2015/12/10

Physical Conditions of Supernova Ejecta Probed with the Sizes of Presolar Al_2O_3 Grains

- 超新星起源プレソーラーAl_2O_3粒子の形成環境 -

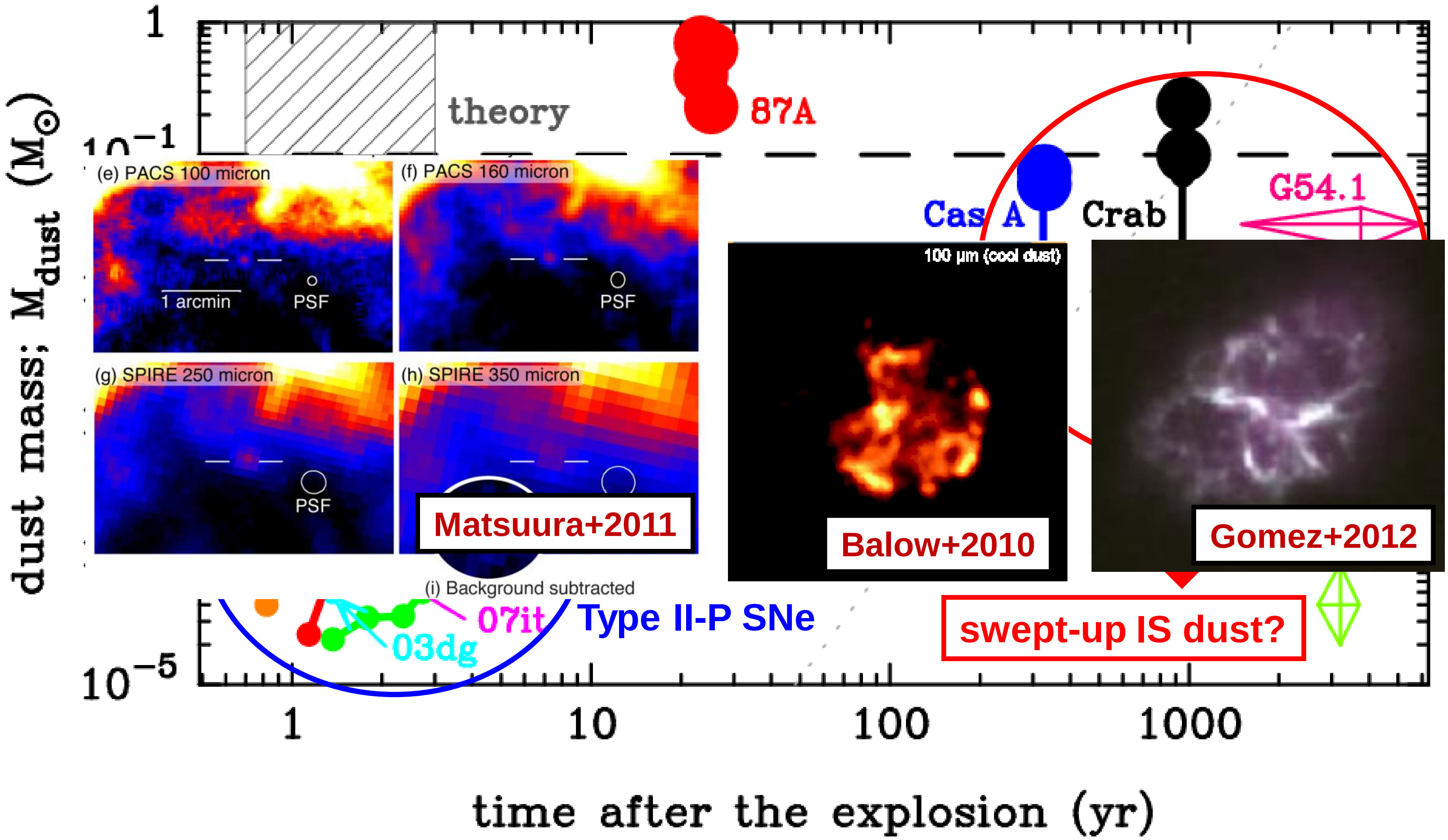
(Nozawa, Wakita, Hasegawa, Kozasa, 2015, ApJ, 811, L39)

野沢 貴也（Takaya Nozawa）

国立天文台　理論研究部

(National Astronomical Observatory of Japan)

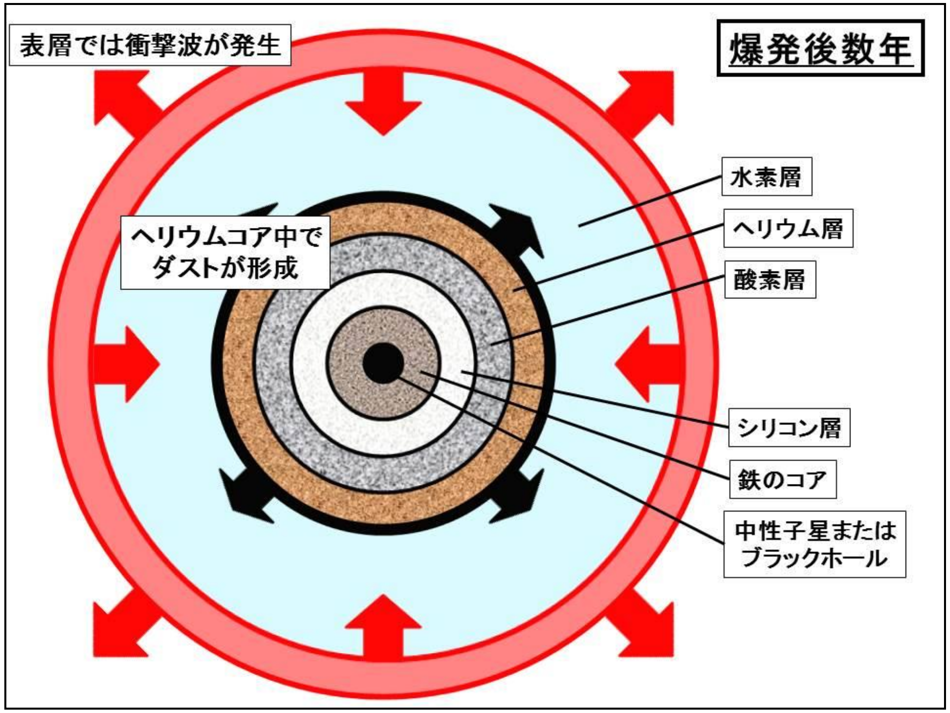
1-1. Summary of observed dust mass in CCSNe

