The Formation and Evolution of Cosmic Dust

Tsutomu T. TAKEUCHI

Ryosuke S. ASANO

Division of Particle and Astrophysical Science, Nagoya University, Japan

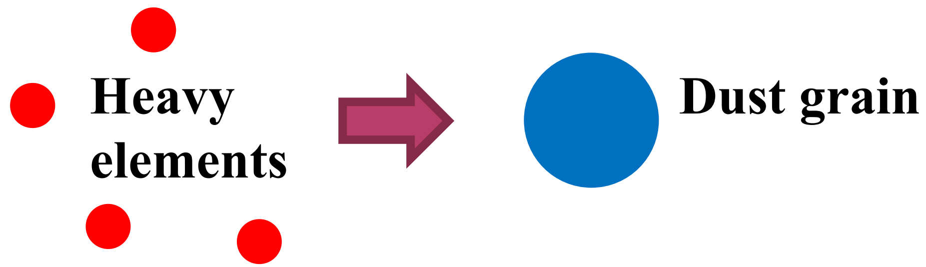
National Astronomical Observatory, Tokyo, 5 June, 2014, Japan

1. General introduction

What is a dust grain?

Dust grains are

- formed by condensation of heavy elements.



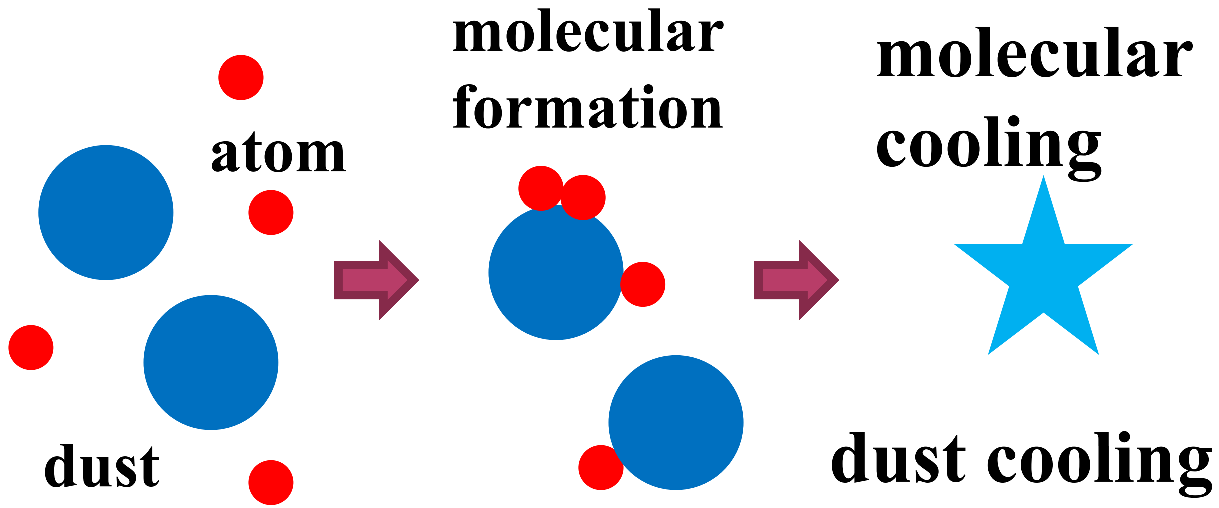
Heavy elements are supplied only by stars.

- tightly connected to the galaxy evolution

There are many important physical quantities affected by dust.

Star formation

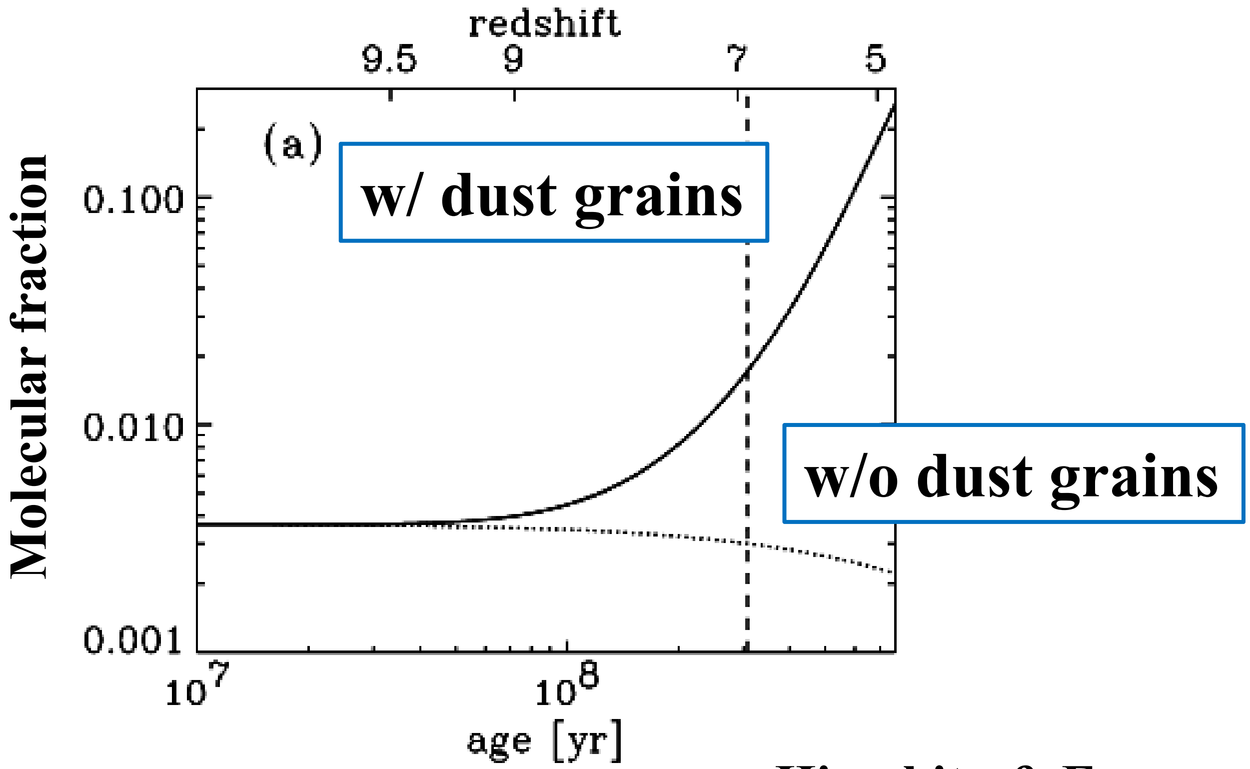
Surface of dust grains



These processes depend strongly on the amount and size distribution of dust grains.

Star formation

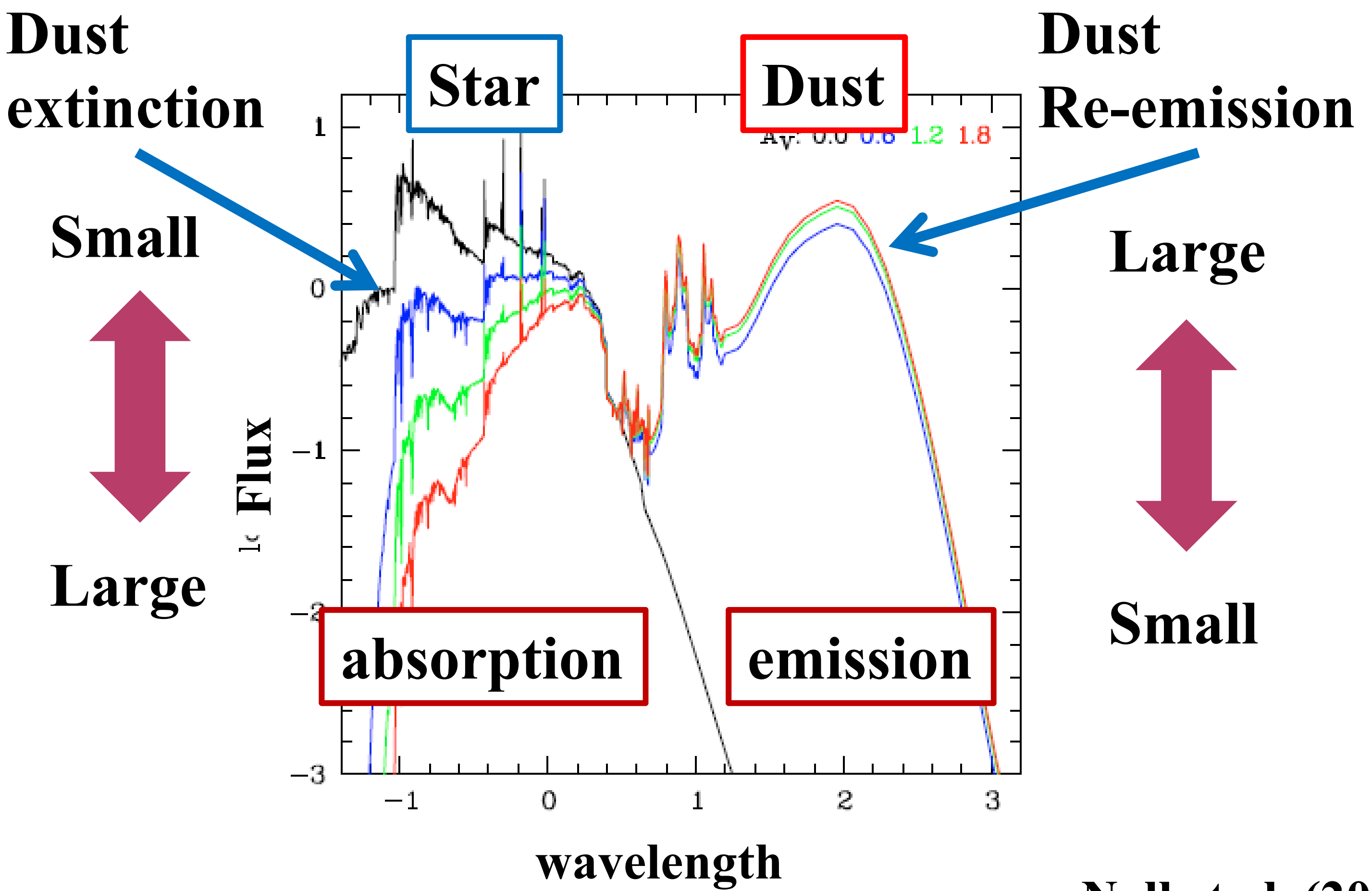
Surface of dust grains



Hirashita & Ferrara (2002)

Dust grains drive the star formation.

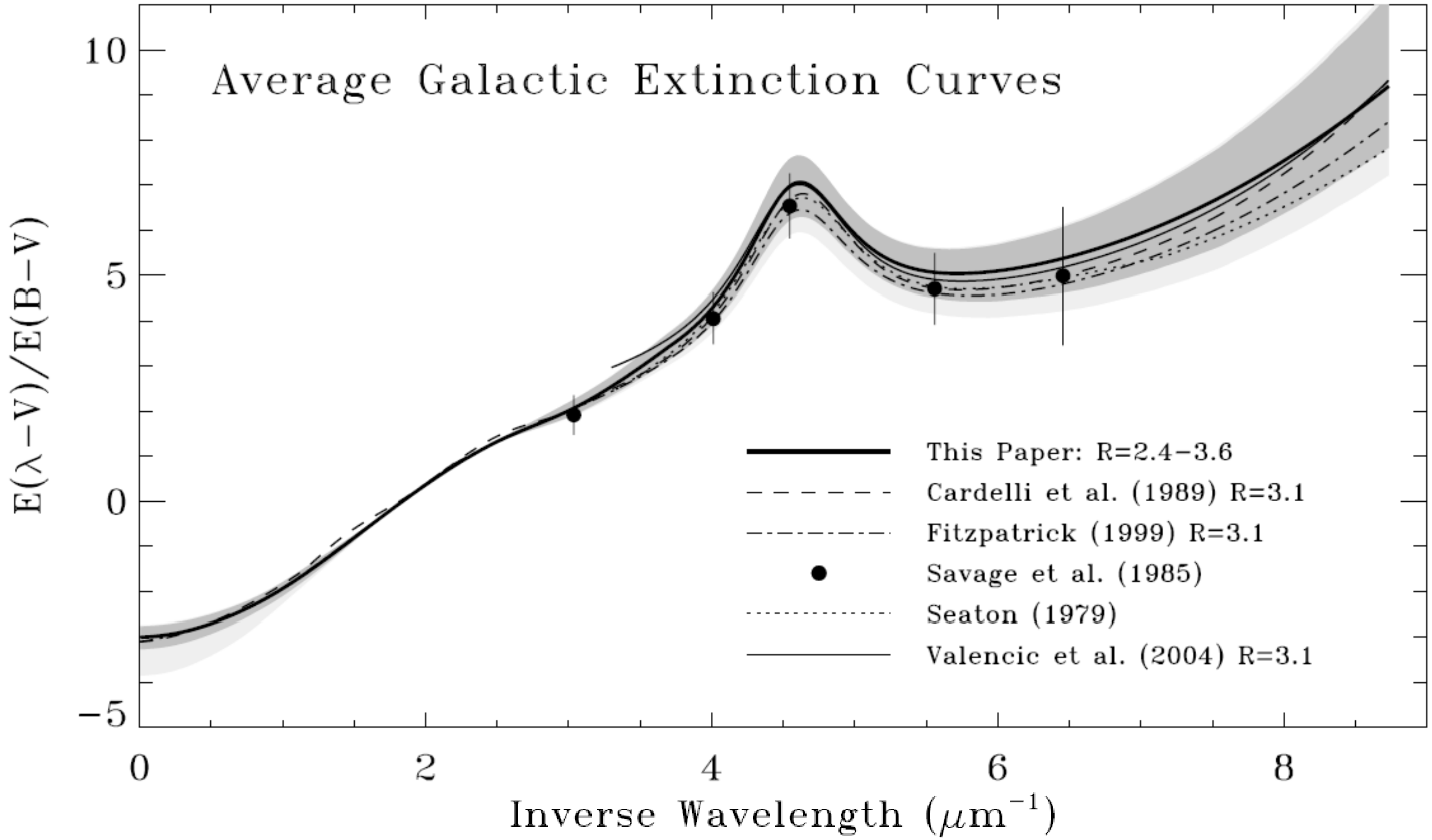
Spectral energy distribution (SED)



