Are Type Ia supernovae important sources of interstellar dust?

（Ia型超新星は星間ダストの重要な供給源か？）

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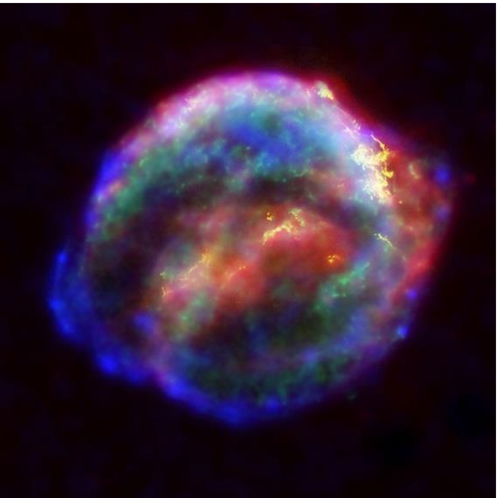

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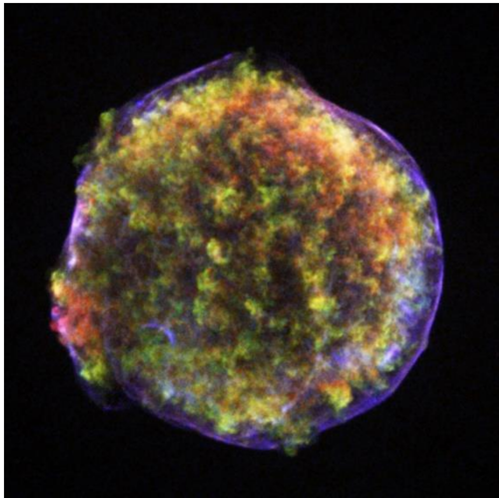
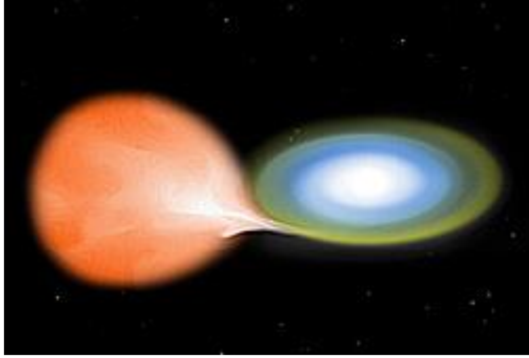


1-1. Introduction



○ 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** **(Khokhlov 91a, 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?**

1-2. Type Ia SNe are sources of dust?

○ Suggestions on dust formation in SNe Ia

- SNe Ia may be producers of Fe grains

(Tielens 98; Dwek 98)

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

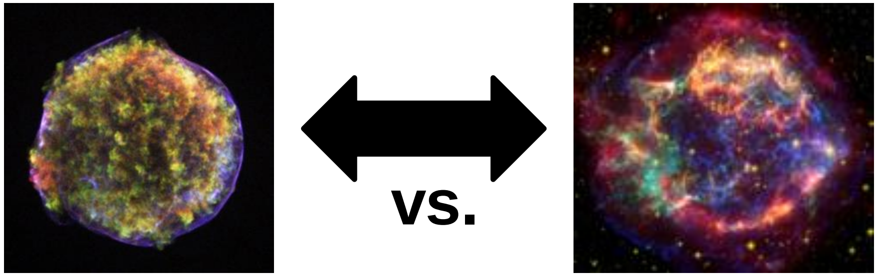
○ IR Observations of SNe Ia and Type Ia SNRs

- no evidence for dust formation in normal SNe Ia
- no evidence for ejecta-dust in young Type Ia SNRs

Tycho SNR (Douvion+01, but see Ishihara+10)
Kepler SNR (Douvion+01, Blair+07)
young Type Ia SNRs in LMC (Borkowski+06, Seok+08)

➔ shock-heated interstellar dust of $< 10^{-2}$ $M_{\rm sun}$

1-3. Aim of our study



○ Questions

- Are there any differences in formation process of dust between SNe Ia and (Type II) CCSNe?
- Is it possible for dust grains to form in SNe Ia ?

○ Dust formation calculation in SNe Ia

➔ chemical composition, size, and mass of dust that can condense in the ejecta of SNe Ia

➔ dependence of dust formation process on SN types

➔ implication on the outermost layer in SNe Ia

➔ survival of newly formed dust against destruction by the reverse shock

2-1. Model of SNe Ia (1)

○ Type Ia SN model

C-deflagration W7 model

(Nomoto+84; Thielemann+86)

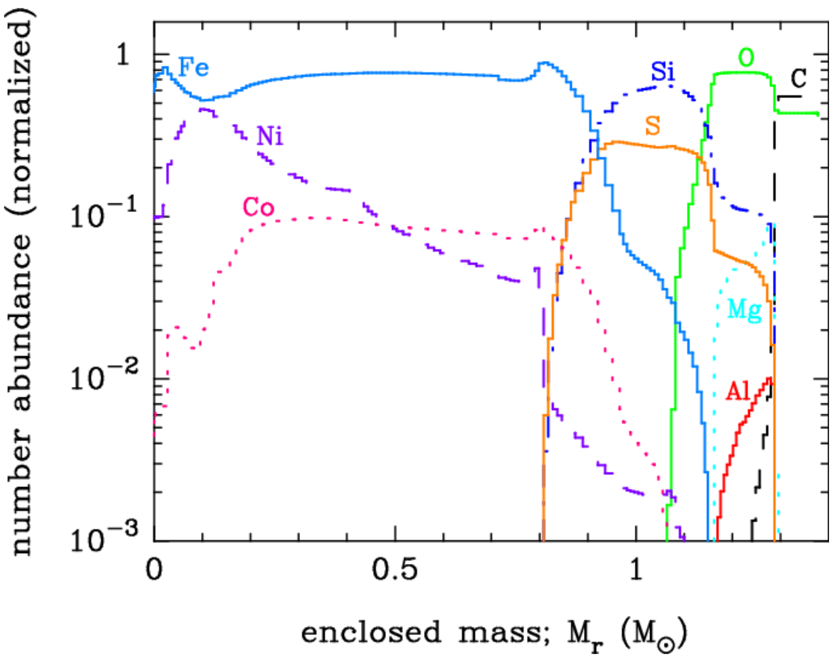
- **M_{eje} = 1.38 M_{sun}**
- **E_{kin} = 1.3x10^{51} erg**
- **M(^{56}Ni) = 0.6 M_{sun}**

M(^{56}Ni) ~ 0.06 M_{sun} in typical CCSNe

- **stratified distribution** (no mixing of elements)

This assumption is supported observationally (e.g. Mazzali+08; Tanaka+11)

