2019/11/07

Dust destruction in supernova remnants

Takaya Nozawa

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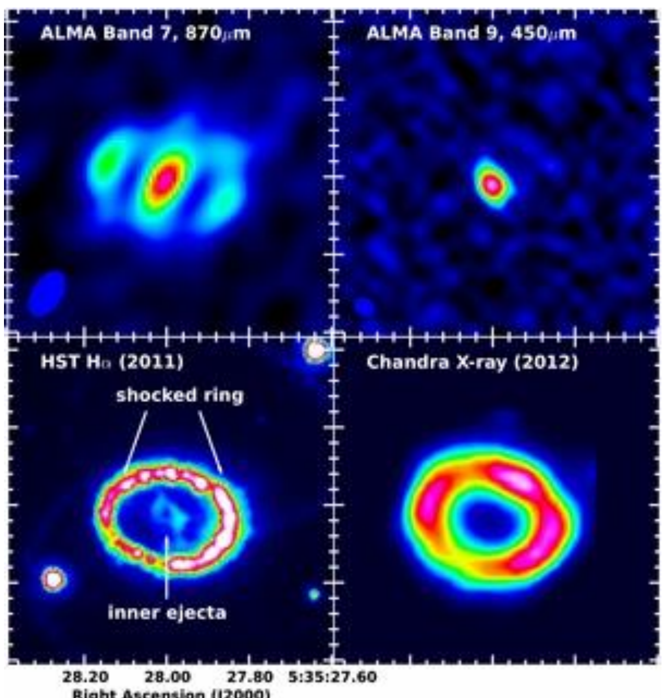
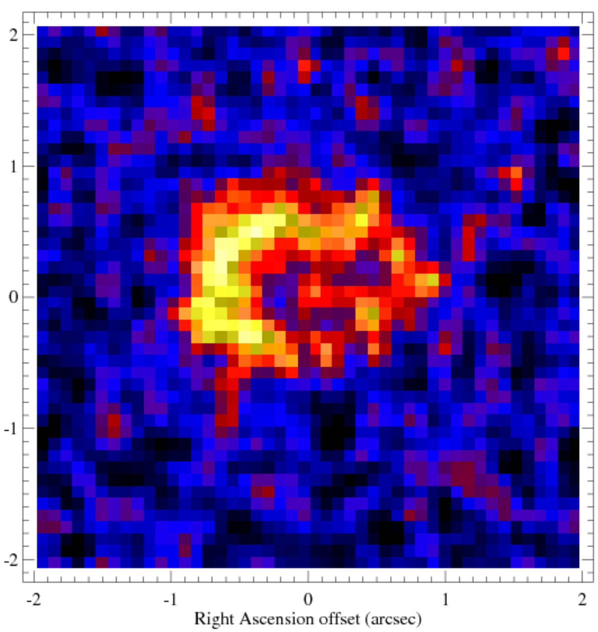
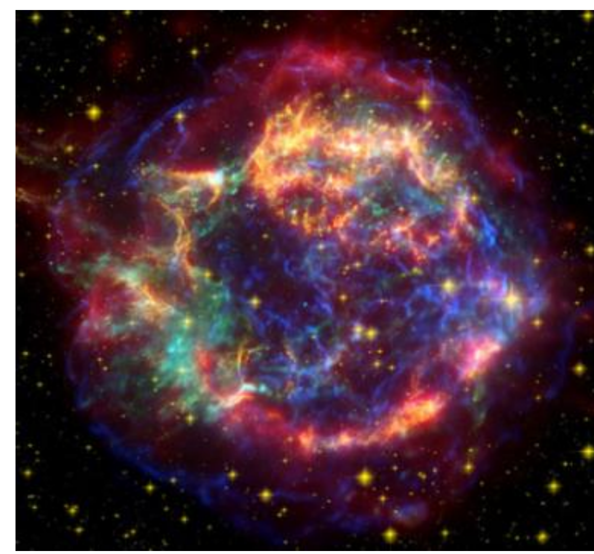
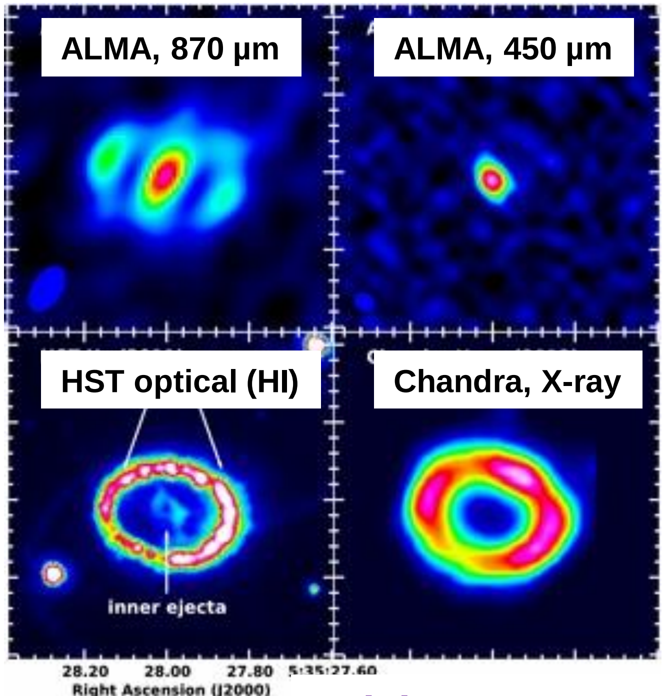






Are core-collapse supernovae (CCSNe) dust producers or dust destroyers?