Noll et al. (2009)

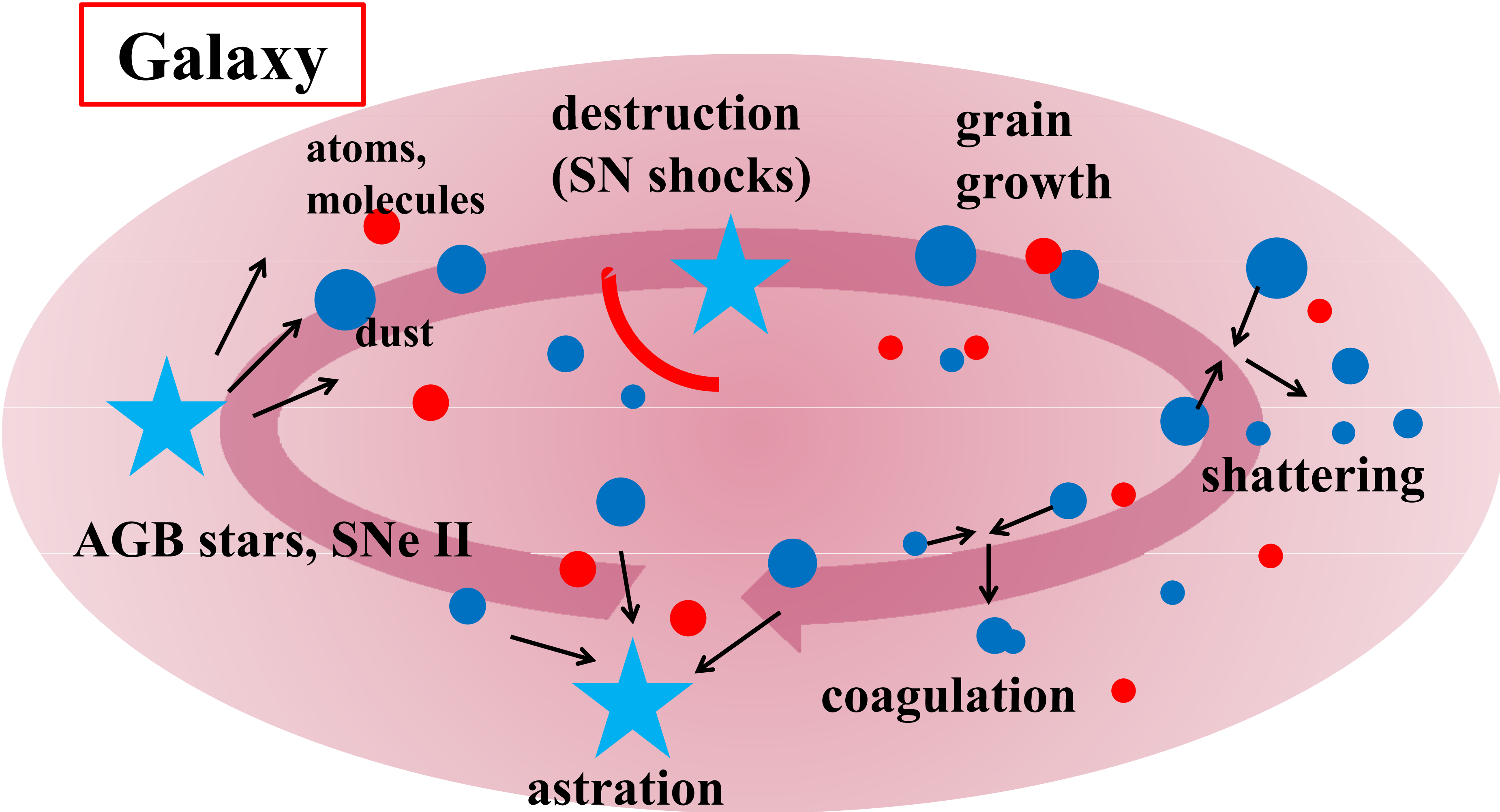
Extinction curve

Wavelength dependence of extinction by dust



Fitzpatrick & Massa (2007)

Dust circulation in galaxies



Dust supply

AGB star

- **log-normal distribution**
- **large size grains are produced**

Winters et al. (1997)
Yasuda & Kozasa (2012)

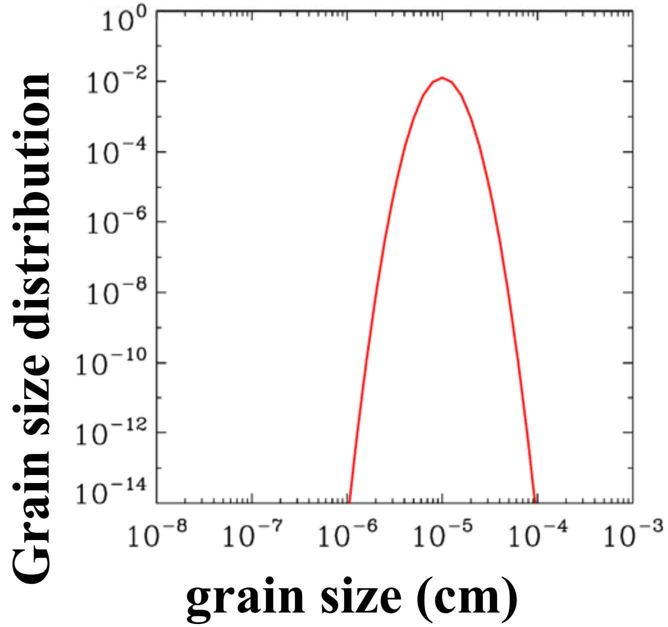
Dust mass data
Zhukovska et al. (2008)

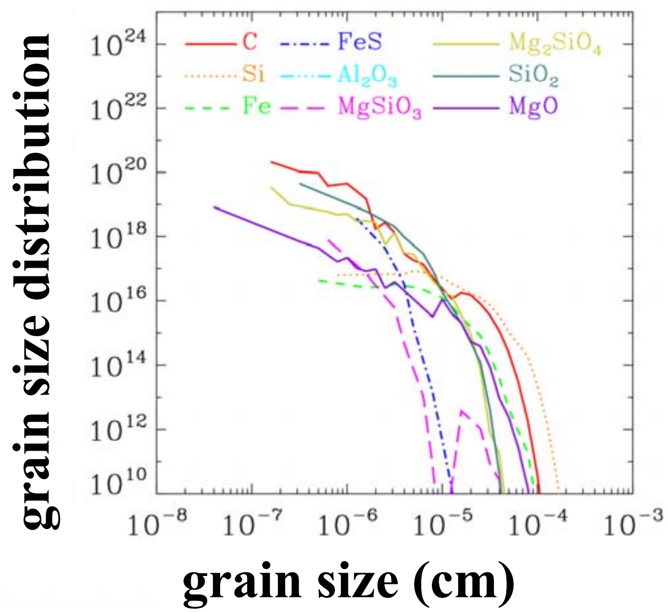
Type II Supernovae (SNe II)

- **broken power-law**
- **biased to large grains**

Nozawa et al. (2007)

Dust mass data
Nozawa et al. (2007)



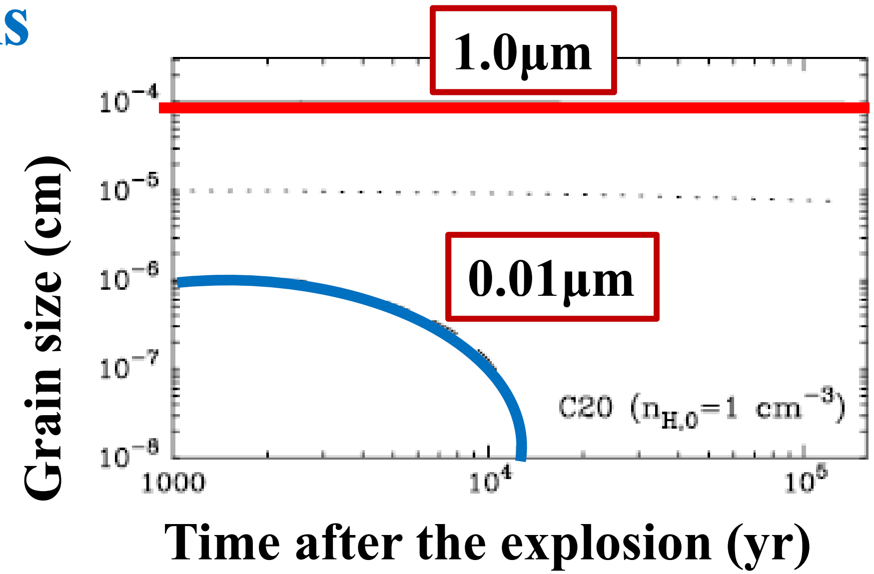


Dust destruction and grain growth

Dust destruction by SN shocks

Smaller grains are predominantly destroyed by SN shocks.

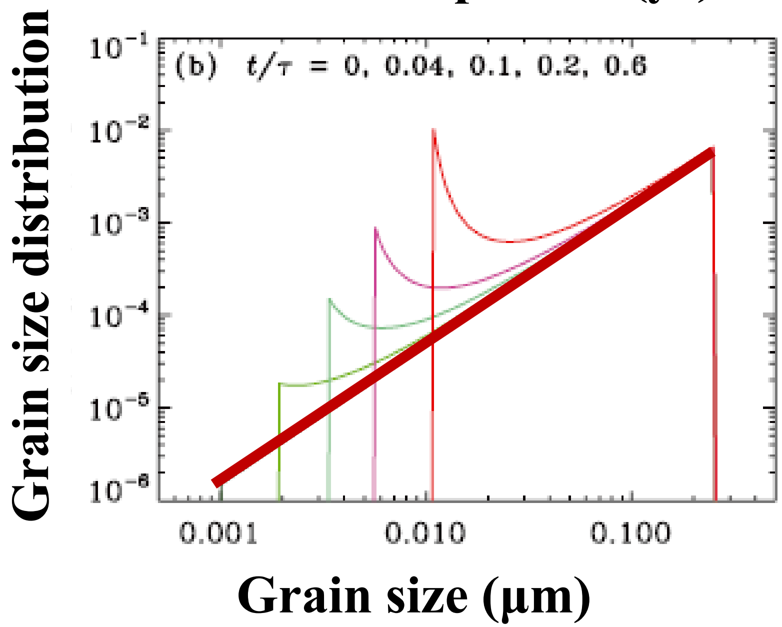
Nozawa et al. (2006)



Grain growth (metal accretion onto grains)

Smaller grains grow to larger grains.

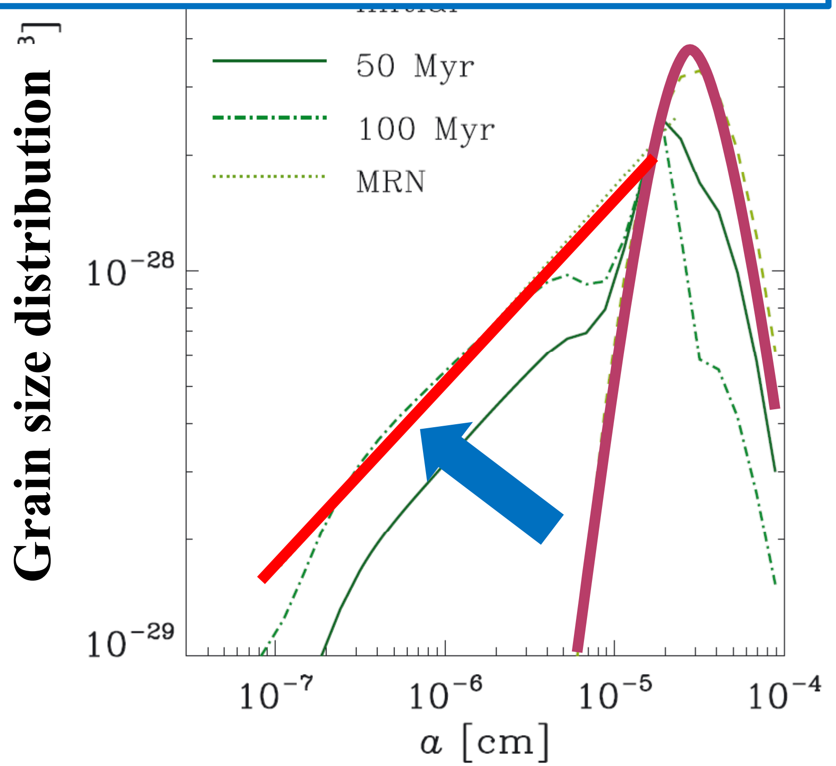
Hirashita & Kuo (2011)



Shattering and coagulation

Shattering

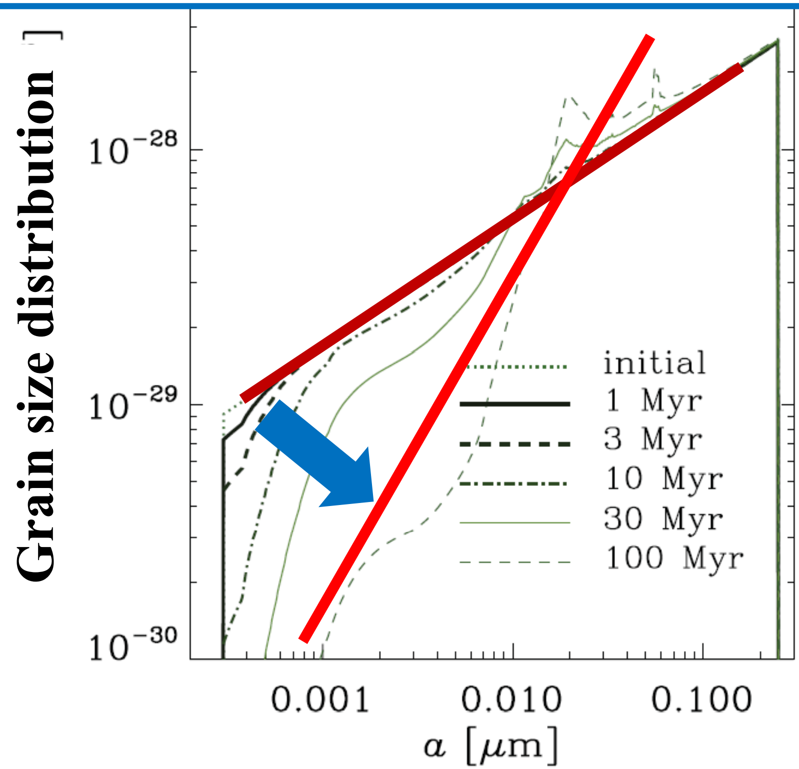
Smaller grains are produced by larger grains



Hirashita (2010)

Coagulation

Larger grains are produced by smaller grains



Hirashita (2012)

Aim of this study

We investigate the evolutions of dust amount, grain size distribution, and extinction curve in galaxies using an evolution model of dust consistent with the chemical evolution of galaxies.

