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超新星爆発時におけるダスト形成研究の現状

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0-1. Introduction

・SNe are important sources of interstellar dust?

- abundant metal (metal : N > 5)
- low temperature (T < ~2000 K)
- high density (n > ~10^6 cm^{-3})

➔

mass-loss winds of AGB stars

expanding ejecta of supernovae

- huge amounts of dust grains (>10^8 $M_{\rm sun}$) are detected in host galaxies of quasars at redshift z > 5

➔ 0.1 $M_{\rm sun}$ of dust per SN is needed to explain such massive dust at high-z (e.g. Dwek et al. 2007)

- contribution of dust mass from AGB stars and SNe

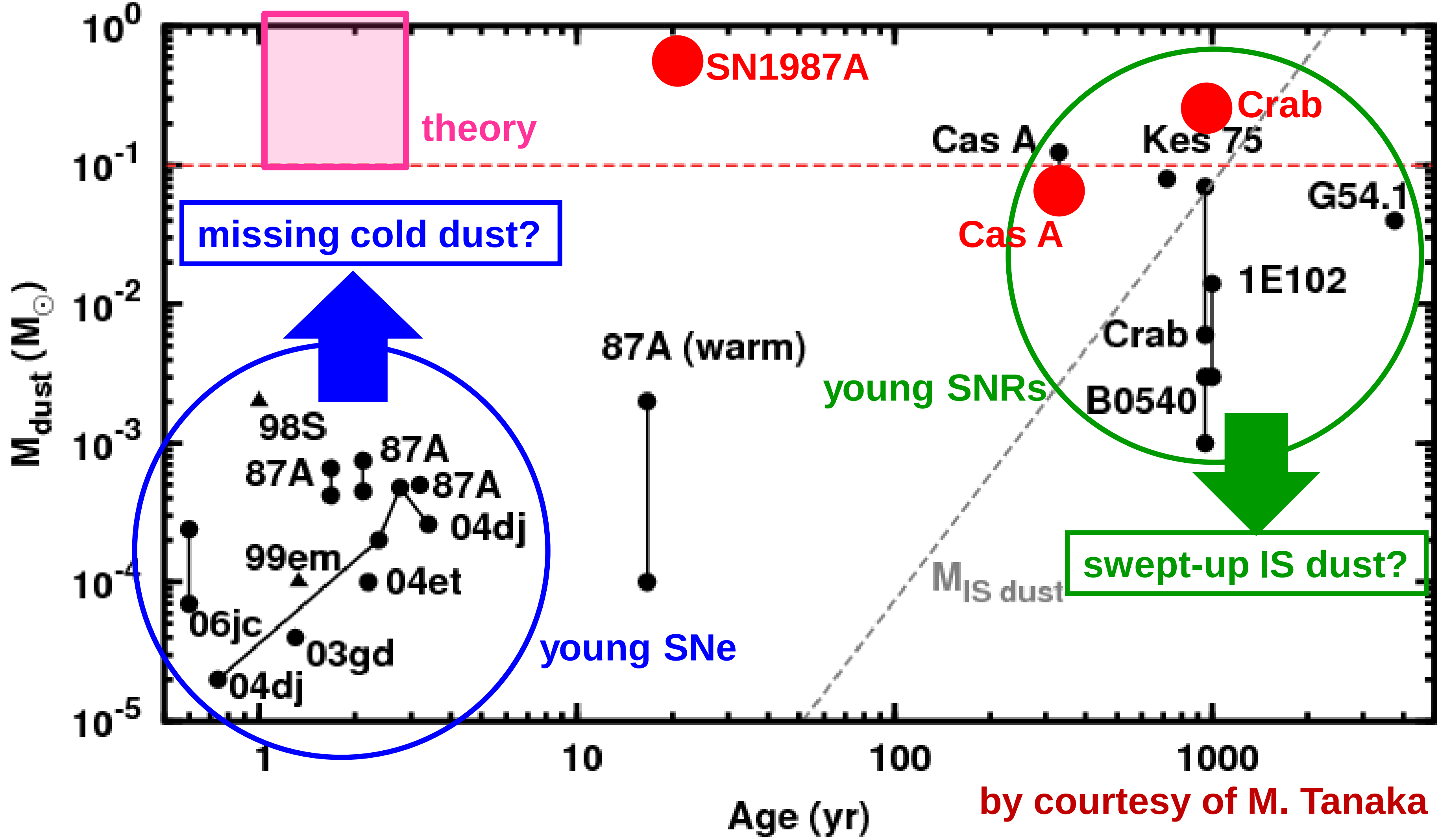
n(AGB stars) / n(SNe) ~ 10-20

$M_{\rm dust}$ = 0.01-0.05 $M_{\rm sun}$ per AGB (Zhukovska & Gail 2008)

$M_{\rm dust}$ = 0.1-1.0 $M_{\rm sun}$ per SN (e.g., Nozawa et al. 2003, 2007)

1. Observations of Dust Formation in SNe (and SNRs)

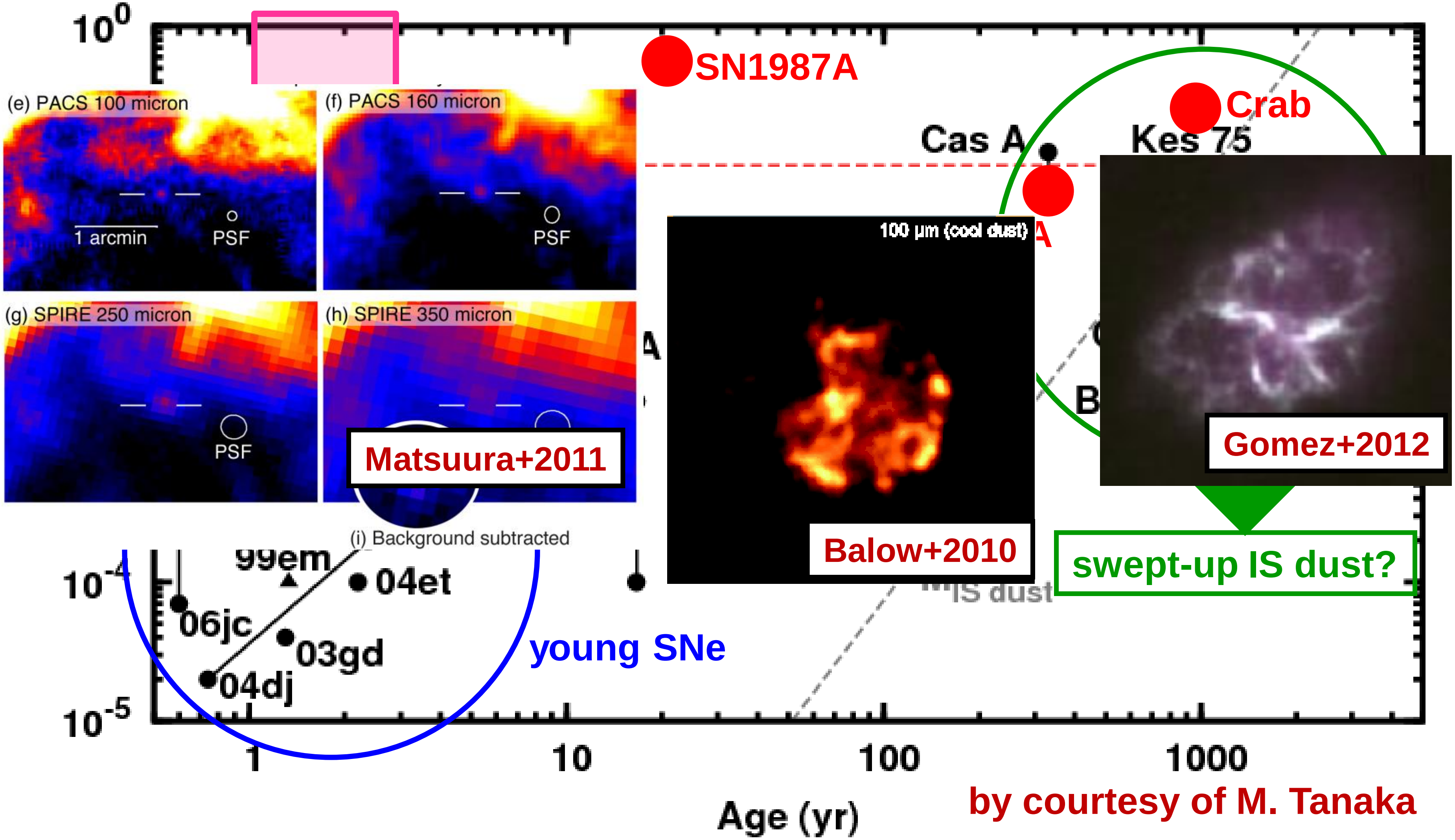
1-1. Summary of observed dust mass in CCSNe



by courtesy of M. Tanaka

Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe

1-1. Summary of observed dust mass in CCSNe



Matsuura+2011

Balow+2010

Gomez+2012

swept-up IS dust?

