2013/08/06

Non-steady-state dust formation in the ejecta of Type Ia supernovae

Takaya Nozawa

(Kavli IPMU, University of Tokyo)

Collaborators:
Takashi Kozasa (Hokkaido University)
Keiichi Maeda, Ken'ichi Nomoto (Kavli IPMU)

1-1. Sources of dust in the early universe

huge amounts of dust grains (>10^8 Msun) are detected in host galaxies of quasars at redshift z > 5 (< 1 Gyr)

➔ Type II SNe arising from short-lived massive stars (> 8 Msun) must be main producers of dust

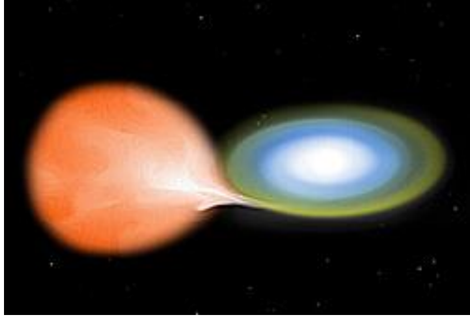
➔ 0.1 Msun of dust per SN is needed (e.g., Dwek+07)

- theoretical works predict that 0.1-1.0 Msun of dust can form in Type II SNe (e.g., Nozawa+03; Nozawa+10)

- FIR observations with Herschel discovered ~0.1 Msun of cool dust in Cas A, SN 1987A, and Crab (Barlow+10; Matsuura+11; Gomez+12b)

What are the main composition and typical size of newly formed dust in the ejecta of SNe?

1-2. Dust formation in Type Ia SNe



○ Type Ia supernovae (SNe Ia)

- thermonuclear explosions of C+O white dwarfs with the mass close to Chandrasekhar limit (~1.4 Msun)

- synthesize a significant amount of heavy elements

  ➔ possible sources of interstellar dust?

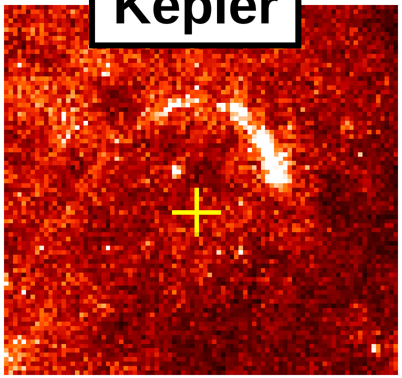
○ No evidence for dust formation in SNe Ia

- no cool dust in Kepler and Tycho SNRs (Gomez+12a)

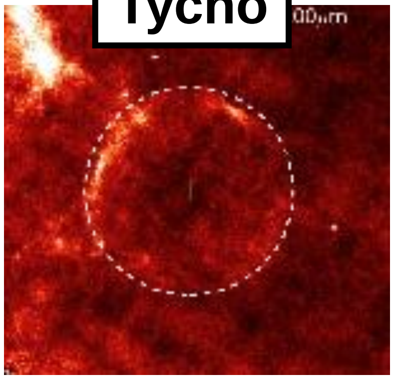
  detection of warm dust of 10^-4 Msun in Tycho (Ishihara+10)

What causes the difference in dust formation process?

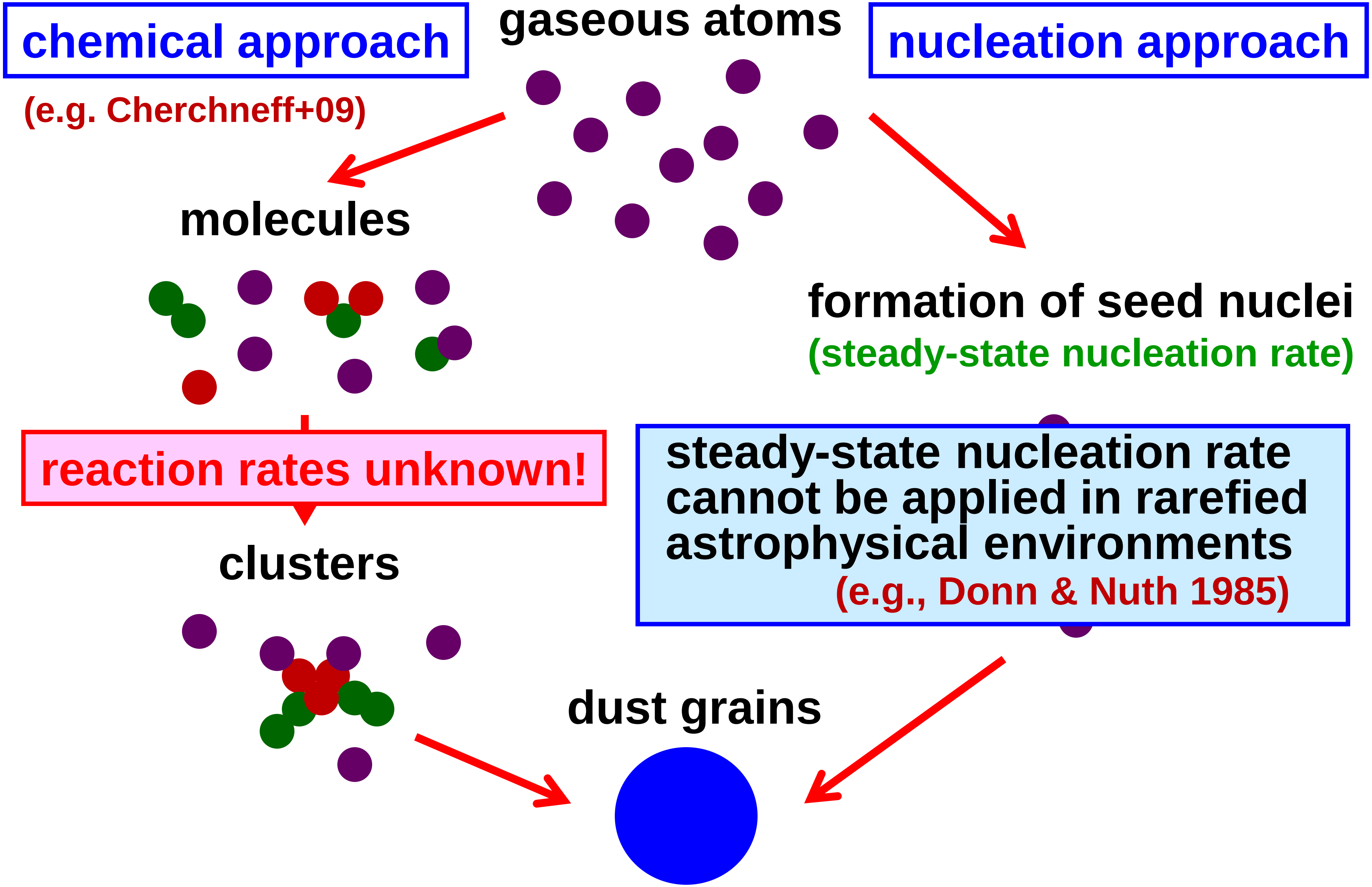
Kepler



Tycho



1-3. How do dust grains form?



gaseous atoms

chemical approach

(e.g. Cherchneff+09)

molecules

reaction rates unknown!

