2018/01/10

Consensus and issues on dust formation in supernovae

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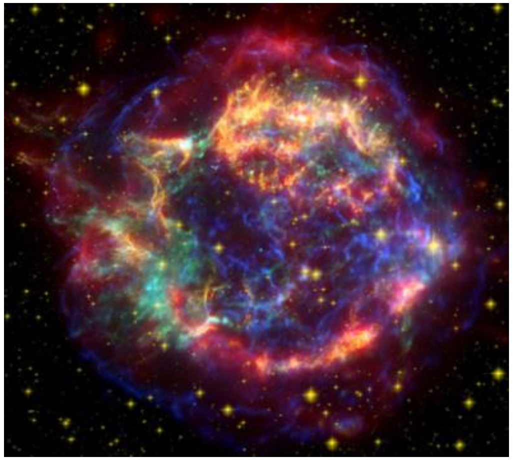
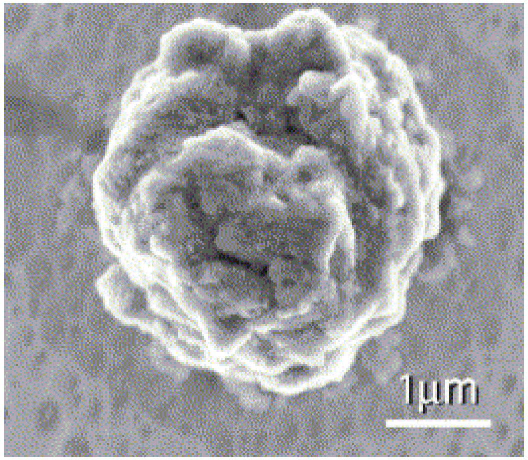
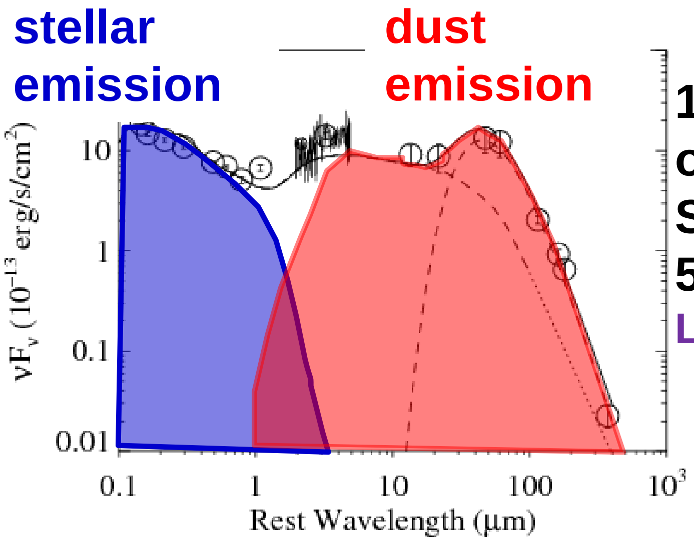




1-1. Discovery of massive dust at z > 5

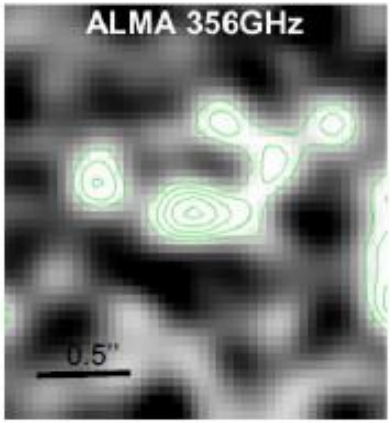
The far-infrared and submm observations have confirmed the presence of dust in excess of 10^8 Msun in 30% of z > 5 quasars



stellar emission

dust emission

10^8-10^9 Msun of dust in SDSS J1148+5251 at z=6.4
Leipski+2010



~10^6 Msun of dust in a galaxy at z = 8.4
Laporte+2017

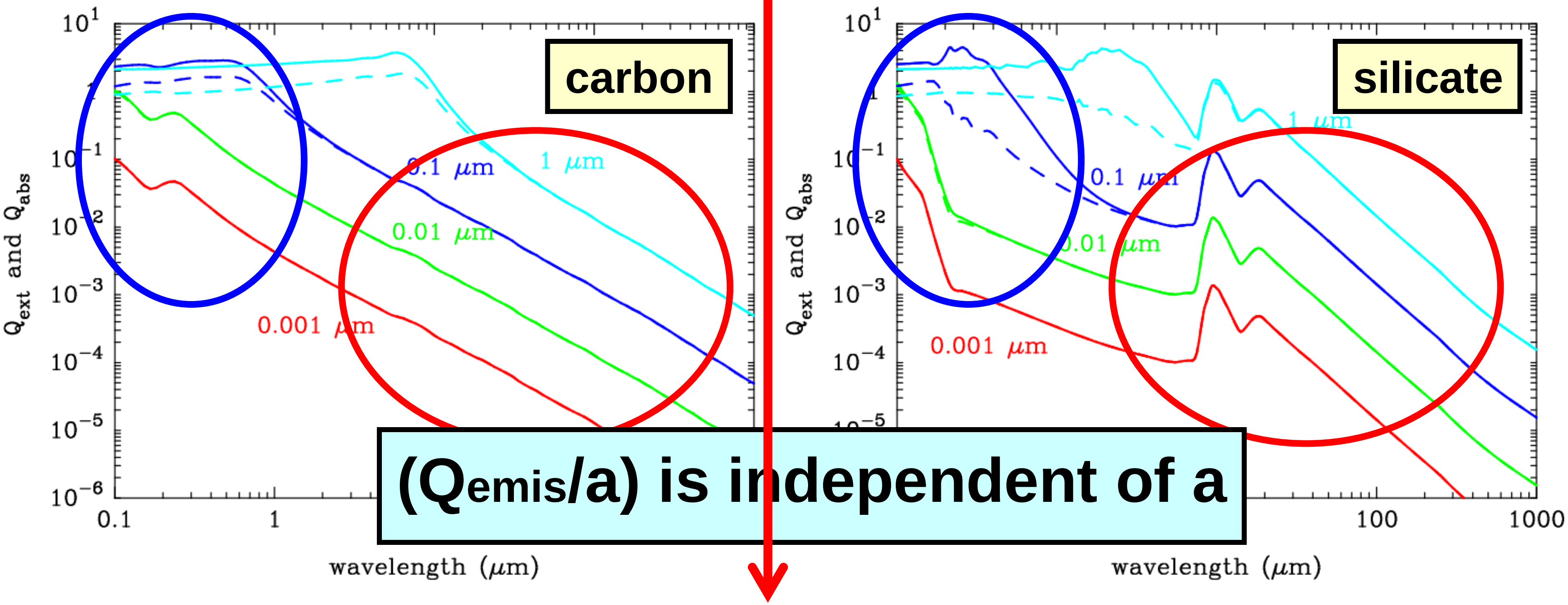
- **In the MW, AGB stars are considered to be major dust sources ➜ too old to supply dust in the early universe**

- **0.1 Msun of dust per SN is needed to explain massive dust at high-z** (e.g. Morgan & Edmunds 2003; Maiolino+2006; Dwek+2007)

1-2. Emission and absorption efficiency of dust

○ Thermal radiation from dust grains

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



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

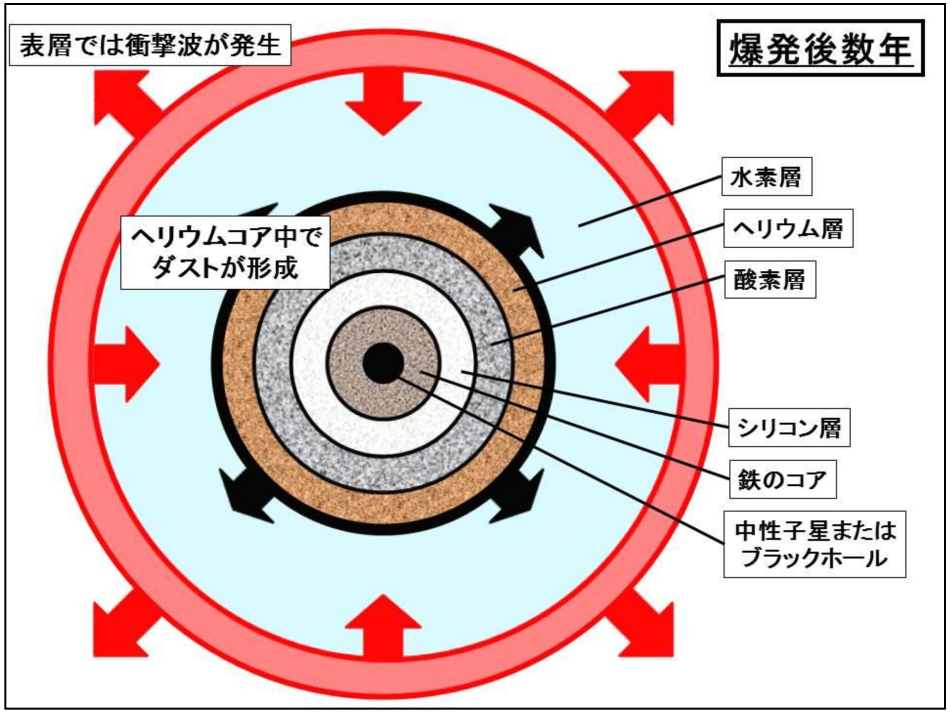
$F_\lambda = N_{dust}\, 4\pi a^3\, (Q_{emis}[a,\lambda]/a)\, \pi B_\lambda(T_{dust})$

