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超新星ダストのサイズ分布

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Contents:

- Introduction
- Dust formation in supernovae (SNe)
- Dust destruction by SN reverse shocks
- Observations of dust size (distribution) in SNe

1-1. Introduction

○ Supernovae (SNe) are major sources of dust?

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

➔

- mass-loss winds of AGB stars
- expanding ejecta of SNe

- contribution of dust mass from AGB stars and SNe

N(AGB stars) / N(SNe) ~ 10-20 (Salpeter IMF)

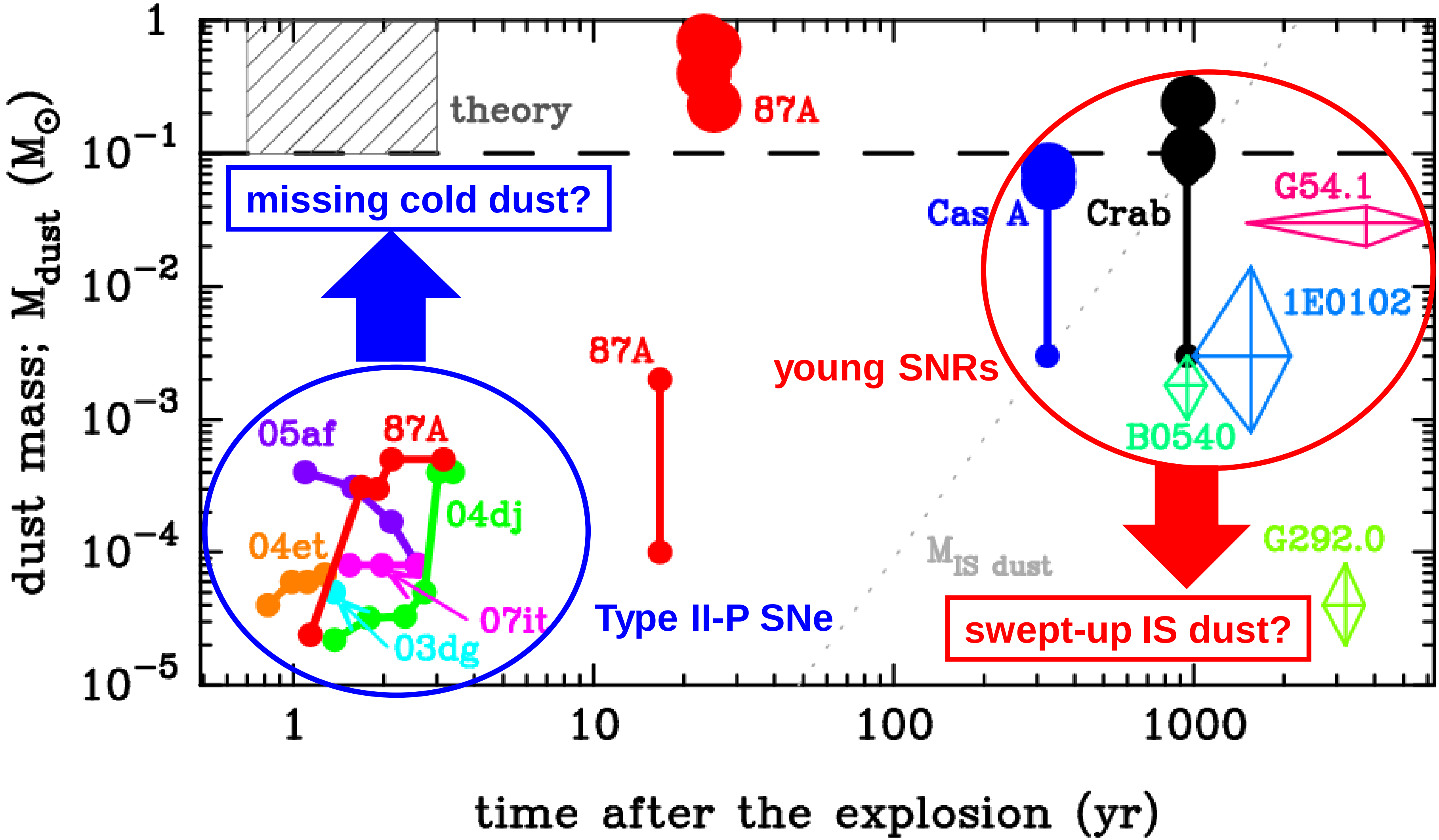
M_{dust} = 0.01-0.05 M_{sun} per AGB star (e.g., Zhukovska & Gail 2008)
M_{dust} = 0.1-1.0 M_{sun} per SN (e.g., Nozawa+2003, 2007)

- huge amounts of dust grains (>10^8 M_{sun}) at redshift z > 5

➔ 0.1 M_{sun} of dust per SN is needed to be ejected (Dwek+2007)

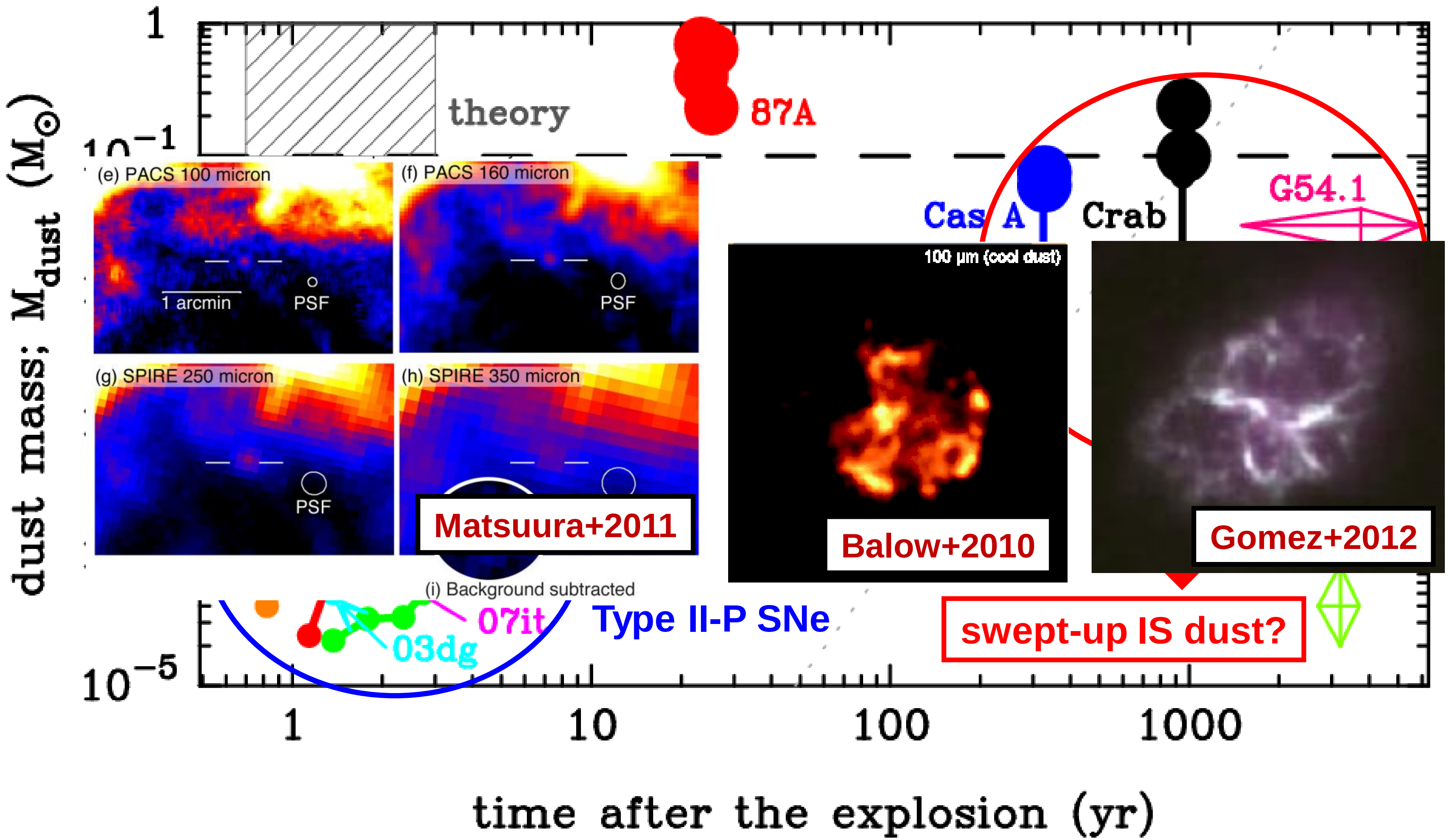
what composition, size, and mass of dust are ejected by SNe?

1-2. 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

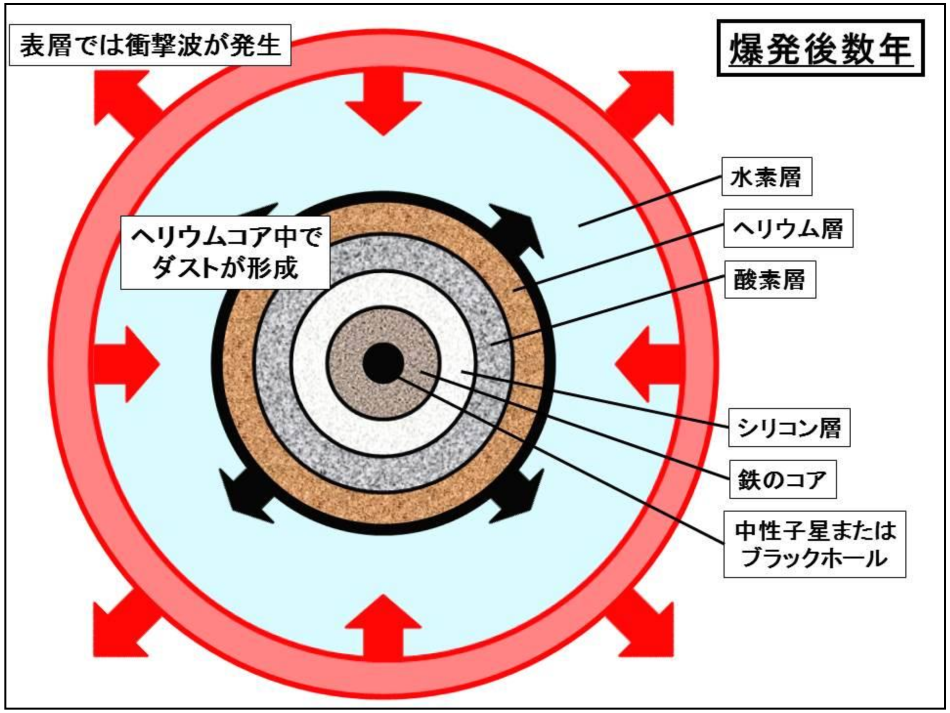
1-2. Summary of observed dust mass in CCSNe

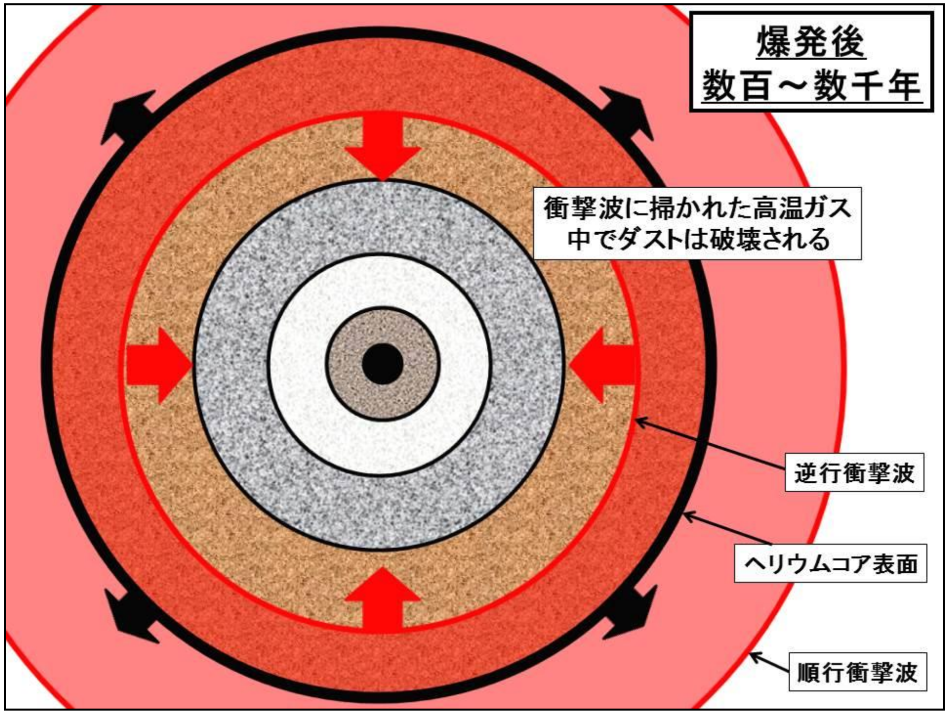


There are increasing pieces of evidence that massive dust in excess of 0.1 Msun is formed in the ejecta of SNe

