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天文学的ダスト形成環境における非定常ダスト形成過程の定式化

(Formulation of Non-steady-state Dust Formation Process in Astrophysical Environments)

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TODIAS 東京大学国際高等研究所 TODAI INSTITUTES FOR ADVANCED STUDY

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1-1. Core-collapse SNe as sources of dust

・Discoveries of massive dust at high redshifts

➔ **CCSNe must be main producers of dust grains**

・Dust formation in the ejecta of CCSNe

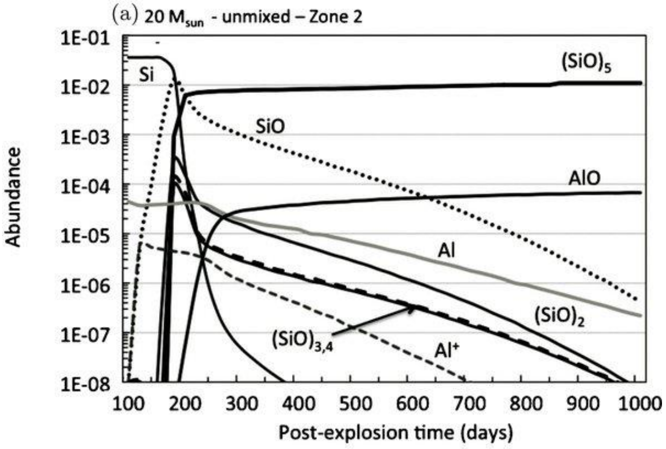
- **theoretical works predict that 0.1-1.0 Msun of dust can form in CCSNe (e.g., Nozawa+03; Nozawa+10)**

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

Some of dust grains formed in the ejecta are
destroyed by the reverse shock (e.g., Nozawa+07)

Necessary to reveal the dust mass and size distribution!

1-2. Aim of this study



Cherchneff & Dwek (2011)

▪ How do dust grains form?

atoms ➔ molecules ➔ clusters
➔ bulk grains??
reaction coefficients unknown!

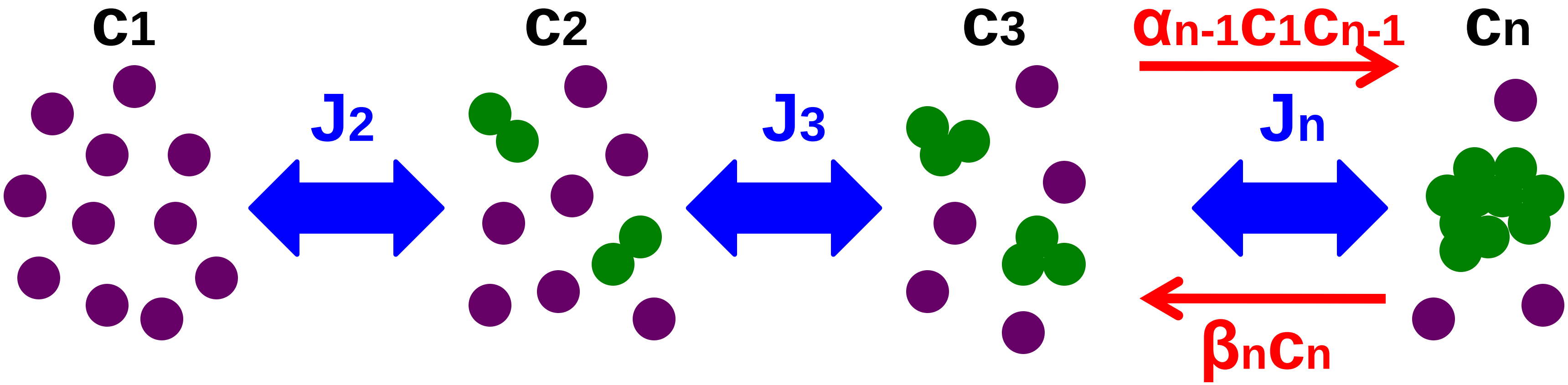
▪ Nucleation accompanied by chemical reactions

− kinetics of dust formation process is controlled by key molecule: gas species with the least collision frequency among reactants (Kozasa & Hasegawa 1987)

− steady-state nucleation rate may not be applied in rarefied environments (e.g., Donn & Nuth 1985)

