Evolution of Grain Size Distribution in the Interstellar Medium

Hiroyuki Hirashita
(ASIAA, Taiwan)

T. Nozawa (IPMU), H. Yan (KIAA),
T. Kozasa (Hokkaido), T.-M. Kuo (ASIAA),
K. Kawara (U. Tokyo)

Topics

Focus: high-redshift ($z > 5$) dust

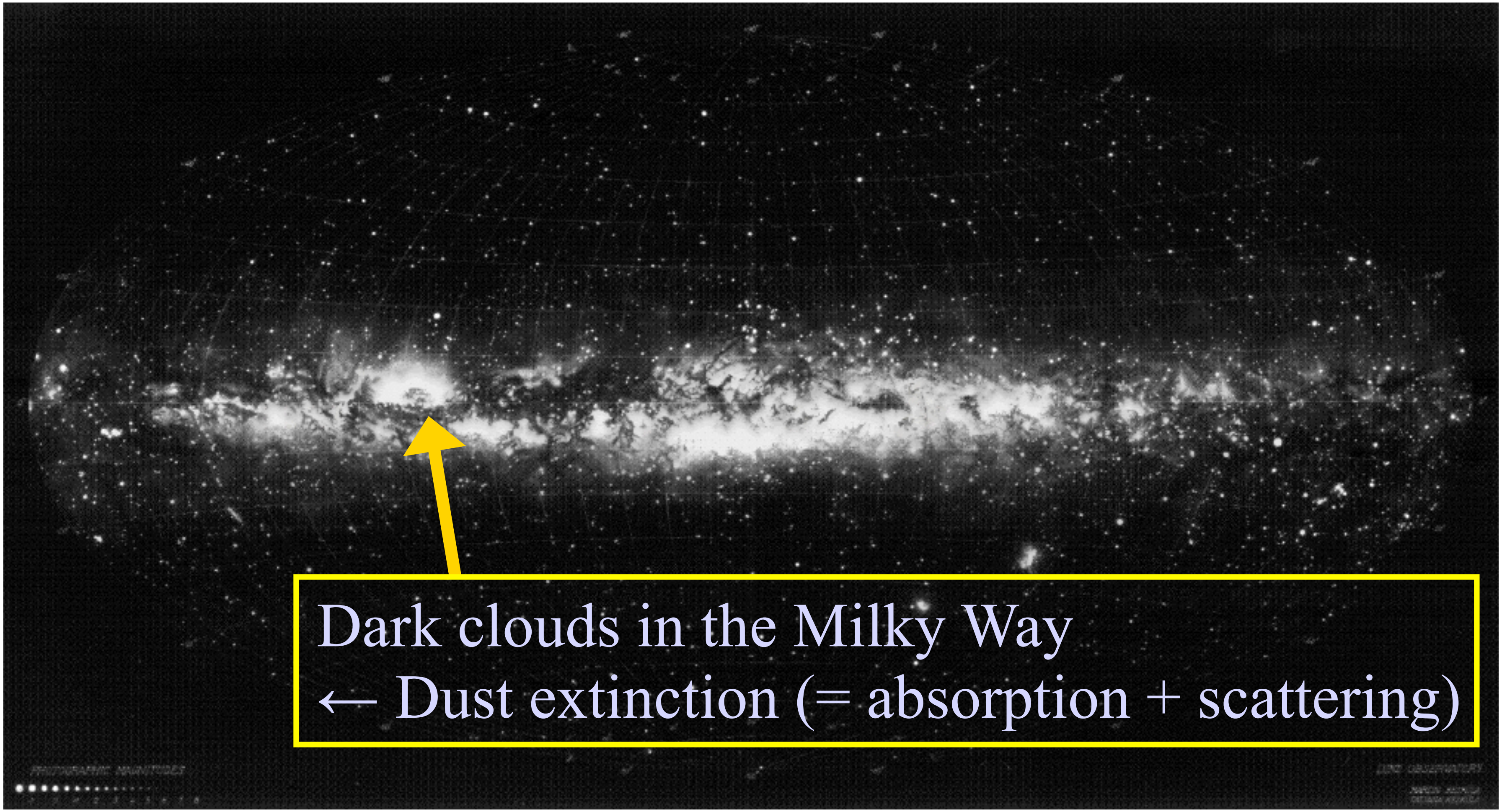
1. Grain Properties and Extinction Curves
2. Dust Formation in Supernovae
3. Interstellar Processing
4. Dust Enrichment
5. Summary

1. Grain Properties and Extinction Curves

Milky Way in the Optical

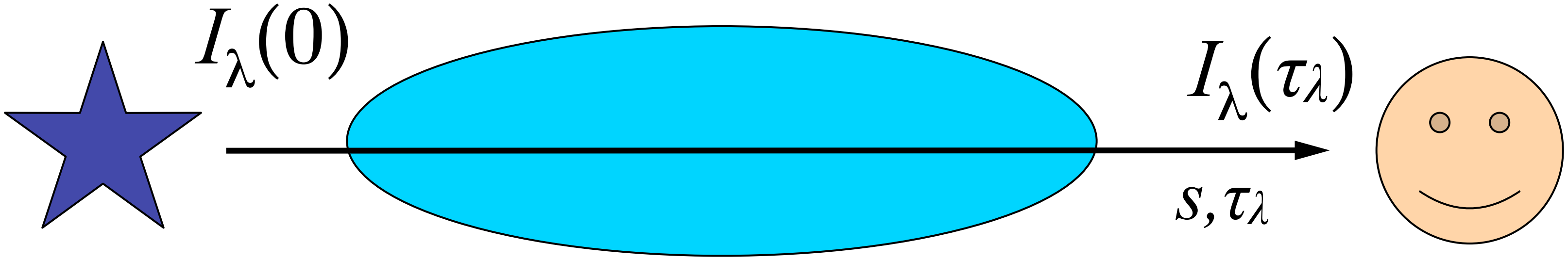
Optical (λ ~ 0.5 μm)

Lund Observatory



Dark clouds in the Milky Way
← Dust extinction (= absorption + scattering)

Extinction



Extinction = Absorption + Scattering

τ_λ: optical depth for extinction

$I_\lambda(\tau_\lambda) = I_\lambda(0)\ e^{-\tau_\lambda}$

Extinction Curve: τ_λ as a function of λ

Theoretical Fitting to Extinction Curves

Pei (1992)

