2017/12/22

超新星ダストの形成と銀河ダストの物理化学進化 －コンセンサスと課題－
(Formation of SN-dust and Evolution of dust in galaxies －consensus and issues－)

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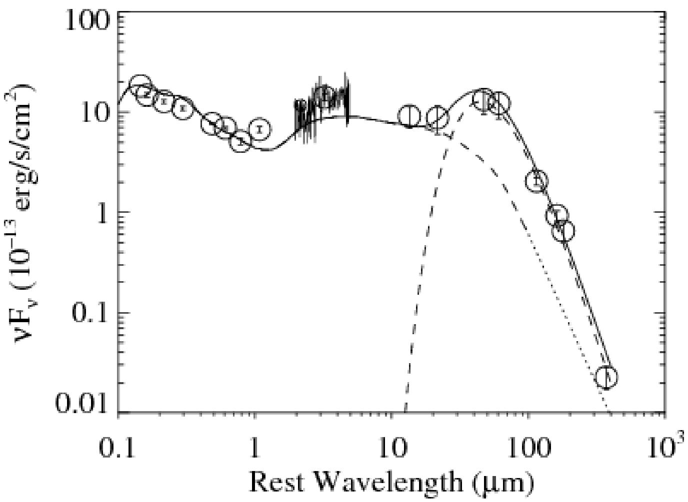
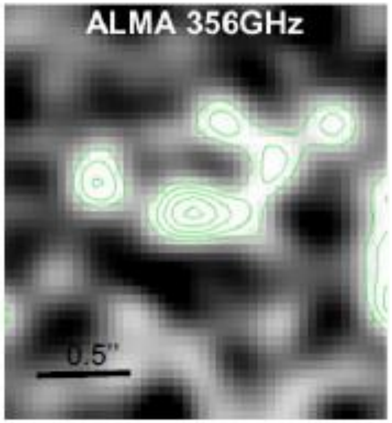
1-1. Discovery of massive dust at z > 5

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



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

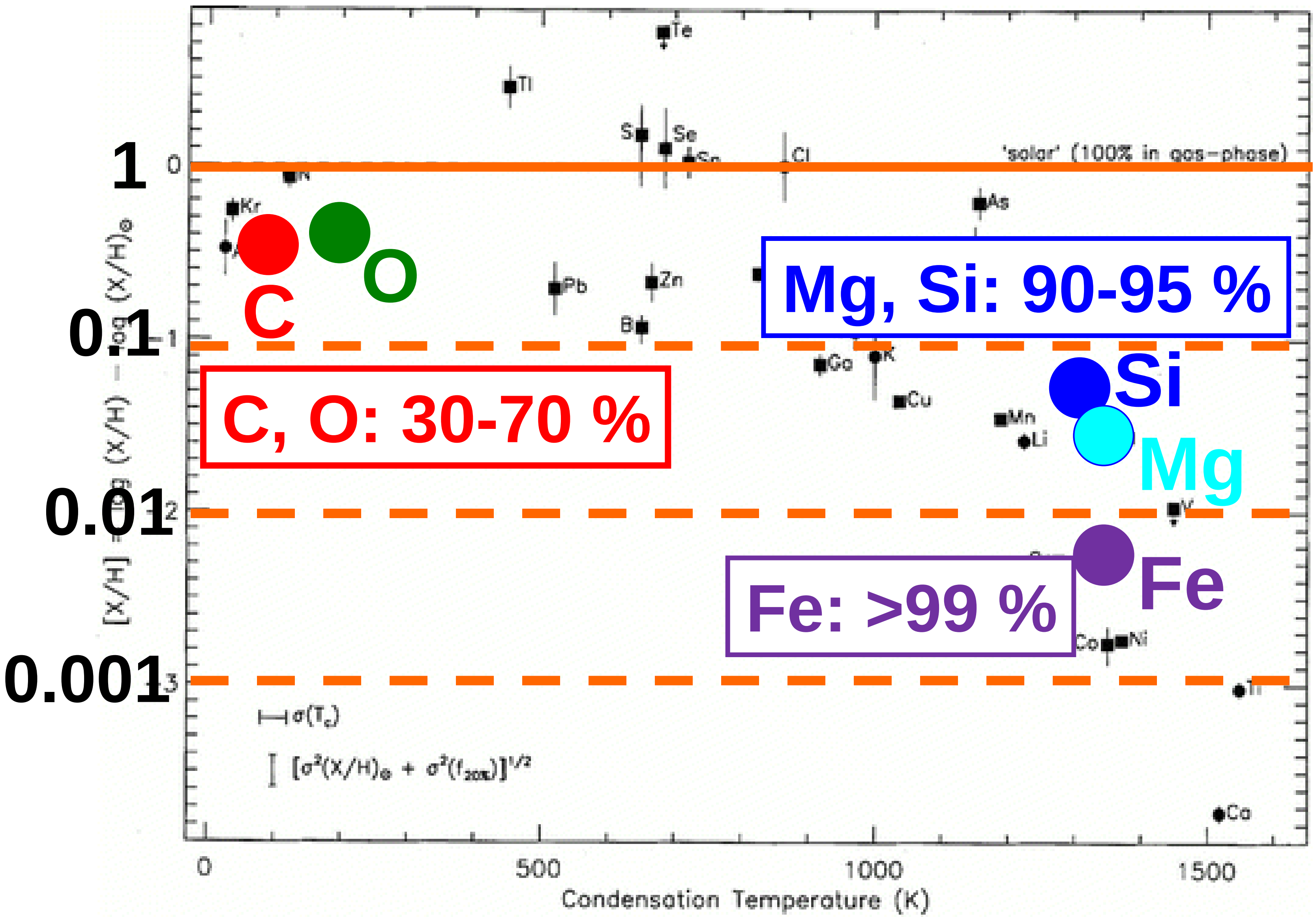


~10^6 Msun of dust in a galaxy at z = 8.4
Laporte+2017

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

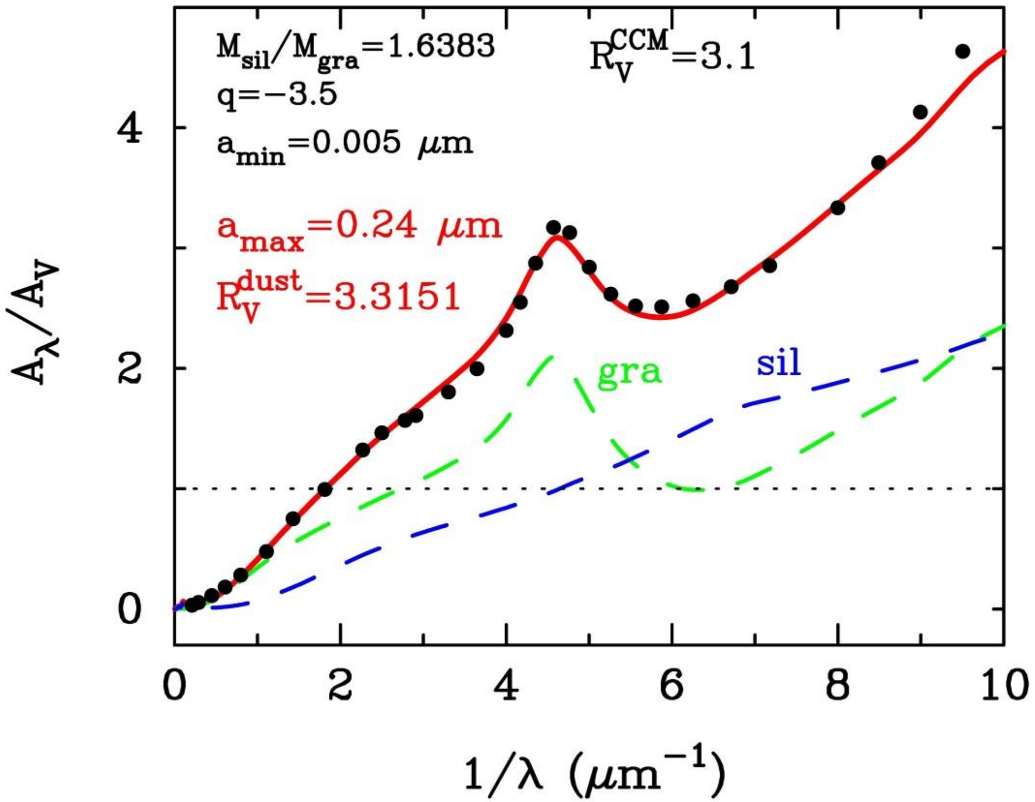
- **0.1 Msun of dust per SN is needed to explain massive dust at high-z** (e.g. Morgan & Edmunds 2003; Maiolino+2006; Dwek+2007)

