Supernovae as sources of interstellar dust

Takaya Nozawa

(IPMU, University of Tokyo)

Thanks to:

T. Kozasa (Hokkaido Univ.), N. Tominaga (Konan Univ.)
K. Maeda, M. Tanaka, K. Nomoto (IPMU, Univ. of Tokyo)
H. Umeda, I. Sakon (University of Tokyo)

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

2011/06/21

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. 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}=1[illegible]0 M_{sun} in pair-instability SNe (PISNe)

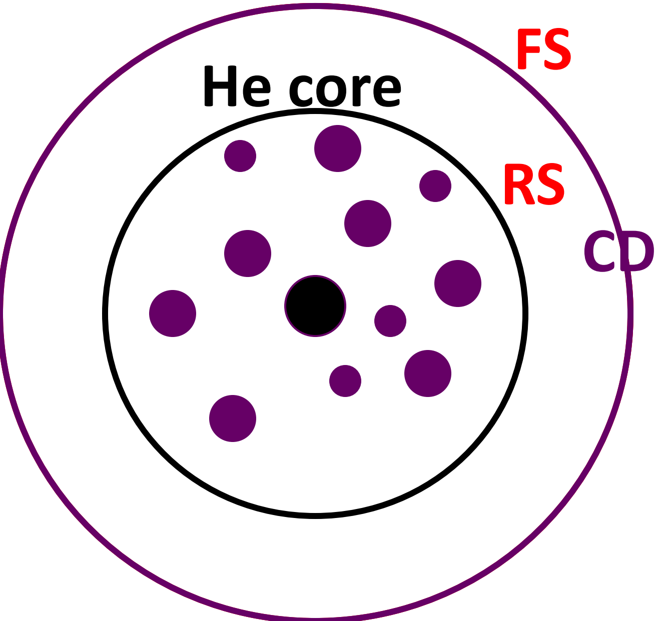
its presence has not been proved observationally

1-2. Dust destruction in supernova remnants

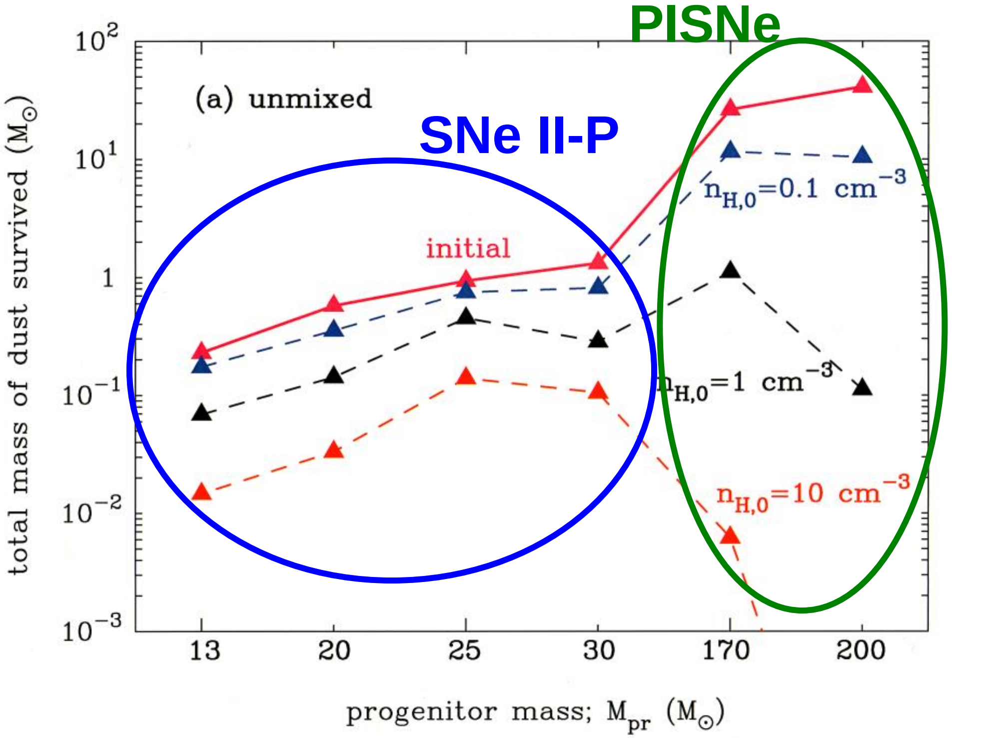
- a part of dust grains formed in SNe are destroyed due to sputtering in the hot gas swept up by the shocks (e.g., Bianchi & Schneider'07; Nozawa+'07, 10)

➔ destruction efficiency of dust depends on the initial size distribution

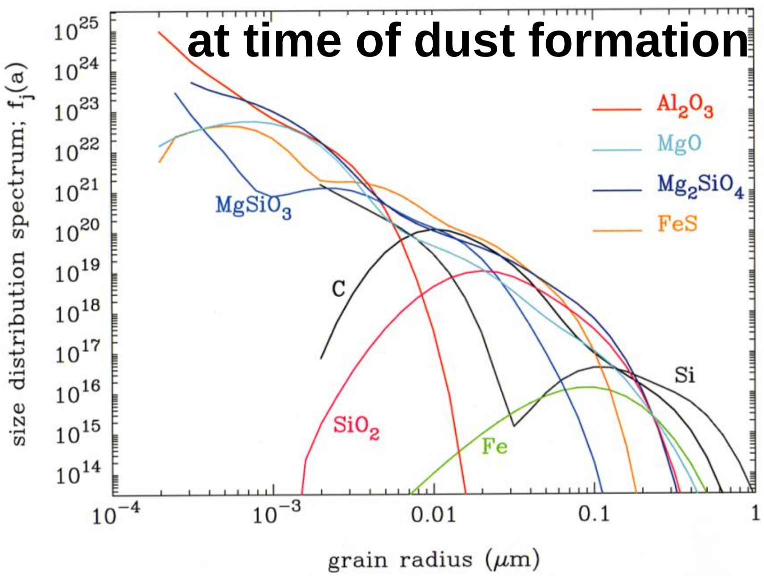
- <u>It is necessary to treat formation and destruction of dust self-consistently</u>



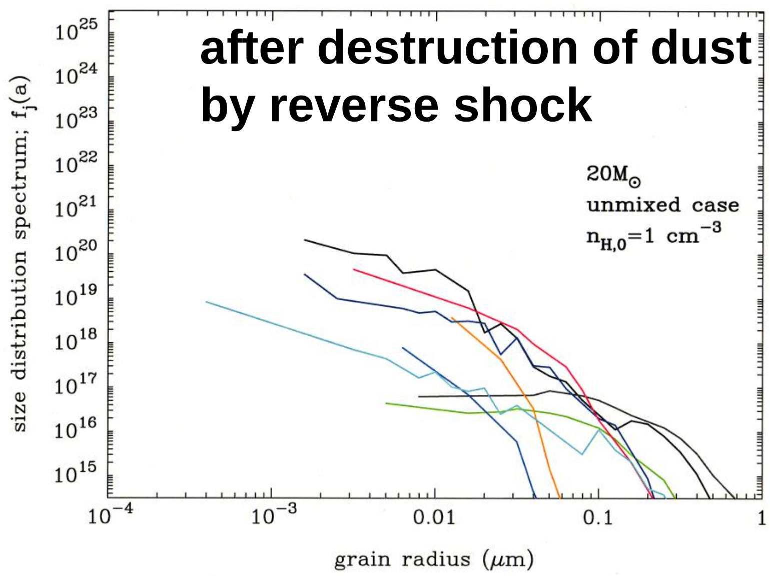
1-3. Mass and size of dust ejected from SN II-P



