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超新星起源プレソーラーAl_2O_3粒子の形成環境

Probing the Physical Condition of Supernova Ejecta with the Measured Sizes of Presolar Al_2O_3 Grains

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

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1-1. Presolar grains

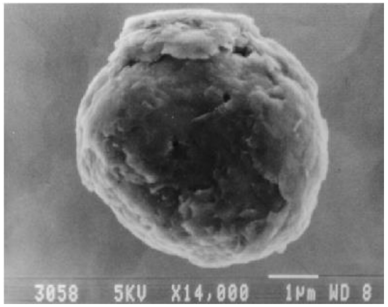
○ Presolar grains

- 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

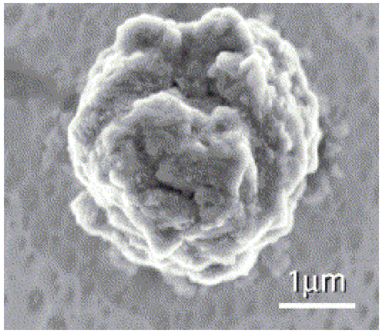
➜ **offering key information on nuclear processes in the parent stars**

red giants, AGB stars, supernovae, novae …

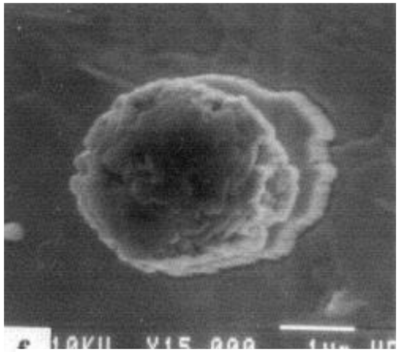
- mineral composition
  graphite, nanodiamond, TiC, SiC, Si_3N_4, Al_2O_3, $MgAl_2O_4$, TiO_2, Mg_2SiO_4, $MgSiO_3$ …



graphite (© Amari)



SiC (Nittler 2003)

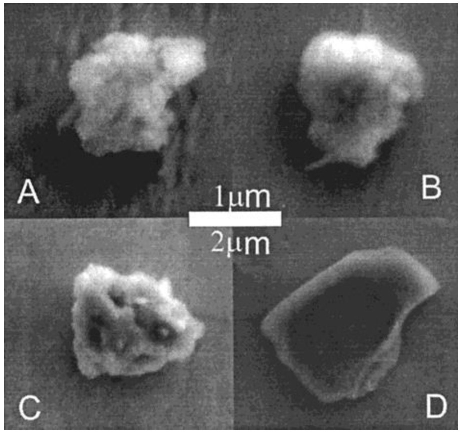


Al_2O_3 (Nittler+1997)

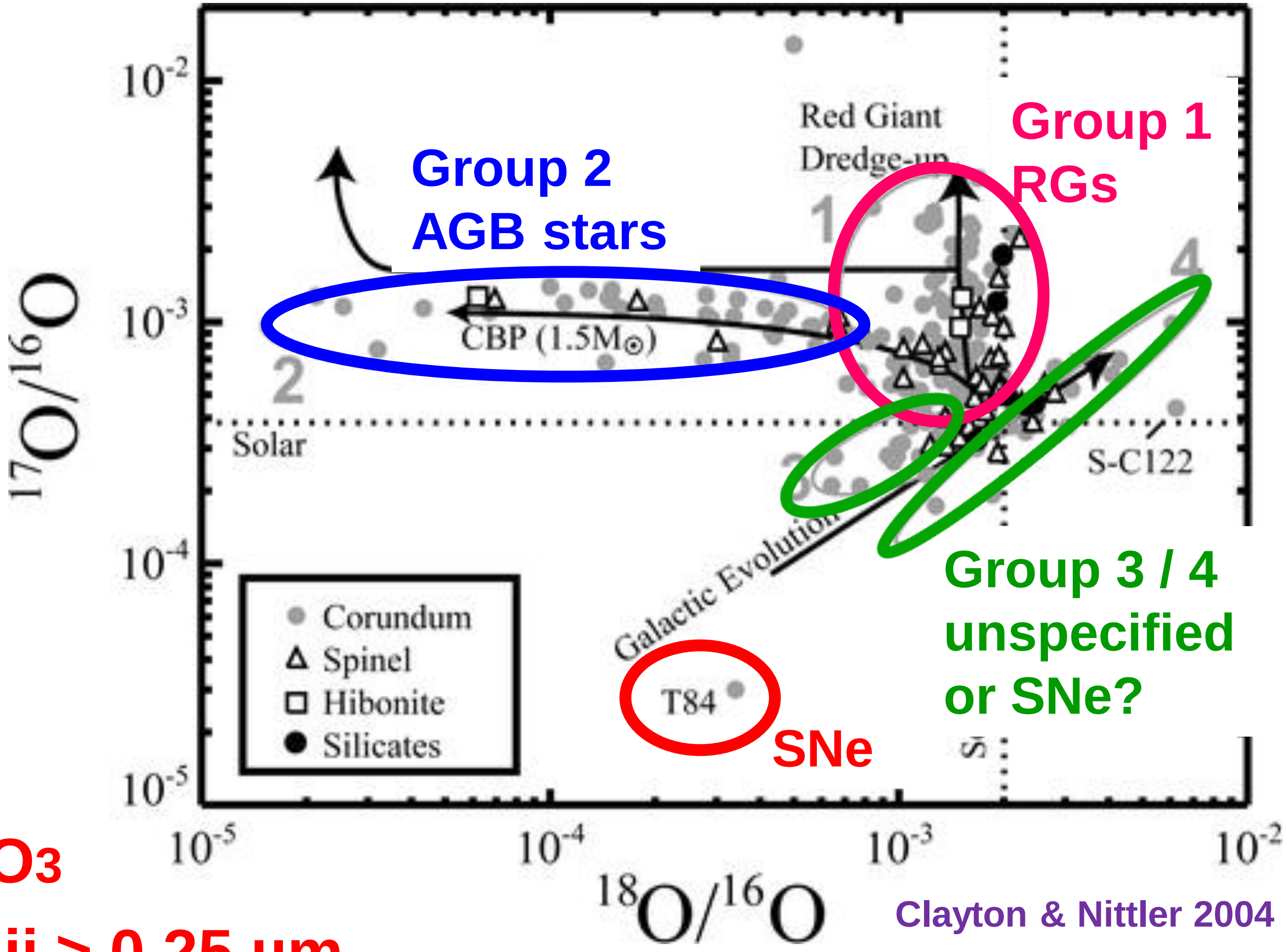
1-2. Isotopic composition of presolar oxides