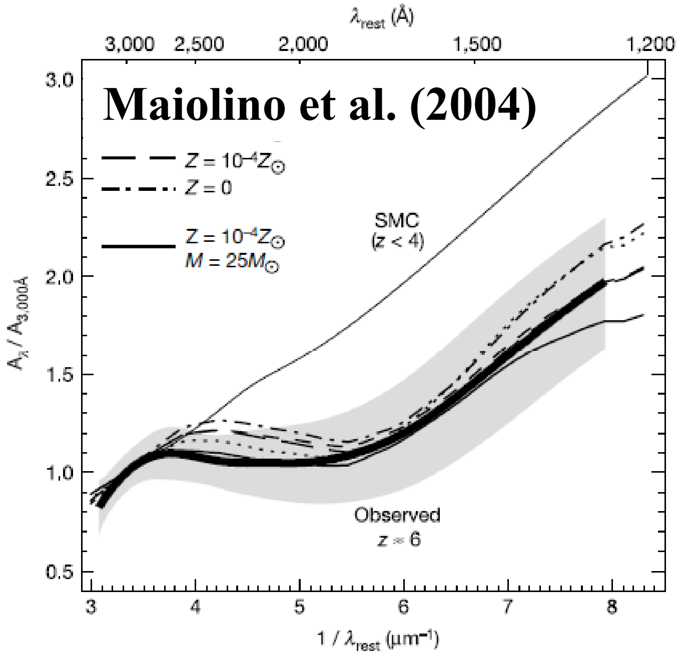
2. Evolution of the Total Dust Amount in Galaxies

Asano et al. 2013, EPS, 65, 213

Total dust amount in galaxies

The evolution of the total dust mass in galaxies is essential factor to resolve the evolution of the galactic SED.

Galaxies at high redshift



SN origin?
How about AGB stars?

Galaxies at low redshift

Injection of dust from stars (~ a few Gyr)

vs.

Dust destruction by SN shocks (< 1 Gyr)

Grain growth in the ISM?

Star Formation Rate (SFR) and Initial Mass Function (IMF)

Star Formation Rate (SFR)

Schmidt law (Schmidt 1959)

$$\mathrm{SFR}(t) \propto M_{\mathrm{ISM}}^{n} \qquad (1 < n < 2)$$

We assume $n = 1$ for simplicity.

Initial Mass Function (IMF)

Larson IMF (Larson 1998)

$$\phi(m) \propto m^{-(\alpha+1.0)} \exp\left(-\frac{m_{\mathrm{ch}}}{m}\right)$$

Normalization: $$\int_{0.1\,\mathrm{M}_\odot}^{100\,\mathrm{M}_\odot} m\phi(m)\mathrm{d}m = 1$$

We adopt $\alpha = 1.35$ and $m_{\mathrm{ch}} = 0.35\ \mathrm{M}_\odot$ in our study.

Model of galaxy evolution

Evolution of the total stellar mass, M_* , ISM mass, M_{ISM}, metal mass, M_{Z}, dust mass, M_{d} in a galaxy

$$\frac{\mathrm{d}M_*(t)}{\mathrm{d}t} = \mathrm{SFR}(t) - R(t),$$

$$\frac{\mathrm{d}M_{\mathrm{ISM}}(t)}{\mathrm{d}t} = -\mathrm{SFR}(t) + R(t),$$

$$\frac{\mathrm{d}M_Z(t)}{\mathrm{d}t} = -Z(t)\mathrm{SFR}(t) + R_Z(t) + Y_Z(t),$$

$$\frac{\mathrm{d}M_{\mathrm{d}}(t)}{\mathrm{d}t} = -\mathcal{D}(t)\mathrm{SFR}(t) + Y_{\mathrm{d}}(t) - \frac{M_{\mathrm{d}}}{\tau_{\mathrm{SN}}} + \eta\frac{M_{\mathrm{d}}(1-\delta)}{\tau_{\mathrm{acc}}}$$

$$Z(t) \equiv M_{\mathrm{Z}}/M_{\mathrm{ISM}}$$

$$\delta \equiv M_{\mathrm{d}}/M_Z$$

$$\mathcal{D} \equiv M_{\mathrm{d}}/M_{\mathrm{ISM}}$$

$$\mathrm{SFR}(t) = \frac{M_{\mathrm{ISM}}(t)}{\tau_{\mathrm{SF}}}$$

Model of galaxy evolution

Evolution of the total stellar mass, M_* , ISM mass, $M_{\rm ISM}$, metal mass, M_Z, dust mass, M_d in a galaxy

$$\frac{\mathrm{d}M_*(t)}{\mathrm{d}t} = \mathrm{SFR}(t) - R(t),$$

$$\frac{\mathrm{d}M_{\rm ISM}(t)}{\mathrm{d}t} = -\mathrm{SFR}(t) + R(t),$$

$$\frac{\mathrm{d}M_Z(t)}{\mathrm{d}t} = -Z(t)\mathrm{SFR}(t) + R_Z(t) + Y_Z(t),$$

$$\frac{\mathrm{d}M_{\rm d}(t)}{\mathrm{d}t} = -\mathcal{D}(t)\mathrm{SFR}(t) + Y_{\rm d}(t) - \frac{M_{\rm d}}{\tau_{\rm SN}} + \eta\frac{M_{\rm d}(1-\delta)}{\tau_{\rm acc}}$$

- **Injection/ejection from stars**
- **Destruction by SN shocks**
- **Grain growth in the ISM**

Model of galaxy evolution

Evolution of the total stellar mass, M_*, ISM mass, M_{ISM}, metal mass, M_Z, dust mass, M_d in a galaxy

$$\frac{\mathrm{d}M_*(t)}{\mathrm{d}t} = \mathrm{SFR}(t) - R(t),$$

$$\frac{\mathrm{d}M_{\mathrm{ISM}}(t)}{\mathrm{d}t} = -\mathrm{SFR}(t) + R(t),$$

$$\frac{\mathrm{d}M_Z(t)}{\mathrm{d}t} = -Z(t)\mathrm{SFR}(t) + R_Z(t) + Y_Z(t),$$

$$\frac{\mathrm{d}M_{\mathrm{d}}(t)}{\mathrm{d}t} = -\mathcal{D}(t)\mathrm{SFR}(t) + Y_{\mathrm{d}}(t) - \frac{M_{\mathrm{d}}}{\tau_{\mathrm{SN}}} + \eta\frac{M_{\mathrm{d}}(1-\delta)}{\tau_{\mathrm{acc}}}$$

Closed-box model is assumed (the infall/outflow changes the star formation timescale but does not change the conclusion in this study).

Timescales of dust destruction and grain growth

Dust destruction by SN shocks in the ISM

$$\tau_{\rm SN} = \frac{M_{\rm ISM}(t)}{\epsilon m_{\rm swept} \gamma_{\rm SN}(t)}$$

ε : dust destruction efficiency
$m_{\rm swept}$: ISM mass swept by a SN shock
$\gamma_{\rm SN}$: SN rate

(e.g., McKee 1989)

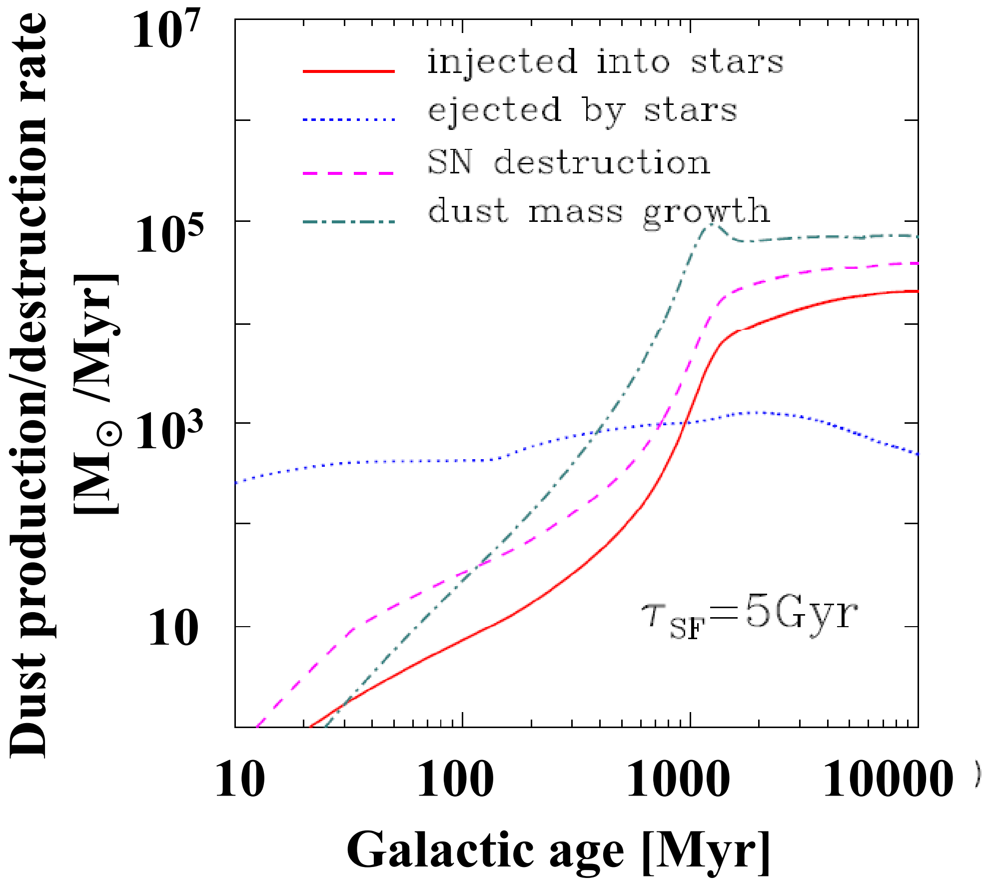
Grain growth by metal accretion

a : mean grain size
$n_{\rm H}$: number density of the ISM
T : ISM temperature

$$\tau_{\rm acc} \approx 2.0 \times 10^7 \times \left(\frac{\bar{a}}{0.1\mu{\rm m}}\right) \left(\frac{n_{\rm H}}{100\ {\rm cm}^{-3}}\right)^{-1} \left(\frac{T}{50\ {\rm K}}\right)^{-\frac{1}{2}} \left(\frac{Z}{0.02}\right)^{-1} [{\rm yr}]$$

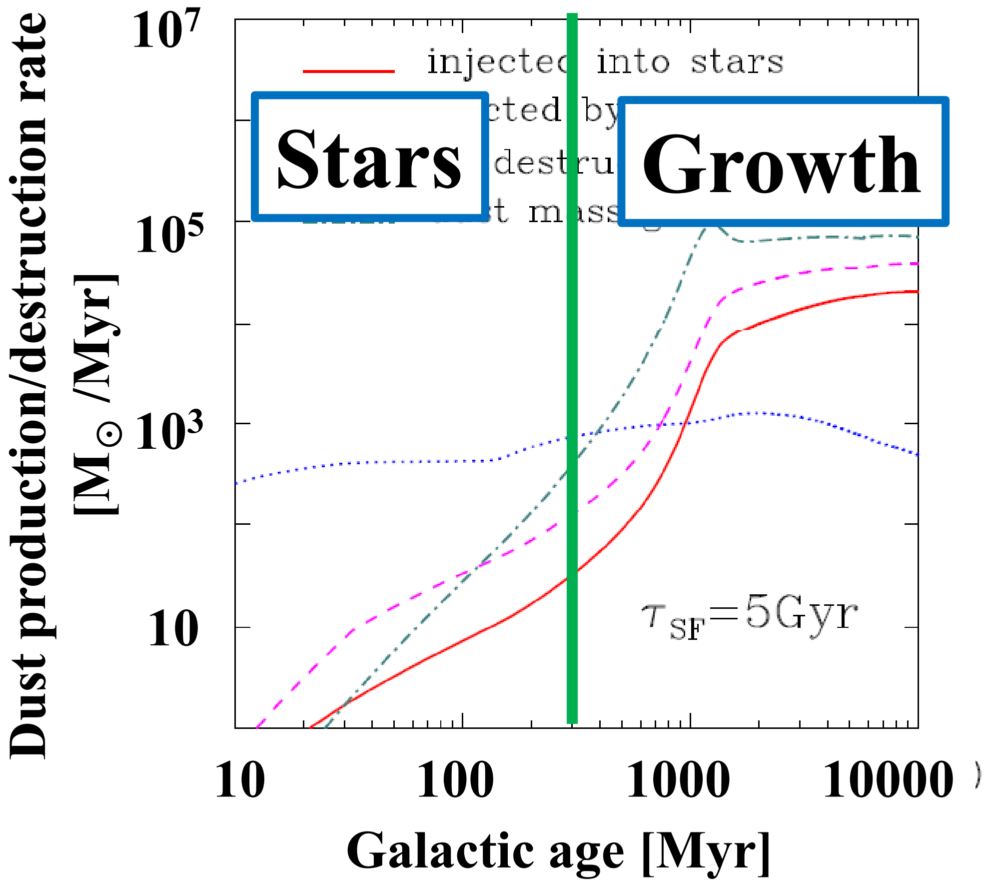
Contribution of each physical process to the total dust mass

Parameter setting :
Total baryon mass : 10^{10} $M_{\odot}$
Star formation timescale : 5 Gyr
Cloud mass fraction : 0.5



