2014/08/07

Dust production in a variety of types of supernovae

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0-1. Introduction

Supernovae (SNe) are major sources of dust?

- huge amounts of dust grains (>10^8 M_{sun}) are detected in host galaxies of quasars at redshift z > 5 (the cosmic age < 1 Gyr)

  ➔ core-collapse SNe (CCSNe) generating from short-lived massive stars must predominantly supply dust to the ISM

- contribution of dust mass from AGB stars and CCSNe in the MW

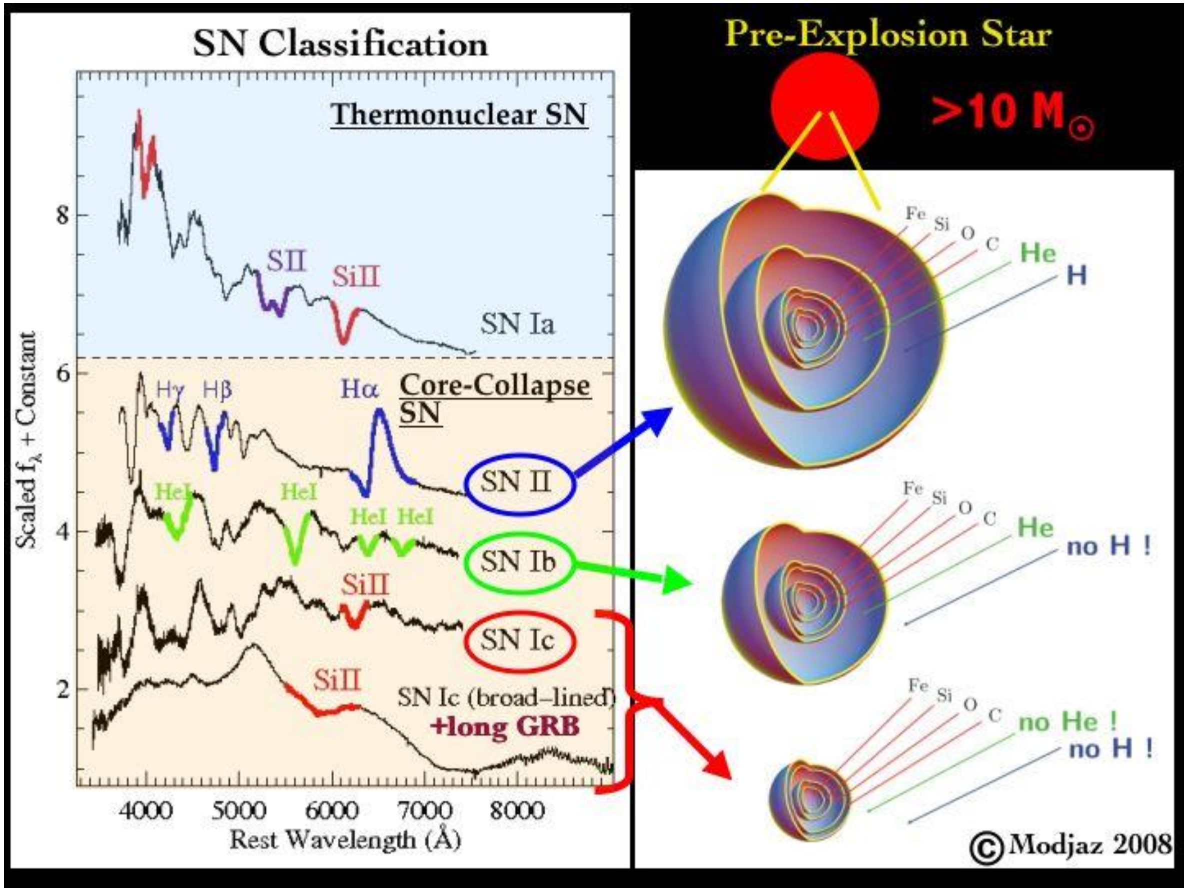
  n(CCSNe) / n(AGB stars) ~ 0.05-0.1 (Salpeter IMF)

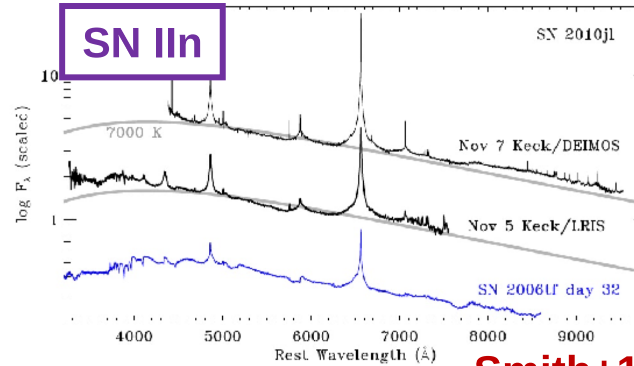
  M_{dust} = 0.01-0.05 M_{sun} per AGB star (Zhukovska & Gail 2008)
  M_{dust} = 0.1-1.0 M_{sun} per SN (e.g., Nozawa et al. 2003, 2007)

  ➔ contribution of interstellar dust from CCSNe is comparable with that from AGB stars

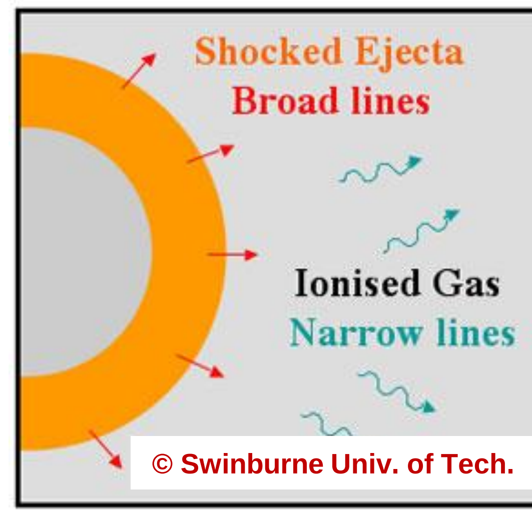
what composition, size, and mass of dust are ejected by CCSNe?

0-2. Classification of core-collapse SNe





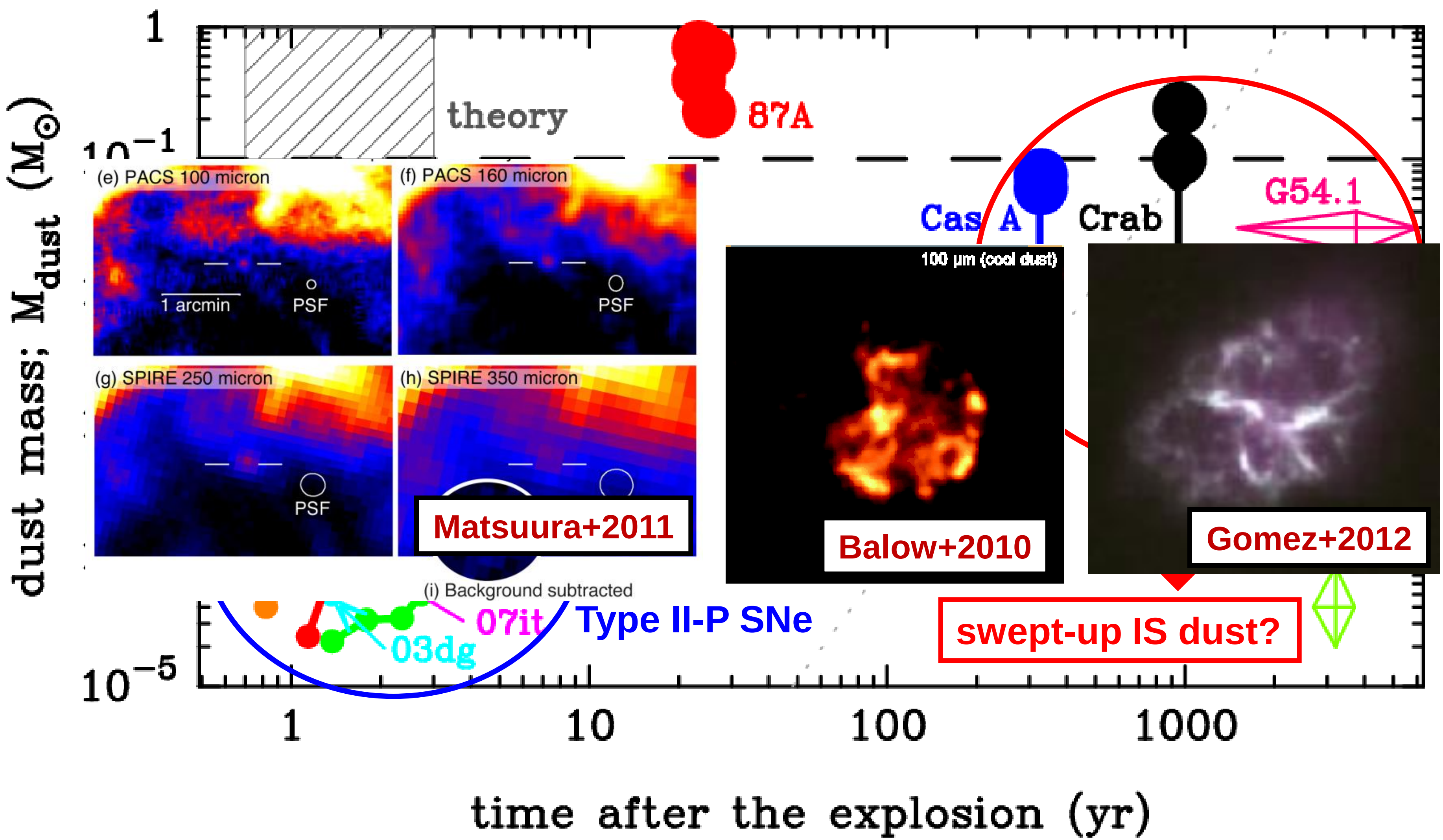
Smith+11



- Type II SNe (SNe II-P) ➜ massive hydrogen envelope
- Type IIb/Ib SNe (SNe IIb/Ib) ➜ very little/no hydrogen envelope
- Type Ic SNe (SNe Ic) ➜ no helium and hydrogen envelope
- Type IIn SNe ➜ dense (massive) circumstellar medium

