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Dust Synthesis in Supernovae and Reprocessing in Supernova Remnants

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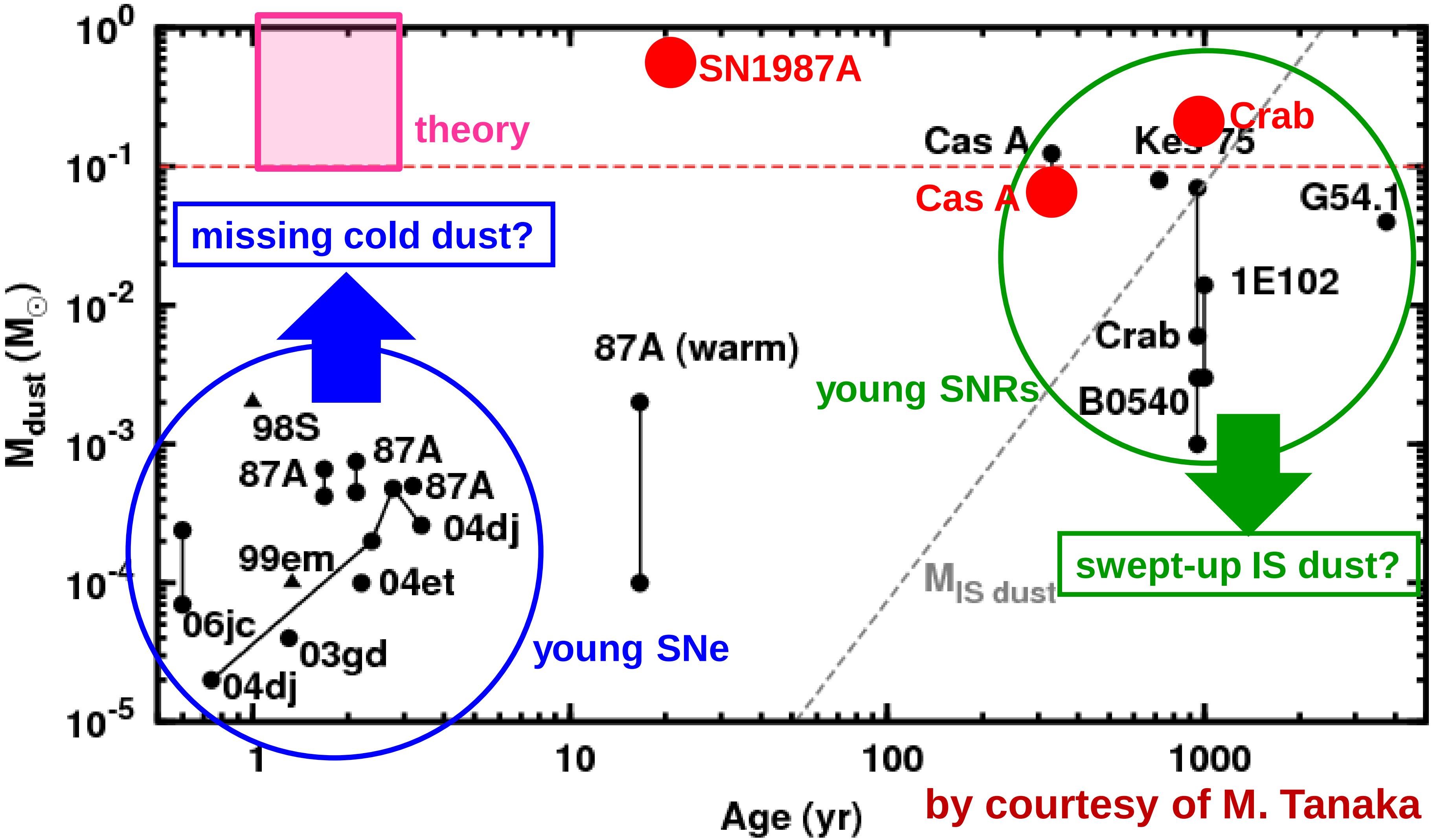
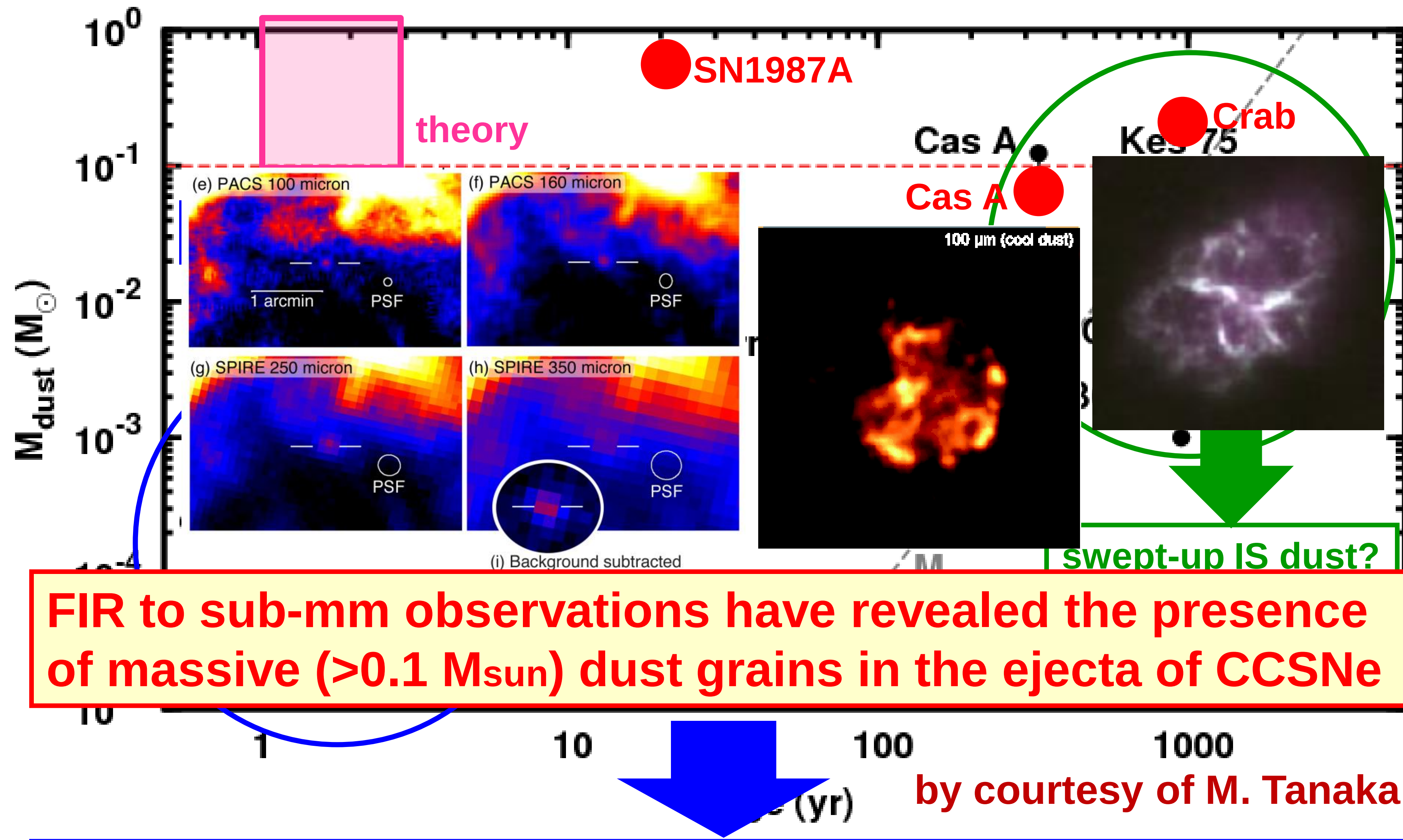
1. Summary of observed dust mass in CCSNe



by courtesy of M. Tanaka

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

1. Summary of observed dust mass in CCSNe



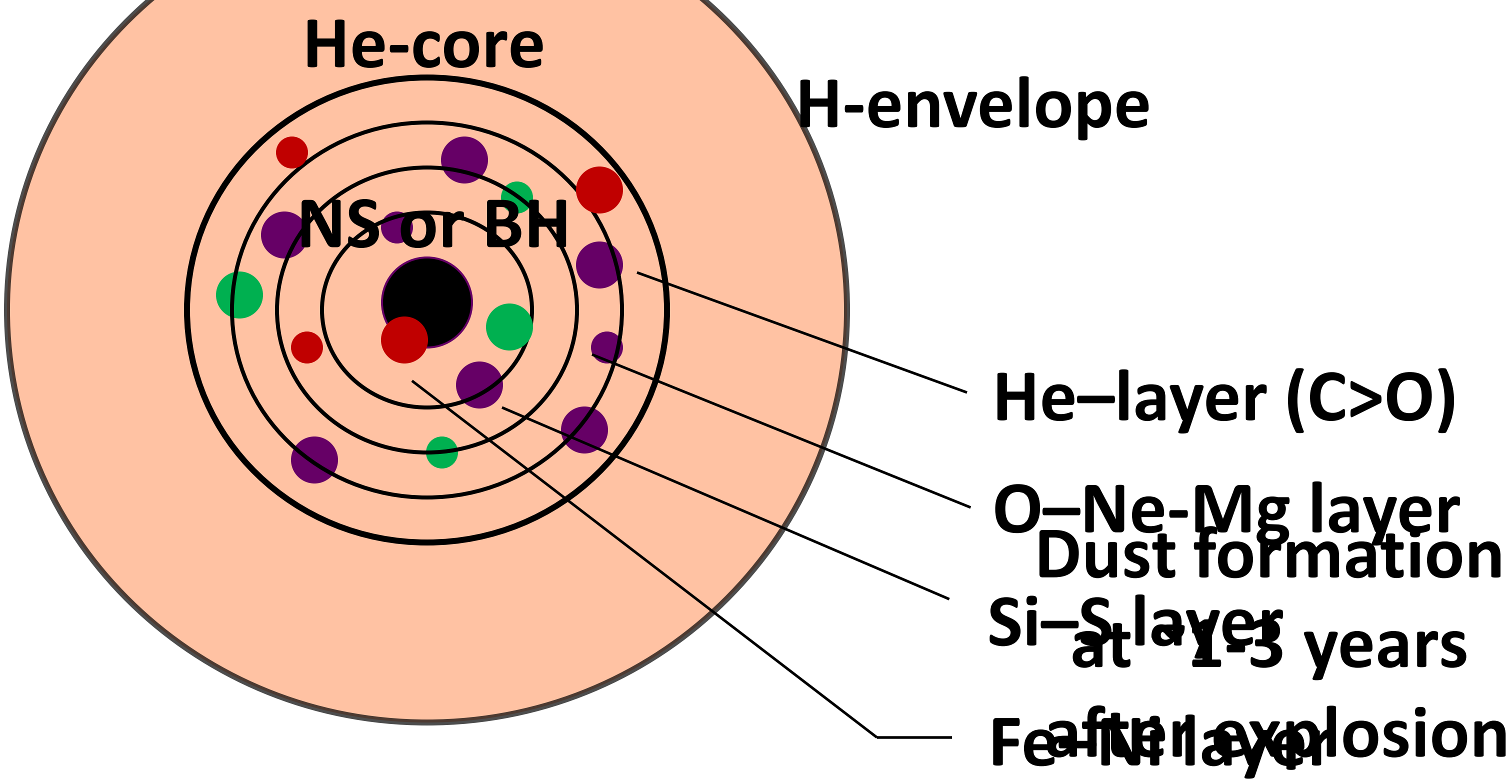
FIR to sub-mm observations have revealed the presence of massive (>0.1 Msun) dust grains in the ejecta of CCSNe

