_0 \left(\frac{2\sigma}{\pi m_1}\right)^{\frac{1}{2}} c_1^2 \exp\left[-\frac{4}{27}\frac{\mu^3}{(\ln S)^2}\right].$$

・ non-steady-state dust formation

$n_* = 100$

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

1-4. Scaling relation of average grain radius



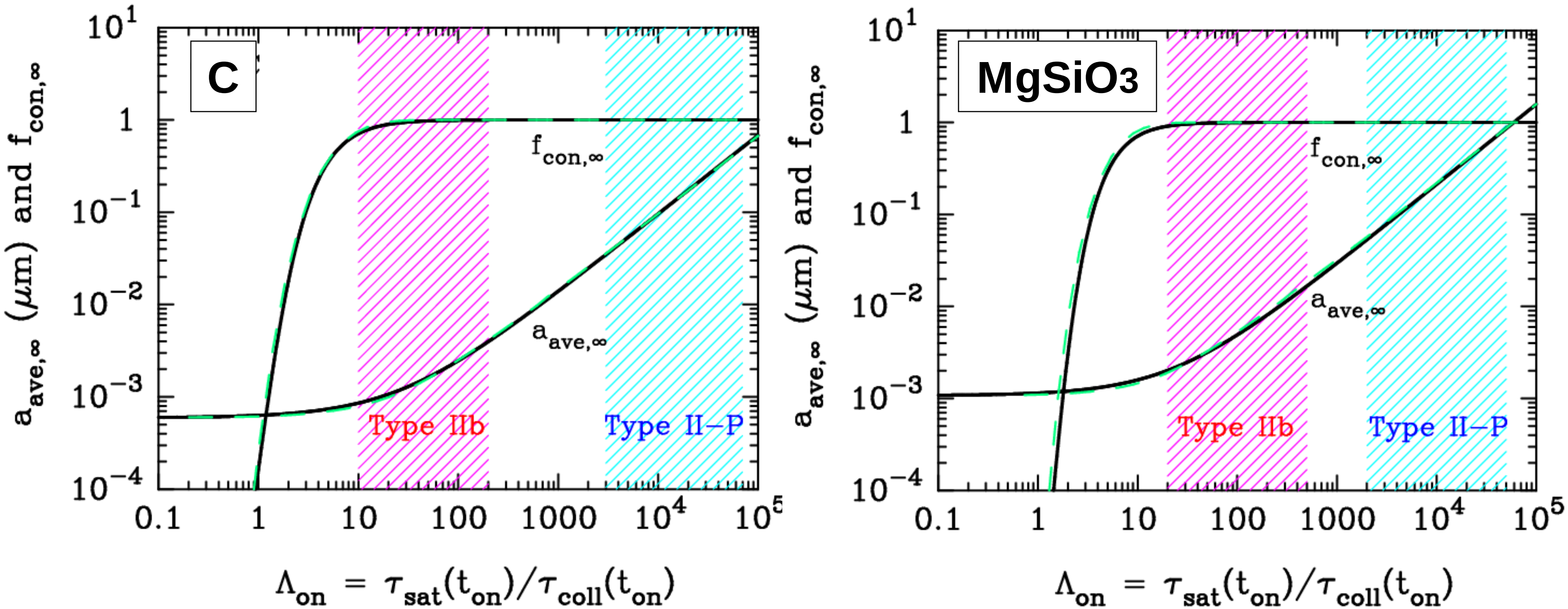
TN & Kozasa 2013

$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: 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 $\Lambda_{on} > 30$

1-5. Scaling relation of average grain radius



average radius

$$\log\left(\frac{a_{\mathrm{ave},\infty}}{a_*} - 1\right) = \epsilon_1 + \epsilon_2 \log \Lambda_{\mathrm{on}}$$

condensation efficiency

$$\log f_{\mathrm{con},\infty} = \chi_1 \left[\tanh\left(\chi_2 \log \Lambda_{\mathrm{on}} + \chi_3\right) - 1\right]$$

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

2. Dust Formation in RSG winds of Very Massive Population III Stars

2-1. Sources of dust in the early unvierse

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

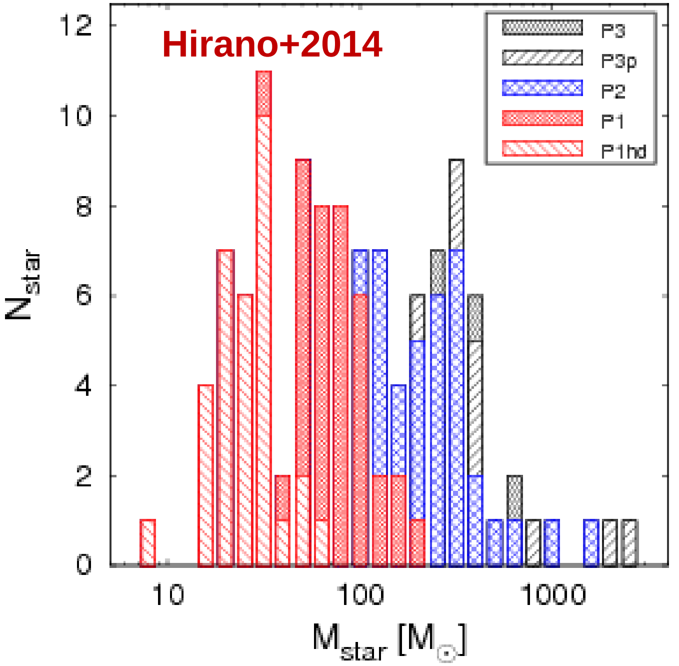
- core-collapse supernovae (CCSNe) may be promising sources of dust grains (e.g., Todini & Ferrara 2001; Nozawa+2003; Dwek+2007)
- the contribution from AGB stars is also invoked to explain the observed dust mass (e.g., Valiante+2009; Dwek & Cherchneff 2011)