Nozawa+'07, ApJ, 666, 955



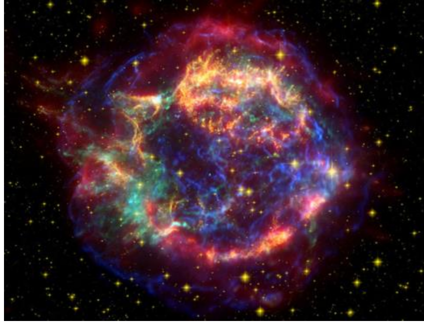
total dust mass surviving the destruction in Type II-P SNRs; 0.07-0.8 M_{sun} ($n_{H,0}$ = 0.1-1 cm^{-3})



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

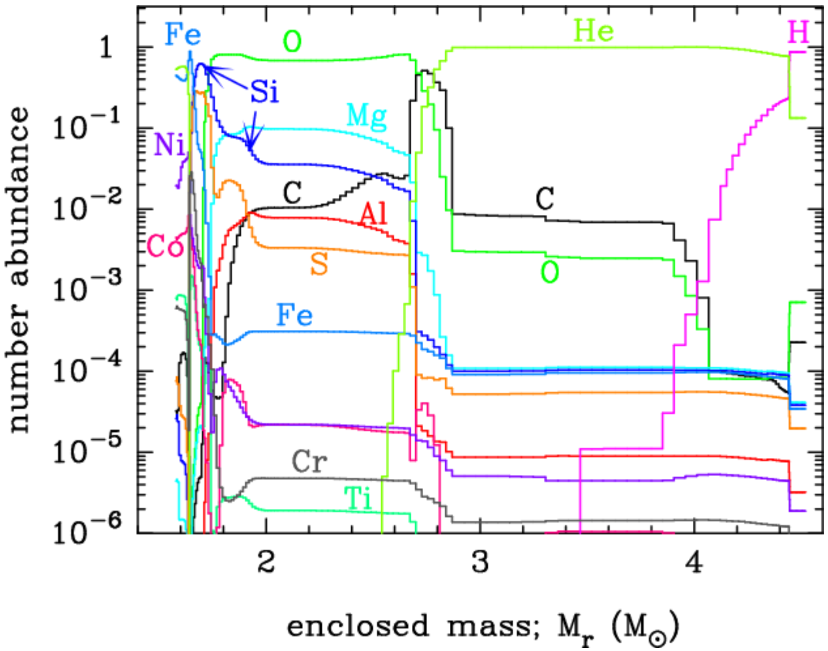
2. Formation and evolution of dust in SNe IIb: Application to Cas A

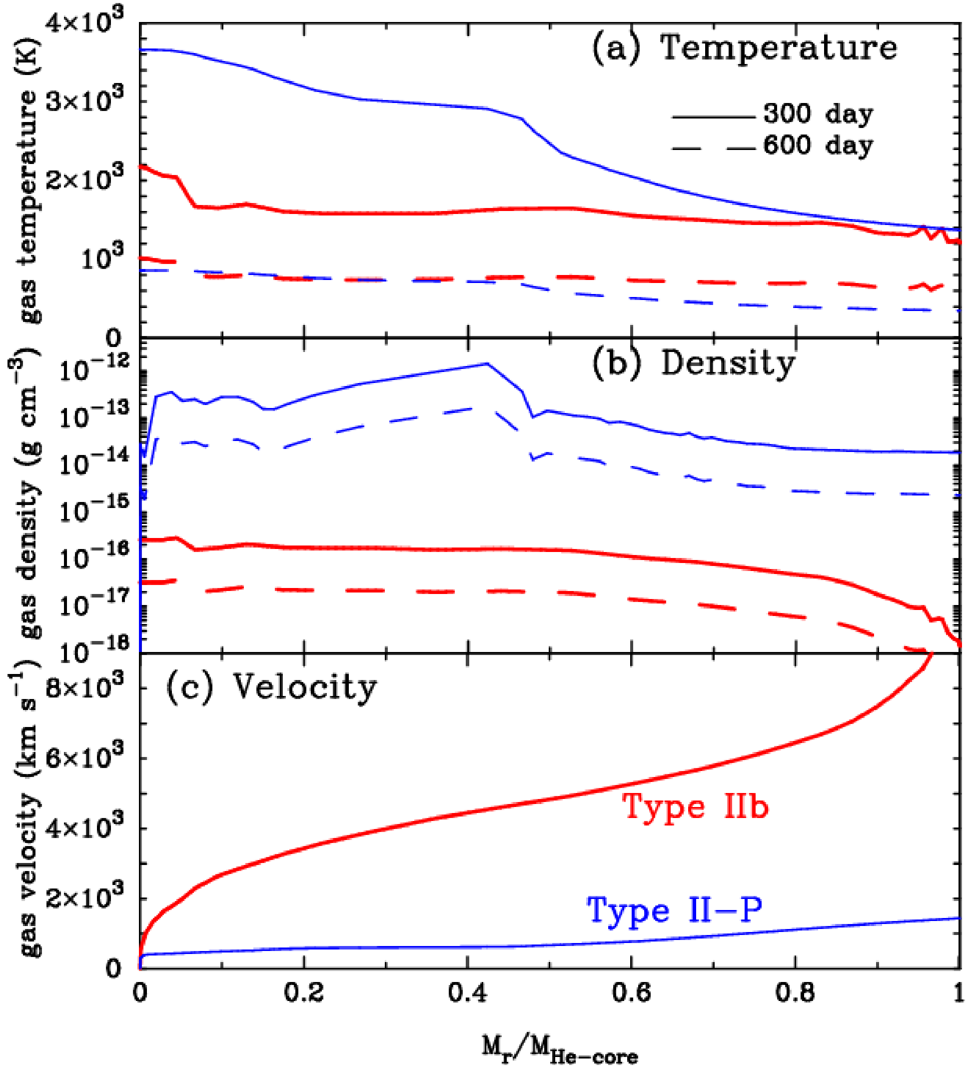
2-1. Dust formation in Type IIb SN



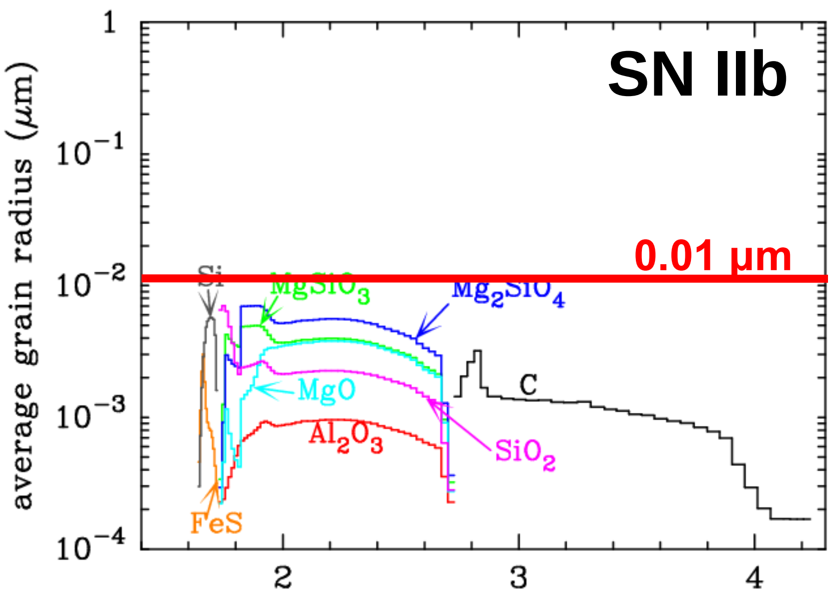
○ SN IIb model (SN1993J-like model)