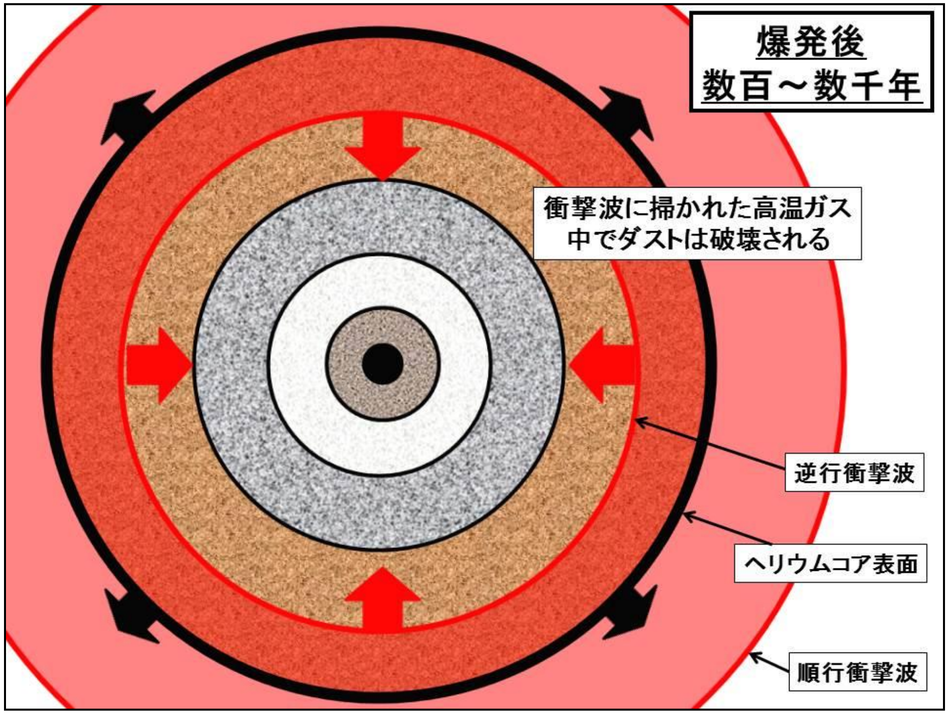


There are increasing pieces of evidence that massive dust in excess of 0.1 Msun is formed in the ejecta of SNe

1-2. Formation and processing of dust in SNe

Nozawa 2014, Astronomical Herald





Destruction efficiency of dust grains by sputtering in the reverse shocks depends on their initial size

The size of newly formed dust is determined by physical condition (gas density and temperature) of SN ejecta

1-3. Presolar grains

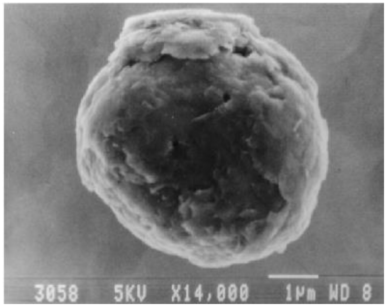
○ Presolar grains

- discovered in meteorites
- showing peculiar isotopic compositions
  (highly different from the solar system's materials)
- thought to have originated in stars before the Sun was formed

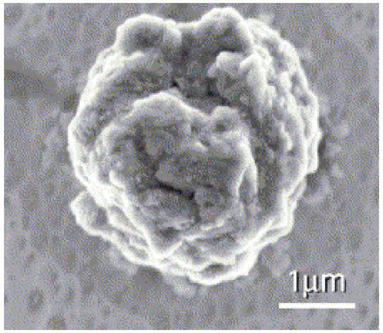
➜ offering key information on nuclear processes in the parent stars

red giants, AGB stars, supernovae, novae …

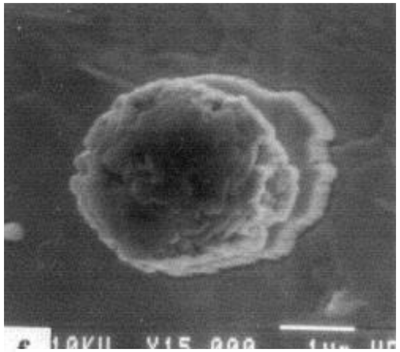
- mineral composition
  graphite, nanodiamond, TiC, SiC, Si_3N_4,
  Al_2O_3, $MgAl_2O_4$, TiO_2, Mg_2SiO_4, $MgSiO_3$ …



graphite (© Amari)



SiC (Nittler 2003)

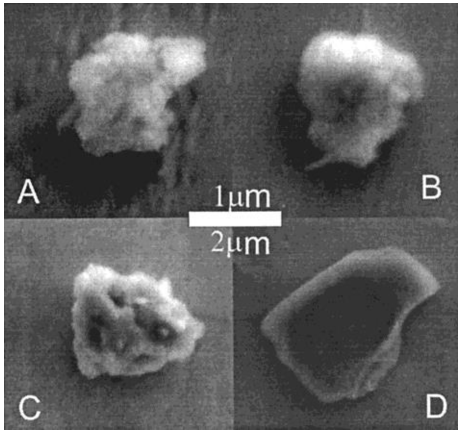


Al_2O_3 (Nittler+1997)