○ Oxygen isotopic composition of presolar oxide grains

presolar Al_2O_3 grains



Choi+1998



Group 2
AGB stars

Group 1
RGs

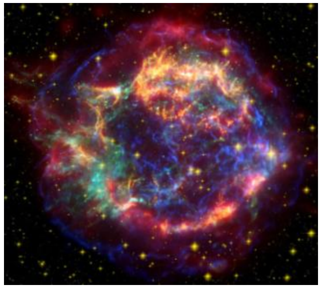
Group 3 / 4
unspecified
or SNe?

SNe

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

1-3. Why we focus on presolar Al_2O_3 grains?

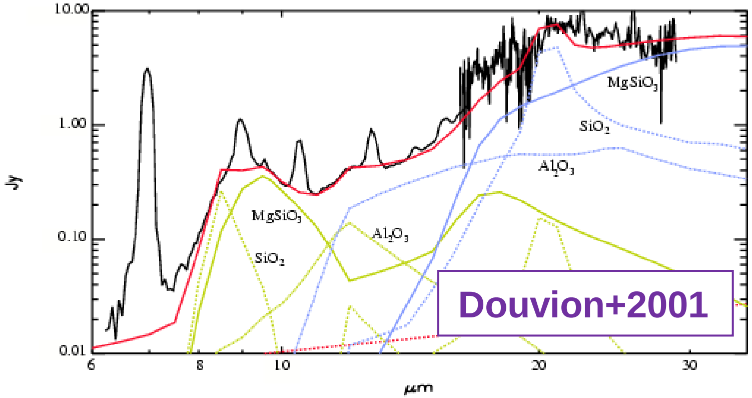


○ Evidence for Al_2O_3 formation in SNe

- 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)

