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超新星爆発時におけるダストの凝縮・放出過程

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1-1. 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_{sun}) are detected in host galaxies of quasars at redshift z > 5

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

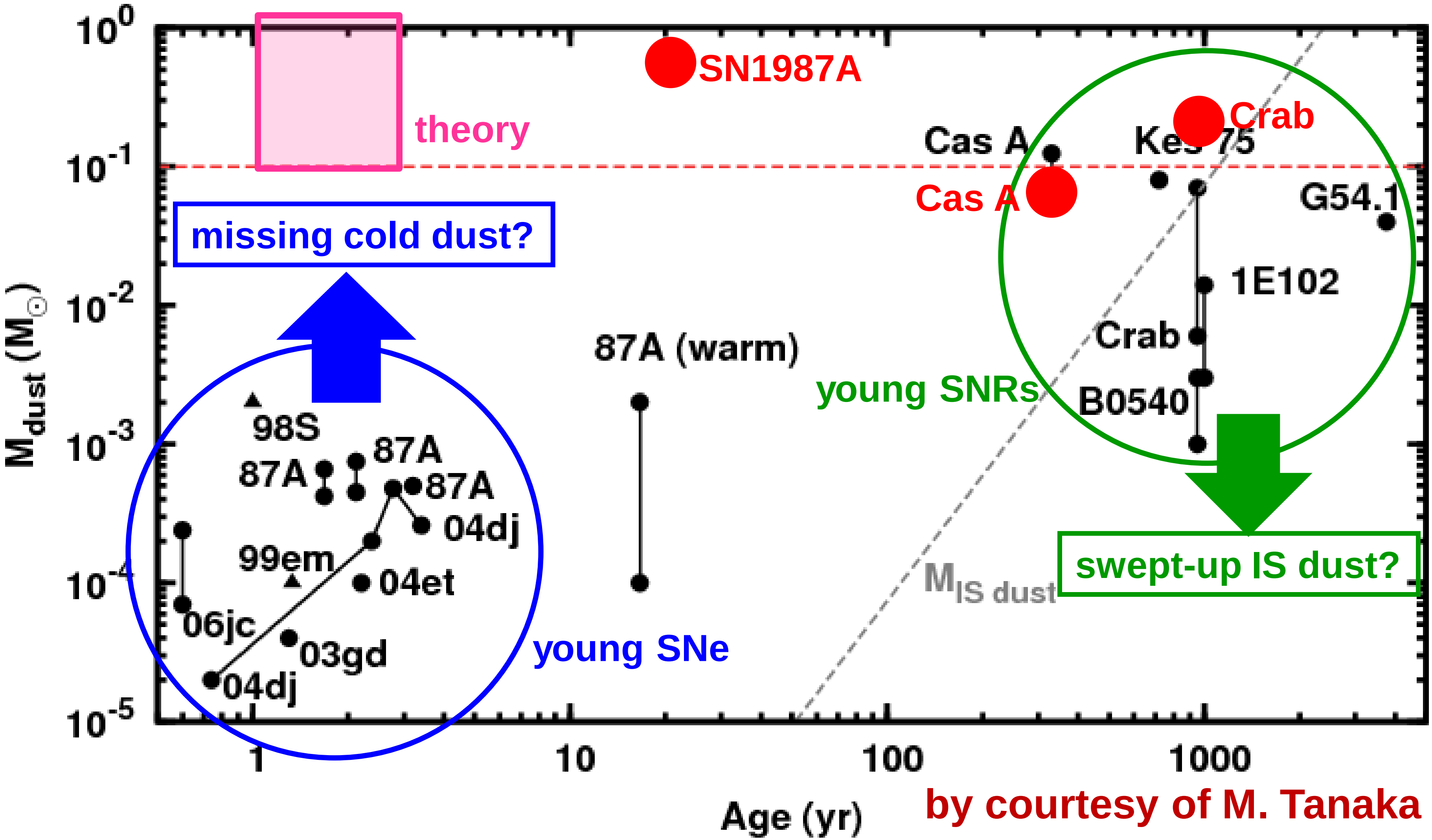
— contribution of dust mass from AGB stars and SNe

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

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

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

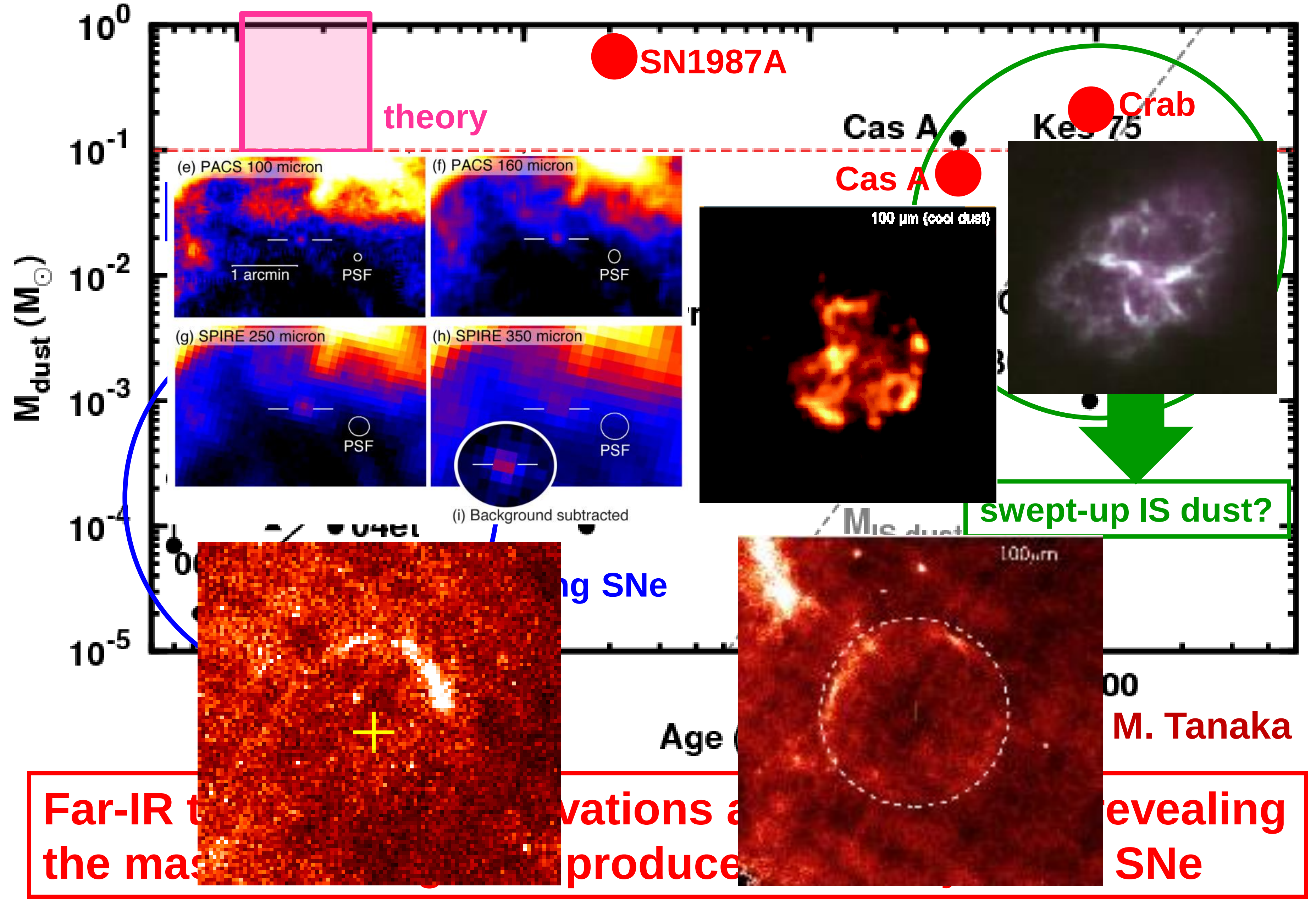
1-2. Summary of observed dust mass in CCSNe