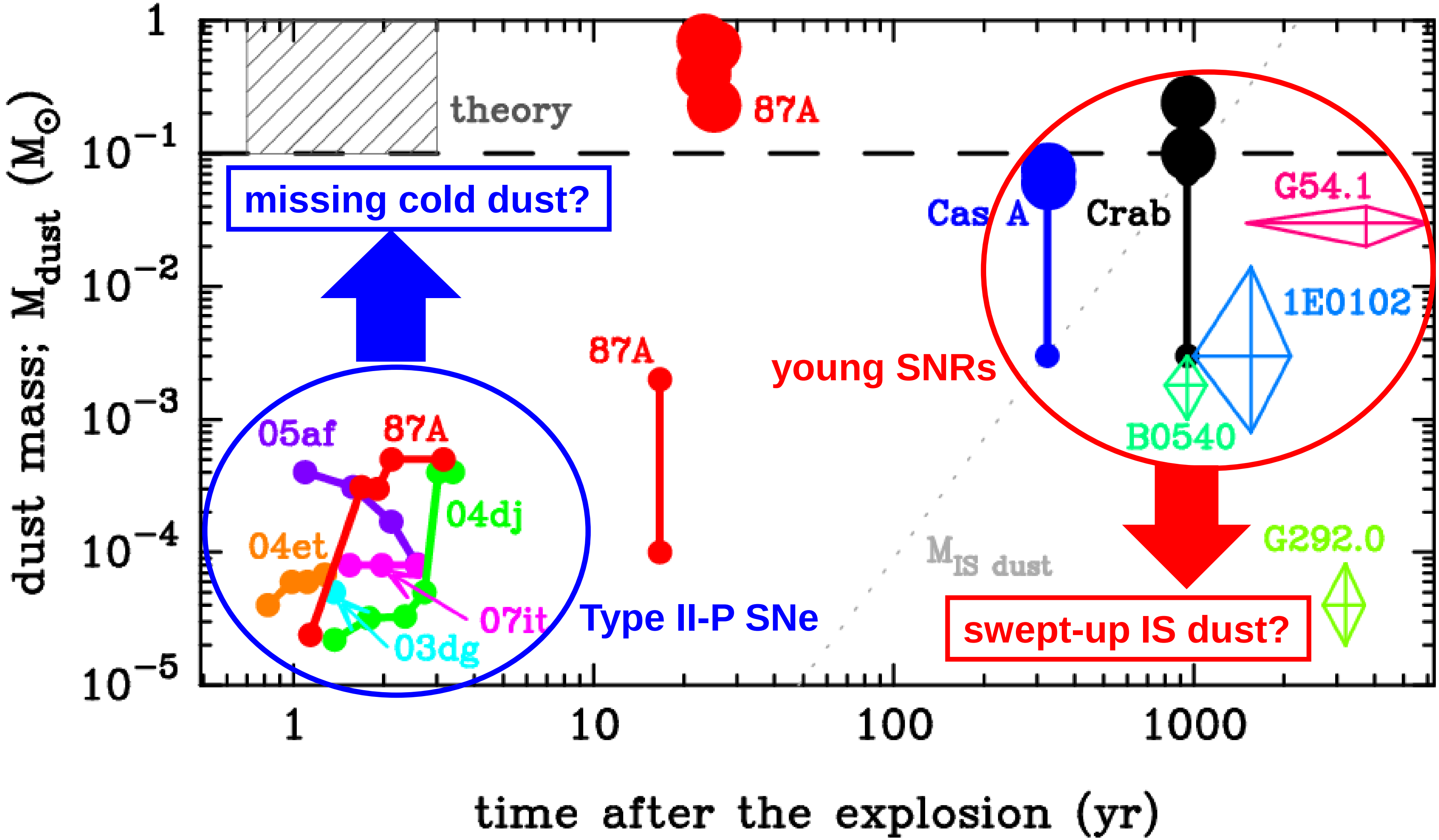
1. Observations of dust formation in SNe (and SNRs)

1-1. Summary of observed dust mass in CCSNe



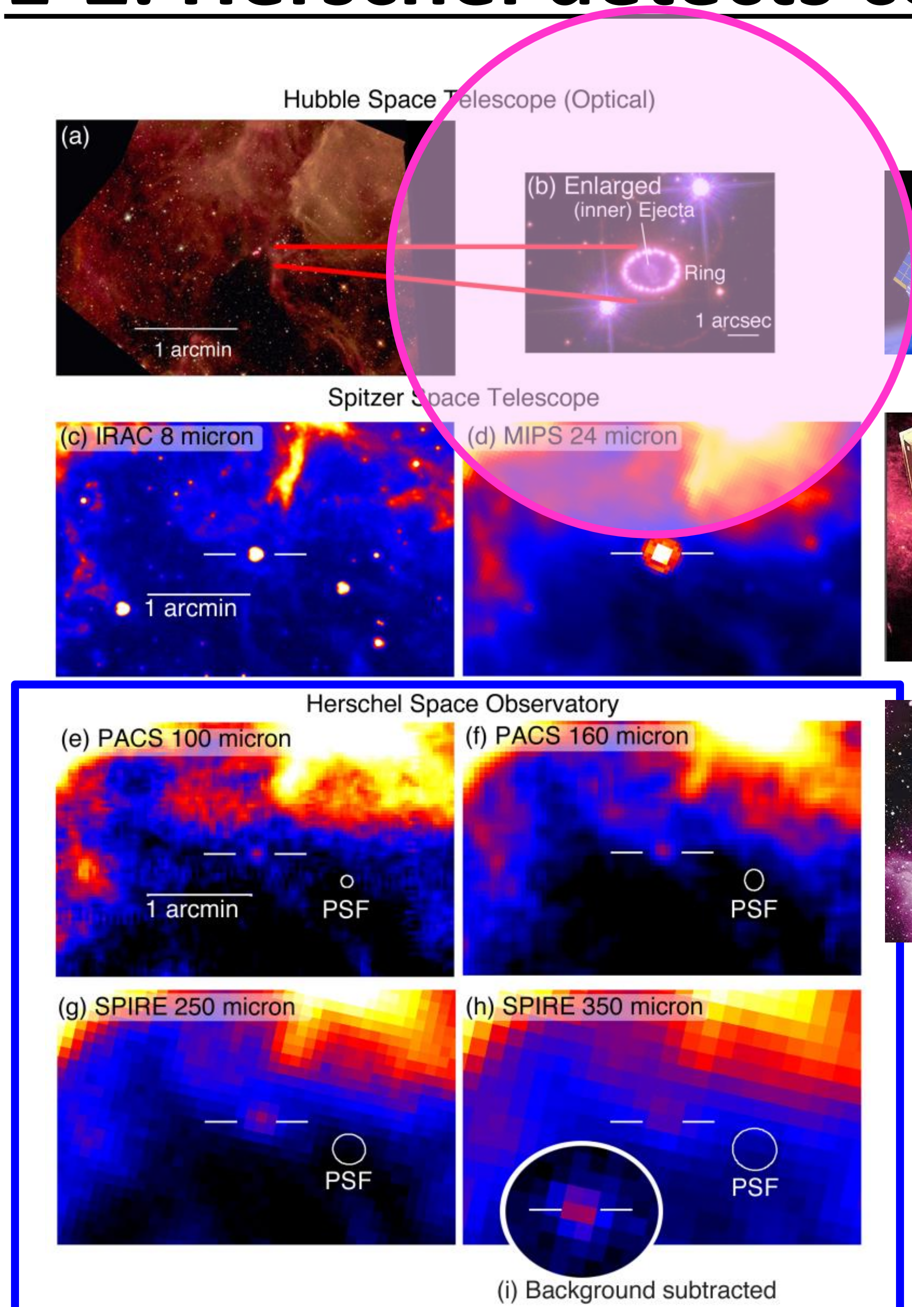
Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe

1-1. Summary of observed dust mass in CCSNe

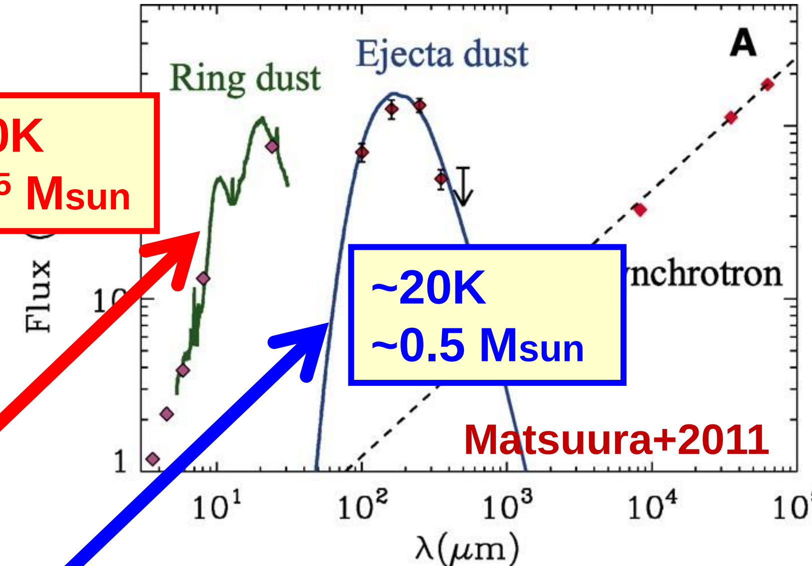


Far-IR to sub-mm observations are essential for revealing the mass of dust grains produced in the ejecta of SNe

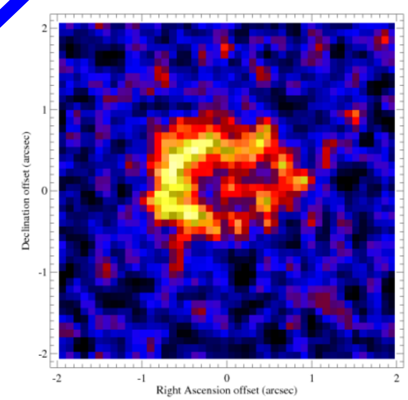
1-2. Herschel detects cool dust in SN 1987A



~180K
~10^{-5} Msun



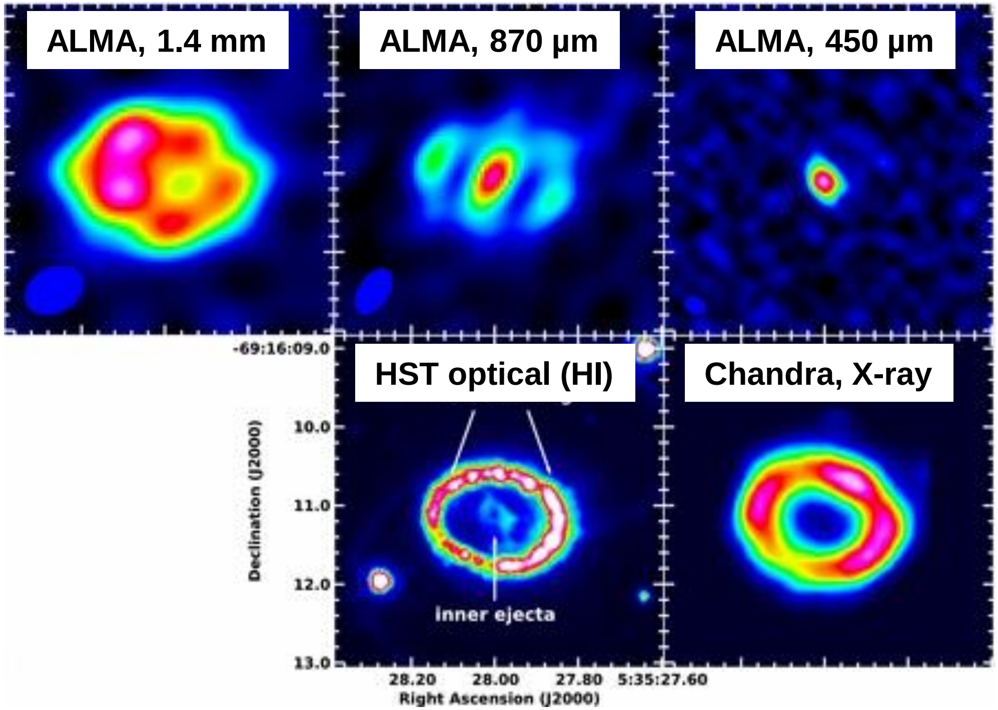
~20K
~0.5 Msun



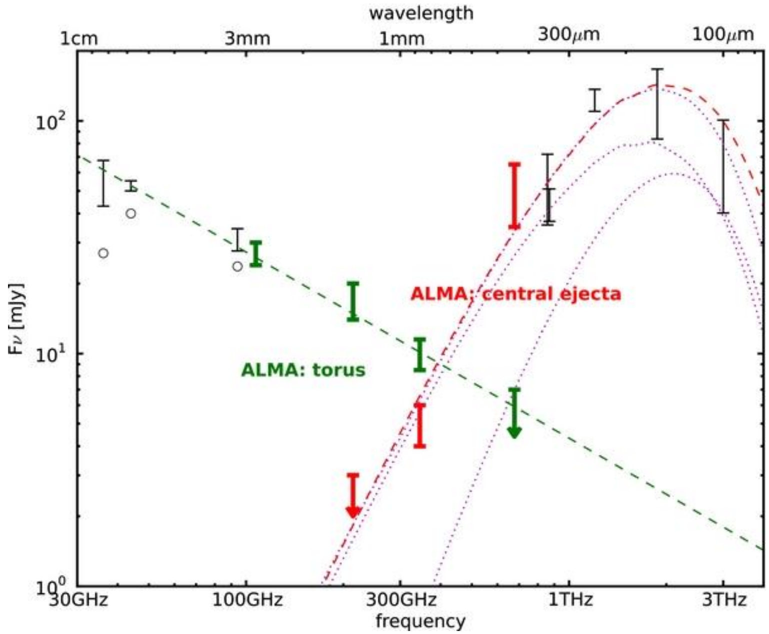
on 4 Oct 2003
Gemini T-ReCS
(λ = 10.36 μm)
2 pixels : 0.18”
(Bouchet+04)

