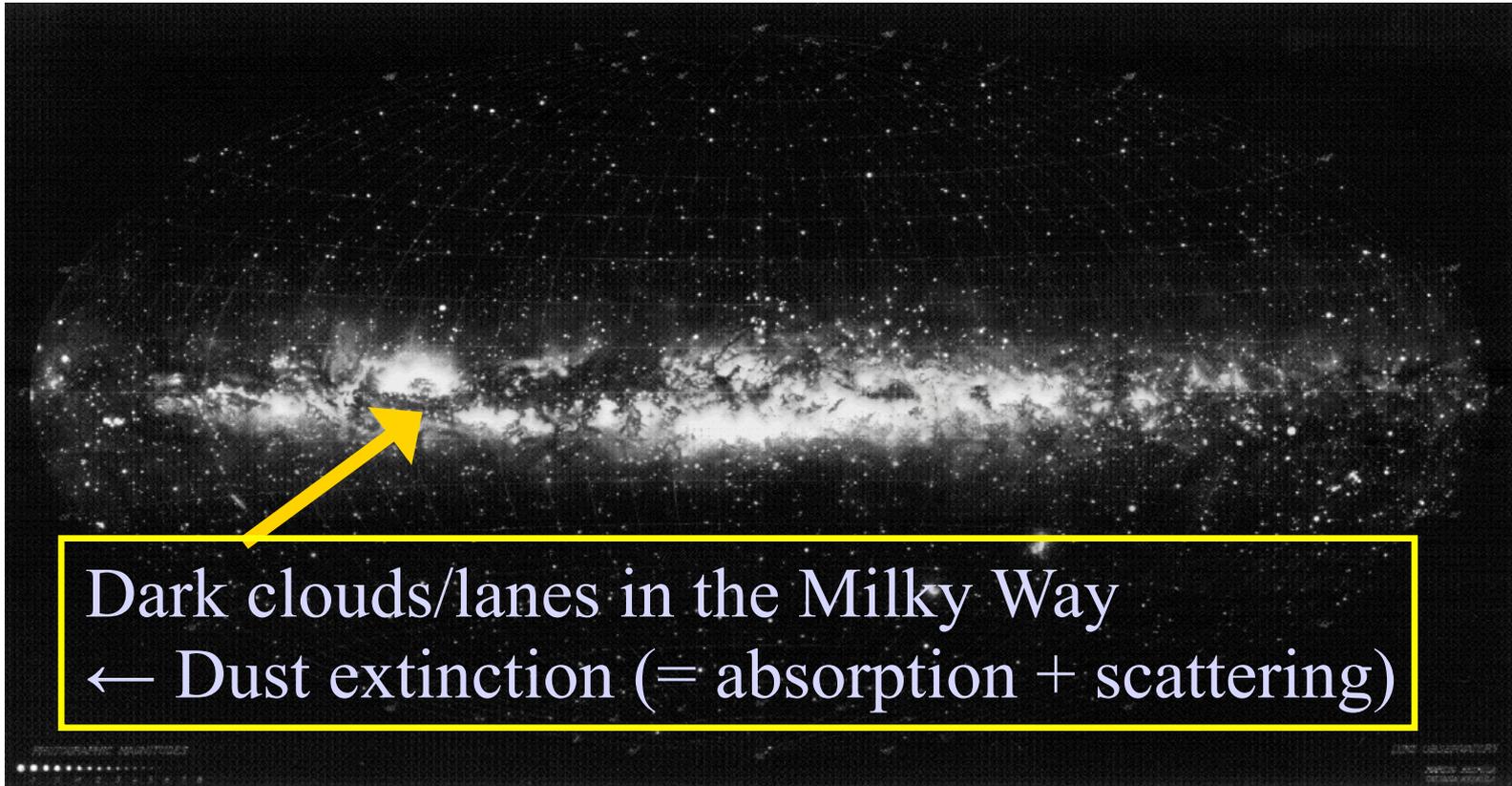


*Dust Processing in the
Interstellar Medium and
Dust Enrichment in Galaxies*

Hiroiyuki Hirashita
(ASIAA, Taiwan)

1. Introduction

Dust extinction in the optical ($\lambda \sim 0.5 \mu\text{m}$)



τ_λ : optical depth for extinction (absorption + scattering)

$$I_\lambda(\tau_\lambda) = I_\lambda(0) e^{-\tau_\lambda} \quad [m_\lambda(\text{obs}) = m_\lambda(0) + A_\lambda]$$

Extinction Curve: τ_λ (or A_λ) as a function of λ

Extinction Curves and Grain Properties

Pei (1992): For nearby galaxies

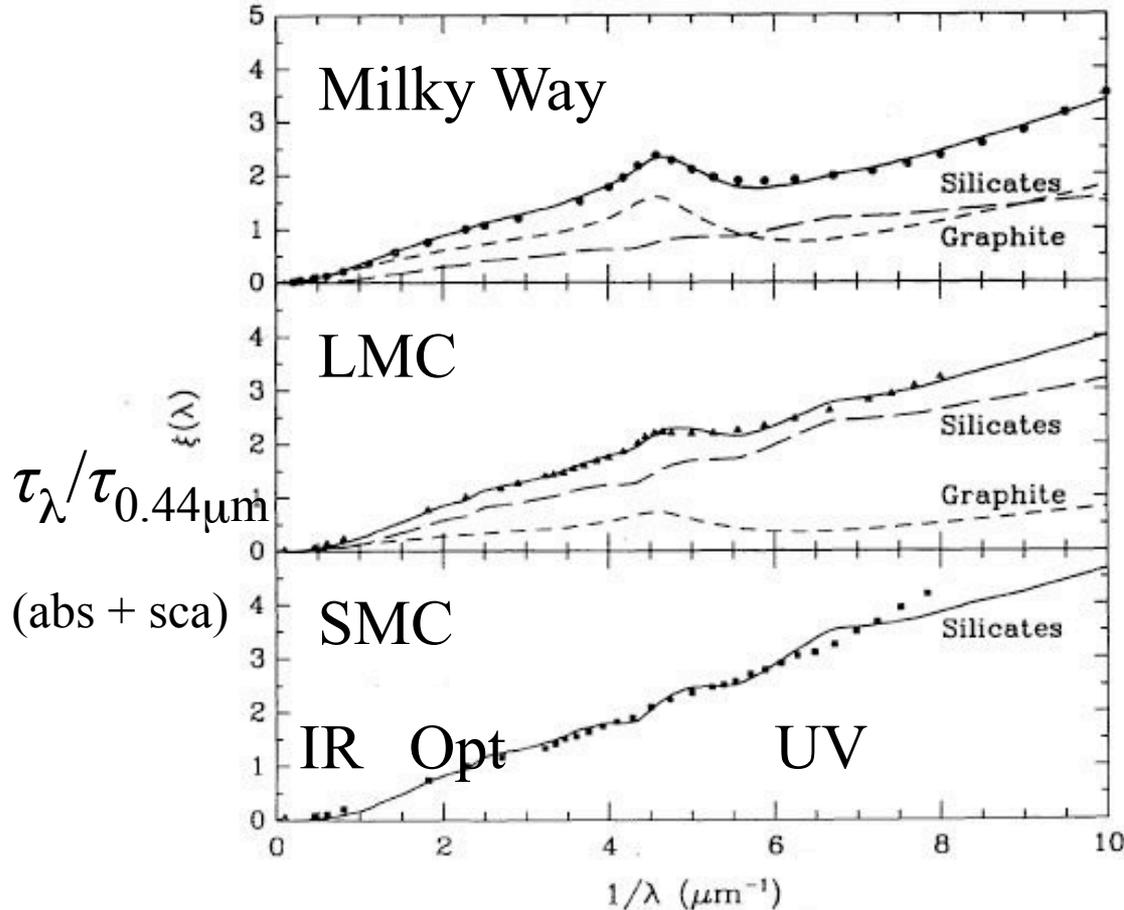


FIG. 5.—Comparisons between the model and empirical extinction curves in the Milky Way, LMC, and SMC. The short and long-dashed lines show, respectively, the relative contributions from graphite and silicate grains, with the sum of the two shown as the solid lines.

Fitting:

Grain size distribution

$$n(a) \propto a^{-3.5}$$

$$a_{\min} = 0.005 \mu\text{m}$$

$$a_{\max} = 0.25 \mu\text{m}$$

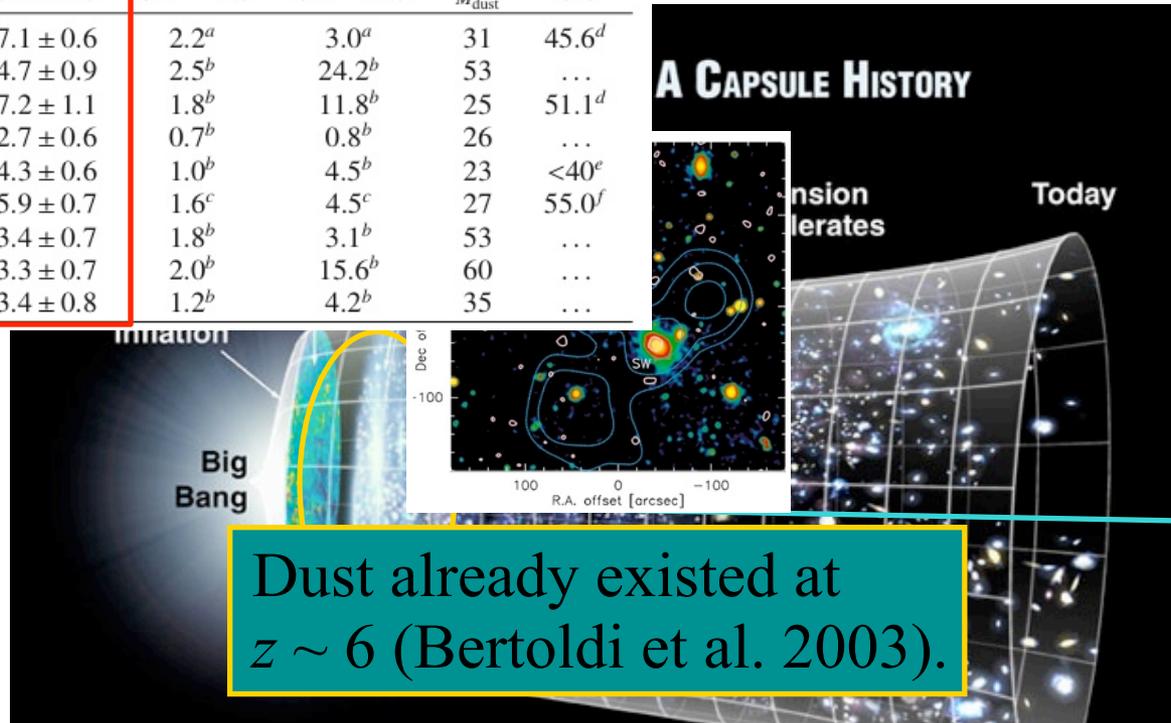
Extinction curves reflect the grain species and **size distribution**.

See also Weingartner & Draine (2001), etc.

Frontier of dust studies at High- z

No.	QSO	z	M_{dust} ($10^8 M_{\odot}$)	M_{gas} ($10^{10} M_{\odot}$)	$M_{\text{dyn}} \sin^2 i$ ($10^{10} M_{\odot}$)	$\frac{M_{\text{gas}}}{M_{\text{dust}}}$	T_{dust} (K)
1	J0338+0021	5.03	7.1 ± 0.6	2.2^a	3.0^a	31	45.6^d
2	J0840+5624	5.85	4.7 ± 0.9	2.5^b	24.2^b	53	...
3	J0927+2001	5.77	7.2 ± 1.1	1.8^b	11.8^b	25	51.1^d
4	J1044-0125	5.74	2.7 ± 0.6	0.7^b	0.8^b	26	...
5	J1048+4637	6.23	4.3 ± 0.6	1.0^b	4.5^b	23	$<40^e$
6	J1148+5251	6.42	5.9 ± 0.7	1.6^c	4.5^c	27	55.0^f
7	J1335+3533	5.93	3.4 ± 0.7	1.8^b	3.1^b	53	...
8	J1425+3254	5.85	3.3 ± 0.7	2.0^b	15.6^b	60	...
9	J2054-0005	6.06	3.4 ± 0.8	1.2^b	4.2^b	35	...