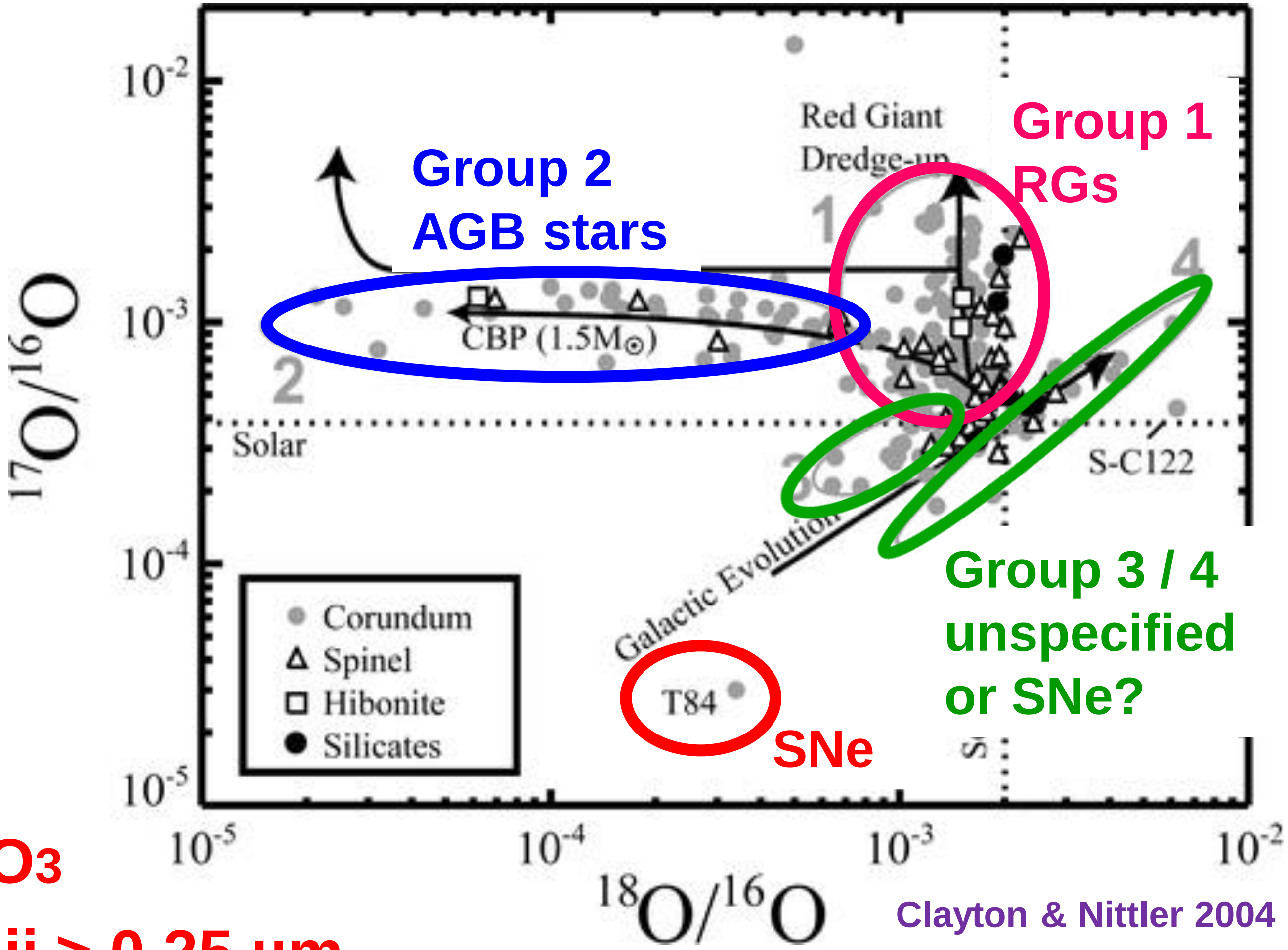
1-4. Isotopic composition of presolar oxides

○ Oxygen isotopic composition of presolar oxide grains

presolar Al_2O_3 grains



Choi+1998

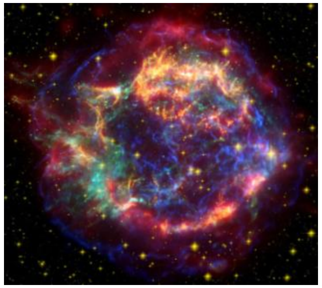


Clayton & Nittler 2004

A few particles of presolar Al_2O_3 grains with radii > 0.25 μm are believed to have been produced in the ejecta of SNe

1-5. Why we focus on presolar Al_2O_3 grains?

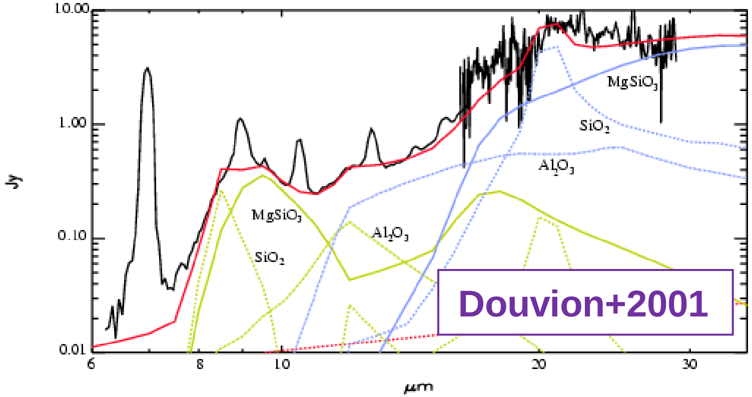
○ Evidence for Al_2O_3 formation in SNe



- **Infrared spectra of Cassiopeia A (Cas A) SNR**

  ➜ **Al_2O_3 is one of the main grain species**

  (Douvion et al. 2001; Rho et al. 2008)