by courtesy of M. Tanaka

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

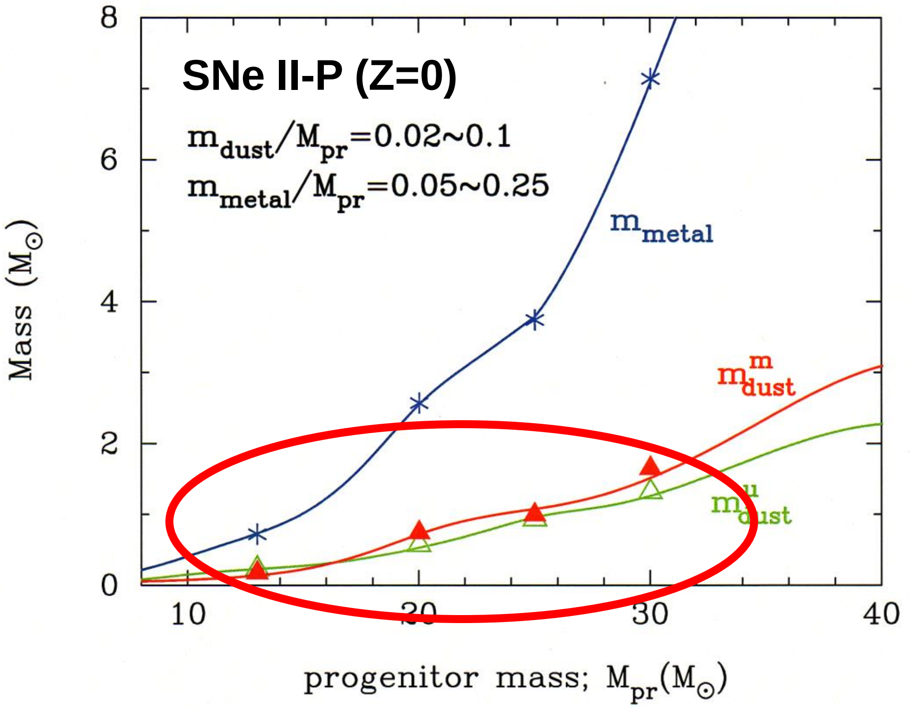
2. Dust Synthesis in the ejecta of SNe

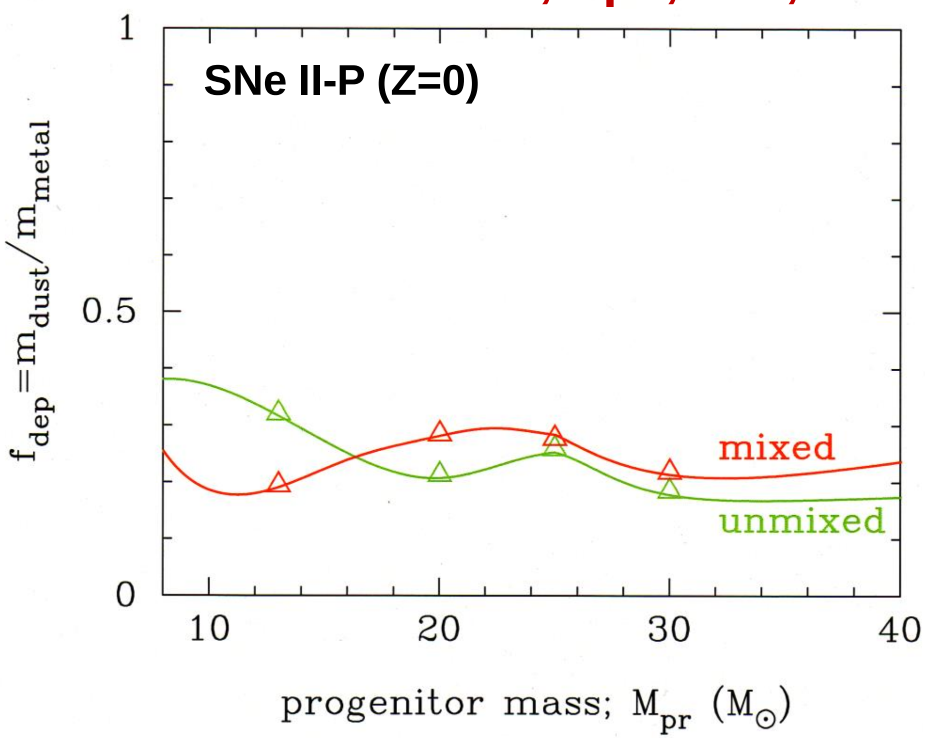
at ~1 days



2-1. Total mass of dust formed

Nozawa+03, ApJ, 598, 785





Total dust mass increases with increasing Mpr

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

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

(also, cf. Raffaella's talk)

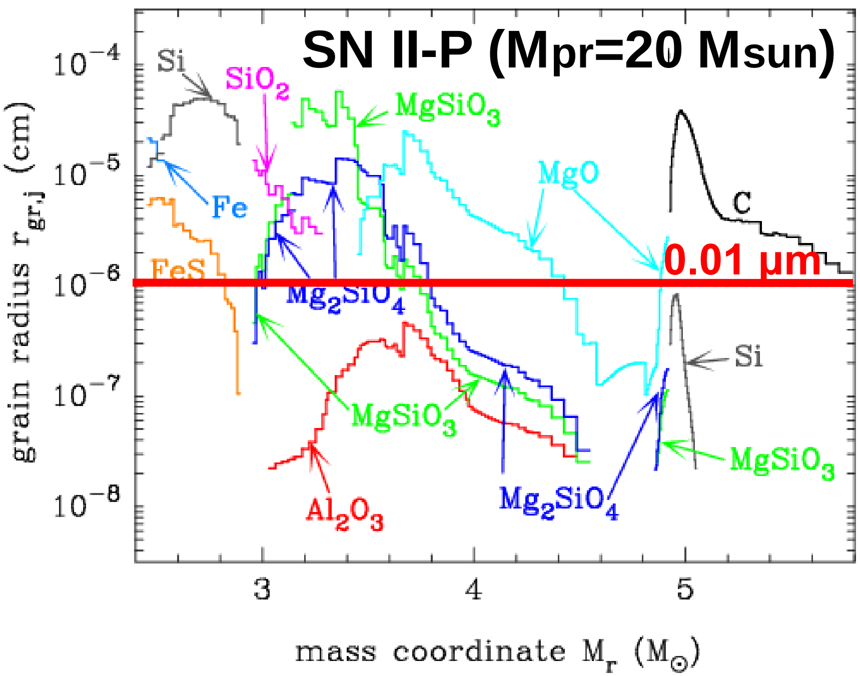
・depletion factor
f_{dep} (M_{dust}/M_{metal}) = 0.2-0.3

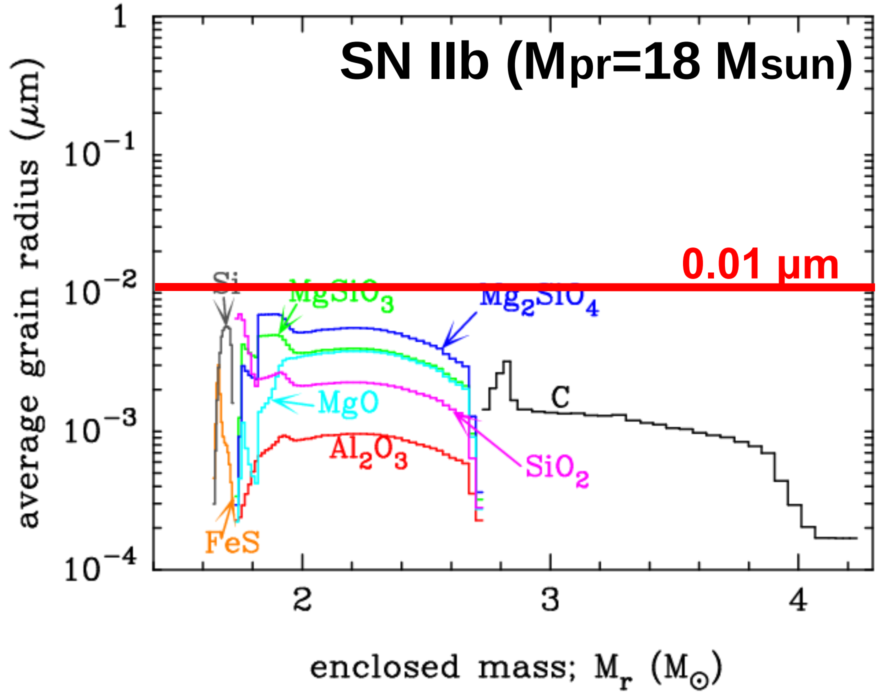
cf. f_{dep} = 0.4-0.5 in the MW

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

2-2. Average radius of dust formed

Nozawa+10, ApJ, 713, 356





- **SN II-P with massive H-env**
  ➔ a_{dust} > 0.01 μm
- **M_{dust} =0.1-1 Msun**

- **SN IIb w/o massive H-env**
  ➔ a_{dust} < 0.01 μm
- **M_{dust} = 0.167 Msun**

The sizes of newly formed dust depend on the SN types and are smaller in less massive-envelope SNe

2-3. Classical nucleation theory

・ classical nucleation theory

– sticking coefficient?

➔ usually $s_n = 1$

– cluster temperature?

➔ $T_{clus} = T_{gas}$

– surface energy of small clusters?