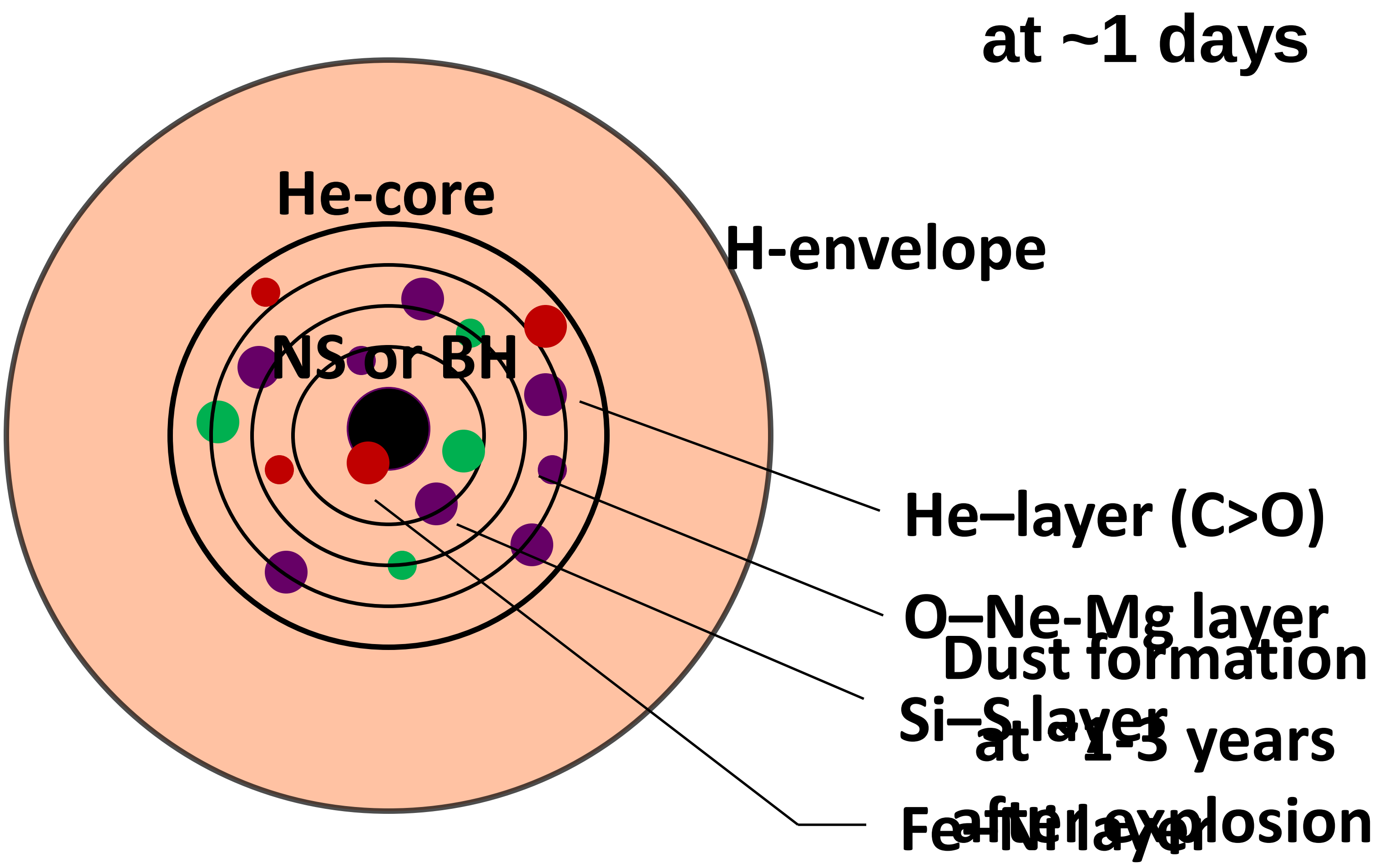
by courtesy of M. Tanaka

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

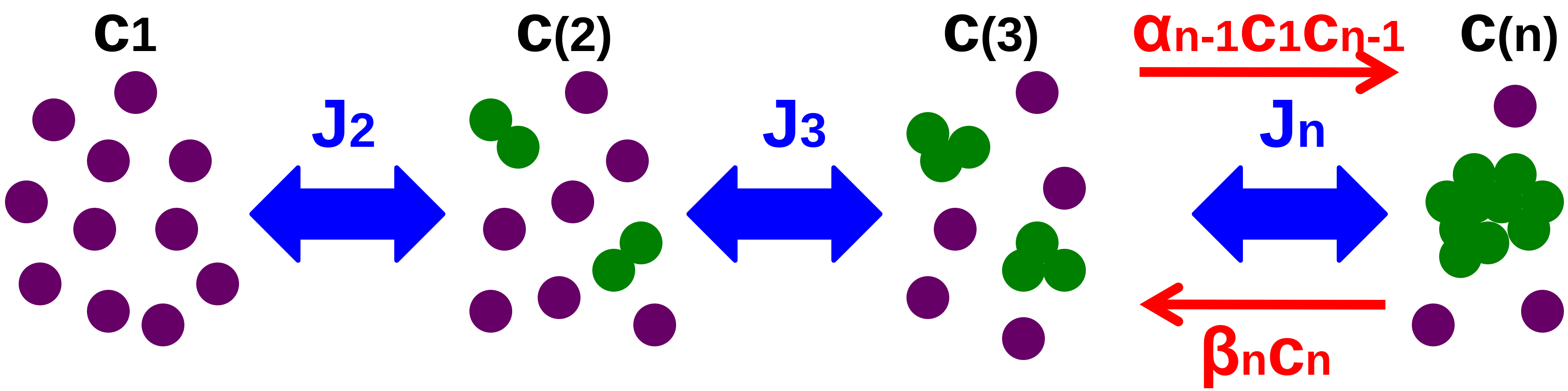
1-2. Summary of observed dust mass in CCSNe



2. Dust Formation in the ejecta of SNe



2-1. Concept of nucleation theory



・ master equations

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

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

Sn = 1

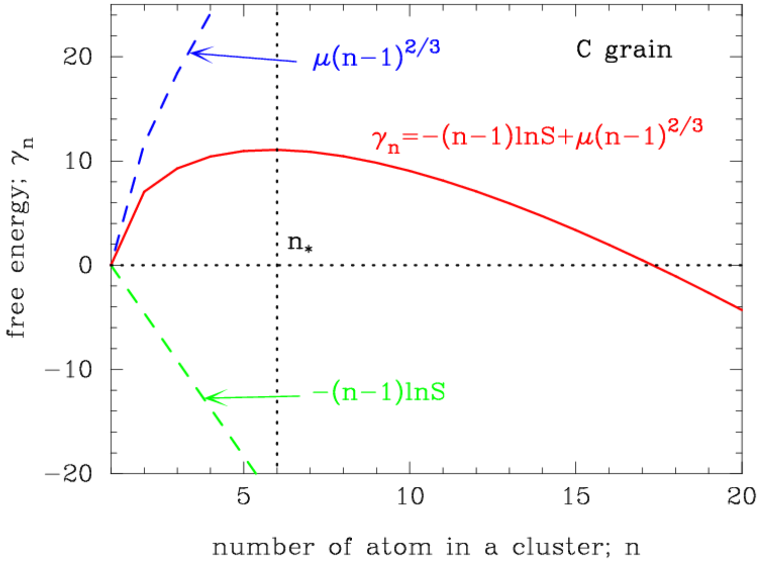
$$\alpha_n = \frac{s_n}{1+\delta_{1n}} 4\pi a_0^2 \, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n}\right)^{\frac{1}{2}},$$

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

2-2. Steady-state nucleation rate

・ steady-state nucleation rate: J_s

$$J_s = J_1 = J_2 = \cdots = J_n$$
$$= \{ 1/(\alpha_1 c_1) + \sum 1/(\alpha_n c_1^2) \exp[g(n)] \}^{-1}$$



$$g(n) = -(n-1)\ln S + \mu(n-1)^{\frac{2}{3}}$$

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

$\mu = 4\pi a_0^2\sigma / kT$
(σ : surface energy)

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

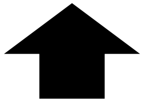
2-3. Basic equations for dust formation

▪ **Equation of mass conservation**

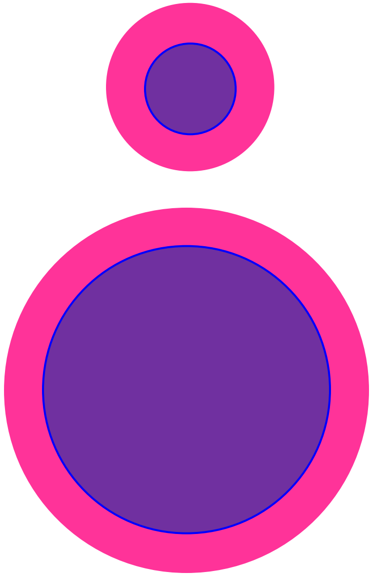
$$c_{10} - c_1 = \int_{t_0}^{t} J_{n_*}(t') \frac{a^3(t,t')}{a_0^3} dt',$$

▪ **Equation of grain growth**

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

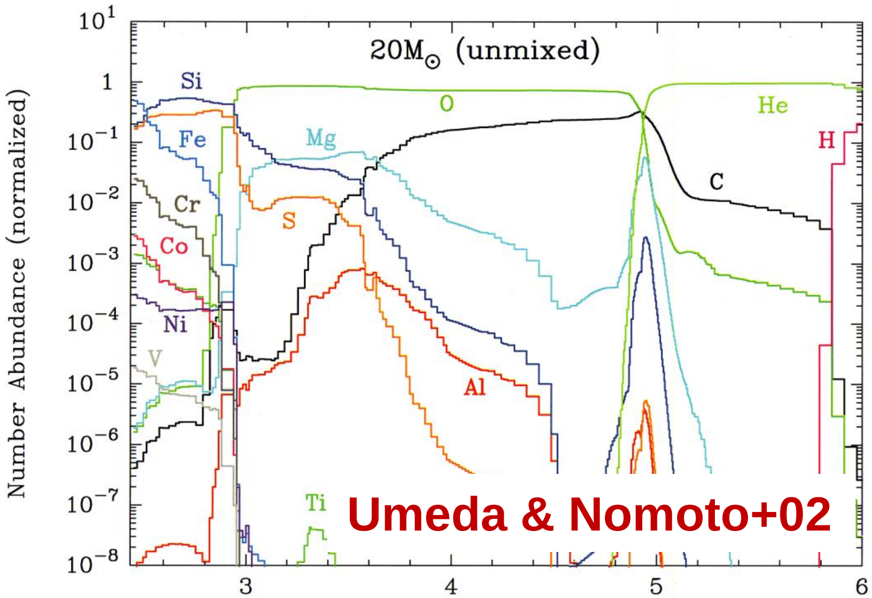


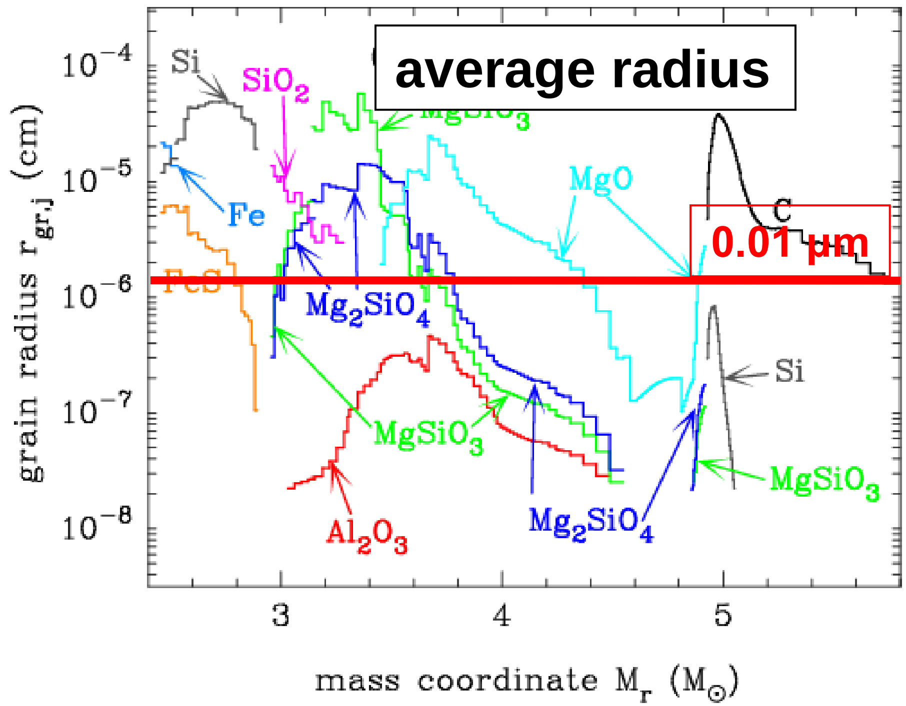
$$\frac{dV}{dt} = s\Omega_0 \, 4\pi a^2 \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S} \right),$$