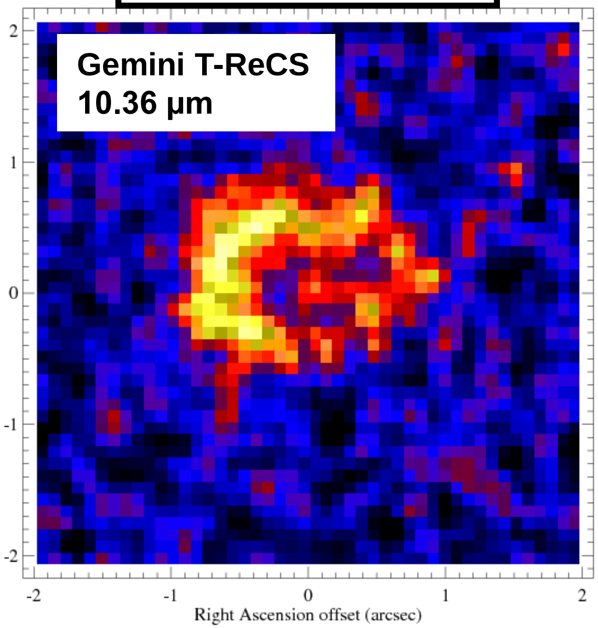
SN 1987A, submm



Indebetouw+2014

Cool dust (~20 K) of ~0.5 Msun formed in the ejecta

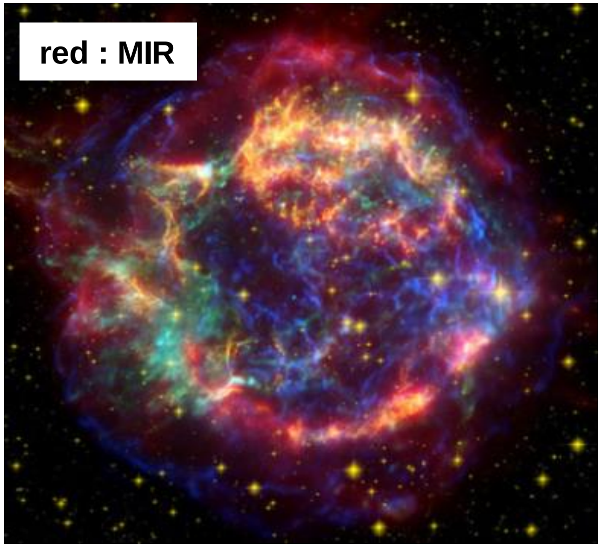
SN 1987A, MIR



Bouchet+2004

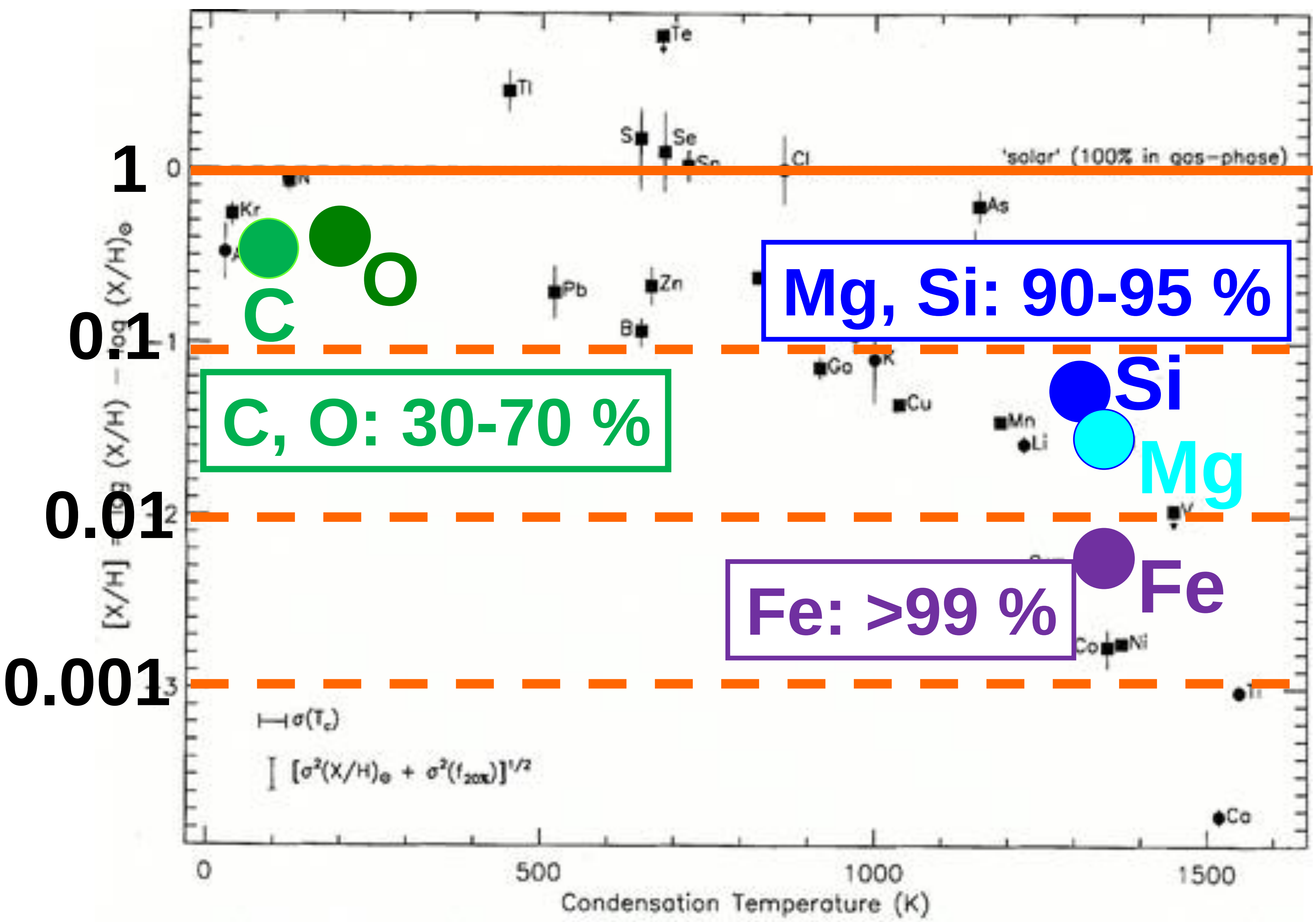
Forward shock hits and destroys dust in equatorial ring

Cas A, composite



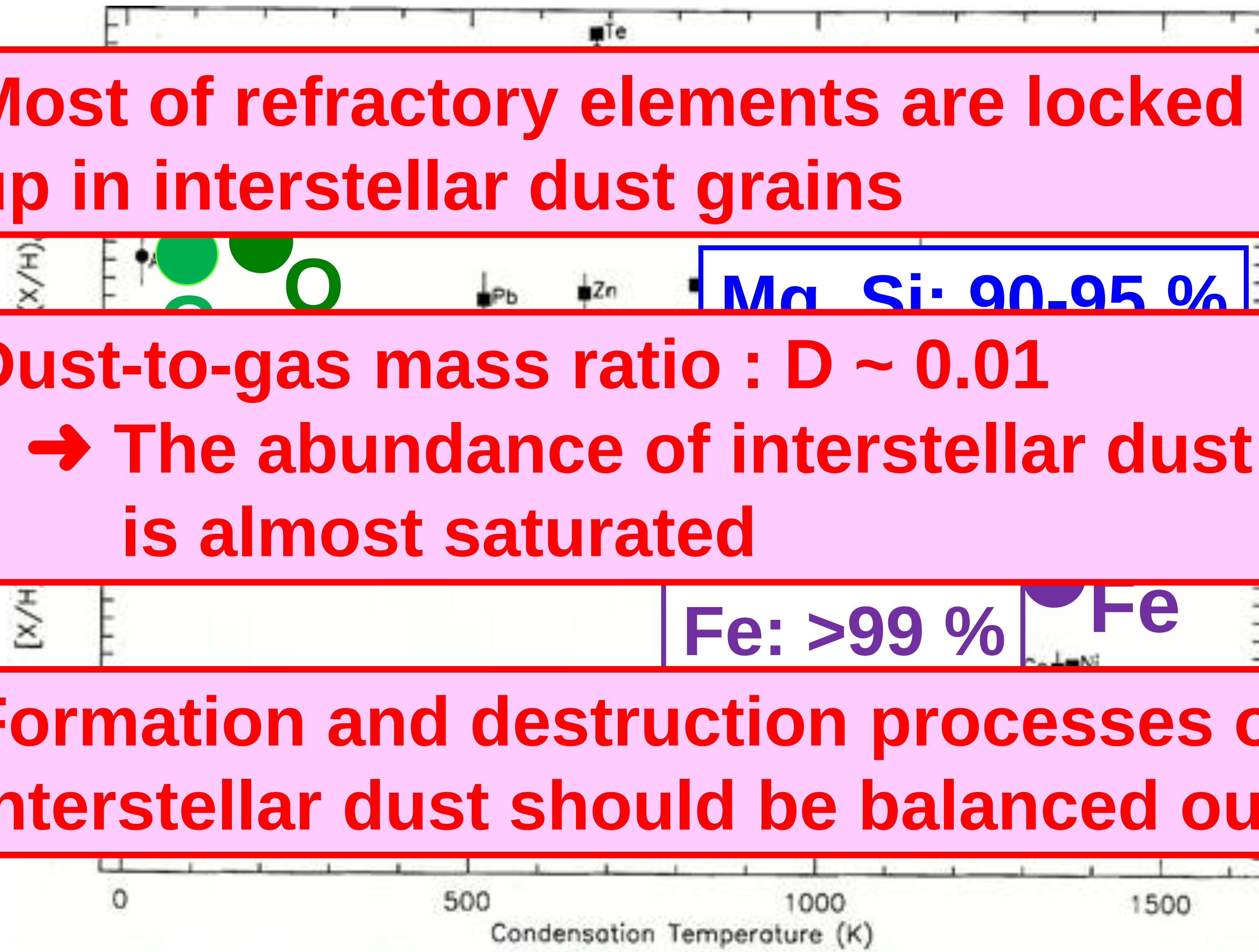
Reverse and forward shocks, respectively, destroy the ejecta dust and interstellar dust

1-1. Depletion of gas metals in the ISM



Savage & Sembach (1996, ARAA, 34, 270)

1-1. Depletion of gas metals in the ISM



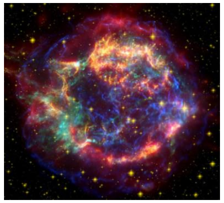
Most of refractory elements are locked up in interstellar dust grains

