2015/12/17

超新星とダスト

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Contents:

- Introduction (10 min)
- Current issues on dust formation in SNe (20 min)
- Our recent work on SN-origin presolar grains (10 min)
- Peculiar extinction laws toward Type Ia SNe (10 min)

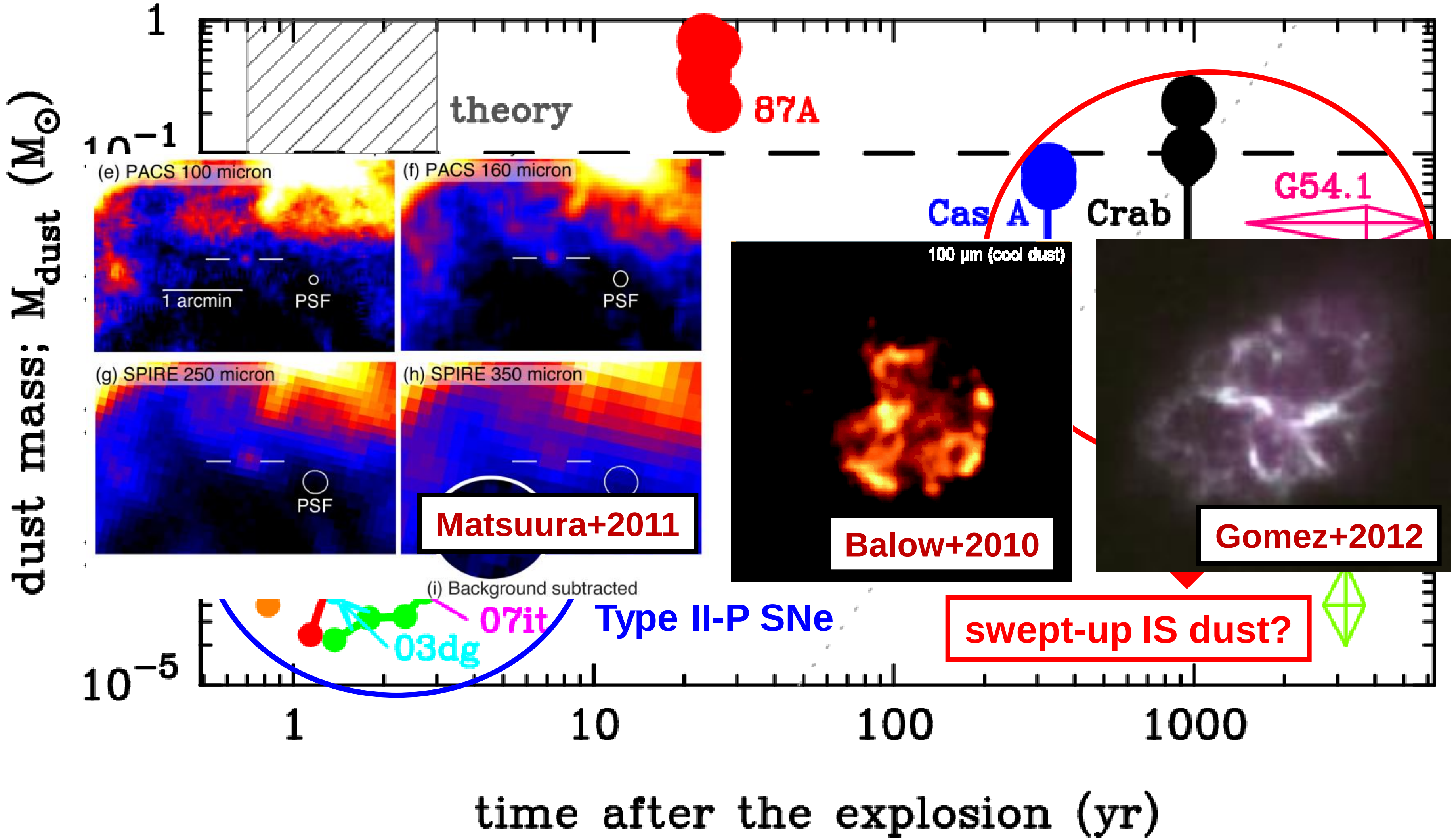
$$\frac{60}{73\text{億}}$$

Answer: number of people working on SN-dust

Fraction of women

$$\frac{20}{60}$$

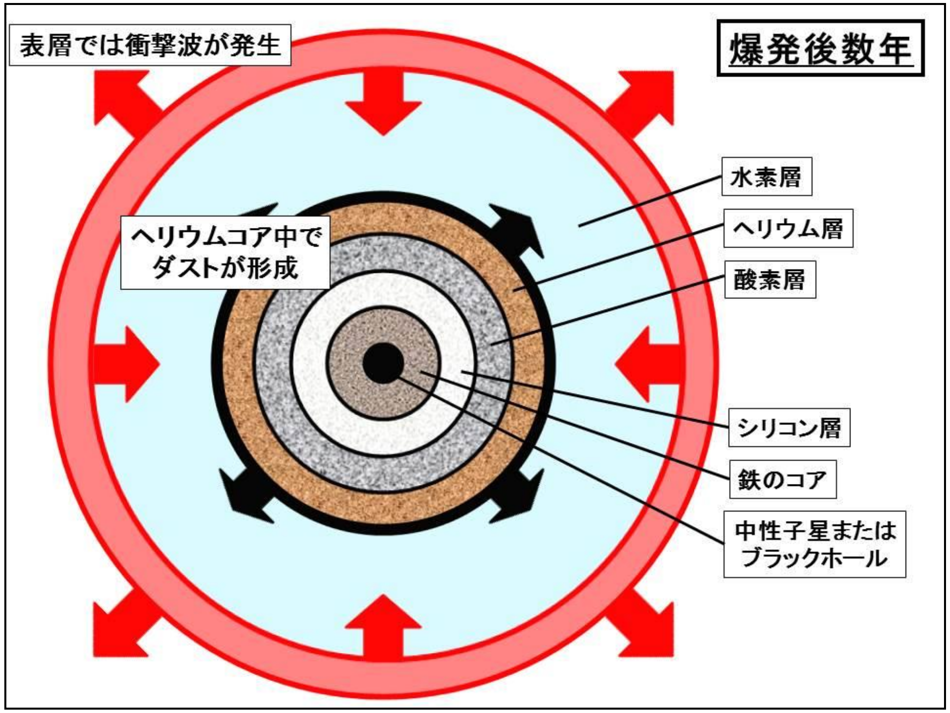
1-1. Summary of observed dust mass in CCSNe

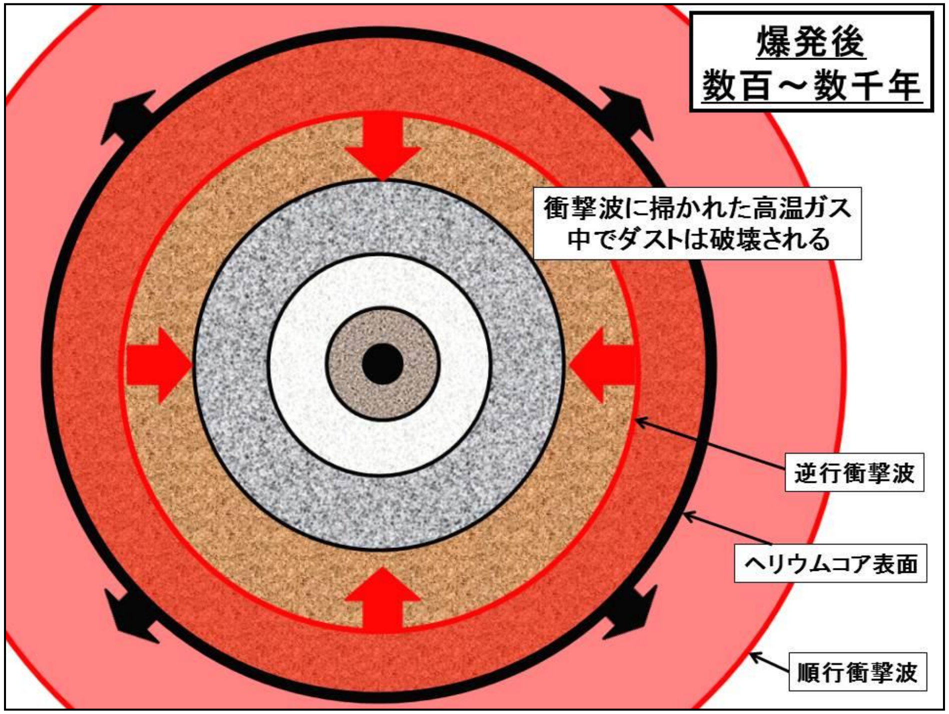


There are increasing pieces of evidence that massive dust in excess of 0.1 Msun is formed in the ejecta of SNe