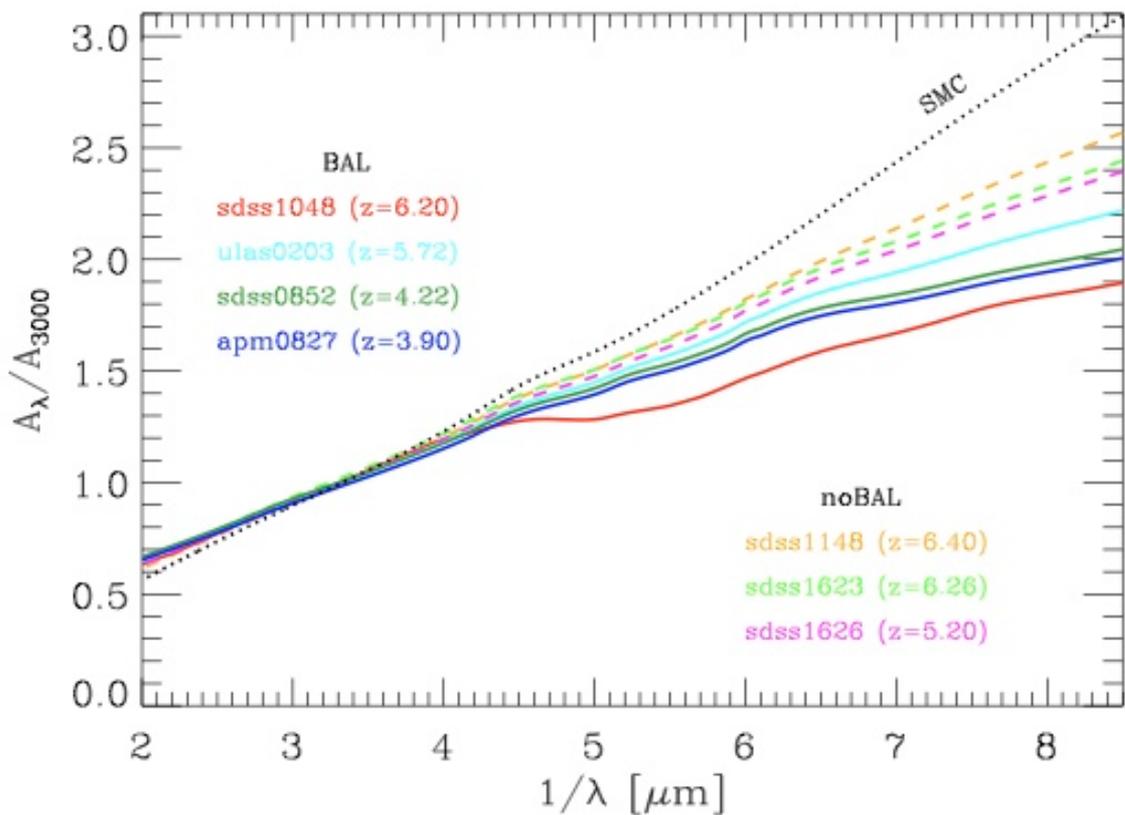
Michalowski et al.
(2010)



Clarifying the origin and evolution of dust in the early Universe is an urgent issue, and is only possible through the understanding of all the processes. NASA

Extinction Curves in High- z Quasars

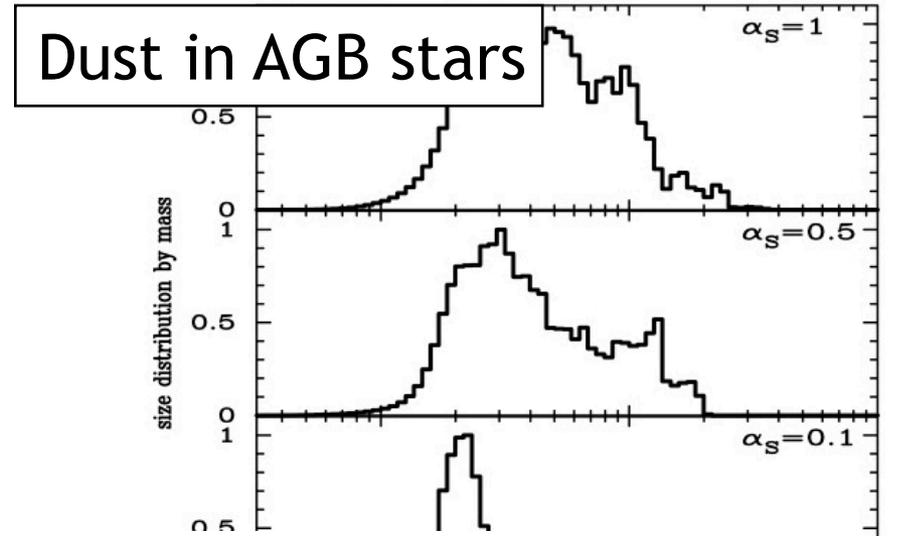
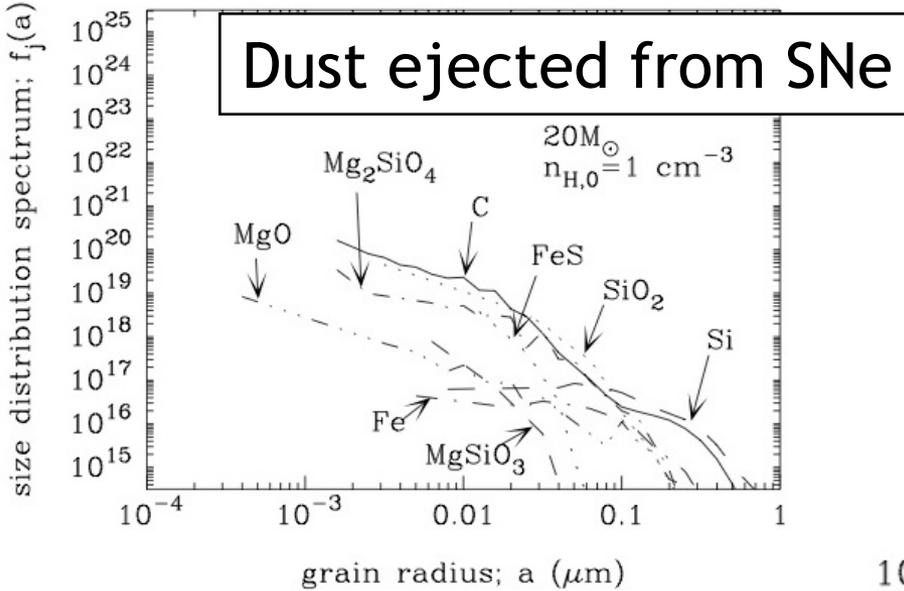
Maiolino et al. (2004); Gallerani et al. (2010)



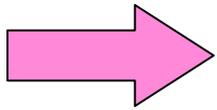
Difference (variation) should be due to various dust formation and processing mechanisms.

see also Hjorth et al. (2013)

Stardusts Are Large (?)

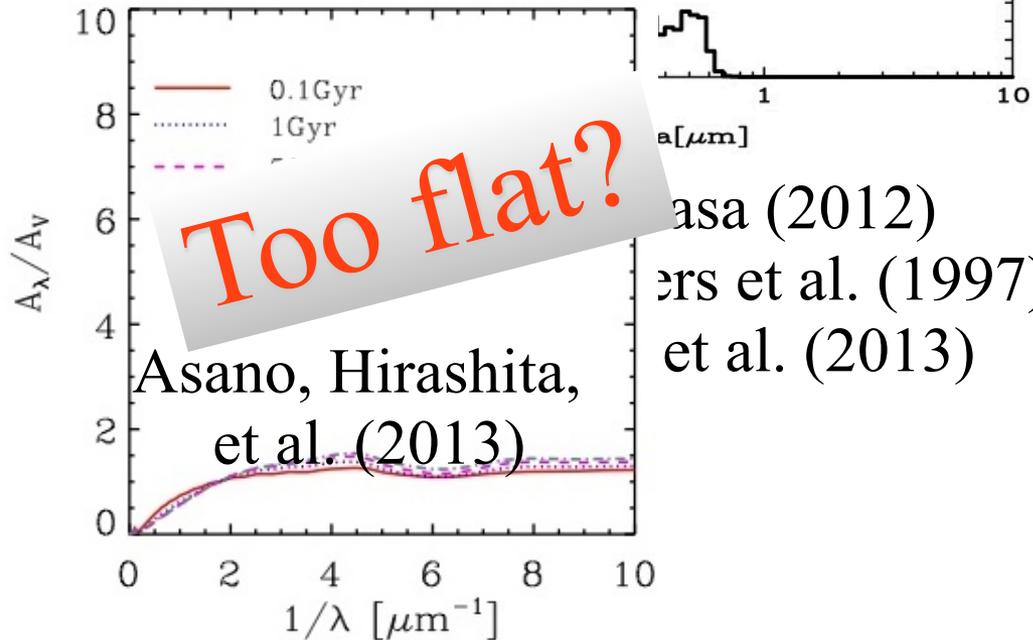


Nozawa et al. (2007); see also Bianchi & Schneider (2007).



Typical grain sizes are large.

⇒ Flat extinction curve.



asa (2012)
ers et al. (1997);
et al. (2013)

Life Cycle of Cosmic Dust

Cosmic dust is omnipresent in the universe, which is closely related to the cycle of star formation.

Dust is present in dense clouds, out of which stars form. High-mass stars, with masses 10 times higher than that of the Sun, burn only a few million years before their fuel is exhausted, and end their lives in a violent explosion, called supernovae. The core of a star forms a neutron star or a black hole. The majority of the star's mass returns to the interstellar cloud from which it came. It is in this way that the cycle of star formation and dust grains created during the star's life is completed. Stars like our own Sun have a similar life cycle, but they live for billions of years, and die at a slower rate of a few tens of millions of years, rather than in a single explosion. The dust that can last for tens of thousands of years, rather than in a single explosion.

In this poster we illustrate the dust life cycle in the middle, with examples of the observation on the two sides.

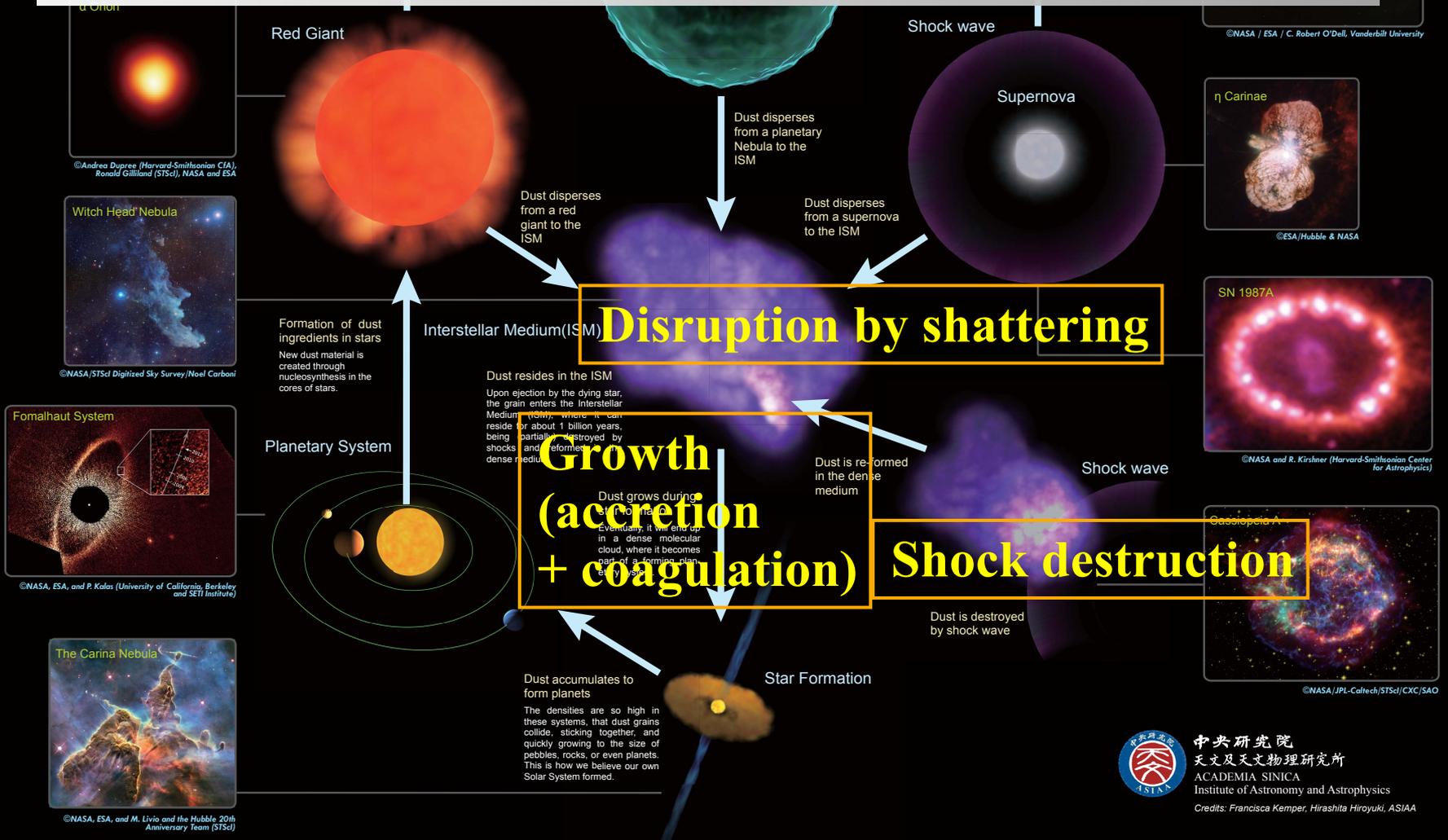
Birth of Dust

The life cycle of dust starts at the end of the life of stars, when stars are dying, the outer layers are blown off, either in an explosive fashion (as in the case of a supernova) or the star is shed in a more gradual fashion (as in the case of a planetary nebula). The dust grains are formed in the cool, dense regions of the interstellar medium (ISM) at temperatures (about 1000 Kelvin) allowing for the formation of dust grains, thus beginning the journey of the astrophysical dust grain.