Dust-to-gas mass ratio : D ~ 0.01
➜ The abundance of interstellar dust is almost saturated

Formation and destruction processes of interstellar dust should be balanced out

Savage & Sembach (1996, ARAA, 34, 270)

1-2. Paradox of interstellar dust mass



SNe
0.006 Msun/yr

○ Injection rate of dust from CCSNe/AGB stars

$$\frac{dM_{\rm dust}}{dt} \simeq 0.01 \left(\frac{\phi_{\rm sf}}{4\ M_\odot\ {\rm yr}^{-1}}\right)\left(\frac{f_{\rm AGB-SN}}{0.3}\right)\left(\frac{f_{\rm gas,ejected}}{0.75}\right)\left(\frac{f_{\rm dust,form}}{0.01}\right) M_\odot\ {\rm yr}^{-1}$$

- SFR = stellar death rate
- Fraction of stars evolving to SNe/AGB
- Mass fraction of gas ejected from SNe/AGB
- Condensation efficiency of dust

AGB stars
0.004 Msun/yr

○ Destruction rate of interstellar dust by SN shocks

$$\frac{dM_{\rm dust}}{dt} \simeq -0.06 \left(\frac{R_{\rm SN}}{0.01\ {\rm yr}^{-1}}\right)\left(\frac{M_{\rm gas,swept}}{2000\ M_\odot}\right)\left(\frac{D_{\rm ISM}}{0.01}\right)\left(\frac{f_{\rm dust,dest}}{0.3}\right) M_\odot\ {\rm yr}^{-1}$$

- SN rate
- Gas mass swept by a SN shock
- Dust-to-gas mass ratio
- Destruction efficiency of dust

Formation rate of dust in stellar sources is lower than destruction rate of dust

➜ Interstellar dust must decrease with time

1-3. What is wrong?

○ Underestimate dust condensation efficiency

- CCSNe eject ~10 M_{sun} gas and ~0.5 M_{sun} dust

  $f_{dust,form}$ = 0.05

  ~90% of dust destroyed by reverse shocks

  $f_{dust,form}$ = 0.005 ($M_{dust,form}$ ~ 0.05 M_{sun} per SN)

○ Overestimate dust destruction efficiency

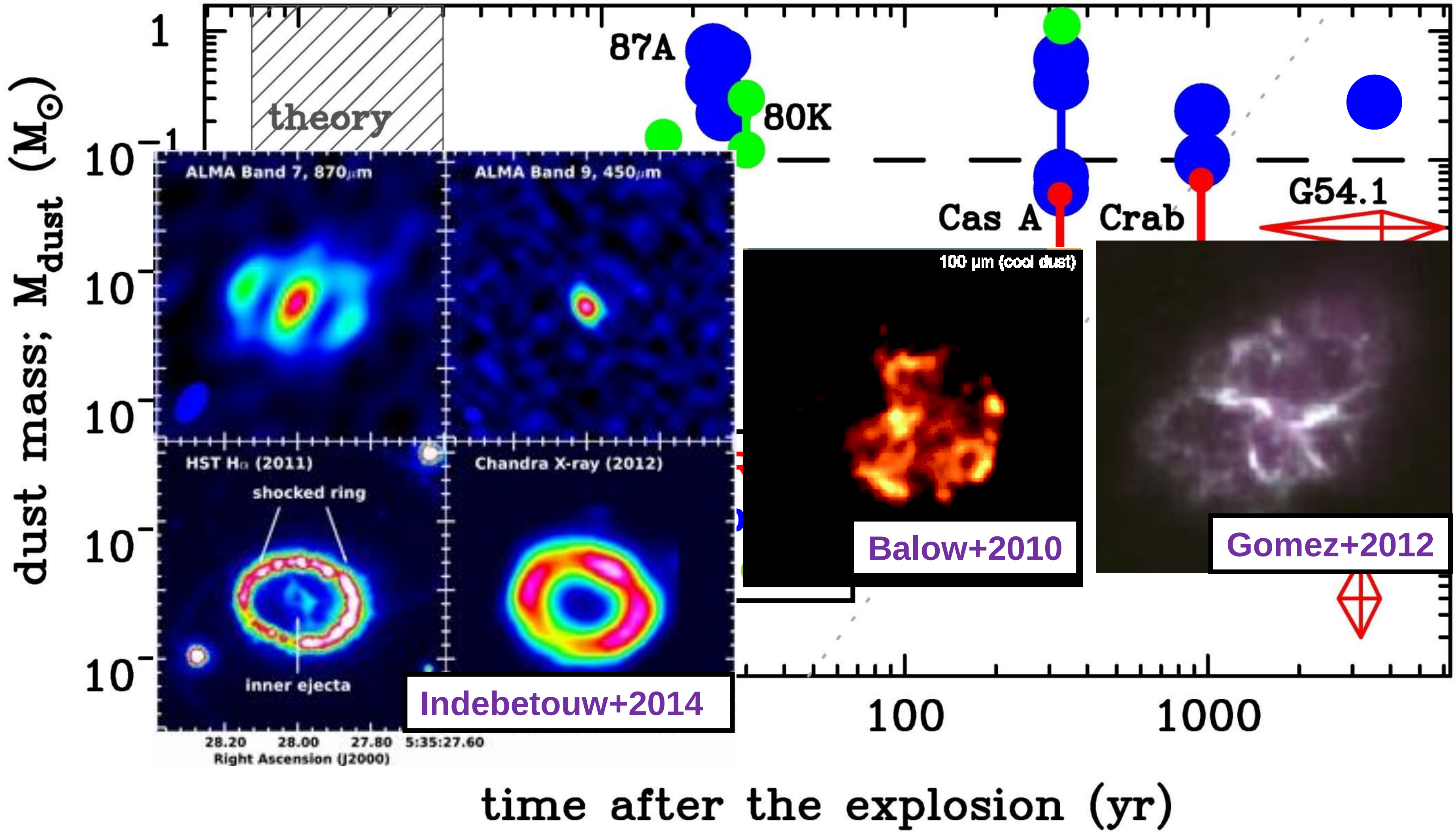
- $M_{dust, dest}$ ~ 6 M_{sun} per SN ~ 2000 M_{sun} x 0.01 x 0.3

  There is uncertainties in destruction efficiency

○ Other sources of interstellar dust?