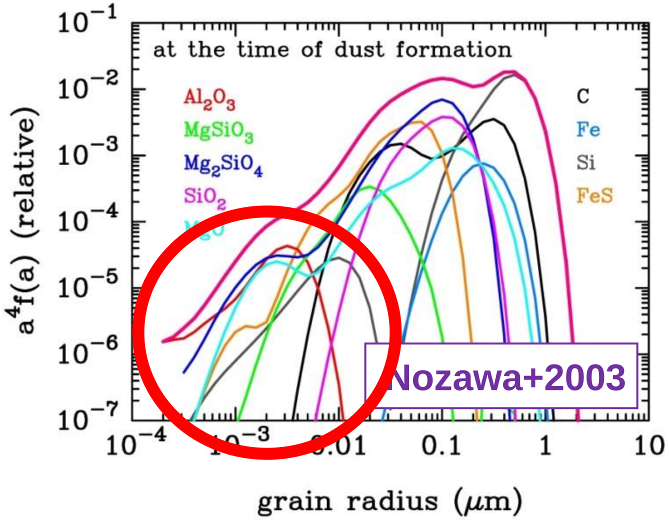
Douvion+2001

○ Dust formation calculations

- **the first condensate among oxide**

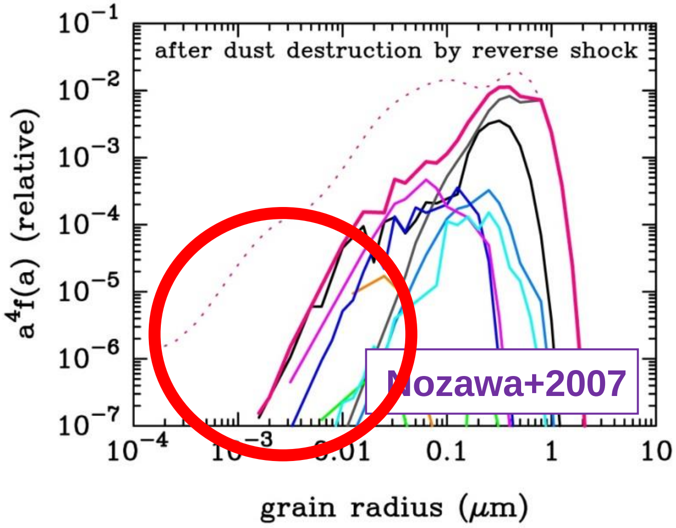
  ➜ **sizes of Al_2O_3 grains : < ~0.03 μm**

  (e.g., Nozawa+2003; Todini & Ferrara+2001)



Nozawa+2003

destruction in SNRs



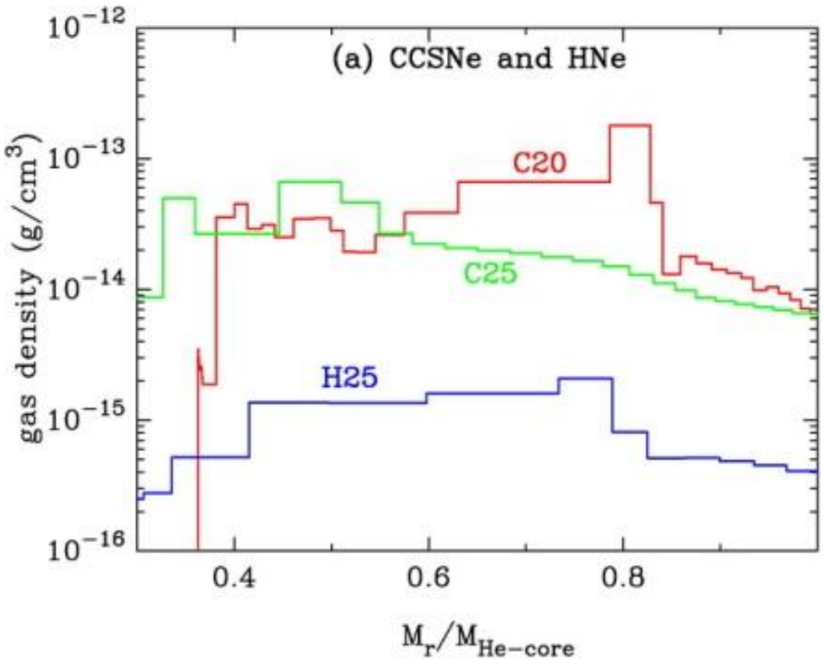
Nozawa+2007

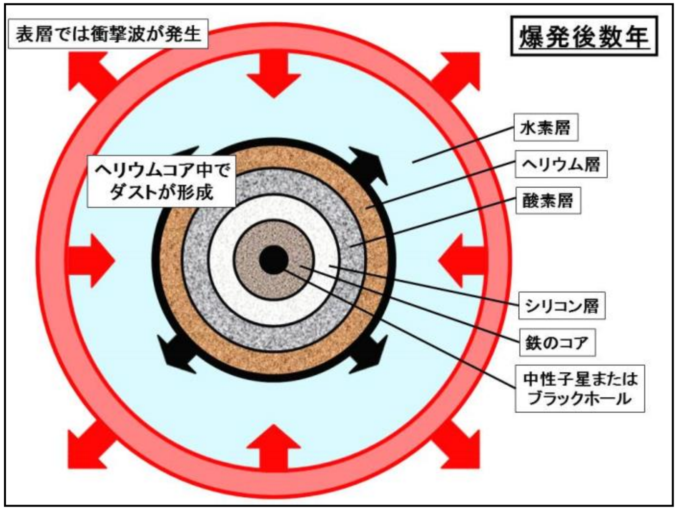
1-6. Why the calculated size of Al_2O_3 is small?

○ One-dimension (1-D) SN models

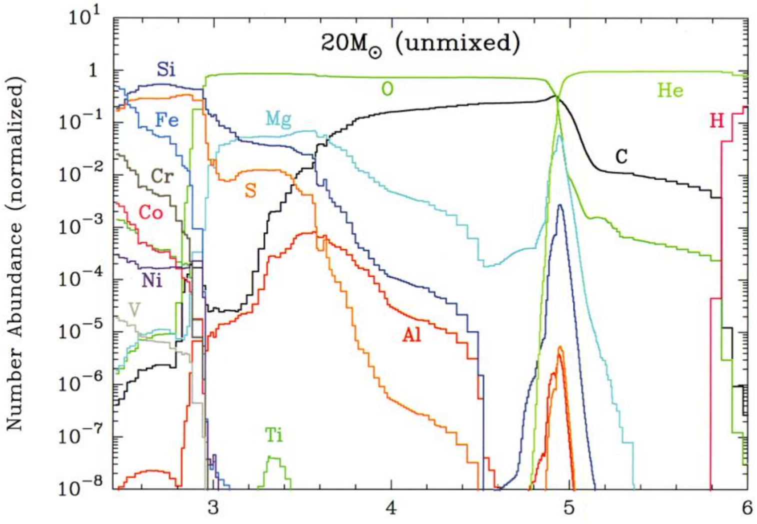
- relatively smooth density profile

  ➜ low number density of Al atoms





Nozawa+2003



- SN ejecta must be inhomogeneous

  ➜ dust formation would proceed in gases with a variety of densities

1-7. Aim of this talk

○ Question

What is the formation condition of sub-μm-sized presolar Al_2O_3 grains identified as the SN-origin?

○ Aim

We investigate the condensation of Al_2O_3 grains for wide ranges of gas density and cooling rate.

