Dust Formation History with Galaxy Evolution

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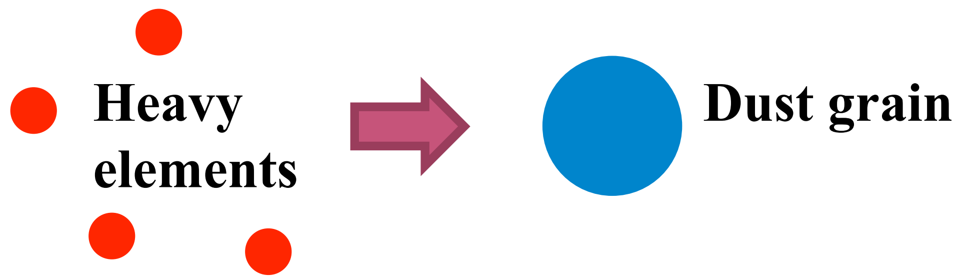
ESTEC, 14 Nov., 2014, the Netherlands

1. Introduction

What are dust grains?

Dust grains are

・formed by condensation of heavy elements.



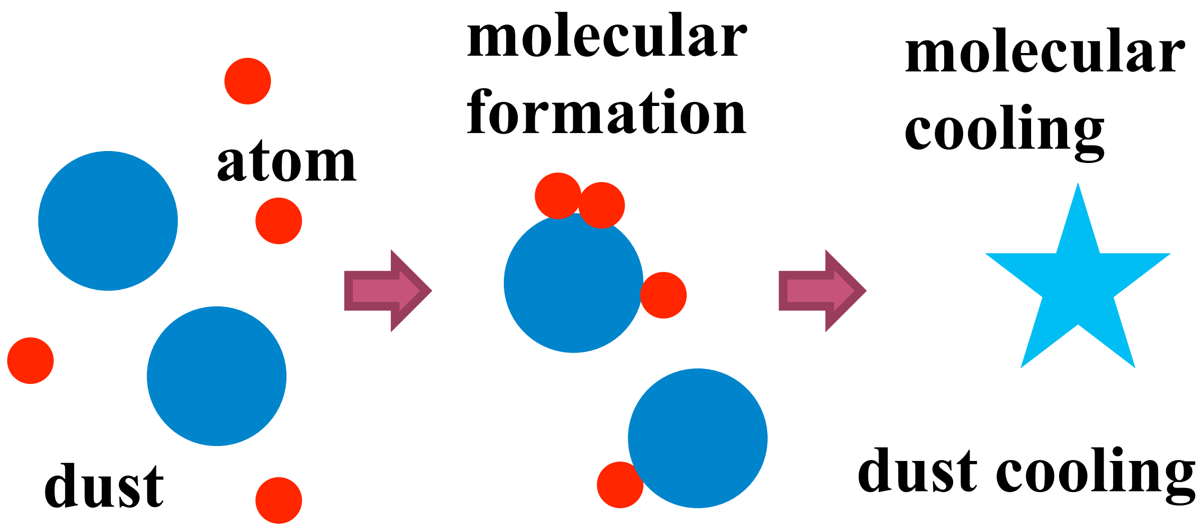
Heavy elements are supplied only by stars.

・tightly connected to galaxy evolution

There are many important physical quantities affected by dust.