➔ 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

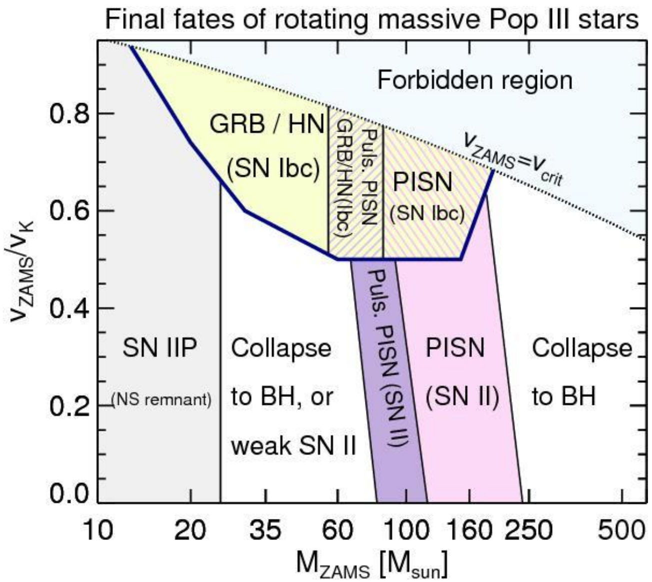
- ~40 Msun (Hosokawa+2011; Susa 2013)
- >300 Msun (Omukai+2003; Ohkubo+2009)
- 10-1000 Msun (Hirano+2014)



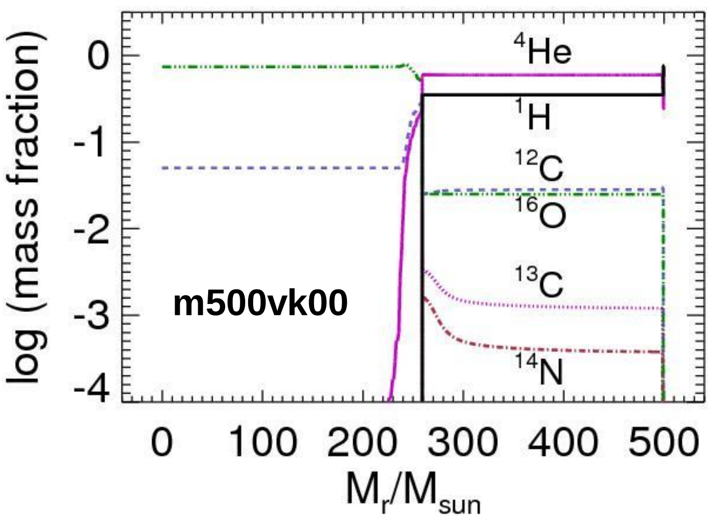
2-2. Very massive Population III stars

・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

2-3. 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}
- $A_C = 3.11\times10^{-3}$, $A_O = 1.75\times10^{-3}$ ➔ C/O = 1.78, Z = 0.034

・Model of circumstellar envelope

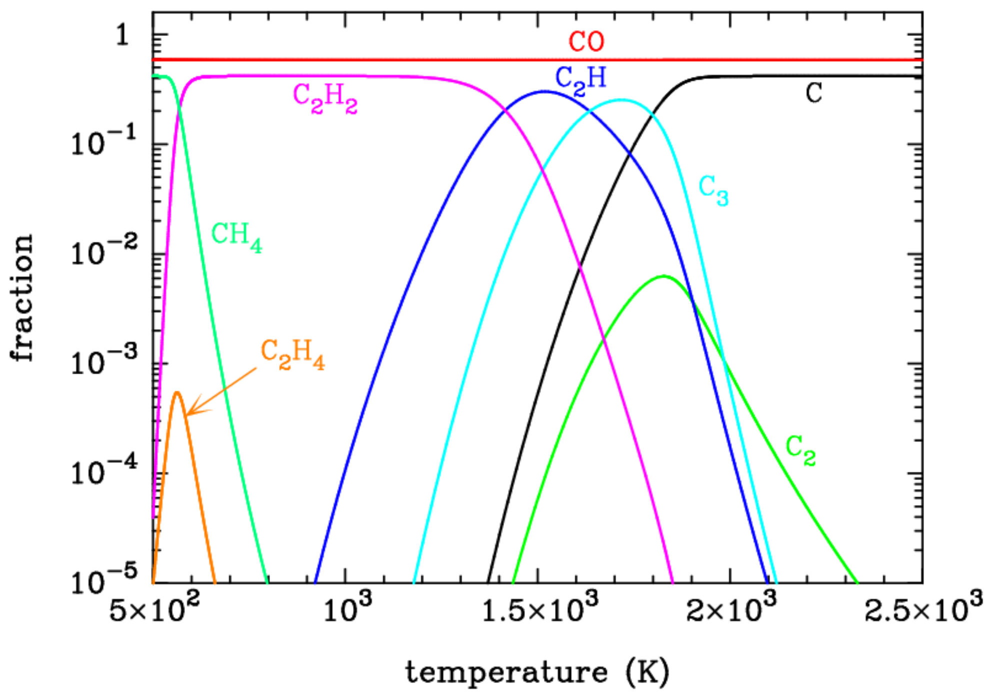
- spherically symmetry, constant wind velocity
- density profile: $$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_{\rm w}} = \rho_* \left(\frac{r}{R_*}\right)^{-2}$$
- temperature profile: $$T(r) = T_* \left(\frac{r}{R_*}\right)^{-\frac{1}{2}}$$