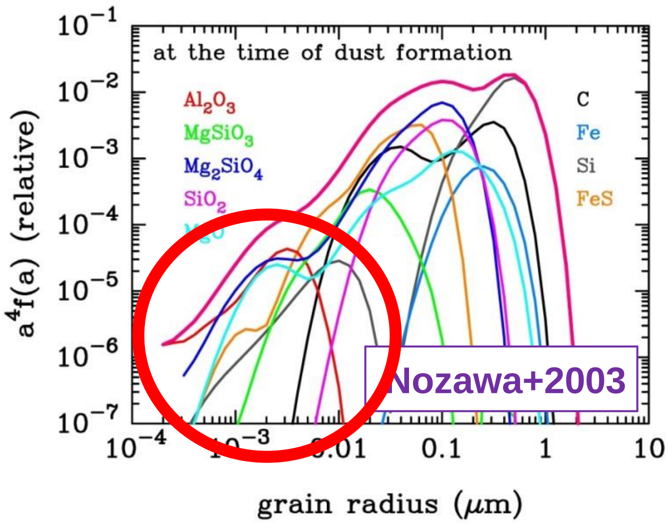


○ Dust formation calculations

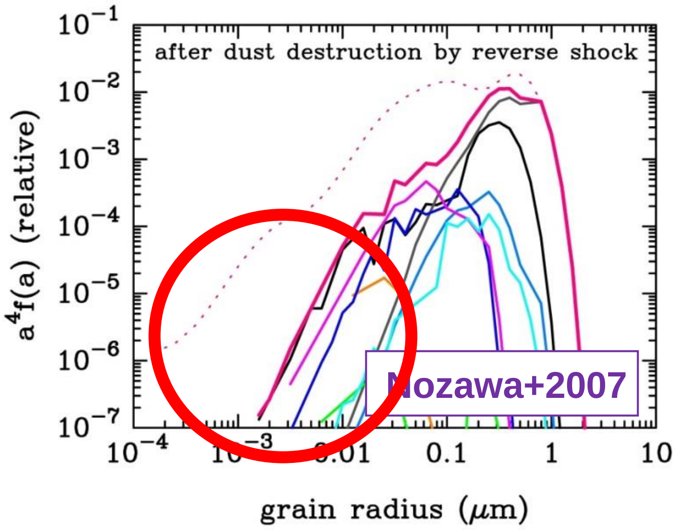
- the first condensate among oxide

➜ sizes of Al_2O_3 grains : < ~0.03 μm

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



destruction in SNRs

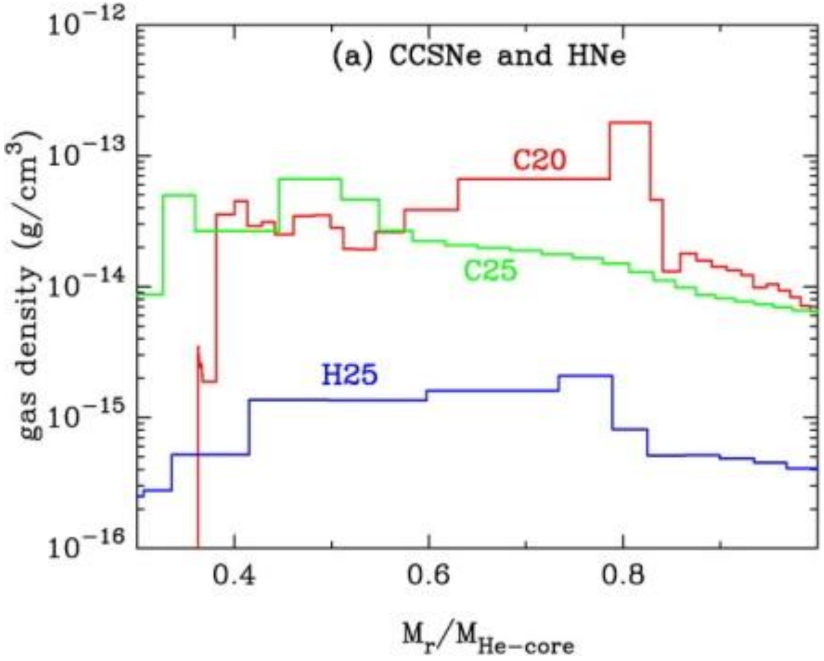


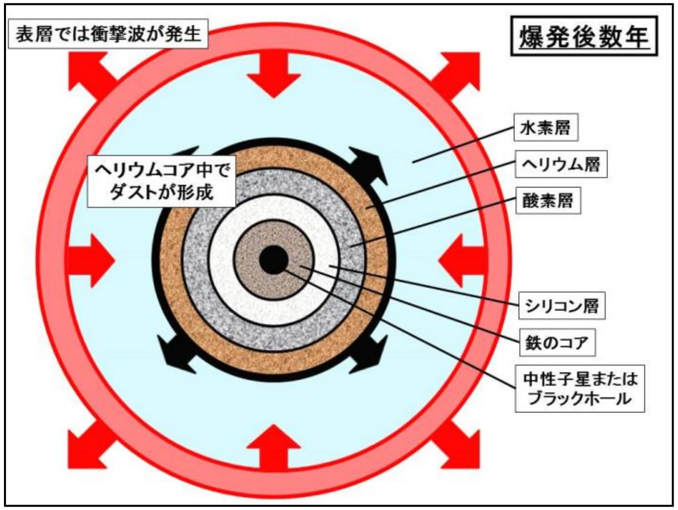
1-4. Why the calculated size of Al_2O_3 is small?