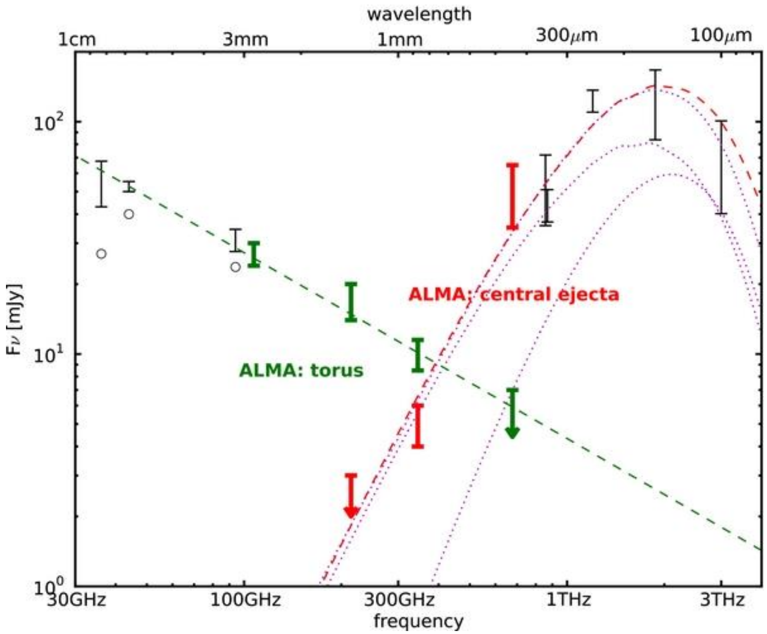
young SNe

by courtesy of M. Tanaka

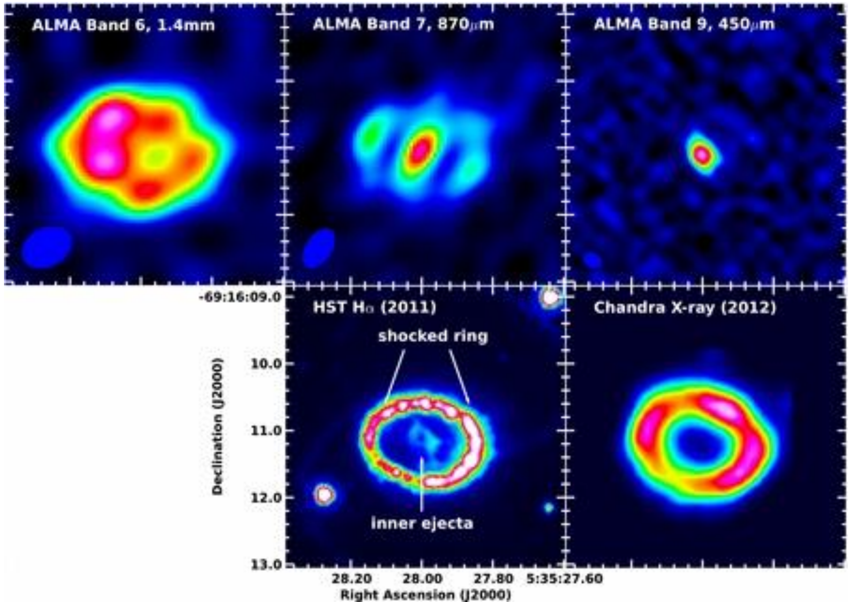
Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe

1-2. ALMA reveals dust formed in SN 1987A

SED of 25-years old SN 1987A



Indebetouw+2014

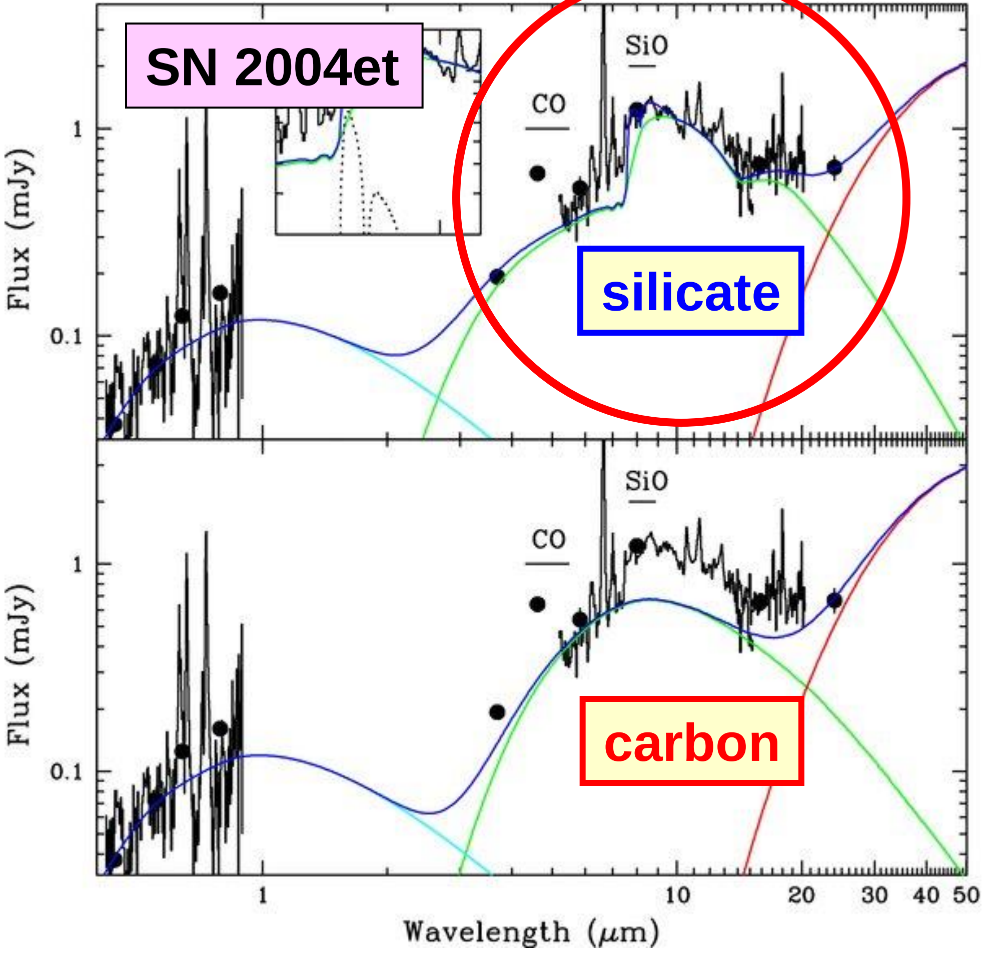


ALMA spatially resolves cool (~20K) dust of ~0.5 Msun formed in the ejecta of SN 1987A

➔ SNe could be production factories of dust grains

1-3. Composition of dust formed in SNe

IS dust : carbonaceous grain and
silicate (MgSiO3, MgFeSiO4, …)

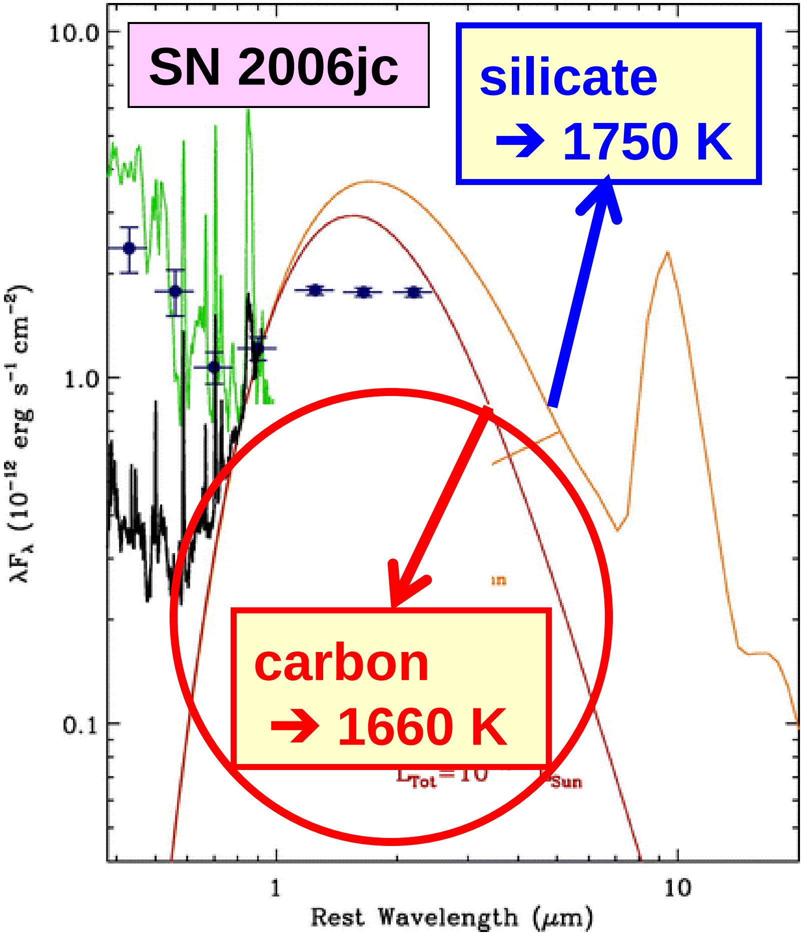


SN 2004et

silicate

carbon

SN 2004et (Kotak+09)