・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

2-4. 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

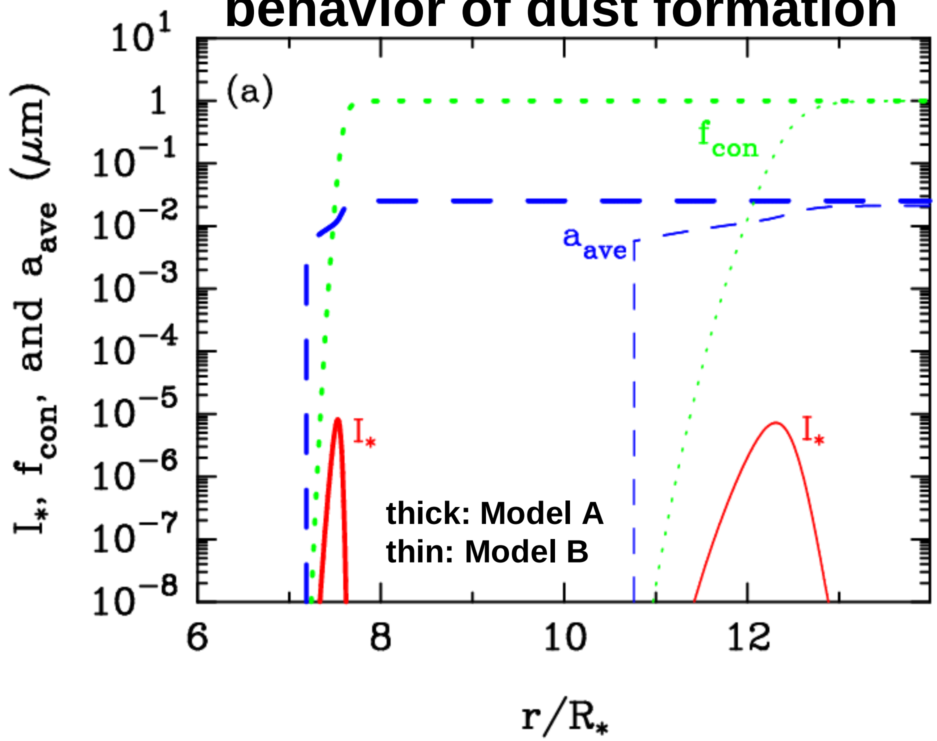
(1) Model A	C	$C_{n-1} + C \rightleftharpoons C_n$	$(n \geq 2)$
(2) Model B	C_2H	$2(C_2H + H) \rightleftharpoons C_{2n} + 2H_2$	$(n = 2)$
		$C_{2(n-1)} + C_2H + H \rightleftharpoons C_{2n} + H_2$	$(n \geq 3)$

