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Dust in the ejecta of supernovae

Takaya Nozawa

Kavli IPMU (Kavli Institute for the Physics and Mathematics of the Universe)

Collaborators:

K. Maeda, K. Nomoto (Kavli IPMU)

T. Kozasa, A. Habe (Hokkaido University)

H. Umeda (U.T.), N. Tominaga (Konan Univ.)

1-1. Introduction

○ **SNe (and SNRs) are sources of**

– **cosmic ray**

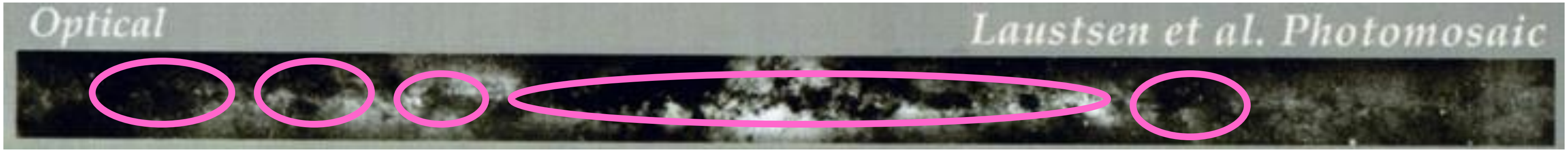
– **kinetic and radiative energies**

– **heavy elements**

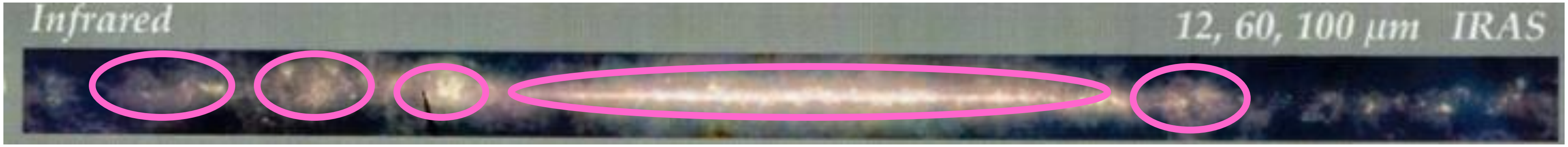
– **dust grains**

1-2. Sources of dust in our Galaxy

Milky Way (optical)



Milky Way (infrared)



SNe are important sources of interstellar dust?

– **number (occurrence) ratio of SNe to AGB stars**

n(SNe) / n(AGB stars) ~ 0.05-0.1

M_{dust} = 0.1-1.0 M_{sun} per SN (Nozawa et al. 2003; 2007)
M_{dust} = 0.01-0.05 M_{sun} per AGB (Zhukovska & Gail 2008)

1-3. Sources of dust in the early universe

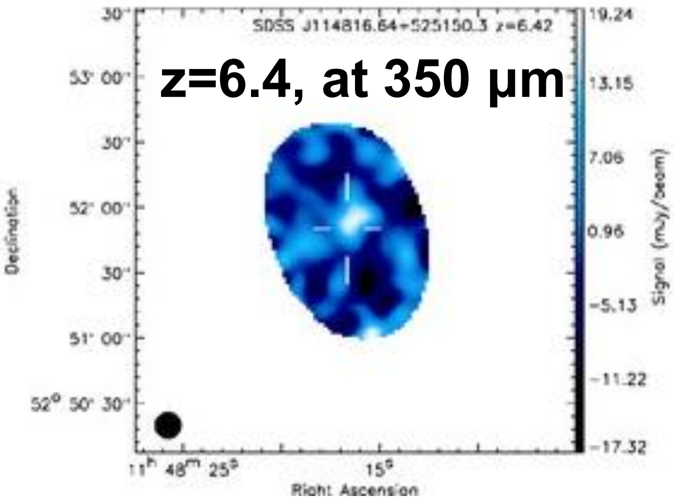
huge amounts of dust grains (>10^8 Msun) are detected in host galaxies of quasars at redshift z > 5 (< 1 Gyr)

➔ **SNe arising from short-lived massive stars must be main producers of dust**

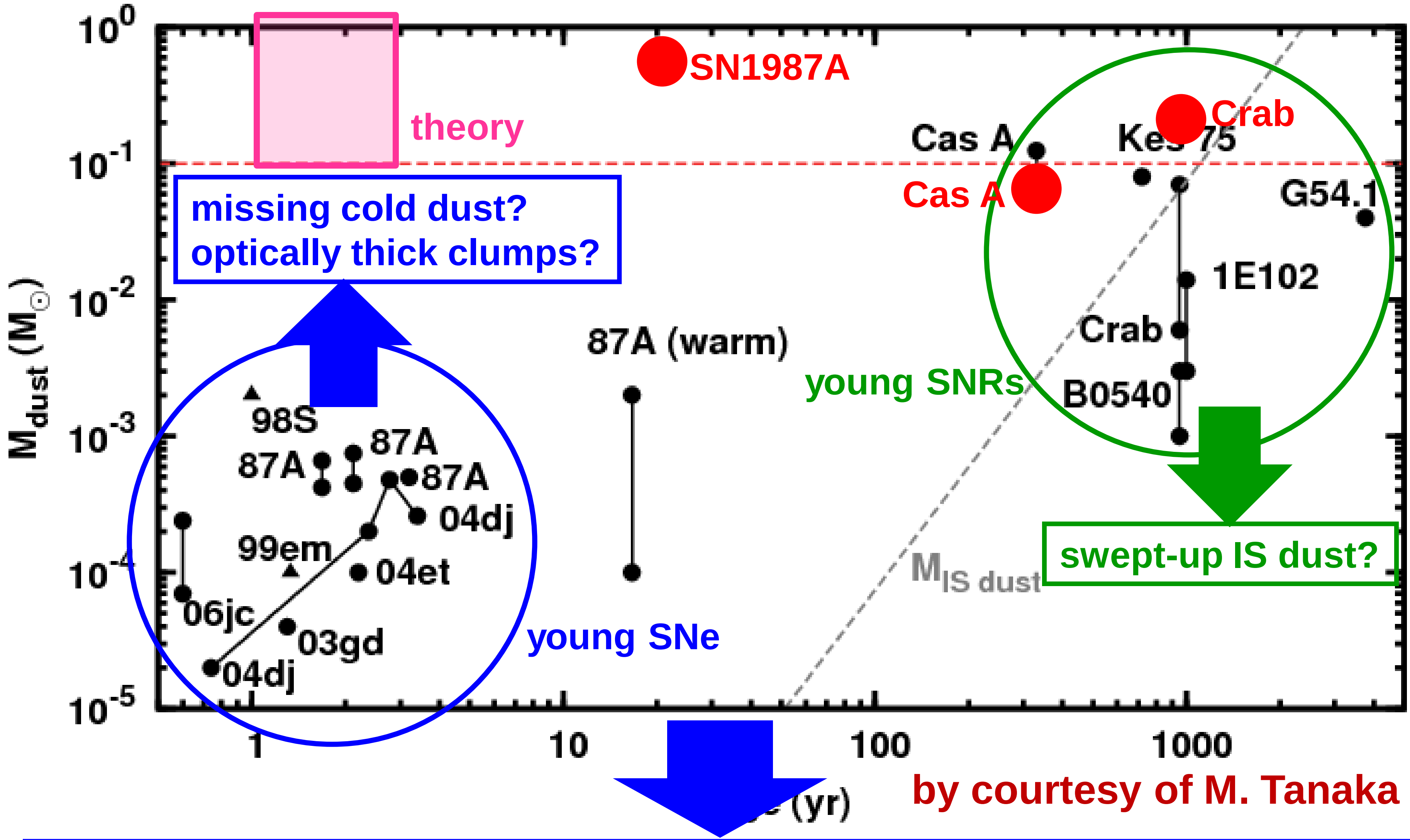
➔ **0.1 Msun of dust per SN is needed to be ejected to explain such massive dust at high-z (Dwek et al. 2007)**

theoretical studies predict that 0.1-1.0 Msun of dust forms in SNe
(e.g., Nozawa et al. 2003)

N/MIR observations of nearby SNe detect only < 10^{-3} Msun
(e.g., Meikle et al. 2011)



