Supply of dust from supernovae: Theory vs. Observation

（超新星爆発によるダストの供給：理論 vs. 観測）

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Outline

1. Introduction

2. Formation and evolution of dust in Type IIb SNe with application to Cassiopeia A SNR

3. Missing-dust problem in core-collapse SNe

4. Formation of dust in the ejecta of SNe Ia

5. Summary

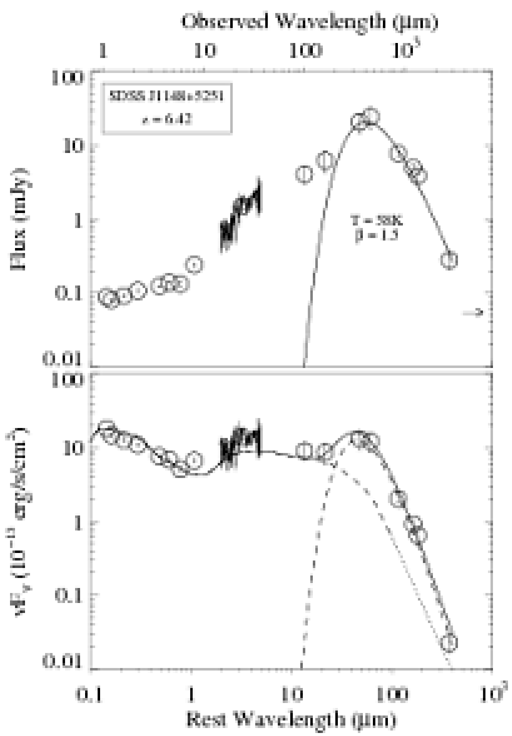
1. Introduction

1-1. Discovery of massive dust at z > 5 quasars

- **The submm observations have confirmed the presence of dust in excess of 10^8 Msun in 30% of z > 5 quasars**

  ➔ **We see warm dust grains heated by absorbing stellar lights in the host galaxies of the quasars**

SDSS J1148+5251



Leipski+'10, A&A, 518, L34

***Herschel**

- **PACS :**
  70 µm
  100 µm
  160 µm
- **SPIRE :**
  250 µm
  350 µm
  500 µm

— age : ~900 Myr (z=6.42)

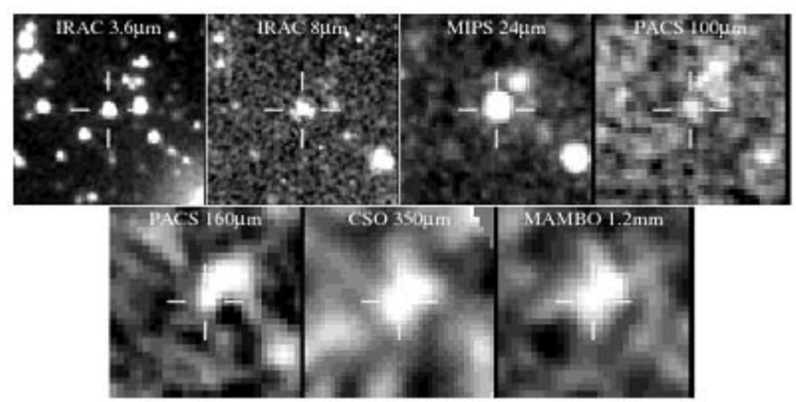
— IR luminosity : ~(1-3)x10^{13} Lsun

— dust mass : (2-7)x10^8 Msun

— SFR : ~3000 Msun/yr (Salpeter IMF)

— gas mass : ~3x10^{10} Msun (Walter+'04)

— metallicity : ~solar



1-2. What are dust sources in high-z quasars?

・ Supernovae (Type II SNe)

➔ ~0.1 M_{sun} per SN is sufficient (Maiolino+'06; Li+'08)

➔ > 1.0 M_{sun} per SN (Dwek+'07, Gall+'10, '11)

・ AGB stars + SNe

(Valiante+'09; Dwek & Cherchneff'11)

➔ 0.01-0.05 M_{sun} per AGB (Zhukovska & Gail '08)

➔ 0.01-1.0 M_{sun} per SN

・ Grain growth in dense clouds + AGB stars + SNe

(Draine'09; Michalowski+'10; Pipino+'11; Mattsson'11, Valiante+'11, Asano+'11)

・ Quasar outflows (Elvis+'02)

1-3. Dust formation in primordial supernovae

Supernovae are important sources of dust?

・ Evolution of dust throughout the cosmic age

- A large amount of dust (> 10^8 M_{sun}) in z > 5 quasars

  ➔ **0.1-1.0 M_{sun} of dust per SN must be ejected**

- Inventory of interstellar dust in our Galaxy

・ Theoretical studies on dust formation in the SN ejecta

(Todini & Ferrara'01; Nozawa+'03; Schneider+'04; Bianchi & Schneider+'07; Cherchneff & Dwek'09, '10)

- M_{dust}=0.1-1 M_{sun} in (primordial) Type II-P SNe (SNe II-P)
- M_{dust}=10-60 M_{sun} in pair-instability SNe (PISNe)

its presence has not been proved observationally!!

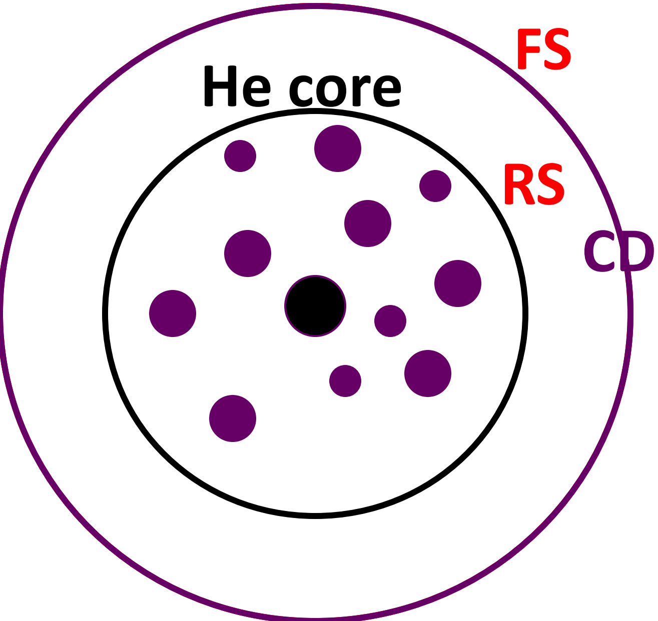
1-4. Dust destruction in supernova remnants

- a part of dust grains formed in SNe are destroyed due to sputtering in the hot gas swept up by the shocks

(e.g., Bianchi & Schneider'07; Nozawa+'07, '10)

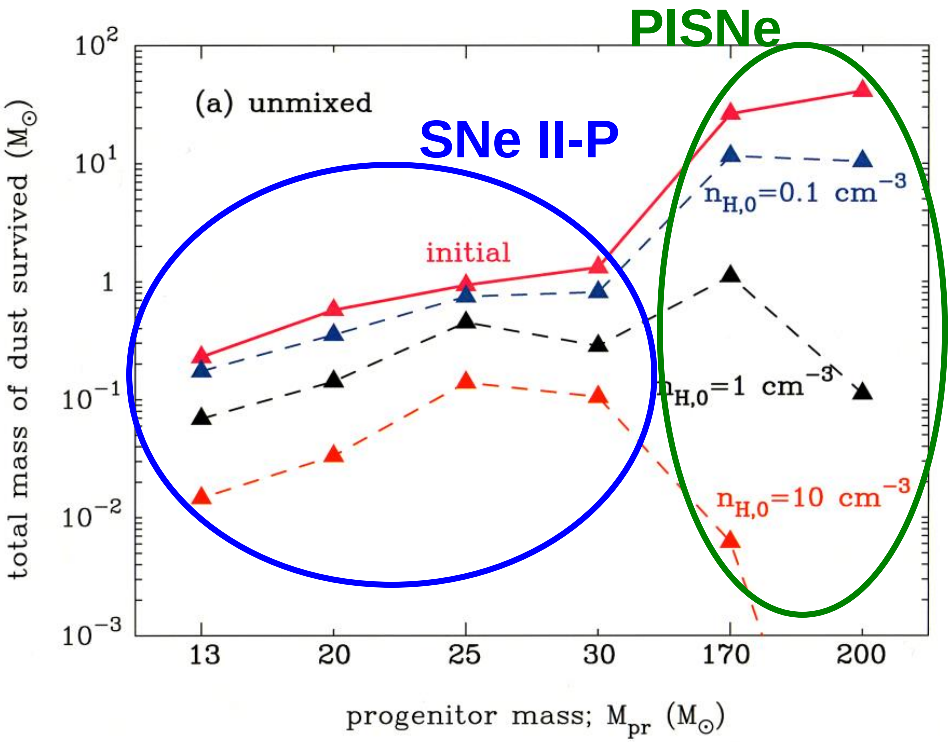
➔ destruction efficiency of dust depends on the initial size distribution

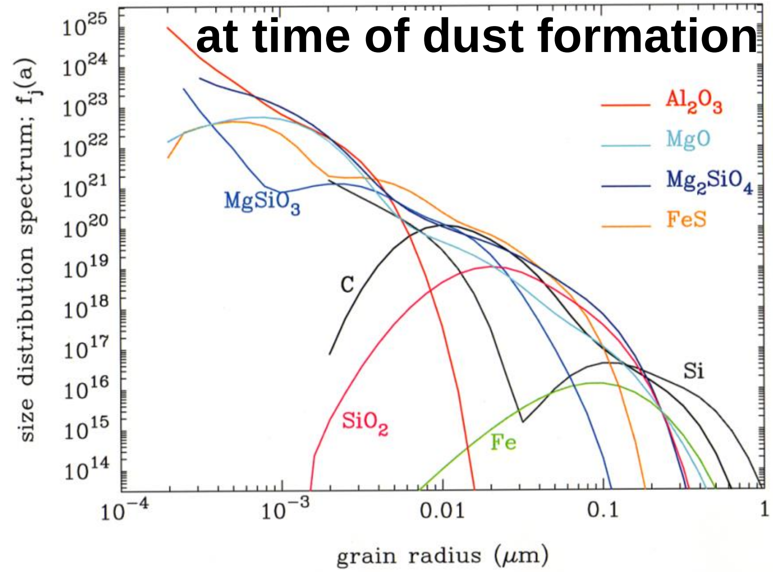
- It is necessary to treat formation and destruction of dust self-consistently