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

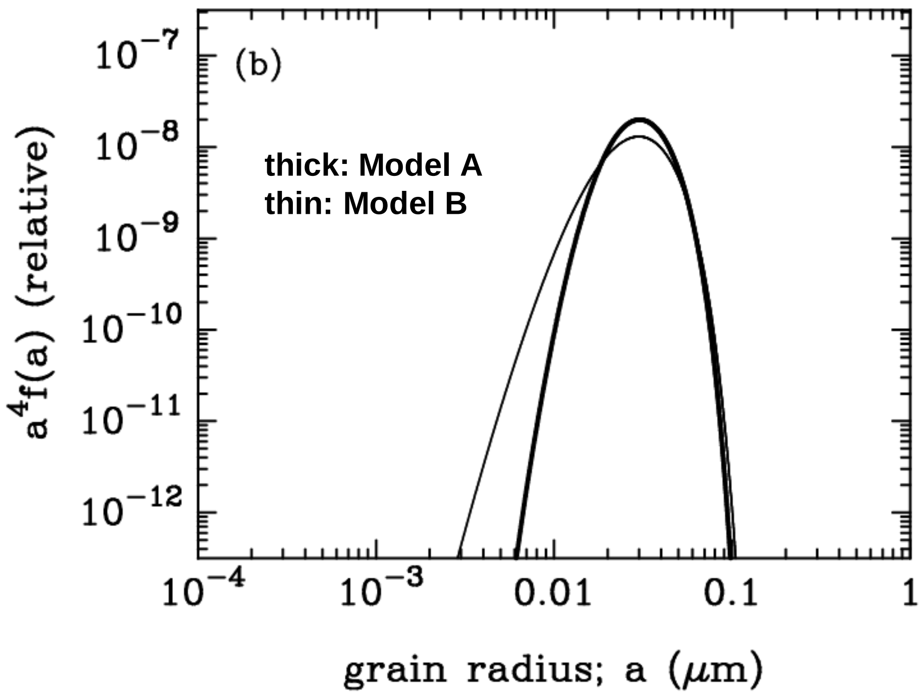
  → fc = 1 as the fiducial case

2-5. Results of dust formation calculations

behavior of dust formation



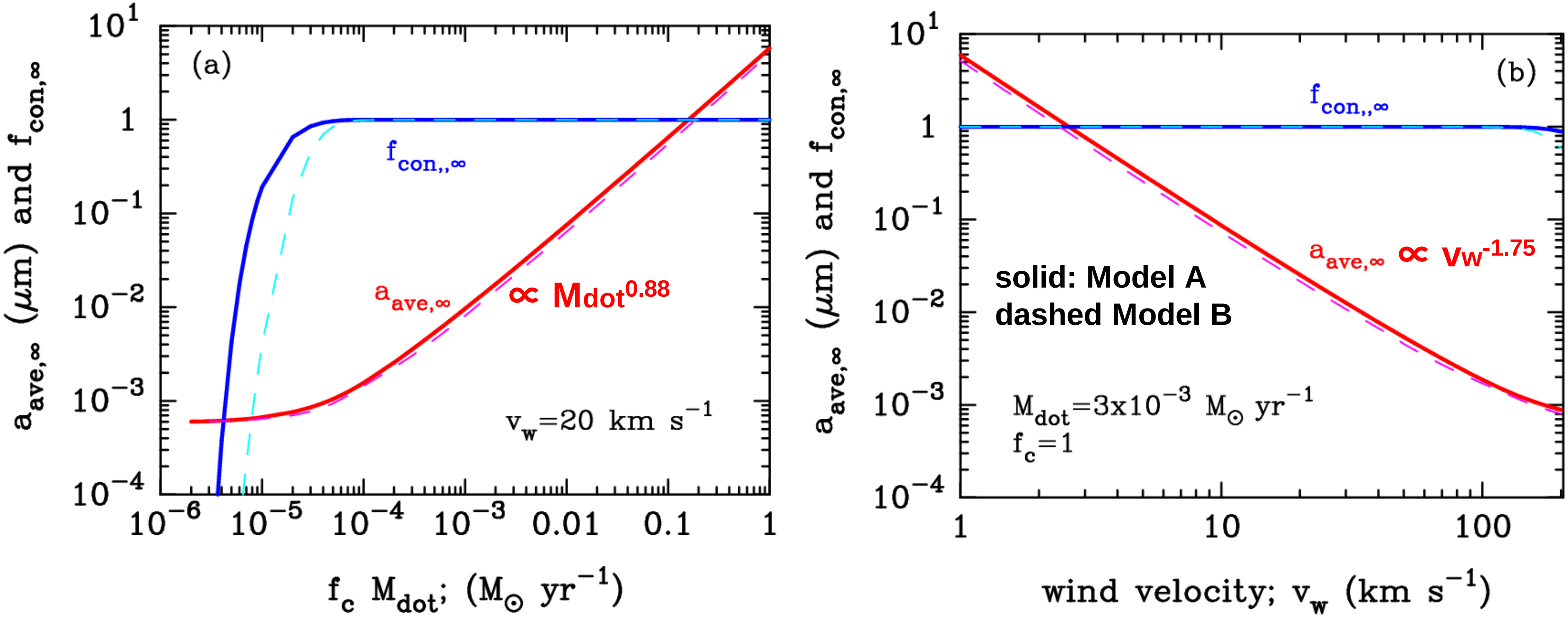
final size distribution of dust



- **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

2-6. Dependence on Mdot and vw



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

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

- 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

2-7. How efficient is dust formation?

・ Dust ejection efficiency by very massive Pop III RSGs

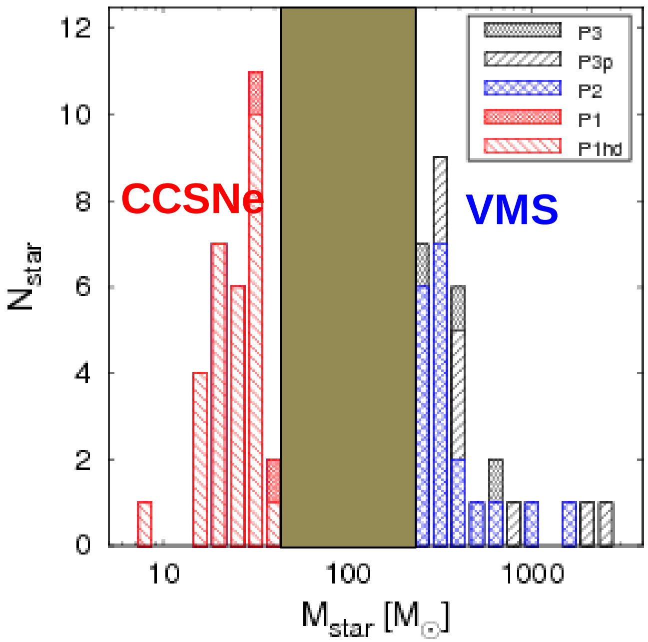
- $X_{VMS} = M_{dust} / M_{ZAMS} < 3.4 \times 10^{-3}$
- $M_{dust} / M_{metal} < 0.24$

・ Dust ejection efficiency by CCSNe (PISNe)