Planetary Nebula

MST

Dust Grains are processed!



List of Relevant Processes

Processes that change the total dust mass:

- Shock destruction [*diffuse*] ($M_{\text{dust}} \downarrow$)
- Accretion of gas-phase metals [*dense*] ($M_{\text{dust}} \uparrow$)

Processes that conserve the total dust mass:

- Coagulation (sticking) [*dense*] ($M_{\text{dust}} \rightarrow$)
- Shattering (disruption) [*diffuse*] ($M_{\text{dust}} \rightarrow$)

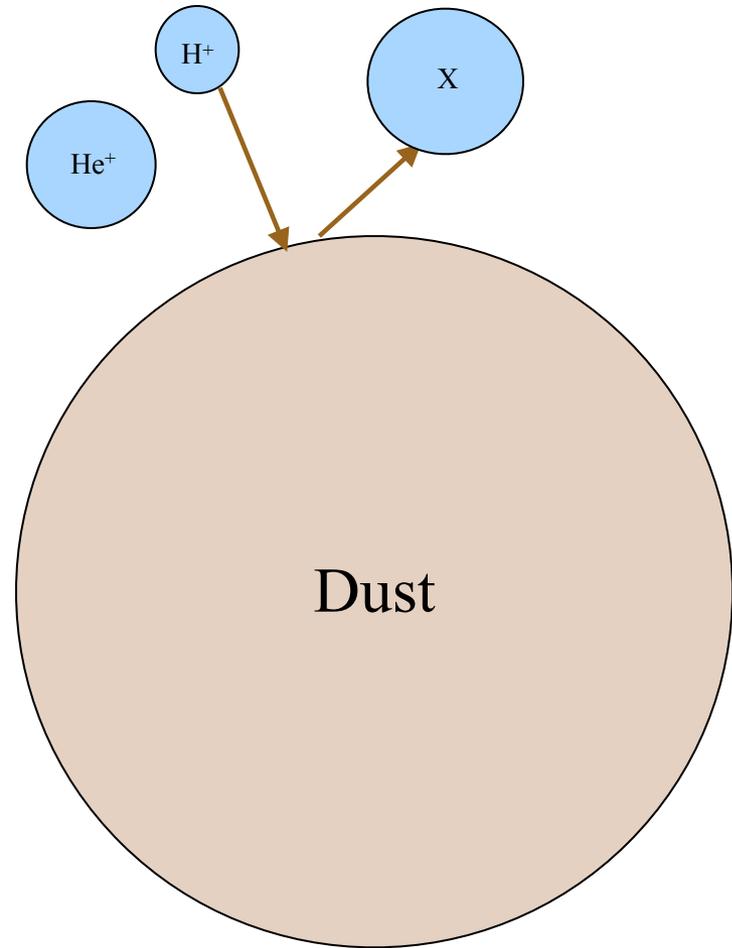
Clarify the effects of each process on **the grain size distribution (or the extinction curve)** in galaxy evolution (both nearby and high- z).

2. Effects of Each Grain Processing

Processes that Increase/Decrease the Total Dust Mass

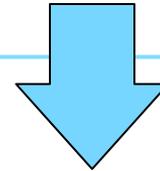
Dust destruction in SN shocks (sputtering)
Grain growth (accretion)

(Thermal) Sputtering (in SN shocks)



timescale of sputtering
 $\propto m/(dm/dt) \propto a$

Smaller grains are more easily destroyed.



Extinction curves become flatter by dust destruction in supernova shocks.

Dust Supply vs. Destruction

Dust destruction timescale

$$\sim M_{\text{gas}} / [\text{SNR} \times \epsilon(\text{Mass Swept by a SN})]$$

$$\sim M_{\text{gas}} / [\text{SFR}(\text{SNR}/\text{SFR}) \times 0.1 (10^4 M_{\odot})]$$

$$\sim 5 \times 10^9 M_{\odot} / [3 M_{\odot}/\text{yr} (0.01/M_{\odot}) \times 10^3 M_{\odot}]$$

$$\sim 2 \times 10^8 \text{ yr} \quad (\text{McKee 1989; Jones et al. 1996; etc.})$$

Dust supply timescale \sim Metal supply timescale

$$\sim ZM_{\text{gas}} / [Y \times (1 - R) \times \text{SFR}]$$

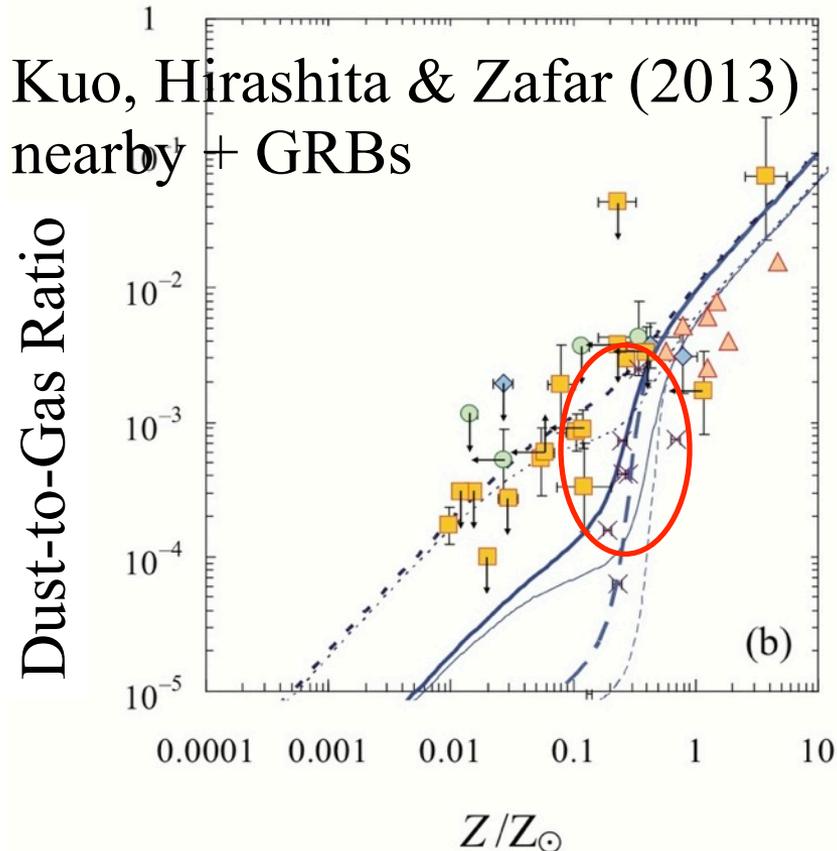
$$\sim 0.02 \ 5 \times 10^9 M_{\odot} / (0.01 \times 0.7 \times 3 M_{\odot}/\text{yr})$$

$$\sim 5 \text{ Gyr}$$

(Z : metallicity, Y : yield, R : returned fraction of gas)

Grain Growth by Accretion

Dust destruction timescale (< 1 Gyr) is much shorter than the dust supply time in the MW (\sim a few Gyr).
 \Rightarrow Grains grow in the ISM (dense medium)?



Strong metallicity dependence:
“Critical metallicity level for grain growth”
(Asano et al. 2013; Inoue 2011)

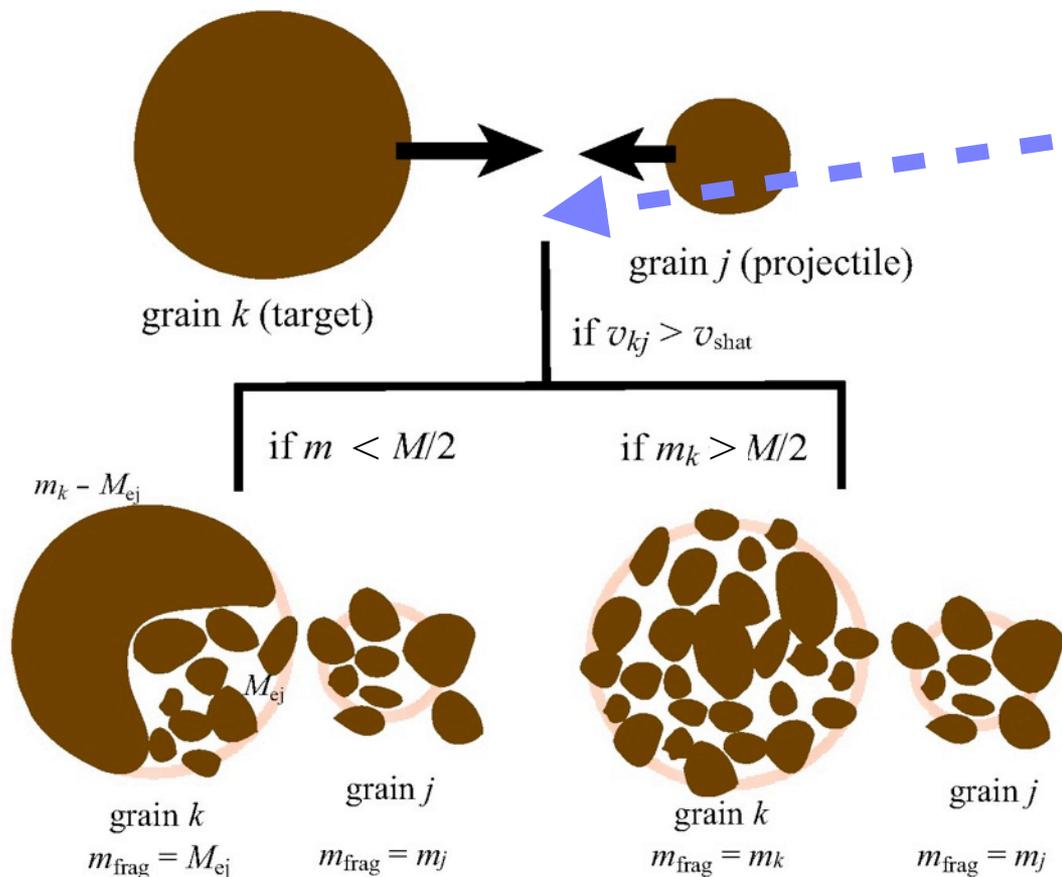
See also

Dwek (1998); Hirashita (1999);
Zhukovska et al. (2008); Draine
(2009); Michalowski et al. (2011);
Mattsson (2011); Valiante et al.
(2011); Kuo & Hirashita (2012)

Processes that Conserves the Total Dust Mass

Shattering
Coagulation

Interstellar Processing by Shattering



Velocities are activated by **turbulence** (Yan et al. 2004) or by the grain size dependence of drag timescale (Jones et al. 1996).