The aim of this study is to formulate a non-steady-state formation process of dust grains

2-1. Formulation of dust formation



· master equations

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

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

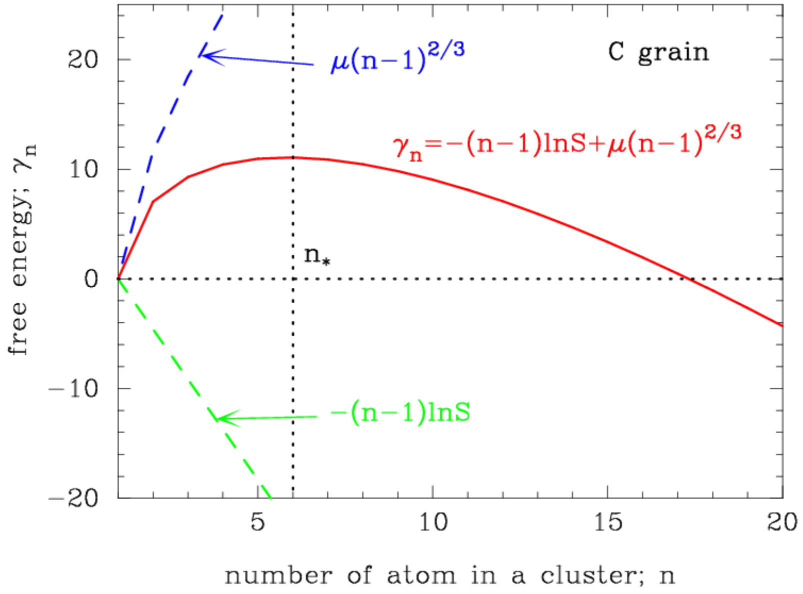
$$\alpha_n = \frac{s_n}{1+\delta_{1n}}\, 4\pi a_0^2\, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n} \right)^{\frac{1}{2}},$$

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

2-2. Steady-state nucleation rate

・ 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

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

σ : surface tension

S : supersaturation ratio

($S = p_1 / p_{1v}$)

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

2-3. Non-steady-state dust formation

- **non-steady-state dust formation**

$n_* = 100$

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

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

$$\gamma_n = \mu \left[\left(n - \frac{1}{\omega} \right)^{\frac{2}{3}} - \left(n - 1 - \frac{1}{\omega} \right)^{\frac{2}{3}} \right] - \ln S$$

- **Non-steady model: solving master equations**
- **Steady model: using a steady-state nucleation rate**

2-4. Basic equations for dust formation

▪ Equation of mass conservation

$$\tilde{c}_1 V - c_1 V = \underbrace{\sum_{n=2}^{n_*-1} n c_n V}_{\text{(clusters)}} + \underbrace{\int_{t_0}^{t} V(t') J_{n_*}(t') \frac{a^3(t,t')}{a_0^3} dt'}_{\text{(grains)}},$$

