2014/05/23

超新星爆発時におけるダストの形成と星間空間へのダスト供給

野沢 貴也（Takaya Nozawa）

(National Astronomical Observatory of Japan)

Main collaborators:

T. Kozasa, A. Habe (Hokkaido University)
H. Umeda (University of Tokyo)
K. Maeda (Kyoto University), K. Nomoto (Kavli IPMU)
N. Tominaga (Konan University)

0-1. Introduction

・ SNe are important sources of interstellar dust?

- abundant metal (metal : N > 5)
- low temperature (T < ~2000 K)
- high density ($n > \sim 10^6$ 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

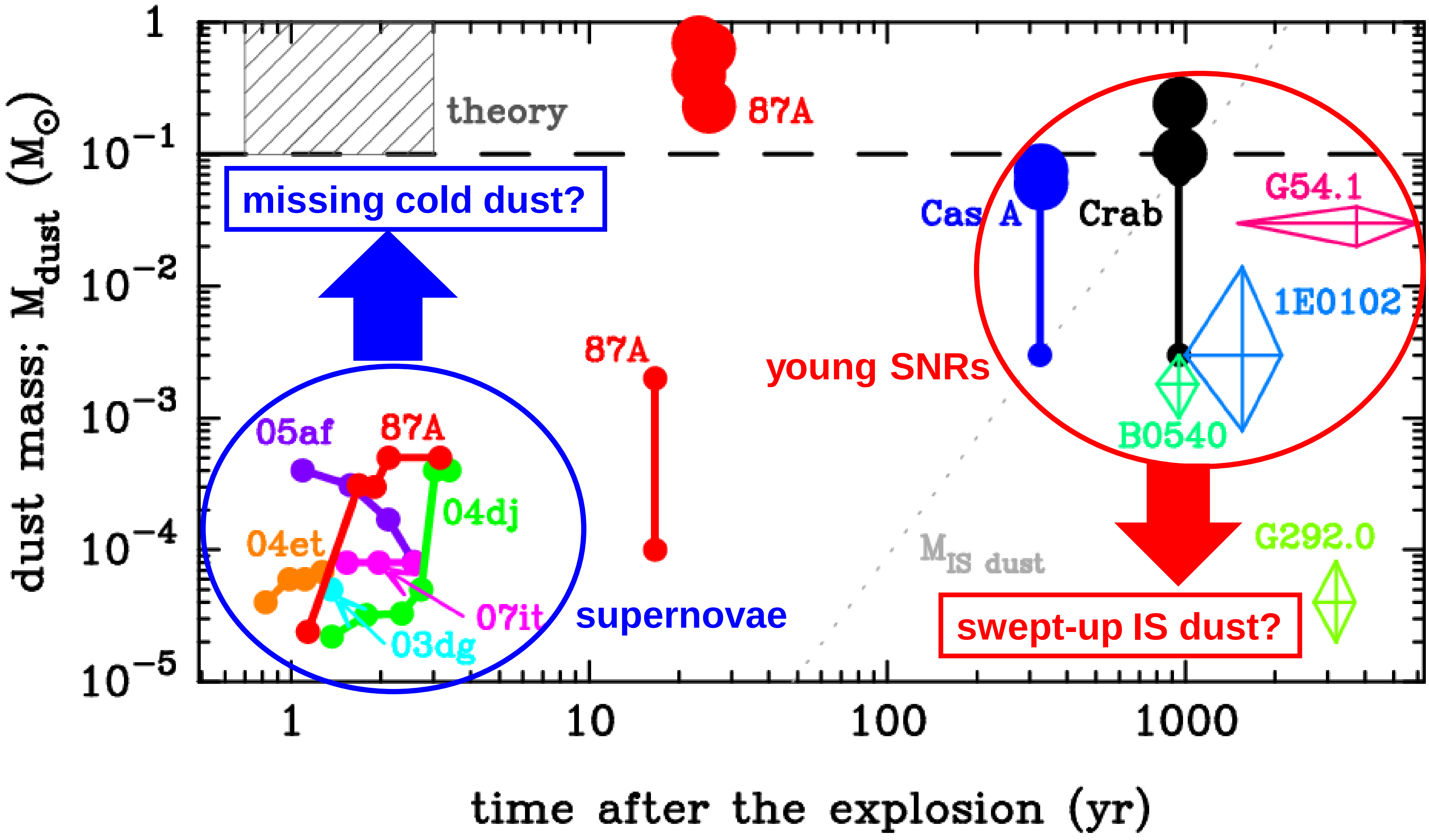
n(AGB stars) / n(SNe) ~ 20-100

M_{dust} = 0.001-0.01 M_{sun} per AGB (Zhukovska & Gail 2008)

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

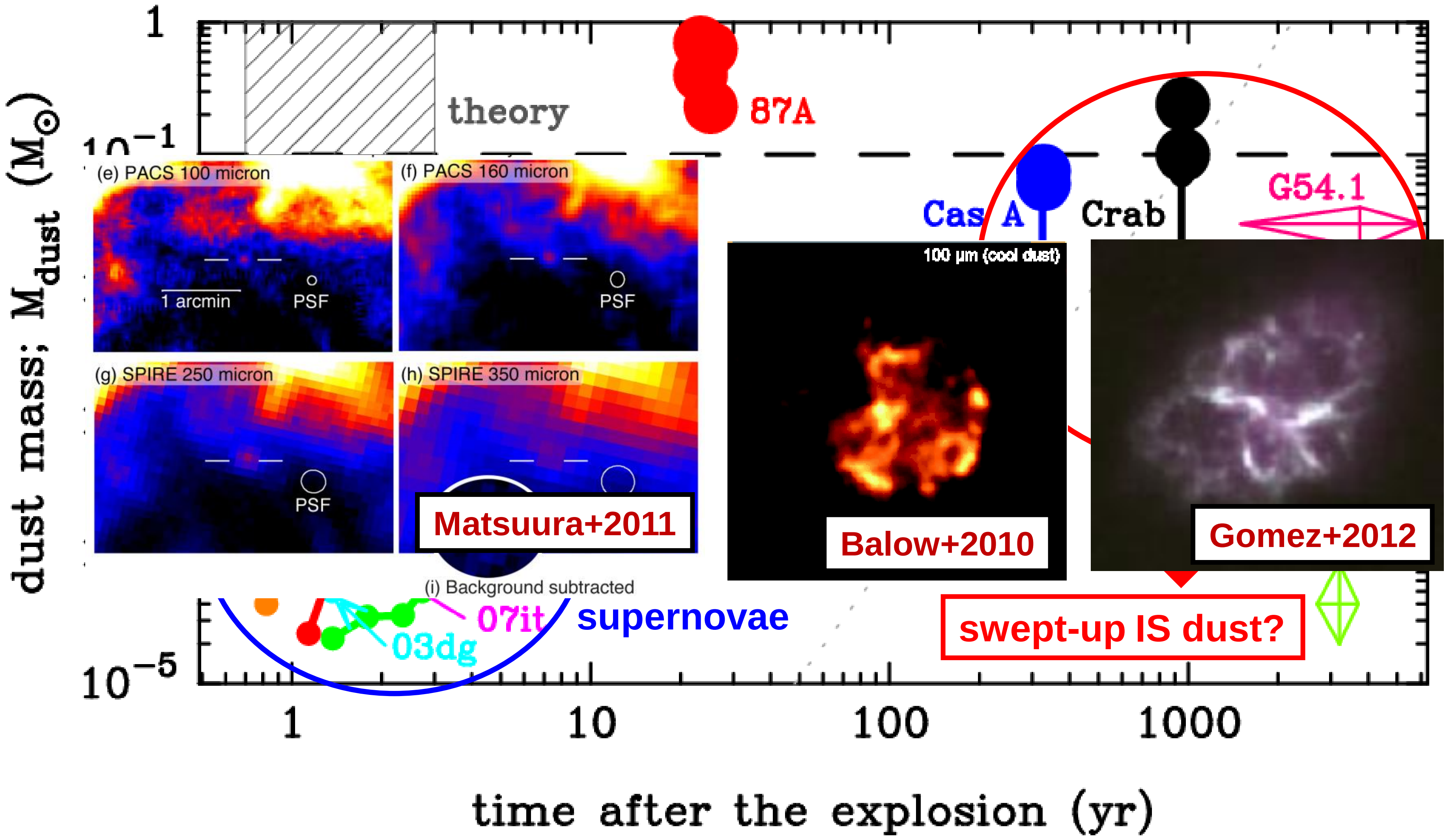
1. Observations of Dust Formation in SNe (and SNRs)

1-1. Summary of observed dust mass in CCSNe



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

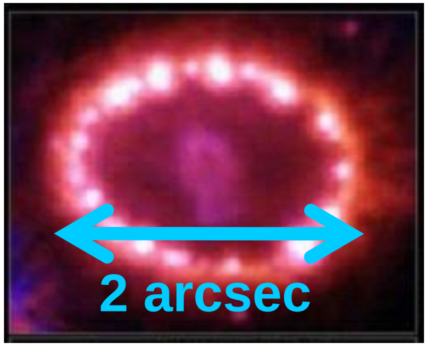
1-1. Summary of observed dust mass in CCSNe

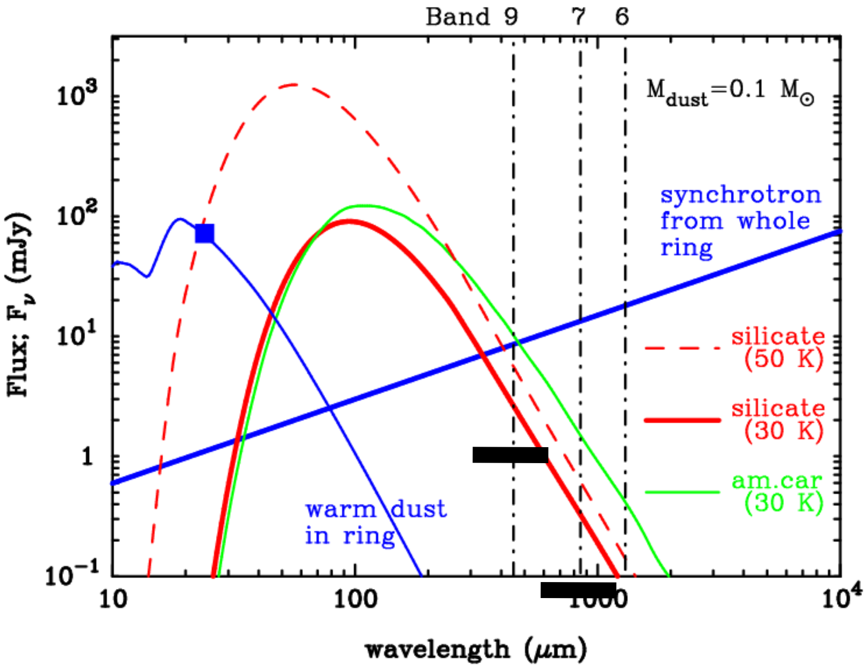


Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe

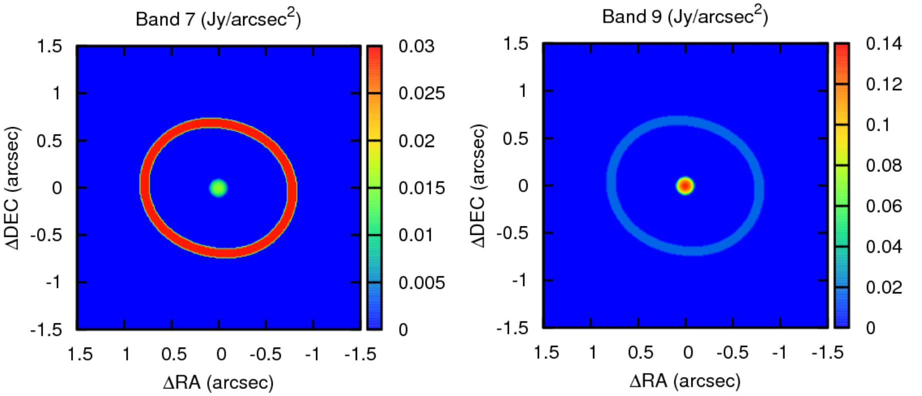
1-2. Resolving cool dust in SN 87A with ALMA

ALMA Cycle 0 Proposal
‘Detecting cool dust in SN1987A’
（TN, Tanaka, et al.)