clusters

nucleation approach

formation of seed nuclei

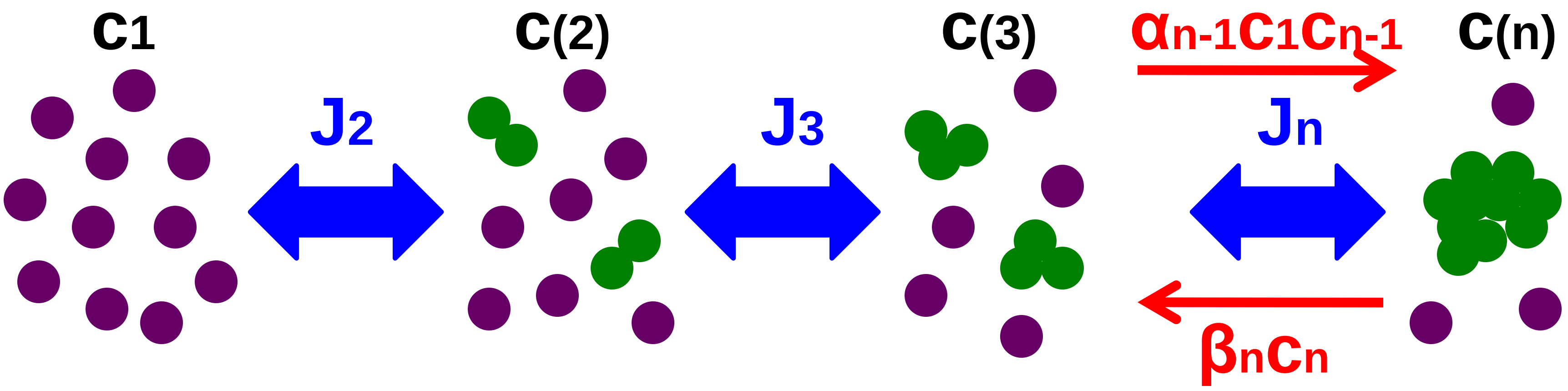
(steady-state nucleation rate)

steady-state nucleation rate cannot be applied in rarefied astrophysical environments

(e.g., Donn & Nuth 1985)

dust grains

2-1. Concept of nucleation theory



・master equations

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

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

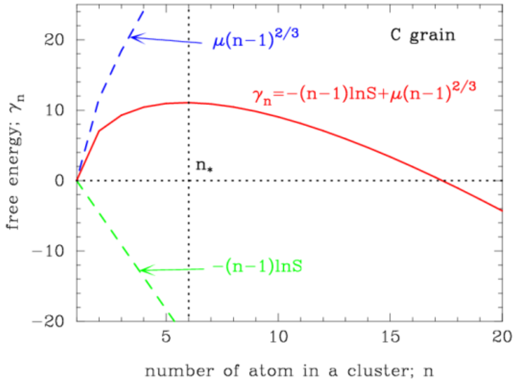
$$\alpha_n = \frac{s_n}{1+\delta_{1n}} 4\pi a_0^2 \, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n}\right)^{\frac{1}{2}},$$

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

2-2. Non-steady-state nucleation

・ steady-state nucleation rate: J_s

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



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

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

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

・ non-steady-state dust formation

$n_* = 100$

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

2-3. Basic equations for dust formation

▪ Equation of mass conservation

$$c_{10} - c_1 = \underbrace{\sum_{n=2}^{n_*-1} n c_n}_{\text{(cluster)}} + \underbrace{\int_{t_0}^{t} J_{n_*}(t') \frac{a^3(t,t')}{a_0^3} dt'}_{\text{(grain)}},$$

= c_{10} x f_{con}

▪ Equation of grain growth

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

▪ Evolutions of gas density and temperature

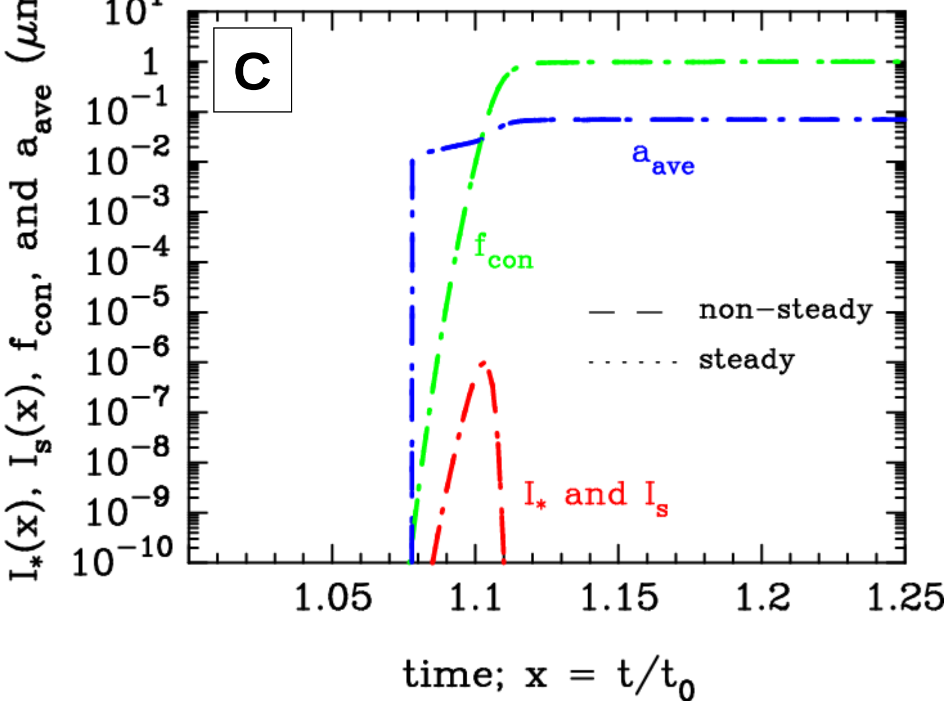
$$\tilde{c}(t) = c_0 \left(\frac{t}{t_0} \right)^{-3} \qquad T(t) = T_0 \left(\frac{t}{t_0} \right)^{-3(\gamma-1)}$$

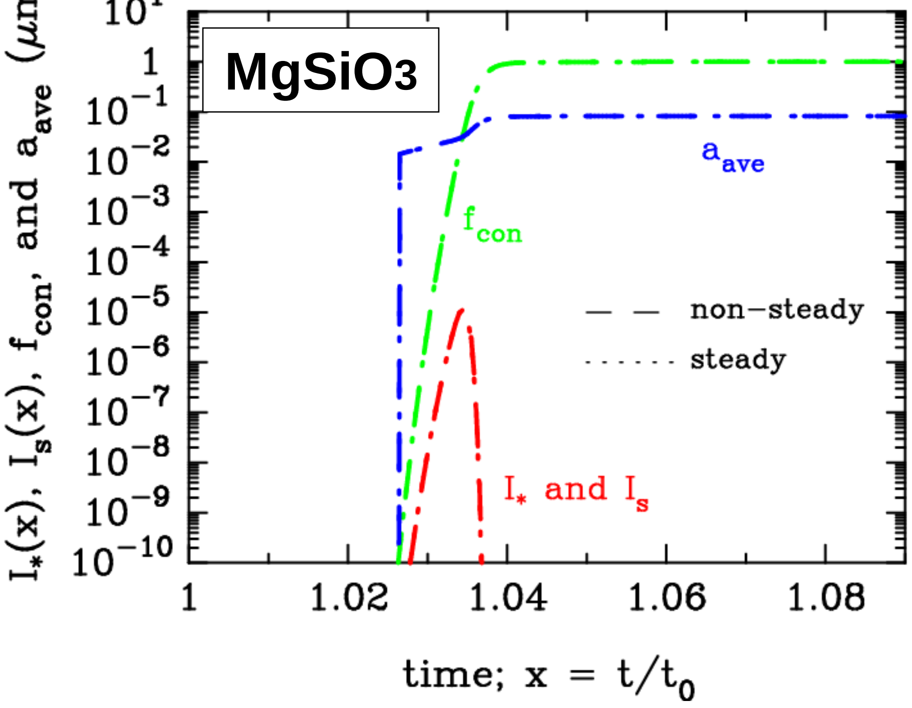
(γ = 1.1-1.7)

Parameters: c0, γ, t0 (the time at which lnS = 0)

fiducial values: γ = 1.25, t0 = 300 day

3-1. Steady vs. Non-steady (1)