Role of dust for the first star formation

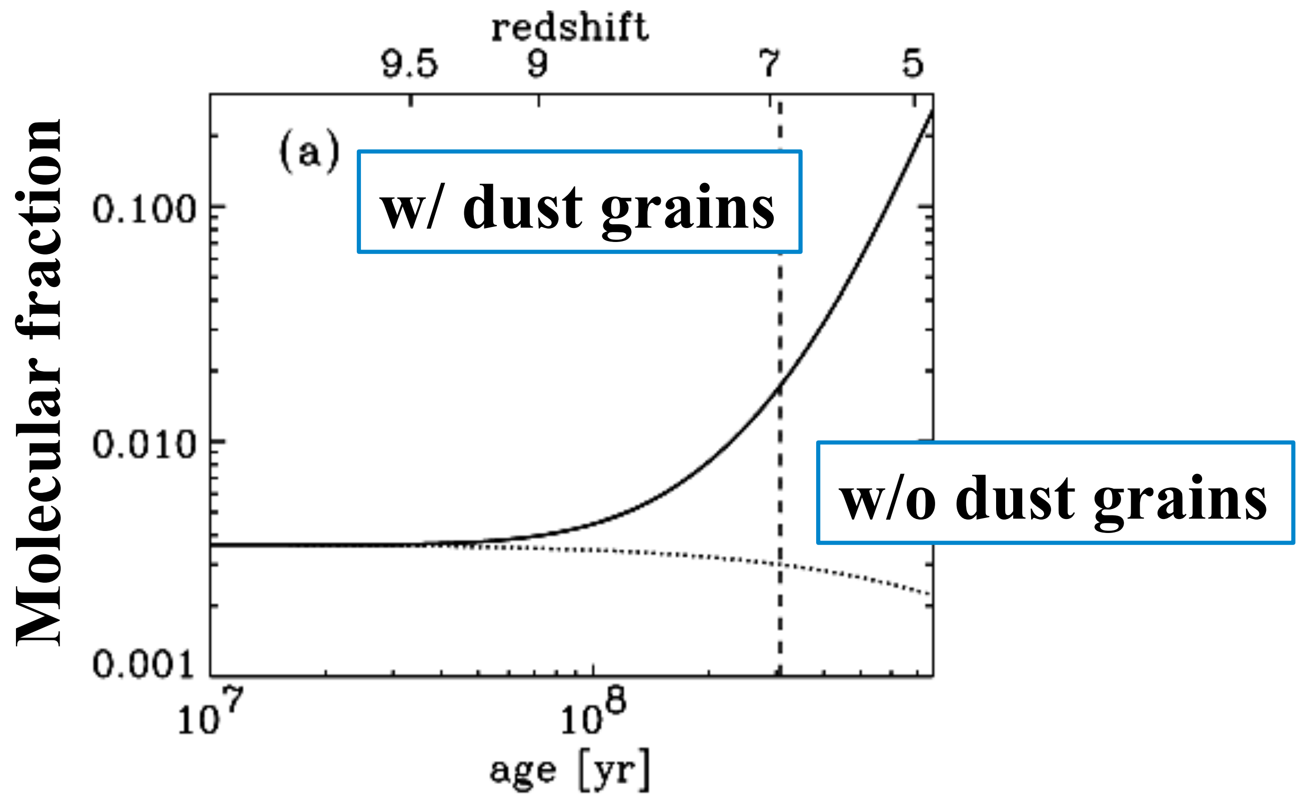
Surface of dust grains



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

Role of dust for the first star formation