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

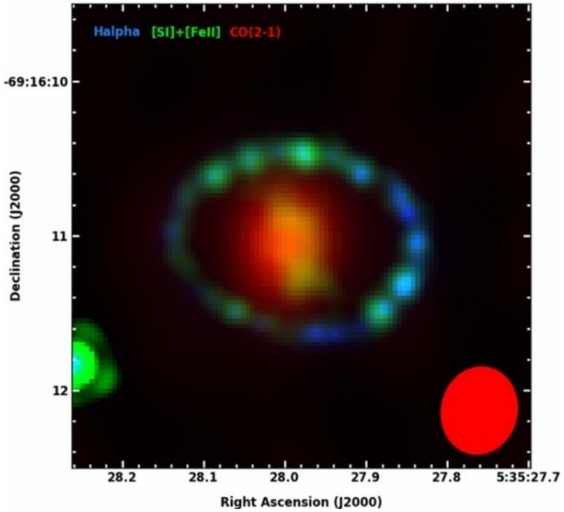
1-3. ALMA reveals dust formed in SN 1987A



SED of 25-years old SN 1987A



Indebetouw+2014



blue: Hα
green: 1.6 μm
red: CO(2-1)

➜ >0.1 Msun of CO

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

1-4. Possible target: SNR 1E0102-72.3 in SMC

Are there any other candidates of SNe/SNRs in which massive cool dust grains can be detected with ALMA?

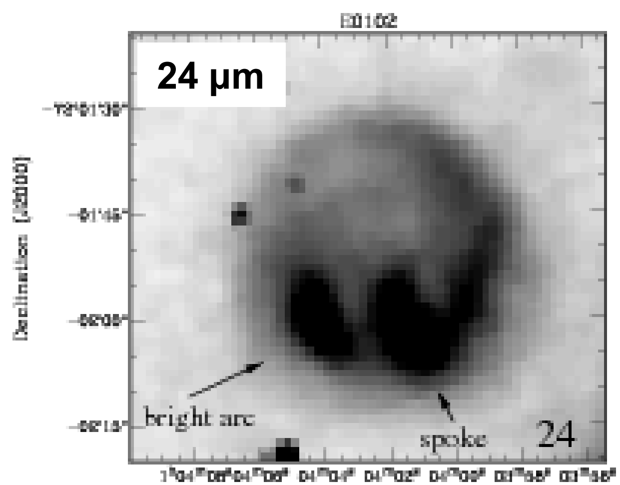
➜ **extragalactic SNe are too far (D > 1 Mpc) to detect the thermal emission from cool dust in SNe even with ALMA**

➜ **young Galactic SNRs are too extended (θ > 1 arcmin) for the good spatial resolution of ALMA (~0.1 arcsec)**

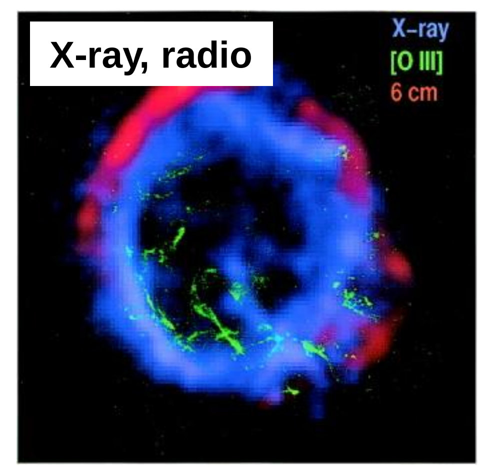
young (compact) SNRs in LMC/SMC !!

▪ SNR 1E0102-72.3

- O-rich (Type Ib?)
- age : ~1000 yr
- Mwarm ~ 10^{-3} Msun
- Mcool ~ ???

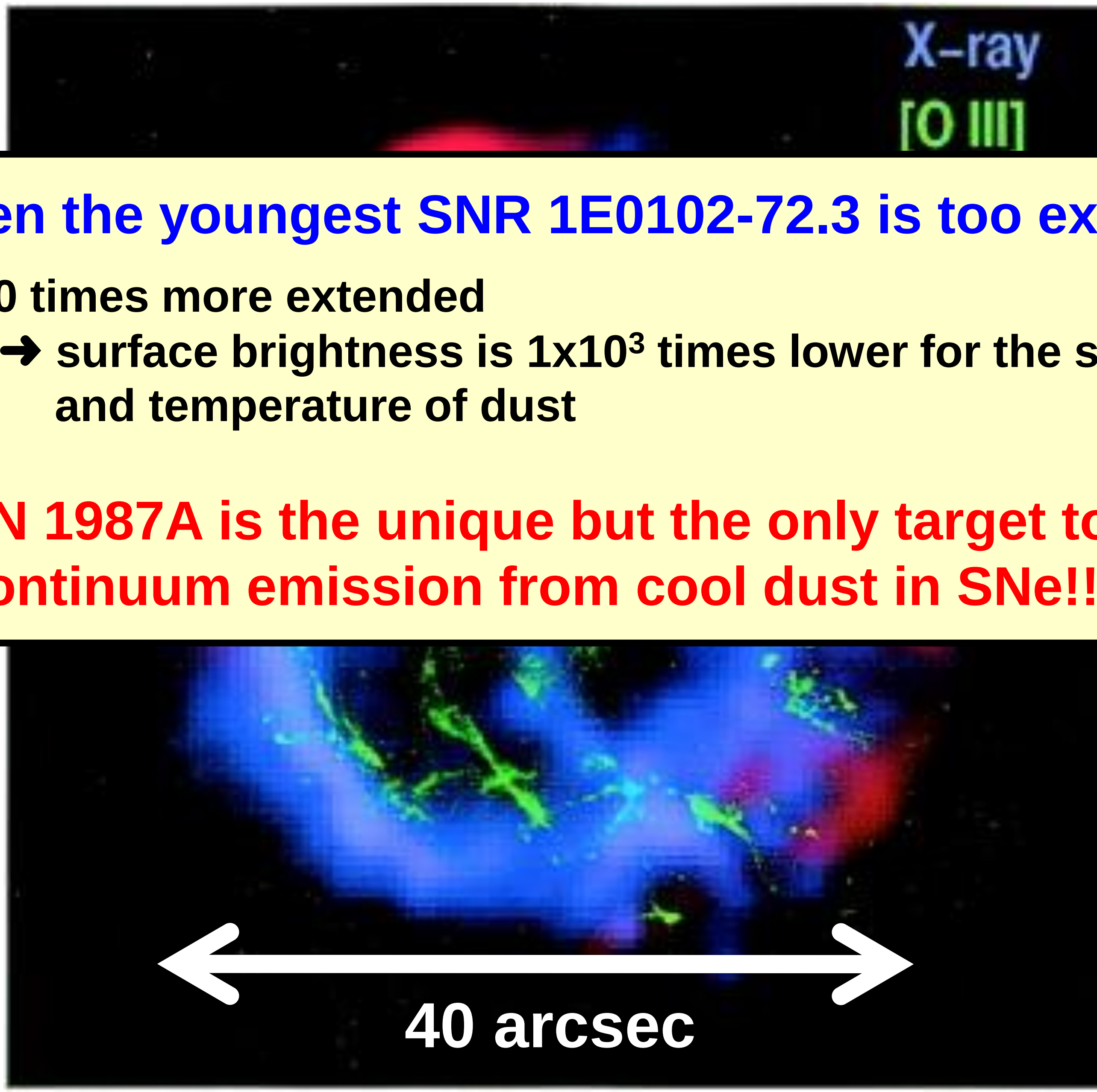


Stanimirovic+05



Gaetz+00

1-5. SNR 1E0102-72.3 is too extended!



even the youngest SNR 1E0102-72.3 is too extended !!

40 times more extended

➜ surface brightness is 1×10^3 times lower for the same mass and temperature of dust

SN 1987A is the unique but the only target to detect continuum emission from cool dust in SNe!!

SN 1987A

1-6. Summary of observations of SN dust

- ALMA confirmed the presence of a large amount of newly formed dust in the ejecta of SN 1987A
  ➜ heavy elements (Si, Mg, Fe, C) are locked up in dust grains
  ➜ CCSNe are efficient production factories of interstellar dust

- It seems too hard to detect thermal emission from cool dust in any SNe/SNRs other than SN 1987A
  ➜ even the youngest SNR in LMC/SMC are too extended

- A part of dust grains formed in the SN ejecta will be destroyed by the reverse shocks

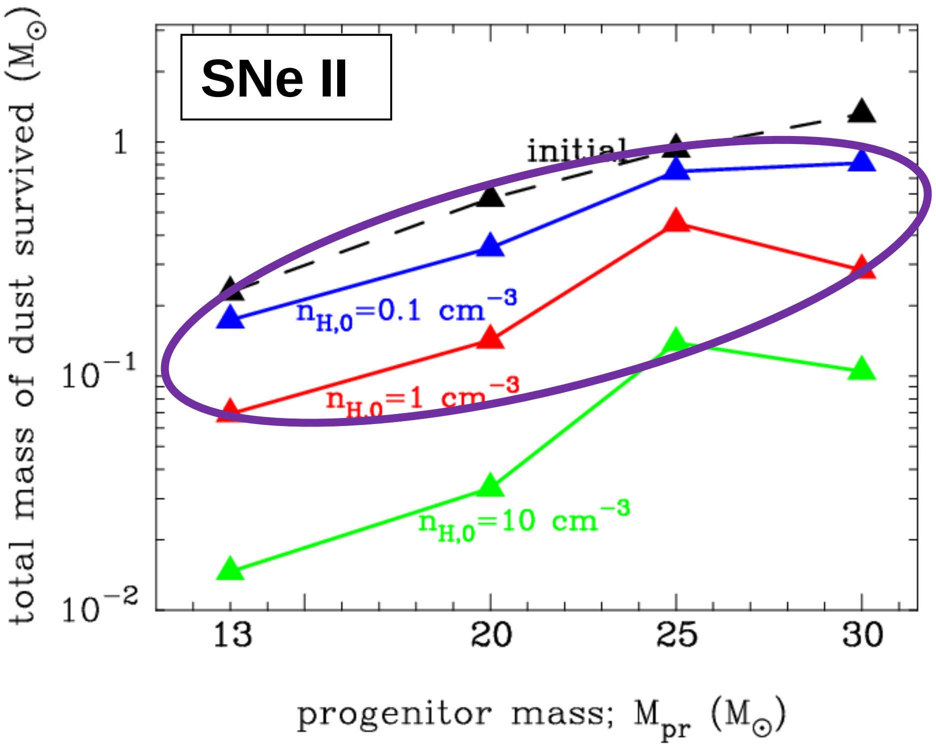
what fraction of dust grains can survive to be injected?