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

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

Hirano+2014

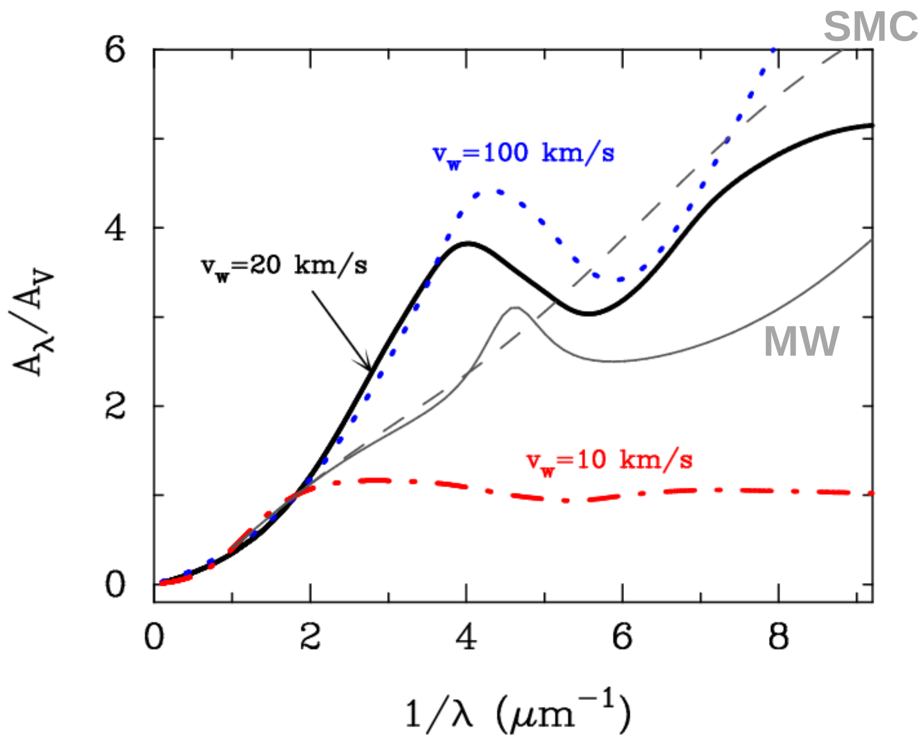


If $N_{VMS} \sim N_{CCSN}$ in the Pop III IMF …

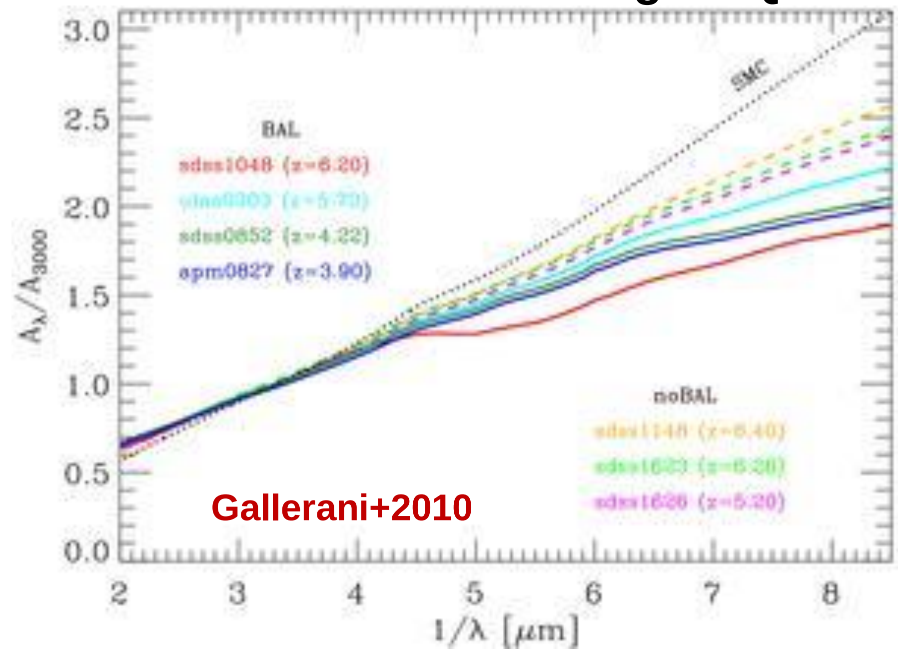
➔ The contribution of dust from very massive RSGs is comparable with, or even higher than that from CCSNe

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

2-8. 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

2-9. 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

2-10. 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

3. Dust Formation in Macronovae

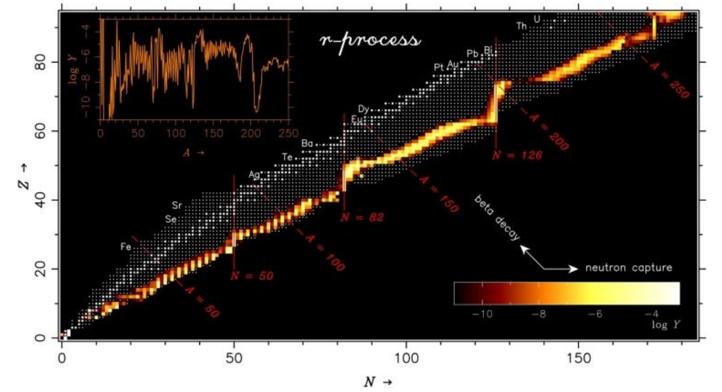
3-1. Sources of r-process elements

・What are sources of r-process elements?