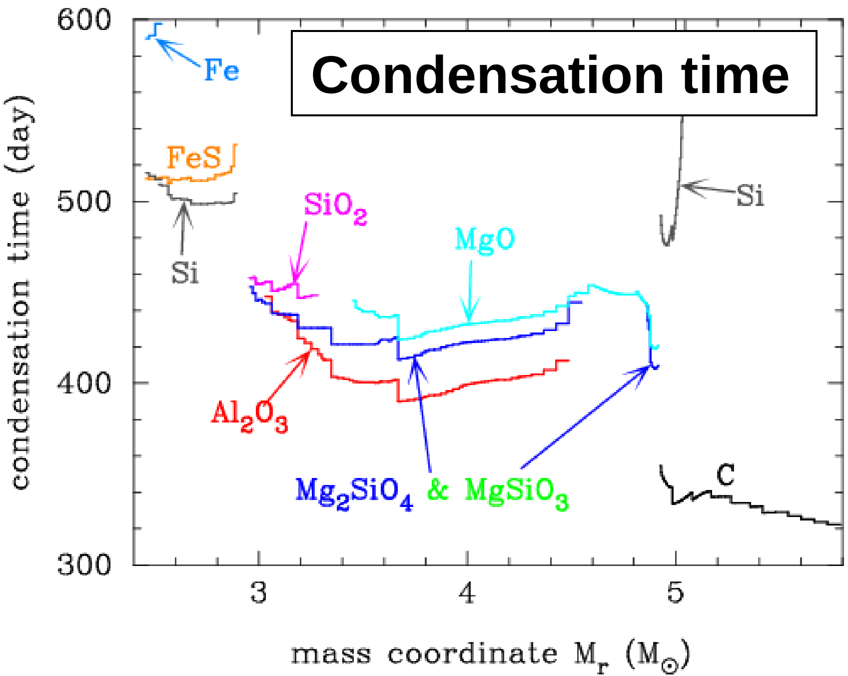


Growth rate is independent of grain radius

2-4. Dust formed in Type II-P SNe



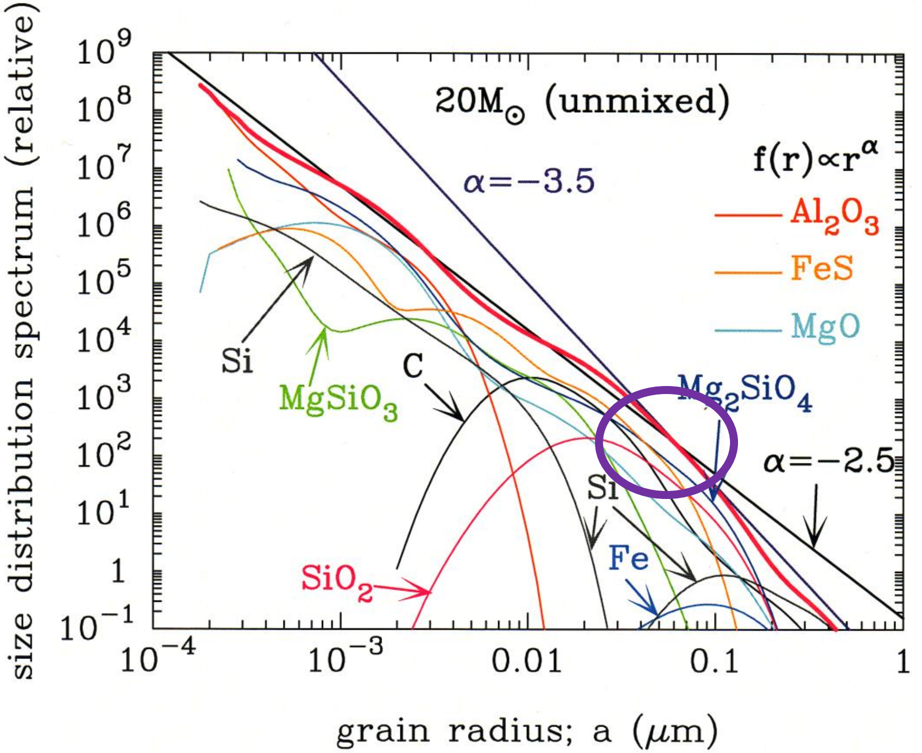


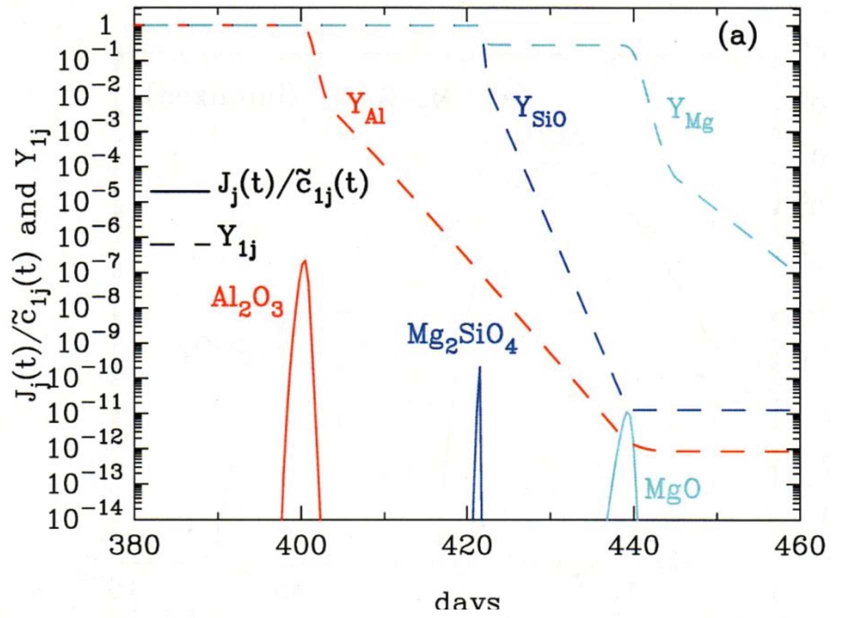


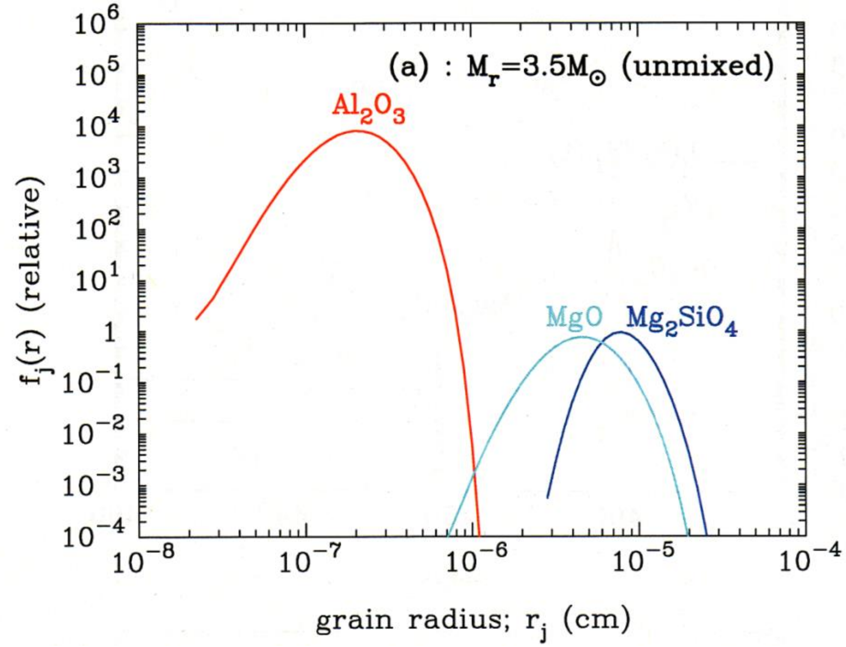
- various dust species form according to composition of gas in each layer
- condensation time: **300-600d** after explosion
- average radii: **>~0.01 μm**