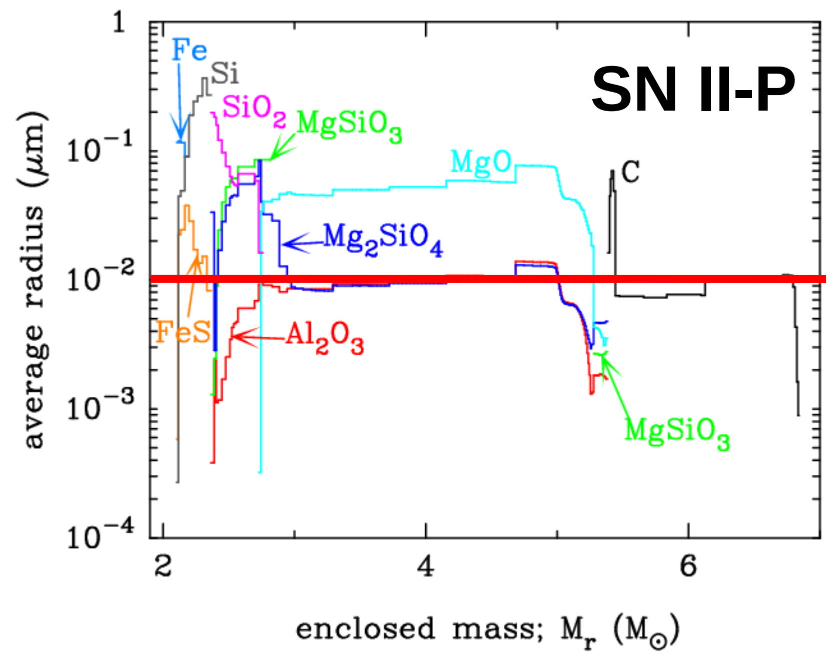
- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1.0
- $M(^{56}Ni)$ = 0.07 Msun