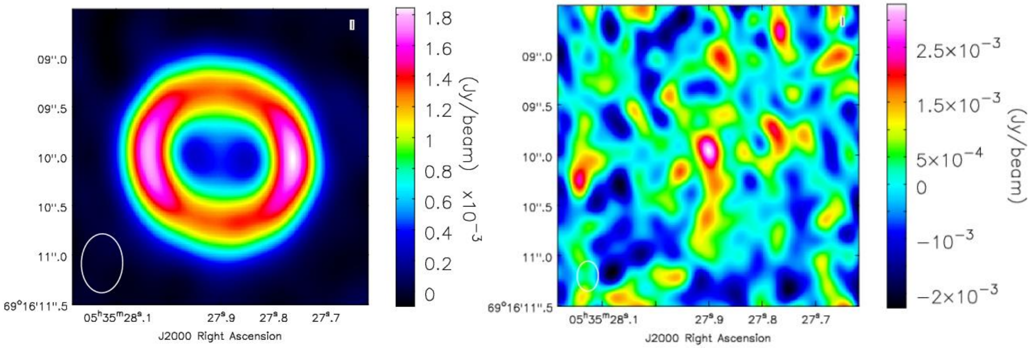




Band 7 (850 μm) **Band 9 (450 μm)**



CASA simulation with extended config. (4 hrs)



0.1 Msun of silicate
➔ 5σ detection at Band 9 !!

1-3. Successful ALMA proposals for SN 1987A

2011.0.00221.S

PI	Exec	Country	Institute
Nozawa, Takaya	EA	Japan	The University of Tokyo
COI			
Tanaka, Masaomi	EA	Japan	The University of Tokyo
Moriya, Takashi	EA	Japan	University of Tokyo
Minamidani. Tetsuhiro	EA	Japan	Hokkaido University
Kozasa, Takashi	EA	Japan	Hokkaido University

This proposal was ranked in the highest priority !!

2011.0.00273.S

PI	Exec	Country	Institute
Indebetouw. Remy	NA	United States	Virginia, University of
COI			
McCray, Richard	NA	United States	Colorado at Boulder. Univ of
Matsuura, Mikako	EU	United Kingdom	London. University of
Andjelic, Milica	OTHER	Serbia	Belgrade, University of
Arbutina, Bojan	OTHER	Serbia	Belgrade, University of
Baes, Maarten	EU	Belgium	Ghent University
Bolatto, Alberto	NA	United States	Maryland, University of
Burrows, David	NA	United States	Pennsylvania State University
Chevalier, Roger	NA	United States	Virginia, University of
Gaensler, Bryan	OTHER	Australia	Sydney, University of
Long, Knox	NA	United States	Space Telescope Science Institute
Lundqvist. Peter	EU	Sweden	Stockholm University
Meixner. Margaret	NA	United States	Space Telescope Science Institute
Marcaide, Jon	EU	Spain	Valencia. University of
Marti-Vidal, Ivan	EU	Germany	Max-Planck-Institute for Radio Astronomy
OTSUKA, Masaaki	EA/NA	Taiwan	Academia Sinica
Sandstrom, Karin	EU	Germany	Max-Planck-Institute for Astronomy
Sonneborn, George	NA	United States	National Aeronautics and Space Administration
Staveley-Smith, Lister	OTHER	Australia	International Centre for Radio Astronomy Research
van Loon, Jacco	EU	United Kingdom	Keele University
Urosevic, Dejan	OTHER	Serbia	Belgrade, University of
Vlahakis, Catherine	CL	Chile	Chile, University of
Zekovic, Vladimir	OTHER	Serbia	Belgrade, University of
Zanardo, Giovanna	OTHER	Australia	International Centre for Radio Astronomy Research
Ng. Chi-Yung	NA	Canada	McGill University
Park. Sangwook	NA	United States	Texas at Arlington. University of
Barlow, Michael	EU	United Kingdom	London, University of
Clayton, Geoffrey	NA	United States	Louisiana State University
Wesson, Roger	EU	United Kingdom	London, University of
Dwek, ELi	NA	United States	National Aeronautics and Space Administration
Bouchet, Patrice	EU	France	CEA Saclay
Lakicevic, Masa	EU	Germany	European Southern Observatory
Potter, Toby	OTHER	Australia	International Centre for Radio Astronomy Research

1-3. Successful ALMA proposals for SN 1987A

2011.0.00221.S

PI	Exec	Country	Institute
Nozawa, Takaya	EA	Japan	The University of Tokyo
COI			
Tanaka, Masa[illegible]i	EA	Japan	The University of Tokyo
Moriya, Takashi	EA	Japan	University of Tokyo
Minamidani, Tetsuhiro	EA	Japan	Hokkaido University
Kozasa, Takashi	EA	Japan	Hokkaido University

Our proposal was not executed

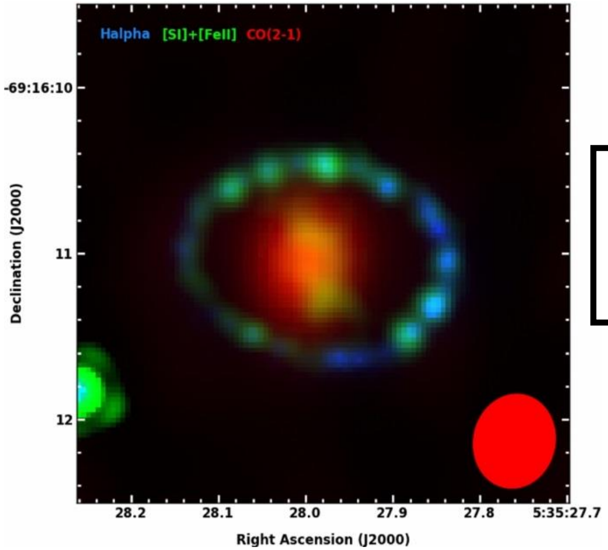
Band 9
extended configuration

2011.0.00273.S

PI	Exec	Country	Institute
Indebetouw, Remy	NA	United States	Virginia, University of
COI			
McCray, Richard	NA	United States	Colorado at Boulder, Univ of
Matsuura, Mikako	EU	United Kingdom	London, University of
Andjelic, Milica	OTHER	Serbia	Belgrade, University of
Arbutina, Bojan	OTHER	Serbia	Belgrade, University of
Baes, Maarten	EU	Belgium	Ghent University
Urosevic, Dejan	OTHER	Serbia	Belgrade, University of
Vlahakis, Catherine	CL	Chile	Chile, University of
Za			
Za			
Ng			
Pa			
Ba			
Cl			
Wesson, Roger	EU	United Kingdom	London, University of
Dwek, Eli	NA	United States	National Aeronautics and Space Administration
Bouchet, Patrice	EU	France	CEA Saclay
Lakicevic, Masa	EU	Germany	European Southern Observatory
Potter, Toby	OTHER	Australia	International Centre for Radio Astronomy Research

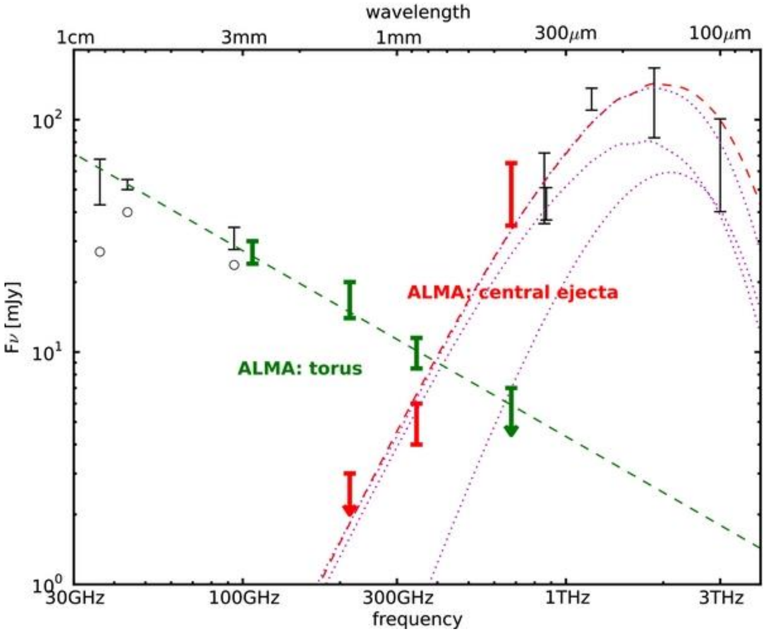
Band 3, 6, 7, 9
compact configuration

1-4. ALMA reveals dust formed in SN 1987A

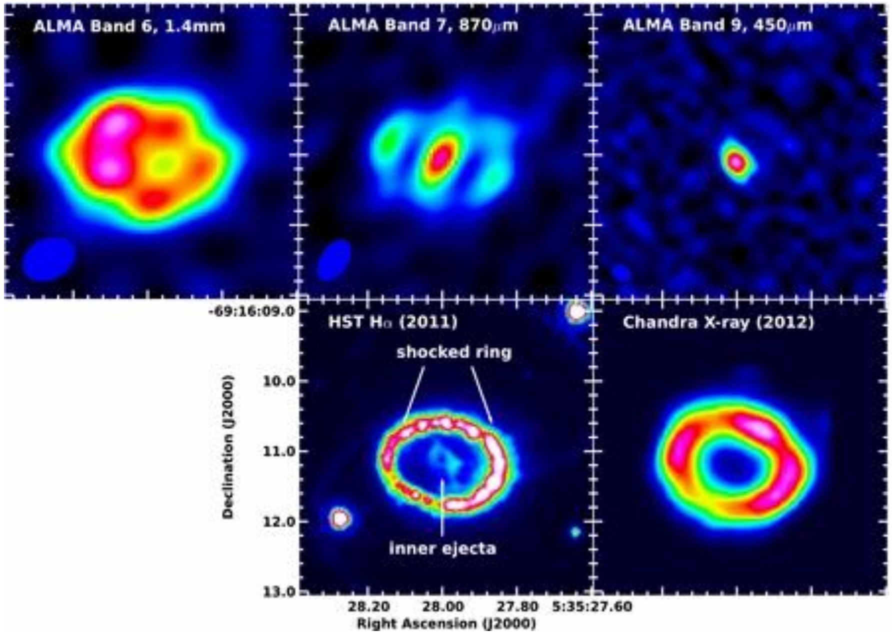


blue: Hα
green: 1.6 μm
red: CO(2-1)

SED of 25-years old SN 1987A



Indebetouw+2014

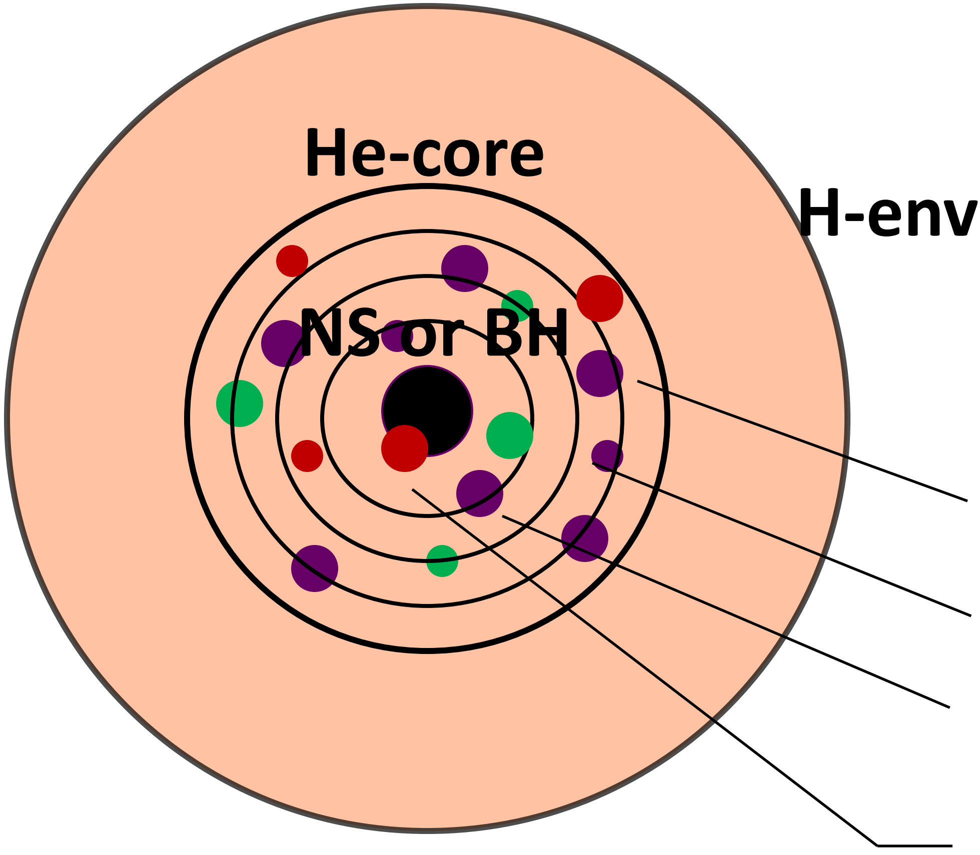


ALMA spatially resolves cool (~20K) dust of ~0.5 Msun formed in the ejecta of SN 1987A