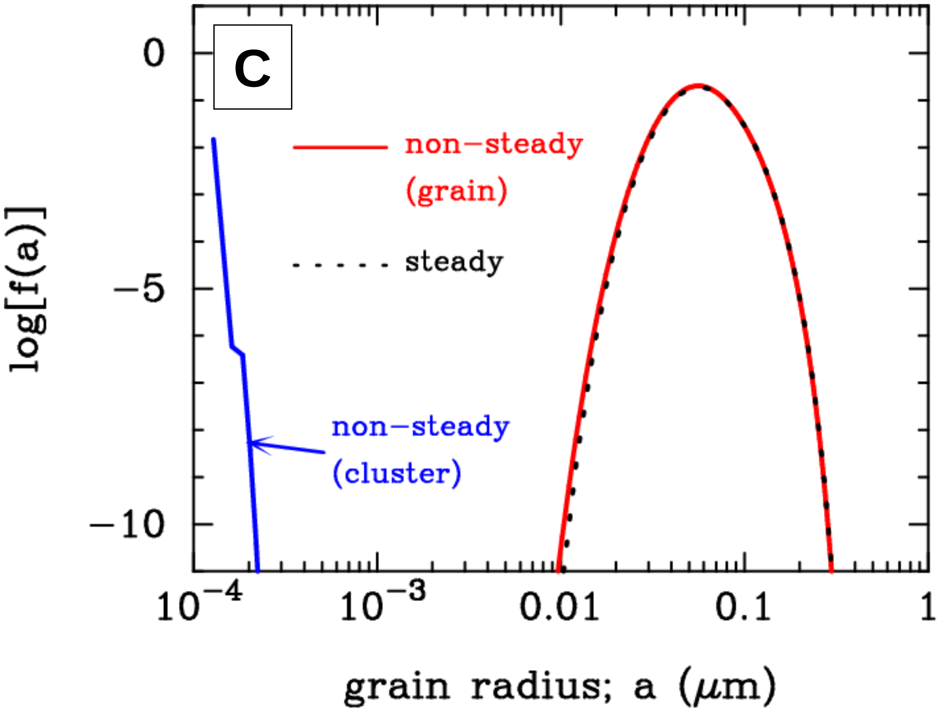

$c_{10} = 10^8$ cm^{-3}


$c_{10} = 10^8$ cm^{-3}

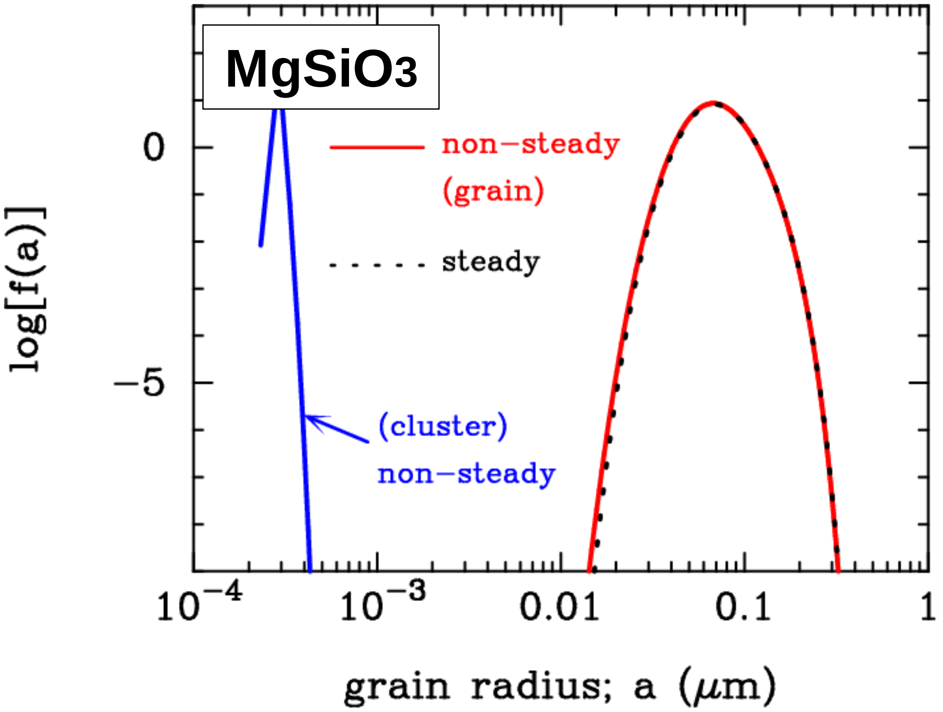
- dashed line : non-steady model
- dotted line : steady model

The results for steady and non-steady models are essentially the same for high gas densities

3-2. Steady vs. Non-steady (1): size distribution



$c_{10} = 10^8$ cm^{-3}

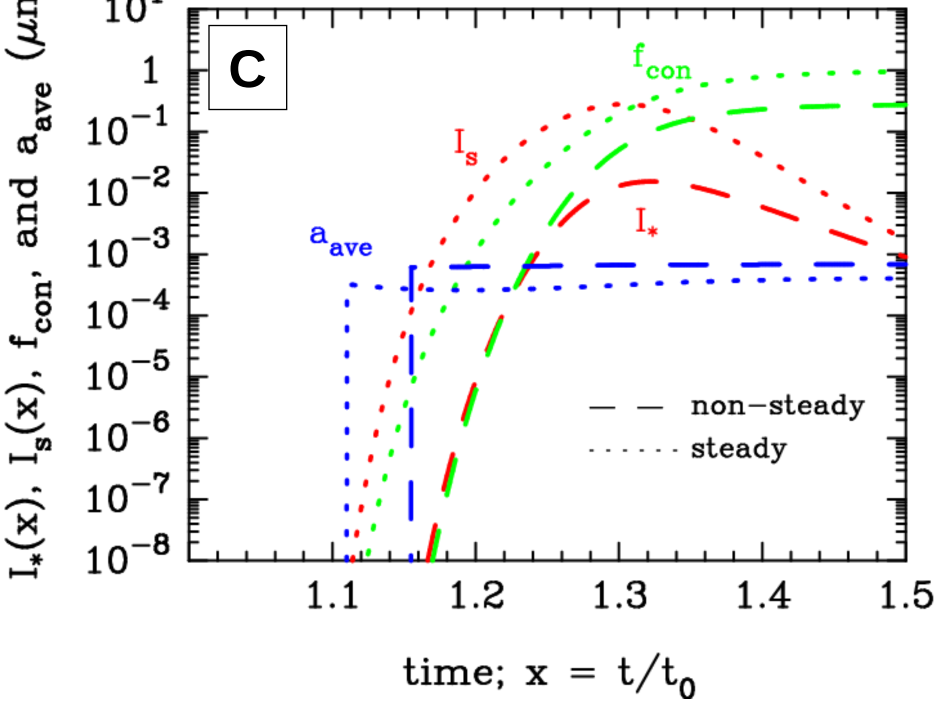


$c_{10} = 10^8$ cm^{-3}

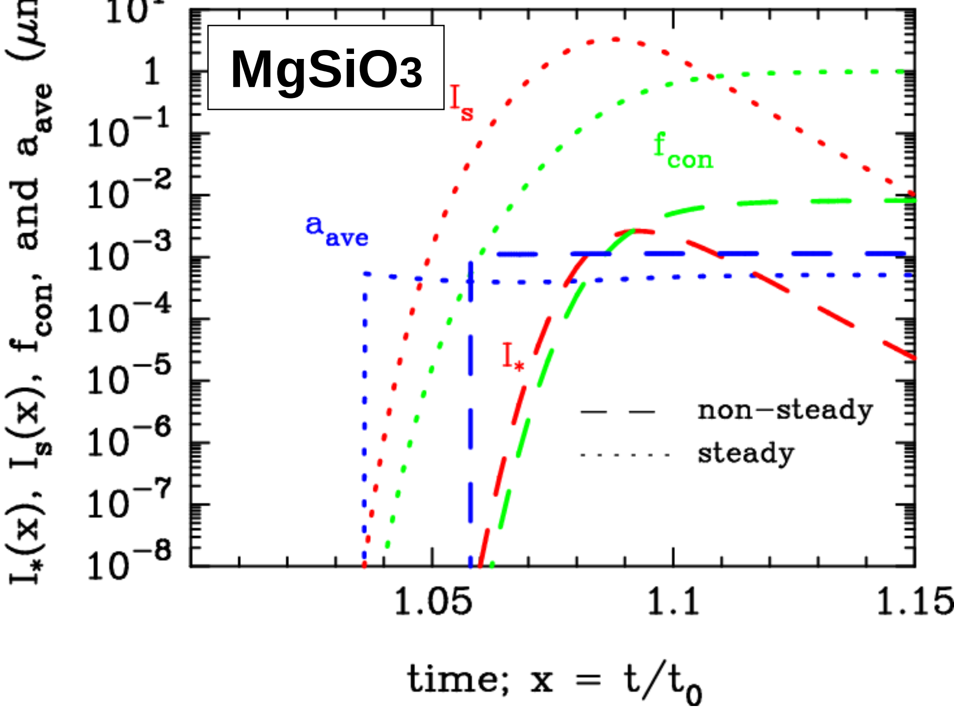
The steady-state nucleation rate is a good approximation for higher initial densities