Contribution of each physical process to the total dust mass

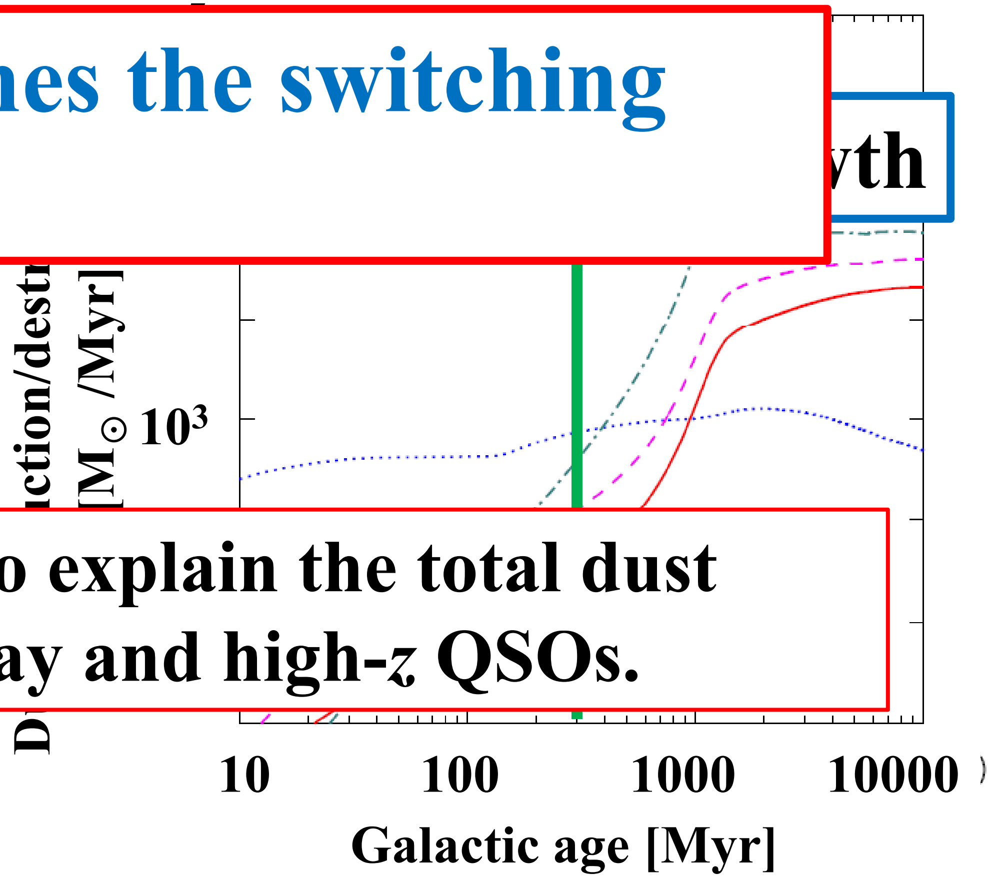
Parameter setting :
Total baryon mass : 10^{10} $M_{\odot}$
Star formation timescale : 5 Gyr
Cloud mass fraction : 0.5



Contribution of each physical process to the total dust mass

Parame
Total ba
Star for
Cloud

What determines the switching point?



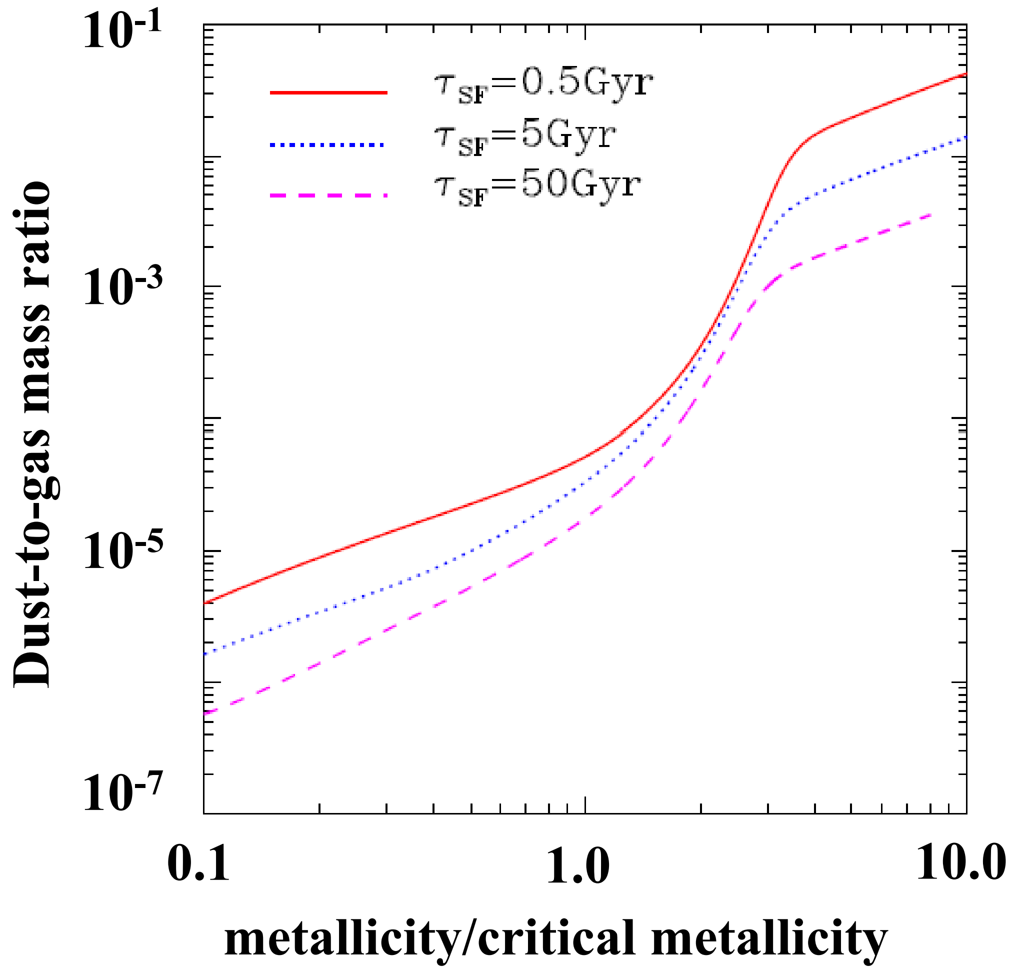
Growth is expected to explain the total dust mass of the Milky Way and high-*z* QSOs.

Critical metallicity for grain growth

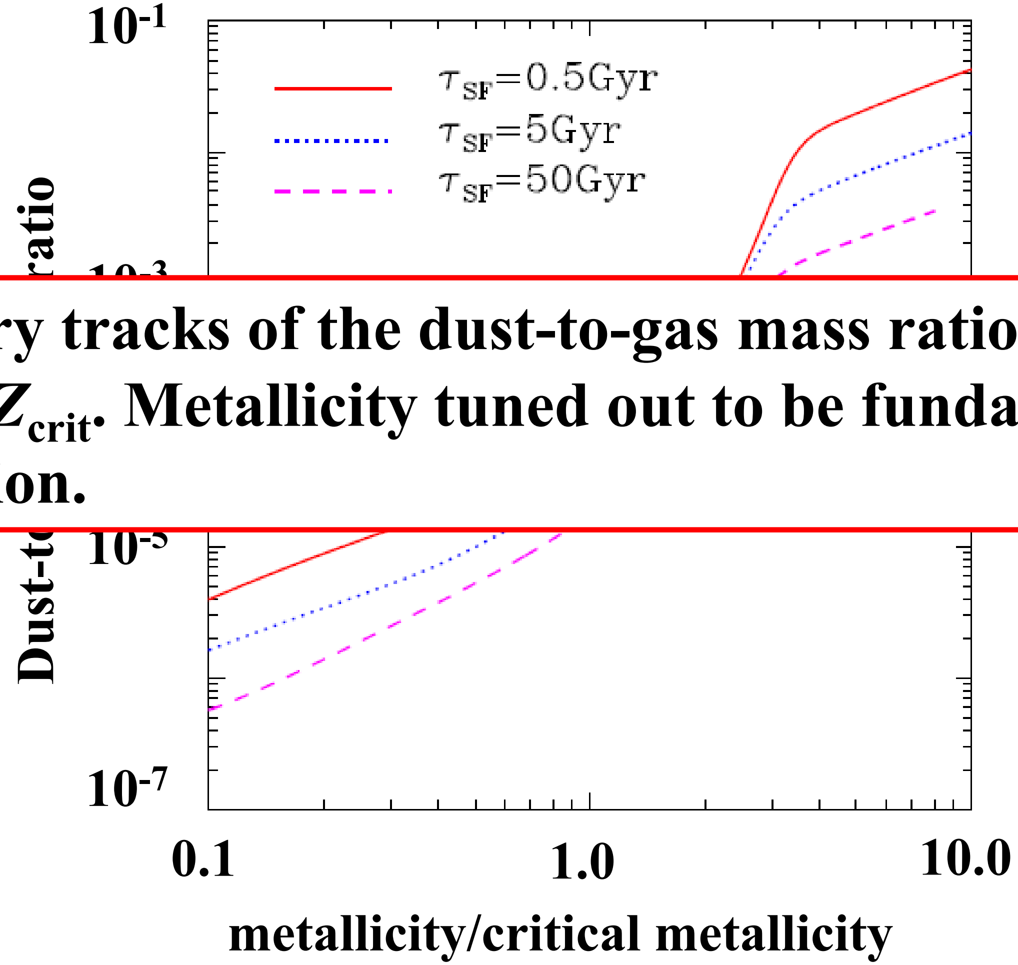
$$Z = \left[\frac{\mathcal{D}}{\eta\delta(1-\delta)}\right]^{\frac{1}{2}}\left(\frac{\tau_{\mathrm{acc},0}}{\tau_{\mathrm{SF}}}\right)^{\frac{1}{2}}$$

$$\frac{\mathrm{d}M_{\mathrm{d}}(t)}{\mathrm{d}t} = -\mathcal{D}(t)\mathrm{SFR}(t) + Y_{\mathrm{d}}(t) - \frac{M_{\mathrm{d}}}{\tau_{\mathrm{SN}}} + \eta\frac{M_{\mathrm{d}}(1-\delta)}{\tau_{\mathrm{acc}}}$$

Critical metallicity for grain growth



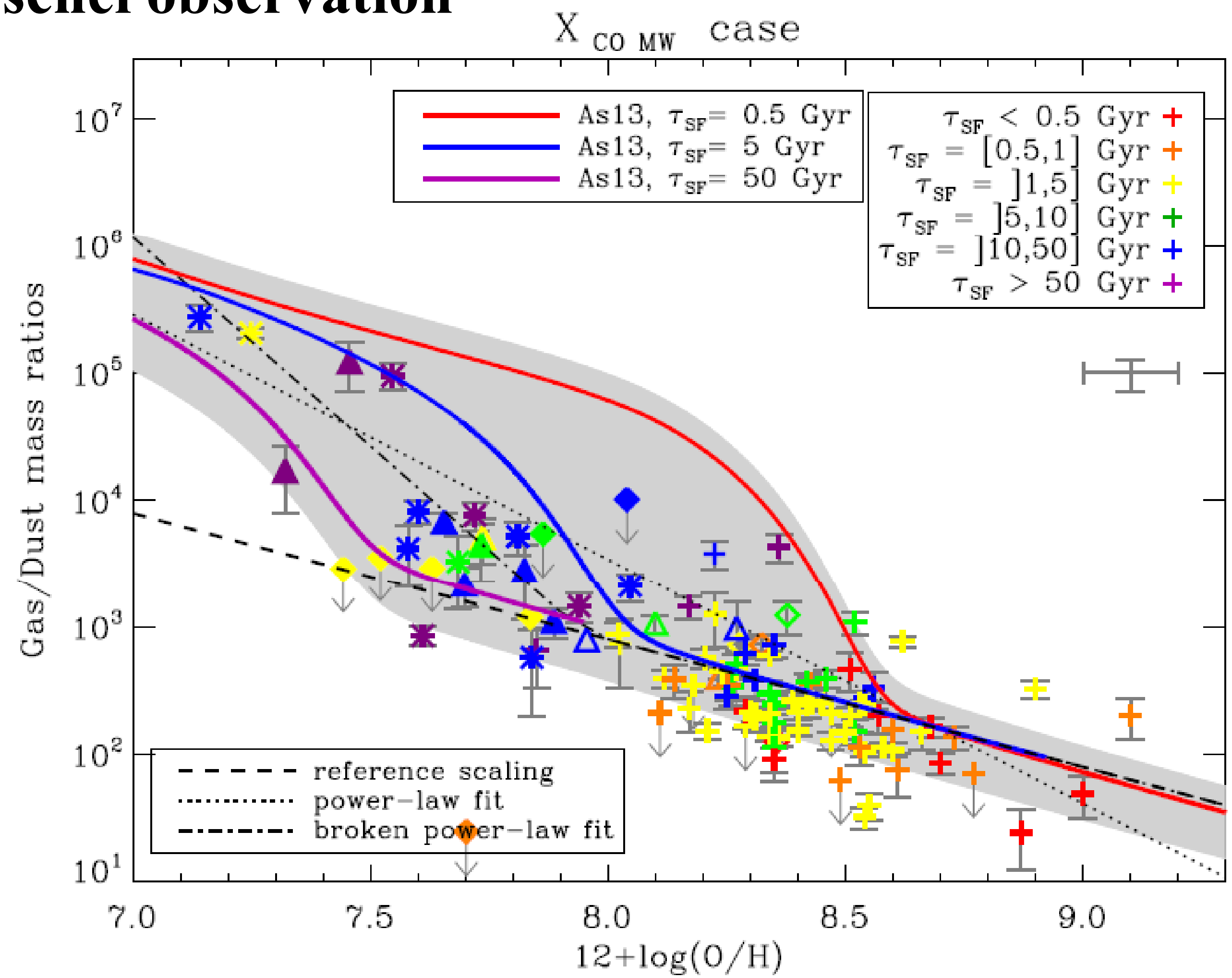
Critical metallicity for grain growth



Evolutionary tracks of the dust-to-gas mass ratio are unified by using Z/Z_{crit}. Metallicity tuned out to be fundamental for dust evolution.