1-3. 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

1-4. Achievement and issues on SN dust

○ これまでの研究でわかったこと

（重力崩壊型）超新星は、放出ガス中で**大量（0.1 Msun以上）のダストを形成する**ことができる

⬇

○ 超新星ダスト研究における現在の二つの課題

1) 観測された大量の**ダストはいつ形成されたのか？**

➜ 中間赤外線と遠赤外線でのダスト量の違いを説明したい

2) 形成される**ダストのサイズはどれくらいか？**

➜ 超新星によるの最終的なダスト放出量を明らかにしたい

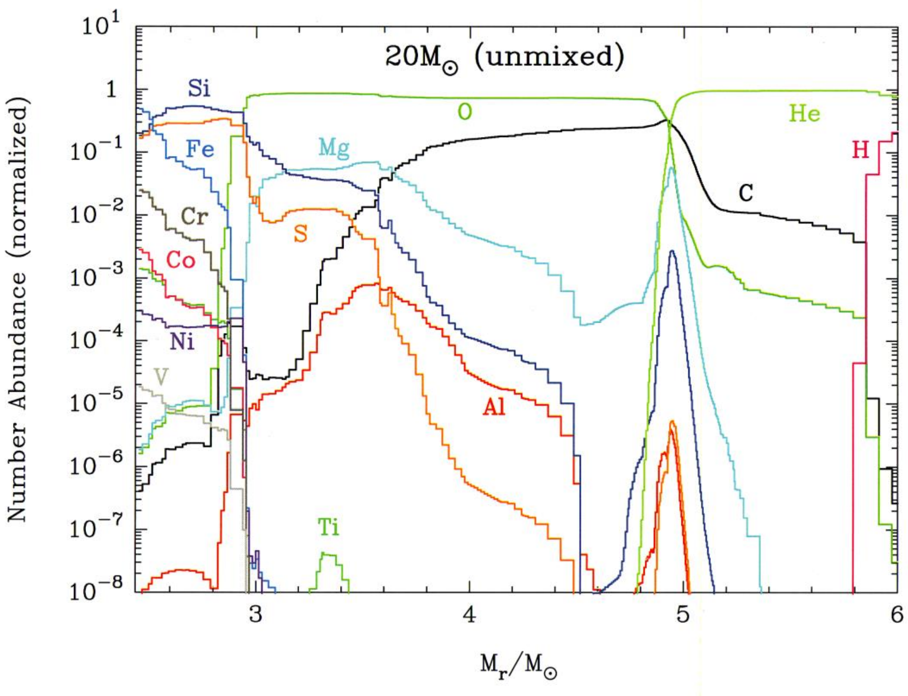
2. Size and mass of dust formed in core-collapse supernovae

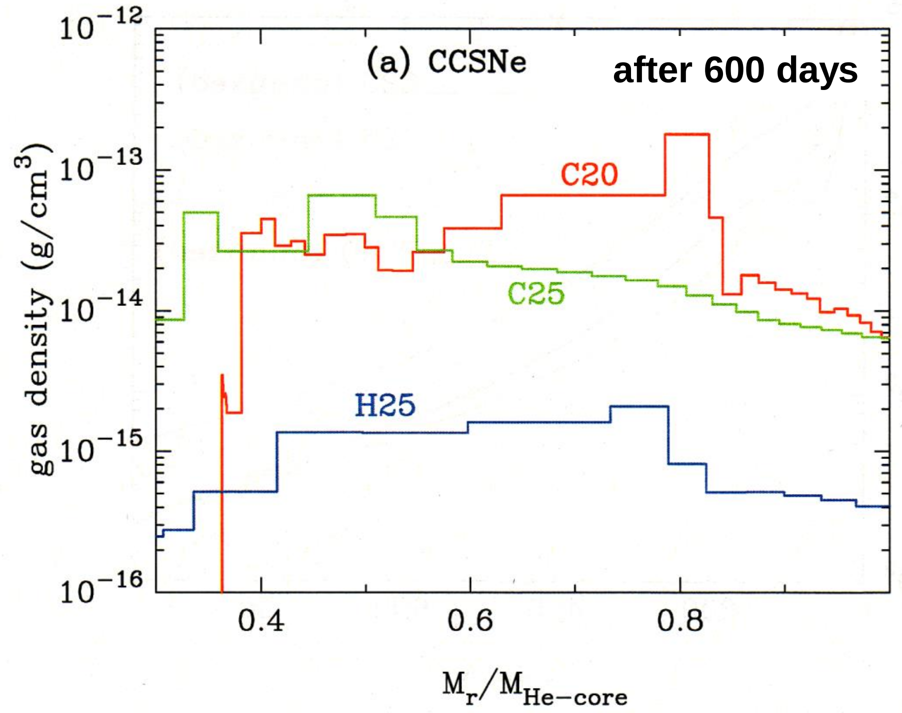
2-1. Dust formation in primordial SNe

Nozawa+2003, ApJ, 598, 785

○ SN model (Population III SNe) (Umeda & Nomoto 2002)

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





- **layered elemental distribution in the metal-rich He core**
- **no mixing of elements within the He-core**
- **gas density: ρ ~ 10^{-14}-10^{-13} g/cm3 ➜ n ~ 10^{8}-10^{10} /cm3**

2-2-1. Grain species considered in this study

○ dust formation theory

- nucleation
- grain growth

taking account of chemical reaction at condensation

key species: gas species with the least collision frequency among reactants

key species controls the kinetics of the nucleation and grain growth

Dust species	Chemical reactions
$Fe_{(s)}$	$Fe_{(g)} \rightarrow Fe_{(s)}$
$FeS_{(s)}$	$Fe_{(g)} + S_{(g)} \rightarrow FeS_{(s)}$
$Si_{(s)}$	$Si_{(g)} \rightarrow Si_{(s)}$
$Ti_{(s)}$	$Ti_{(g)} \rightarrow Ti_{(s)}$
$V_{(s)}$	$V_{(g)} \rightarrow V_{(s)}$
$Cr_{(s)}$	$Cr_{(g)} \rightarrow Cr_{(s)}$
$Co_{(s)}$	$Co_{(g)} \rightarrow Co_{(s)}$
$Ni_{(s)}$	$Ni_{(g)} \rightarrow Ni_{(s)}$
$Cu_{(s)}$	$Cu_{(g)} \rightarrow Cu_{(s)}$
$C_{(s)}$	$C_{(g)} \rightarrow C_{(s)}$
$SiC_{(s)}$	$Si_{(g)} + C_{(g)} \rightarrow SiC_{(s)}$
$TiC_{(s)}$	$Ti_{(g)} + C_{(g)} \rightarrow TiC_{(s)}$
$Al_2O_{3(s)}$	$2Al_{(g)} + 3O_{(g)} \rightarrow Al_2O_{3(s)}$
$MgSiO_{3(s)}$	$Mg_{(g)} + SiO_{(g)} + 2O_{(g)} \rightarrow MgSiO_{3(s)}$
$Mg_2SiO_{4(s)}$	$2Mg_{(g)} + SiO_{(g)} + 3O_{(g)} \rightarrow Mg_2SiO_{4(s)}$
$SiO_{2(s)}$	$SiO_{(g)} + O_{(g)} \rightarrow SiO_{2(s)}$
$MgO_{(s)}$	$Mg_{(g)} + O_{(g)} \rightarrow MgO_{(s)}$
$Fe_3O_{4(s)}$	$3Fe_{(g)} + 4O_{(g)} \rightarrow Fe_3O_{4(s)}$
$FeO_{(s)}$	$Fe_{(g)} + O_{(g)} \rightarrow FeO_{(s)}$

2-2-2. Nucleation rate

Steady-state nucleation rate

$$J_s(t) = \alpha_s \Omega \left(\frac{2\sigma}{\pi m_1} \right)^{\frac{1}{2}} \Pi c_1^2(t) \exp \left[-\frac{4}{27} \frac{\mu^3}{(\ln S)^2} \right]$$

Supersaturation ratio

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

α_s : sticking probability of key species ($\alpha_s = 1$, in the calculations)

Ω : volume of the condensate per key species ($\Omega = 4\pi a_0^3/3$)

σ : surface energy of the condensate

m_1 : mass of key species

$c_1(t)$: number density of key species

μ : $\mu \equiv 4\pi a_0^2 \sigma / kT$; energy barrier for nucleation

2-2-3. Basic equations for dust formation

▪ Equation of mass conservation

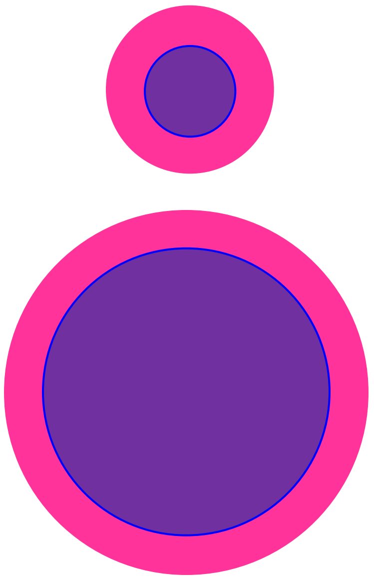
$$c_{10} - c_1 = \int_{t_0}^{t} J_{n_*}(t') \frac{a^3(t,t')}{a_0^3} dt',$$

▪ Equation of grain growth

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

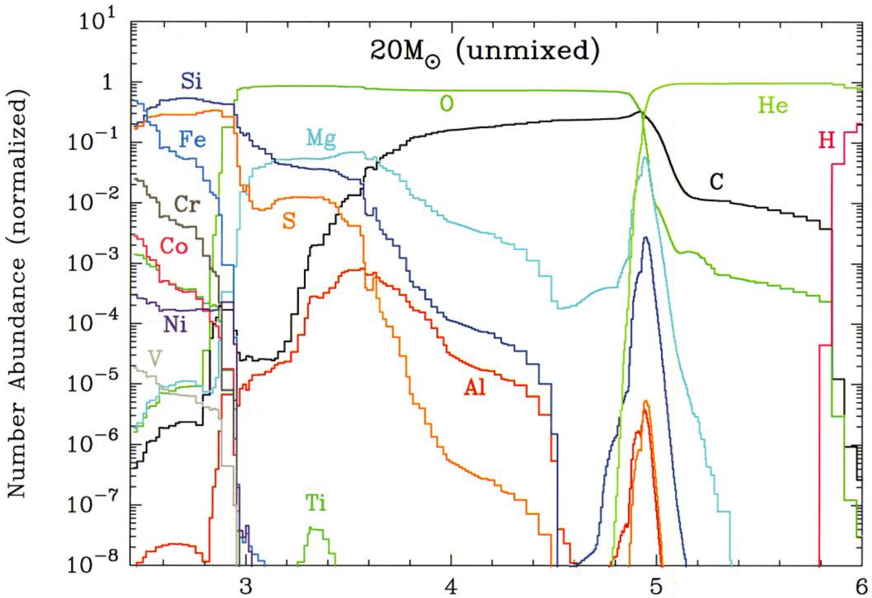
⬆

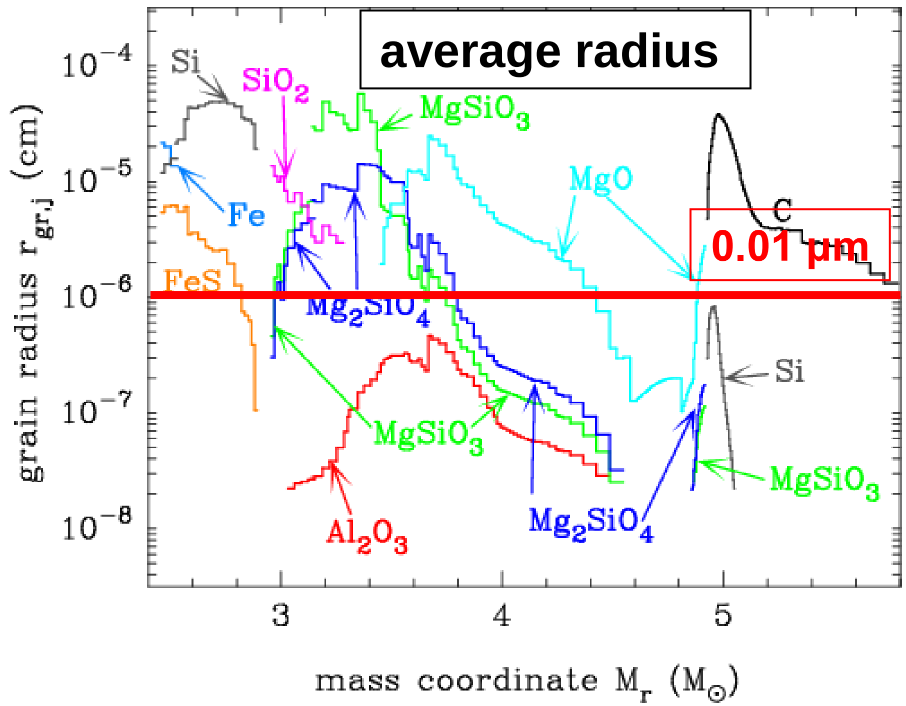
$$\frac{dV}{dt} = s\Omega_0 \, 4\pi a^2 \left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S}\right),$$