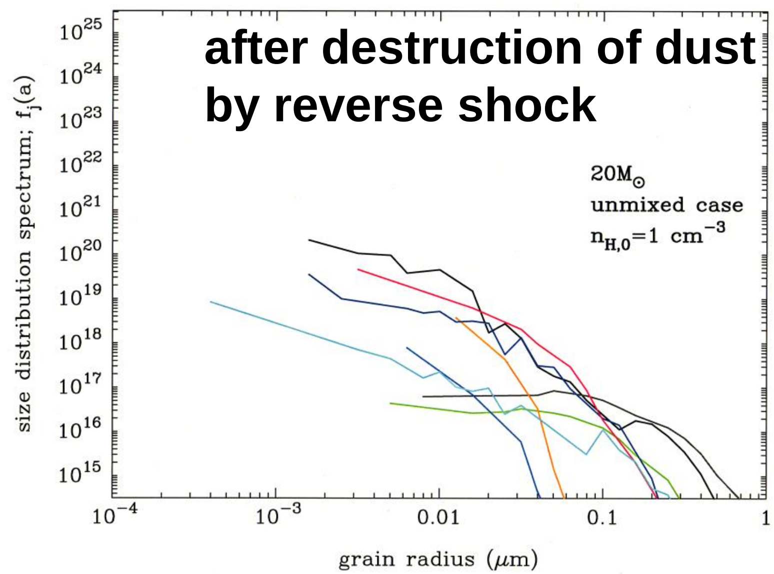


1-5. Mass and size of dust ejected from SN II-P

Nozawa+2007, ApJ, 666, 955





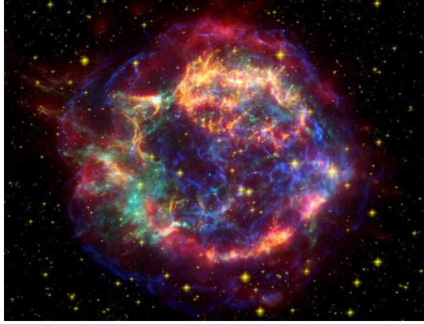


total dust mass surviving the destruction in Type II-P SNRs; 0.07-0.8 M_{sun} ($n_{H,0}$ = 0.1-1 cm^{-3})

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

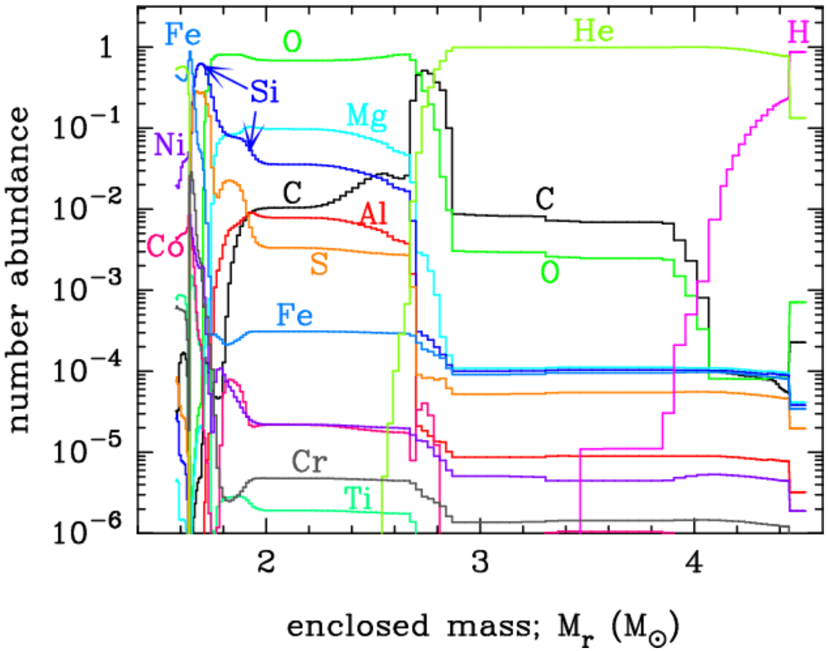
2. Formation and evolution of dust in SNe IIb: Application to Cas A

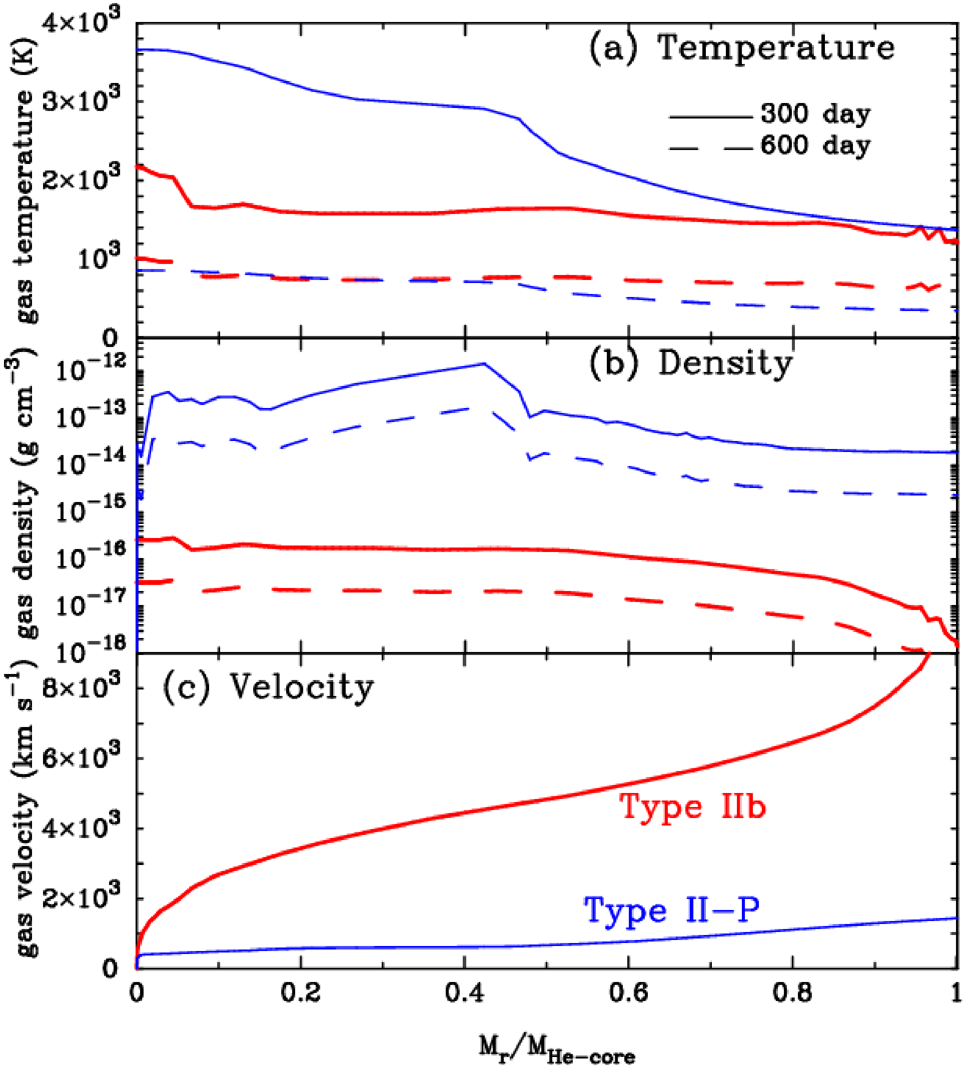
2-1. Dust formation in Type IIb SN



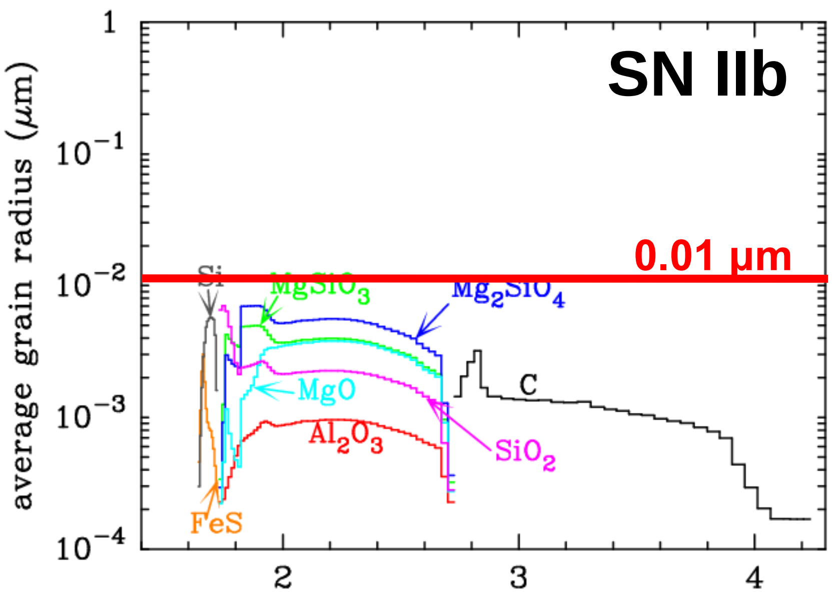
○ SN IIb model (SN1993J-like model)

