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ダスト形成から探る超新星爆発

Supernovae probed by dust formation

野沢　貴也（Takaya Nozawa）

東京大学 国際高等研究所

カブリ数物連携宇宙研究機構（Kavli IPMU）

1-1. 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)

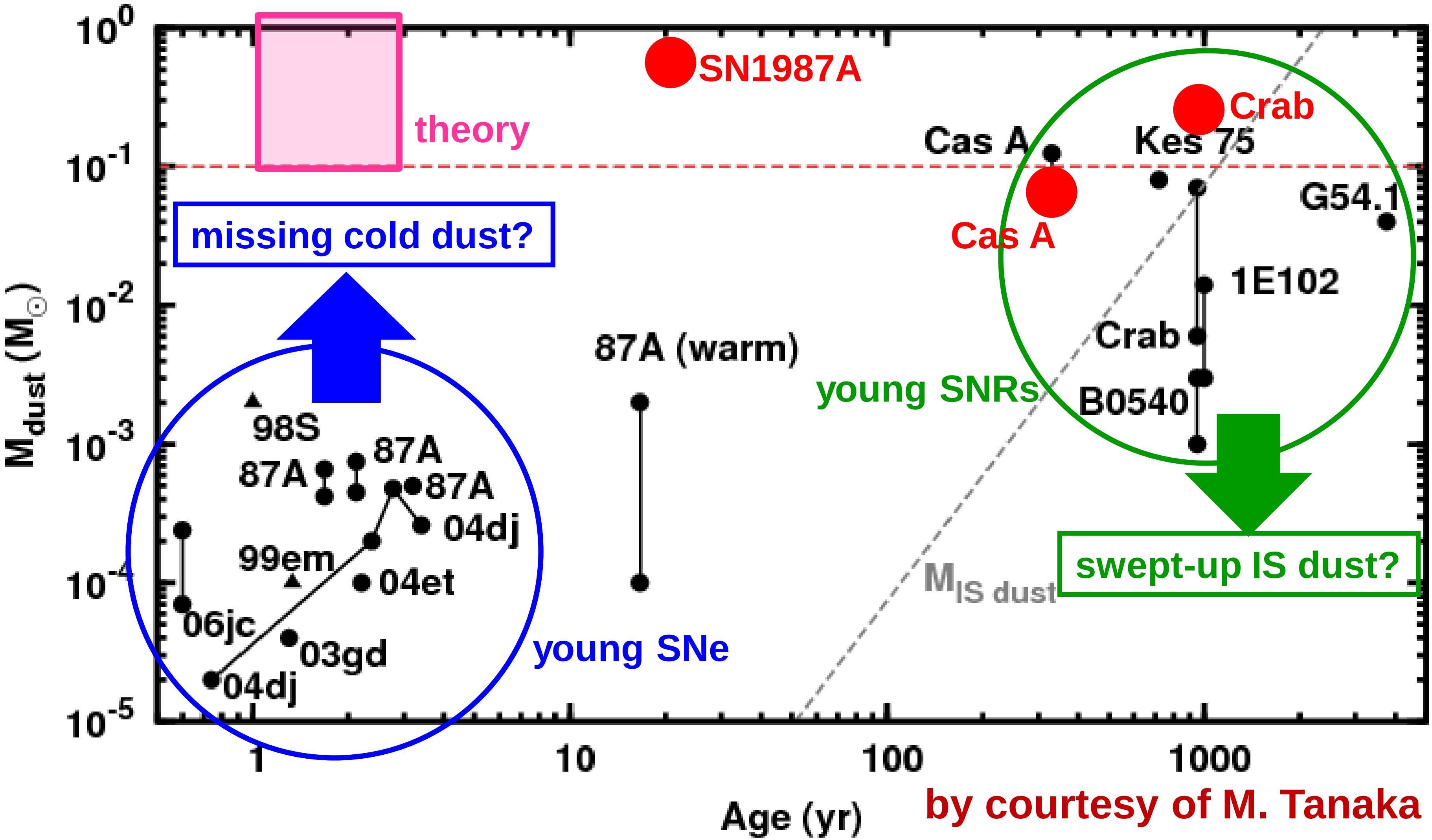
— contribution of dust mass from AGB stars and SNe

n(AGB stars) / n(SNe) ~ 10-20

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

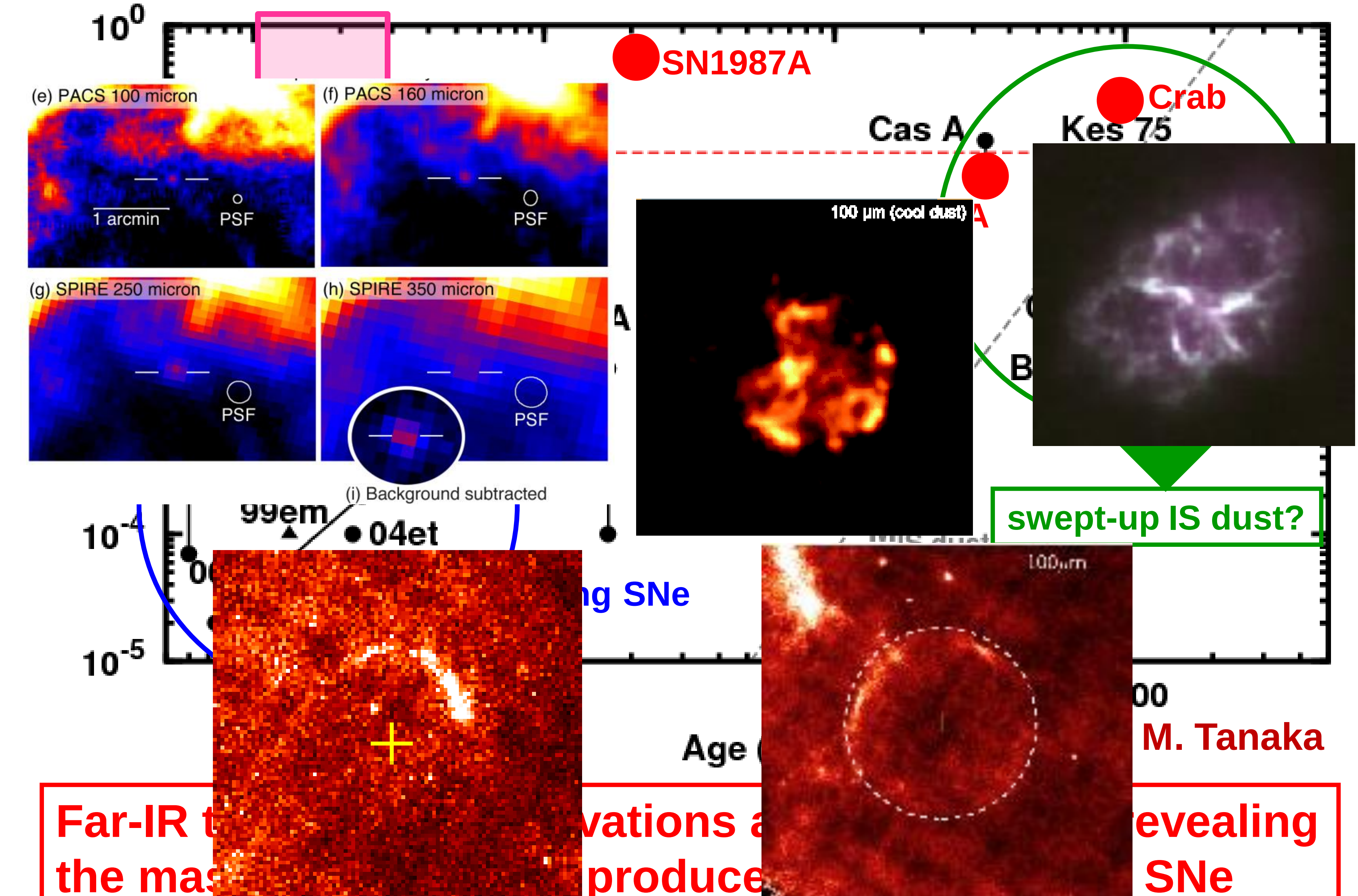
M_{dust} = 0.1-1.0 M_{sun} per SN (Nozawa et al. 2003; 2007)