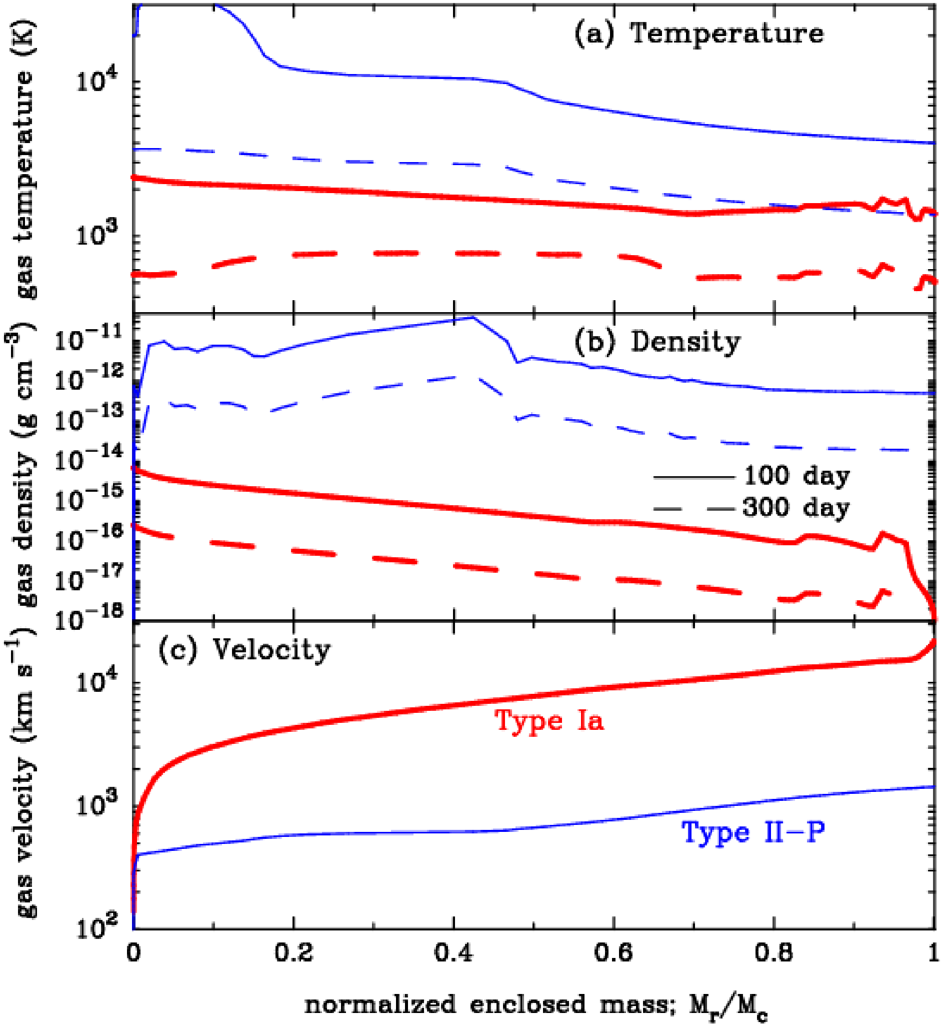
elemental composition



0.1 M_{sun} of C and O remained unburned in the outermost layer with M_C/M_O ~ 1

2-2. Model of SNe Ia (2)

hydrodynamic model



red lines : SNe Ia

- $M_{eje} = 1.38\ M_{sun}$
- $E_{kin} = 1.3 \times 10^{51}$ erg

blue lines : Type II-P SNe

- $M_{eje} = 20\ M_{sun}$
- $E_{kin} = 1.0 \times 10^{51}$ erg
- $M_{env} = 13.2\ M_{sun}$

- The gas density in SNe Ia is more than 3 orders of magnitude lower than that in SNe II-P
- The gas temperature in SNe Ia decreases more quickly

2-3. Calculation of dust formation

○ nucleation and grain growth theory

(Nozawa+03, 08, 10)

- steady-state nucleation rate

$$J_j^s(t) = \alpha_{sj}\Omega_j \left(\frac{2\sigma_j}{\pi m_{1j}}\right)^{1/2} \left(\frac{T}{T_d}\right)^{1/2} \Pi_j c_{1j}^2 \exp\left[-\frac{4}{27}\frac{\mu_j^3}{(\ln S_j)^2}\right],$$

- grain growth rate

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

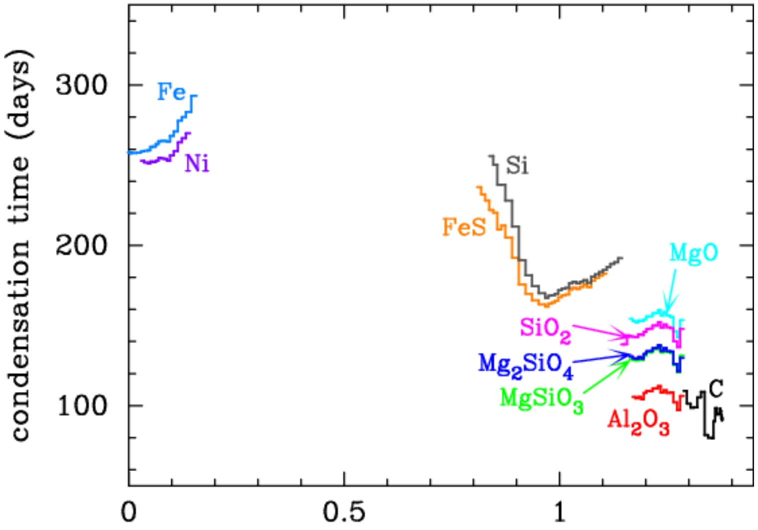
- **sticking probability : α_s = 1.0 and 0.1**
- **LTE condition : $T_d = T$**

  (newly formed dust has the same temperature as the gas)

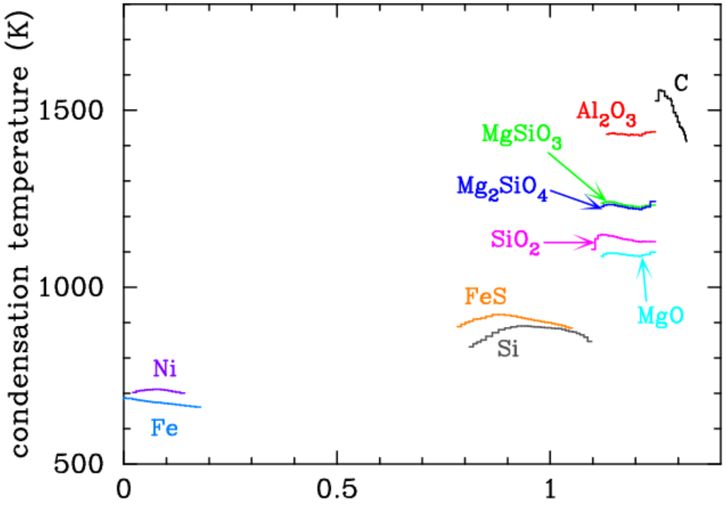
The use of the same prescription enables the direct comparison with our earlier results for SNe II