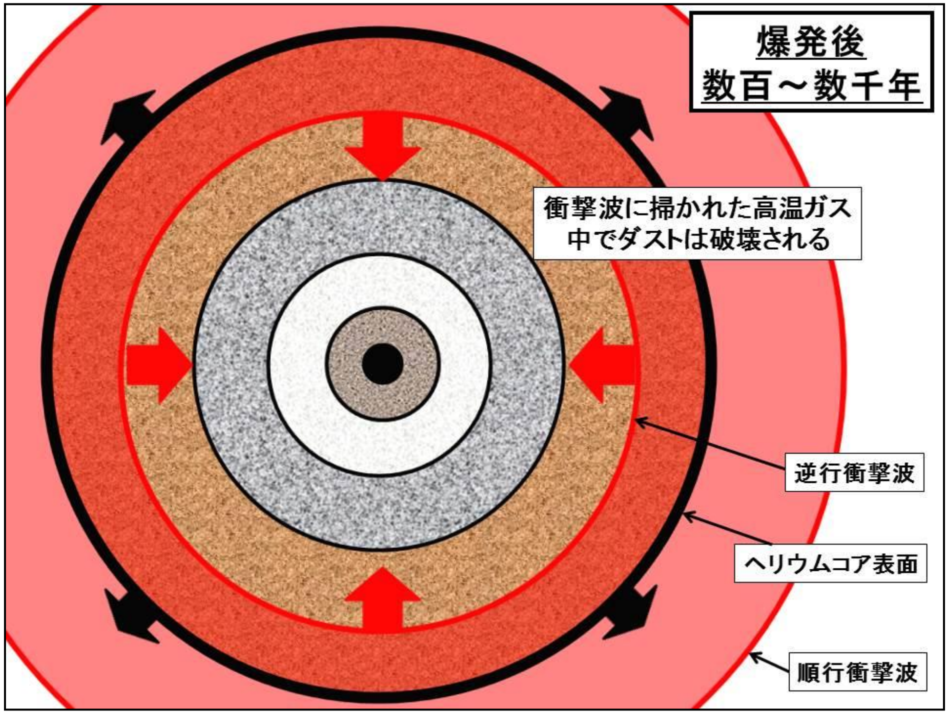
$= 4\, M_{dust}\, \kappa_{abs}(\lambda)\, \pi B_\lambda(T_{dust})$

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

1-3. Formation and processing of dust in SNe

Nozawa 2014, Astronomical Herald





Destruction efficiency of dust grains by sputtering in the reverse shocks depends on their initial size

The size of newly formed dust is determined by physical condition (gas density and temperature) of SN ejecta

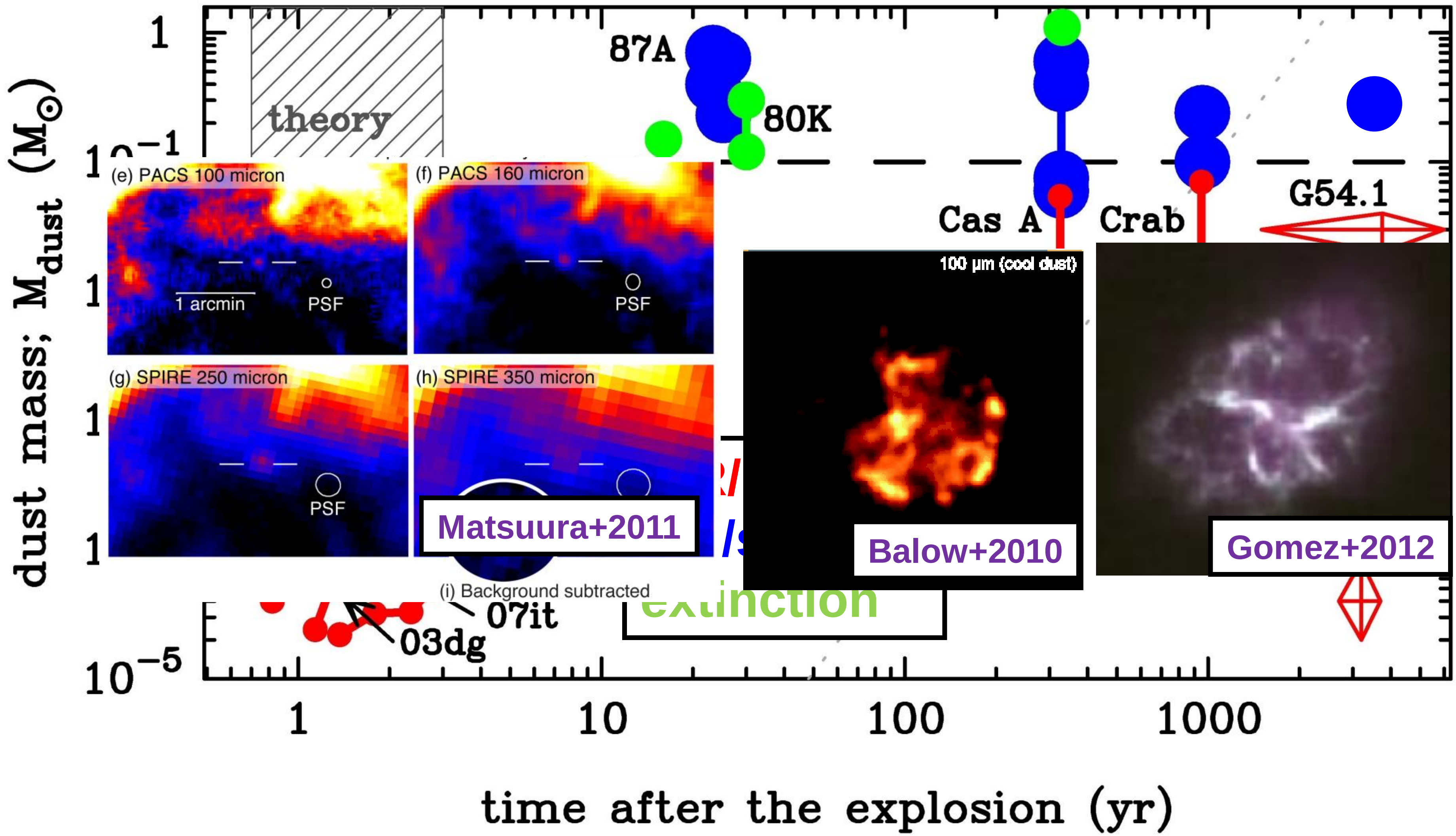
1-4. Key questions for dust formation in SNe

1. How much dust grains form?

2. What is the size distribution of dust?

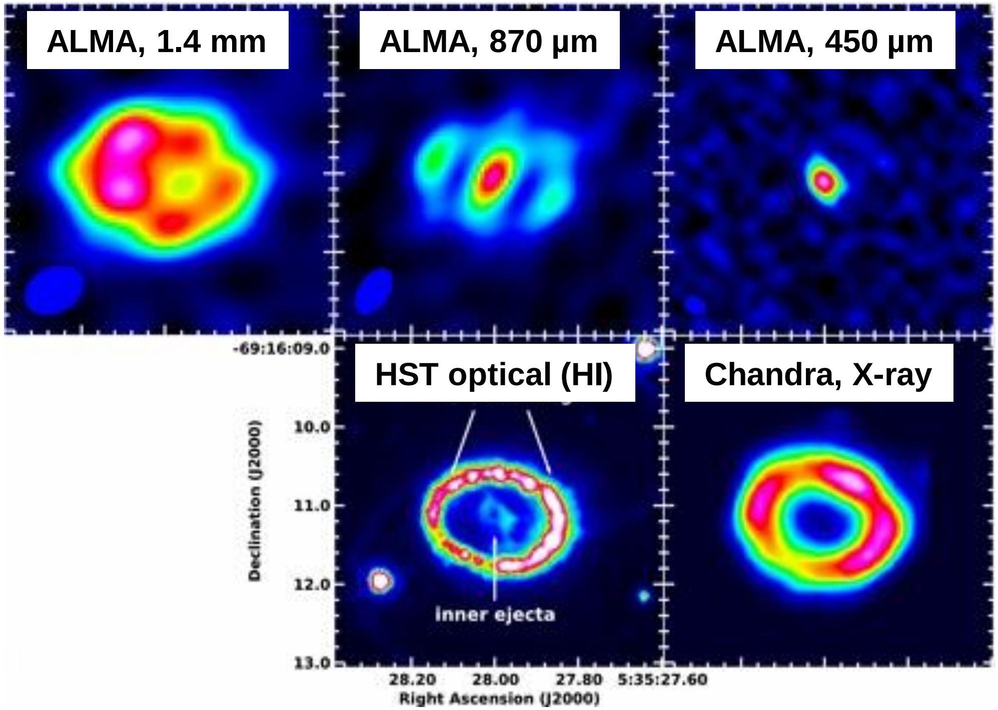
3. When do the majority of grains form?