1-2. 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

1-3. Achievement and issues on SN dust

○ これまでの研究でわかったこと

（重力崩壊型）超新星は、放出ガス中で**大量（0.1 Msun以上）のダスト**を形成することができる

○ 超新星ダスト研究における現在の二つの課題

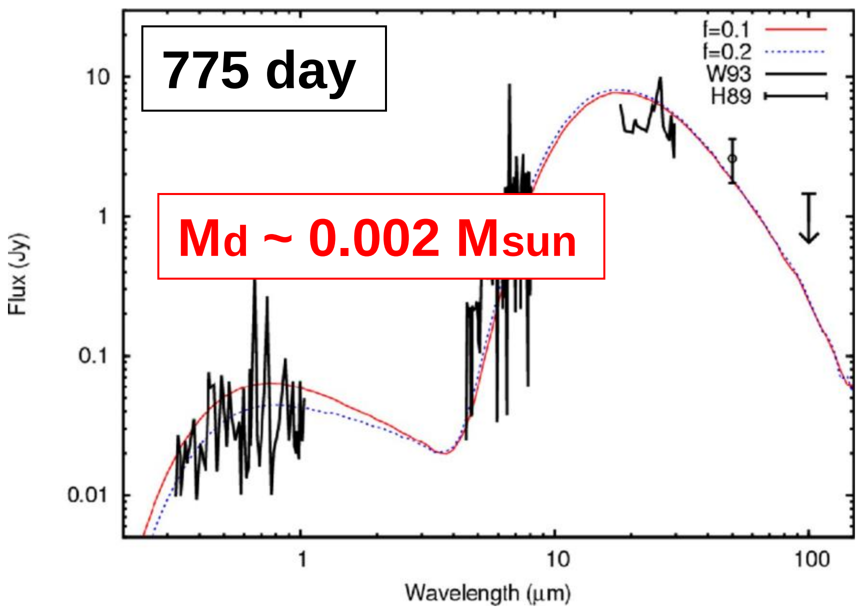
1) 観測された大量の**ダストはいつ形成されたのか？**

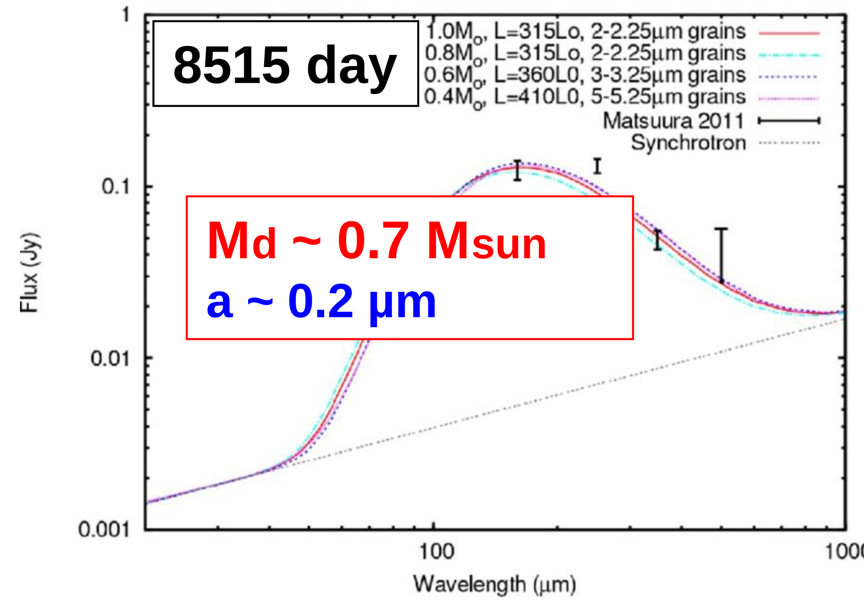
➜ 中間赤外線と遠赤外線でのダスト量の違いを説明したい

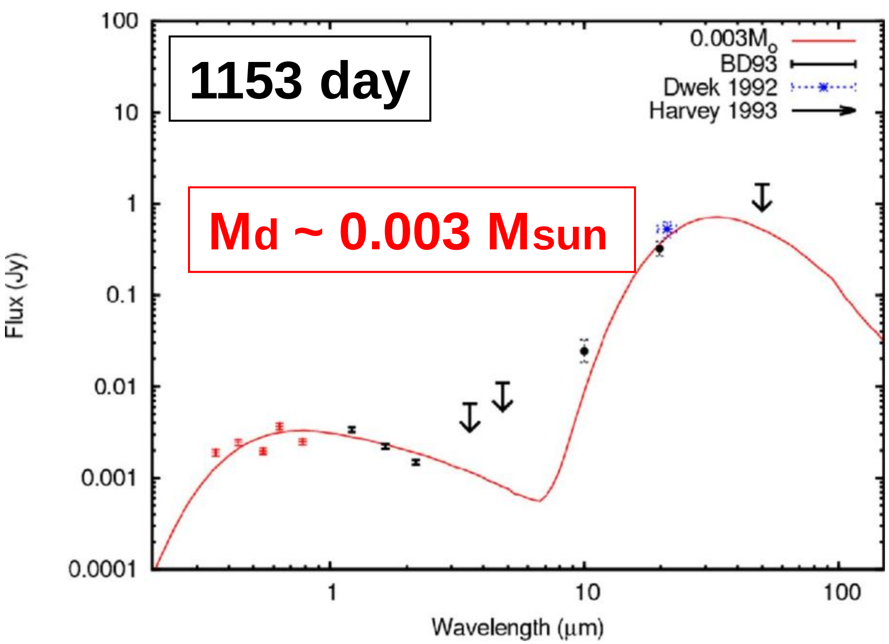
2) 形成される**ダストのサイズはどれくらいか？**

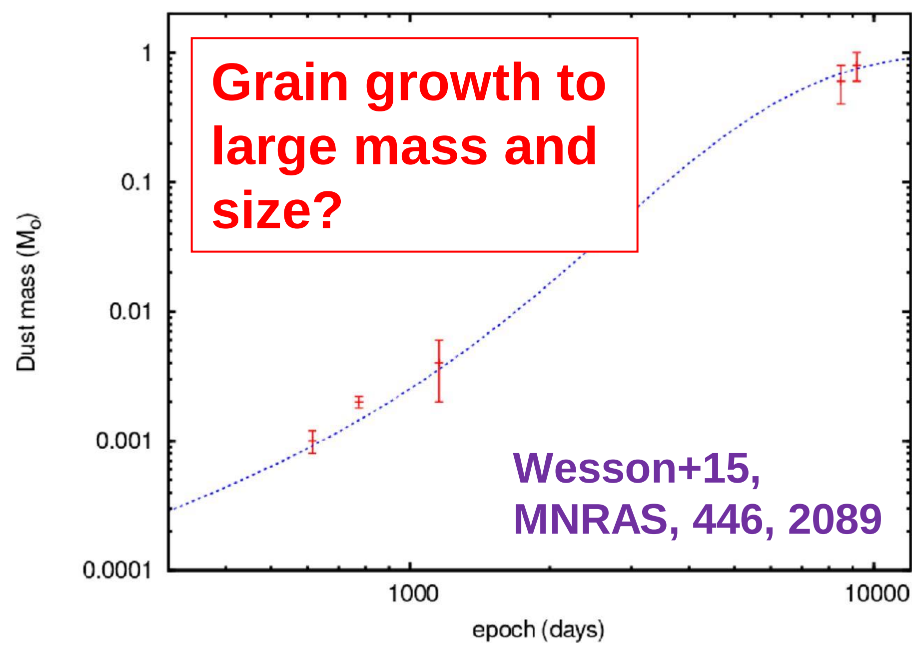
➜ 超新星による最終的なダスト放出量を明らかにしたい

2-1. Revisiting dust mass formed in SN 1987A



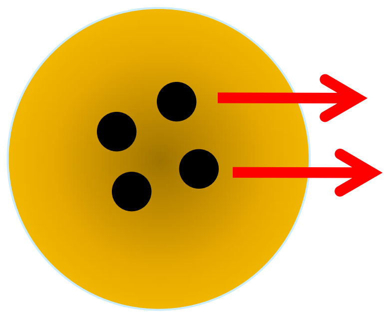




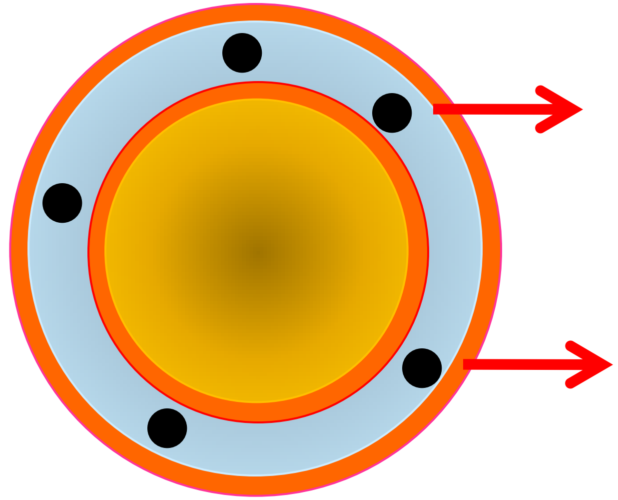


2-2. Origin of IR emission from SNe

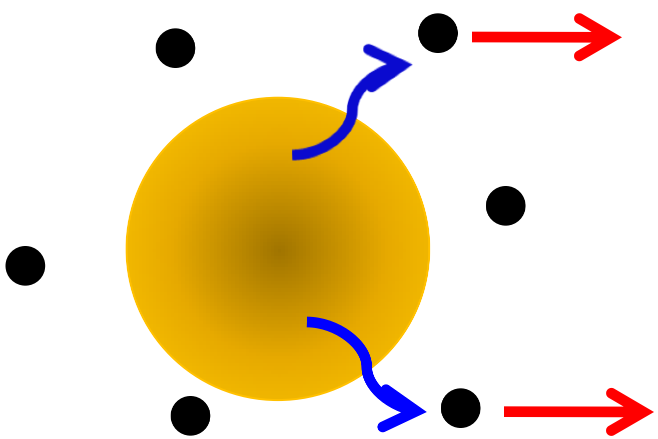
Dust formation in the ejecta



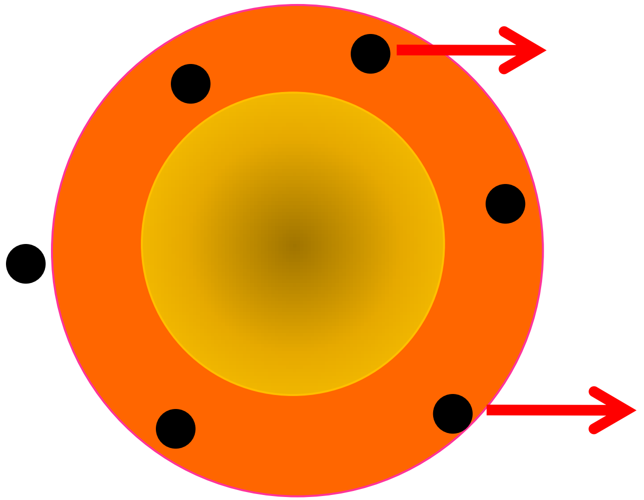
Dust formation in dense shell



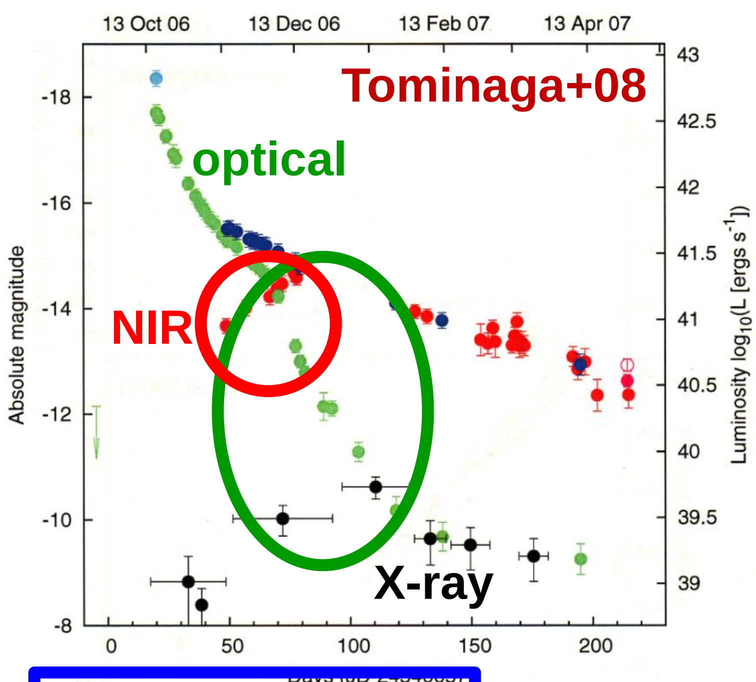
IR echo by CS dust



Shock heating of CS dust

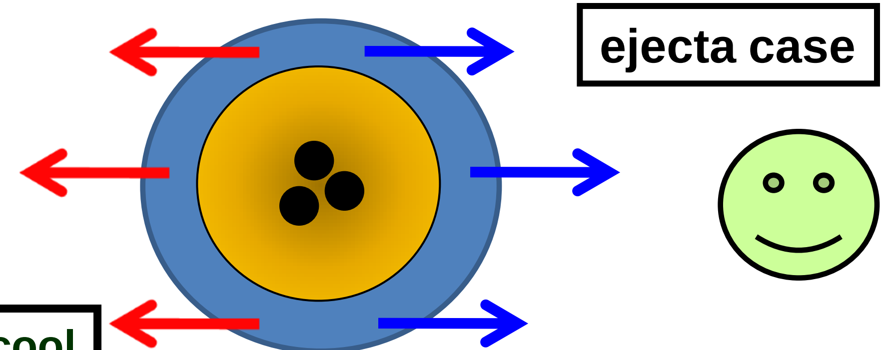


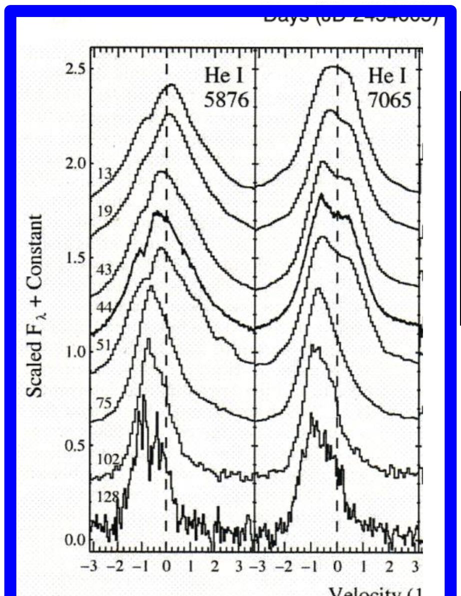
2-3. Evidence for dust formation in SN 2006jc



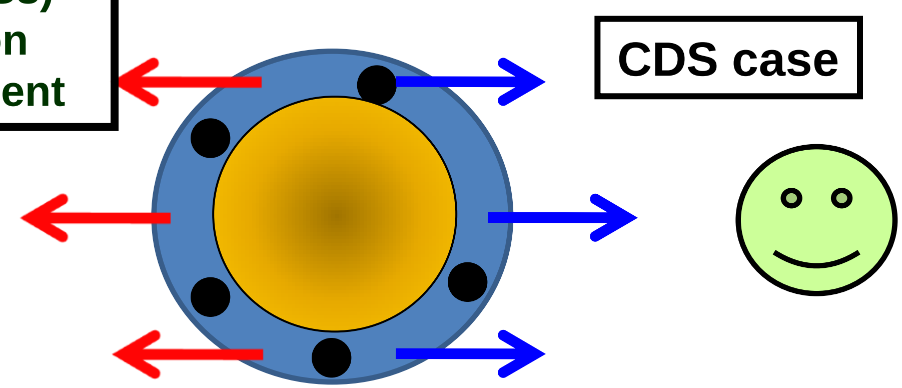
- brightening of IR
- rapid decline of optical light
- blueshift of emission lines