Application to observational data

Herschel observation



Rémy-Ruyer et al. (2014)

3. Evolution of the grain size distribution in galaxies

Asano et al. 2013, MNRAS, 432, 637

Dust evolution model

Summary of model setting

- **Closed-box model**

(total baryon mass is a constant)

- **Two-phase ISM (WNM and CNM)**
- **Schmidt law : SFR(t) = $M_{ISM}(t)/\tau_{SF}$**

- **Dust formation by SNe II and AGB stars**
- **Dust reduction through the astration**
- **Dust destruction by SN shocks in the ISM**
- **Grain growth in the CNM**
- **Grain-grain collisions (shattering and coagulation) in the ISM**

Formulation of the grain-size dependent evolution of dust mass

$$\mathrm{SFR}(t) = \frac{M_{\mathrm{ISM}}(t)}{\tau_{\mathrm{SF}}}$$

$M_{\mathrm{d}}(a,t) = m(a)f(a,t)\mathrm{d}a$: dust mass with a grain radius [a, a+da] at a galactic age t

$$\begin{aligned}
\frac{\mathrm{d}M_{\mathrm{d}}(a,t)}{\mathrm{d}t} &= -\frac{M_{\mathrm{d}}(a,t)}{M_{\mathrm{ISM}}(t)}\mathrm{SFR}(t) + Y_{\mathrm{d}}(a,t) \\
&- \frac{M_{\mathrm{swept}}}{M_{\mathrm{ISM}}(t)}\gamma_{\mathrm{SN}}(t)\left[M_{\mathrm{d}}(a,t) - m(a)\int_0^{\infty}\xi(a,a^{'})f(a^{'},t)\mathrm{d}a\right] \\
&+ \eta_{\mathrm{CNM}}\left[\mathrm{d}m\frac{\partial[m(a)f_m(m,t)]}{\partial t}\right] \\
&+ \eta_{\mathrm{WNM}}\left[\frac{\mathrm{d}M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{shat,WNM}} + \eta_{\mathrm{CNM}}\left[\frac{\mathrm{d}M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{shat,CNM}} \\
&+ \eta_{\mathrm{WNM}}\left[\frac{\mathrm{d}M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{coag,WNM}} + \eta_{\mathrm{CNM}}\left[\frac{\mathrm{d}M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{coag,CNM}}
\end{aligned}$$

Formulation of the grain-size dependent evolution of dust mass

$$\mathrm{SFR}(t) = \frac{M_{\mathrm{ISM}}(t)}{\tau_{\mathrm{SF}}}$$

$M_{\mathrm{d}}(a,t) = m(a)f(a,t)\mathrm{d}a$: dust mass with a grain radius [a, a+da] at a galactic age t

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

Stellar effects

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

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

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

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

Formulation of the grain-size dependent evolution of dust mass

$$\mathrm{SFR}(t) = \frac{M_{\mathrm{ISM}}(t)}{\tau_{\mathrm{SF}}}$$

$M_{\mathrm{d}}\,(a,t) = m(a)f(a,t)\mathrm{d}a$ **: dust mass with a grain radius** $[a,\, a+\mathrm{d}a]$ **at a galactic age** t

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

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

Destruction by SN shocks

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

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

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

$$\mathrm{SFR}(t) = \frac{M_{\mathrm{ISM}}(t)}{\tau_{\mathrm{SF}}}$$

Formulation of the grain-size dependent evolution of dust mass

$M_{\mathrm{d}}(a,t) = m(a)f(a,t)\mathrm{d}a$: dust mass with a grain radius [a, a+da] at a galactic age t

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

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

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

Grain growth

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

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

Formulation of the grain-size dependent evolution of dust mass

$$\mathrm{SFR}(t) = \frac{M_{\mathrm{ISM}}(t)}{\tau_{\mathrm{SF}}}$$

$M_\mathrm{d}(a,t) = m(a)f(a,t)\mathrm{d}a$: dust mass with a grain radius [a, a+da] at a galactic age t

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

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

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

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

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

$$\mathrm{SFR}(t) = \frac{M_{\mathrm{ISM}}(t)}{\tau_{\mathrm{SF}}}$$

Formulation of the grain-size dependent evolution of dust mass

$M_{\mathrm{d}}(a,t) = m(a)f(a,t)\mathrm{d}a$ **: dust mass with a grain radius [*a*, *a*+d*a*] at a galactic age *t***

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

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

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

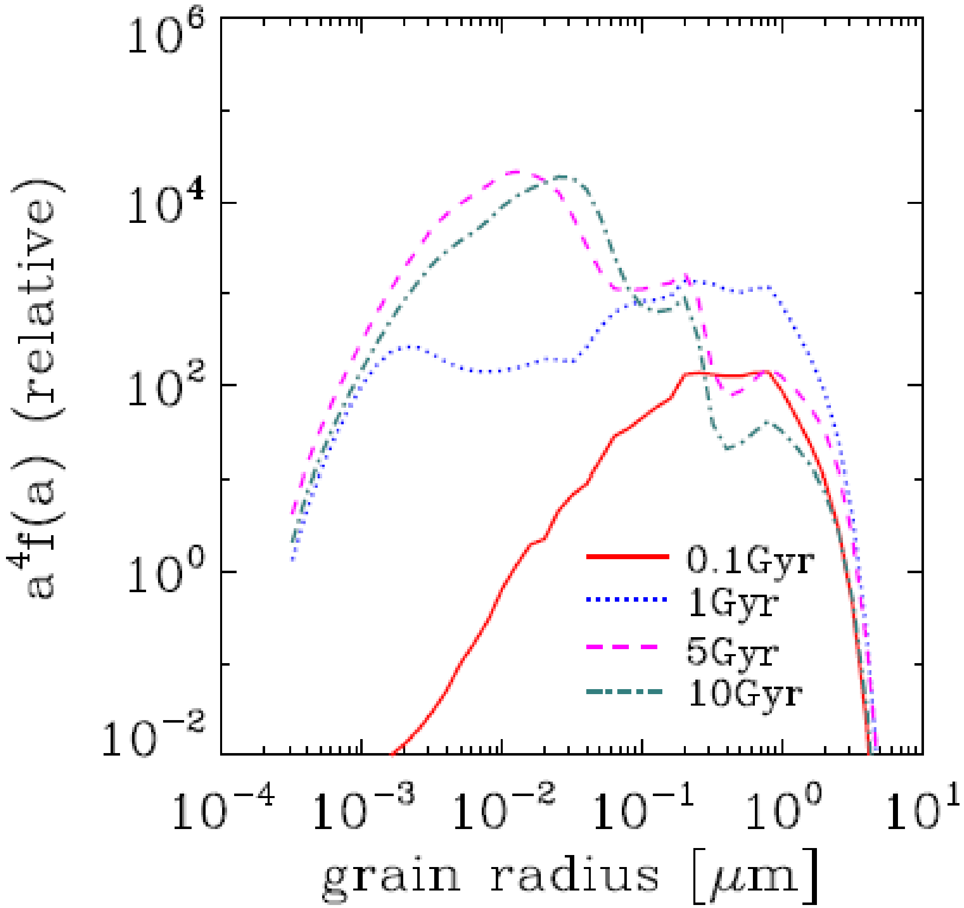
$$+\eta_{\mathrm{WNM}}\left[\frac{\mathrm{d}M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{shat,WNM}} + \eta_{\mathrm{CNM}}\left[\frac{\mathrm{d}M_{\mathrm{d}}(a,t)}{\mathrm{d}t}\right]_{\mathrm{shat,CNM}}$$

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

Coagulation

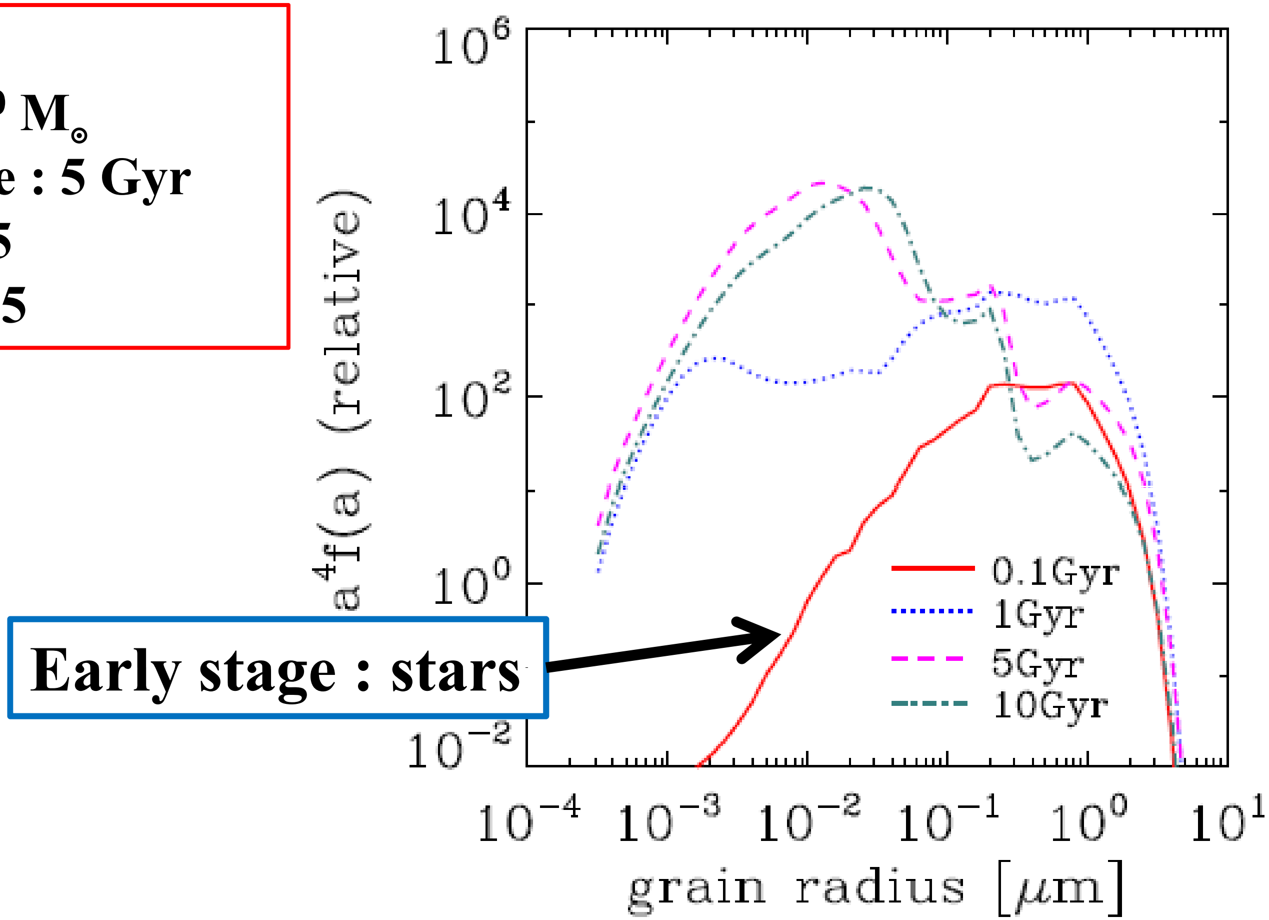
Evolution of the grain size distribution

Parameter setting :
Total baryon mass : 10^{10} $M_{\odot}$
Star formation timescale : 5 Gyr
CNM mass fraction : 0.5
WNM mass fraction : 0.5



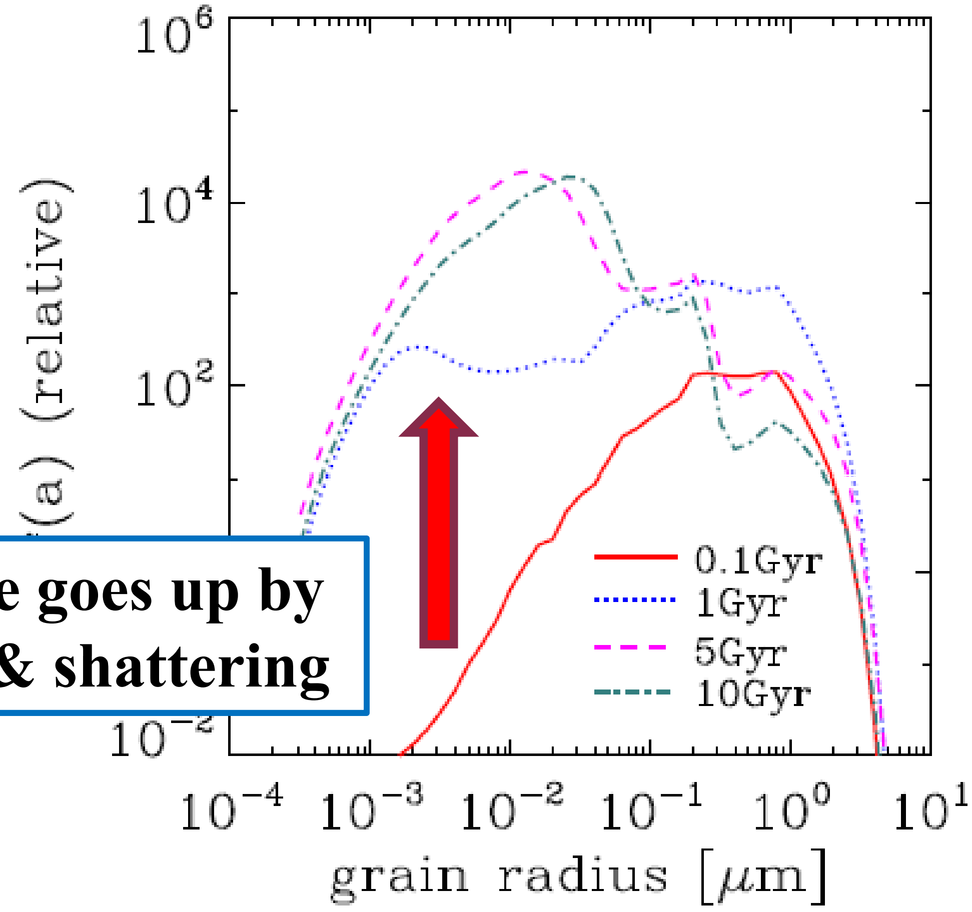
Evolution of the grain size distribution

Parameter setting :
Total baryon mass : 10^{10} $M_\odot$
Star formation timescale : 5 Gyr
CNM mass fraction : 0.5
WNM mass fraction : 0.5