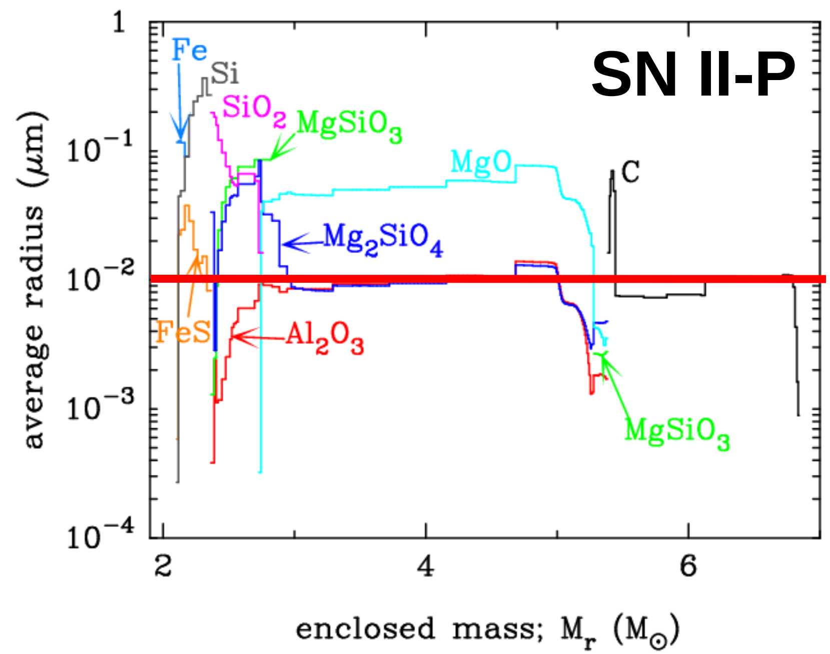
- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1.0
- $M(^{56}Ni)$ = 0.07 Msun

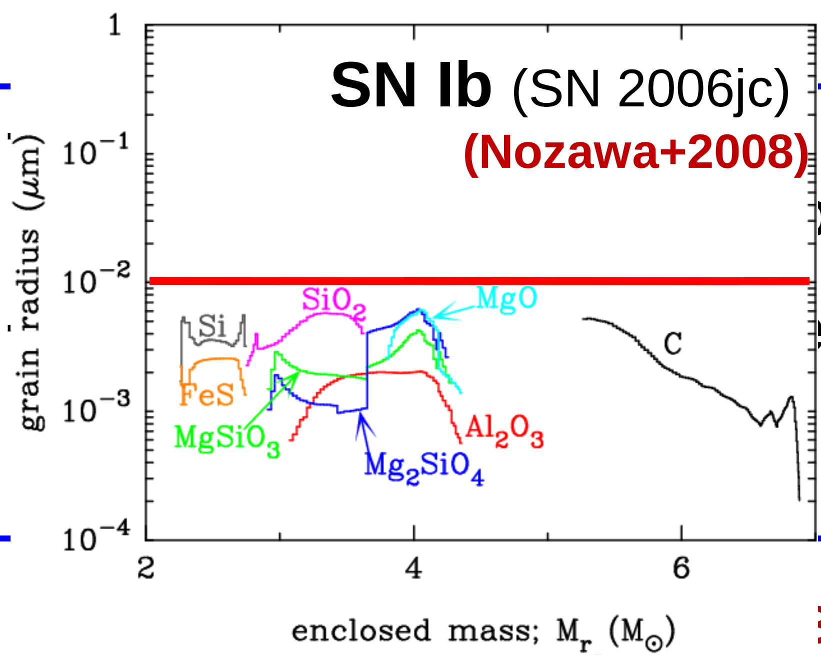




2-2. Dependence of dust radii on SN type







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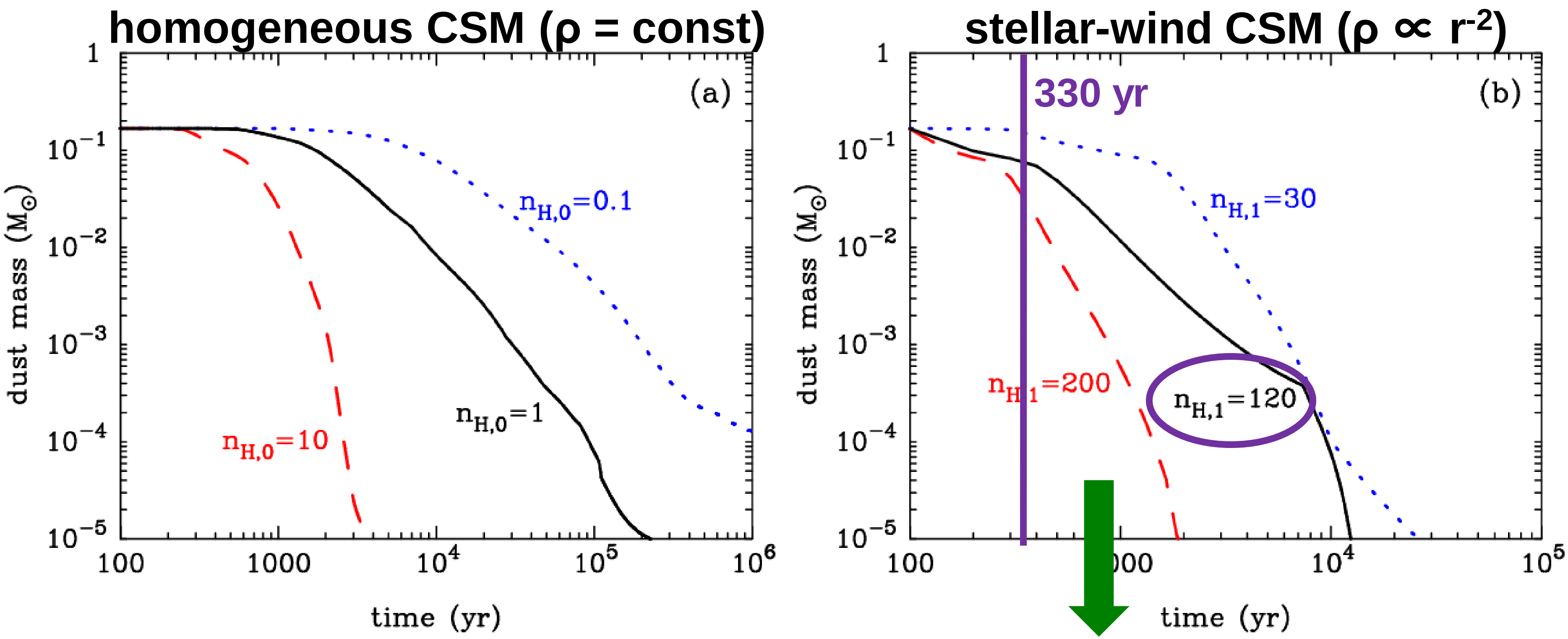
— the radius of dust formed in H-stripped SNe is small

- SN IIb without massive H-env ➔ adust < 0.01 μm
- SN II-P with massive H-env ➔ adust > 0.01 μm

2-3. Destruction of dust in Type IIb SNR



$n_{H,1}$ = 30, 120, 200 /cc ➔ dM/dt = 2.0, 8.0, 13x10^{-5} M_{sun}/yr for v_W=10 km/s

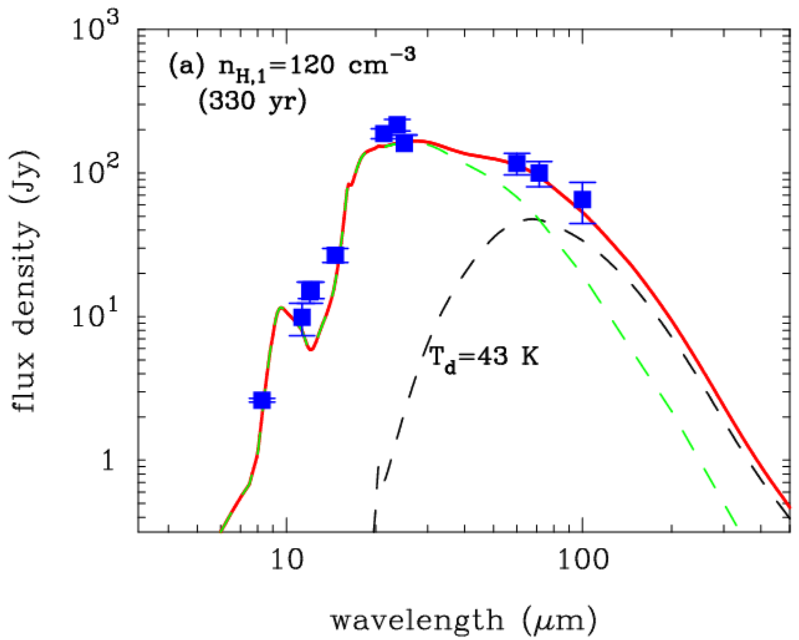
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

➔ **small radius of newly formed dust**

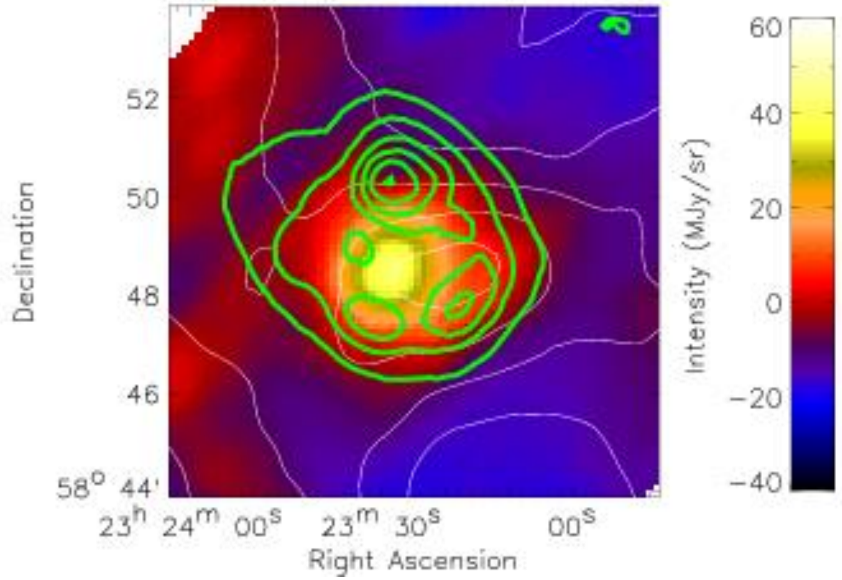
➔ **early arrival of reverse shock at dust-forming region**