Nozawa+03, ApJ, 598, 785

2-5. Size distribution of newly formed dust



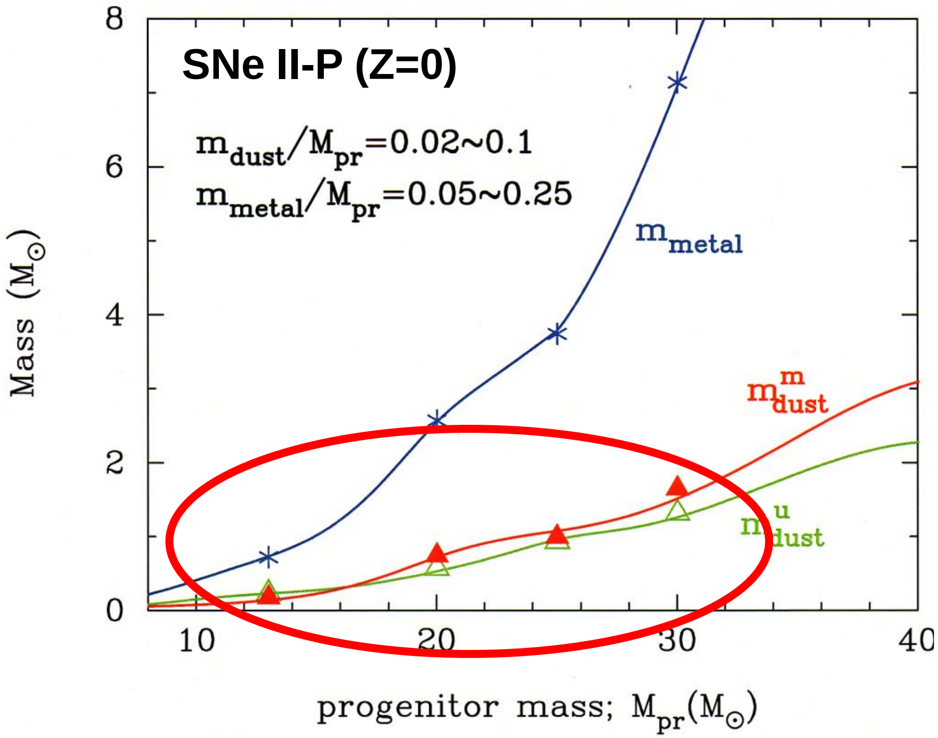


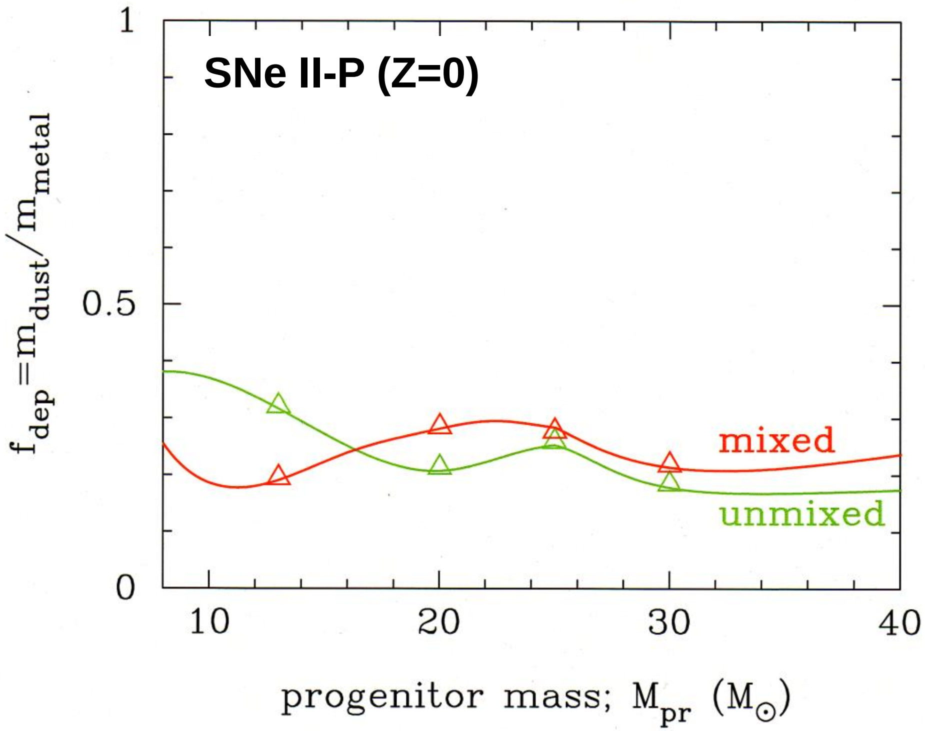


- C, SiO_2, and Fe grains have log-normal size distribution,
- the other grain species have power-law size distribution

2-6. Total mass of dust formed

Nozawa+03, ApJ, 598, 785





Total dust mass increases with increasing M_{pr}

M_{dust} = 0.1-1.5 M_{sun}

➔ almost all Mg, Si, and Fe are locked in dust

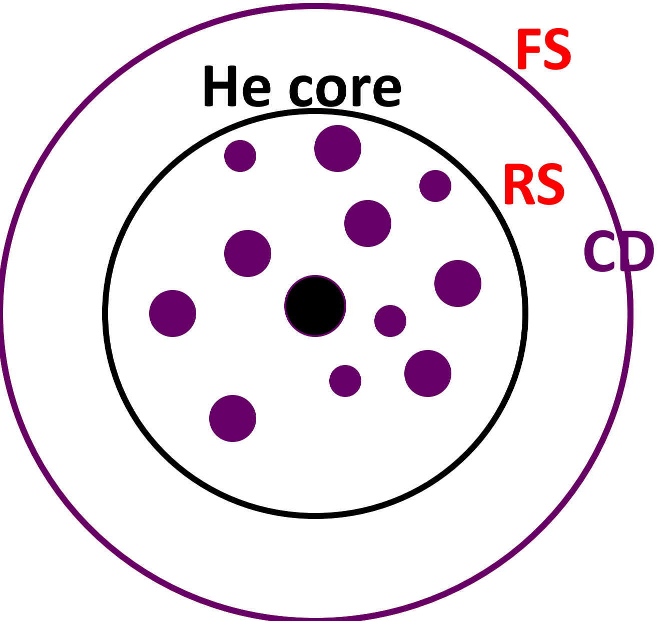
・depletion factor
f_{dep} (M_{dust}/M_{metal}) = 0.2-0.3

cf. f_{dep} = 0.4-0.5 in the MW

➔ incorporation of C and O into dust in MCs needed?

3. Evolution of dust in SNRs

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



3-1. 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 $s_i^2 = m_i w_{\rm d}^2 / 2kT$

3-2. 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

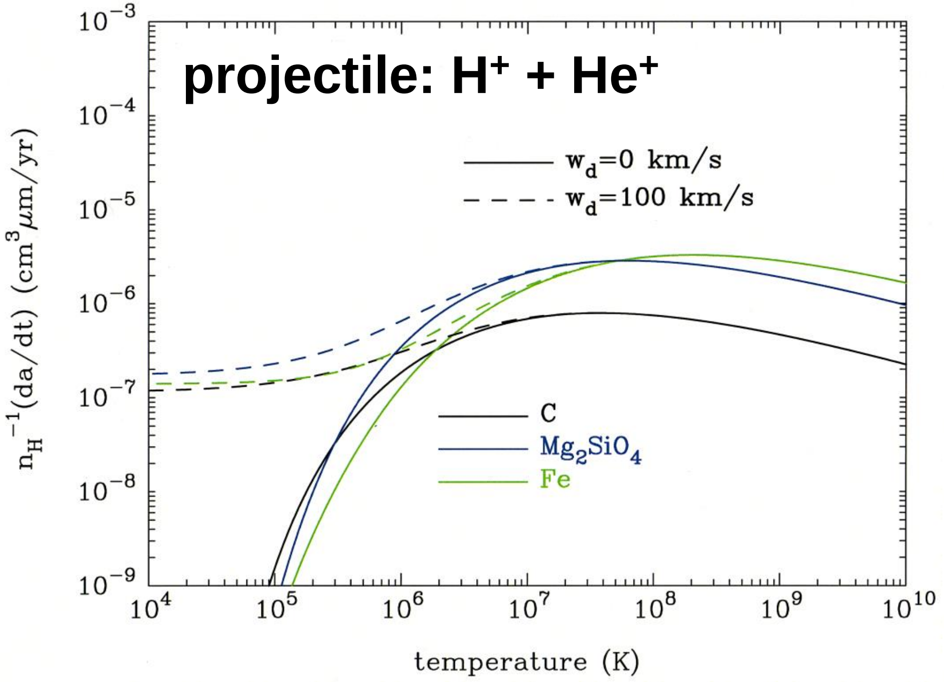
· rate equation over a modified Maxwellian distribution of gas taken account of relative velocity of dust to gas (e.g., Shull 1978)

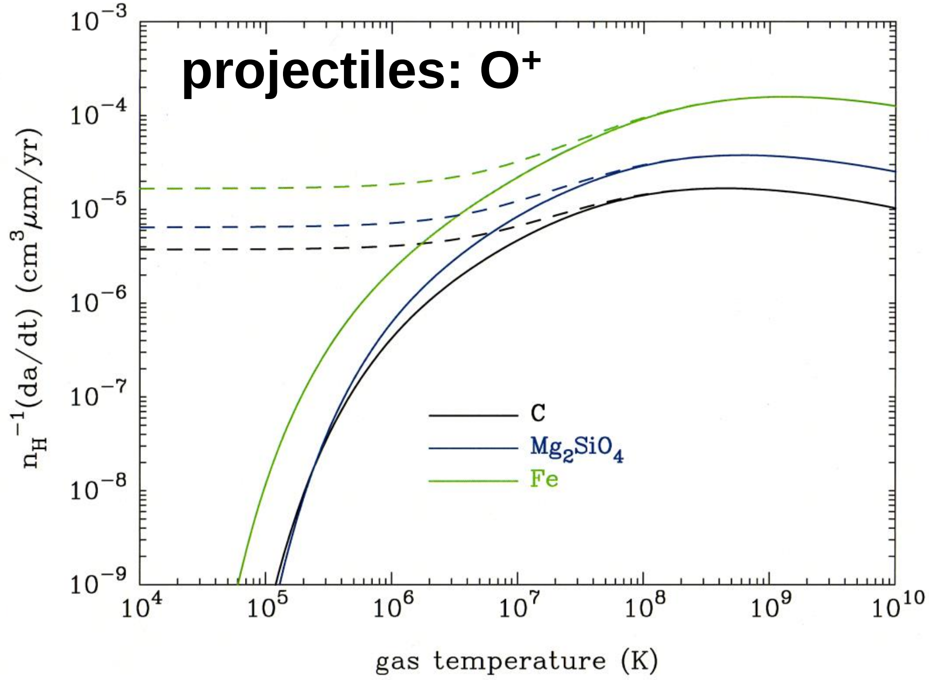
$$\mathcal{R}(X_i(\epsilon)) = n_{\rm H} A_i \pi a^2 \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} \frac{e^{-s_i^2}}{2s_i} \int \sqrt{\epsilon} e^{-\epsilon} \sinh(2s_i\sqrt{\epsilon}) X_i(\epsilon) d\epsilon$$

where $\epsilon = E/kT$

3-3. Erosion rate of dust by sputtering

Nozawa+06, ApJ, 648, 435





- erosion rate at $T > 10^6$ K:

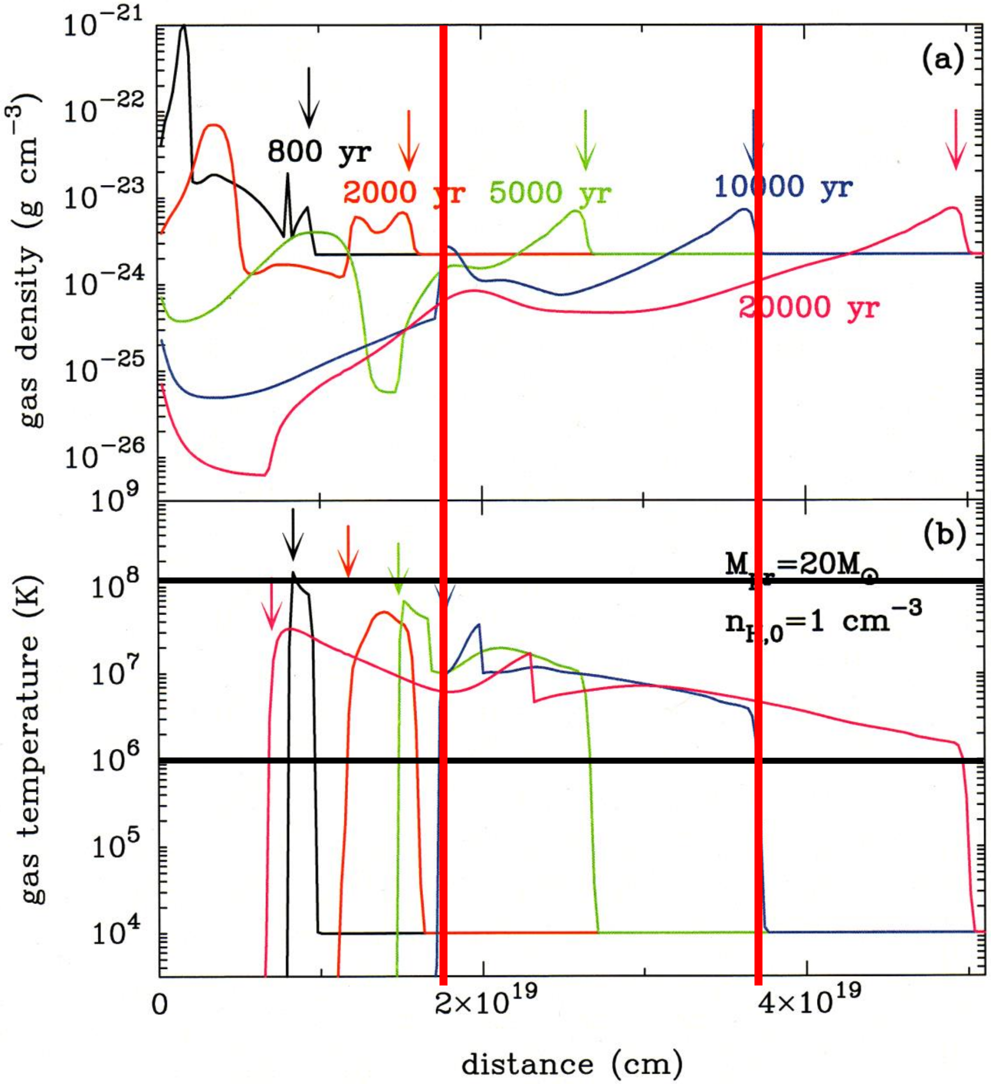
  $da/dt \sim 10^{-6}\, n_H\ \mu m\ yr^{-1}\ cm^3$

- destruction timescale by sputtering:

  $\tau_{sput} \sim 10^6\ yr\ (1\ cm^{-3}/n_H)\ (a/1.0\ \mu m)\ yr$

3-4. Temperature and density of gas in SNRs

Nozawa+07, ApJ, 666, 955



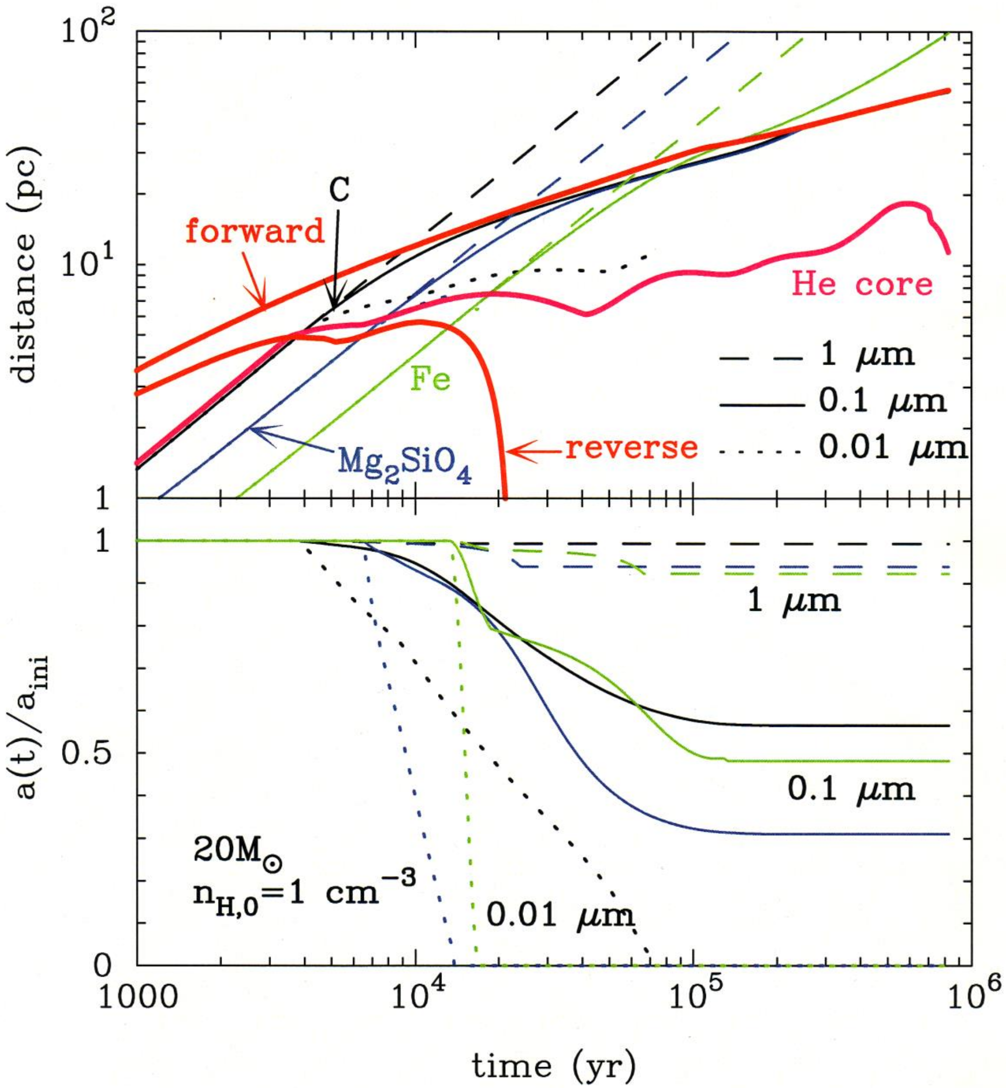
Model : M_{pr}= 20 Msun (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

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

3-5. Evolution of dust in SNRs

Nozawa+07, ApJ, 666, 955



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

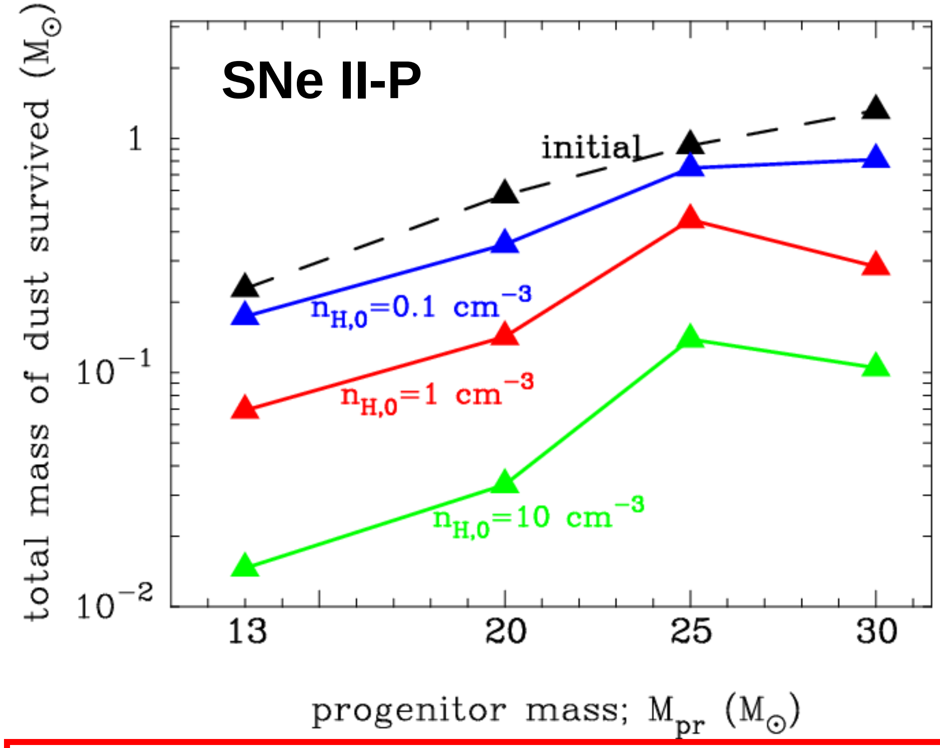
Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