3-3. Steady vs. Non-steady (2)

$c_{10} = 10^5$ cm^{-3}



$c_{10} = 10^5$ cm^{-3}



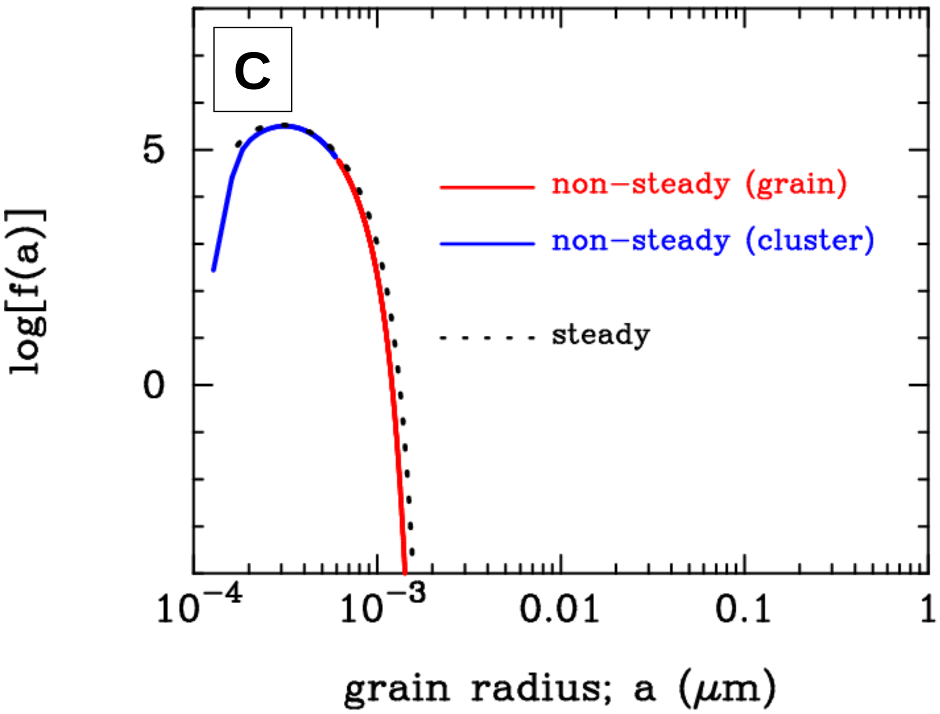
- **I_* : formation rate of grains with $n_* = 100$**
- **I_s : formation rate of grains with $n = n_c$**

for $\tau_{coll}/t_0 << 1$ ➔ $I_s = \ldots = I_n = I_{n+1} = \ldots = I_*$

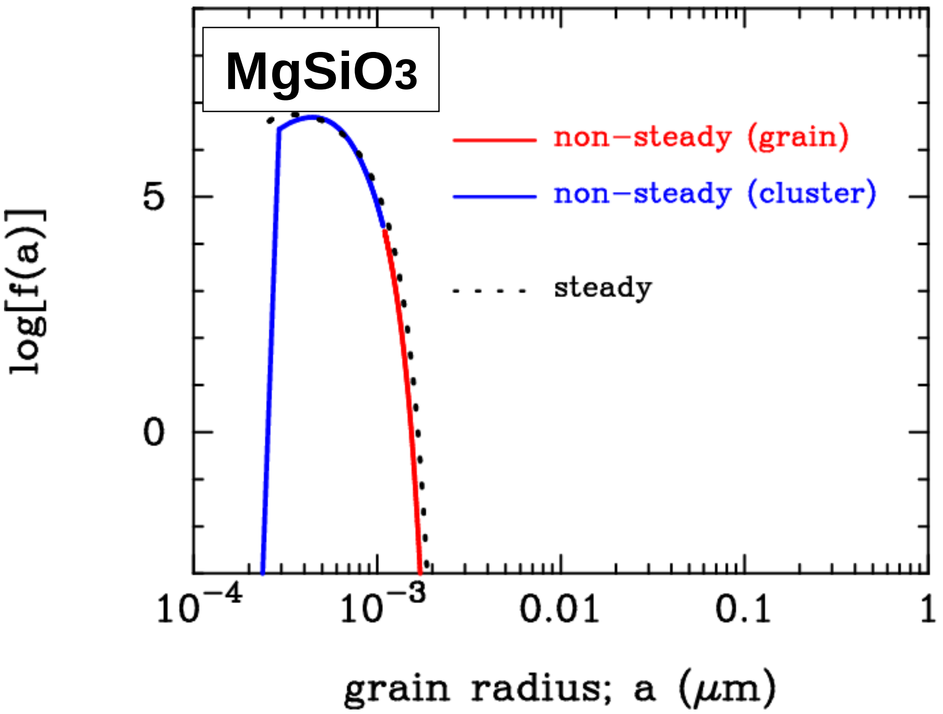
for $\tau_{coll}/t_0 << 1$ ➔ $I_s > \ldots > I_n > I_{n+1} > \ldots > I_*$