Shattering threshold:
2.7 km/s (silicate),
1.2 km/s (graphite)
(Jones et al. 1996)

Source of Grain Velocities

Interstellar turbulence

Gas drag (friction):

$$\tau_d = (3m_{gr}) / (4c_g \rho_g \sigma) = (sa) / (c_g \rho_g)$$

Gyroresonance

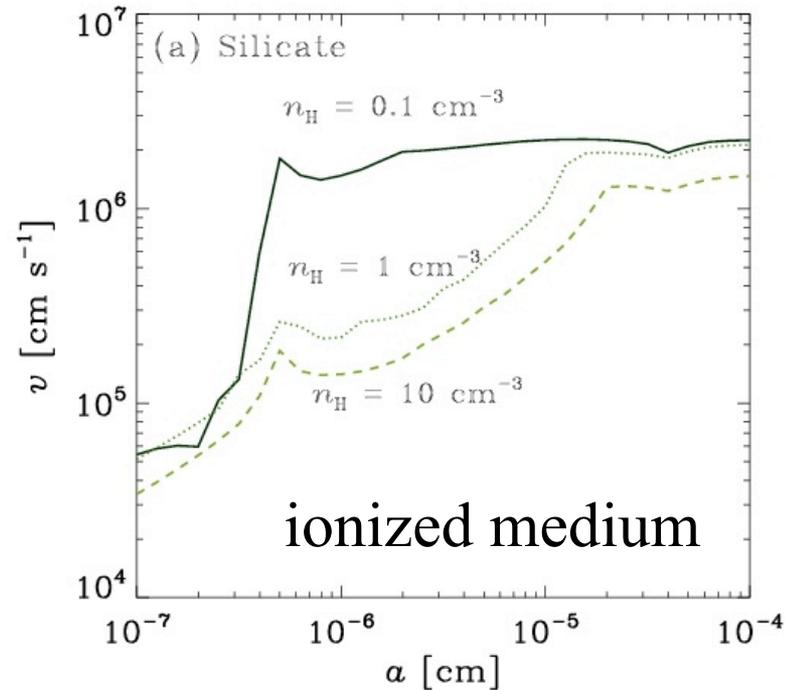
(resonance between wave and gyro-motion):

$$\omega - k_{||} v \cos \theta = n\omega_{gyro}$$

These processes increase the grain-grain collision rate:

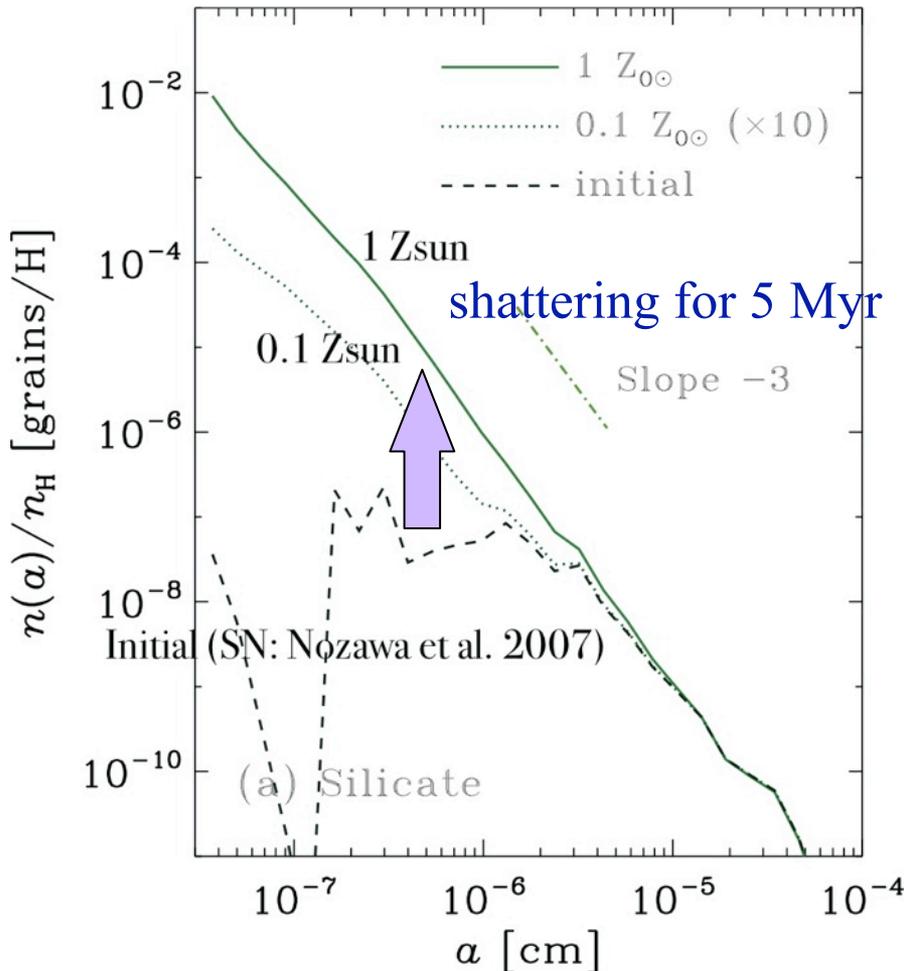
Diffuse medium: **shattering**↑

Dense medium: **coagulation**↑

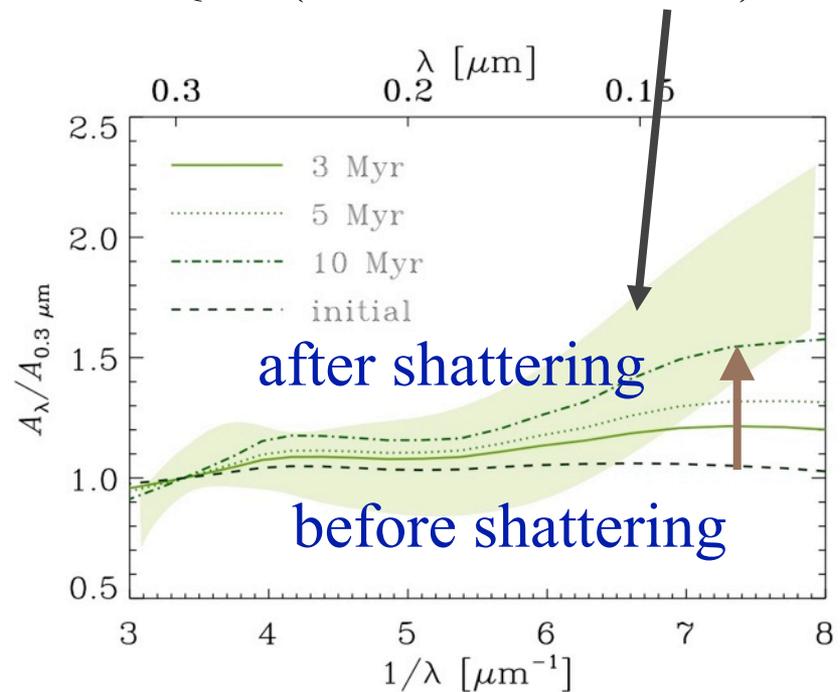


Yan et al. (2004)

Shattering: Unique Small Grain Production Mechanism



Hirashita et al. (2010)
 Observed extinction curve in $z = 6.2$ QSO (Maiolino et al. 2004)

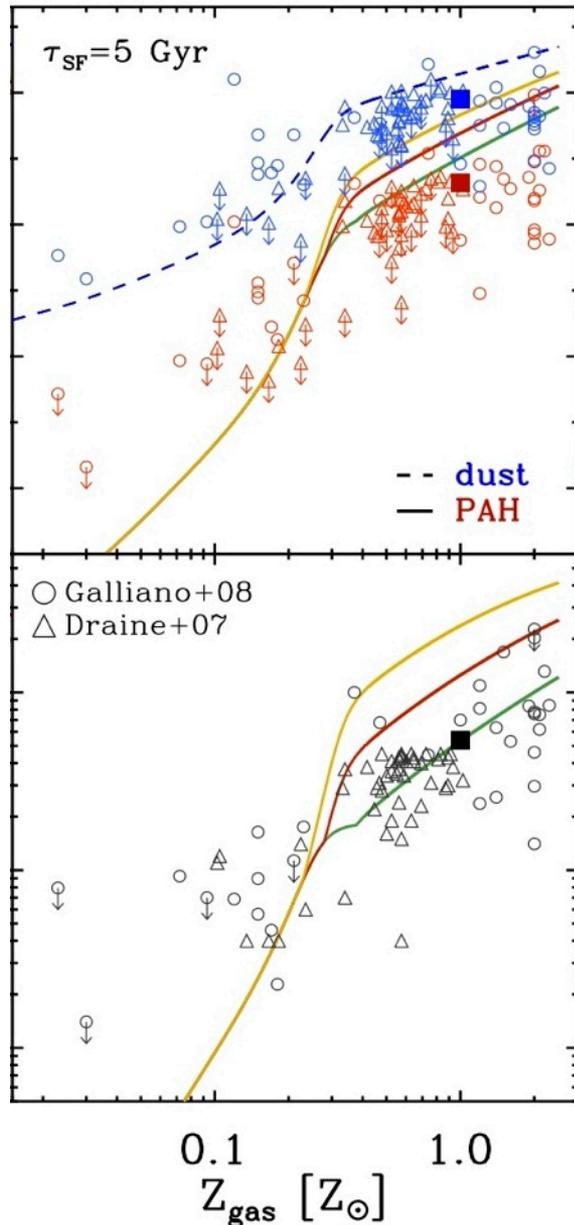


Small grain production by shattering contributes to the steepness of the UV extinction curve.

Shattering as a Source of PAH

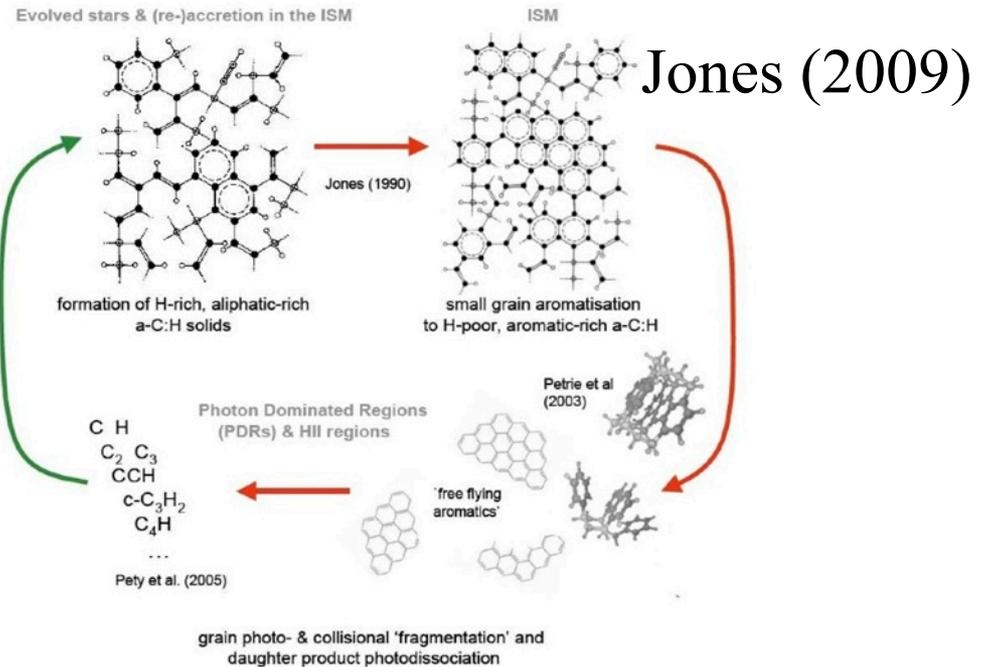
Dust-to-Gas Ratio

PAH-to-Dust Ratio



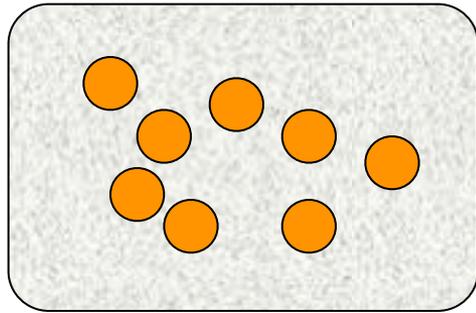
Seok, Hirashita, & Asano (2013)

Shattered fragments of carbonaceous dust as a source of PAHs.

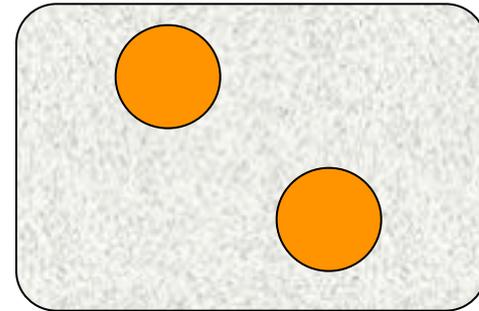


Strong metallicity dependence is a natural consequence of shattering.

Impact of Shattering on Dust Growth



Accretion (growth)
rate of gas-phase
metals



Shattering induces the dust mass increase
by accretion ($\propto \langle a^2 \rangle / \langle a^3 \rangle$)?