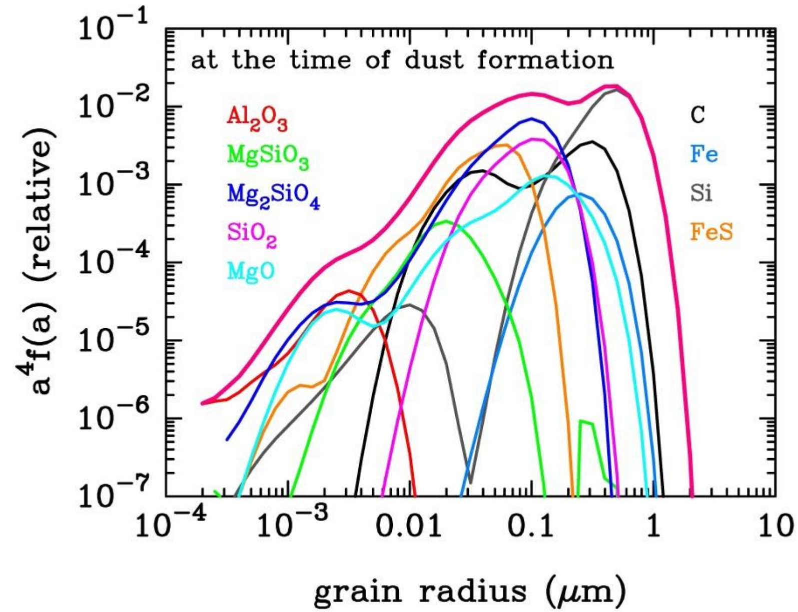
➜ destruction efficiency depends on dust composition and size
➜ infrared to submm observations have few information on the the composition and size distribution of dust

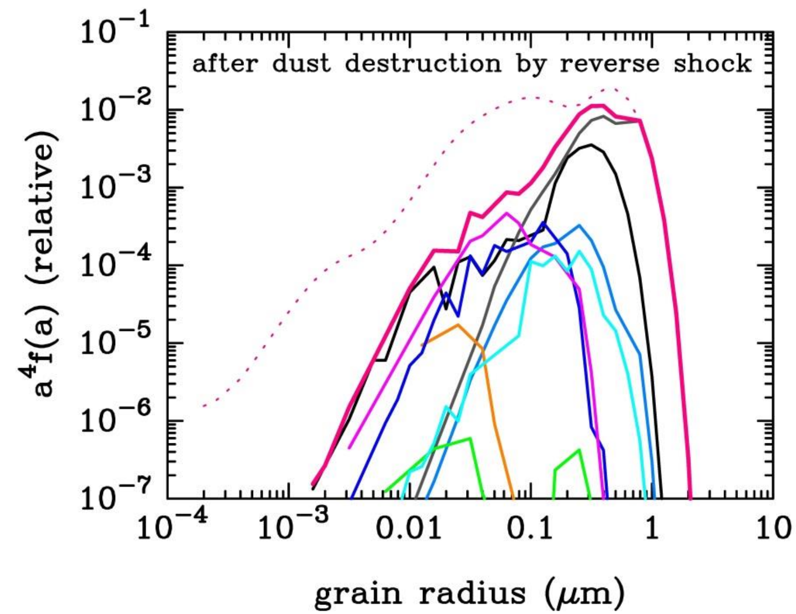
2. Size and mass of dust ejected by core-collapse SNe

2-1. Dust mass and size ejected from SNe II

Nozawa+07, ApJ, 666, 955



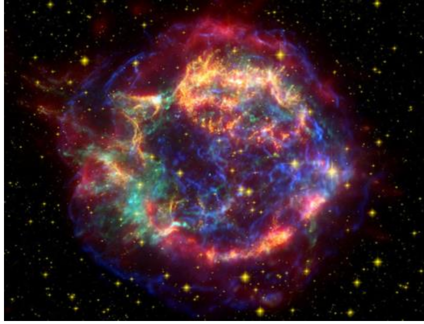




total mass of dust surviving the destruction in Type II SNRs;
0.07-0.8 Msun ($n_{H,0}$ = 0.1-1 cm^{-3})

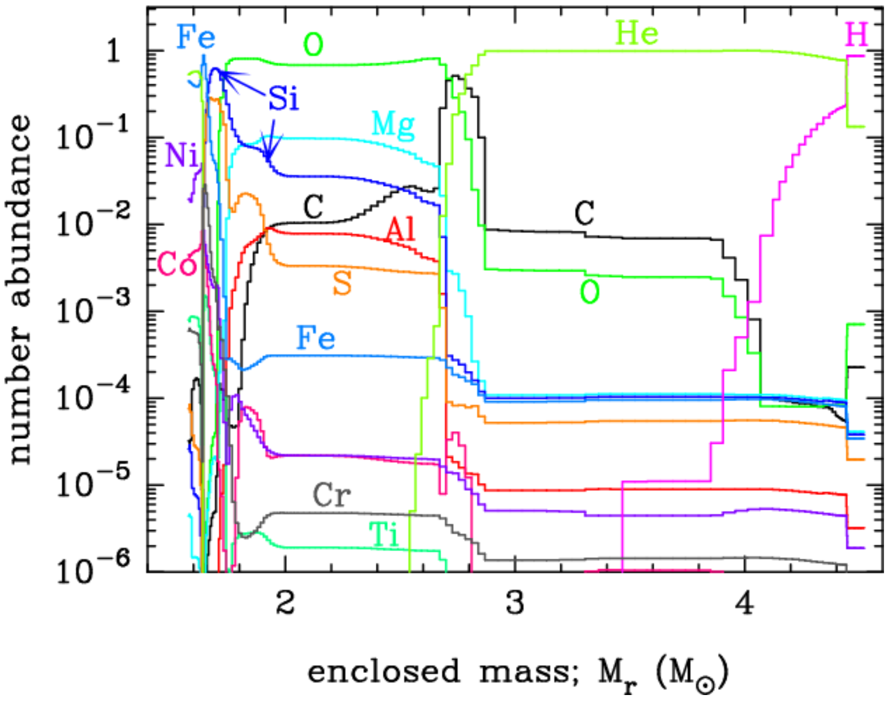
size distribution of dust after the shock-destruction is domimated by large grains (> 0.1 μm)

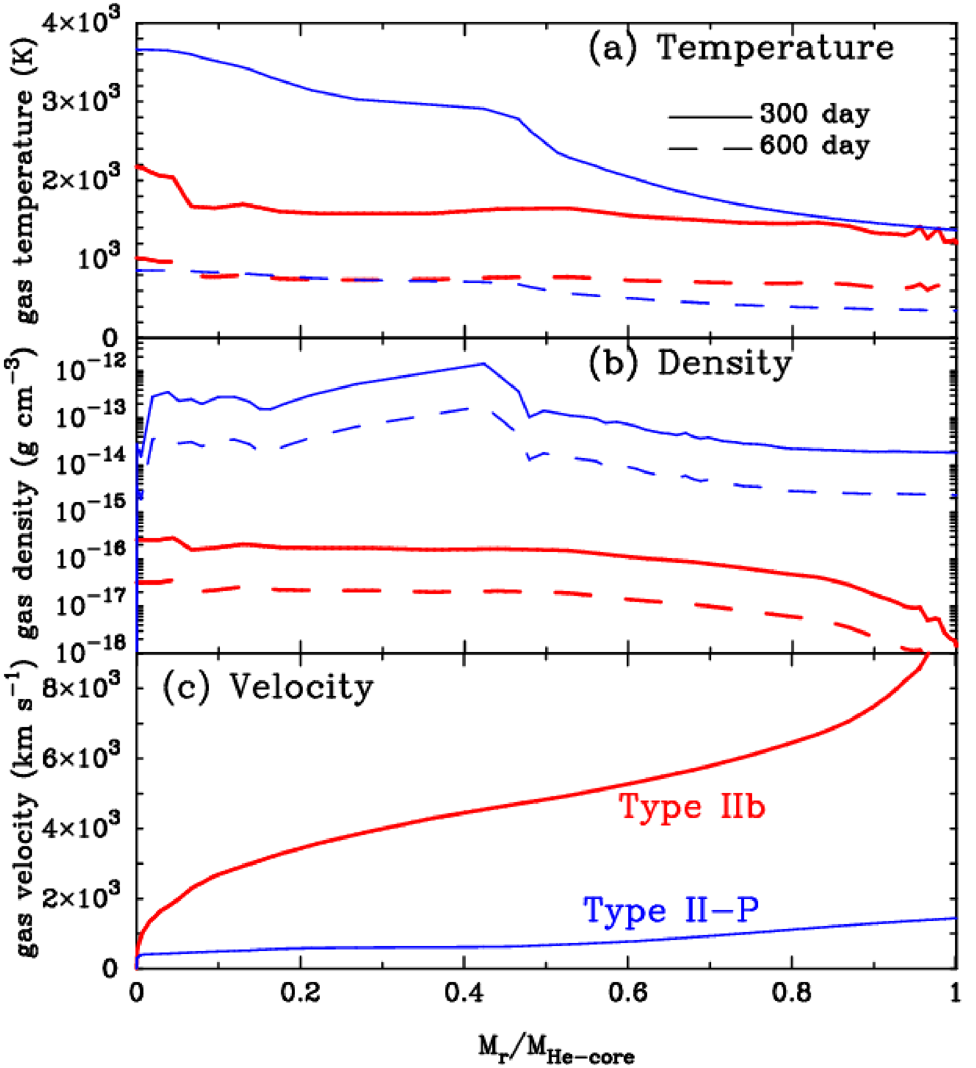
2-2. Dust formation in Type IIb SN



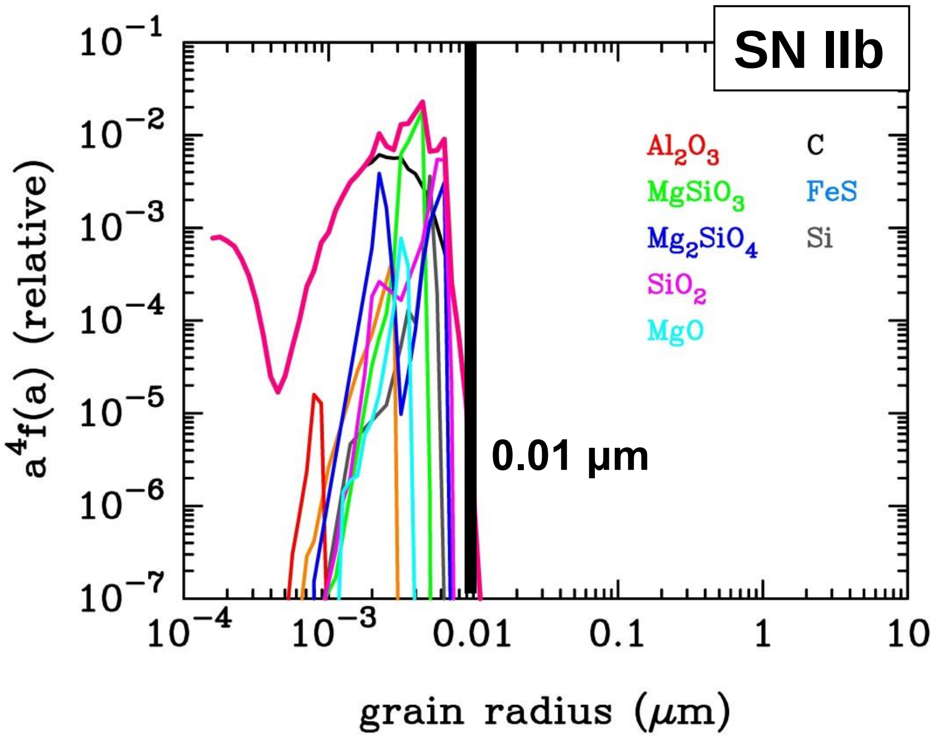
○ SN IIb model (SN1993J-like model)