1-2. Summary of observed dust mass in CCSNe

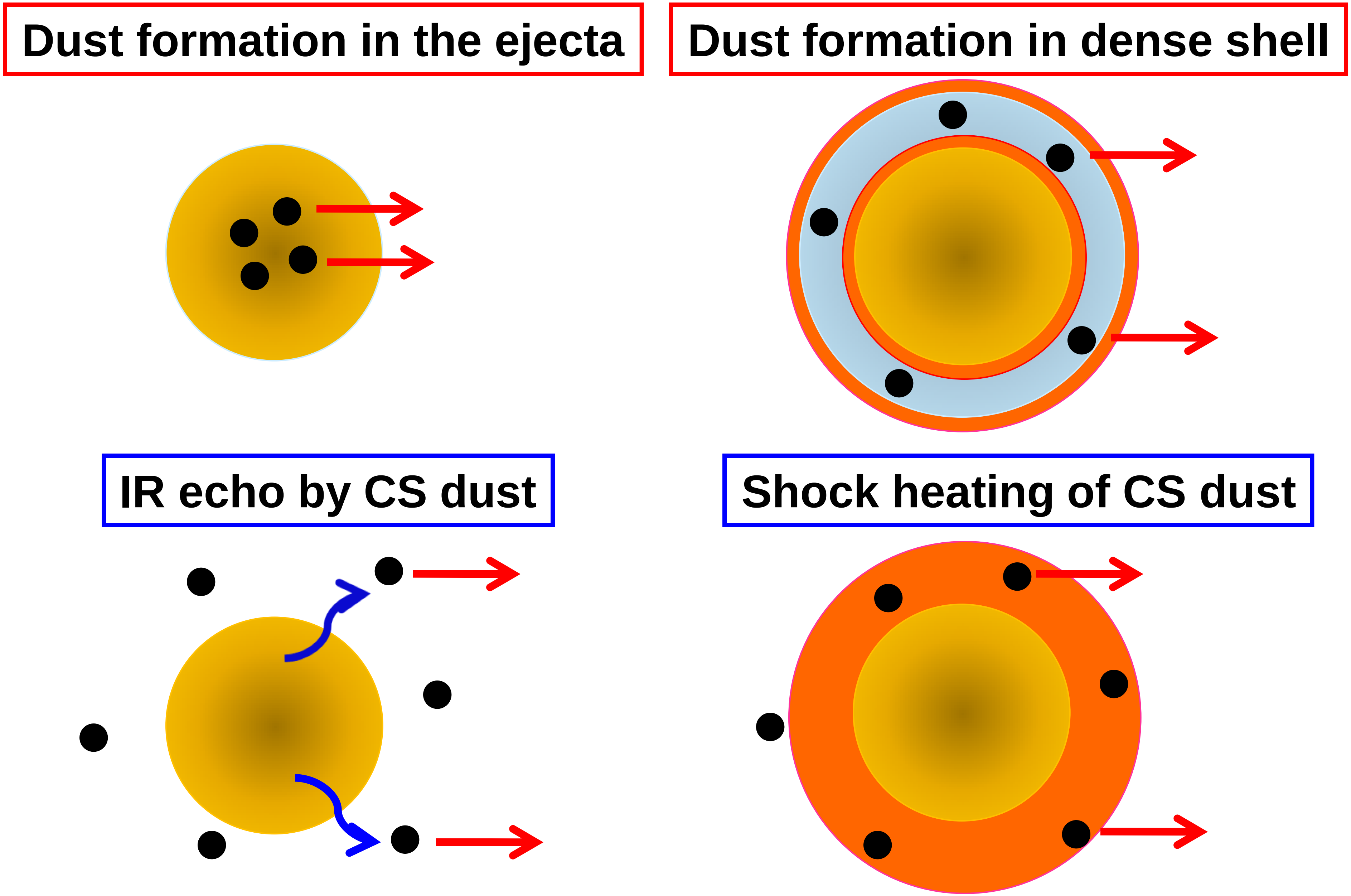


Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe

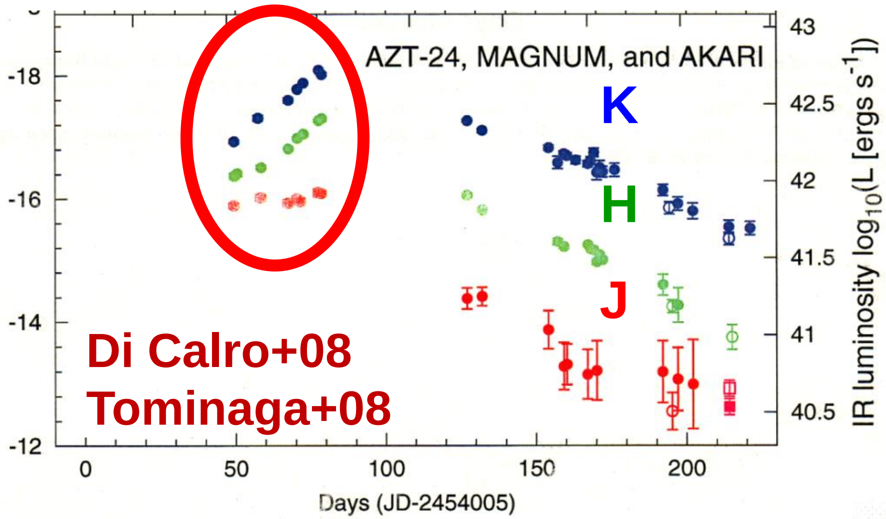
1-2. Summary of observed dust mass in CCSNe



1-3. Origin of IR emission from SNe

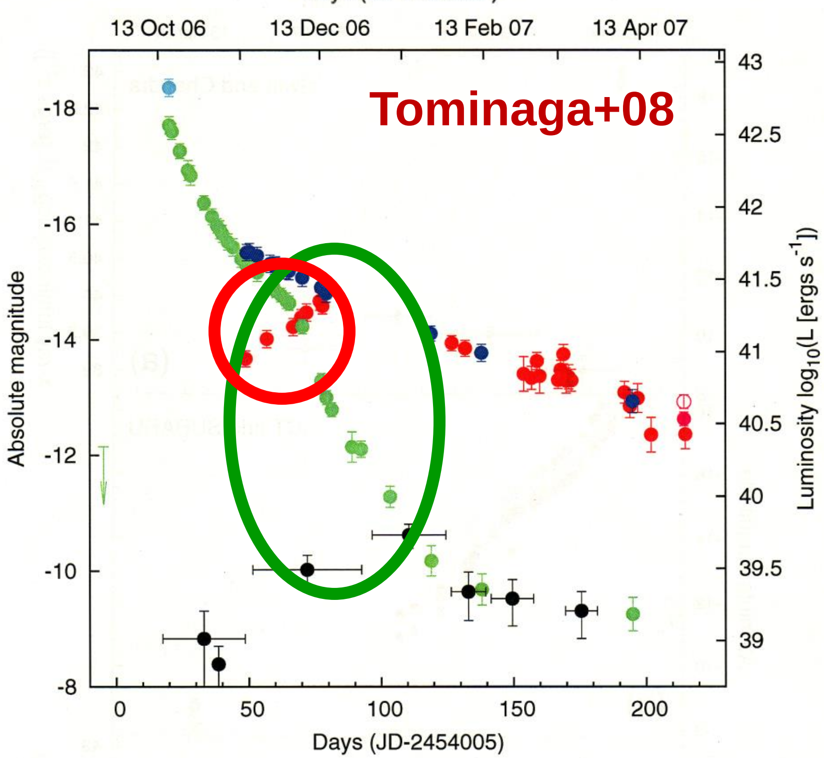


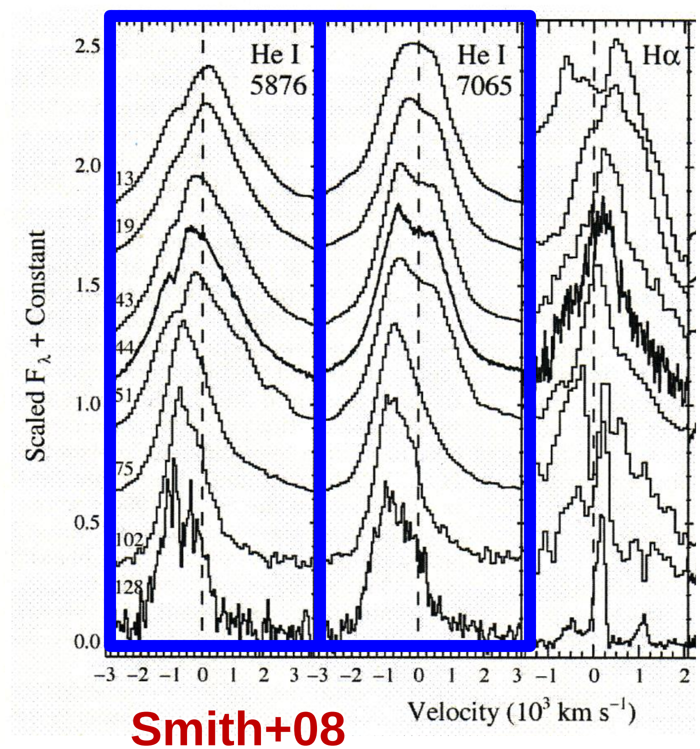
1-4. Evidence for dust formation in SN 2006jc