3-4. Steady vs. Non-steady (2): size distribution

$c_{10} = 10^5\ \mathrm{cm^{-3}}$

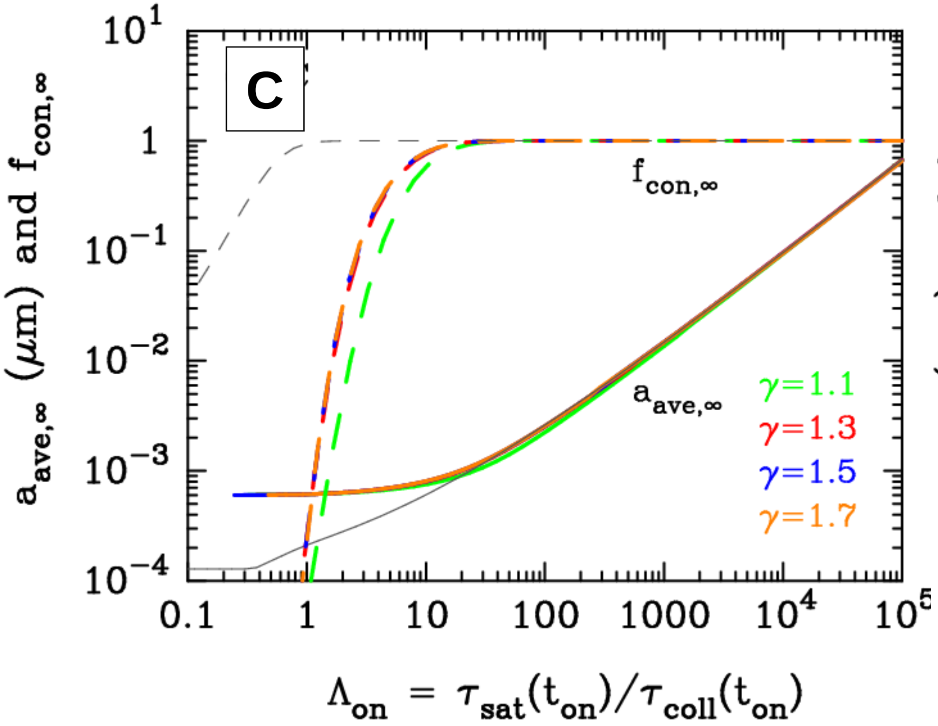


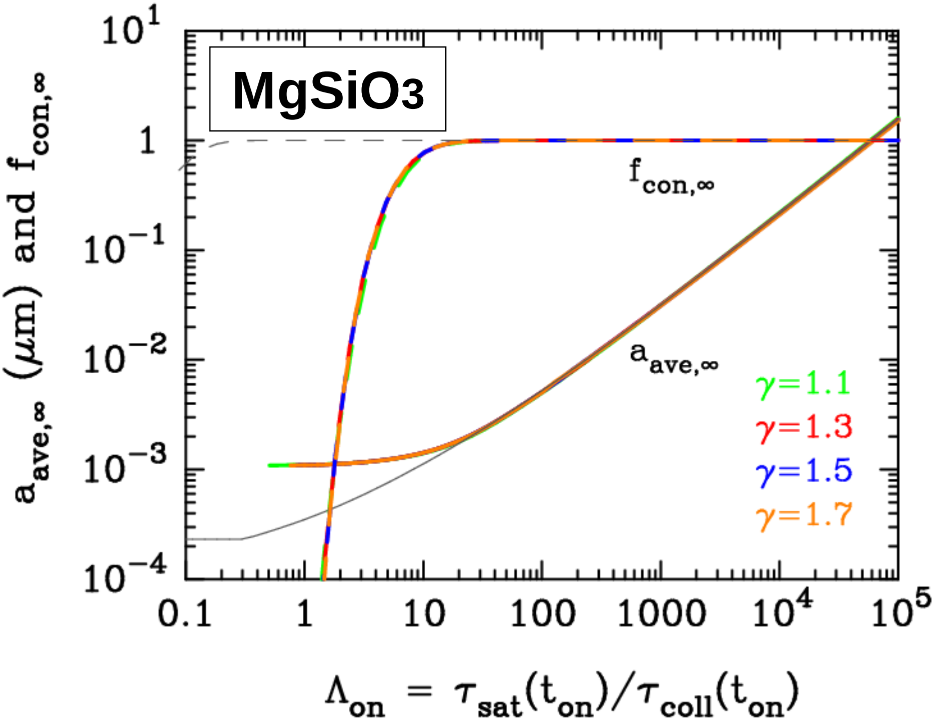
$c_{10} = 10^5\ \mathrm{cm^{-3}}$



The combined size distribution of clusters and grains is in good agreement with the grain size distribution calculated with the steady-state nucleation rate

3-5. Scaling relation of average grain radius





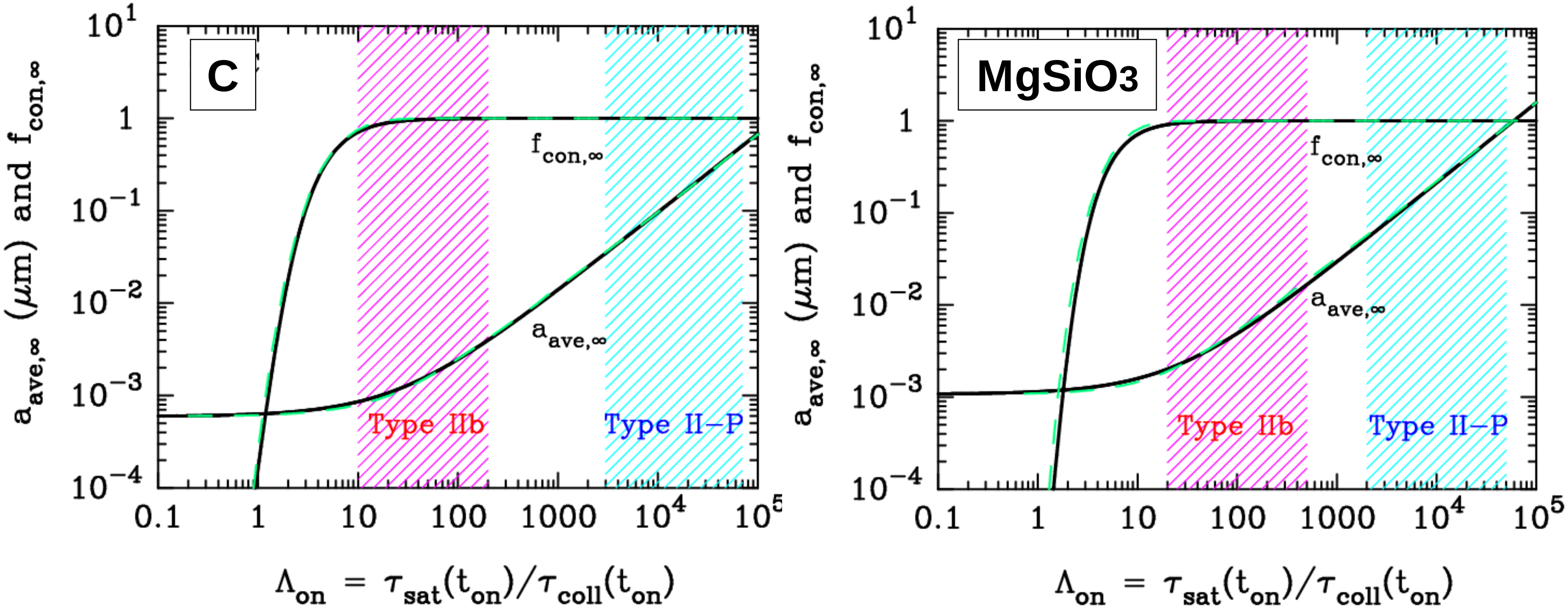
Λ_{on}: ratio of supersaturation timescale to gas collision timescale at the onset time of dust formation

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

where $\tau_{cool} = t_{on} / 3 (\gamma - 1)$

Nozawa & Kozasa, submitted

3-6. Scaling relation of average grain radius



average radius

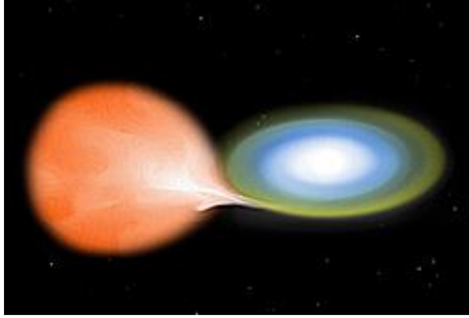
$$\log\left(\frac{a_{\mathrm{ave},\infty}}{a_*} - 1\right) = \epsilon_1 + \epsilon_2 \log \Lambda_{\mathrm{on}}$$