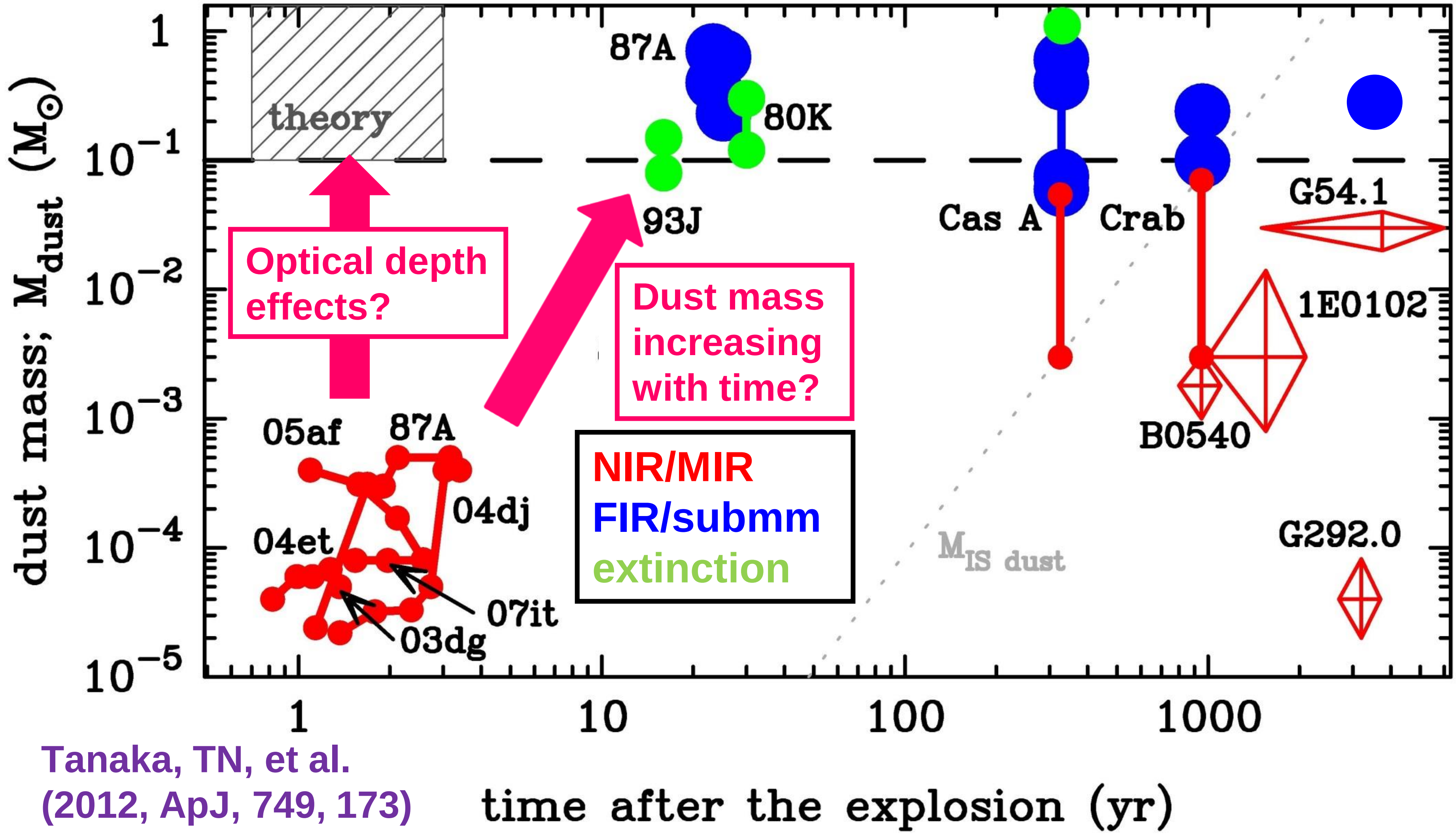
- RGs, RSGs, sAGB stars, LBVs, WR stars, novae, …
- Grain growth in molecular clouds

2-1. Observed dust mass in CCSNe/SNRs



Dust mass formed in the ejecta is dominated by cold dust

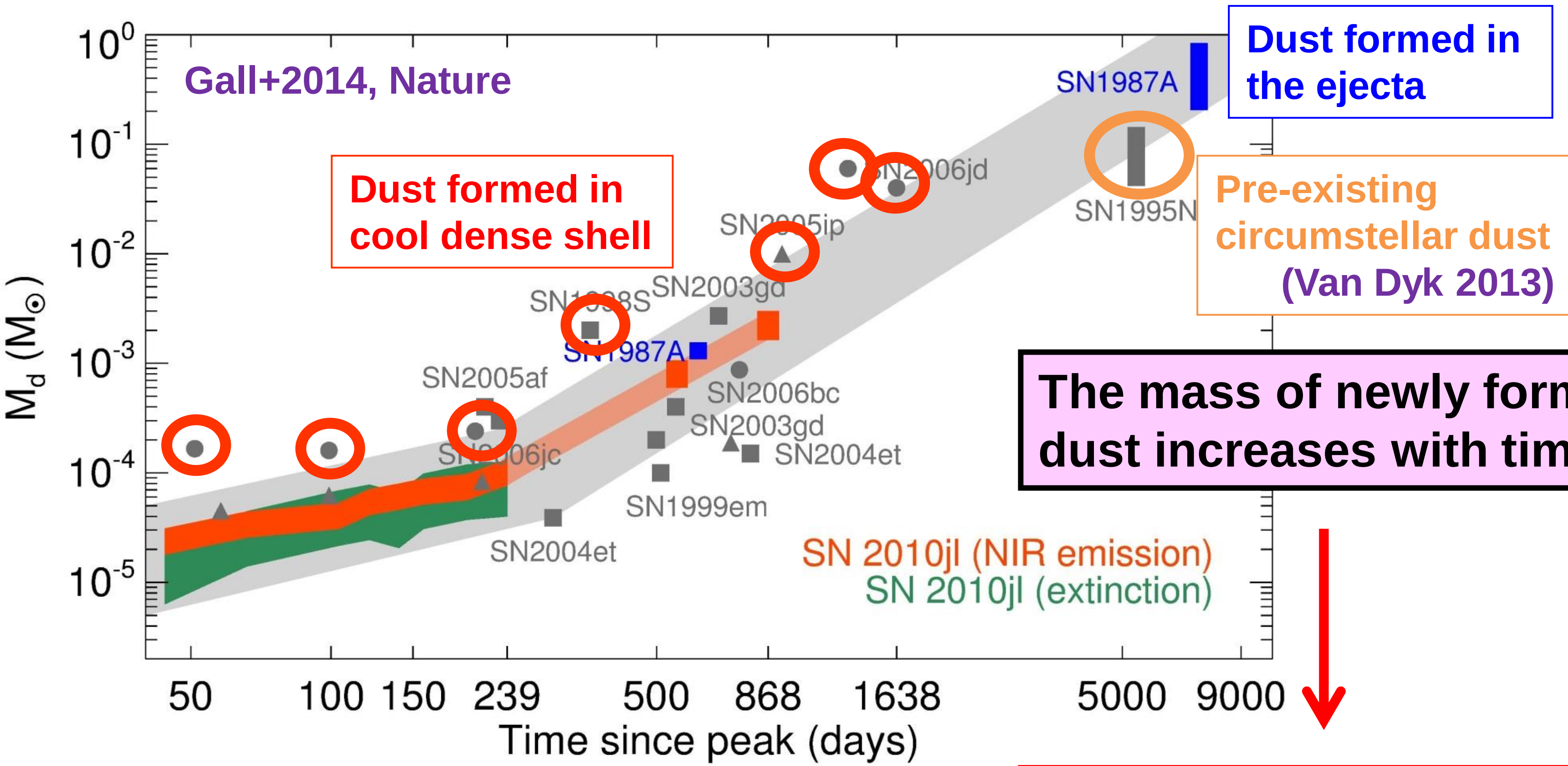
2-1. Observed dust mass in CCSNe/SNRs



Tanaka, TN, et al.
(2012, ApJ, 749, 173)

Dust mass formed in the ejecta is dominated by cold dust

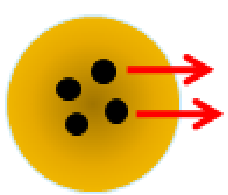
2-2. Mass of SN dust increases with time?



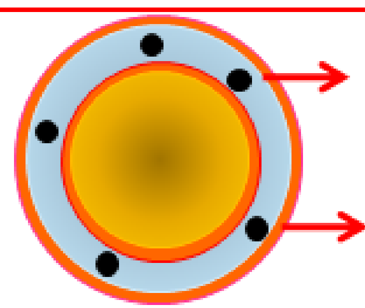
The mass of newly formed dust increases with time?