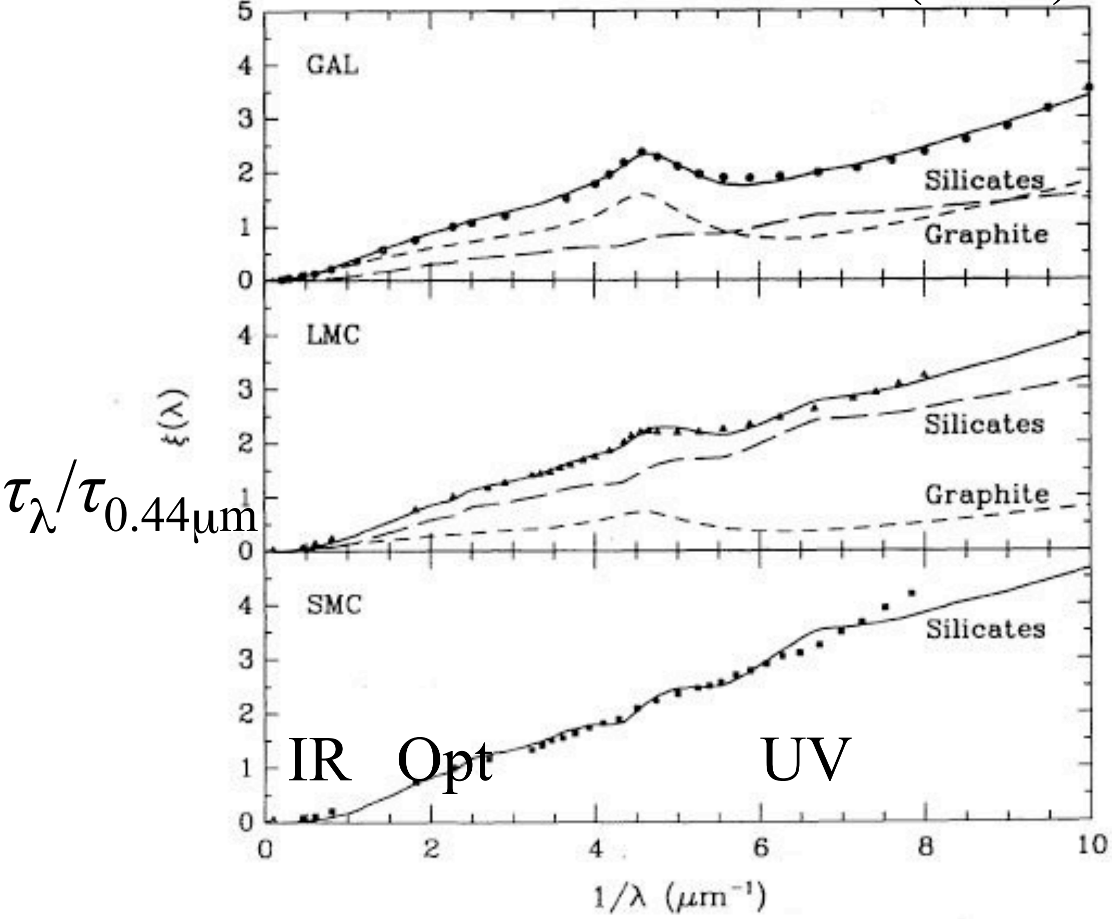


FIG. 5.—Comparisons between the model and empirical extinction curves in the Milky Way, LMC, and SMC. The short and long-dashed lines show, respectively, the relative contributions from graphite and silicate grains, with the sum of the two shown as the solid lines.

Fitting:

Grain size distribution

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

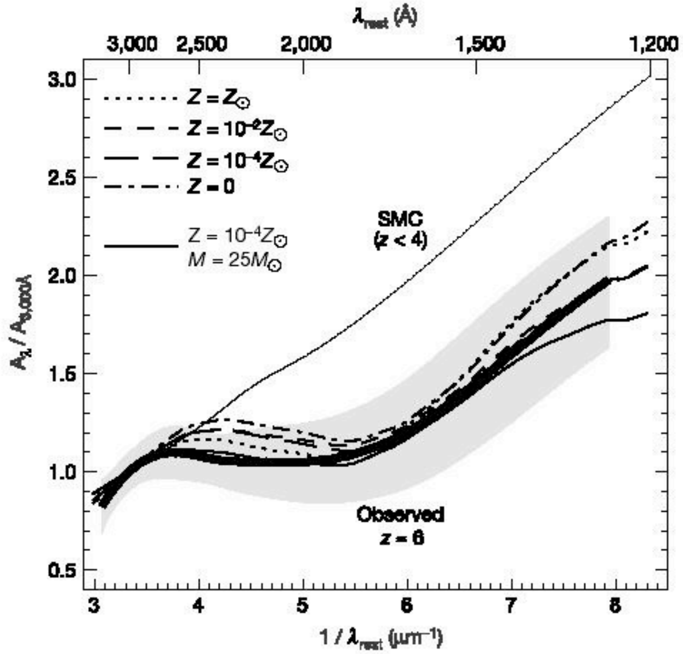
Silicate and graphite

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

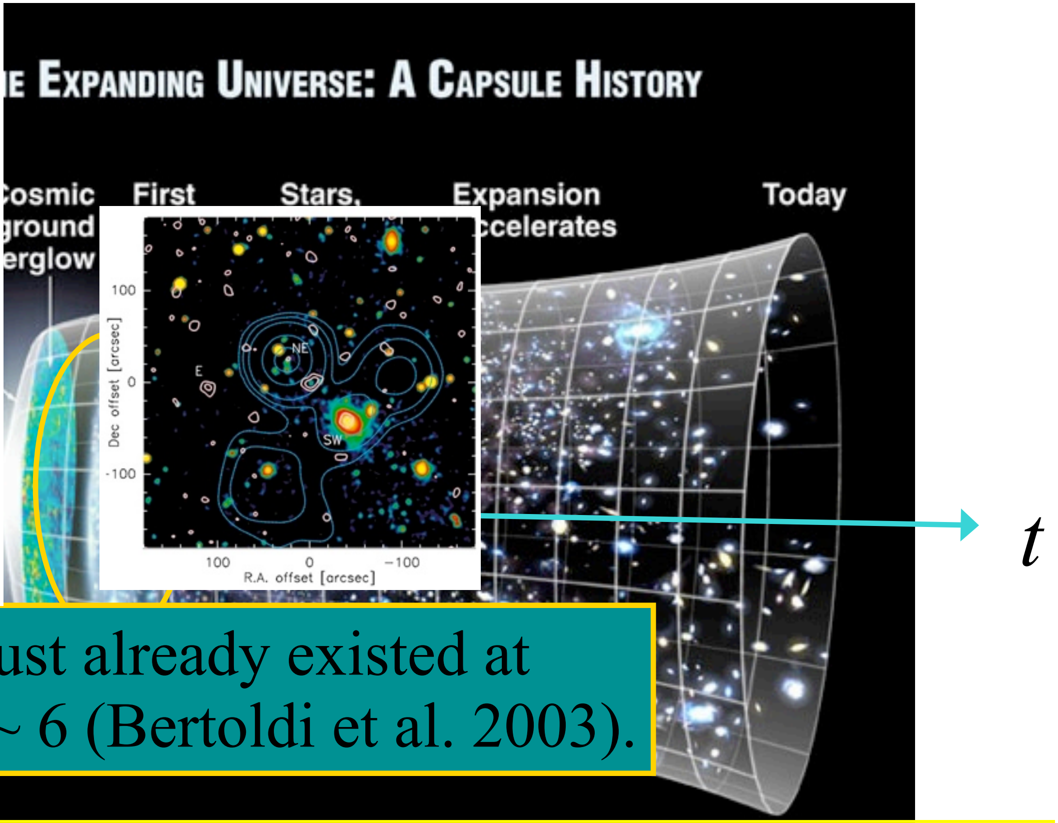
$a_{\text{max}} = 0.25\ \mu\text{m}$

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

Early Universe (age < 10^9 yr)



Maiolino et al. (2004)



Dust already existed at $z \sim 6$ (Bertoldi et al. 2003).

Clarifying the origin and evolution of dust in the early Universe is an urgent issue.

NASA

Major Questions for Dust

What is the mechanism that determines the dust grain properties (especially, size distribution)?

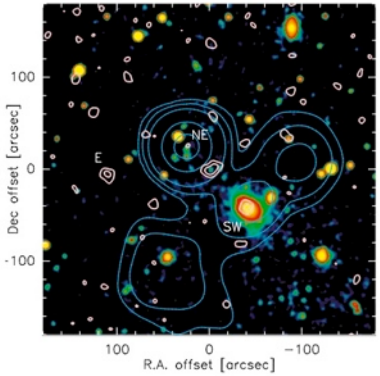
(1) Formation in stellar ejecta.

(2) Processing in the interstellar medium.

2. Dust Formation in Supernovae

High-Redshift Dust

(1) Stellar source of dust:
supernovae rather than AGB stars
(2) Processing in the ISM
(especially by turbulence)
(3) Dust growth in molecular
clouds



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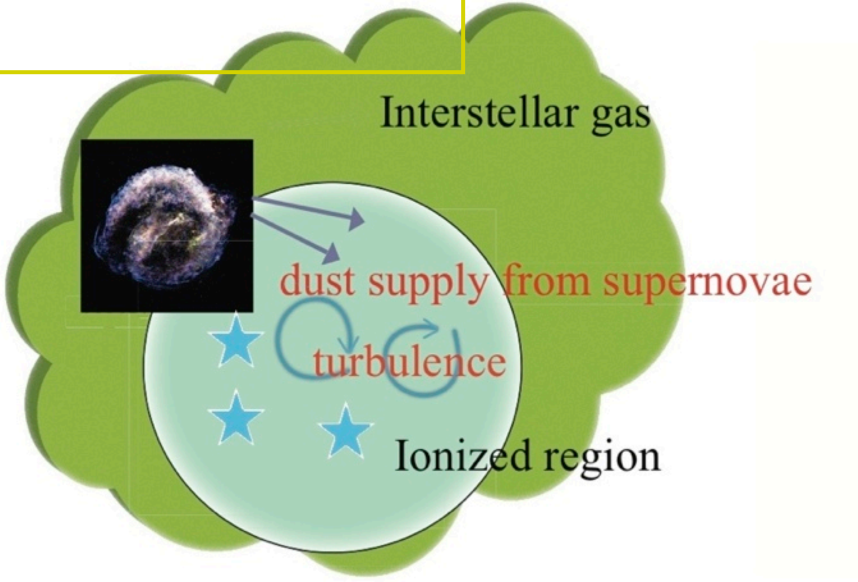
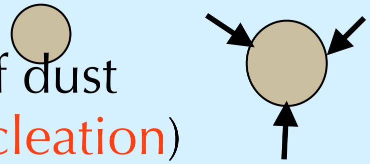