➔ same as the bulk

– shape of small clusters? ➔ sphere

– the steady-state nucleation cannot be applied in rarefied astrophysical environments

(e.g., Donn & Nuth 1985; Stefan's talk; Isabelle's talk)

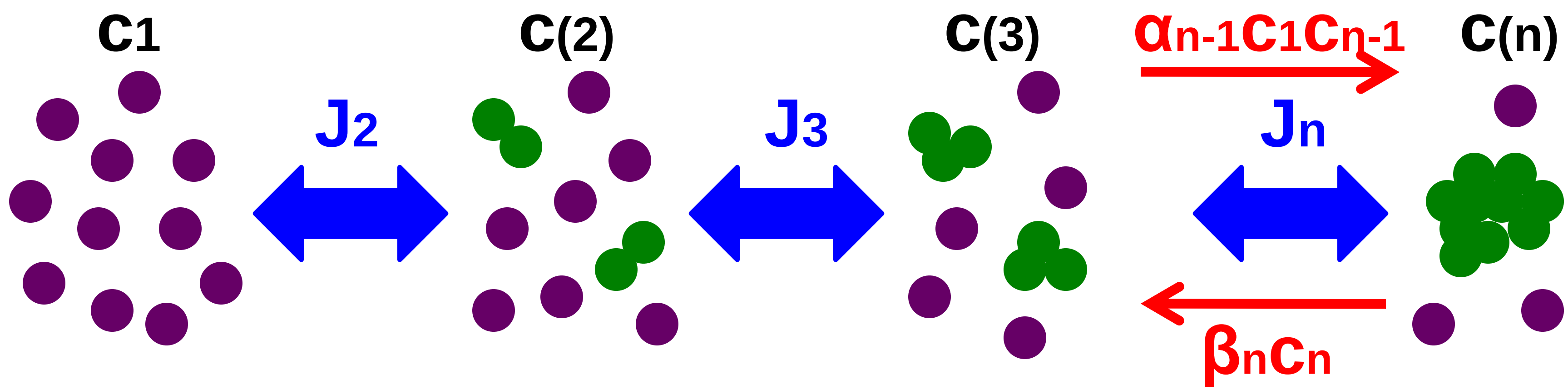
・ chemical approach
➔ Isabelle's talk

・ kinetic approach
➔ Davide's talk

molecular formation? (cf. Claes's talk)

➔ complete formation of CO and SiO molecules

2-4. Concept of nucleation theory



・ master equations

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

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

$s_n = 1$

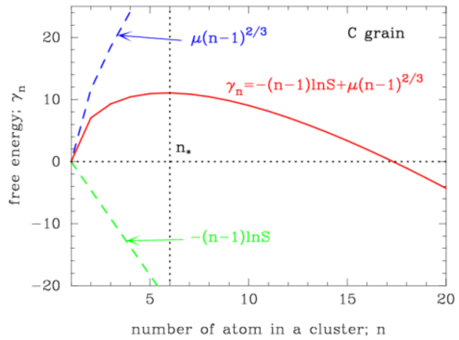
$$\alpha_n = \frac{s_n}{1 + \delta_{1n}} 4\pi a_0^2 \, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n} \right)^{\frac{1}{2}},$$

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

2-5. Non-steady-state nucleation

・ steady-state nucleation rate: J_s

➔ assuming $J_s = J_2 = J_3 = \cdots = J_\infty$



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

$\mu = 4\pi a_0^2\sigma / kT$

(σ = 1400 erg cm^{-2} for bulk C)

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

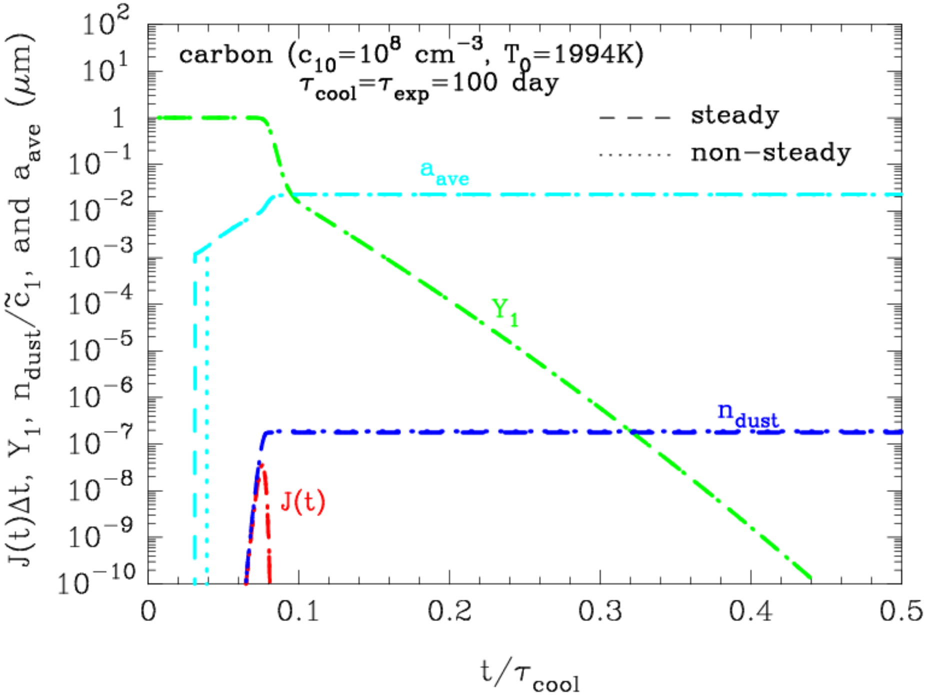
・ non-steady-state nucleation

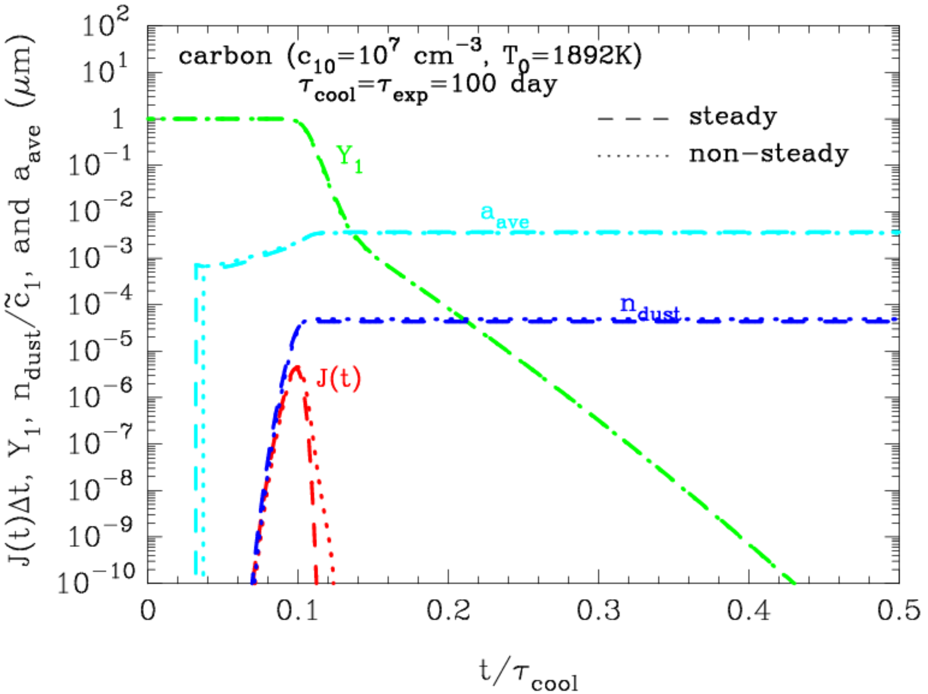
$n_* = 100$

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

2-6. Steady vs. Non-steady (1)

$c_{10} = 10^8$ cm^{-3} $\qquad$ $c_{10} = 10^7$ cm^{-3}



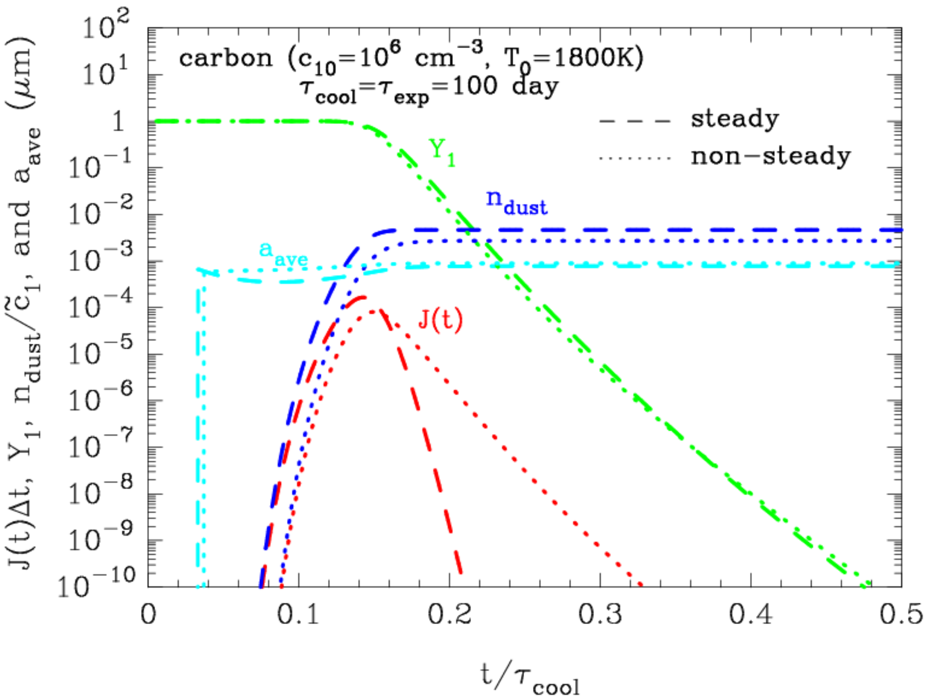


- dashed line : steady-state nucleation
- dotted line : non-steady-state nucleation

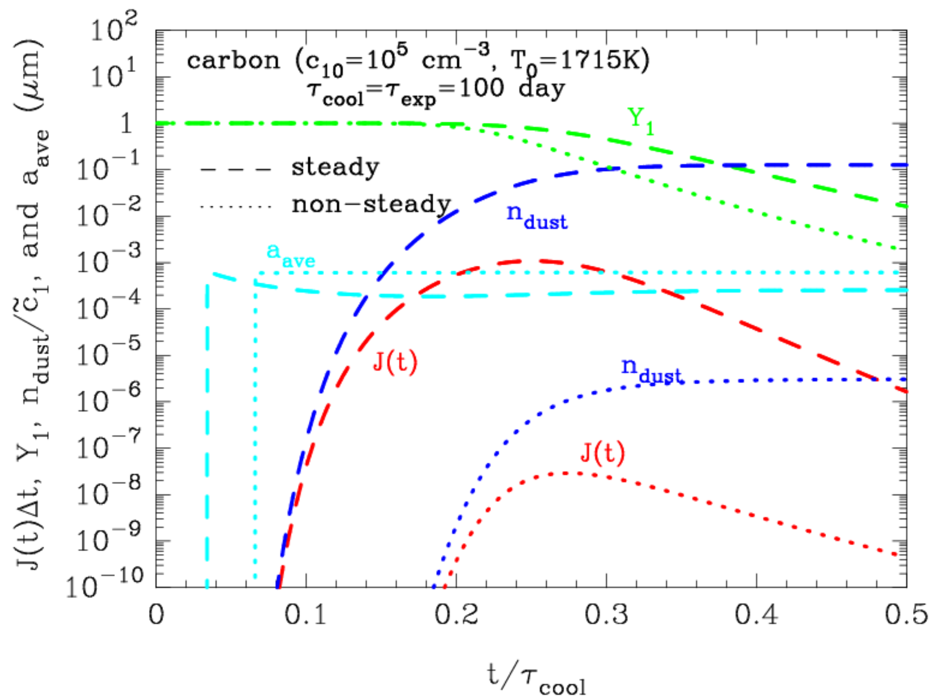
The difference between steady and non-steady nucleation is small for higher initial densities