➔ SNe could be production factories of dust grains

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

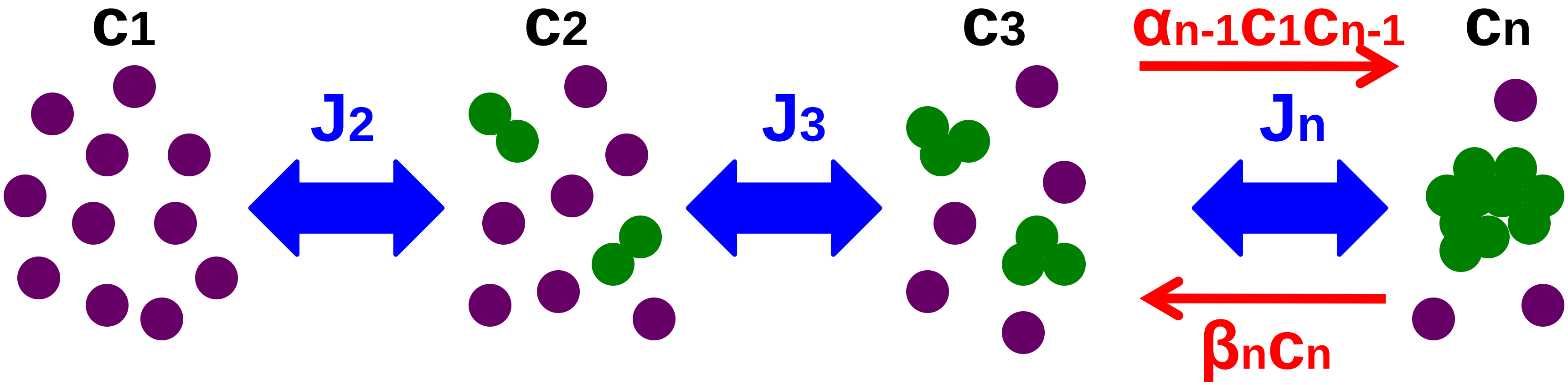
Fe–Ni layer

Dust formation

at ~1-3 years

after explosion

2-1. Formulation of dust formation



・ master equations

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

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

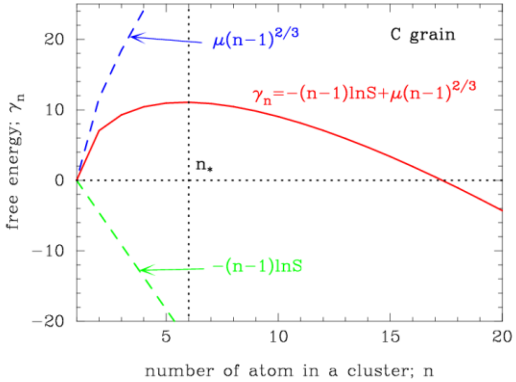
$$\alpha_n = \frac{s_n}{1+\delta_{1n}} \, 4\pi a_0^2 \, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n}\right)^{\frac{1}{2}},$$

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

2-2. Non-steady-state nucleation

・ 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 $\mu = 4\pi a_0^2 \sigma / kT$

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

・ non-steady-state dust formation

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

2-3. Basic equations for dust formation

- **Equation of mass conservation**

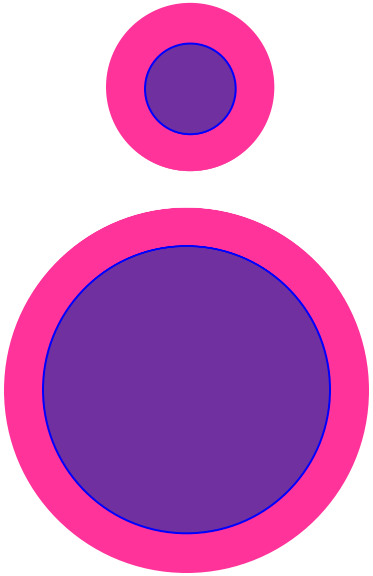
$$c_{10} - c_1 = \int_{t_0}^{t} J_{n_*}(t') \frac{a^3(t,t')}{a_0^3} dt',$$

- **Equation of grain growth**

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

$$\Uparrow$$

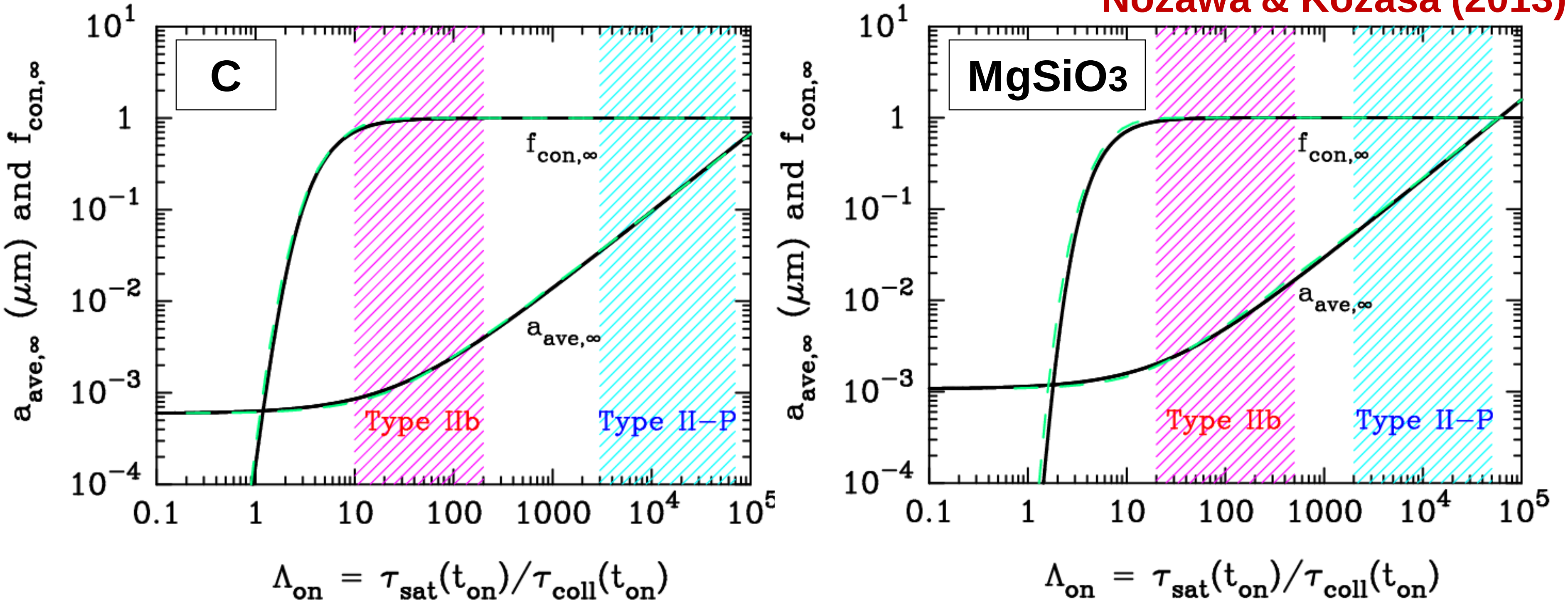
$$\frac{dV}{dt} = s\Omega_0 \, 4\pi a^2 \left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S}\right),$$



Growth rate is independent of grain radius

2-4. Scaling relation of average grain radius

Nozawa & Kozasa (2013)



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

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

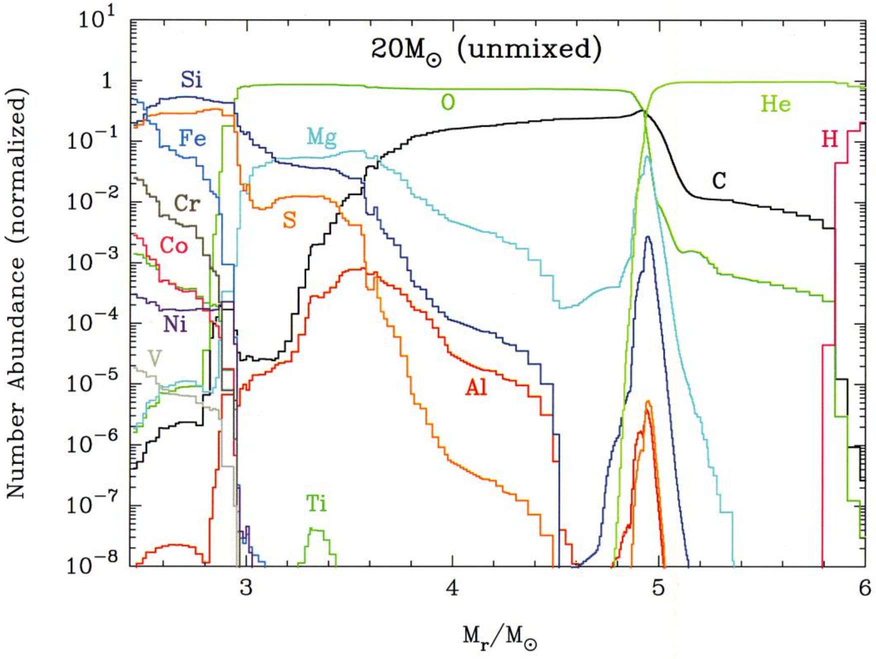
- $f_{\rm con,\infty}$ and $a_{\rm ave,\infty}$ are uniquely determined by $\Lambda_{\rm on}$
- steady-state nucleation rate is applicable for $\Lambda_{\rm on} > 30$

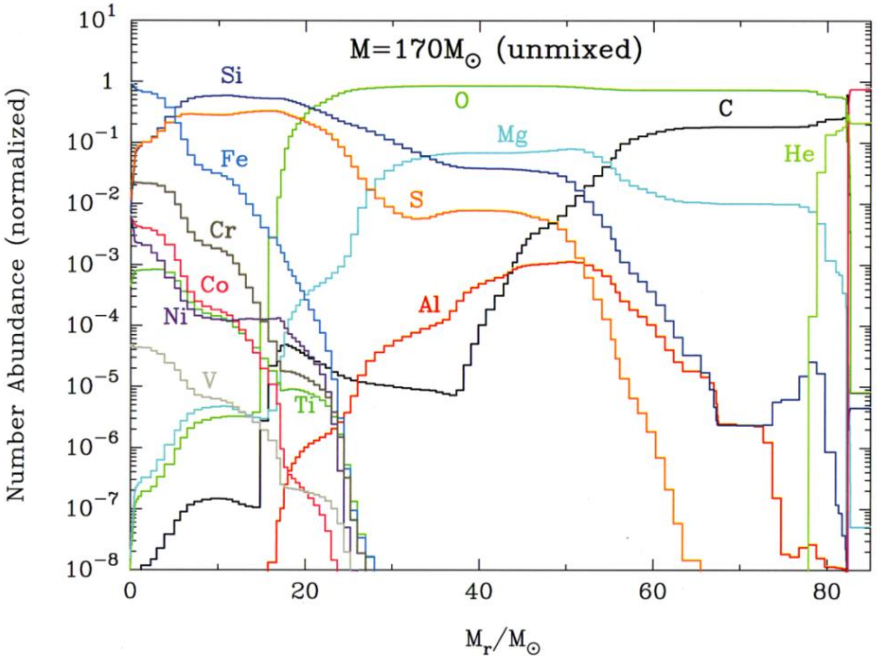
2-5. Dust formation in primordial SNe

Nozawa+2003, ApJ, 598, 785

○ Population III SNe model (Umeda & Nomoto 2002)

