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Formation and Destruction Processes of Dust in Supernovae

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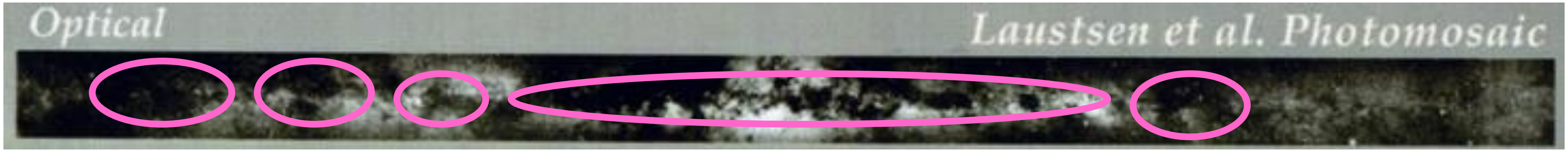
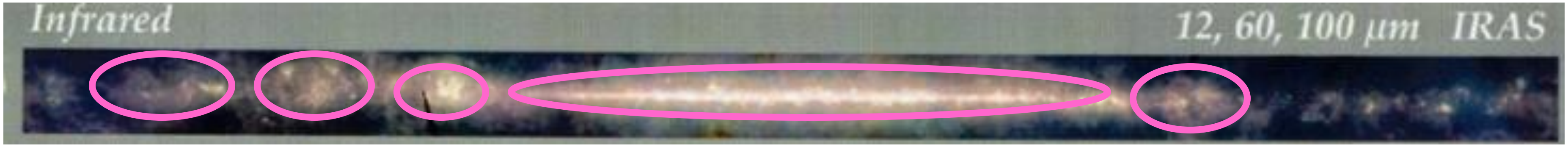
0-1. Sources of dust in our Galaxy

Milky Way (optical)



Milky Way (infrared)



SNe are important sources of interstellar dust?

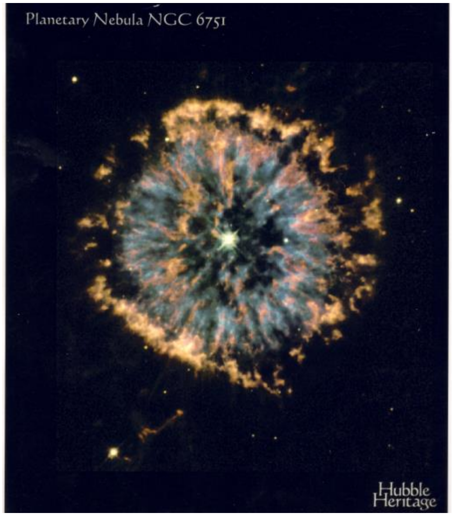
- **number (occurrence) ratio of SNe to AGB stars**

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

$M_{\rm dust}$ = 0.1-1.0 $M_{\rm sun}$ per SN **(Nozawa et al. 2003; 2007)**

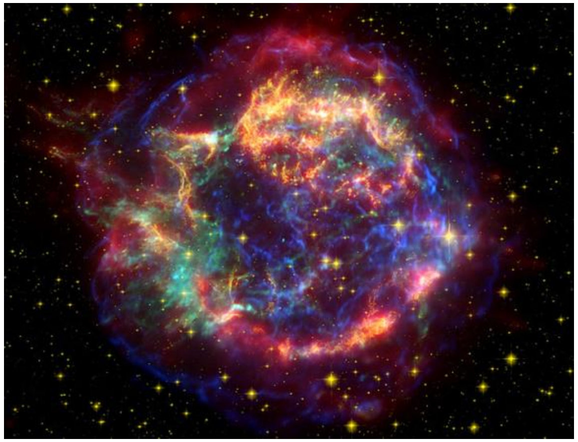
$M_{\rm dust}$ = 0.01-0.05 $M_{\rm sun}$ per AGB **(Zhukovska & Gail 2008)**

0-2. Formation site of dust



○ Formation sites of dust

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

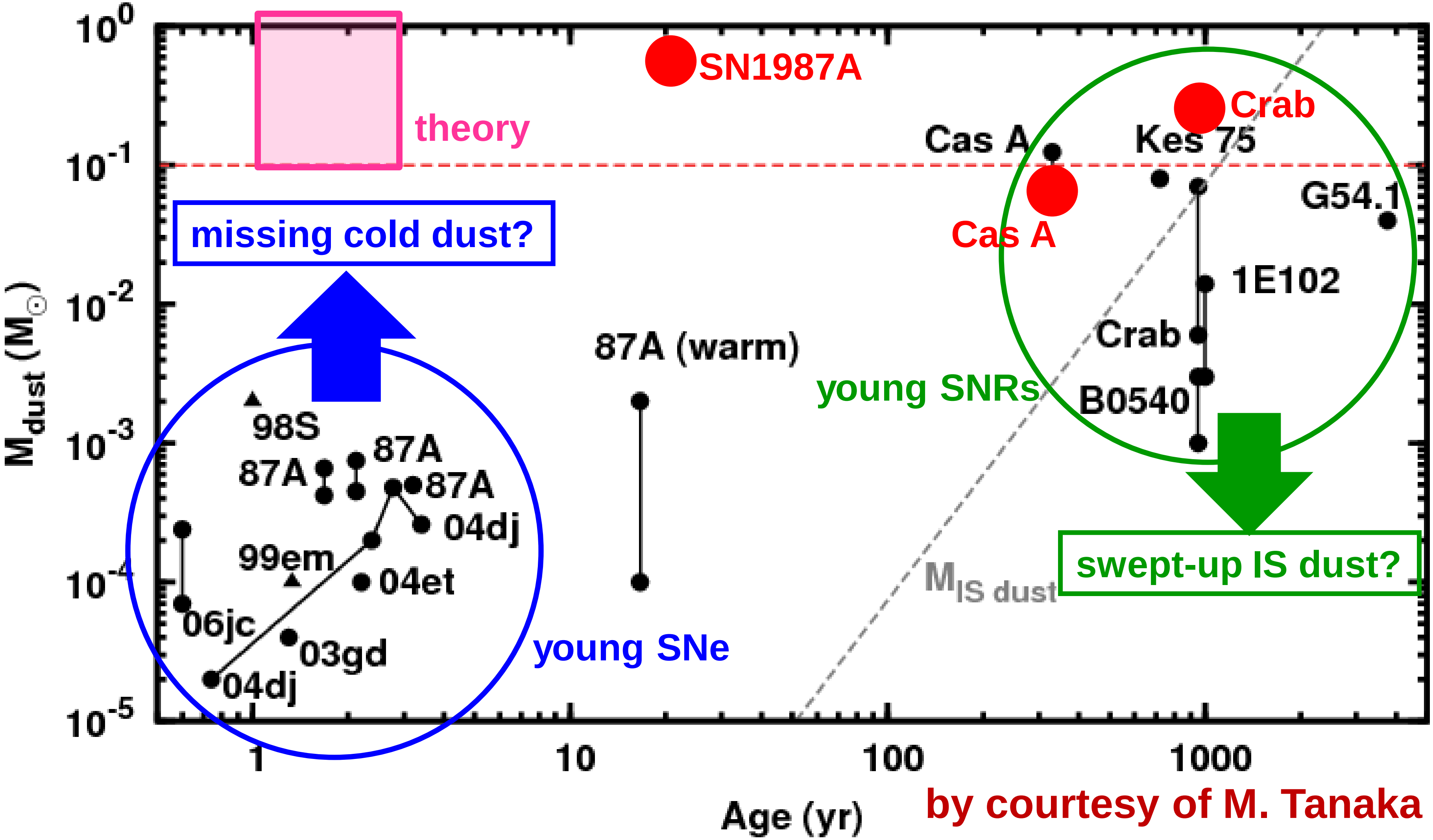


- **mass-loss winds of AGB stars**
- **expanding ejecta of supernovae**
- molecular clouds (grain growth only)
- red giant, W-R stars, novae, protoplanetary disk …

➔ relative contribution of these sources is unclear!

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

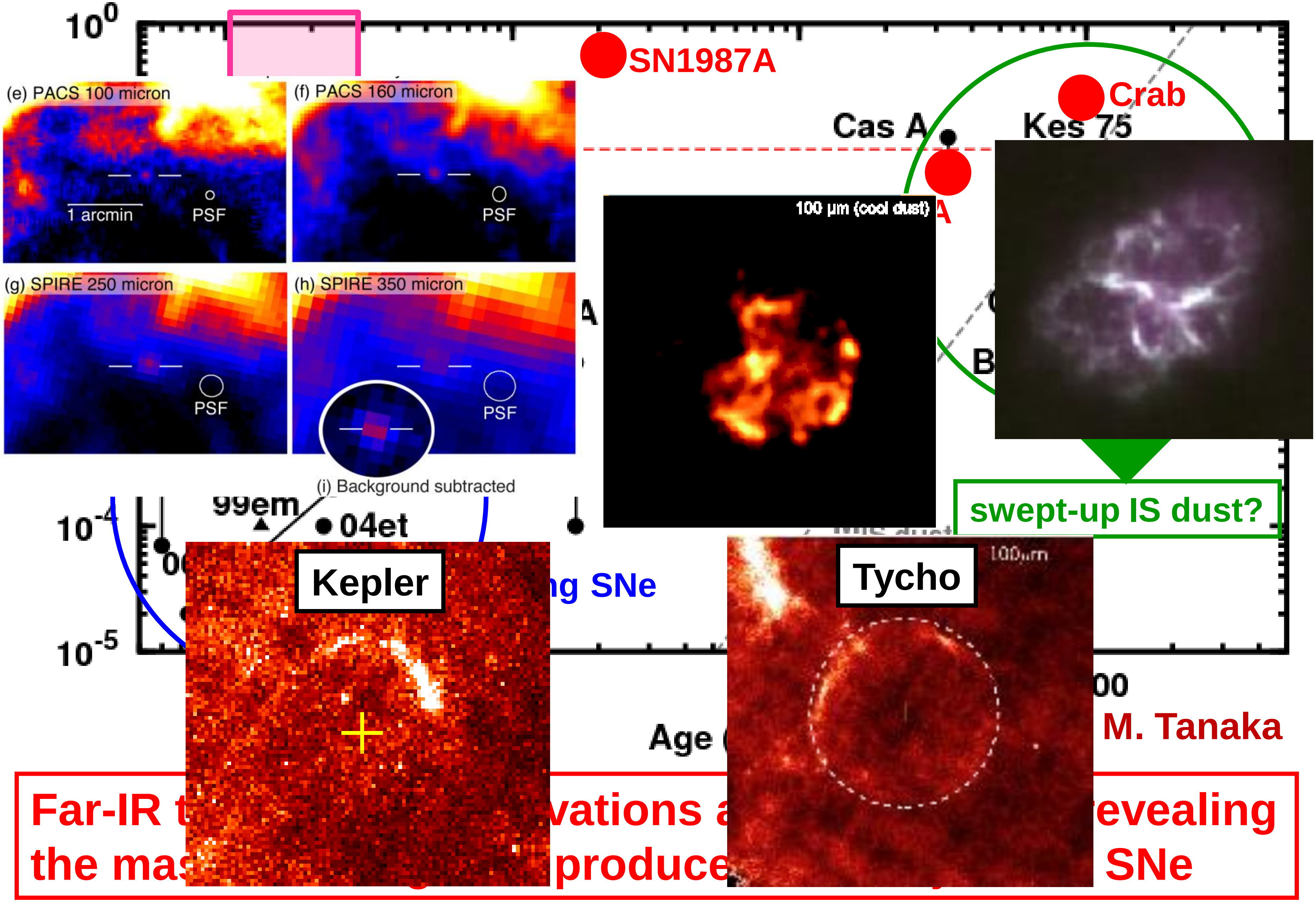
1-1. Summary of observed dust mass in CCSNe