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





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

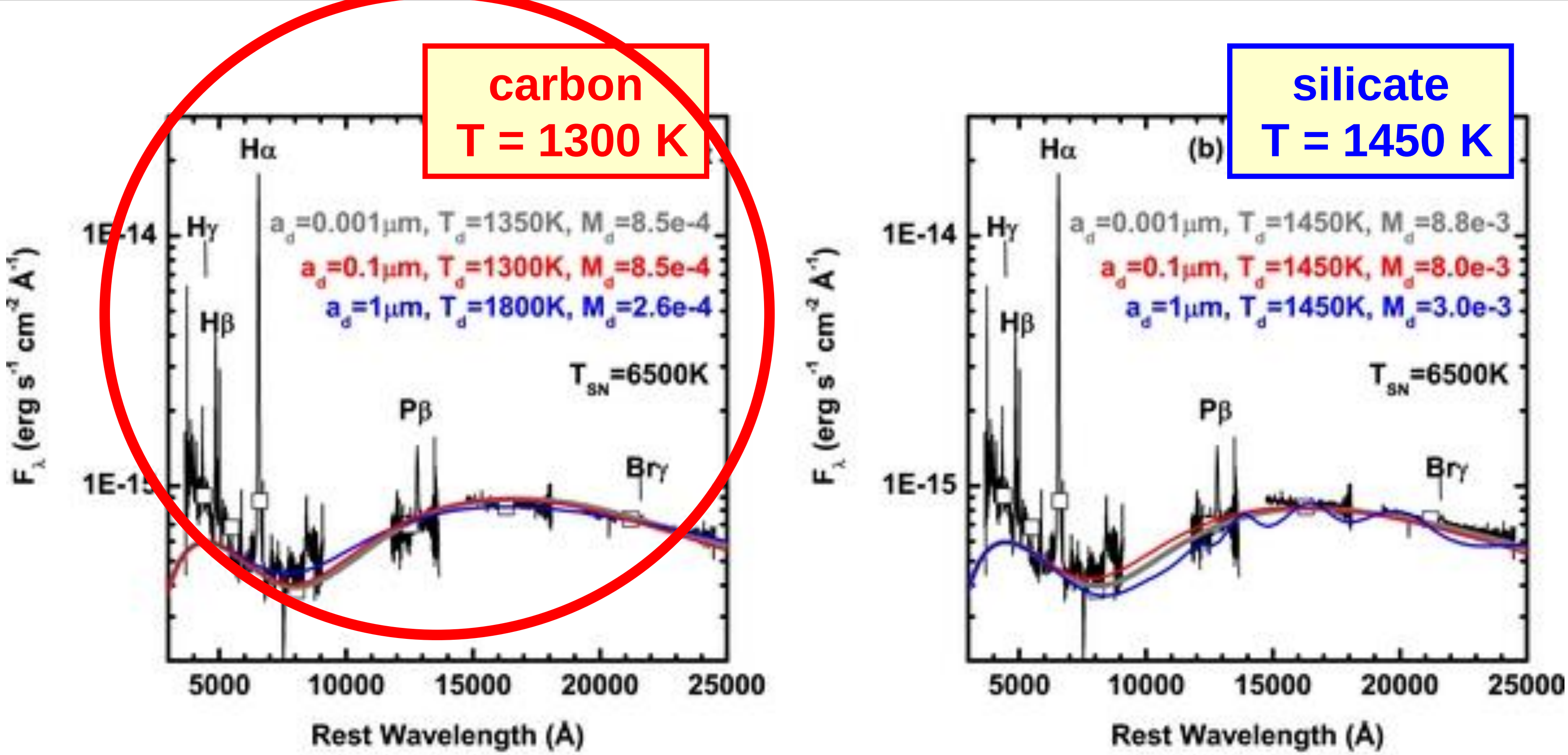


2-4. Dust formation in Type IIn SN 2010jl

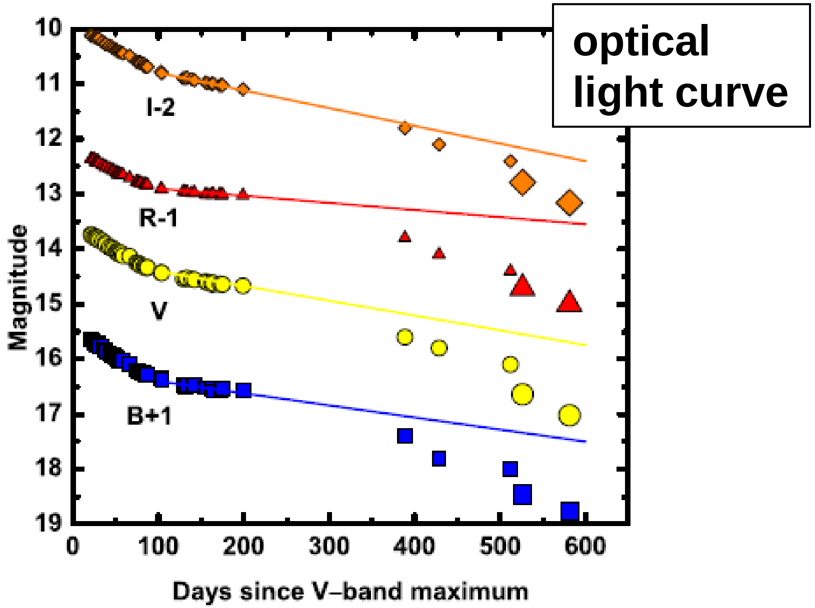
The Astrophysical Journal, 776:5 (16pp), 2013 October 10
doi:10.1088/0004-637X/776/1/5

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]



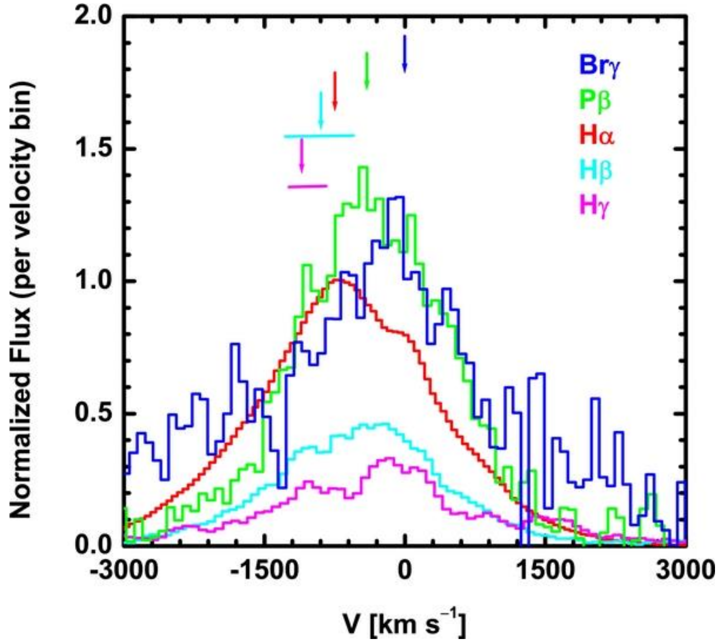
2-5. Dust properties in Type IIn SN 2010jl

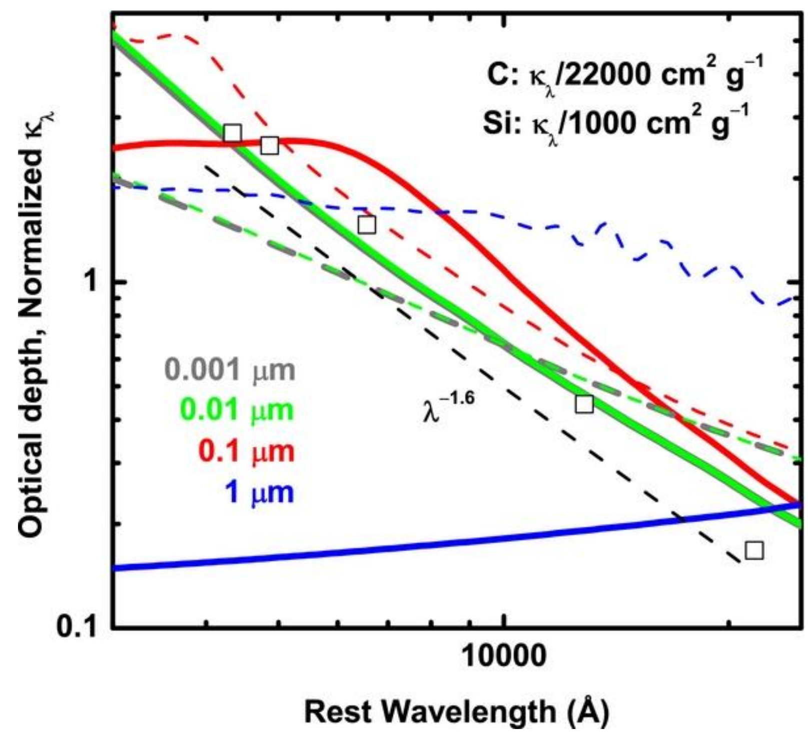


Dust in SN 2010jl

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

Maeda, TN, et al. (2013)



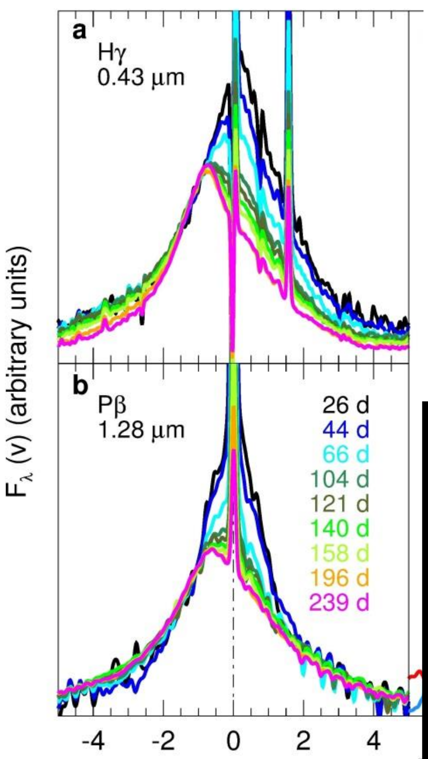


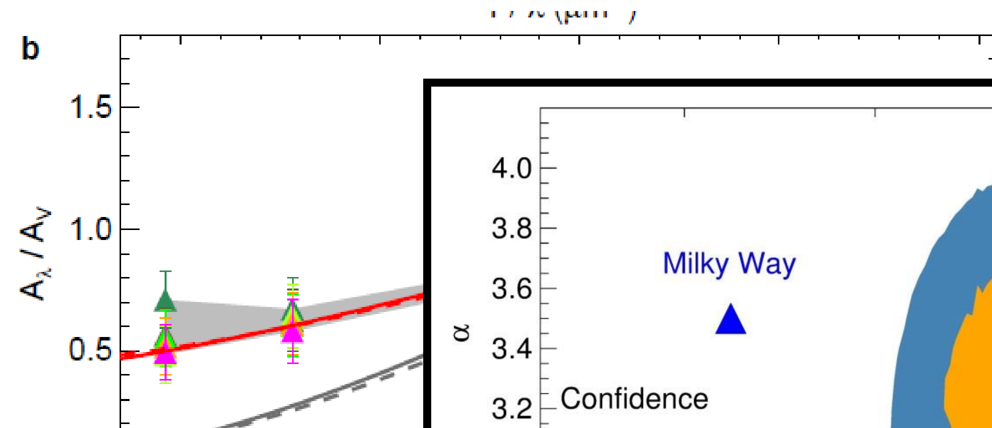
2-6. Dust formation in Type IIn SN 2010jl

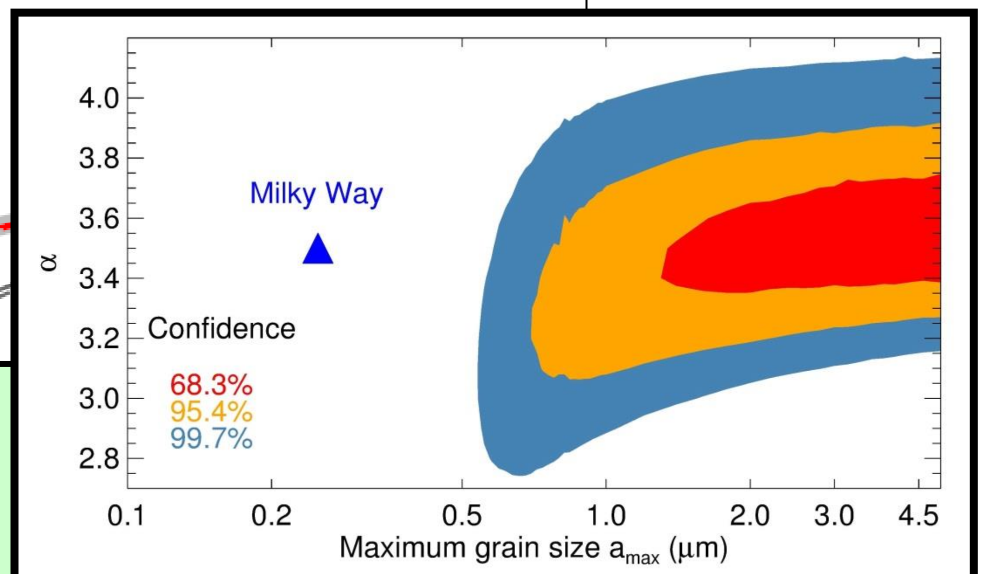
doi:10.1038/nature13558

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]





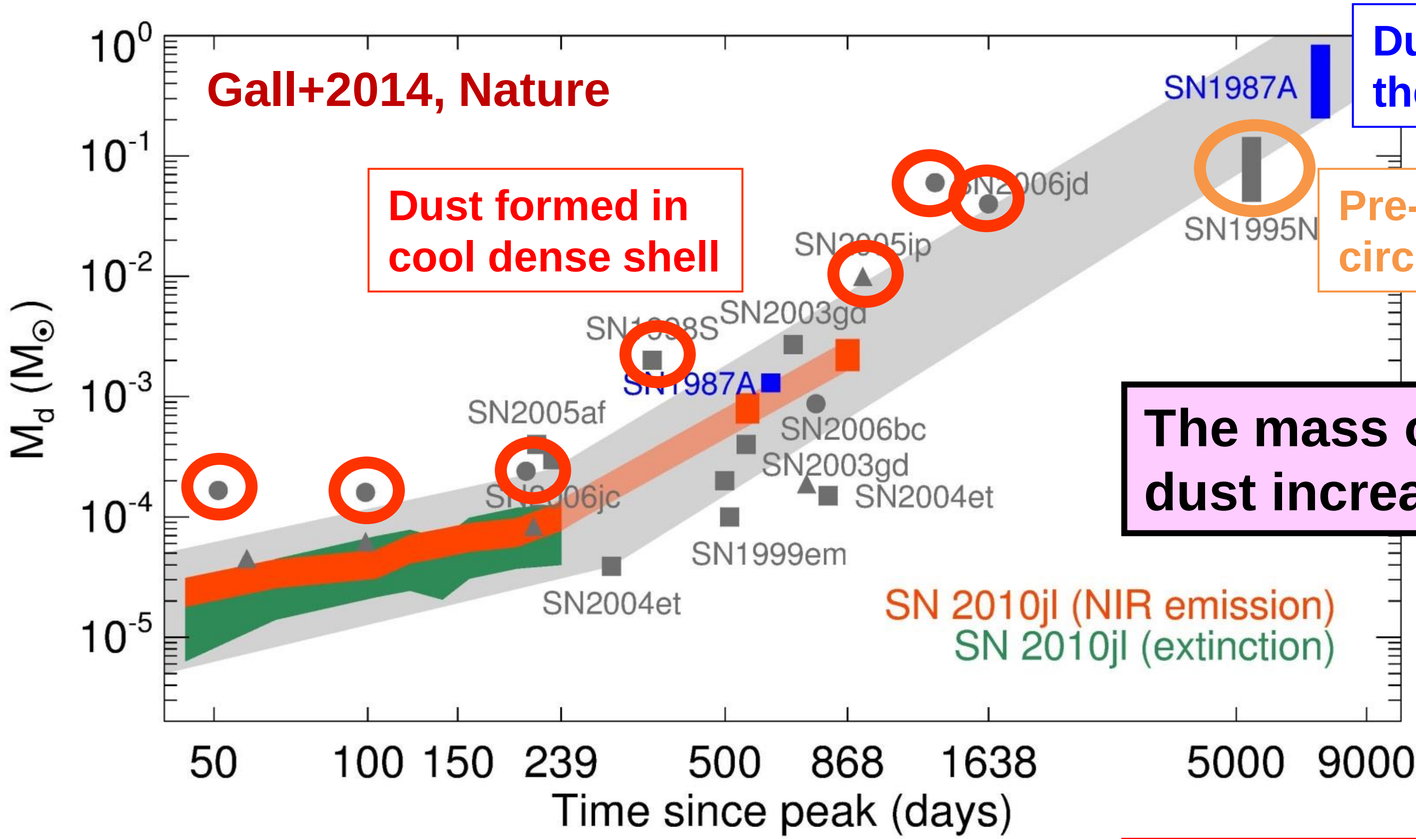


Power-law size distribution

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

Gall+2014, Nature

2-7. Caveats on Gall et al. (2014) paper

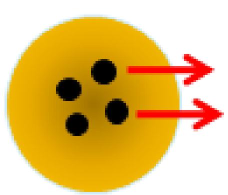


Dust formed in the ejecta

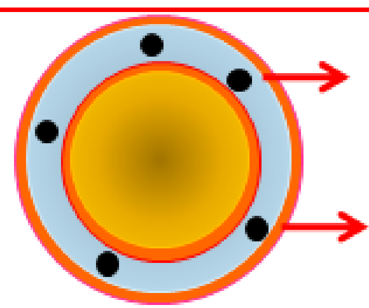
Pre-existing circumstellar dust

The mass of newly formed dust increases with time?