➔ r-process elements (N > 56) must be created in neutron-rich environments

- core-collapse supernovae and/or proto-neutron star wind

(e.g., Wanajo+2011; Wanajo 2013)



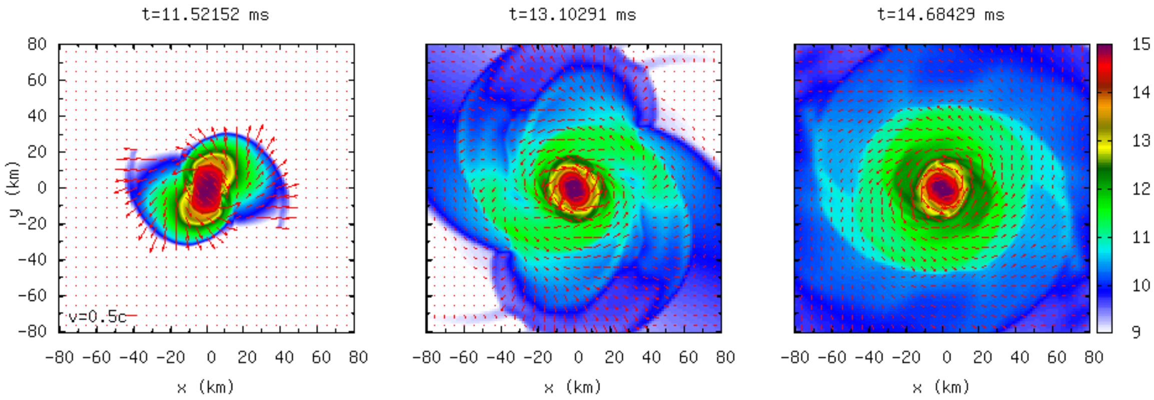
from Wanajo's website

- mergers of neutron stars (NS)-NS and/or NS-BH binary

(e.g., Korobkin et al. 2012; Bauswein et al. 2013)

↓

- ejecta mass:
  M_{ej}=0.01-0.1 M_{sun}
- ejecta velocity:
  β=v/c=0.1-0.3



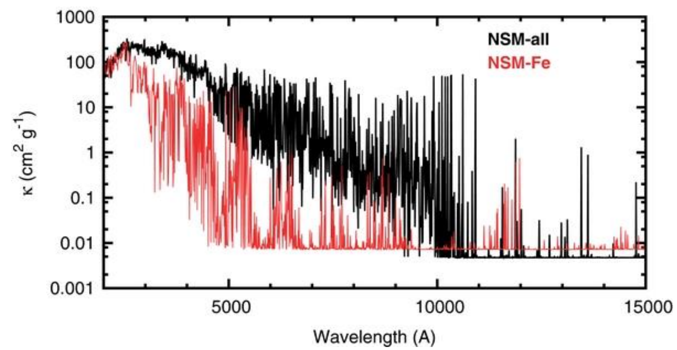
Hotokezaka+2013

3-2. Emission from NS-NS/NS-BH mergers

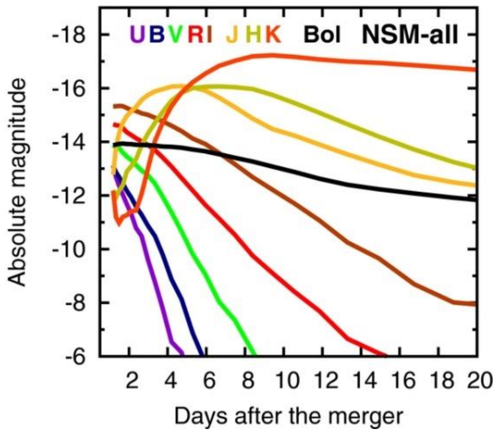
・Compact star mergers: promising sources of GWs

- position determination with GWs are very uncertain
  ➔ it is needed to probe emission at other wavelengths

- r-process elements, especially lanthanoids, give high opacity in optical: κ~10 cm^2/g compared to κ~0.1 cm^2/g in SNe
  ➔ emission from radioactive nuclei is emitted at infrared wavelengths



Tanaka & Hotokezaka+2013



・Macronovae (or called kilonovae)

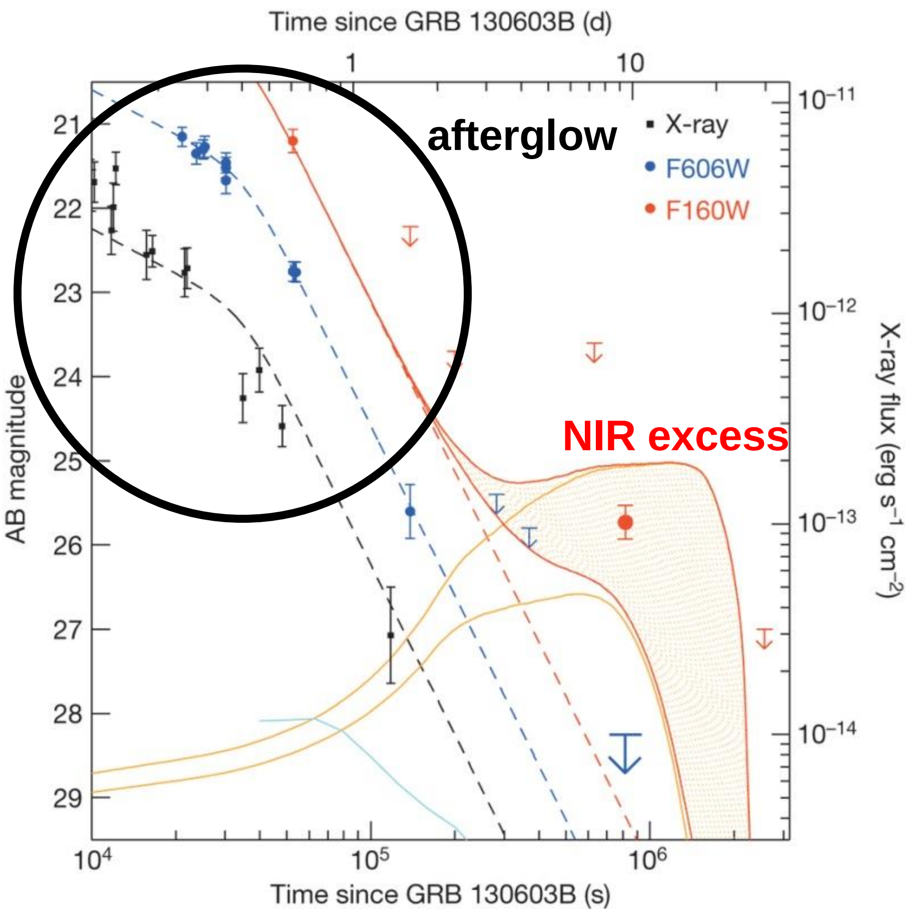
➔ electromagnetic emission involved in NS-NS and/or NS-BH mergers
(energy inputs may be due to decay of radioactive r-process elements)