$\propto f_{\rm con}$

▪ 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

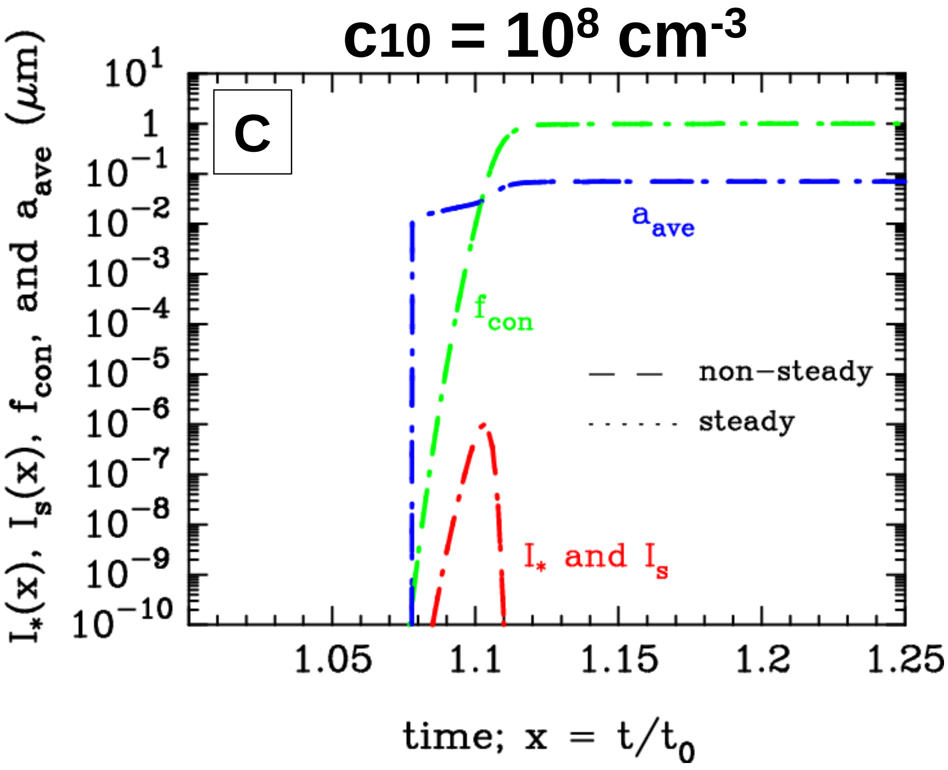
$$\tilde{c}(t) = c_0 \left(\frac{t}{t_0} \right)^{-3} \qquad T(t) = T_0 \left(\frac{t}{t_0} \right)^{-3(\gamma-1)}$$

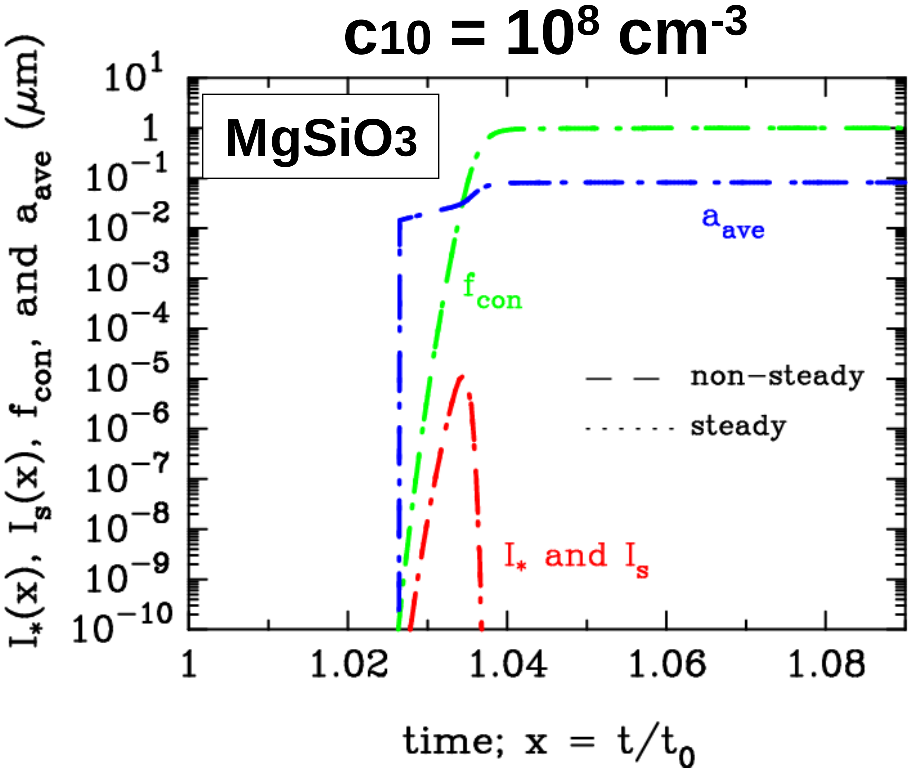
(γ = 1.1-1.7)

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)