Dust Formation in Supernovae

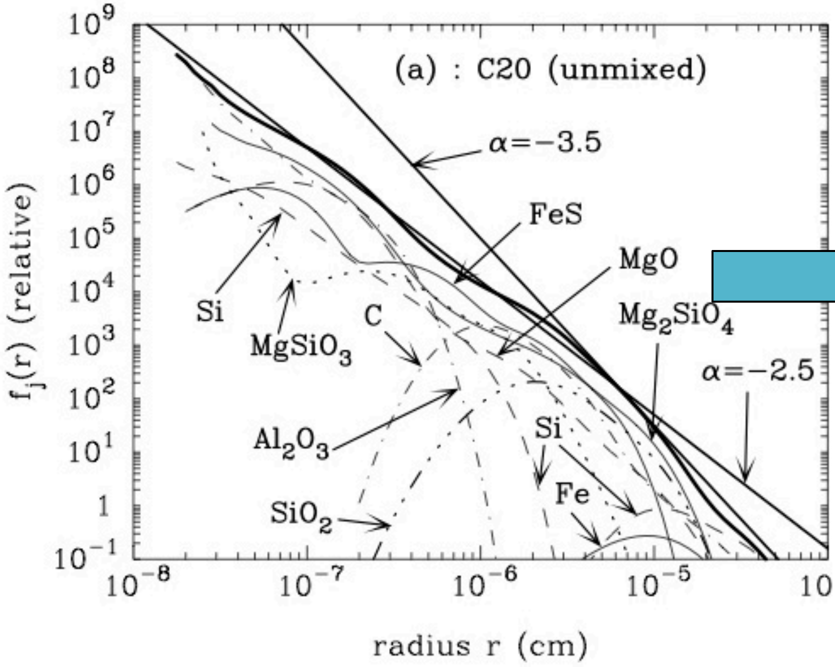
Nozawa et al. (2003)



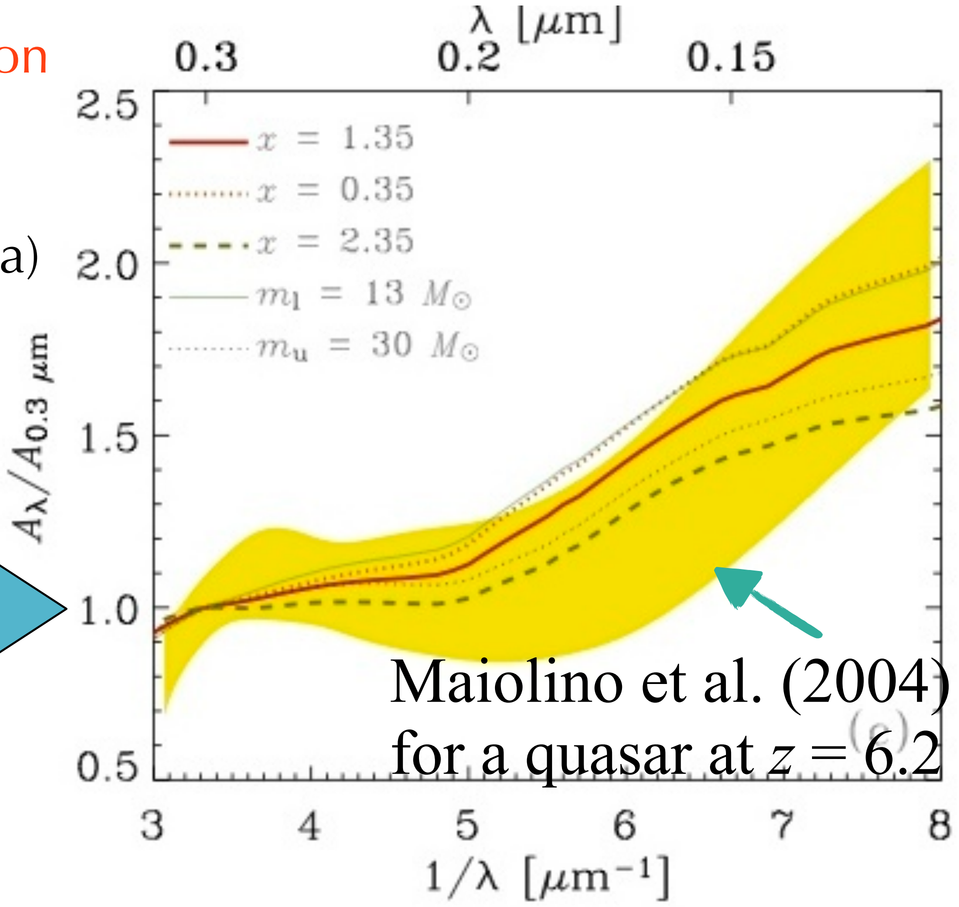
Formation of dust nucleus (nucleation)

Accretion

Super-saturated gas (after adiabatic expansion of supernova)



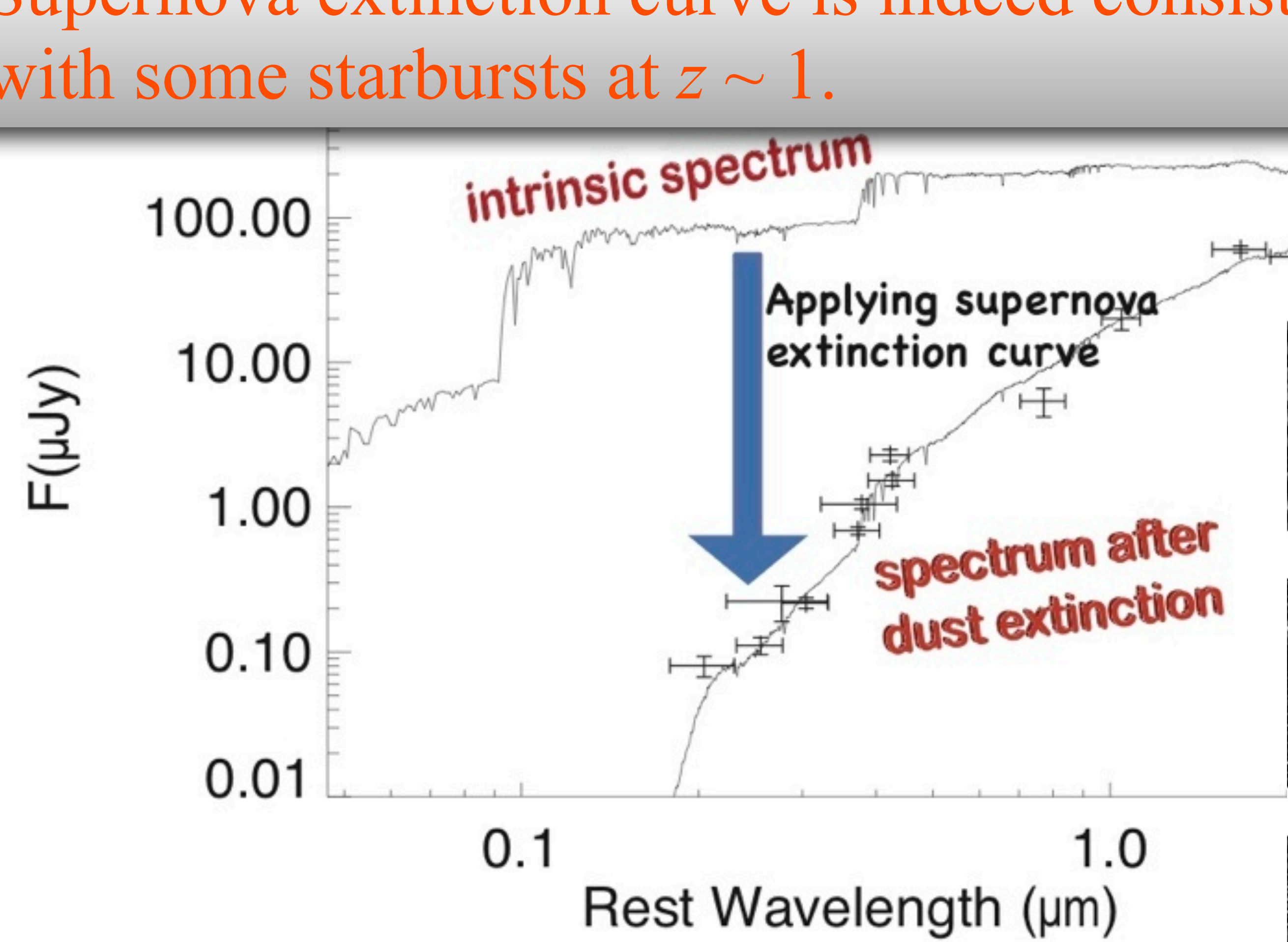
Hirashita et al. (2005)