○ One-dimension (1-D) SN models

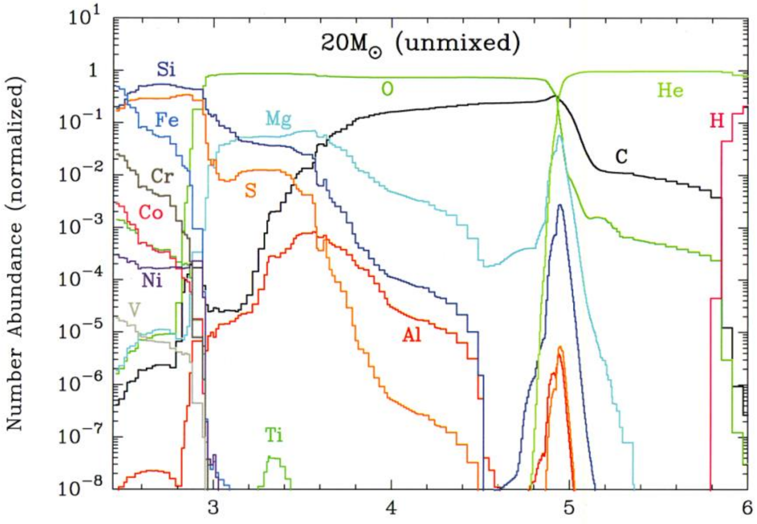
- relatively smooth density profile

  ➜ low number density of Al atoms





Nozawa+2003



- SN ejecta must be inhomogeneous

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

1-5. 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**

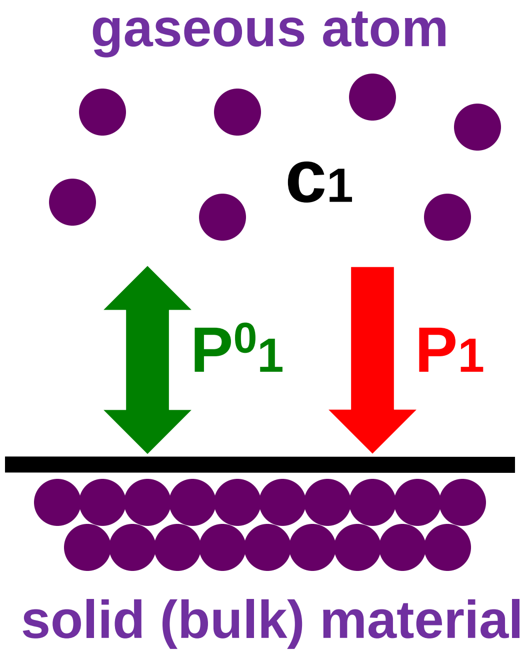
We investigate the condensation of Al_2O_3 grains for wide ranges of gas density and cooling rate.

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,

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

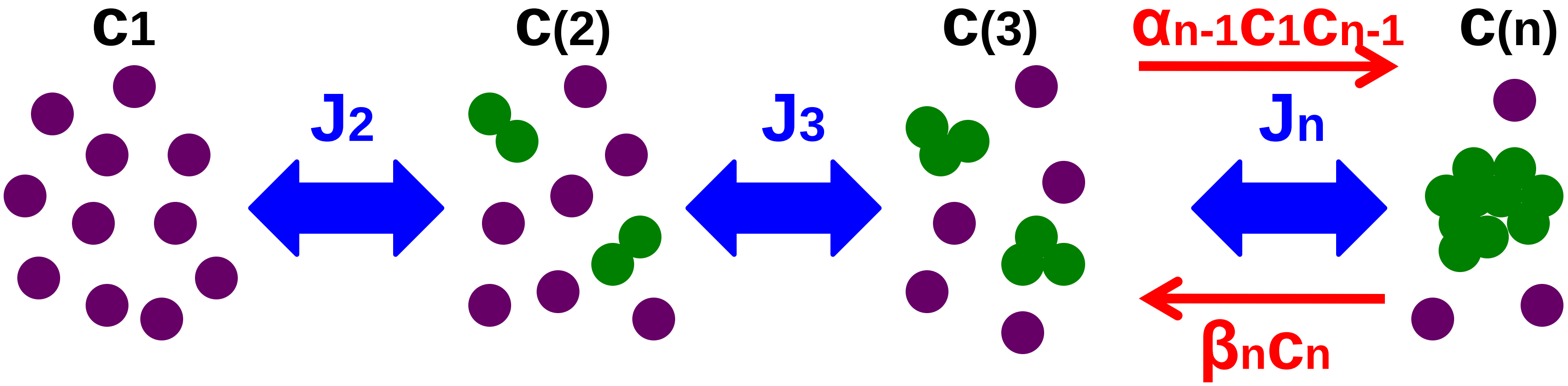
➔ $\ln S = \ln(P_1 / P^0_1) > 0$

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

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

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

$n_* = 100$

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

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

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

growth rate is independent of grain radius

2-4. Model of calculations for Al_2O_3 formation

○ Time evolution of gas density (free expansion)