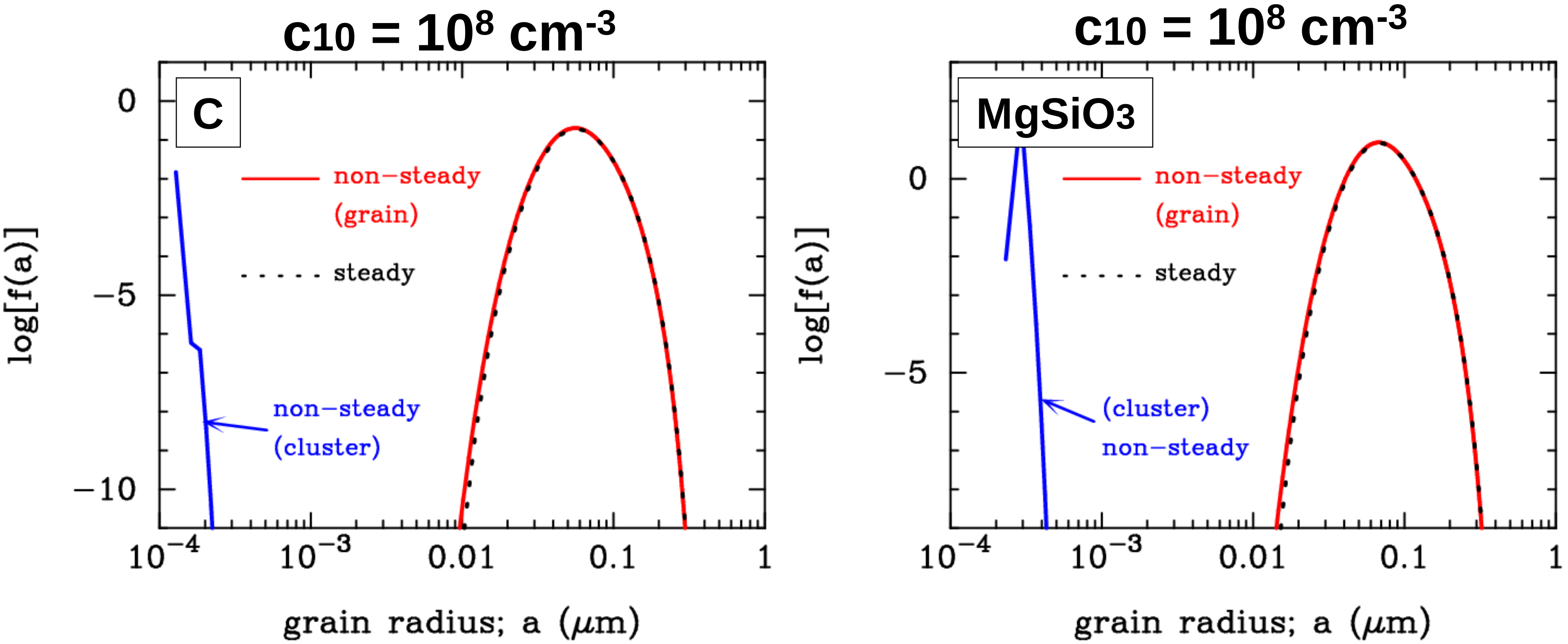

$c_{10} = 10^8$ cm^{-3}


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

**decrease in temperature → increase in S → increase in I_* (I_s)
→ grain growth → consumption of gas → decrease in I_* (I_s)**