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



2-3. Timescale of grain growth

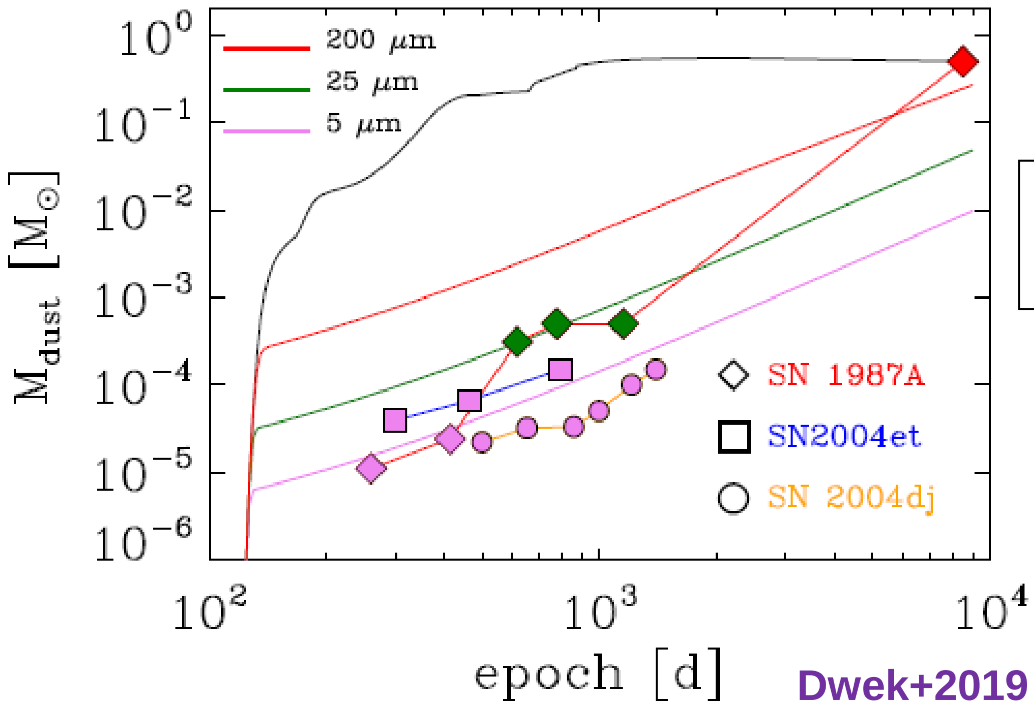
$$\tau_{\rm grow}^{-1} = \frac{1}{a}\left(\frac{da}{dt}\right) = \left(\frac{1}{a}\right)\eta_g \Omega_0 c_1 \left(\frac{kT}{2\pi m_1}\right)^{\frac{1}{2}}$$

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

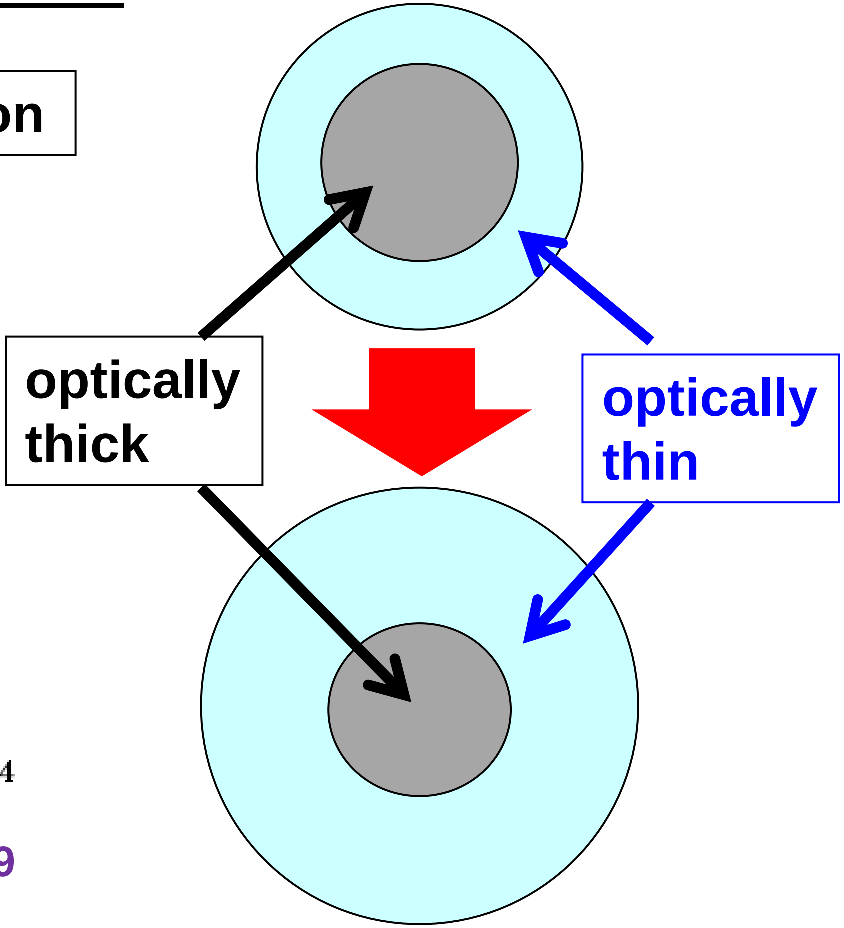
At 20 yr, the gas density is too low to form dust grains in the freely expanding ejecta

2-4. Optical depth effects?

Apparent dust mass from IR emission

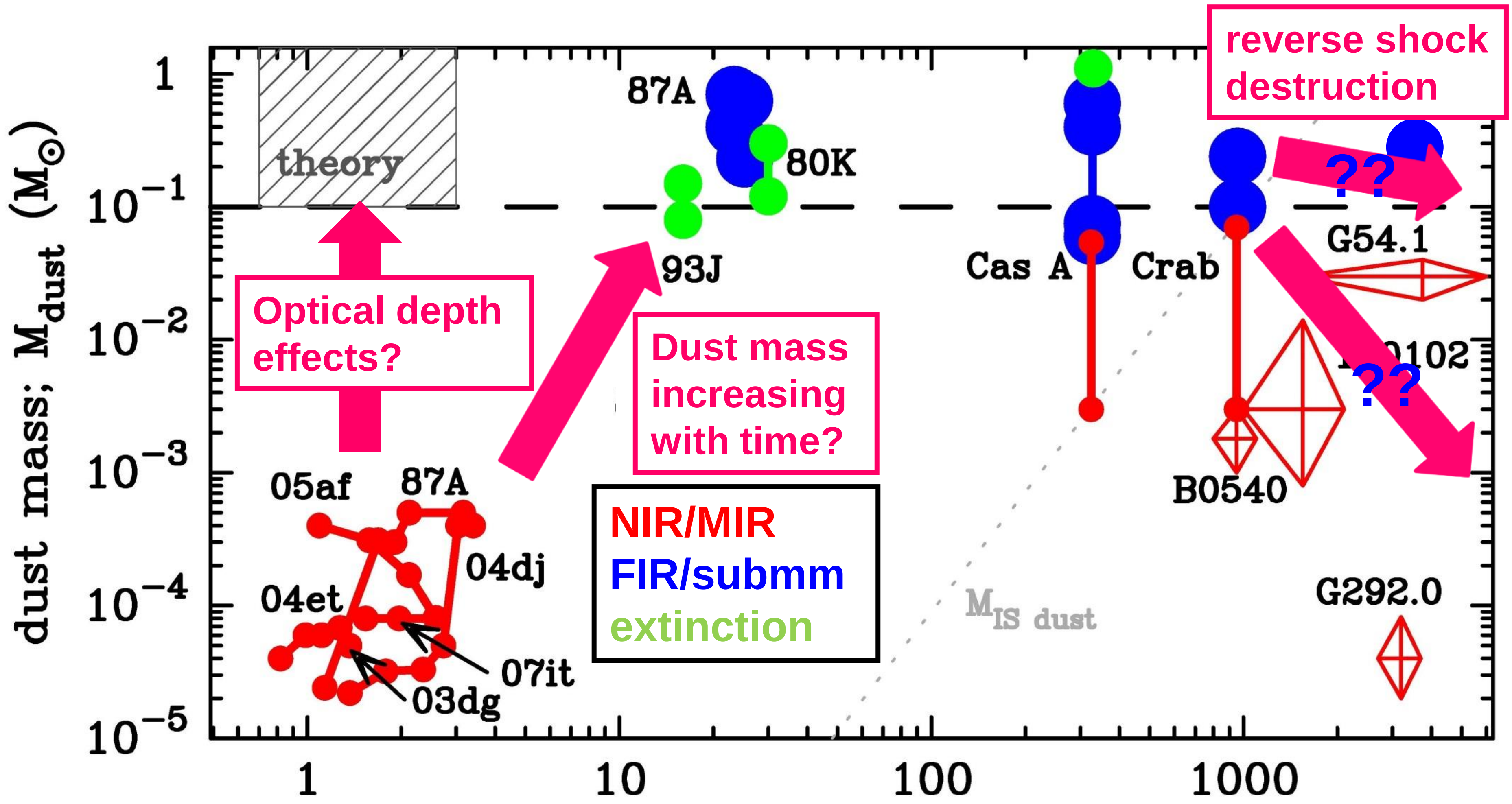


Dwek+2019



- Dust formation can be completed until a few years
- The apparent increase in dust mass may be due to opacity effects of dust thermal emission