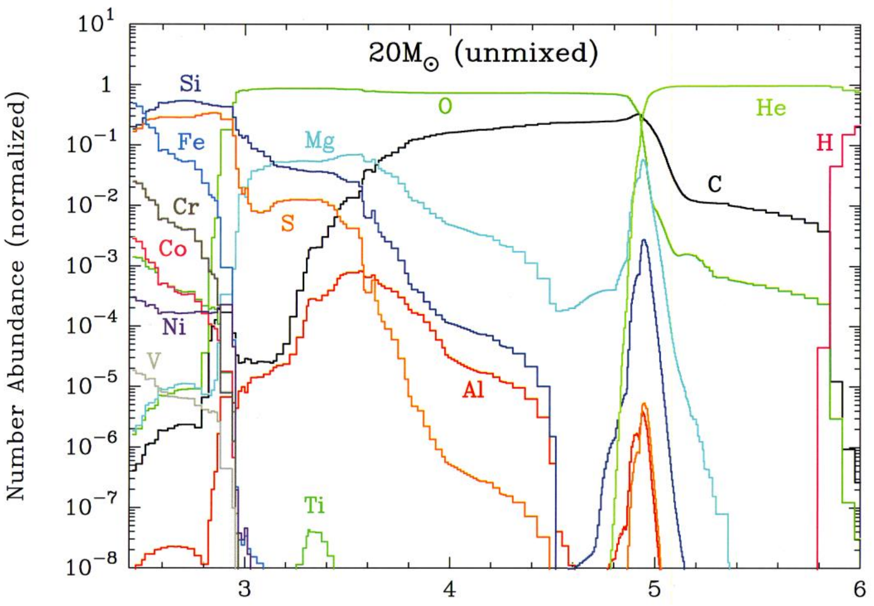
- **SNe II** : **M_{ZAMS} = 13, 20, 25, 30 Msun** (E_{51}=1)
- **PISNe** : **M_{ZAMS} = 170 Msun** (E_{51}=20), **200 Msun** (E_{51}=28)

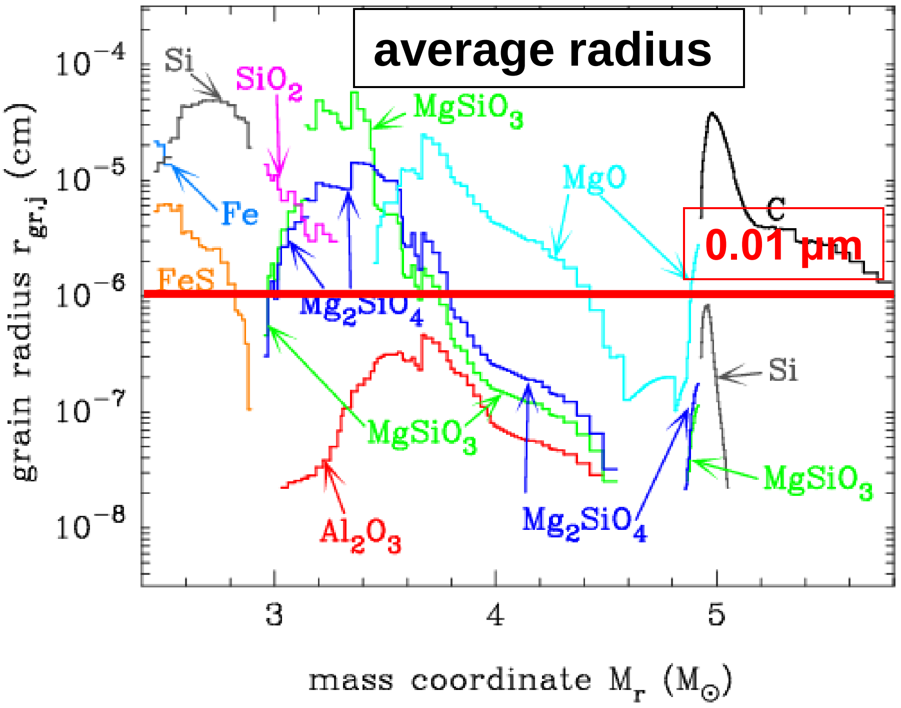


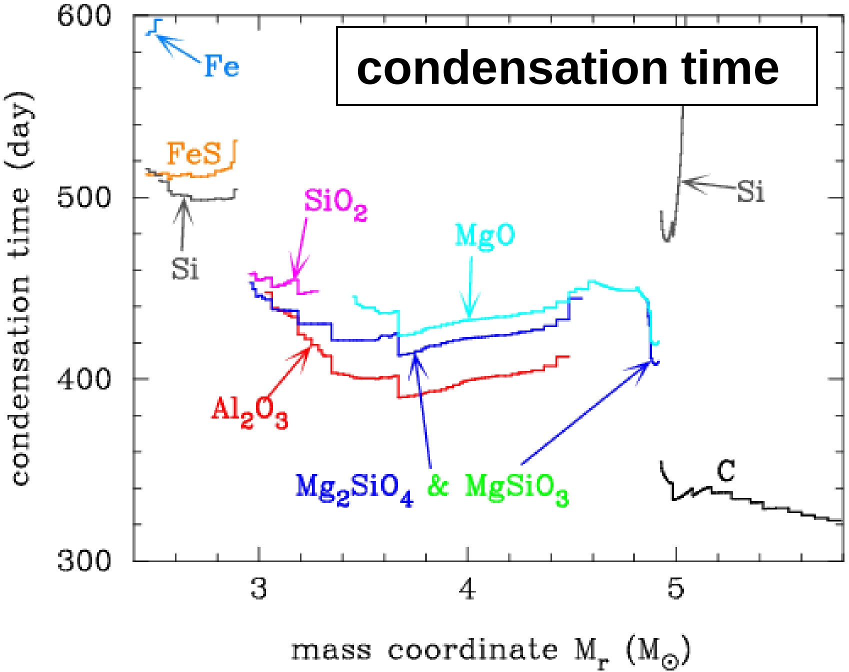


- **nucleation and grain growth theory** (Kozasa & Hasegawa 1987)
- **no mixing of elements within the He-core**
- **complete formation of CO and SiO**

2-6. Dust formed in Type II-P SNe





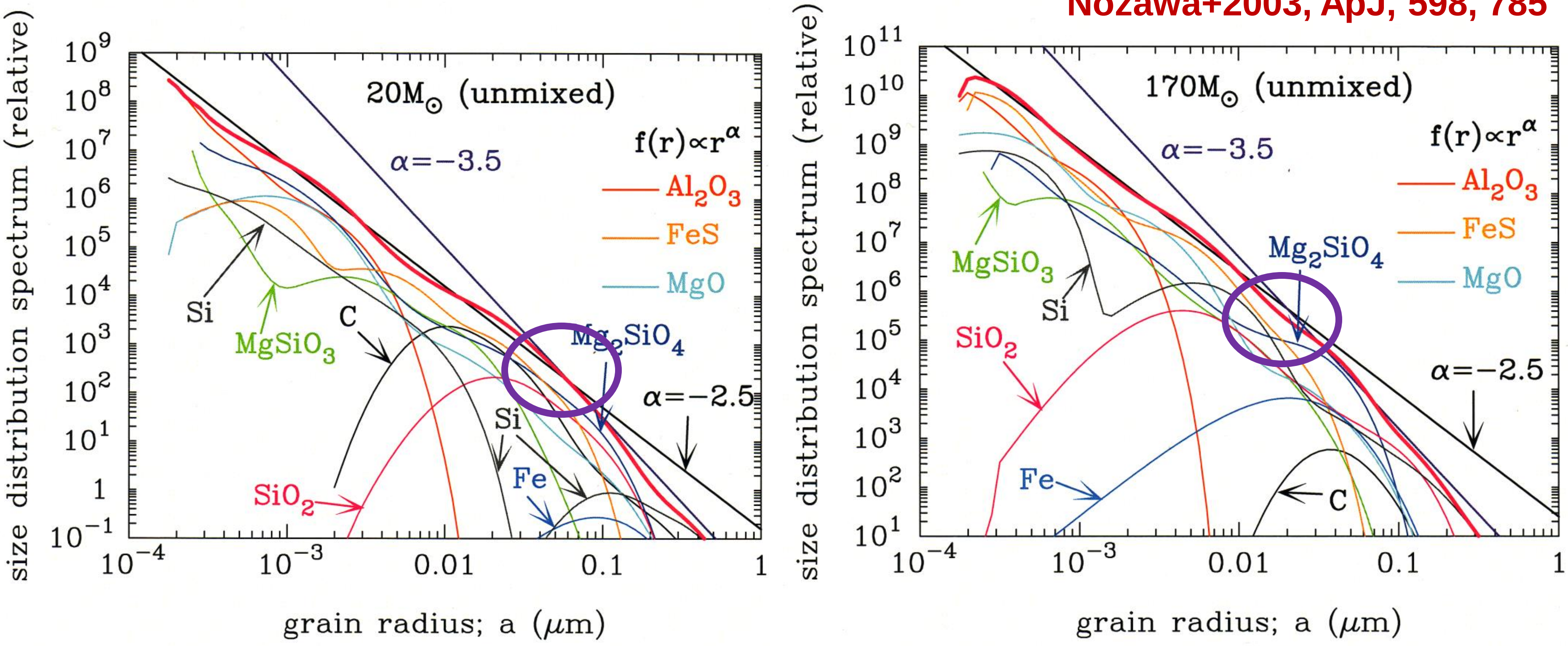


- **a variety of grain species can condense according to elemental composition in each layer**
- **condensation time: 300-600d after explosion**
- **average grain radii: >~0.01 μm**