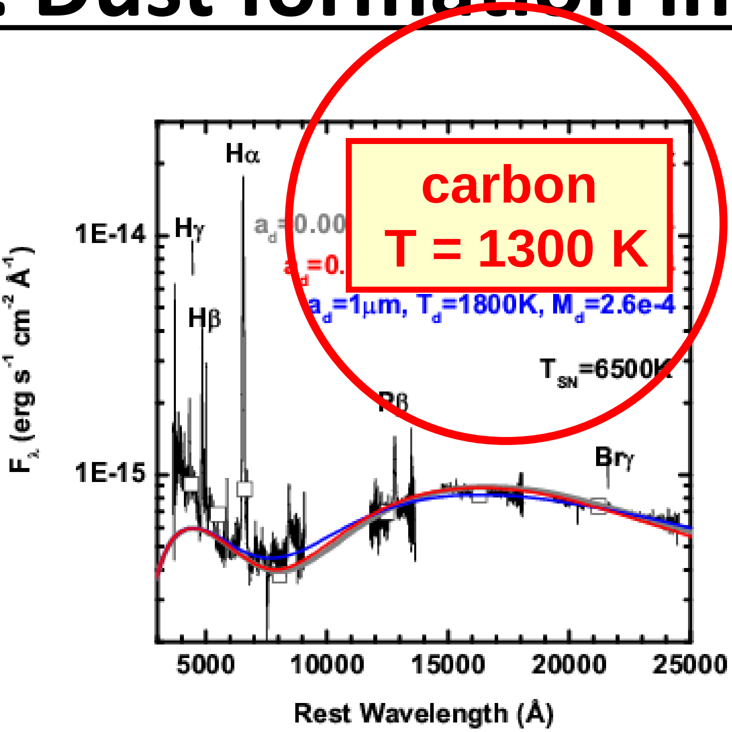
SN 2006jc

silicate
➔ 1750 K

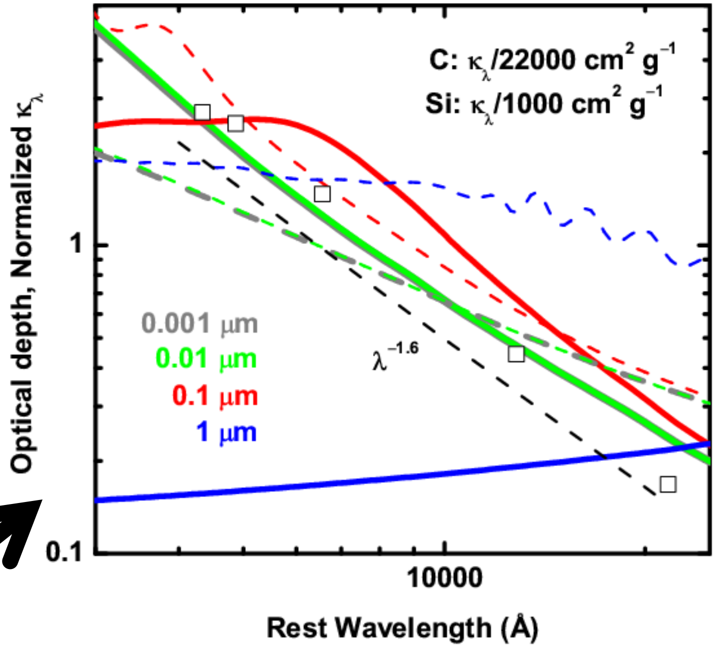
carbon
➔ 1660 K

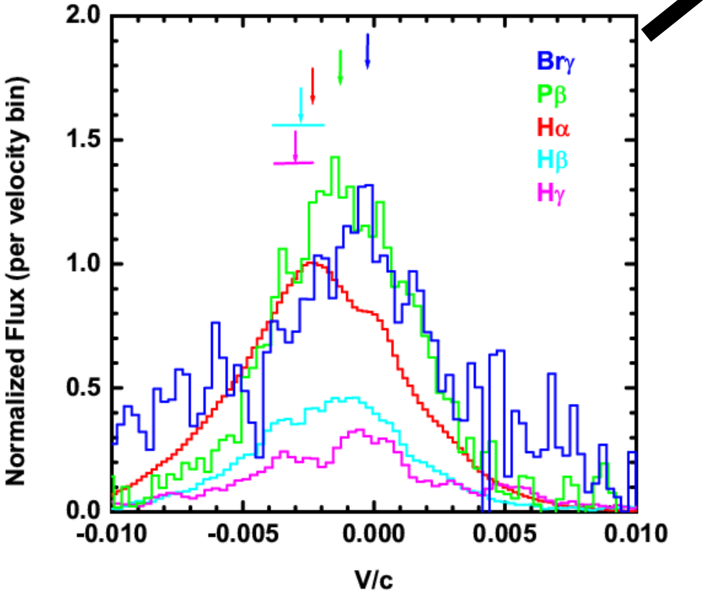
SN 2006jc (Smith+08)

1-4. Dust formation in Type IIn SN 2010jl



carbon
T = 1300 K





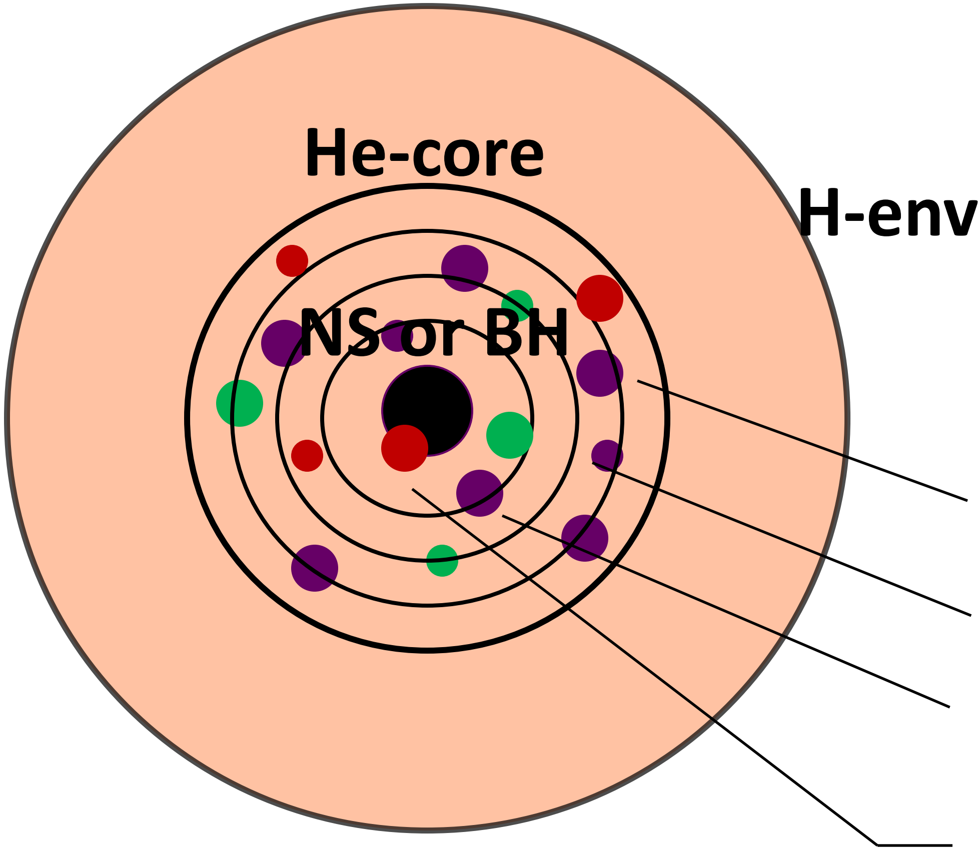
Dust in SN 2010jl

- carbon grains
- grain radius: <0.1μm
  (possibly <0.01 μm)
- dust mass: ~10^{-3} Msun

Maeda, TN, et al. 2013

2. Dust Formation in the ejecta of SNe

at ~1 days



He-core

H-envelope

NS or BH

He–layer (C>O)