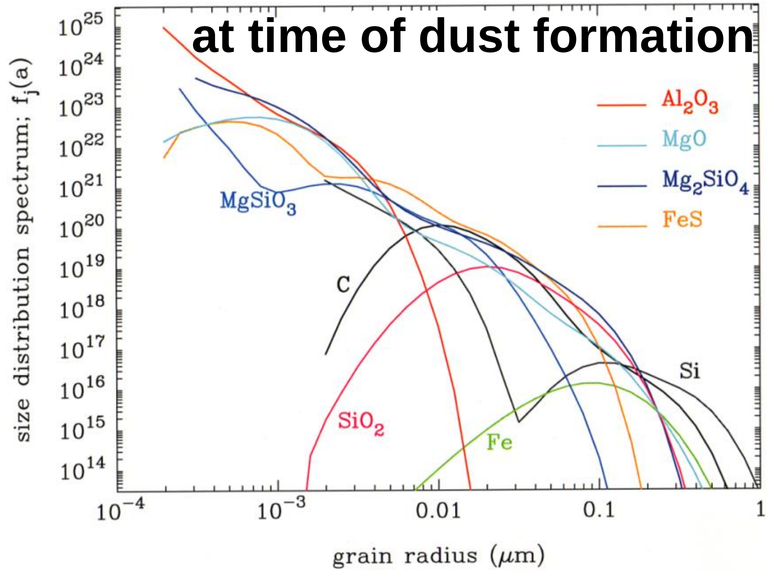
The evolution of dust heavily depends on the initial radius and composition

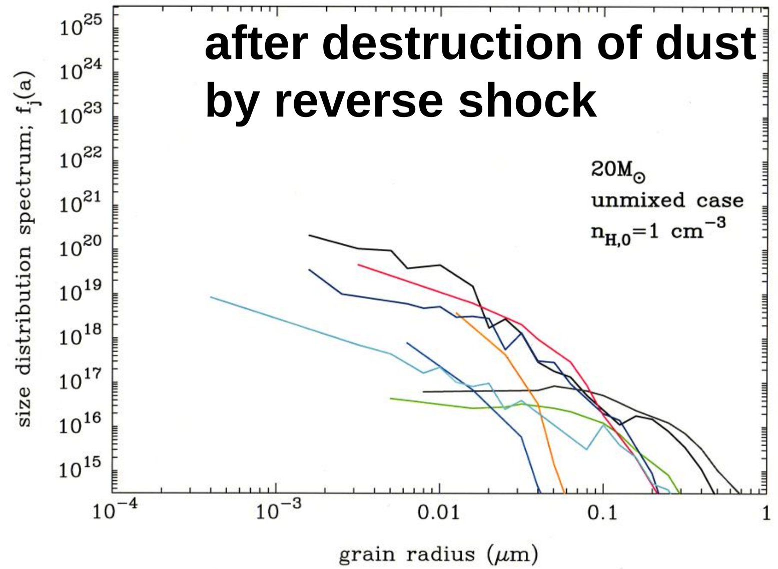
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

3-6. Mass and size of dust ejected from SN II-P

Nozawa+07, ApJ, 666, 955







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

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

3-7. Summary of dust production in CCSNe

- Various species of dust form in the unmixed ejecta
  (almost all Fe, Mg, and Si atoms are locked in dust)

- 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

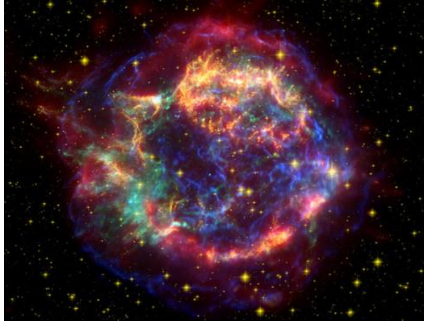
  for $n_{H,0}$ = 0.1-1 cm^{-3}

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

  (high enough to account for massive dust at high z)

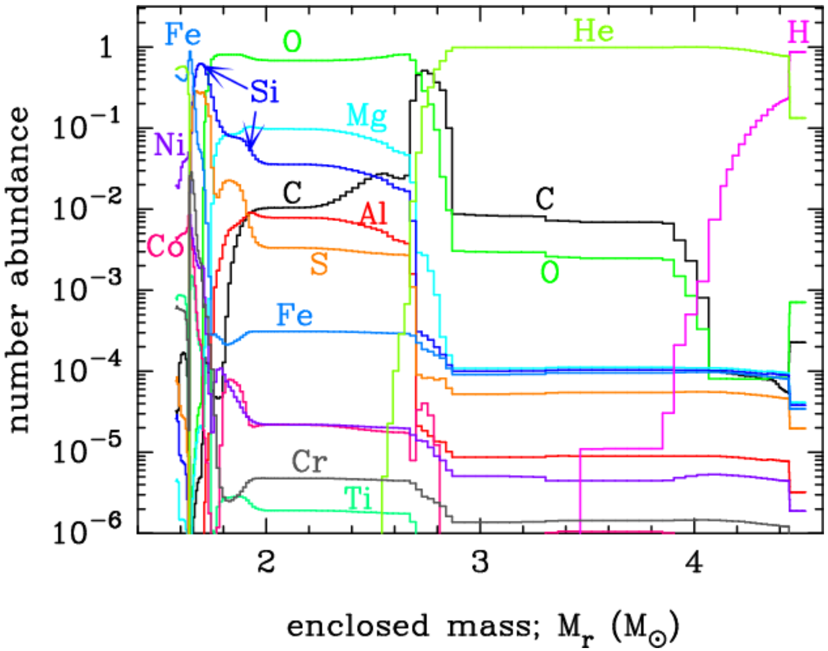
3. Formation of dust grains in various types of SNe

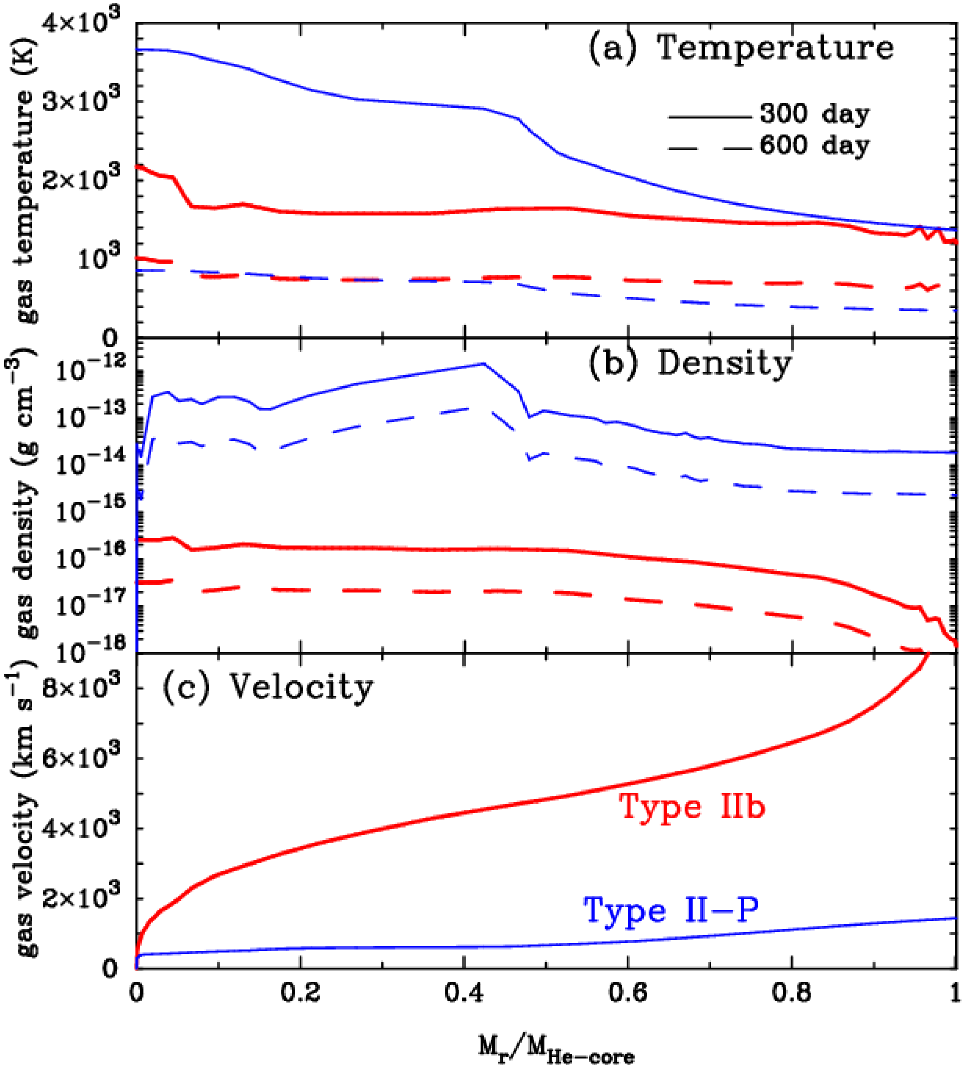
4-1. Dust formation in Type IIb SN



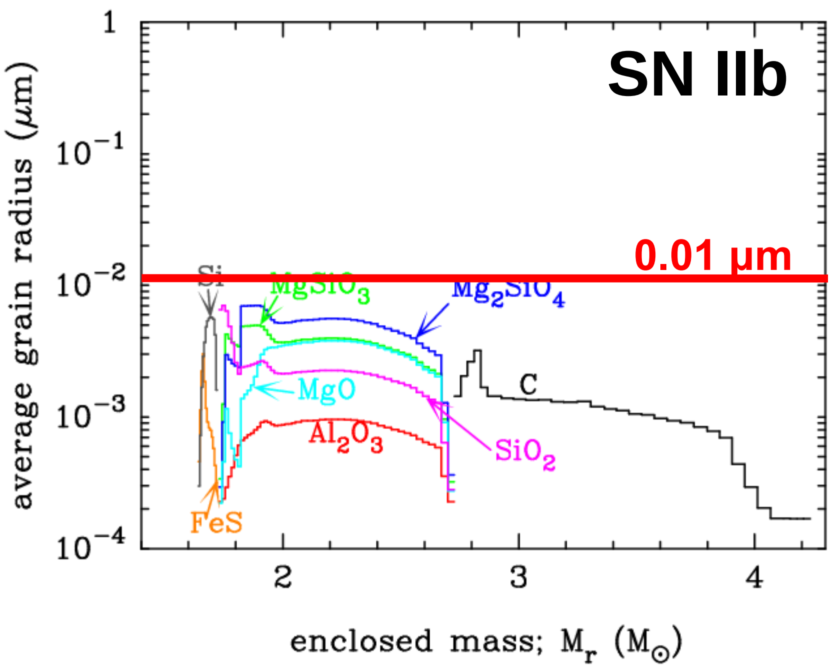
○ SN IIb model (SN1993J-like model)