Nozawa+03, ApJ, 598, 785

2-7. Size distribution of newly formed dust

Nozawa+2003, ApJ, 598, 785

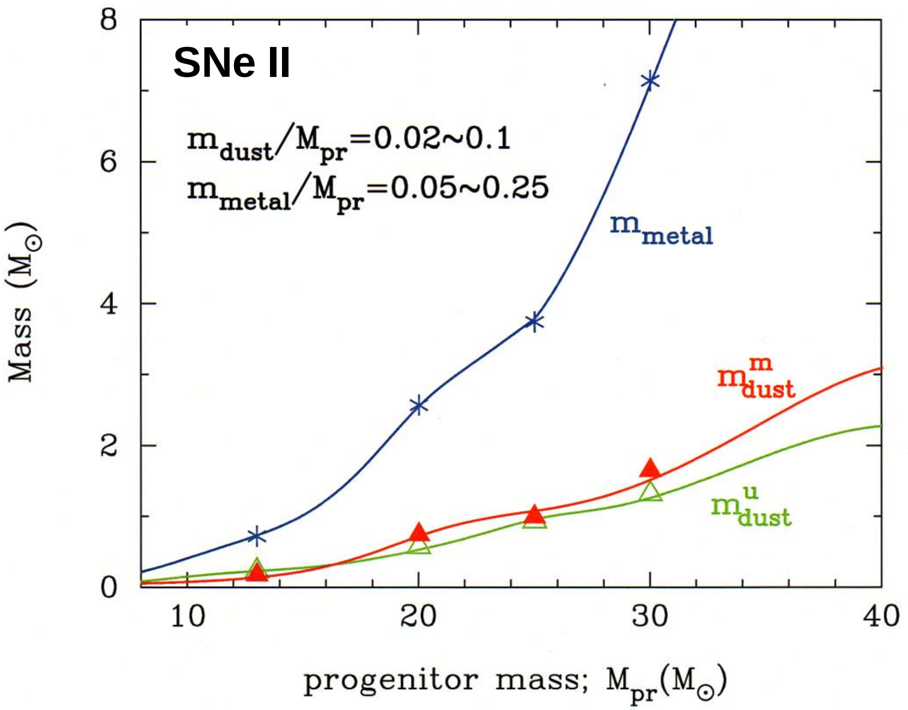


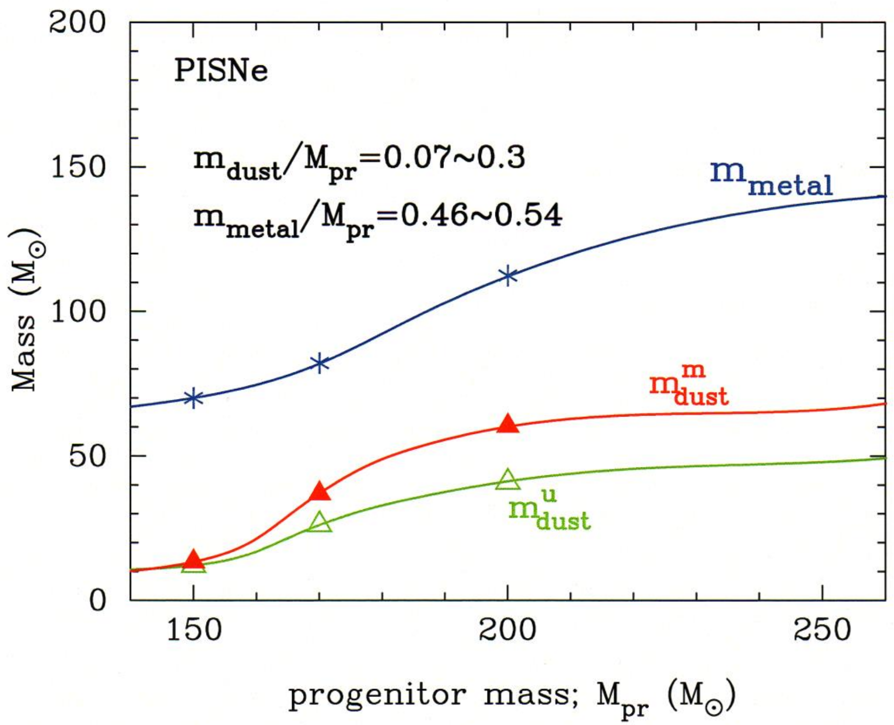
- C, SiO2, and Fe grains have lognormal-like size distribution, while the other grains have power-law size distribution

- 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

2-8. Total mass of dust formed in the ejecta



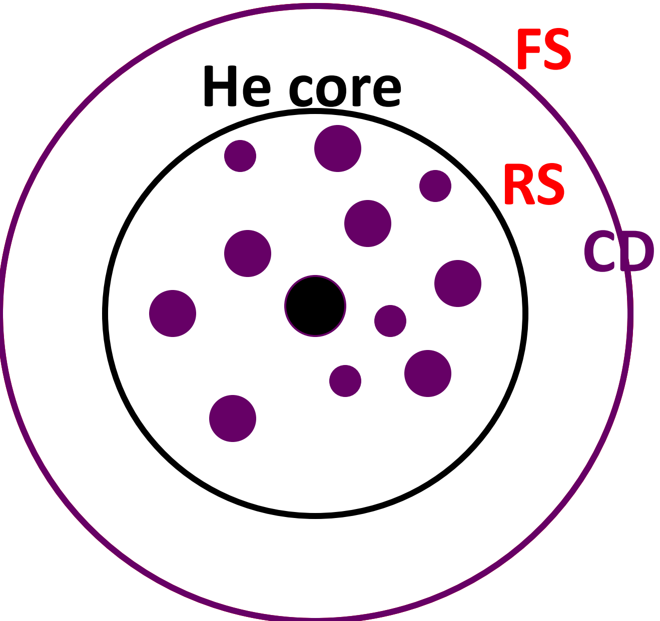


- Total mass of dust is higher for a higher progenitor mass ($M_{\rm ZAMS}$)
  SNe II : $m_{\rm dust}$ = 0.1-1.5 $M_{\rm sun}$, $m_{\rm dust}$ / $m_{\rm metal}$ = 0.2-0.3
  PISNe : $m_{\rm dust}$ = 10-30 $M_{\rm sun}$, $m_{\rm dust}$ / $m_{\rm metal}$ = 0.3-0.4

- 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)

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

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

$$\frac{\partial}{dt}\left(\frac{\rho v^2}{2} + \frac{P}{\gamma - 1}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left[\frac{\rho v^2}{2} + \frac{\gamma P}{\gamma - 1}\right] v\right)$$

$$= -(n_{\mathrm{e}} n_{\mathrm{H}} \Lambda_{\mathrm{gas}}(T) + \Lambda_{\mathrm{ic}}(T) + \Lambda_{\mathrm{d}}(n_{\mathrm{H}}, T))$$

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

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

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

$\Lambda_{\mathrm{d}}(n_{\mathrm{H}}, T)$: 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)

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

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

m_{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)

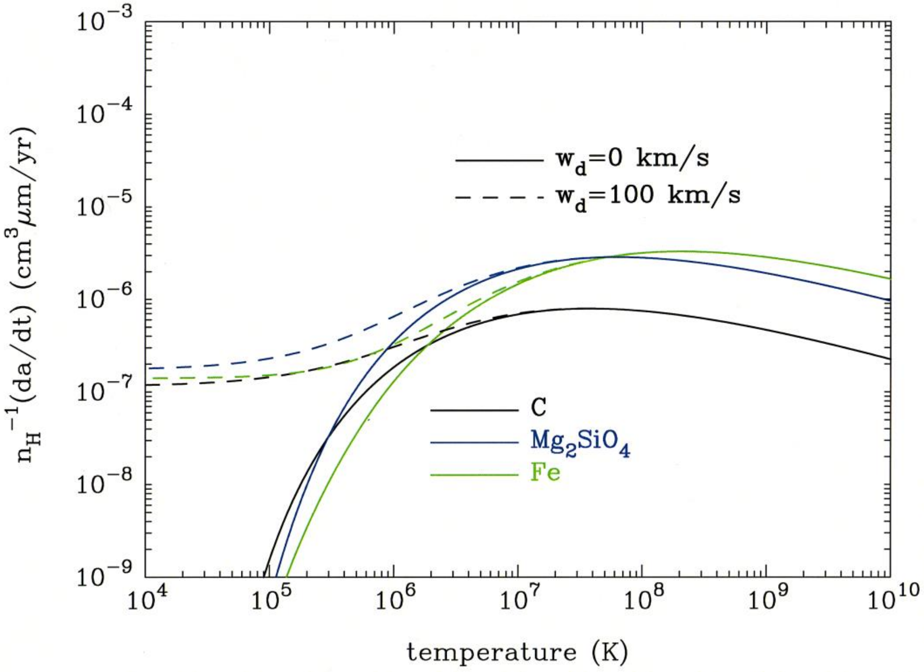
$$\mathcal{R}(X_i(\epsilon)) = n_{\mathrm{H}} A_i \pi a^2 \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} \frac{e^{-s_i^2}}{2s_i} \int \sqrt{\epsilon} e^{-\epsilon} \sinh(2s_i\sqrt{\epsilon}) X_i(\epsilon) d\epsilon$$

where $\epsilon = E/kT$

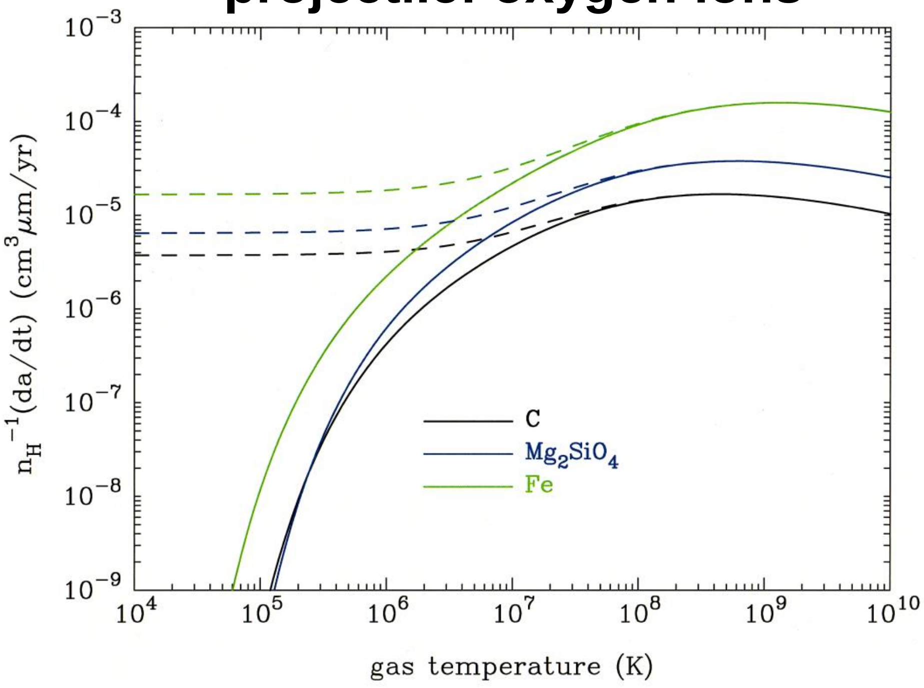
3-4. Erosion rate of dust by sputtering

Nozawa+2006, ApJ, 648, 435

projectile: H and He



projectile: oxygen ions

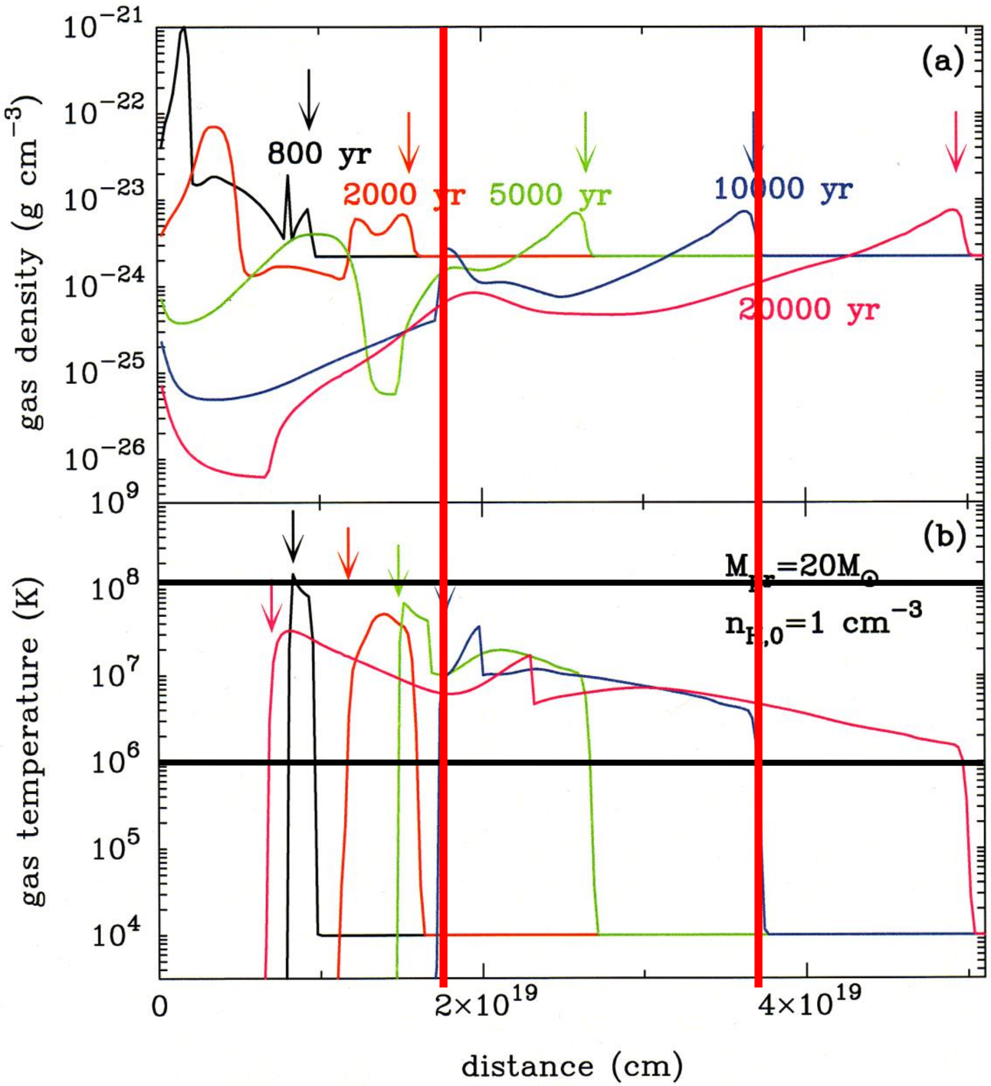


- erosion rate by sputtering quickly increases above 10^5 K and peaks at 10^7 -10^8 K