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



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

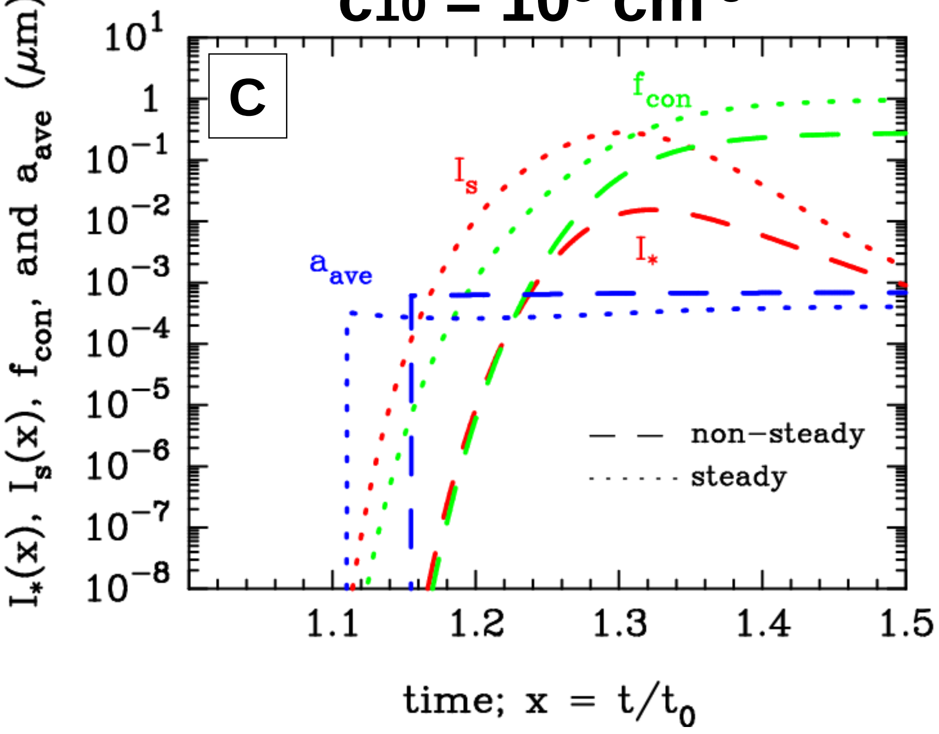
$c_{10} = 10^8\ \mathrm{cm}^{-3}$

The size distribution of grains for steady and non-steady models are identical

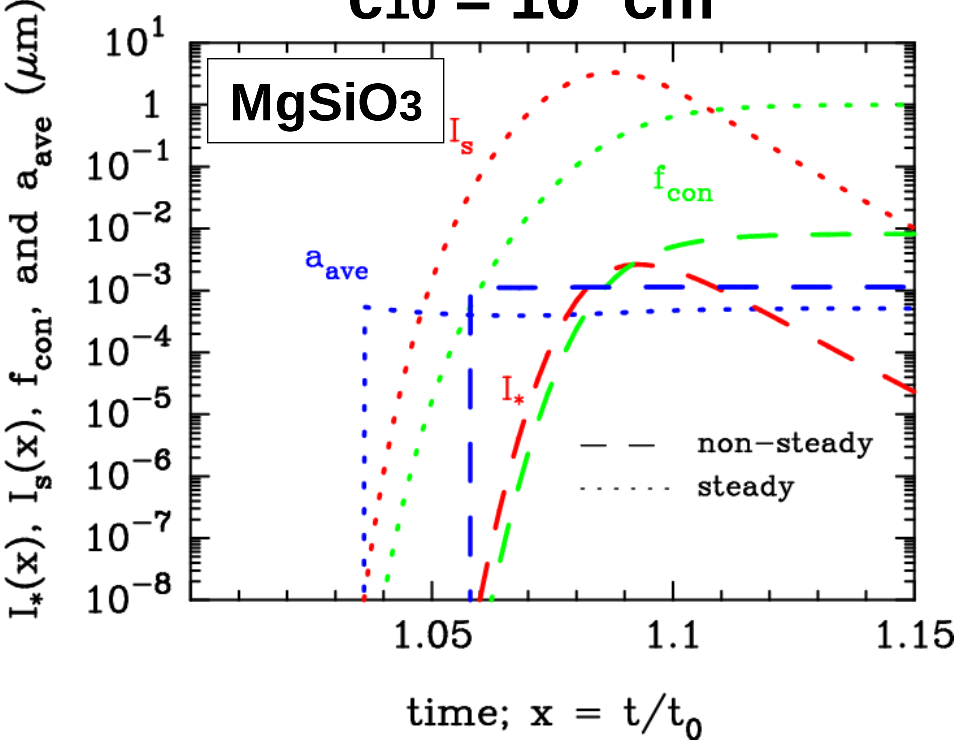
➔ The steady-state nucleation rate is a good approximation for higher initial densities