Nozawa et al. 2010, ApJ, 713, 356

2-4. IR emission from dust in Cas A SNR



AKARI corrected 90 μm image



- **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

Nozawa et al. 2010, ApJ, 713, 356

AKARI observation

$M_{d,cool}$ = 0.03-0.06 M_{sun}

T_{dust} = 33-41 K

(Sibthorpe+'10)

Herschel observation

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

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

3. Missing-dust problem in CCSNe

3-1. Difference in estimate of dust mass in SNe

・Theoretical studies

— at time of dust formation : M_{dust}=0.1-1 M_{sun} in CCSNe
(Nozawa+'03; Todini & Ferrara'01; Cherchneff & Dwek'10)

— after destruction of dust by reverse shock (SNe II-P) :
M_{surv}~0.01-0.8 M_{sun} (Nozawa+'07; Bianchi & Schneider'07)

dust amount needed to explain massive dust at high-z

・Observational works

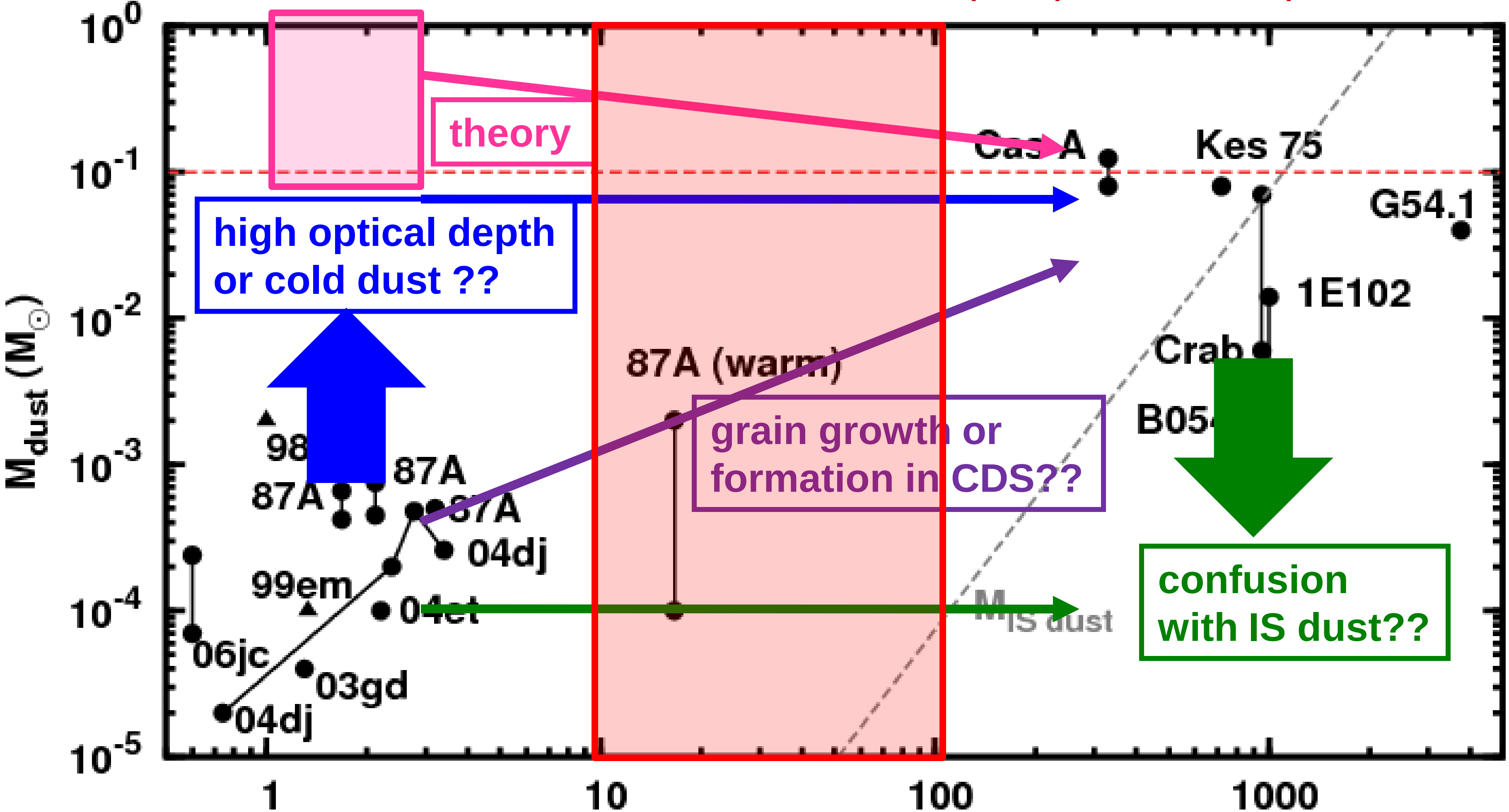
— NIR/MIR observations of SNe : M_{dust} < 10^{-3} M_{sun}
(e.g., Ercolano+'07; Sakon+'09; Kotak+'09)

— submm observations of SNRs : M_{dust} > 1 M_{sun}
(Dunne+'03; Morgan+'03; Dunne+'09)

— MIR/FIR observation of Cas A : M_{dust}=0.02-0.075 M_{sun}
(Rho+'08; Sibthorpe+'09; Barlow+'10)

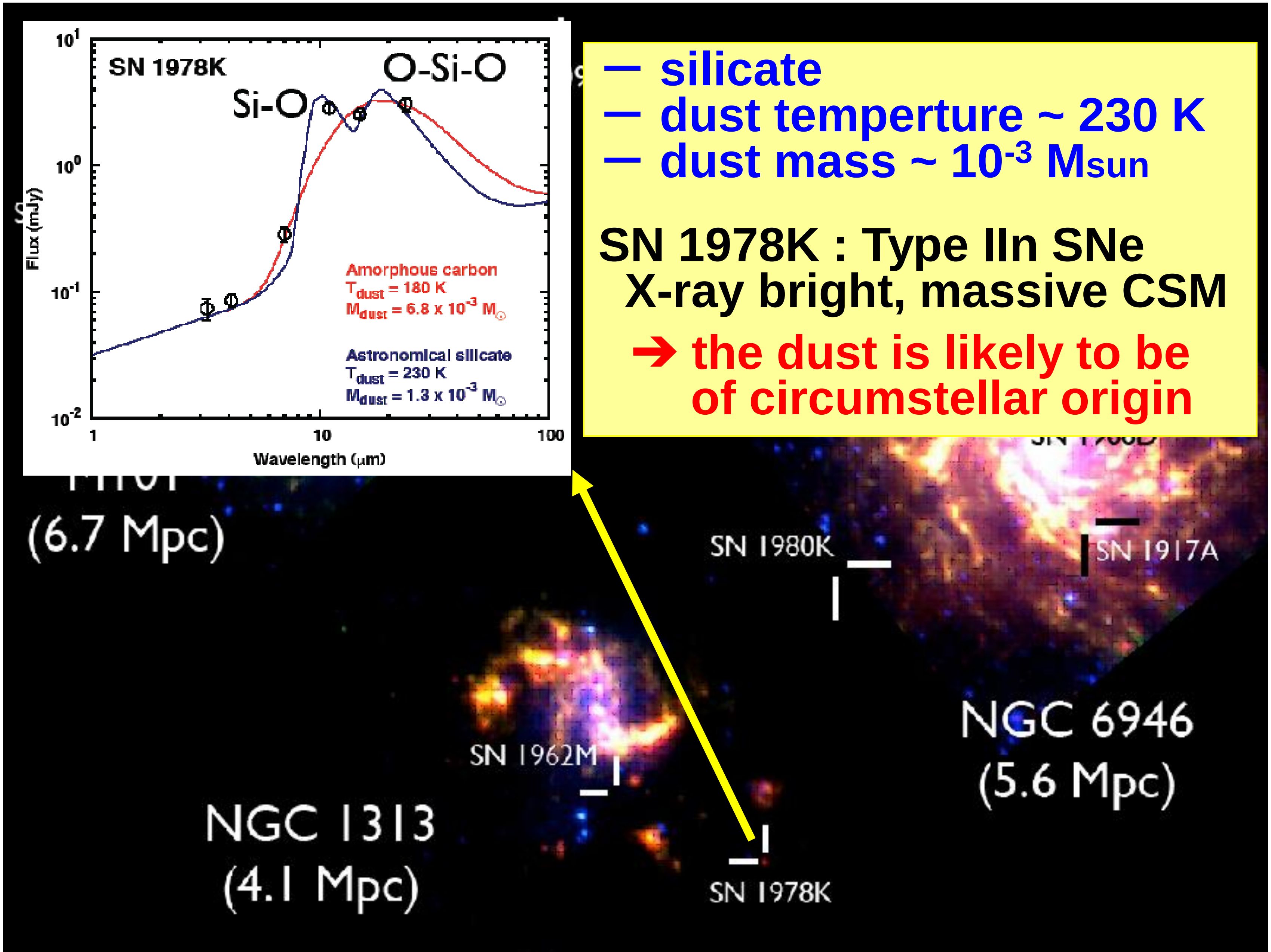
3-2. Missing-dust problem in CCSNe

Tanaka, TN, et al. 2011, submitted



Middle-aged SNe with ages of 10-100 yrs are good targets to measure the mass of dust formed in SNe!!