Dust formation in the ejecta

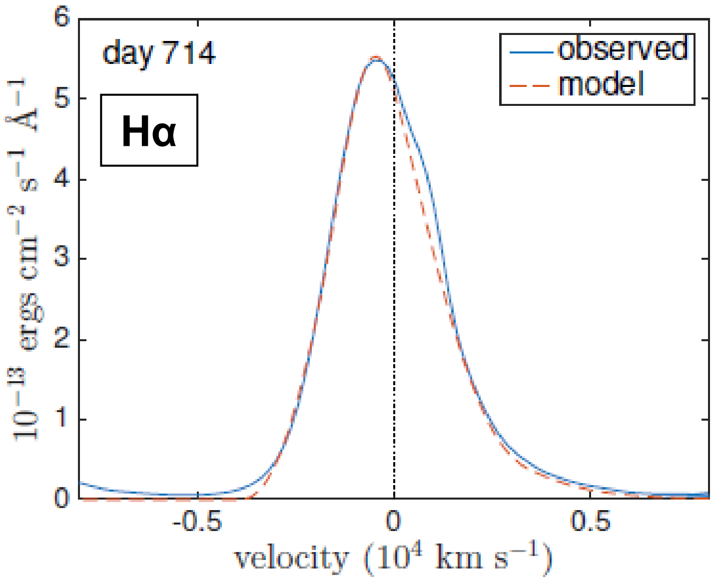


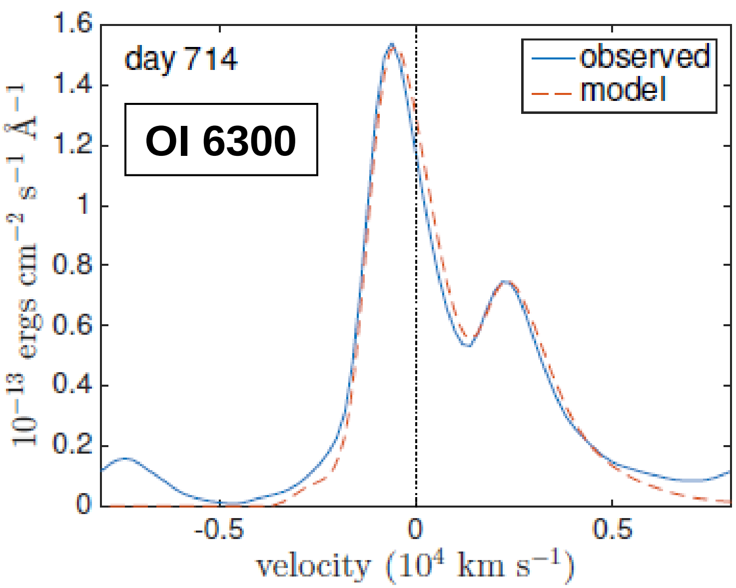
Dust formation in dense shell

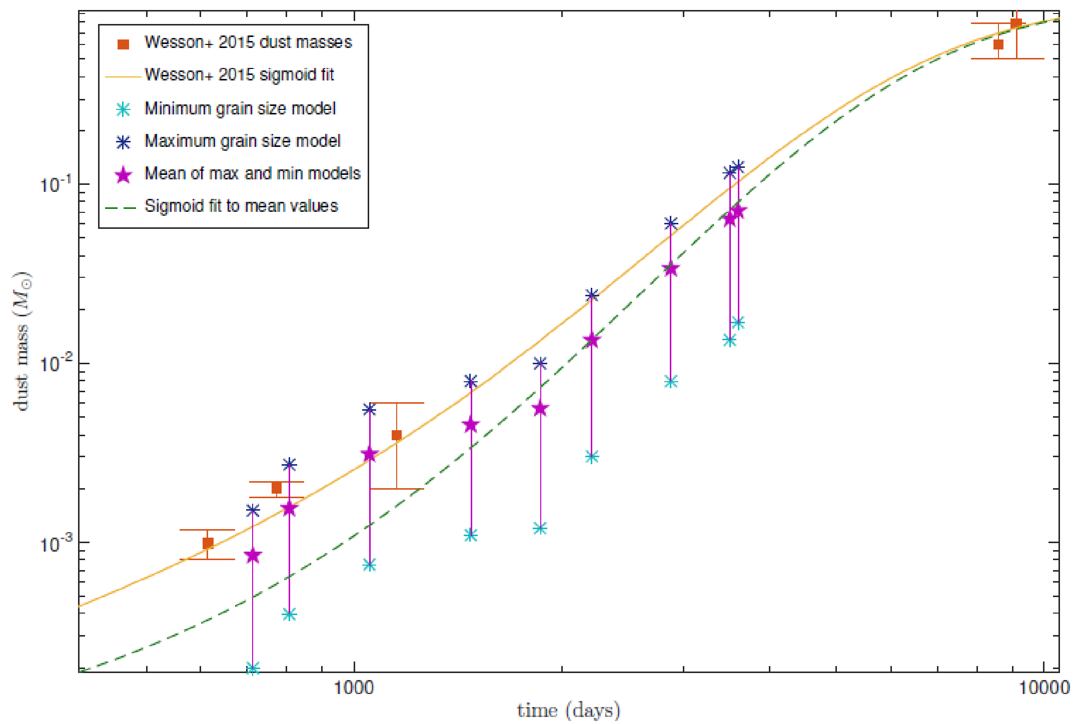


We should not discuss the mass of newly formed grains by integrating the formation of dust in the ejecta and CDS

2-8. Dust mass from line profiles in SN 1987A





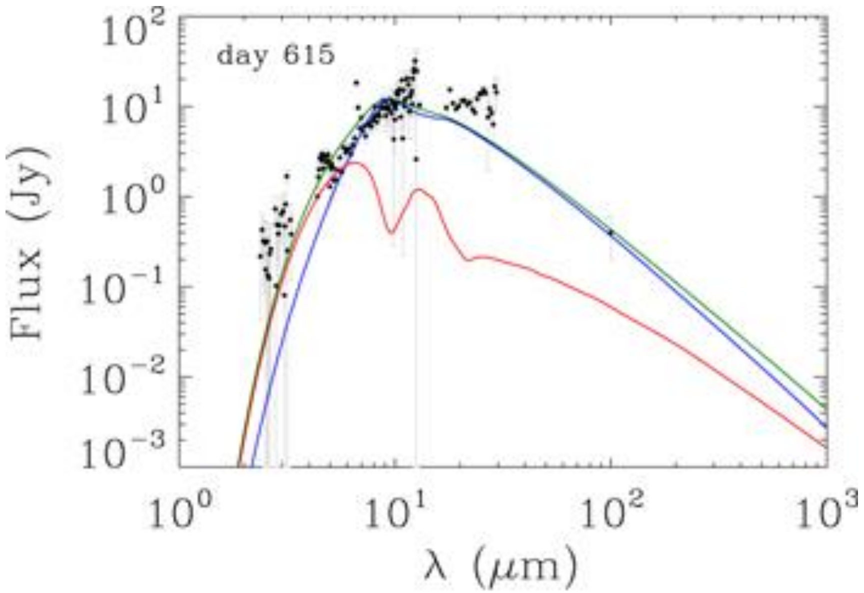


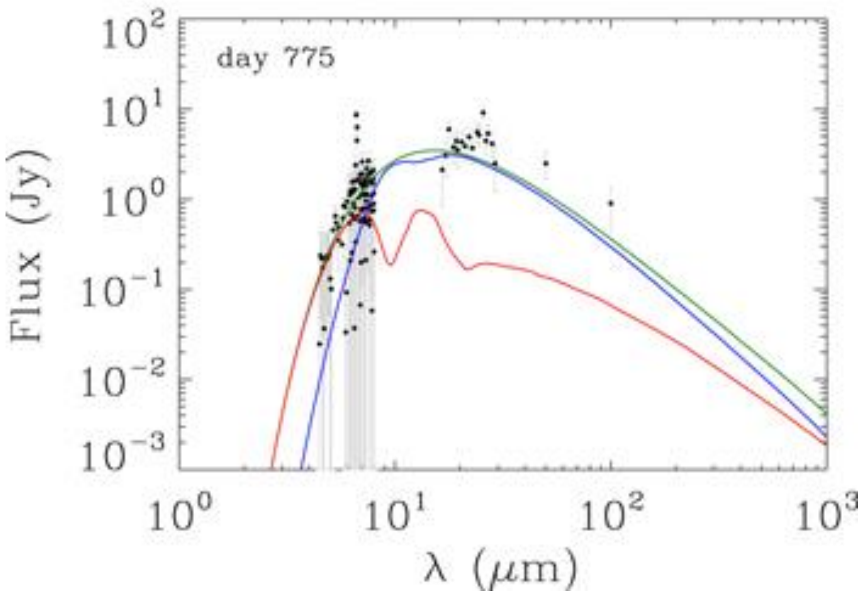
At 714 day

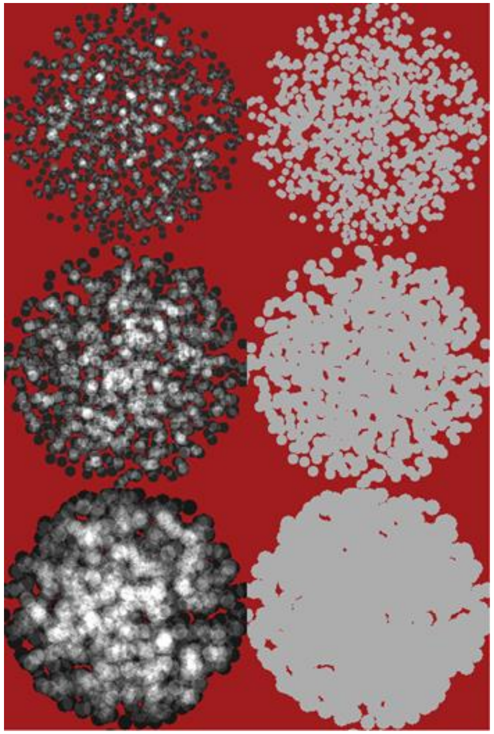
- **dust mass < 3×10^{-3} Msun (< 0.07 Msun if silicate)**
- **grain radius > ~0.6 μm**

Bevan & Barlow 2015, submitted

2-9. Evolution of dust mass in SN 1987A







At 615 and 714 day

- dust mass: ~0.4 M_{sun}
- silicate-dominated

Dwek & Arendt 2015, ApJ, 810, 75

2-10. Summary

○ 超新星ダスト研究における現在の二つの課題

1) 観測された大量のダストはいつ形成されたのか？
➜ 中間赤外線と遠赤外線でのダスト量の違いを説明したい

2) 形成されるダストのサイズはどれくらいか？
➜ 超新星による最終的なダスト放出量を明らかにしたい

未解決の問題

超新星イジェクタは、クランプ状になっている必要がある
ではどれくらい、クランプ状になっているか？
➜ 輻射輸送だけでなく、形成するダストのサイズにも影響

3-1. Presolar grains

○ Presolar grains

- discovered in meteorites
- showing peculiar isotopic compositions
  (highly different from the solar system's materials)
- thought to have originated in stars before the Sun was formed

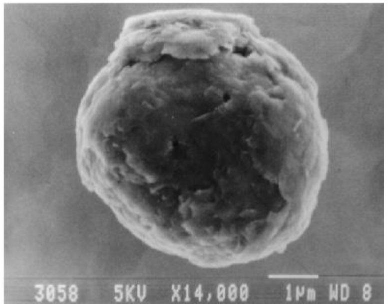
➜ **offering key information on nuclear processes in the parent stars**

red giants, AGB stars, supernovae, novae …

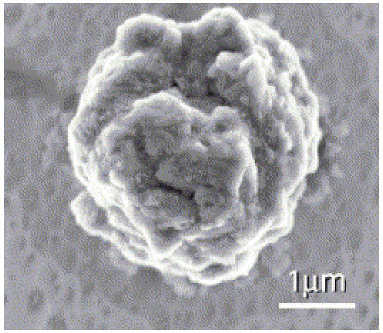
- mineral composition

  graphite, nanodiamond, TiC, SiC, Si_3N_4,

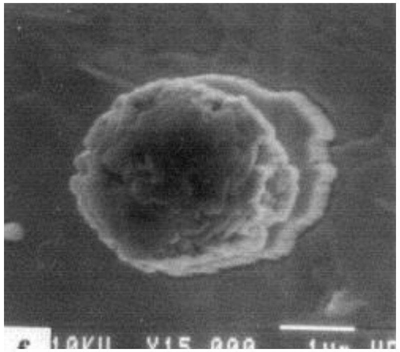
  Al_2O_3, $MgAl_2O_4$, TiO_2, Mg_2SiO_4, $MgSiO_3$ …



graphite (© Amari)