2-1. Observed dust mass in CC-SNe/SNRs

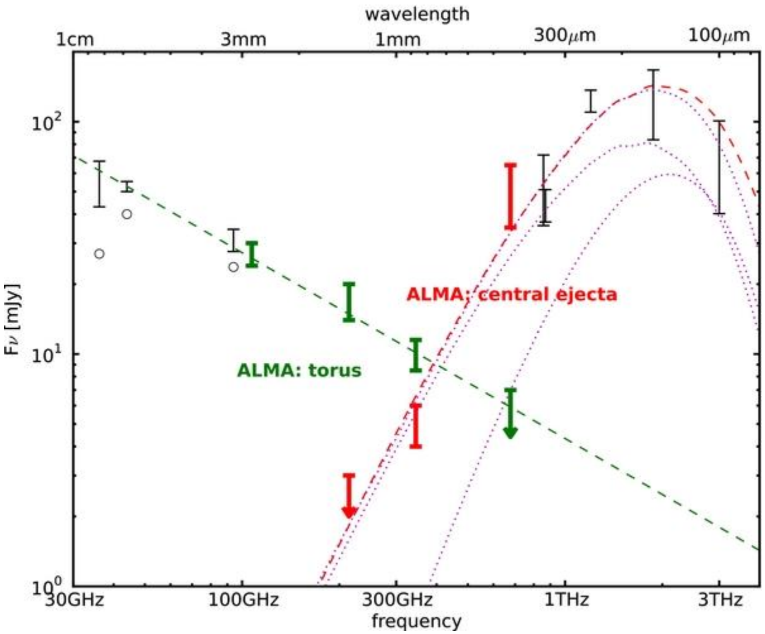


Dust mass formed in the ejecta is dominated by cold dust

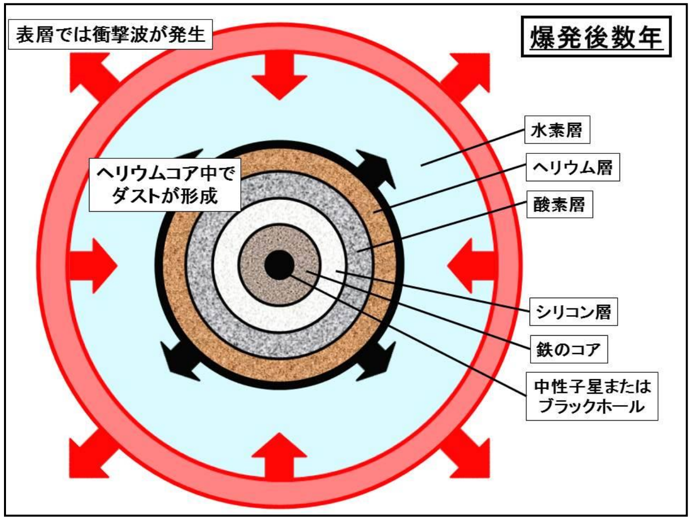
2-2. ALMA reveals dust formed in SN 1987A



SED of 25-years old SN 1987A



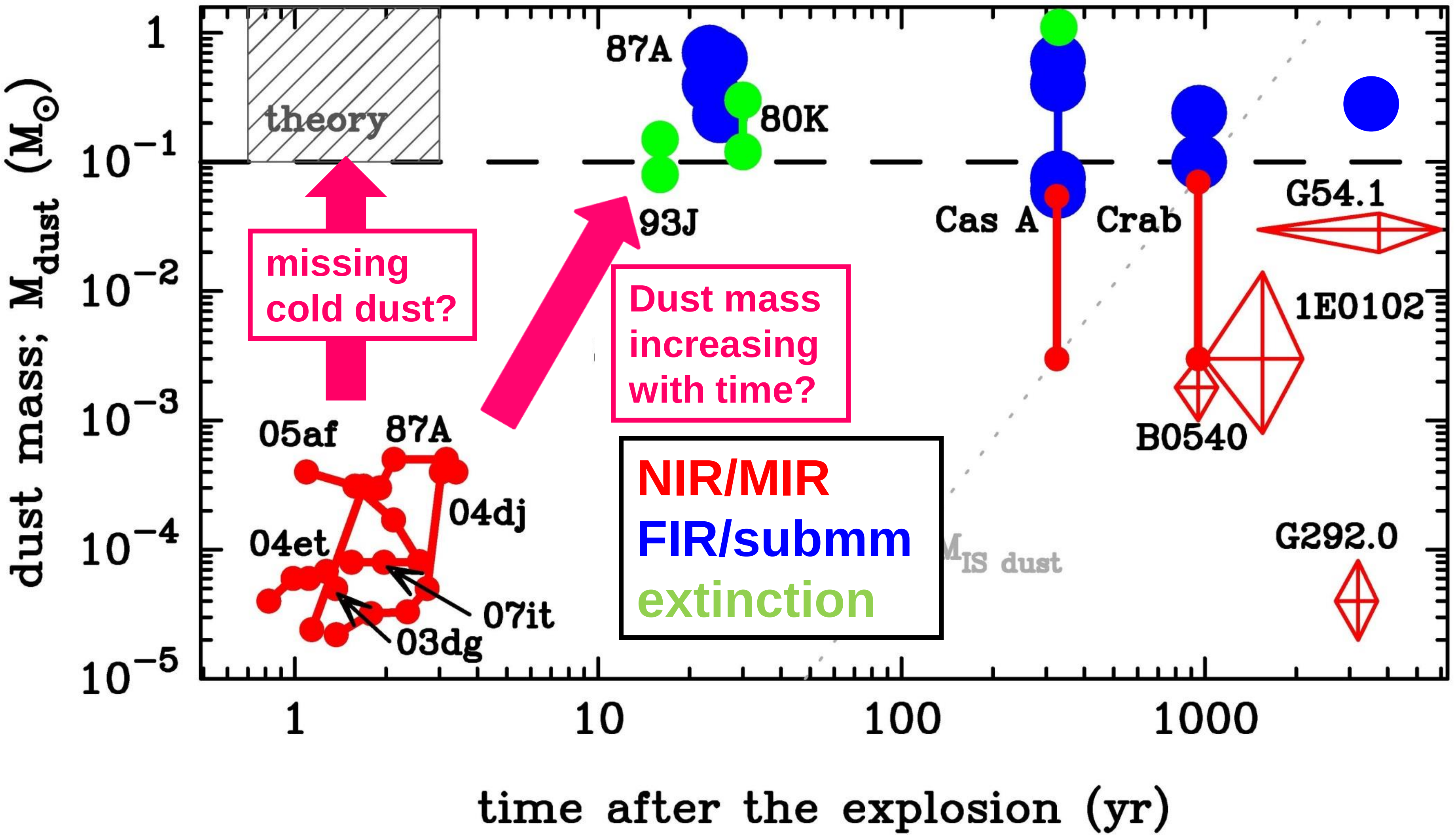
Indebetouw+2014



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

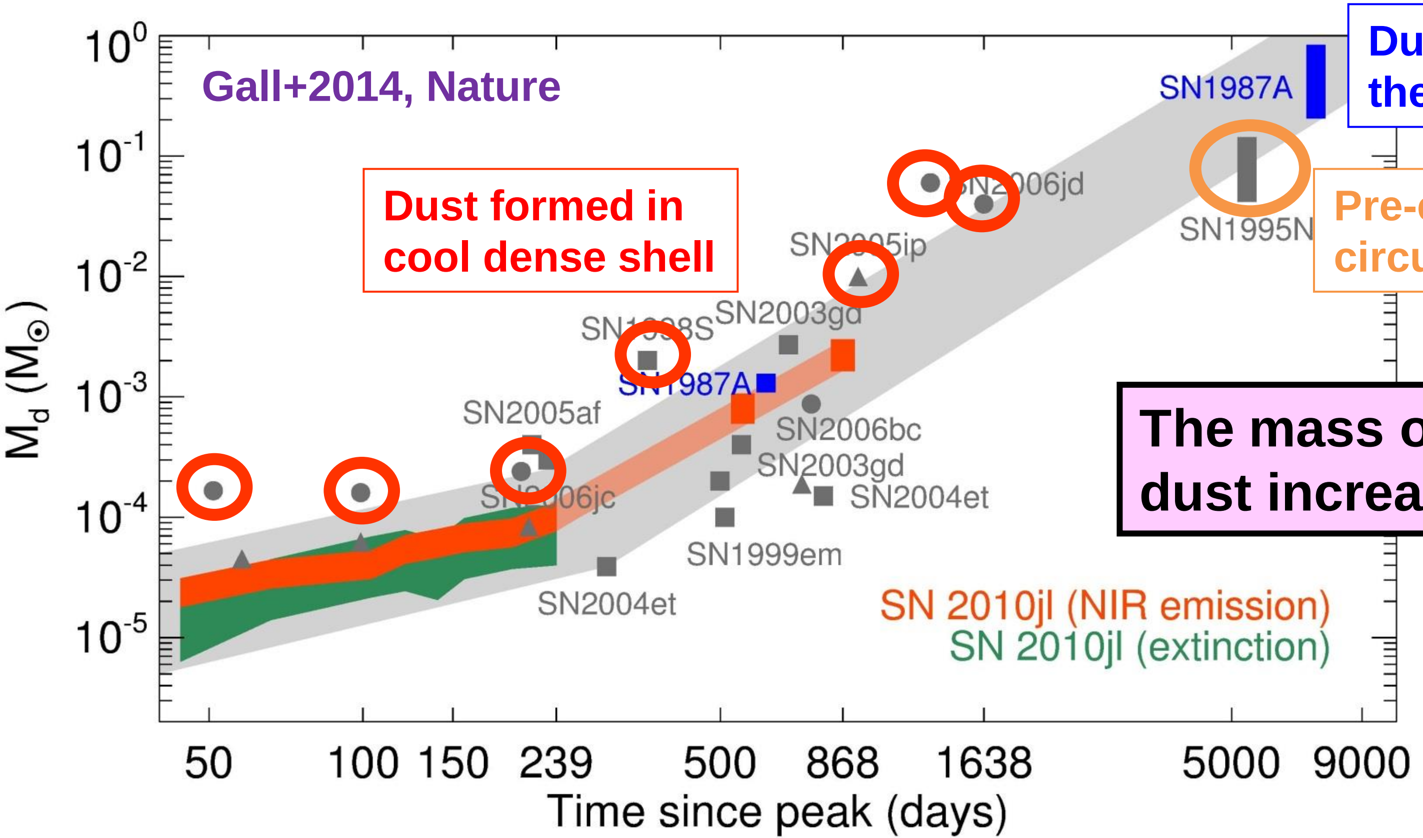
➔ SNe could be production factories of dust grains

2-3. Observed dust mass in CC-SNe/SNRs



Dust mass formed in the ejecta is dominated by cold dust

2-4. Interpretation of Gall et al. (2014) paper



Dust formed in the ejecta

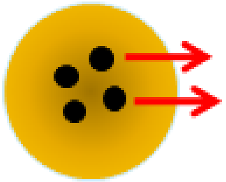
Dust formed in cool dense shell

Pre-existing circumstellar dust

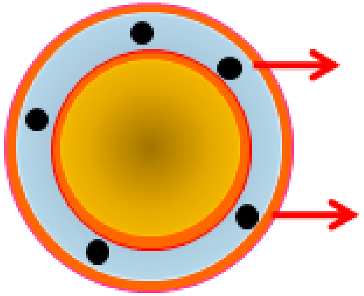
The mass of newly formed dust increases with time?