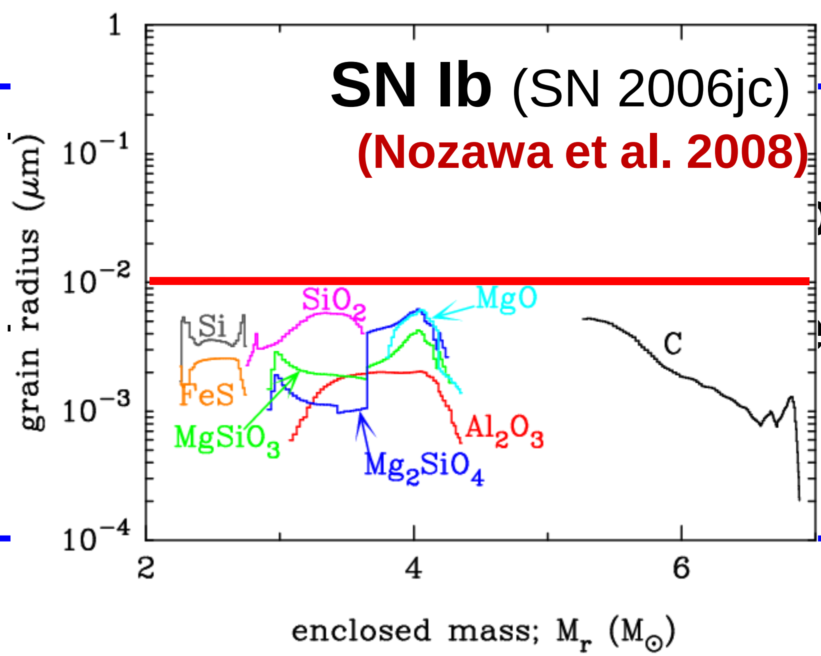




2-2. Dependence of dust radii on SN type



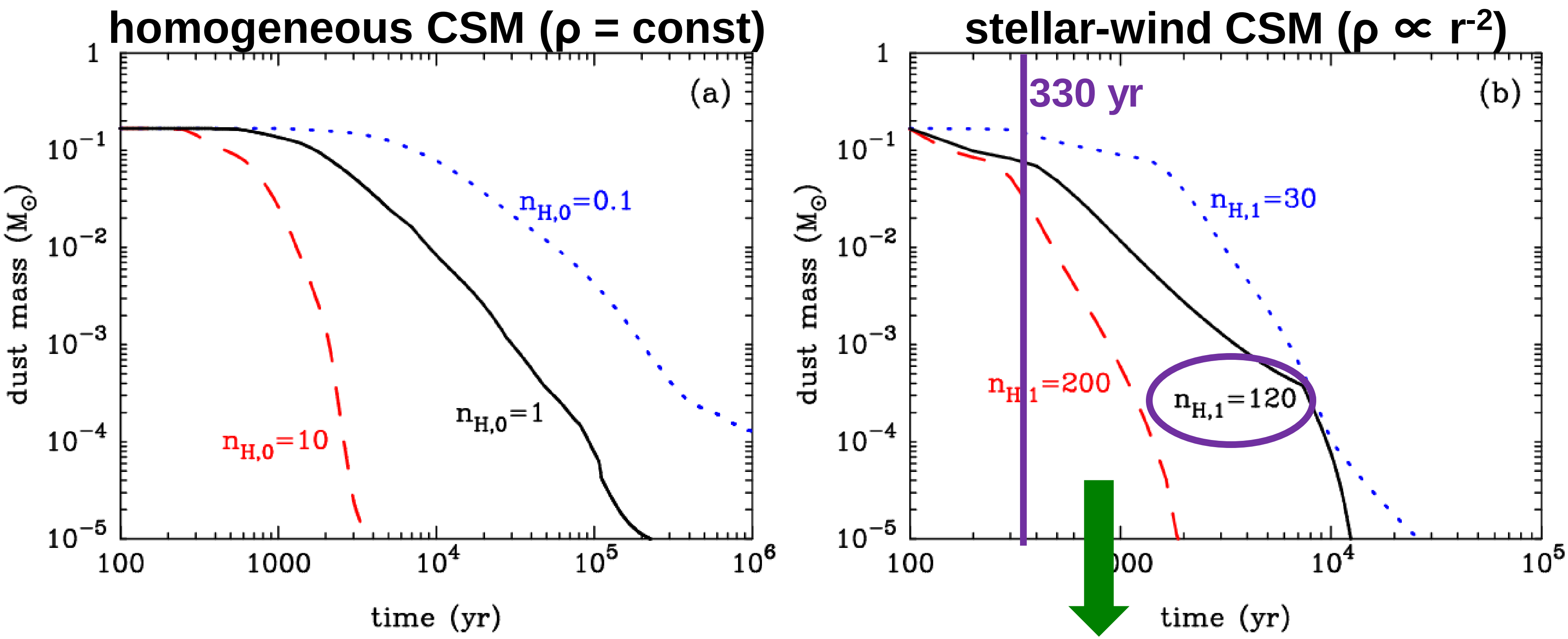




— the radius of dust formed in H-stripped SNe is small

- **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

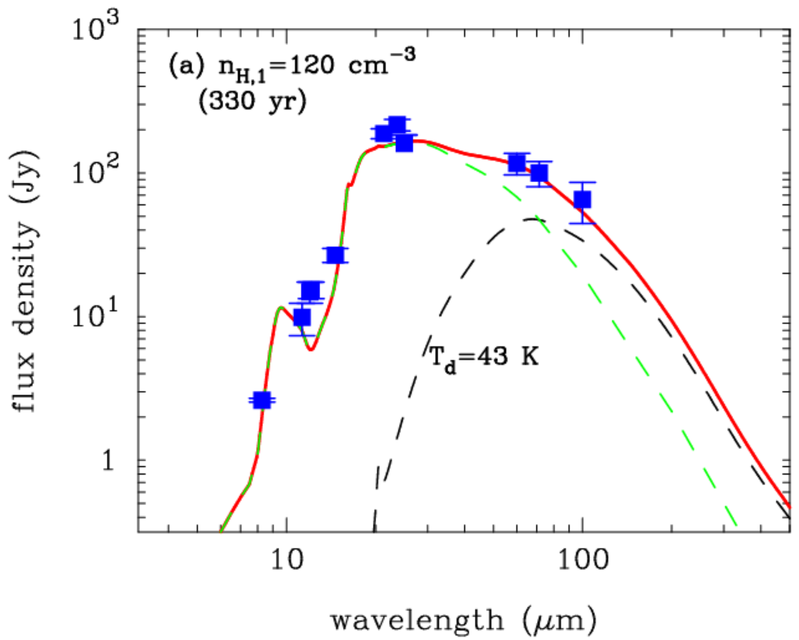
Almost all newly formed grains are destroyed in shocked gas within the SNR for CSM gas density of n_H > 0.1 /cc

→ small radius of newly formed dust

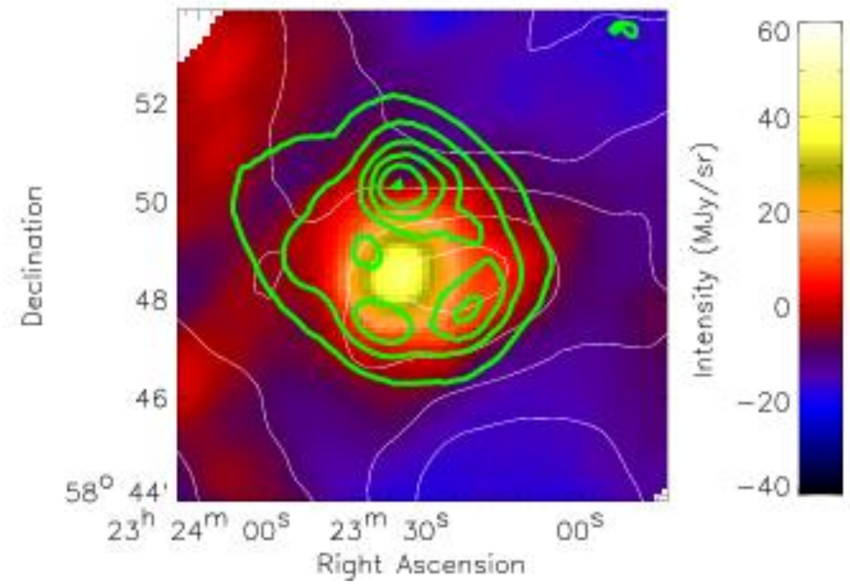
→ early arrival of reverse shock at dust-forming region

Nozawa+'10, 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+'10, 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

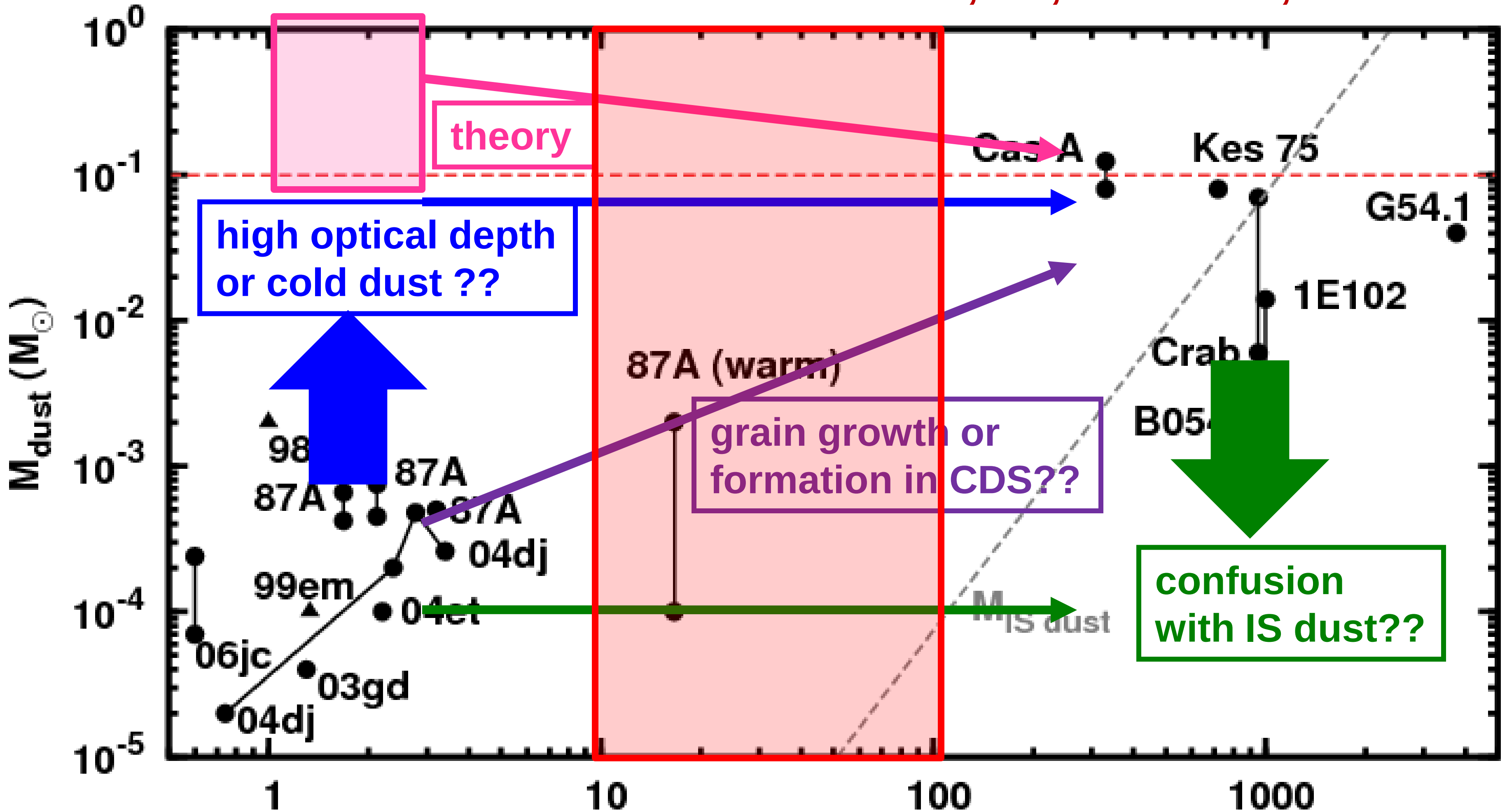
– NIR/MIR observations of SNe : $M_{dust} < 10^{-3}$ M_{sun}
(e.g., Ercolano+'07; Sakon+'09; Kotak+'09)

– 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)