3-3. Search for dust in middle-aged CCSNe



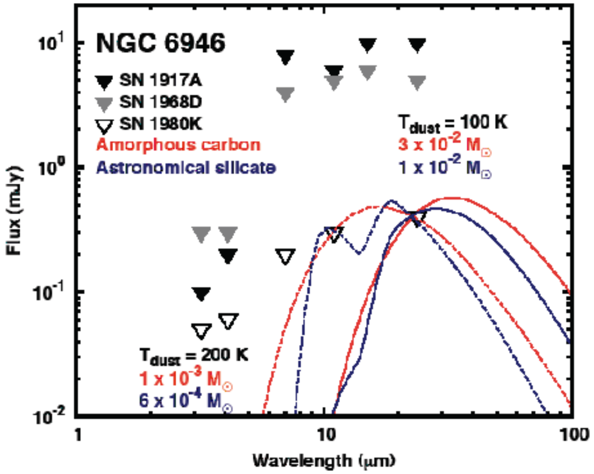
- silicate
- dust temperture ~ 230 K
- dust mass ~ 10^{-3} Msun

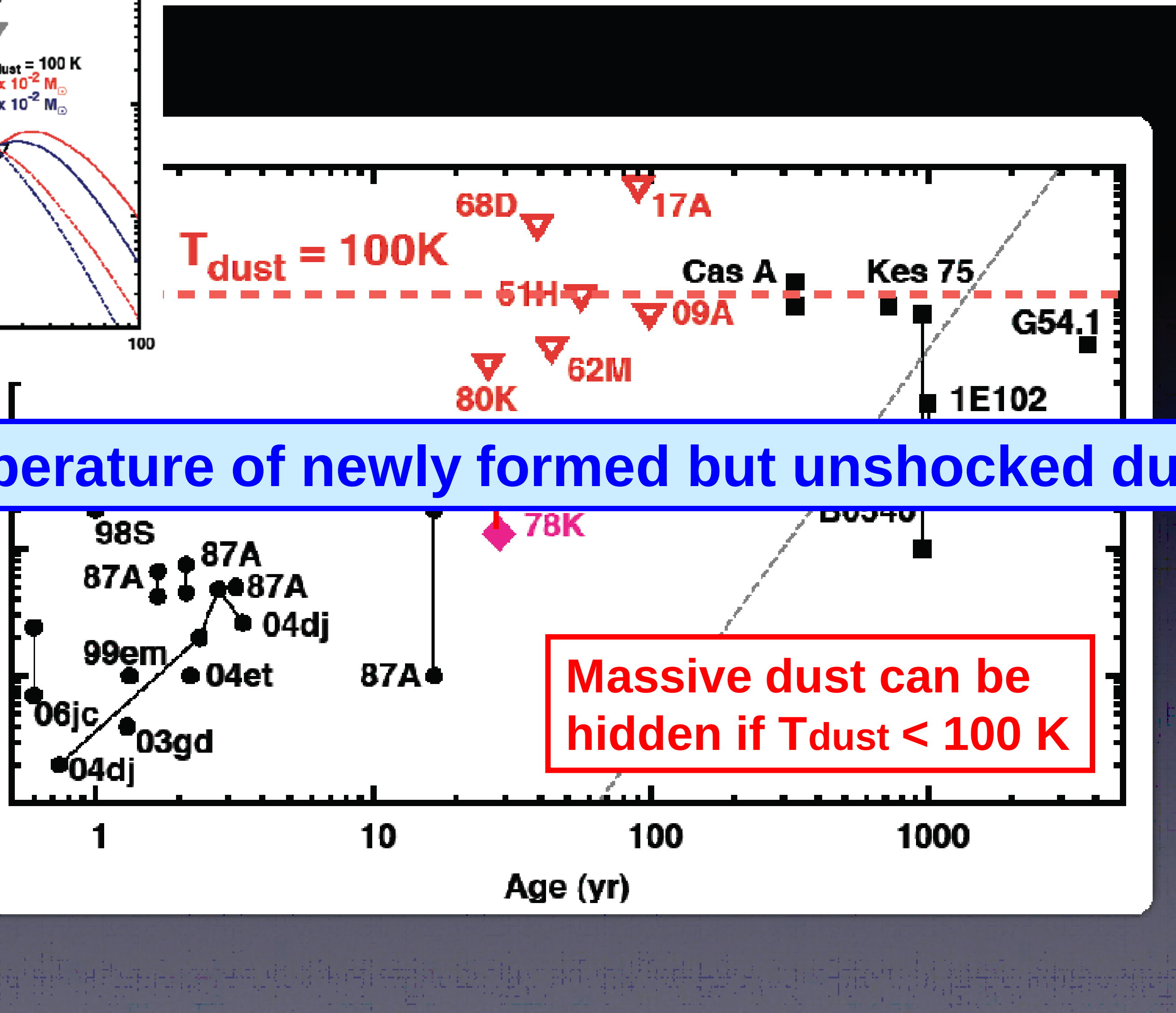
SN 1978K : Type IIn SNe
X-ray bright, massive CSM

➔ the dust is likely to be of circumstellar origin

3-4. Estimate of dust mass in middle-aged SNe

Tanaka, TN, et al. 2011, submitted

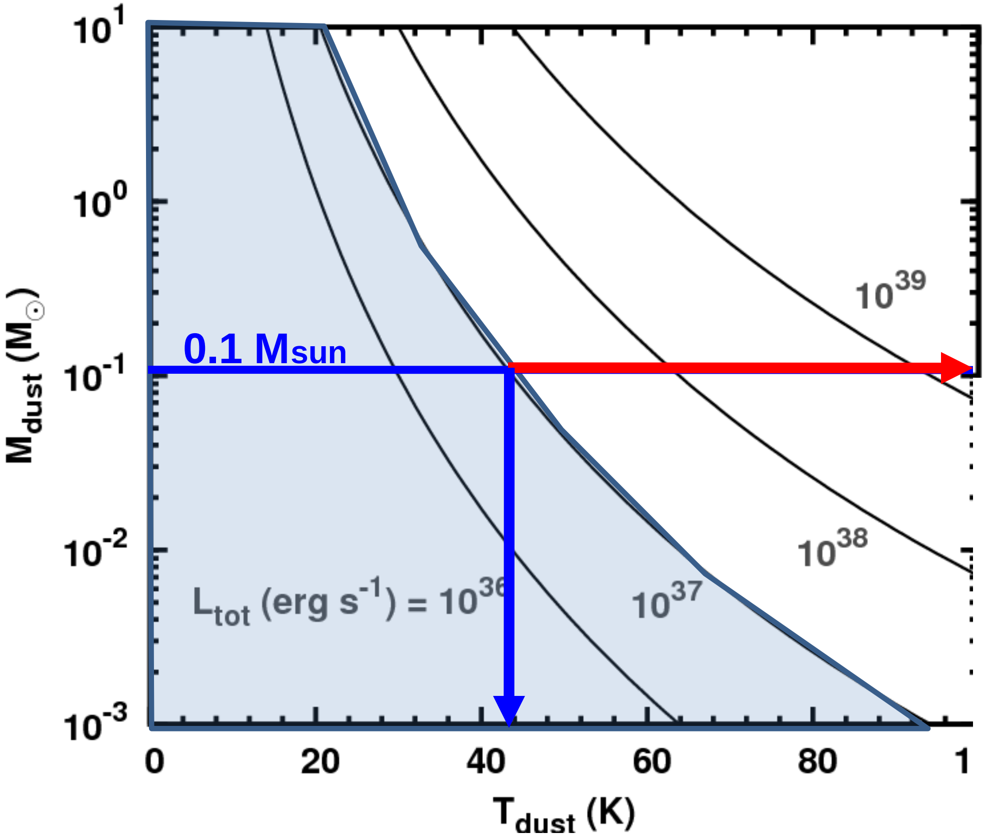




What is temperature of newly formed but unshocked dust?

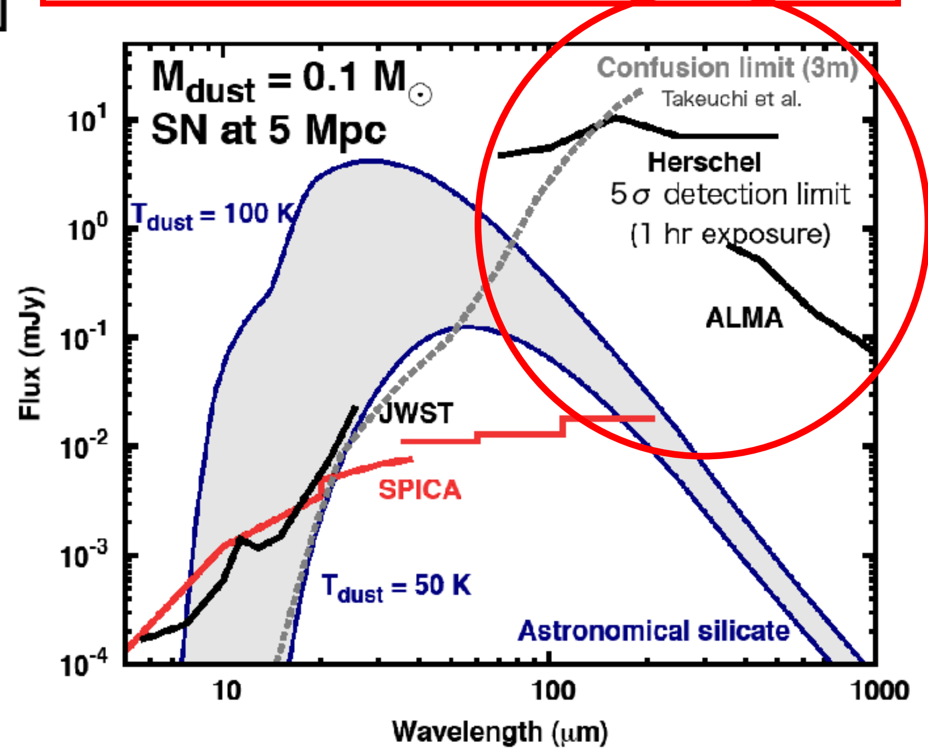
Massive dust can be hidden if T_{dust} < 100 K