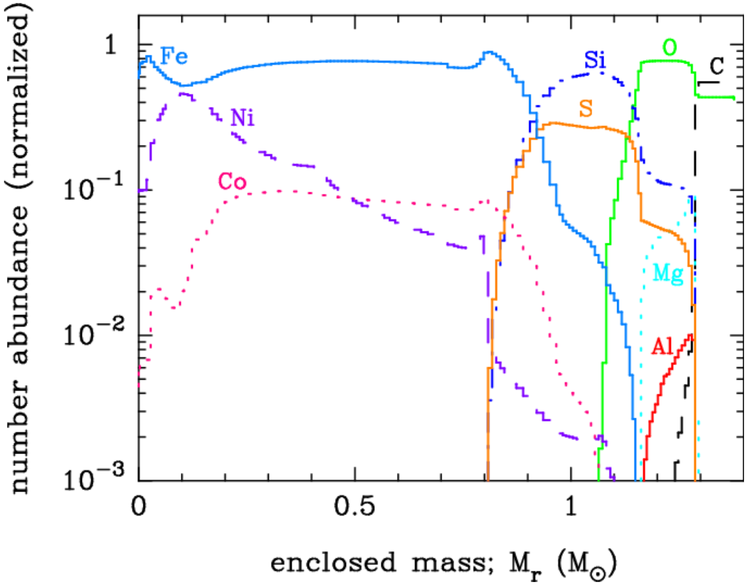
3-1. Results (1): Condensation time of dust

Condensation time



Condensation temperature



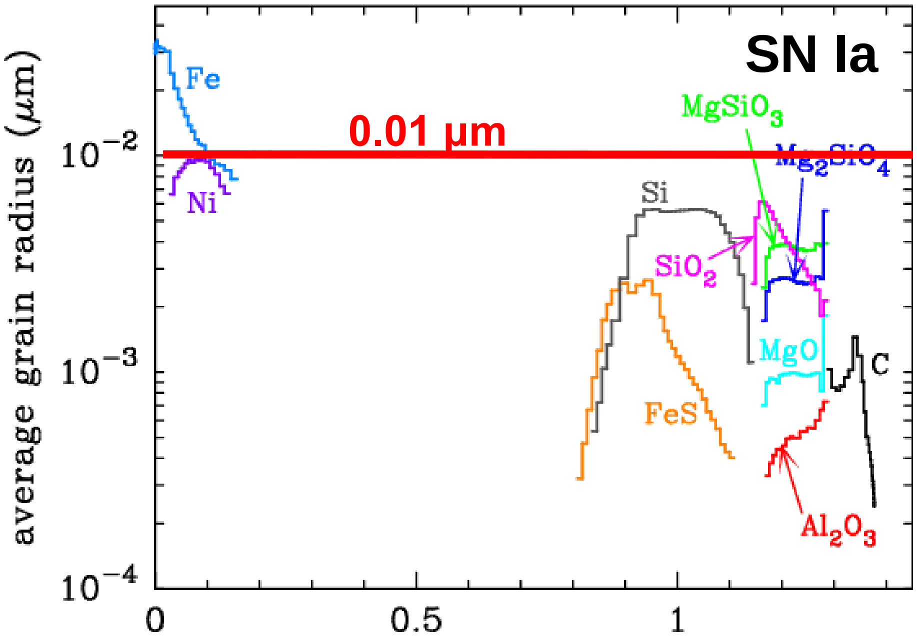


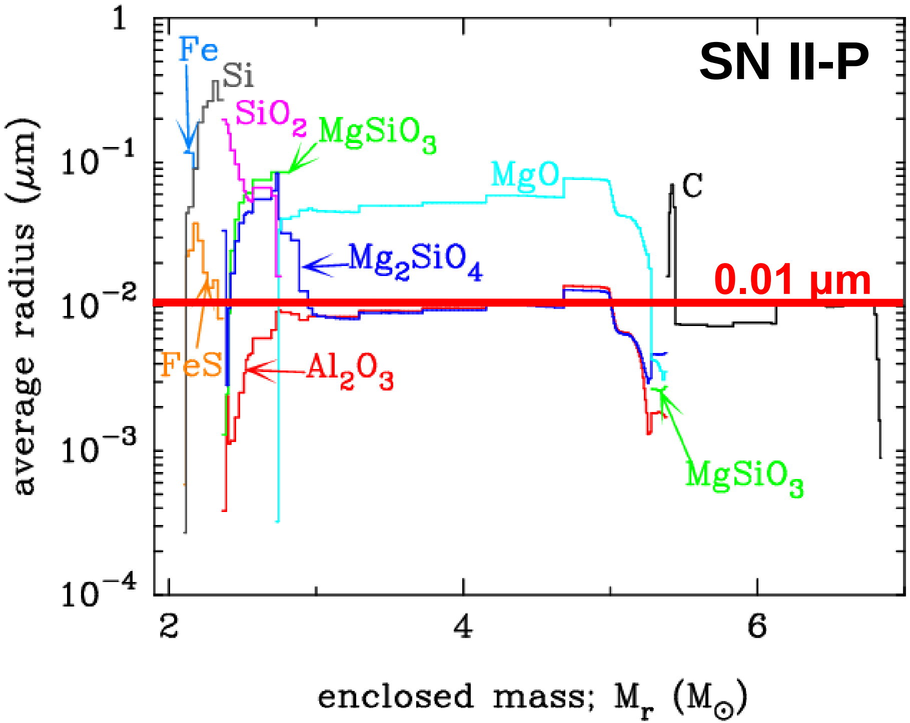
Nozawa+11, ApJ, 736, 45

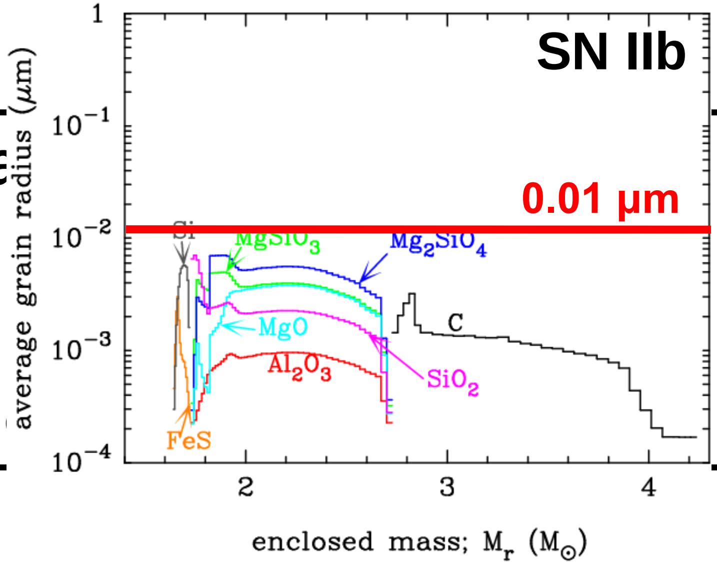
- **different dust species form in different layers**
  - **Fe and Ni grains cannot condense significantly**
  - **SiC can never condense**
- **condensation time of dust : tc = 100-300 days**

  (tc > ~300 days in SNe II)