by courtesy of M. Tanaka

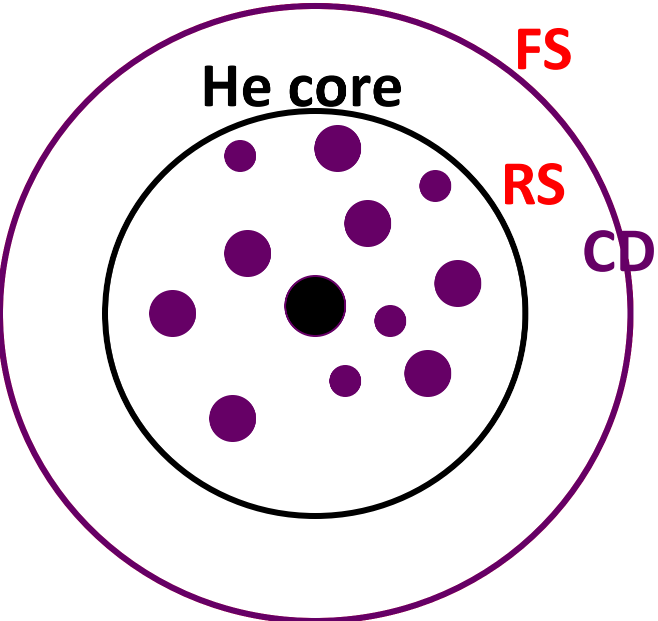
Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe

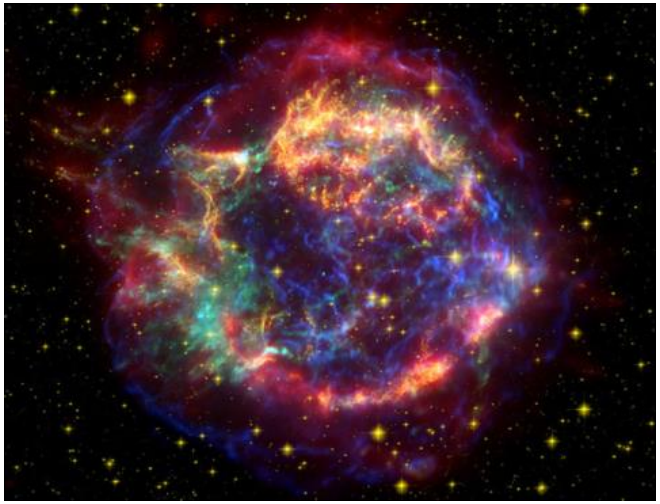
1-1. Summary of observed dust mass in CCSNe

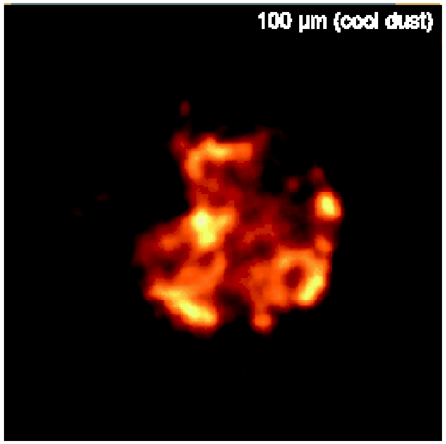


Far-IR t vations a revealing
the mas produce SNe

Dust Evolution in SNRs

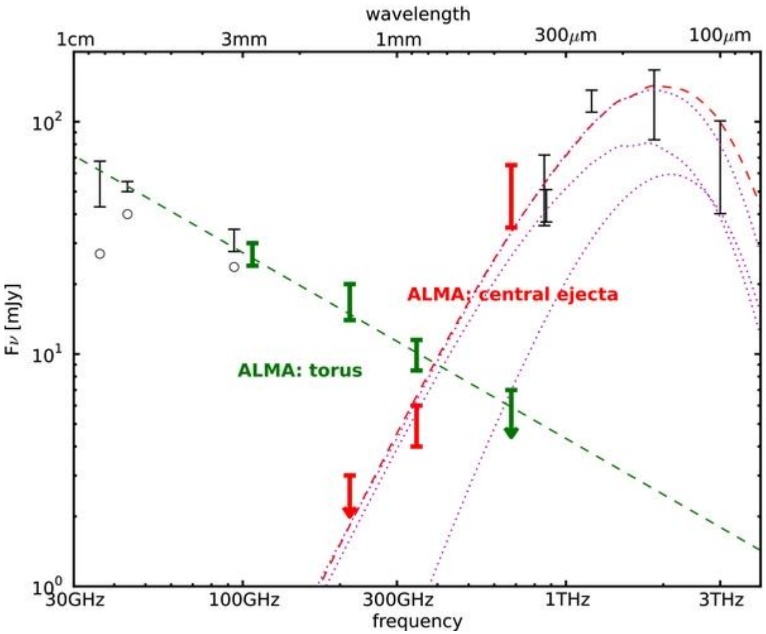




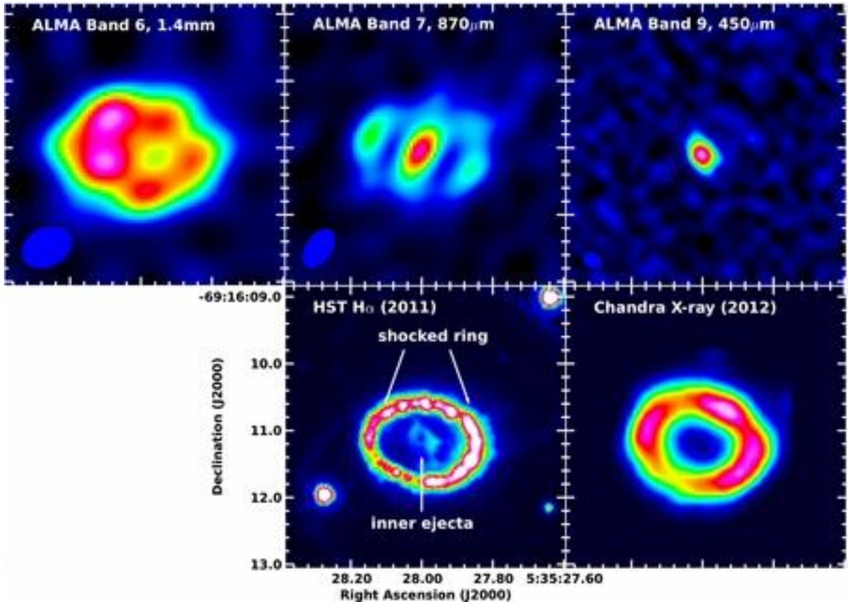


1-2. ALMA reveals dust formed in SN 1987A

SED of 25-years old SN 1987A



Indebetouw+2014



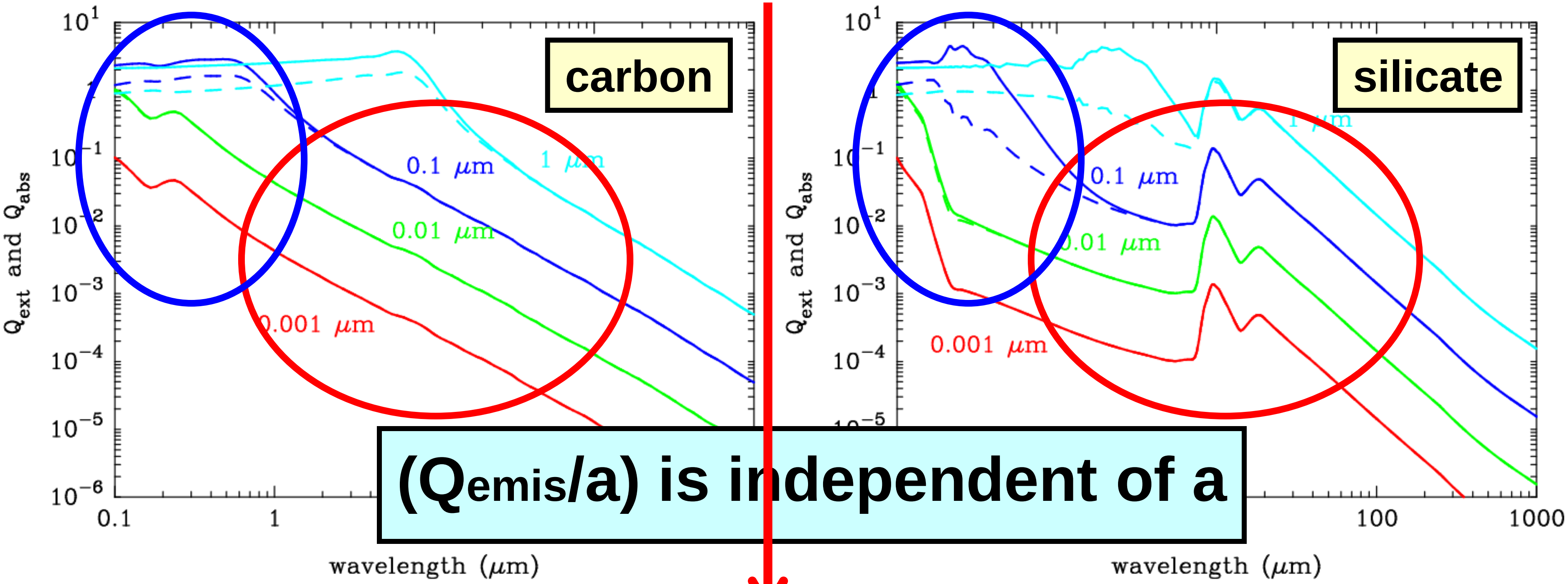
ALMA spatially resolves cool (~20K) dust of ~0.5 Msun formed in the ejecta of SN 1987A

➔ SNe could be production factories of dust grains

1-3. Emission and absorption efficiency of dust

○ Thermal radiation from a dust grain

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



(Q_{emis}/a) is independent of a

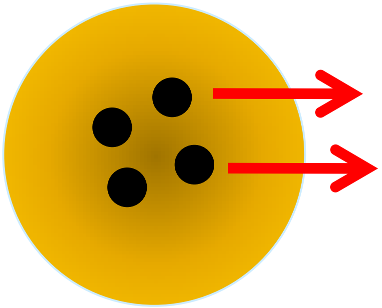
$$F_\lambda \propto 4\pi a^3\, (Q_{emis}[a,\lambda]/a)\, \pi B_\lambda(T_{dust})$$

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

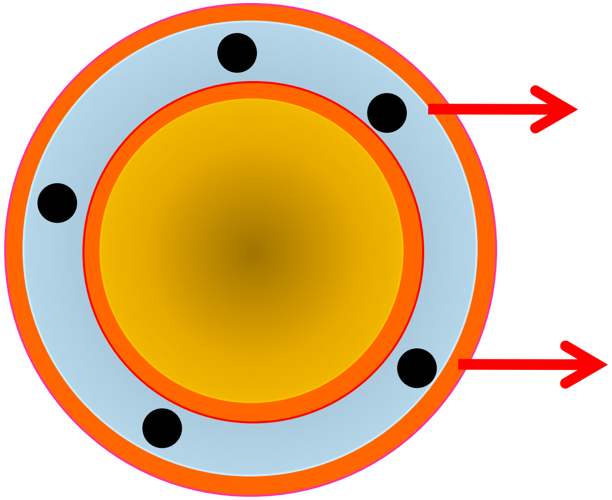
➔ IR emission is derived given M_{dust}, κ_{abs}, and T_{dust}