1-2. Depletion of gas metals in the present ISM



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

1-3. Average extinction curve in the Milky Way



○ MRN dust model

(Mathis, Rumpl, & Nordsieck 1977)

- dust composition: silicate and graphite
- size distribution: power-law
  $n(a) \propto a^{-q}$ with $q=3.5$,
  $a_{max} = 0.25\ \mu m$
  $a_{min} = 0.005\ \mu m$
- mass ratio: $M_{sil} / M_{gra} \sim 2$

astronomical silicate (Draine & Lee 1984)

- hypothetical material to account for observed spectra from UV to infrared (i.e. its optical constant is artificial)
  assumed chemical composition: $Mg_{1.1}Fe_{0.9}SiO_4$

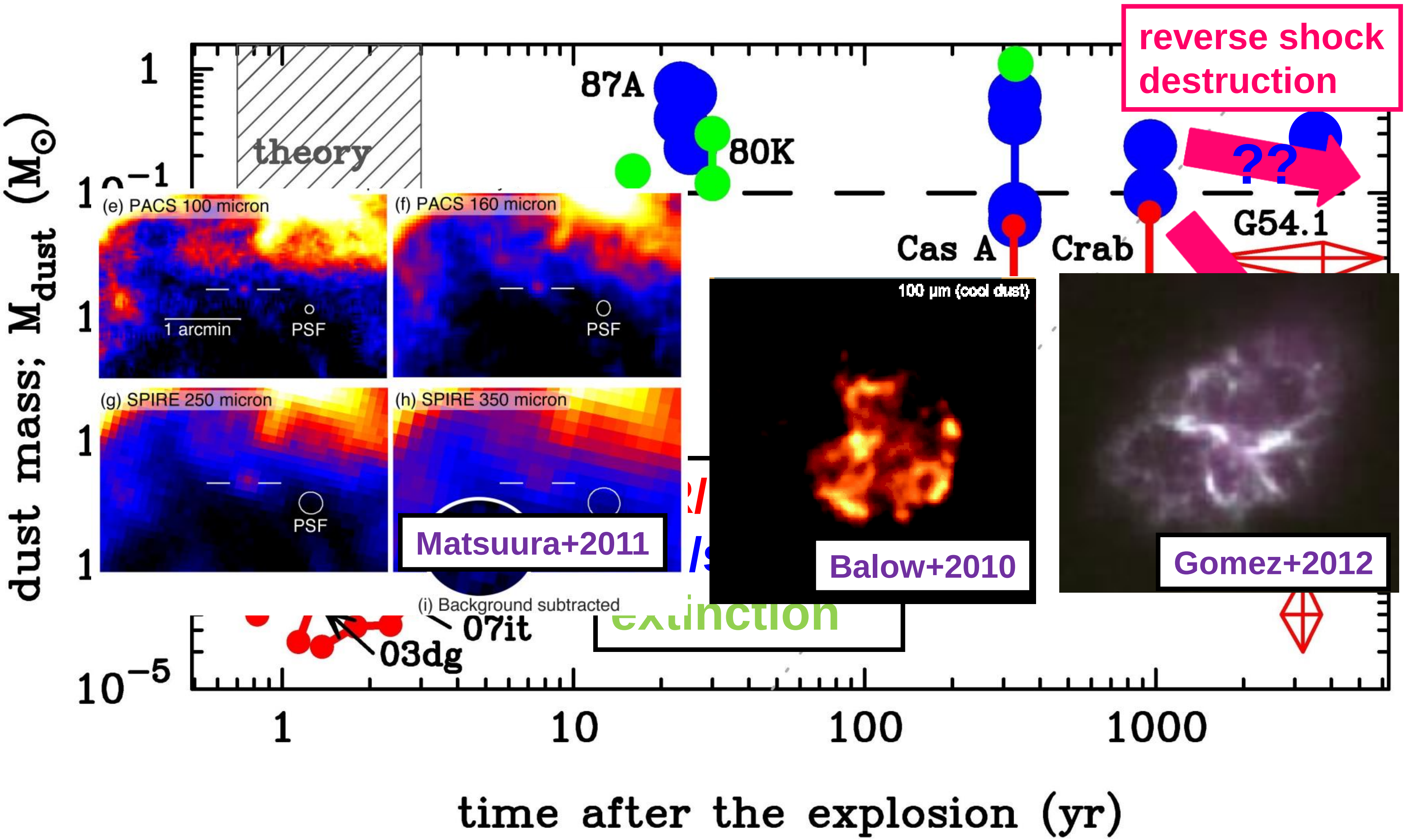
2-1. Key questions for dust formation in SNe

1. How much dust grains form?

2. What is the size distribution of dust?

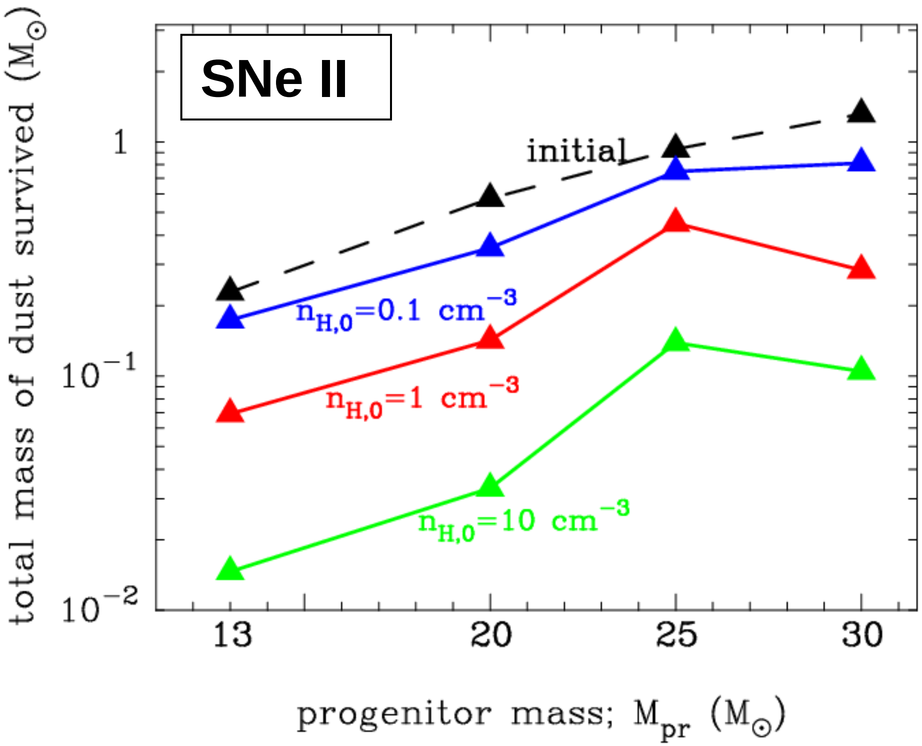
3. When do the majority of grains form?