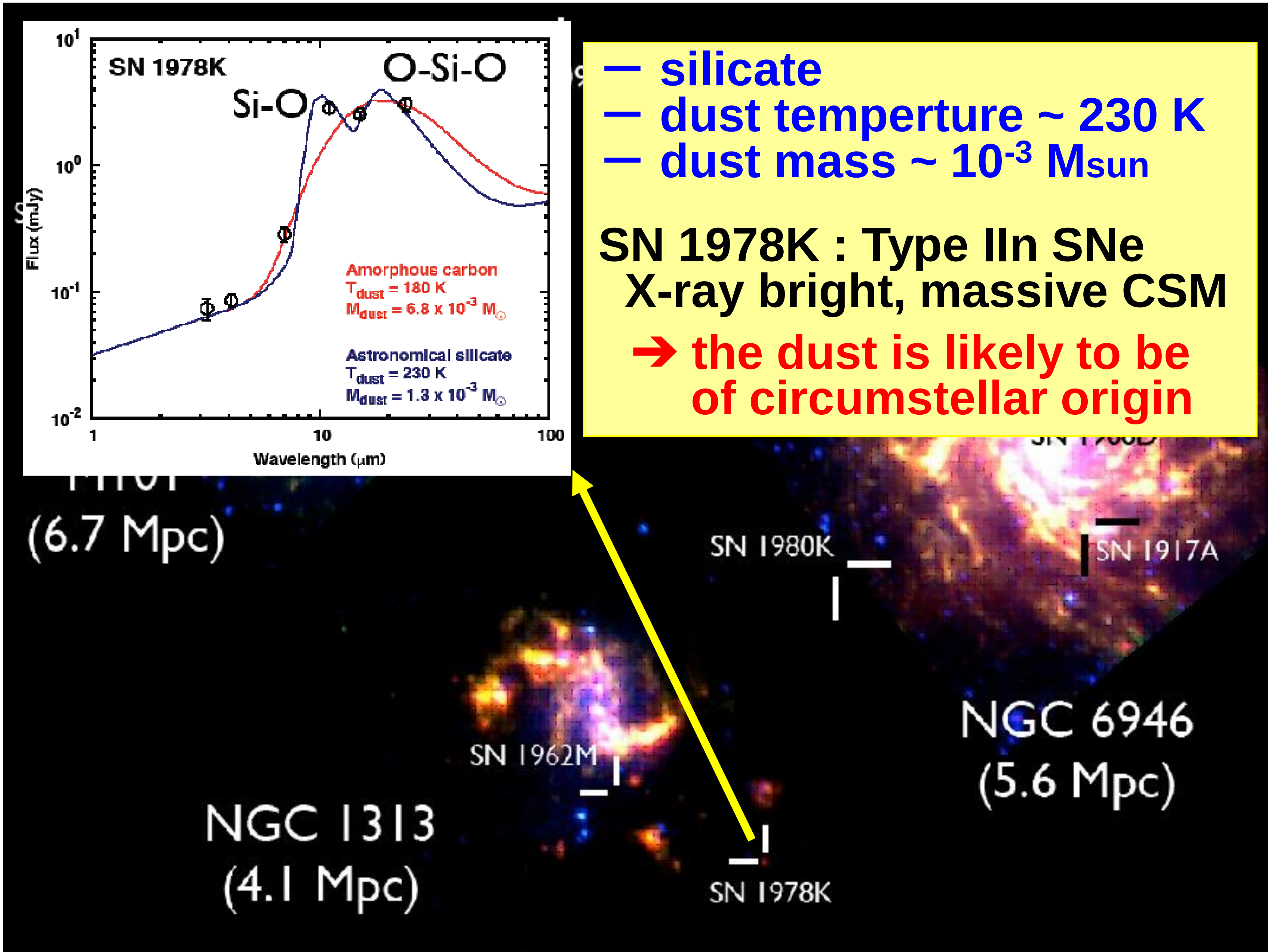
3-2. Missing-dust problem in CCSNe

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



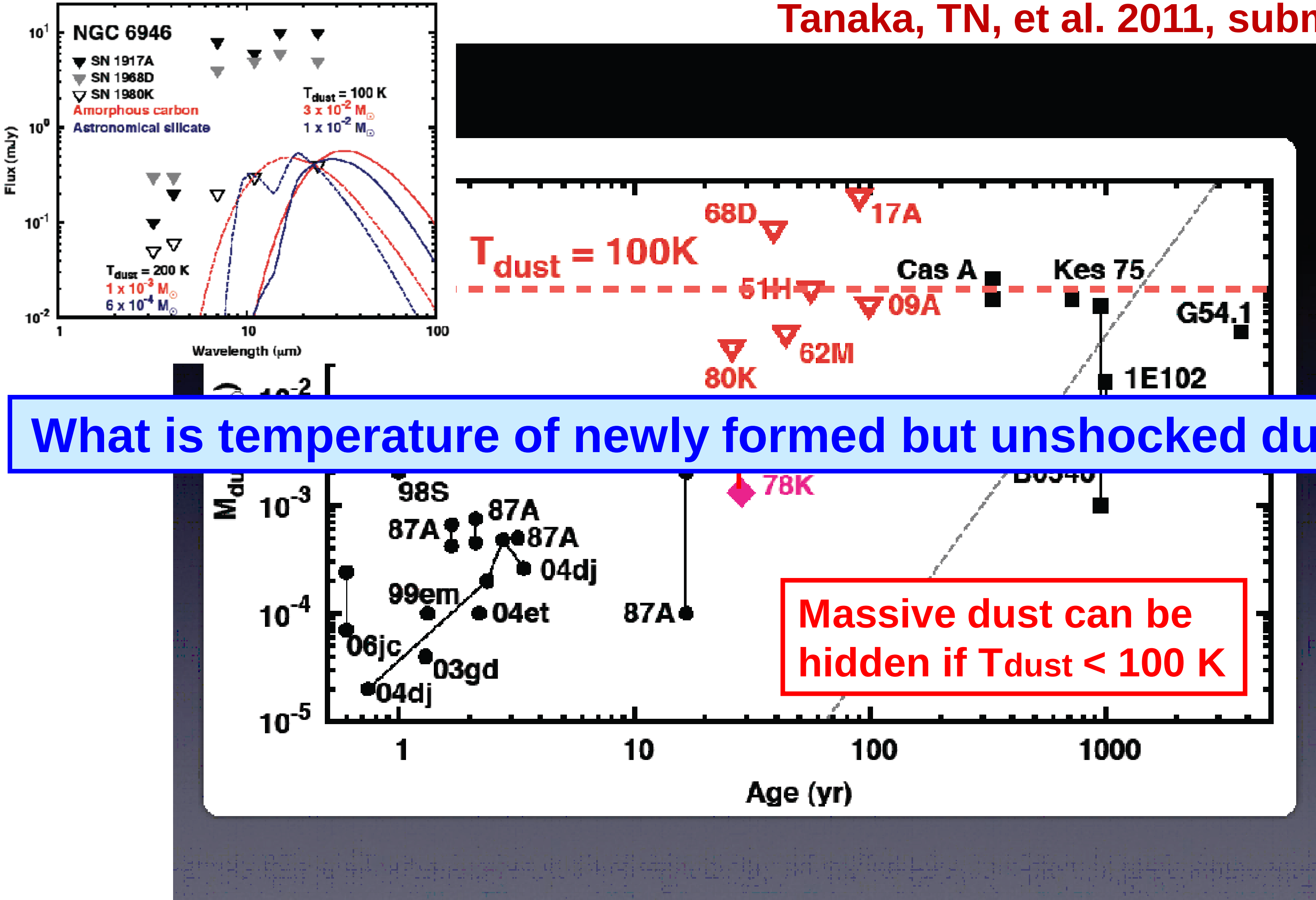
- silicate
- dust temperture ~ 230 K
- dust mass ~ 10^{-3} Msun