ref. Energy inputs of other eruptive objects

- novae: explosive nucleosynthesis on the surface
- supernovae: decay of 56Ni produced at explosion

3-3. Macronovae: GRB 130603B

Short GRB 130603B (z = 0.356)



Tanvir+2014, Nature

Gamma-ray bursts (GRBs)

- **Short GRBs (<~2 sec):** originating from mergers of compact objects
- **Long GRBs (~2-10 sec):** originating from collapses of massive stars (accompnied with SNe Ib/Ic)

excess of NIR around 7 day

- **processing of optical light by r-process elements**
- **NS-NS (NS-BH) merger is the formation sites of r-process elements**

3-4. Dust formation in Macronovae

・Dust formation calculations

- gas density

$$\rho \sim 1.4 \times 10^{-16} \left(\frac{\kappa}{10\ \mathrm{cm^2 g^{-1}}}\right)^{-1} \left(\frac{\beta}{0.2}\right)^{-2} \left(\frac{t}{7\ \mathrm{days}}\right)^{-3}\ \mathrm{g\,cm^{-3}}.$$

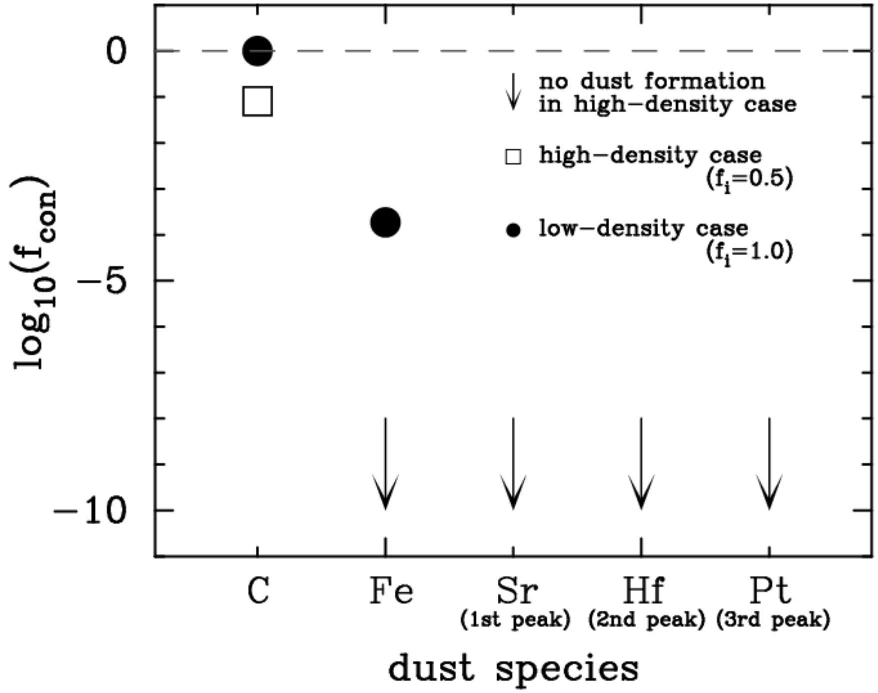
- gas temperature

$$T = T_0 \left(\frac{t}{7\ \mathrm{days}}\right)^{-s}.$$

T_0=2000K, s=0.8

- **r-process elements cannot condense into dust grains**
- **formation of C (and Fe) grains could be possible**