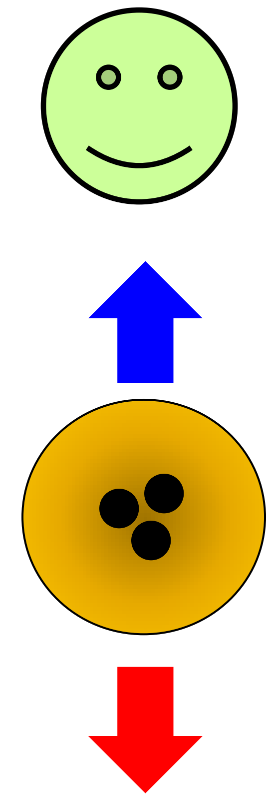


- brightening of IR
- rapid decline of optical light
- blueshift of emission lines

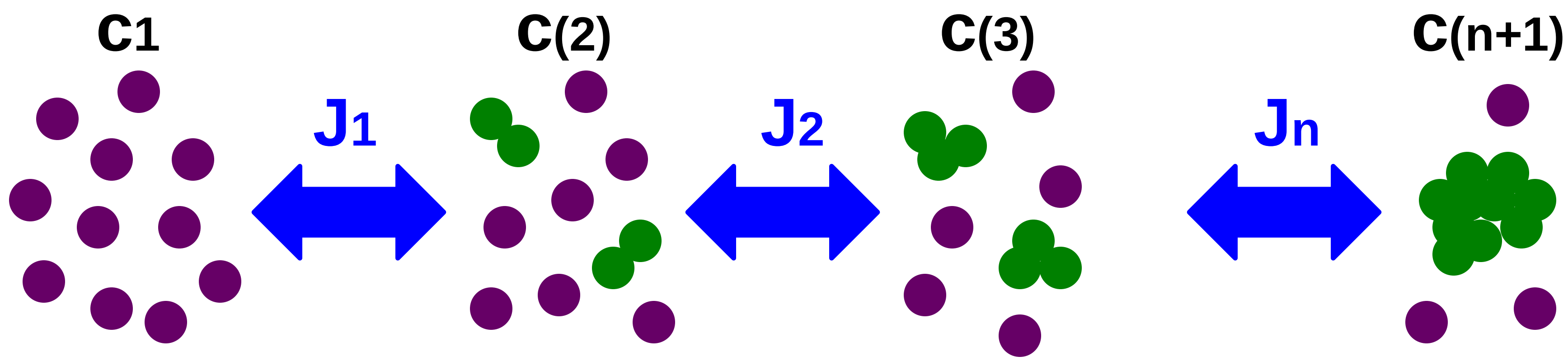
formation of CO and SiO molecules
(more robust if SiO are depleted)







2-1. Dust formation theory



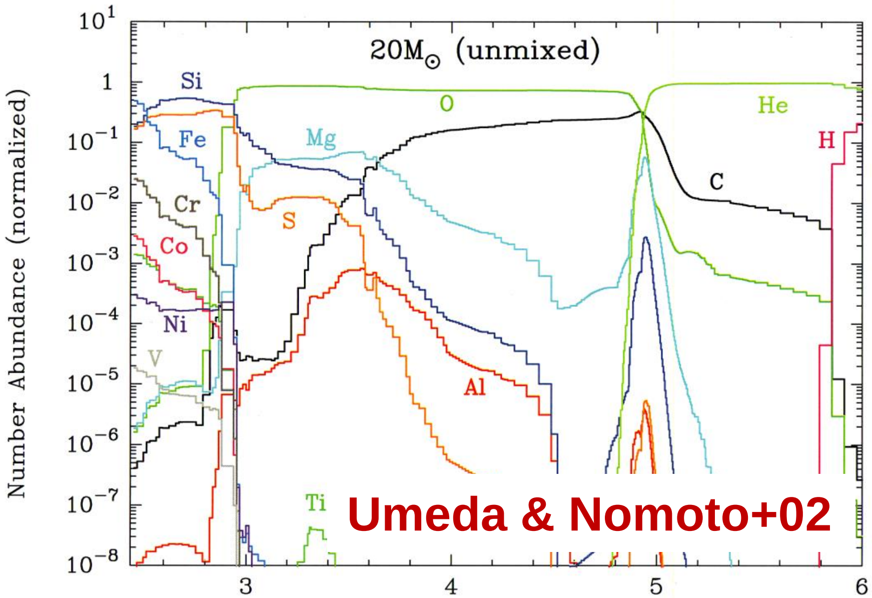
○ Nucleation and grain growth theory

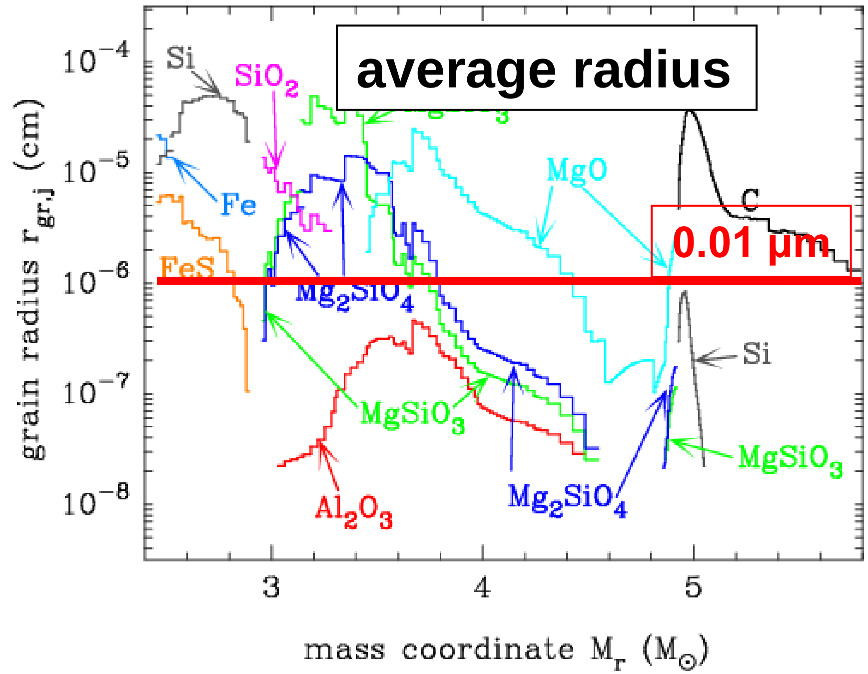
$$J_s(t) = \alpha_s \Omega \left(\frac{2\sigma}{\pi m_1} \right)^{\frac{1}{2}} \Pi c_1^2(t) \exp \left[-\frac{4}{27} \frac{\mu^3}{(\ln S)^2} \right]$$

$$\frac{\partial r}{\partial t} = \alpha_s \frac{4\pi a_0^3}{3} \left(\frac{kT}{2\pi m_1} \right)^{\frac{1}{2}} c_1(t) = \frac{1}{3} a_0 \tau_{\rm coll}^{-1}$$

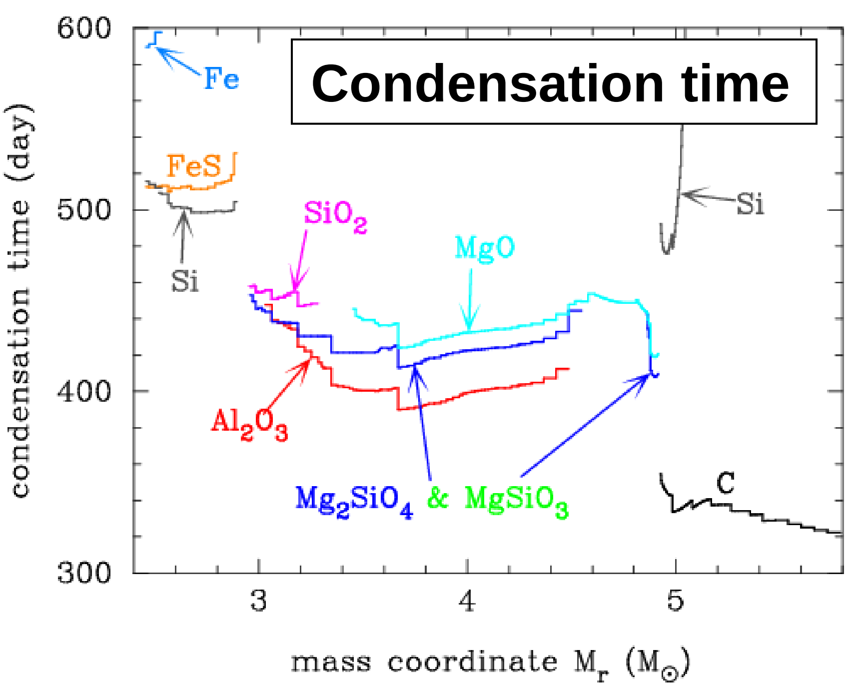
α_s: sticking coefficient ➔ $\alpha_s = 1$