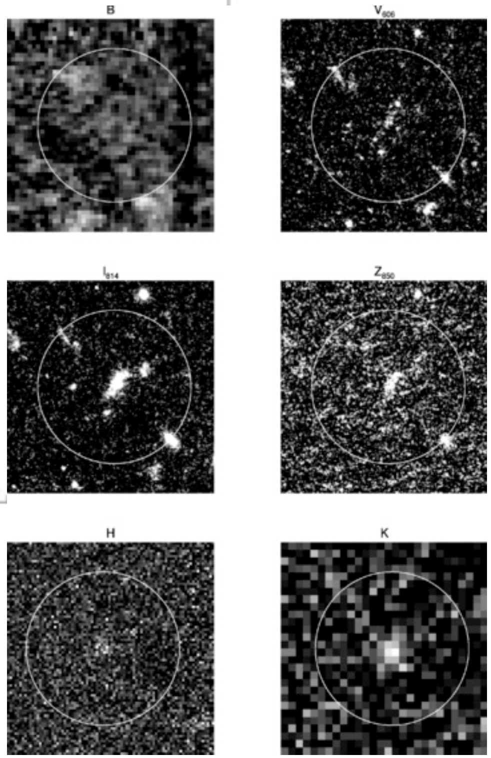


Maiolino et al. (2004) for a quasar at $z = 6.2$

Consistent with $z \sim 1$ Starbursts

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



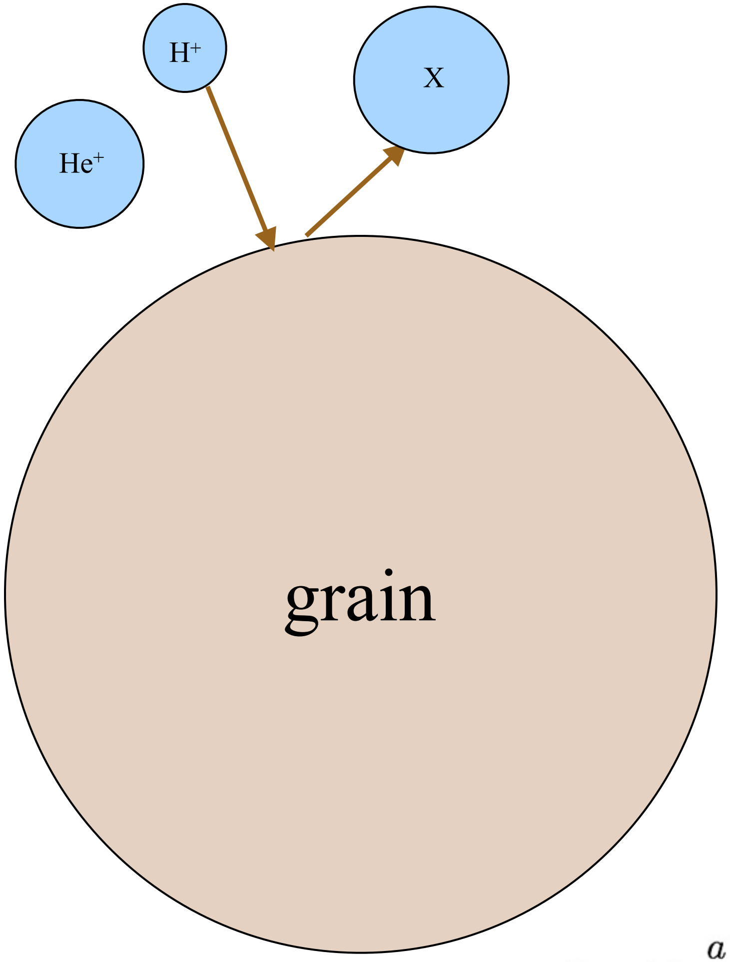


Kawara, HH, et al. (2011): SST J1604+4304
(See also Shimizu et al. 2011)

SN-dust is successful.

But this does NOT exclude a possibility that other physical processes also work.

Dust Destruction by Sputtering

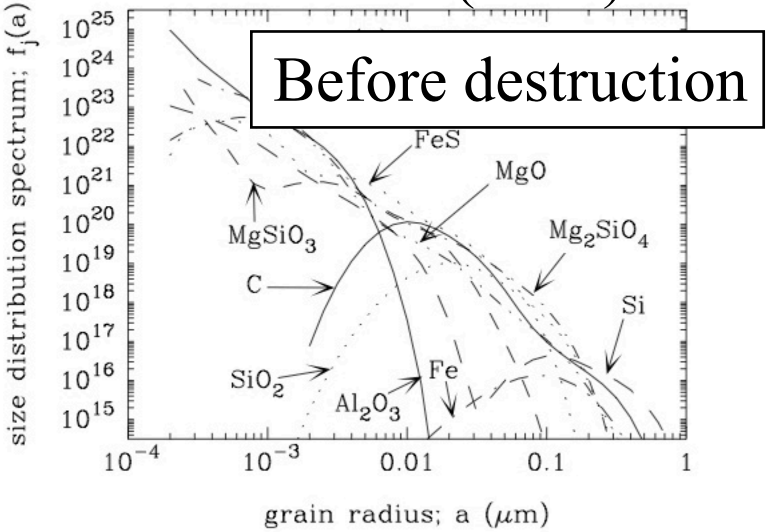


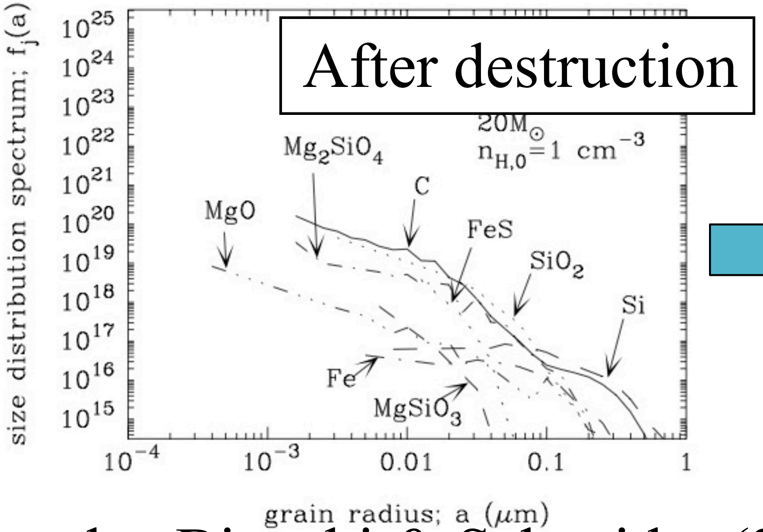
Effective in supernova shocks (← Any dust grain has to pass through the shocked region before being injected into the ISM):
Small grains are more easily destroyed.

$$\tau_{\rm sput} \equiv \frac{a}{-\dot{a}} = \frac{a}{\frac{n_{\rm H} Y_{\rm s}}{\rho}\left(\frac{kTm_{\rm H}}{2\pi}\right)^{1/2}} = \frac{10^5\ {\rm yr}}{n_{\rm H}}\left(\frac{T}{10^7\ {\rm K}}\right)^{1/2}\left(\frac{a}{0.1\ \mu{\rm m}}\right)\left(\frac{Y_{\rm s}}{0.1}\right)$$