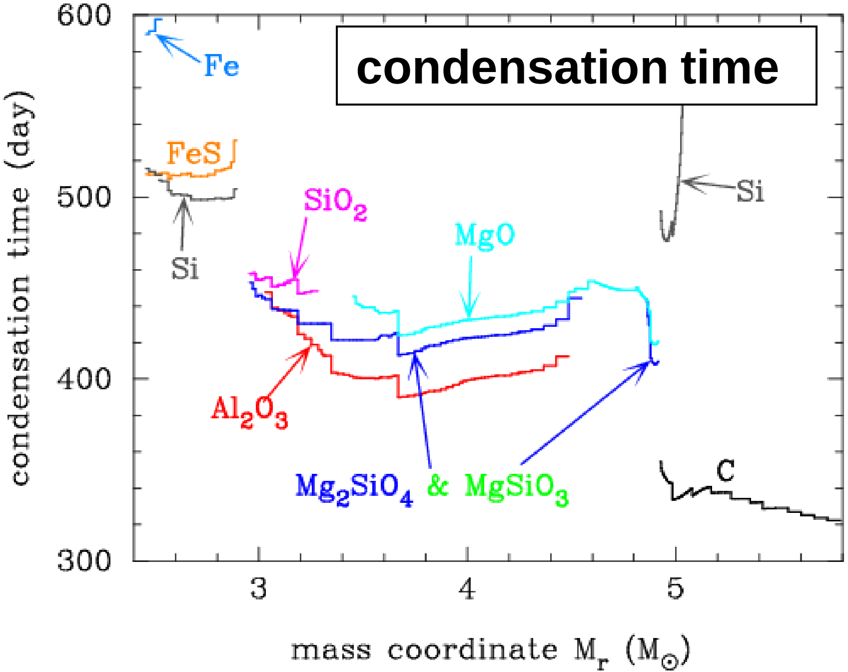


Growth rate is independent of grain radius

2-3. Dust formed in Type II-P SNe





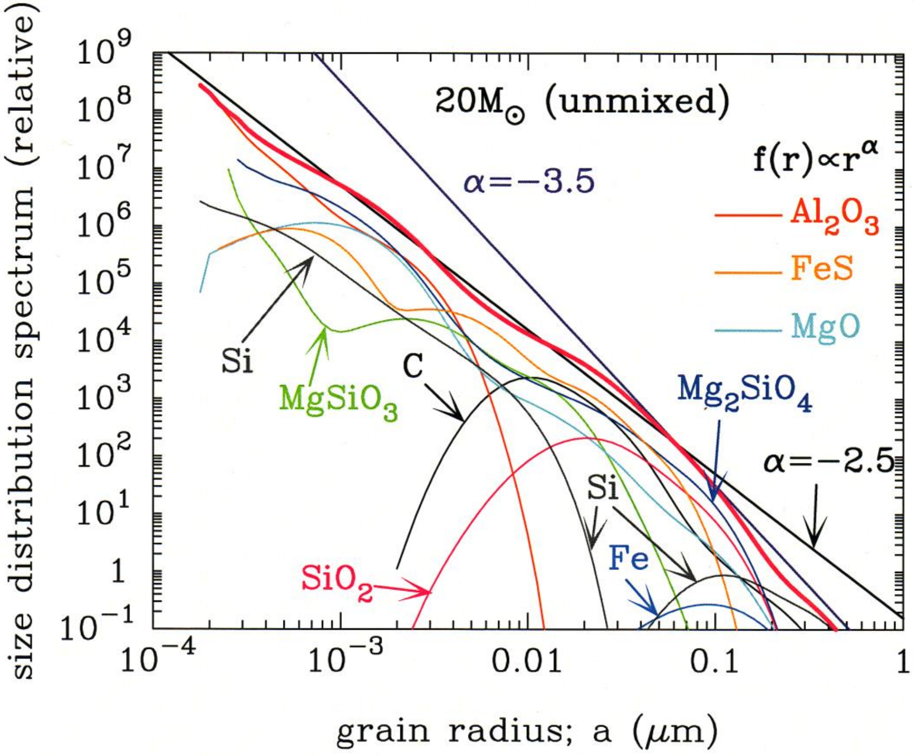


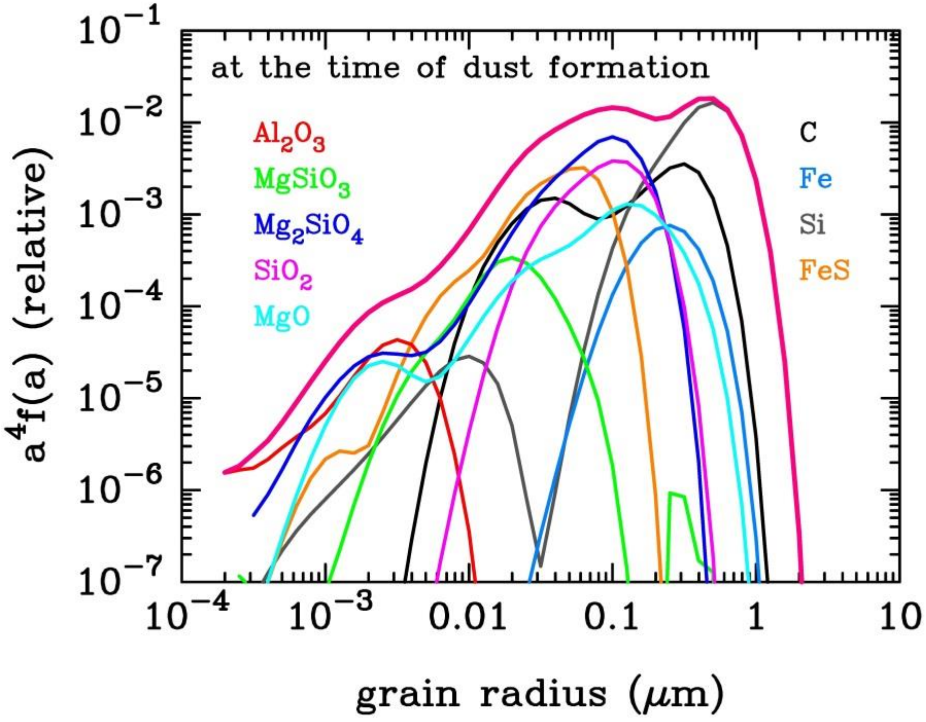
- a variety of grain species can condense according to elemental composition in each layer
- condensation time: **300-600d** after explosion
- average grain radii: **>~0.01 μm**

Nozawa+03, ApJ, 598, 785

2-5. Size distribution of newly formed dust

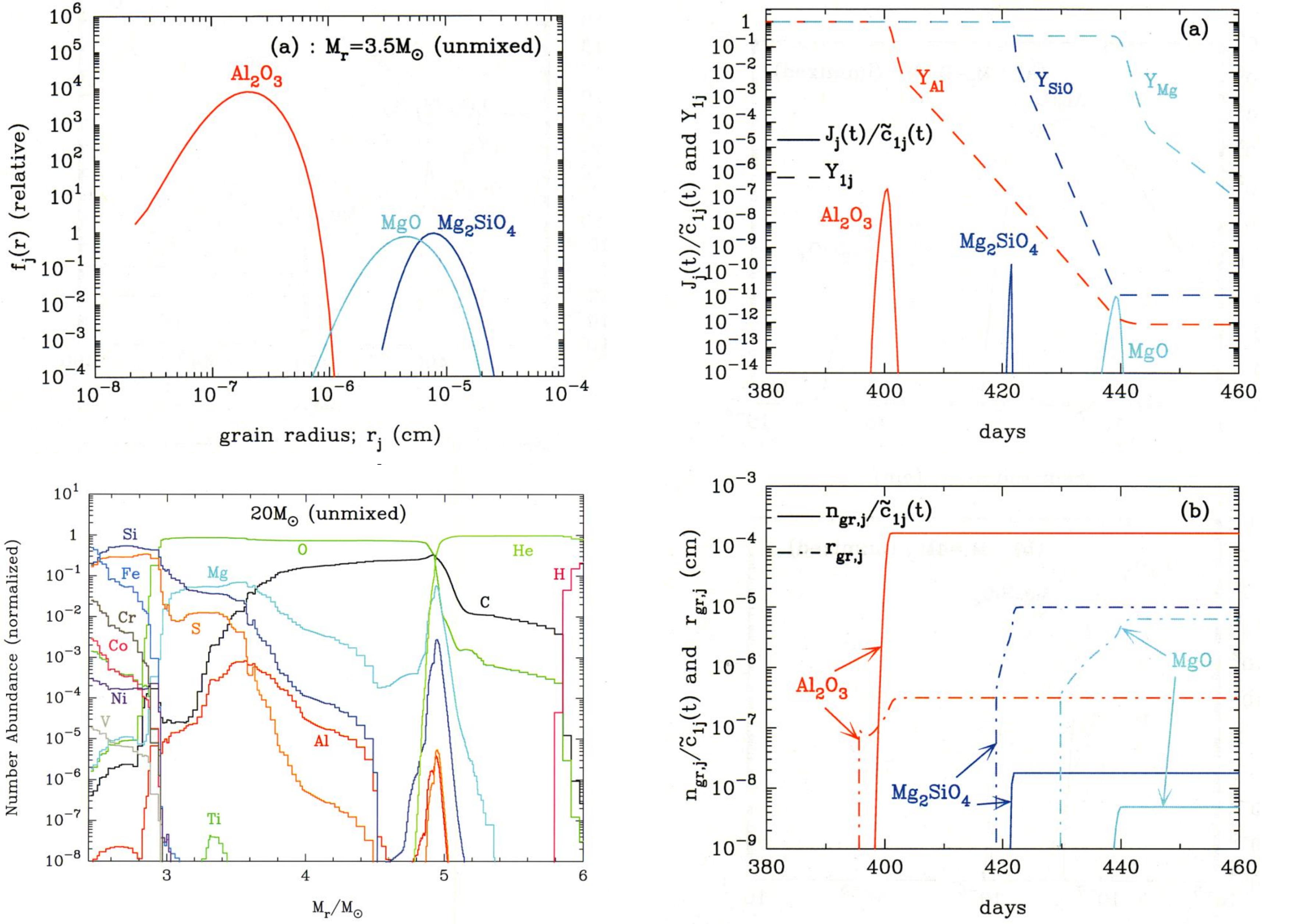
Nozawa+2003, ApJ, 598, 785





- C, SiO2, and Fe grains have lognormal-like size distribution, while the other grains have power-law size distribution
- Size distribution summed up over all grain species is roughly described by a broken power-law with the index of -2.5 and -3.5
- Size distribution of dust in mass has a peak around 0.1-1 μm

2-4. Behavior of dust formation



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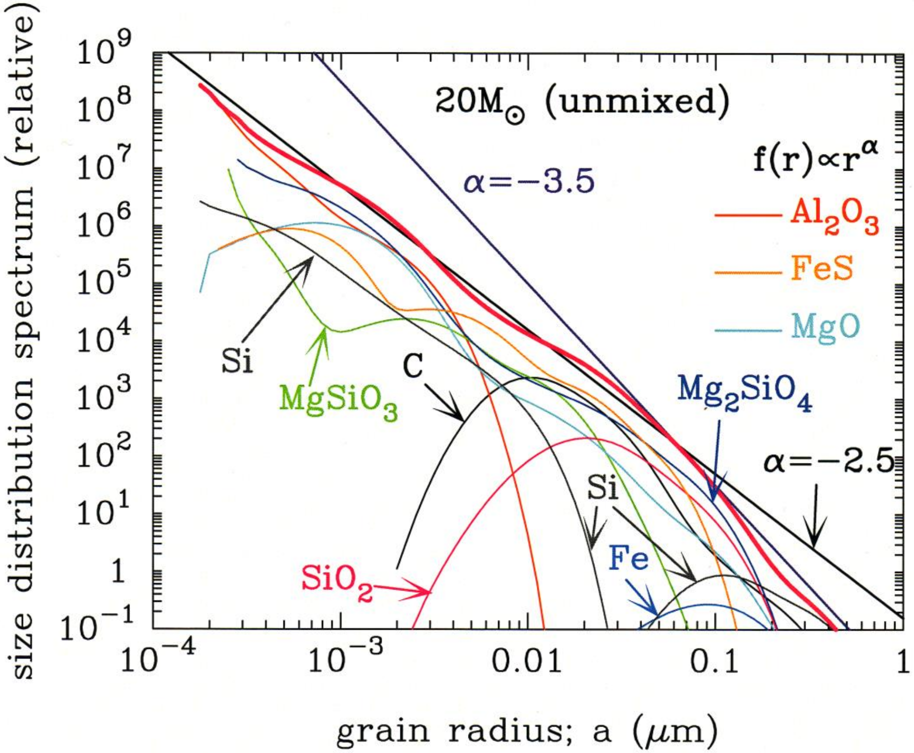
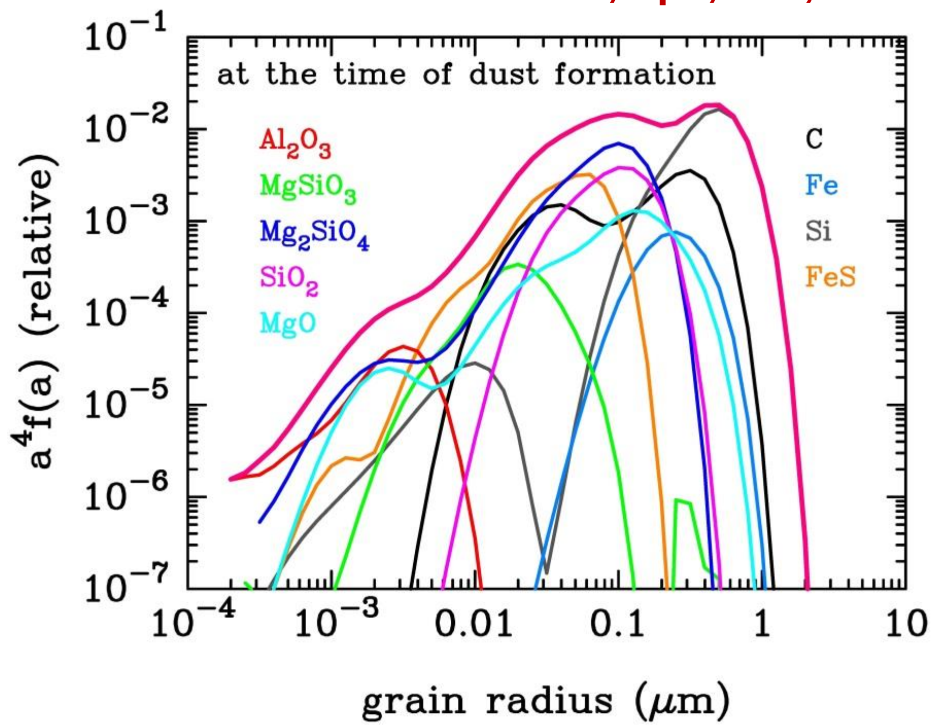
Nozawa+2003, ApJ, 598, 785