condensation efficiency

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

Nozawa & Kozasa, submitted

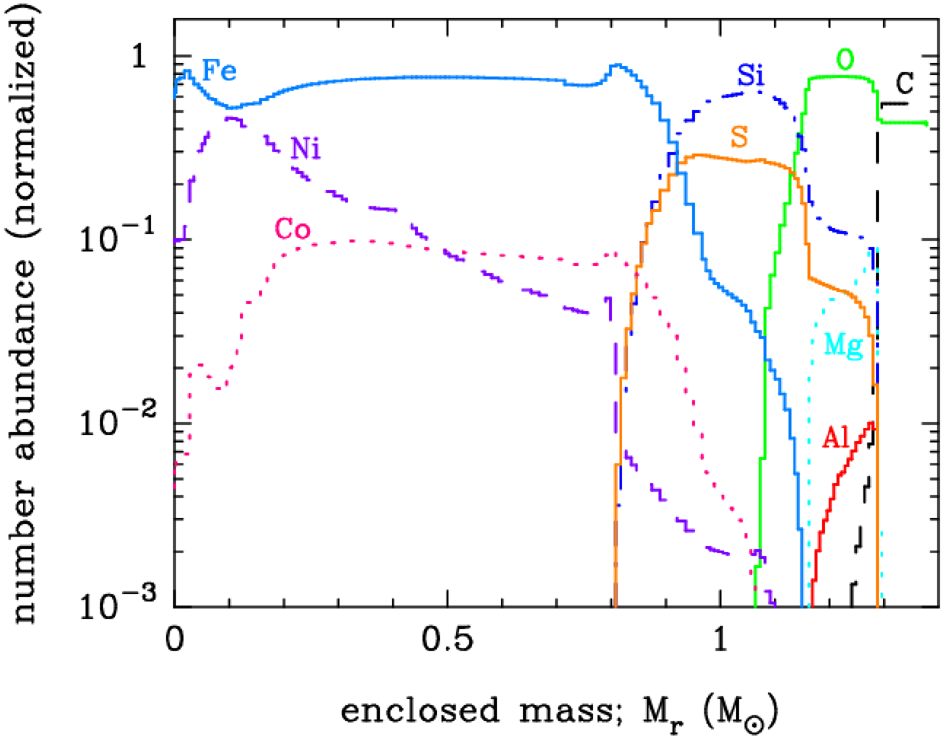
4-1. Dust formation in Type Ia SN

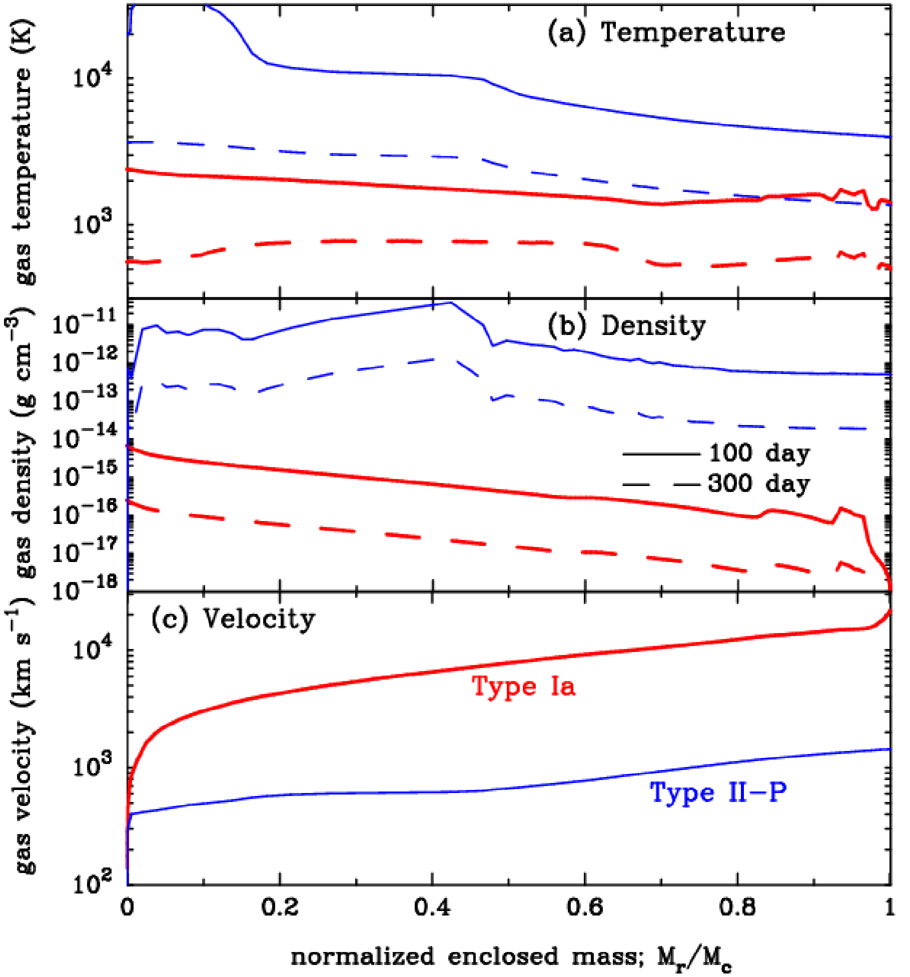


○ Type Ia SN model

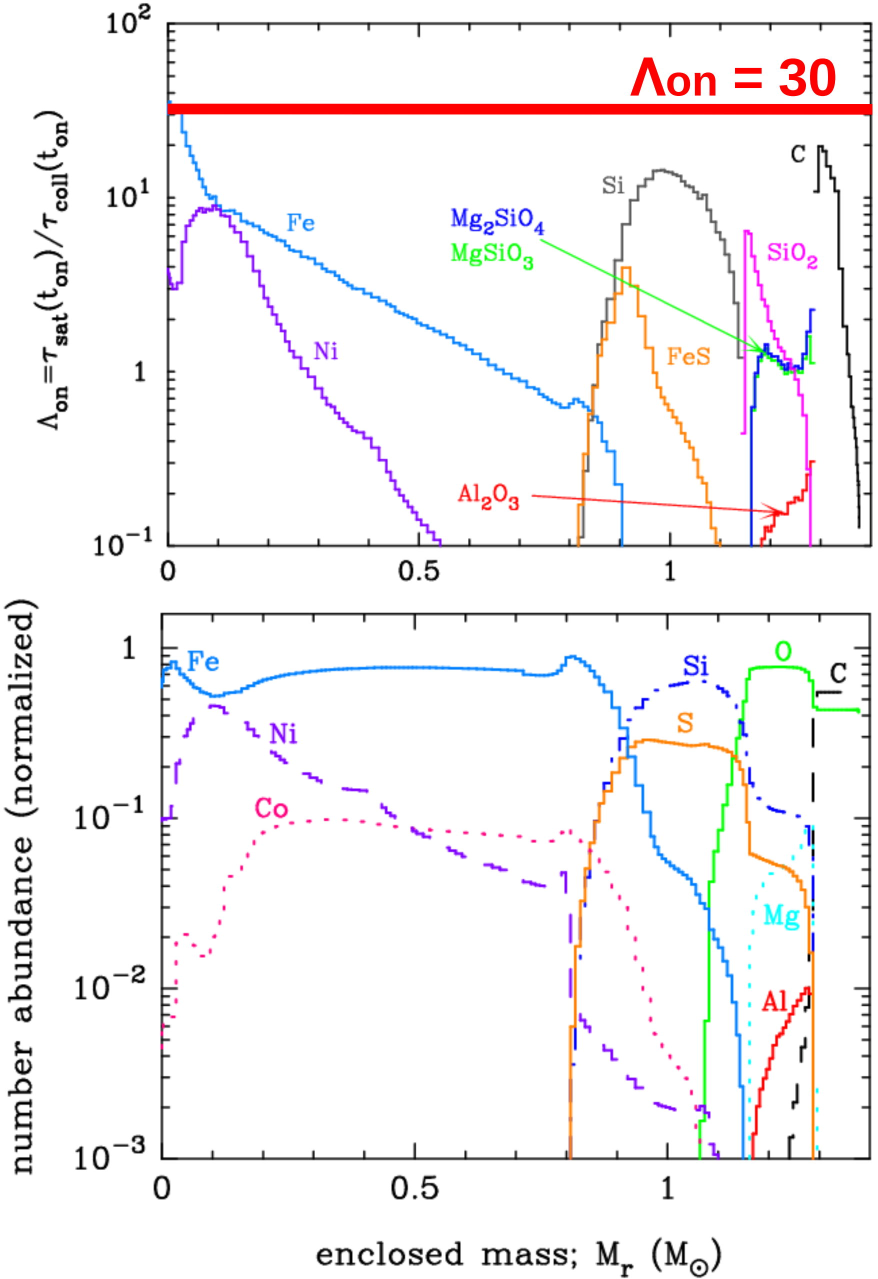
W7 model (C-deflagration) (Nomoto+84; Thielemann+86)