2-7. Steady vs. Non-steady (2)

$c_{10} = 10^6\ cm^{-3}$



$c_{10} = 10^5\ cm^{-3}$

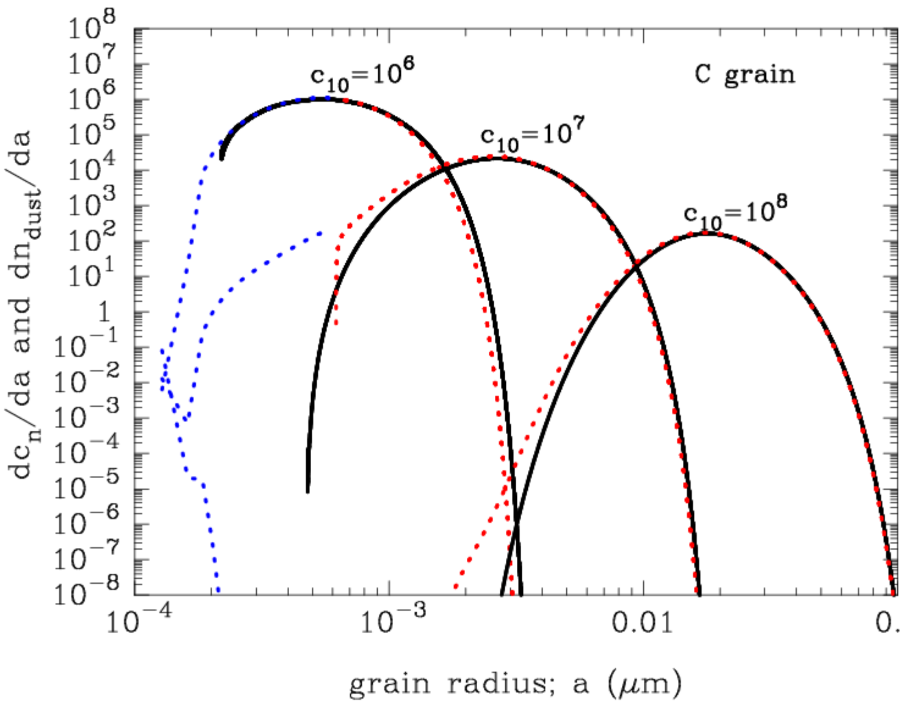


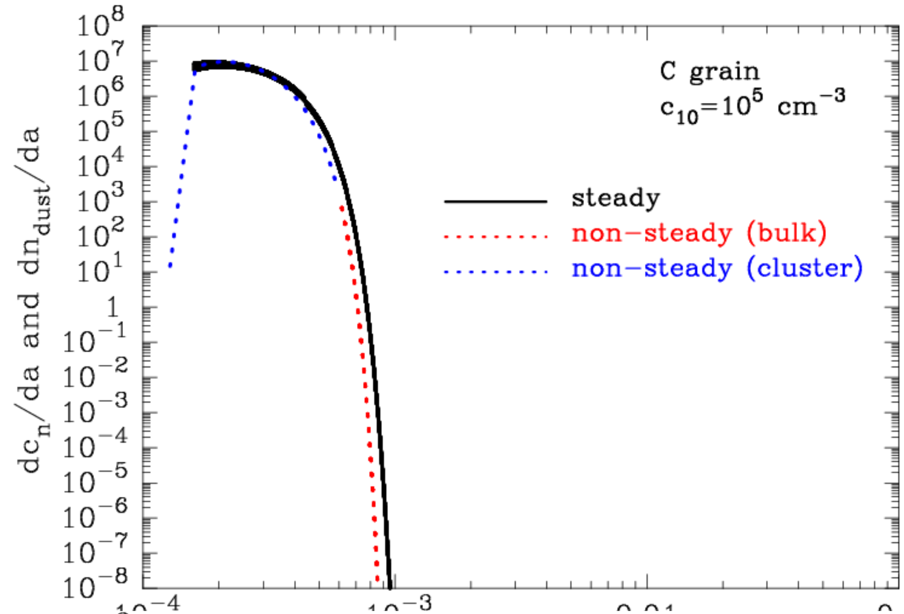
- **dashed line : steady-state nucleation**
- **dotted line : non-steady-state nucleation**

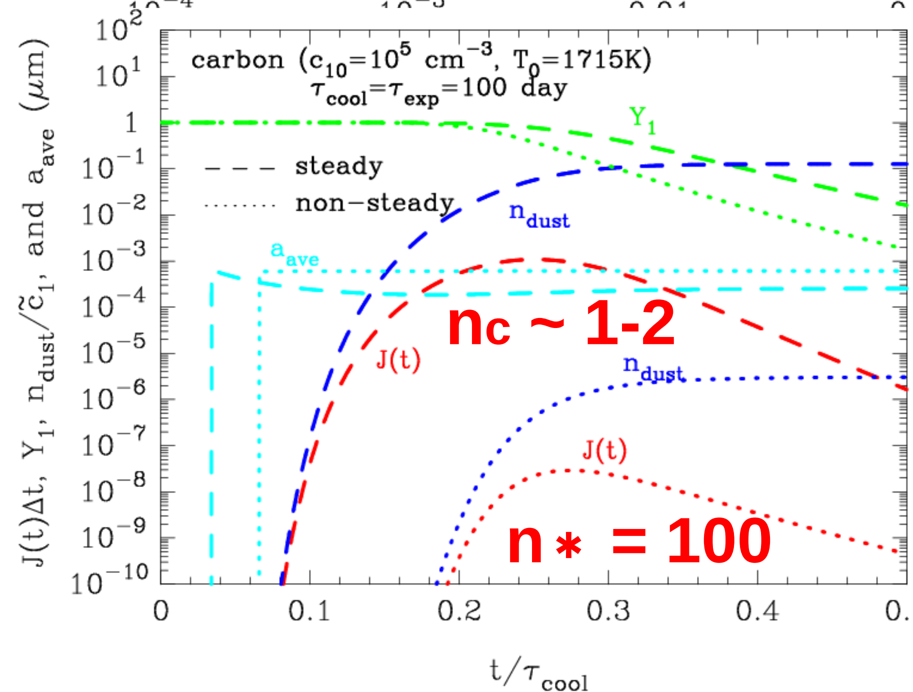
The difference between steady and non-steady seems significant for lower densities

2-8. Steady vs. Non-steady: size distribution

Nozawa & Kozasa in prep.



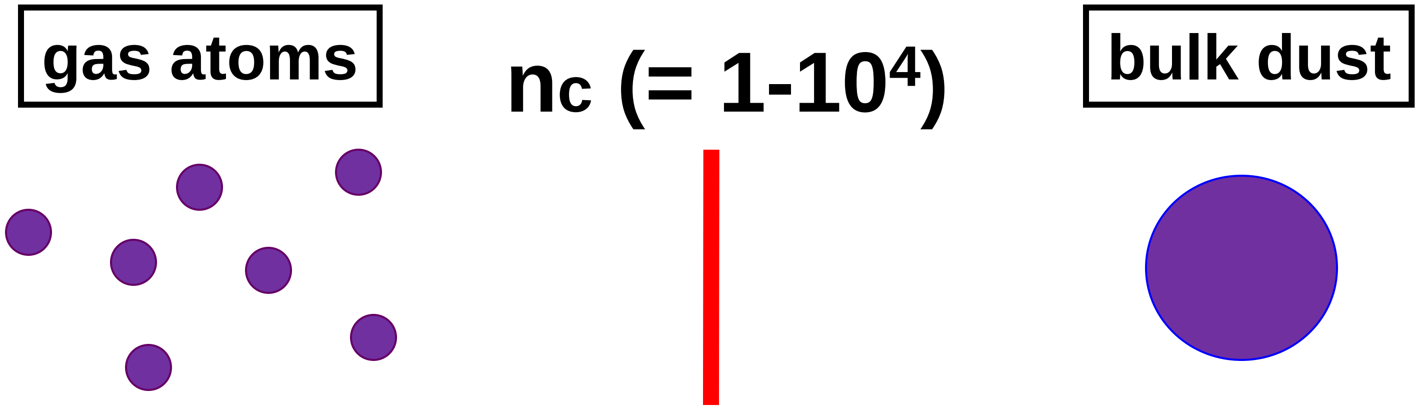




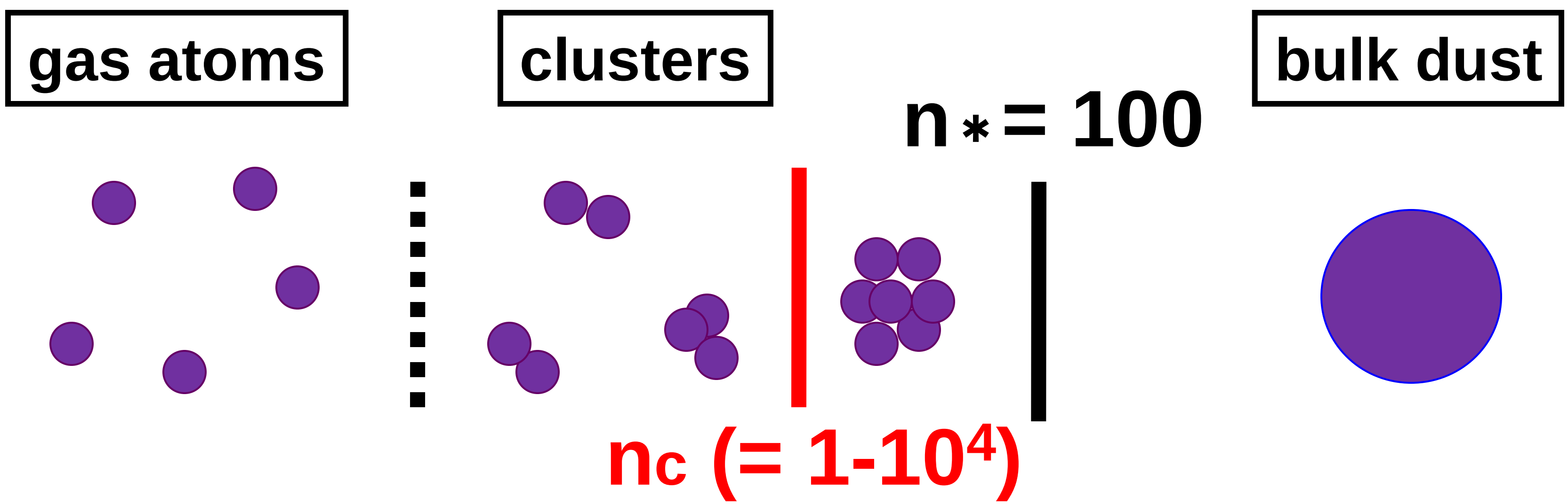
The size distribution of bulk grains from non-steady-state is consistent with that from steady-state