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

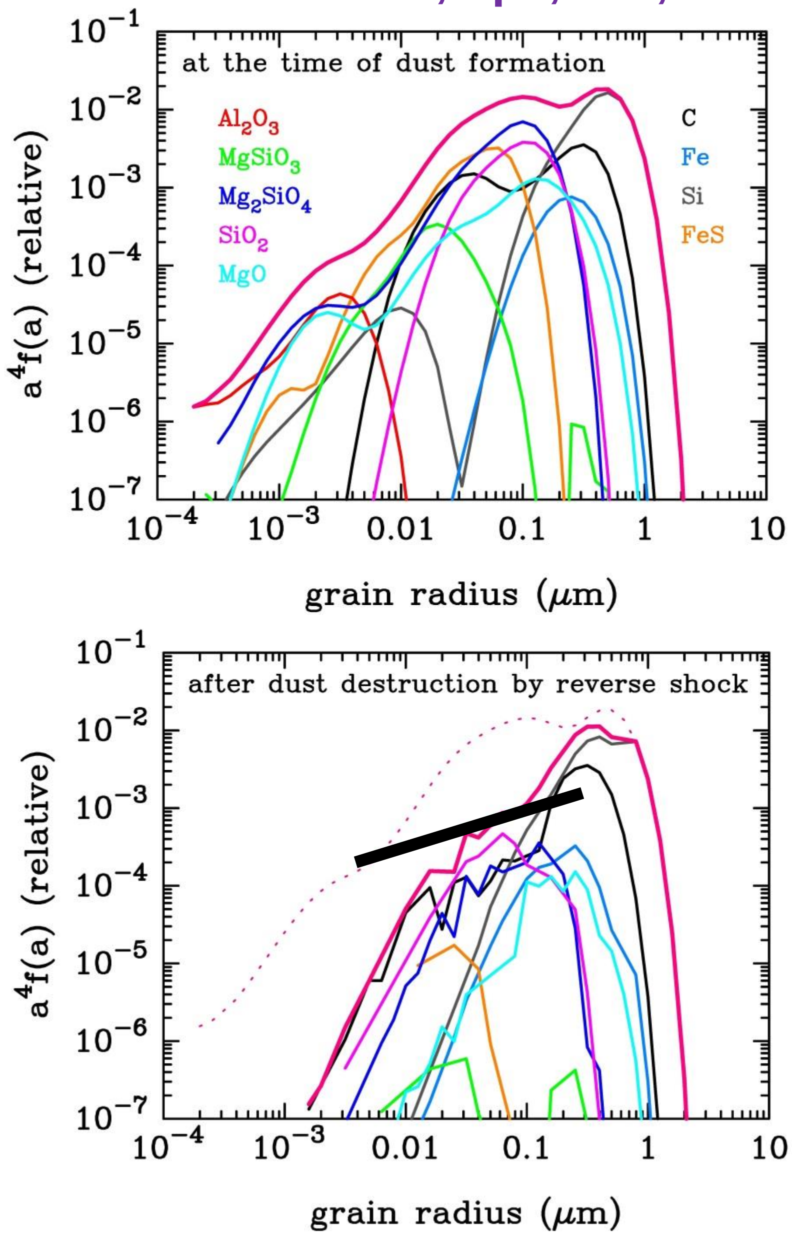


Dust mass formed in the ejecta is dominated by cold dust

2-3. Properties of dust ejected from SNe II-P



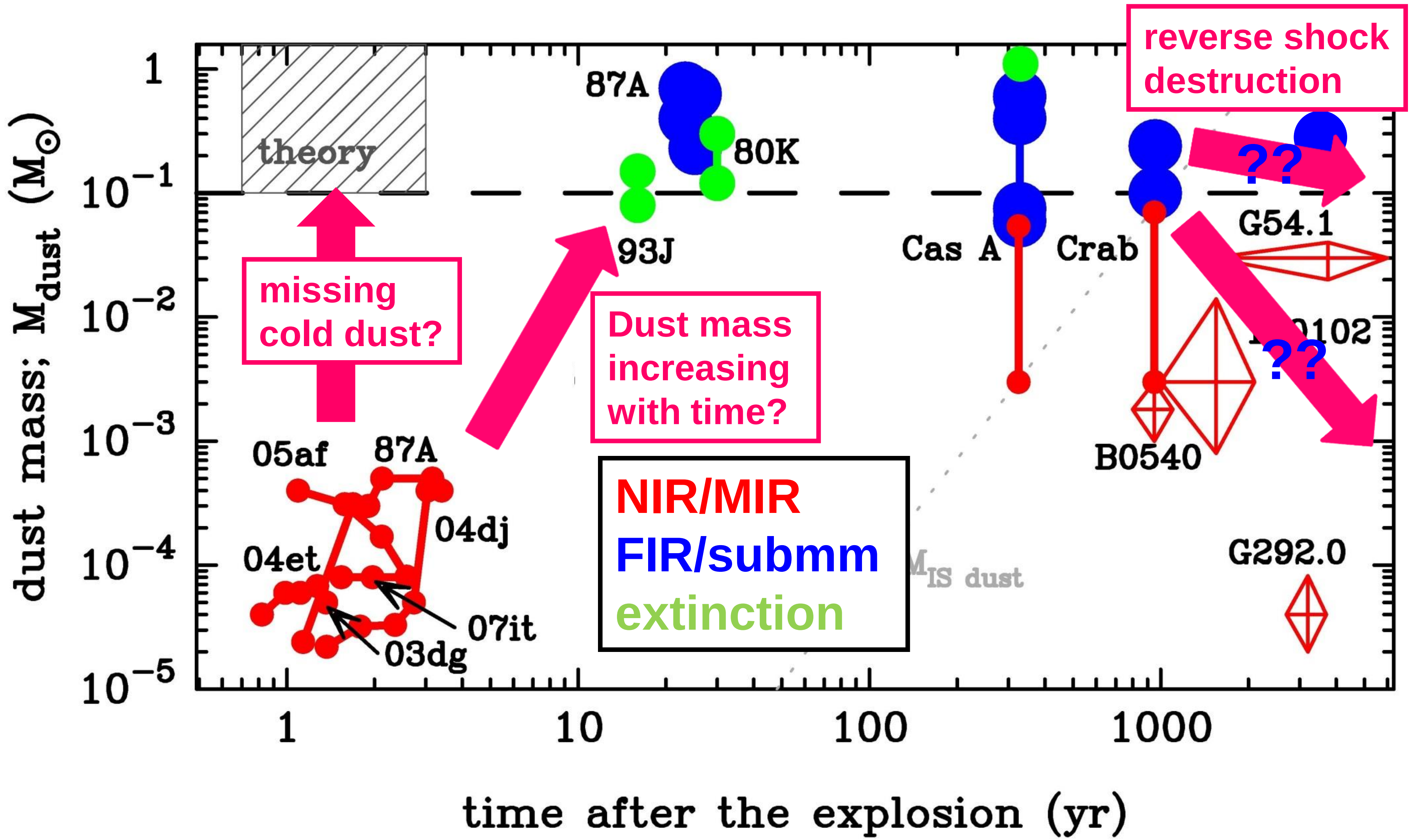
Nozawa+07, ApJ, 666, 955



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

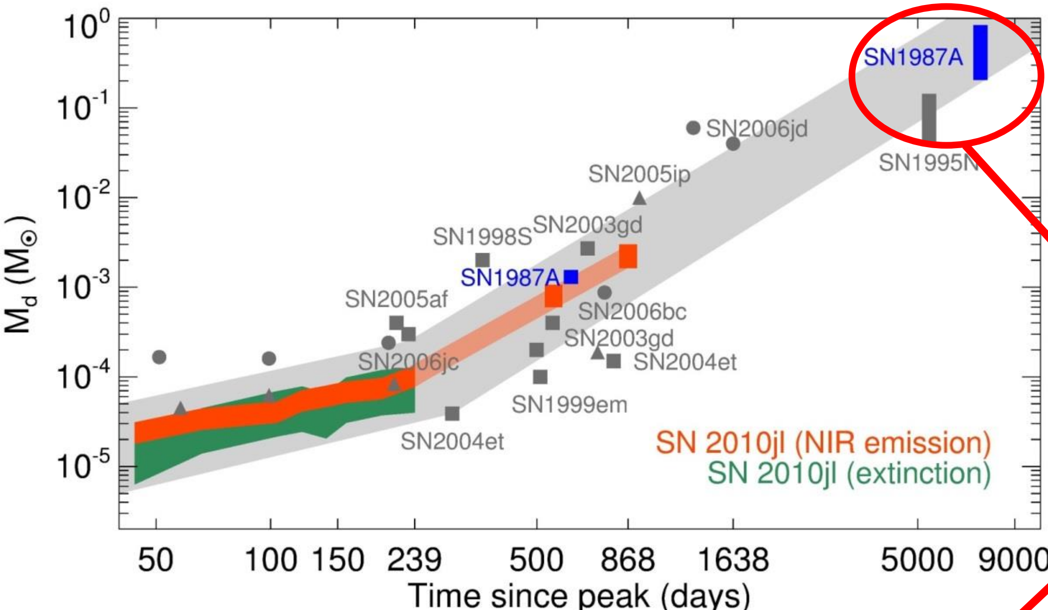
size distribution of dust after the shock-destruction is domimated by large grains (> 0.1 μm)