2-1. Dust formed in Type II-P SNe





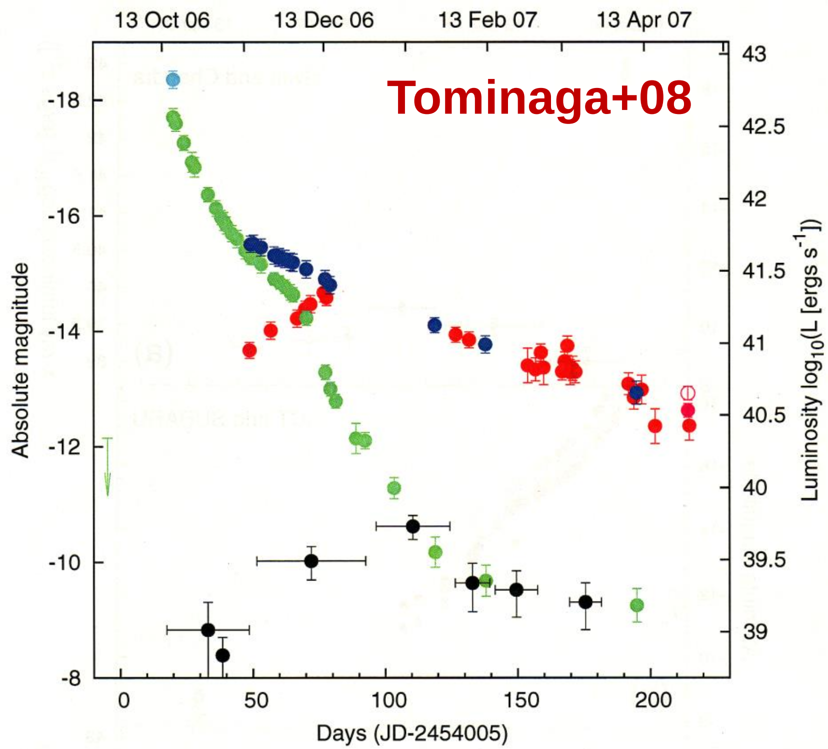
Nozawa+03, ApJ, 598, 785

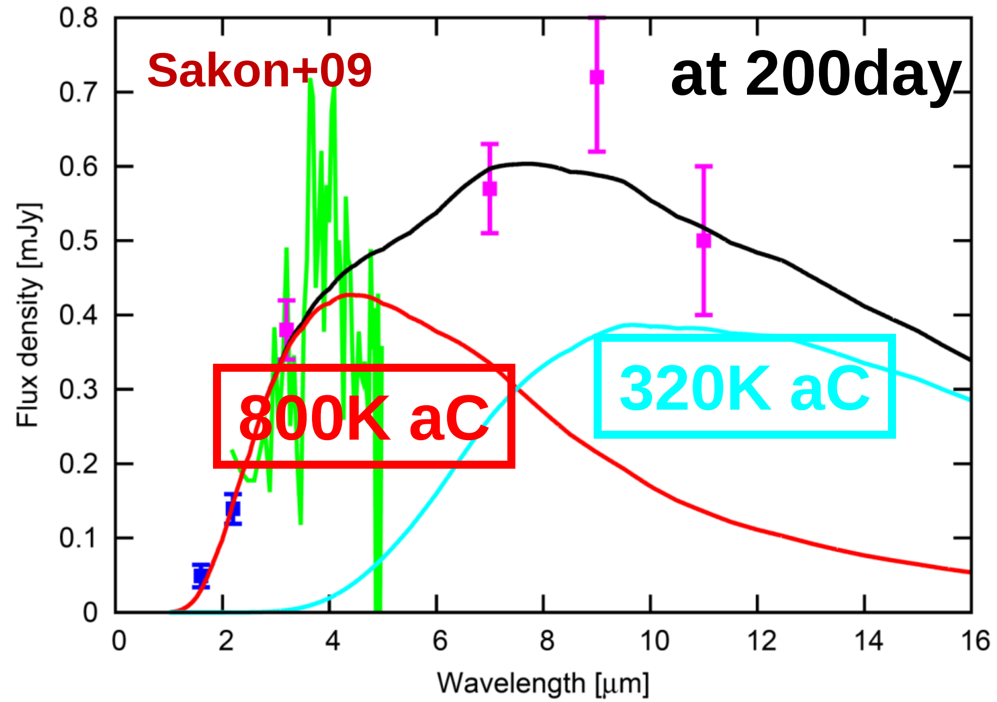


- condensation time: **300-600d** after explosion
- average radii: **>~0.01 μm**
- total dust mass: **0.57 Msun**

➔ **dust mass injected into the ISM: ~0.1-0.8 Msun**

3-1. Peculiar dust-forming SN : SN 2006jc





- re-brightning of NIR
- rapid decline of optical light
- blueshift of He I narrow lines

⇩

ongoing formation of dust from ~50 days in SN2006jc

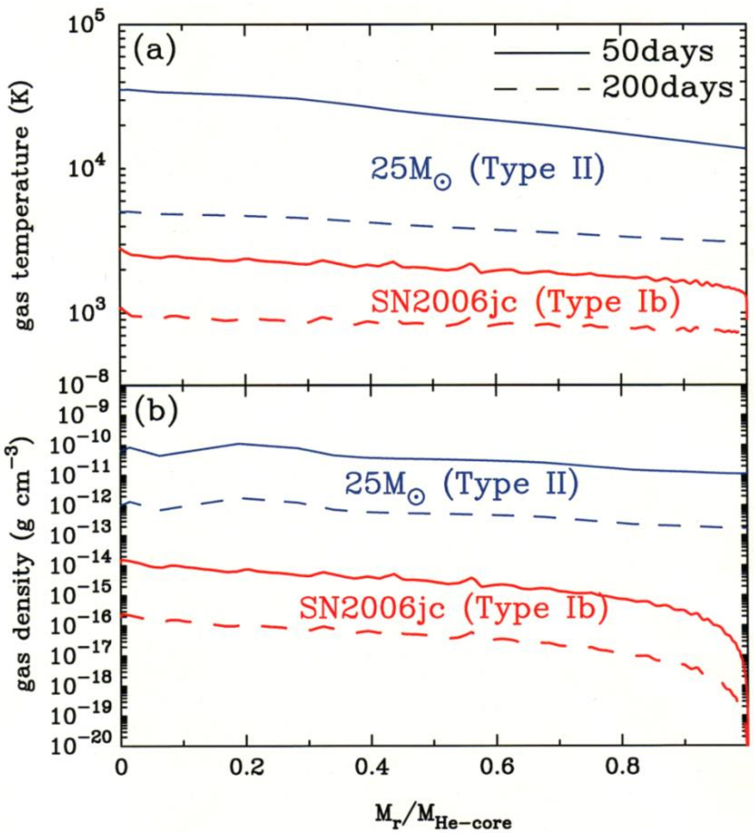
- **800 K aC**
  ➔ newly formed dust:
  $M_{dust} = 7 \times 10^{-5}\ M_{sun}$

- **320 K aC**
  ➔ preexisting CS dust:
  $M_{dust} = 3 \times 10^{-3}\ M_{sun}$

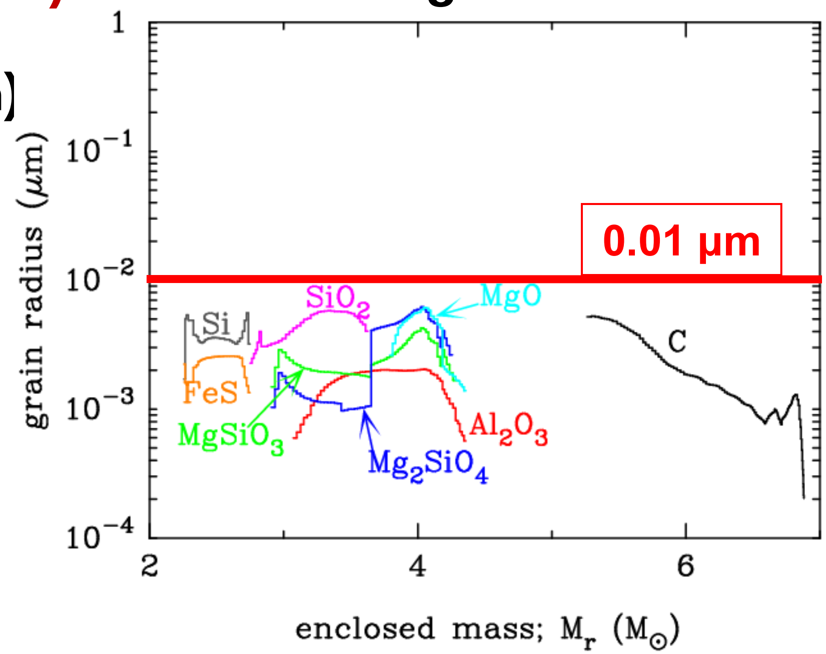
3-2. Dust formation in Type Ib SN : SN 2006jc

○ SN 2006jc model (Tominaga+08)

- M_{eje} = 4.9 Msun (M_{ZAMS} = 40 Msun)
- E_{51} = 10 (hypernova-like)
- $M(^{56}Ni)$ = 0.22 Msun