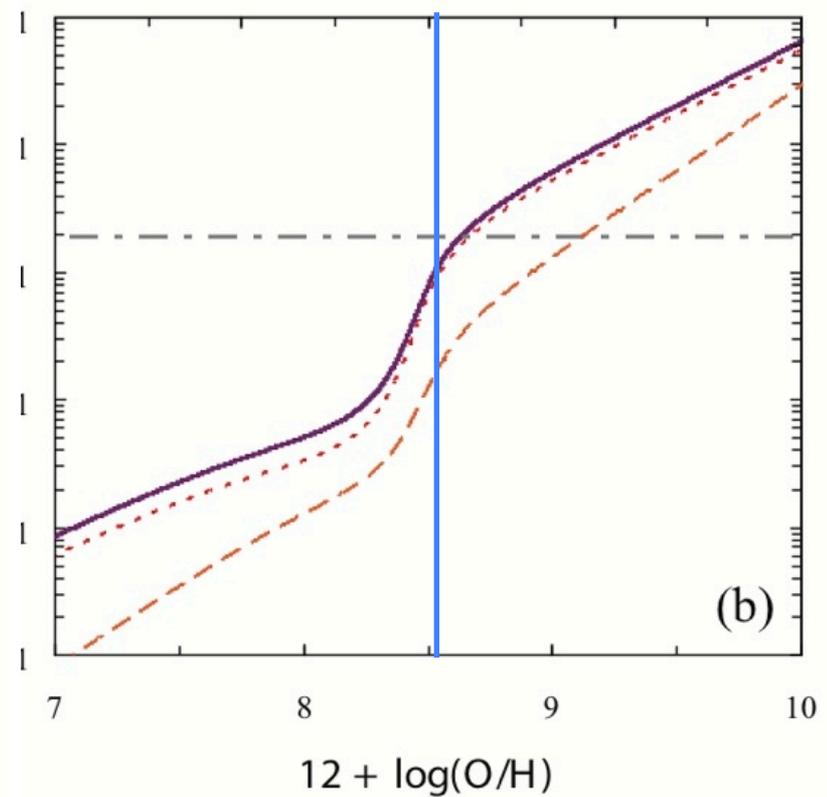
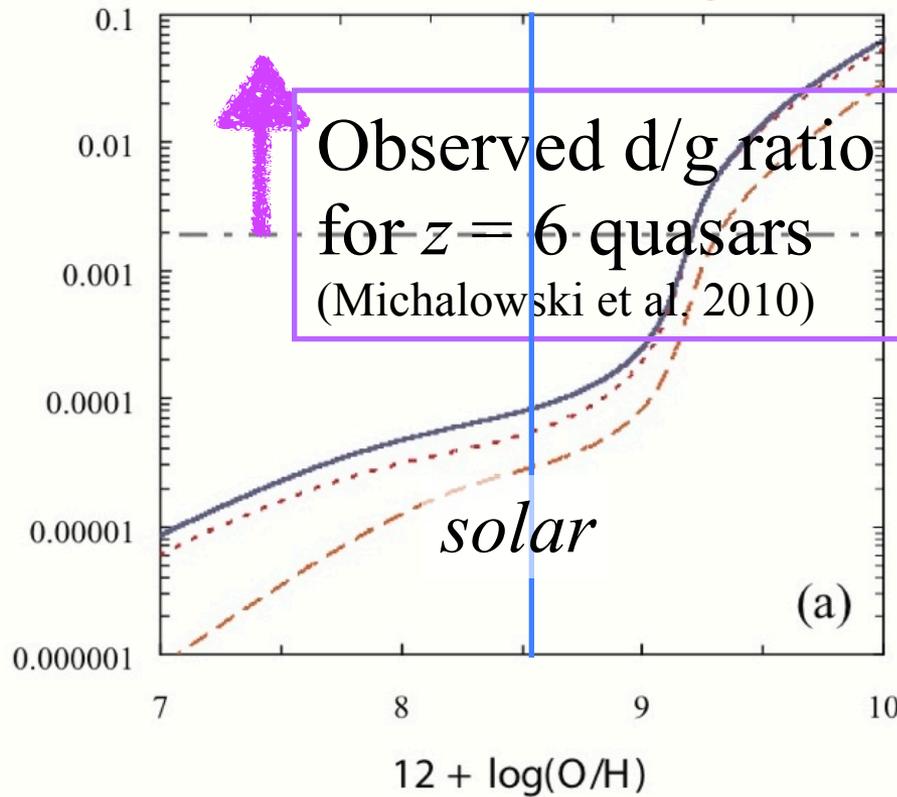
Effects of size distribution on dust growth

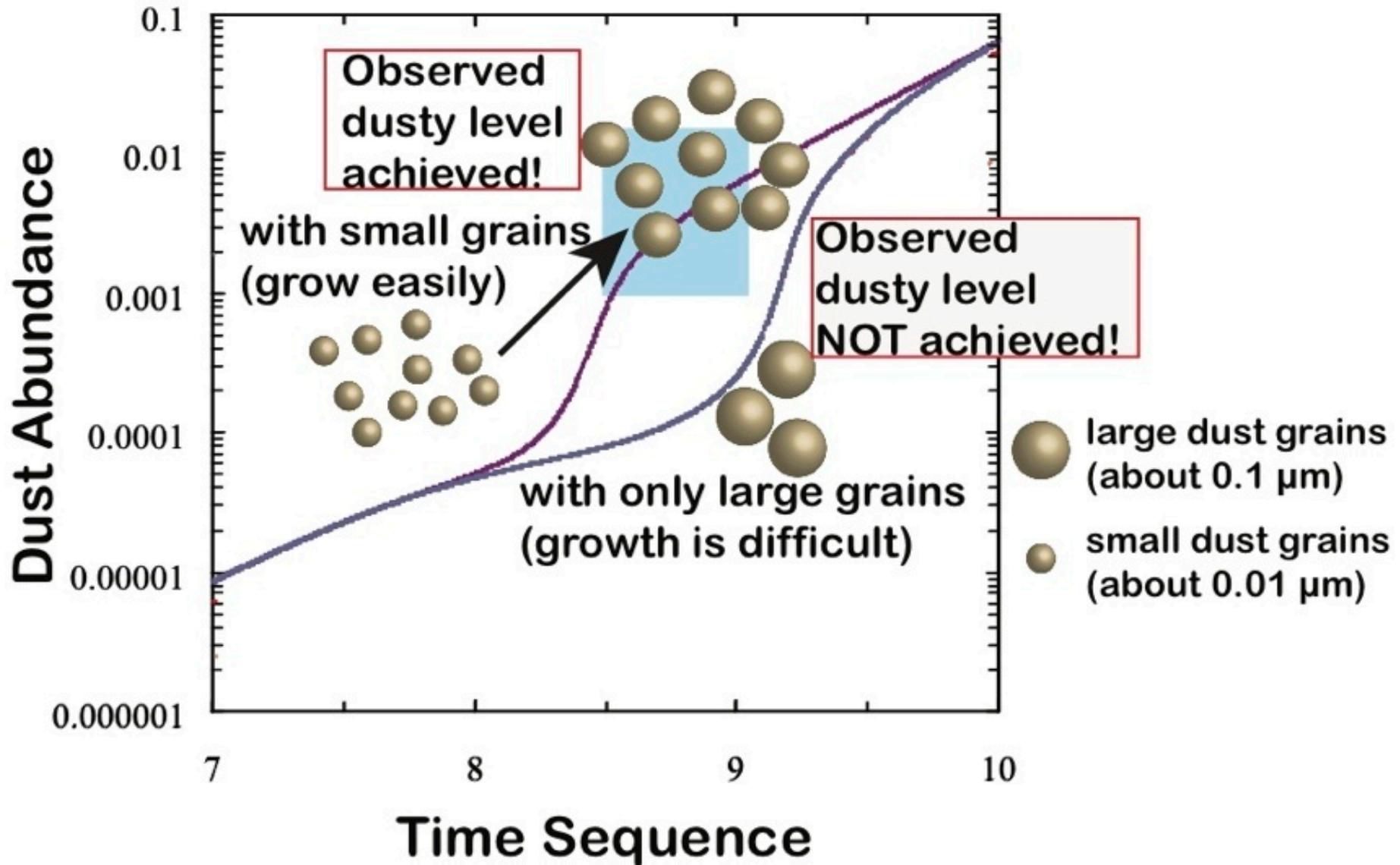
Kuo & Hirashita (2012)

Without shattering

With shattering

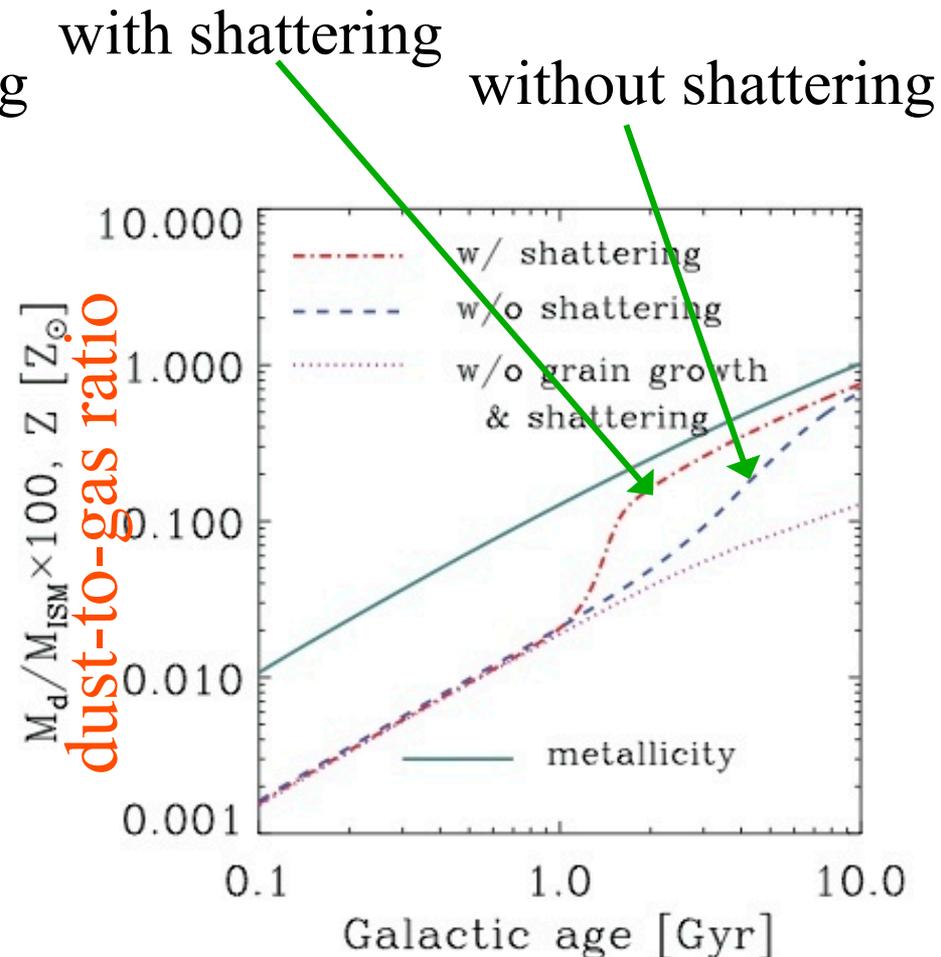
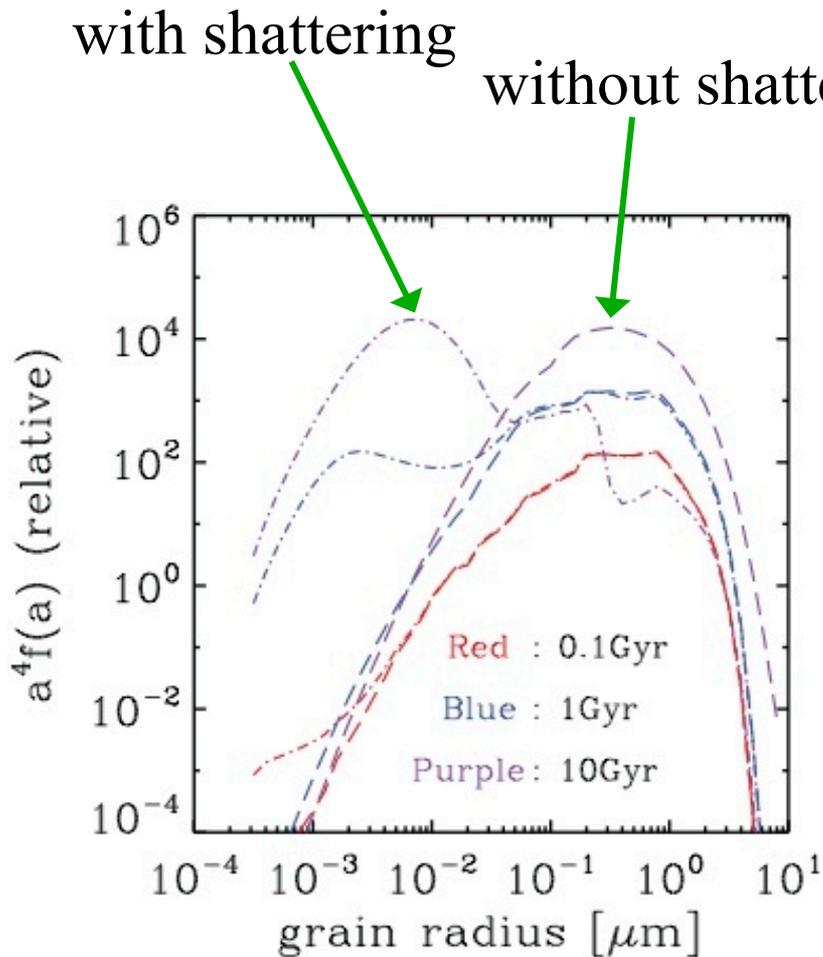
Dust-to-Gas Ratio