1-4. Origin of IR emission from SNe

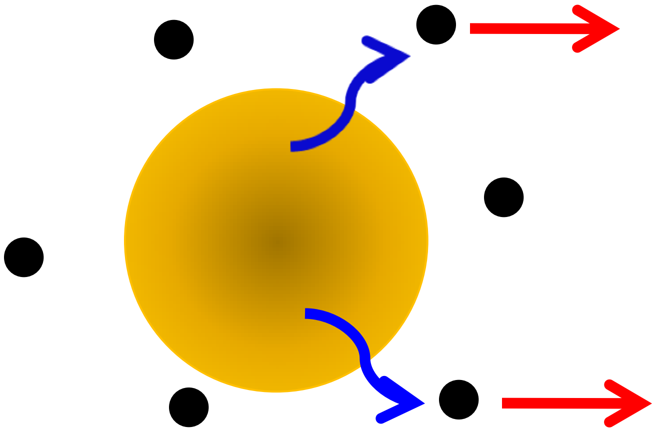
Dust formation in the ejecta



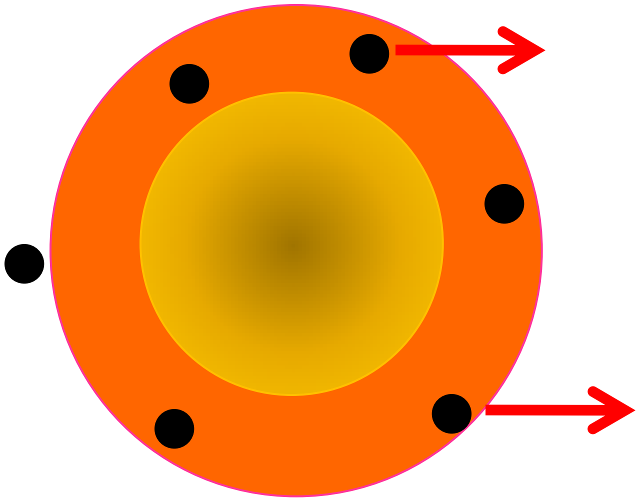
Dust formation in dense shell



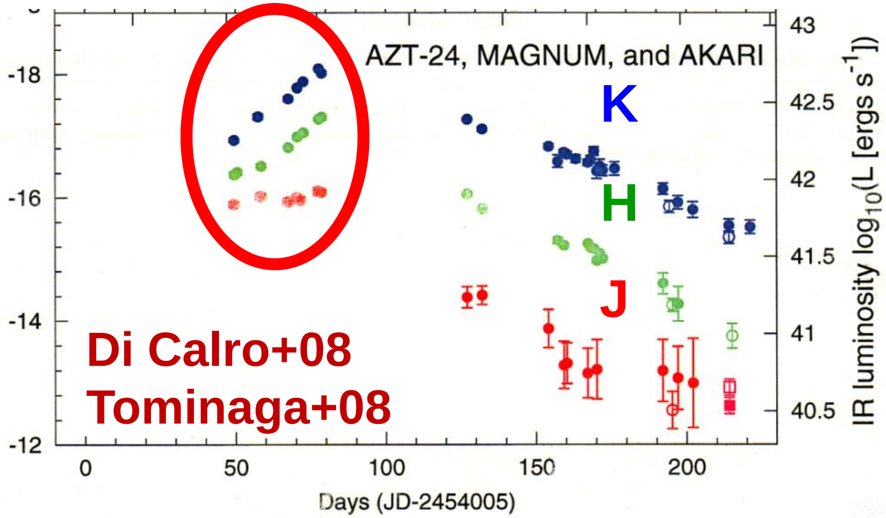
IR echo by CS dust



Shock heating of CS dust



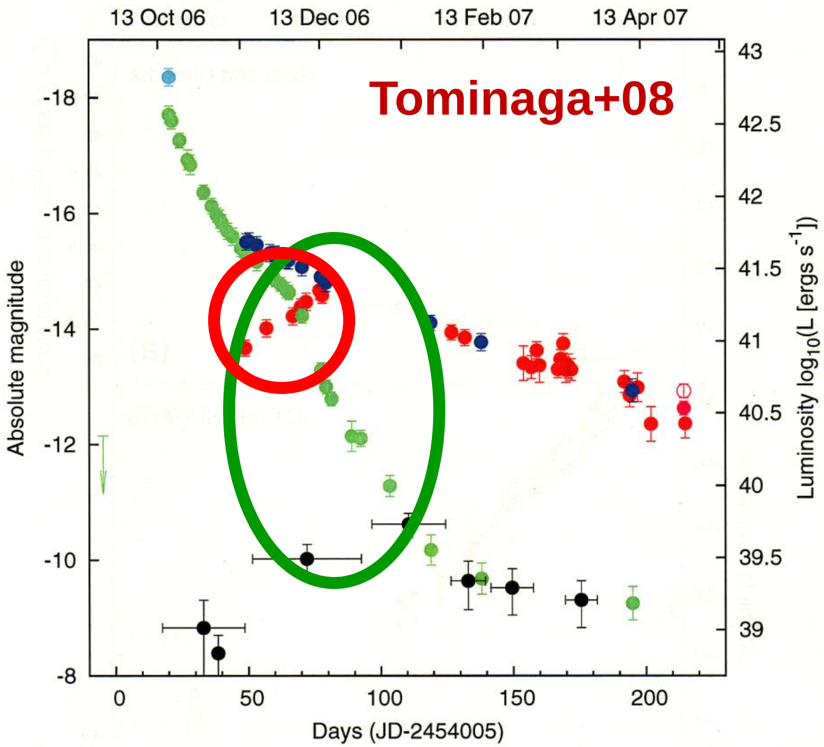
1-5. Evidence for dust formation in SN 2006jc



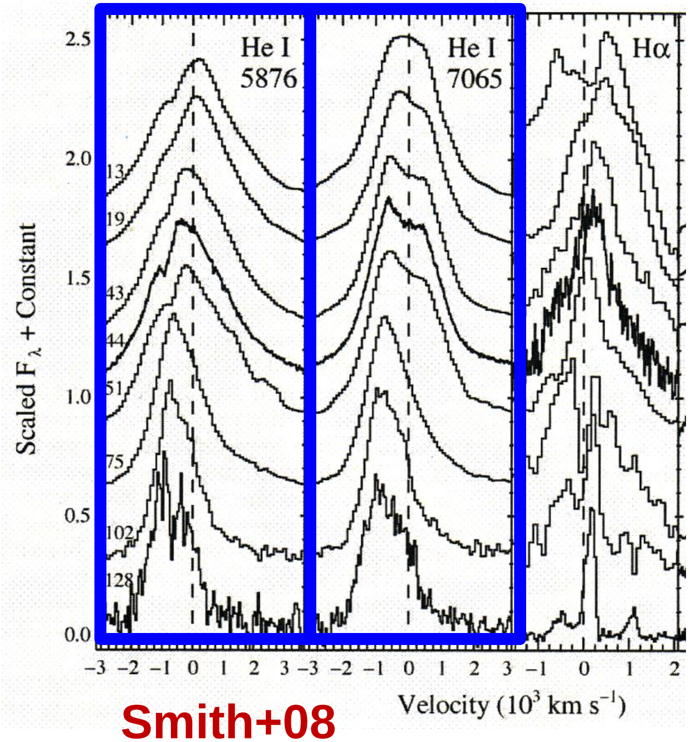
Di Calro+08
Tominaga+08

- **brightening of IR**
- **rapid decline of optical light**
- **blueshift of emission lines**

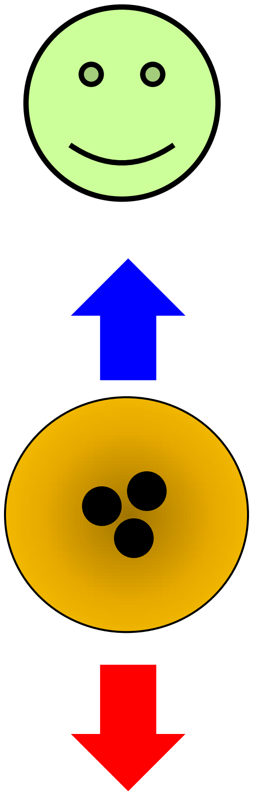
formation of CO and SiO molecules
(more robust if SiO are depleted)