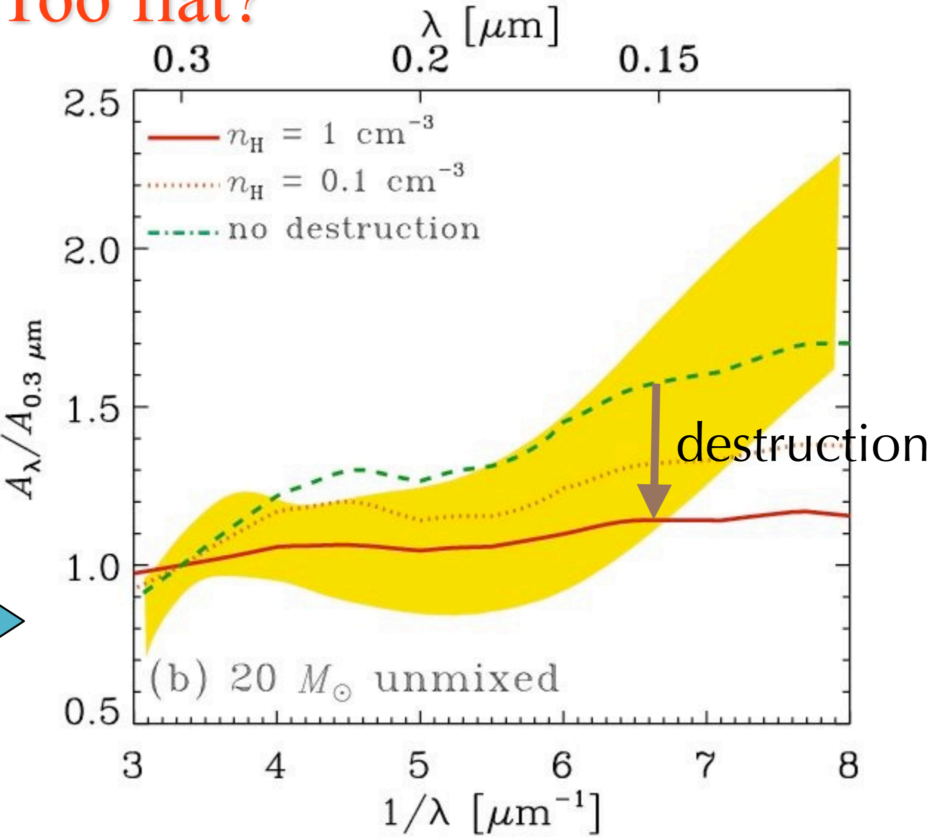
Extinction Curve after Destruction

Nozawa et al. (2007)





Extinction curve is flat after shock destruction.
Too flat?



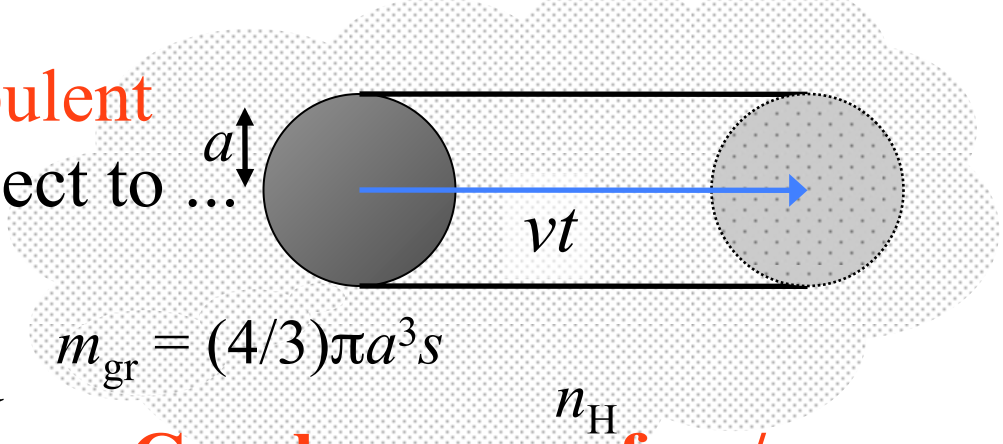
Hirashita et al. (2008)

See also Bianchi & Schneider (2007)

3. Interstellar Processing

Fate of Grains in Interstellar Turbulence

Grains injected into the turbulent interstellar medium are subject to ...



1. Gas drag

Larger grains are coupled with larger-scale turbulence.

Gas drag ∝ surface/mass

$\propto a^2/a^3$

2. Gyro-resonance

→ MHD wave + gyro-motion of grains

Resonance between wave and gyro-motion

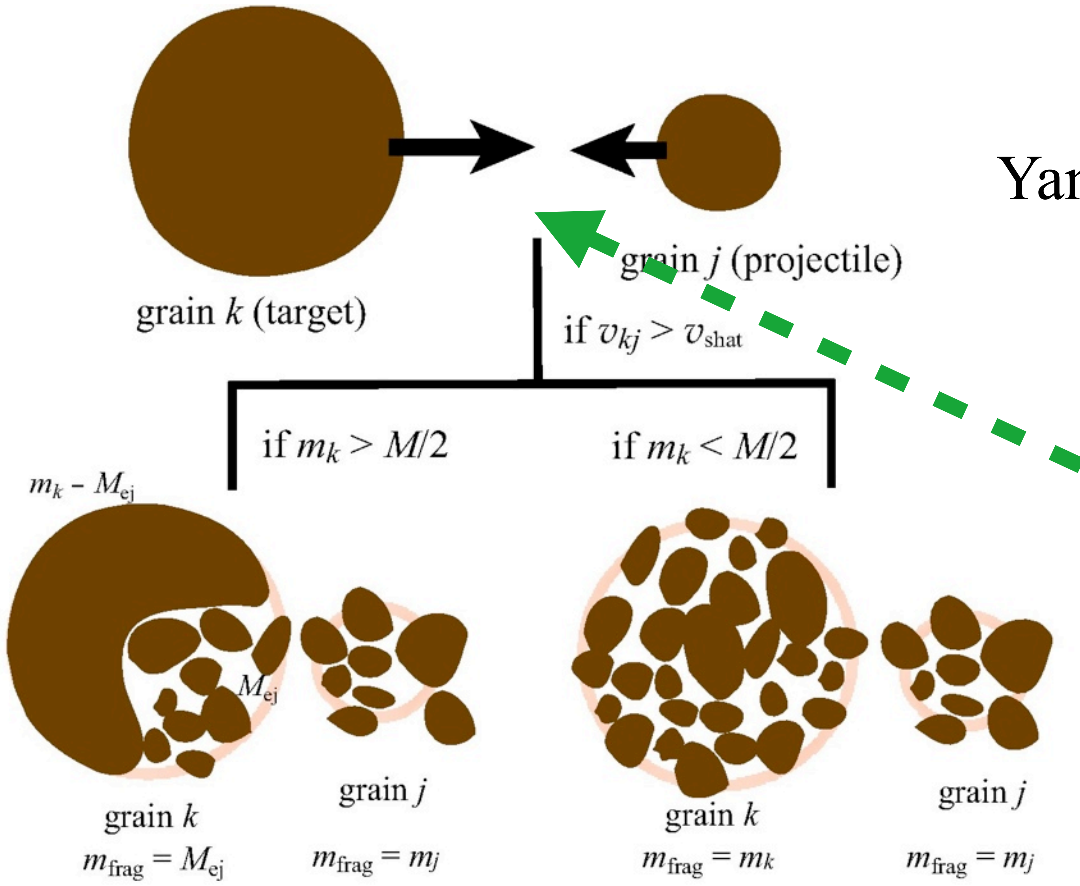
$$\boxed{\omega - k_{//} v \cos\theta} = n\boxed{\omega_{\rm gyro}}$$

Doppler-shifted wave frequency

gyro-frequency

Effects of grain-grain collision under the velocities induced by turbulence is investigated in this work.