condensation efficiency



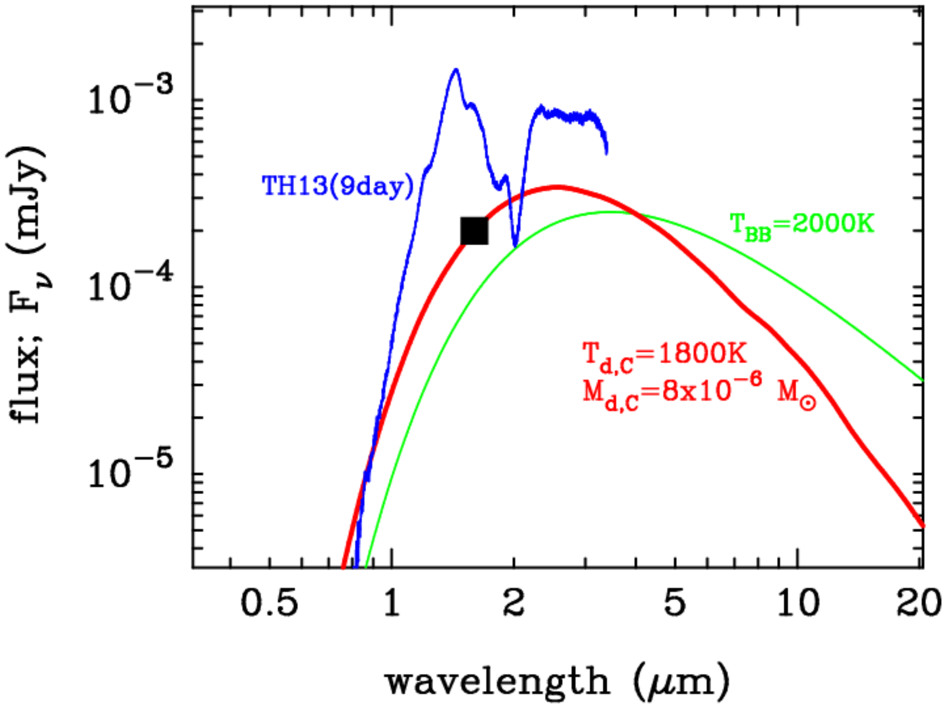
Takami, TN, Ioka 2014 in prep

$$\frac{\tau_{\mathrm{coll}}}{\tau_{\mathrm{exp}}} = \frac{3A_i m_{\mathrm{H}}}{\pi a_0^2 f_i \rho_0 t_0} \left(\frac{A_i m_{\mathrm{H}}}{2kT_0}\right)^{\frac{1}{2}} \left(\frac{T}{T_0}\right)^{-\frac{2}{s}-\frac{1}{2}}$$

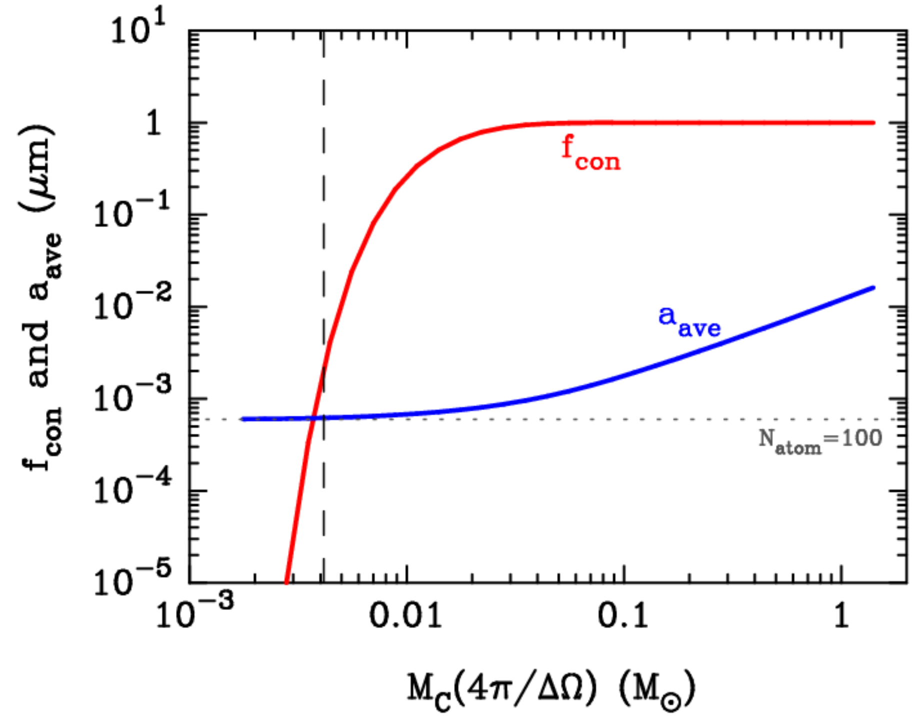
$$= 0.32 f_i^{-1} \left(\frac{A_i}{100}\right)^{\frac{3}{2}} \left(\frac{\kappa}{10\ \mathrm{cm^2\ g^{-1}}}\right) \left(\frac{\beta}{0.2}\right)^{2} \left(\frac{T}{2000\ \mathrm{K}}\right)^{-\frac{1}{2}\frac{\alpha+18}{\alpha+2}}$$

3-5. Dust in Macronovae

thermal emission from C grains



condensation efficiency of C grains



- NIR detection of GRB 130603B around 7 day can be explained by thermal emission from hot (~1800 K) C grains with the mass of ~10^{-5} Msun

Takami, TN, Ioka 2014 in prep

amount of C atom to achieve 10^{-5} Msun of C grains

- NS-NS merger ($\Delta\Omega/4\pi \sim 1$)
  ➔ Mc = 4×10^{-3} Msun
- NS-BH merger ($\Delta\Omega/4\pi \sim 0.1$)
  ➔ Mc = 4×10^{-4} Msun

3-6. Summary

We have examined the possibility of dust formation in the ejecta of macronovae based on observed properties of GRB 130603B

- **In the high-density case with efficient r-process nucleosynthesis, r-process elements never condense into dust grains even if they are abundantly produced**

- **In the low-density case with inefficient r-process nucleosynthesis, carbon grains can form with quite small radius (<0.02 μm)**

- **The near-infrared excess observed for GRB 130603B is explained by thermal emission of carbon dust formed in the ejecta**

 # sources of cosmic dust :

- **SNe (Type II SNe and Type Ia SNe),**
- **mass-loss winds of evolved stars (AGB, RSG and WR stars)**
- **mass-loss winds of massive main-sequence stars**

➔ Extreme astronomical objects are good laboratories for examining the process of dust formation (testing the theory of dust formation)