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

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

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

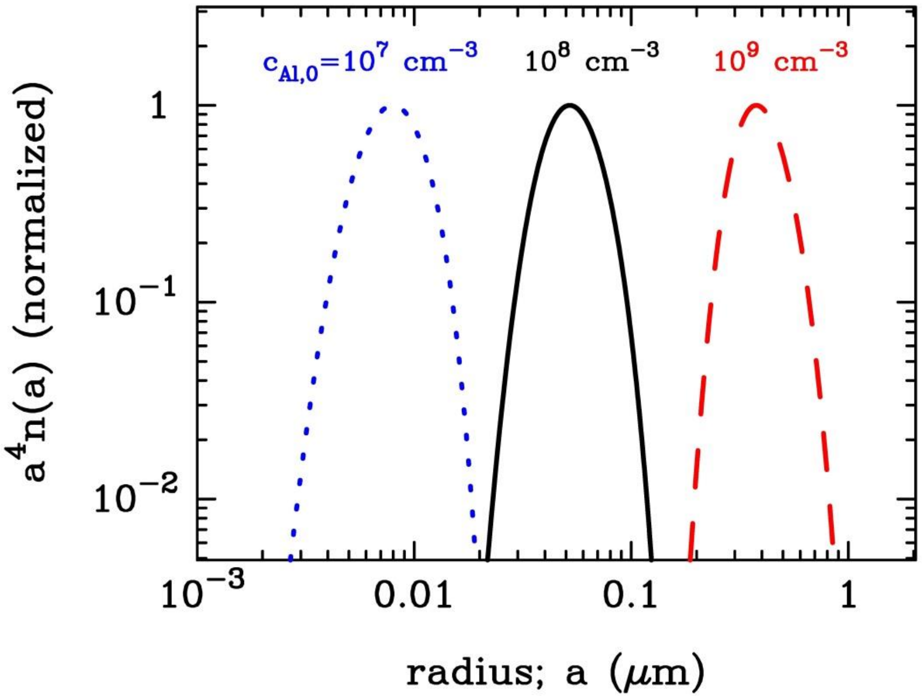
T_0 : gas temperature at t_0
γ: adiabatic constant

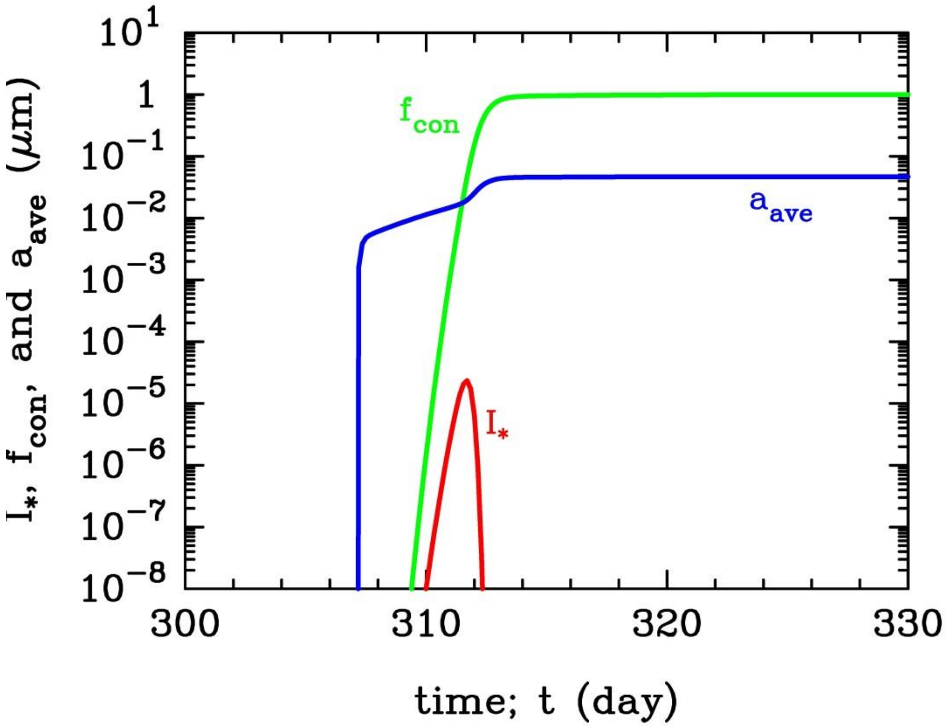
Parameters:

- 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, f_{con} :
a fraction of Al atoms that are locked up in dust grains