2-1. Supersaturation ratio

○ Supersaturation ratio, S

➔ ratio of partial pressure P_1 to equilibrium partial pressure $P^0{}_1$

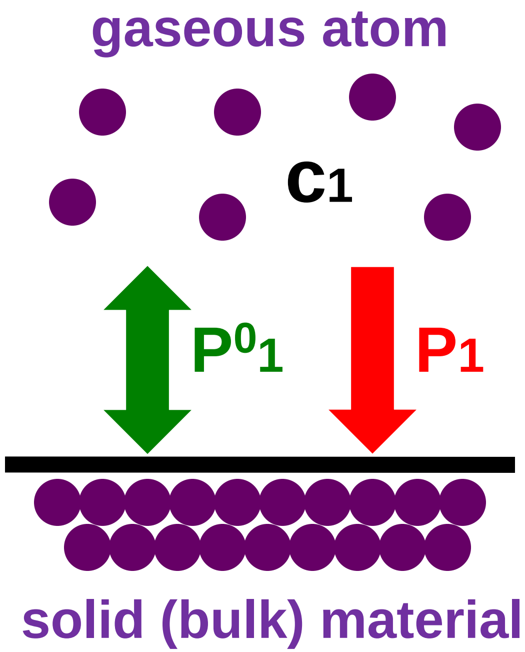
$$\ln S = \ln\left(\frac{p_1}{\mathring{p}_1}\right) = -\frac{1}{kT}\left(\mathring{g}_s - \mathring{g}_1\right) + \ln\left(\frac{p_1}{p_0}\right)$$

For condensation of dust,

$S = P_1 / P^0{}_1 > 1$

➔ $\ln S = \ln(P_1 / P^0{}_1) > 0$

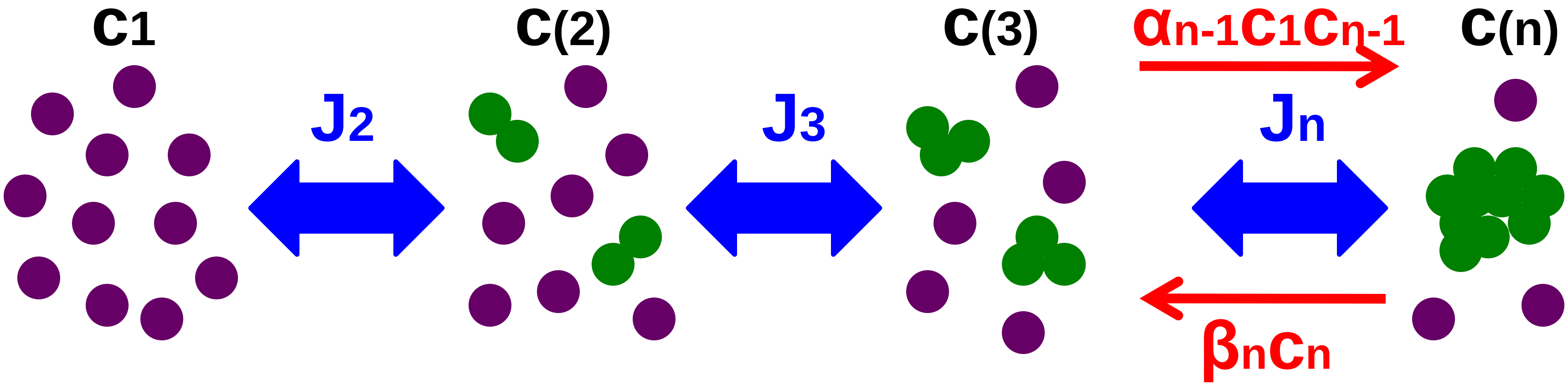
$$\ln S = \frac{A}{T} - B + \ln\left(\frac{c_1 kT}{p_0}\right)$$



T_{dust} is assumed to equal to $T=T_{gas}$

lnS is higher for lower T and higher c_1

2-2. Concept of nucleation theory



· master equations

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

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

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

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

2-3. Dust formation calculations (Nozawa & Kozasa 2013)

○ Master equations of cluster formation

$n_* = 100$

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

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

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

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

σ : surface tension

○ Equation of grain growth

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

$$\boxed{\frac{dV}{dt} = s\Omega_0 \, 4\pi a^2 \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S} \right),}$$

growth rate is independent of grain radius

2-4. Model of calculations for Al_2O_3 formation

○ Time evolution of gas density (free expansion)

$$\tilde{c}(t) = \boxed{c_0} \left(\frac{t}{t_0} \right)^{-3},$$

t_0 : the time at which lnS = 0 (S = 1)
c_0 : number density of Al atom at t_0

○ Time evolution of gas temperature

$$T(t) = T_0 \left(\frac{t}{t_0} \right)^{\boxed{-3(\gamma-1)}},$$

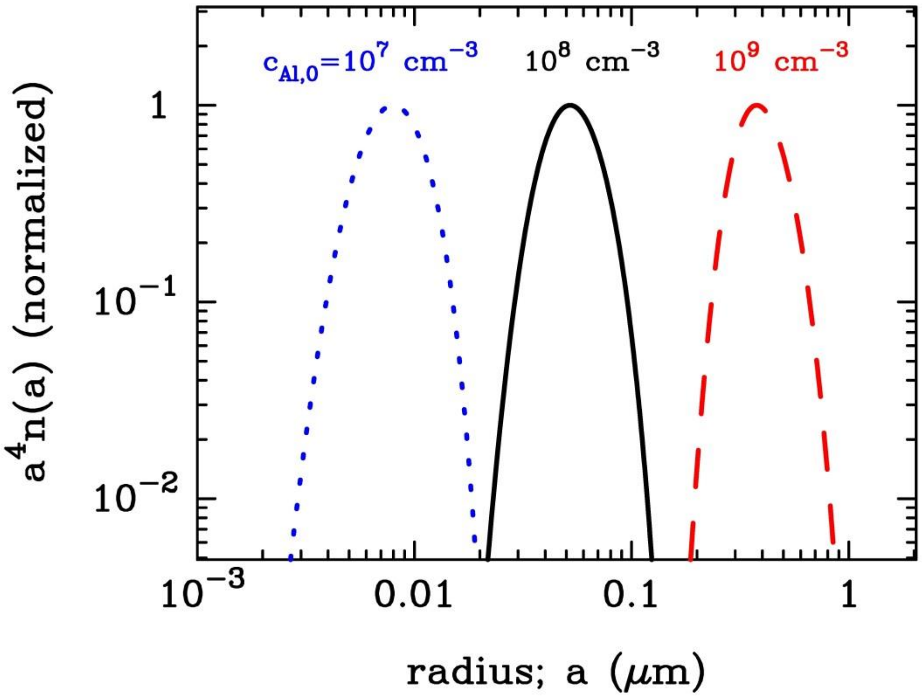
T_0 : gas temperature at t_0
γ: adiabatic constant