We should not discuss the mass of newly formed grains by integrating the formation of dust in the ejecta and CDS

Dust formation in the ejecta



Dust formation in dense shell



2-5. Timescale of grain growth

$$\boxed{\tau_{\mathrm{grow}}^{-1} = \frac{1}{a}\left(\frac{da}{dt}\right) = \left(\frac{1}{a}\right)\eta_g \Omega_0 c_1 \left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}}}$$

$$\begin{aligned}\tau_{\mathrm{grow}} \simeq 50 \; &\left(\frac{\eta_g}{1.0}\right)^{-1} \left(\frac{a}{0.01\ \mu\mathrm{m}}\right) \left(\frac{T}{50\ \mathrm{K}}\right)^{-\frac{1}{2}} \left(\frac{M_C}{0.01\ M_\odot}\right)^{-1} \\ &\times \left(\frac{V_{\mathrm{core}}}{10^3\ \mathrm{km\ s^{-1}}}\right)^{3} \left(\frac{t}{20\ \mathrm{yr}}\right)^{3} \left(\frac{f_{\mathrm{density}}}{10}\right)^{-1} \ \mathrm{yr}\end{aligned}$$

At 20 yr, the gas density is too low to form dust grains in the freely expanding ejecta

2-6. Key questions for dust formation

1. How much dust grains form?

- theoretical works ➜ 0.1-1 M_{sun}
- FIR/submm obs. ➜ 0.1-1 M_{sun}

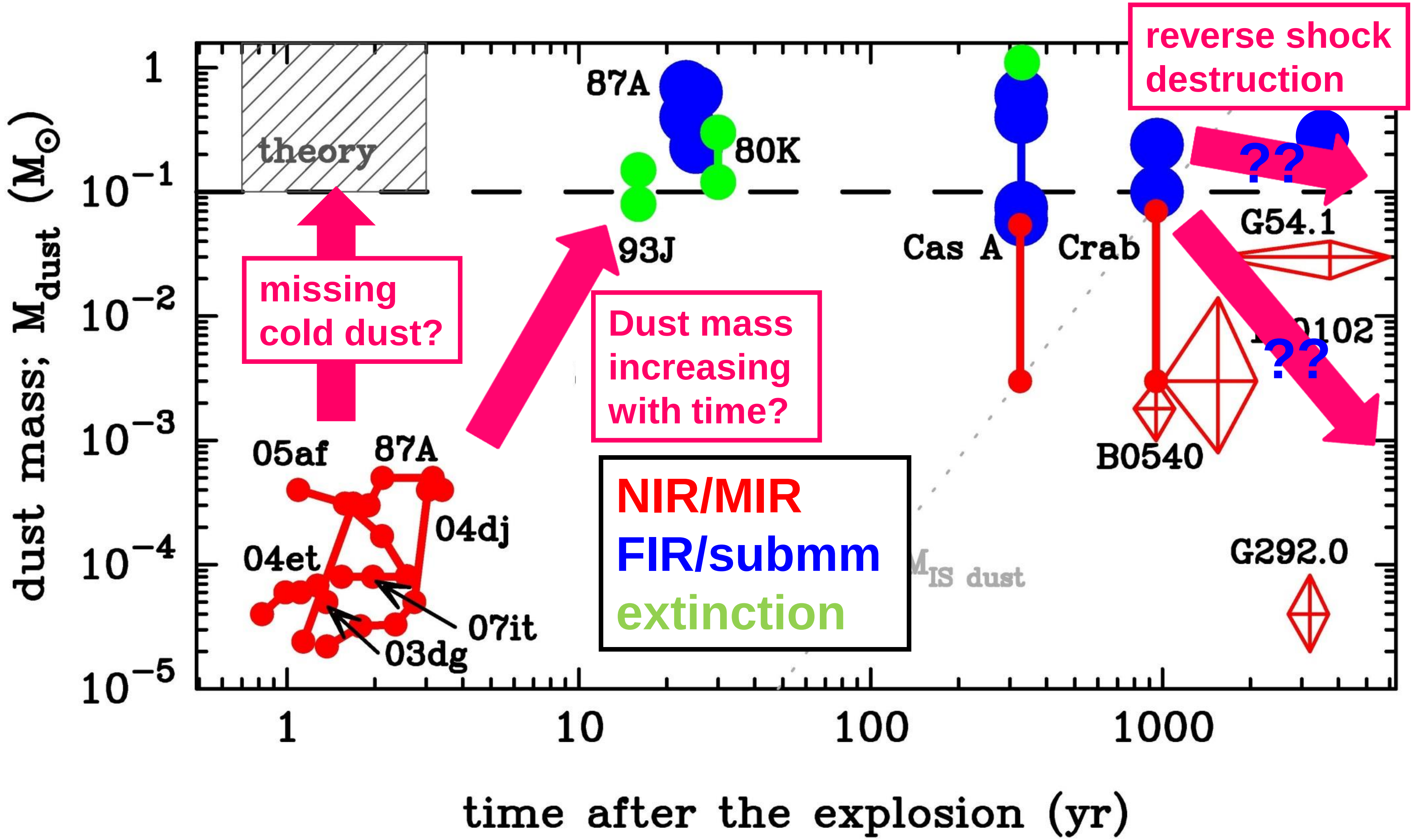
2. What is the size distribution of dust?

➜ what fraction of dust is destroyed by RS?
➜ smaller grains are destroyed more efficiently

3. When do the majority of grains form?

- theory ➜ ~1-3 yr (within 5 yr; earlier is better)
- obs. ➜ ~20 yr (dust mass gradually increases with time)

2-7. Observed dust mass in CC-SNe/SNRs



reverse shock destruction

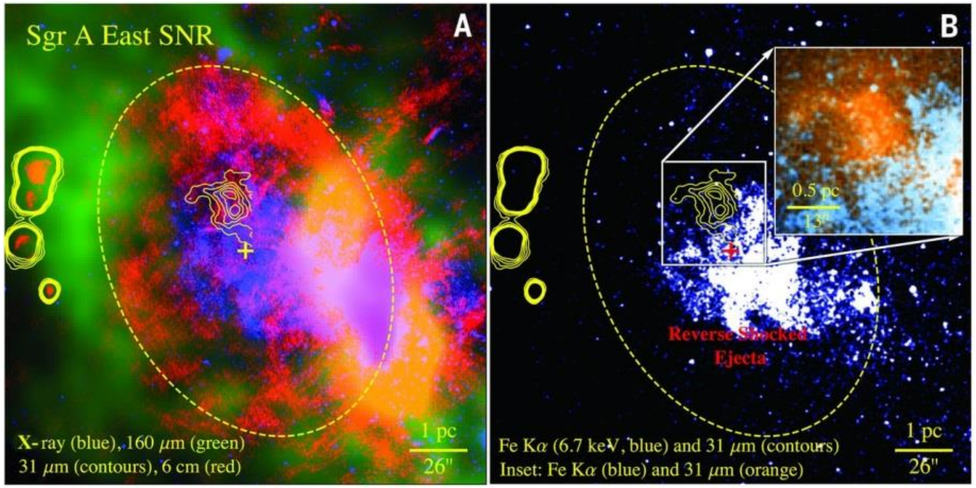
missing cold dust?

Dust mass increasing with time?