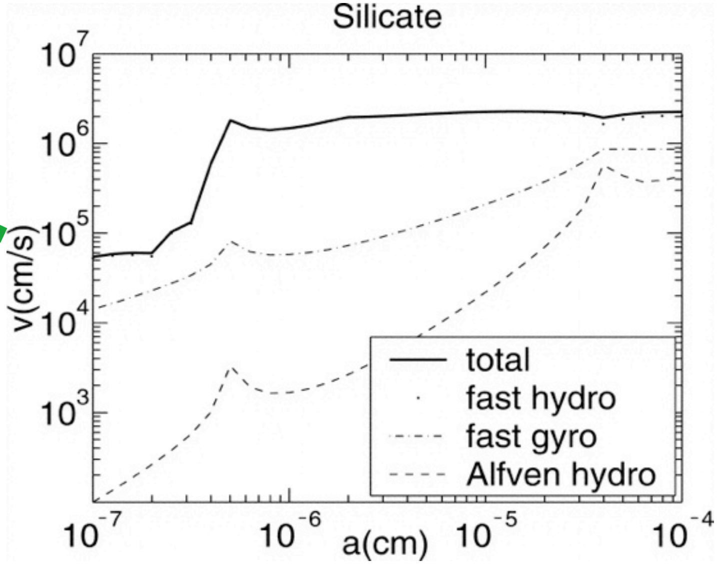
Shattering



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

MHD turbulence model

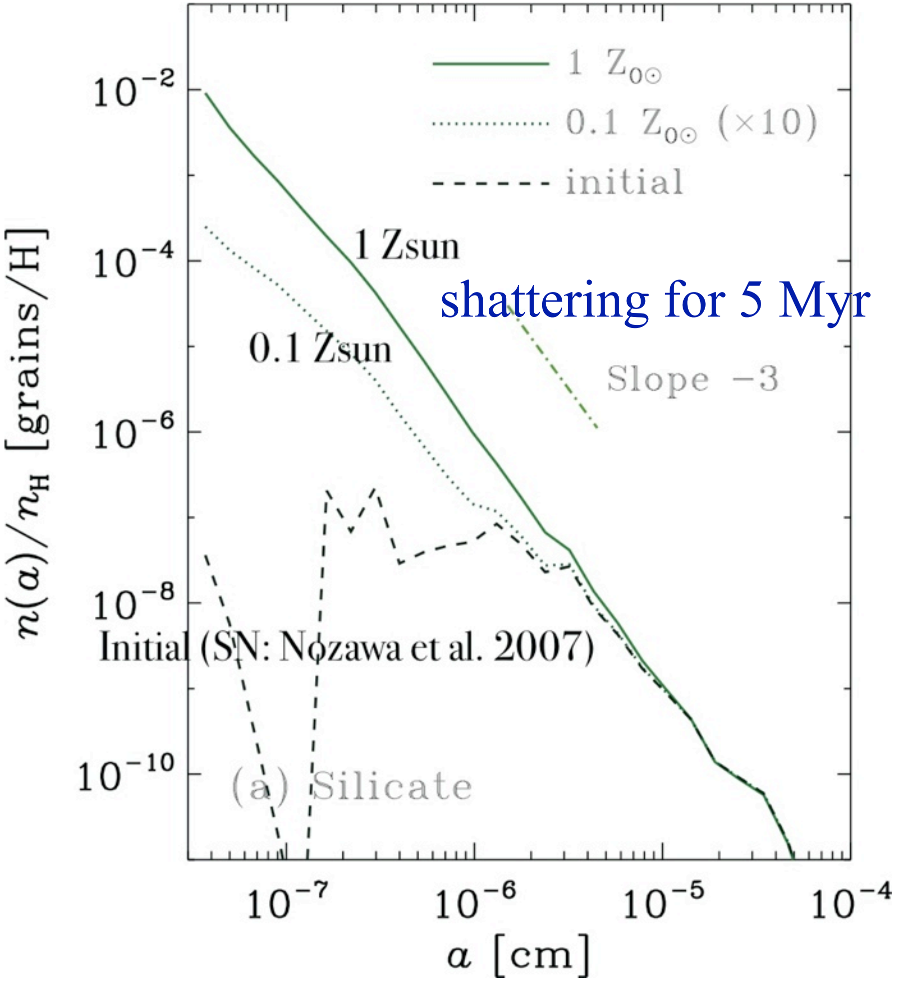
Yan, Lazarian, & Draine (2004)



Warm ionized medium
$T = 8000$ K
$n_{\rm H} = 0.1$ cm^{-3}
$B = 3.4$ μG

Shattering of SN Dust

Hirashita et al. (2010)



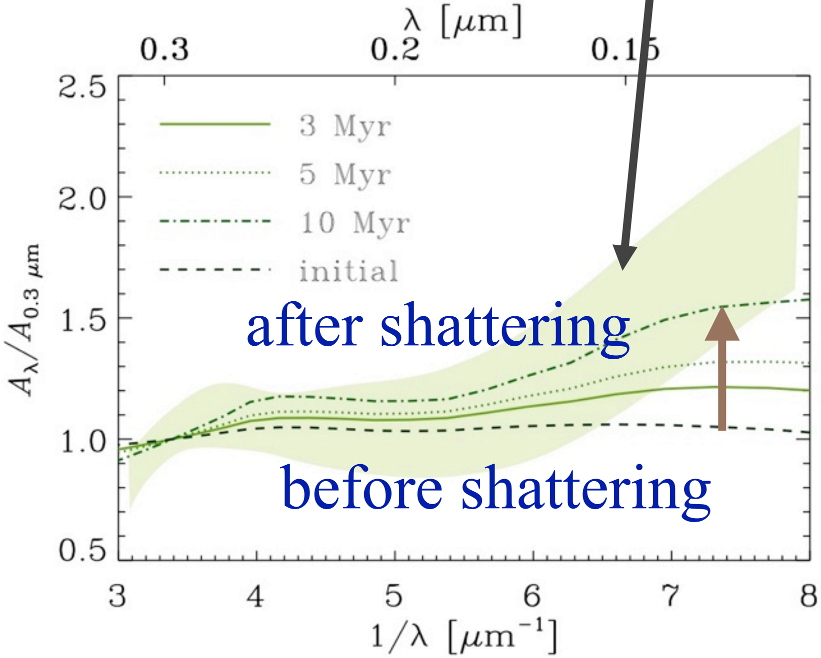
1 Zsun

0.1 Zsun

shattering for 5 Myr

Initial (SN: Nozawa et al. 2007)

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



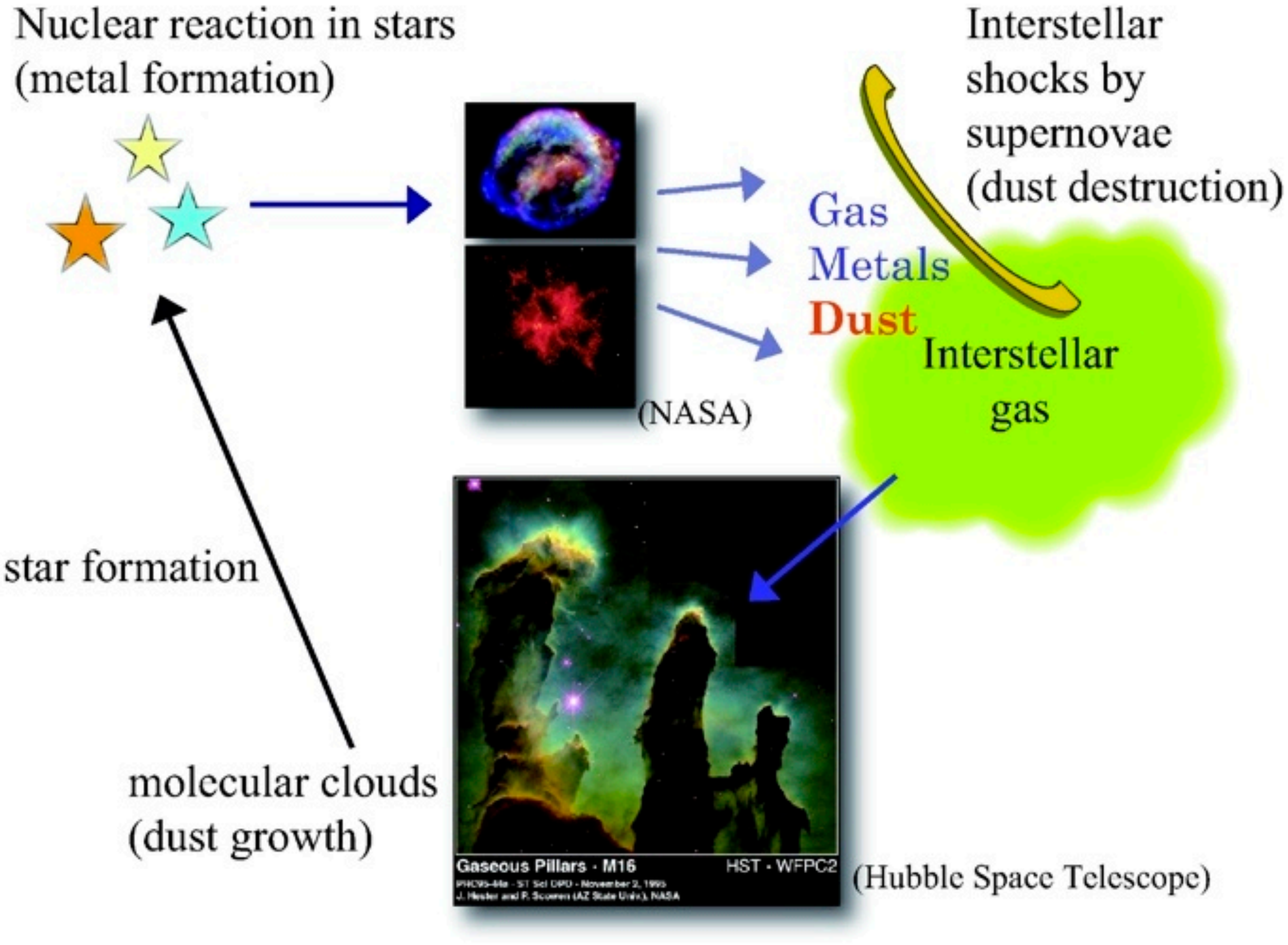
after shattering

before shattering

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

4. Dust Enrichment

Dust Budget in a Galaxy



Nuclear reaction in stars
(metal formation)