3-1. Size distribution of newly formed grains

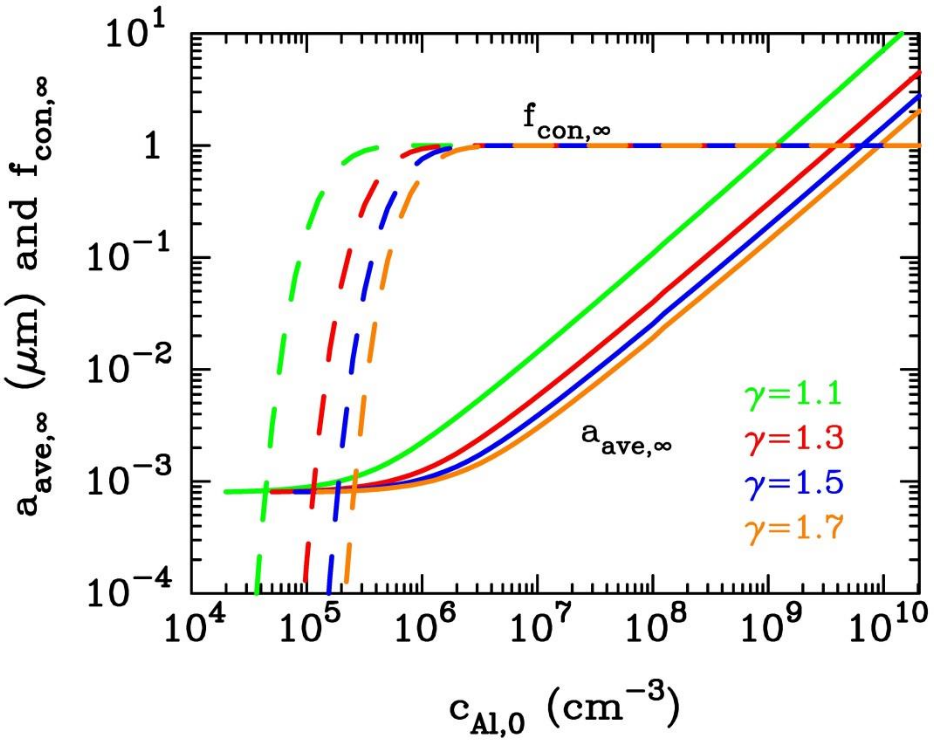


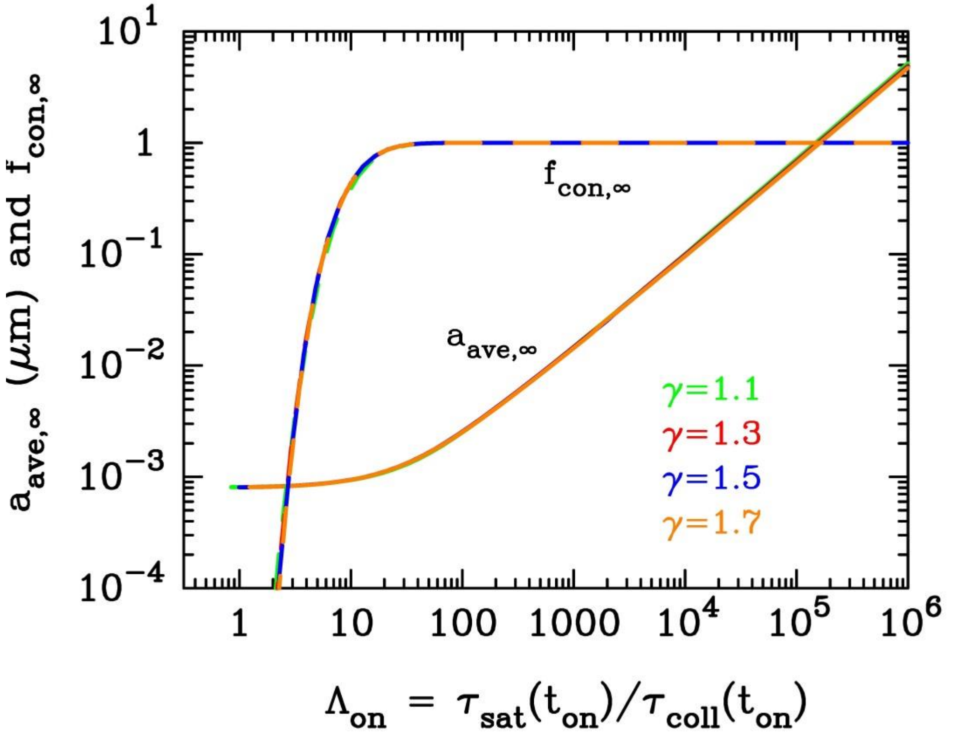


- **Size distribution of newly formed grains is lognormal-like with a narrower width for a higher gas density**
- **Average grain radius increases with increasing c_{Al,0}**
  ➜ a higher gas density leads to more efficient growth of grains