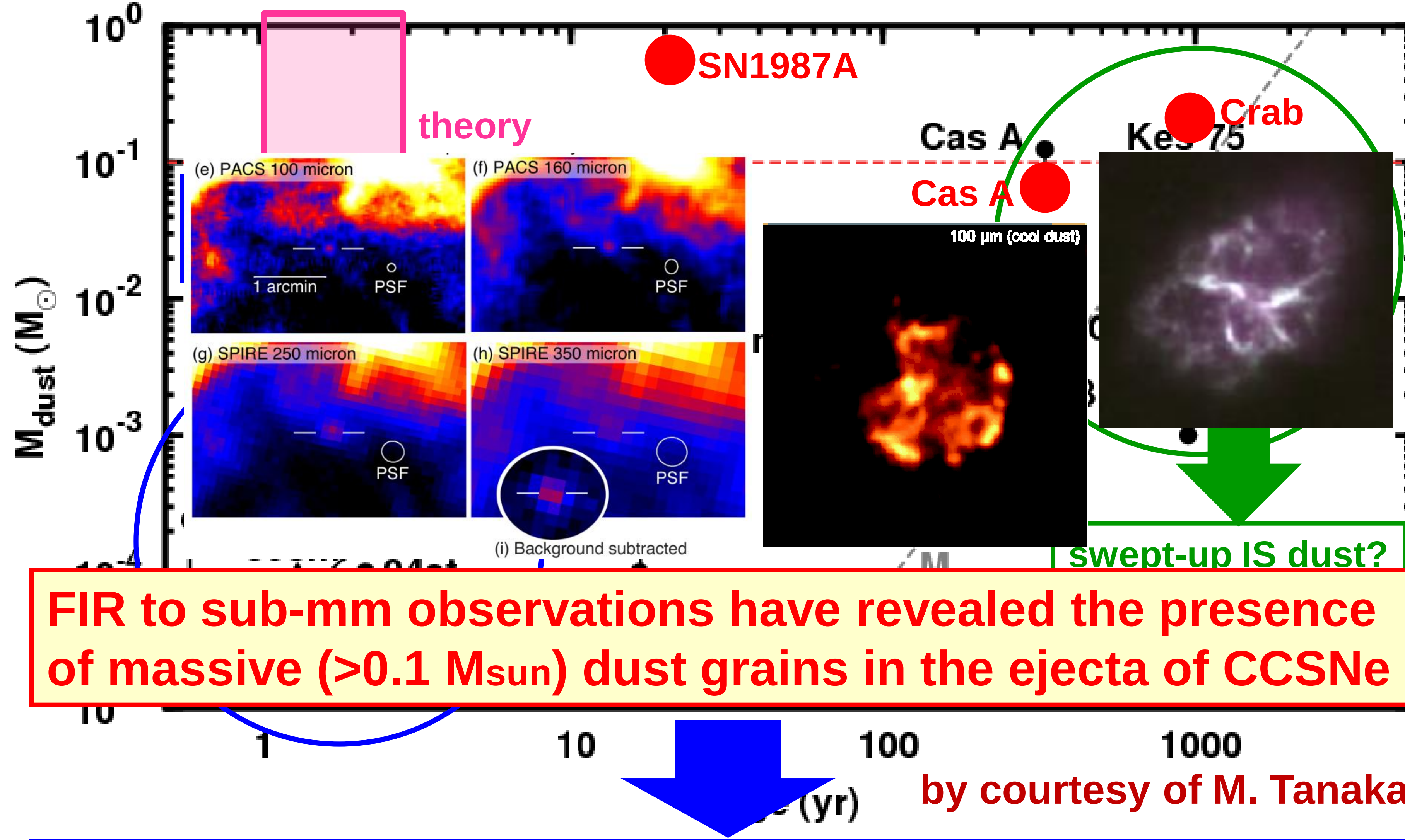
2-1. Summary of observed dust mass in CCSNe



by courtesy of M. Tanaka

What fraction of the newly formed grains can survive to be injected into the interstellar space?

2-1. Summary of observed dust mass in CCSNe



FIR to sub-mm observations have revealed the presence of massive (>0.1 Msun) dust grains in the ejecta of CCSNe

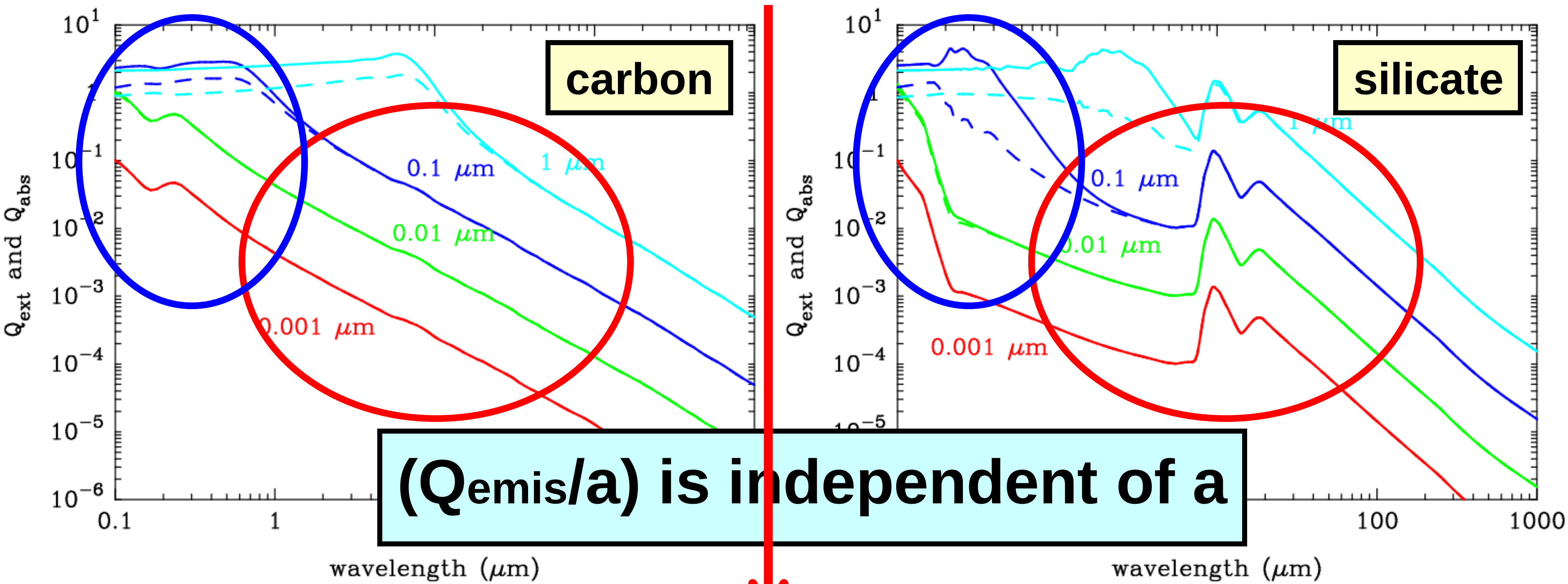
by courtesy of M. Tanaka

What fraction of the newly formed grains can survive to be injected into the interstellar space?