NIR/MIR
FIR/submm
extinction

Dust mass formed in the ejecta is dominated by cold dust

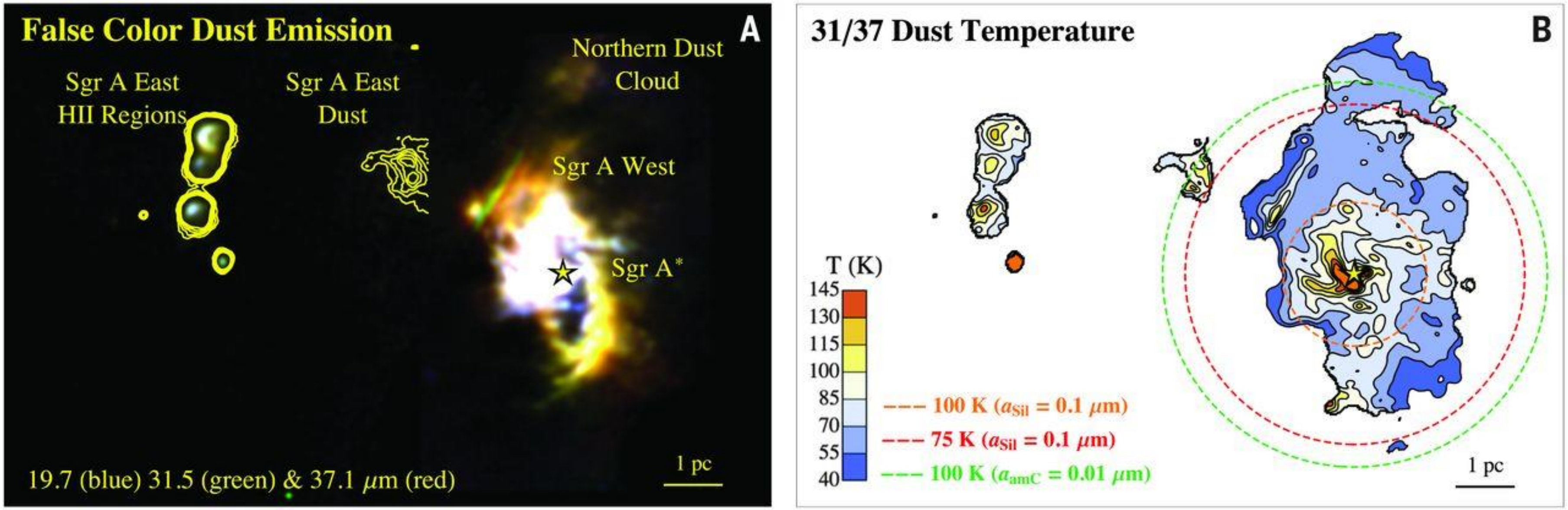
3-1. Survival of dust within an old SNR



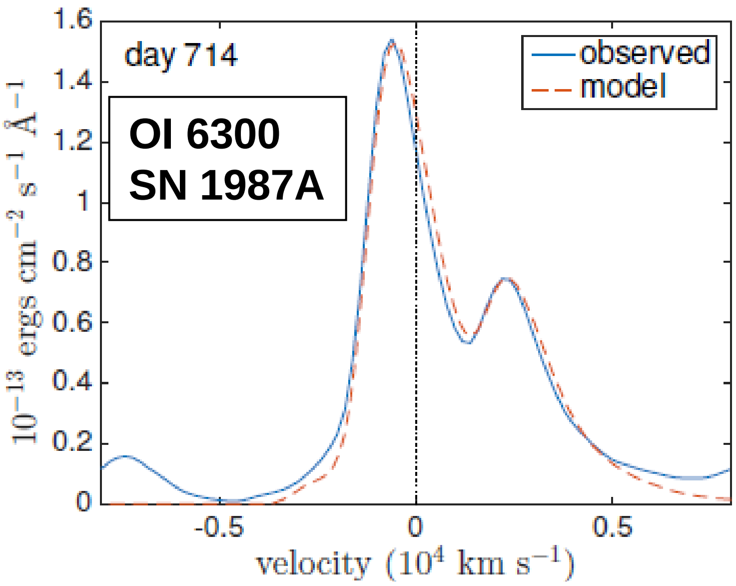
Sagittarius A East SNR

- age: ~10,000 yr
- dust mass: ~0.02 Msun
- dust temperature: ~100 K

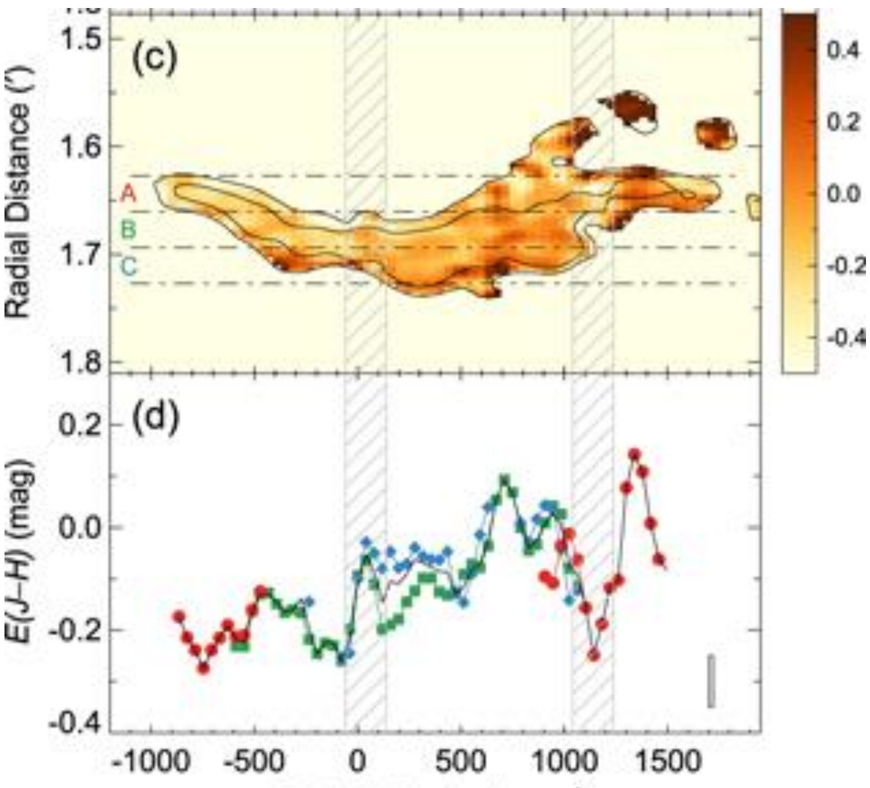
Lau+2015, Science



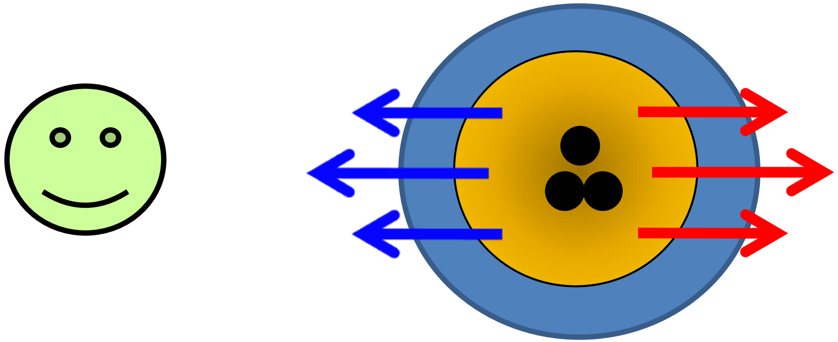
3-2. Constraining dust size from extinction



Bevan & Barlow 2016



Lee+2015

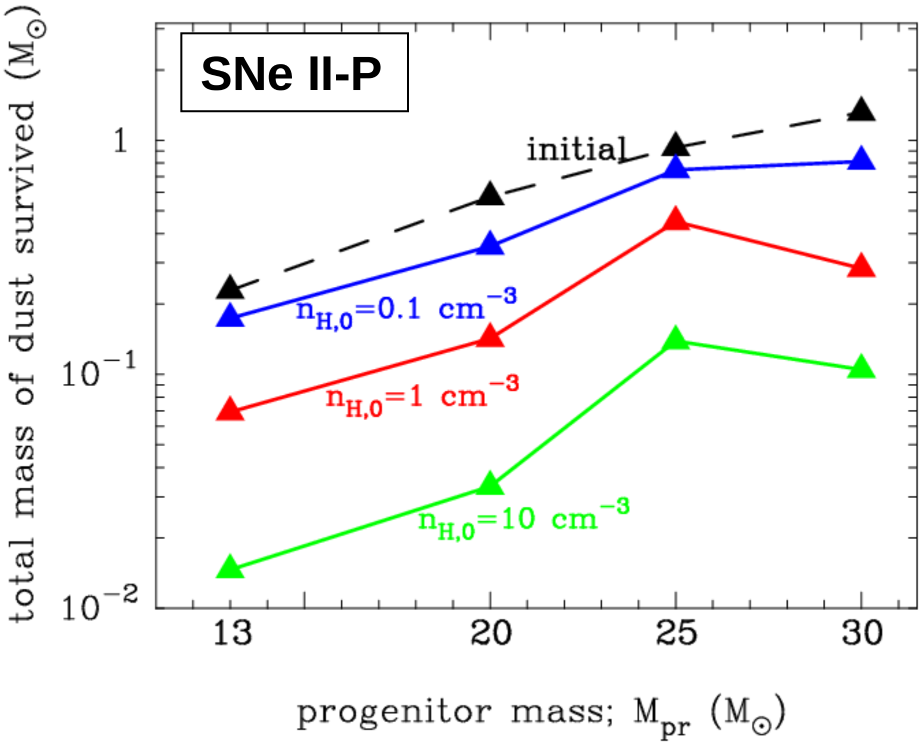


- **dust mass < 3×10^{-3} Msun (< 0.07 Msun if silicate)**
- **grain radius > ~0.6 μm**