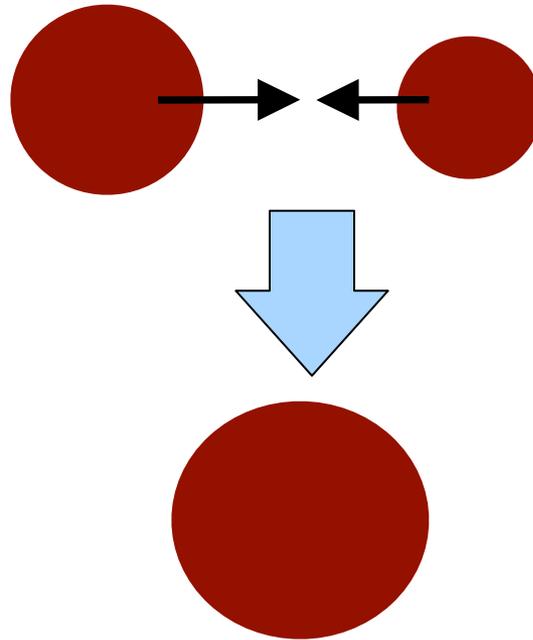


Full Treatment of Size Distribution

Asano, Takeuchi, Hirashita, Nozawa (2013)



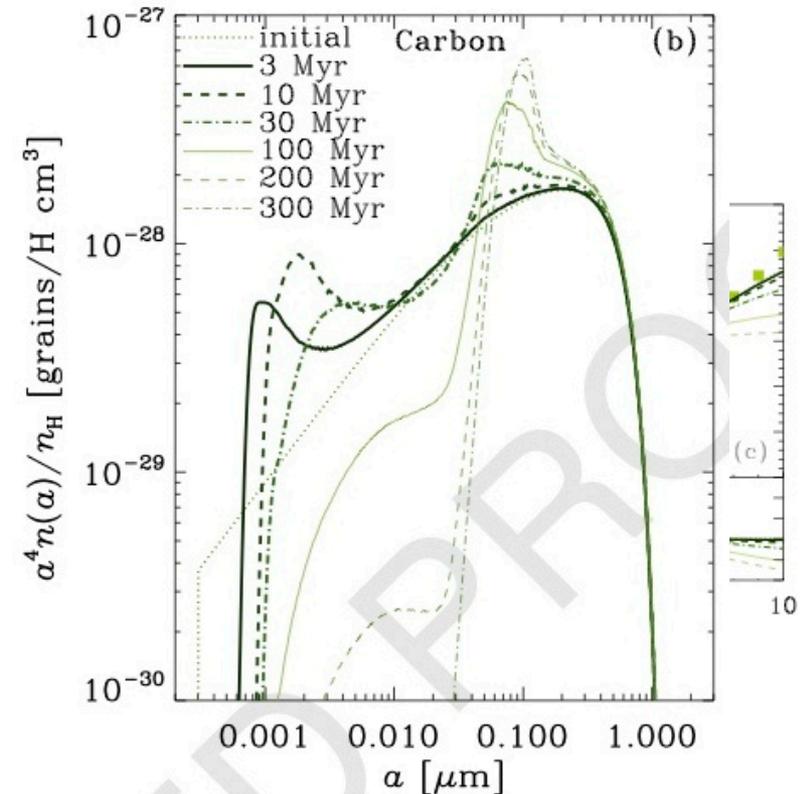
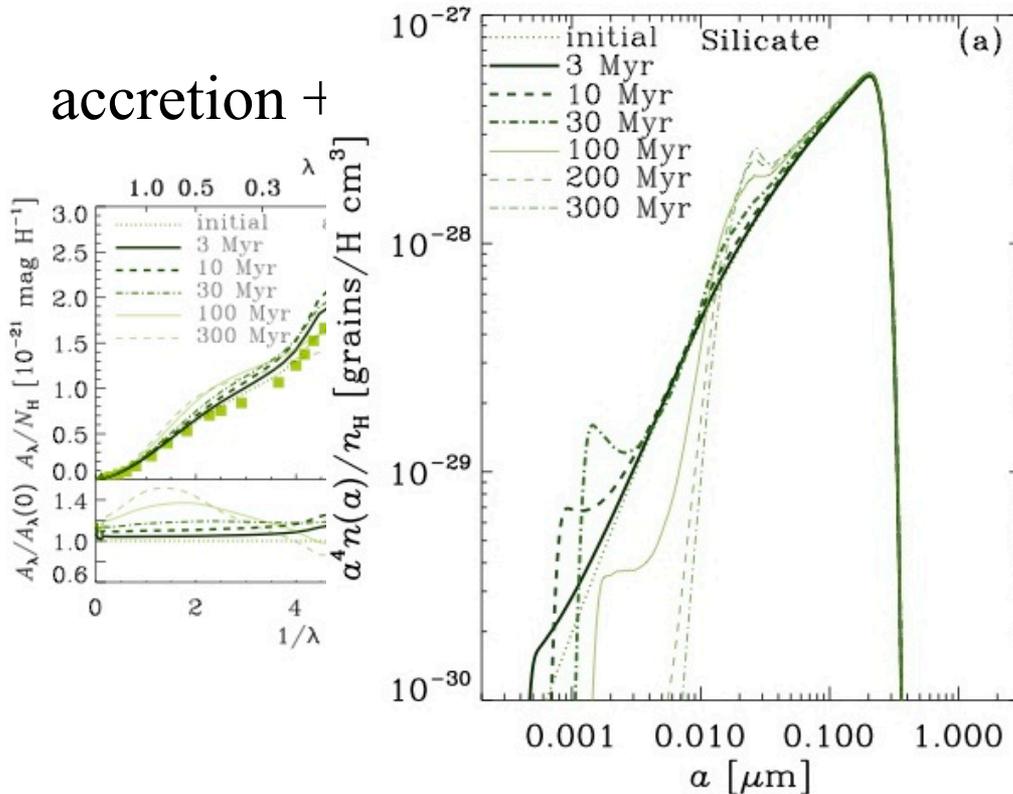
Coagulation



Grain Growth vs. Extinction Curves

Grain growth by accretion \Rightarrow Steepens

Coagulation (grain-grain sticking) \Rightarrow Flattens the extinction curve.



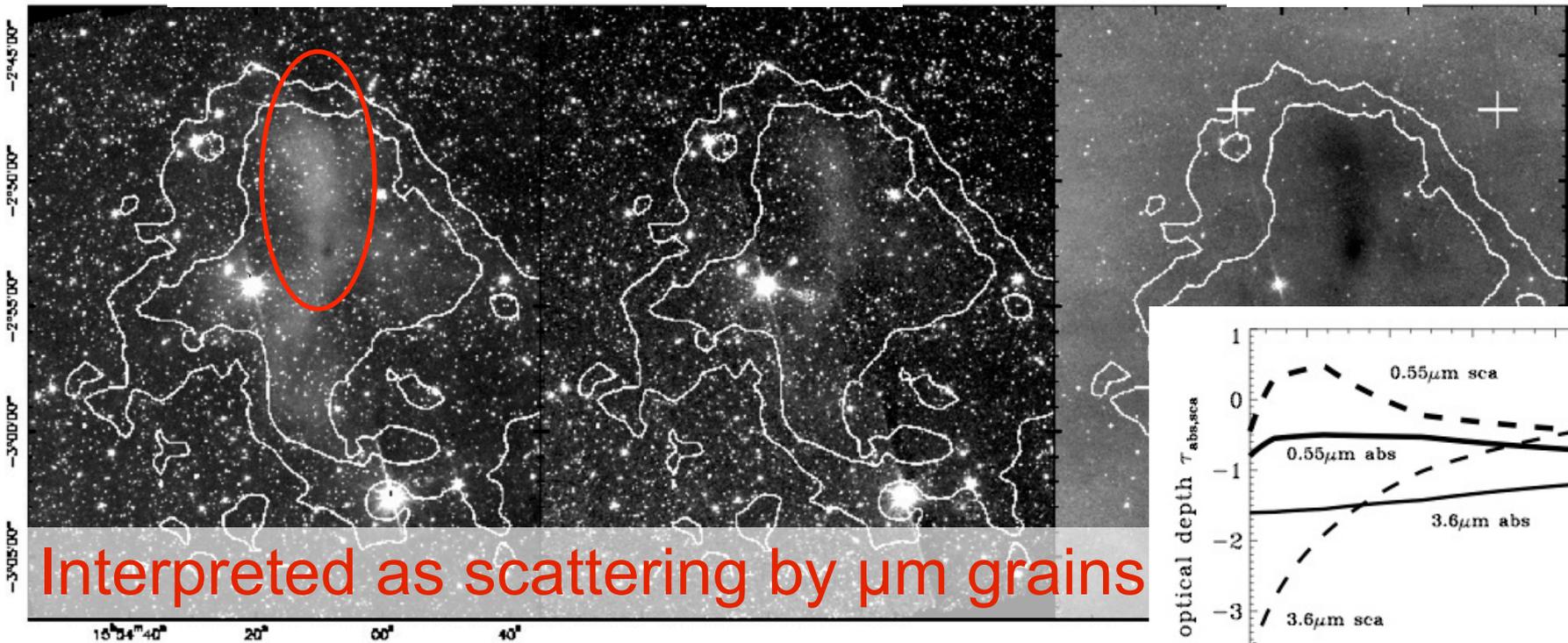
Coagulation is Stronger? μm -Sized Grains in Dense Cores

Coreshine: Shining at $\sim 3 \mu\text{m}$ in dense molecular cores

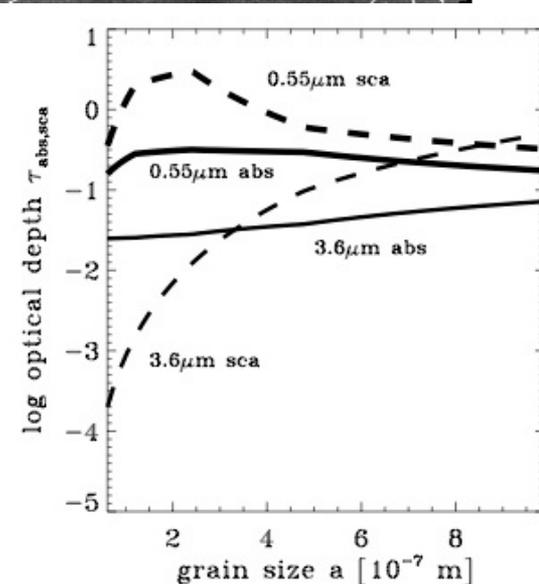
$\lambda = 3.6 \mu\text{m}$

$4.5 \mu\text{m}$

$8 \mu\text{m}$

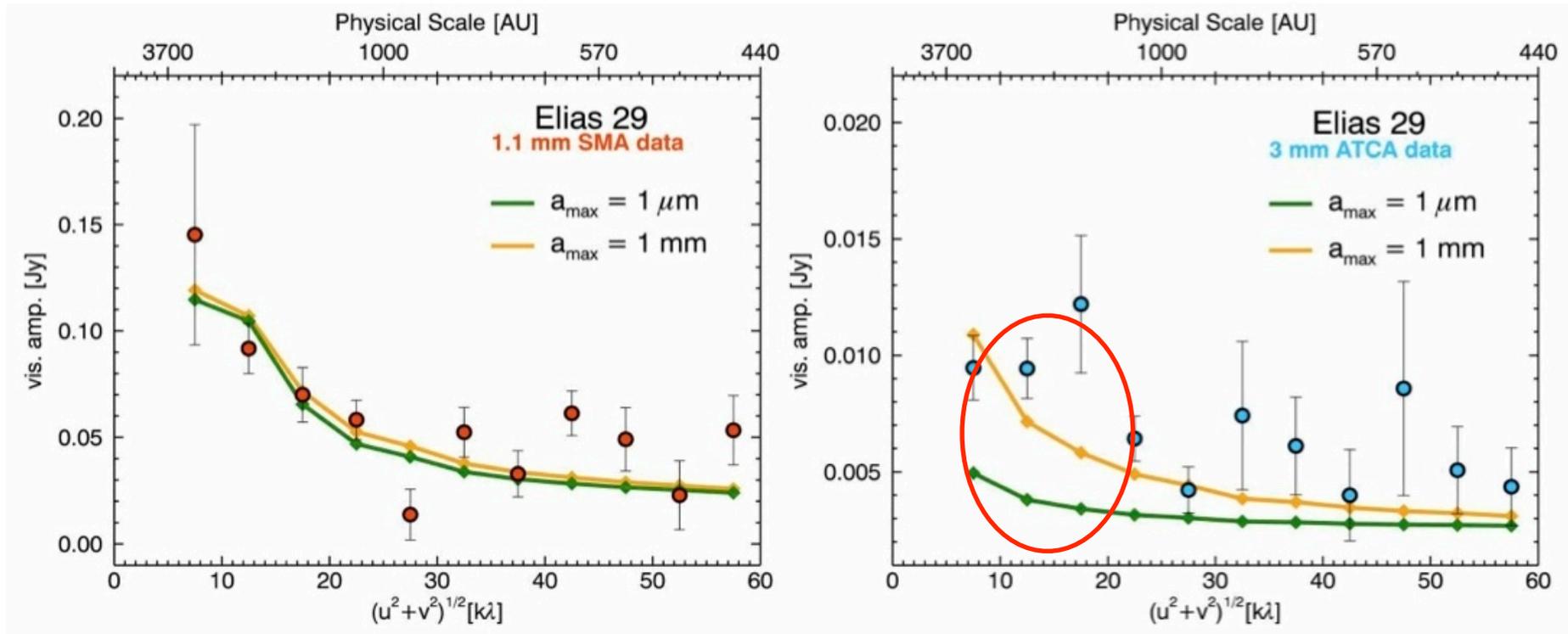


Steinacker et al. (2010)



Even mm-Sized Grains!