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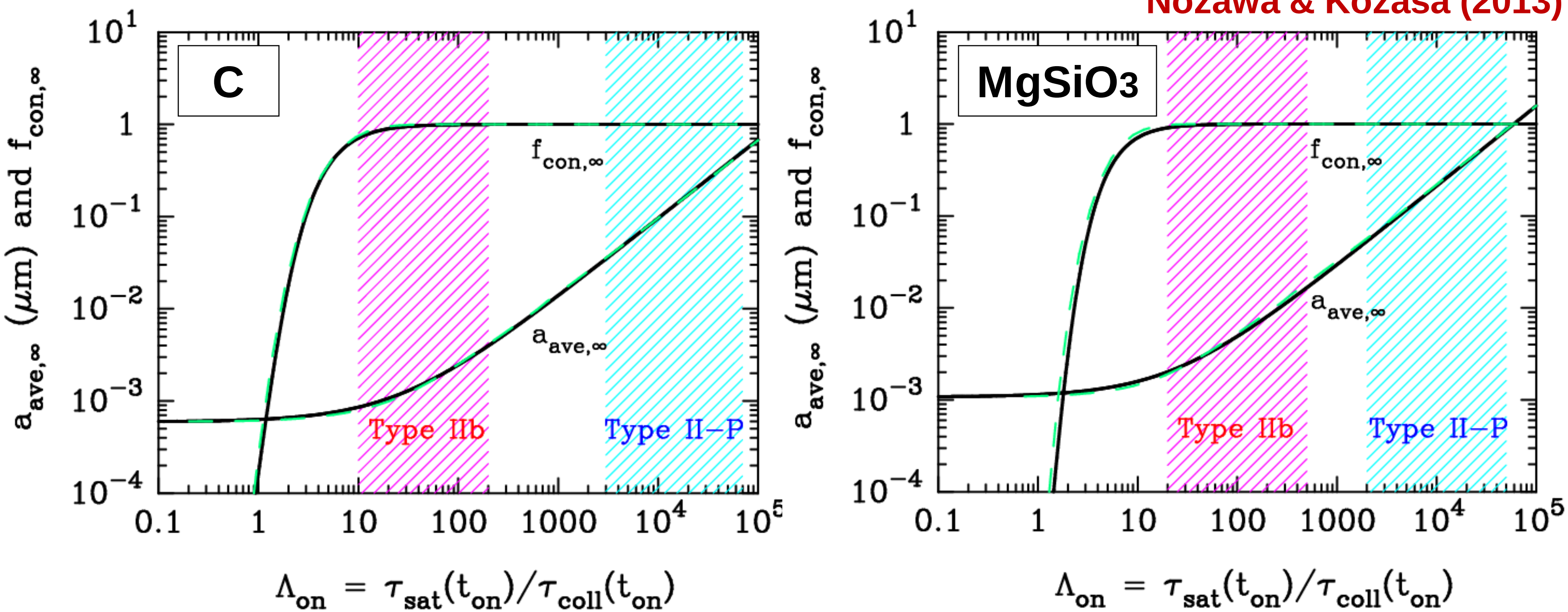
2-6. Scaling relation of average grain radius

Nozawa & Kozasa (2013)



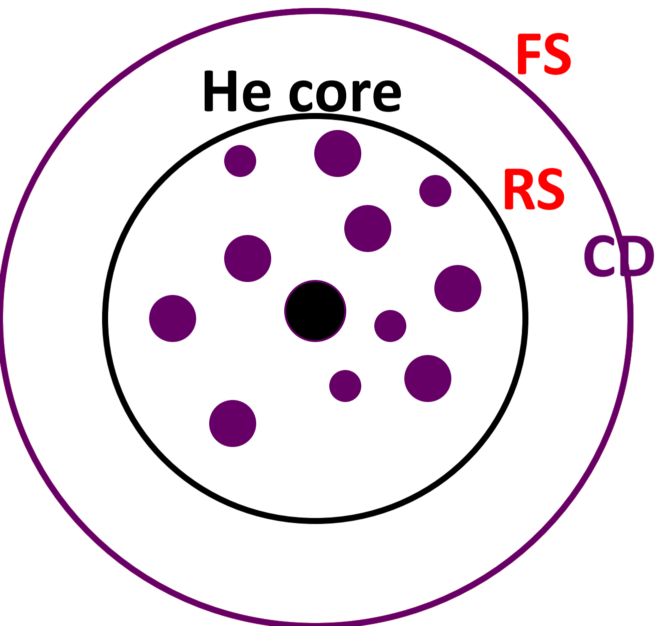
$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: ratio of supersaturation timescale to gas collision timescale at the onset time (t_{on}) of dust formation

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

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

3. Destruction of dust grains by SN reverse shocks

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



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)

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

$$F_\mathrm{drag} = m_\mathrm{d}\frac{dw_\mathrm{d}}{dt} = -\pi a^2 \sum n_i \langle v_i m_i v_i \cos\theta \rangle$$

$$\frac{dw_\mathrm{d}}{dt} = -\frac{\pi a^2}{\frac{4}{3}\pi a^3 \rho_d} n_\mathrm{H} \sum A_i \langle v_i m_i v_i \cos\theta \rangle$$

$$= -\frac{3n_\mathrm{H}}{4a\rho_d} kT \sum A_i G_i$$

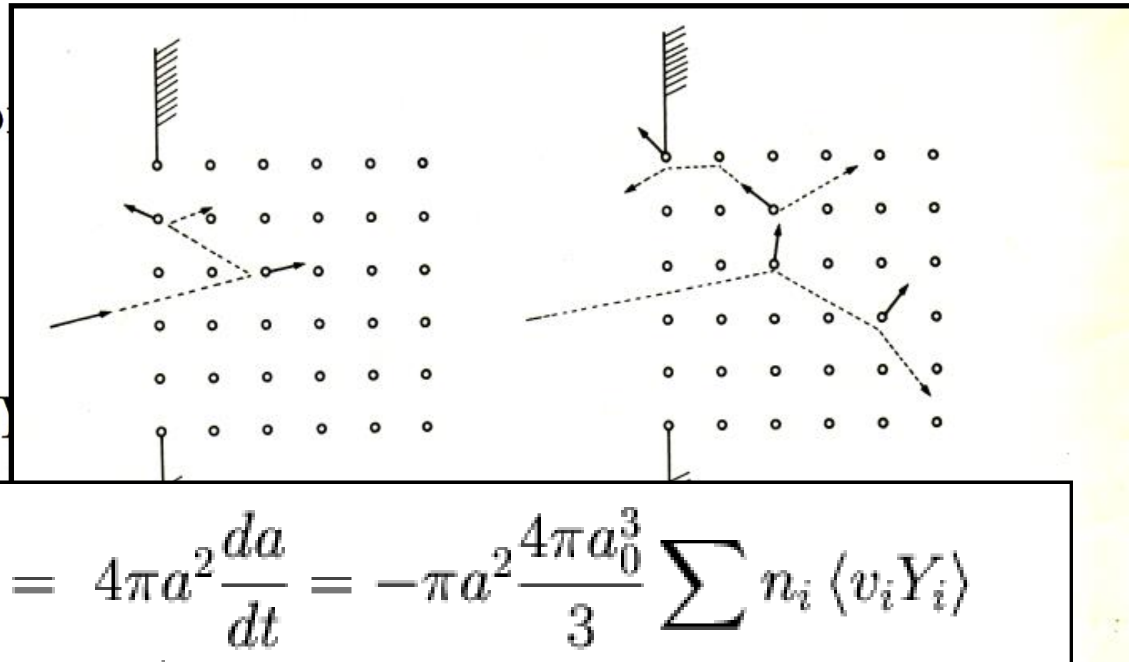
by n_H

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

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

3-3. Erosion rate of dust by sputtering

• dust destructio… 996)



$Y_i(E) = 2$…

· rate … s taken

acco…)

$\mathcal{R}($ … $)X_i(\epsilon)d\epsilon$

w

$$\frac{dV_{\rm d}}{dt} = 4\pi a^2 \frac{da}{dt} = -\pi a^2 \frac{4\pi a_0^3}{3} \sum n_i \langle v_i Y_i \rangle$$

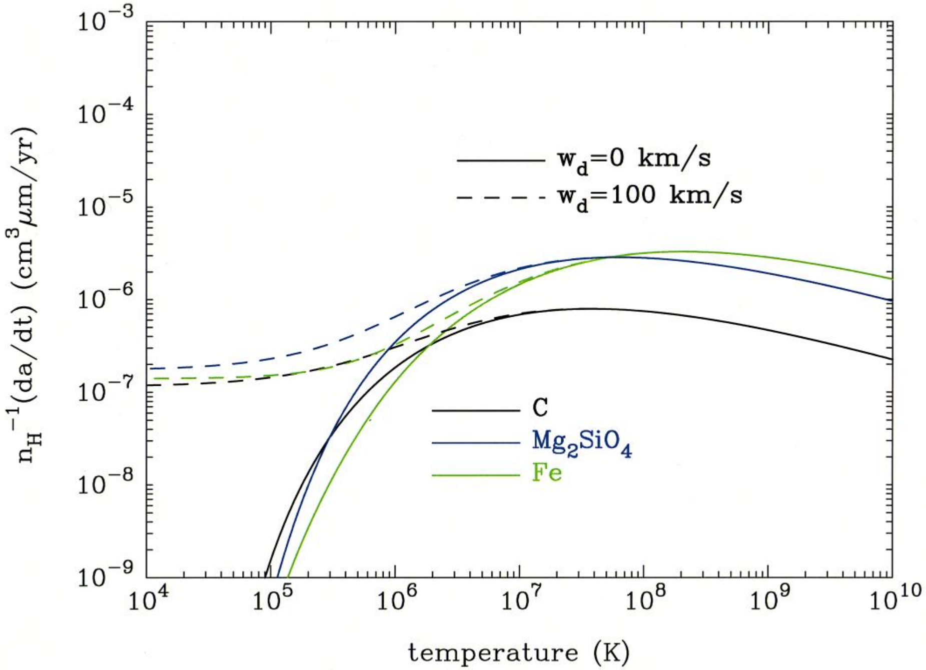
$$\frac{da}{dt} = -\frac{1}{4}\Omega n_{\rm H} \sum A_i \langle v_i Y_i \rangle$$

$$\frac{da}{dt} = -\frac{m_{\rm sp}}{2\rho_{\rm d}} n_{\rm H} \sum A_i \left(\frac{8kT}{\pi m_i}\right)^{1/2} \frac{e^{-s_i^2}}{2s_i} \times \int \epsilon^{\frac{1}{2}} e^{-\epsilon_i} \sinh(2 s_i \epsilon_i^{\frac{1}{2}}) Y_i^0(\epsilon_i) d\epsilon_i$$