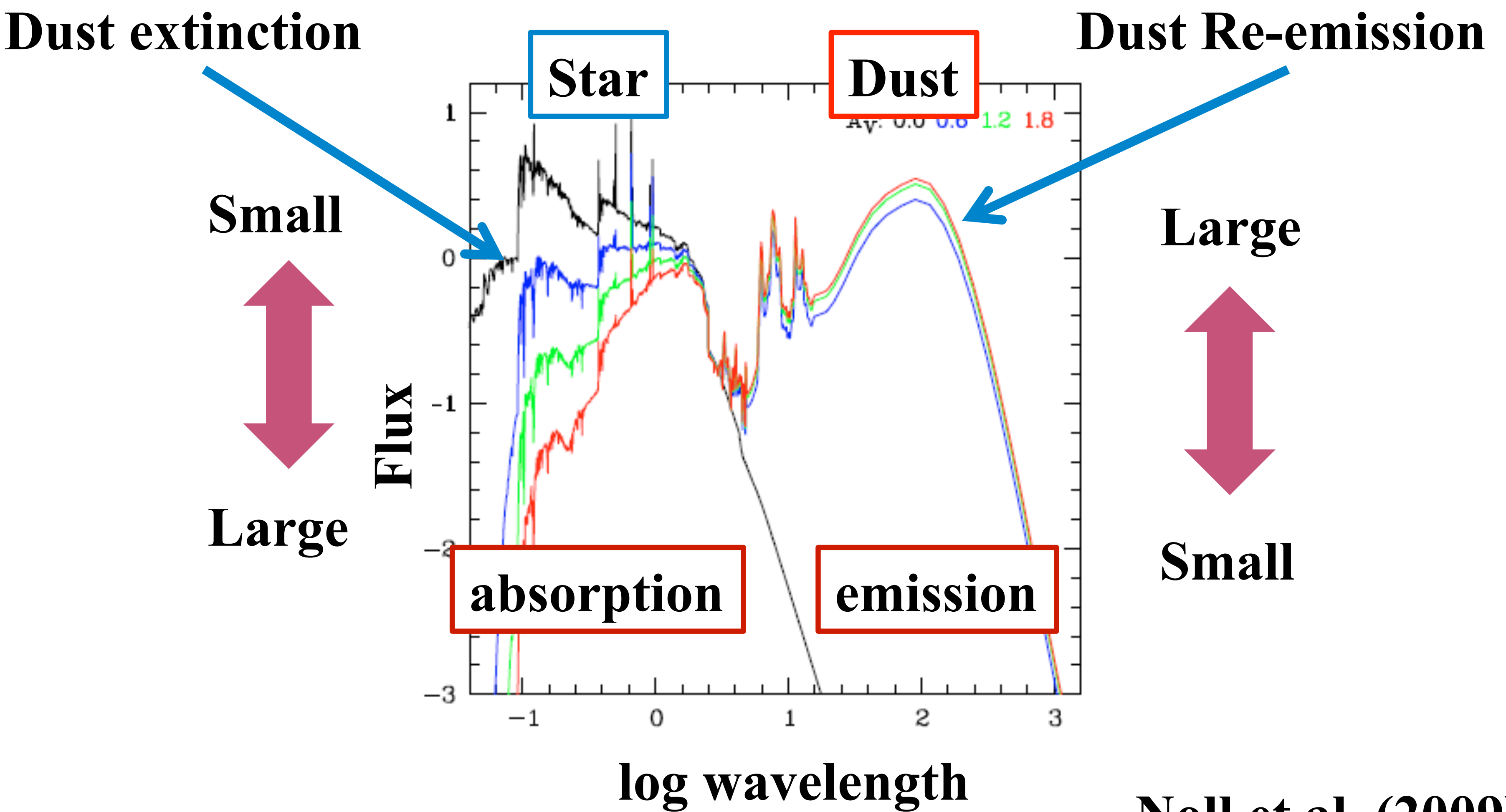
Surface of dust grains



Hirashita & Ferrara (2002)

Dust grains drive the star formation.

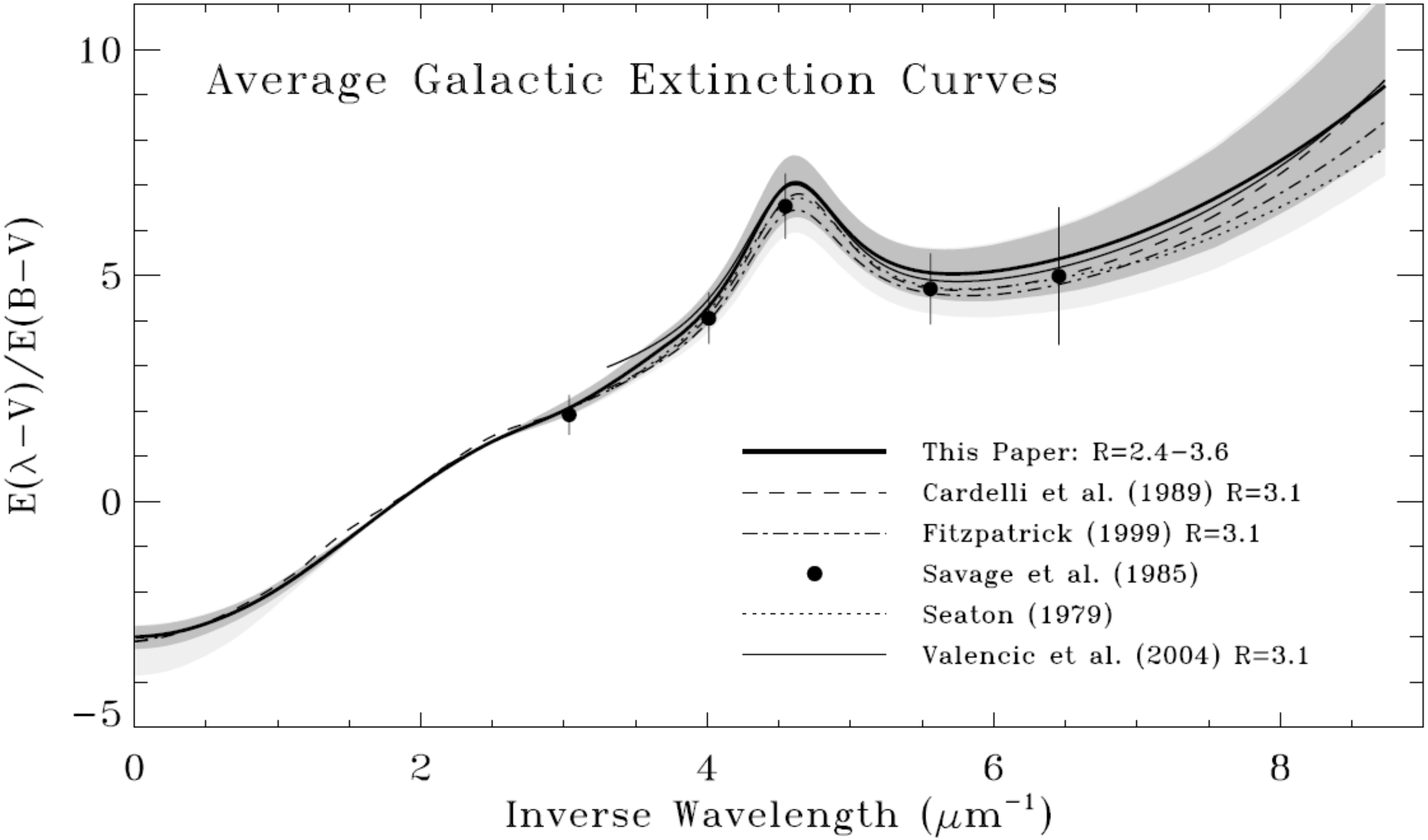
Spectral energy distribution (SED)