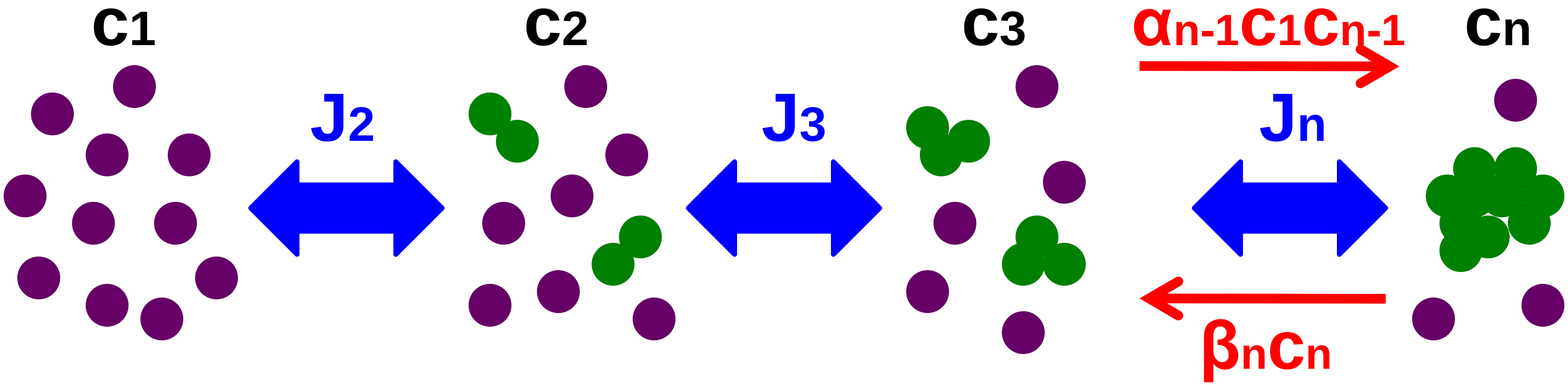
O–Ne-Mg layer

Si–S layer

Fe–Ni layer

Dust formation
at ~1-3 years
after explosion

2-1. Formulation of dust formation



・ master equations

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

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

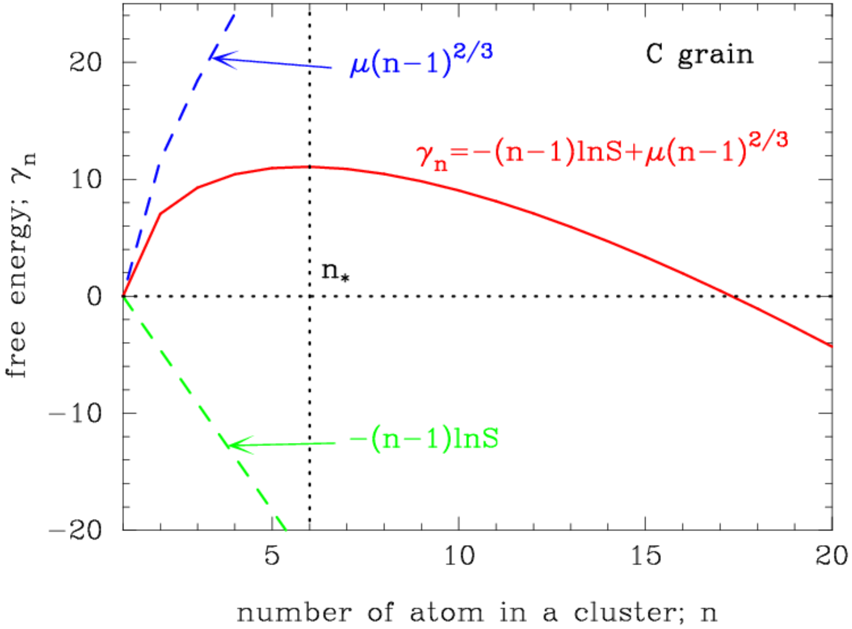
$$\alpha_n = \frac{s_n}{1+\delta_{1n}} \, 4\pi a_0^2 \, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n} \right)^{\frac{1}{2}},$$

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

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. Basic equations for dust formation

- **Equation of mass conservation**

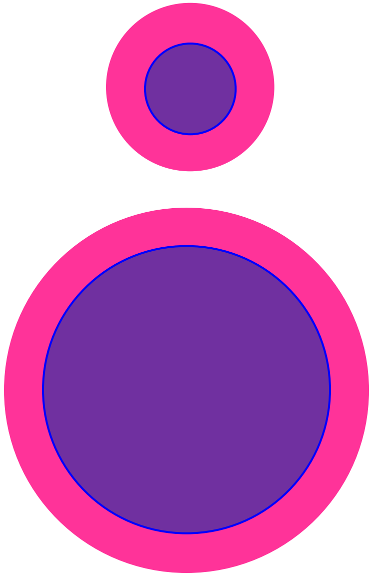
$$c_{10} - c_1 = \int_{t_0}^{t} J_{n_*}(t') \frac{a^3(t,t')}{a_0^3} dt',$$

- **Equation of grain growth**

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

$$\Uparrow$$

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



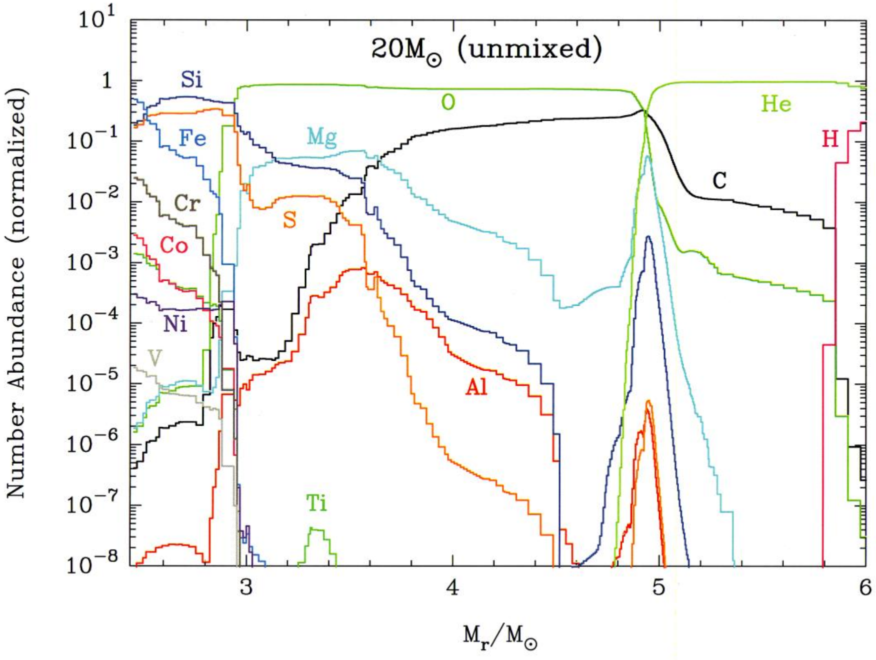
Growth rate is independent of grain radius

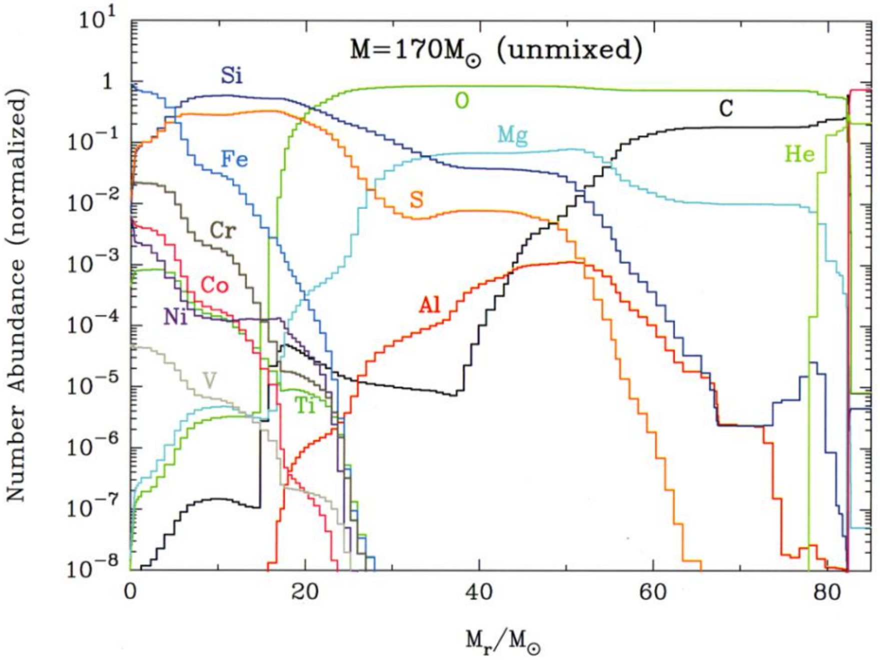
2-4. Dust formation in primordial SNe

Nozawa+2003, ApJ, 598, 785

○ Population III SNe model (Umeda & Nomoto 2002)

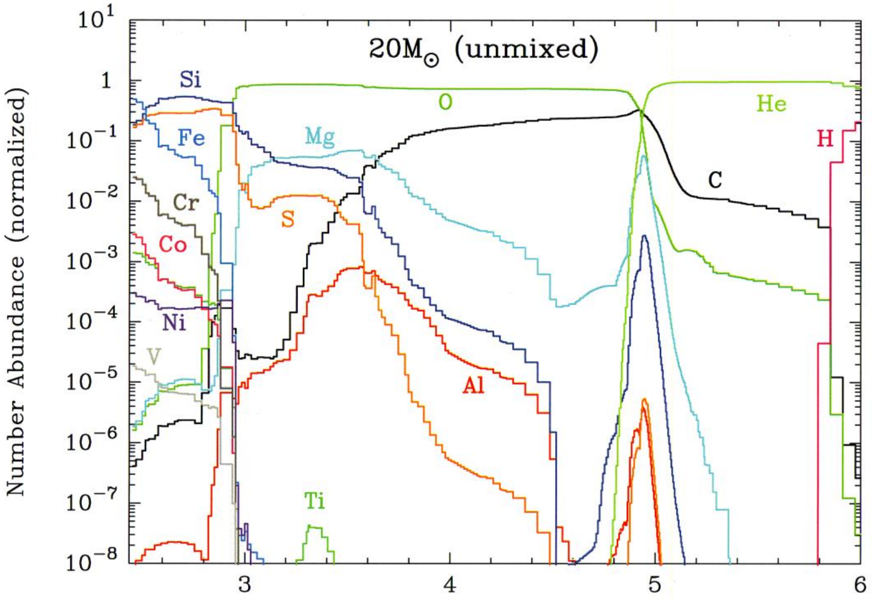
- **SNe II : M_{ZAMS} = 13, 20, 25, 30 M_{sun} (E_{51}=1)**
- **PISNe : M_{ZAMS} = 170 M_{sun} (E_{51}=20), 200 M_{sun} (E_{51}=28)**