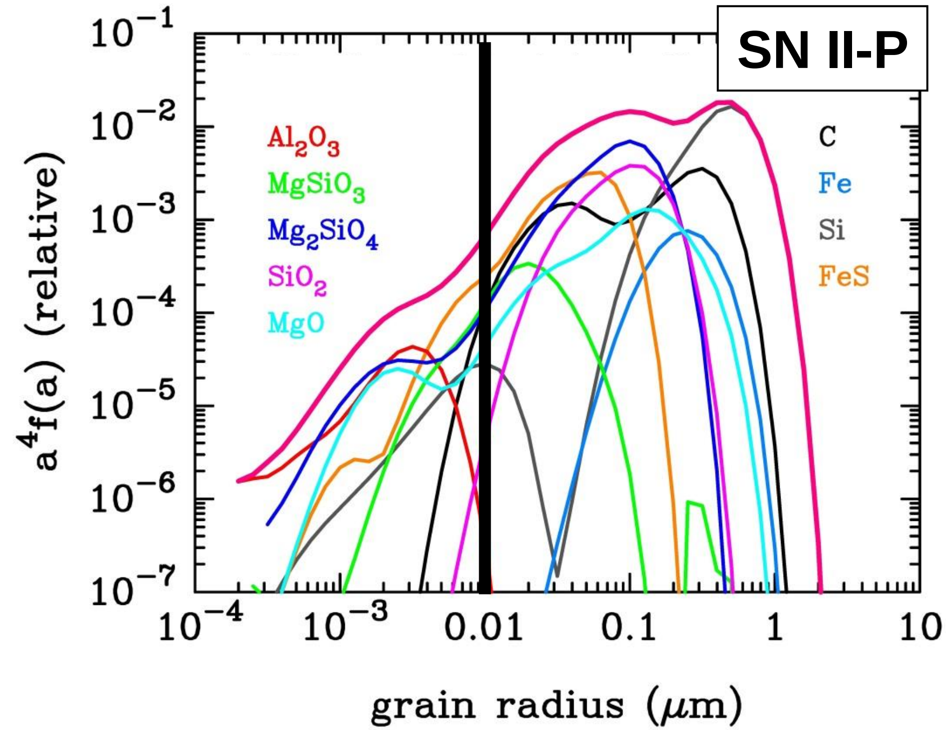
- M_{eje} = 2.94 Msun
  M_{ZAMS} = 18 Msun
  $M_{H\text{-}env}$ = 0.08 Msun
- E_{51} = 1
- $M(^{56}Ni)$ = 0.07 Msun





2-3. Dependence of grain radii on SN type



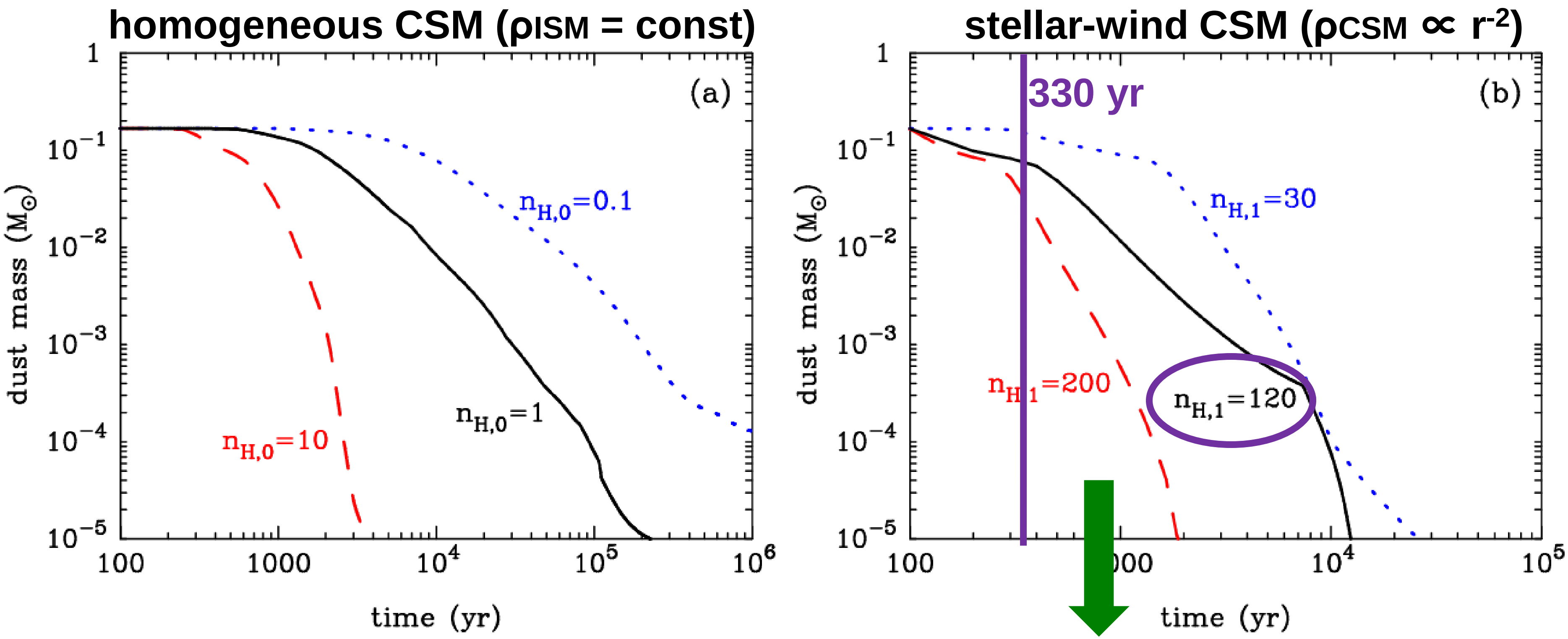


- condensation time of dust 300-700 days after explosion
- total mass of dust formed
  - 0.167 Msun in SN IIb
  - 0.1-1 Msun in SN II-P

- 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

2-4. Destruction of dust in Type IIb SNR



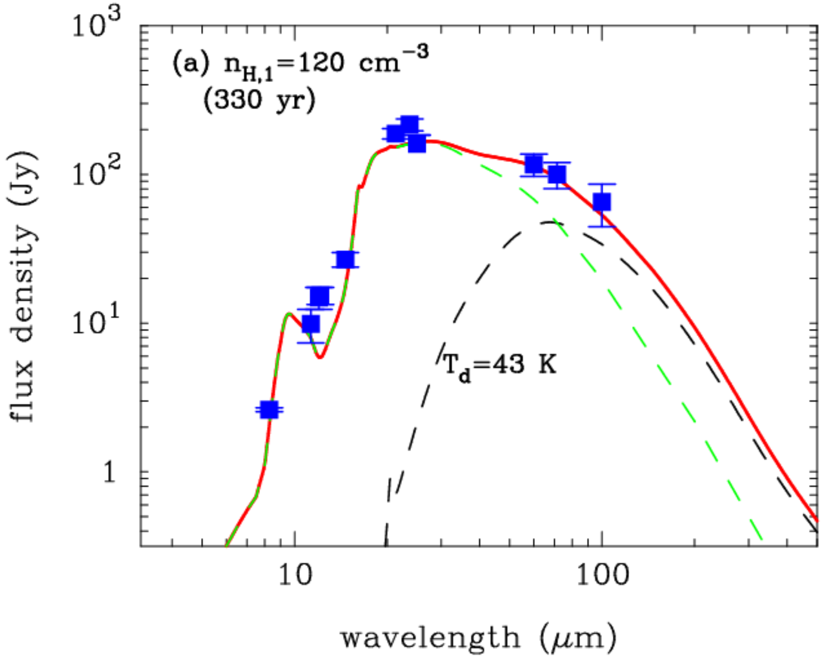
$n_{H,1}$ = 30, 120, 200 /cc ➔ dM/dt = 2.0, 8.0, 13x10^{-5} M_{sun}/yr for v_W=10 km/s

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

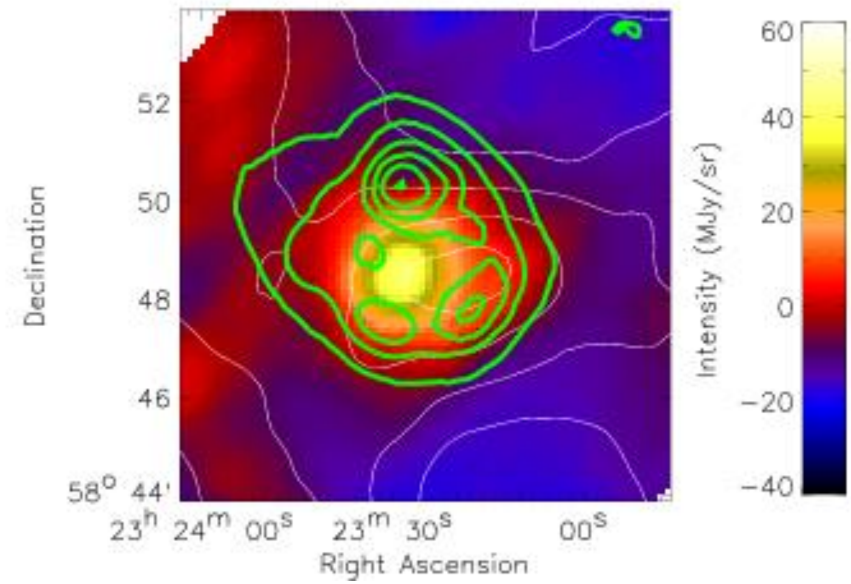
- ➔ small radius of newly formed grains
- ➔ early arrival of reverse shock at dust-forming region

Nozawa+10, ApJ, 713, 356

2-5. IR emission from dust in Cas A SNR



AKARI 90 μm image (color)



- total mass of dust formed
  Mdust = 0.167 Msun
- shocked dust : 0.095 Msun
  Md,warm = 0.008 Msun
- unshocked dust :
  Md,cool = 0.072 Msun
  with Tdust ~ 40 K