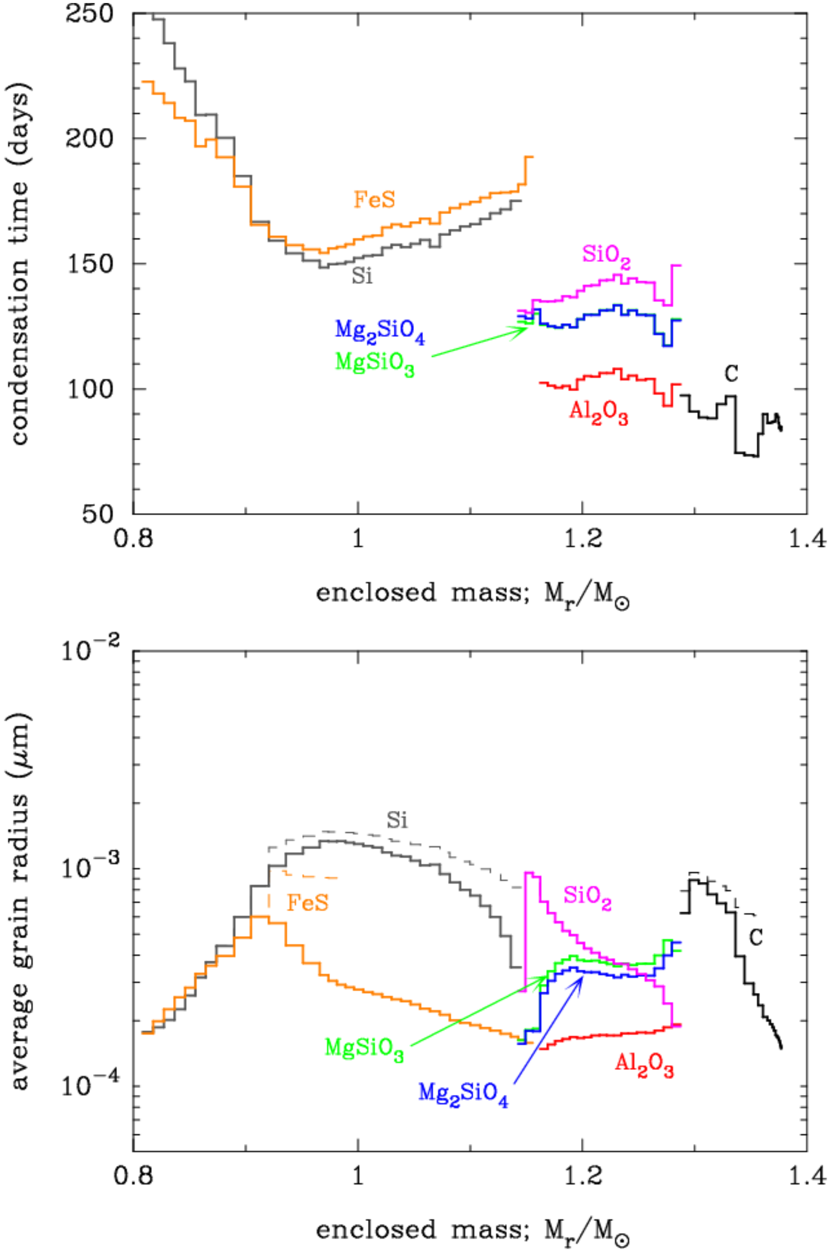
- $M_{\rm eje} = 1.38\ M_{\rm sun}$
- $E_{51} = 1.3$
- $M(^{56}{\rm Ni}) = 0.6\ M_{\rm sun}$





4-2. Results of dust formation calculations





4-3. Mass of dust formed in Type Ia SNe

in units of M_{sun}

Dust species	Steady	Non-steady
C	8.08x10-3	3.99x10-3
Mg_2SiO_4	8.79x10-3	1.21x10-5
$MgSiO_3$	2.34x10-2	3.64x10-6
SiO_2	3.40x10-2	8.39x10-3
Al_2O_3	1.89x10-3	0.00
FeS	6.06x10-2	2.83x10-3
Si	1.10x10-1	9.04x10-2
Fe	4.72x10-2	4.71x10-2
Ni	1.10x10-2	1.09x10-2
Total	0.305	0.164

4-4. Discussion on dust formation in SNe Ia

○ Issues to be addressed

- sticking probability: s = 1 in the calculations
  ➔ if s < 0.1, any dust grain cannot condense

- SN (W7) model: massive carbon (Mc ~ 0.05 Msun)
  ➔ observationally estimated carbon mass in SNe Ia : Mc < 0.01 Msun (Marion+06; Tanaka+08)

- M(56Ni) ~ 0.6 Msun in SNe Ia (cf. ~0.06 Msun in SNe II)
  ➔ energetic photons and electrons resulting from 56Ni decay destroy small clusters (e.g., Nozawa+11)

5. Summary of this talk

○ Steady-state nucleation rate is a good approximation if the gas density is high ($\tau_{sat} / \tau_{coll} >> 1$)

➔ otherwise, non-steady effect becomes remarkable, leading to a lower $f_{con,\infty}$ and a larger $a_{ave,\infty}$

○ Steady-state nucleaition rate is applicable for $\Lambda_{on} > 30$

➔ $f_{con,\infty}$ and $a_{ave,\infty}$ are determined by $\Lambda_{on} = \tau_{sat} / \tau_{coll}$ at the onset time (t_{on}) of dust formation

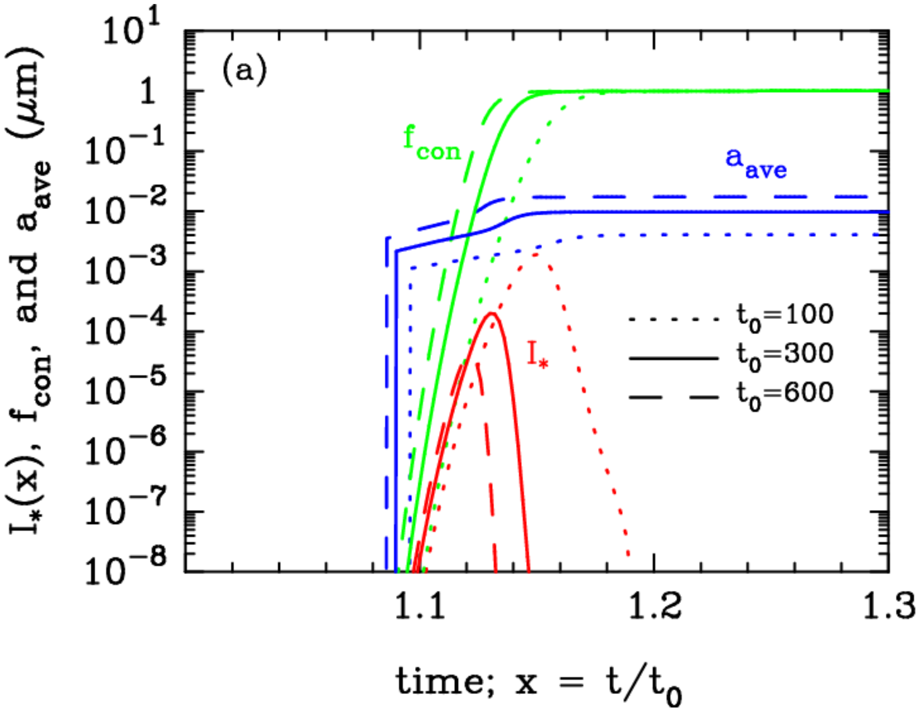
➔ The approximation formulae for $f_{con,\infty}$ and $a_{ave,\infty}$ are given as a function of Λ_{on}