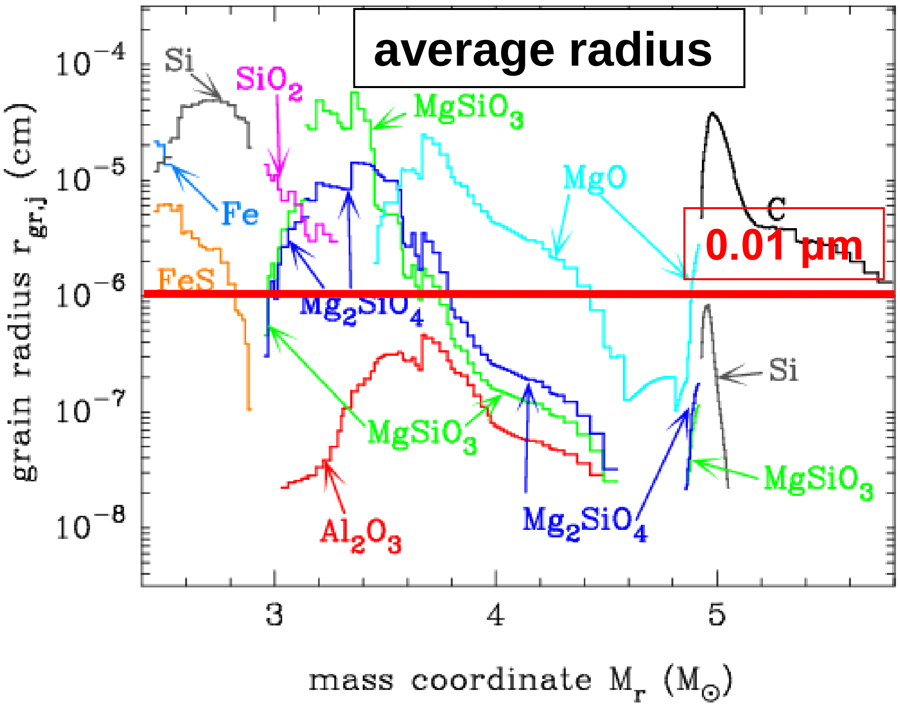


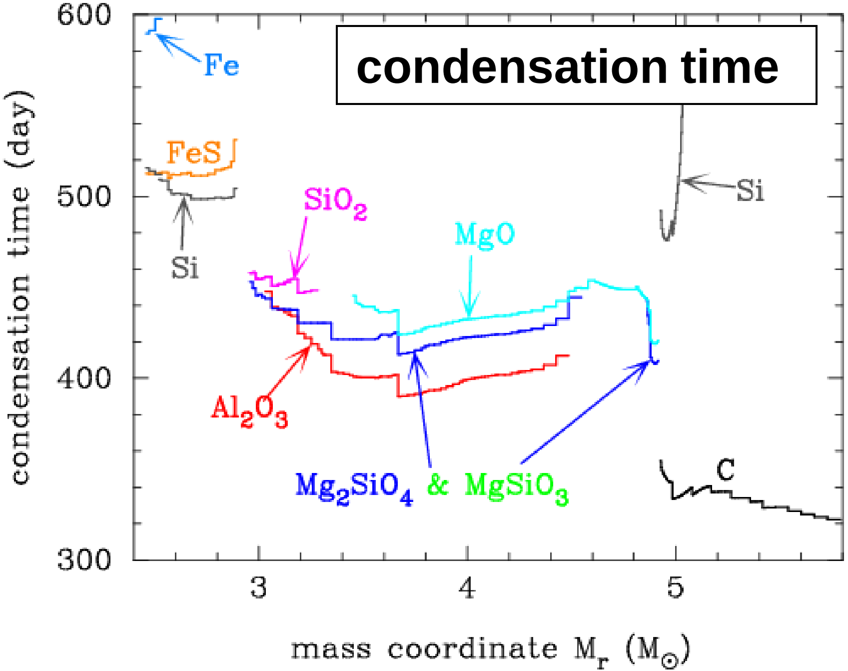


- **nucleation and grain growth theory (Kozasa & Hasegawa 1987)**
- **no mixing of elements within the He-core**
- **complete formation of CO and SiO**

2-5. Dust formed in Type II-P SNe





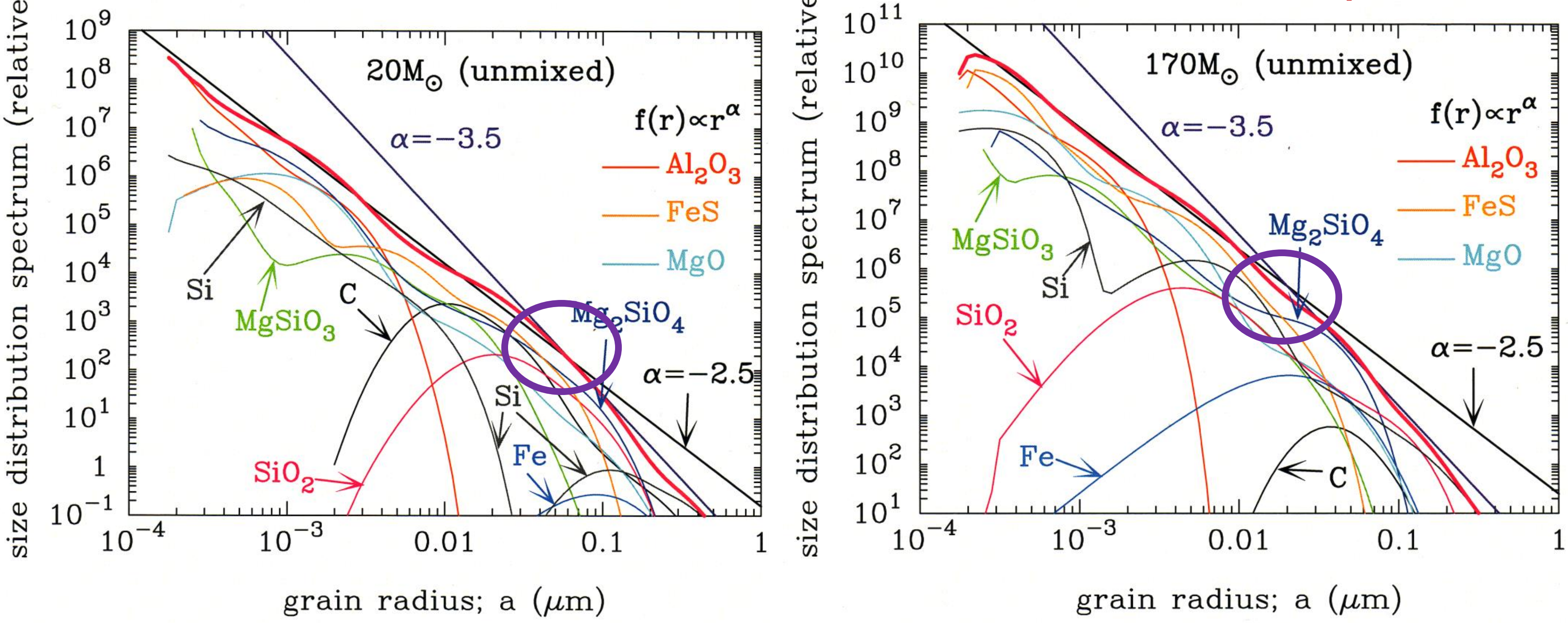


- **a variety of grain species can condense according to elemental composition in each layer**
- **condensation time: 300-600d after explosion**
- **average grain radii: >~0.01 μm**