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

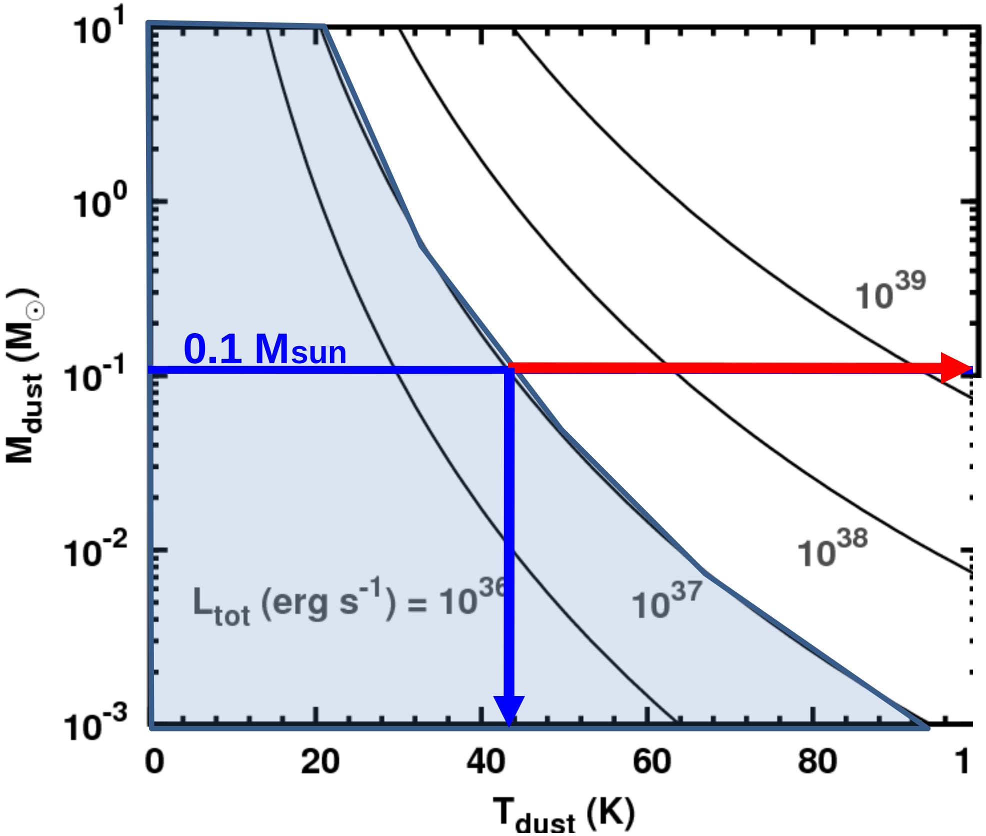
Tanaka, TN, et al. 2011, submitted



What is temperature of newly formed but unshocked dust?

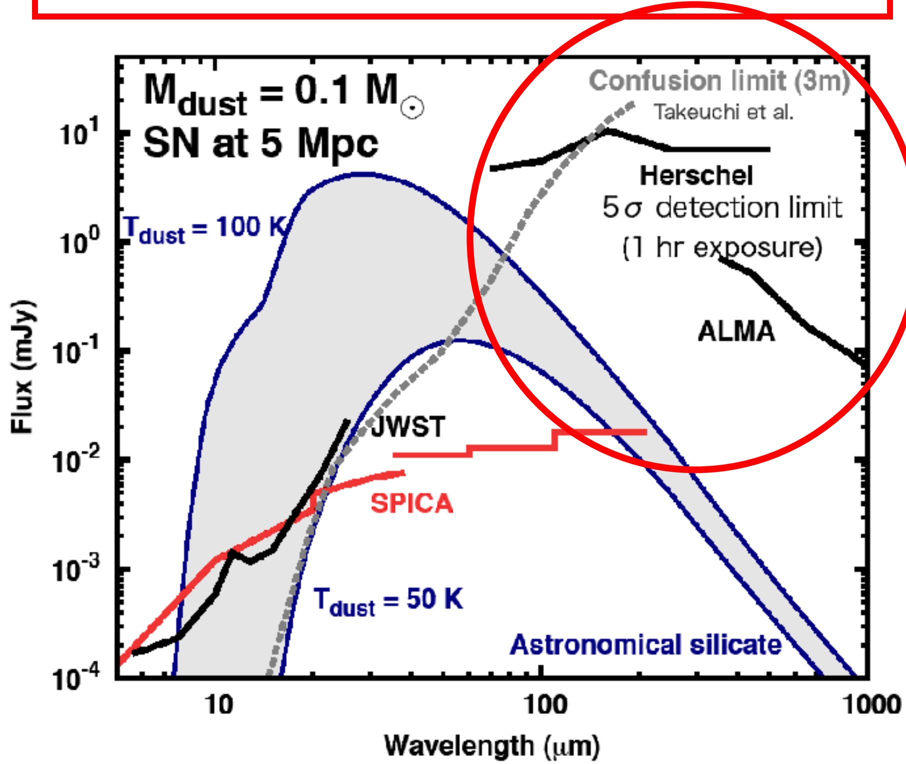
Massive dust can be hidden if T_{dust} < 100 K

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
  → a few x10^{36} erg/s

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

3-6. Non-dimming of optical light curves

Formation of massive dust 2-3 years after explosions should leds to the fading optical light curves of SNe