Interstellar
shocks by
supernovae
(dust destruction)

(NASA)

Gas
Metals
Dust

Interstellar
gas

star formation

molecular clouds
(dust growth)

(Hubble Space Telescope)

Framework of Dust Enrichment

"Chemical evolution model" of galaxies

Gas ⇒ Star ⇒ metal/dust injection

Gas

$$\frac{dM_{\rm g}}{dt} = -\psi + E,$$

SF

Supply from stars

Metal *i*

$$\frac{dM_i}{dt} = -X_i\psi + E_i,$$

Dust

$$\frac{dM_{{\rm d},i}}{dt} = f_{{\rm in},i}E_i - f_iX_i\psi + \boxed{\frac{M_{{\rm d},i}(1-f_i)}{\tau_{\rm acc}}} - \frac{M_{{\rm d},i}}{\tau_{\rm SN}}.$$

from stars

SF

Growth in clouds

$\tau_{\rm acc} \propto$

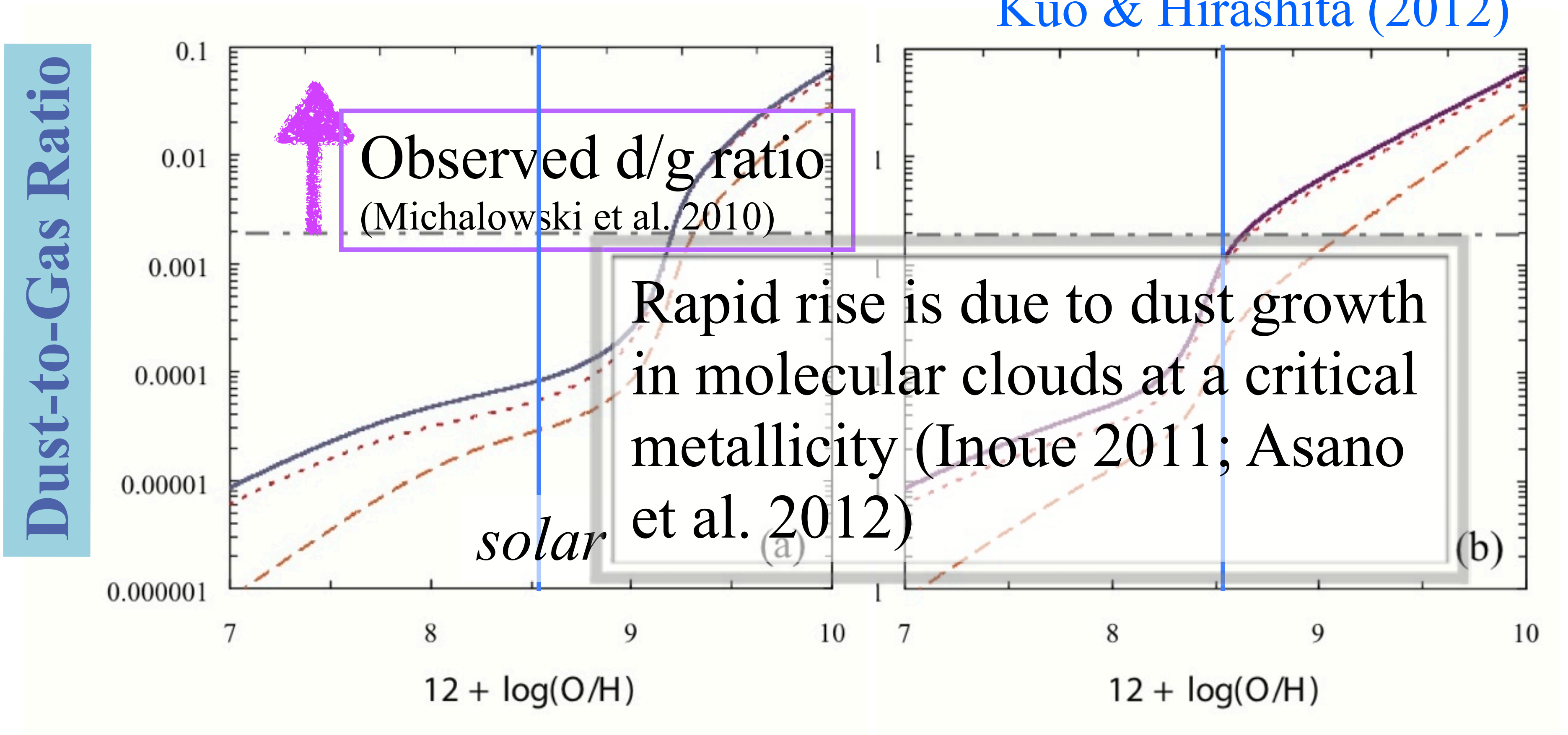
$1/nZ \times \boxed{<a^2>/<a^3>}$

Destruction by

SNe ～ 10^8 yr

Dust Enrichment and Metallicity

Kuo & Hirashita (2012)



Observed d/g ratio
(Michalowski et al. 2010)

Rapid rise is due to dust growth in molecular clouds at a critical metallicity (Inoue 2011; Asano et al. 2012)

Supernova Dust

Supernova Dust + Shattering

Production of small grains by shattering activates the grain mass growth by accretion ($\propto \langle a^2\rangle/\langle a^3\rangle$)

Dust Enrichment in High-*z* Quasars

Scenario:
(1) Dust production by supernovae.
(2) Dust grains are processed in the ISM by shattering.
(3) Dust growth becomes active under an increased surface area by shattering.

Small grain production by shattering is important in
(a) steepening extinction curves in high-*z* quasars, and
(a) determining the grain abundance in high-*z* quasars.

5. Summary

(1) Extinction curves in high-*z* quasars provide important observational clues to dust properties in the early Universe.
(2) SN-dust tends to predict a flat extinction curve because of dust destruction by sputtering.
(3) Shattering steepens the extinction curve, which is again consistent with high-redshift extinction curves.
(4) Grain size distributions are also important for grain growth in high-redshift quasars.
(5) These processes considered should be important also in the local Universe.

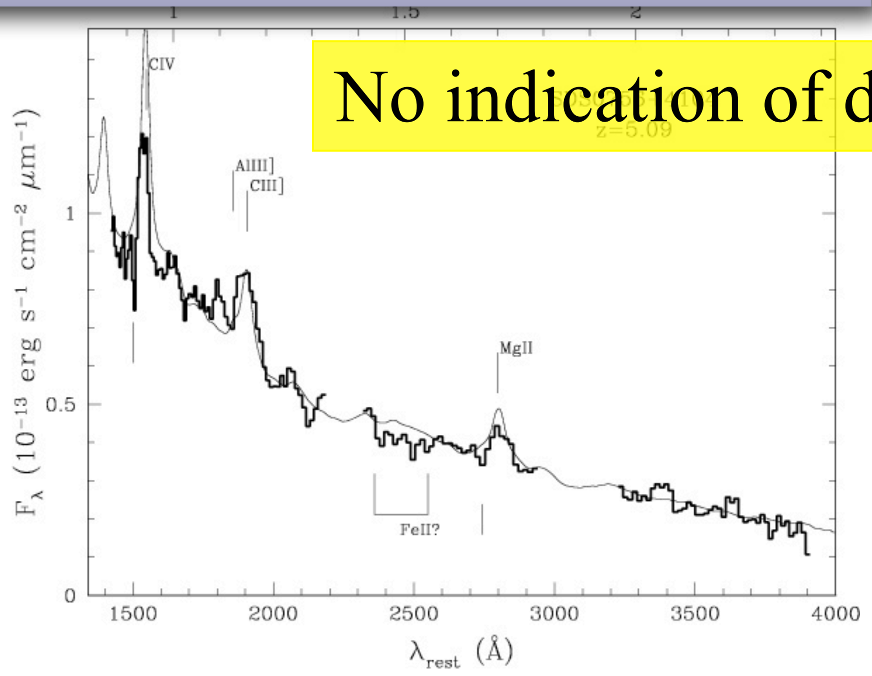
Thank you.