3-2. Results (2): Average radius of dust





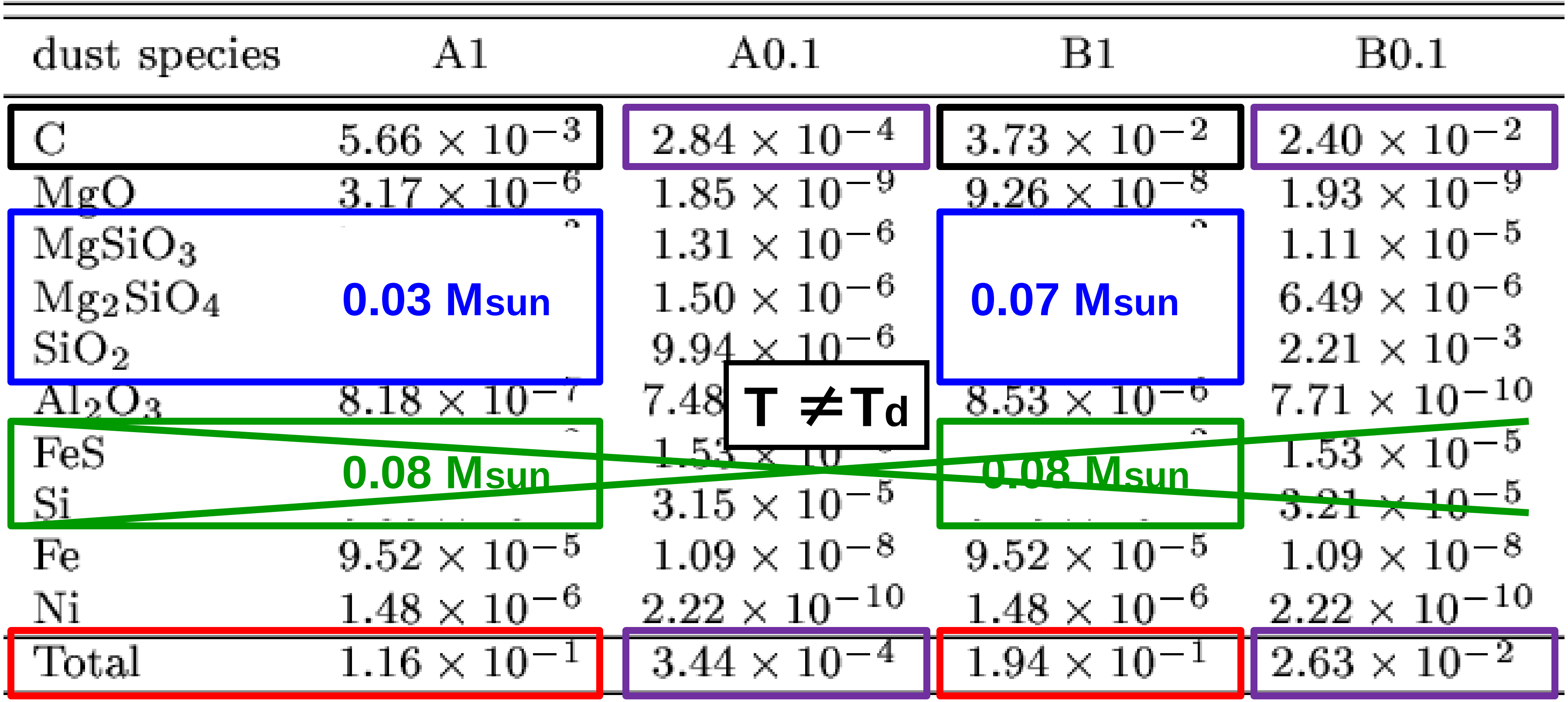


the radius of dust formed in H-stripped SNe is small

- SNe IIb/Ia with thin/no H-env ➔ a$_{ave}$ < 0.01 µm
- SN II-P with massive H-env ➔ a$_{ave}$ > 0.01 µm

3-3. Results (3): Mass of each dust species

with molecule formation | **with no molecule formation**



dust species	A1	A0.1	B1	B0.1
C	5.66×10^{-3}	2.84×10^{-4}	3.73×10^{-2}	2.40×10^{-2}
MgO	3.17×10^{-6}	1.85×10^{-9}	9.26×10^{-8}	1.93×10^{-9}
$MgSiO_3$		1.31×10^{-6}		1.11×10^{-5}
Mg_2SiO_4	**0.03 Msun**	1.50×10^{-6}	**0.07 Msun**	6.49×10^{-6}
SiO_2		9.94×10^{-6}		2.21×10^{-3}
Al_2O_3	8.18×10^{-7}	7.48	8.53×10^{-6}	7.71×10^{-10}
FeS	**0.08 Msun**	1.53×10	**0.08 Msun**	1.53×10^{-5}
Si		3.15×10^{-5}		3.21×10^{-5}
Fe	9.52×10^{-5}	1.09×10^{-8}	9.52×10^{-5}	1.09×10^{-8}
Ni	1.48×10^{-6}	2.22×10^{-10}	1.48×10^{-6}	2.22×10^{-10}
Total	1.16×10^{-1}	3.44×10^{-4}	1.94×10^{-1}	2.63×10^{-2}

T ≠ Td

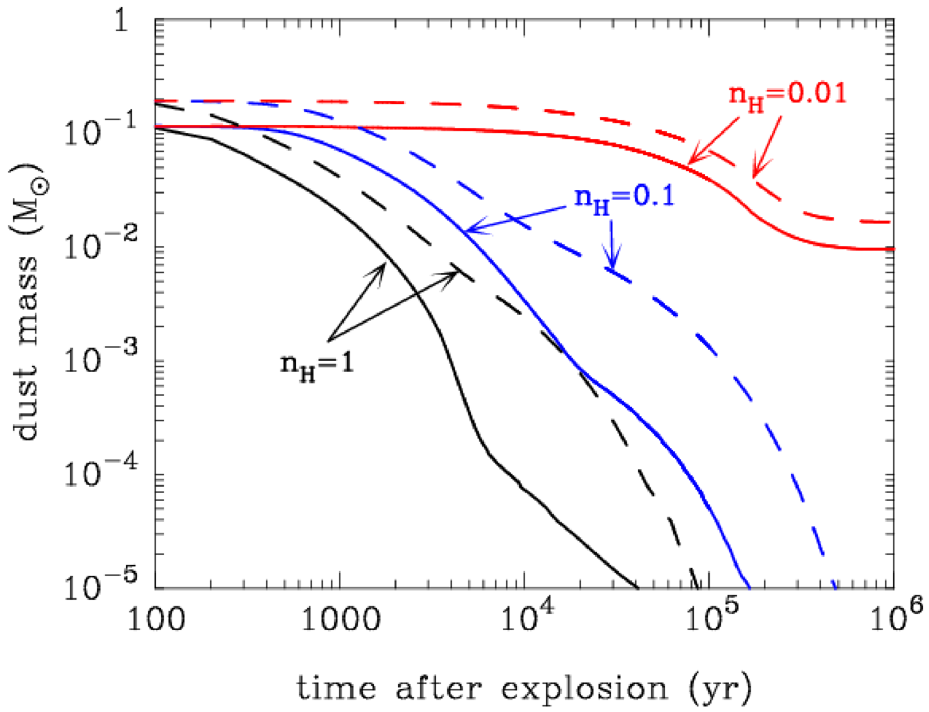
Maximum mass of dust formed in SNe Ia : 0.1-0.2 Msun

ref. 0.1-1.0 Msun for SNe II

Formation of C grain follows the presence of C atoms

Nozawa+11, ApJ, 736, 45

3-4. Survival of dust in Type Ia SNRs



- 10^{-3} Msun of dust can survive for n_H ~ 0.01 cm^{-3} but too low ISM density
- typical gas density around SNe Ia