2-2. Emission and absorption efficiency of dust

○ Thermal radiation from a dust grain

$$F_\lambda \propto 4\pi a^2 \, Q_{emis}(a,\lambda) \, \pi B_\lambda(T_{dust})$$ # $Q_{emis} = Q_{abs}$



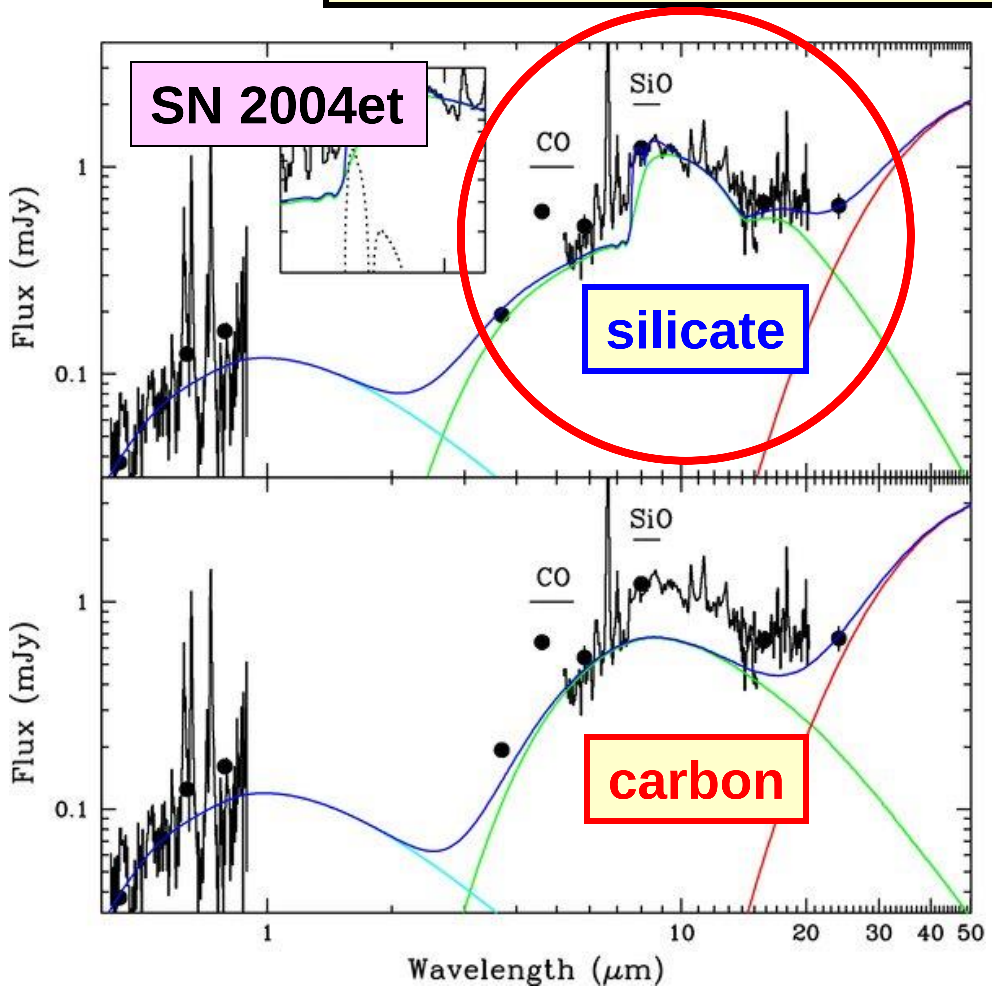
$$F_\lambda \propto 4\pi a^3 \, (Q_{emis}[a,\lambda]/a) \, \pi B_\lambda(T_{dust})$$

$$\propto 4 \, M_{dust} \, \kappa_{emis}(\lambda) \, \pi B_\lambda(T_{dust})$$

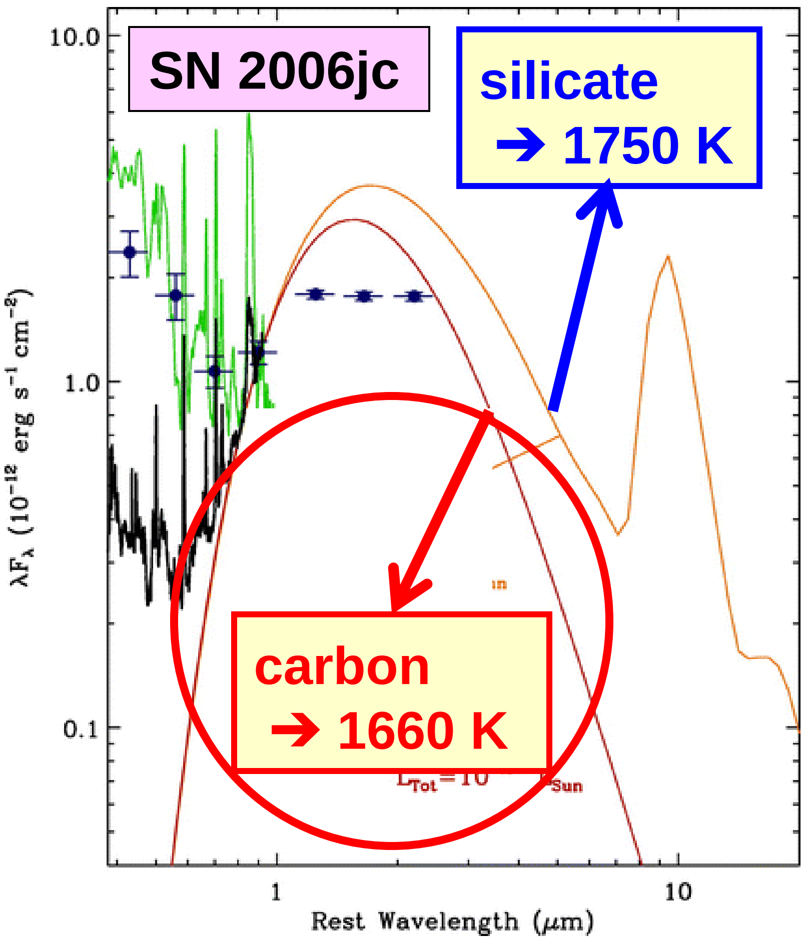
➔ IR emission is derived given M_{dust}, κ_{abs}, and T_{dust}

2-3. Composition of dust formed in SNe

IS dust : carbonaceous grain and silicate ($MgSiO_3$, $MgFeSiO_4$, …)