Tominaga+08

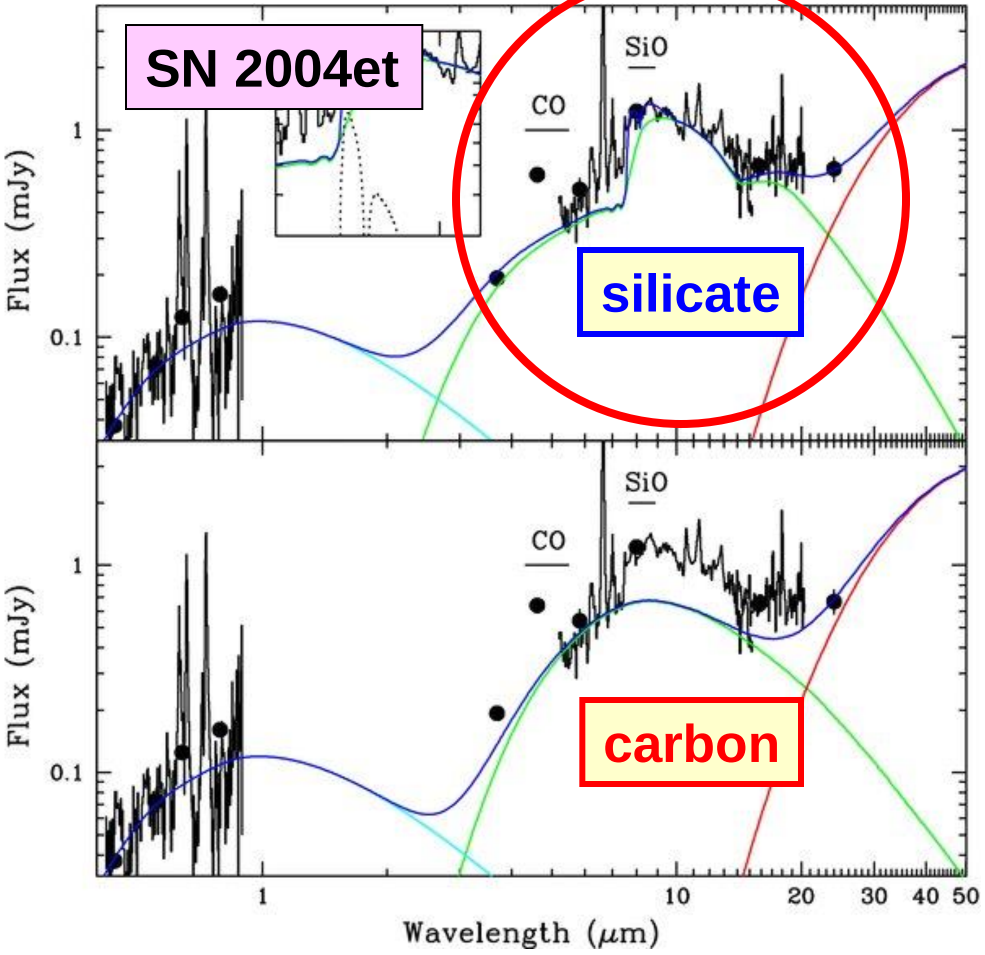


Smith+08



1-6. Composition of dust formed in SNe

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

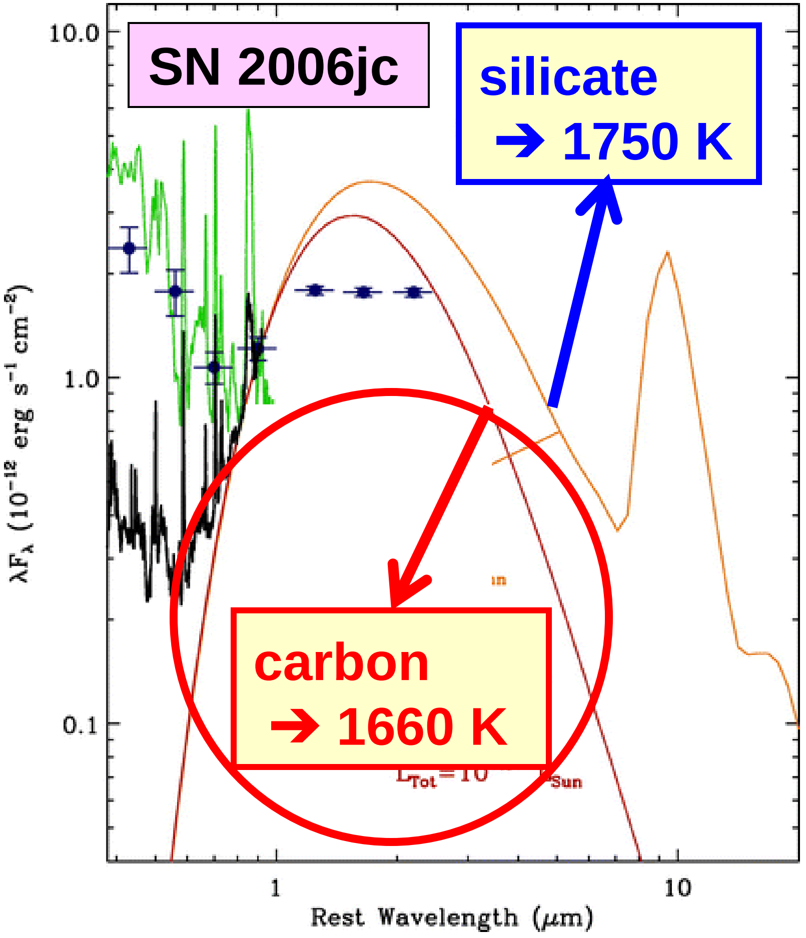


SN 2004et

silicate

carbon

SN 2004et, Kotak+09



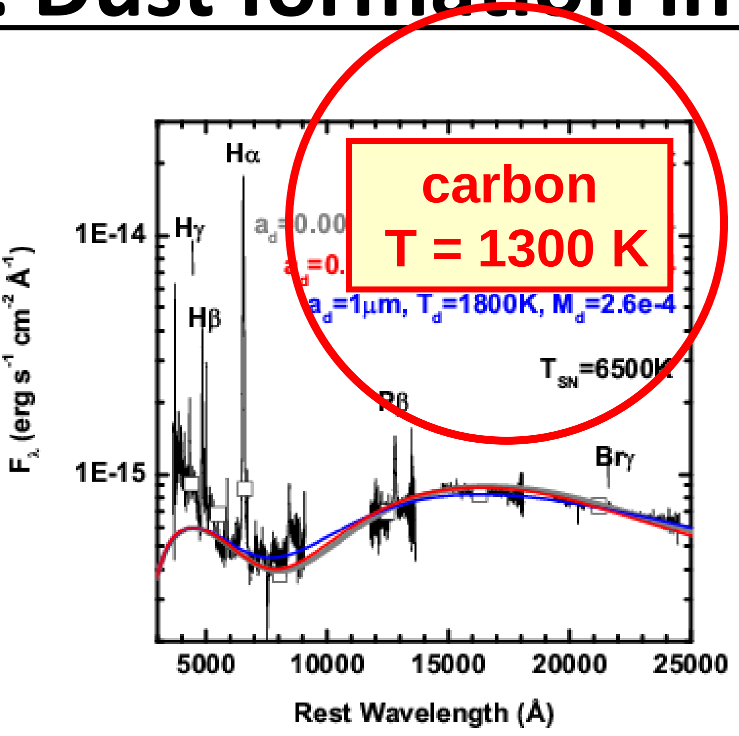
SN 2006jc

silicate
➔ 1750 K

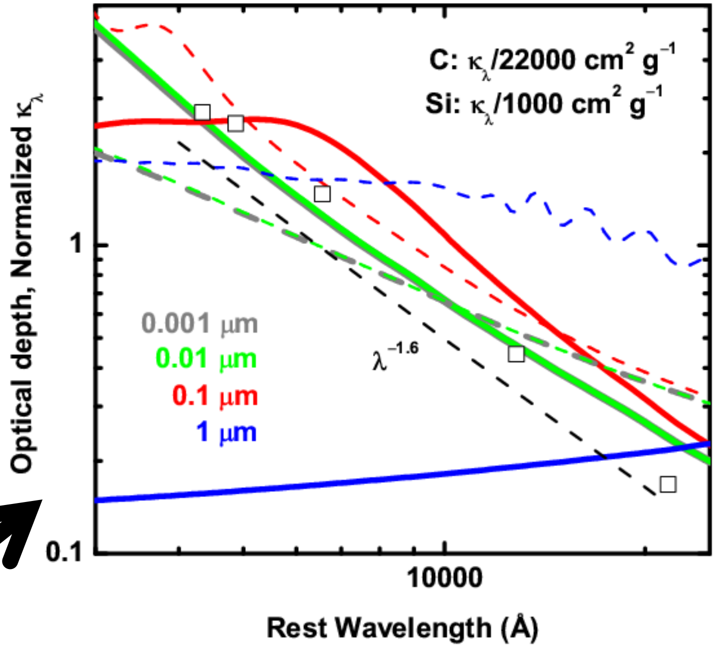
carbon
➔ 1660 K

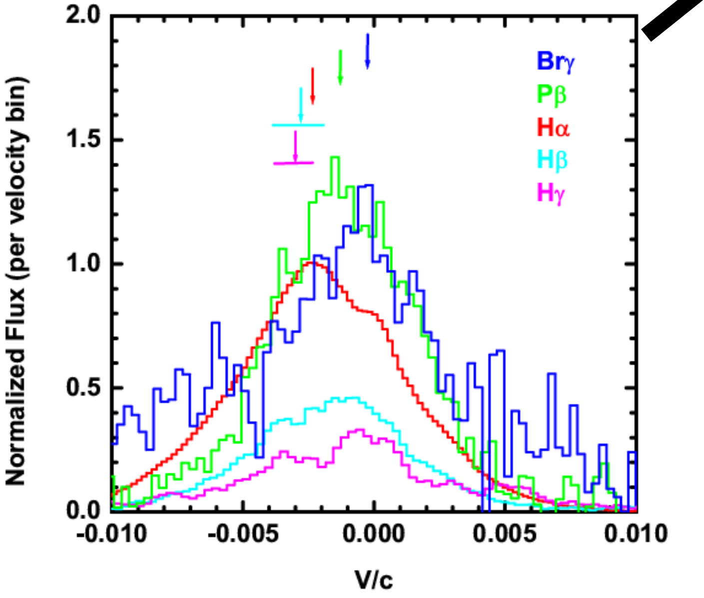
SN 2006jc, Smith+08

1-7. Dust formation in Type IIn SN 2010jl



carbon
T = 1300 K





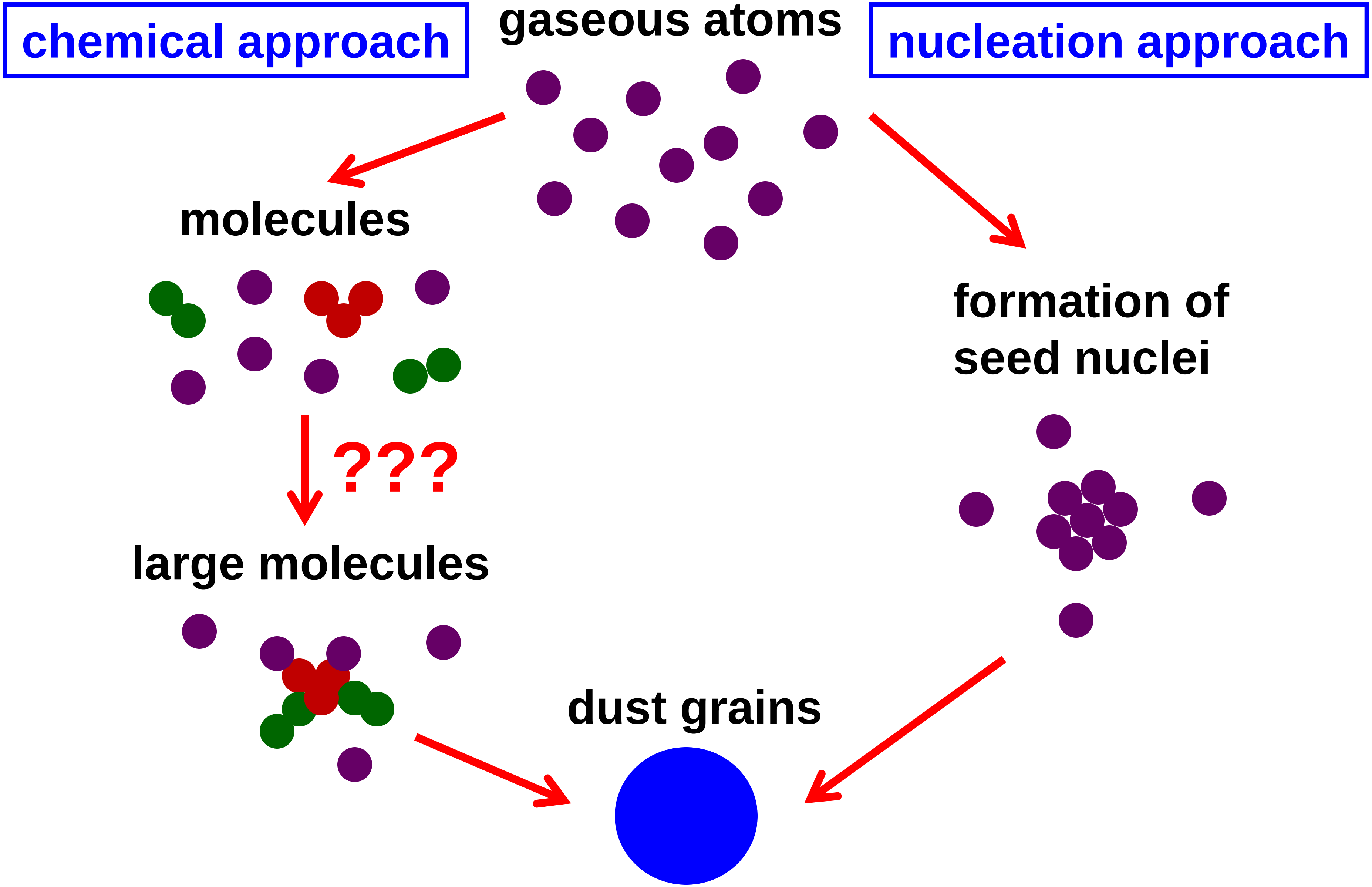
Dust in SN 2010jl

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

Maeda, TN, et al. 2013

2. Dust Formation in Type IIb SNe

2-0. How do dust grains form?