Nozawa+03, ApJ, 598, 785

2-6. Size distribution of newly formed dust

Nozawa+2003, ApJ, 598, 785

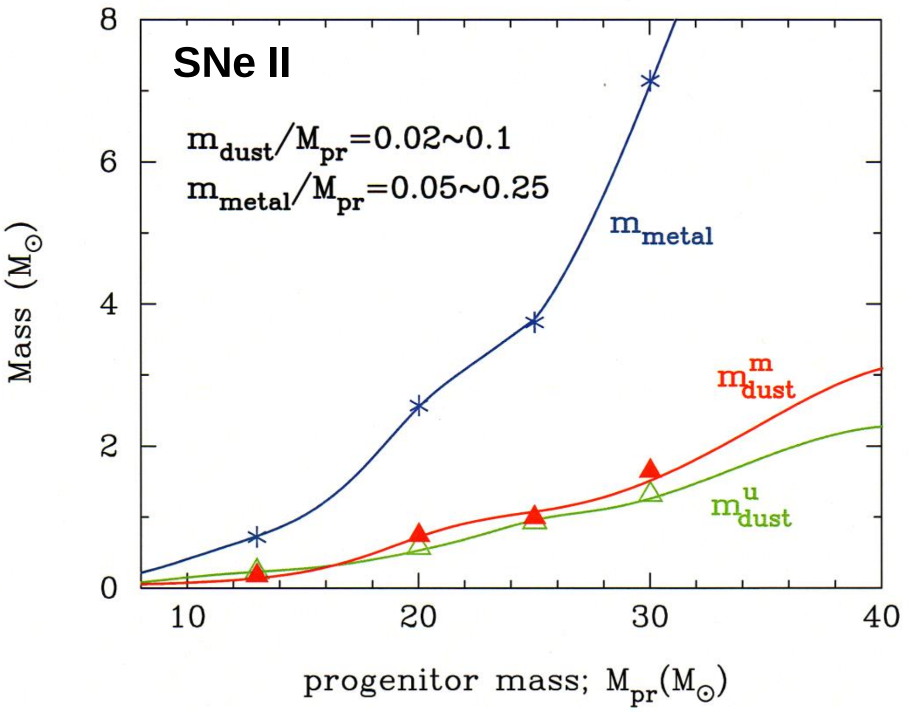


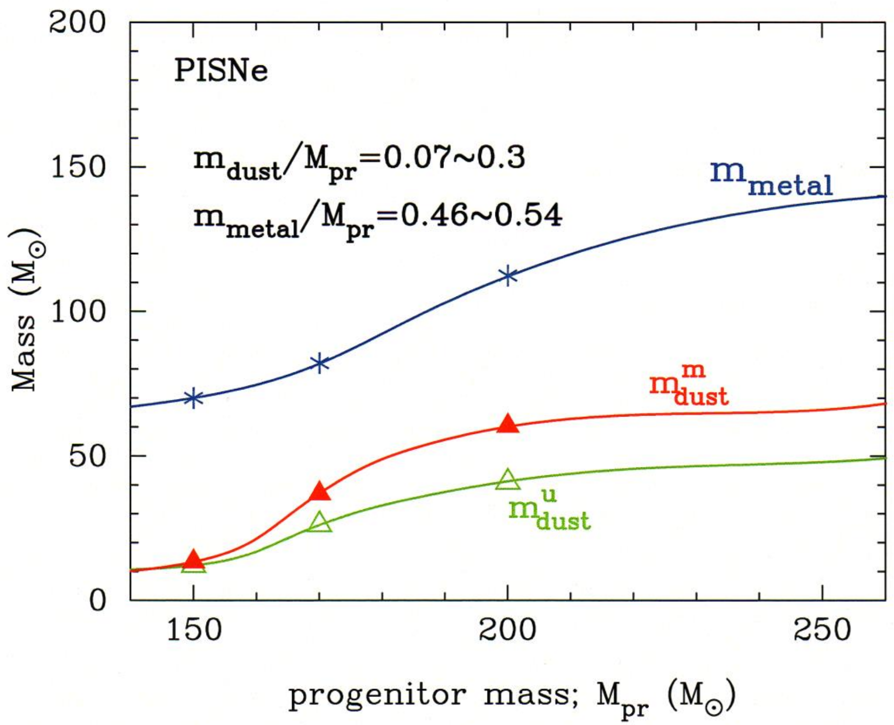
- C, SiO2, and Fe grains have lognormal-like size distribution, while the other grains have power-law size distribution

- The composition and size distribution of dust formed are almost independent of types of supernova

average grain radius is smaller for PISNe than SNe II-P

2-7. Total mass of dust formed in the ejecta



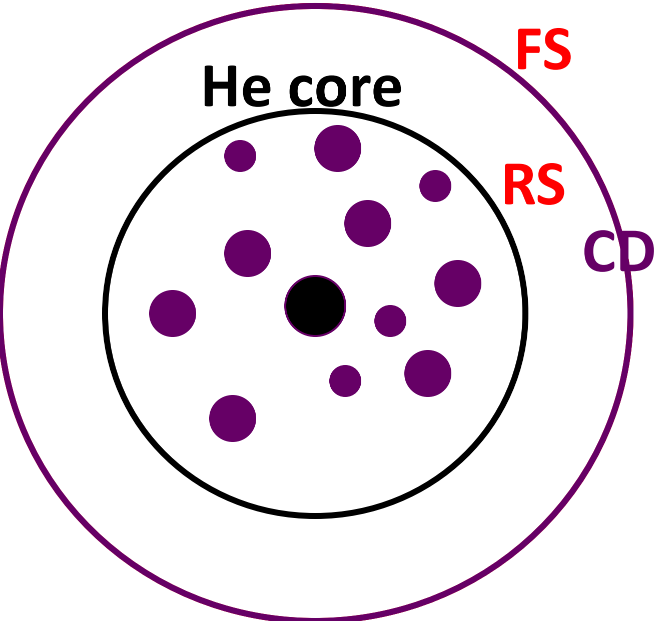


- Total mass of dust is higher for a higher progenitor mass (M_{ZAMS})
  SNe II : m_{dust} = 0.1-1.5 M_{sun}, m_{dust} / m_{metal} = 0.2-0.3
  PISNe : m_{dust} = 10-30 M_{sun}, m_{dust} / m_{metal} = 0.3-0.4

- almost all Fe, Mg, and Si are locked up in dust grains, while most of C and O remain in the gas-phase (such as CO)
  ➔ dust-to-metal mass ratio is not high for SNe II

3. Evolution of dust in SN remnants

$T = (1\text{-}2)\times 10^4$ K
$n_{H,0} = 0.1\text{-}1\ \mathrm{cm^{-3}}$



3-1. Time evolution of SNRs

- Basic equations (spherical symmetry)

$$\frac{\partial \rho}{dt} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v) = 0$$

$$\frac{\partial}{dt}(\rho v) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v^2) = -\frac{\partial P}{\partial r}$$

$$\frac{\partial}{dt}\left(\frac{\rho v^2}{2} + \frac{P}{\gamma - 1}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left[\frac{\rho v^2}{2} + \frac{\gamma P}{\gamma - 1}\right] v\right)$$
$$= -(n_{\rm e} n_{\rm H} \Lambda_{\rm gas}(T) + \Lambda_{\rm ic}(T) + \Lambda_{\rm d}(n_{\rm H}, T))$$

$\Lambda_{\rm gas}(T)$: cooling function of gas by the atomic process
(Sutherland & Dopita 1993; Smith et al. 2001)

$\Lambda_{\rm ic}(T)$: inverse Compton cooling (Ikeuchi & Ostriker 1986)

$\Lambda_{\rm ic}(T) = 5.41 \times 10^{-32} (1+z)^4 n_e (T/10^4\ {\rm K})$ (we adopt $z = 20$)

$\Lambda_{\rm d}(n_{\rm H}, T)$: cooling of gas through thermal emission of dust

· numerical code : flux splitting method (van Albada et al. 1982)

3-2. Dynamics of dust

- deceleration of dust due to drag force (Baines et al. 1965)

$$\frac{dw_{\rm d}}{dt} = \frac{F_{\rm drag}}{m_{\rm d}} = -\frac{3n_{\rm H}kT}{2a\rho_{\rm d}} \sum_i A_i G_i(s_i) \quad (w_{\rm d} \text{ : relative velocity})$$

$\rho_{\rm d}$; mass density of a grain

A_i ; the number abundance of gas species i normarized by $n_{\rm H}$

$$G_i(s_i) = \left(s_i^2 + 1 - \frac{1}{4s_i^2}\right) erf(s_i) + \left(s_i + \frac{1}{2s_i}\right) \frac{e^{-s_i^2}}{\sqrt{\pi}}$$

$$\Downarrow$$

$$G_i(s_i) \approx \frac{8s_i}{3\sqrt{\pi}} \left(1 + \frac{9\pi}{64} s_i^2\right)^{\frac{1}{2}} \quad \text{(Draine \& Salpeter 1979)}$$

where $s_i^2 = m_i w_{\rm d}^2 / 2kT$

3-3. Erosion rate of dust by sputtering

- dust destruction by sputtering (e.g., Dwek, Foster & Vancura 1996)

$$\frac{da}{dt} = -\frac{m_{\rm sp}}{4\pi a^2 \rho_{\rm d}} \sum_i \mathcal{R}(Y_i(E))$$

$Y_i(E) = 2Y_i^0(E)$; the angle-averaged sputtering yield

$m_{\rm sp}$; average mass of the sputtered atoms

· rate equation over a modified Maxwellian distribution of gas taken account of relative velocity of dust to gas (e.g., Shull 1978)