Noll et al. (2009)

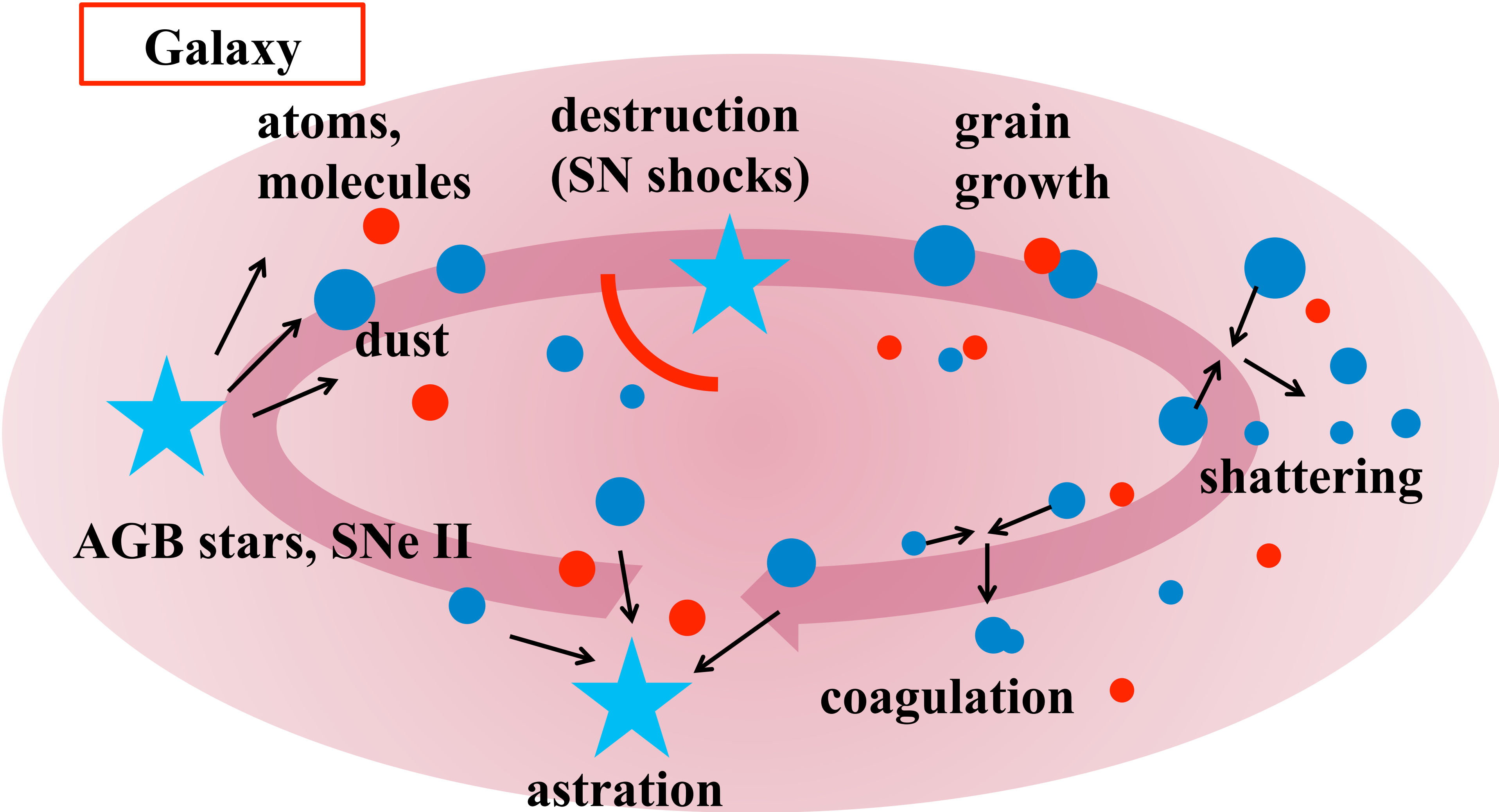
Extinction curve

Wavelength dependence of extinction by dust



Fitzpatrick & Massa (2007)