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



Dust mass formed in the ejecta is dominated by cold dust

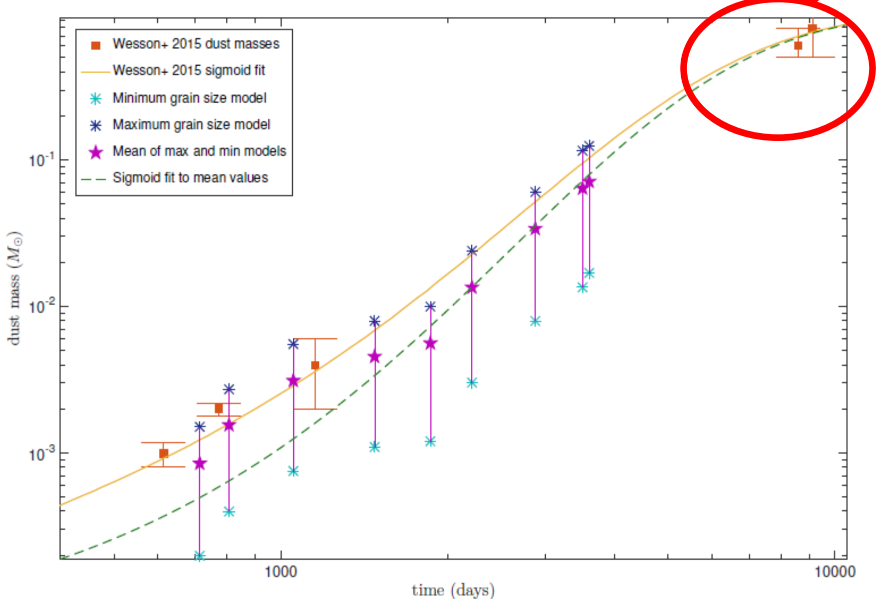
2-4. Dust mass increases with time?



Dust mass estimated from IR SEDs

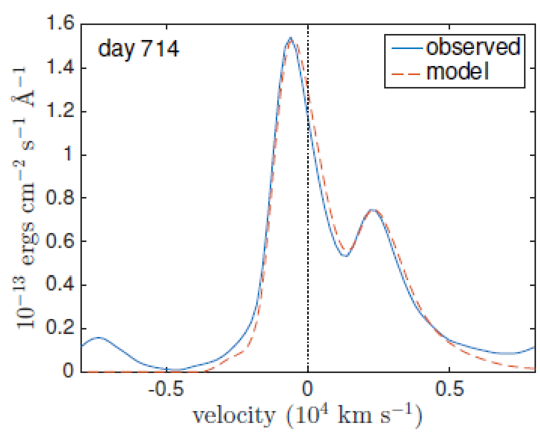
Gall et al. (2014, Nature)

Most of dust grains (> 0.1 Msun) form at ~20 yr post-explosion

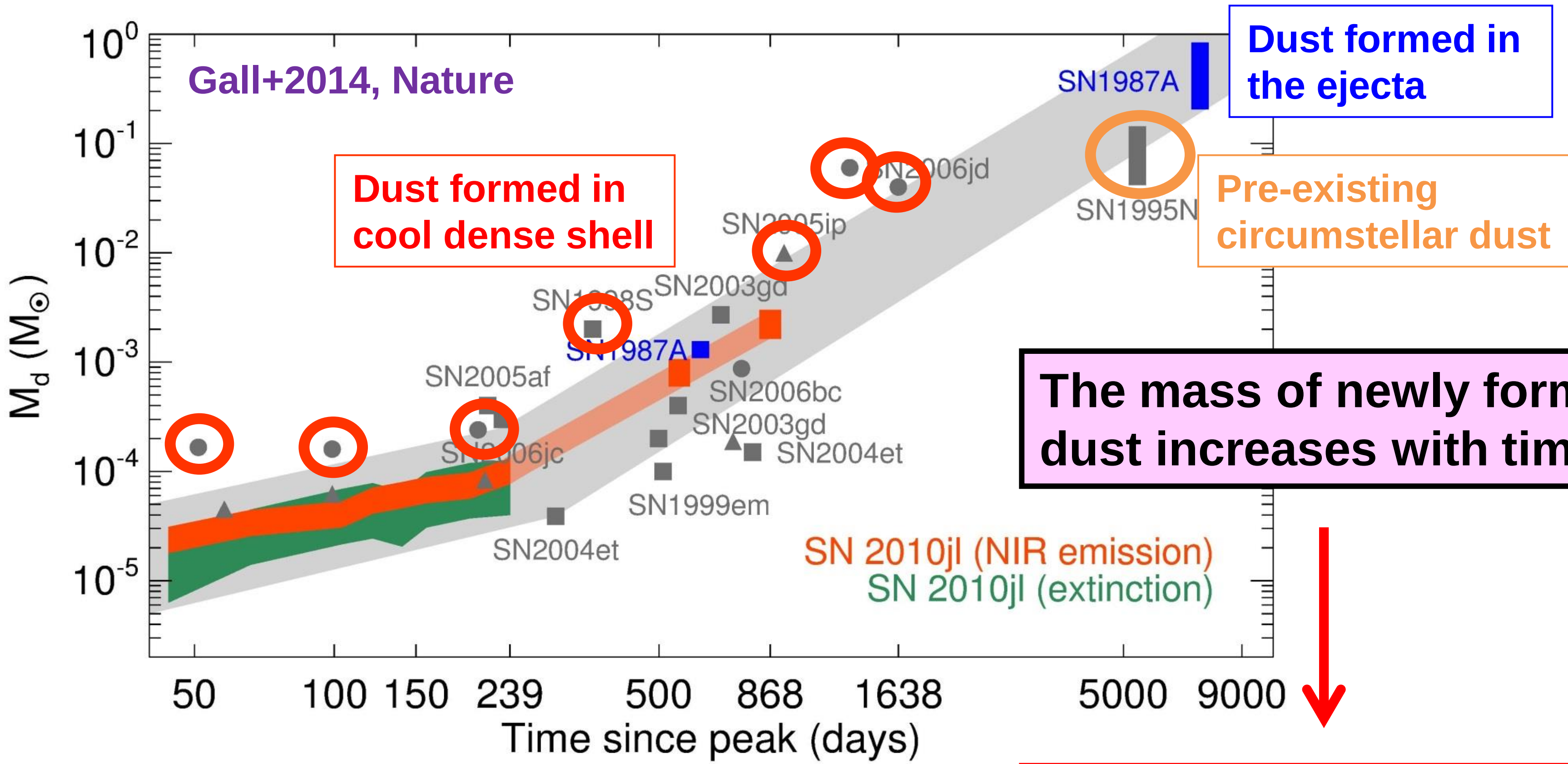


Evolution of dust mass in SN 1987A derived from extinction of optical emission lines

Bevan & Barlow (2016)

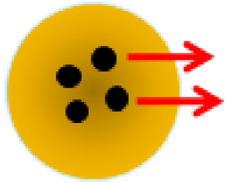


2-5. Interpretation of Gall et al. (2014) paper

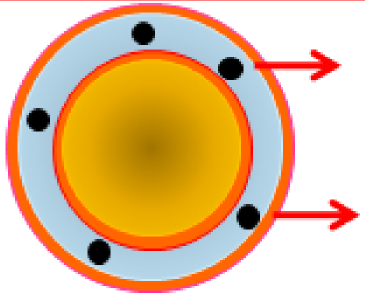


The mass of newly formed dust increases with time?