2-9. Steady and non-steady

・ steady-state nucleation rate: J_s

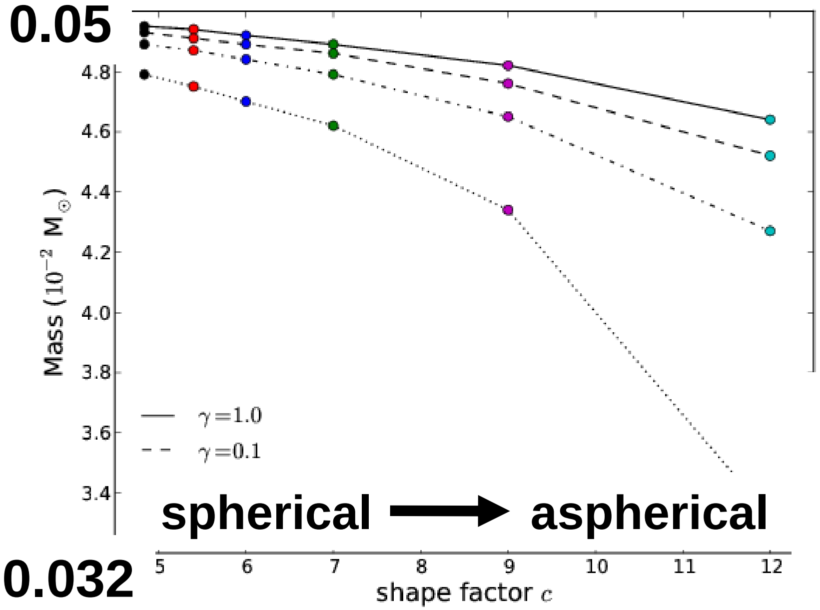


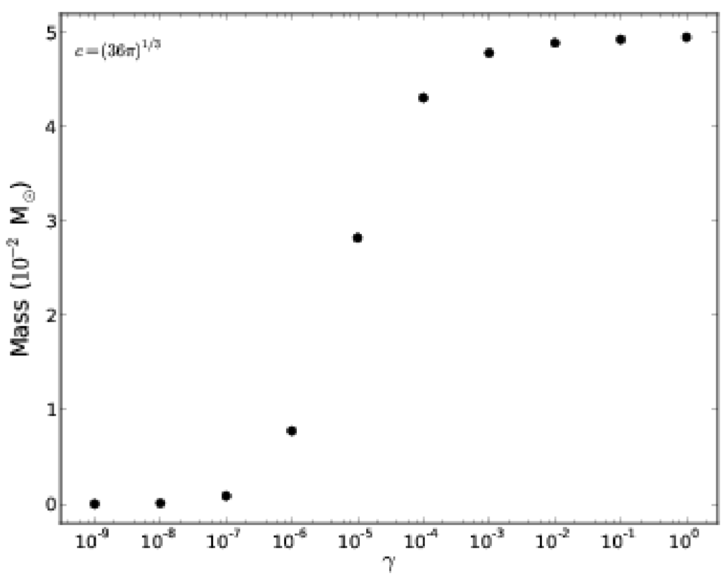
・ non-steady-state nucleation rate: J_*



2-10. Effects of microphysics on dust formation

Carbon mass in SNe II-P

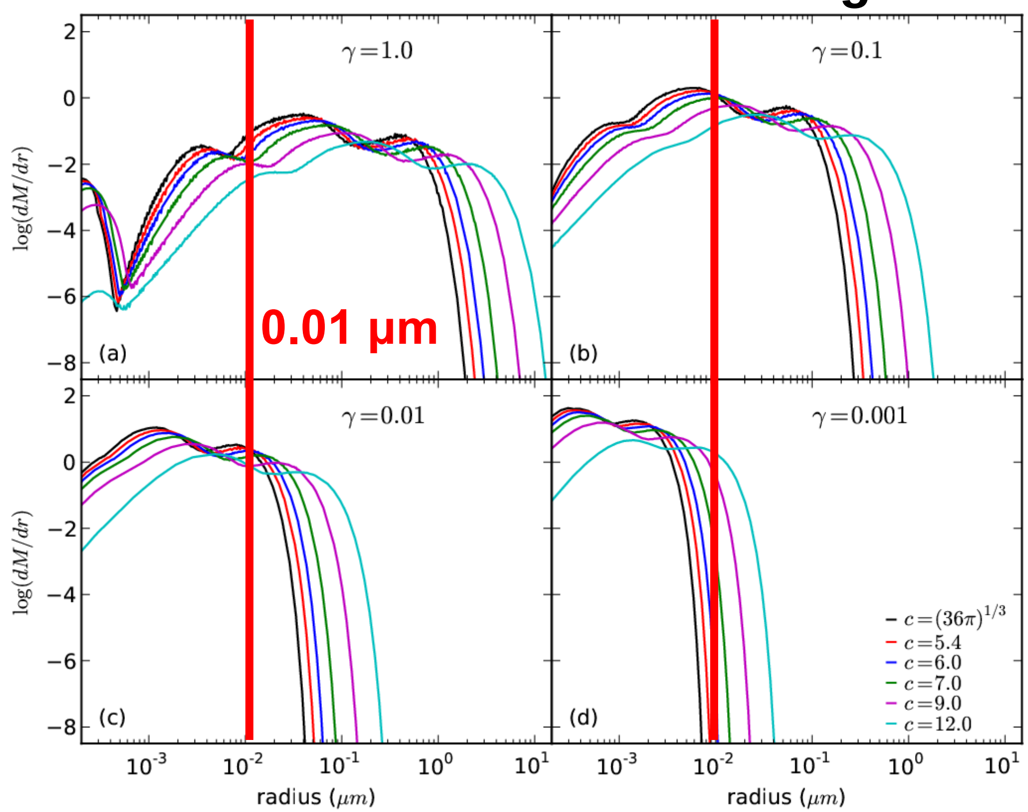




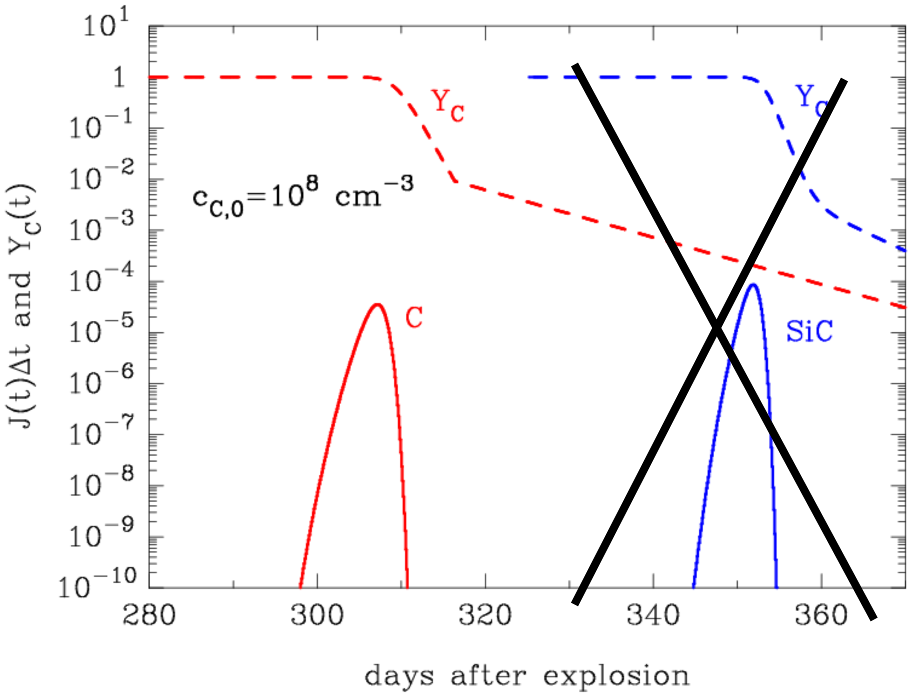
Fallest, TN,+2011, MNRAS, 418, 571

Mass of C grains formed is not sensitive to sticking coefficient and cluster shape

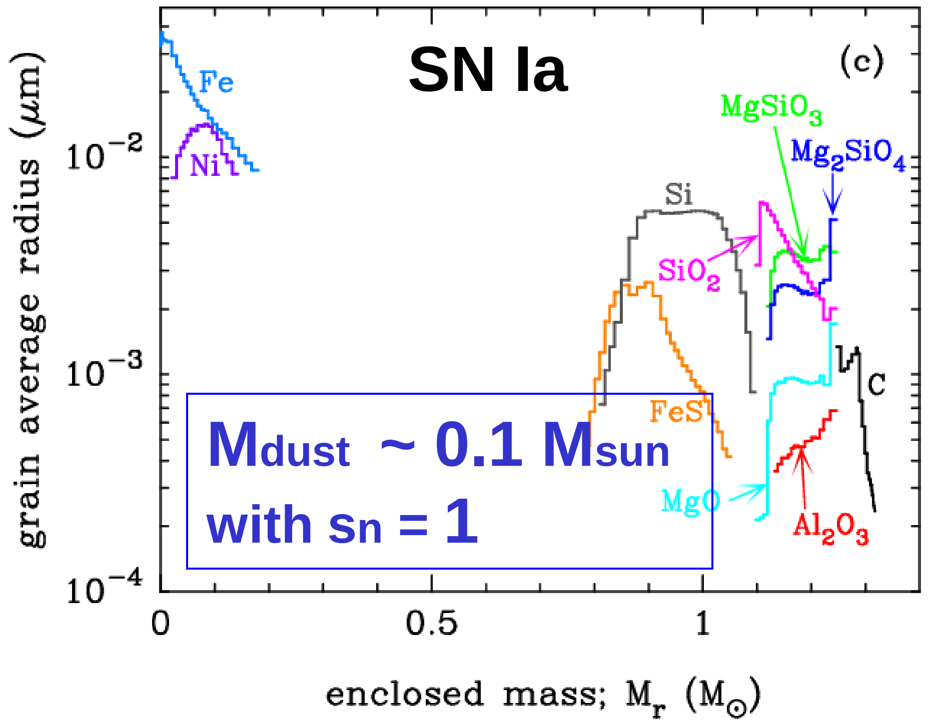
Size distribution of carbon grains



2-11. No formation of SiC in the calculations



Nozawa+11, ApJ, 736, 45



The earlier formation of C grains necessarily prevents condensation of SiC

Formation of C dust in AGB is suppressed by radiation
(e.g., Yasuda & Kozasa 2012)