- erosion rate : $da / dt \sim 10^{-6} n_H$ μm 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



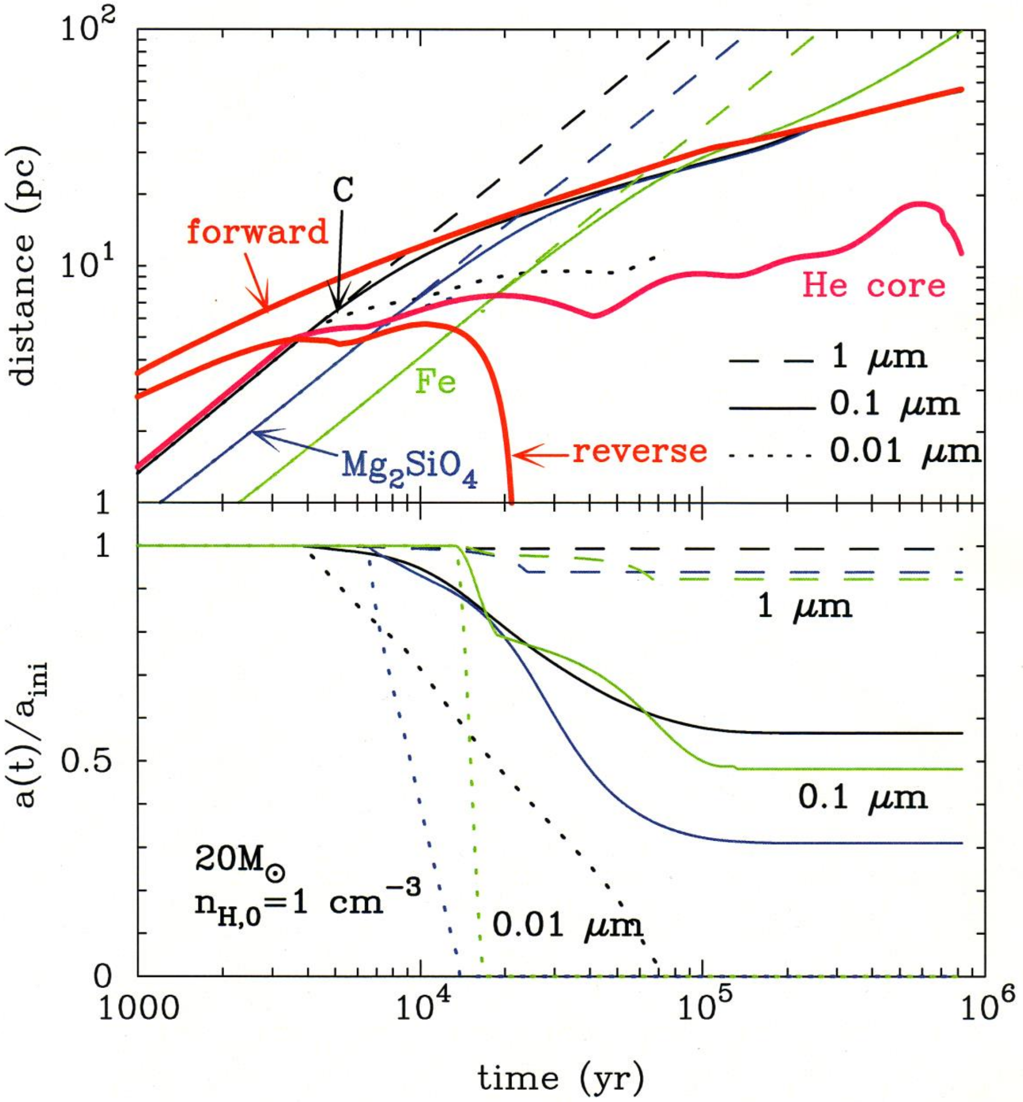
Model : M_{pr}= 20 Msun (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

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

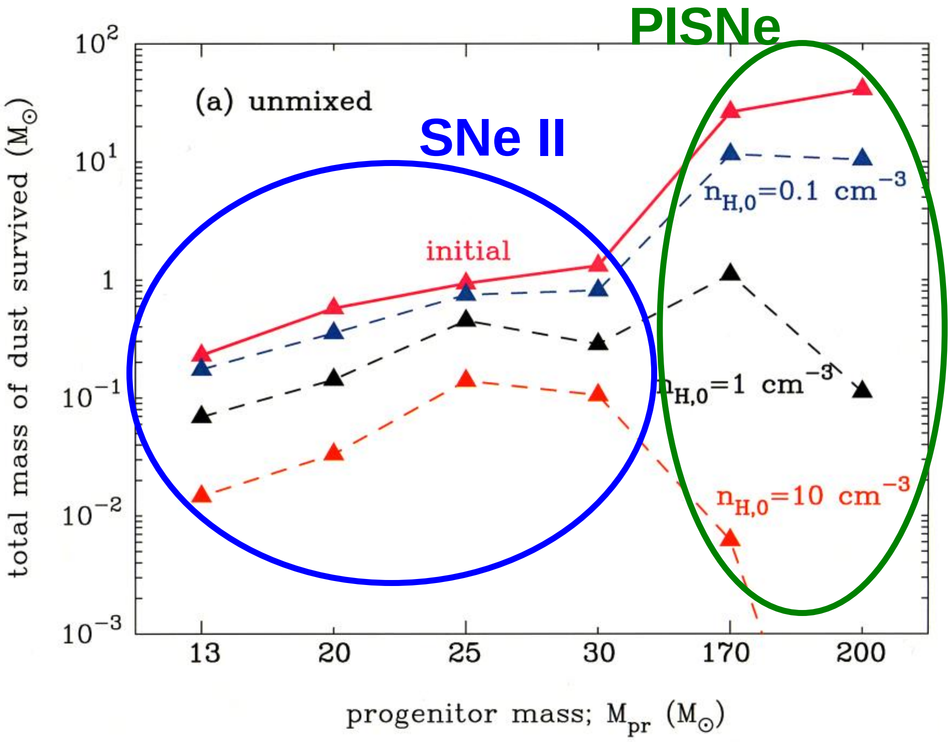
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed

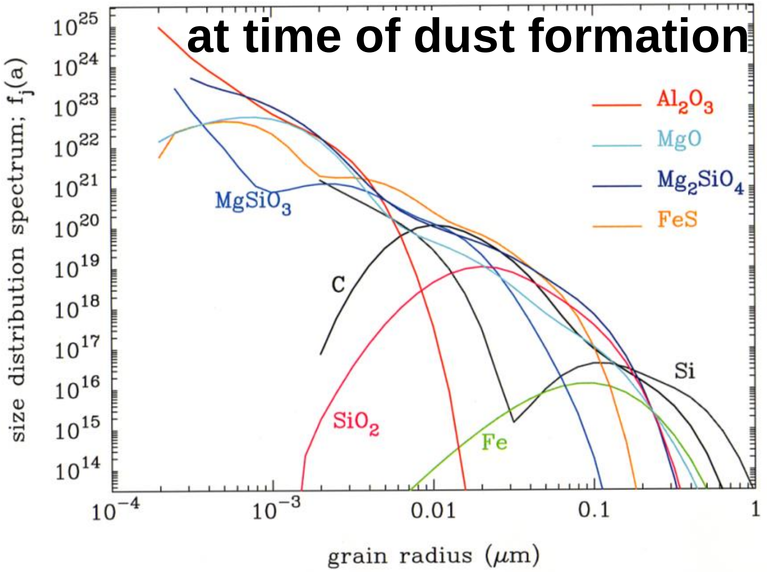
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell

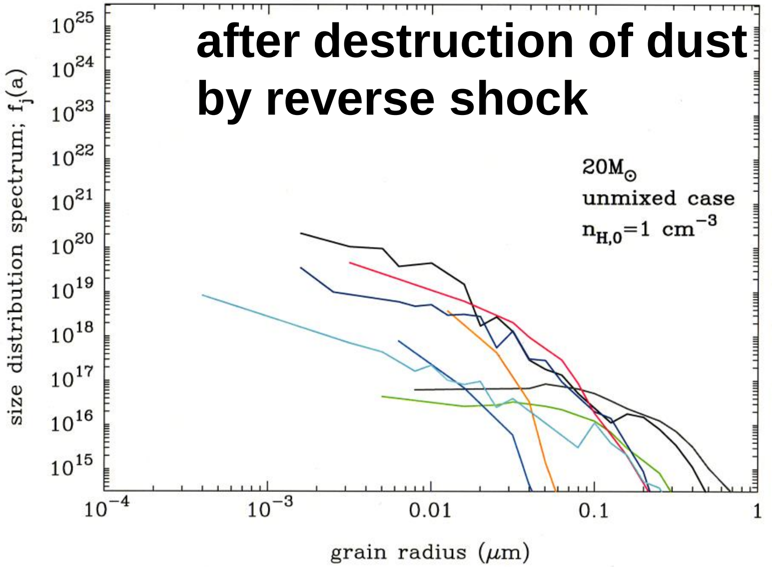
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

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

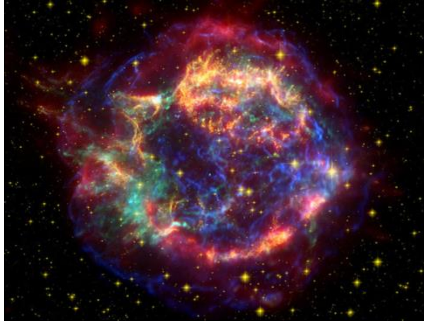
  for $n_{H,0} = 0.1\text{-}1\ \mathrm{cm}^{-3}$