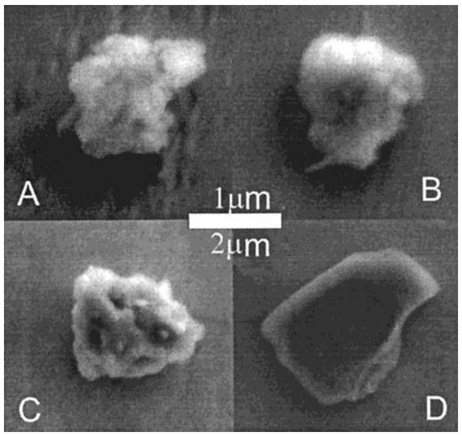
SiC (Nittler 2003)


Al_2O_3 (Nittler+1997)

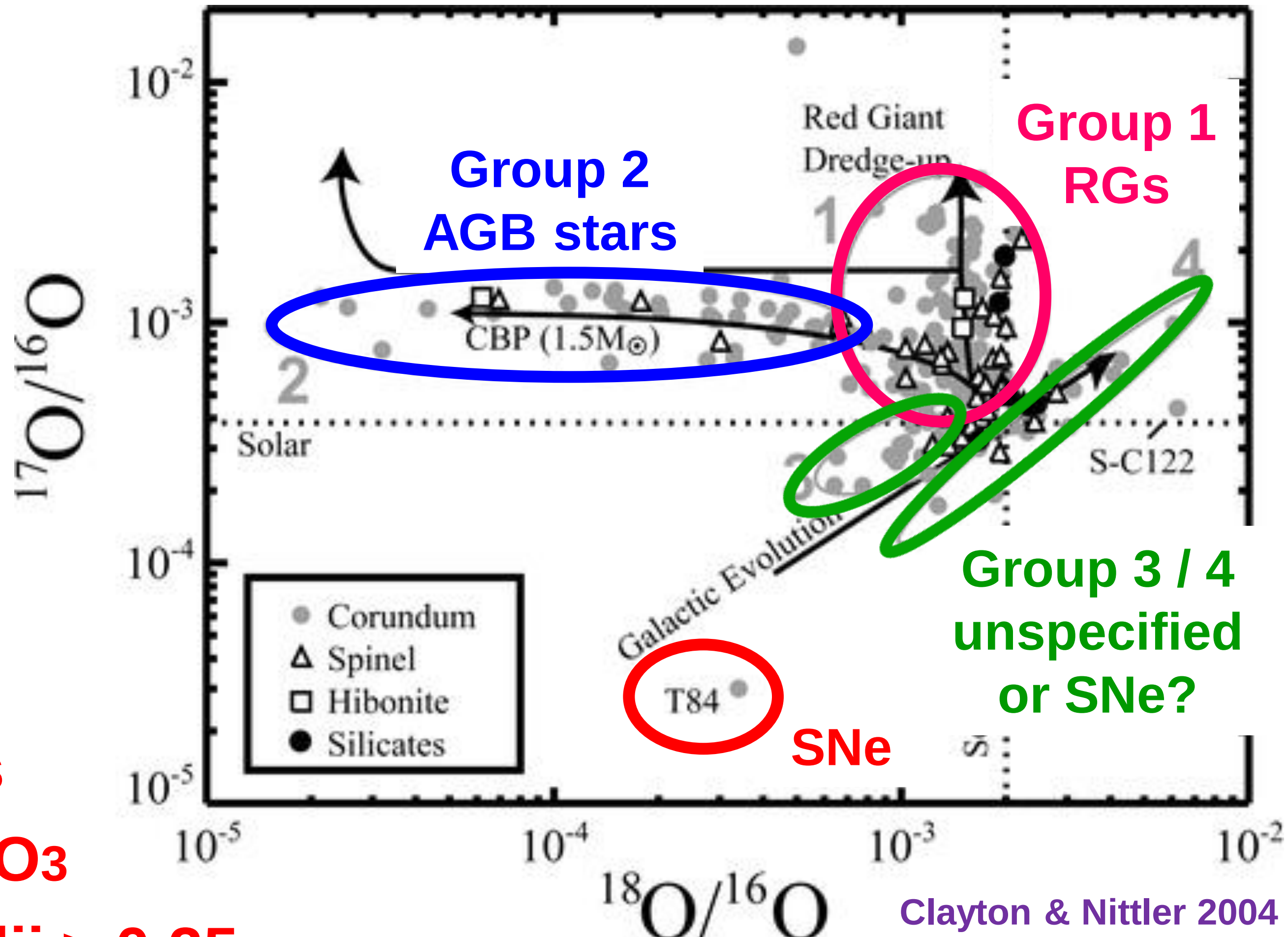
3-2. Isotopic composition of presolar oxides

○ Oxygen isotopic composition of presolar oxide grains

presolar Al_2O_3 grains



Choi+1998

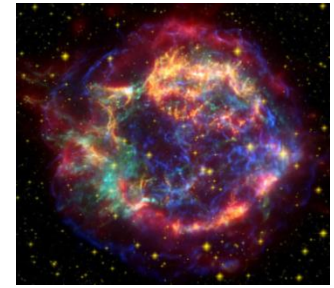


Clayton & Nittler 2004

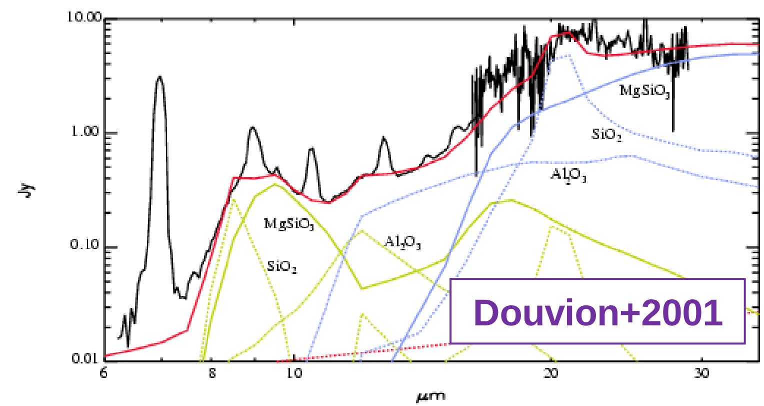
A few particles of presolar Al_2O_3 grains with radii > 0.25 μm are believed to have been produced in the ejecta of SNe

3-3. Why we focus on presolar Al_2O_3 grains?

○ Evidence for Al_2O_3 formation in SNe

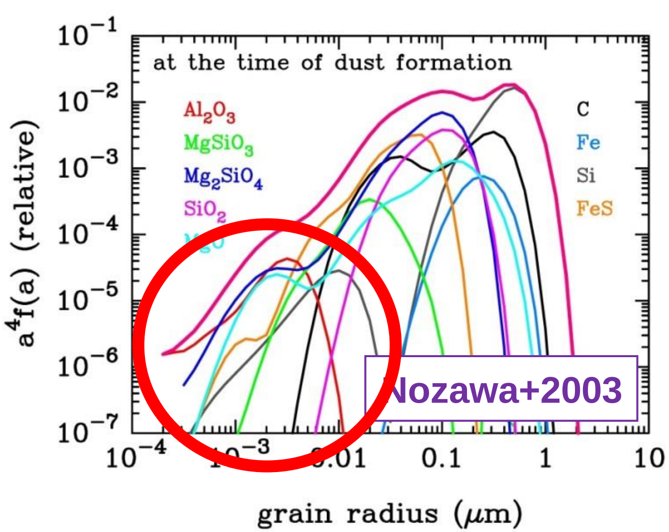


- Infrared spectra of Cassiopeia A (Cas A) SNR
  ➜ Al_2O_3 is one of the main grain species
  (Douvion et al. 2001; Rho et al. 2008)

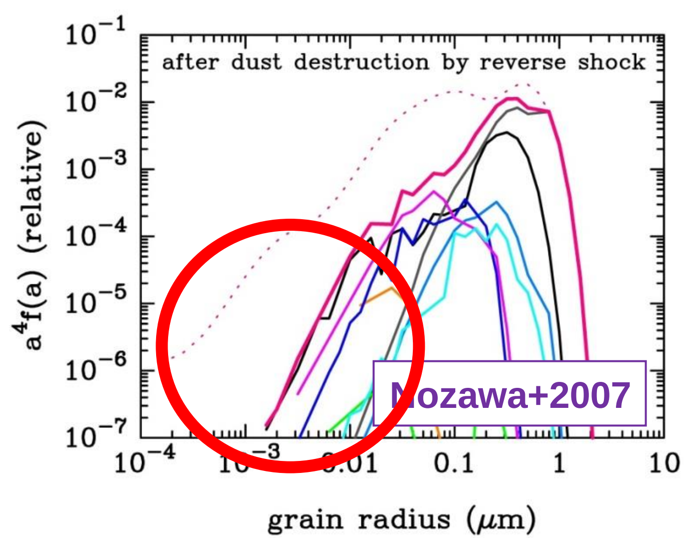


○ Dust formation calculations

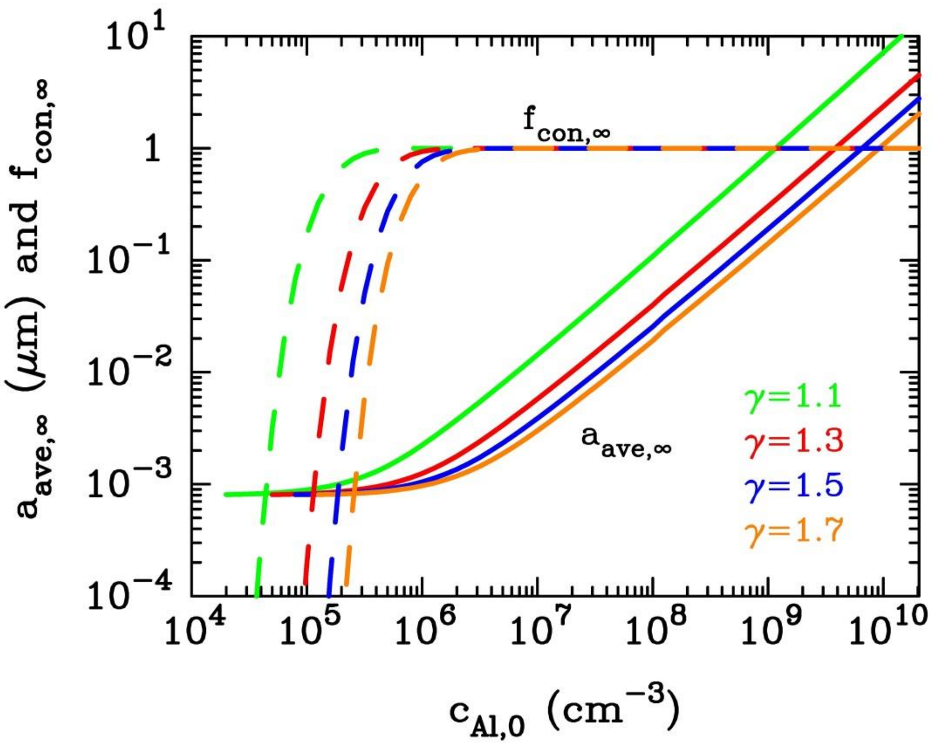
- the first condensate among oxide
  ➜ sizes of Al_2O_3 grains : < ~0.03 μm
  (e.g., Nozawa+2003; Todini & Ferrara+2001)