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

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



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



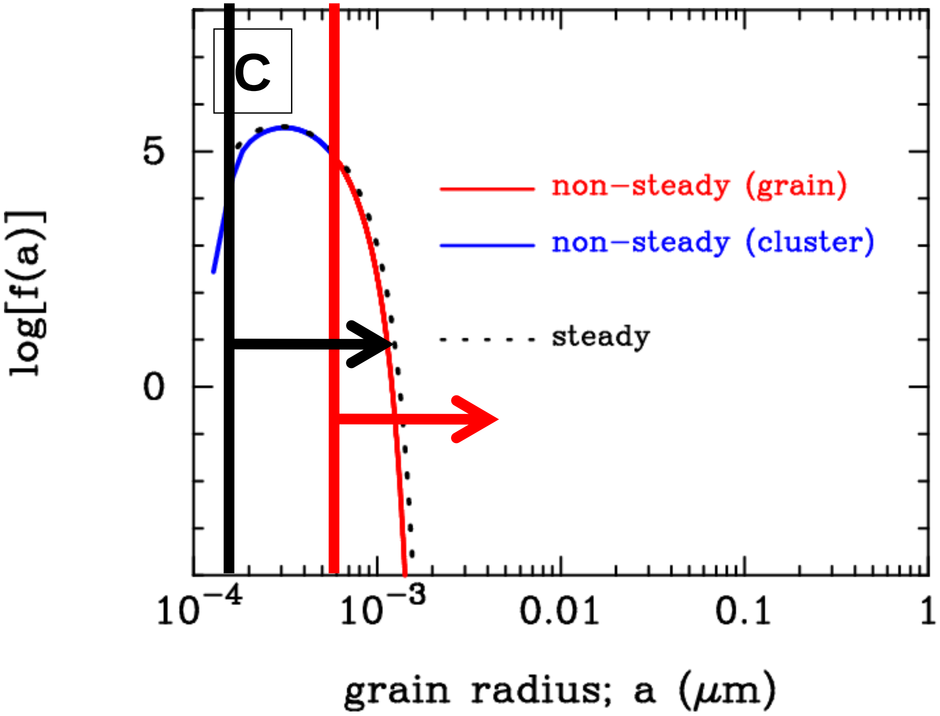
- **I_* : formation rate of clusters with $n_* = 100$**
- **I_s : formation rate of clusters with $n = n_c$ (<100)**