○ Effect of non-steady state is remarkable in SNe Ia

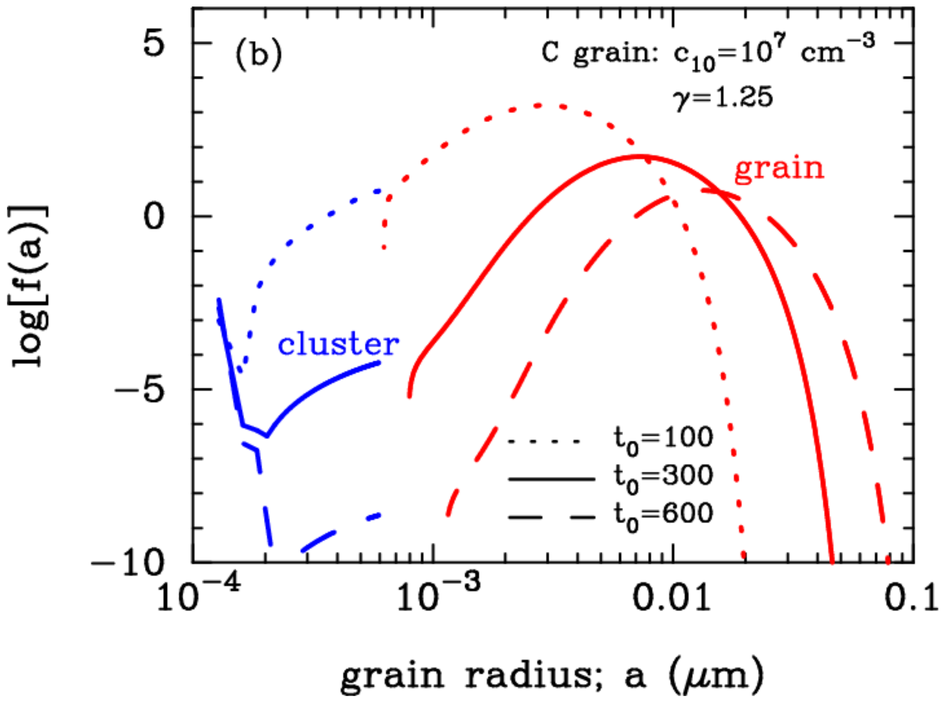
➔ Masses of silicate/oxide grains are significantly reduced, compared to the results by steady model

5-1. Dependence on t0

c10 = 10^7 cm^{-3}

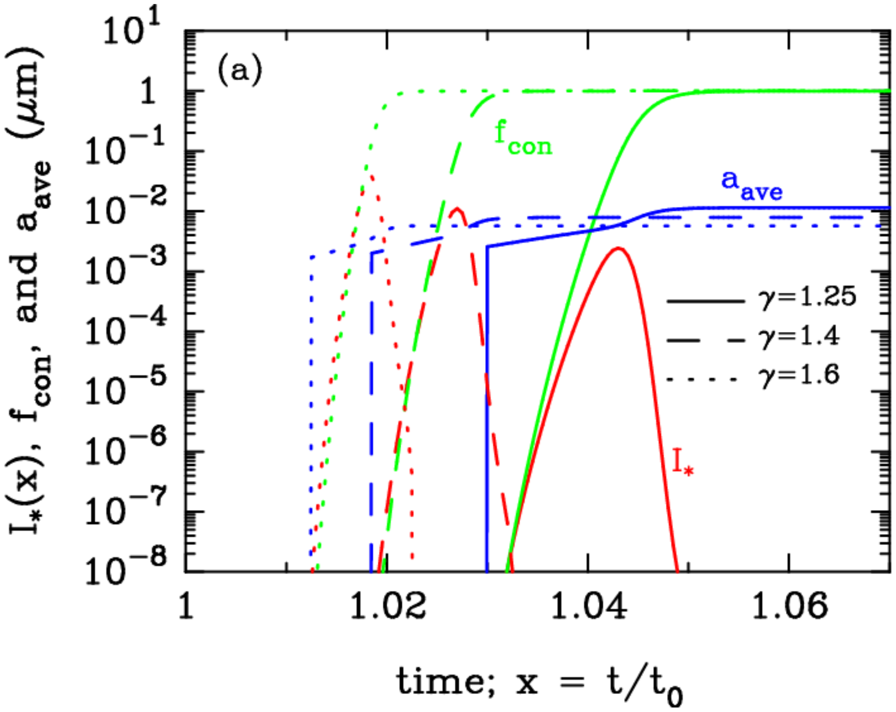


c10 = 10^5 cm^{-3}

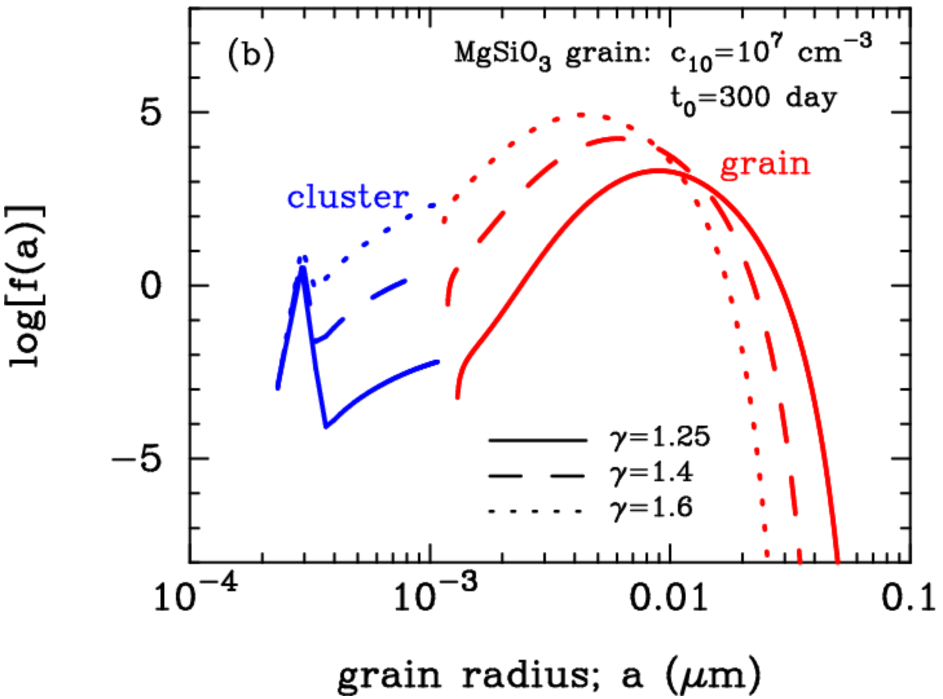


5-2. Dependence on gas cooling rate (γ)

c_{10} = 10^7 cm^{-3}

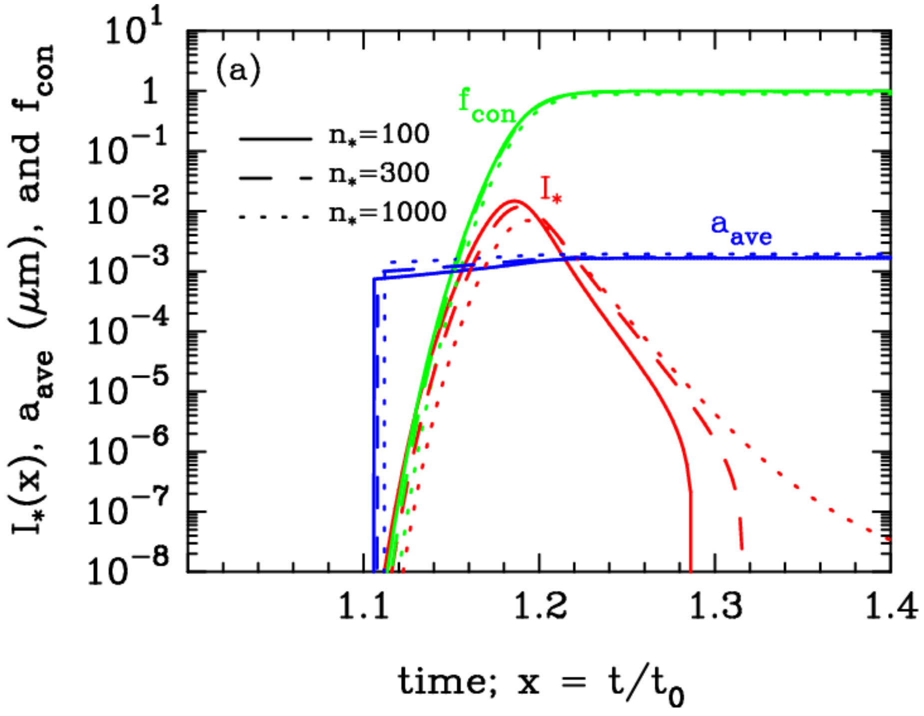


c_{10} = 10^5 cm^{-3}



5-3. Dependence on n_*

$c_{10} = 10^6$ cm^{-3}



$c_{10} = 10^5$ cm^{-3}