Existence of mm-sized grains in the envelopes ($\sim 10^{4-5} \text{ cm}^{-3}$) of Class I protostars

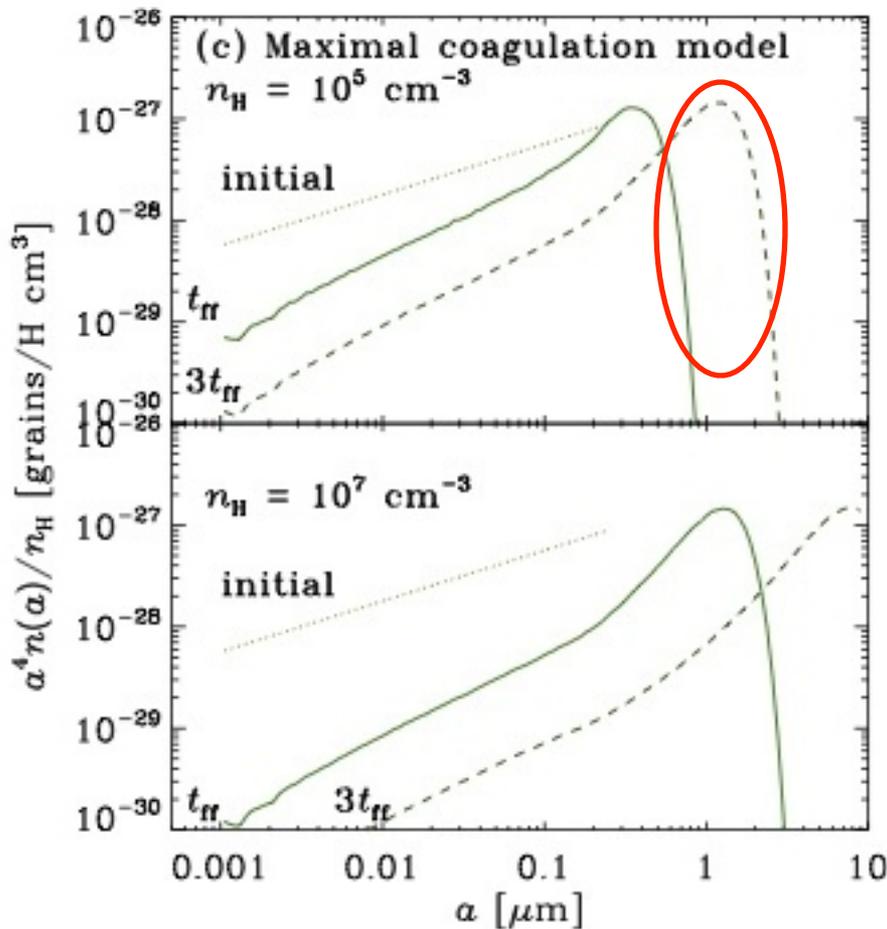


Miotello et al. (2014)

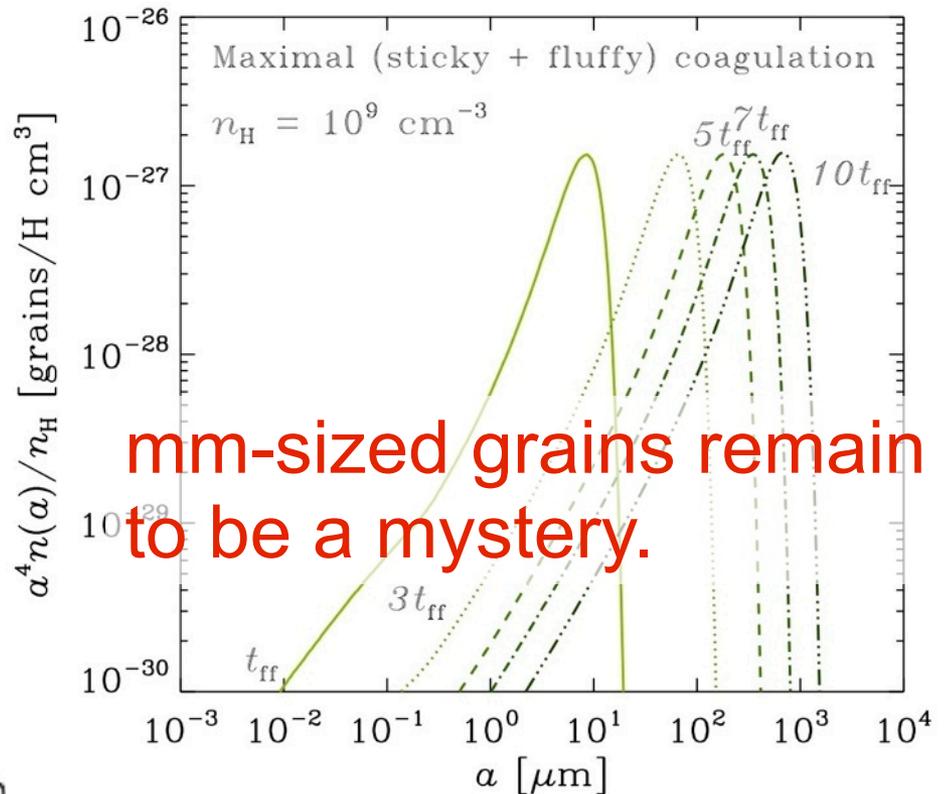
Theoretical Possibility of $\mu\text{m}/\text{mm}$ Grains

μm -sized grains can be formed if MC cores survive \sim a few t_{ff} .

mm-sized grains is difficult to form in a Class I envelope.



Hirashita & Li (2013)



Wong & Hirashita (2014, in prep.)

3. Summary

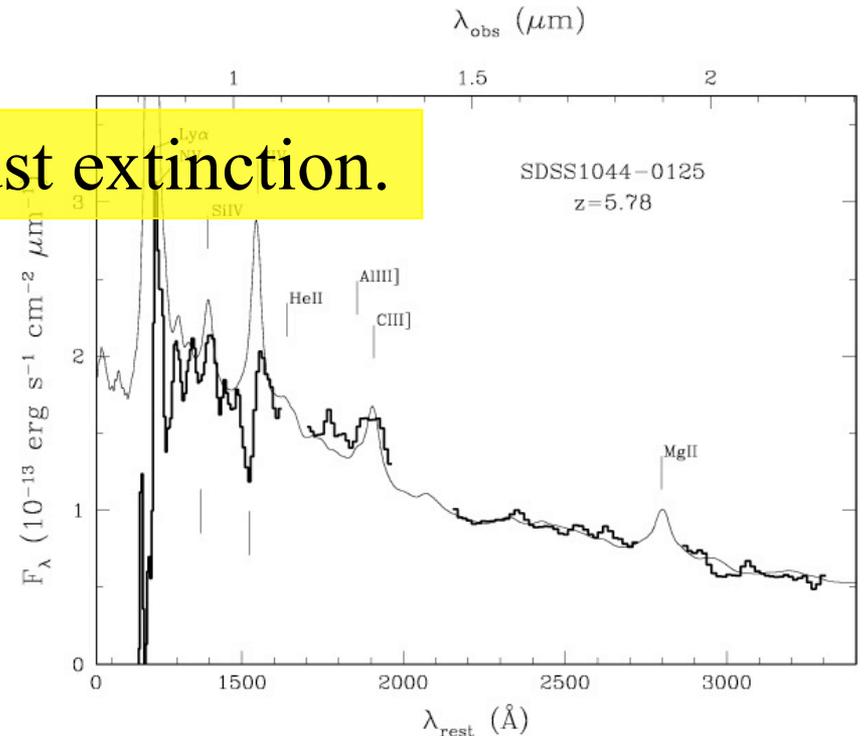
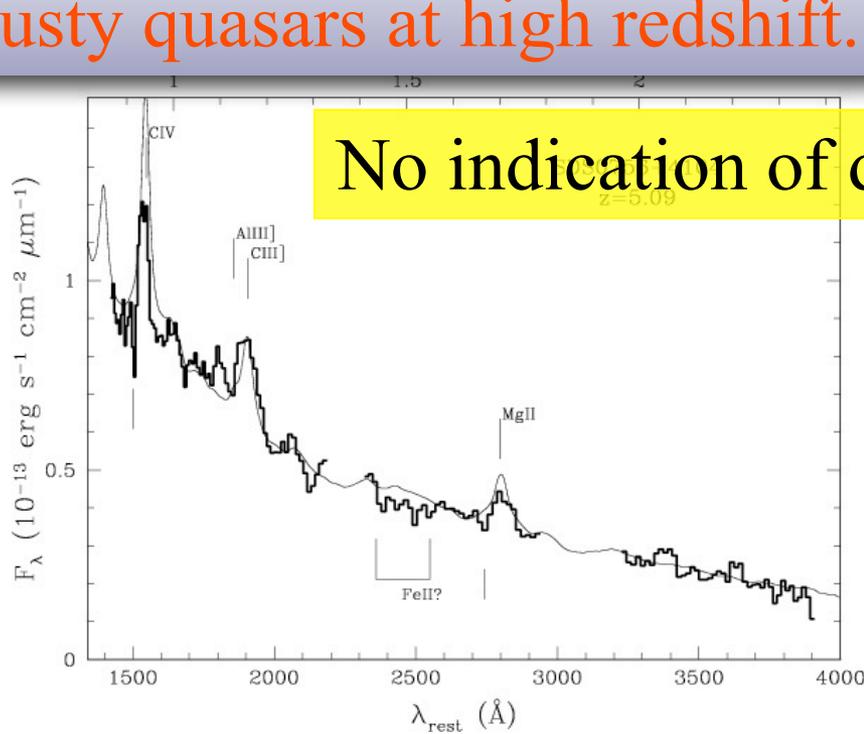
- (1) Flattening the extinction curve (large grains):
 - a. Stardust (SNe, AGB) ($M_{\text{dust}} \uparrow$)
 - b. SN shock destruction ($M_{\text{dust}} \downarrow$)
 - c. Coagulation ($M_{\text{dust}} \rightarrow$)
- (2) Steepening the extinction curve (enhancement of small grains):
 - a. Shattering ($M_{\text{dust}} \rightarrow$)
 - b. Accretion of gas-phase metals ($M_{\text{dust}} \rightarrow$)
- (3) Those processes **are not independent, so we should consider all in a single model.**
- (4) Existence of large grains implies that we need to work more on coagulation.

Thank you.

Flat Extinction Curves...

Can explain unreddened dusty quasars at high redshift.