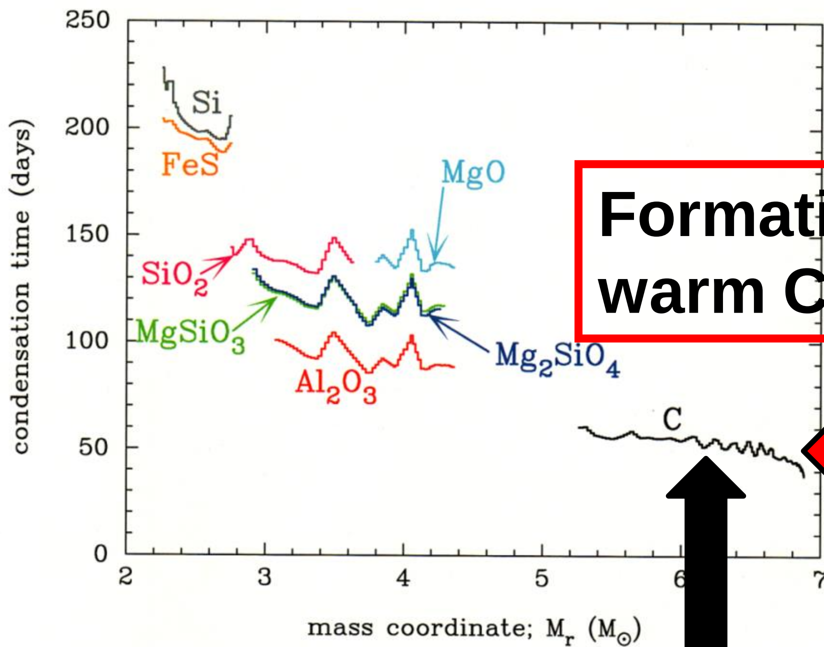
average radius



low ejecta mass and high explosion energy leads too low gas density

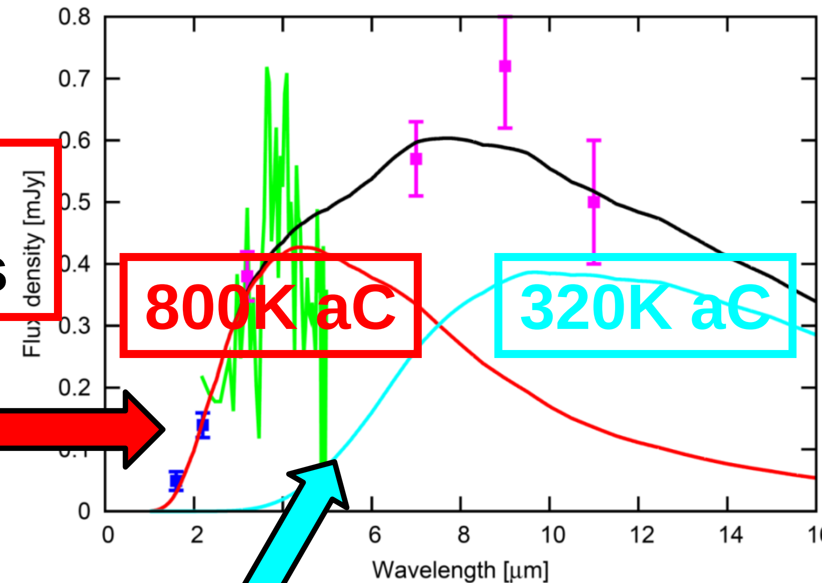
➔ The radii of newly formed grains are below <0.01 μm

3-3. Unified understanding of SN 2006jc



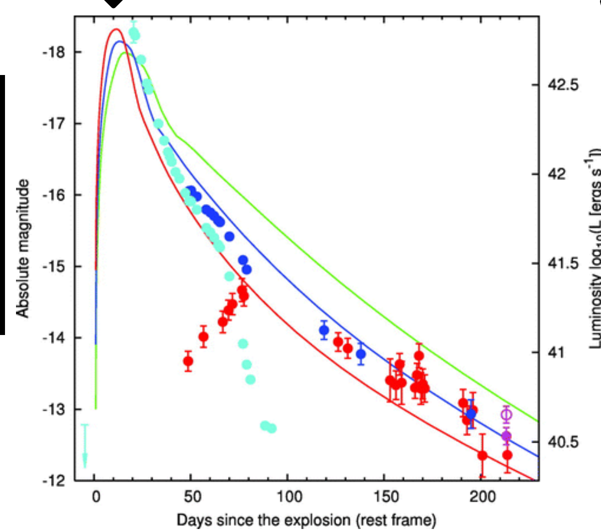
Nozawa+08

Formation of warm C grains



Sakon+09

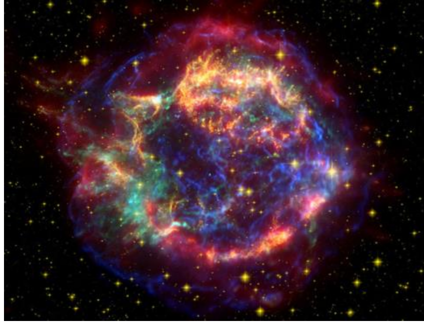
energetic Type Ib
➔ early formation of C dust