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

2-6. 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

2-7. 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}

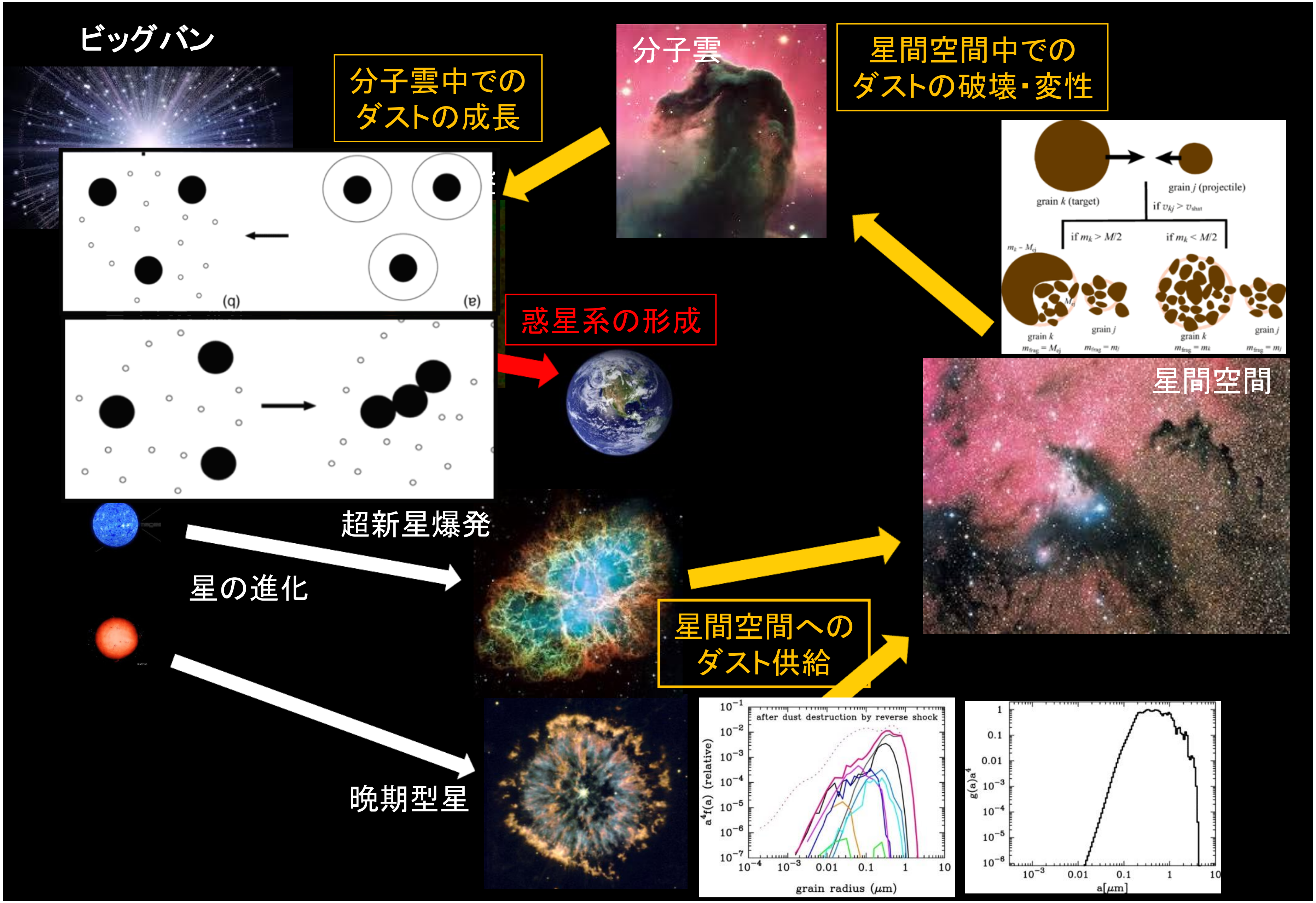
2. What is the size distribution of dust?

- theory ➜ relatively large grains (>0.1 μm)
- obs.➜ very large (~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)

3-1. Cycling of interstellar dust in the universe



3-2. Dust evolution model in a galaxy (1)

Asano+2013, 2014

- one-zone closed-box model (no inflow and no outflow)

- star formation rate (SFR)

  Schmidt law with n = 1: $SFR(t) = M_{gas}(t)/\tau_{SF}$ with $\tau_{SF} = 5$ Gyr

- initial mass function (IMF)

  Salpeter IMF: $\varphi(m) = m^{-q}$ with $q=2.35$ for $M_{star} = 0.1\text{-}100\ M_{sun}$

- two-component dust model

  graphite (carbonaceous grains)

  astronomical silicate (silicate and the other grains species)

- two-phase ISM

  WNM (warm neutral medium): $T = 6000$ K, $n = 0.3\ cm^{-3}$

  CNM (cold neutral medium): $T = 100$ K, $n = 30\ cm^{-3}$

  ➜ $\eta_{WNM} = \eta_{CNM} = 0.5$

3-3. Dust evolution model in a galaxy (2)

Asano+2013, 2014

- mass evolution of dust $\Delta M_d(a,t)$ with radii between a and $a+da$

xSFR(t), astration

$$\frac{\mathrm{d}\Delta M_\mathrm{d}(a,t)}{\mathrm{d}t} = -\frac{\Delta M_\mathrm{d}(a,t)}{M_\mathrm{ISM}(t)} + \Delta Y_\mathrm{d}(a,t)$$

dust production by SNe II and AGB stars

$$-\frac{M_\mathrm{swept}}{M_\mathrm{ISM}(t)}\gamma_\mathrm{SN}(t)\left[\Delta M_\mathrm{d}(a,t) - m(a)\int_0^\infty \xi(a,a')\Delta a f(a',t)\mathrm{d}a'\right]$$

shock destruction

$$+\eta_\mathrm{CNM}\left[m(a)\Delta a\frac{\partial[f(a,t)]}{\partial t}\right]$$

grain growth

$$+\eta_\mathrm{WNM}\left[\frac{\mathrm{d}\Delta M_\mathrm{d}(a,t)}{\mathrm{d}t}\right]_\mathrm{shat,WNM} + \eta_\mathrm{CNM}\left[\frac{\mathrm{d}\Delta M_\mathrm{d}(a,t)}{\mathrm{d}t}\right]_\mathrm{shat,CNM}$$

shattering

$$+\eta_\mathrm{WNM}\left[\frac{\mathrm{d}\Delta M_\mathrm{d}(a,t)}{\mathrm{d}t}\right]_\mathrm{coag,WNM} + \eta_\mathrm{CNM}\left[\frac{\mathrm{d}\Delta M_\mathrm{d}(a,t)}{\mathrm{d}t}\right]_\mathrm{coag,CNM},$$

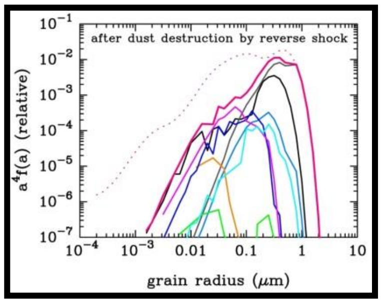
coagulation

$$\Delta Y_\mathrm{d}(a,t) = \int_{m_\mathrm{cut}(t)}^{100\,\mathrm{M}_\odot} \Delta m_\mathrm{d}(m, Z(t-\tau_m), a)\phi(m)\mathrm{SFR}(t-\tau_m)\mathrm{d}m,$$

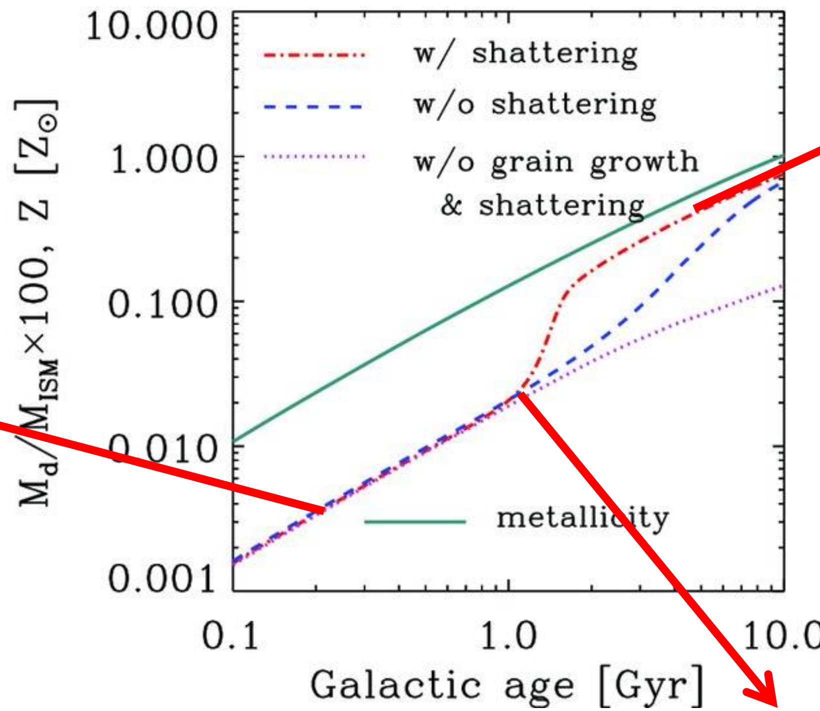
3-4. How dust mass increases in the ISM

Shattering and grain growth necessary for achieving the observed high dust content