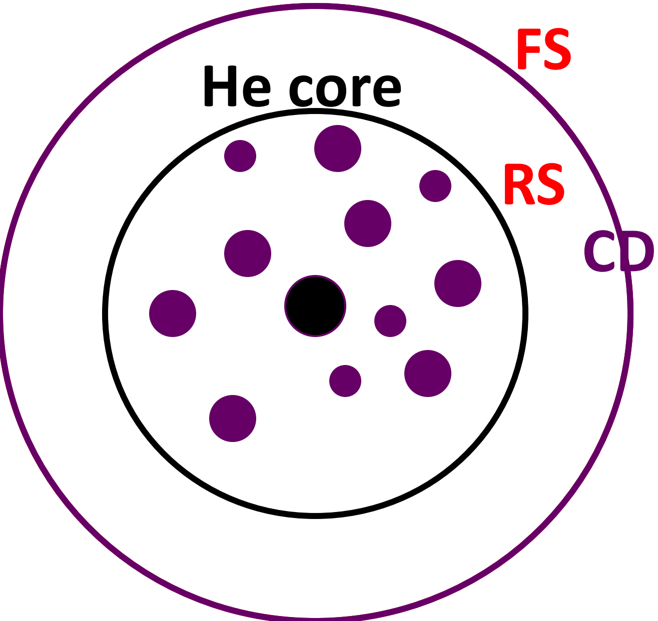
M(^{56}Ni) in SNe Ia ~ 0.6 M_{sun}

➔ much stronger radiation fields may prevent the condensation of dust

(cf. Rubina's talk, Davide's talk)

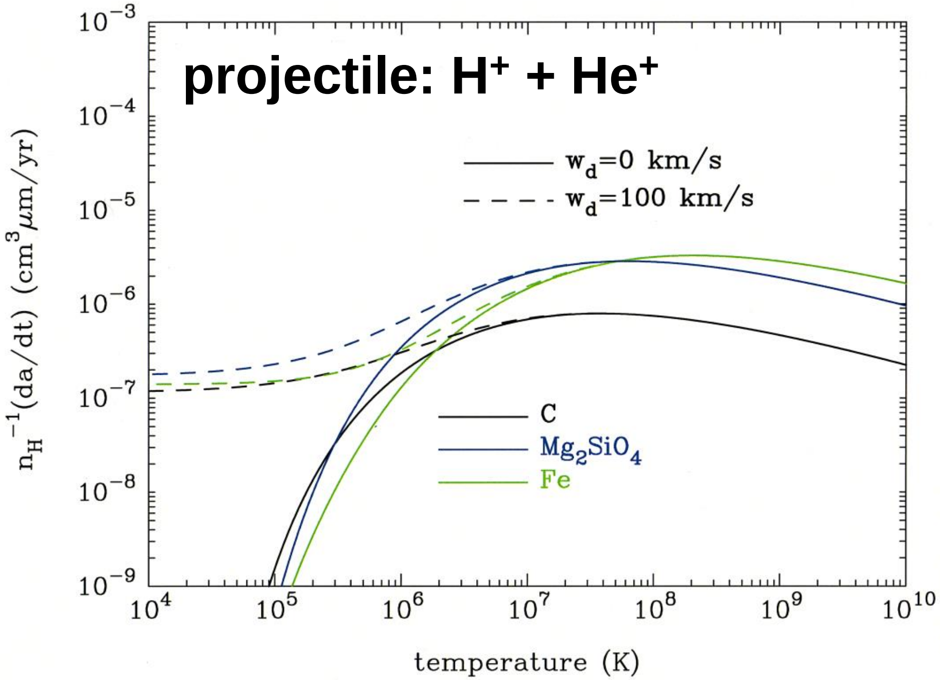
3. Reprocessing of Dust in SNRs

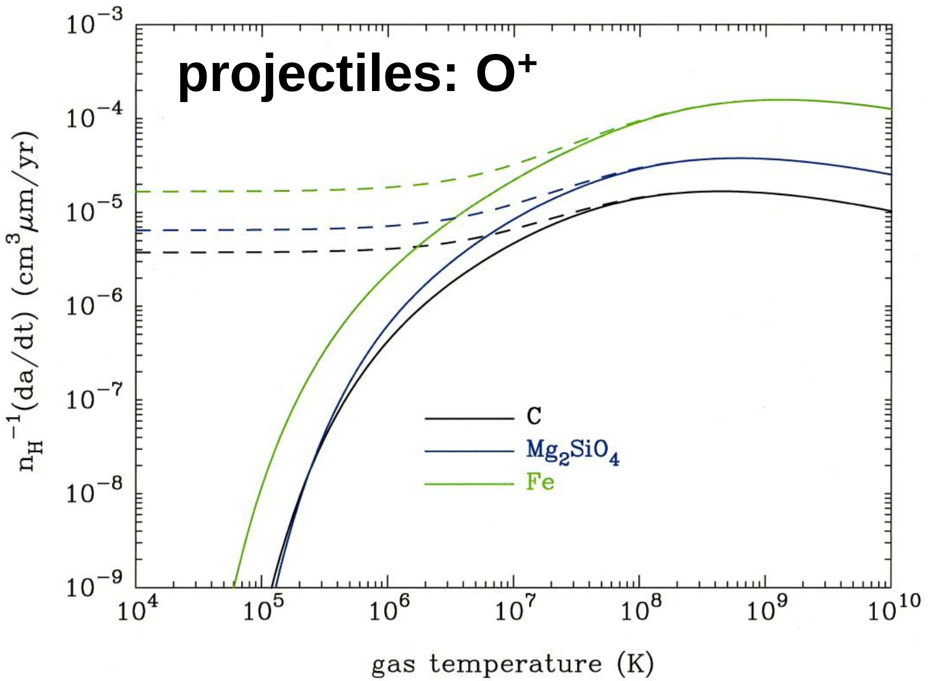
$T = (1\text{-}2)\times10^4$ K
$n_{H,0} = 0.1\text{-}1\ cm^{-3}$



3-1. Erosion rate of dust by sputtering

Nozawa+06, ApJ, 648, 435





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

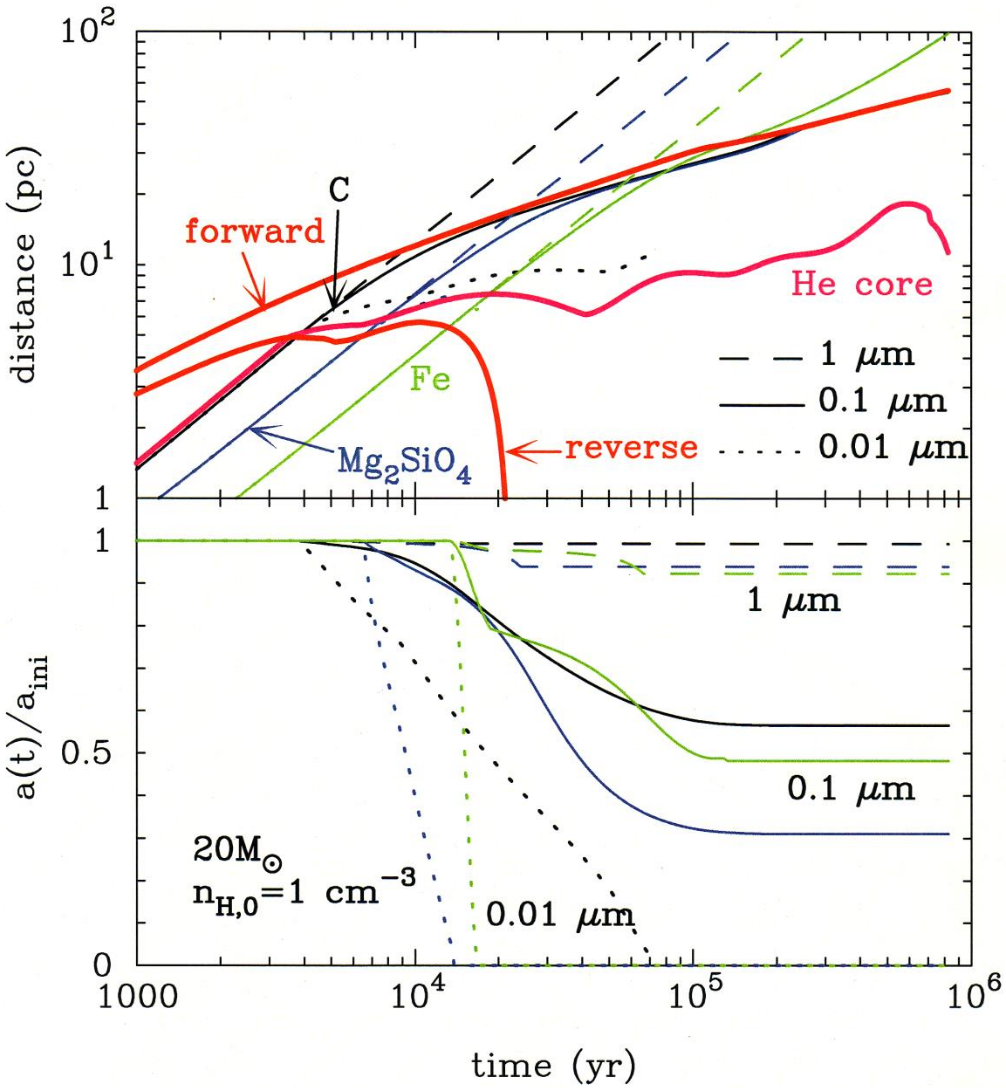
  $da/dt \sim 10^{-6}\, n_H$ μm yr^{-1} cm^3