・Reducing (effective) optical depth in optical bands

➔ **condensation of dust in dense clumps**

➔ **much lower opacity for large grain (a_{dust} > 1.0 μm)**

・Delayed condensation of dust

➔ **slower cooling of the gas in the ejecta**

➔ **grain growth of pre-existing circumstellar dust**

➔ **formation in cool dense shell**

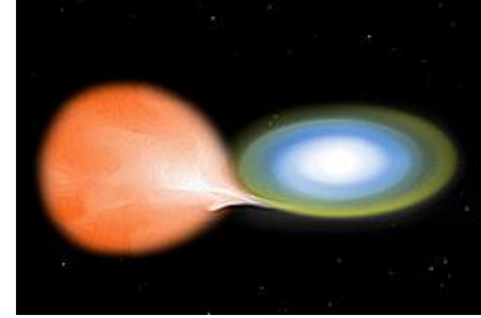
・No formation of massive dust

➔ **Theoretical studies overestimate dust mass**

sticking probability = 1.0

4. Formation of dust in SNe Ia

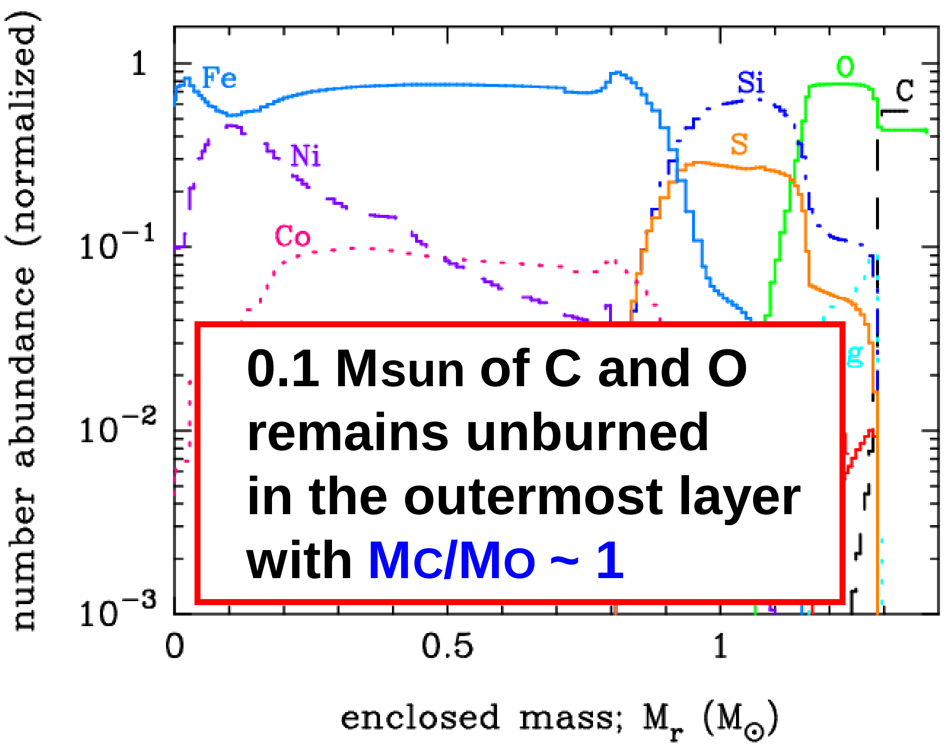
4-1. Dust formation in Type Ia SNe



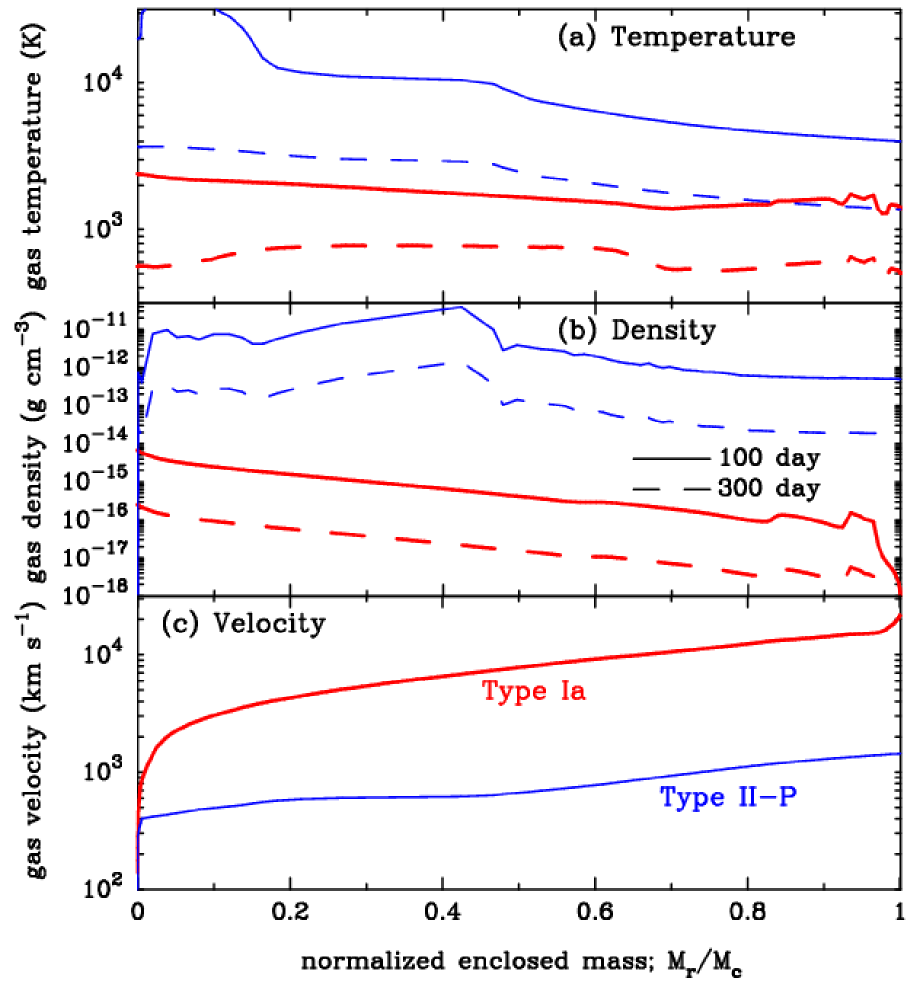
○ Type Ia SN model

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

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



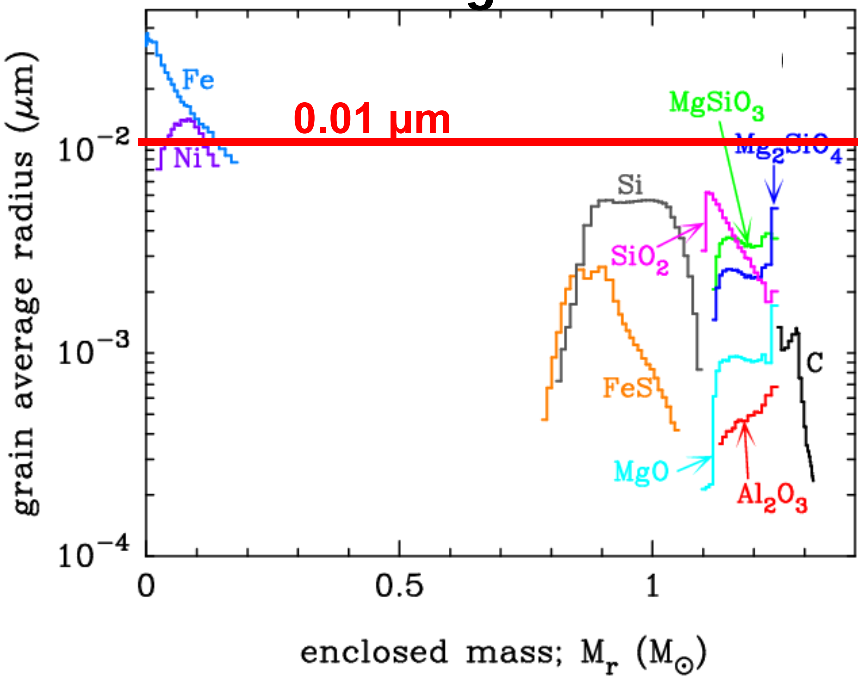
0.1 Msun of C and O remains unburned in the outermost layer with Mc/Mo ~ 1



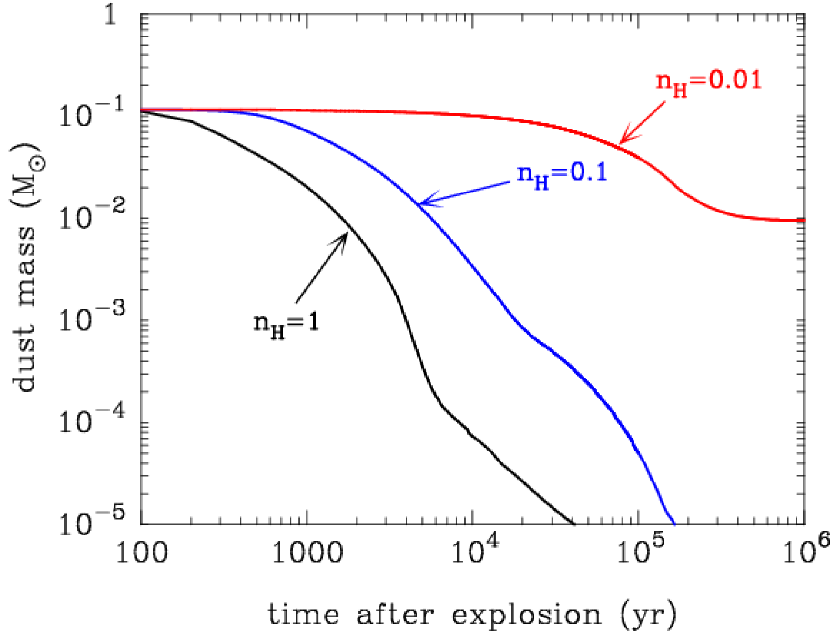
4-2. Dust formation and evolution in SNe Ia