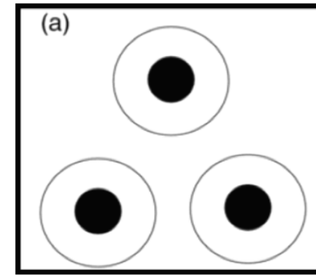
Ejection of large grains from SNe/AGB stars



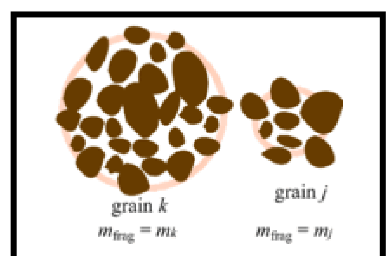
Asano+2013



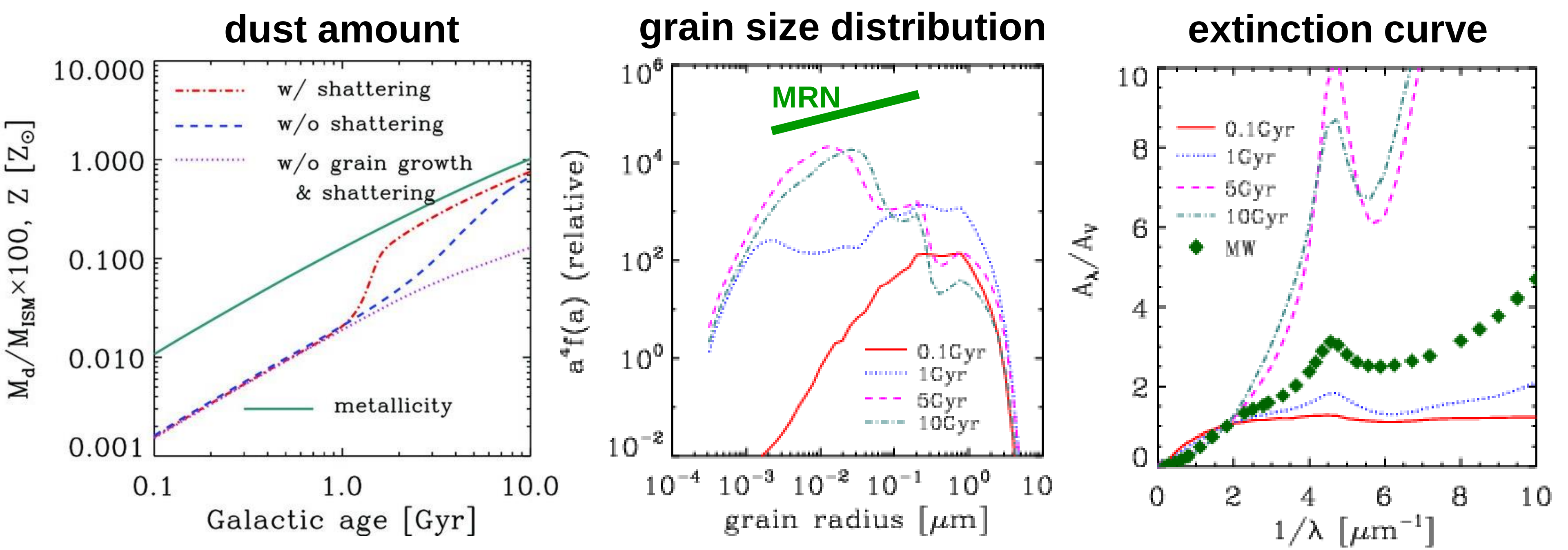
Growth of small grains via accretion of gas in the MCs



Production of small grains via shattering in the ISM



3-5. Evolution of extinction curves in galaxies



Asano+2014

- **early phase** : formation of dust in SNe II and AGB stars
  ➔ large grains (>0.1 μm) are dominant ➔ flat extinction curve

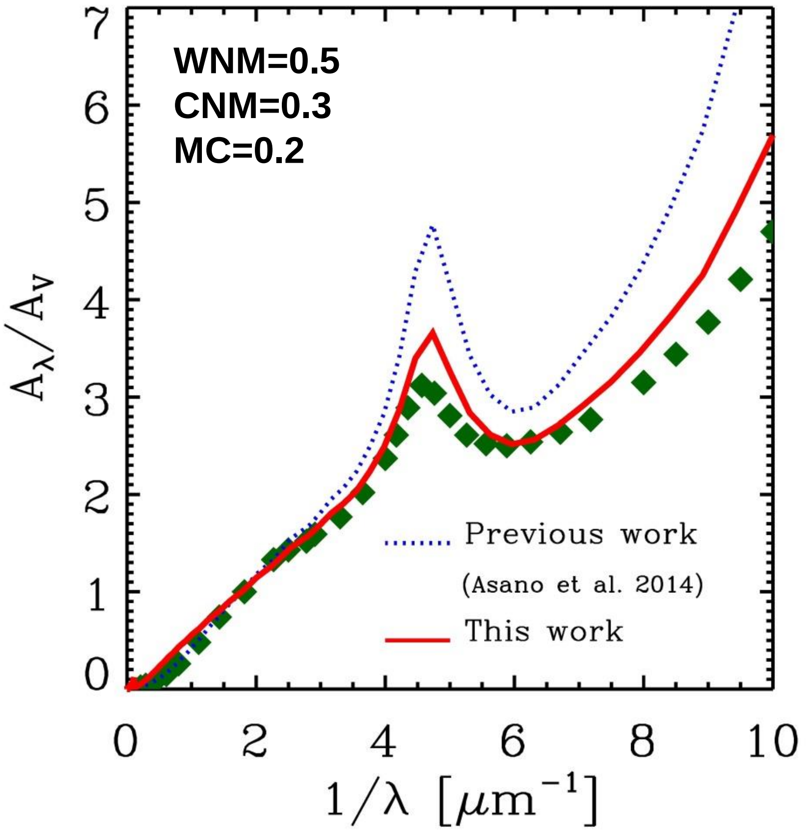
- **middle phase** : shattering, grain growth due to accretion of gas metal
  ➔ small grains (< 0.03 μm) are produced ➔ steep extinction curve

- **late phase** : coagulation of small grains
  ➔ shift of peak of size distribution ➔ making extinction curve flatter

3-6. Reproducing the MW extinction curve

- two-phase ISM
  - WNM (T = 6000 K, n = 0.3 cm^{-3})
  - CNM (T = 100 K, n = 30 cm^{-3})

- three-phase ISM
  - WNM (T = 6000 K, n = 0.3 cm^{-3})
  - CNM (T = 100 K, n = 30 cm^{-3})
  - MC (molecular clouds)
    ➜ T = 25 K, n = 300 cm^{-3}



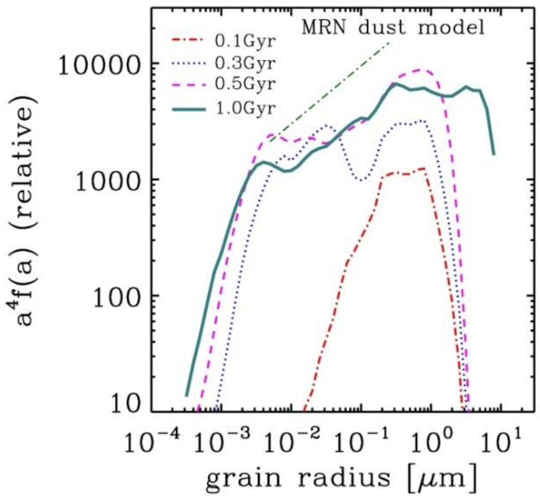
Nozawa+2015

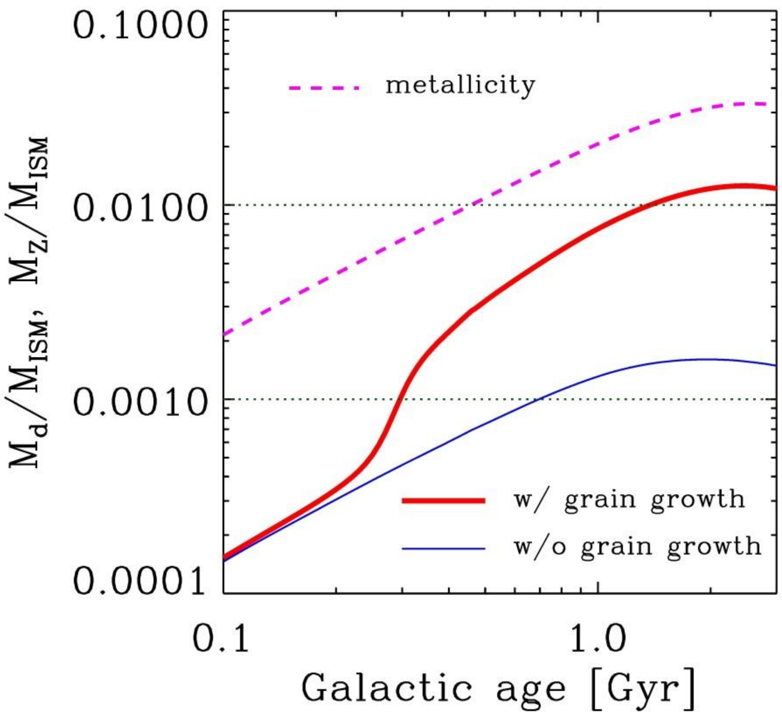
- three-phase ISM model including the MC phase can reproduce the average extinction curve in the MW
- ISM phase is one of the important quantities in constructing the evolution model of interstellar dust