Evolution of the grain size distribution

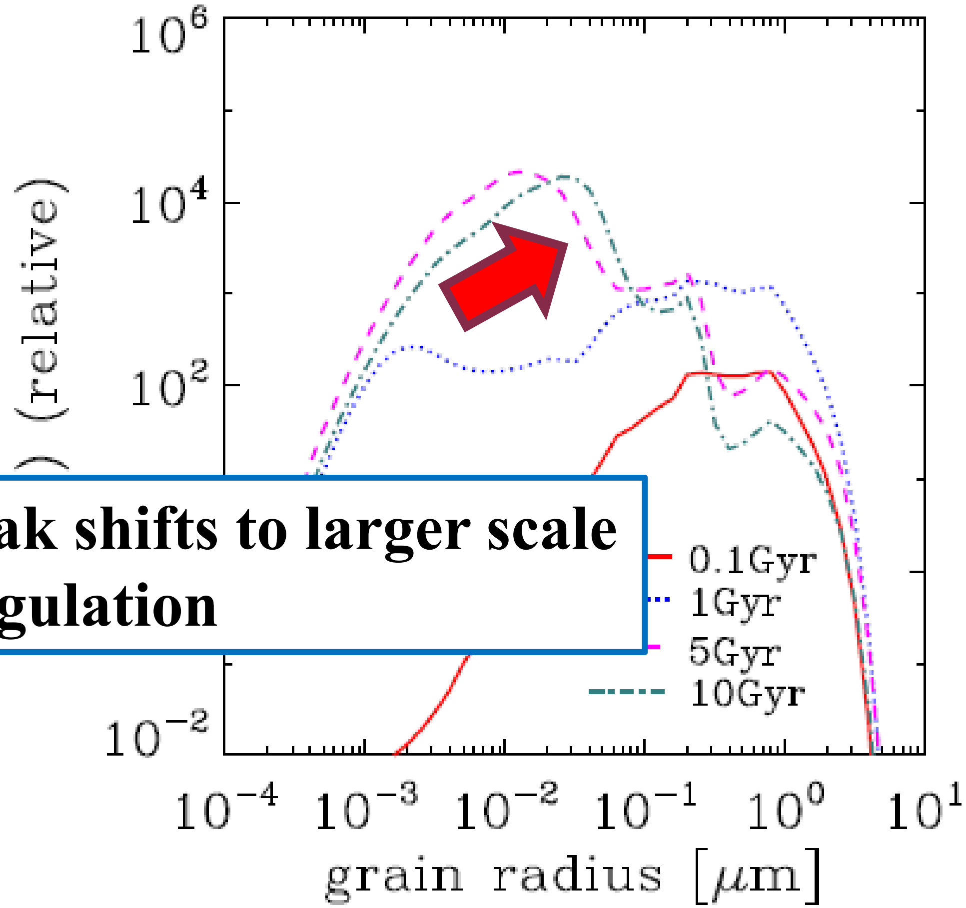
Parameter setting :
Total baryon mass : 10^{10} $M_{\odot}$
Star formation timescale : 5 Gyr
CNM mass fraction : 0.5
WNM mass fraction : 0.5



Small scale goes up by accretion & shattering

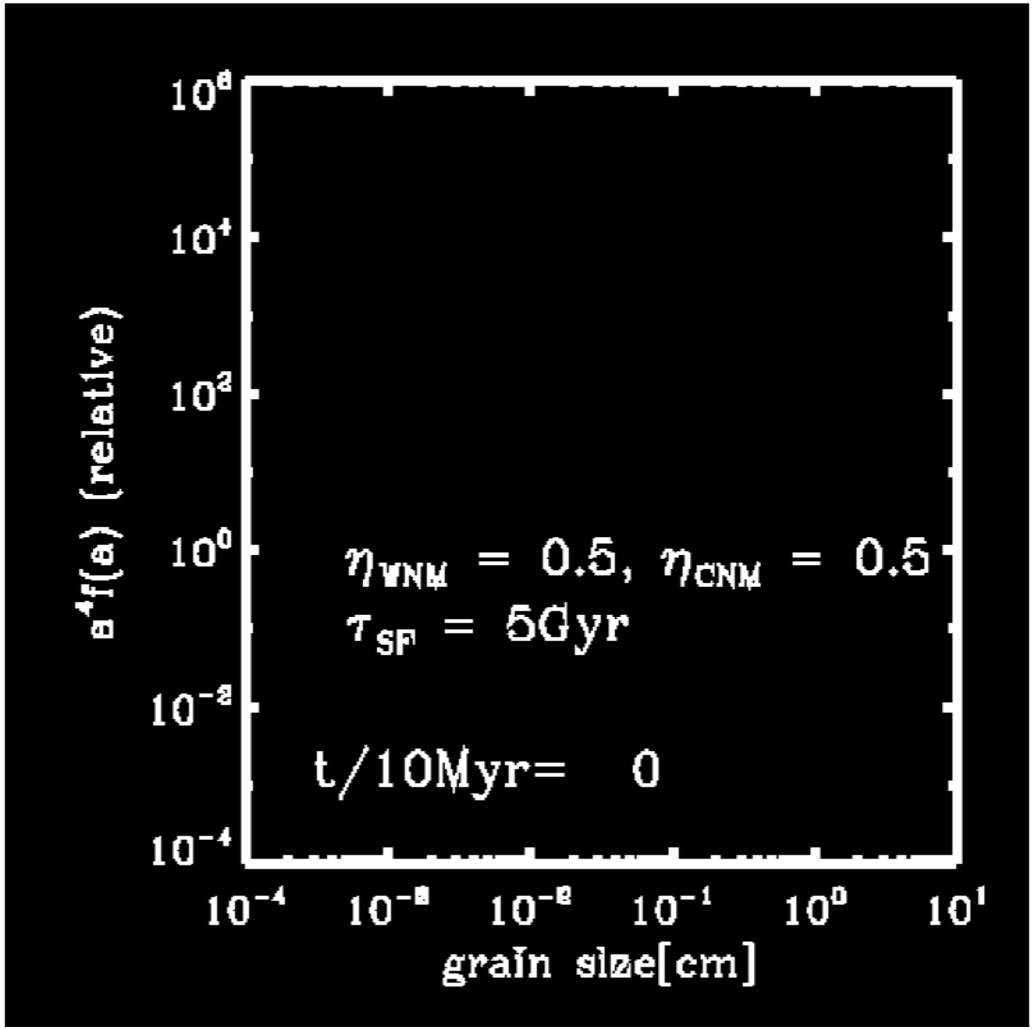
Evolution of the grain size distribution

Parameter setting :
Total baryon mass : 10^{10} $M_\odot$
Star formation timescale : 5 Gyr
CNM mass fraction : 0.5
WNM mass fraction : 0.5

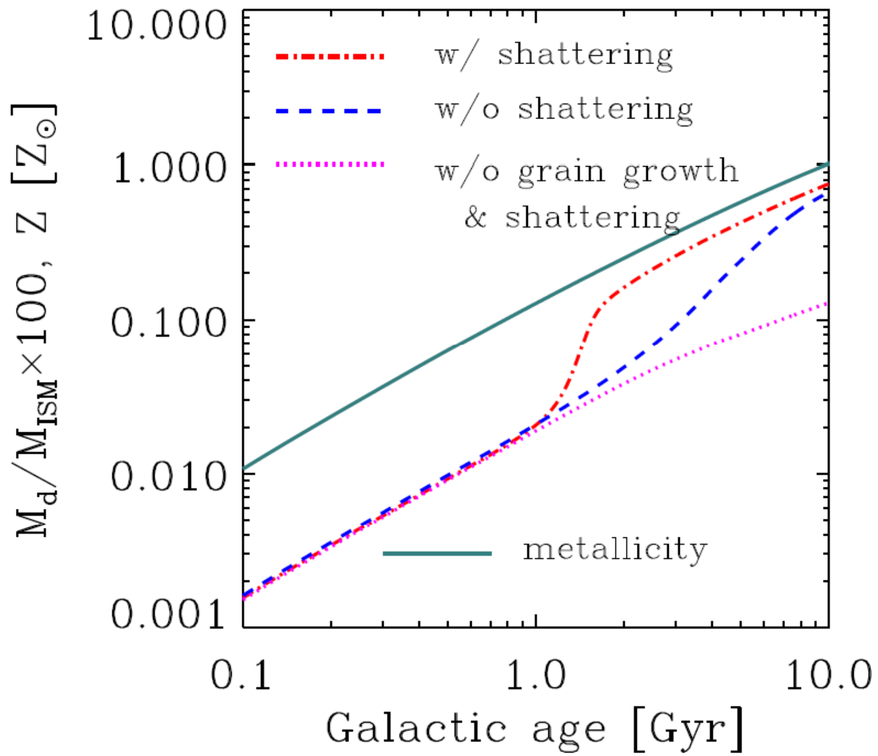


The peak shifts to larger scale by coagulation

Evolution of the grain size distribution



Effect of the evolution of the grain size distribution in galaxies



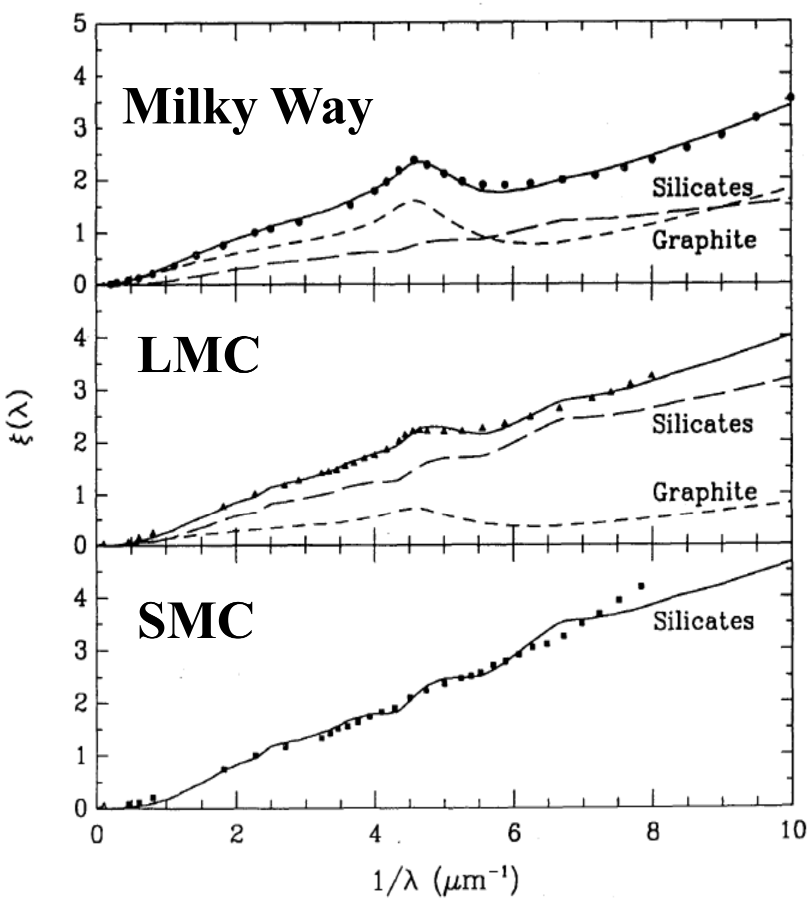
Small grains production by shattering activates grain growth

4. Evolution of the extinction curve in galaxies

Asano et al. 2014, MNRAS, 440, 134

Extinction curve and dust properties

Nearby galaxies



Pei (1992)

By fitting:

Grain size distribution

$f(a)\mathrm{d}a \propto a^{-3.5}\,\mathrm{d}a$

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

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

(Mathis et al., 1977)

Feature

2175Å bump

UV slope

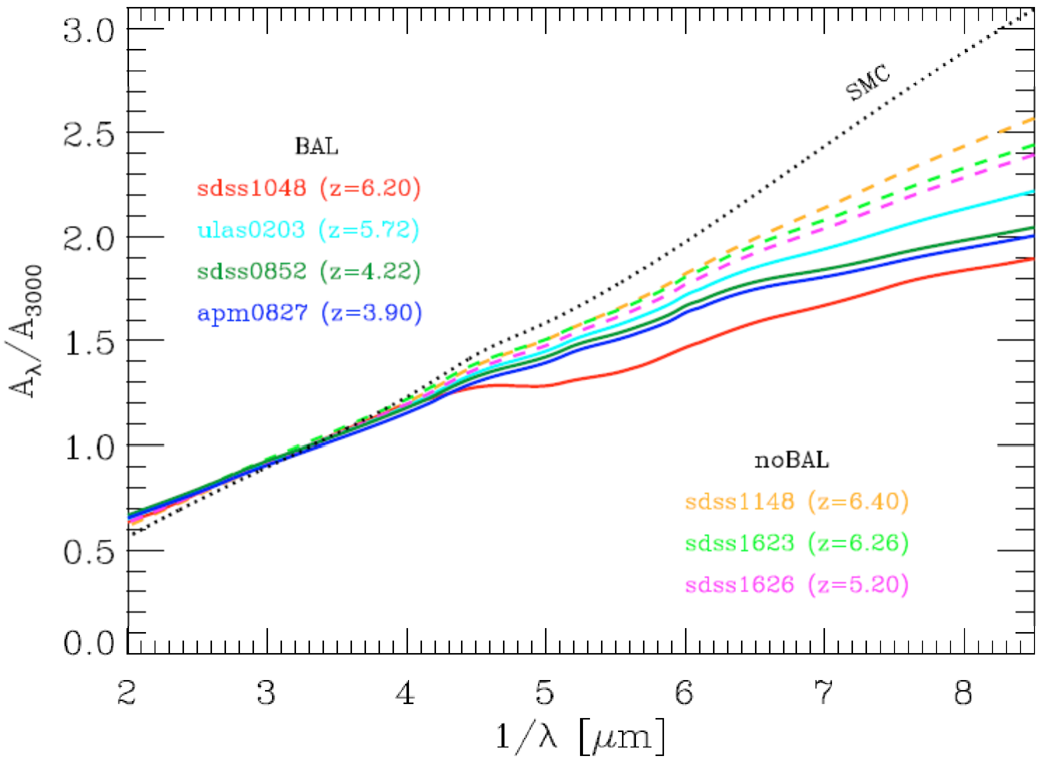
Component

Carbonaceous

Silicate

Extinction curve and dust properties

High-*z* quasars



Different from nearby galaxies (no bump, flat)