Dust and matter circulation in a galaxy



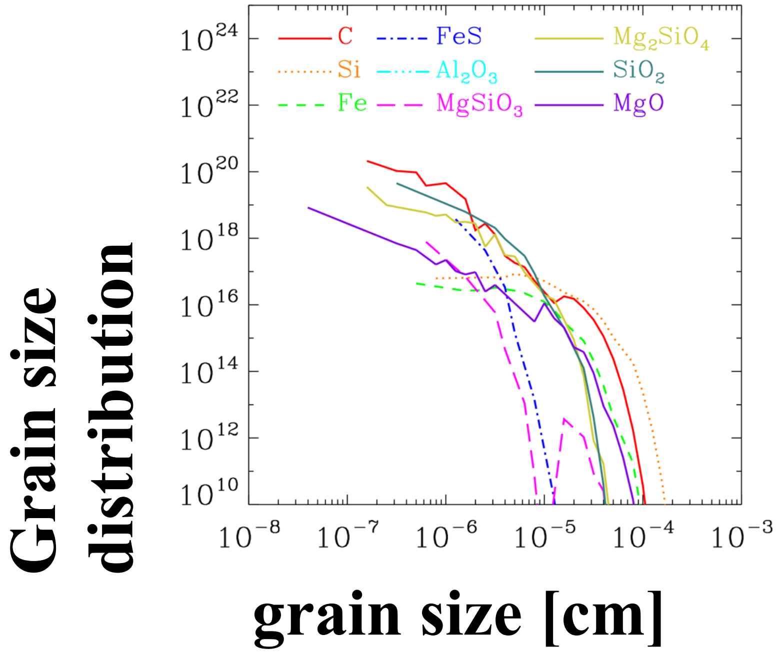
Asano (2014) PhD Thesis

Dust supply

Type II Supernovae (SNe II)

Broken power-law
Biased to large grains
Nozawa et al. (2007)

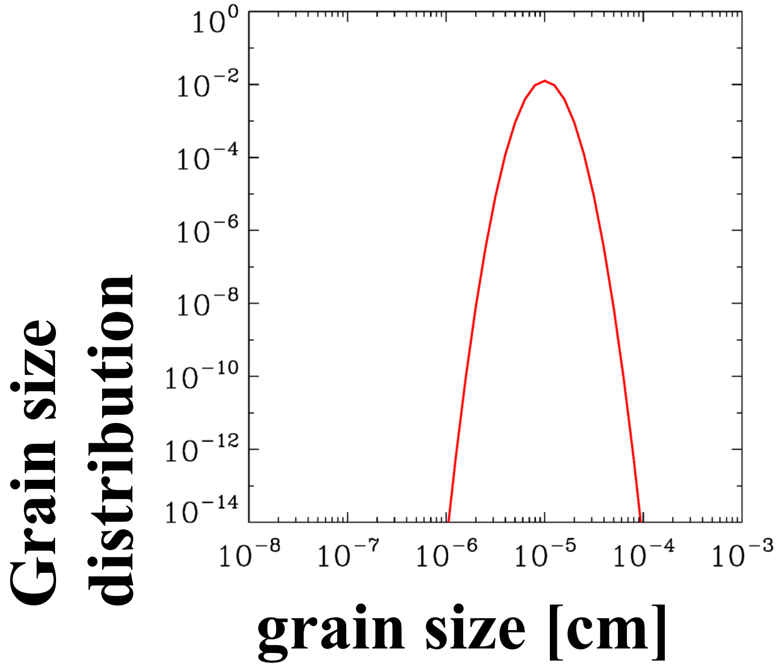
Dust mass data
Nozawa et al. (2007)



AGB stars

Log-normal distribution
Large size grains are produced
Winters et al. (1997)
Yasuda & Kozasa (2012)

Dust mass data
Zhukovska et al. (2008)

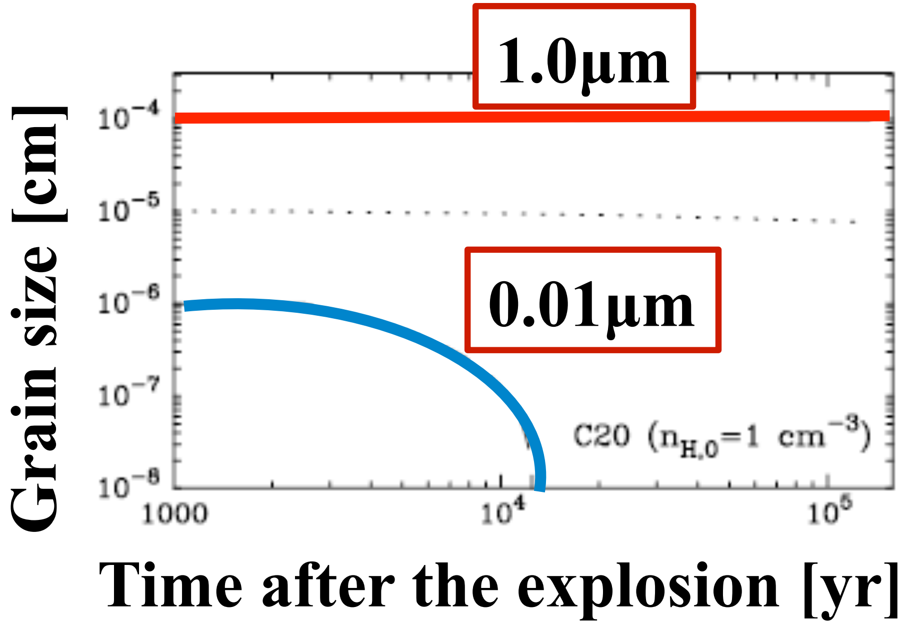


Dust destruction and grain growth

Dust destruction by SN shocks

Smaller grains are mainly destroyed by SN shocks.