chemical approach

gaseous atoms

nucleation approach

molecules

???

large molecules

formation of
seed nuclei

dust grains

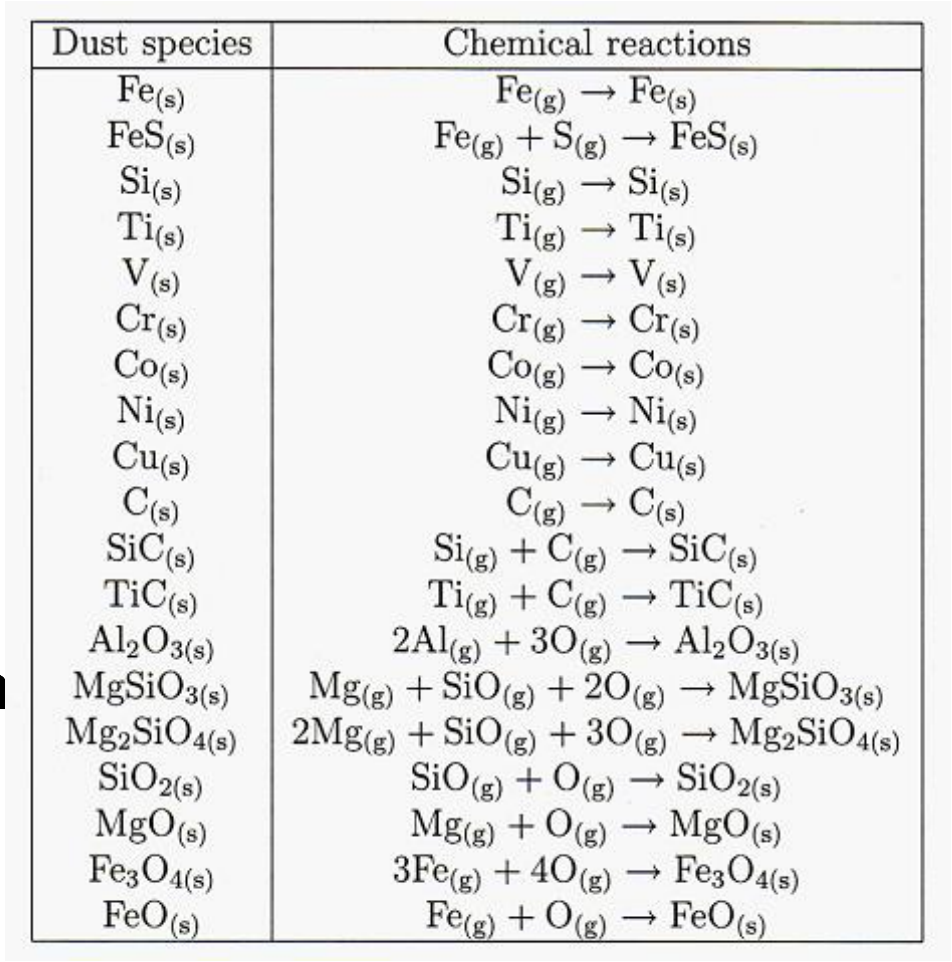
2-1. Calculations of dust formation

- **nucleation and grain growth theory taking account of chemical reaction at condensation**

(Kozasa & Hasegawa'87)

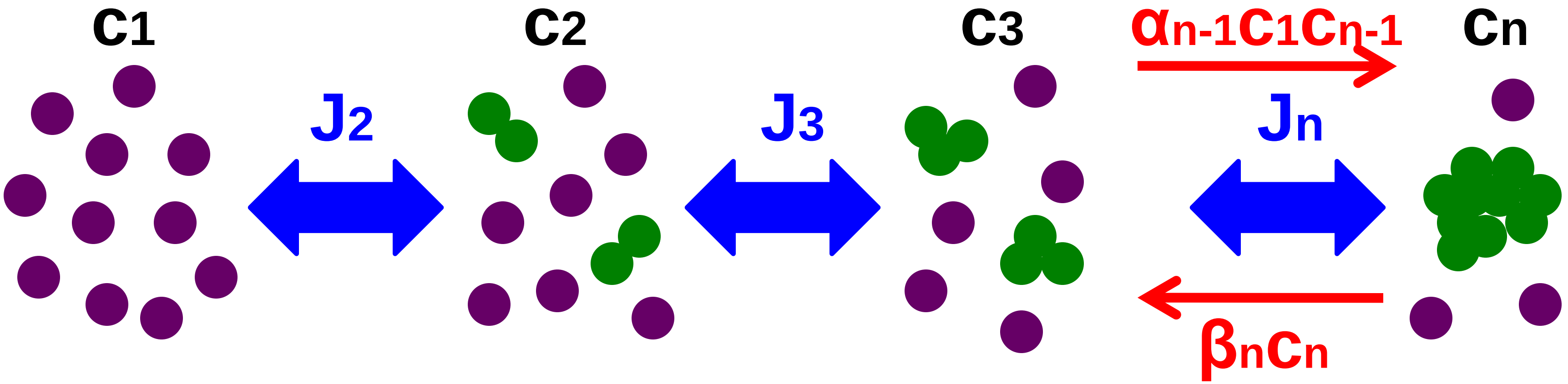
- **key species:**
  gas species with the least collision frequency among reactants

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. Formulation of dust formation



・ master equations

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

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

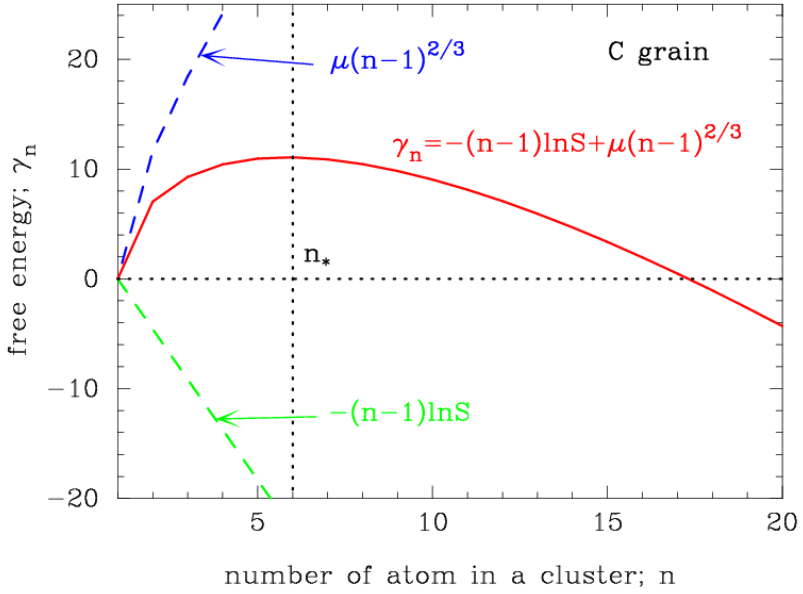
$$\alpha_n = \frac{s_n}{1+\delta_{1n}} 4\pi a_0^2 \, n^{\frac{2}{3}} \left(\frac{kT}{2\pi m_n} \right)^{\frac{1}{2}},$$

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

2-3. Steady-state nucleation rate

・ 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

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

σ : surface tension

S : supersaturation ratio

($S = p_1 / p_{1v}$)

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

2-4. Basic equations for dust formation

- **Equation of mass conservation**

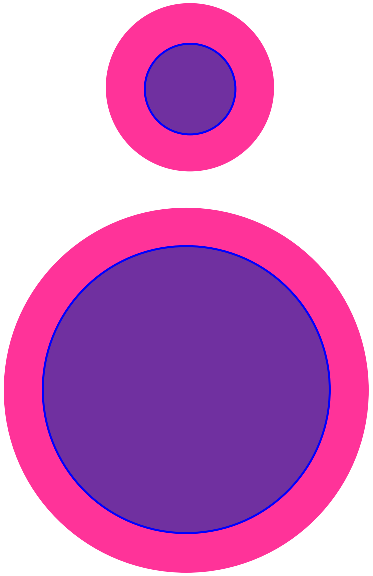
$$c_{10} - c_1 = \int_{t_0}^{t} J_{n_*}(t') \frac{a^3(t, t')}{a_0^3} dt',$$

- **Equation of grain growth**

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

⬆

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



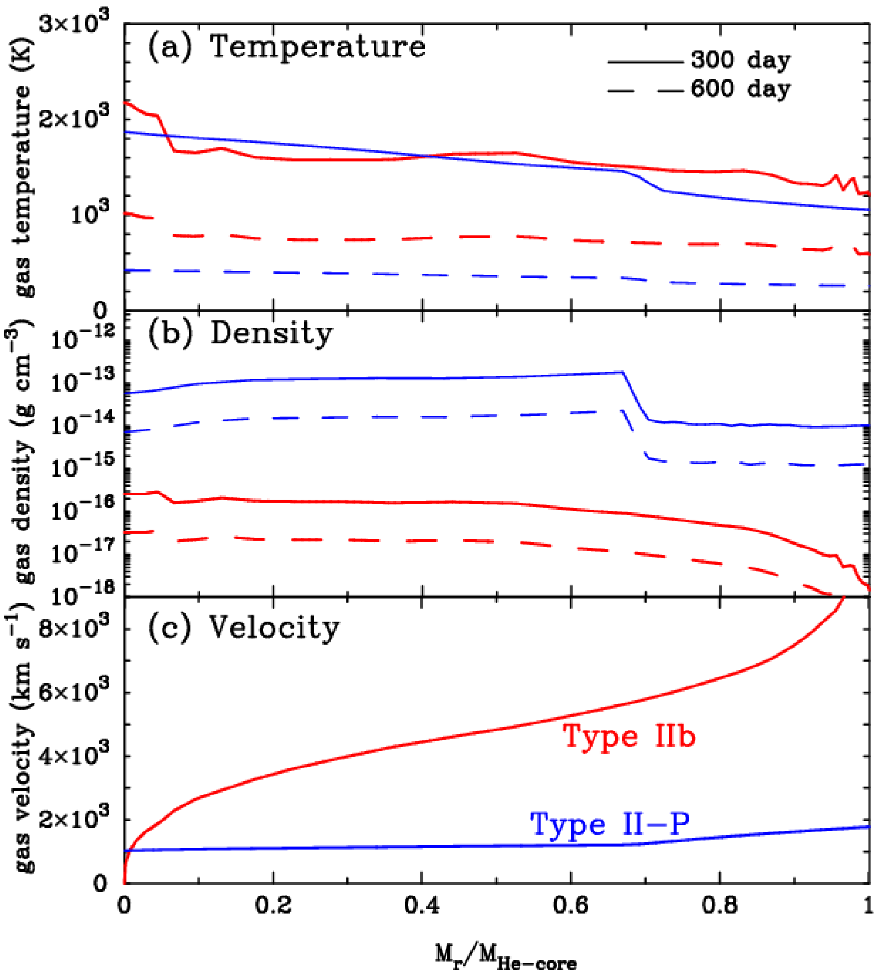
Growth rate is independent of grain radius

2-5. Dust formation calculation in the ejecta

○ Dust formation calculation

- non-steady nucleation and grain growth theory

(Nozawa et al. 2003)