- **destruction timescale by sputtering:**

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

3-2. Evolution of dust in SNRs

Nozawa+07, ApJ, 666, 955



Model : Type II-P

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

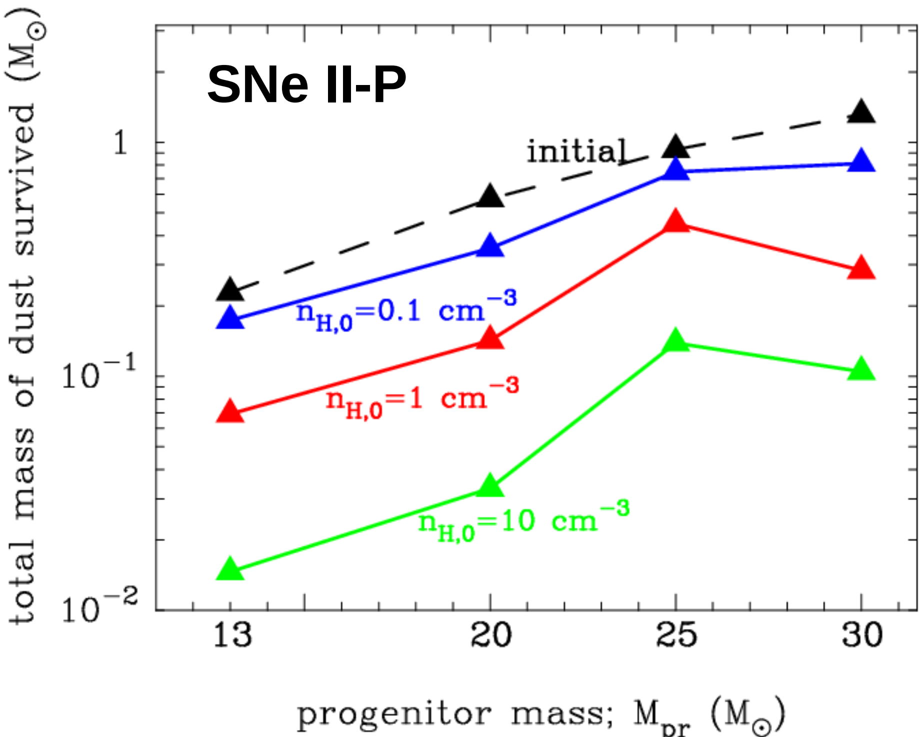
$n_{H,0}$ = 1 cm^{-3}

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

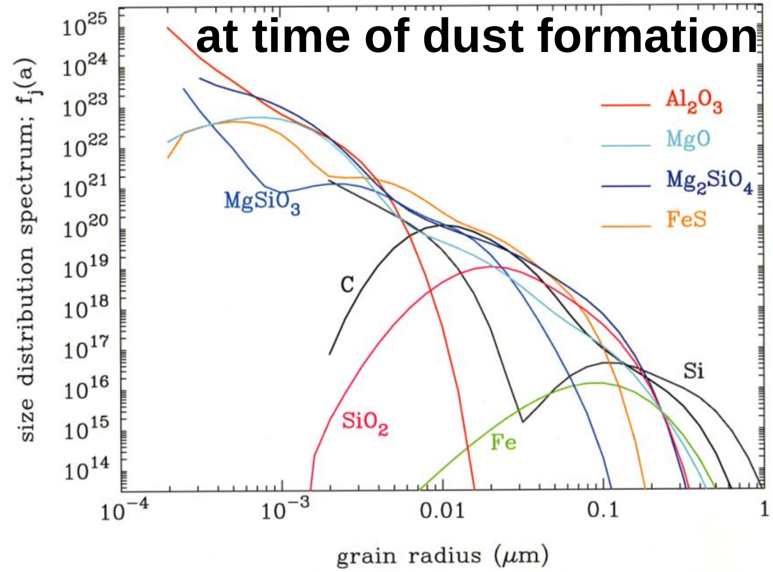
The evolution of dust heavily depends on the initial radius and composition

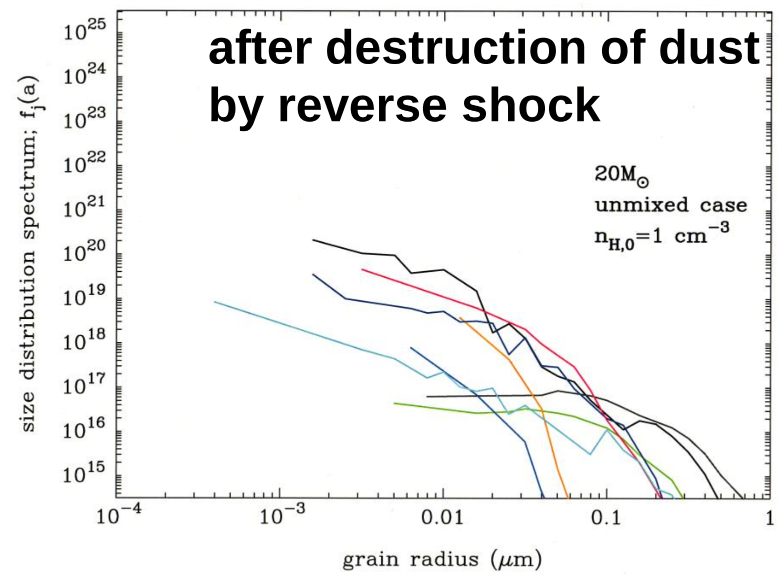
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed
a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

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



Nozawa+2007, ApJ, 666, 955



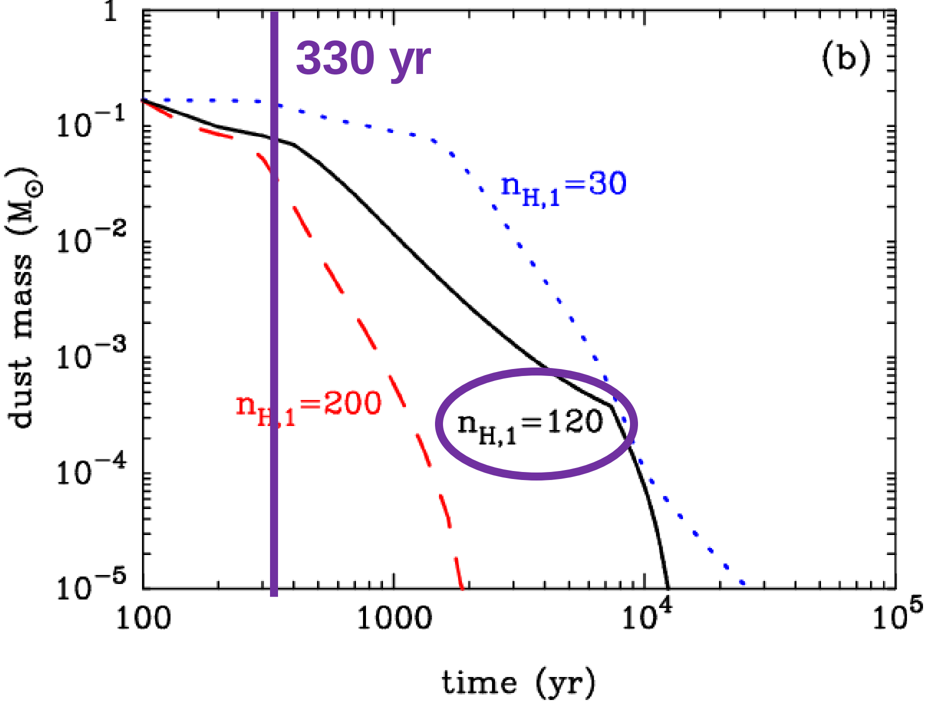


total dust mass surviving the destruction in Type II-P SNRs; 0.07-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

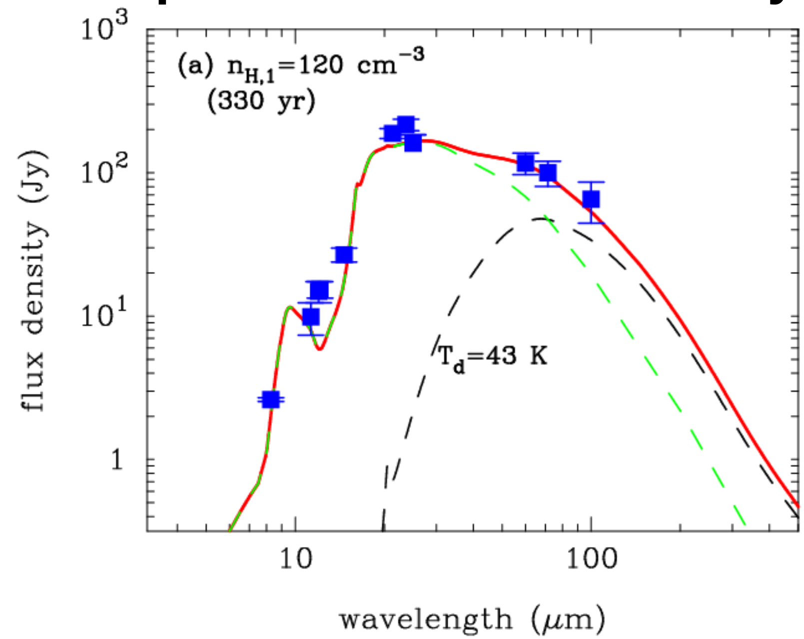
size distribution of dust after RS destruction is domimated by large grains (> 0.01 μm)