  ➔ $n_{H,0}$ = 1.0-5.0 cm^{-3}

  (Borkowski+06)

newly formed grains are completely destroyed for ISM density of n_H > 0.1 cm^{-3}

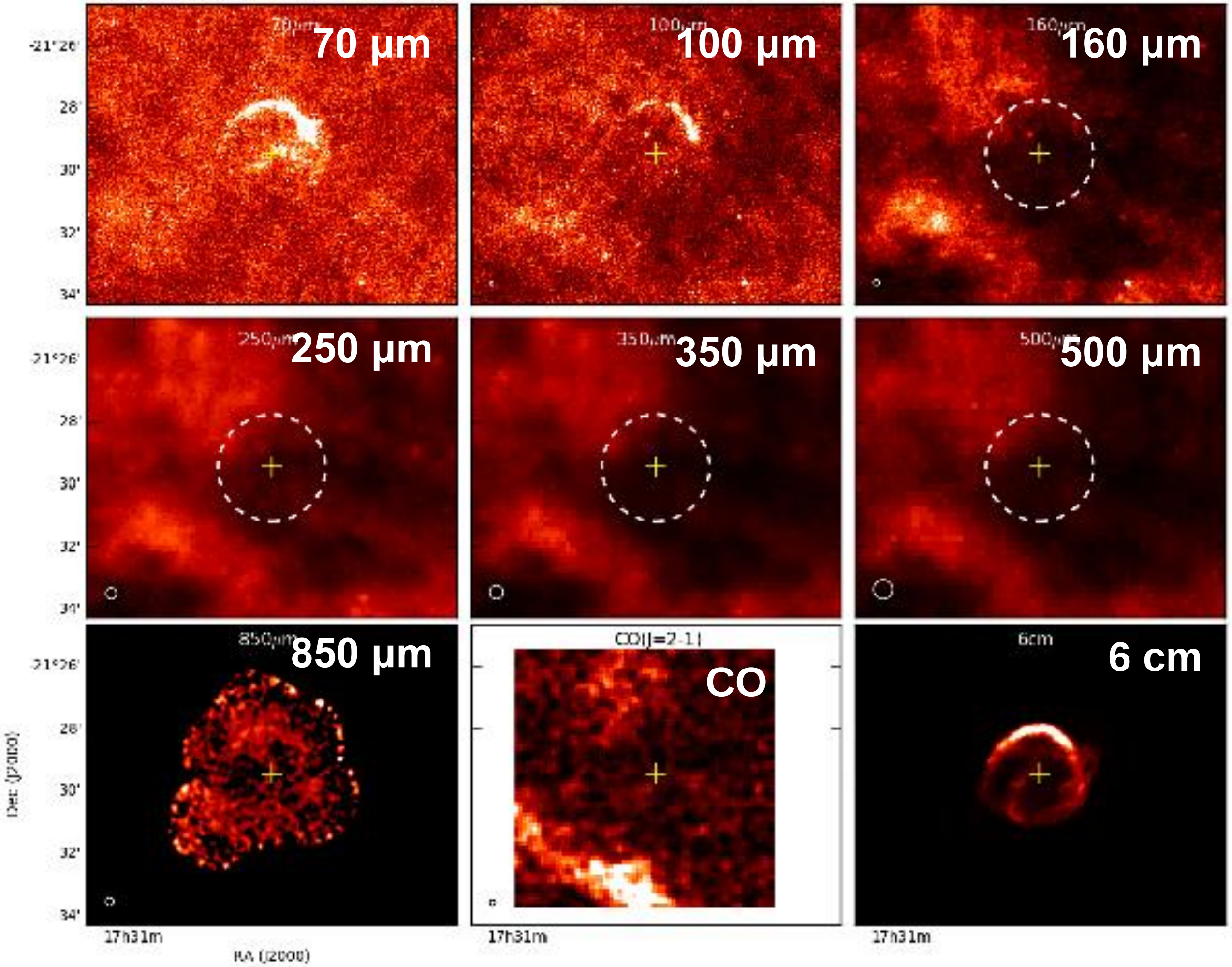
SNe Ia are unlikely to be major sources of dust

4-1. Multi-wavelength view of Kepler SNR

○ Kepler

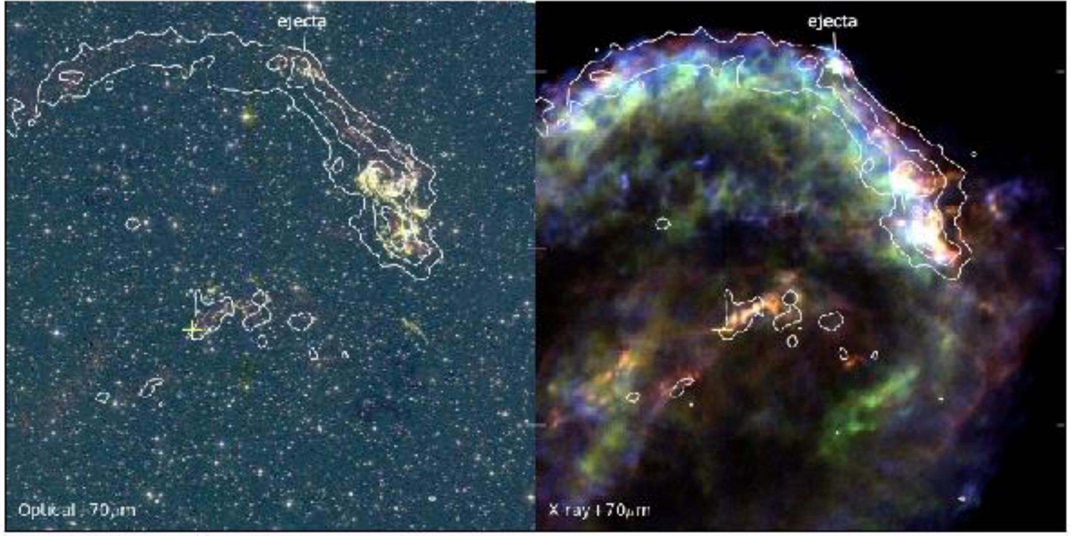
- Type Ia or Ib
- t = 407 yr
- d ~ 4.0 kpc (Blair+07)
- radius of FS: 103”(2.0 pc)
- radius of RS: 80”(1.6 pc)
- ambient gas density: $n_0 \sim 5.0$ cm^{-3}