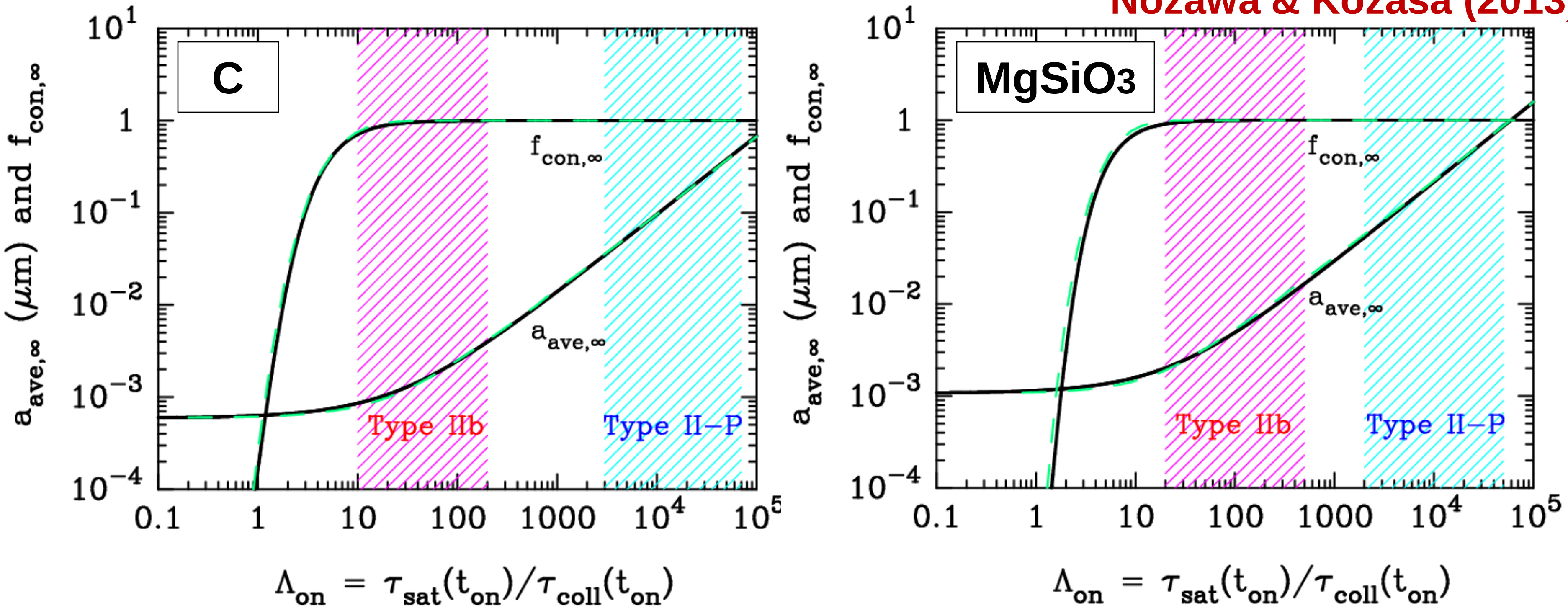
Nozawa+10, ApJ, 713, 356

AKARI observation
Md,cool = 0.03-0.06 Msun
Tdust = 33-41 K
(Sibthorpe+10)

Herschel observation
Md,cool = 0.075 Msun
Tdust ~ 35 K (Barlow+10)

2-6. Scaling relation of average grain radius

Nozawa & Kozasa (2013)



$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: ratio of supersaturation timescale to gas collision timescale at the onset time (t_{on}) of dust formation

$\Lambda_{on} = \tau_{sat}/\tau_{coll} \propto \tau_{cool}\, n_{gas}$

- $f_{con,\infty}$ and $a_{ave,\infty}$ are uniquely determined by Λ_{on}
- steady-state nucleation rate is applicable for $\Lambda_{on} > 30$

2-7. Summary of dust formation in SNe II-P/IIb

- **Size of newly formed dust depends on types of SNe**
  - **H-retaining SNe (Type II-P) : $a_{ave} > 0.01$ μm**
    - ➜ a significant fraction of newly formed dust can survive
    - ➜ H-retaining SNe can be major sources of interstellar dust
  - **H-stripped SNe (Type IIb/Ib/Ic) : $a_{ave} < 0.01$ μm**
    - ➔ dust is almost completely destroyed by the reverse shocks
    - ➔ H-stripped SNe may be poor sources of interstellar dust

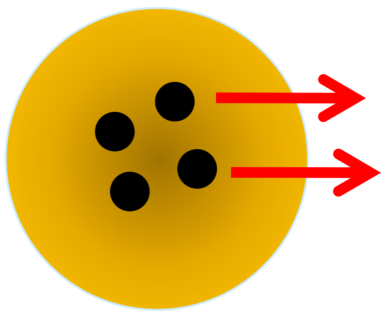
- **Our model treating dust formation and evolution self-consistently can reproduce IR emission from Cas A**

- **Condensation efficiency and average radius of dust are uniquely determined by $\Lambda_{on} = \tau_{sat} / \tau_{coll}$ at the onset time (t_{on}) of dust formation**

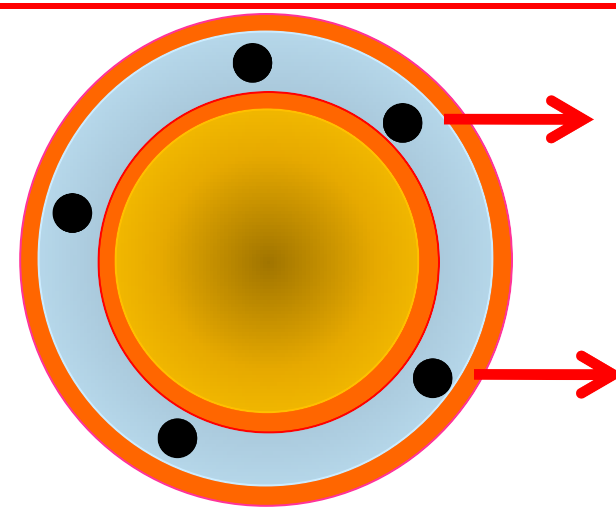
3. Dust formation in a cool dense shell (CDS) behind the SN shock

3-1. Origin of IR emission from SNe

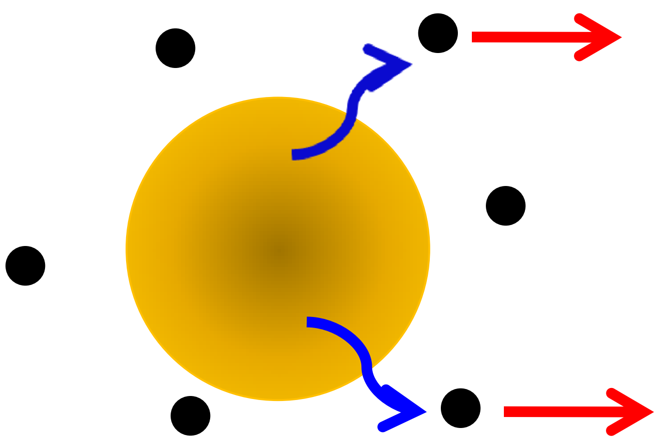
Dust formation in the ejecta



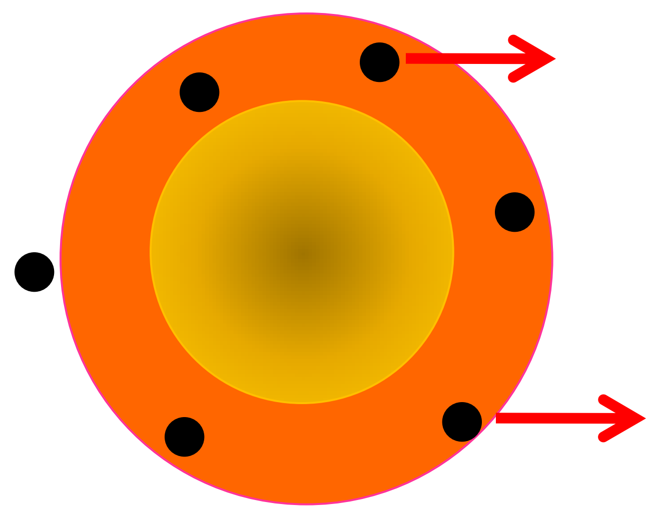
Dust formation in dense shell



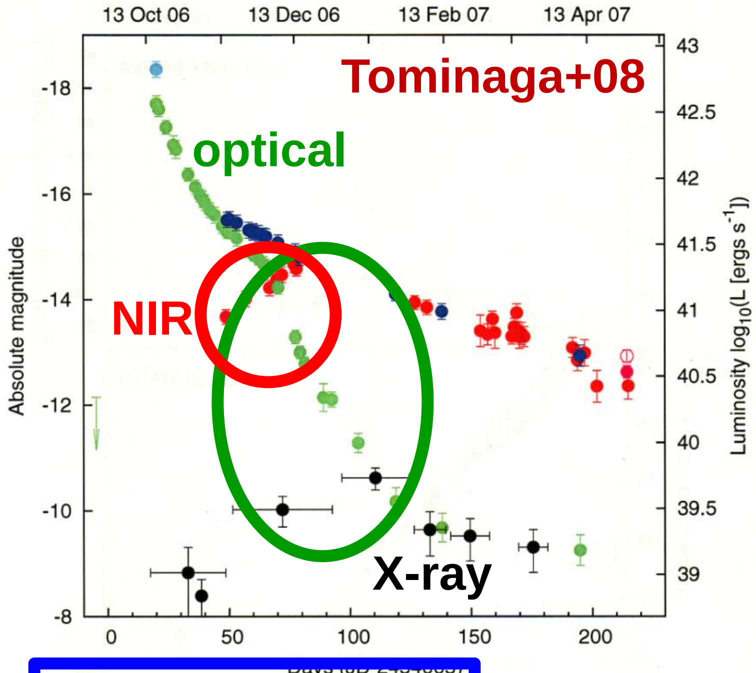
IR echo by CS dust



Shock heating of CS dust

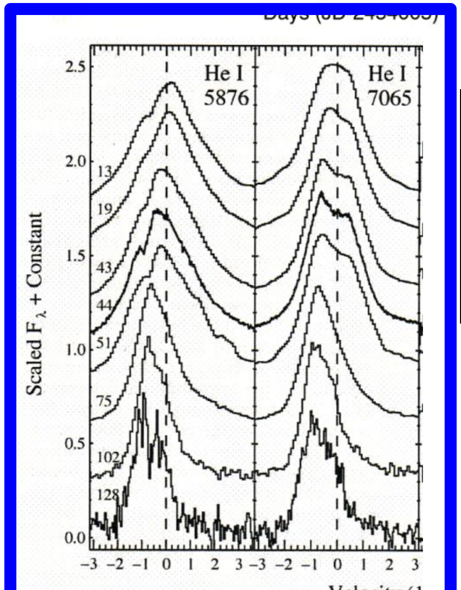


3-2. Evidence for dust formation in SN 2006jc



- brightening of IR
- rapid decline of optical light
- blueshift of emission lines