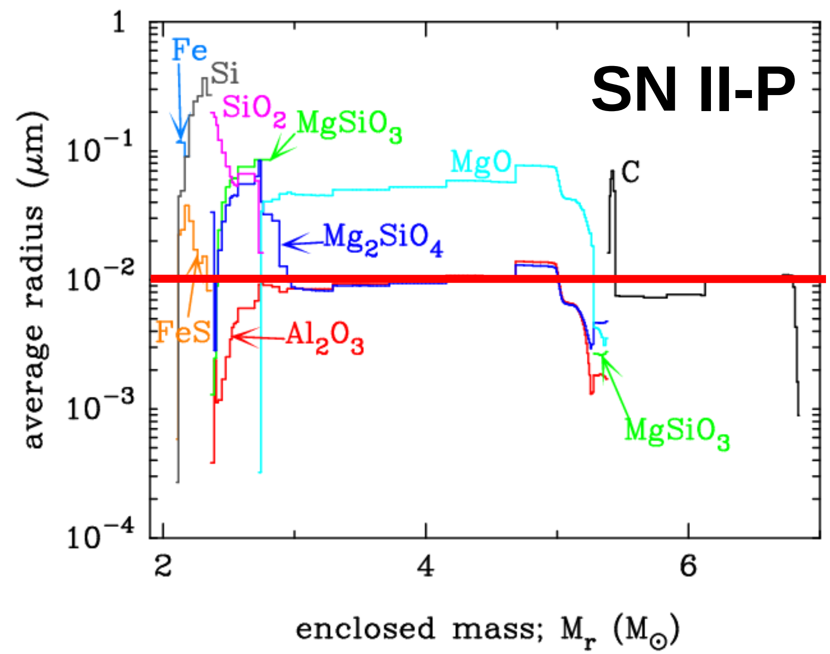
- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1
- $M(^{56}Ni)$ = 0.07 Msun





4-2. Dependence of dust radii on SN type





— condensation time of dust **300-700 d** after explosion

— total mass of dust formed

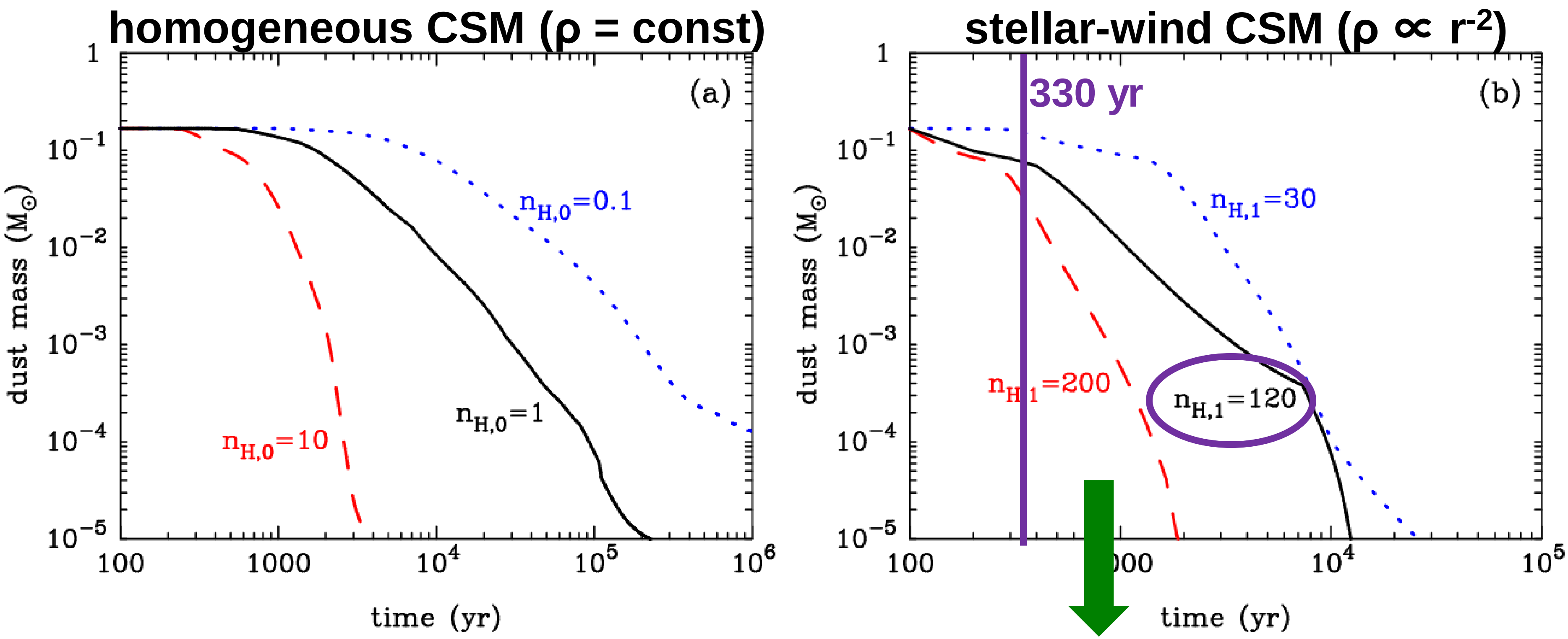
- **0.167 Msun in SN IIb**
- **0.1-1 Msun in SN II-P**

— the radius of dust formed in H-stripped SNe is small

- **SN IIb without massive H-env ➔ adust < 0.01 μm**
- **SN II-P with massive H-env ➔ adust > 0.01 μm**

Nozawa+10, ApJ, 713, 356

4-3. Destruction of dust in Type IIb SNR



$n_{H,1}$ = 30, 120, 200 /cc ➔ dM/dt = 2.0, 8.0, 13x10^{-5} M_{sun}/yr for v_W=10 km/s

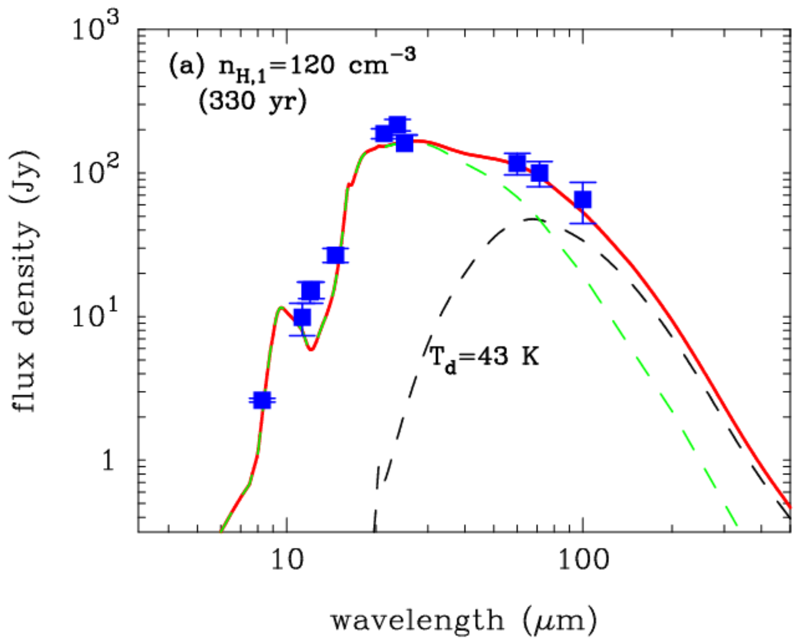
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

➔ small radius of newly formed dust

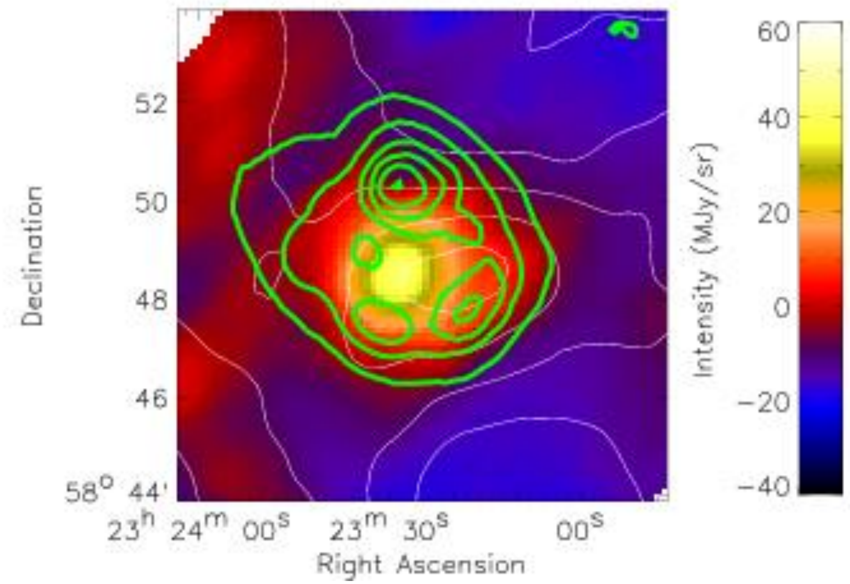
➔ early arrival of reverse shock at dust-forming region

Nozawa+10, ApJ, 713, 356

4-4. IR emission from dust in Cas A SNR



AKARI corrected 90 μm image



- total mass of dust formed
  M_{dust} = 0.167 M_{sun}
- shocked dust : 0.095 M_{sun}
  $M_{d,warm}$ = 0.008 M_{sun}
- unshocked dust :
  $M_{d,cool}$ = 0.072 M_{sun}
  with T_{dust} ~ 40 K

Nozawa+10, ApJ, 713, 356

AKARI observation

$M_{d,cool}$ = 0.03-0.06 M_{sun}

T_{dust} = 33-41 K

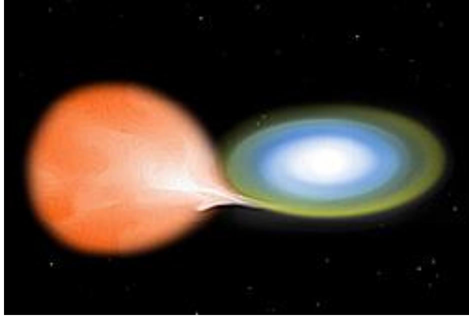
(Sibthorpe+'10)