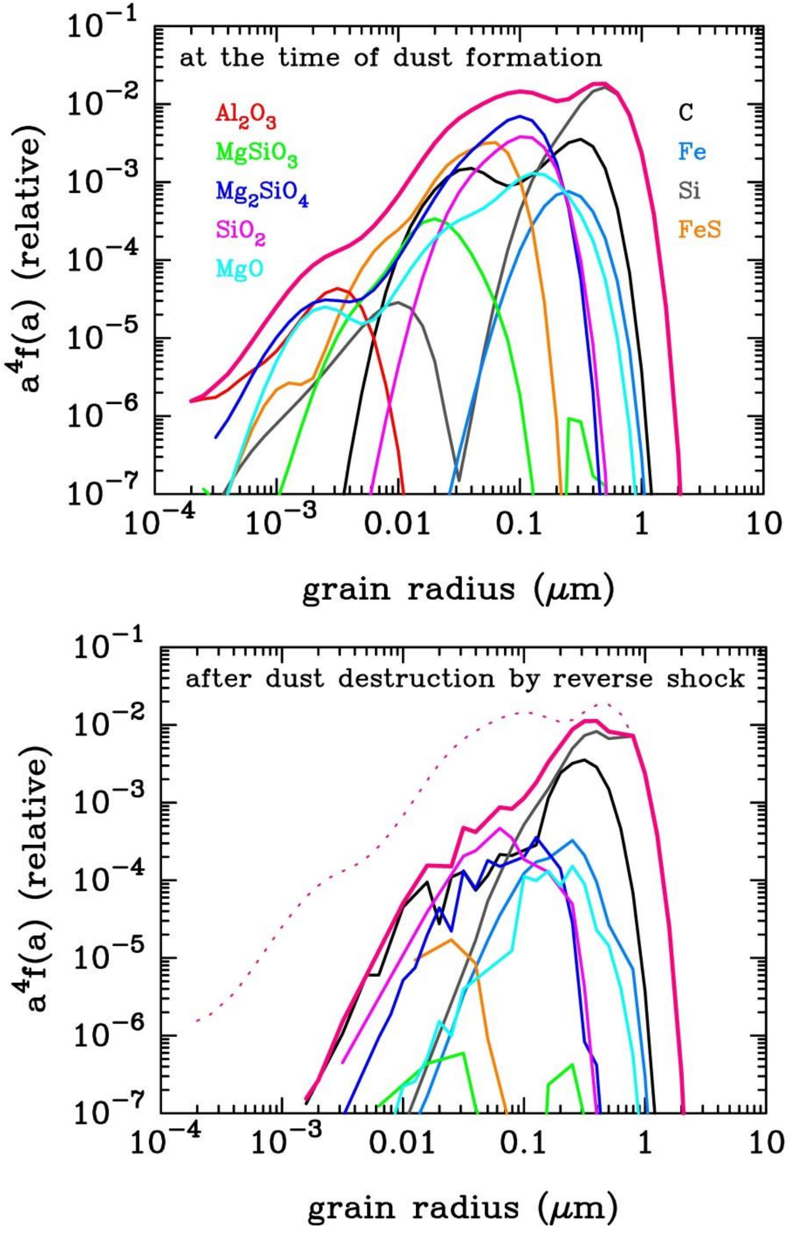
cool dust component

➜ **Fe with a < 0.01 μm (or large Si dust)**

3-3. Dust mass and size ejected from SNe II



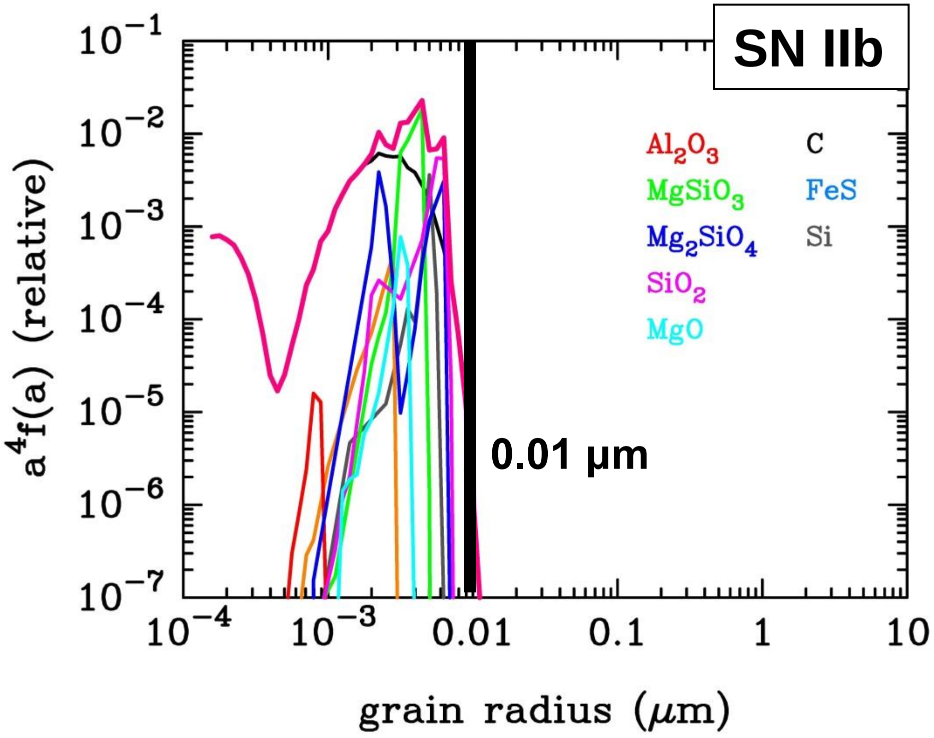
Nozawa+07, ApJ, 666, 955

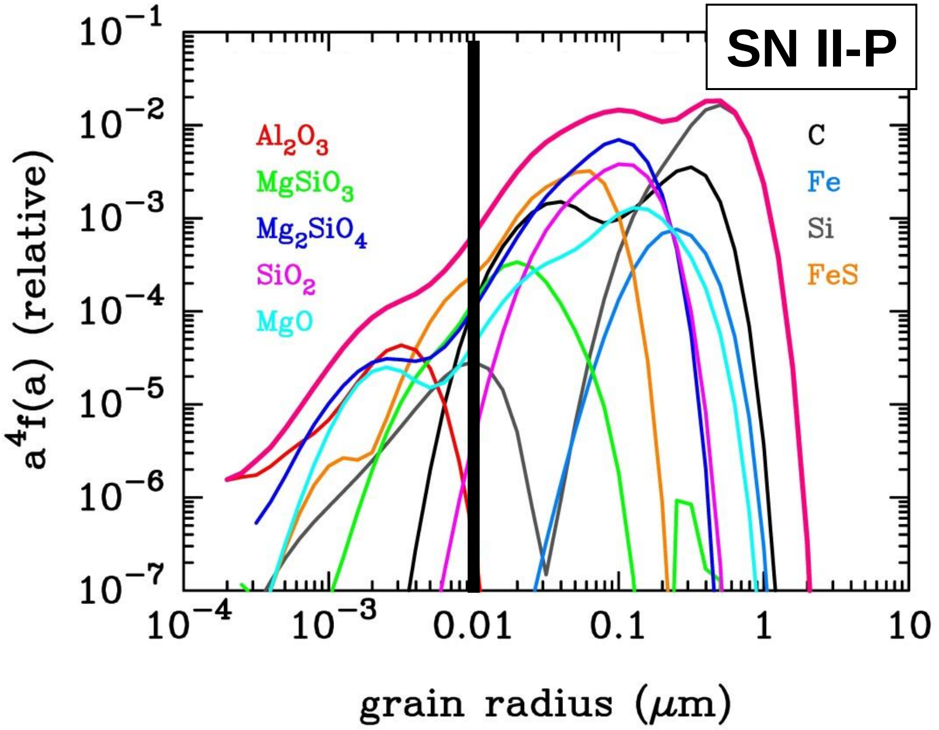


total mass of dust surviving the destruction in Type II SNRs;
0.07-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

size distribution of dust after the shock-destruction is domimated by large grains (> 0.1 μm)

3-4. Dependence of grain radii on SN type



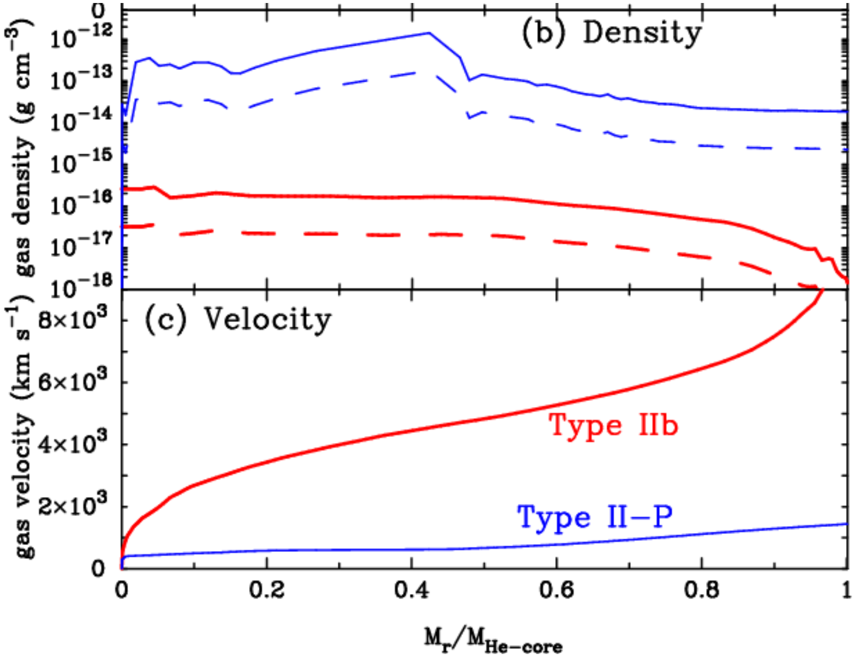


- **condensation time of dust 300-700 days after explosion**
- **total mass of dust formed**
  - **0.167 Msun in SN IIb**
  - **0.1-1 Msun in SN II-P**

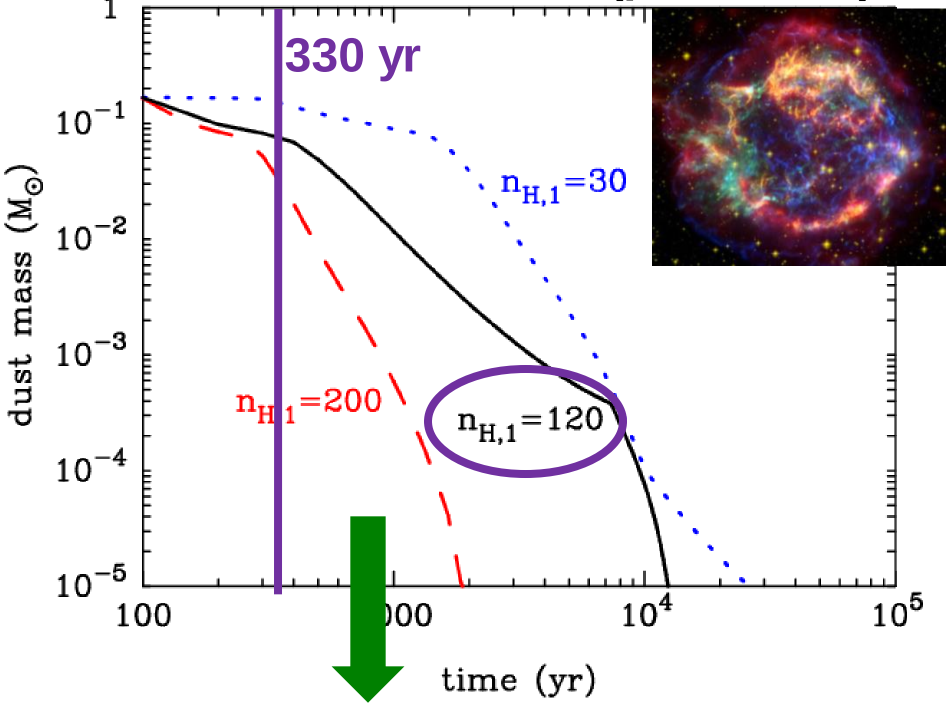
- **the radius of dust formed in H-stripped SNe is small**
  - **SN IIb without massive H-env**
    ➔ adust < 0.01 μm
  - **SN II-P with massive H-env**
    ➔ adust > 0.01 μm