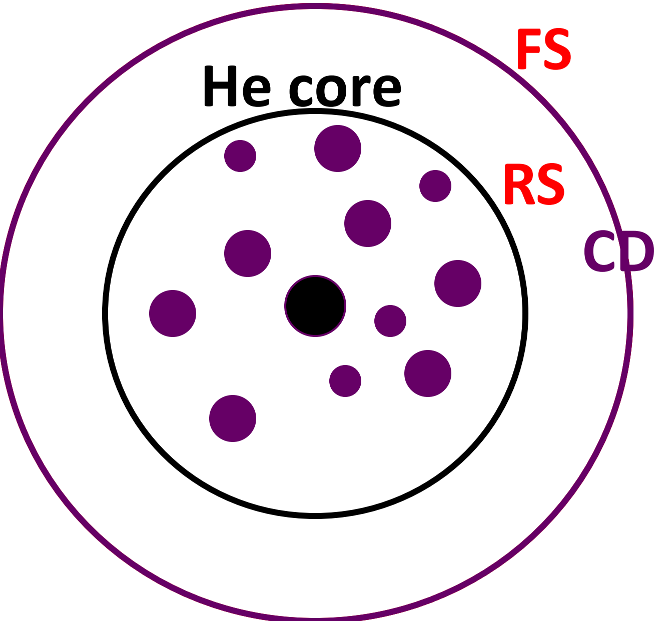


SN 2004et, Kotak+09

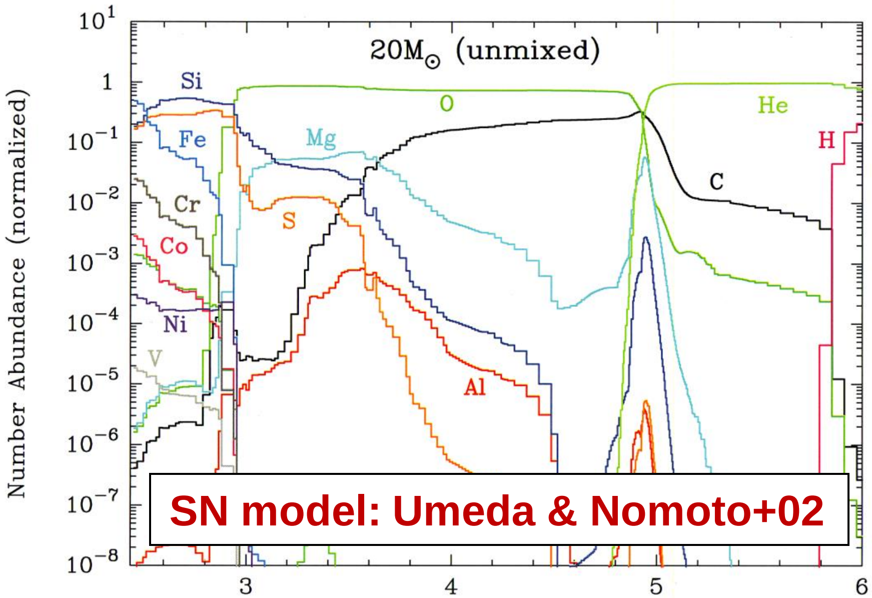


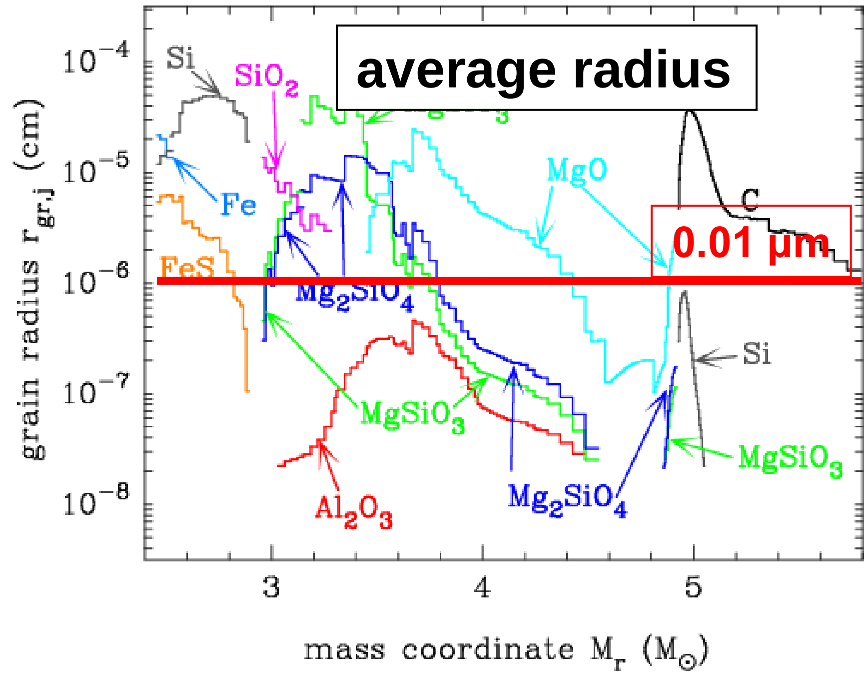
SN 2006jc, Smith+08

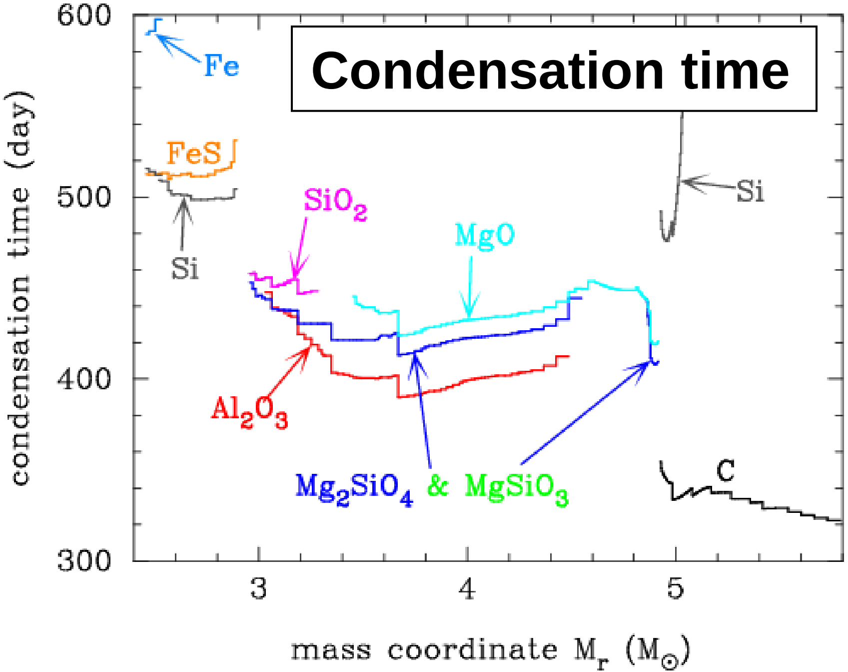
3. Formation and evolution of dust in supernovae



3-1. Dust formed in Type II-P SNe





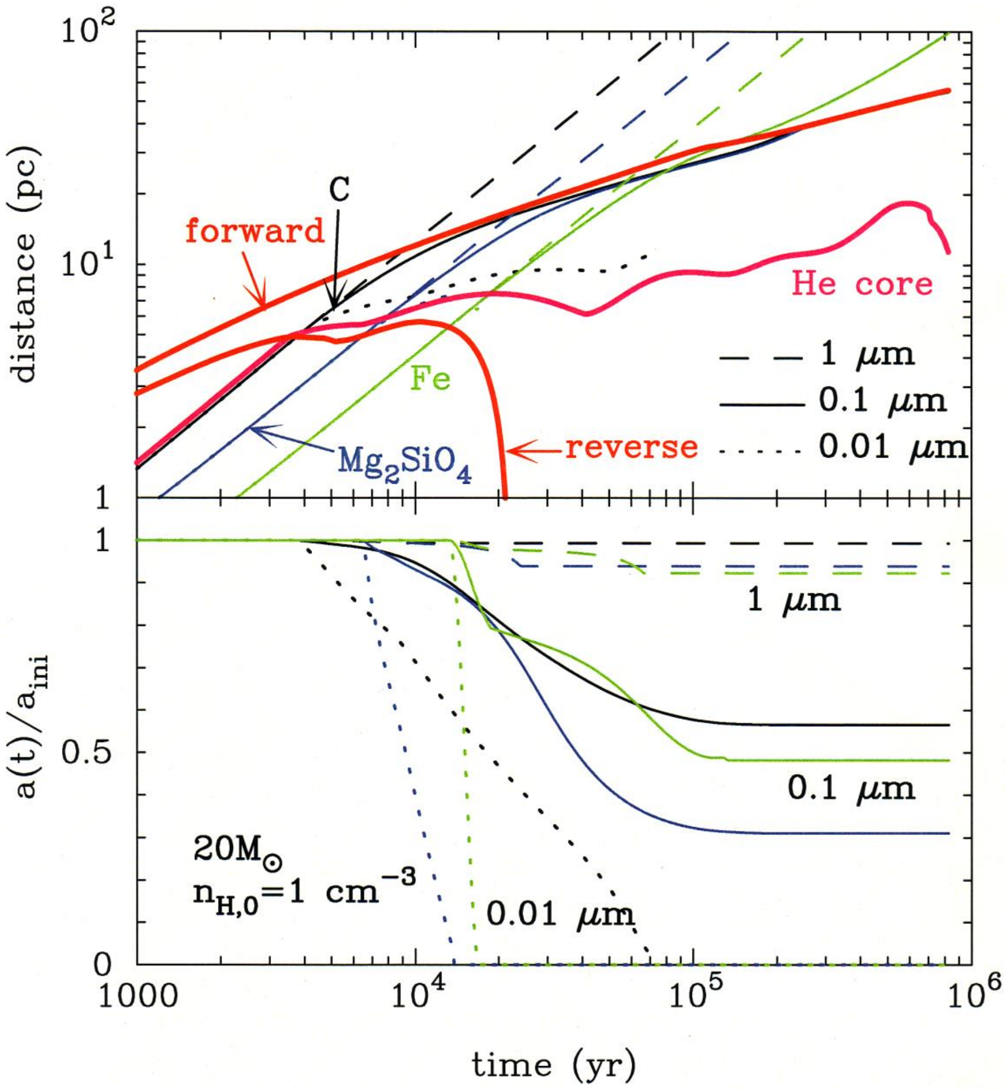


- various dust species form according to composition of gas in each layer
- condensation time: **300-600d** after explosion
- average radii: **>~0.01 μm**

Nozawa+03, ApJ, 598, 785

3-2. Evolution of dust in SNRs

Nozawa+07, ApJ, 666, 955



Model : Type II-P

M_{pr}= 20 Msun (E_{51}=1)