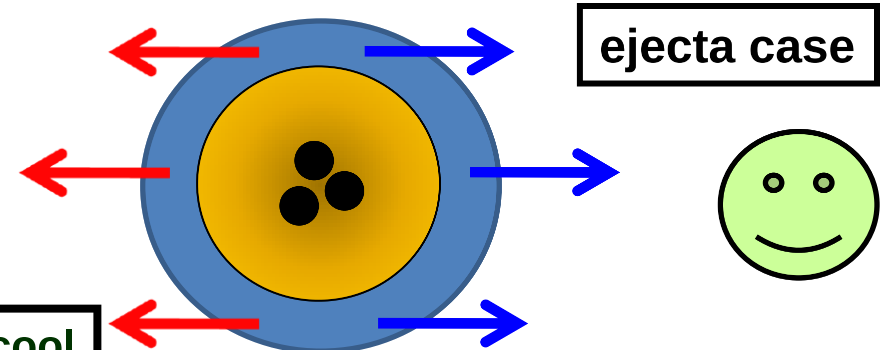
formation of CO/SiO molecules
(more robust if SiO are depleted)



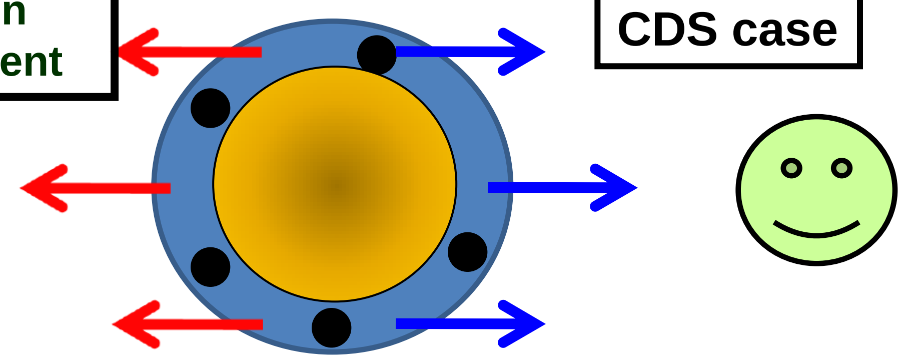
Smith+08

dust formation in cool dense shells (CDSs) explains extinction of zero-v component

ejecta case



CDS case

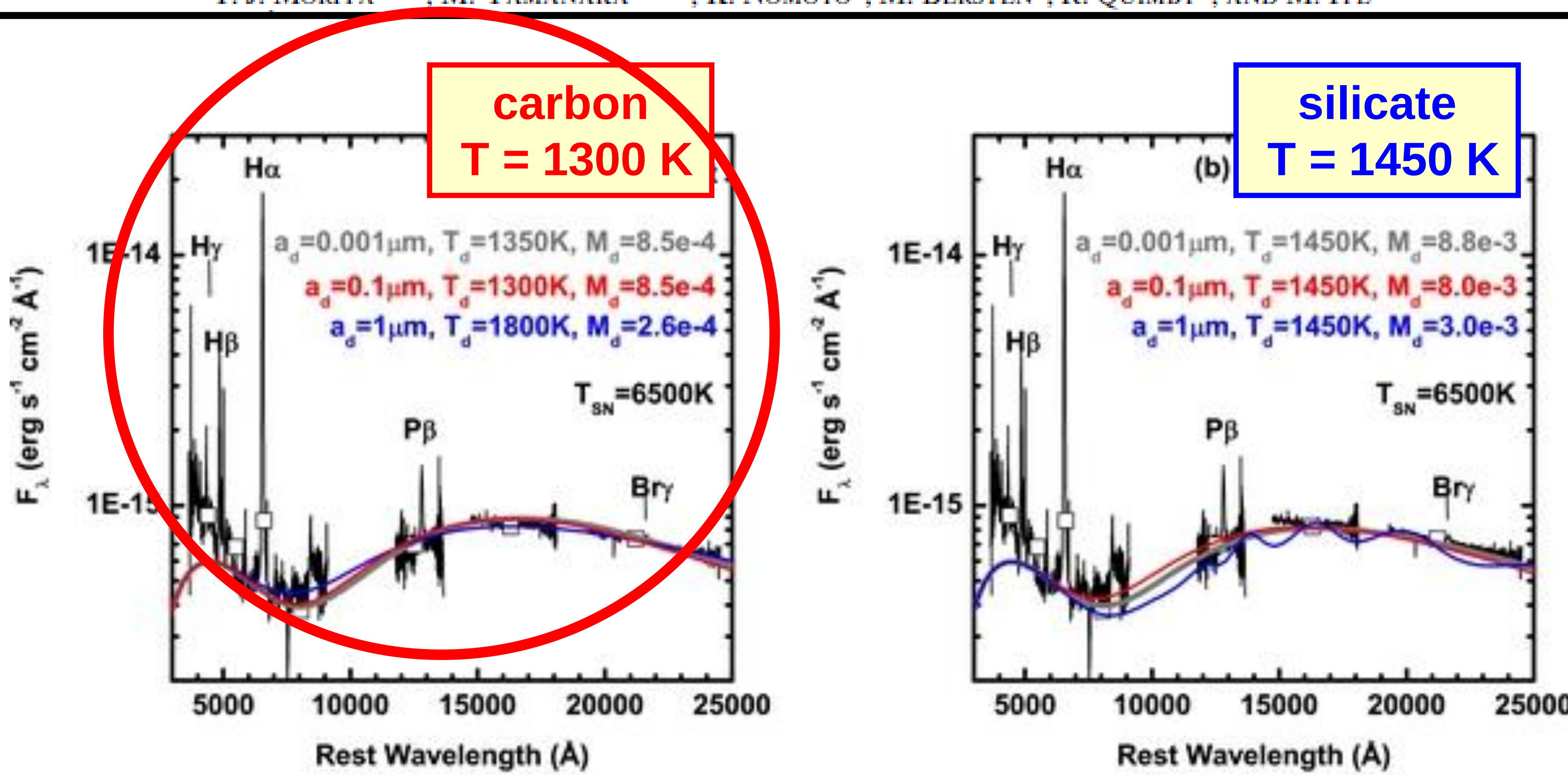


3-3. Dust formation in Type IIn SN 2010jl

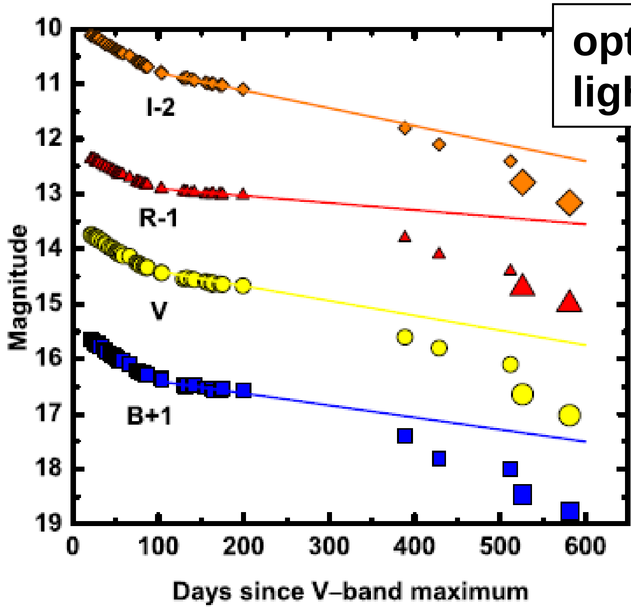
THE ASTROPHYSICAL JOURNAL, 776:5 (16pp), 2013 October 10
doi:10.1088/0004-637X/776/1/5

PROPERTIES OF NEWLY FORMED DUST GRAINS IN THE LUMINOUS TYPE IIn SUPERNOVA 2010jl*

K. MAEDA[1], T. NOZAWA[1], D. K. SAHU[2], Y. MINOWA[3], K. MOTOHARA[4], I. UENO[5], G. FOLATELLI[1], T.-S. PYO[3], Y. KITAGAWA[4], K. S. KAWABATA[5], G. C. ANUPAMA[2], T. KOZASA[6], T. J. MORIYA[1,7,8], M. YAMANAKA[5,9,10], K. NOMOTO[1], M. BERSTEN[1], R. QUIMBY[1], AND M. IYE[11]



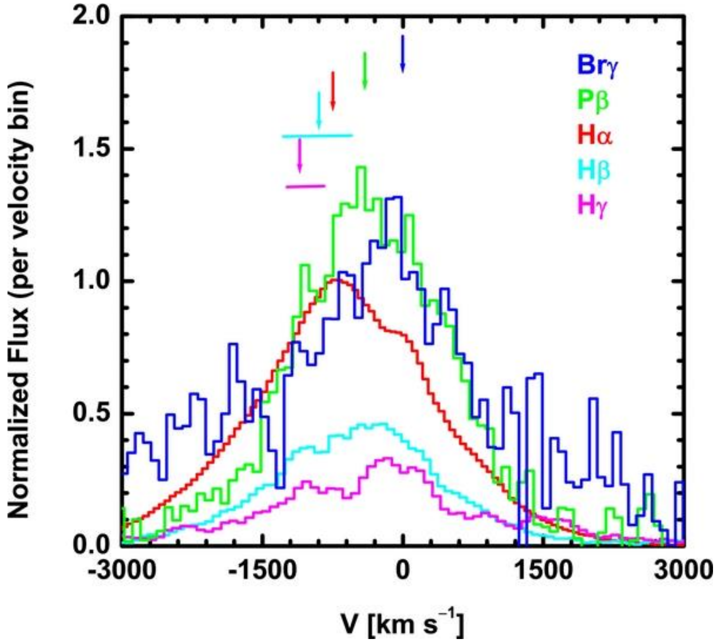
3-4. Dust properties in Type IIn SN 2010jl

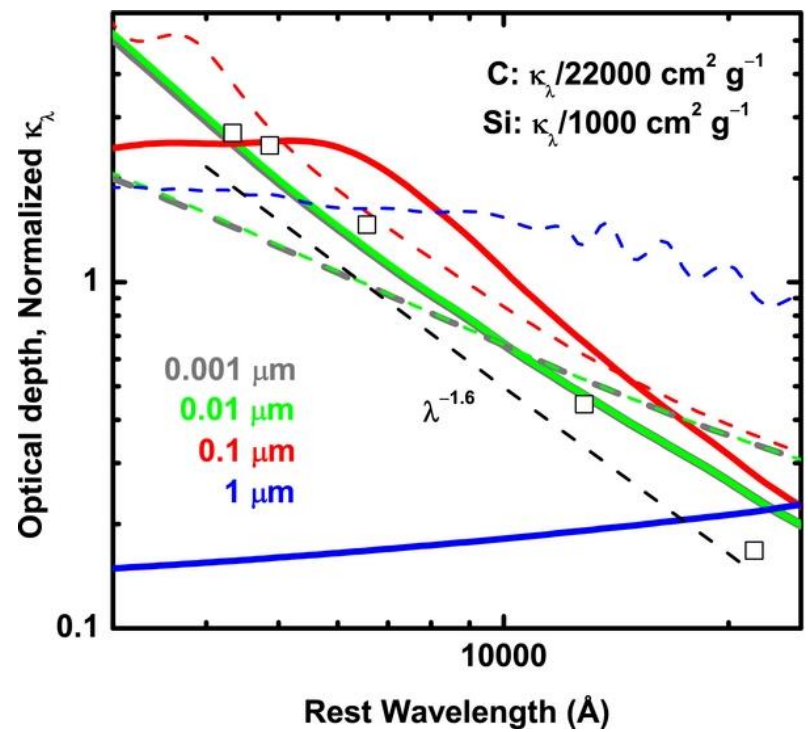


Dust in SN 2010jl

- carbon grains
- dust mass: ~10^{-3} Msun
- grain radius: <0.1μm
  (possibly <0.01 μm)