3-1. Observed dust mass in CCSNe/SNRs

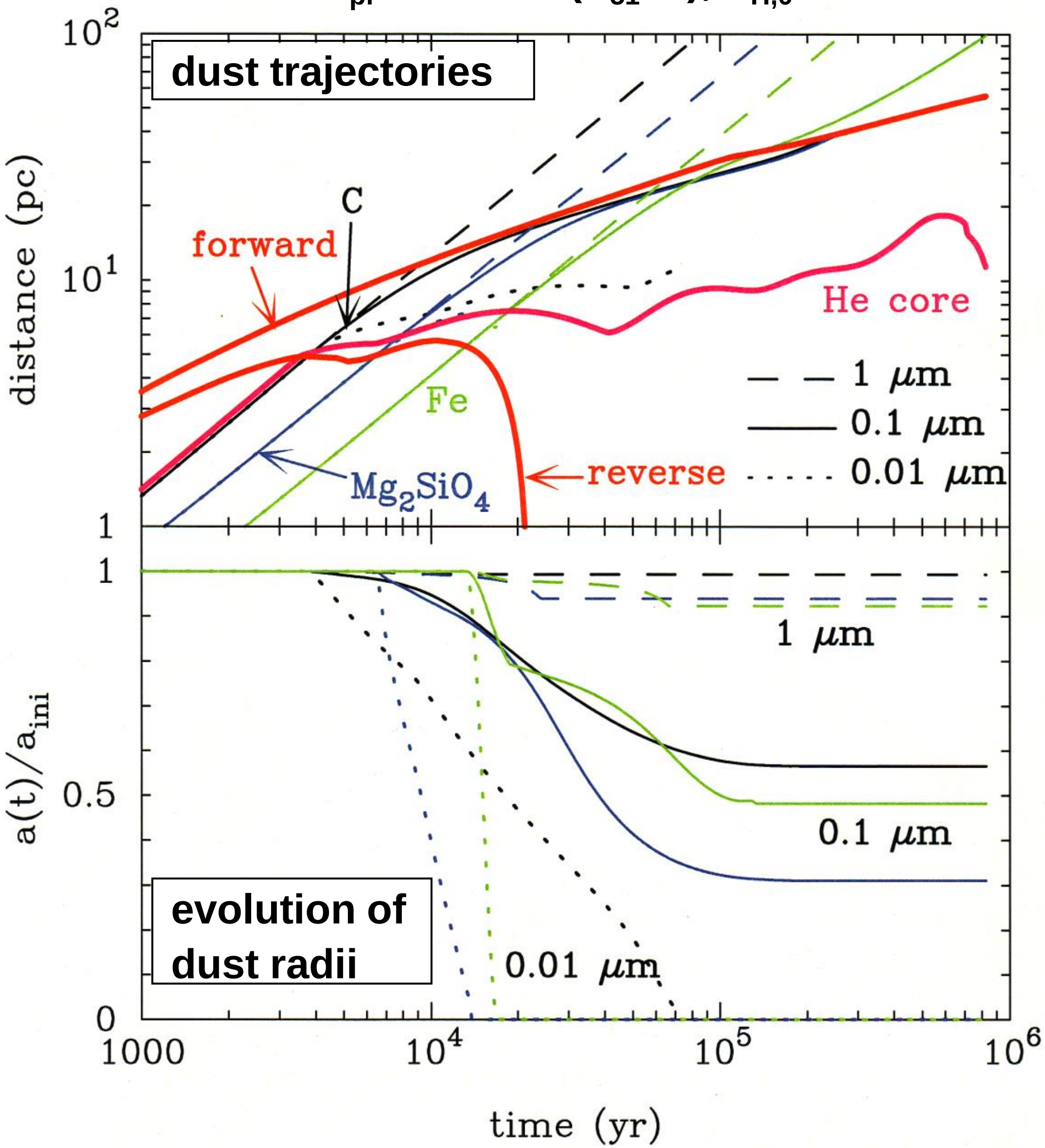


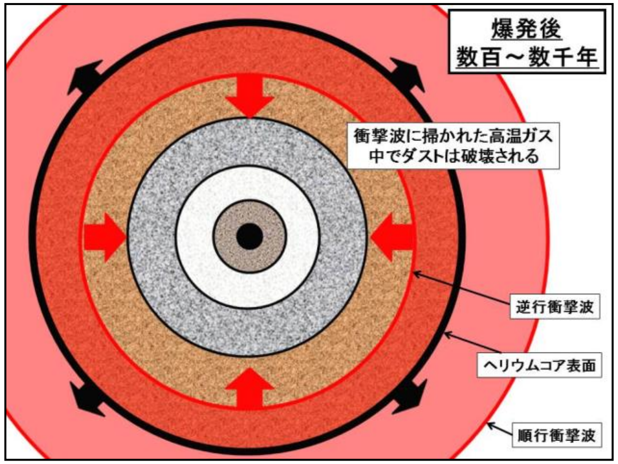
Tanaka, TN, et al.
(2012, ApJ, 749, 173)

Dust mass formed in the ejecta is dominated by cold dust

3-2. Evolution of dust in SNRs

Model : M_{pr}= 20 Msun (E_{51}=1), $n_{H,0}$ = 1 cm^{-3}





The evolution of dust heavily depends on the initial radius and composition

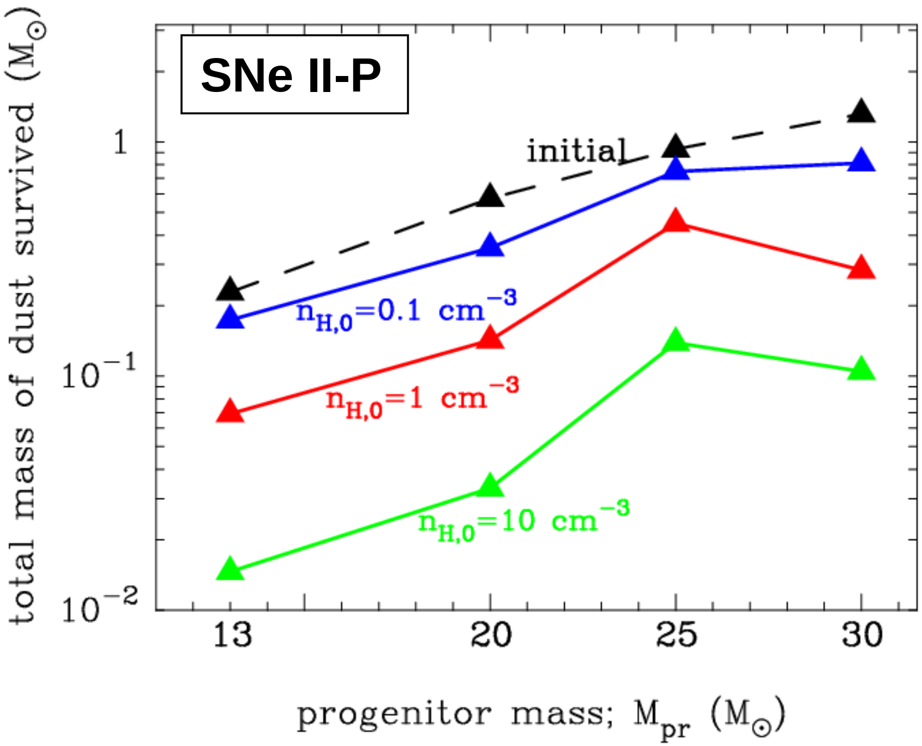
a_{ini} = 0.01 μm (dotted lines)
➔ completely destroyed