Maiolino et al. (2004)



SDSS1044-0125 (z = 5.78)

SDSS0756+4104 (z = 5.09)

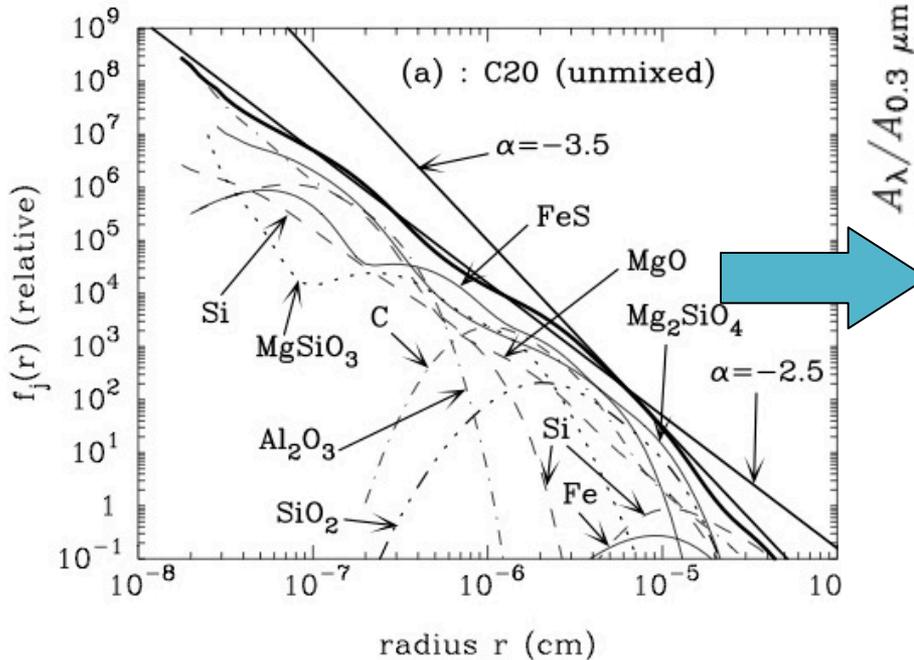
$10^8 - 10^9 M_\odot$ of dust is detected in submm
(Priddey 2003).

Dust Formation in Supernovae

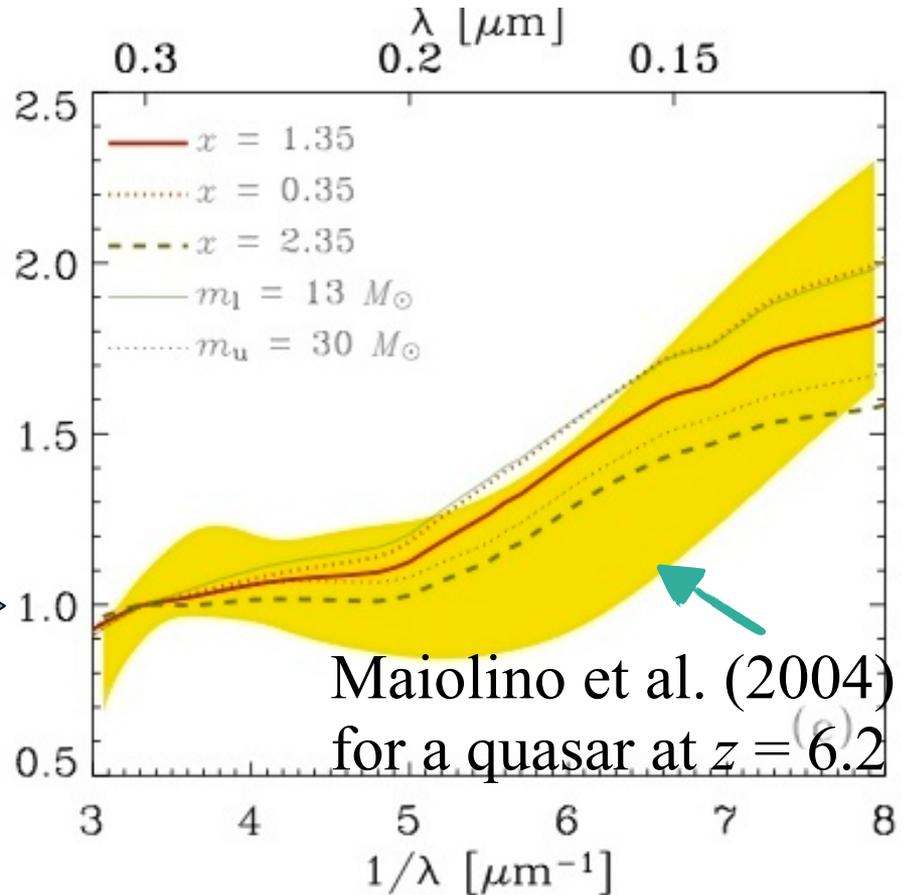
Nozawa et al. (2003)



Super-saturated gas (after adiabatic expansion of supernova)

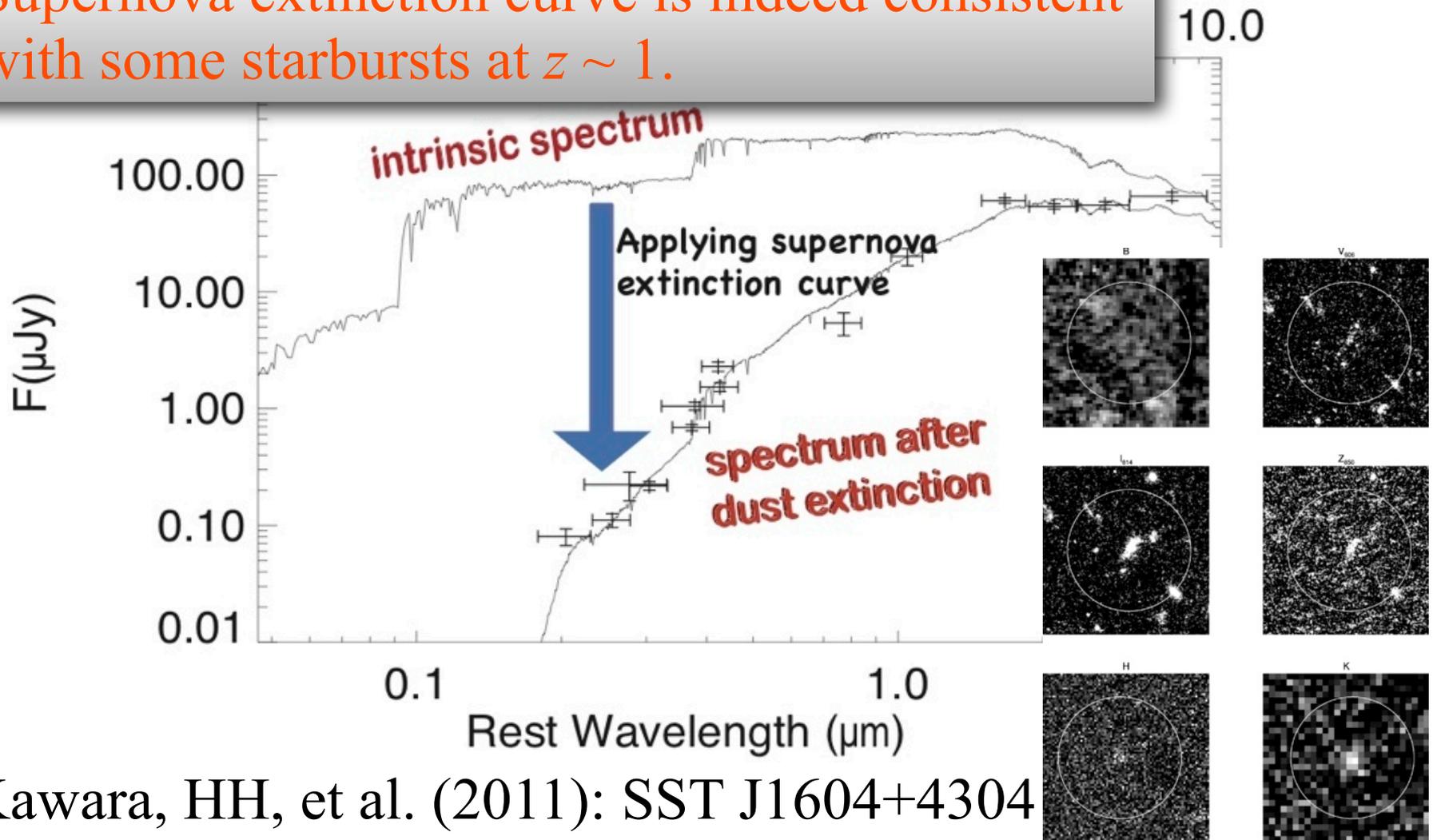


Hirashita et al. (2005)



Consistent with $z \sim 1$ Starbursts

Supernova extinction curve is indeed consistent with some starbursts at $z \sim 1$.



Kawara, HH, et al. (2011): SST J1604+4304
(See also Shimizu et al. 2011)

3. Dust Enrichment at High Redshift

“Chemical evolution model” of galaxies
 Gas \Rightarrow Star \Rightarrow metal/dust injection

Gas

$$\frac{dM_{\text{gas}}}{dt} = -\psi + E$$

Metal i

$$\frac{dM_Z}{dt} = -Z\psi + E_Z$$

Dust

$$\frac{dM_{\text{dust}}}{dt} = -\mathcal{D}\psi + f_{\text{in}}E_Z - \frac{M_{\text{dust}}}{\tau_{\text{SN}}} + \frac{M_{\text{dust}}}{\tau_{\text{acc}}}$$

Supply from stars

SF

SF

Destruction by
 SNe $\sim 10^8$ yr

Growth in clouds

$\tau_{\text{acc}} \propto$

$1/nZ \times \langle a^2 \rangle / \langle a^3 \rangle$

Constraint on the Lifetime

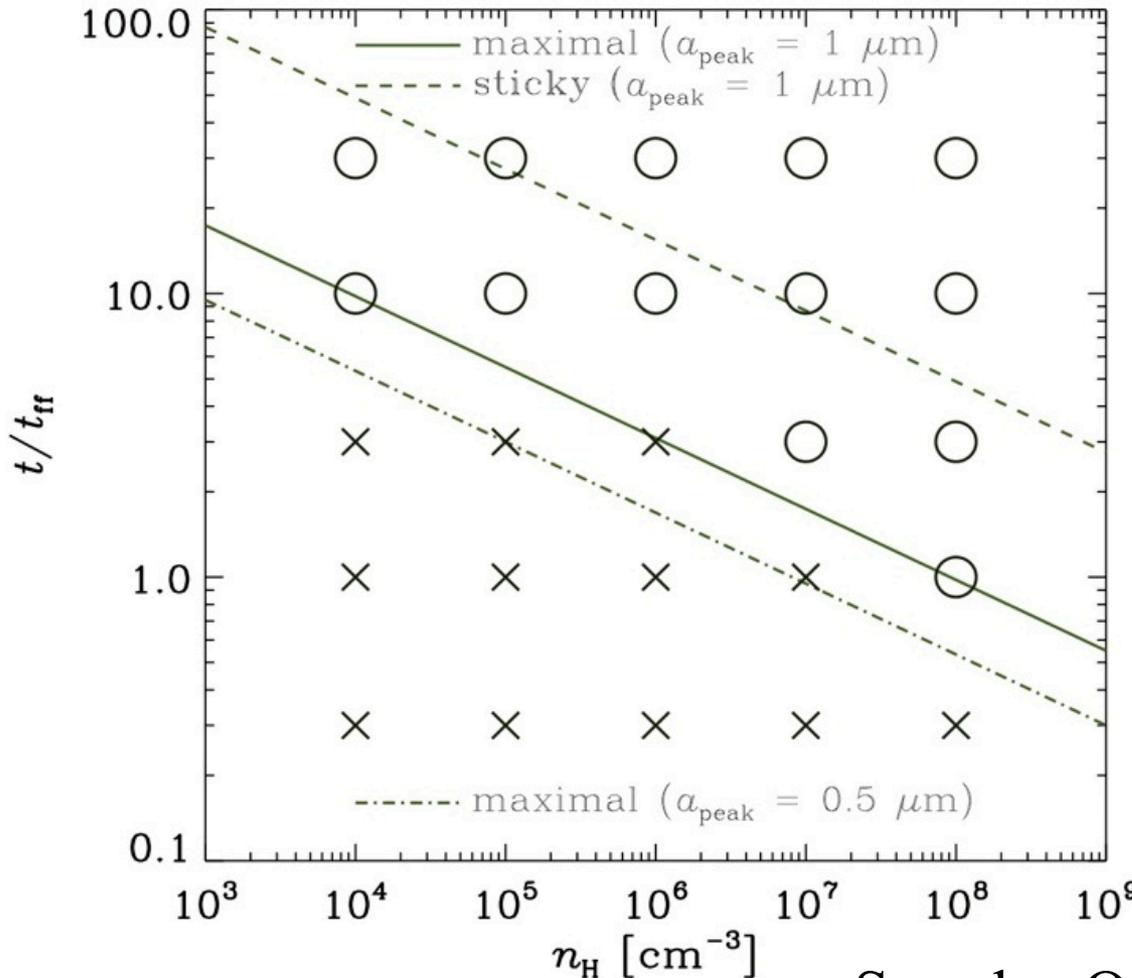
Success diagram of the grain growth to 1 μm

Hirashita & Li (2013)

○: Success

×: Failure

At a typical density of molecular cloud cores $\sim 10^5 \text{ cm}^{-3}$, it takes **5 t_{ff}** to produce 1- μm grains.



Molecular clouds are long-lived objects with lifetimes > several free-fall times

See also Ormel et al. (2009)