Nozawa+10, ApJ, 713, 356

3-5. Destruction of dust in Type IIb SNR



stellar-wind CSM ($\rho_{CSM} \propto r^{-2}$)



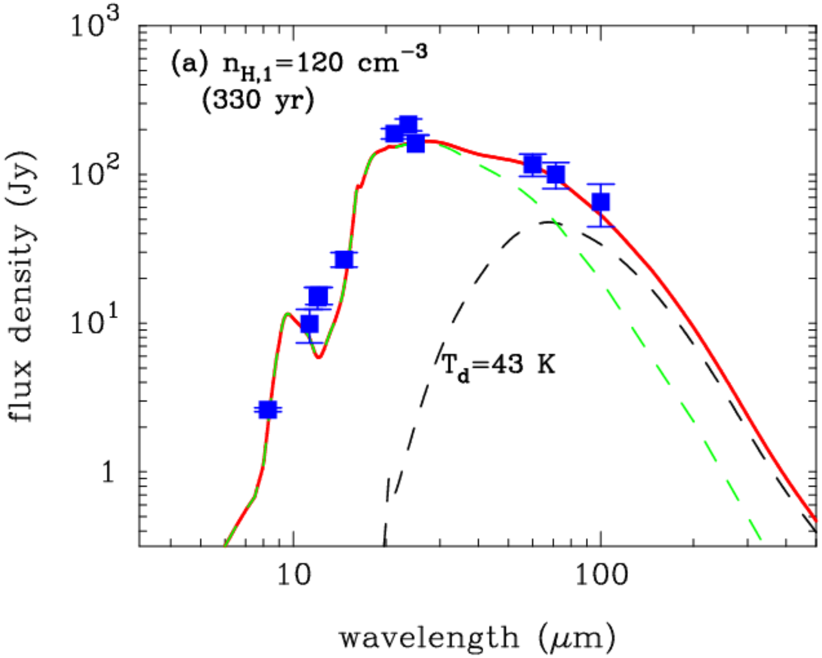
$n_{H,1}$ = 30, 120, 200 /cc ➔ dM/dt = 2.0, 8.0, 13x10^{-5} M_{sun}/yr for v_w=10 km/s

Almost all newly formed grains are destroyed in the hot gas that was swept up by the reverse shocks

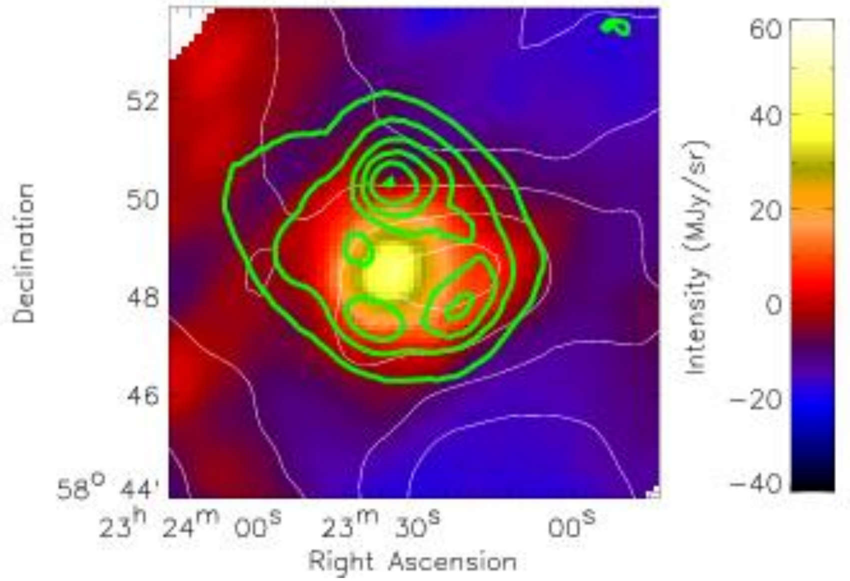
- **➔ small radius of newly formed grains**
- **➔ early arrival of reverse shock at dust-forming region**

Nozawa+10, ApJ, 713, 356

3-6. IR emission from dust in Cas A SNR



AKARI 90 μm image (color)



- **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

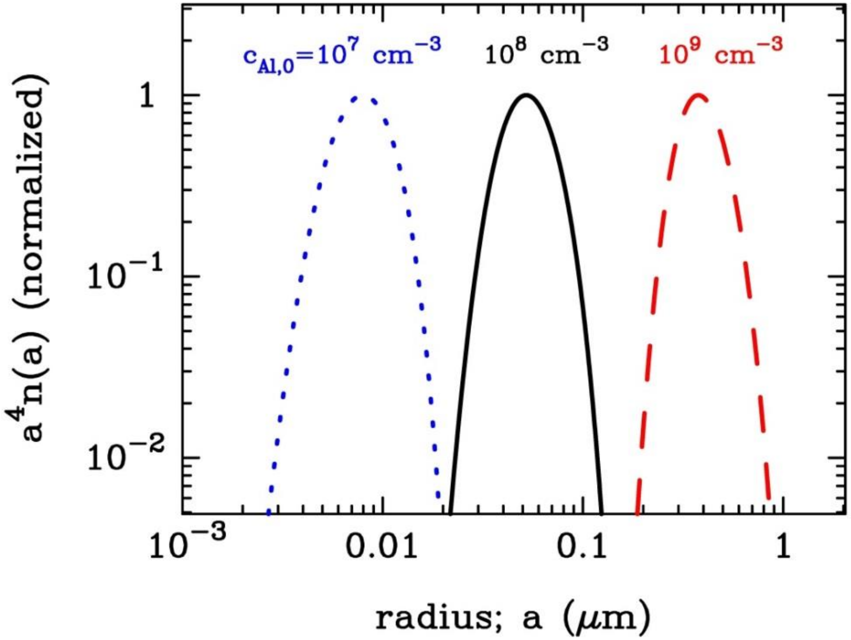
AKARI observation

$M_{d,cool}$ = 0.03-0.06 M_{sun}
T_{dust} = 33-41 K
(Sibthorpe+10)

Herschel observation

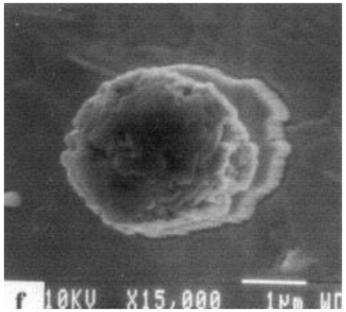
$M_{d,cool}$ = 0.075 M_{sun}
T_{dust} ~ 35 K (Barlow+10)

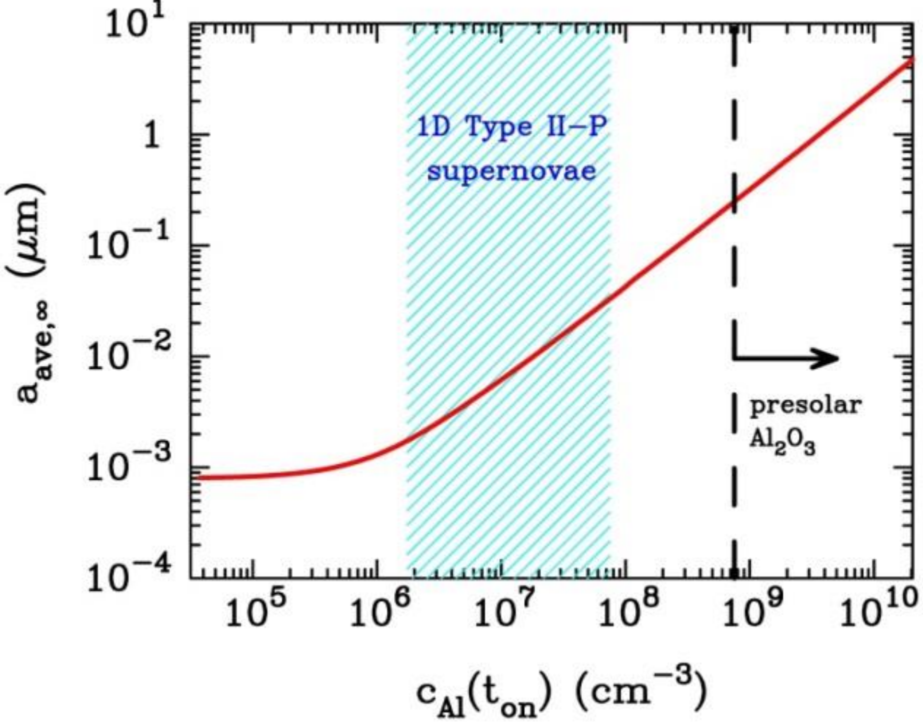
3-7. Formation condition of presolar Al_2O_3



presolar Al_2O_3 grains

Al_2O_3 (Nittler+1997)