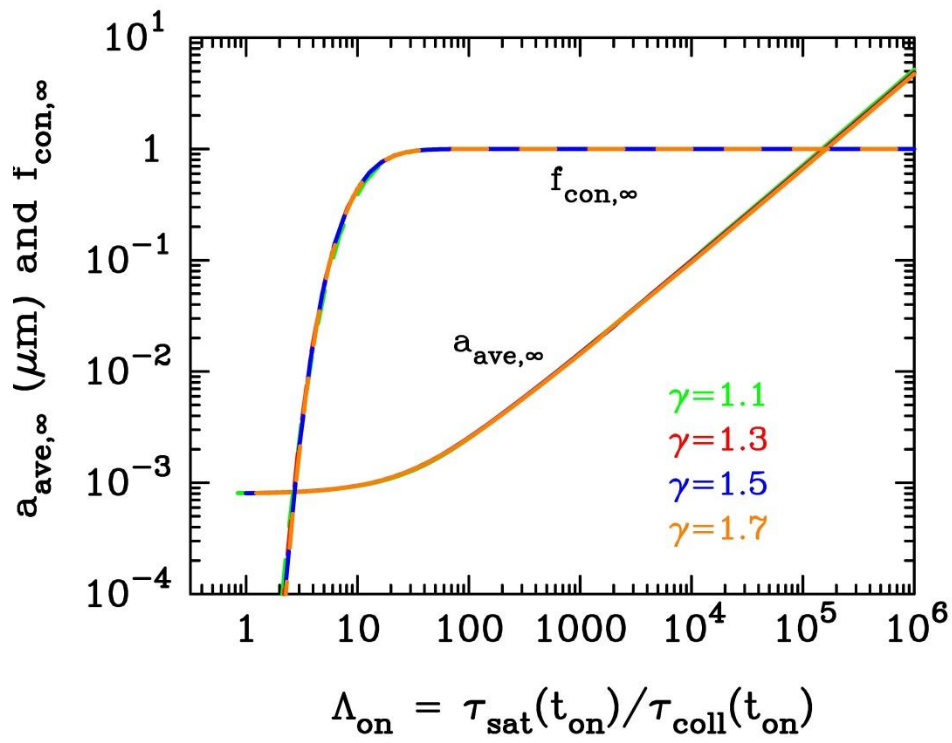


destruction in SNRs



3-4. Scaling relation for $f_{con,\infty}$ and $a_{ave,\infty}$





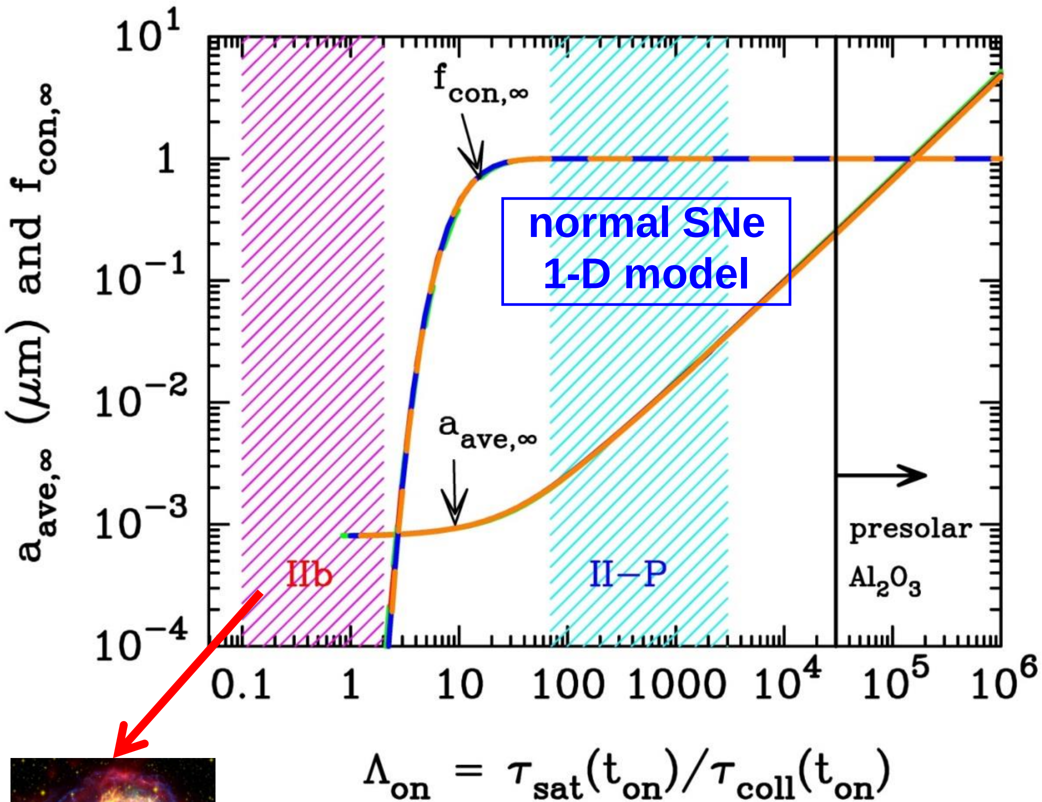
$\Lambda_{on} = \tau_{sat}/\tau_{coll}$: ratio of supersaturation timescale to gas collision timescale at the onset time (t_{on}) of dust formation

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

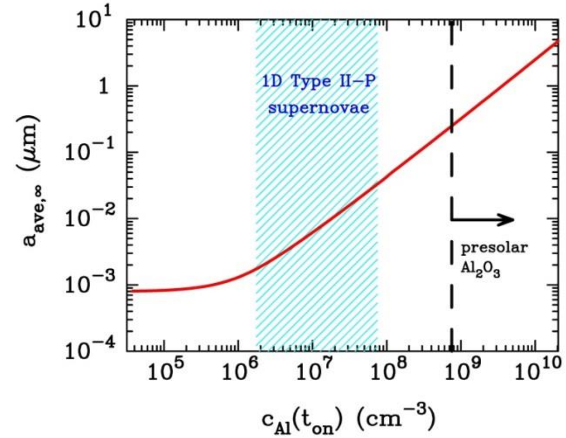
- $f_{con,\infty}$ and $a_{ave,\infty}$ are uniquely determined by Λ_{on}

this is true for the formation of carbon and silicate grains

3-5. Formation condition of presolar Al_2O_3



Nozawa+2015, ApJ, 811, L39



Λon > 30,000 required
➜ at least 10 times higher gas density than those predicted by 1-D SN models

$$\Lambda_{on} \simeq \frac{1082}{\gamma - 1}\left(\frac{t_{on}}{300\ \mathrm{days}}\right)\left[\frac{\tilde{c}_{Al}(t_{on})}{10^8\ \mathrm{cm}^{-3}}\right]\left[\frac{T(t_{on})}{2000\ \mathrm{K}}\right]^{\frac{3}{2}}.$$

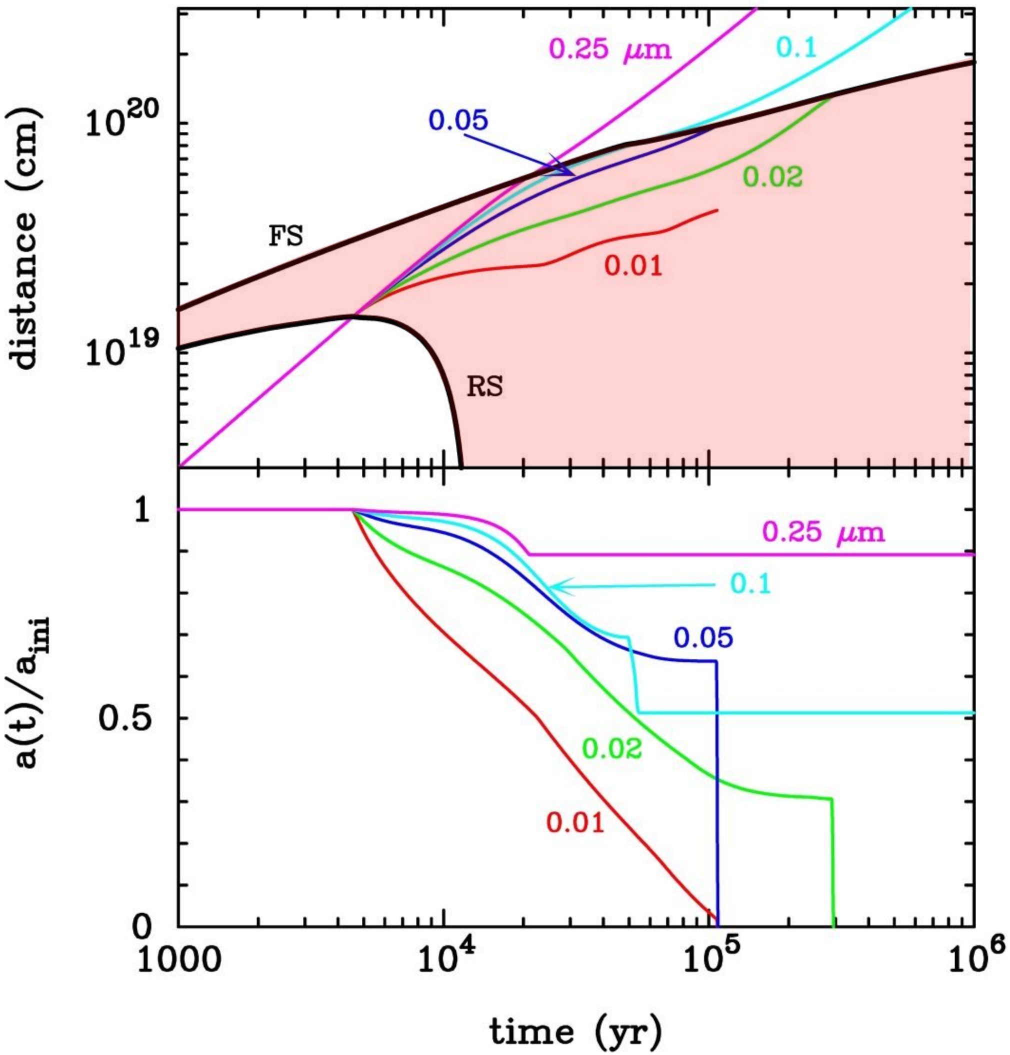
Submicron-sized presolar Al_2O_3 grains identified as SN-origin were formed in dense clumps in the ejecta

3-6. Newly formed grains can survive in SNR?

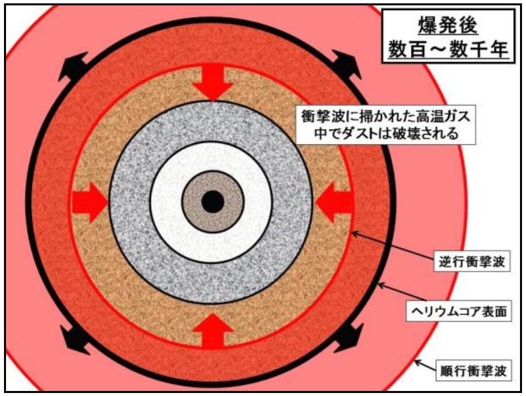
Model of the calculation:

M_{SN} = (3 + 12) Msun, E_{exp} = 1.8×10^{51} erg,

n_{ISM} = 1 cm^{-3}



Nozawa+2015, ApJ, 811, L39



Evolution of dust in SNRs depends on the initial radii

- a_{ini} < 0.01 μm
  ➔ completely destroyed

- 0.02 μm < a_{ini} < 0.1 μm
  ➔ eroded in dense shell

- a_{ini} > 0.1 μm
  ➔ injected into the ISM

3-7. Summary

We investigate the formation of Al_2O_3 grains for a variety of densities and cooling rates of the gas.

1) **The average radius and condensation efficiency of newly formed Al_2O_3 grains are uniquely described by the non-dimensional quantity Λ_{on}.**

2) **Presolar Al_2O_3 grains with radii above 0.25 μm can be formed only in the gas with more than 10 times higher density than those estimated by 1-D SN models.**
   ➜ indicating the presence of dense clumps in the SN ejecta

3) **The measured sizes of presolar grains are powerful probes for constraining the physical conditions and structure in which they formed.**

4-1. Extinction law towards Type Ia SNe

○ Type Ia supernovae (SNe Ia)

- thermonuclear explosion of a white dwarf (WD)
  - progenitor system: (WD+MS) or (WD+WD)?
- discovered in all types of galaxies
  - star-forming, elliptical, irregular, etc …
- used as cosmic standard candles

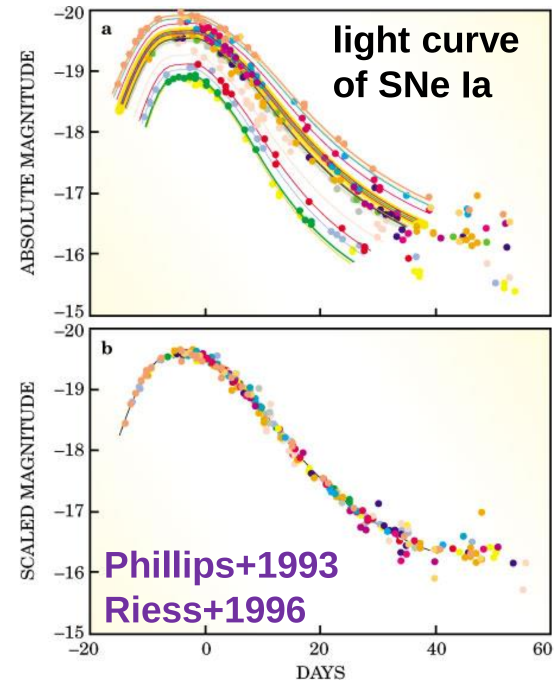
$$M_B = m_B - 5 \log_{10}(D_L) - A_B - 5$$

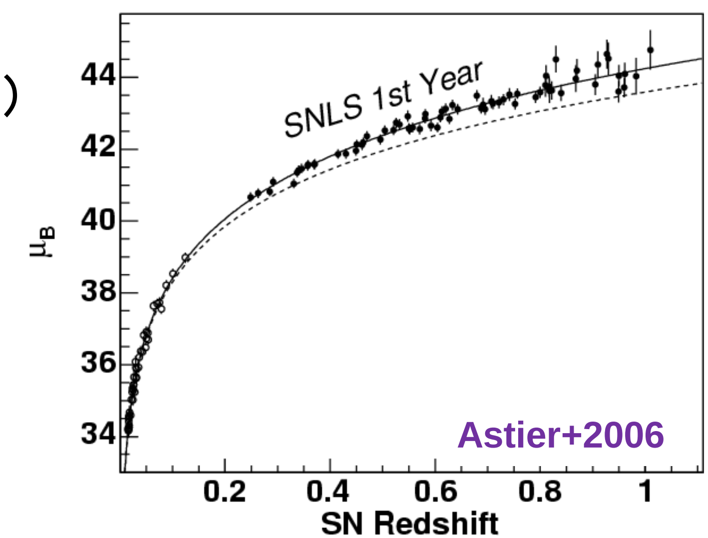
➜ $R_V = 1.0 \sim 2.5$ ($R_V = A_V/(A_B - A_V)$)

to minimize the dispersion of Hubble diagram

(e.g., Tripp+1998; Conley+2007; Phillips+2013)

cf. $R_V = 3.1$ for the average extinction curvei n the Milky-Way (MW)