Different origin of dust grains and processing mechanism

Gallerani et al. (2010)

How to construct

Extinction = absorption + scattering by dust grains

Extinction in unit of magnitude at a wavelength: A_λ

$$A_\lambda = 1.086 \sum_j \tau_{j,\lambda}$$

$$\tau_{\lambda,j} = \int_0^\infty \pi a^2 Q_{\mathrm{ext},j}(\lambda, a) C f_j(a)\,\mathrm{d}a$$

λ: wavelength
a **: radius of a grain**
j **: grain species**

Optical constant:
graphite and astronomical silicate **($Mg_{1.}Fe_{0.9}SiO_4$)**

Draine & Lee (1984)

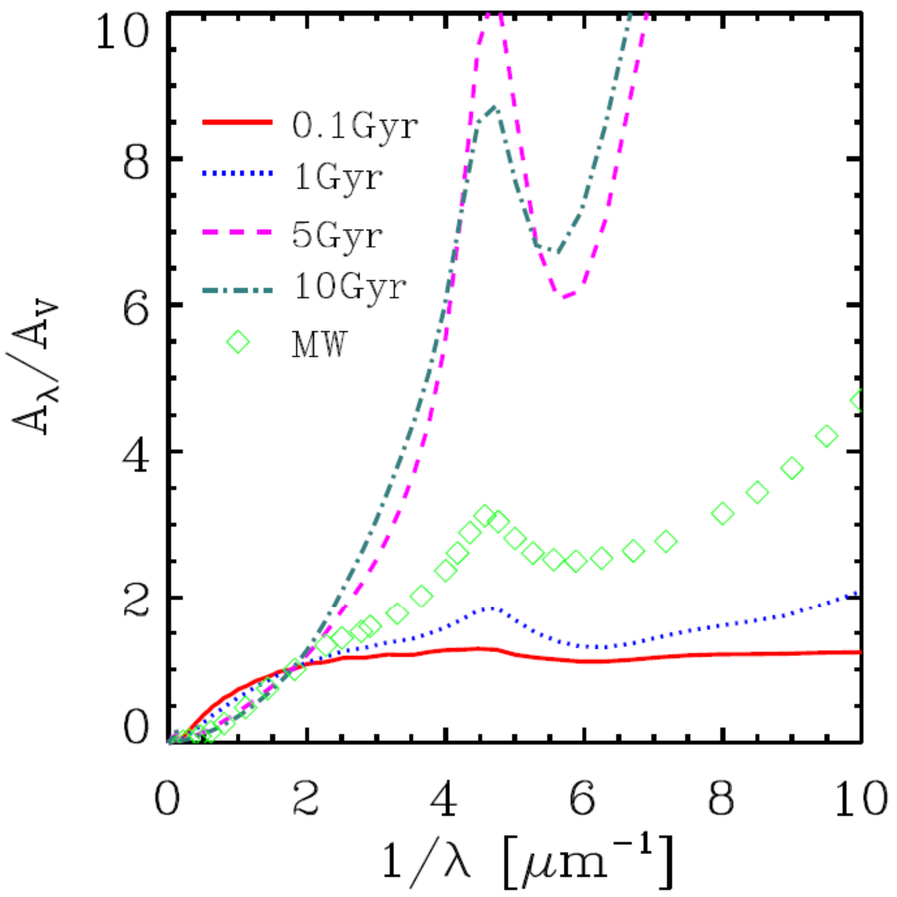
Grain size distribution:

Evolution model of grain size distribution

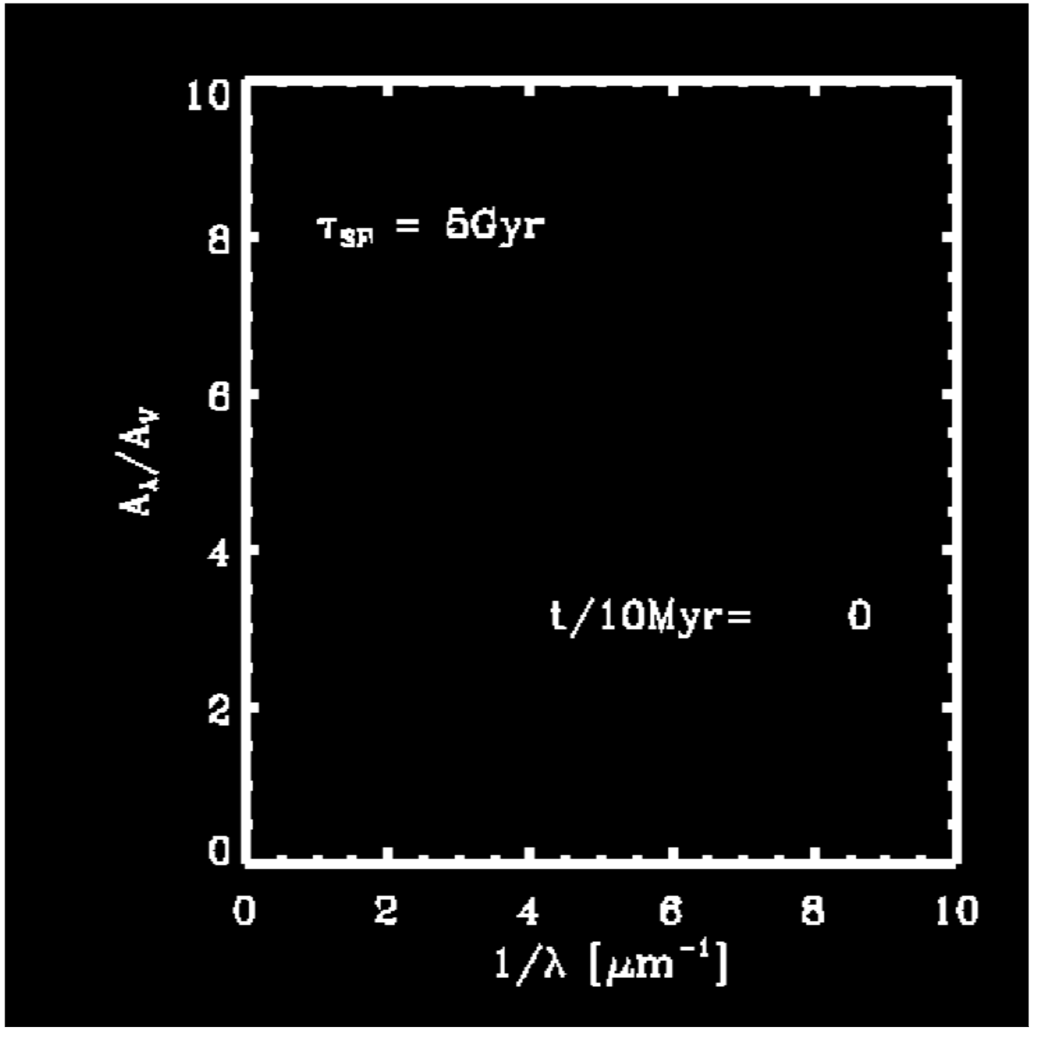
Asano et al. (2013)

Evolution of the extinction curve in galaxies

Parameter setting :
Total baryon mass : 10^{10} $M_{\odot}$
Star formation timescale : 5 Gyr
CNM mass fraction : 0.5
WNM mass fraction : 0.5