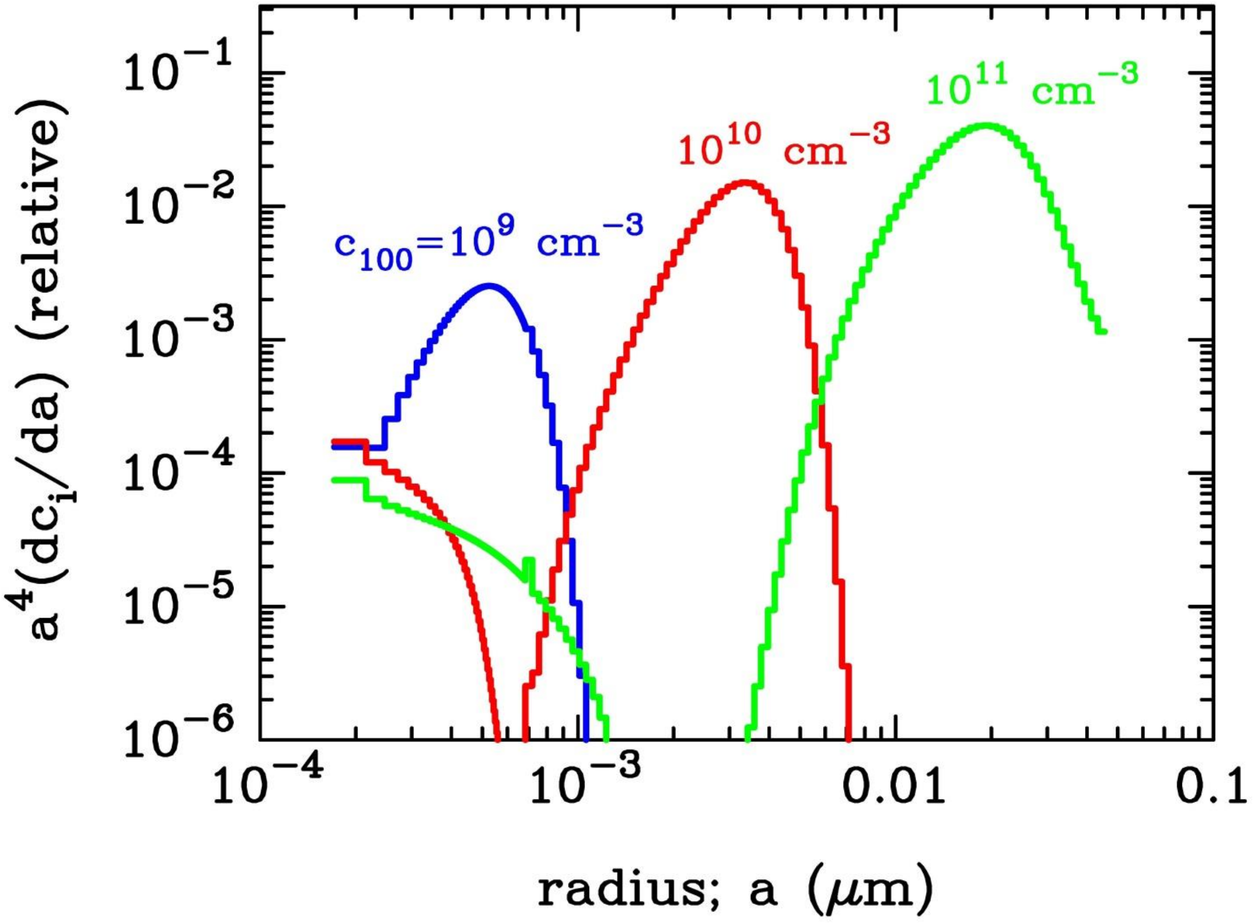




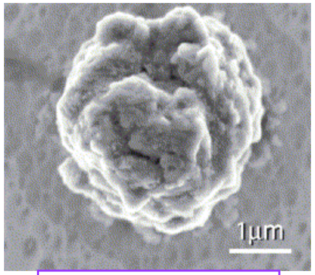
Nozawa+2015, ApJ, 811, L39

Submicron-sized presolar Al_2O_3 grains identified as SN-origin were formed in dense clumps in the ejecta

3-8. Calculated size distribution of SiC grains



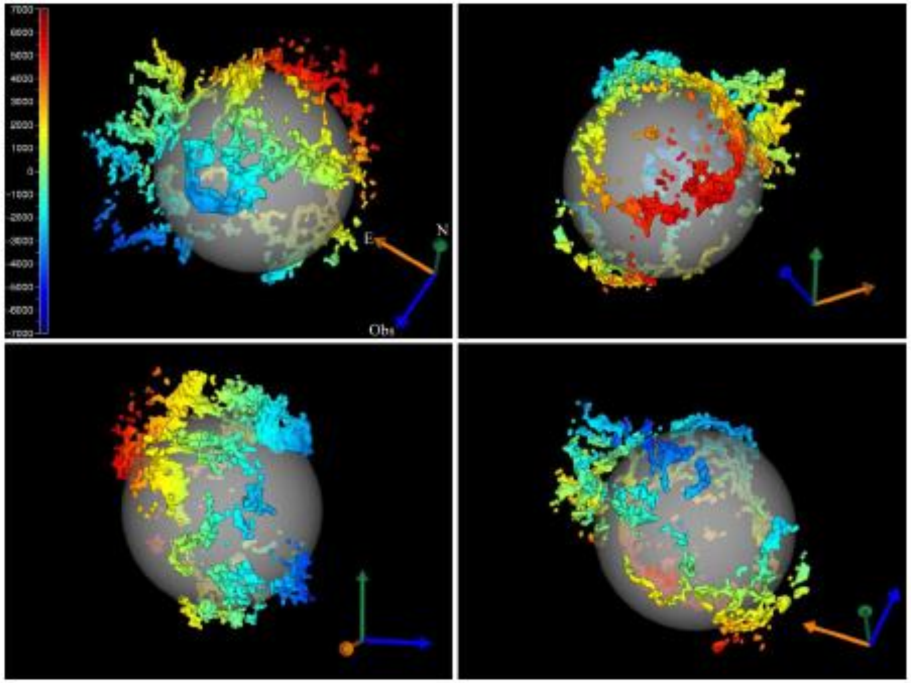
presolar SiC grains



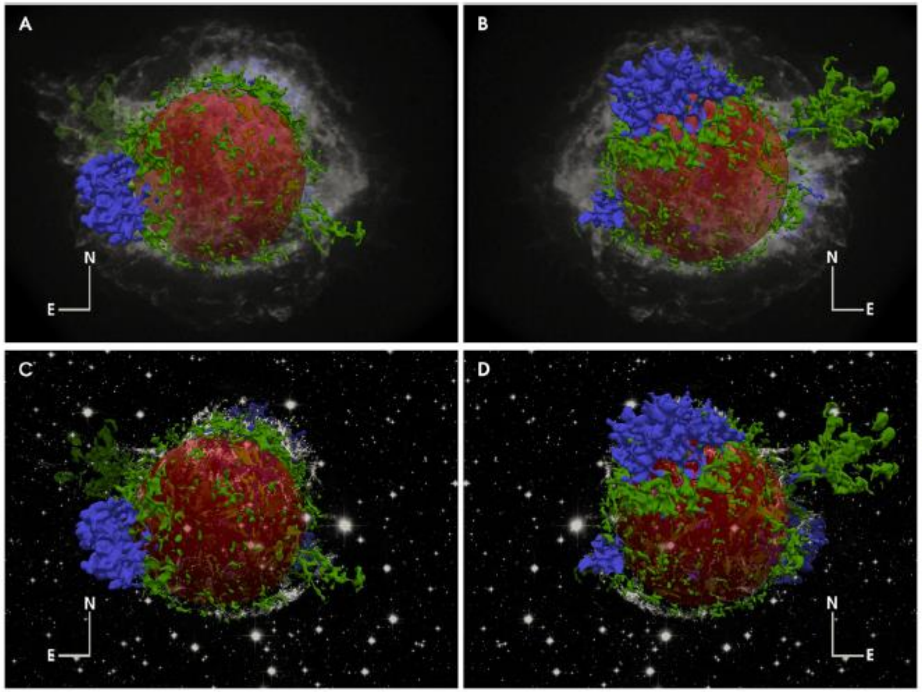
Nittler 2003

- **Radius of newly formed grains is larger for higher gas density**
- **In the density range considered in this study, grain radius is not large enough to reproduce ones observed in presolar SiC grains**

3-9. 3-D structure of Cas A SNR



Milisavljevic+2013



Orlando+2016

Calculations of dust formation and destruction in 3-D simulations of SNe/SNRs would be highly useful.

3-10. Key questions for dust formation

1. How much dust grains form?

- theoretical works ➜ 0.1-1 Msun
- FIR/submm obs. ➜ 0.1-1 Msun

2. What is the size distribution of dust?

- theory ➜ >0.1 μm in Type II, <0.01 μm in Type IIb
- obs.➜ large (~0.1-1 μm) at the dust formation

3. When do the majority of grains form?

- theory ➜ ~1-3 yr (within 5 yr; earlier is better)
- obs. ➜ ~20 yr (dust mass gradually increases with time)

4. How we tackle unsolved problems?

2. What is the size distribution of dust?

- would not easy to constrain grain sizes from optical/NIR extinction

➜ Calculations of dust formation/destruction in 3-D SN simulations are critical to predict grain sizes

➜ SN-origin presolar grains are useful tools to probe the condition of SN ejecta

3. When do the majority of grains form?

- JWST will not do a good job to answer this question

➜ SPICA will be able to resolve this problem

➜ We just expect that a supernova explosion occurs in MW/LMC/SMC in near future