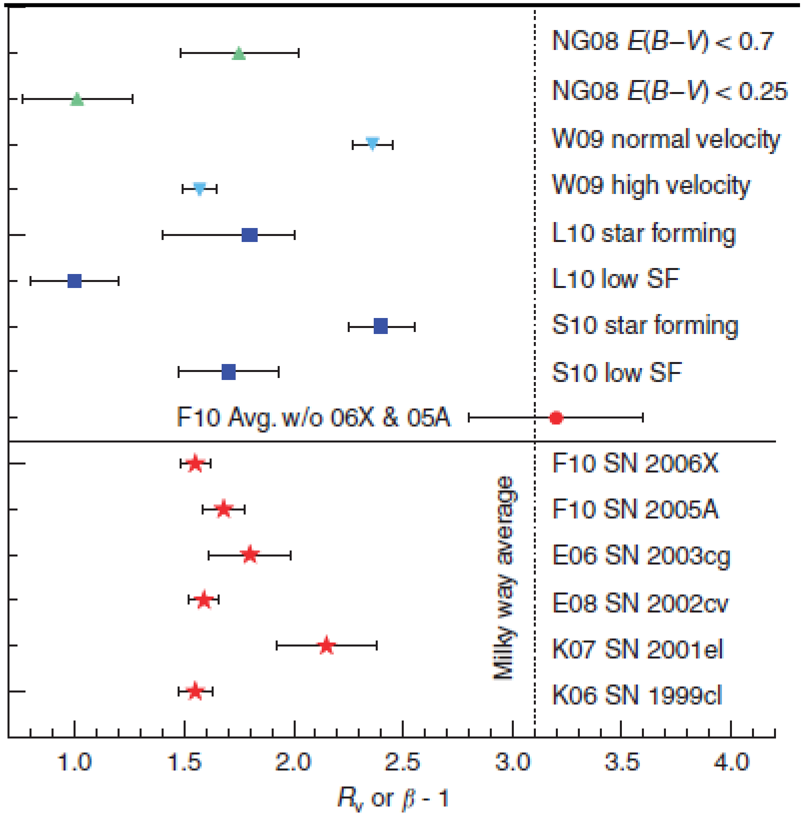




4-2. Other examples of reddening for SNe Ia

○ Other examples of Rv for SNe Ia

- average of ensembles of SNe Ia
  Rv = 1.0-2.3
- from obtained colors of SNe Ia in near-UV to near-infrared (NIR)
  Rv ~ 3.2 (Folatelli+2010)
  Rv = 1.5-2.2
  (e.g., Elisa-Rosa+2008; Kriscinuas+2007)



Howell+2011

○ Extinction in nearby galaxies

- M 31 (Andromeda Galaxy)
  Rv = 2.1-3.1 (e.g., Melchior+2000; Dong+2014)
- elliptical galaxies
  Rv = 2.0-3.5 (Patil+2007)

➜ Rv is moderately low or normal

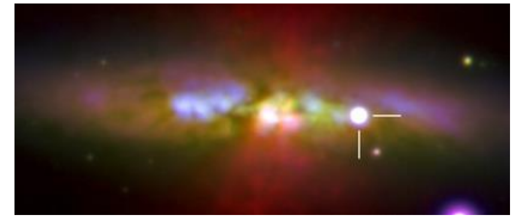
4-3. Peculiar extinction towards SN 2014J

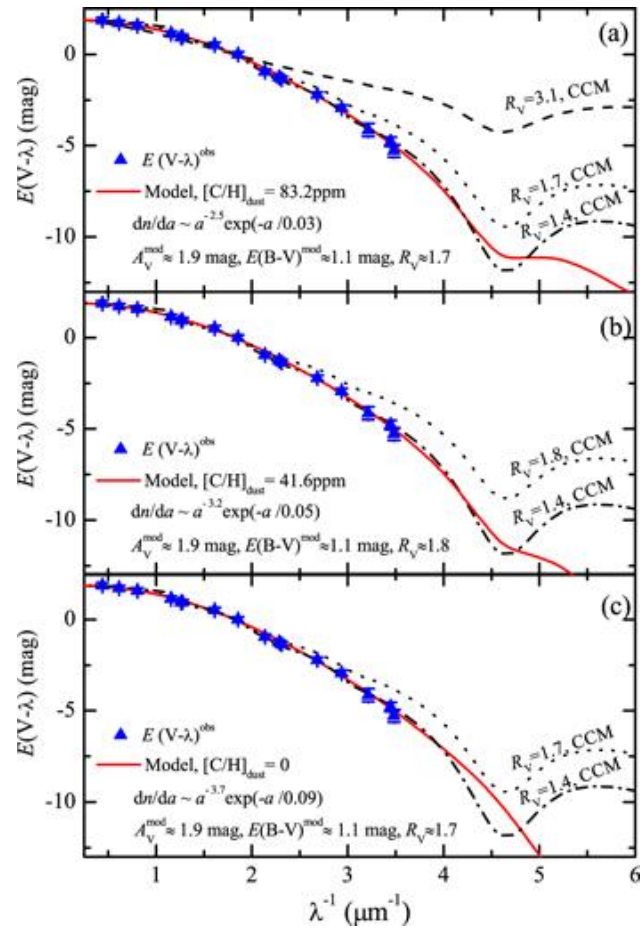
○ Type Ia SN 2014J

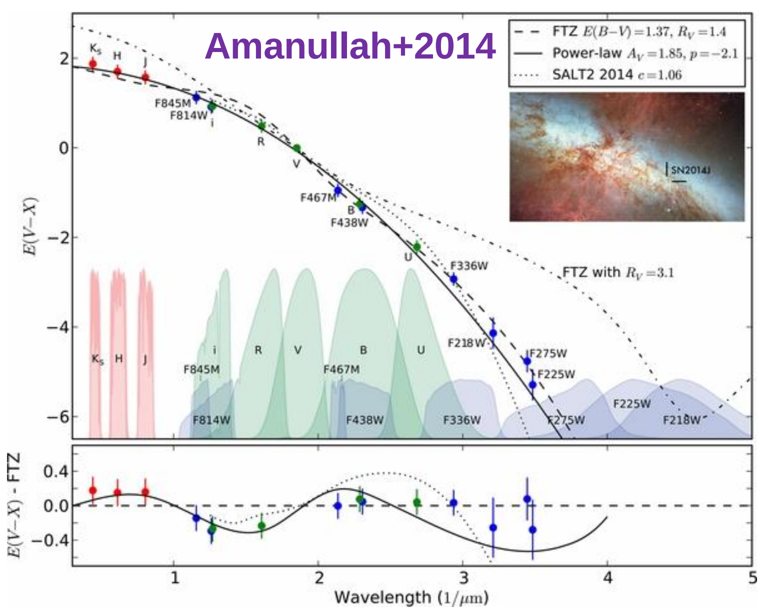
- discovered in M 82 (D ~ 3.5±0.3 Mpc)
  - closest SN Ia in the last thirty years
  - highly reddened (Av ~ 2.0 mag)

- reddening law is reproduced by CCM relation with **Rv ~ 1.5**

(Ammanullah+2014; Foley+2014; Gao+2015)

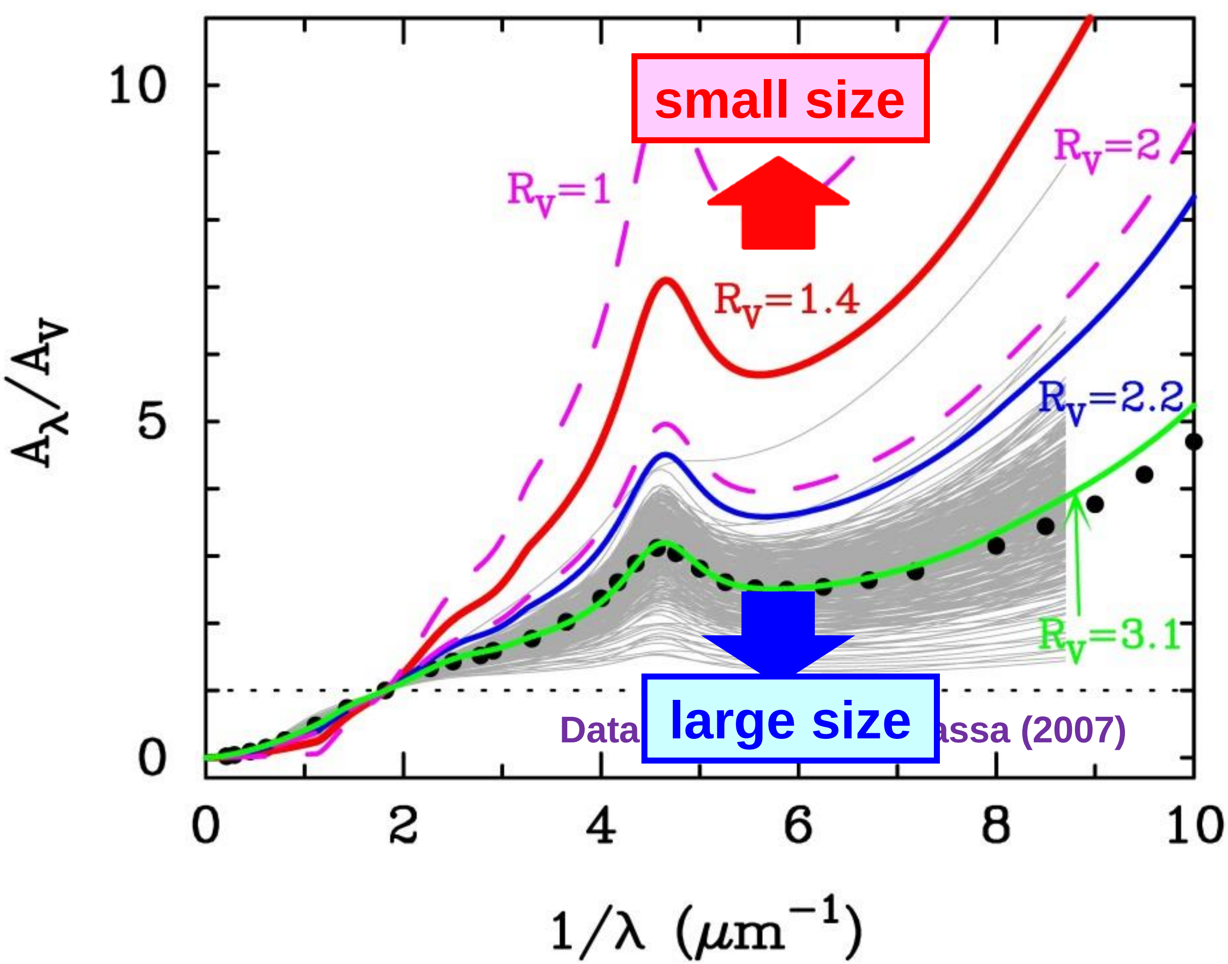






Gao+2015, Li's talk

4-4. How peculiar is SNe Ia extinction curves?



○ CCM relation
(Cardelli, Clayton, Mathis 1989)

Rv : ratio of total-to-selective extinction

$R_V = A_V / E(B - V)$
$= A_V / (A_B - A_V)$

$A_\lambda/A_V = a(x) + b(x) / R_V$
where $x = 1 / \lambda$

in our Galaxy
$R_V = 2.2\text{-}5.5$
$R_{V,ave} \sim 3.1$

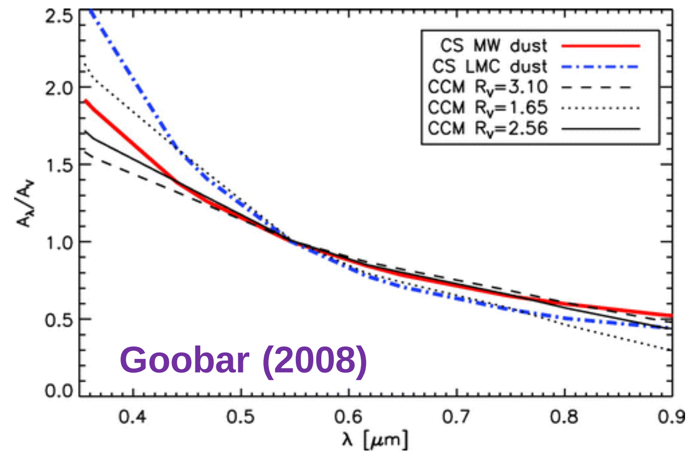
- **steeper** extinction curve (**lower** Rv) ➜ **smaller** grains
- **flatter** extinction curve (**higher** Rv) ➜ **larger** grains

4-5. Low Rv: interstellar or circumstellar origin?