3-5. Temp. of cool dust and its detectability



Tanaka, TN, et al. 2011, submitted

L_{IR} < L_{tot} < 10^{37} erg/s
➔ T_{dust} < 45 K for 0.1 Msun
T_{dust} < 90 K for 10^{-3} Msun



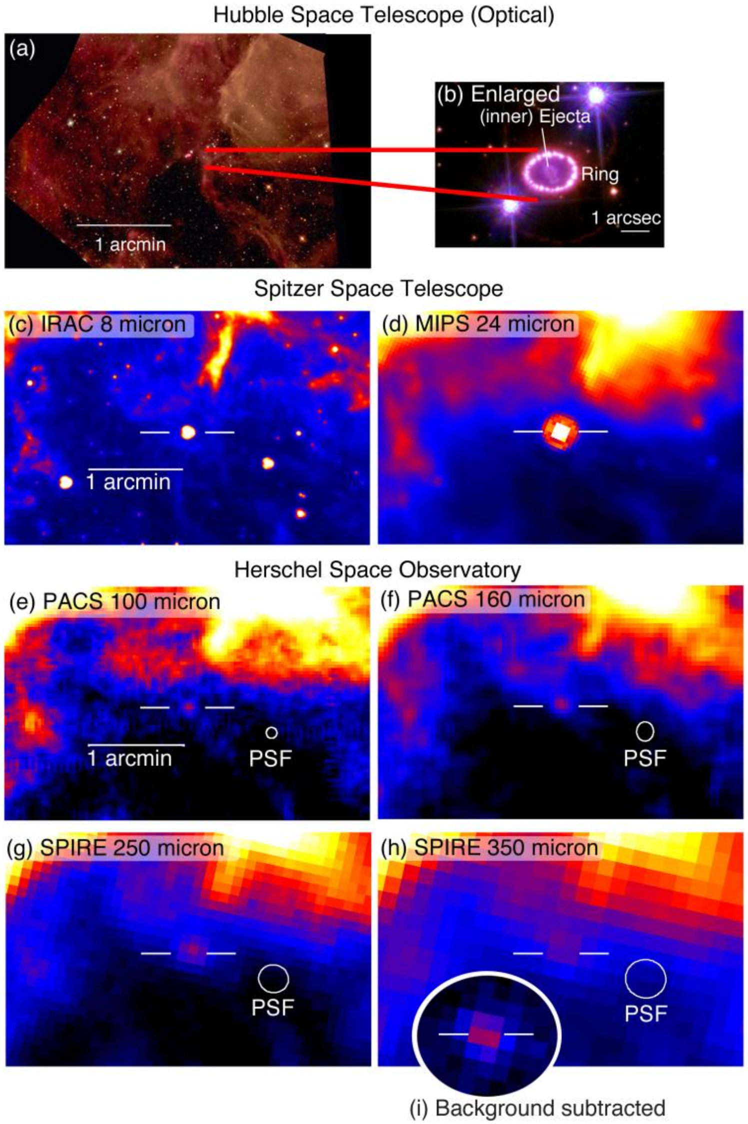
heating sources of dust

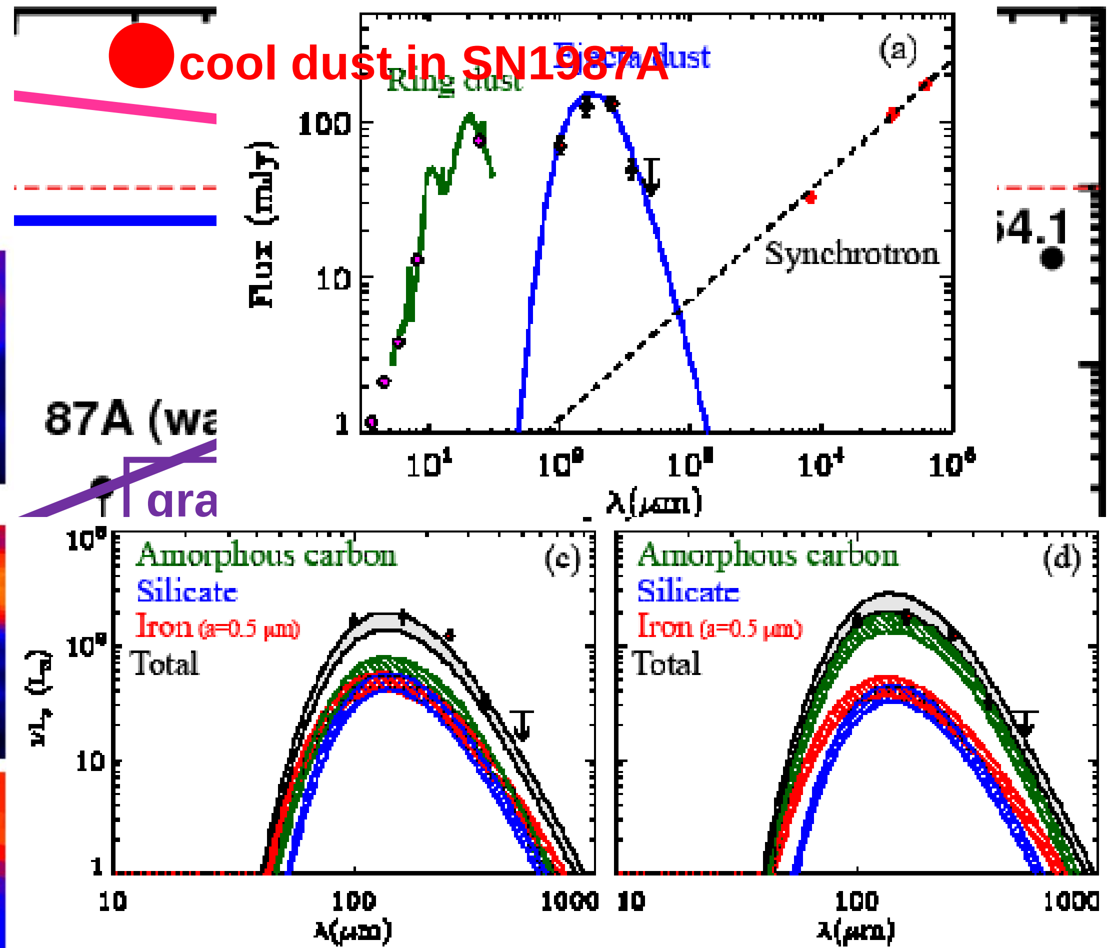
- **44Ti ➔ ~10^{36} erg/s**
- **X-ray emission**
  ➔ < ~10^{37} erg/s

· Possible targets
SN 1978K, 93J, 04dj, 04et

3-6. Herschel detects massive dust in SN 1987A

Matsuura, ..., TN, et al. 2011, Science

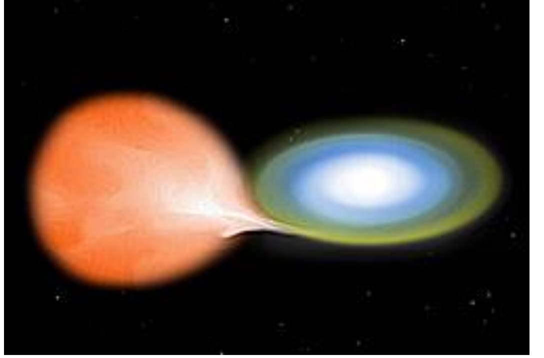




Herschel detects cool (~20K) dust of 0.4-0.7 Msun toward SN 1987A!

4. Formation of dust in SNe Ia

4-1. Introduction



○ Type Ia supernovae (SNe Ia)

— thermonuclear explosions of C+O white dwarfs with the mass close to Chandrasekhar limit (~1.4 M_{sun})

- **deflagration** (Nomoto+76, 84)
  - ➔ subsonic wave, unburned C in the outer layer
- **(delayed) detonation** (Khokhlov91a, 91b)
  - ➔ supersonic wave, burning almost all C

— synthesize a significant amount of Fe-peak and intermediate-mass elements such as Si, Mg, and Ca

➔ play a critical role in the chemical evolution

➔ possible sources of interstellar dust?

4-2. Type Ia SNe are sources of dust?