Herschel observation

$M_{d,cool}$ = 0.075 M_{sun}

T_{dust} ~ 35 K (Barlow+'10)

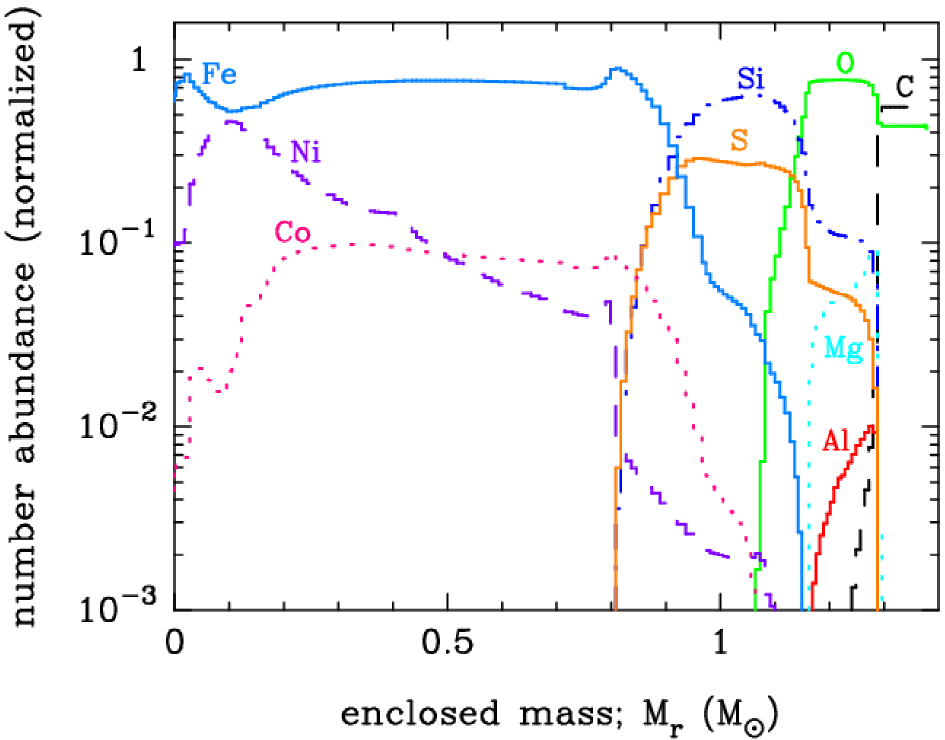
5-1. Dust formation in Type Ia SN

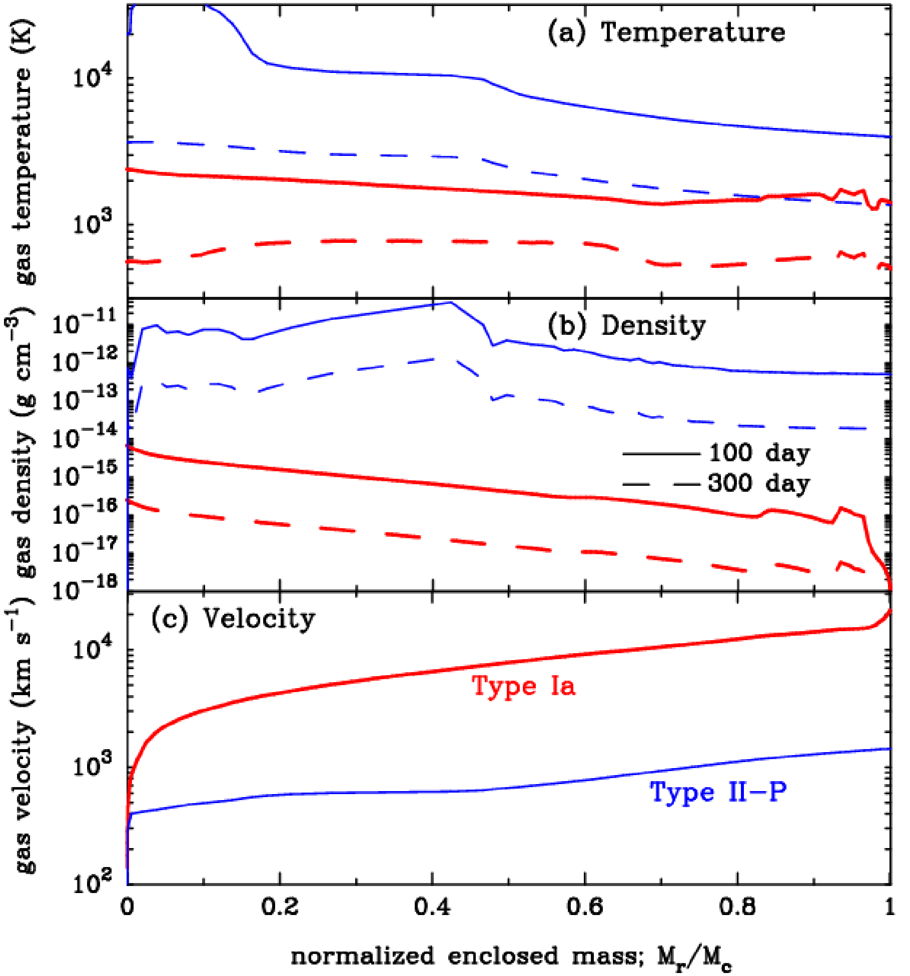


○ Type Ia SN model

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

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

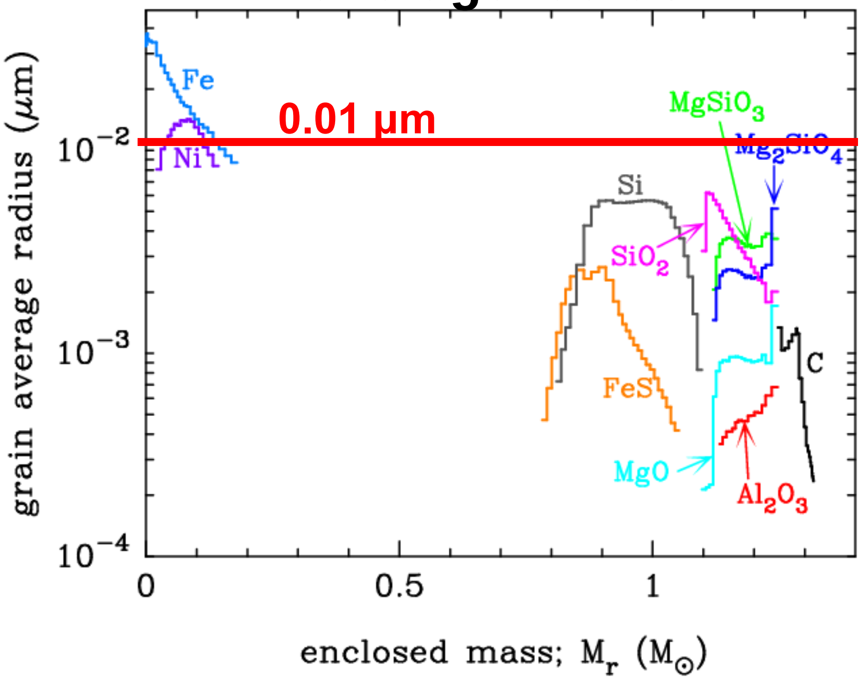




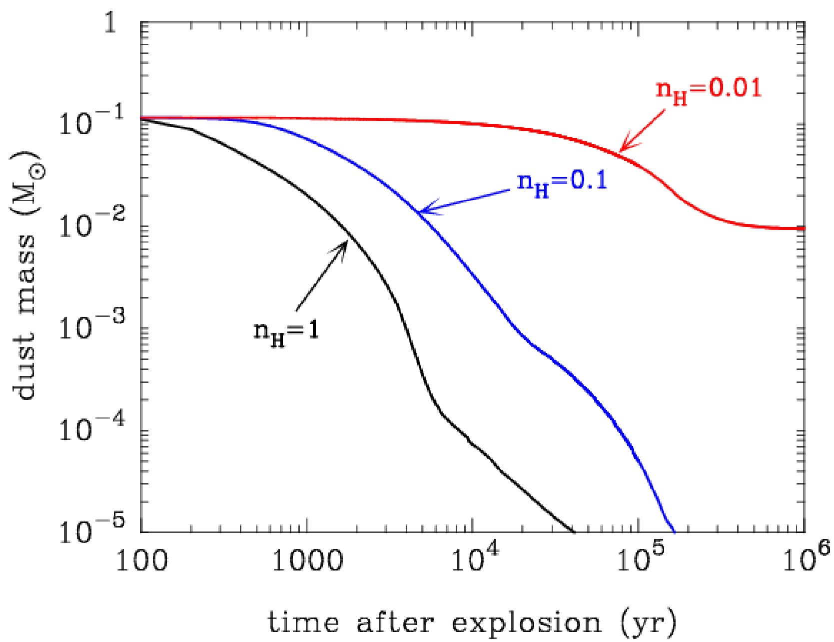
5-2. Dust formation and evolution in SNe Ia

Nozawa+11, ApJ, 736, 45

average radius



dust destruction in SNRs



- **condensation time :**
  100-300 days
- **average radius of dust :**
  a_{ave} <~ 0.01 μm
- **total dust mass :**
  M_{dust} ~ 0.1 M_{sun}

newly formed grains are completely destroyed for ISM density of n_H > 0.1 cm^{-3}

➔ SNe Ia are unlikely to be major sources of dust

6. Summary of this talk

・SNe II-P can inject a large amount of dust (>0.1 M_{sun})

— almost all Mg, SI, and Fe atoms are trapped in dust

— FIR observations of SNe support massive dust

・Size of newly formed dust depends on types of SNe

— H-retaining SNe (Type II-P) : a_{ave} > 0.01 μm

— H-stripped SNe (Type IIb/Ib/Ic and Ia) : a_{ave} < 0.01 μm

➔ dust is almost completely destroyed in the SNRs

➔ H-stripped SNe may be poor producers of dust

・Our model treating dust formation and evolution self-consistently can reproduce IR emission from Cas A

・Observations of nearby young SNRs with *SPICA* will be able to resolve the role of SNe as sources of dust