Tominaga+08

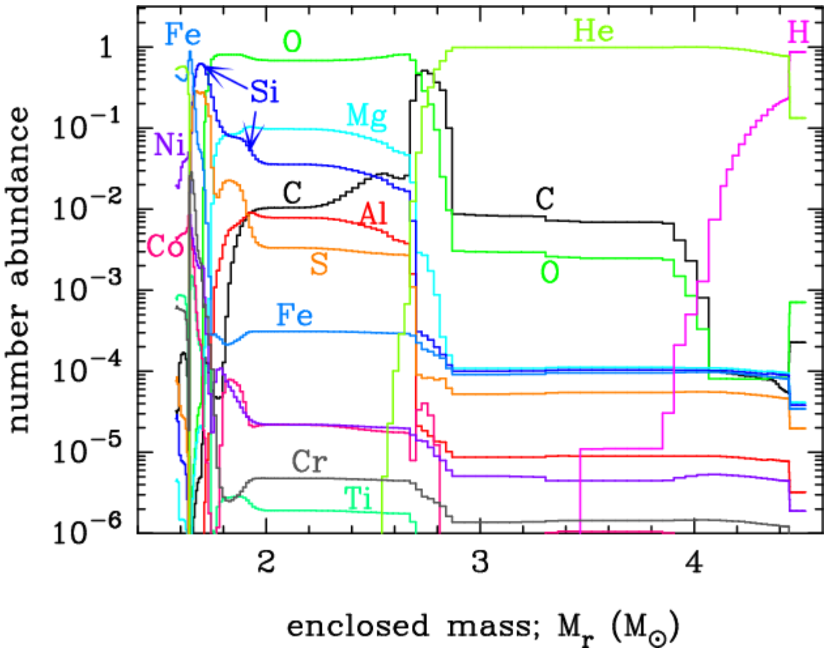
preexisting C dust
➔ WC progenitor

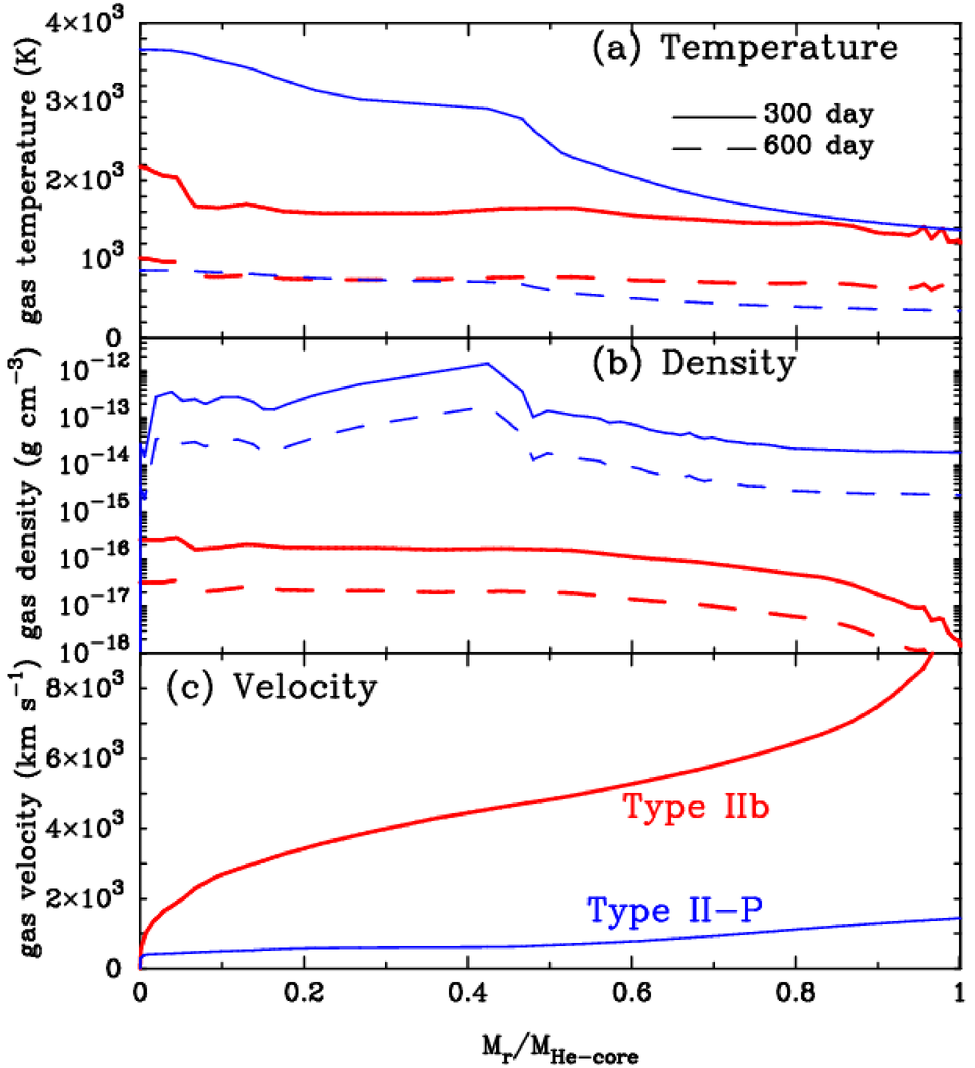
4-1. Dust formation in Type IIb SN



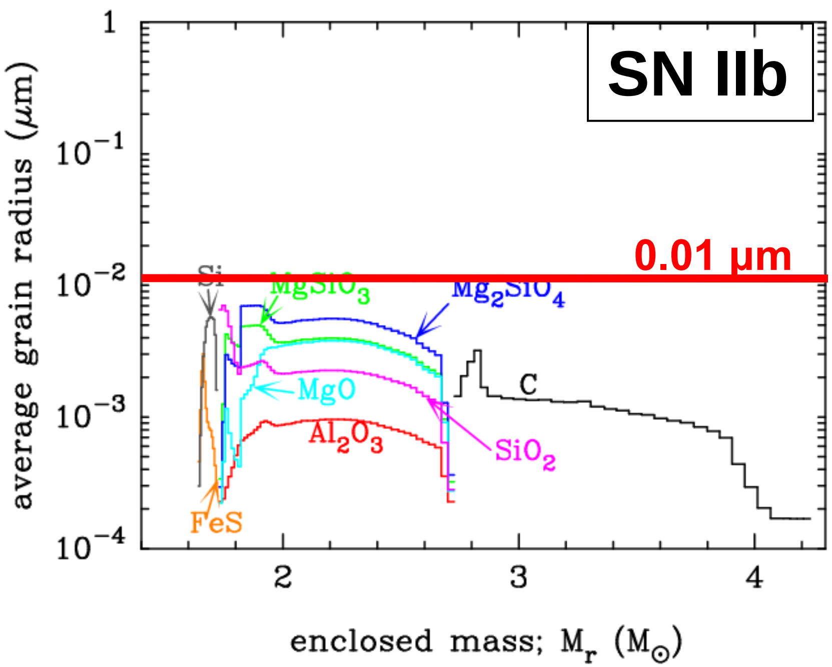
○ SN IIb model (SN1993J-like model)

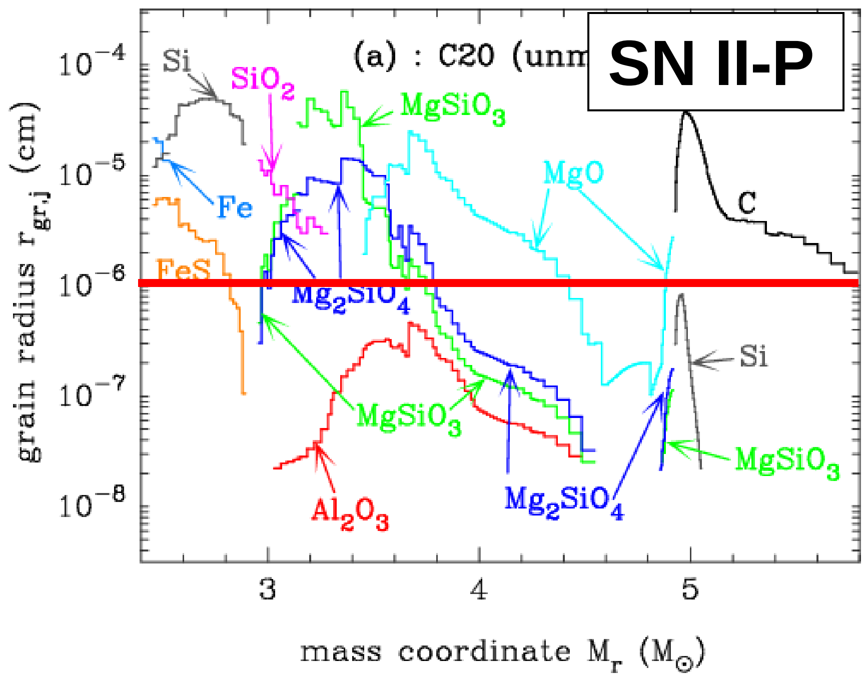
- M_{eje} = 2.94 M_{sun}
  M_{ZAMS} = 18 M_{sun}
  $M_{H\text{-}env}$ = 0.08 M_{sun}
- E_{51} = 1
- $M(^{56}Ni)$ = 0.07 M_{sun}