○ Suggestions on dust formation in SNe Ia

- SNe Ia may be producers of Fe grains
  (Tielens98; Dwek98)

- the isotopic signature of presolar type X SiC grains can be explained if produced in SNe Ia (Clayton+'97)

○ Observations of normal SNe Ia

- no increase of IR dust continuum (and no CO emission)

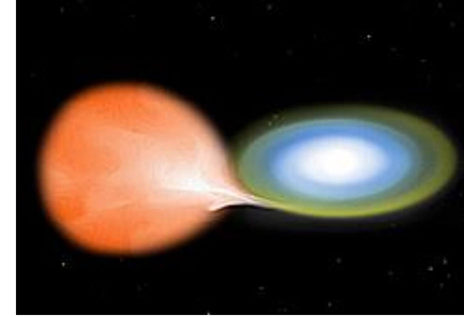
- no rapid decrease of the optical light curve

- no blueshift of atomic line emissions

  ➔ these signatures have been reported for CCSNe

- no evidence for ejecta-dust in Tycho SNR (Douvion+'01)

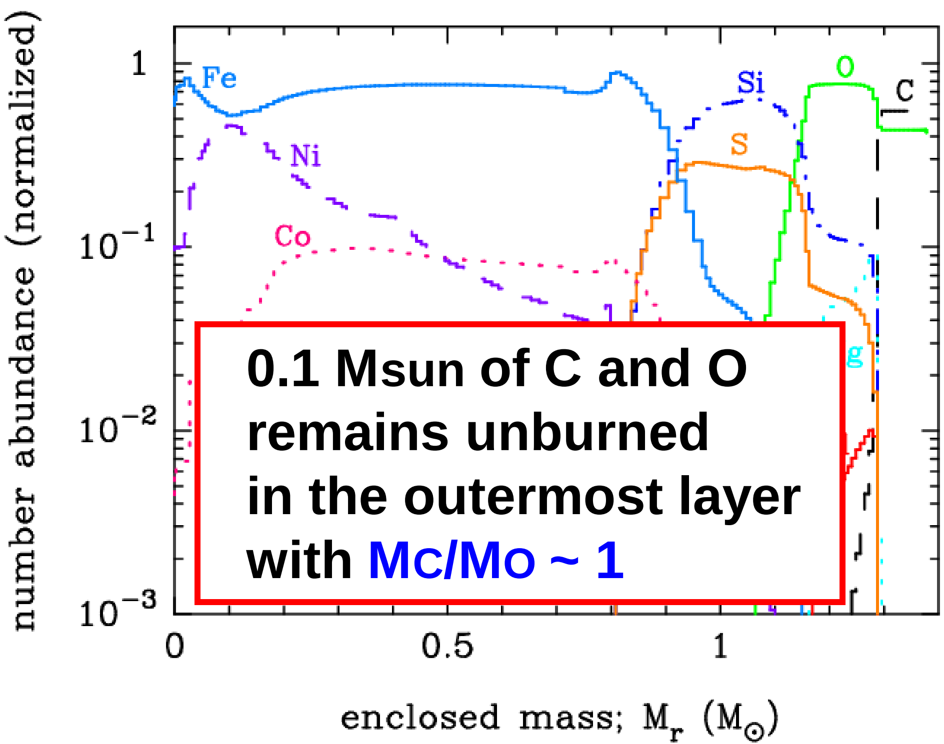
4-3. Dust formation in Type Ia SNe



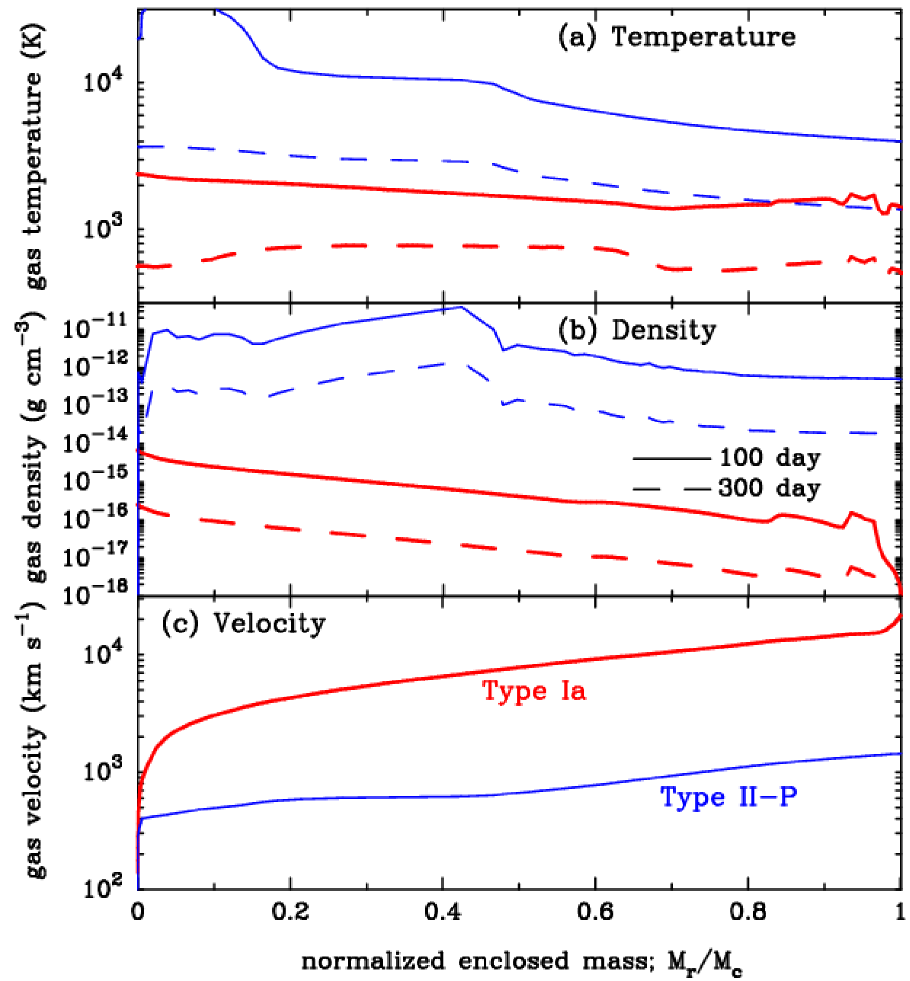
○ Type Ia SN model

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

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



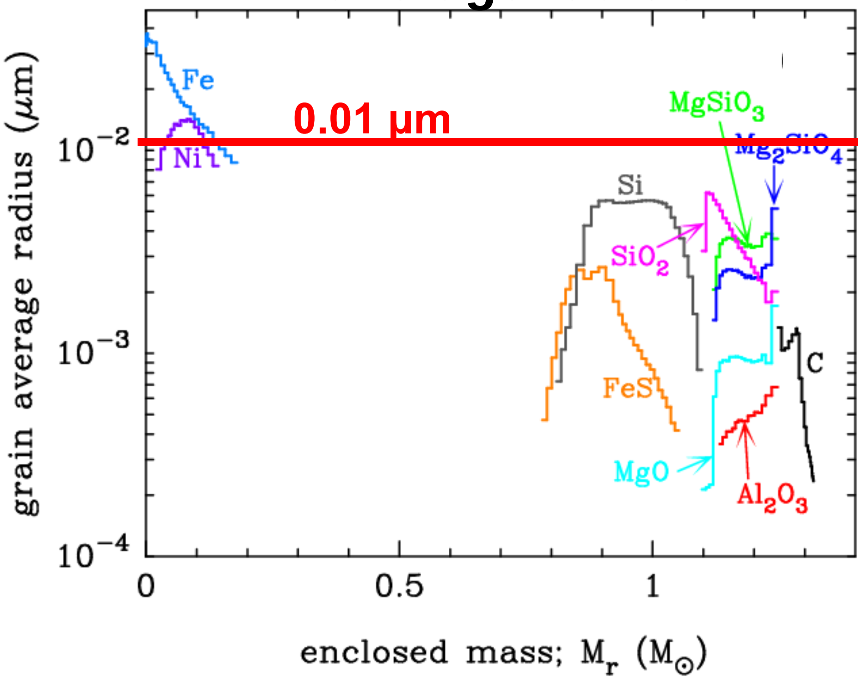
0.1 Msun of C and O remains unburned in the outermost layer with Mc/Mo ~ 1



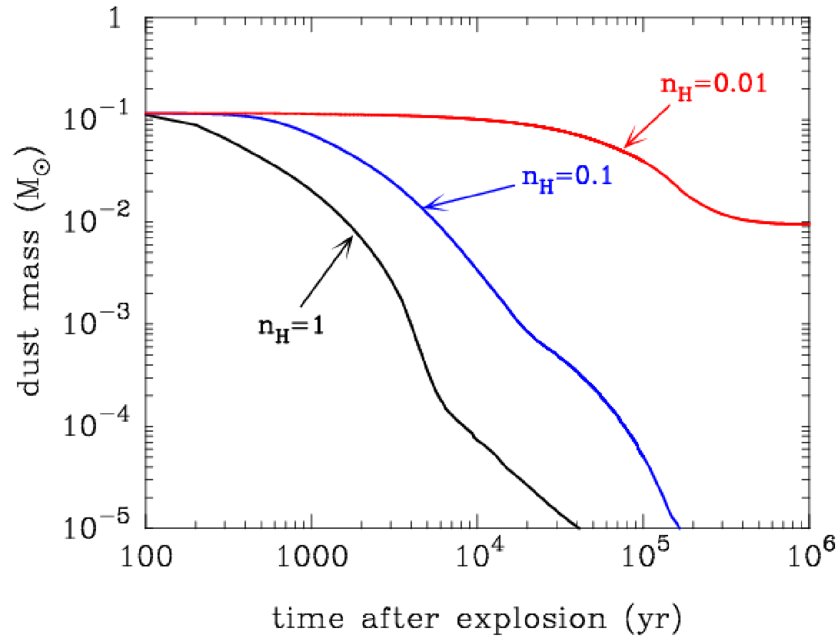
4-4. Dust formation and evolution in SNe Ia