○ SN IIb model

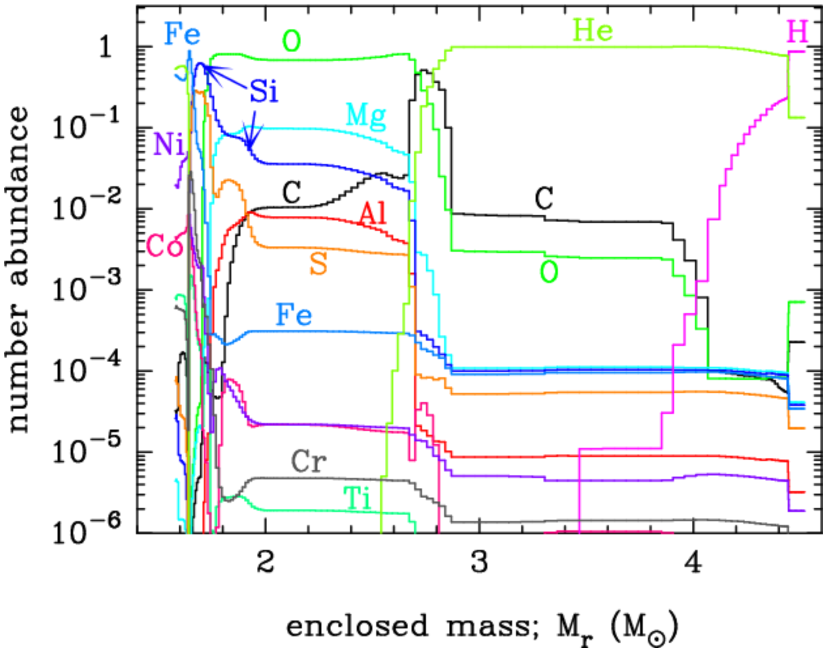
(SN1993J-like model)

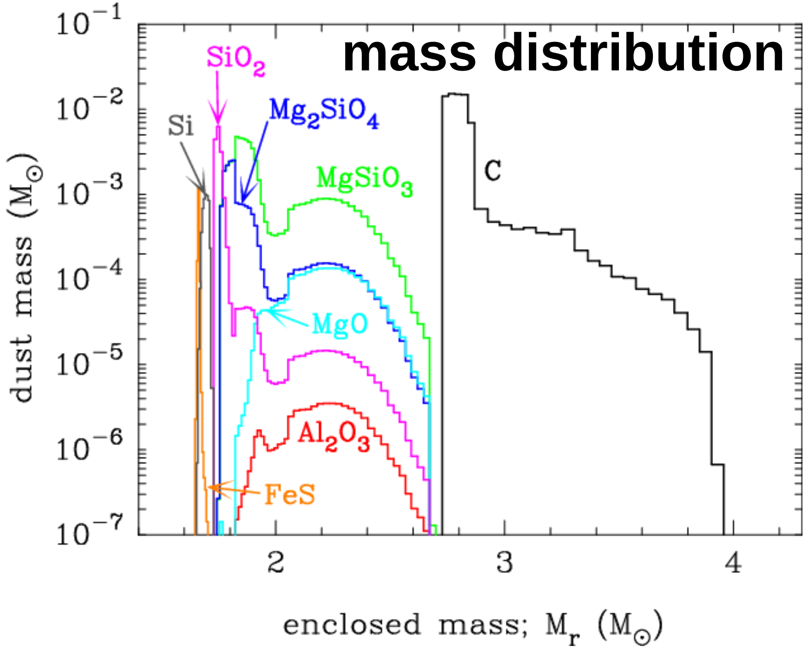
- **$M_{\rm H\text{-}env} = 0.08\ M_{\rm sun}$**
  $M_{\rm ZAMS} = 18\ M_{\rm sun}$
  $M_{\rm eje} = 2.94\ M_{\rm sun}$
- $E_{51} = 1$
- $M(^{56}{\rm Ni}) = 0.07\ M_{\rm sun}$

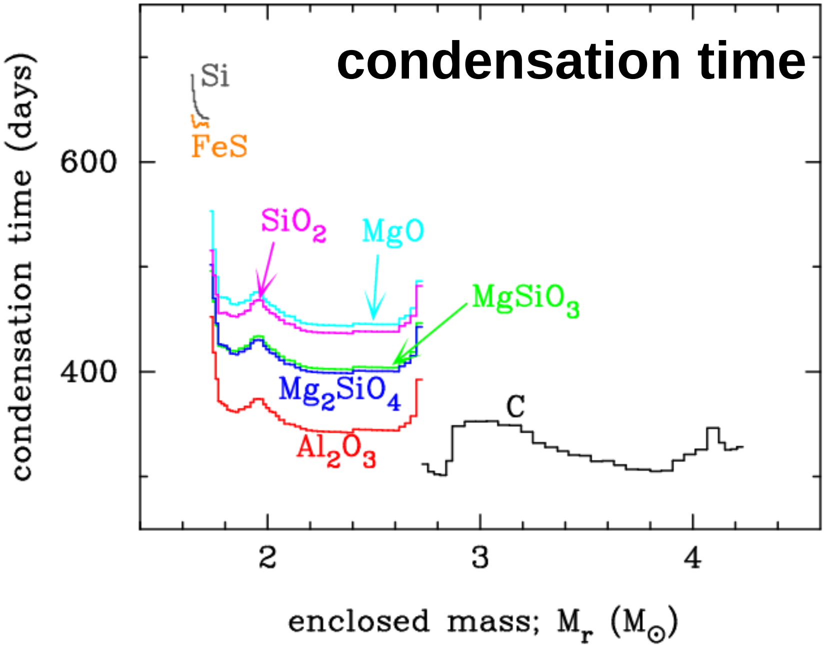
○ SN II-P model : $M_{\rm H\text{-}env} = 13\ M_{\rm sun}$, $M_{\rm ZAMS} = 20\ M_{\rm sun}$, $E_{51} = 1$

(Umeda & Nomoto 2002)

2-6. Birth of dust in the ejecta of Cas A




mass distribution


condensation time

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

— **total mass of dust formed**

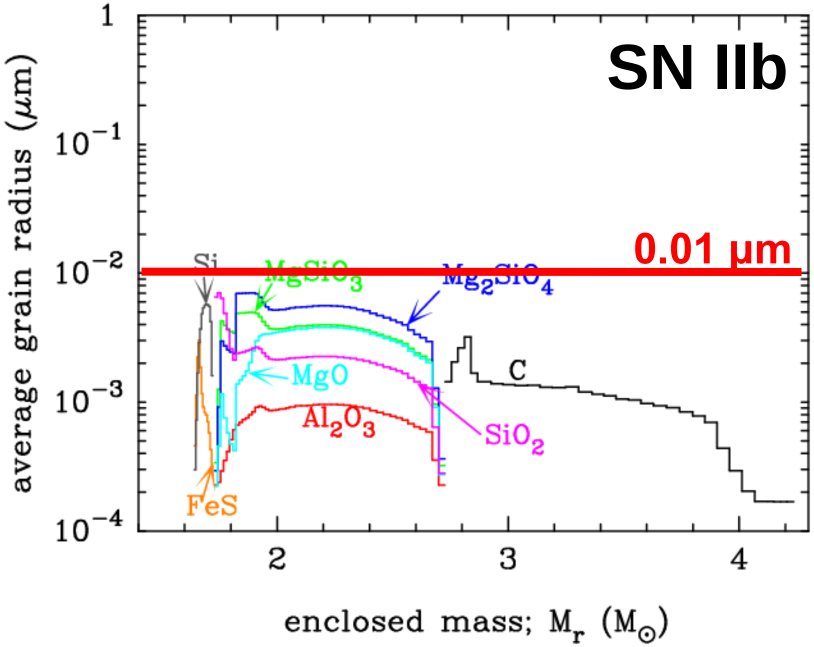
- **0.167 Msun in SN IIb**

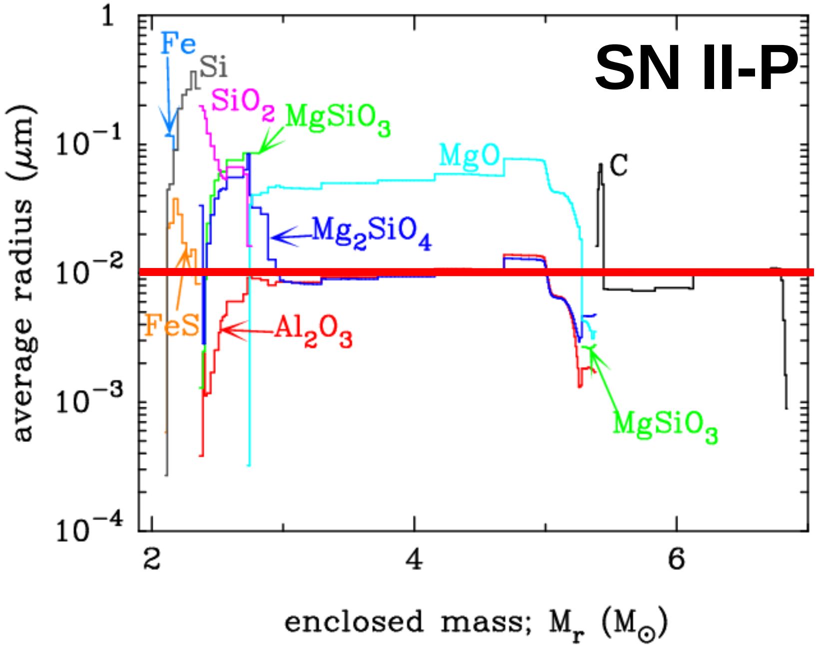
  Mc=0.07 Msun

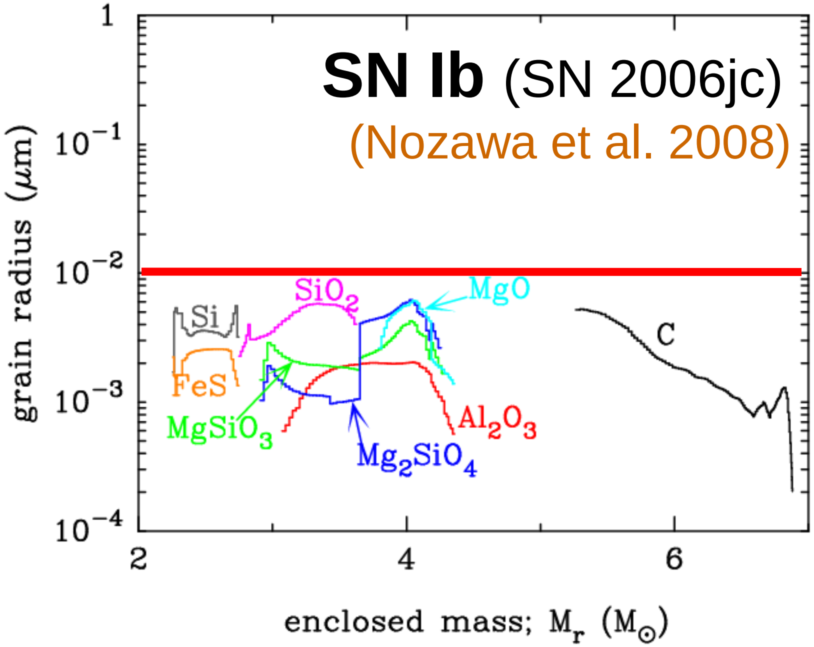
  Msilcate=0.08 Msun

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

2-7. Dependence of dust radii on SN type







The radius of dust formed in H-stripped SNe is small

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

3. Dust Destruction in Cas A

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)