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 $f_{con,\infty}$ and $a_{ave,\infty}$





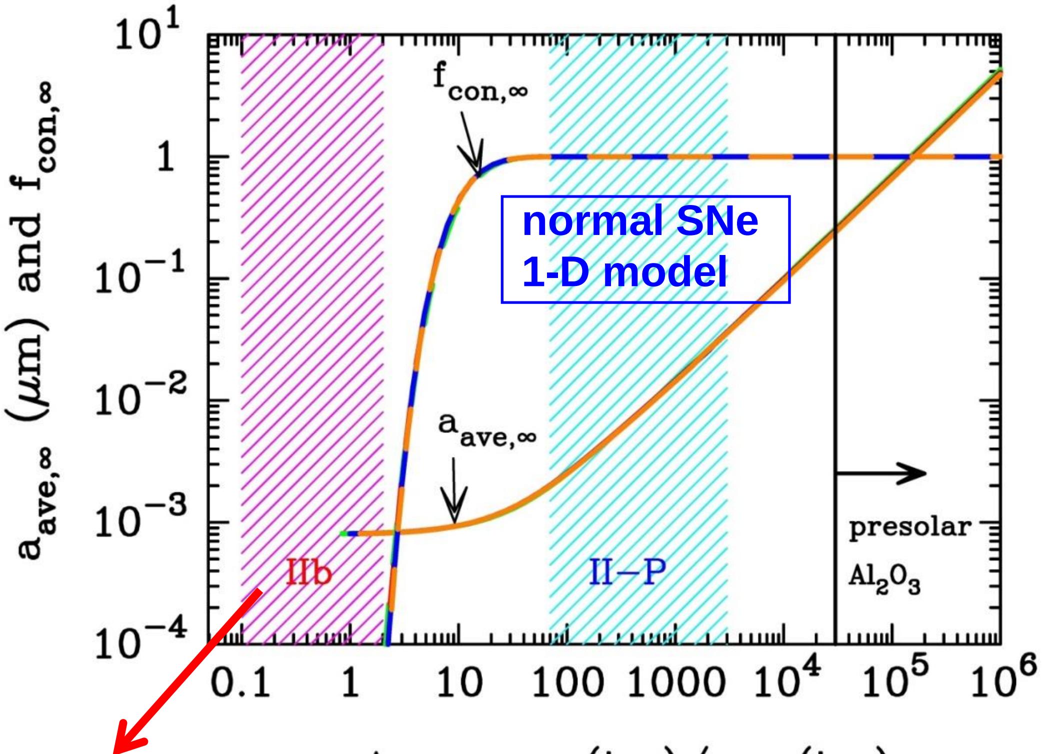
$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: ratio of supersaturation timescale to gas collision timescale at the onset time (t_{on}) of dust formation

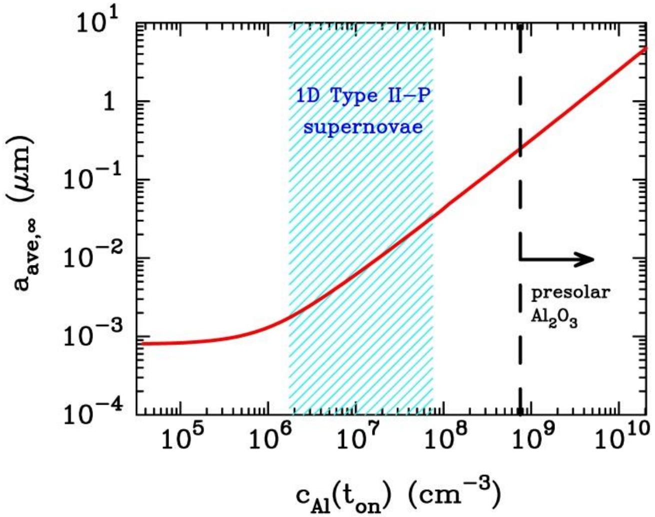
$\Lambda_{on} = \tau_{sat}/\tau_{coll} \propto \tau_{cool}\, n_{gas}$