Maeda, TN, et al. (2013)



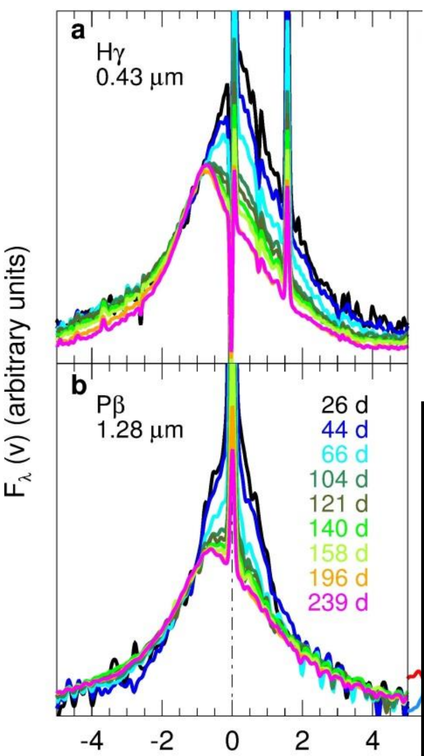


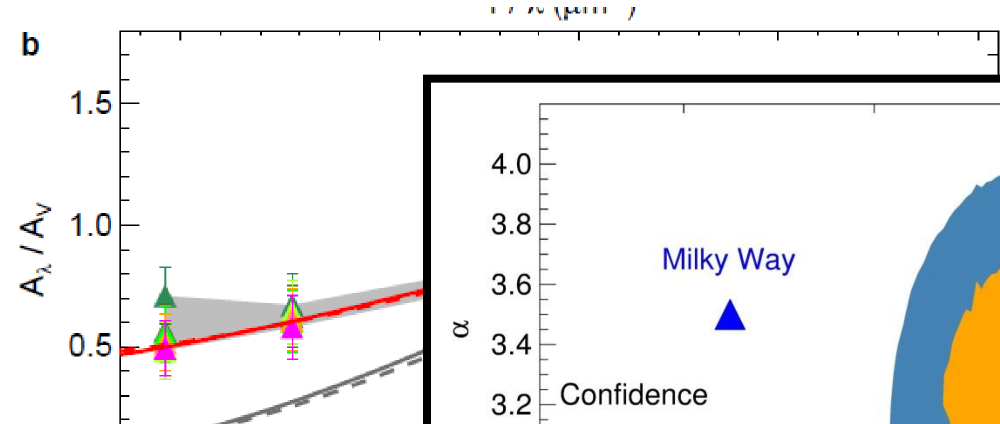
3-5. Dust formation in Type IIn SN 2010jl

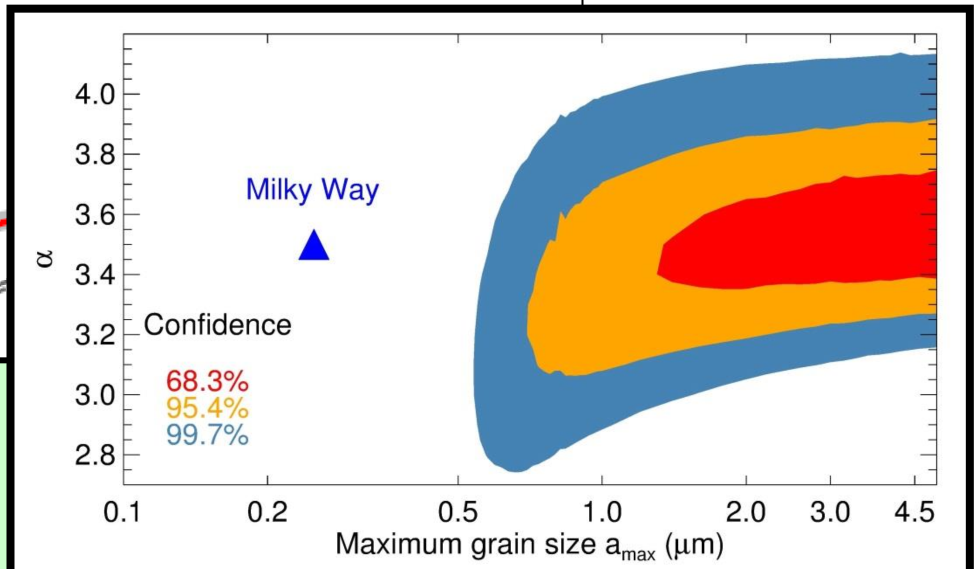
doi:10.1038/nature13558

Rapid formation of large dust grains in the luminous supernova 2010jl

Christa Gall[1,2,3], Jens Hjorth[2], Darach Watson[2], Eli Dwek[3], Justyn R. Maund[2,4], Ori Fox[5], Giorgos Leloudas[2,6], Daniele Malesani[2] & Avril C. Day-Jones[7]





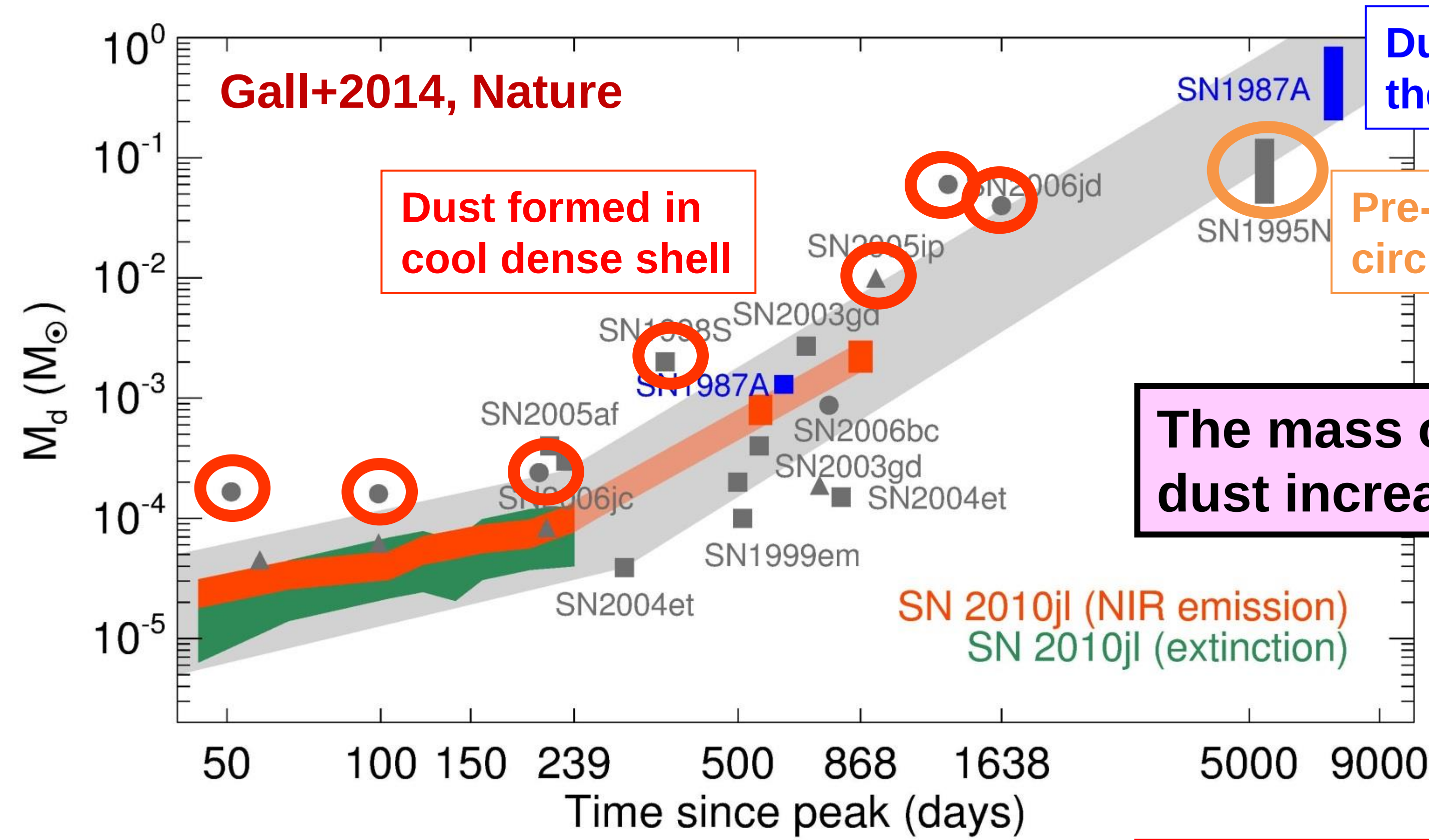


Power-law size distribution

- **α : ~3.5**
- **maximum radius : ~3-4 μm (>0.5 μm)**

Gall+2014, Nature

3-6. Caveats on Gall et al. (2014) paper



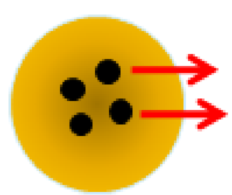
Dust formed in the ejecta

Pre-existing circumstellar dust

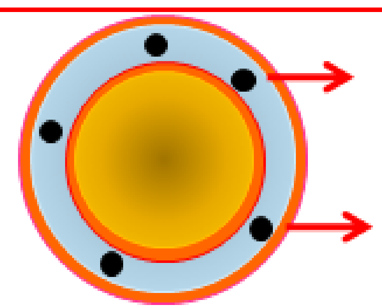
The mass of newly formed dust increases with time?

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



3-7. Summary of dust formation in CDSs

- Dust formation in cool dense shells (CDSs) is another formation path of dust in SNe

  ➜ seems common for Type IIn SNe surrounded by dense gas

- The wavelength-dependence of extinction of emission lines is a powerful tool to derive the size of dust

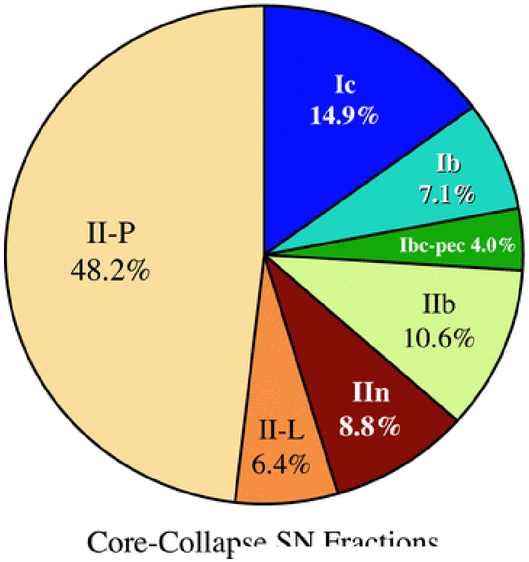
  for Type IIn SN 2010jl

  a_{ave} < 0.1 μm (Maeda+2013)

  a_{ave} > 0.5 μm (Gall+2014)

- We should distinguish between dust formation in the ejecta and in CDSs

  ➜ Properties of dust formed in the CDSs should not be adopted universally as the properties of dust formed in CCSNe



Smith+2011