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

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

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

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



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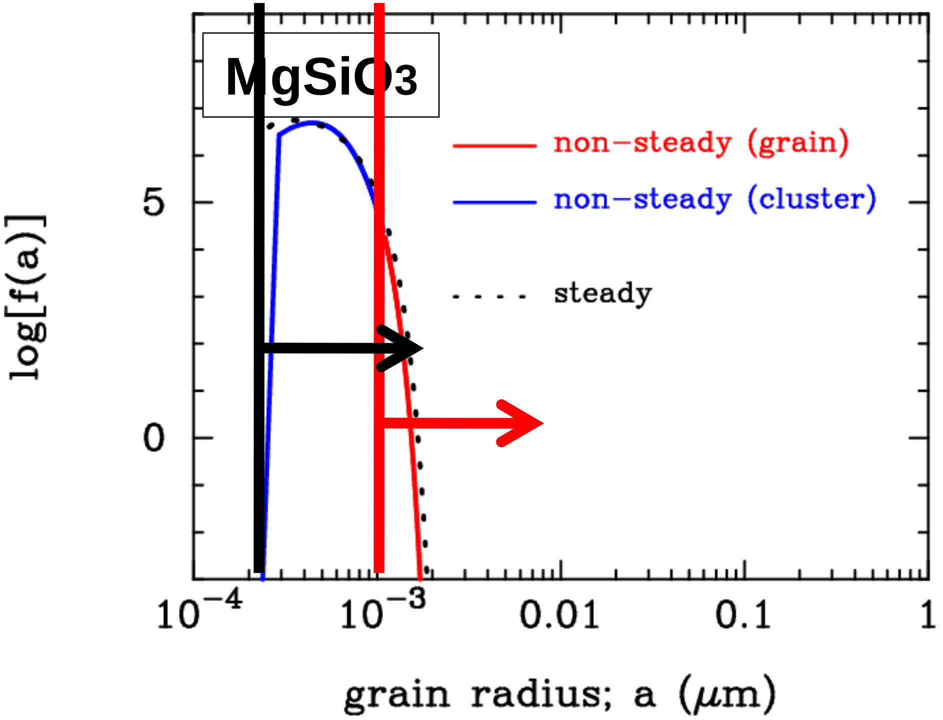
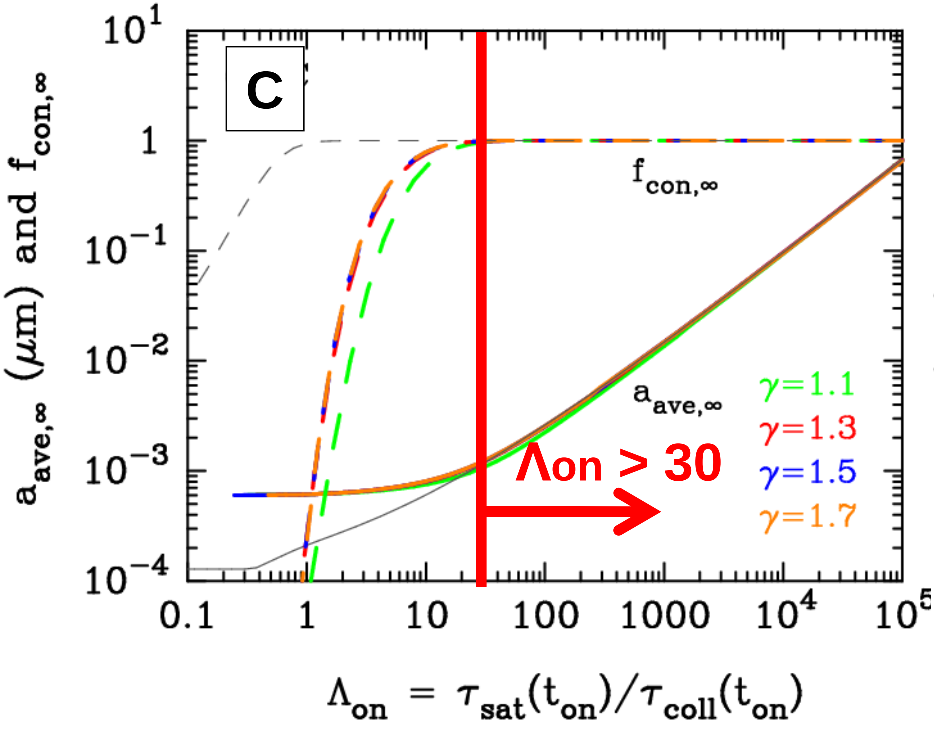
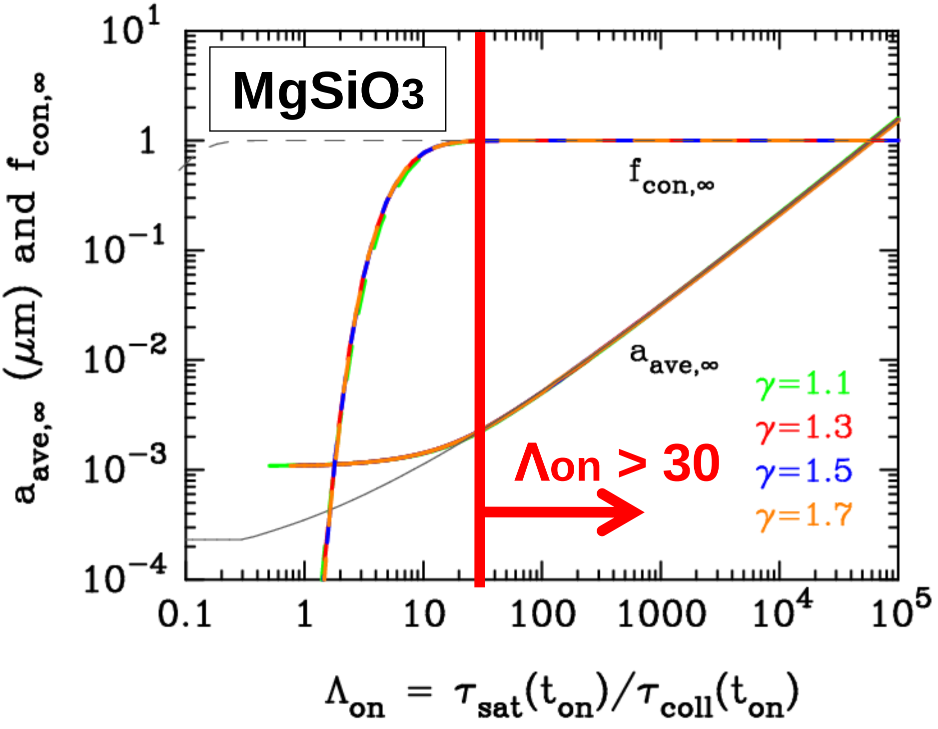