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

  ➔ significant contribution to dust budget at high z

4. Dust Formation in Type IIb SNe

4-1. Dust formation in Type IIb SN

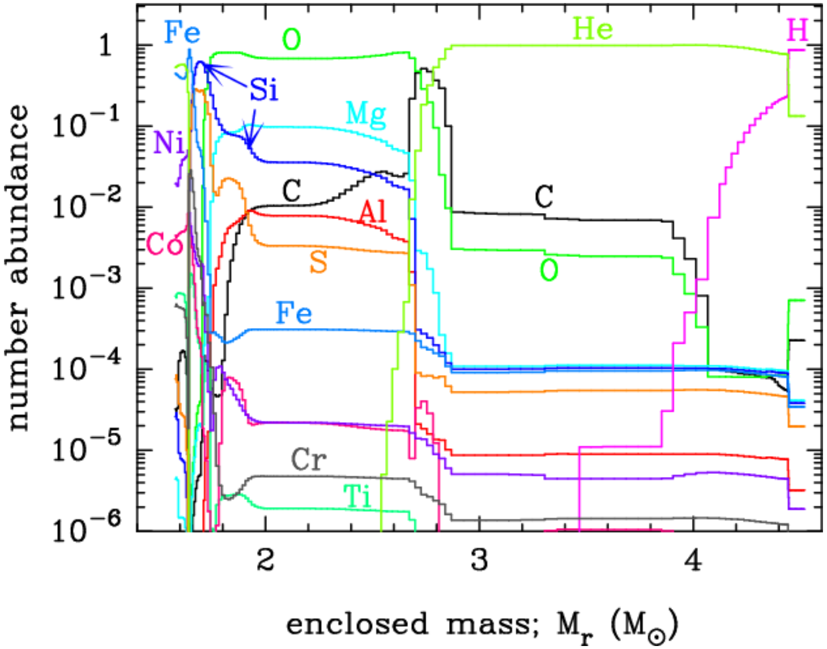


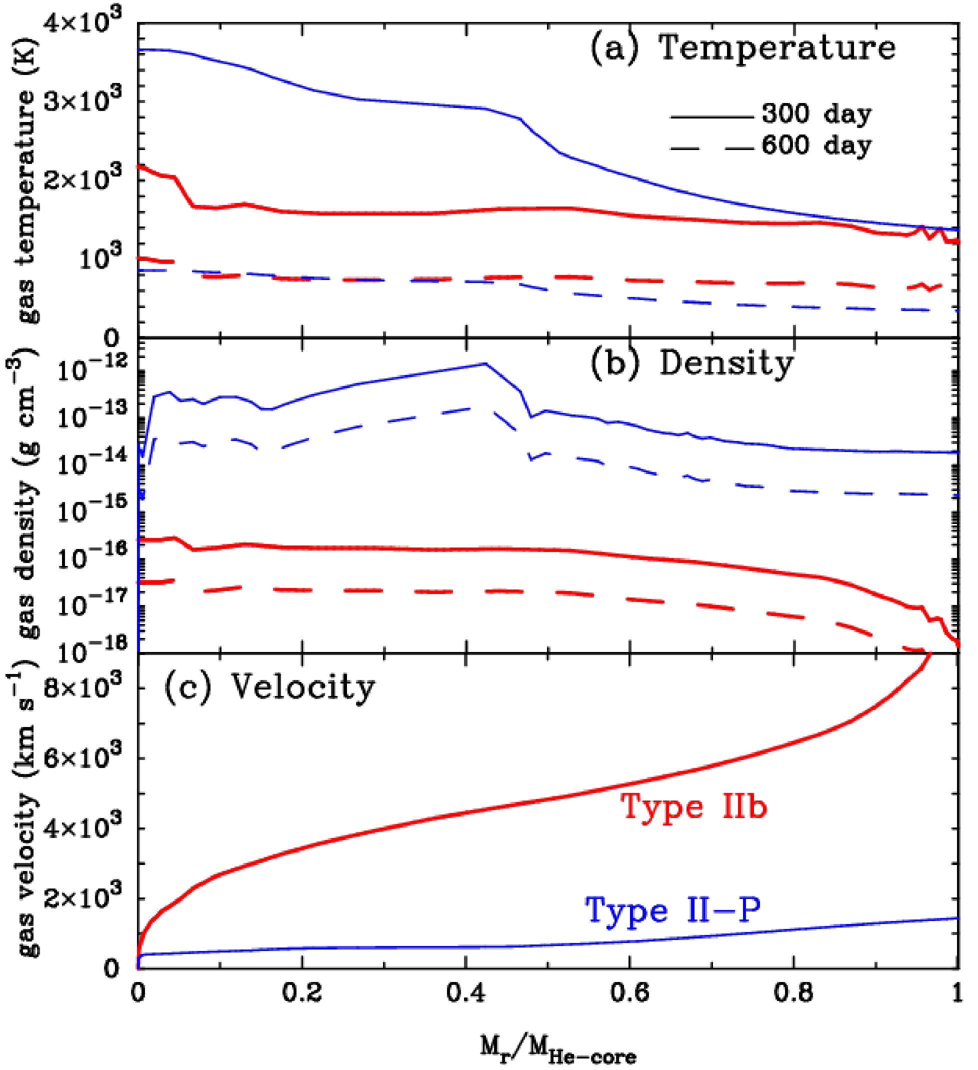
○ SN IIb model (SN1993J-like model)

- **$M_{\rm eje} = 2.94\ M_{\rm sun}$**

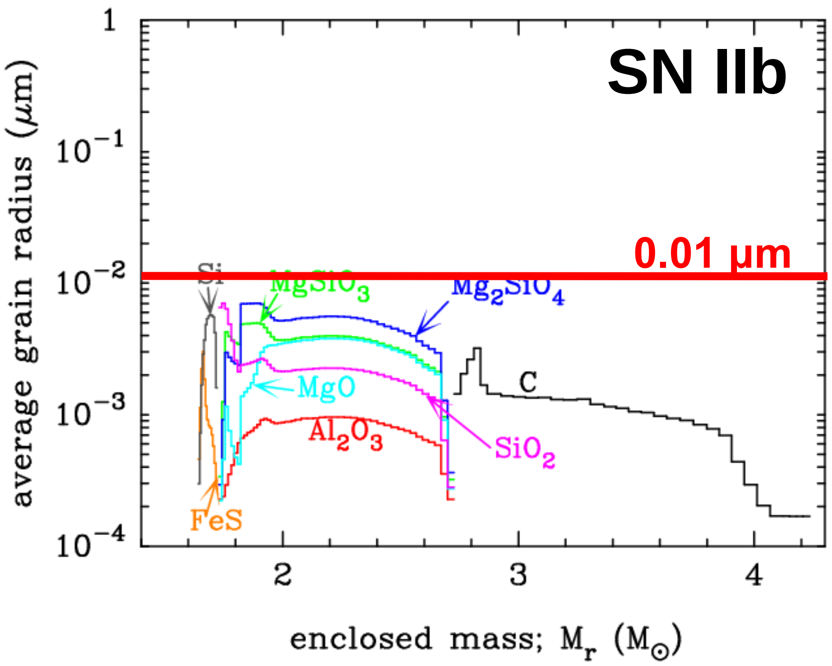
  $M_{\rm ZAMS} = 18\ M_{\rm sun}$

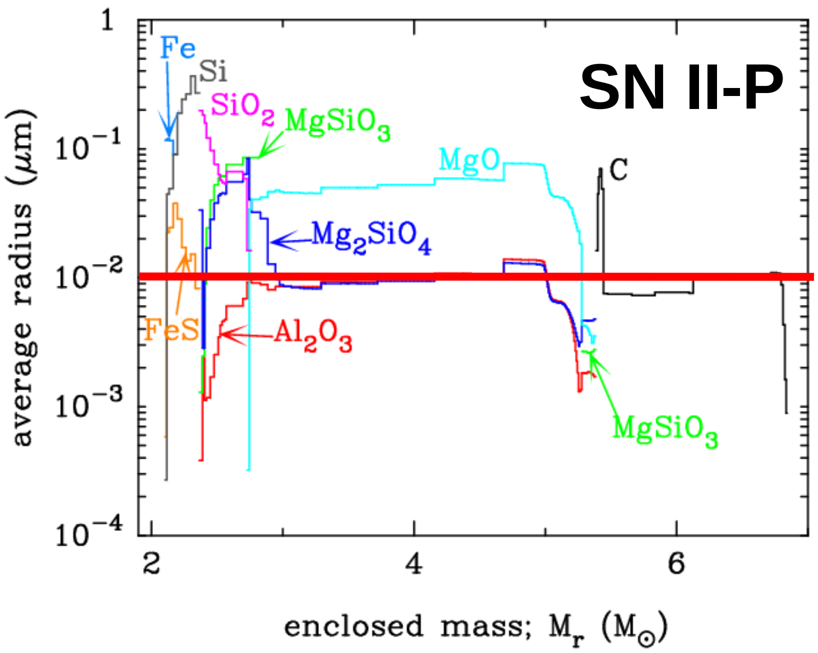
  $M_{\rm H\text{-}env} = 0.08\ M_{\rm sun}$
- **$E_{51} = 1$**
- **$M(^{56}{\rm Ni}) = 0.07\ M_{\rm sun}$**





4-2. Dependence of dust radii on SN type





- condensation time of dust 300-700 d after explosion

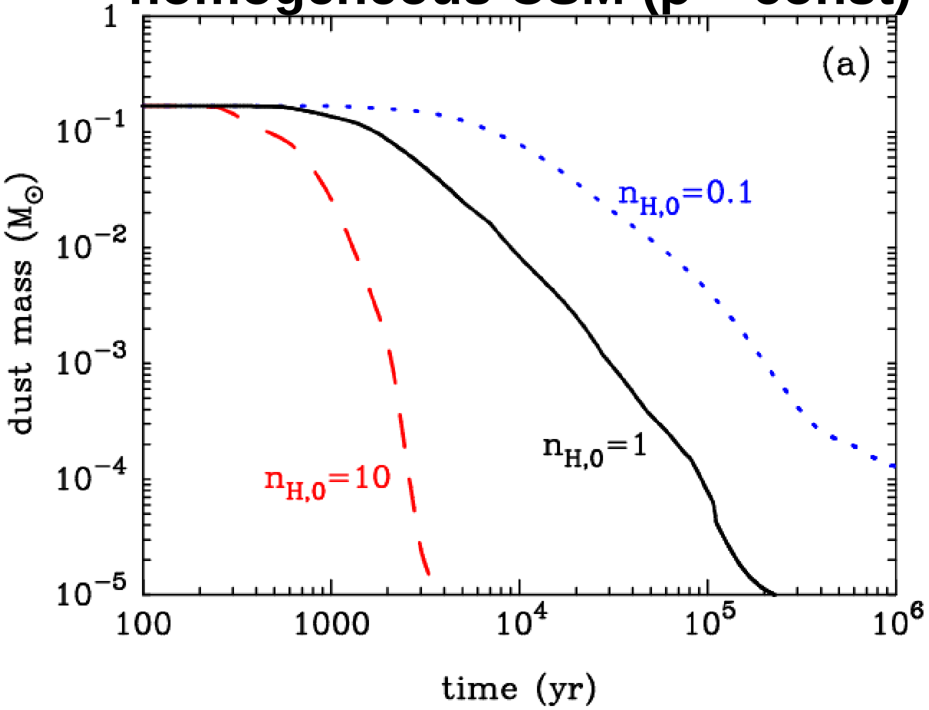
- total mass of dust formed
  - ・0.167 Msun in SN IIb
  - ・0.1-1 Msun in SN II-P

Nozawa+10, ApJ, 713, 356

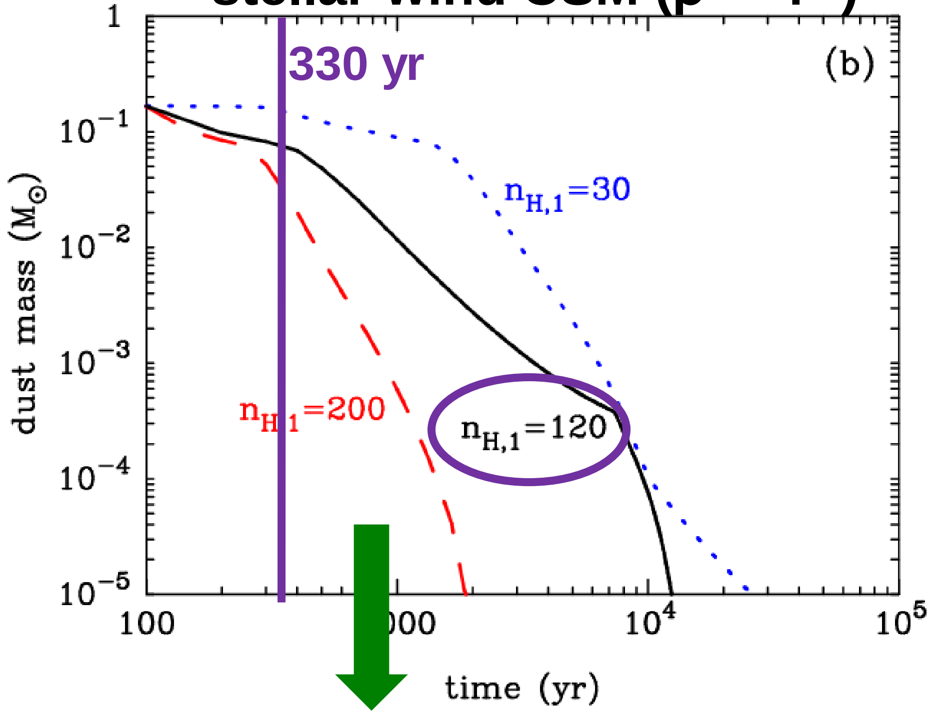
- the radius of dust formed in H-stripped SNe is small
  - ・SN IIb without massive H-env ➔ adust < 0.01 µm
  - ・SN II-P with massive H-env ➔ adust > 0.01 µm

4-3. Destruction of dust in Type IIb SNR

homogeneous CSM (ρ = const)



stellar-wind CSM (ρ ∝ r^{-2})