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

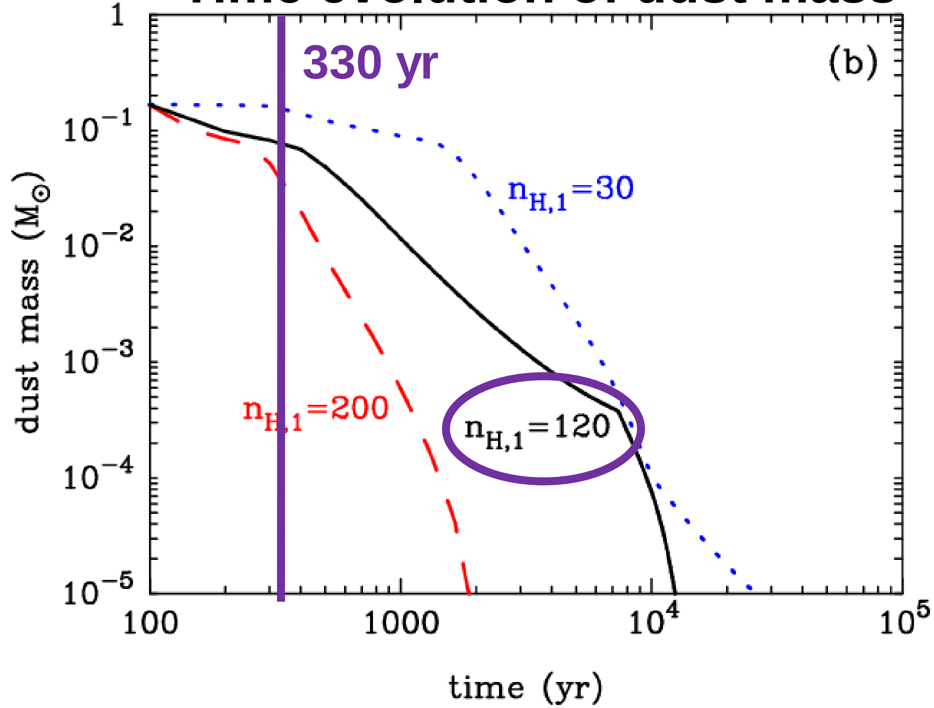
— total mass of dust formed

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

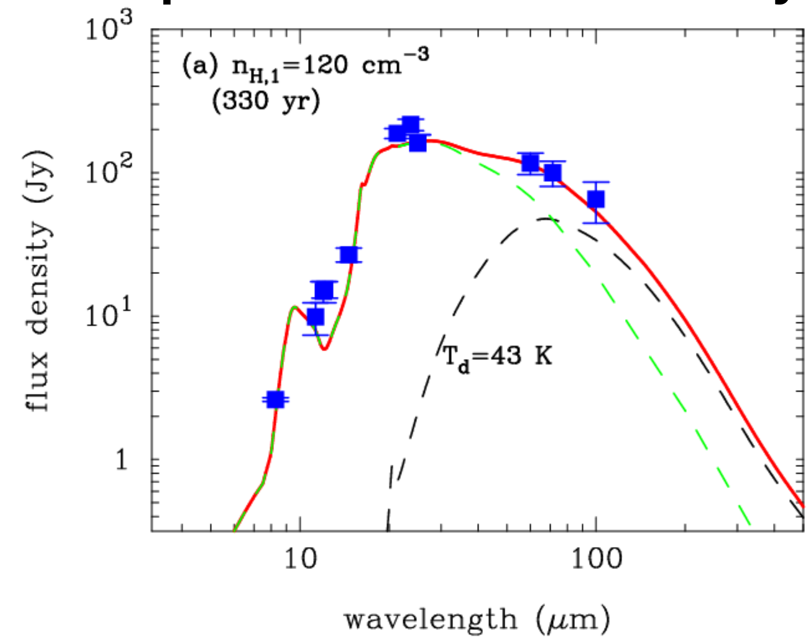
Nozawa+10, ApJ, 713, 356

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

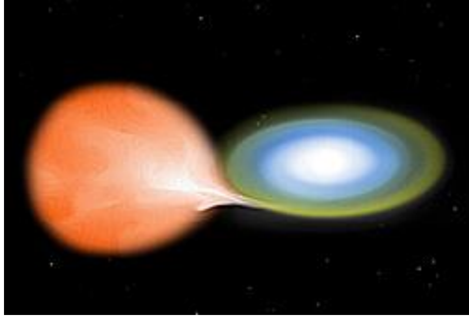
Herschel observation

$M_{d,cool}$ = 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

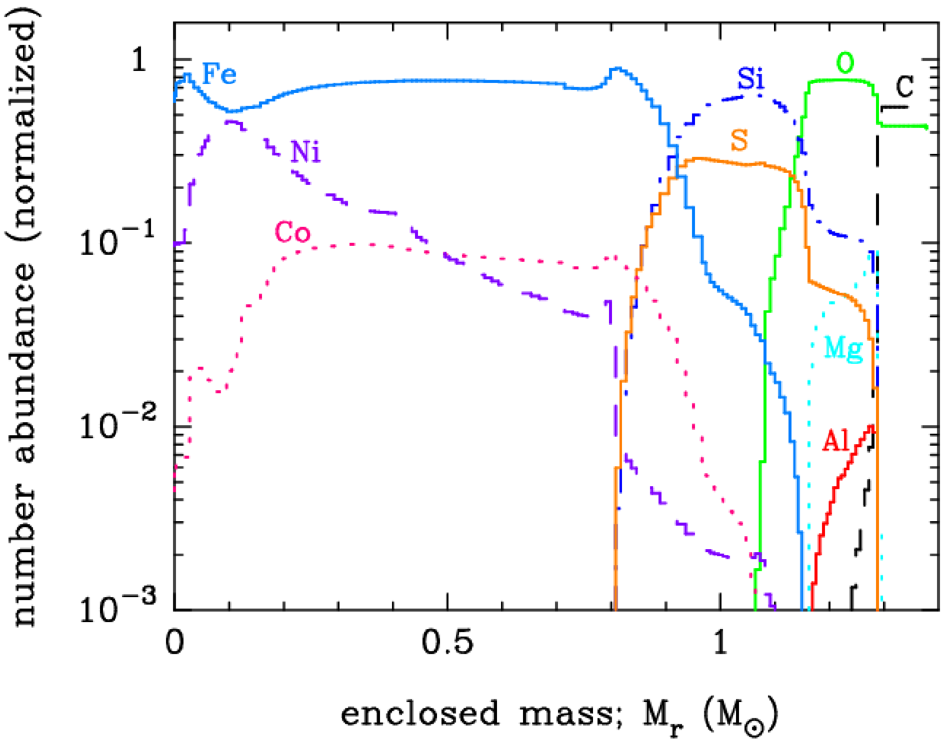
5-1. Dust formation in Type Ia SN

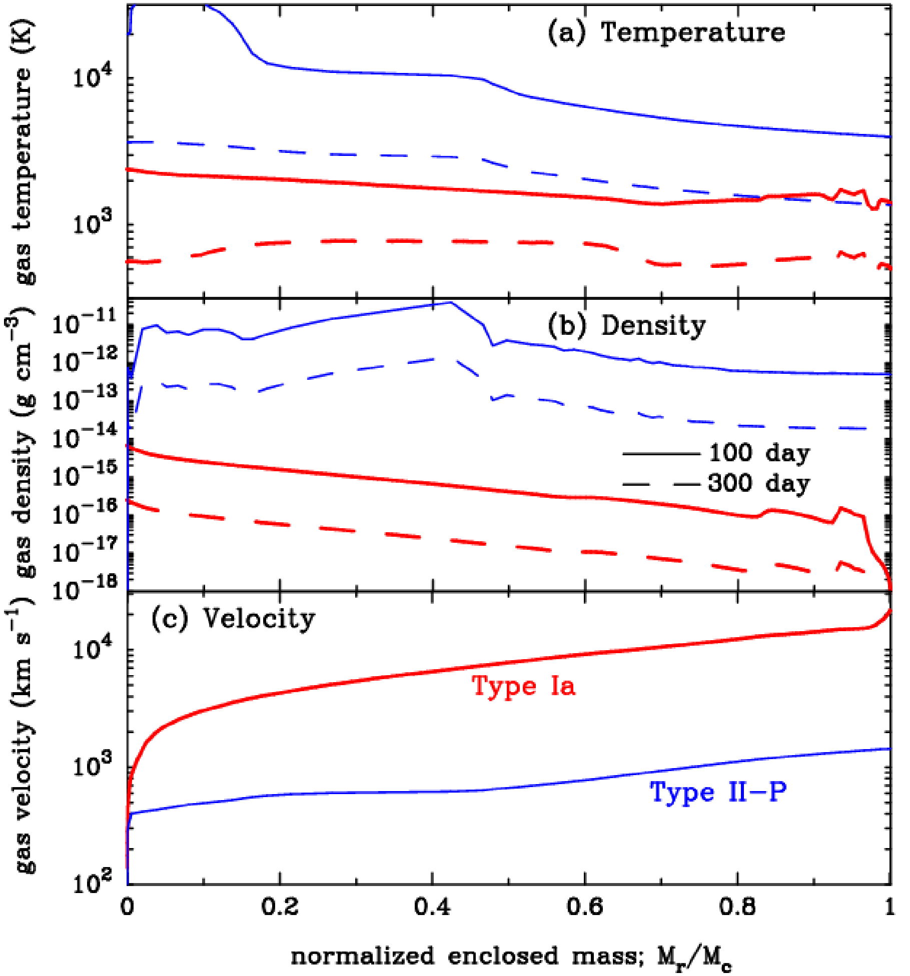


○ Type Ia SN model

W7 model (C-deflagration) (Nomoto+84; Thielemann+86)

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

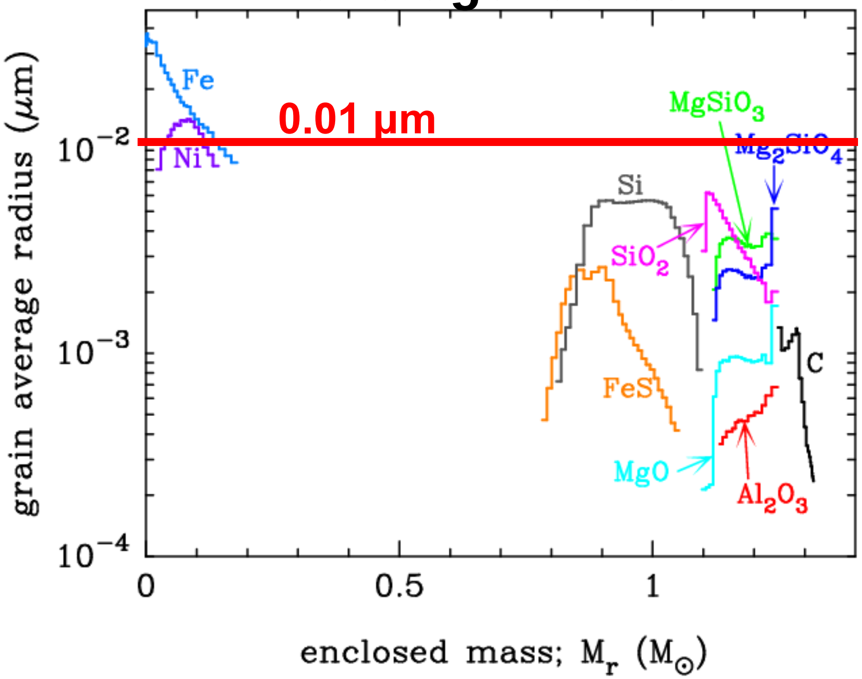




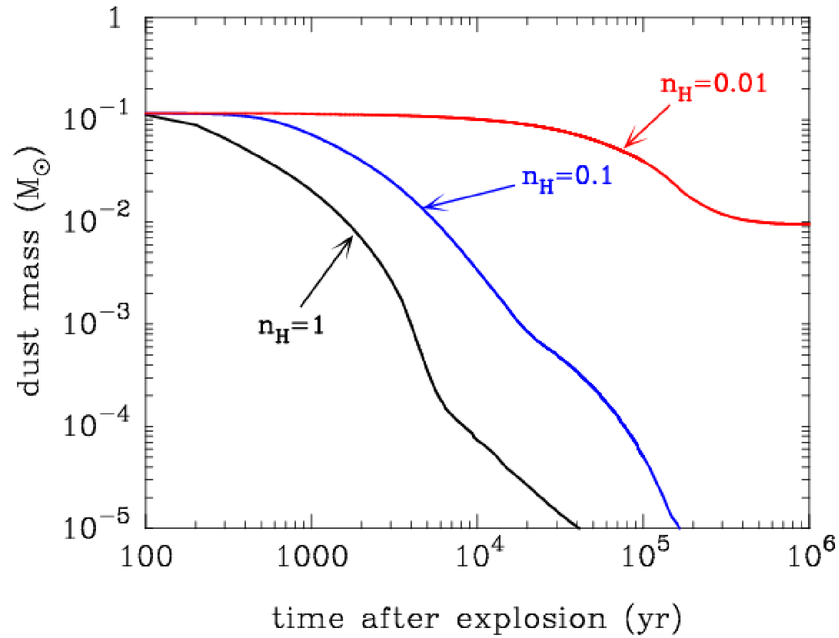
5-2. Dust formation and evolution in SNe Ia