For lower gas densities, the steady model overestimates the condensation efficiency and underestimates the average grain radius

3-5. Scaling relation of average grain radius

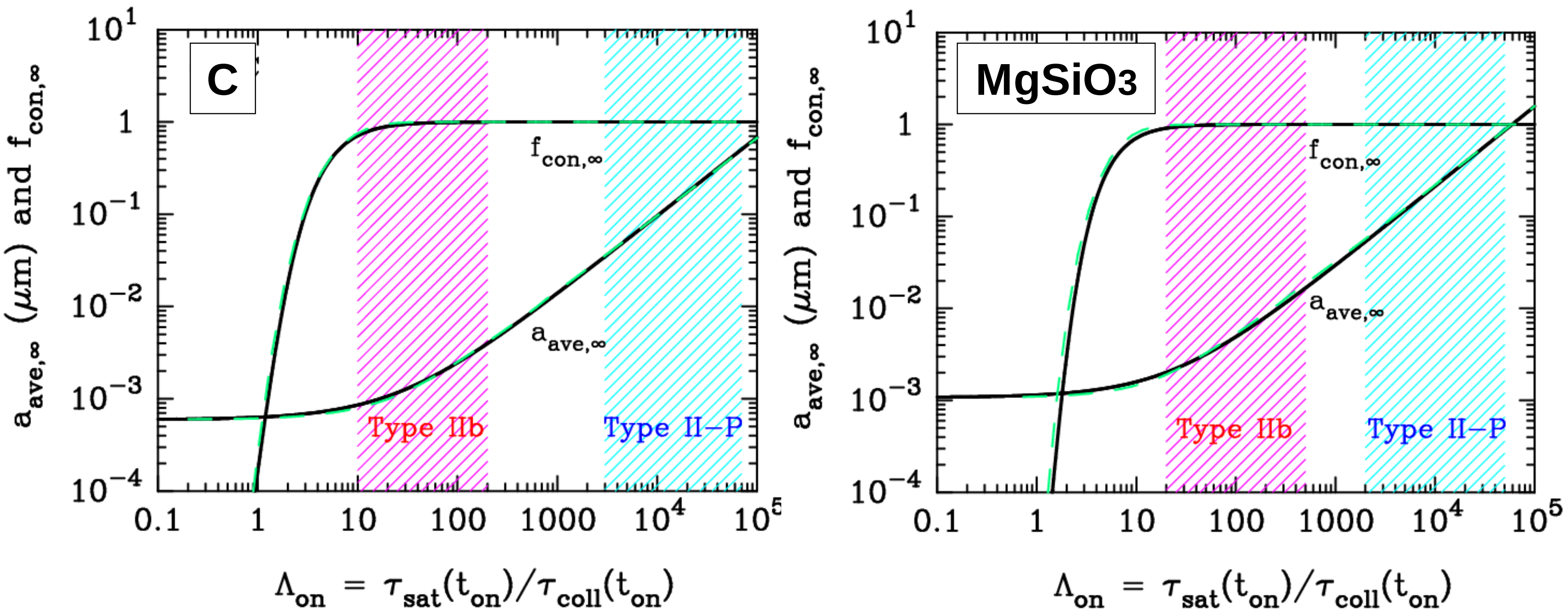




- **$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: ratio of supersaturation timescale to gas collision timescale at the onset time (t_{on}) of dust formation**
- **t_{on} : the time at which f_{con} reaches 10^{-10}**

- **$f_{con,\infty}$ and $a_{ave,\infty}$ are uniquely determined by Λ_{on}**
- **steady-state nucleation rate is applicable for Λ_{on} > 30**

3-6. Scaling relation of average grain radius



average

condens
efficiency

- **a ~ 0.1 μm in Type II-P SNe (Nozawa+03)**
- **a ~ 0.001 μm in Type IIb SNe (Nozawa+10)**

$\Lambda_{\rm on}$ = $\tau_{\rm sat}/\tau_{\rm coll}$ ∝ $\tau_{\rm cool}$ $n_{\rm gas}$

5. Summary of this talk

We develop a new formulation describing nonsteady-state formation of small clusters and grains in a self-consistent manner, taking account of chemical reactions

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

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

○ **Steady-state nucleation 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}**