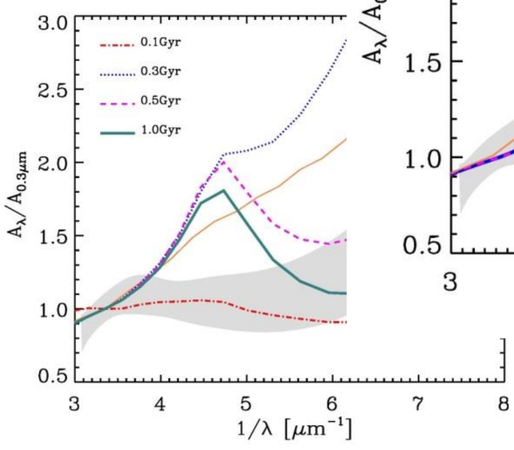
3-7. Explaining massive dust in high-z quasars

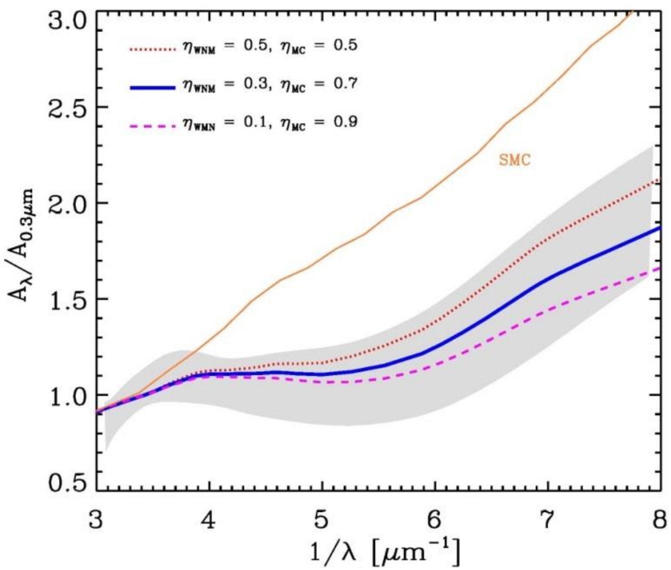
- two-phase ISM:
  WNM=0.3 and MC=0.7
- τ_{SF} = 0.5 Gyr

high-z quasar host: starburst galaxies
➜ indicating a high fraction of MC
$M_{H2}/M_{H,total}$ ~ 0.7-0.97 (Calura+2014)









Nozawa+2015

4-1. Issues of dust evolution model (1)

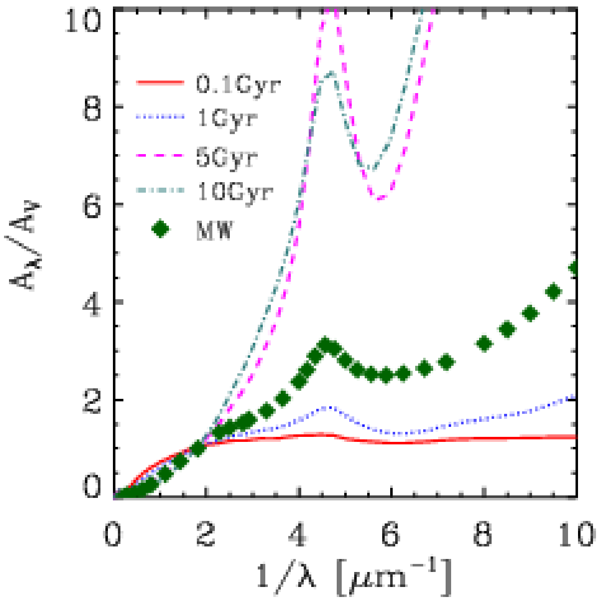
○ What is property of C grains?

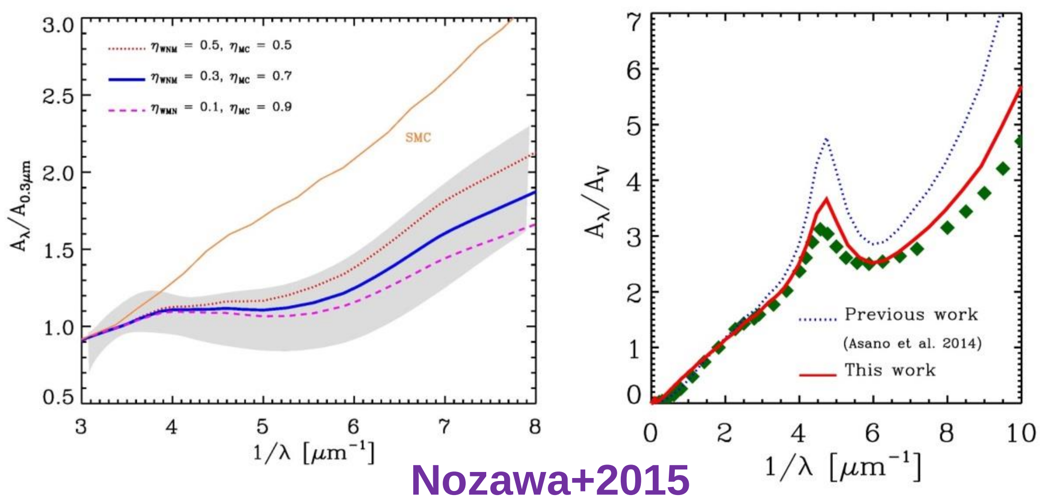
- Asano dust evolution model
  high-z : amorphous carbon
  present : graphite

silicate and graphite (am.car)
➜ three-component dust model
consisting of silicate, am.car, PAH

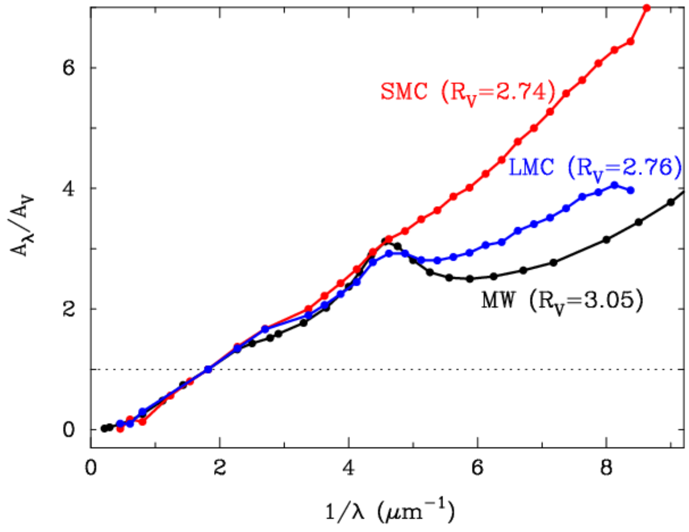
cannot explain the SMC dust

Asano+2014





Nozawa+2015



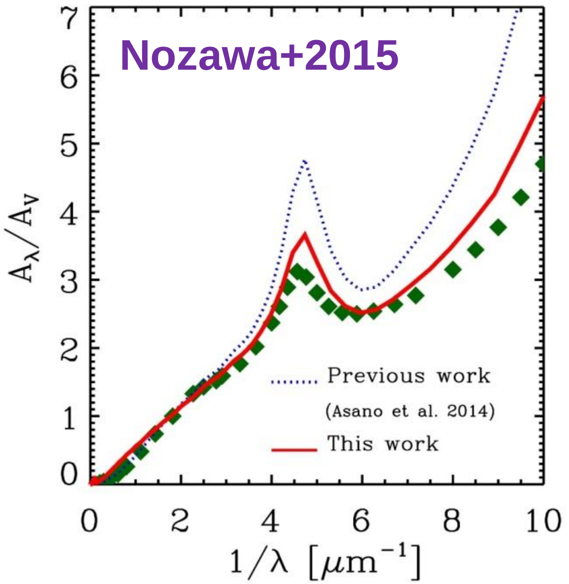
4-2. Issues of dust evolution model (2)