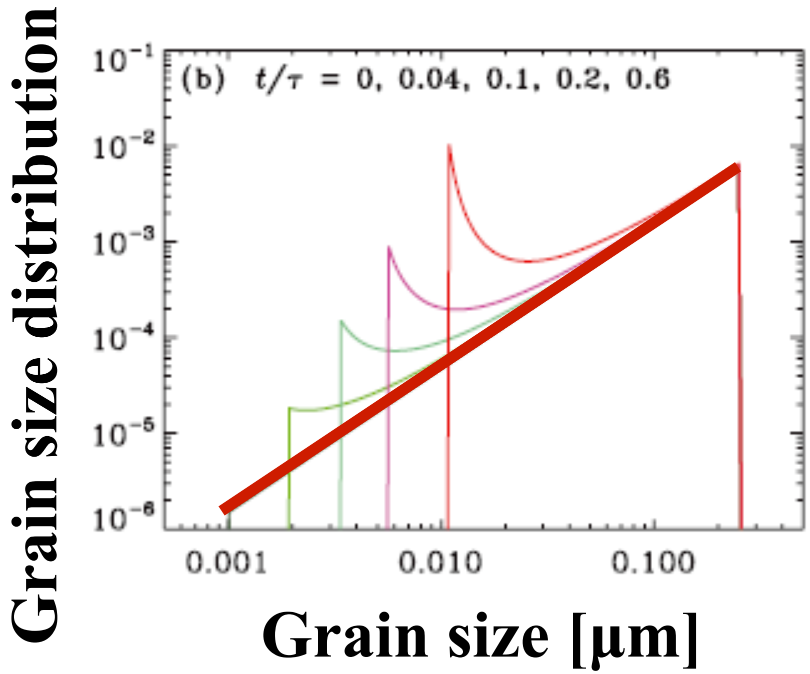
Nozawa et al. (2006)



Grain growth (metal accretion onto grains)

Smaller grains grow to larger grains.

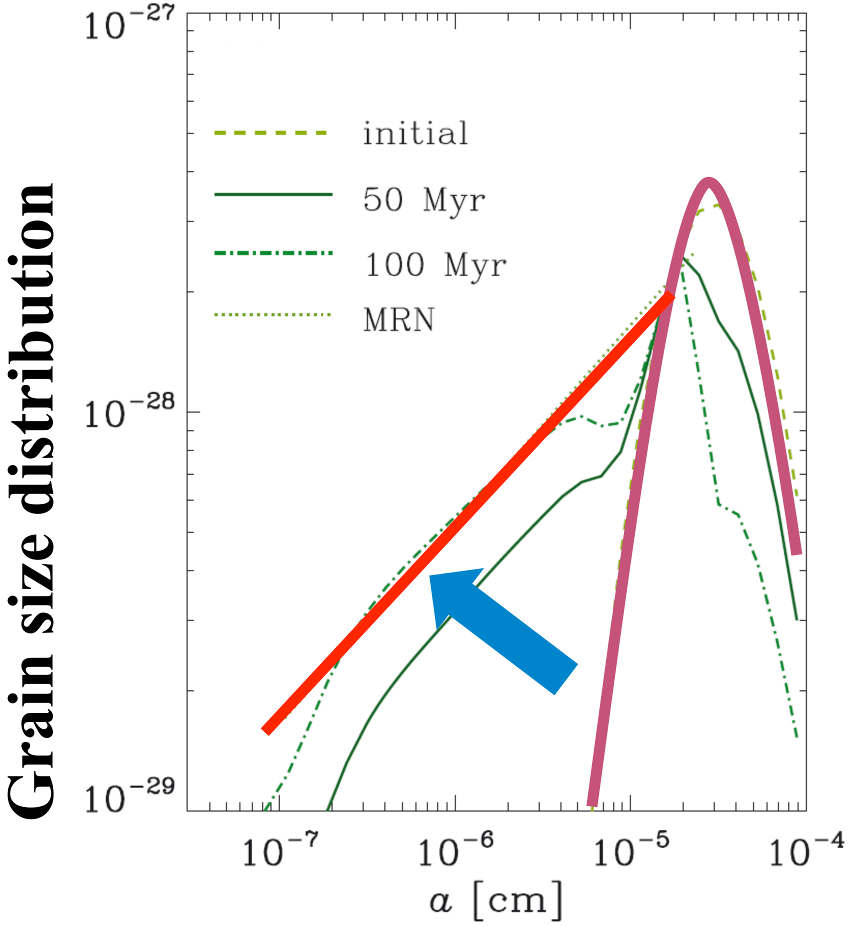
Hirashita & Kuo (2011)