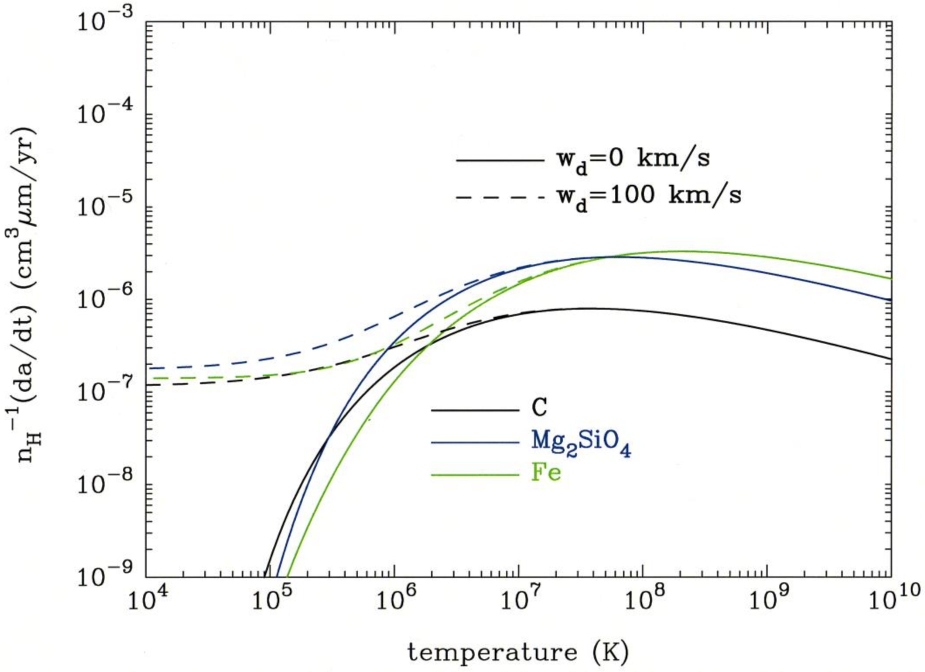
$$\mathcal{R}(X_i(\epsilon)) = n_{\rm H} A_i \pi a^2 \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} \frac{e^{-s_i^2}}{2s_i} \int \sqrt{\epsilon} e^{-\epsilon} \sinh(2s_i\sqrt{\epsilon}) X_i(\epsilon) d\epsilon$$

where $\epsilon = E/kT$

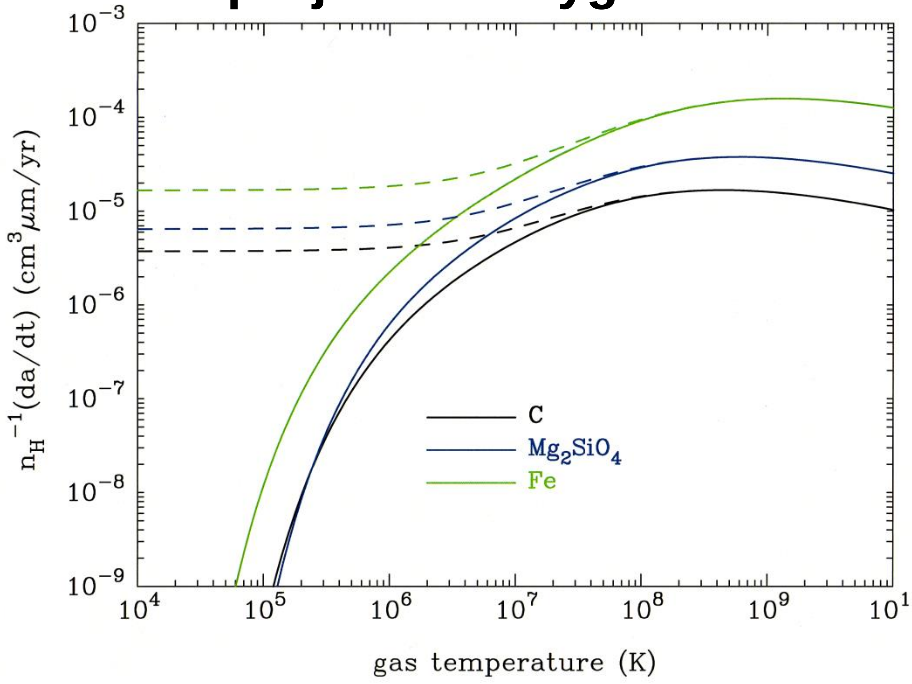
3-4. Erosion rate of dust by sputtering

Nozawa+2006, ApJ, 648, 435

projectile: H and He



projectile: oxygen ions

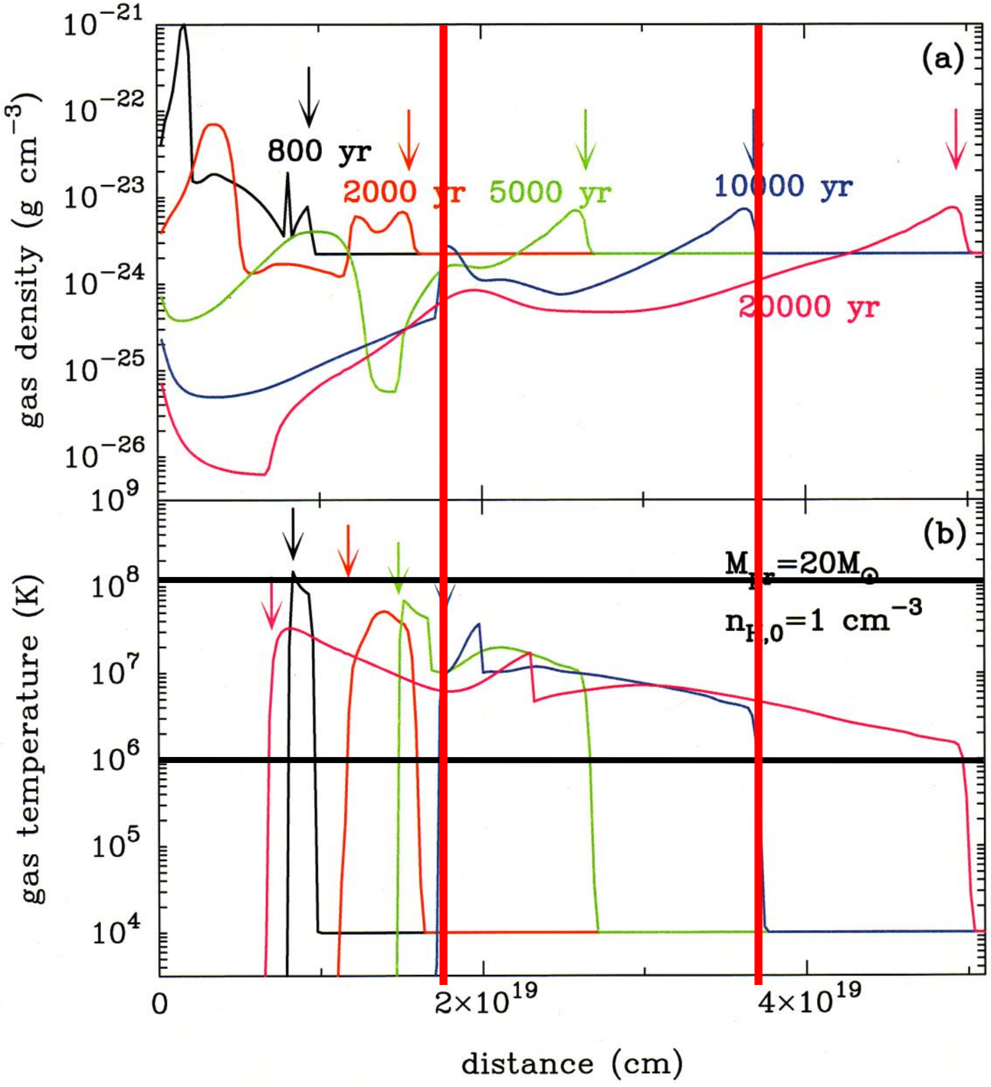


- erosion rate by sputtering quickly increases above 10^5 K and peaks at 10^7 -10^8 K

- erosion rate : $da / dt \sim 10^{-6}\, n_H$ $\mu m\ yr^{-1}\ cm^3$
  for the primordial gas (H and He) at $T > 10^6$ K

3-5. Temperature and density of gas in SNRs

Nozawa+07, ApJ, 666, 955



Model : M_{pr}= 20 Msun (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

Downward-pointing arrows:
forward shock in upper panel
reverse shock in lower panel