Gomez, Clark, TN, +11, MNRAS, accepted

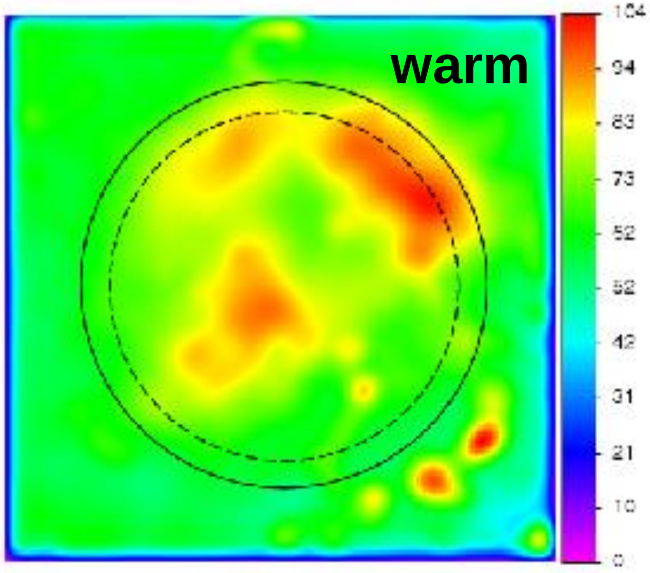


At λ >= 160 μm, it is difficult to disentangle any SNR emission from the large-scale interstellar structure

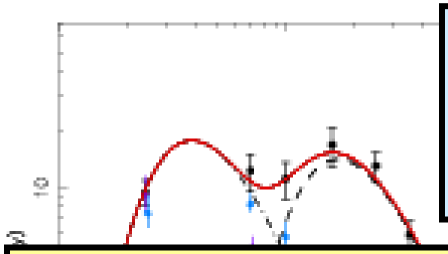
4-2. Origin of dust in Kepler



Hα and 70 μm **X-ray and 70 μm**



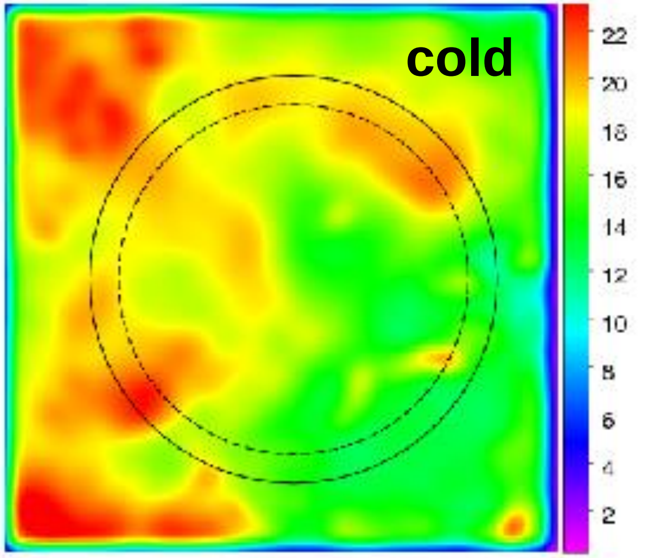
(a)



Two-component dust

warm: 84 K, 3.5×10^{-3} Msun

cold: 19 K, 2.2 Msun



(b)

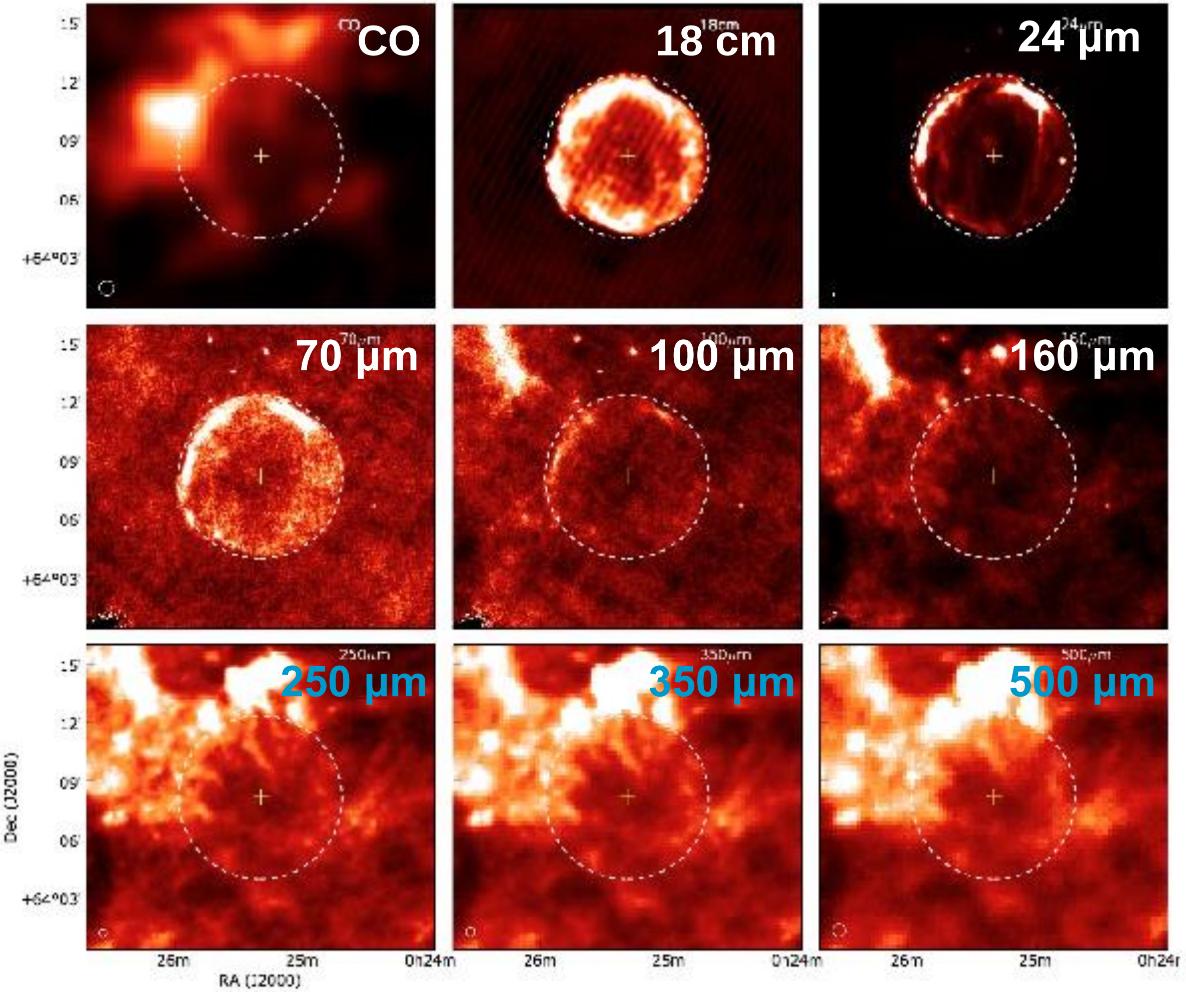
- **The dust originates from the shocked circumstellar medium**
- **There is no evidence for a cool dust component in the ejecta**