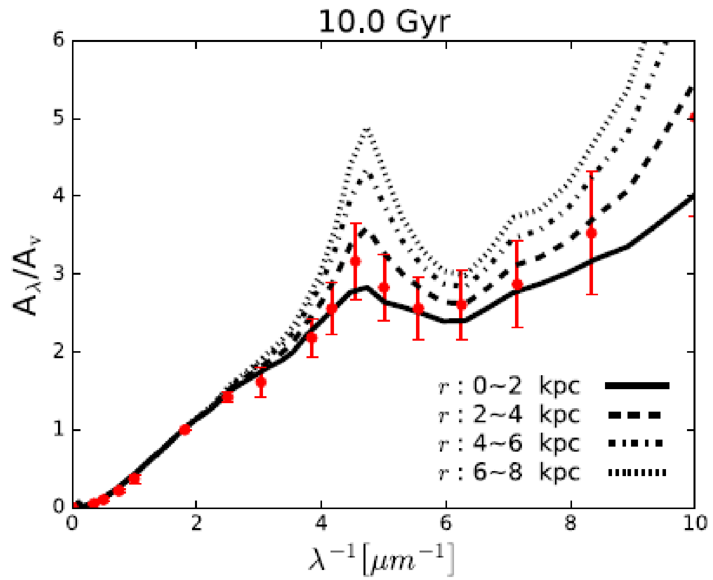
○ Too much (small) C grains

- stronger (sharper) 2175A bump than observed in the MW
  ➜ larger amount of (small) C grains

- dust evolution model efficient grain growth in MCs
  ➜ almost all C atoms (>90%) accrete onto dust grains

- depletion of C atoms in the ISM
  50-70% of C locked in dust grains





Aoyama+2017; Hou+2017

4-3. Issues of dust evolution model (3)

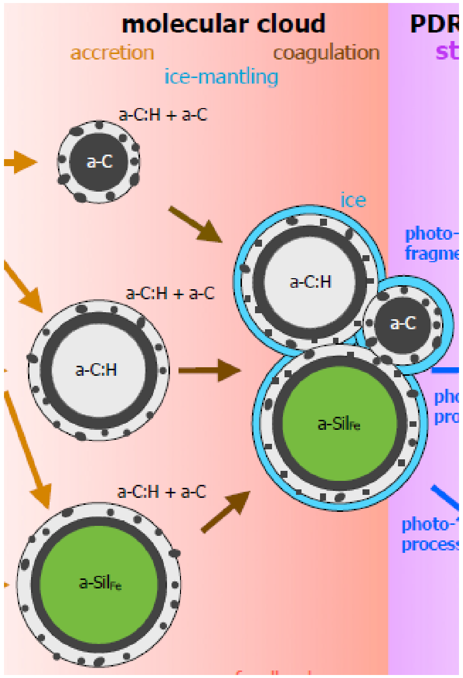
○ Gas accretion onto dust grains in MCs really works?

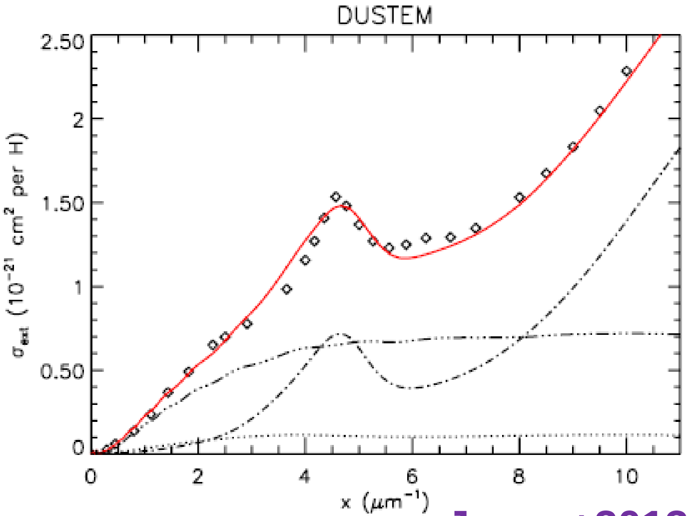
- selective accretion (coagulation)
  Si, Mg, Fe, O ➜ silicate grains
  C ➜ carbon grains

heterogeneous dust grain model (Jones+2013, 2016, 2017)

- formation of ice mantle in MCs
  ➜ ice mantle would form before efficient accretion of metal gas (Ferrara+2016)

high CMB temperature would suppress grain growth at high z





Jones+2013

4-4. Issues of dust evolution model (4)

○ Fe-missing problem

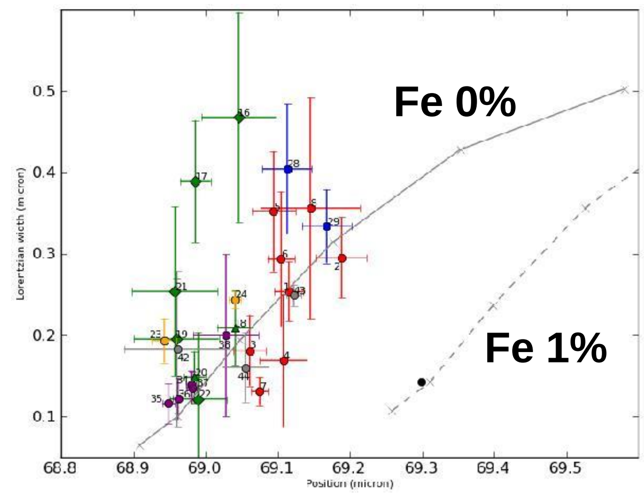
- two-component dust model
  Si, Mg, Fe, O ➜ silicate grains

astronomical silicate: $Mg_{1.1}Fe_{0.9}SiO_4$

- no evidence for Fe-rich silicate grains
- no evidence for formation of pure Fe grains in Type Ia SNe

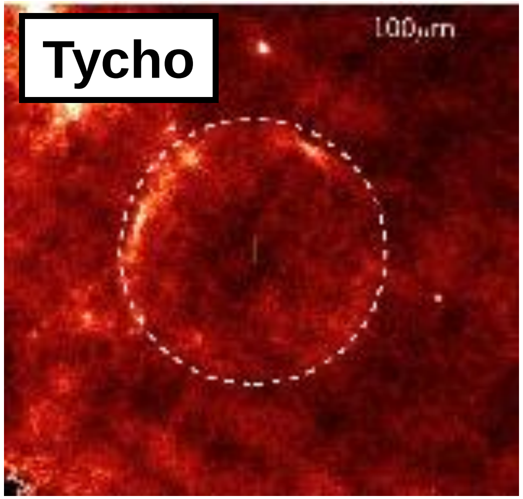
99% of Fe locked up in the ISM

- Fe atoms must be incorporated into dust grains in dense MCs (Dwek 2016)



Brommaert et al. (2014)

Herschel 100 μm image



Gomez+2012

4-5. Consensus and issues for dust evolution

Consensus

Grain growth is needed to account for a large amount of interstellar dust in both high-z and nearby galaxies

(Draine2009; Michalowski+2010; Gall+2011a, 2011b; Pipino+2011; Mattsson+2011; Inoue2011; Valiante+2011, 2014; Kuo & Hirashita 2012; Asano+2013a, 2013b, 2014; Calura+2014; Dwek+2014; Nozawa+2015; Michalowski+2015; Aoyama+2017; Hou+2017; Hirashita & TN 2017)

Issues

- **Grain growth efficiently takes place in the MCs?**
- **Grain growth is an important process to regulate the composition, size, and mass of interstellar dust?**
- **Grain growth naturally explain the properties of interstellar dust extracted from observations?**