Flat Extinction Curves...

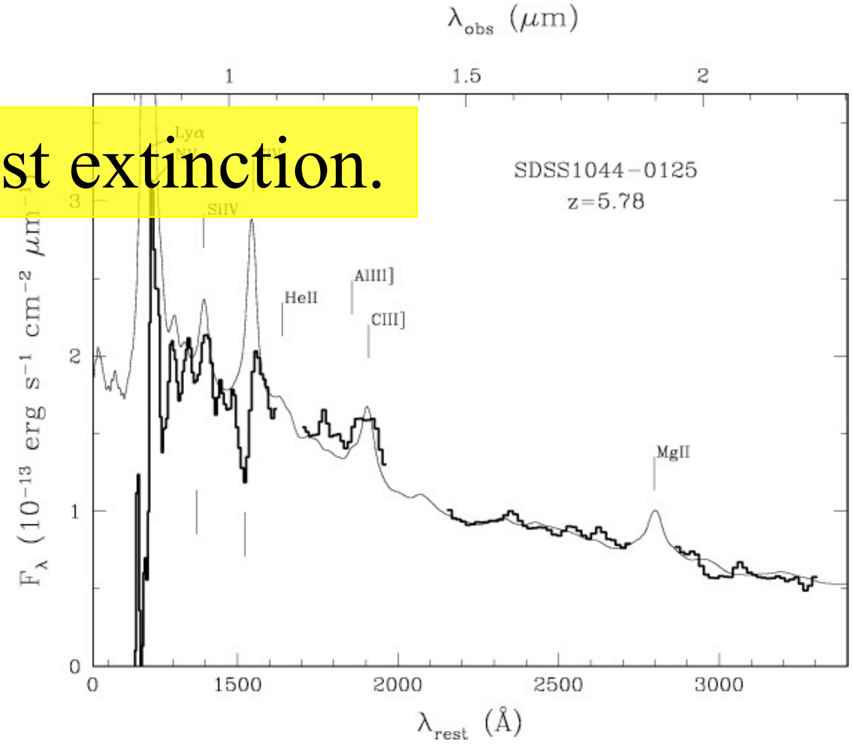
Can explain unreddened dusty quasars at high redshift.

Maiolino et al. (2004)

No indication of dust extinction.



SDSS1044-0125 (*z* = 5.78)

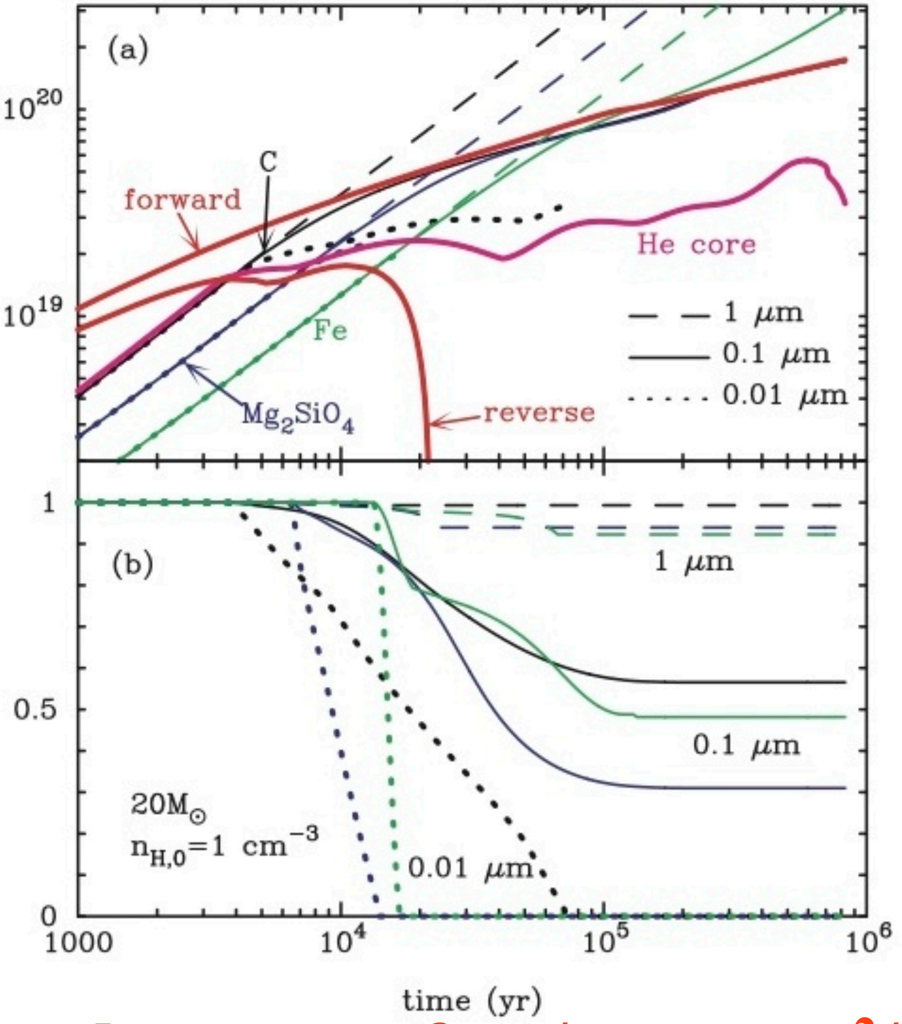


SDSS0756+4104 (*z* = 5.09)

10^8 – 10^9 M$_\odot$ of dust is detected in submm (Priddey 2003).

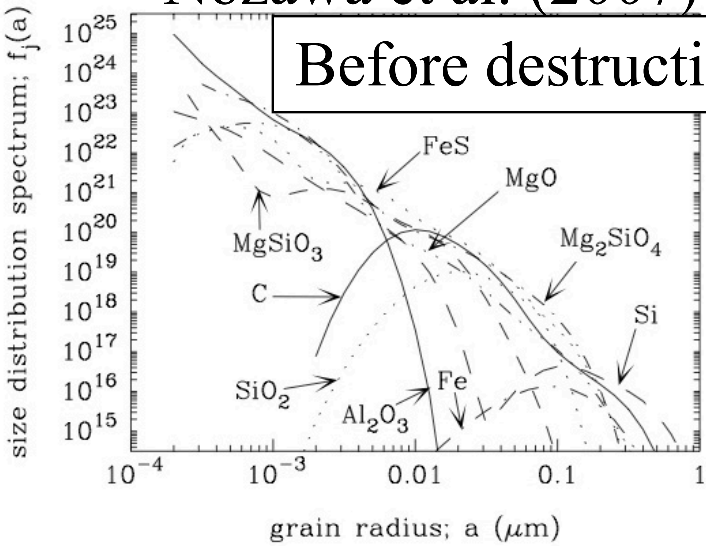
Destruction of Dust in SNe

Distance from the center



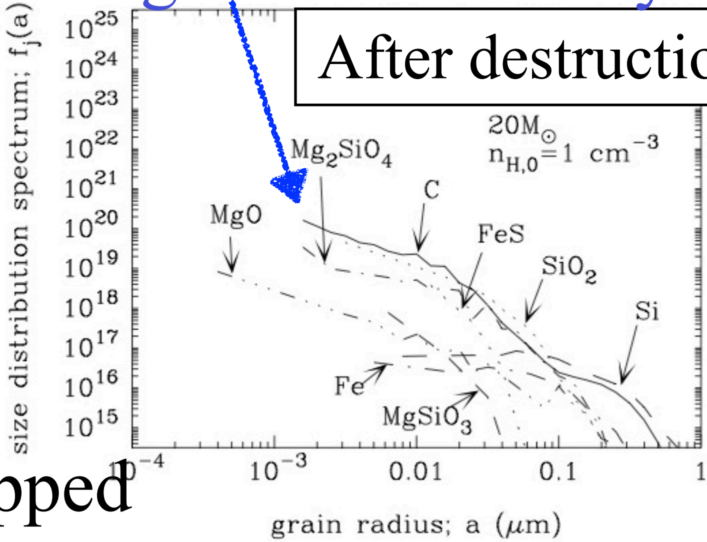
Nozawa et al. (2007)

Before destruction



Small grains are destroyed.

After destruction



Gas drag ∝ surface/mass ∝ a^2/a^3

⇒ small grains are more easily trapped