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

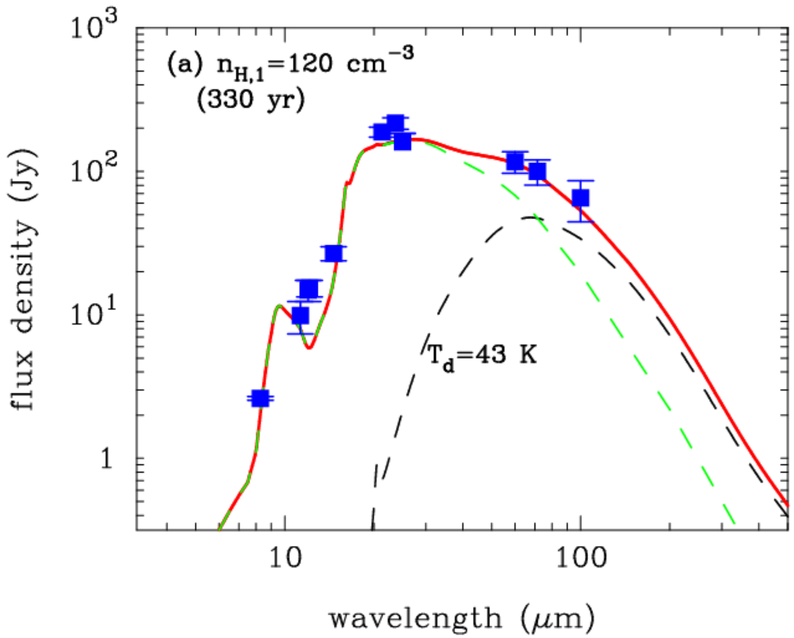
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

➔ small radius of newly formed dust

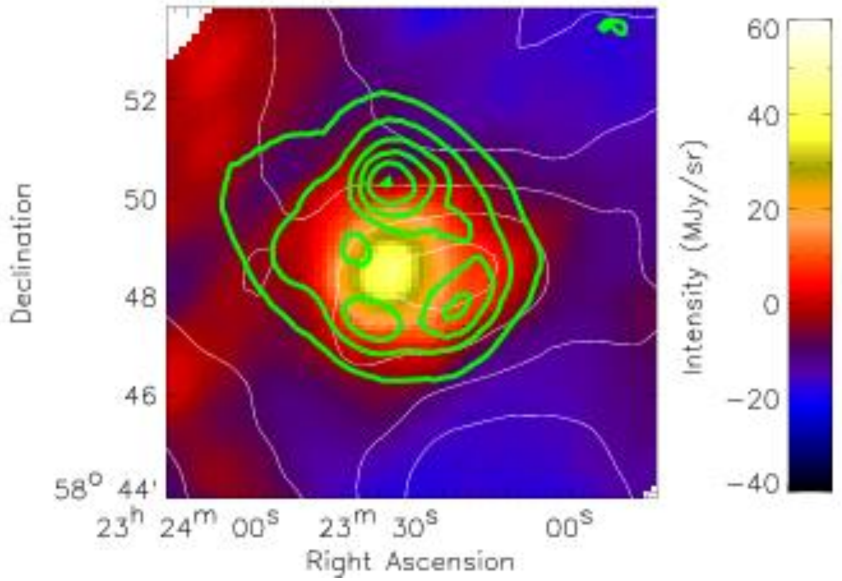
➔ early arrival of reverse shock at dust-forming region

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

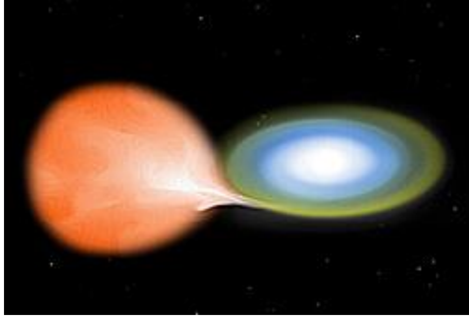
(Sibthorpe+10)

Herschel observation

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

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

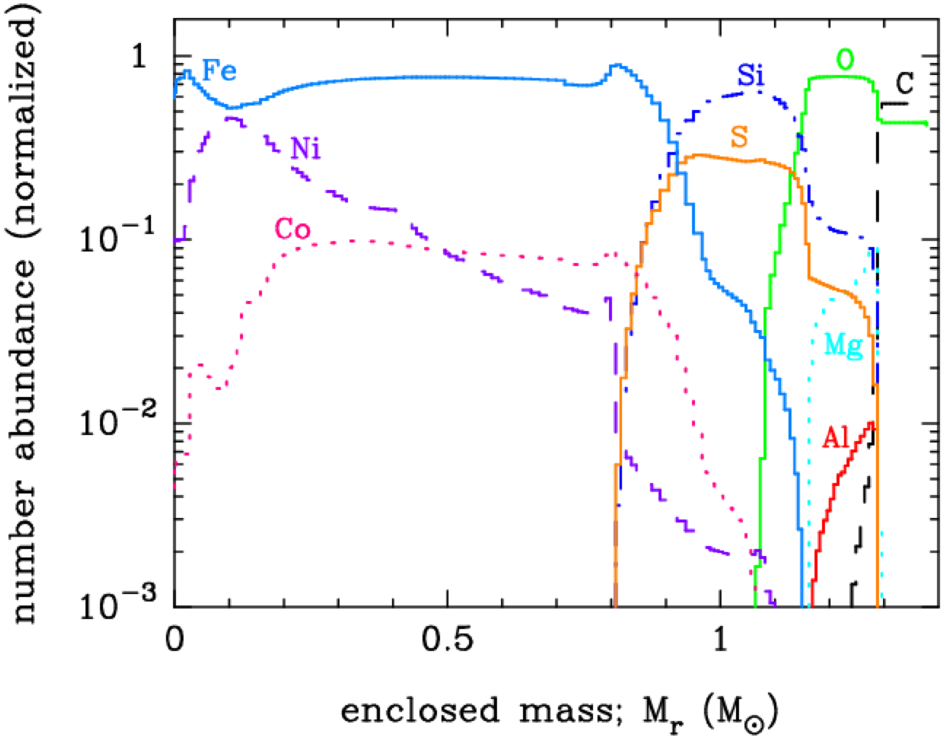
5-1. Dust formation in Type Ia SN

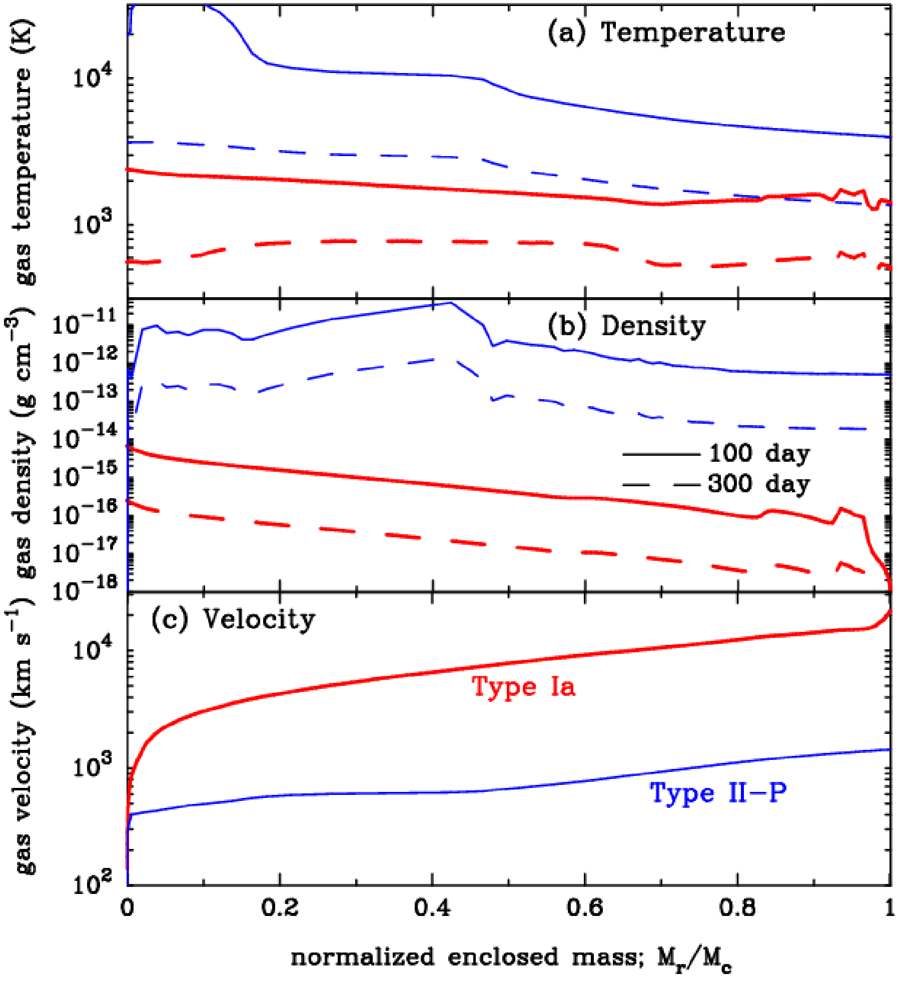


○ Type Ia SN model

W7 model (C-deflagration) (Nomoto+1984; Thielemann+1986)

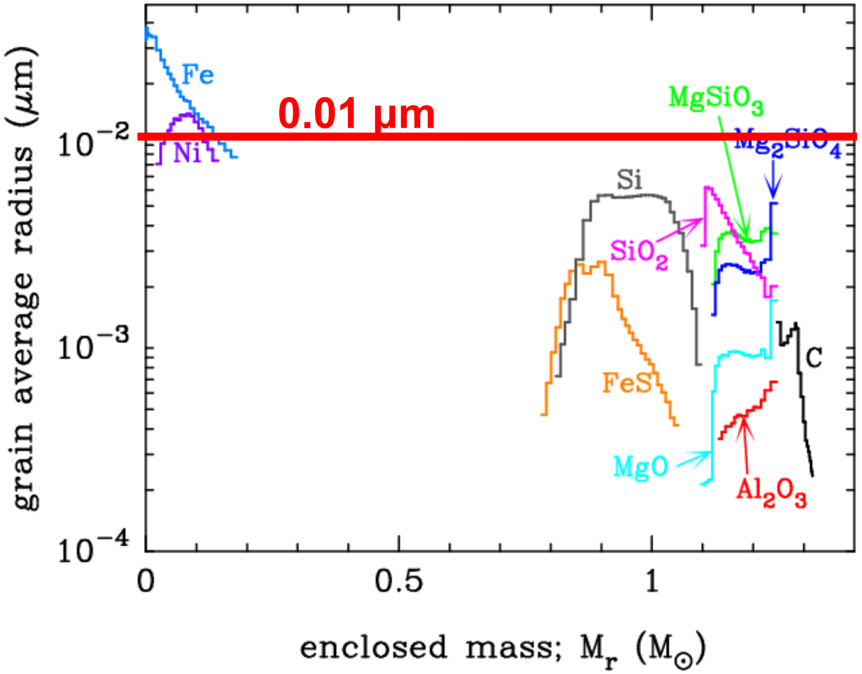
- M_{eje} = 1.38 Msun
- E_{51} = 1.3
- $M(^{56}Ni)$ = 0.6 Msun



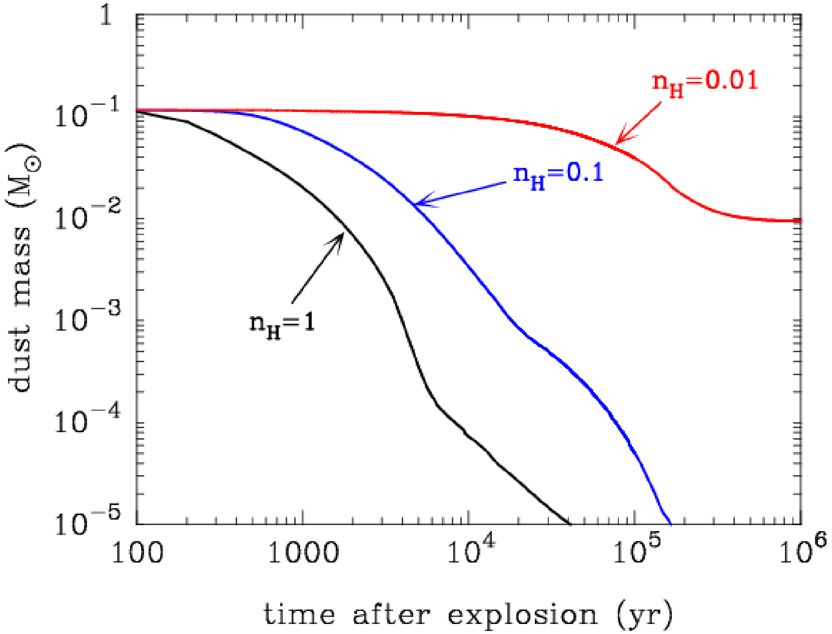


5-2. Dust formation and evolution in SNe Ia

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