4-3. Multi-wavelength view of Tycho SNR

○ Tycho

- Type Ia
- t = 439 yr
- d ~ 3.8 kpc (Krause+07)
- radius of FS: 251”(4.6 pc)
- radius of RS: 183”(3.4 pc)
- ambient gas density: $n_0 \sim 3.0$ cm^{-3}

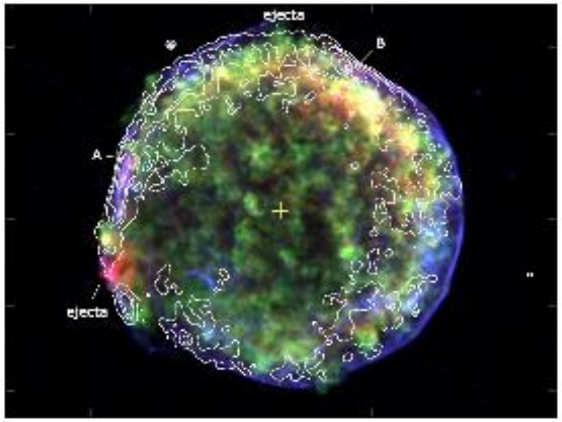
Gomez, Clark, TN, +11, MNRAS, accepted



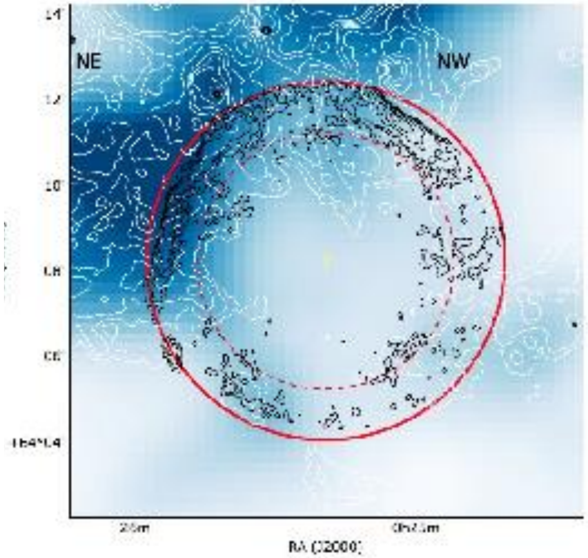
Two bright components in the NE and NW at 70 µm corresponds to peaks in 24 µm emission

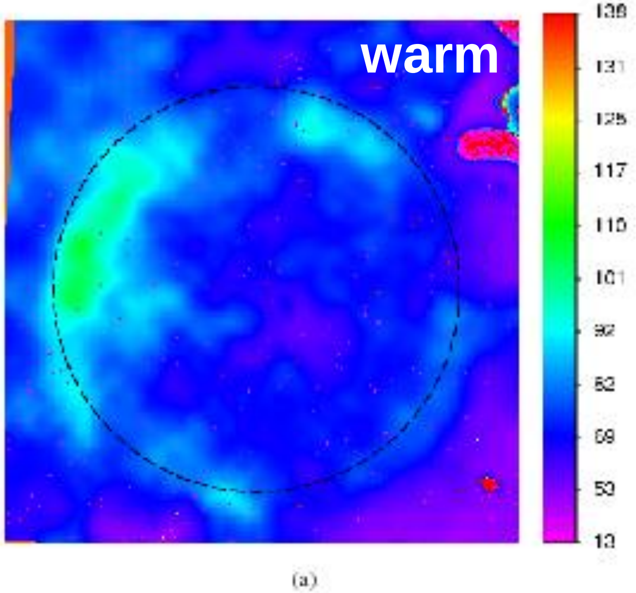
4-4. Origin of dust in Tycho

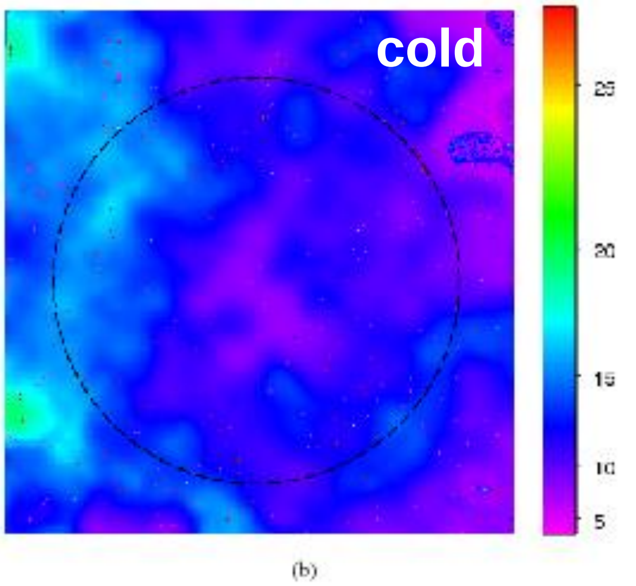
X-ray and 70 µm

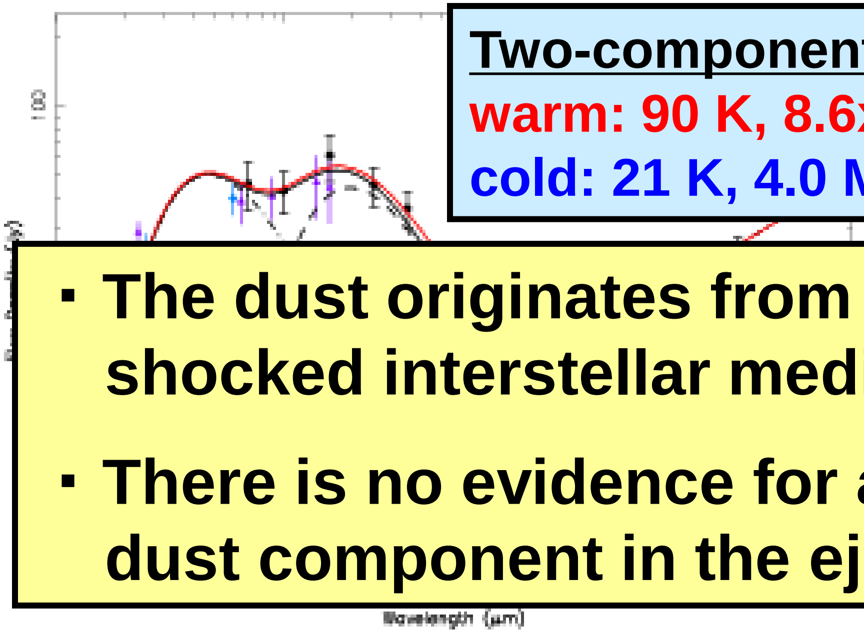


CO and 70 and 250 µm









Two-component dust

warm: 90 K, 8.6×10^{-3} Msun

cold: 21 K, 4.0 Msun

- The dust originates from the shocked interstellar medium
- There is no evidence for a cool dust component in the ejecta