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

ρ_{d} ; mass density of a grain

A_i ; the number abundance of gas species i normarized by n_{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 $s_i^2 = m_i w_{\mathrm{d}}^2 / 2kT$

3-3. Erosion rate of dust by sputtering

- dust destruction by sputtering (e.g., Dwek, Foster & Vancura 1996)

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

$Y_i(E) = 2Y_i^0(E)$; 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)

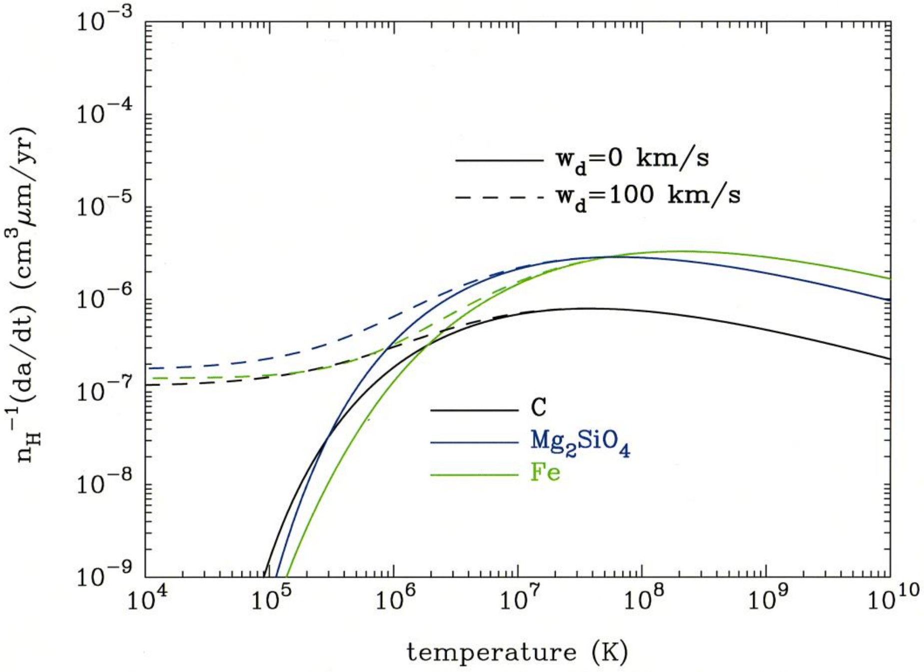
$$\mathcal{R}(X_i(\epsilon)) = n_{\rm H} A_i \pi a^2 \left(\frac{8kT}{\pi m_i}\right)^{\frac{1}{2}} \frac{e^{-s_i^2}}{2s_i} \int \sqrt{\epsilon} e^{-\epsilon} \sinh(2s_i\sqrt{\epsilon}) X_i(\epsilon) d\epsilon$$

where $\epsilon = E/kT$

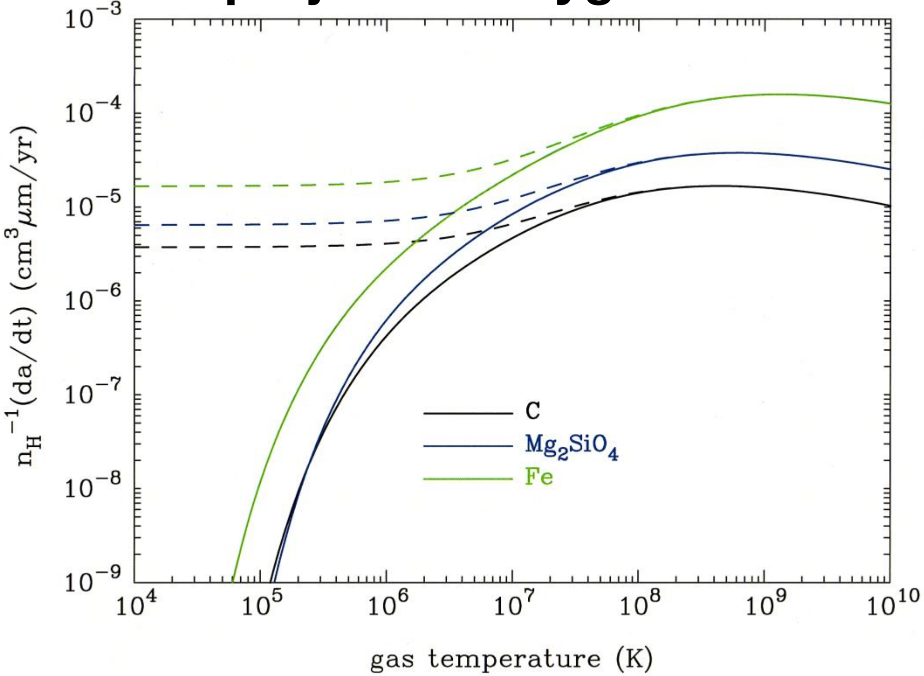
3-4. Erosion rate of dust by sputtering

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. Calculation of dust evolution in SNRs

○ Dust evolution calculations (Nozawa et al. 2006, 2007)

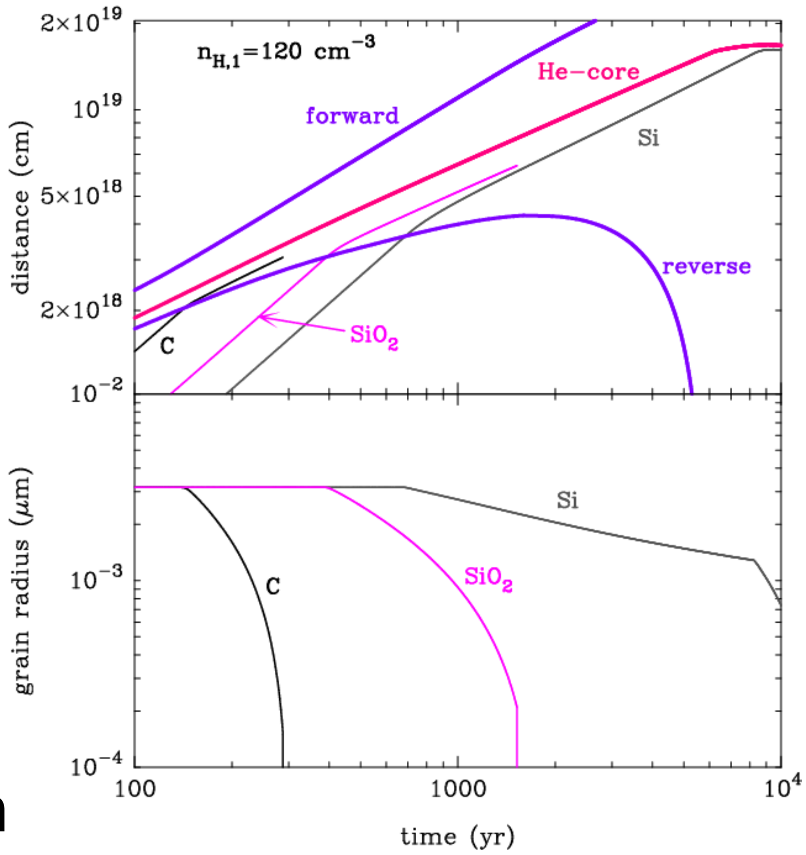
- spherical symmetric hydrodynamic calculation based on the ejecta model of the SN IIb
- treating dust as a test particle
  - erosion by sputtering
  - deceleration by gas drag
  - collsional stochastic heating
- **density profile of CSM**

$$n_H(r) = n_{H,1}\,(r / r_1)^{-2}\ /\mathrm{cc}$$
$$= 1\ /\mathrm{cc} \quad \text{for } n_H < 1\ /\mathrm{cc}$$

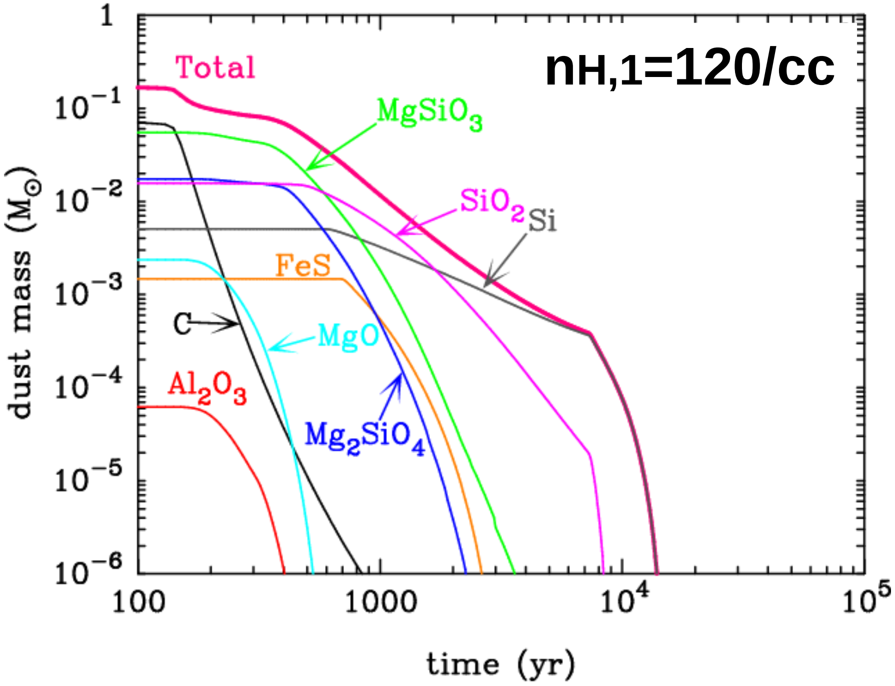
r_1 = r(at 10 yr) = 1.2×10^{18}cm

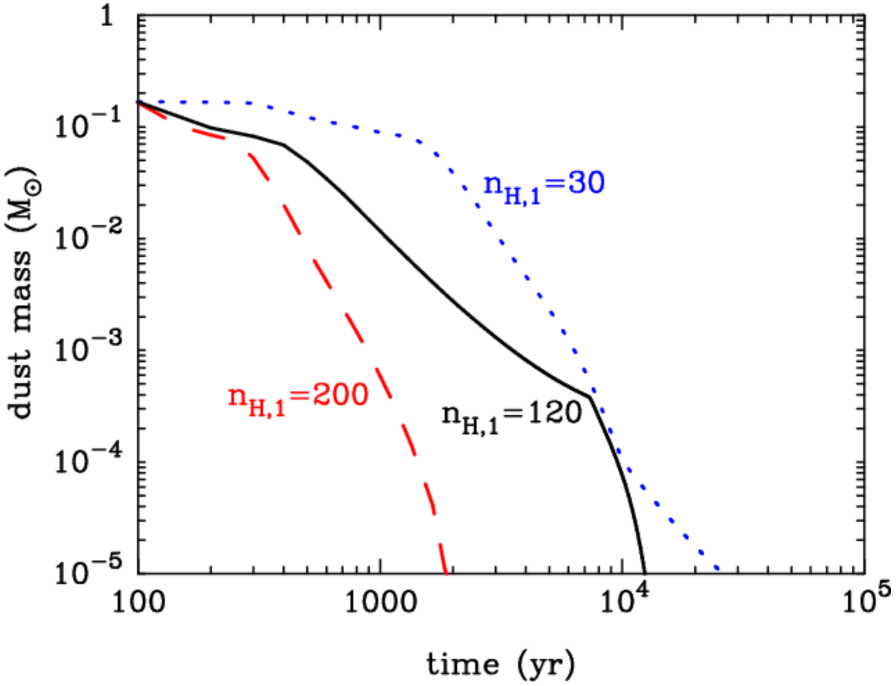
$n_{H,1}$ = 30, 120, 200 /cc

(➔ dM/dt = 2.0, 8.0, 13×10^{-5} M_{sun}/yr for v_w=10 km/s)