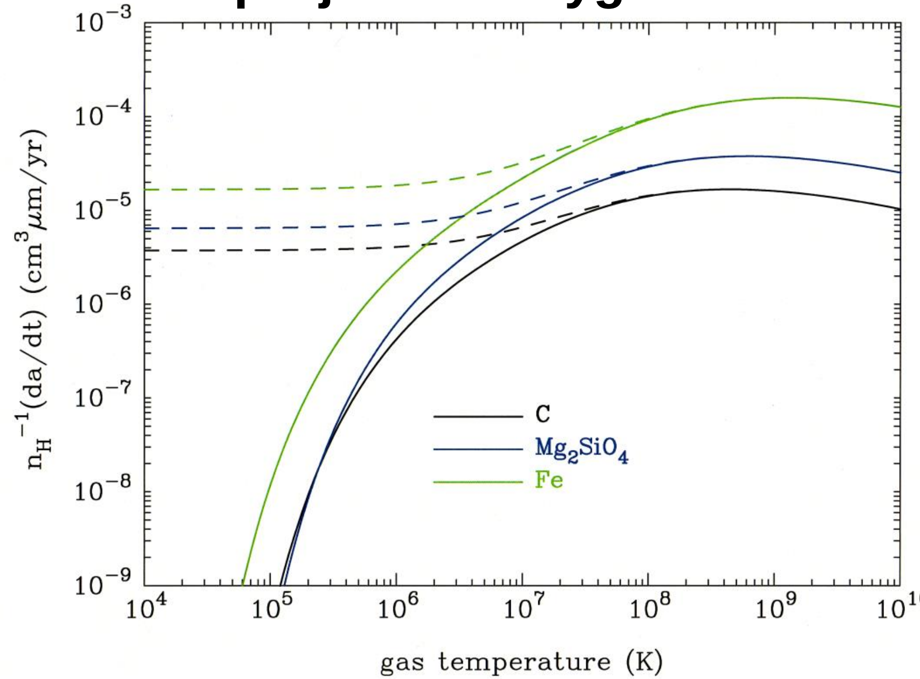
3-4. Erosion rate of dust by sputtering

Nozawa+2006, ApJ, 648, 435

projectile: H and He



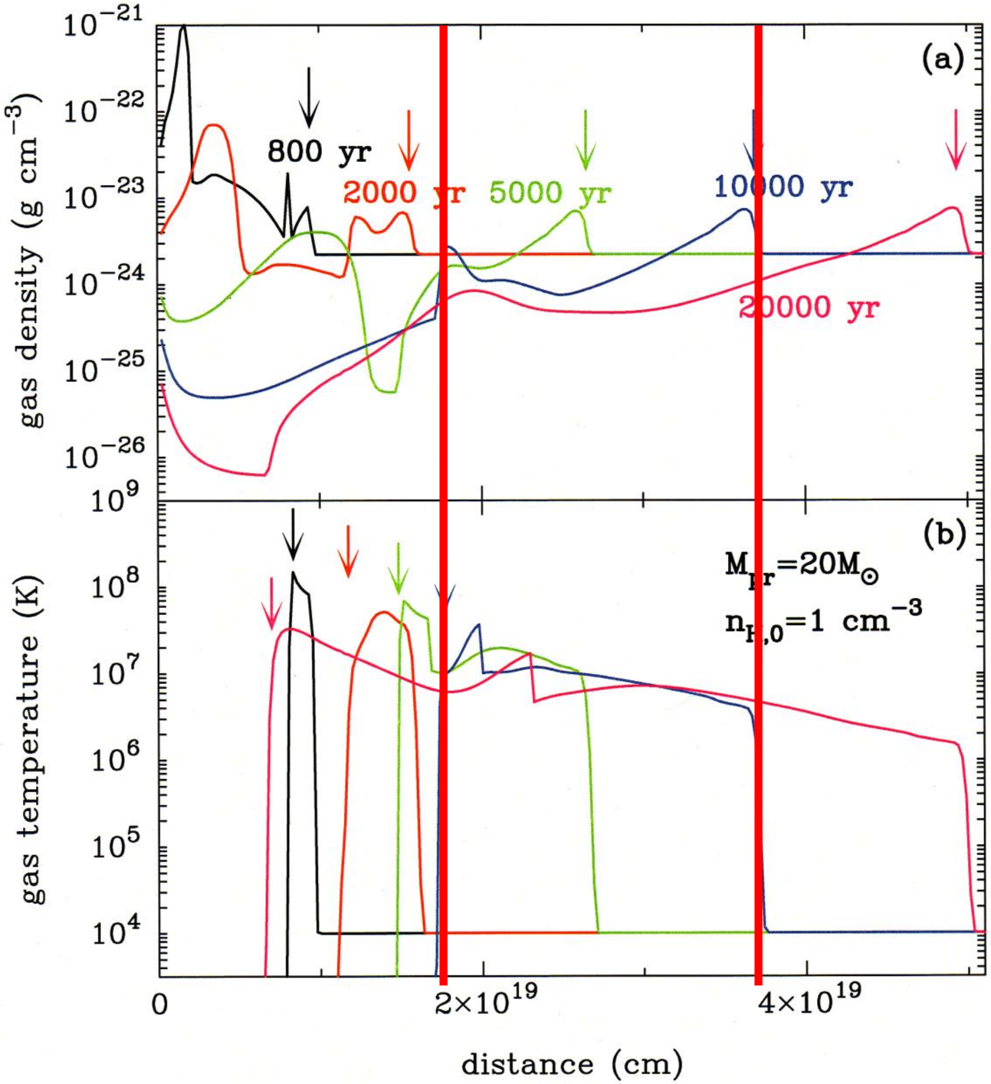
projectile: oxygen ions



- **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



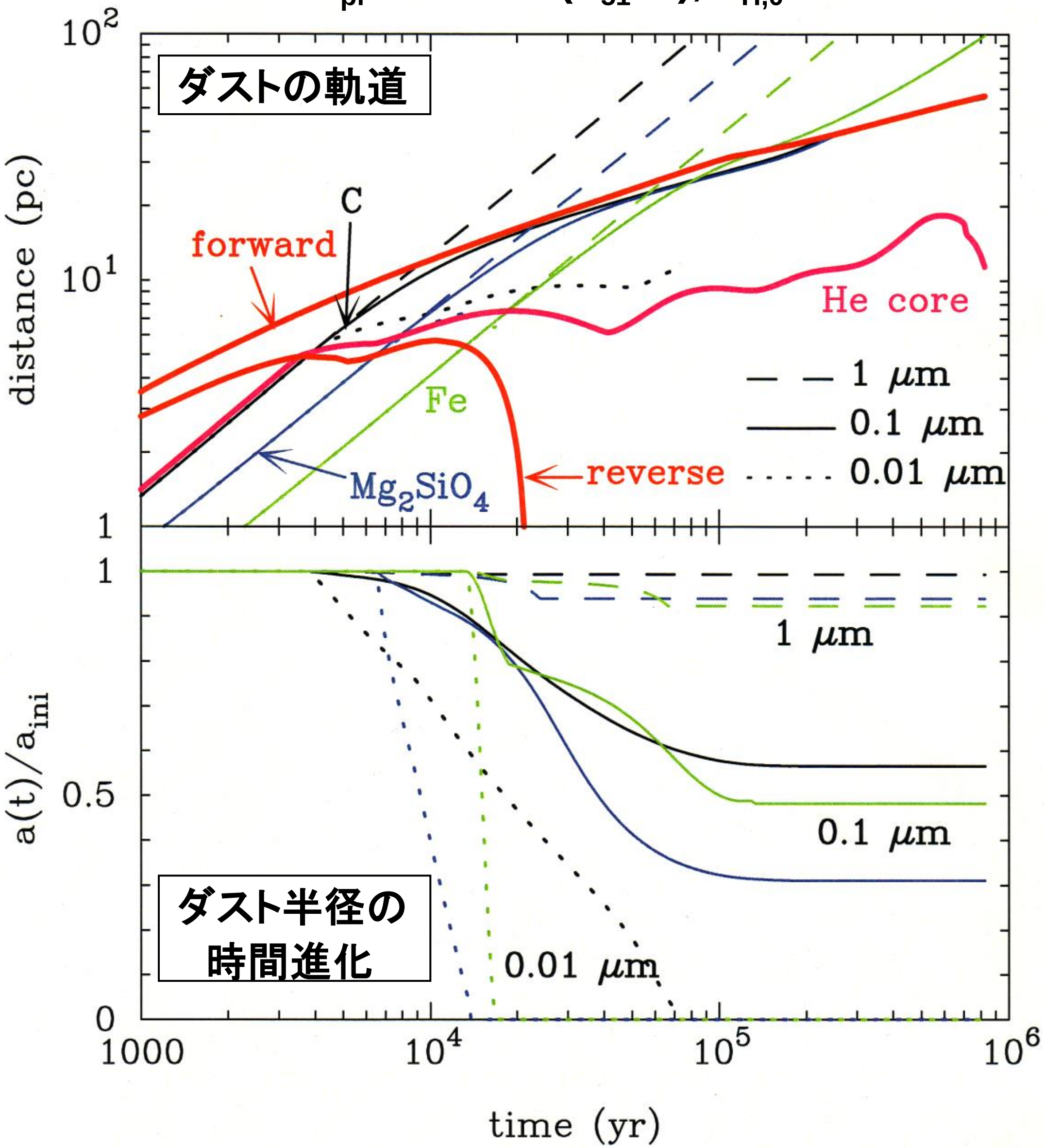
Model : M_{pr}= 20 Msun (E_{51}=1)
$n_{H,0}$ = 1 cm^{-3}

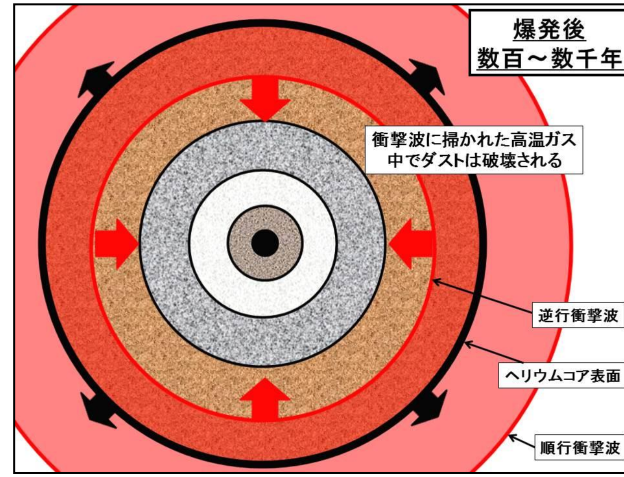
Downward-pointing arrows:
forward shock in upper panel
reverse shock in lower panel

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

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





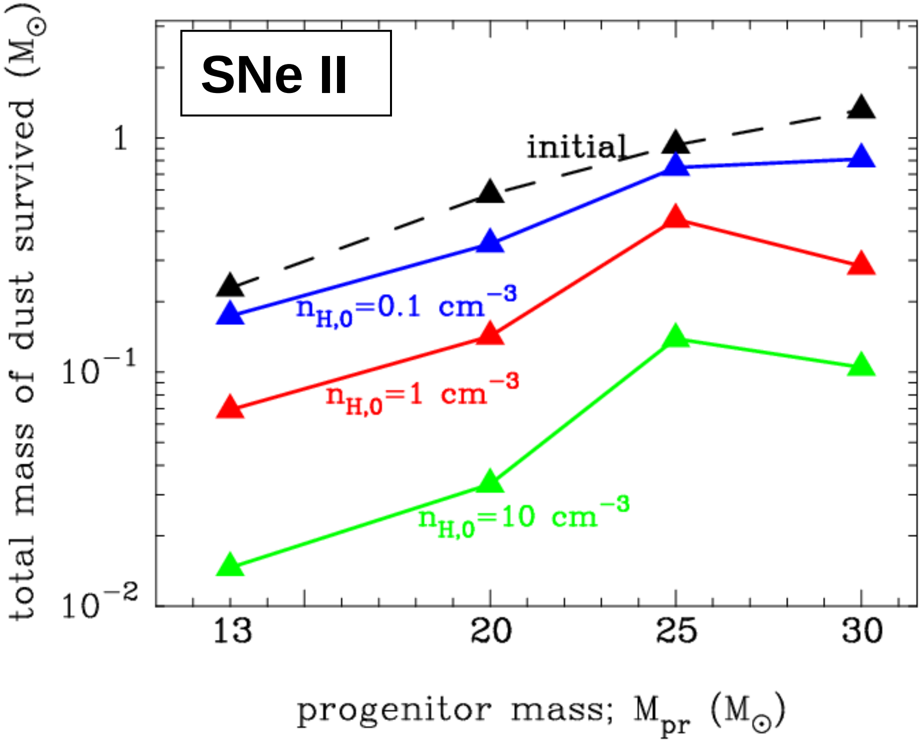
○ 超新星残骸内でのダストの進化は、ダストの初期半径と組成に強く依存する

a_{ini} = 0.01 μm (dotted lines)
➔ 完全に破壊される

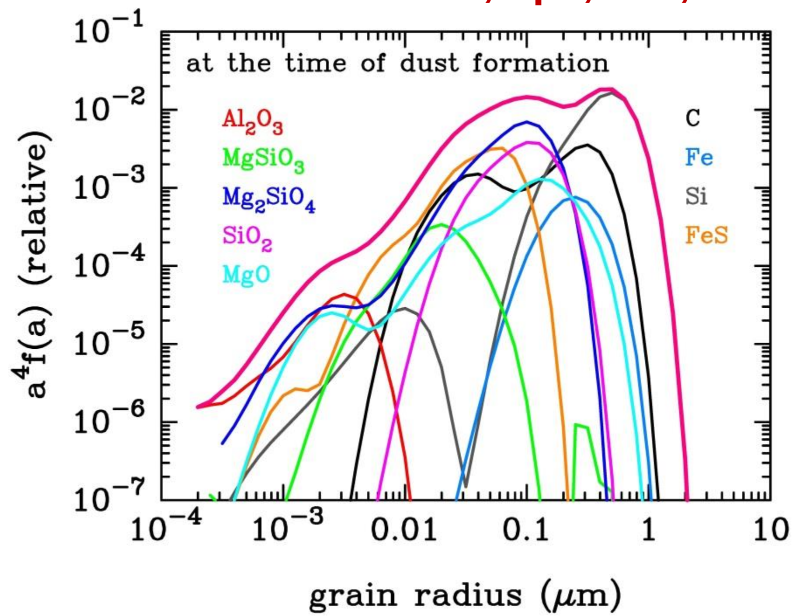
a_{ini} = 0.1 μm (solid lines)
➔ shell中に捕獲される

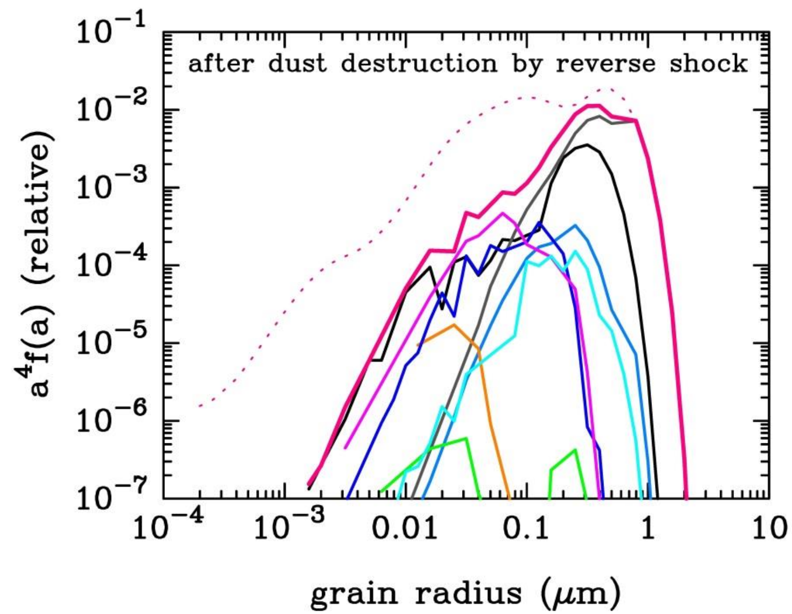
a_{ini} = 1 μm (dashed lines)
➔ 星間空間に放出される