3-4. Evolution of dust in Type IIb SNR

Time evolution of dust mass



predicted IR SED at 330 yr

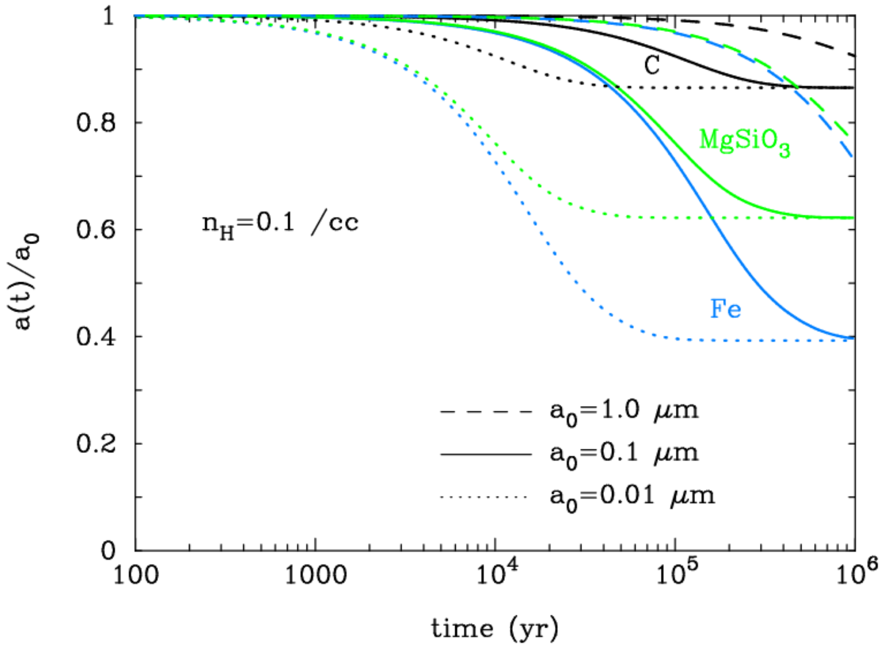


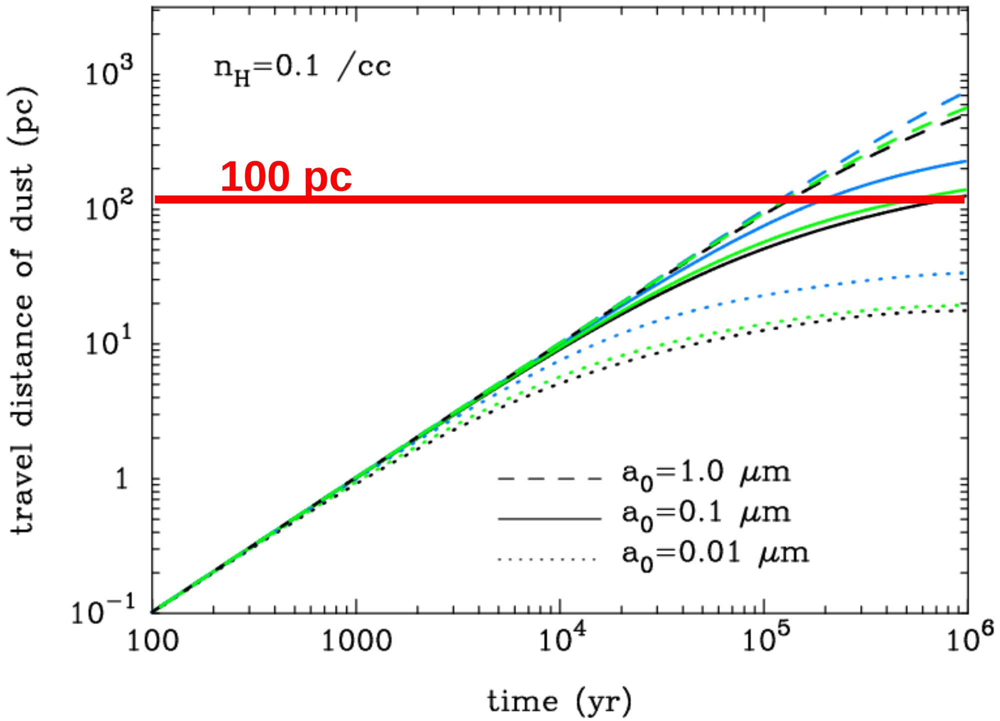
Almost all newly formed grains are destroyed in shocked gas in the SNR

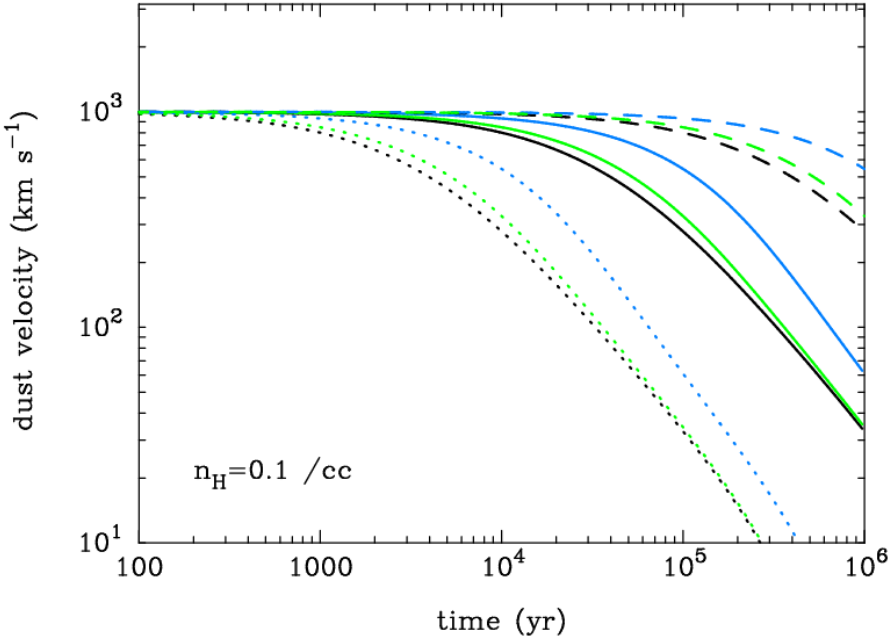
Herschel observation
$M_{d,cool}$ = 0.075 Msun
T_{dust} ~ 35 K (Barlow+10)

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

3-5. Fates of large grains ejected from CCSNe



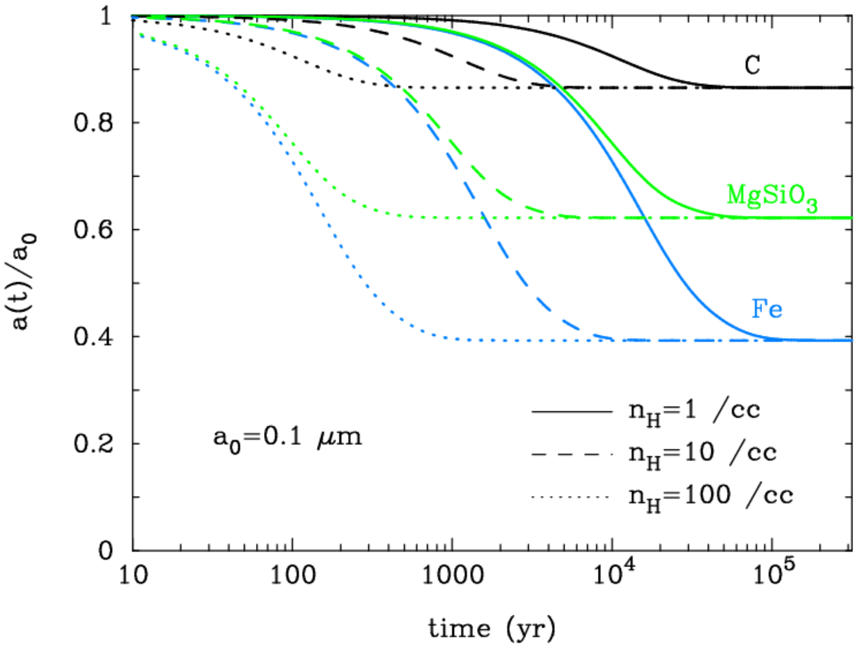


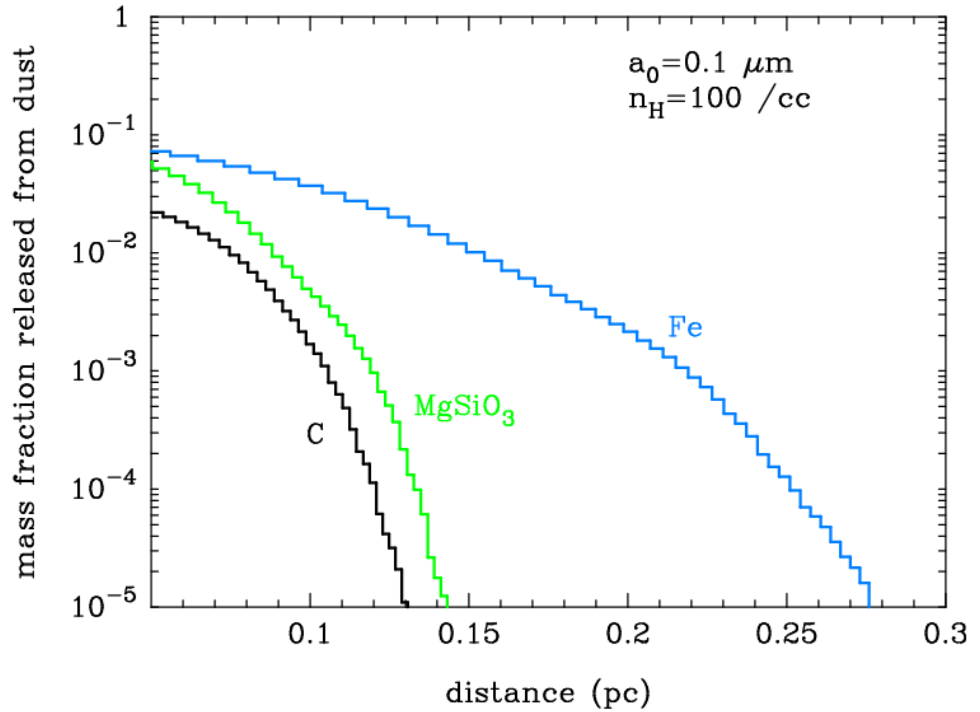


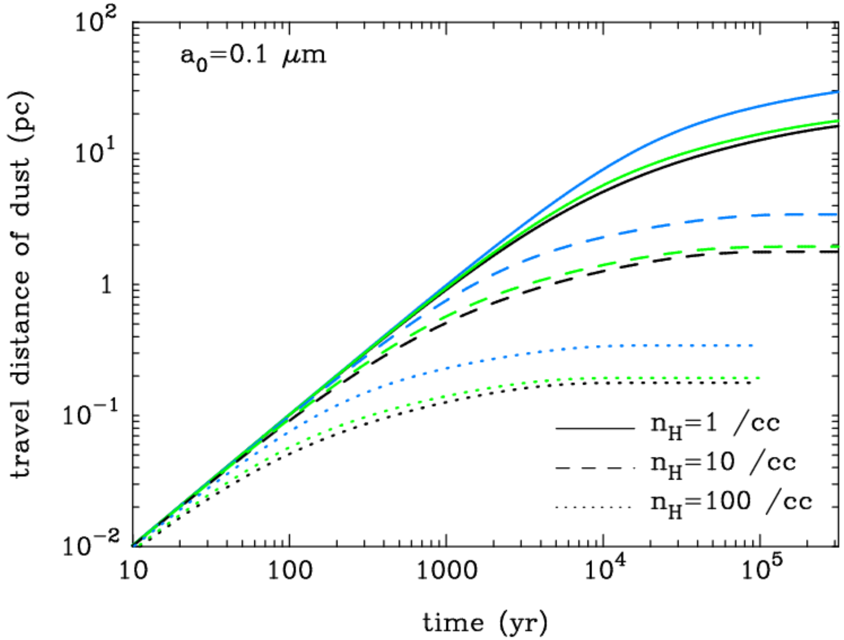
For n_H < 0.1 /cc, large grains (> 0.1 μm) ejected from SNe can travel more than 100 pc

➔ transporting metals and dust to the intergalactic medium

3-6. Mixing of metals in MCs via dust







The segregated motion of large grains (> 0.1 μm) from the gas can carry metals efficiently deep inside the molecular clouds with the size of ~1-10 pc

4. Summary of this talk

・ Size of newly formed dust depends on types of SNe

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

➔ may be important producers of interstellar dust

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

➔ may be poor producers of interstellar dust (dust is almost completely destroyed in the SNRs)

・ radiative effects on small clusters may be the most important factor for dust formation in SNe

— sticking coefficient and cluster shape affect the size of newly formed grains

— steady-state approximation is accetable in nucleation theory

・ Large grains ejected from SNe may play a critical role in the metal enrichment of MCs and IGM

➔ It should be considered how dust grains from SNe (and AGB stars) are distributed into the ISM