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

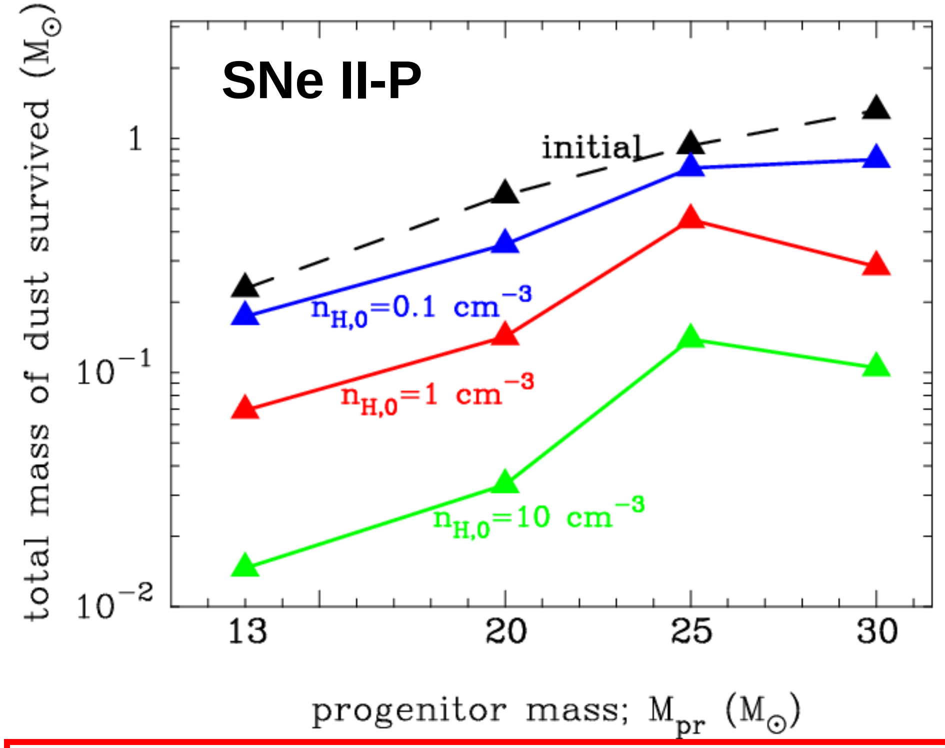
Dust grains in the He core collide with reverse shock at (3-13)x10^3 yr

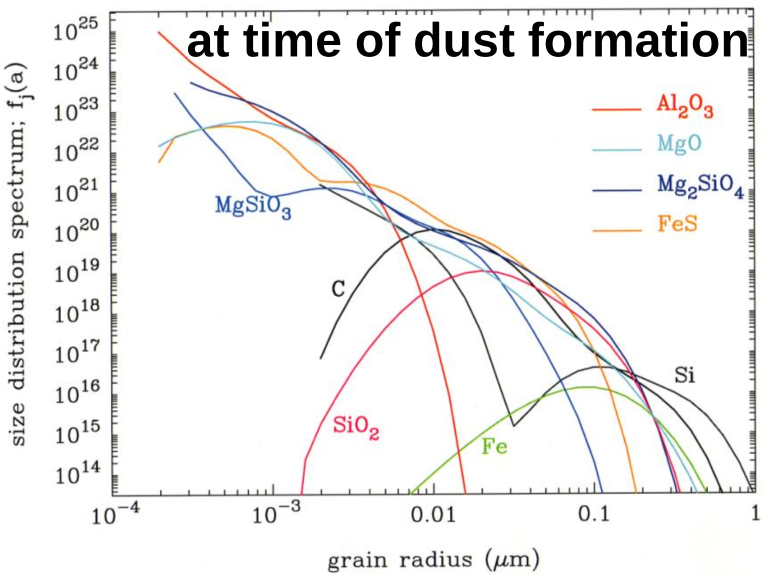
The evolution of dust heavily depends on the initial radius and composition

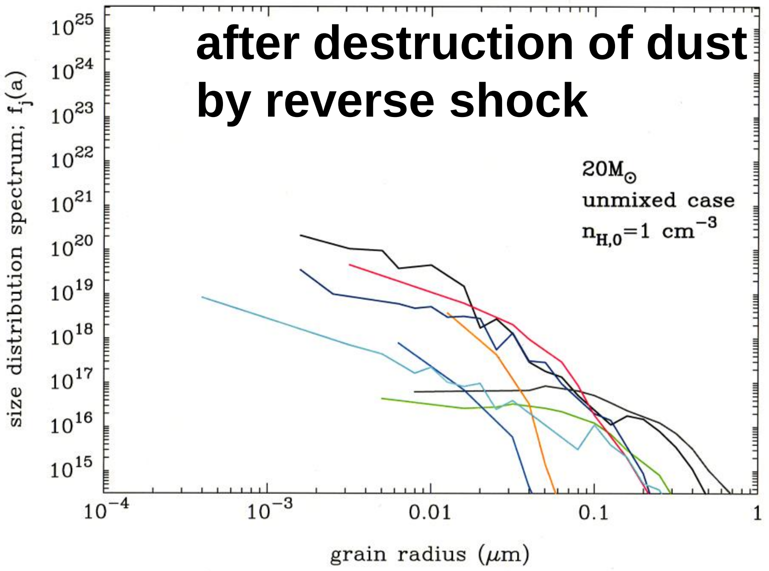
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

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

Nozawa+2007, ApJ, 666, 955



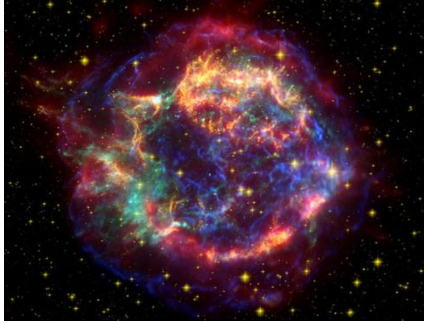




total dust mass surviving the destruction in Type II-P SNRs; 0.07-0.8 M_{sun} ($n_{H,0}$ = 0.1-1 cm^{-3})

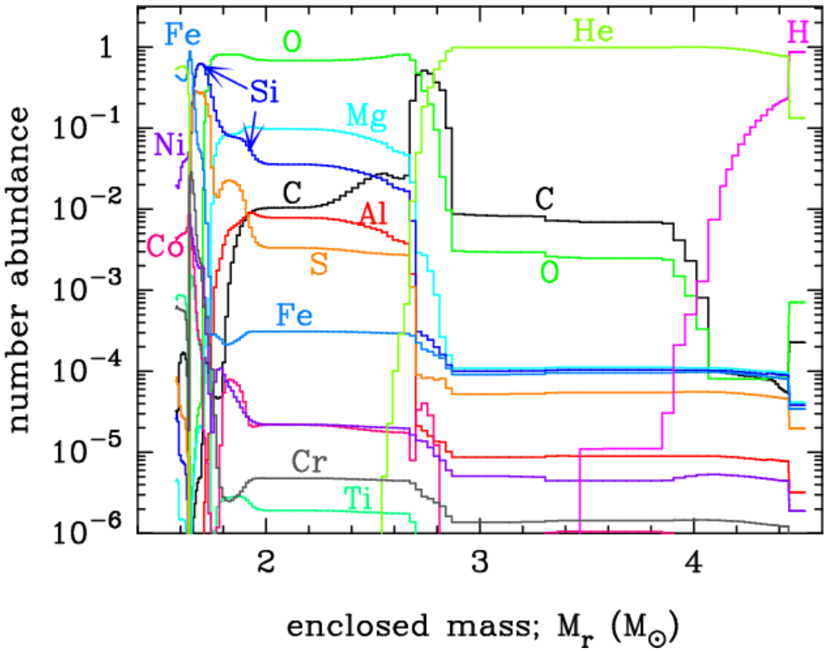
size distribution of dust after RS destruction is <u>domimated by large grains (> 0.01 μm)</u>