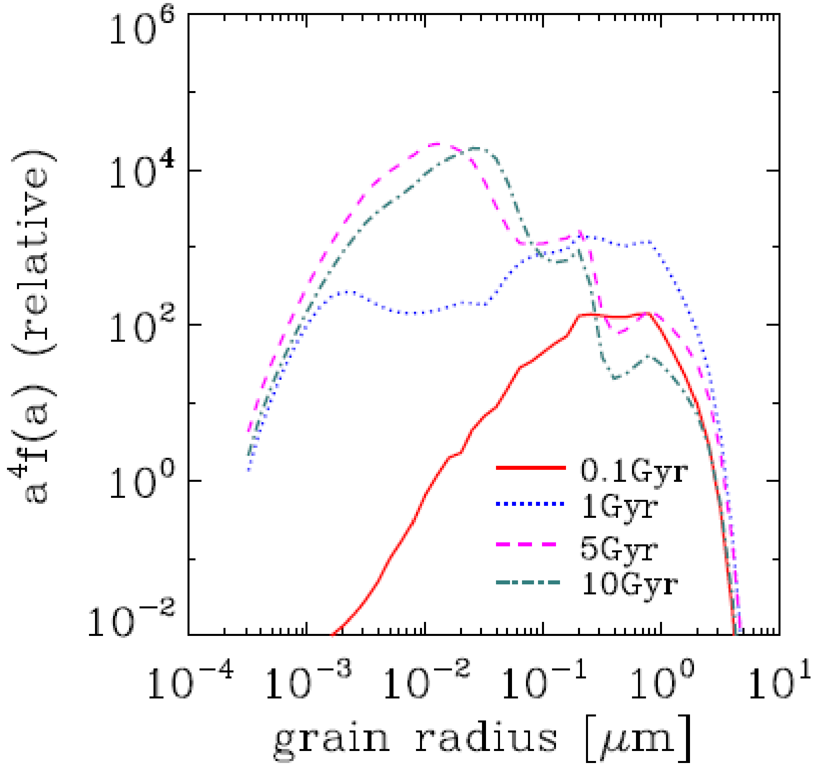


Evolution of the extinction curve in galaxies

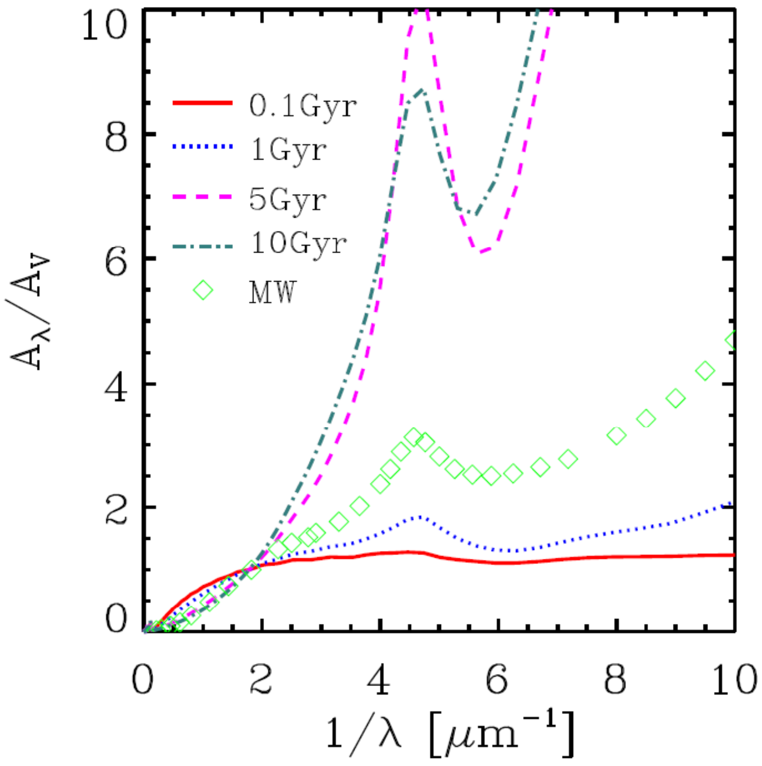


Evolution of the extinction curve in galaxies

Size distribution

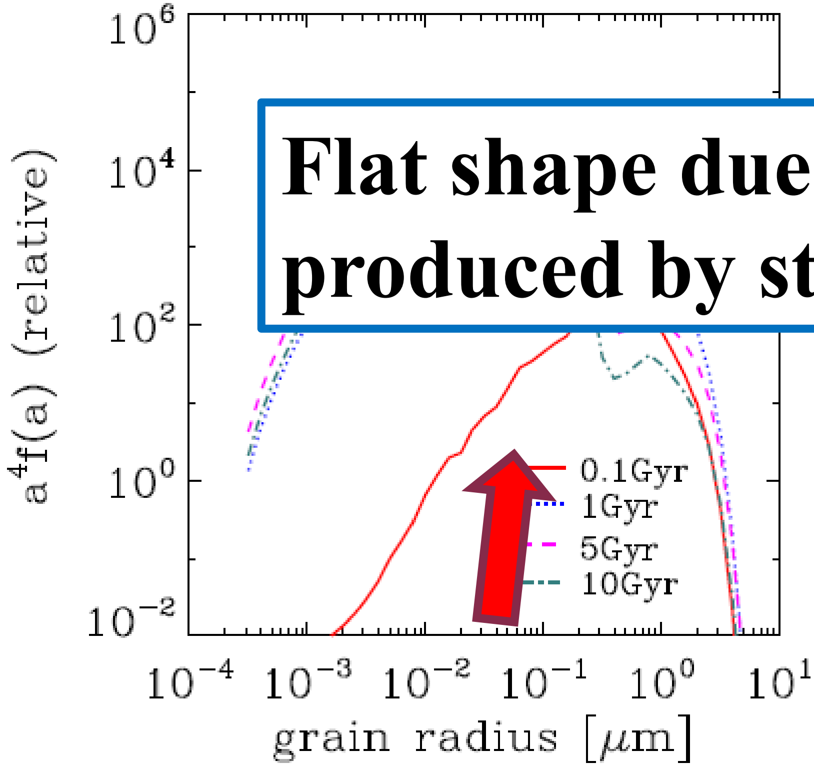


Extinction curve

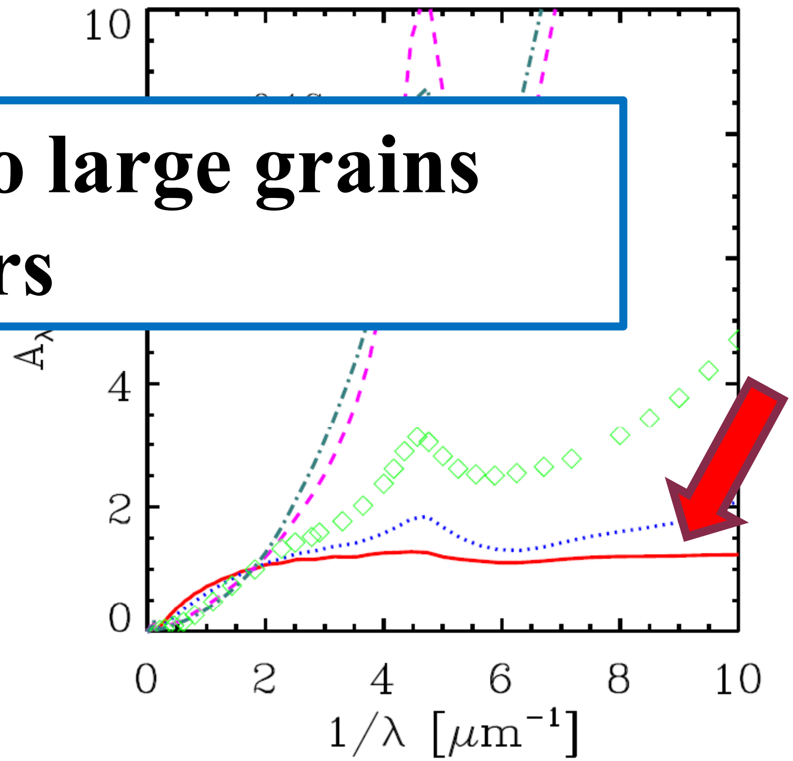


Evolution of the extinction curve in galaxies

Size distribution



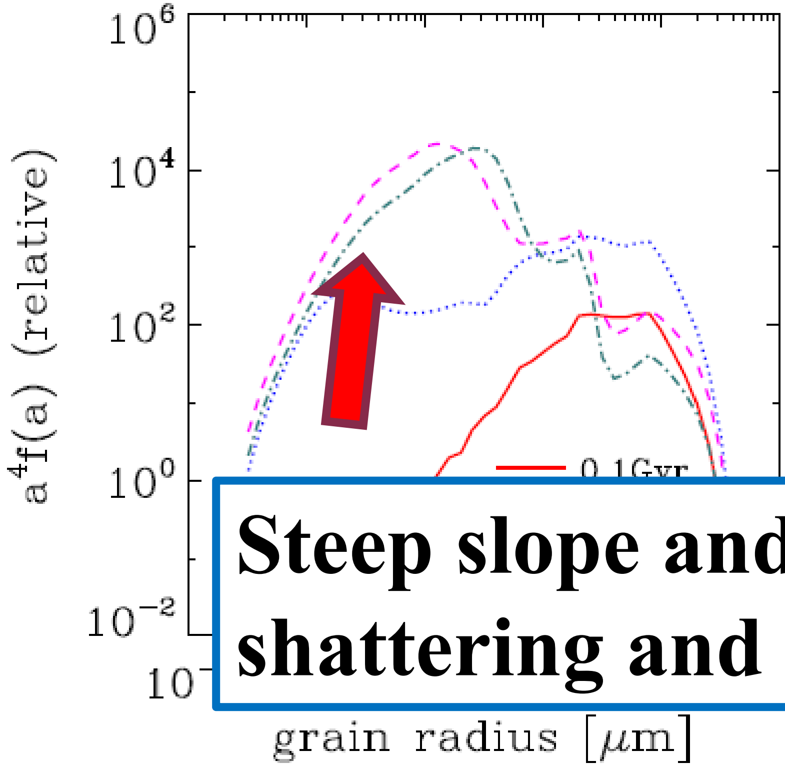
Extinction curve



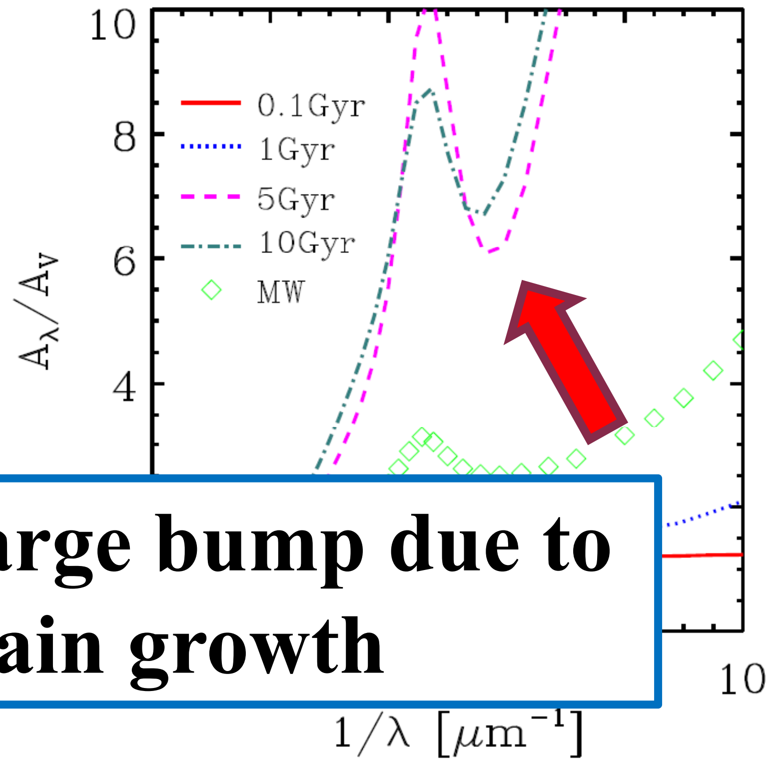
Flat shape due to large grains produced by stars

Evolution of the extinction curve in galaxies

Size distribution



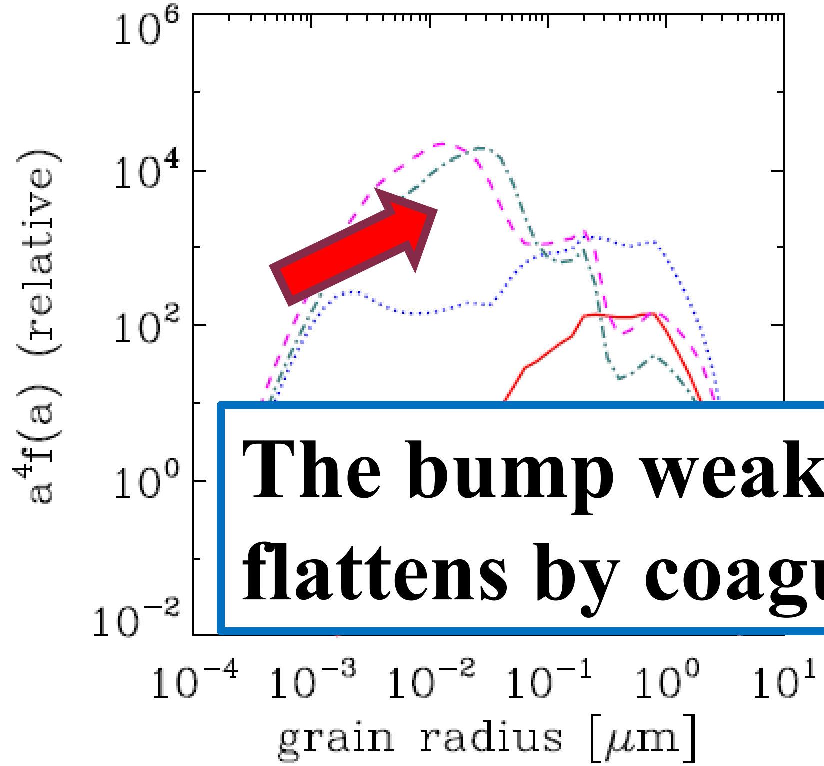
Extinction curve



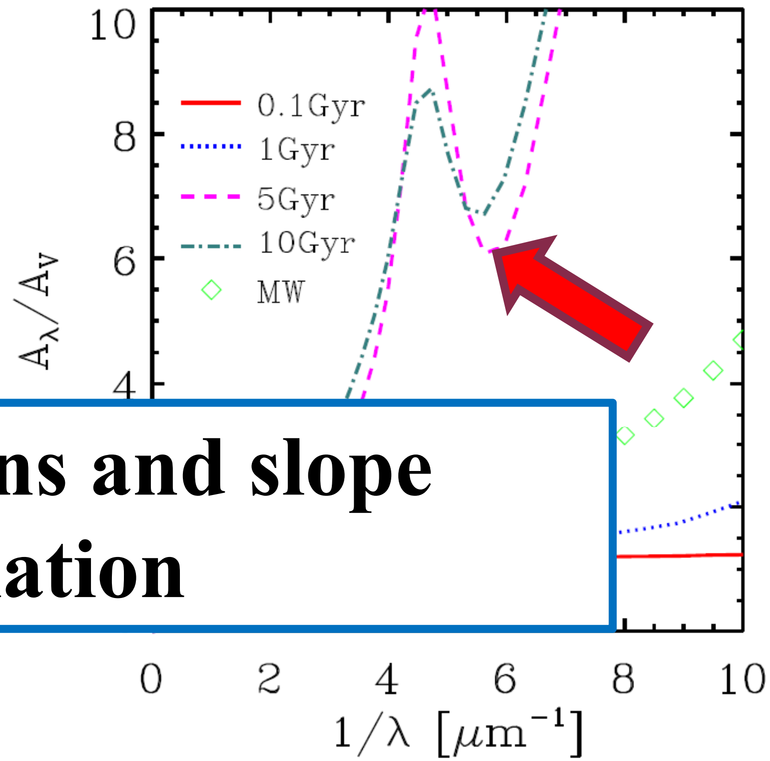
Steep slope and large bump due to shattering and grain growth

Evolution of the extinction curve in galaxies

Size distribution



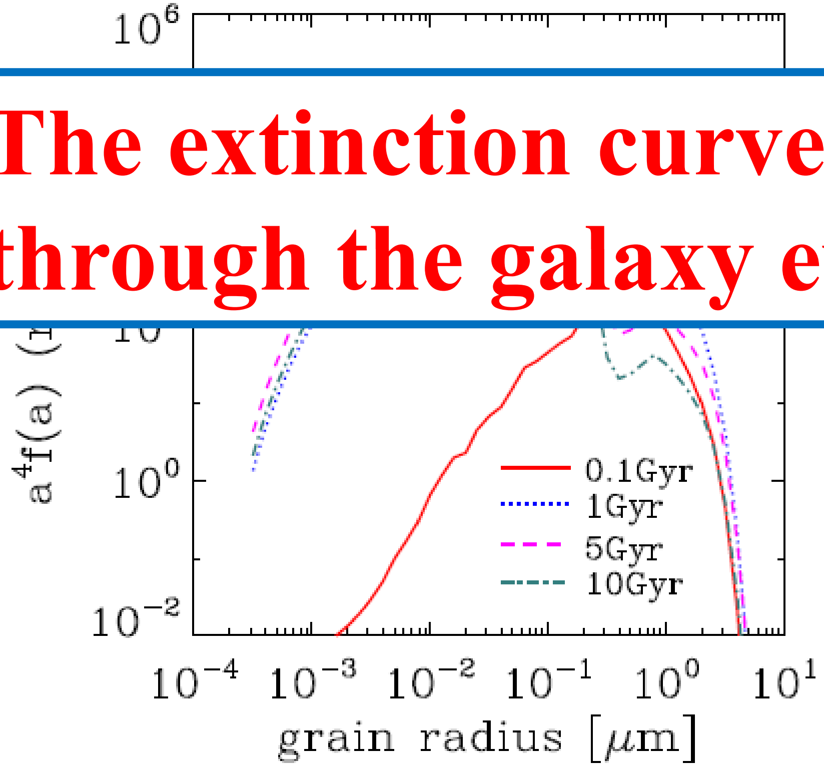
Extinction curve



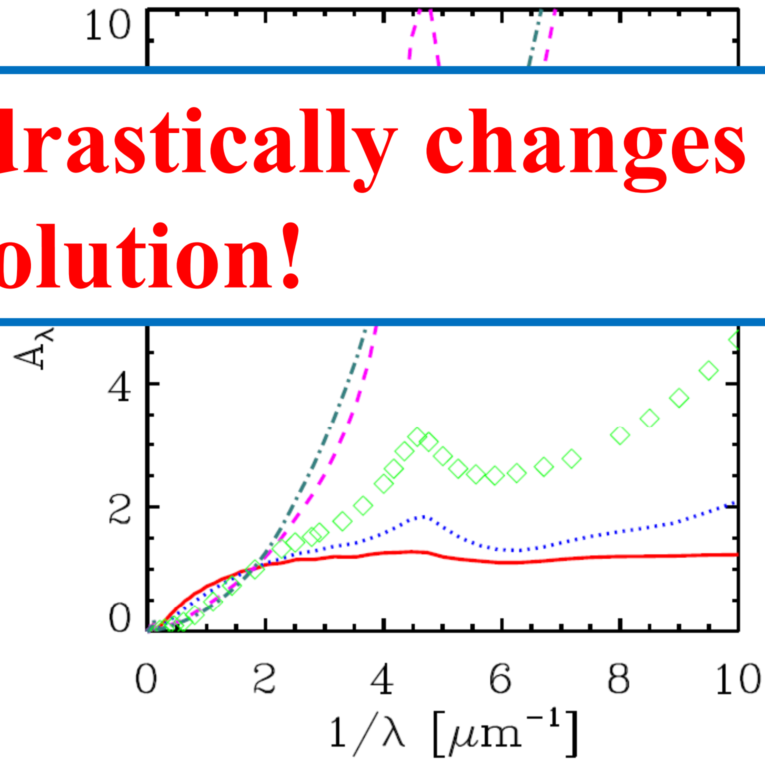
The bump weakens and slope flattens by coagulation

Evolution of the extinction curve in galaxies

Size distribution



Extinction curve



The extinction curve drastically changes through the galaxy evolution!

5. Conclusions and Future Prospects

Conclusion

1. **Dust amount**:
   Dust supply alters from stars to grain growth in the ISM when the metallicity exceeds the critical metallicity.

2. **Grain size distribution**:
   The grain size changes from large grains (stars) to small grains (processes in the ISM)

3. **Extinction curve**:
   The Extinction curve transforms from flat (large grains) to steep (small grains)

This model can predict the dust evolution of galaxies at high-*z* Universe, which have recently been observed by Herschel and ALMA as well as next generation facilities like SPICA, SKA as well as optical facilities.

Future works

This work can be extended to various directions.

(1) Evolution of the multi-phase considering dust evolution

(2) Evolution of the spectral energy distribution

(3) Evolution of the attenuation curves