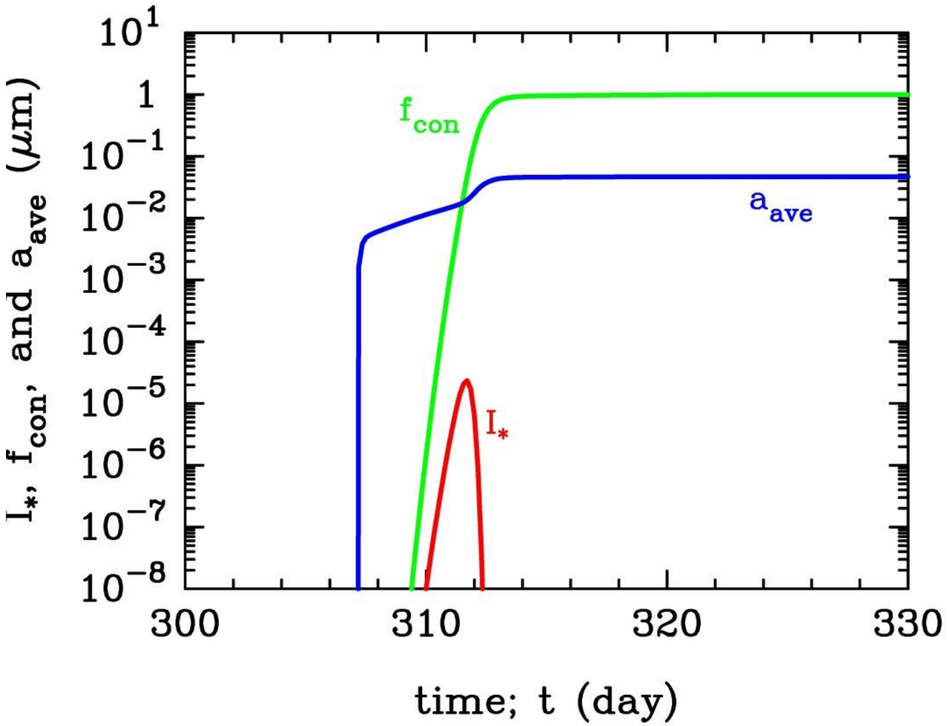
Parameters:

- c_{Al,0} = 10^3-10^{11} cm^{-3} (initial number density of Al atoms)
- γ = 1.1-1.7 (cooling rate)
- t_0 = 300 day (fixed)

condensation efficiency, fcon :
a fraction of Al atoms that are locked up in dust grains