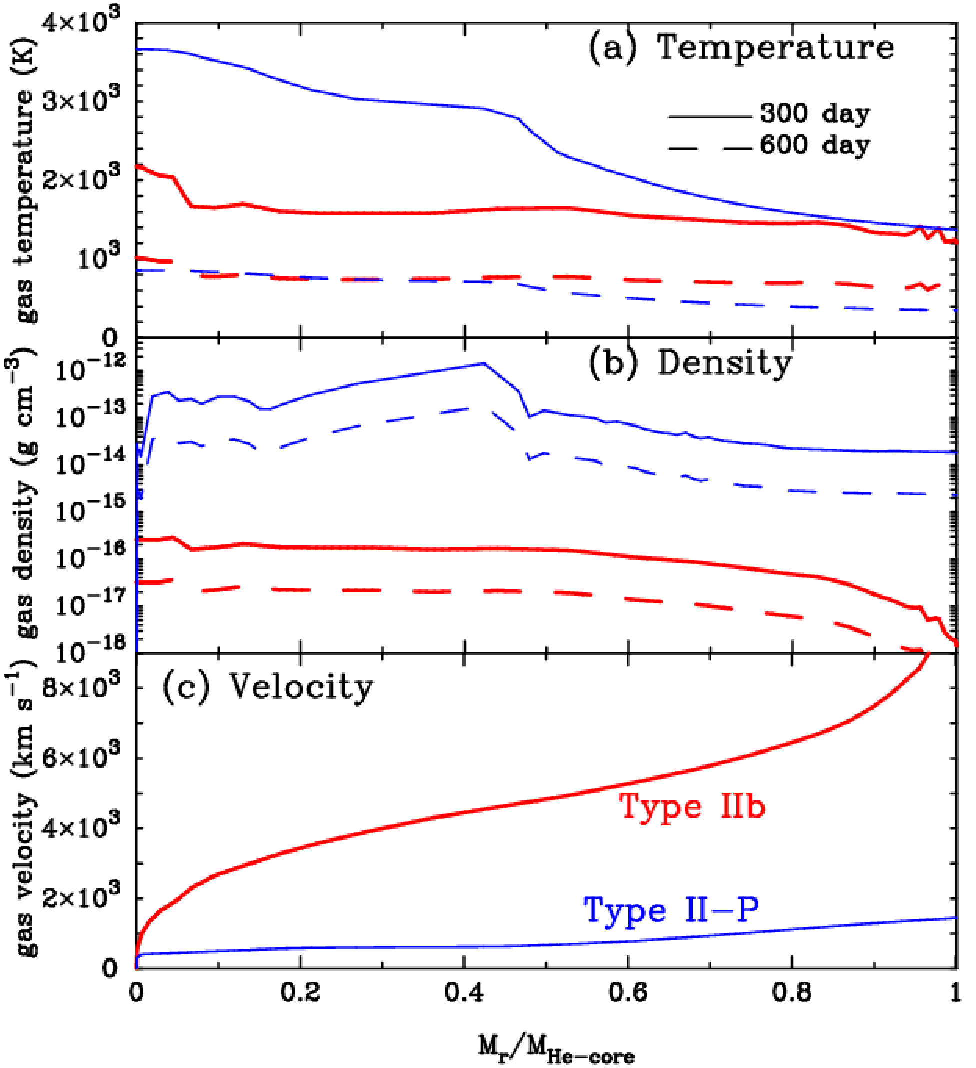
4-1. Dust formation in Type IIb SN



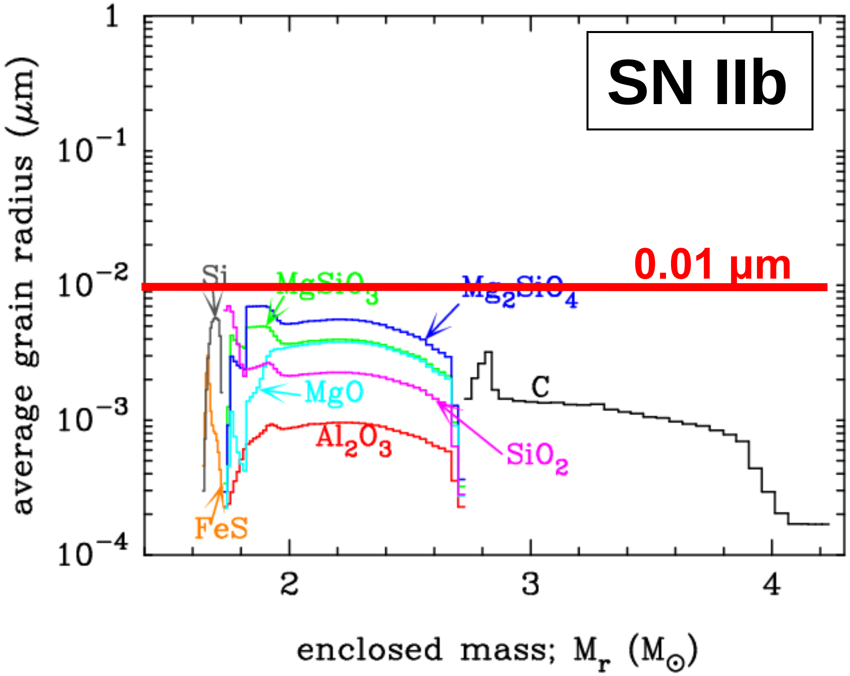
○ SN IIb model (SN1993J-like model)

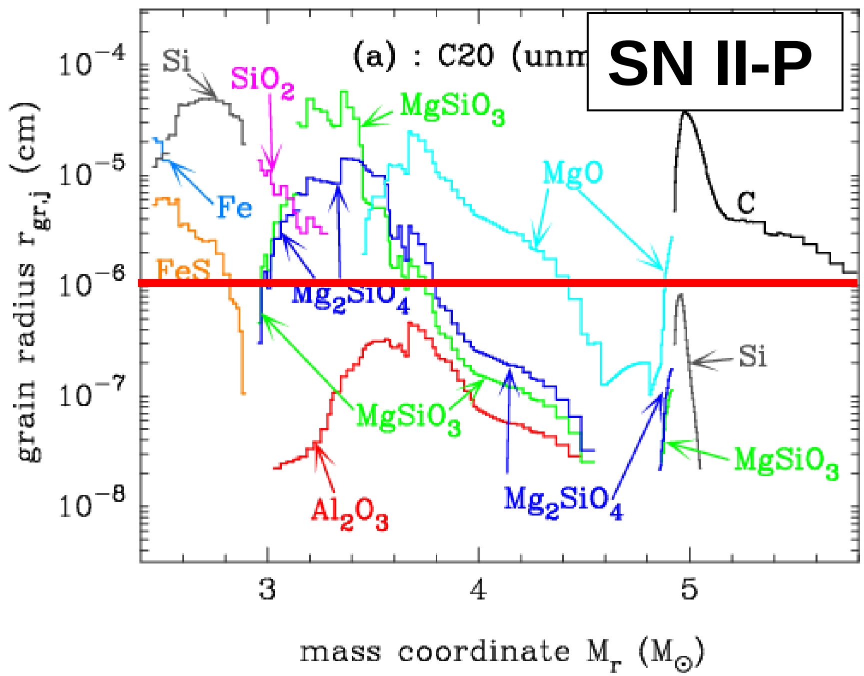
- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1
- $M(^{56}Ni)$ = 0.07 Msun





4-2. Dependence of dust radii on SN type





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

- SN IIb without massive H-env ➔ a_{dust} < 0.01 μm
- SN II-P with massive H-env ➔ a_{dust} > 0.01 μm