Nozawa+11, ApJ, 736, 45

average radius



dust destruction in SNRs



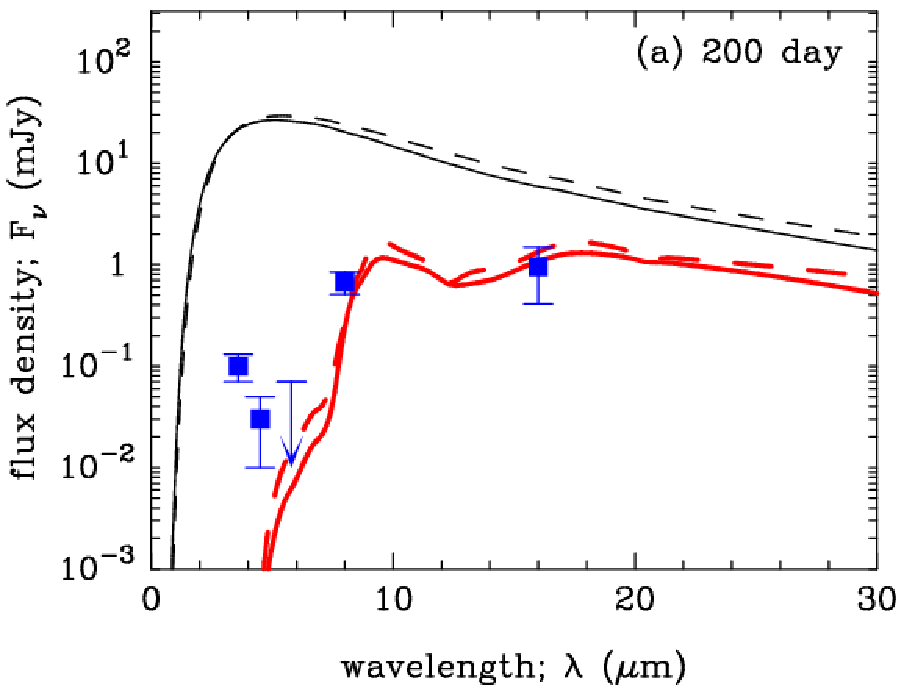
- **condensation time :**
  100-300 days
- **average radius of dust :**
  a_{ave} <~ 0.01 μm
- **total dust mass :**
  M_{dust} ~ 0.1 M_{sun}

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

5-3. Carbon dust and outermost layer

- **There has been no evidence for dust formation in SNe Ia**
  ➔ Formation of massive carbon dust does not match the observations



Observational data: SN 2005df at day 200 and 400 (Gerardy+07)

— C dust mass: ~0.001 Msun

— massive unburned carbon (~0.05 Msun) in deflagration

observationally estimated carbon mass in SNe Ia : Mc < 0.01 Msun

(Marion+06; Tanaka+08)

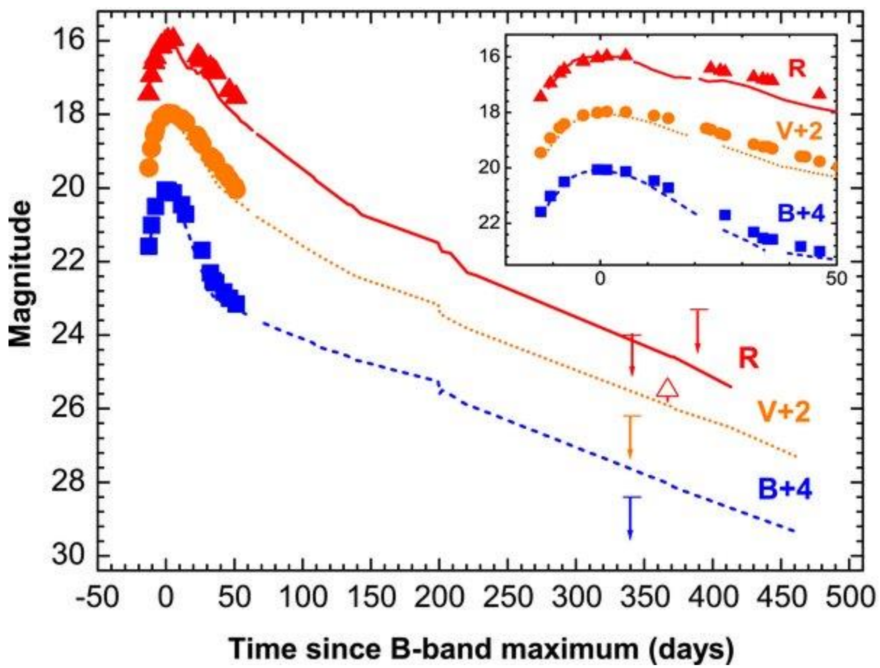
The presence of unburned carbon-rich layer always involve formation of C dust

5-4. Dust formation in super-Chandra SNe?

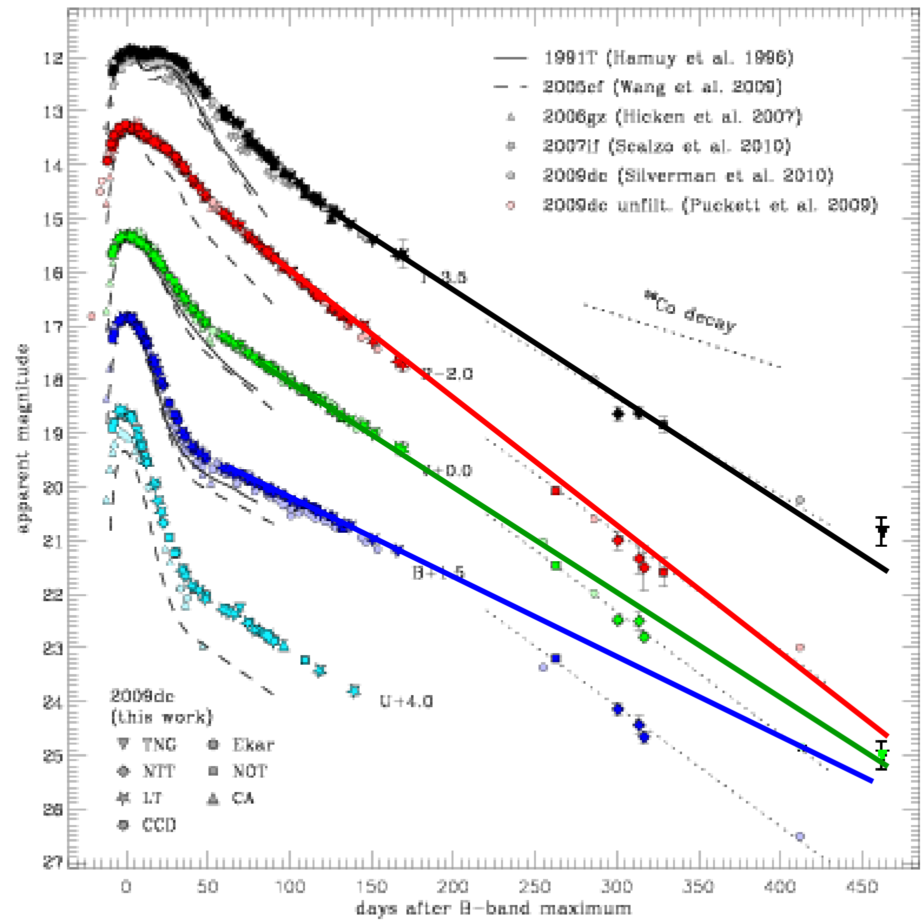
– super-Chandra SNe :
M(56Ni) ~ 1.0 Msun

detection of CII line
➔ presence of massive unburned carbon

SN 2006gz, Maeda+09



SN 2009dc, Tarbenberger+'10



enhanced fading at ~200 day
➔ formation of carbon 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

・ Formation of C dust in SNe Ia may give some hints on the composition of outermost layers