3-6. Fate of dust in Cas A SNR



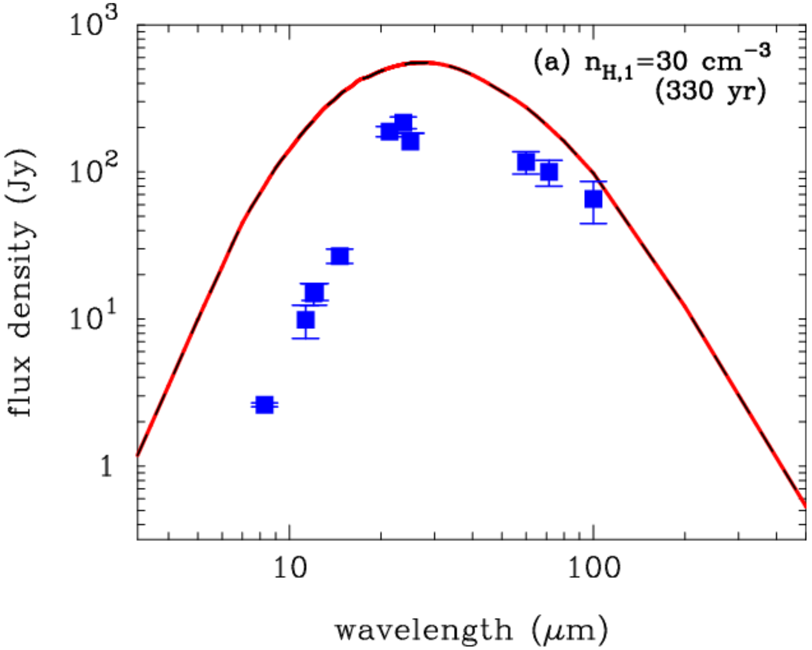


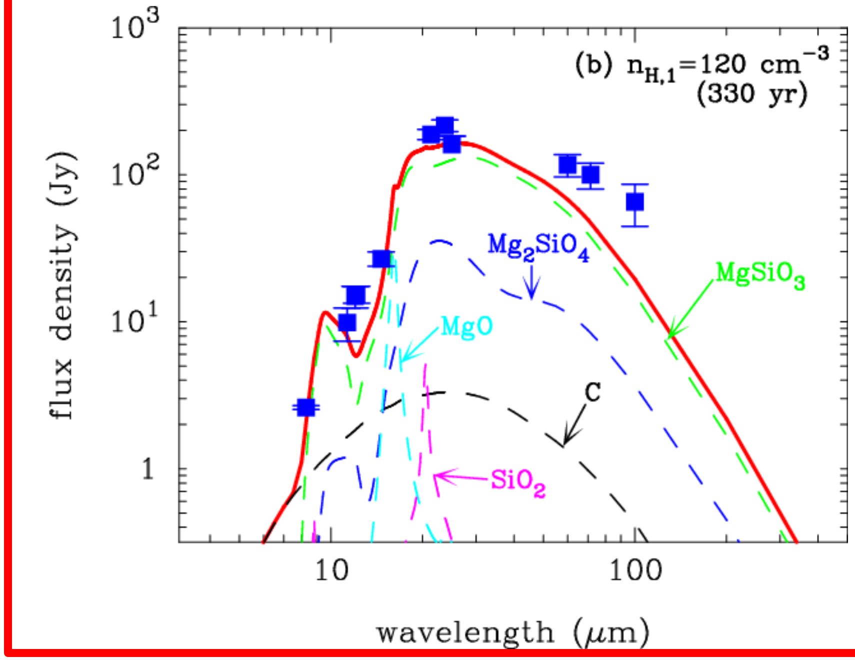
- **All of the dust grains in Cas A would be destroyed in the shocked gas within the SNR before ~2x10^4 yr**
  - **➔ small grain size of newly formed dust**
  - **➔ early arrival of the reverse shock at the He core**

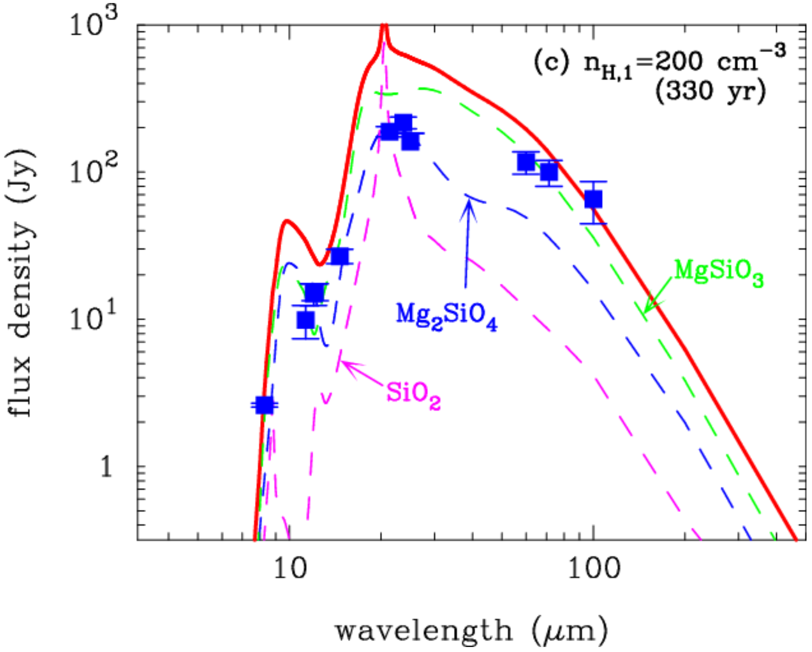
H-deficient SNe may not be major contributors of dust

- **0.01-0.8 Msun of dust survive for SNe II-P (Nozawa+2007)**

3-7. Comparison with observations of Cas A







— **$M_{IR, d}$ = 0.008 M_{sun}**

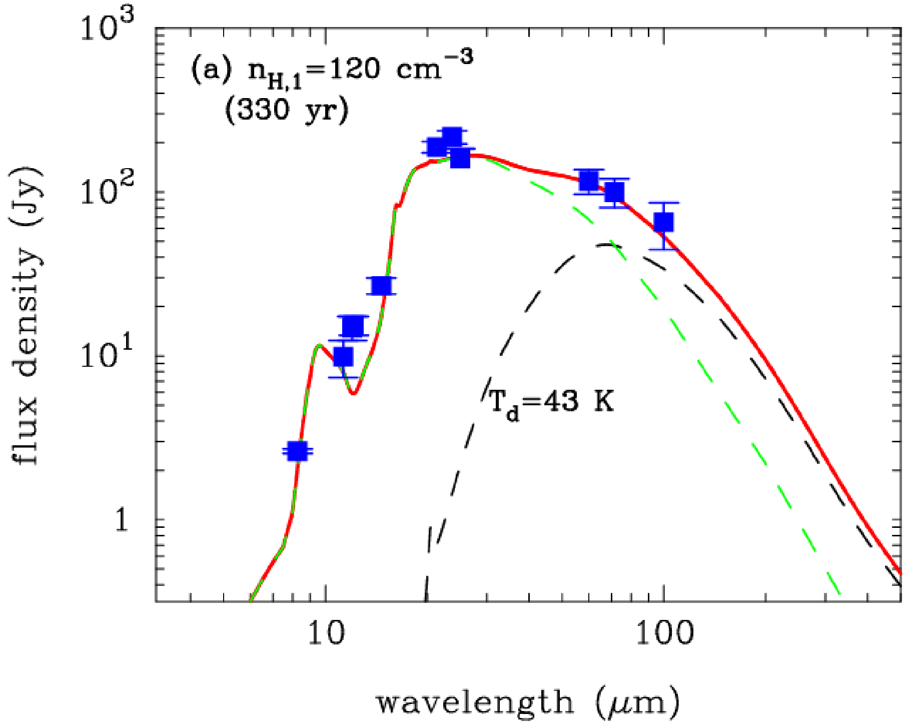
($M_{shocked, d}$ ~ 0.1 M_{sun})

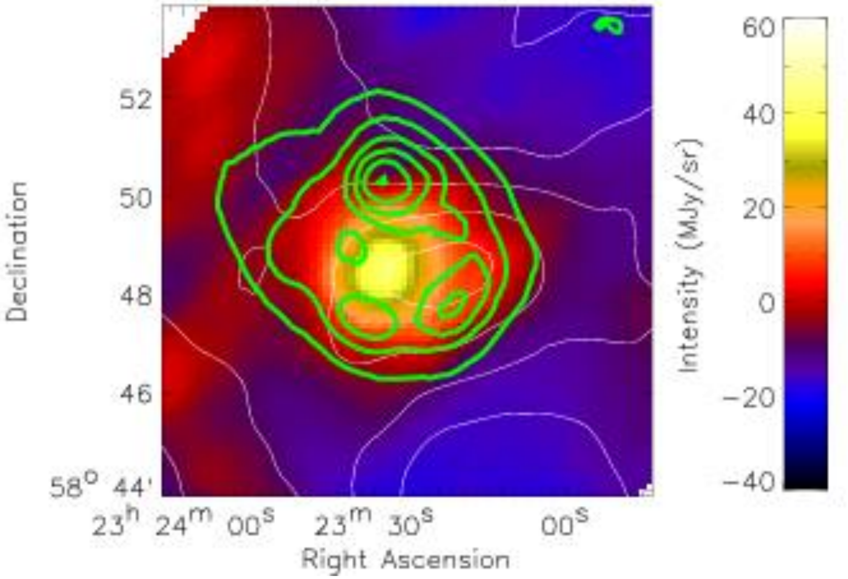
— **dM/dt = 8×10^{-5} M_{sun}/yr**

➔ dM/dt ~ 2×10^{-5} M_{sun}/yr for Cas A (Chevalier & Oishi 2003)

➔ dM/dt = (3-4)$\times10^{-5}$ M_{sun}/yr for 93J (Suzuki & Nomoto1995)

3-8. Contribution from unshocked dust





Sibthorpe et al. 2009

observed IR SED can be well reproduced !

↑

- **$M_{d,warm}$ ~ 0.008 M_{sun}**
- **$M_{d,cool}$ ~ 0.07 M_{sun} with T_{dust} ~ 40 K**

AKARI reduced 90μm image
➔ centrally peaked cool dust component

↓

$M_{d,cool}$ = 0.03-0.06 M_{sun}
with T_{dust} = 33-41 K

Summary

1) Birth of Dust in the ejecta of Cas A

Dust formed in Cas A was formed at 300-700 days after the explosion with $a_{dust} < 0.01$ μm and $M_{dust} = 0.167\ M_{sun}$

2) Brightening of dust in the shocked hot gas

Model of dust destruction and heating in Type IIb SNR can reasonably reproduce the observed SED of Cas A;

$M_{d,warm} = 0.008\ M_{sun}$, $M_{d,cool} = 0.07\ M_{sun}$

$dM/dt = \sim 8 \times 10^{-5}\ M_{sun}/yr$

3) Fate of dust in Cas A SNR

Small dust grains in Cas A will be completely destroyed in the shocked gas without being injected into the ISM