The temperature of the gas swept up by the shocks

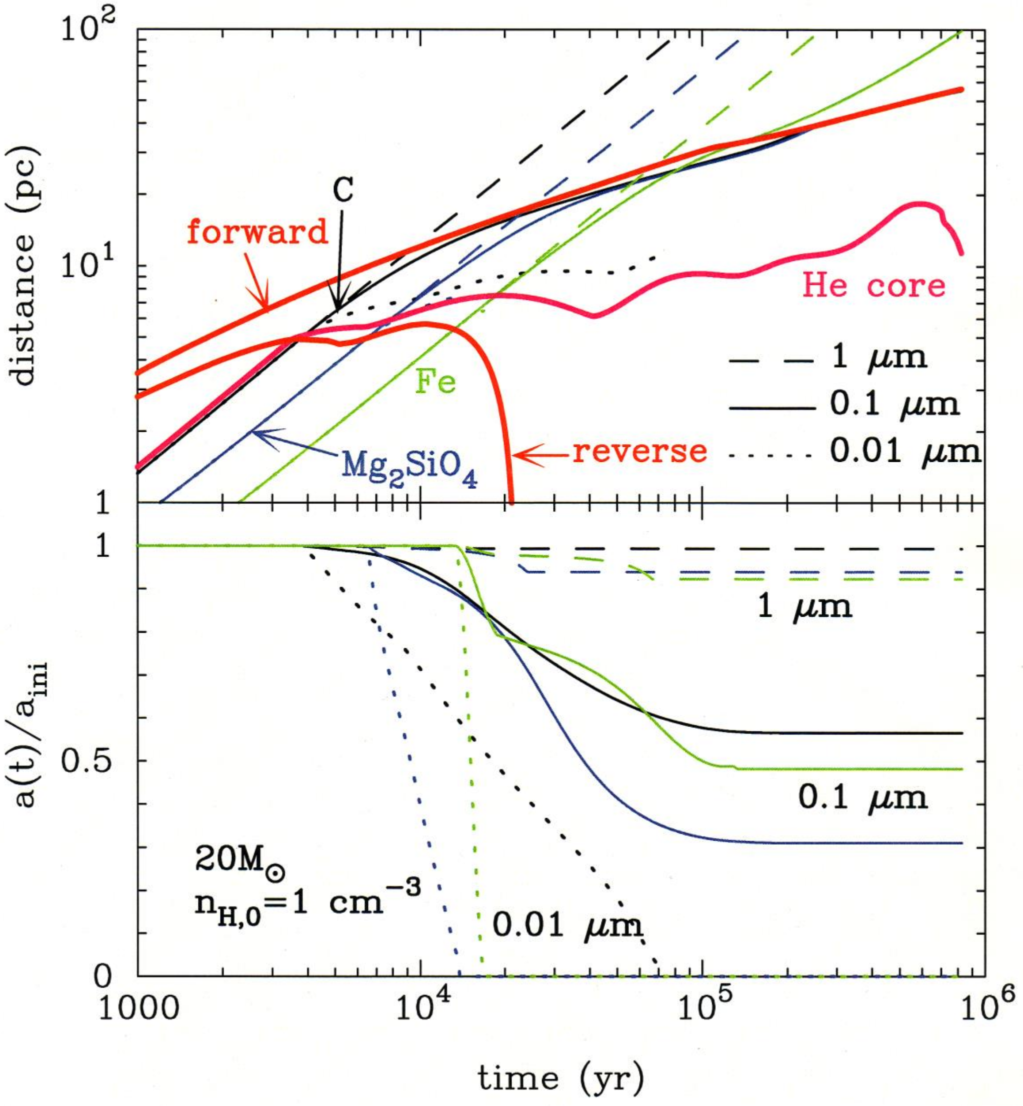
➔ 10^6-10^8 K

↓

Dust grains residing in the shocked hot gas are eroded by sputtering

3-6. Evolution of dust in SNRs

Nozawa+07, ApJ, 666, 955



Model : M_{pr}= 20 Msun (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

The evolution of dust heavily depends on the initial radius and composition

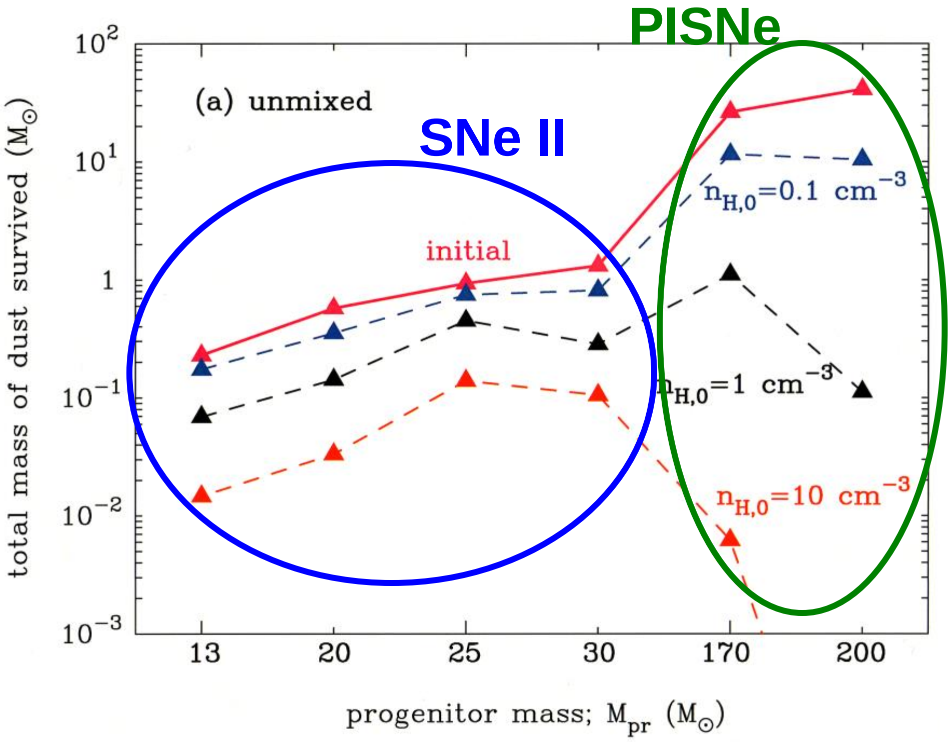
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed

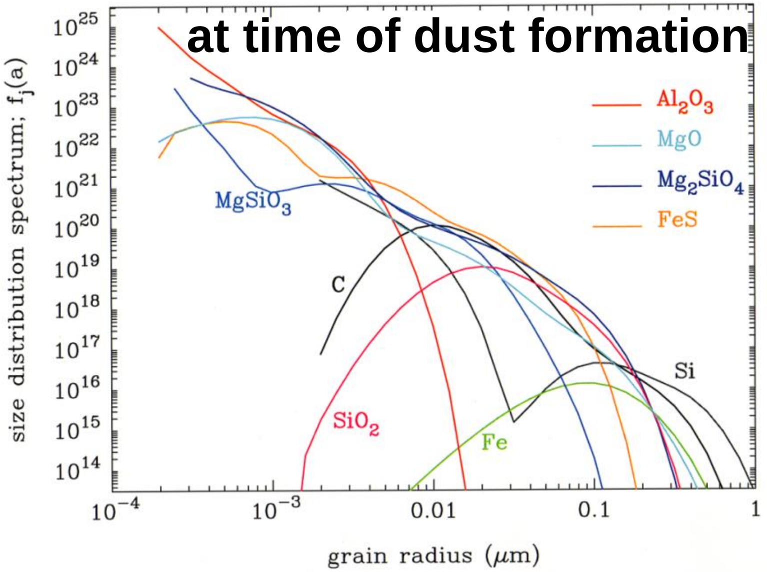
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell

a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

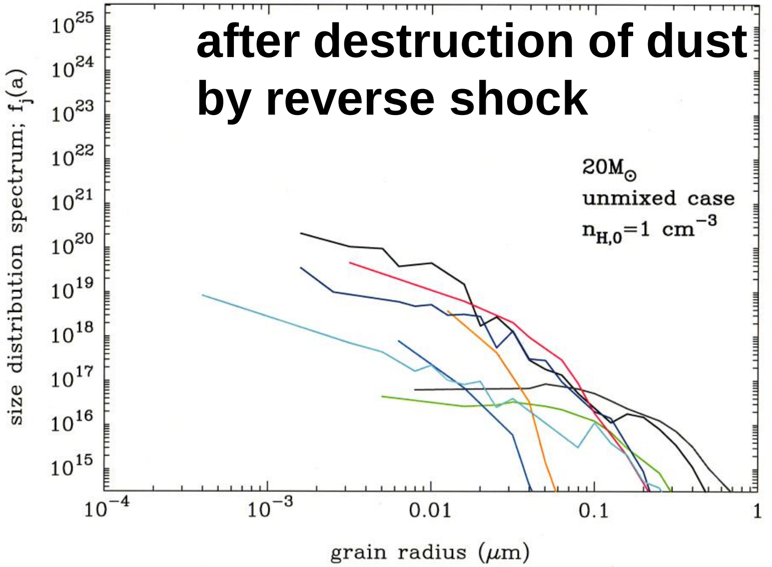
3-7. Dust mass and size ejected from SN II-P

Nozawa+07, ApJ, 666, 955





at time of dust formation



after destruction of dust by reverse shock

total mass of dust surviving the destruction in Type II SNRs;
0.07-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

size distribution of dust after the shock-destruction is domimated by large grains (> 0.01 μm)

3-8. Summary of dust production in Pop III SNe

- Various grain species can condense in the ejecta
  ➔ almost all Fe, Mg, and Si are locked up in grains

- The fate of newly formed dust within SNRs strongly depends on the initial radii and compositions

- The size distribution of dust surviving the destruction in SNRs is weighted to relatively large size (> 0.01 μm).

- The total mass of dust injected into the ISM decreases with increasing the ambient gas density

  for $n_{H,0}$ = 0.1-1 cm^{-3}

  SNe II-P ➔ M_{dust} = 0.1-0.8 M_{sun}

  ➔ significant contribution to dust budget at high z