3-1. Size distribution of newly formed grains



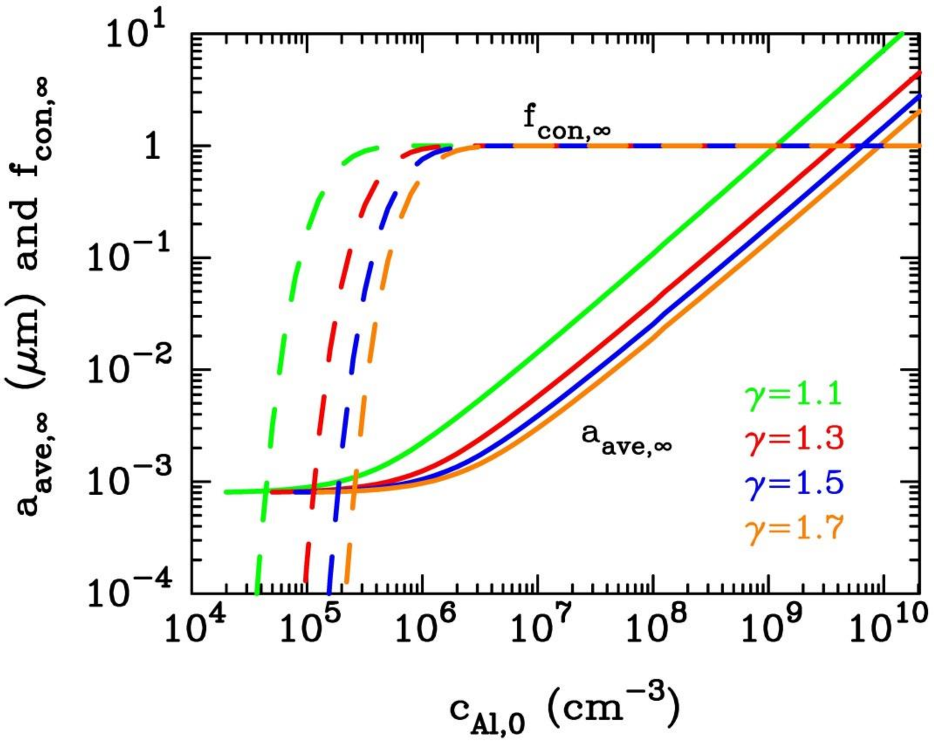


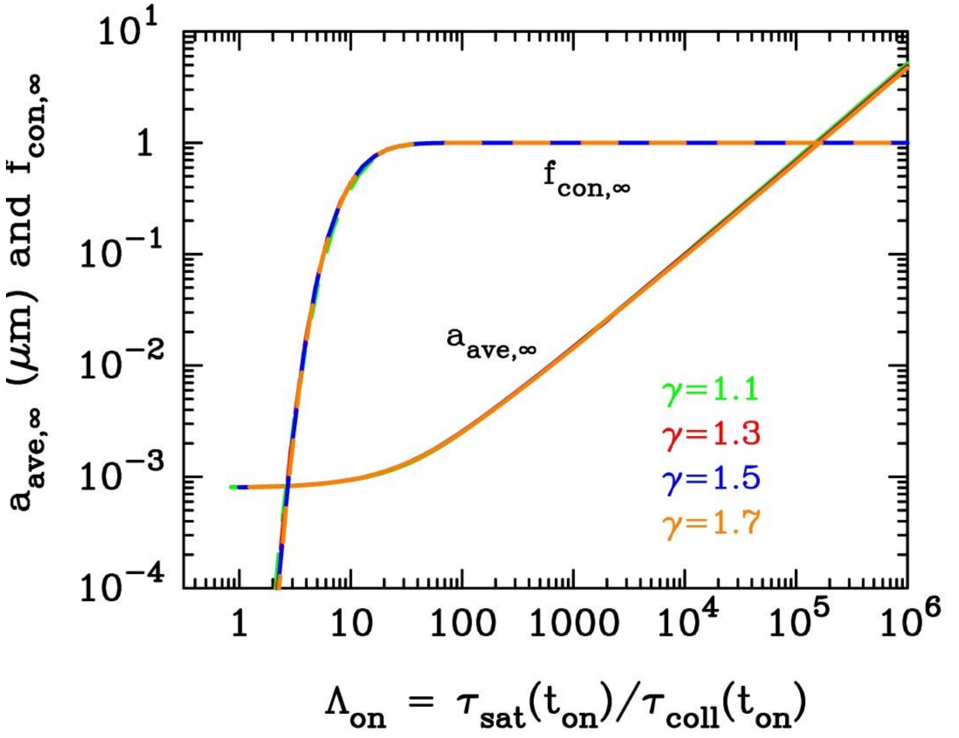
- **Size distribution of newly formed grains is lognormal-like with a narrower width for a higher gas density**

- **Average grain radius increases with increasing c_{Al,0}**
  ➜ a higher gas density leads to more efficient growth of grains

c_{Al,0} should be higher than ~5x10^8 cm^{-3} for the formation of Al_2O_3 grains with radii larger than ~0.25 μm (diameter of 0.5 μm)

3-2. Scaling relation for $f_{\mathrm{con},\infty}$ and $a_{\mathrm{ave},\infty}$





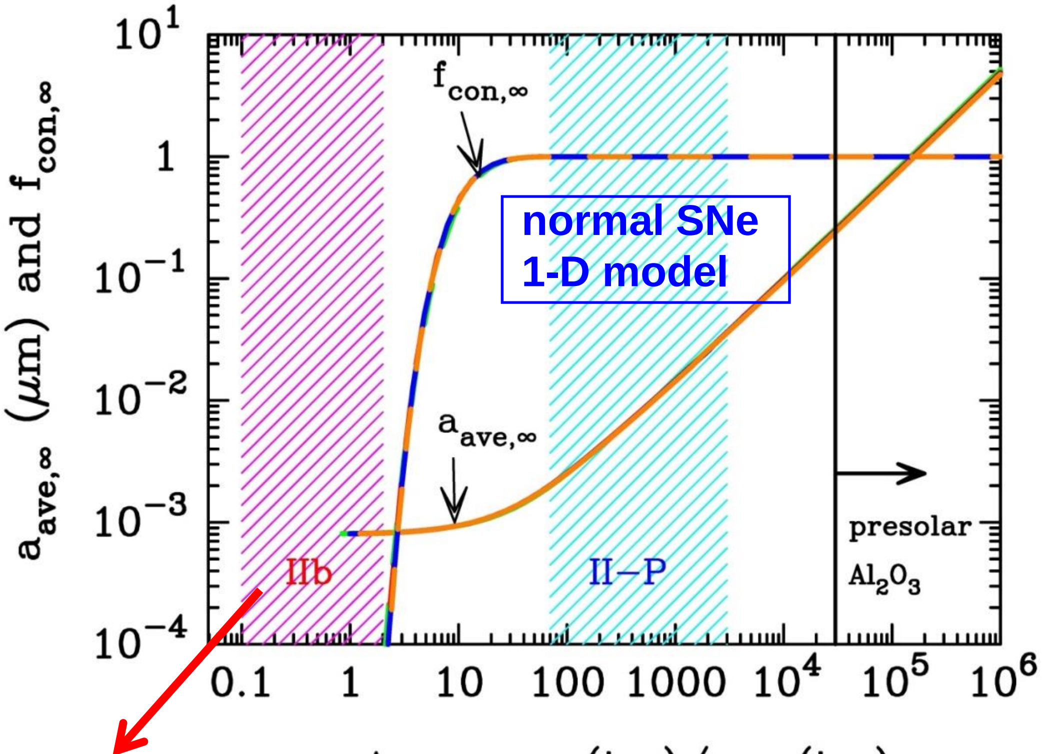
$\Lambda_{\mathrm{on}} = \tau_{\mathrm{sat}}/\tau_{\mathrm{coll}}$: ratio of supersaturation timescale to gas collision timescale at the onset time (t_{on}) of dust formation

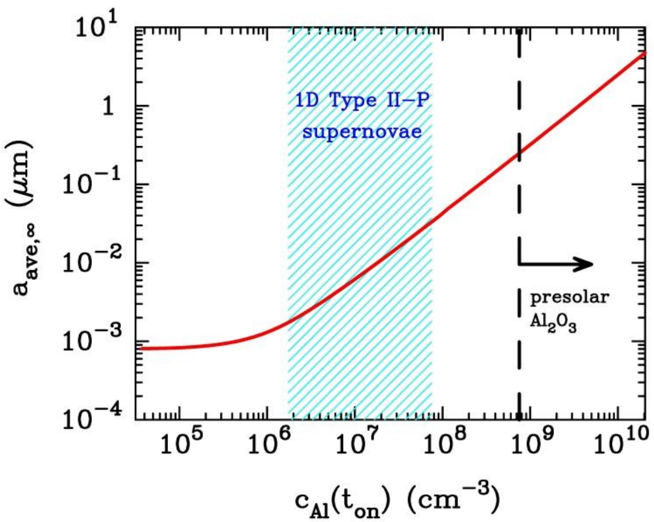
$\Lambda_{\mathrm{on}} = \tau_{\mathrm{sat}}/\tau_{\mathrm{coll}} \propto \tau_{\mathrm{cool}}\ n_{\mathrm{gas}}$