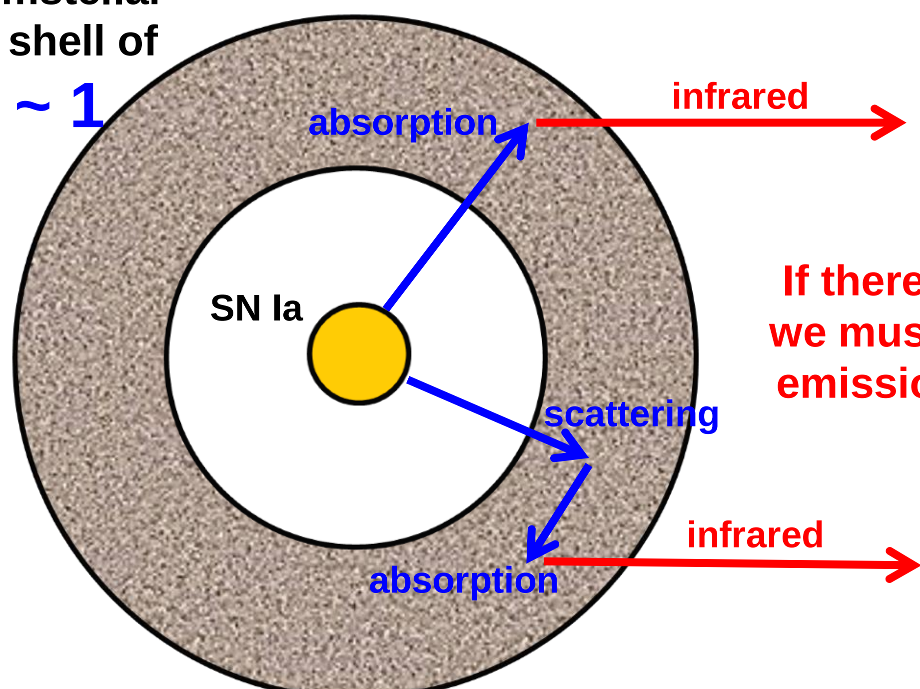
○ Origin of low Rv observed for SNe Ia

- odd properties of interstellar dust
  (e.g., Kawabata+2014; Foley+2014)

- multiple scattering by circumstellar dust
  (Wang 2005; Goobar 2008; Amanullah & Goobar 2011)



circumstellar dust shell of $\tau_V \sim 1$

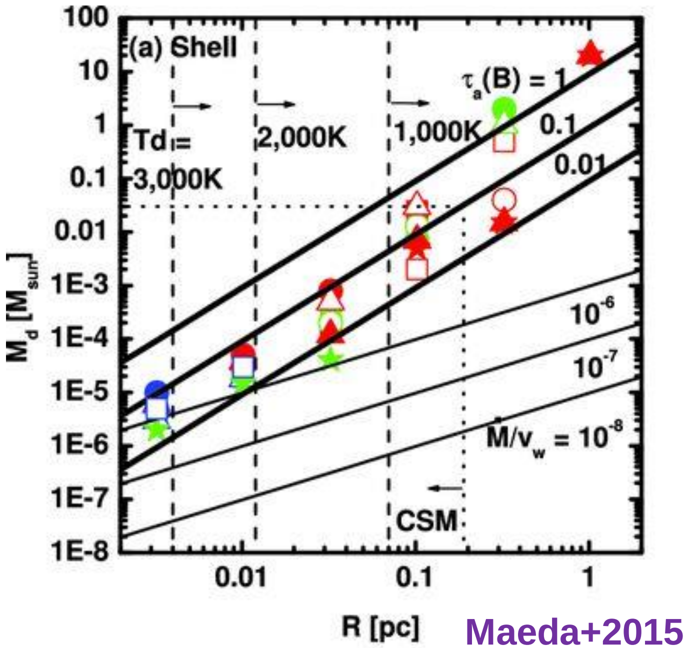


If there is a thick dust shell, we must detect thermal dust emission as infrared echoes

4-6. Near-infrared observations of SNe Ia

○ Near-infrared (NIR) observations

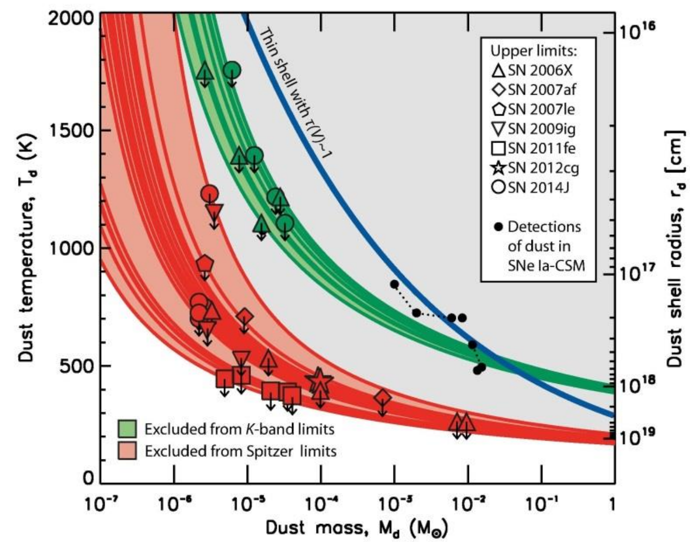
- no excess flux at *JHK* bands
- IR echo model (thin shell approximation)
  constrain the mass of dust for a given position of the dust shell (Maeda, TN+2015)
  ➜ conservative upper limits of optical depths in B band is τB < ~0.1



Maeda+2015

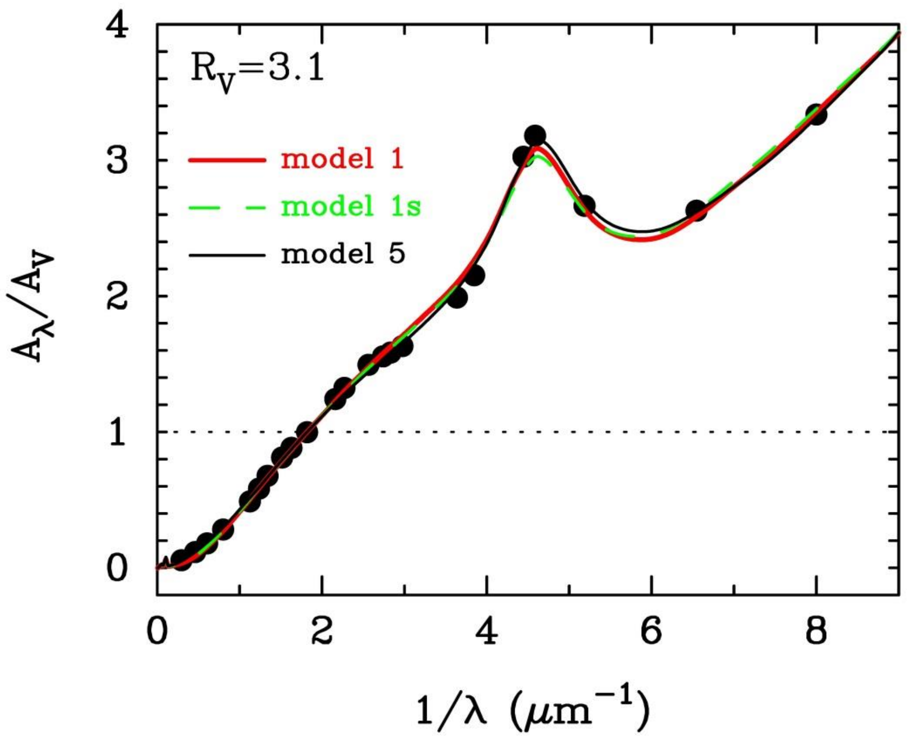
○ Spitzer observations

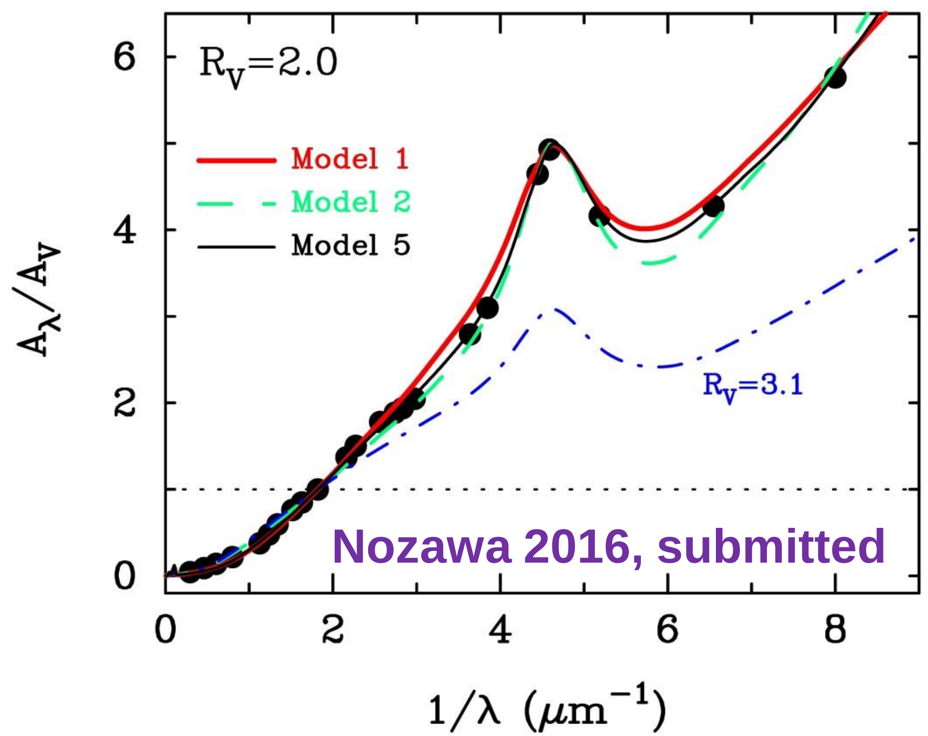
- no excess flux at 3.5/4.5 μm
  (Johansson+2015)
- upper limit of dust mass: ~10^{-4} Msun
  ➜ optical depth τ << 1



Johansson+2015

4-7. Dust model for Rv = 1.5 CCM curve





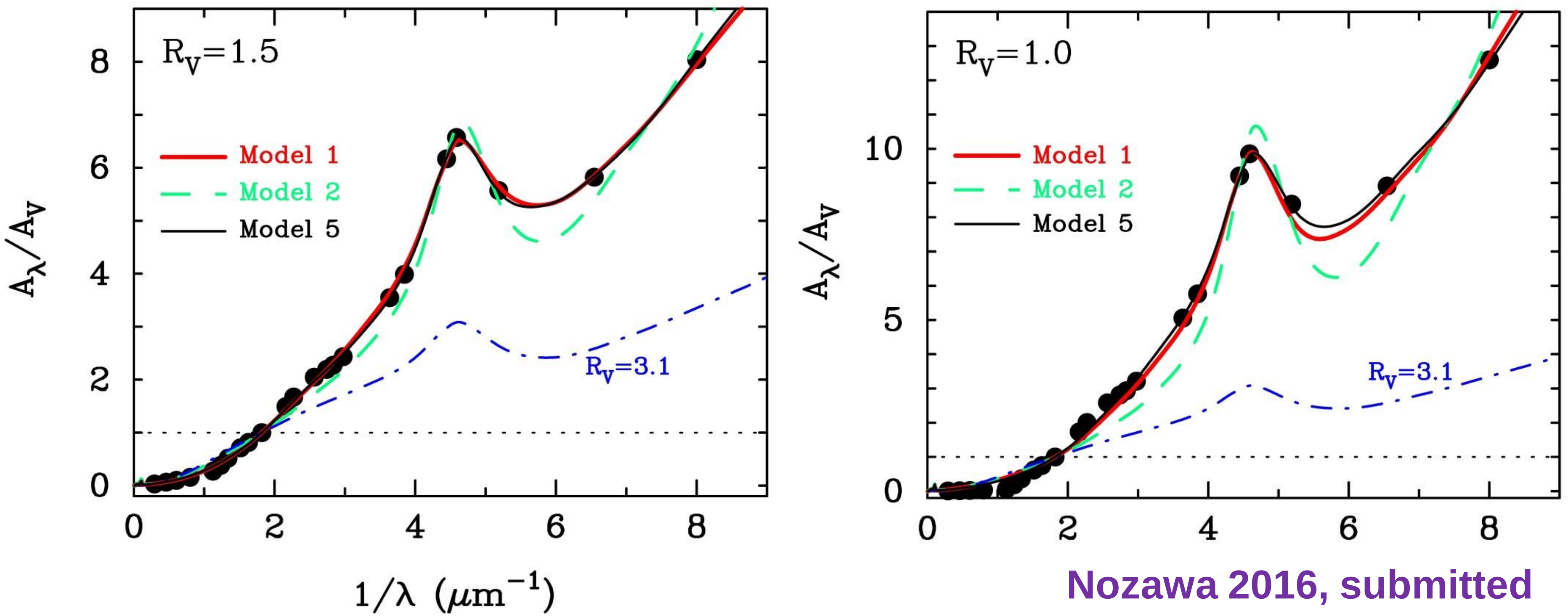
○ MRN dust model (Mathis, Rumpl, & Nordsieck 1977)

- dust composition : silicate ($MgFeSiO_4$) & graphite (C)
- size distribution : power-law distribution

  $n(a) \propto a^{-q}$ with q=3.5, a_{max} = 0.24 μm, a_{min} = 0.005 μm

Rv = 2.0 curve ➜ a_{max} = 0.129 μm, a_{min} = 0.005 μm

4-8. Dust models for Rv = 1.0 and 2.0 curve



Nozawa 2016, submitted

Rv = 1.5 curve ➜ a_{max} = 0.0925 μm, a_{min} = 0.005 μm
Rv = 1.0 curve ➜ a_{max} = 0.057 μm, a_{min} = 0.005 μm

But, the values of Rv obtained from the MRN dust model are higher than Rv used for the CCM relation

$R_{V,CCM}$ = 1.5 curve ➜ $R_{V,\ dust}$ = 1.72
$R_{V,CCM}$ = 1.0 curve ➜ $R_{V,\ dust}$ = 1.49

4-9. Summary

1) Many studies (mainly SNe Ia cosmology) suggest that the Rv values toward SNe Ia are very low (Rv ~ 1-2.5), compared with Rv = 3.1 in our Galaxy

2) Non-detection of IR echoes towards SNe Ia indicates that the low Rv is not due to the circumstellar dust but due to the interstellar dust in the host galaxies

3) The CCM curves with Rv = 1-2 can be reasonably fitted by the power-law dust model (graphite/astronomical silicate) with a_{max} = 0.06-0.13 μm (instead of a_{max} = 0.24 μm for Rv = 3.1)