TN, Maeda, et al. 2011 in press

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} **= 0.1-0.2** 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

4-3. Optical depths by newly formed dust

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

$M_{C} = 0.006\ M_{sun}$ → $\tau_{C} = 22$

$M_{silicate} = 0.030\ M_{sun}$ → $\tau_{silicate} = 0.01$

~~$M_{FeS} = 0.018\ M_{sun}$~~ → ~~$\tau_{FeS} = 14$~~

~~$M_{Si} = 0.063\ M_{sun}$~~ → ~~$\tau_{Si} = 78$~~

$M_{total} = 0.116\ M_{sun}$ → $\tau_{total} = 114$

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

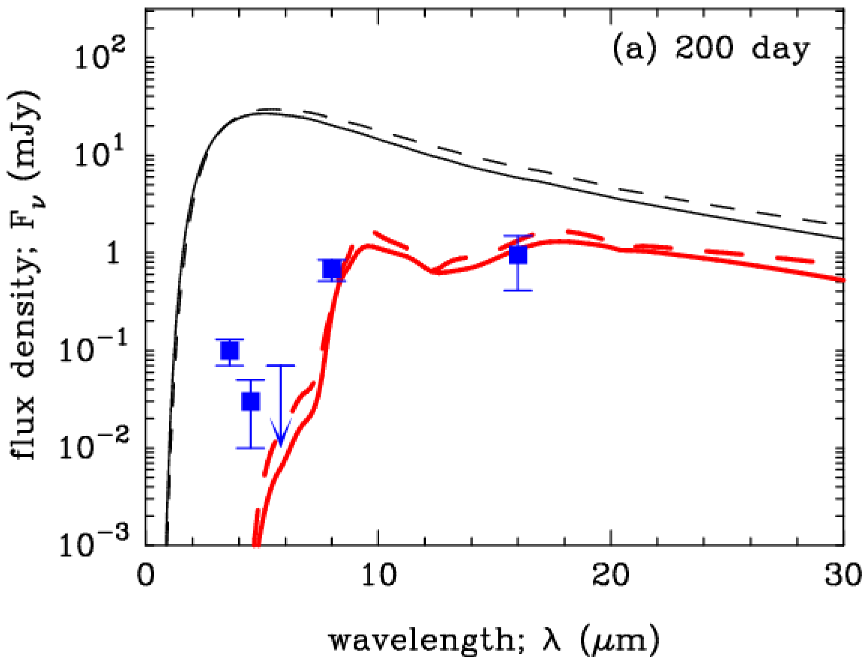
$M_{total} \sim 3\times10^{-4}\ M_{sun}$ → $\tau_{total} = 1$

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

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

- 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)



TN, Maeda, et al. 2011 in press

— **massive unburned carbon (~0.05 M_{sun}) in deflagration**

➔ **change of composition of WD by He-shell flash**

➔ **burning of carbon by a delayed detonation**

observationally estimated carbon mass in SNe Ia :

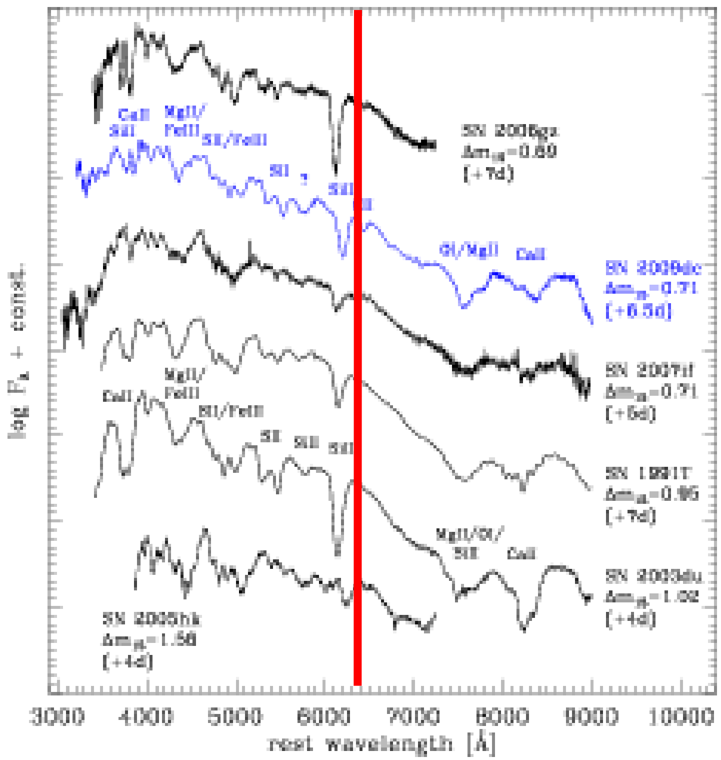
Mc < 0.01 M_{sun}

(Marion+'06; Tanaka+'08)

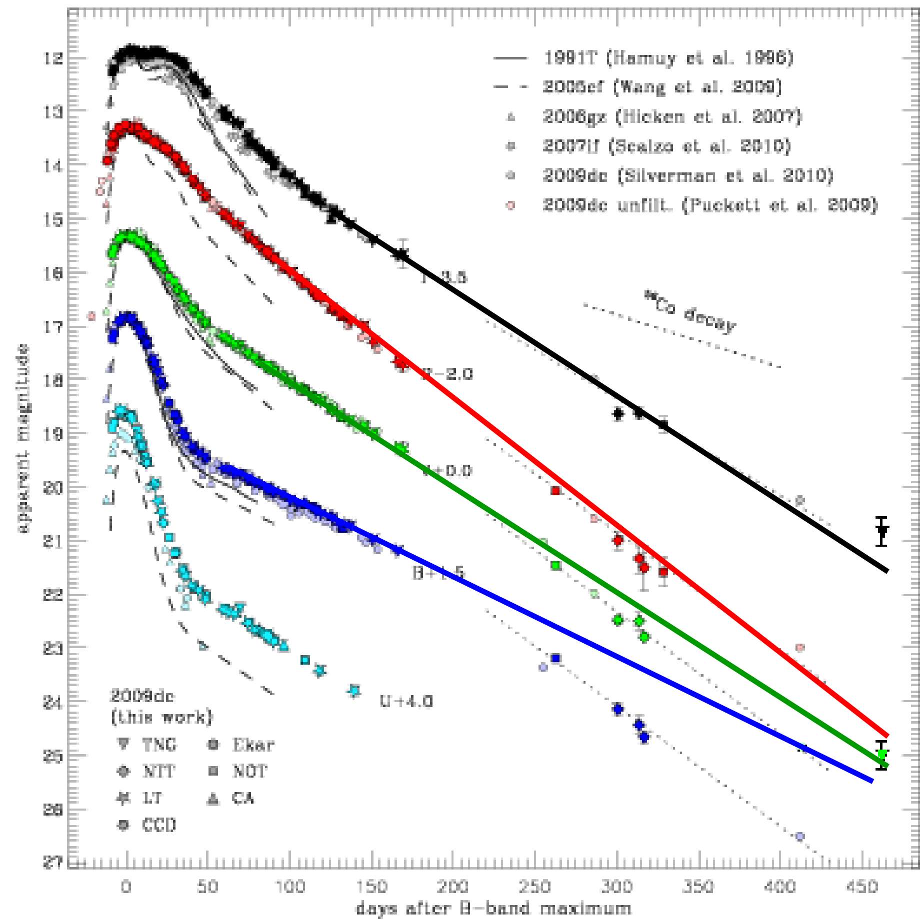
4-5. Dust formation in super-Chandra SNe?

– 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**