Nozawa et al. 2011, 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

4-5. Optical depths by newly formed dust

V band (0.55 μm) opacity at 300 days for γ = 1

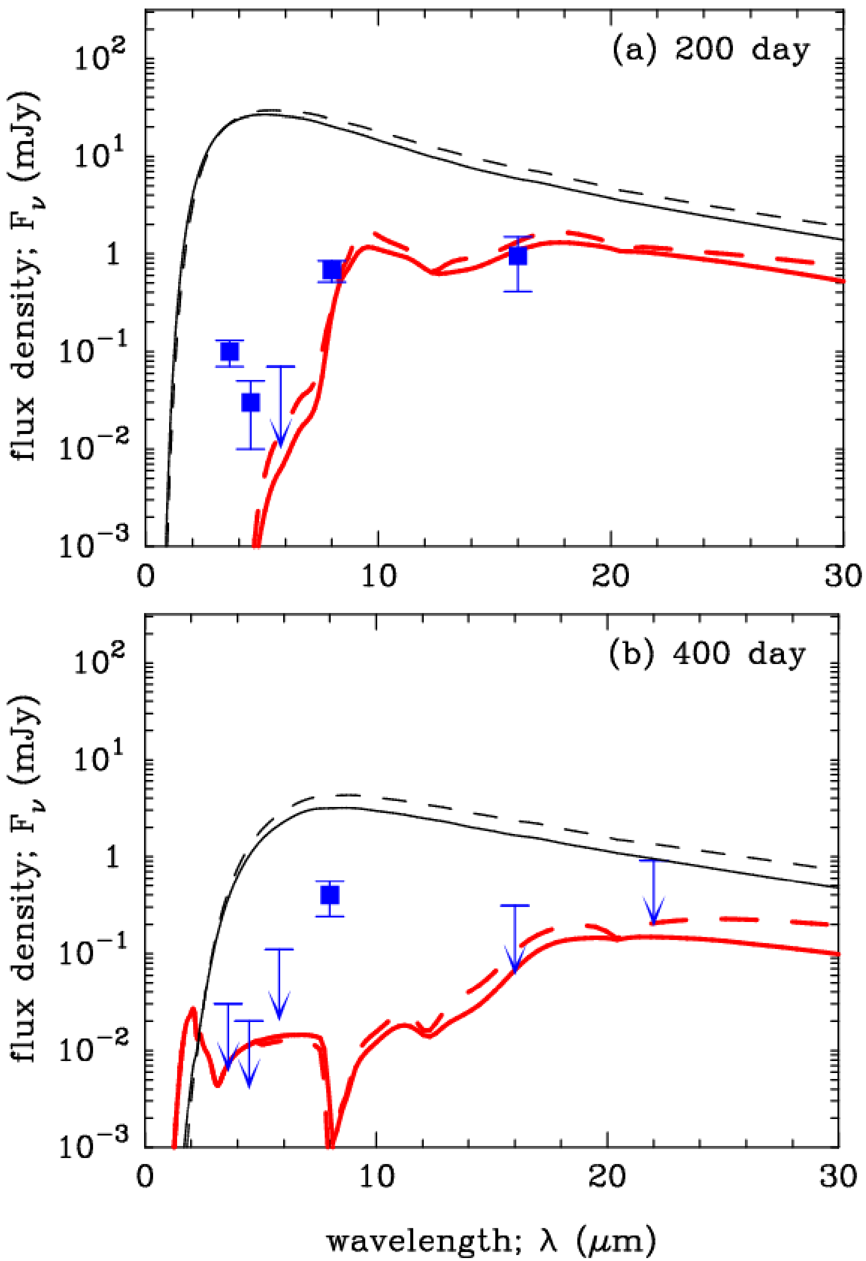
M_C = 0.006 M_{sun}	→	τ_C = 22
$M_{silicate}$ = 0.030 M_{sun}	→	$\tau_{silicate}$ = 0.01
~~M_{FeS} = 0.018 M_{sun}~~	→	~~τ_{FeS} = 14~~
~~M_{Si} = 0.063 M_{sun}~~		~~τ_{Si} = 78~~
M_{total} = 0.116 M_{sun}	→	τ_{total} = 114

V band (0.55 μm) opacity at 300 days for γ = 0.1

M_{total} ~ 3×10^{-4} M_{sun} → τ_{total} = 1

Formation of dust grains (C, Si, and Fe) should be suppressed to be consistent with the observations

4-6. Infrared thermal emission from dust



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

black solid lines :
SEDs including emission from C grains
➔ much higher than the observational results

red solid lines :
SEDs not including emission from C grains
➔ not contradict with the observational results
0.03 Msun of silicate can be allowed as dust mass

4-7. Carbon dust and outermost layer of SNe Ia

○ Formation of massive carbon dust

- high sticking probability of α = 0.1-1
  ➔ if α < ~0.01, any dust grain cannot condense

- dust formation around 100 days, M(56Ni) ~ 0.6 M_{sun}
  ➔ dust formation can be destroyed by energetic photons and electrons prevailing in the ejecta

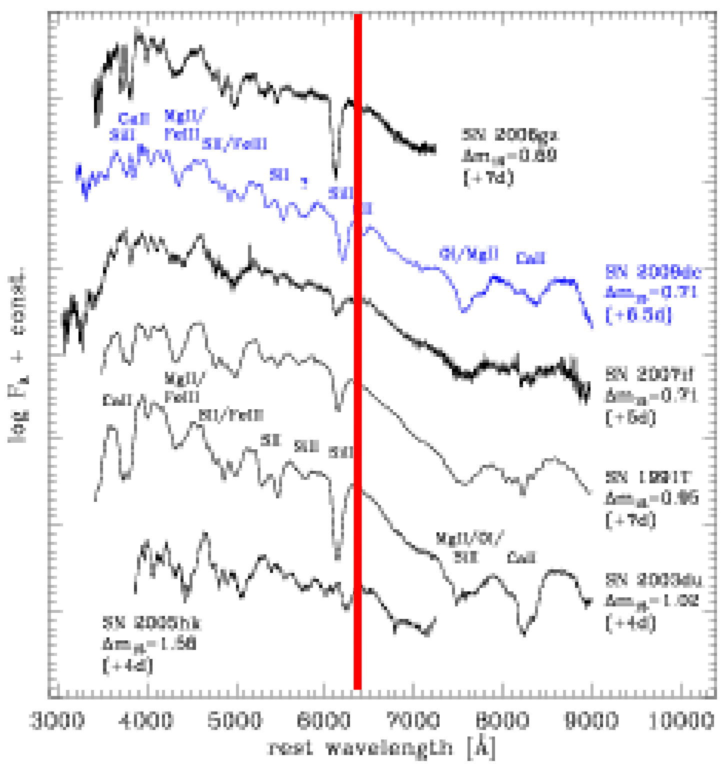
- massive unburned carbon (~0.05 M_{sun}) in deflagration
  ➔ change of WD composition by the He-shell flash
  ➔ burning of carbon by a delayed detonation wave

observationally estimated carbon mass in SNe Ia :
M_c < 0.01 M_{sun} (Marion+06; Tanaka+08)

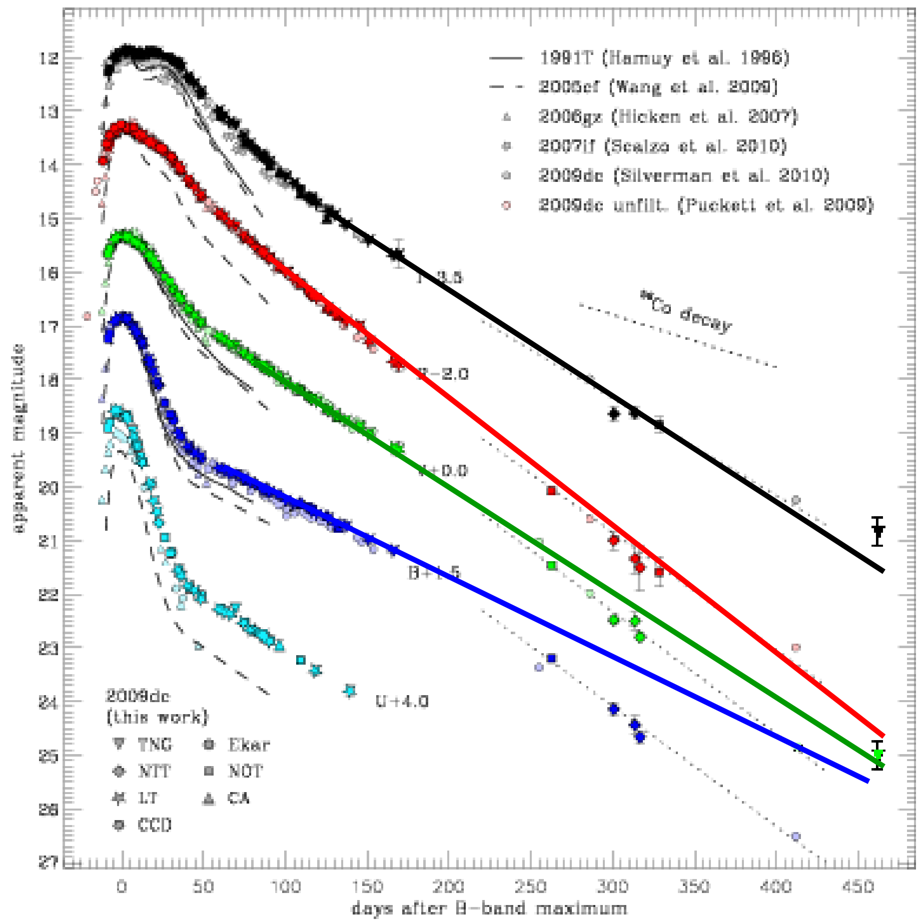
4-8. Dust formation in super-Chandra SNe?

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

detection of CII line
➔ presence of massive unburned carbon



SN 2009dc, Tarbenberger+'10



enhanced fading at ~200 day
➔ formation of carbon dust?

5. 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
  - 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

- Middle-aged SNe with the ages of 10-100 yr are good targets to measure the mass of dust formed in SNe
  - We detect emission from SN 1978K, which is likely from shocked circumstellar silicate dust with 1.3×10^{-3} M_{sun}
  - The non-detection of the other 6 objects seems to be natural because our present search is sensitive only to $L_{tot} > 10^{38}$ erg/s

- Mass of dust in young SNRs may be dominated by cool dust

    ➔ FIR and submm observations of SNRs are essential

    ➔ Herschel detects massive cool dust toward SN 1987A