3-7. Dust mass and size ejected from SNe II



Nozawa+07, ApJ, 666, 955

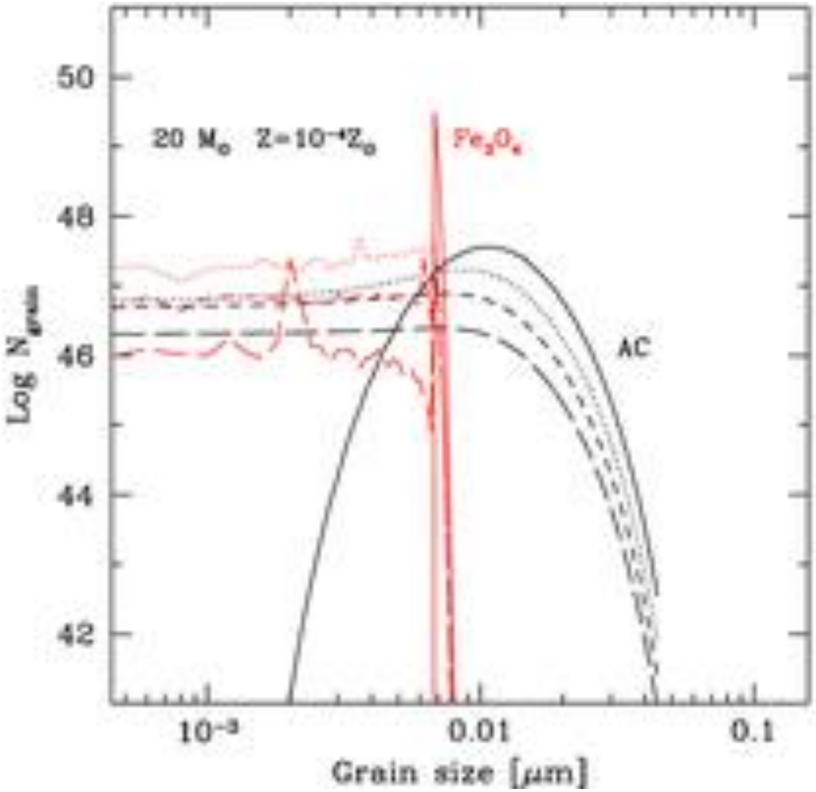




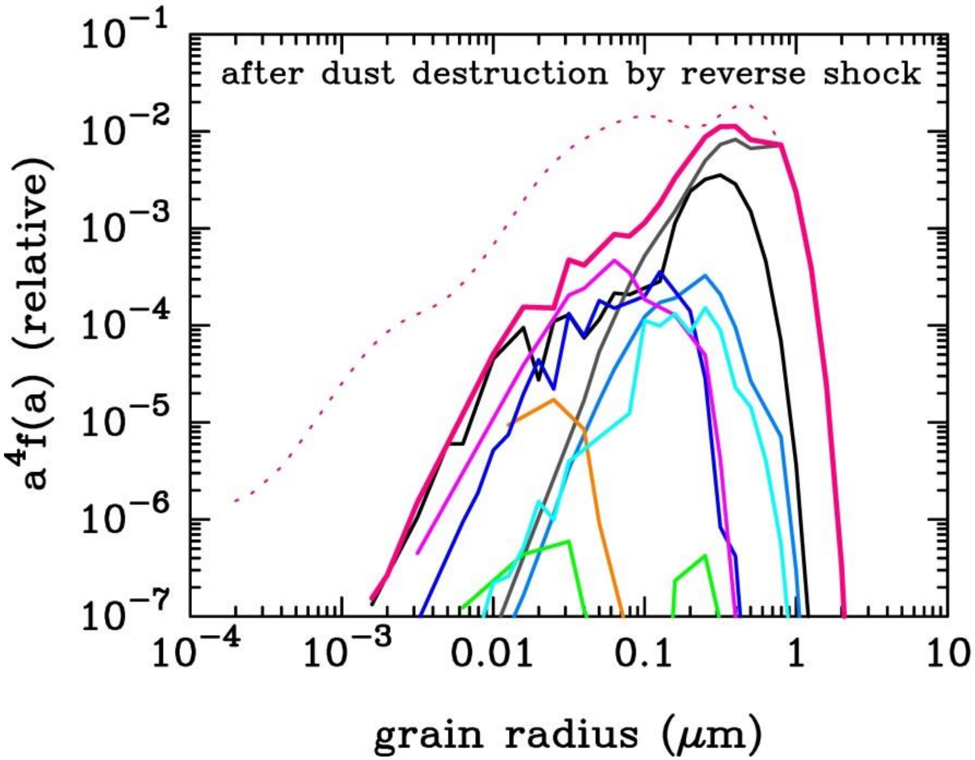
total mass of dust surviving the destruction in Type II SNRs;
0.07-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

size distribution of dust after the shock-destruction is domimated by large grains (> 0.1 μm)

3-8. Comparison with other studies



Schneider+2011



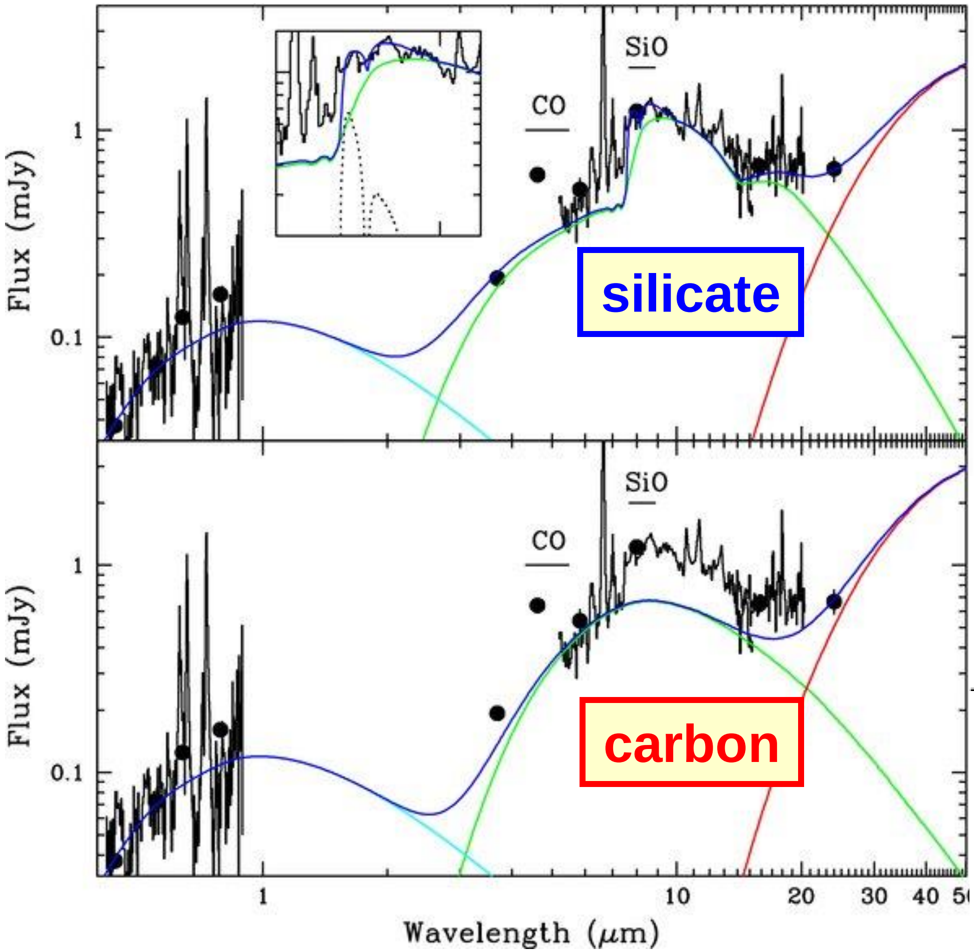
Nozawa+2007

- dust formation in the one-zone ejecta of SNe
  ➜ log-normal size distribution at dust formation
- reverse shock destruction increases small grains
  ➜ larger grains must be dominant in mass

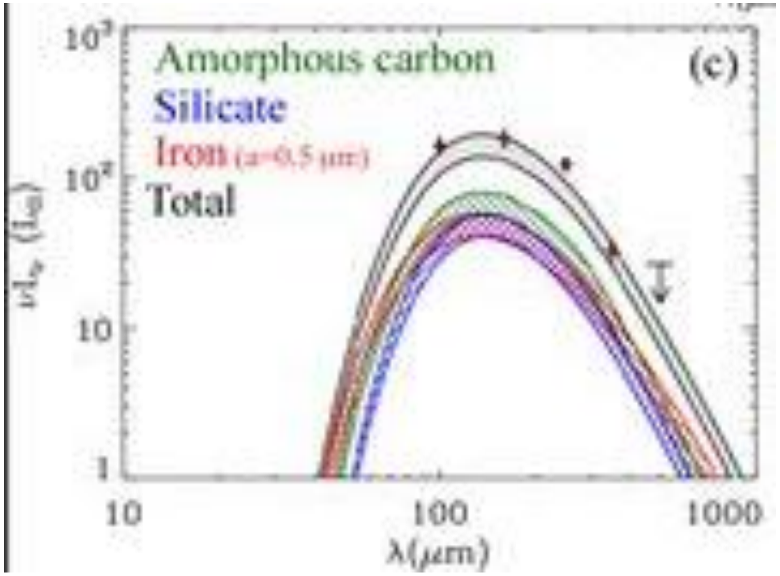
4. Observations of size distribution of dust in SNe

4-1. Composition of dust formed in SNe

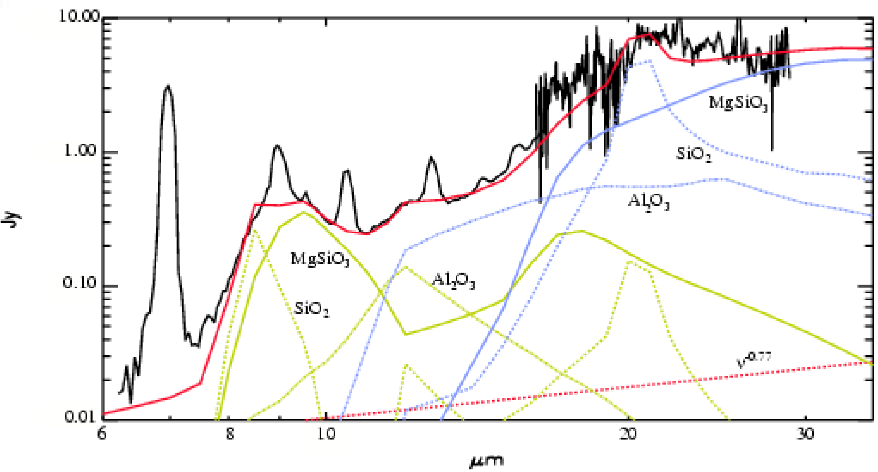
interstellar dust : carbonaceous grain
silicate (MgFeSiO4?)