Shattering and coagulation (driven by ISM turbulence)

Shattering

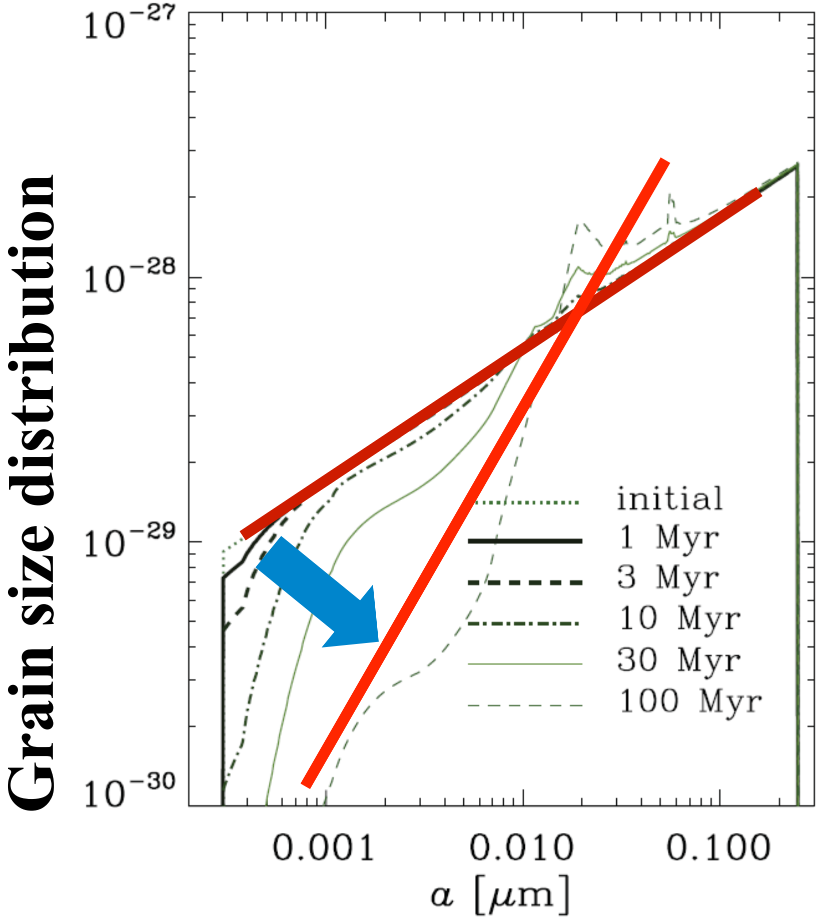
Smaller grains are produced by larger grains



Hirashita (2010)

Coagulation

Larger grains are produced by smaller grains



Hirashita (2012)

2. Evolution of the Total Dust Amount

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

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

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

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

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

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

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

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

Asano, TTT, Hirashita, Inoue (2013)

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

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

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

Star Formation Rate (SFR)

Schmidt law (Schmidt 1959) with index $n = 1$

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

This determines the SFH.

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 this study.

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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