5-1. Comparison with theoretical calculations

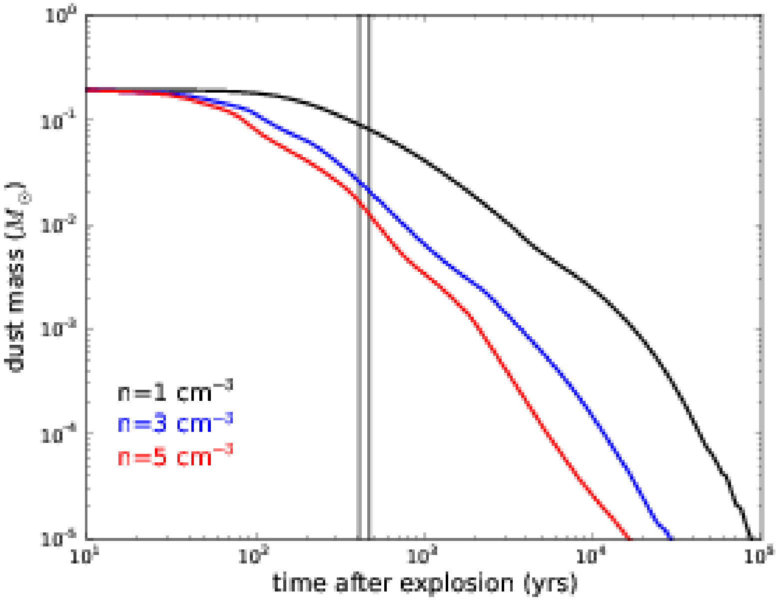
- **Nozawa et al. (2011) model**

— dust mass at dust formation
0.2 Msun for α_s = 1 and no molecular formation

＊ observed dust masses :
3.1x10^{-3} Msun for Kepler
8.6x10^{-3} Msun for Tycho

dust mass at 400 (440) yr
8.8(8.4)x10^{-2} Msun for n=1 /cc
2.6(2.3)x10^{-2} Msun for n=3 /cc
1.7(1.4)x10^{-2} Msun for n=5 /cc

➔ the surviving dust mass is higher than observed ones



(a)

- **0.1 Msun case with molecular formation**

dust mass at 400 yr
6x10^{-2} Msun for n=1 /cc
1x10^{-2} Msun for n=3 /cc
8x10^{-3} Msun for n=5 /cc

5-2. Comparison with theoretical calculations

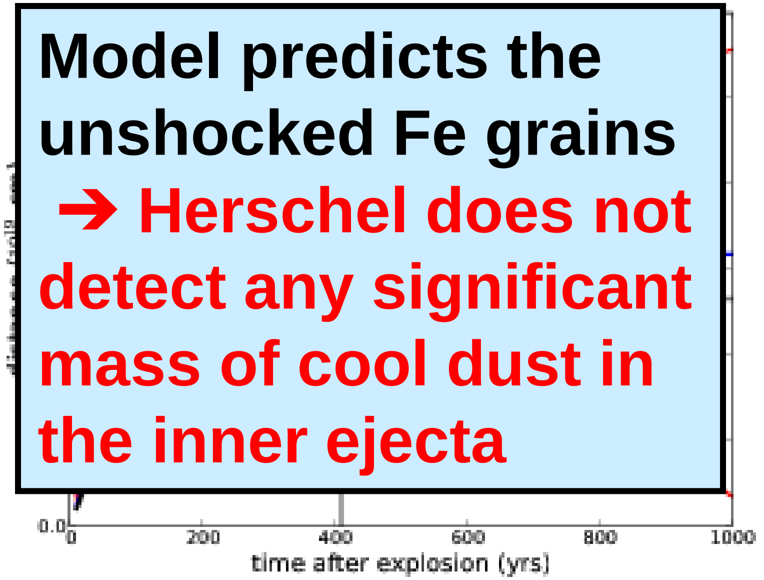
▪ IR emission region

— in Kepler
95”-103” (1.8-2.0 pc)

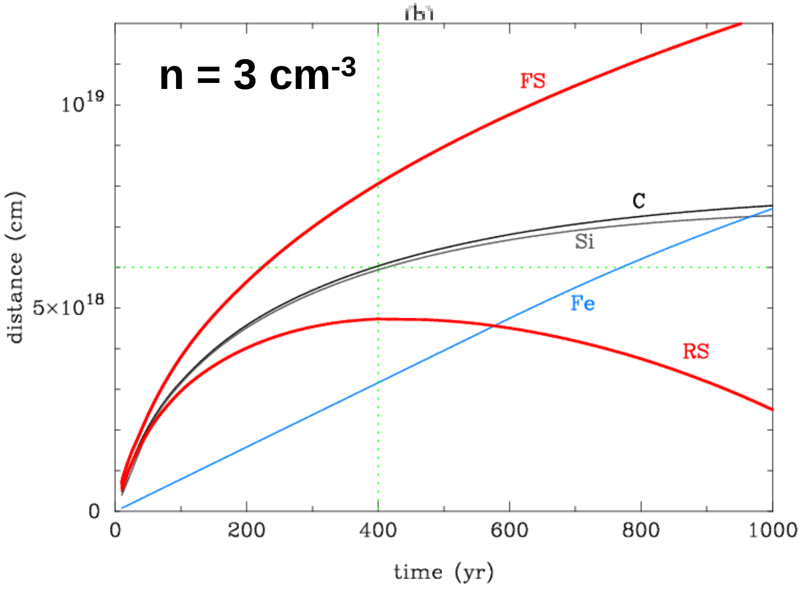
— in Tycho
220”-251” (4.0-4.6 pc)

The model-predicted position of newly formed dust
~90” for Kepler (n0 ~ 5.0 cm^{-3})
~190” for Tycho (n0 ~ 3.0 cm^{-3})

➔ The positions of supernova dust do not match emission region seen with Herschel



Model predicts the unshocked Fe grains
➔ Herschel does not detect any significant mass of cool dust in the inner ejecta



Summary

- C, silicate, Si, and FeS grains can condense in the ejecta of SNe Ia at 100-300 days (>300 days in SNe II)

- Due to the low ejecta density, the average radii of dust are below 0.01 μm, smaller than those in SNe II-P

- The total mass of dust that can form in the ejecta of SNe Ia is up to 0.1-0.2 M_{sun}

- For the IS density of $n_{H,0} > 0.1$ cm^{-3}, the newly formed grains are completely destroyed within SNRs

  ➔ SNe Ia are unlikely to be main producers of dust

- Herschel observations do not find evidence for freshly-formed supernova dust in Kepler and Tycho SNRs

5. Conclusion

- Herschel observations do not find evidence for freshly-formed supernova dust in Kepler and Tycho SNRs
  ➔ Type Ia SNe do not produce massive iron grains

- warm dust in Kepler
  dust mass of 3.1x10^{-3} M_{sun}, which originates from swept-up circumstellar dust

- warm dust in Tycho
  dust mass of 8.6x10^{-3} M_{sun}, which originates from swept-up interstellar dust

- The observed mass of warm dust is lower than the model predicts
  ➔ dust formation in SNe Ia may be inhibited, or newly formed dust may be destroyed efficiently