Kotak+09, 2004et

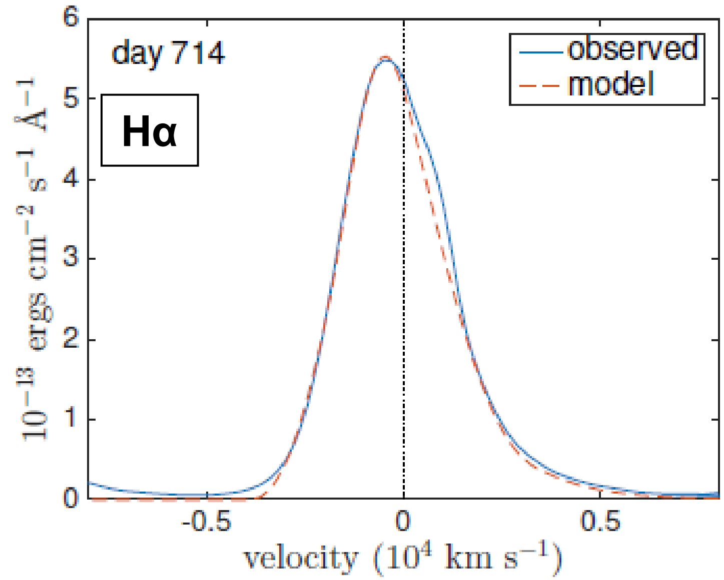


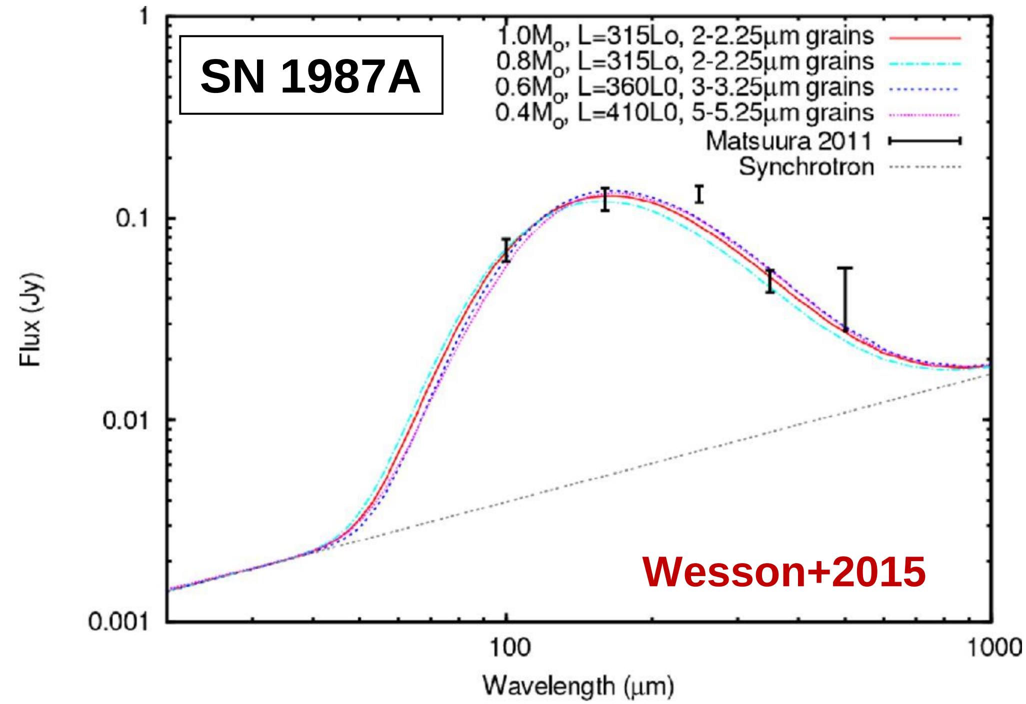
Matuura+2011, SN 1987A

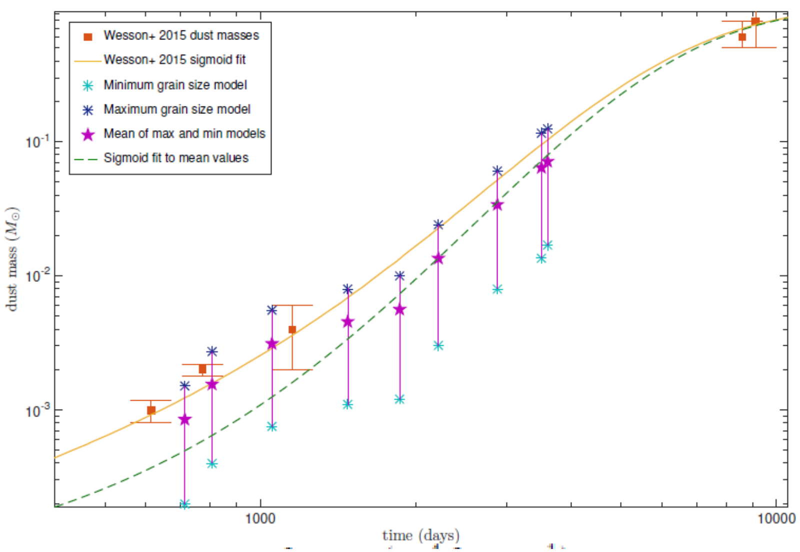


Douvion+01, Cassiopeia A SNR

4-2. Properties of dust in SN 1987A







Bevan & Barlow 2016

- M_d ~ 0.7 Msun
- a ~ 0.2 μm
  large radius is required to have Tdust ~ 20 K in LMC

At 714 day

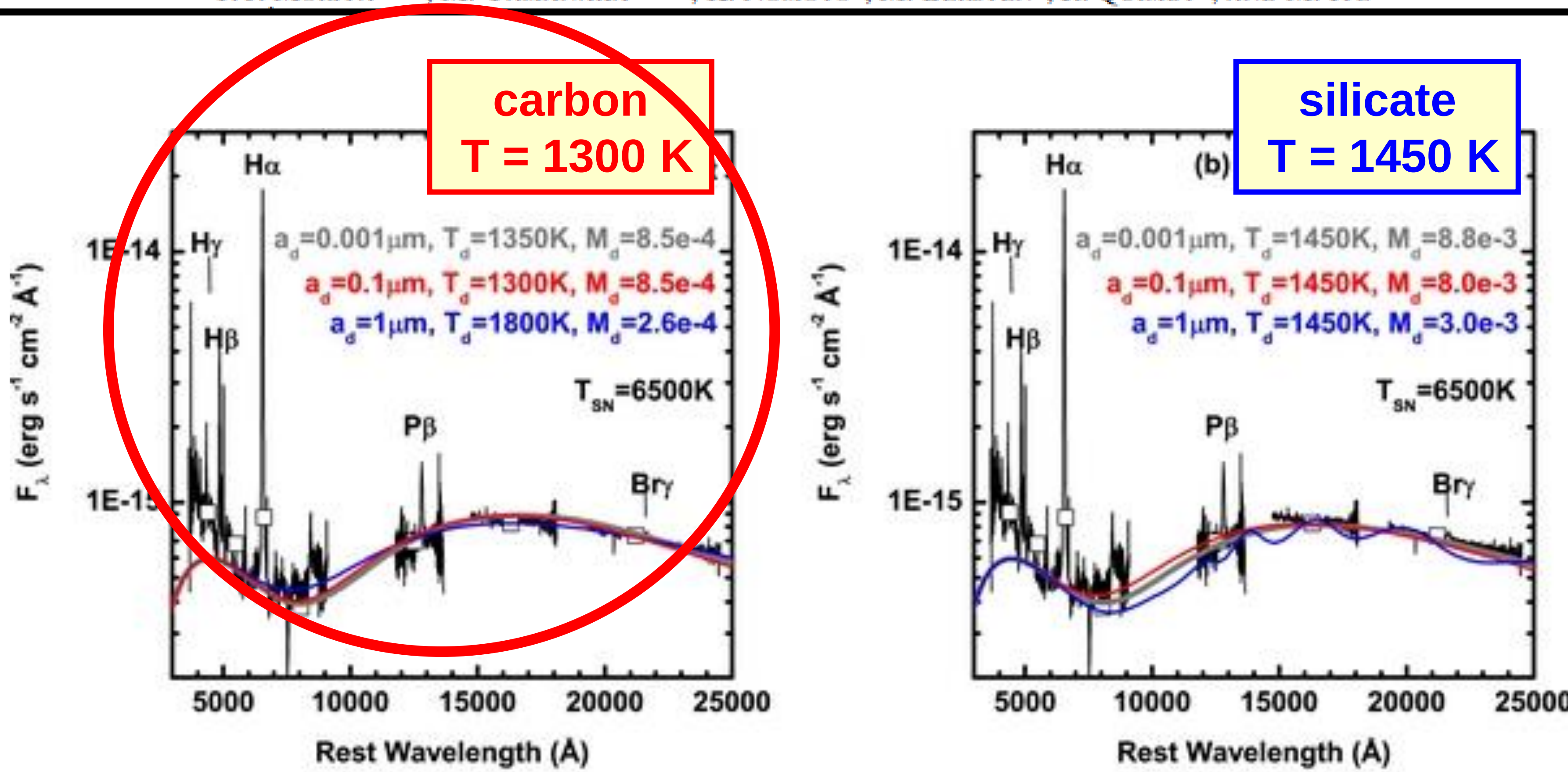
- dust mass < 7×10^{-2} Msun
- grain radius > ~0.6 μm

4-3. Dust formation in Type IIn SN 2010jl

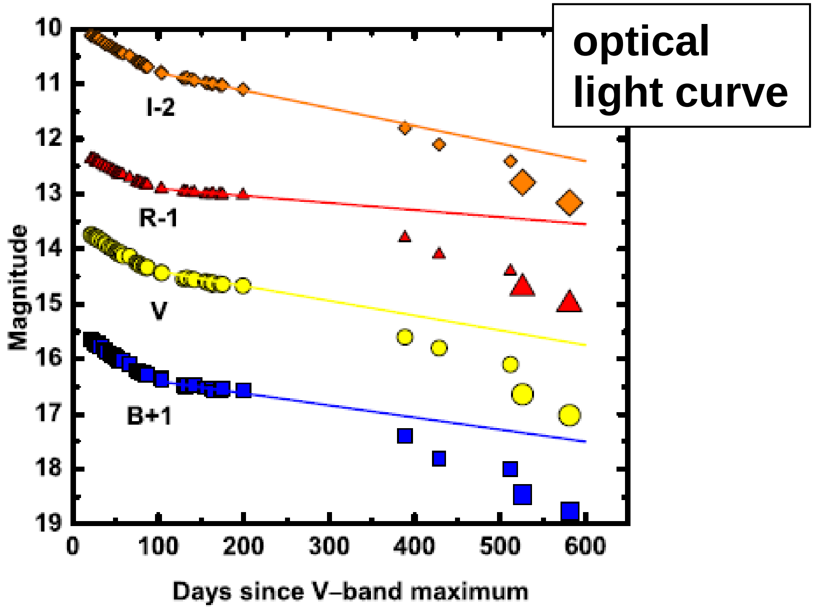
The Astrophysical Journal, 776:5 (16pp), 2013 October 10
doi:10.1088/0004-637X/776/1/5

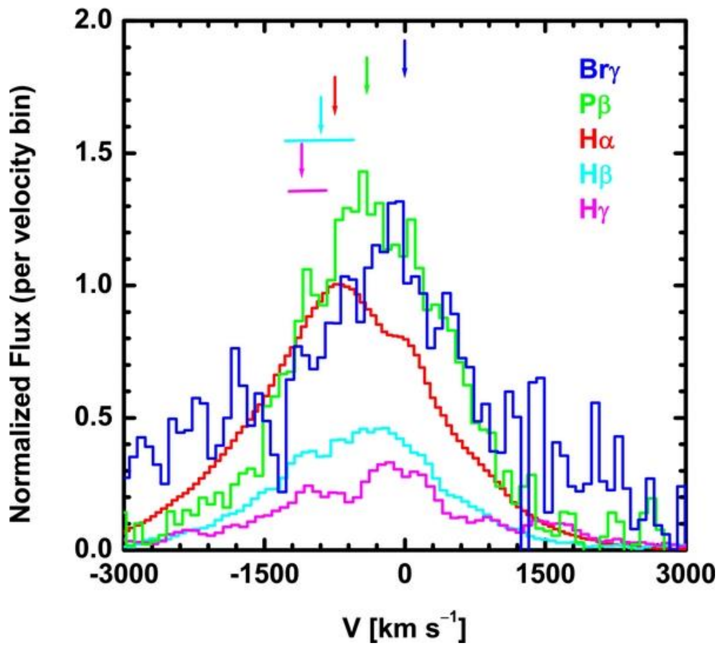
PROPERTIES OF NEWLY FORMED DUST GRAINS IN THE LUMINOUS TYPE IIn SUPERNOVA 2010jl*

K. Maeda[1], T. Nozawa[1], D. K. Sahu[2], Y. Minowa[3], K. Motohara[4], I. Ueno[5], G. Folatelli[1], T.-S. Pyo[3], Y. Kitagawa[4], K. S. Kawabata[5], G. C. Anupama[2], T. Kozasa[6], T. J. Moriya[1,7,8], M. Yamanaka[5,9,10], K. Nomoto[1], M. Bersten[1], R. Quimby[1], and M. Iye[11]



4-4. Dust properties in Type IIn SN 2010jl

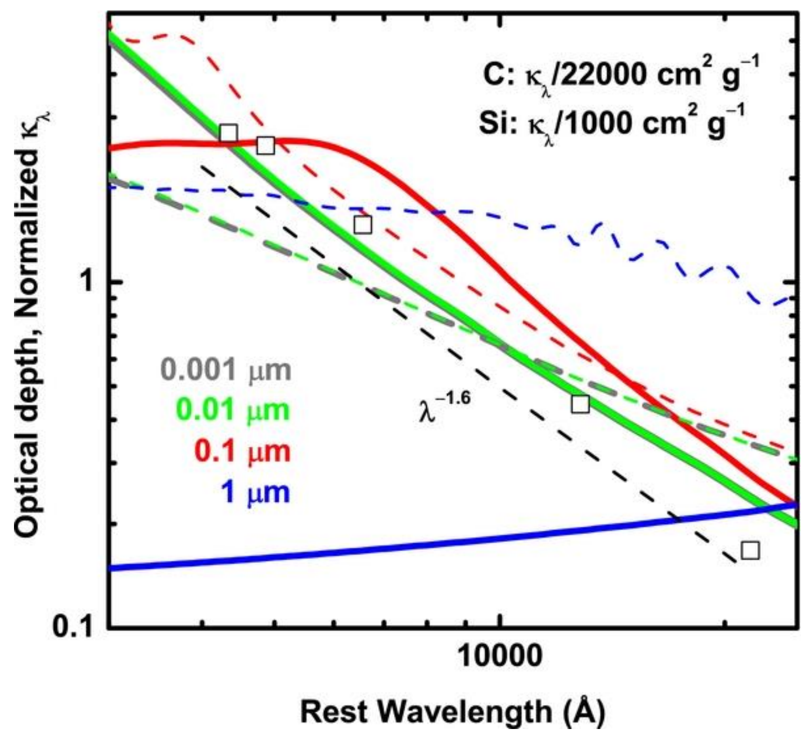




Dust in SN 2010jl

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

Maeda, TN, et al. (2013)