- **$f_{\mathrm{con},\infty}$ and $a_{\mathrm{ave},\infty}$ are uniquely determined by Λ_{on}**

this is true for the formation of carbon and silicate grains

3-3. Formation condition of presolar Al_2O_3





Λ_{on} > 30,000 required

➜ at least 10 times higher gas density than those predicted by 1-D SN models

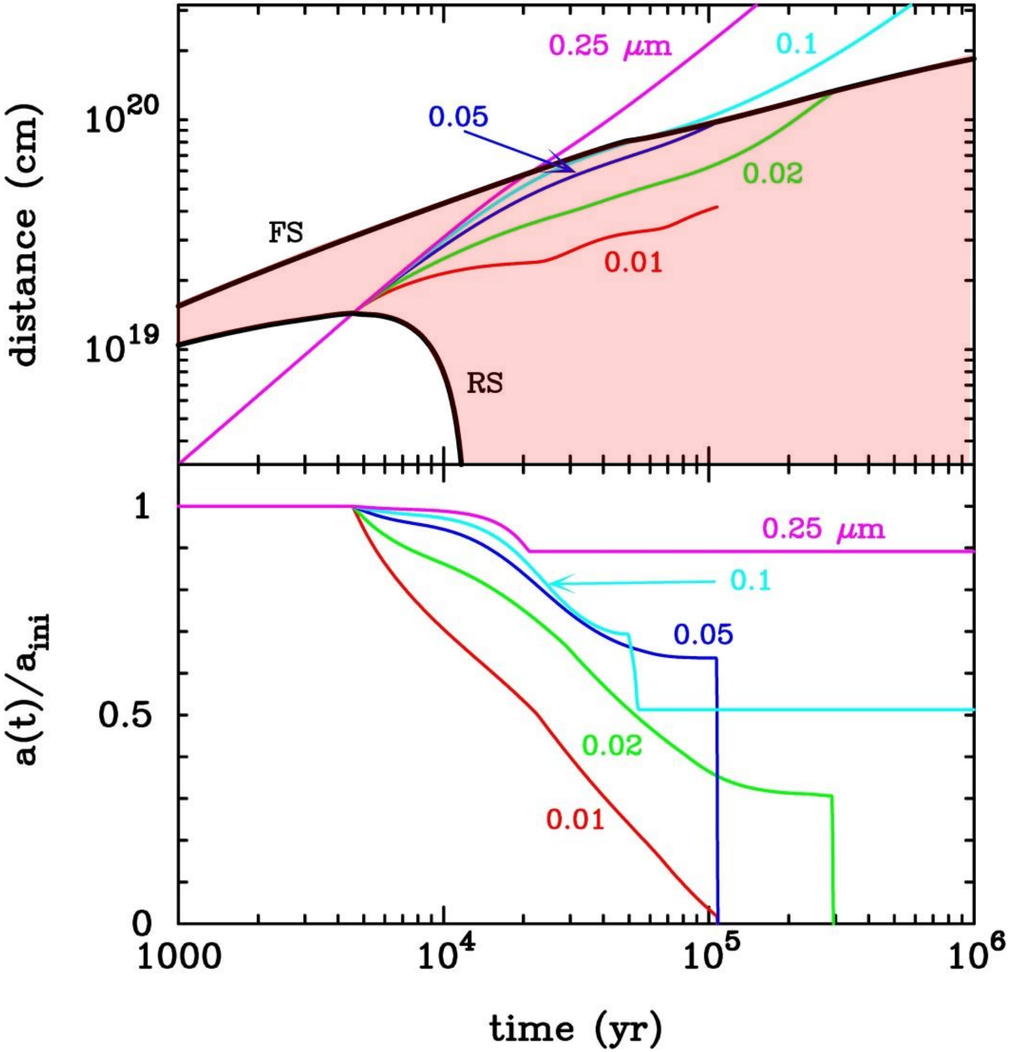
$$\Lambda_{\rm on} \simeq \frac{1082}{\gamma - 1}\left(\frac{t_{\rm on}}{300\ {\rm days}}\right)\left[\frac{\tilde{c}_{\rm Al}(t_{\rm on})}{10^8\ {\rm cm}^{-3}}\right]\left[\frac{T(t_{\rm on})}{2000\ {\rm K}}\right]^{\frac{3}{2}}.$$

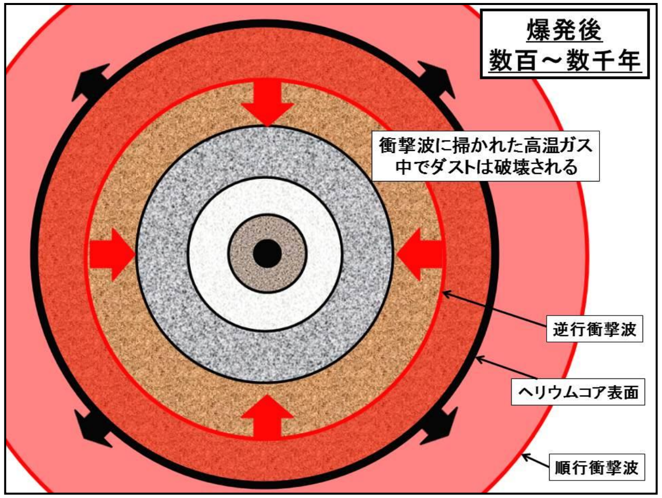
Submicron-sized presolar Al_2O_3 grains identified as SN-origin were formed in dense clumps in the ejecta

3-4. Newly formed grains can survive in SNR?

Model of the calculation:

M_{SN}= (3 + 12) Msun, E_{exp}=1.8×10^{51} erg,
n_{ISM} = 1 cm^{-3}





Evolution of dust in SNRs depends on the initial radii

- a_{ini} < 0.01 μm
➔ completely destroyed

- 0.02 μm < a_{ini} < 0.1 μm
➔ eroded in dense shell

- a_{ini} > 0.1 μm
➔ injected into the ISM

4. Summary of this talk

We investigate the formation of Al_2O_3 grains for a variety of densities and cooling rates of the gas.

1) The average radius and condensation efficiency of newly formed Al_2O_3 grains are uniquely described by the non-dimensional quantity Λ_{on}.

2) Presolar Al_2O_3 grains with radii above 0.25 μm can be formed only in the gas with more than 10 times higher density than those estimated by 1-D SN models.
   ➜ indicating the presence of dense clumps in the SN ejecta

3) The measured sizes of presolar grains are powerful probes for constraining the physical conditions and structure in which they formed.