— condensation time of dust 300-700d after explosion

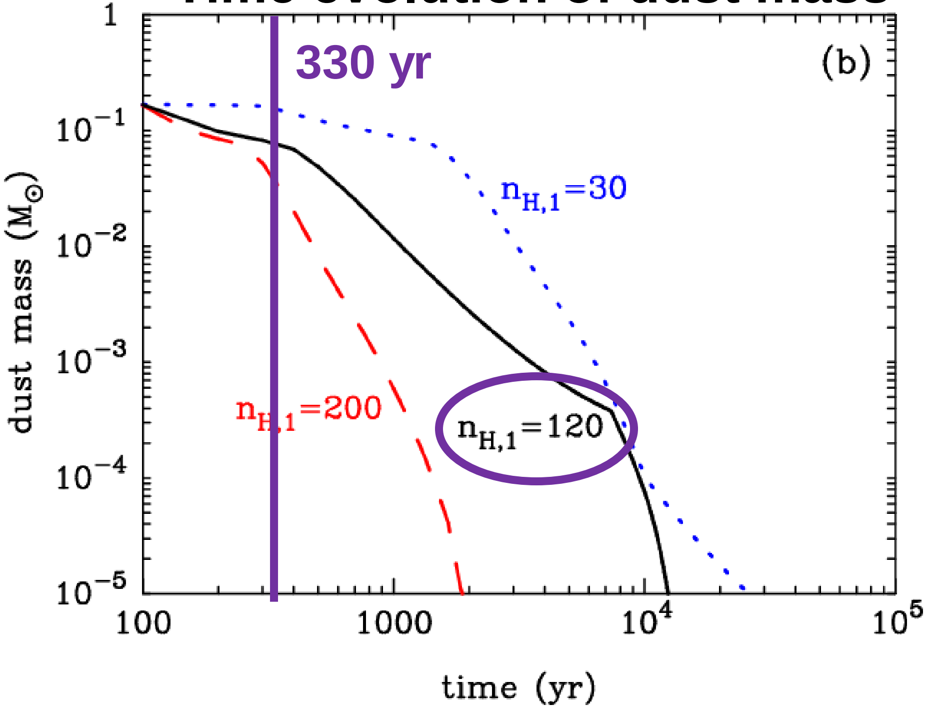
— total mass of dust formed

- 0.167 M_{sun} in SN IIb
- 0.1-1 M_{sun} in SN II-P

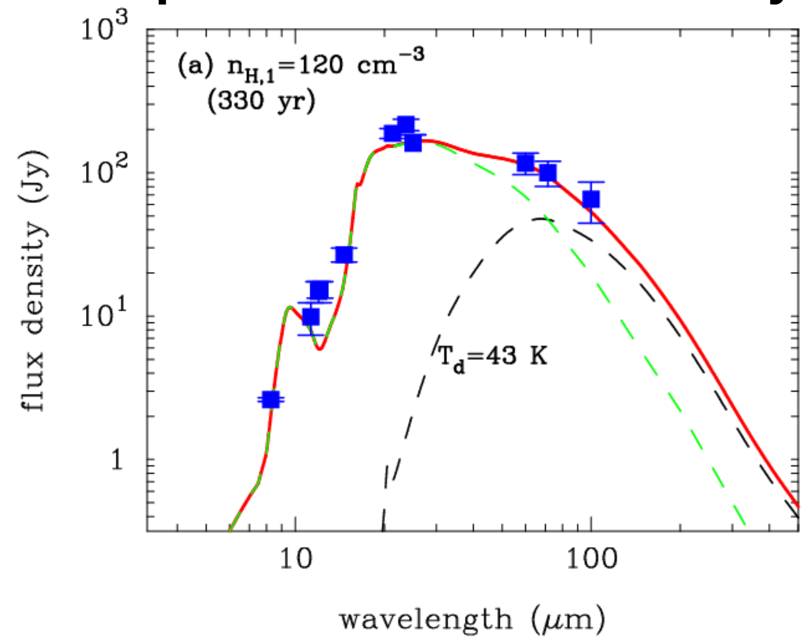
Nozawa+10, ApJ, 713, 356

4-3. Evolution of dust in Type IIb SNR

Time evolution of dust mass



predicted IR SED at 330 yr



Almost all newly formed grains are destroyed in shocked gas in the SNR

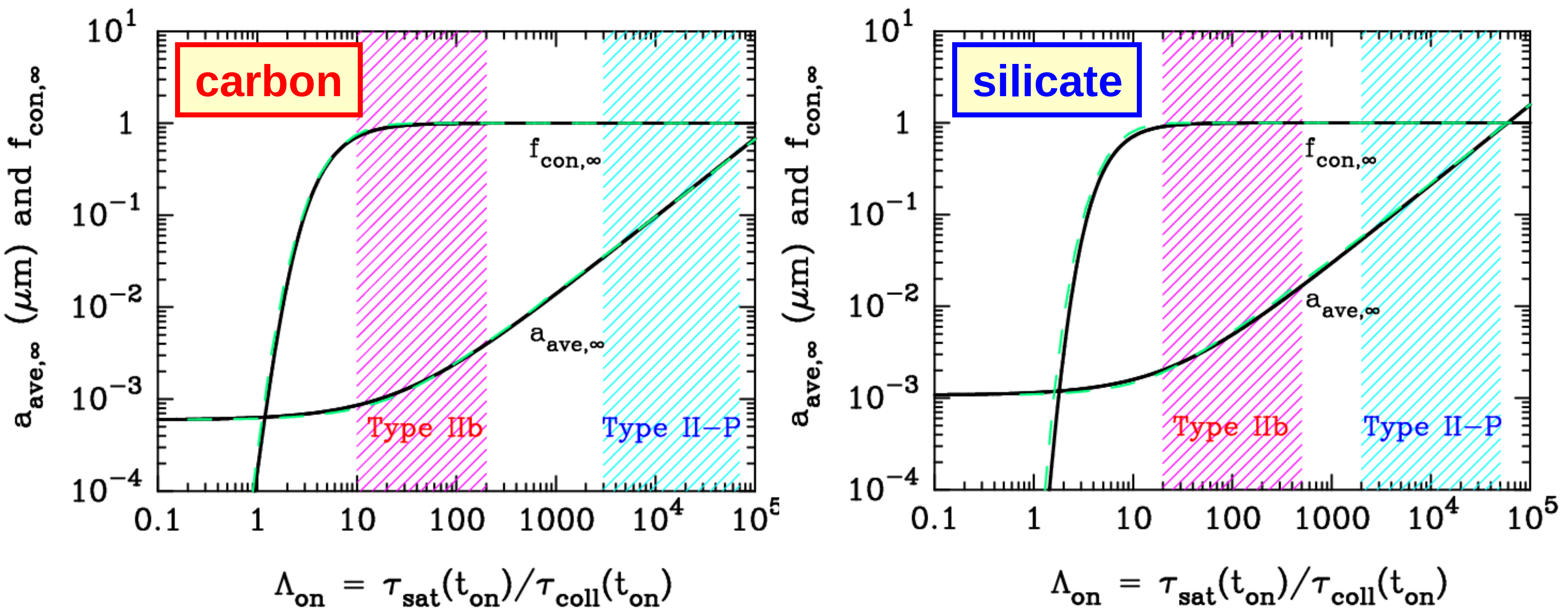
Herschel observation

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

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

- **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

5-1. Scaling relation of average grain radius



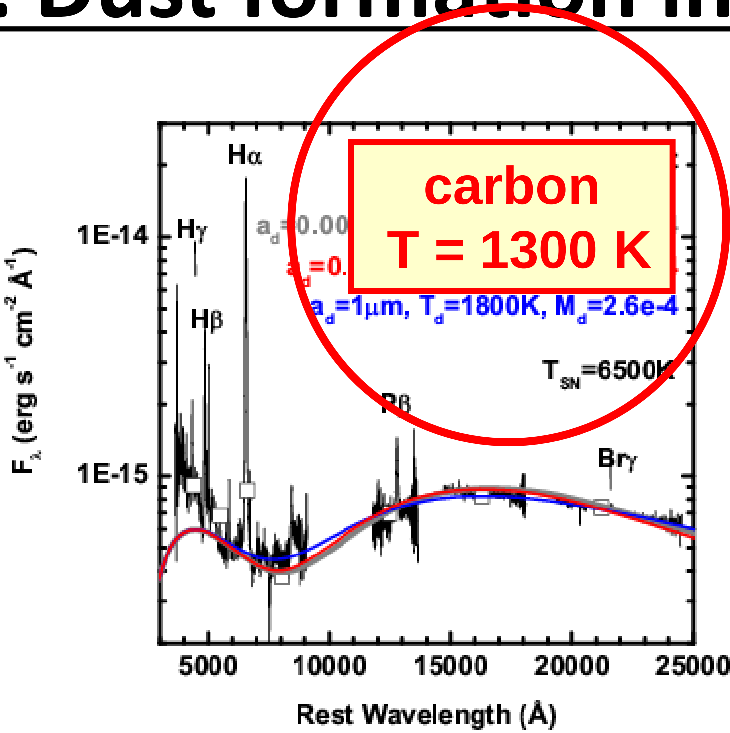
Λ_{on}: ratio of supersaturation timescale to gas collision timescale at the time of dust formation