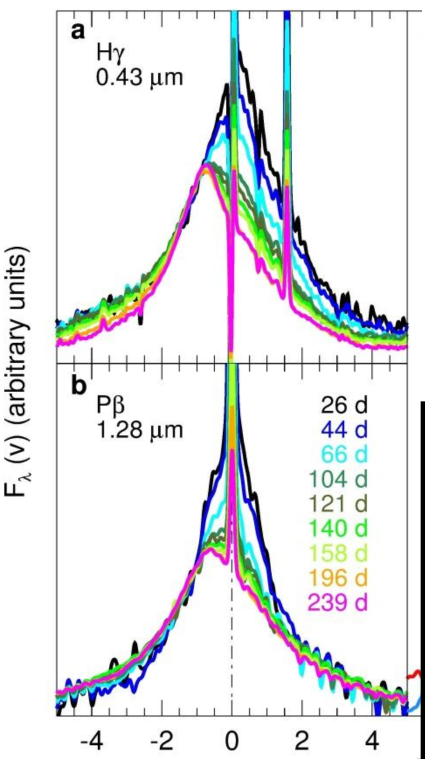


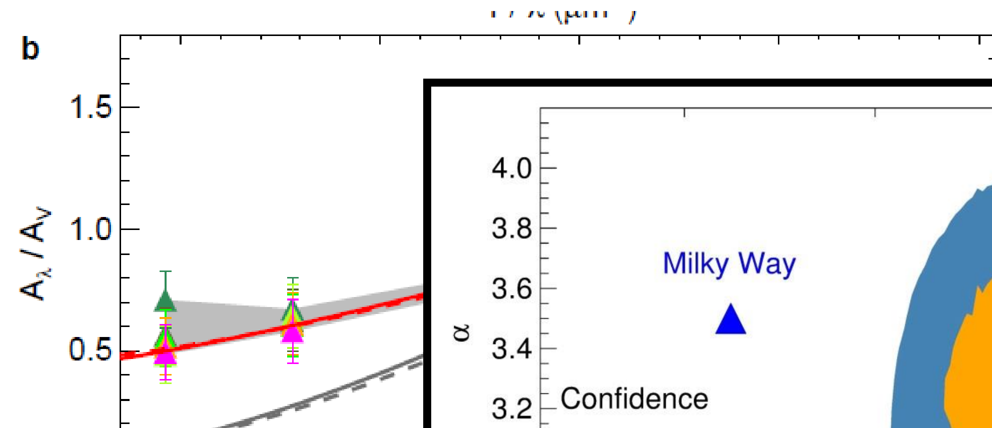
4-5. Dust formation in Type IIn SN 2010jl

doi:10.1038/nature13558

Rapid formation of large dust grains in the luminous supernova 2010jl

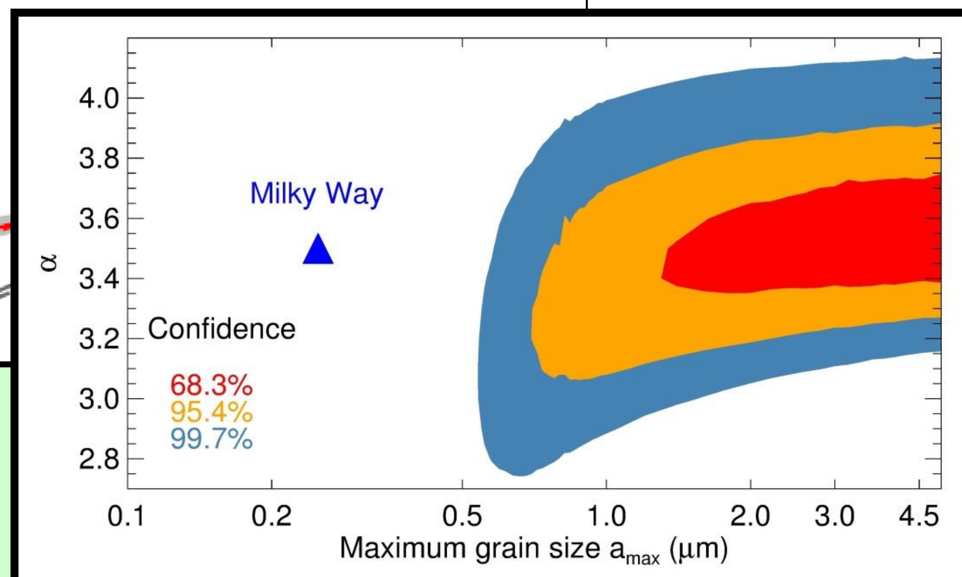
Christa Gall[1,2,3], Jens Hjorth[2], Darach Watson[2], Eli Dwek[3], Justyn R. Maund[2,4], Ori Fox[5], Giorgos Leloudas[2,6], Daniele Malesani[2] & Avril C. Day-Jones[7]





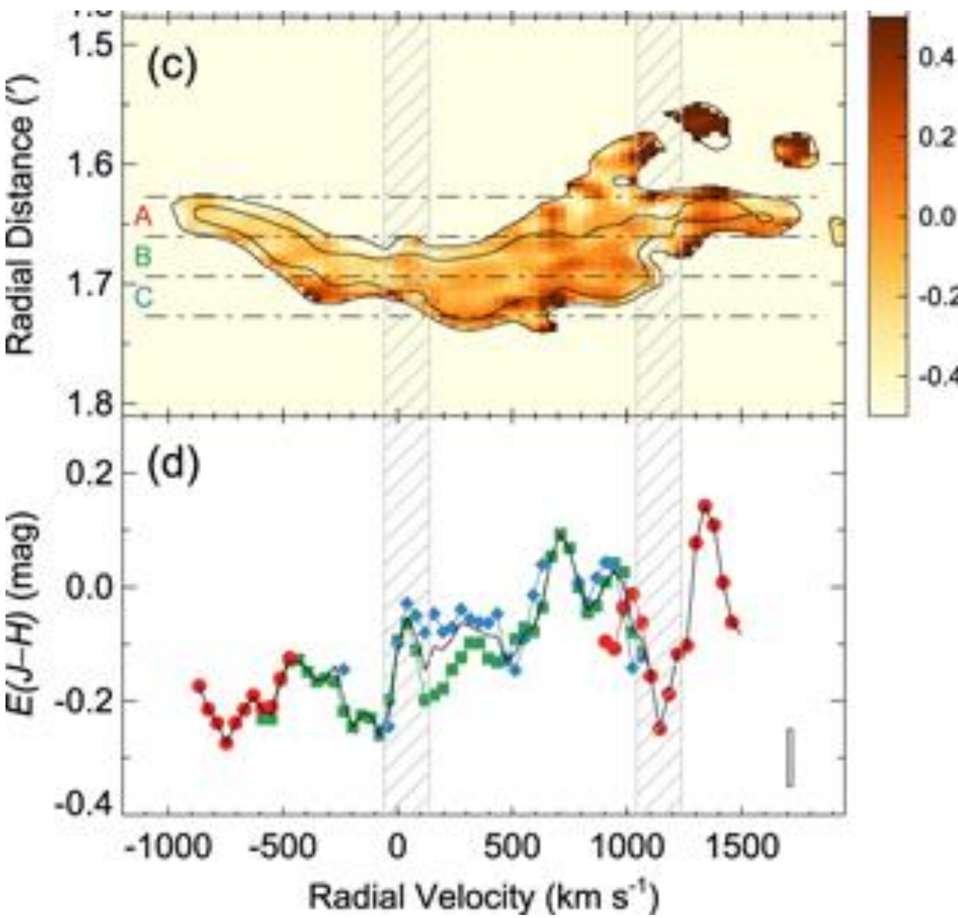
Power-law size distribution

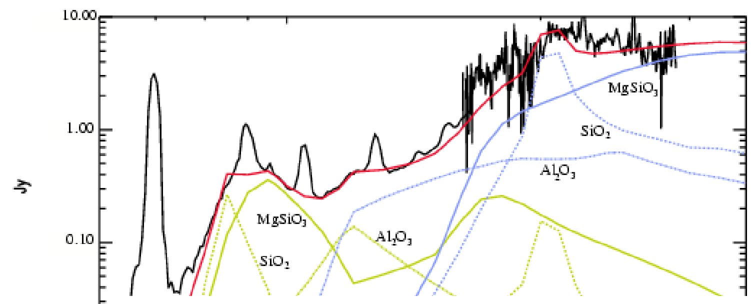
- α : ~3.5
- maximum radius : ~3-4 μm (>0.5 μm)



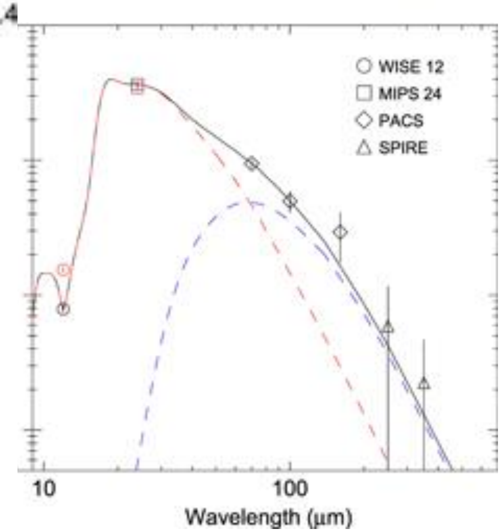
Gall+2014, Nature

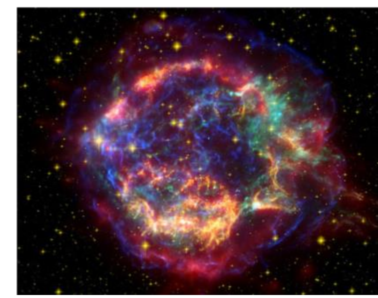
4-6. Dust properties in one knot of Cas A SNR





Douvion+01, Cassiopeia A SNR





Far-side is more obscured han near-side

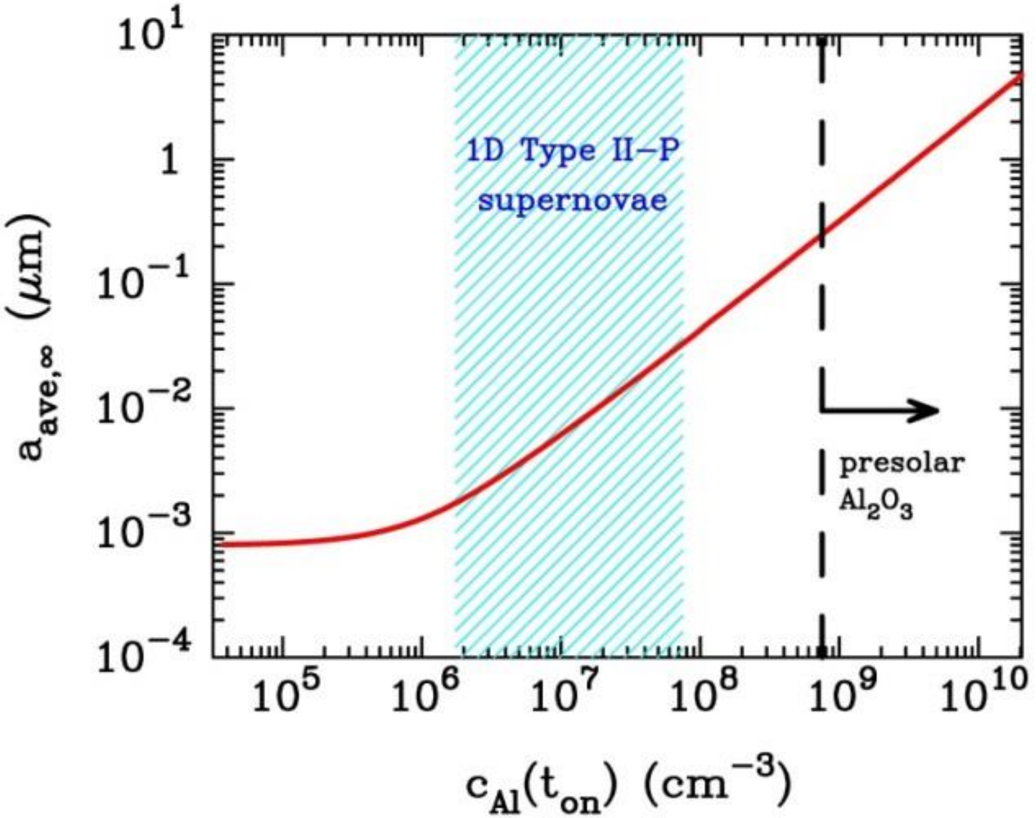
E(B-V) = 0.23

Cool dust component

- Fe with < ~0.01 Msun (or large Si dust)

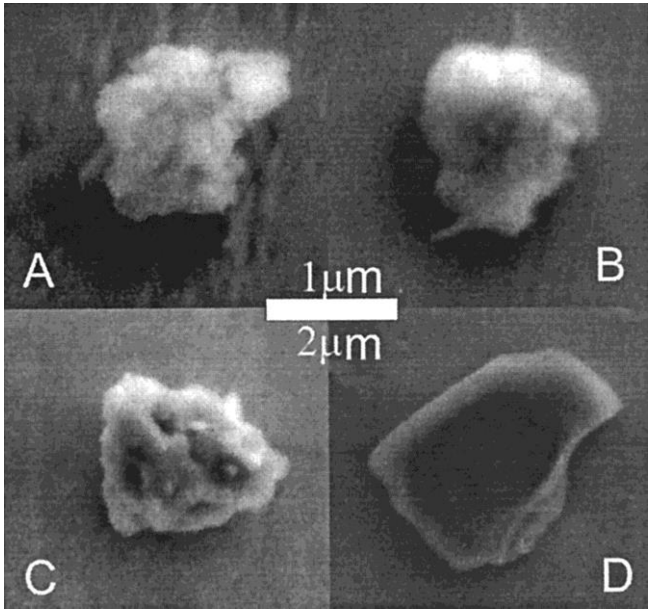
Lee, Koo et al. 2015, ApJ, 808, 98

4-7. Formation condition of presolar Al_2O_3



Nozawa+2015, ApJ, 811, L39

presolar Al_2O_3 grains



Choi+1998

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

5. Summary

(1) 超新星でのダスト形成

様々なサイズ（数Å～1μm）のダストが形成される

➜ 0.1-1 μmあたりにピークを持ちそう （ガス密度に依存）

(2) リヴァース衝撃波によるダスト破壊

小さいサイズ（~0.01 μm以下）のダストは破壊される

➜ 大きいダスト（~0.1 μm以上）が支配的に放出される

(3) 超新星ダストのサイズ（分布）の観測

SN 1987Aでは、0.1 μmより大きいであろう

Cassiopeia Aのダストは小さめかも

プレソーラーグレインは、かなり大きい（>1 μm）ものもある

➜ 超新星放出ガスがクランプ状になっている必要がある