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

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

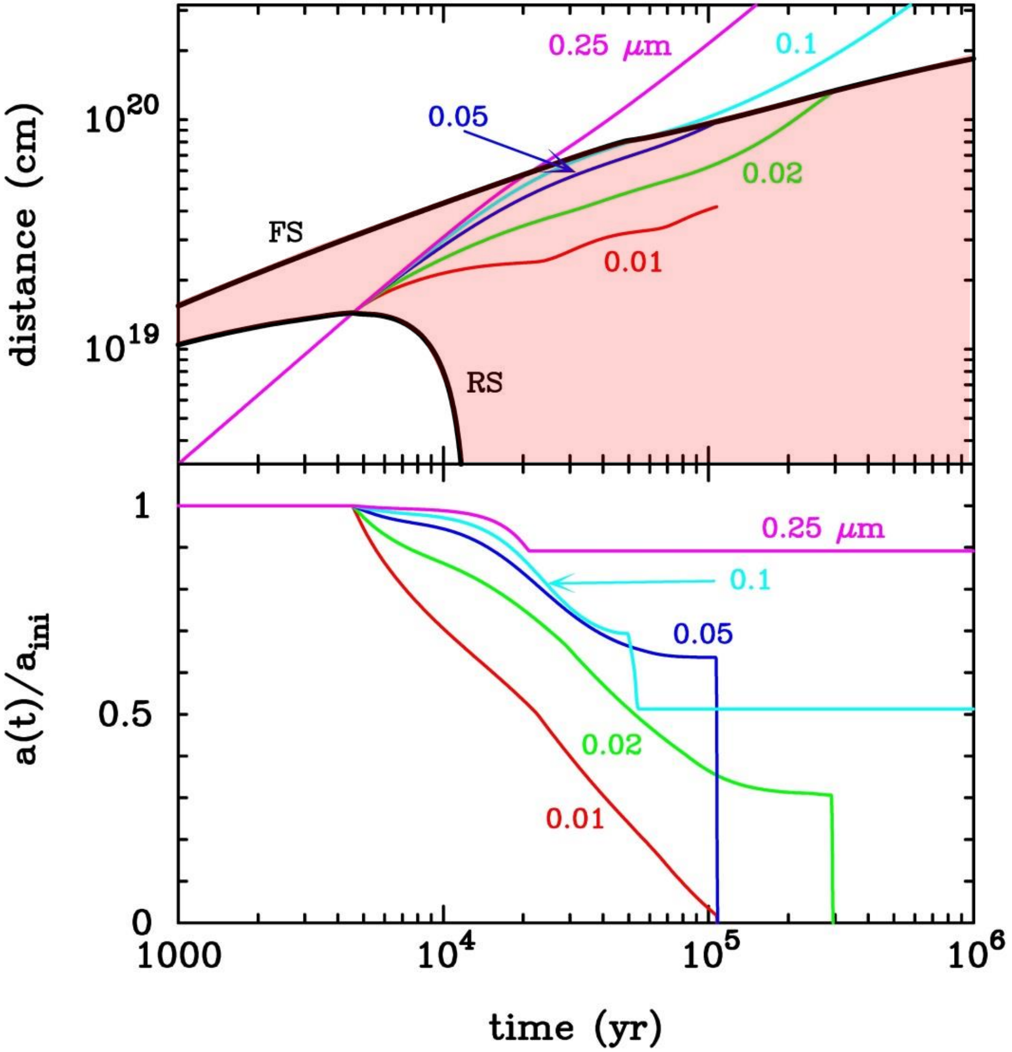
$$\Lambda_{on} \simeq \frac{1082}{\gamma - 1}\left(\frac{t_{on}}{300\ \text{days}}\right)\left[\frac{\tilde{c}_{Al}(t_{on})}{10^8\ \text{cm}^{-3}}\right]\left[\frac{T(t_{on})}{2000\ \text{K}}\right]^{\frac{3}{2}}.$$

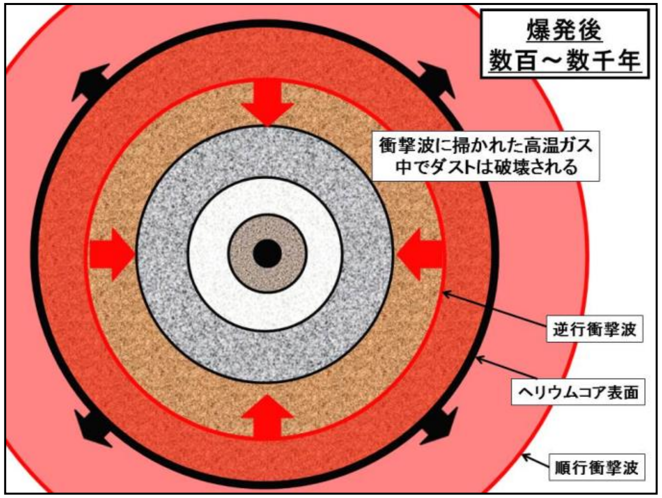
Submicron-sized presolar Al_2O_3 grains identified as SN-origin were formed in dense clumps in the ejecta

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.**