a_{ini} = 0.1 μm (solid lines)
➔ trapped in the shell

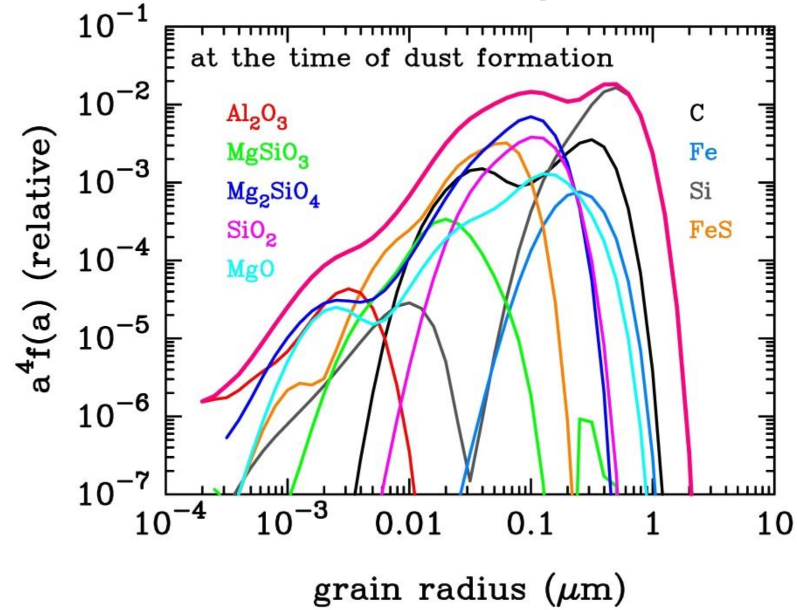
a_{ini} = 1 μm (dashed lines)
➔ injected into the ISM

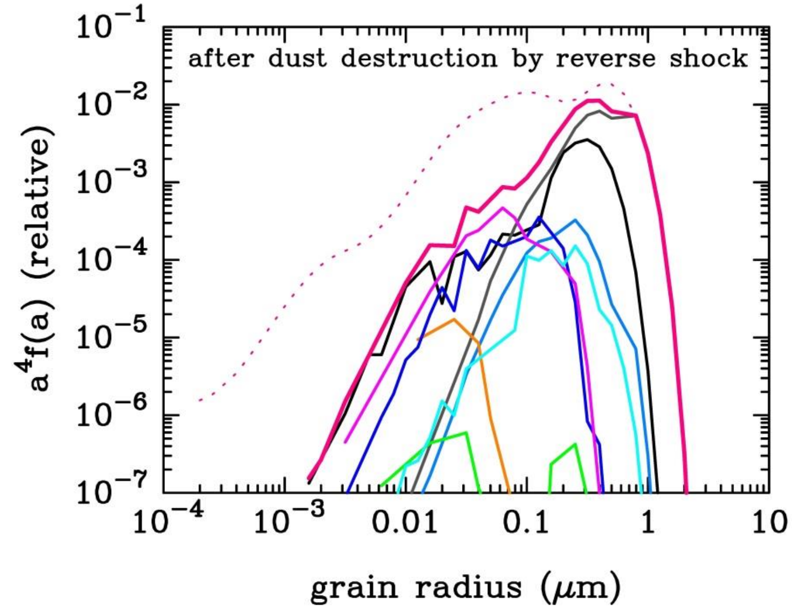
Nozawa+07, ApJ, 666, 955

3-3. Dust mass and size ejected from SNe



Nozawa+07, ApJ, 666, 955



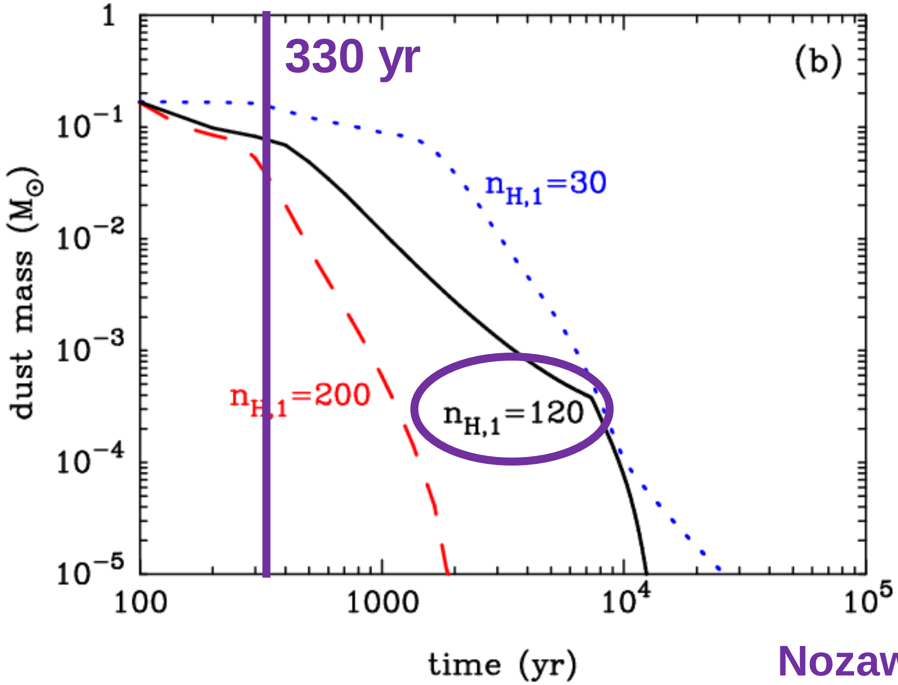


total mass of dust surviving the destruction in Type II SNRs; 0.07-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

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

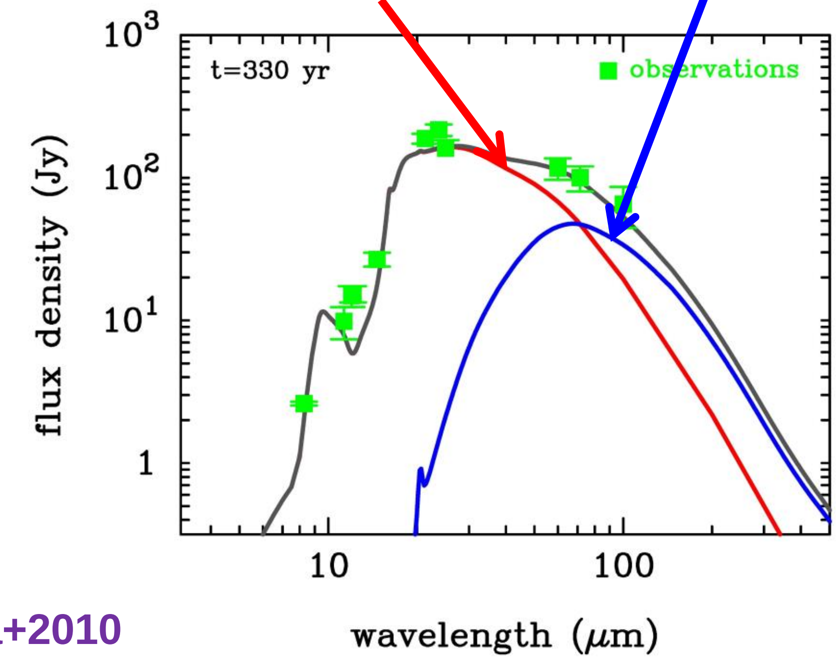
3-4. Destruction of dust in Cas A SNR

Dust mass for SNe IIb model



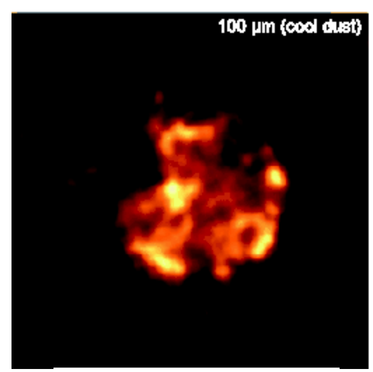
0.008Msun of shocked warm dust

0.07Msun of unshocked cool dust

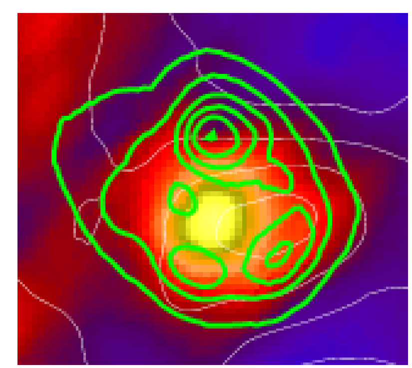


Nozawa+2010

- **All newly formed grains are destroyed by reverse shock**
- **FIR observations**
  $M_{d,cool}$ ~ 0.06 Msun
  T_{dust} ~ 35 K