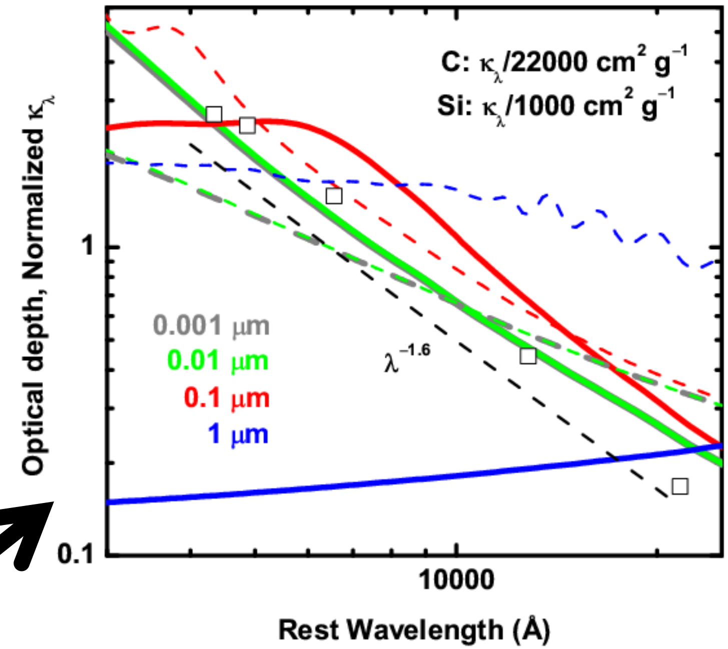
$$\Lambda_{on} = \tau_{sat}/\tau_{coll} \propto \tau_{cool}\, n_{gas}$$

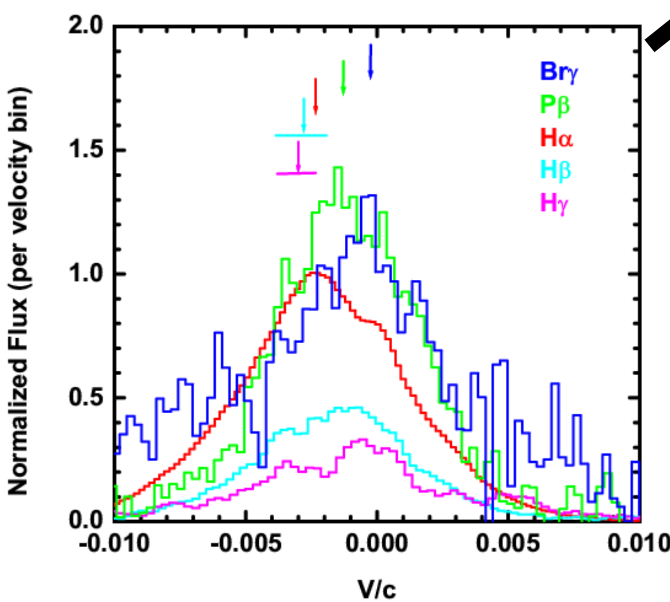
where $\tau_{cool} = t_{on} / 3 (\gamma - 1)$

Nozawa & Kozasa in prep

5-2. Dust formation in Type IIn SN 2010jl





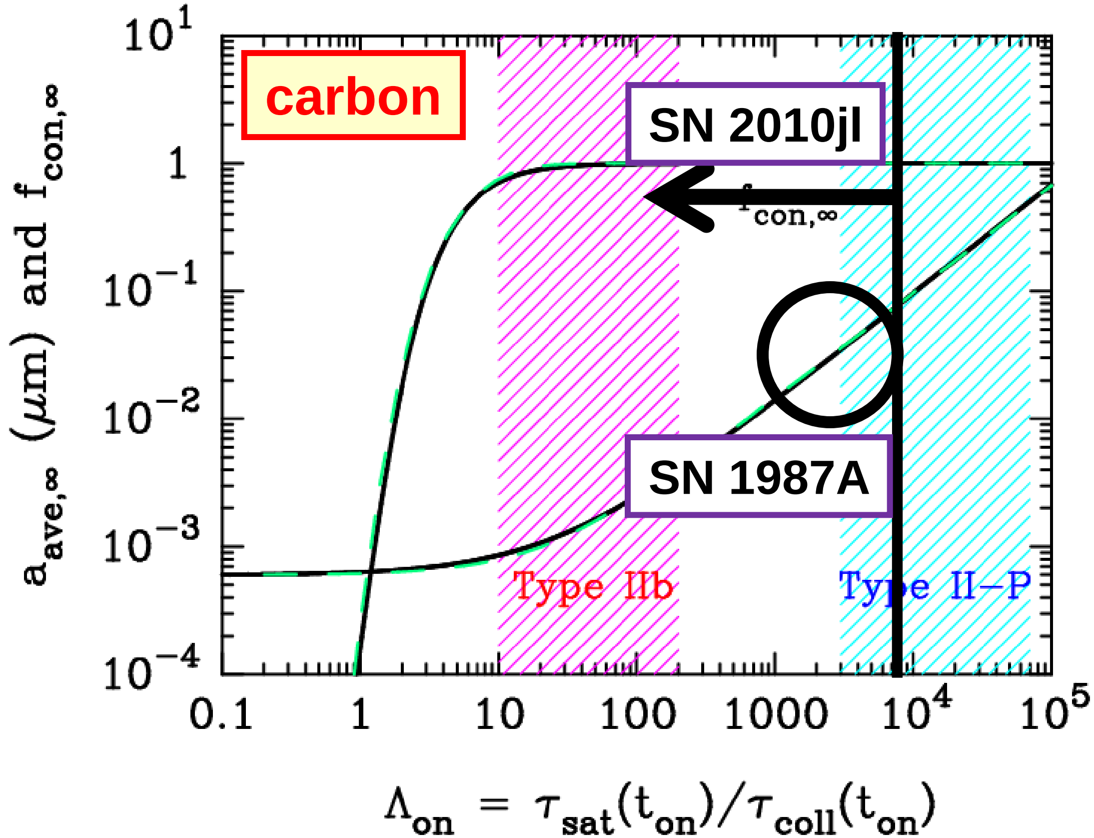


Dust in SN 2010jl

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

Maeda, TN, et al. 2013

5-3. Average grain size in SNe 2010jl and 1987A



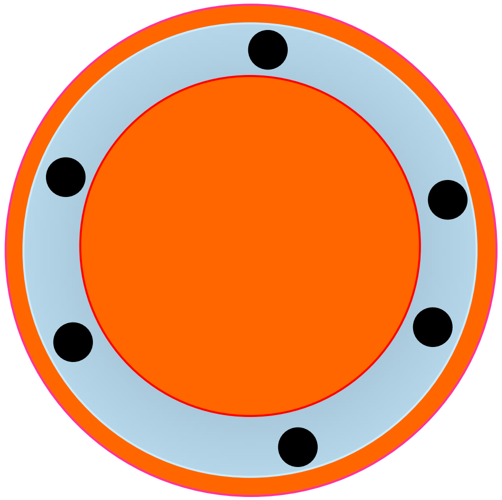
SN 2010jl

- t_{on}: 550 day
- $n_{gas} < 10^{9}$ cm^{-3}

↓

grain radius < 0.08 μm

Dust formation in cool dense shell



SN 1987A

- **grain radius: ~0.01-0.05 μm**
  (Kozasa et al. 1989; Todini & Ferrara 2001)
- **dust formation in clumps?**

6. Summary of this talk

○ **There are increasing pieces of observational evidence that CCSN is a production factory of massive dust**

➔ **in good agreement with 0.1-1 M_{sun} predicted by theory**

➔ **few observation to identify the composition and size of 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) : a_{ave} < 0.01 μm**

➔ **H-stripped SNe are likely to be poor producers of dust**

○ **We construct the universal relation to describe the average radius of newly formed dust grains**

➔ **being useful, given gas density and formation time of dust**

➔ **explaining grain size derived from observations of SN 2010jl**