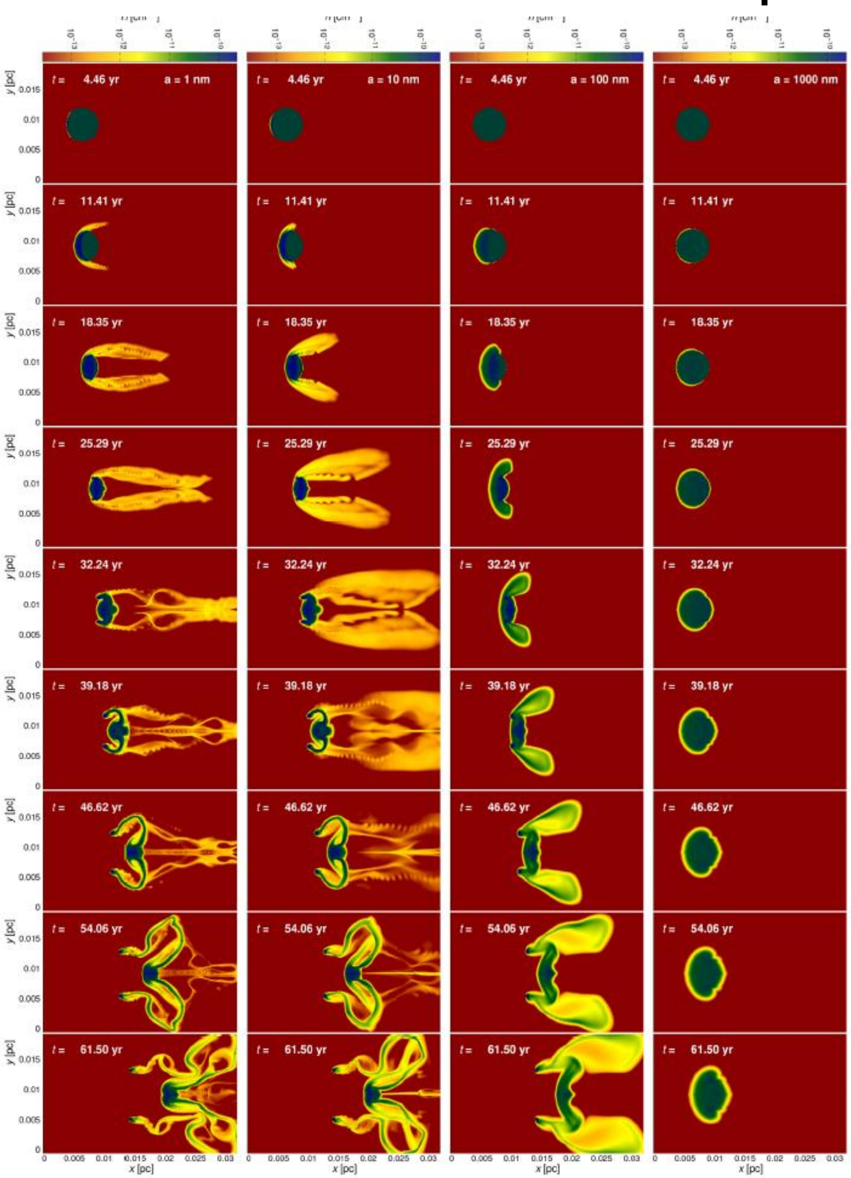
Balow+2011

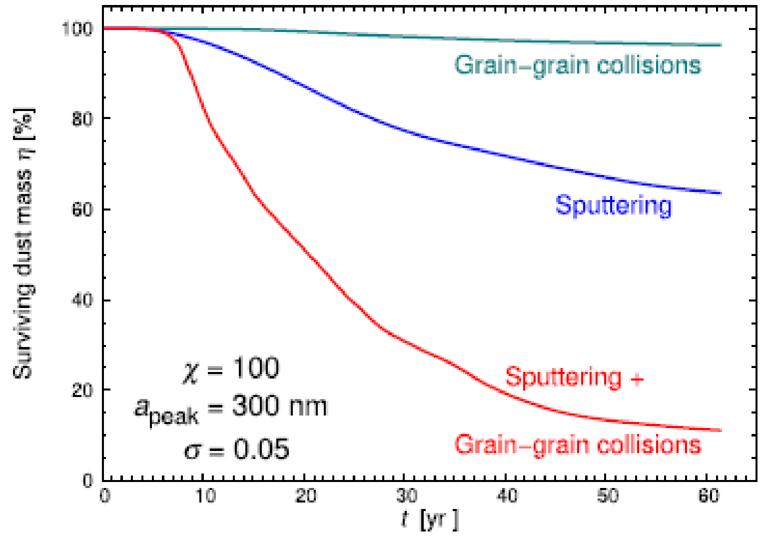


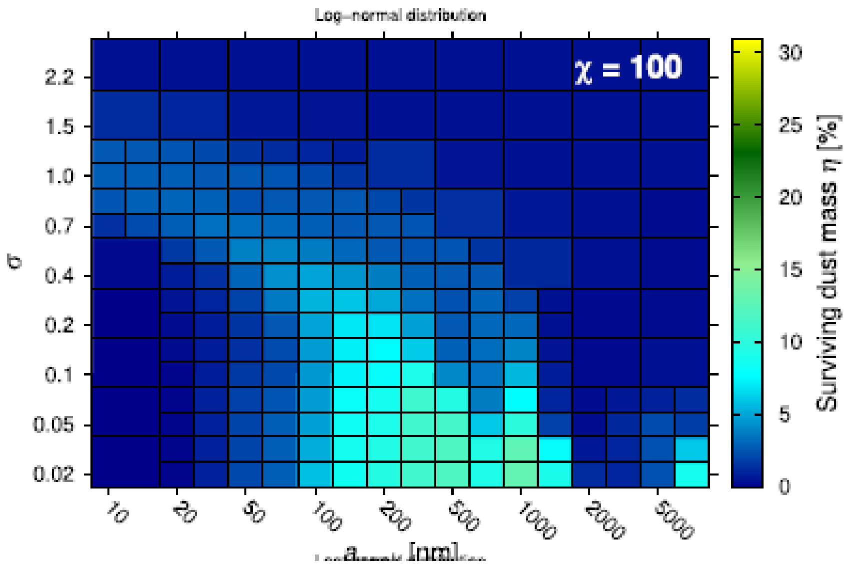
Sibthorpe+2010

3-5. Dust destruction in clumpy gas

a = 0.001 a = 0.01 a = 0.1 a = 1 μm







Kirchschlager+2019

3-6. How much dust grains are destroyed?

- Theoretical studies predict that too much dust grains would be destroyed in the shocked gas
  ➜ destruction fraction : f_{dest} = 0.3-1.0

- Dust destruction efficiency heavily depends on the initial grain size and gas density
  ➜ need the dust formation and destruction calculations based on 3D ejecta structures

- There are uncertainties in the efficiency of dust destruction by sputtering
  ➜ need the re-evaluation of sputtering yields theoretically and observationally

Summary of this talk

- Are CCSNe producers or destroyers of dust?

➜ $M_{dust, form}$ = 0.01-0.1 M_{sun} per SN

➜ $M_{dust, dest}$ = 5-10 M_{sun} per SNR

- When do dust grains form in the SN ejecta?

➜ observationally : ~20 yr (increase with time)

➜ theoretically : ~2-3 yr

- What fraction of dust can be destroyed by the reverse shock?

➜ f_{dest} = 0.3-1.0 (surviving dust mass: f_{surv} = 0-0.7)

➜ need the 3-D dust formation/destruction and re-evaluation of sputtering yield