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

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

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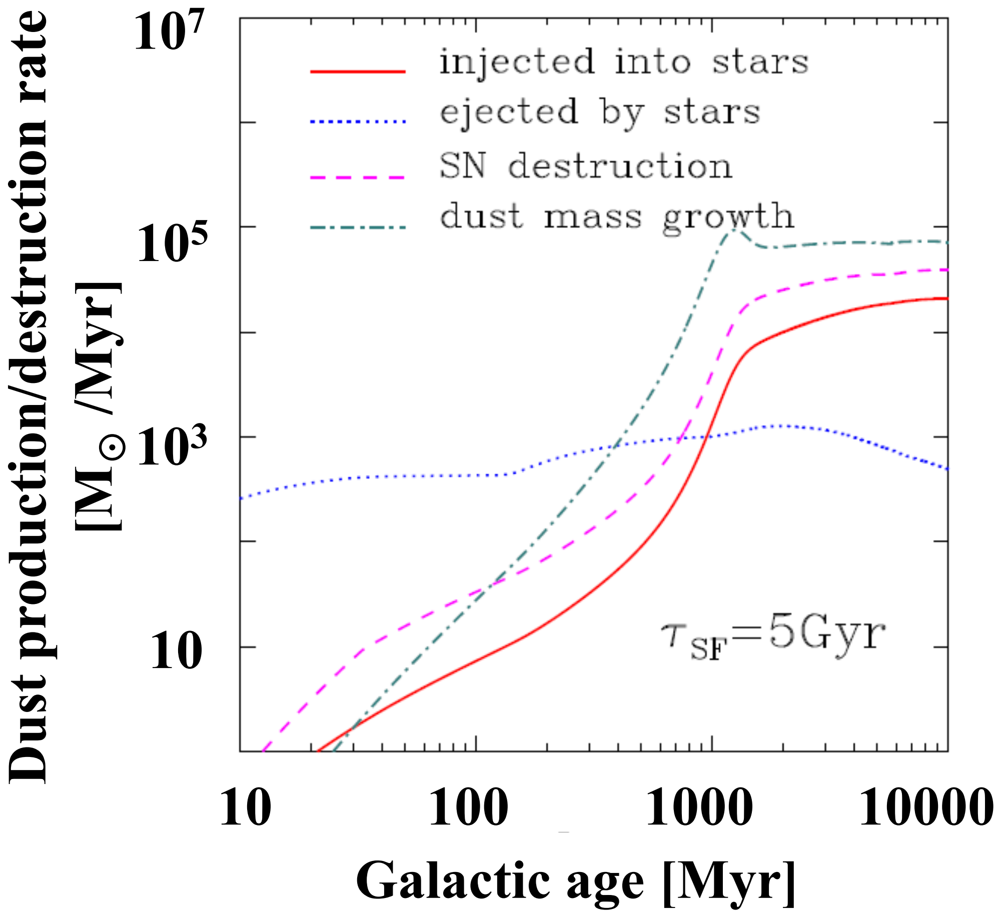
Contribution of each physical process to the total dust mass

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

What determines the switching point?

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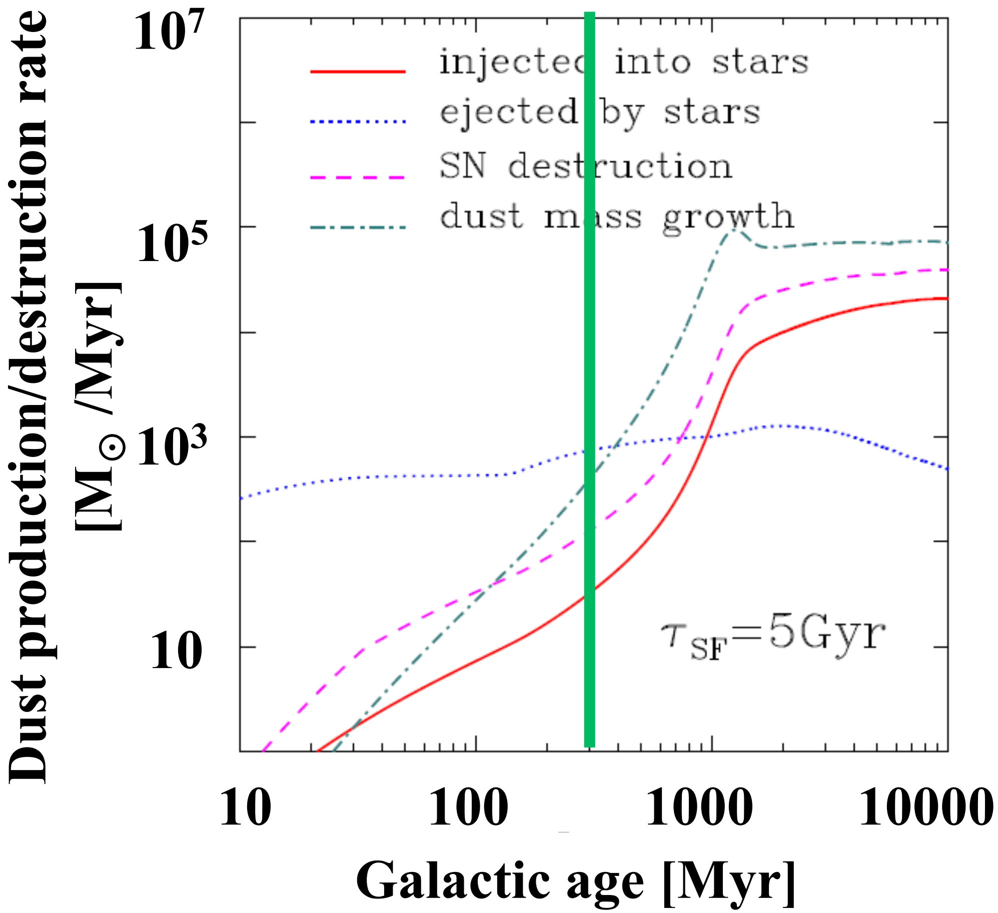

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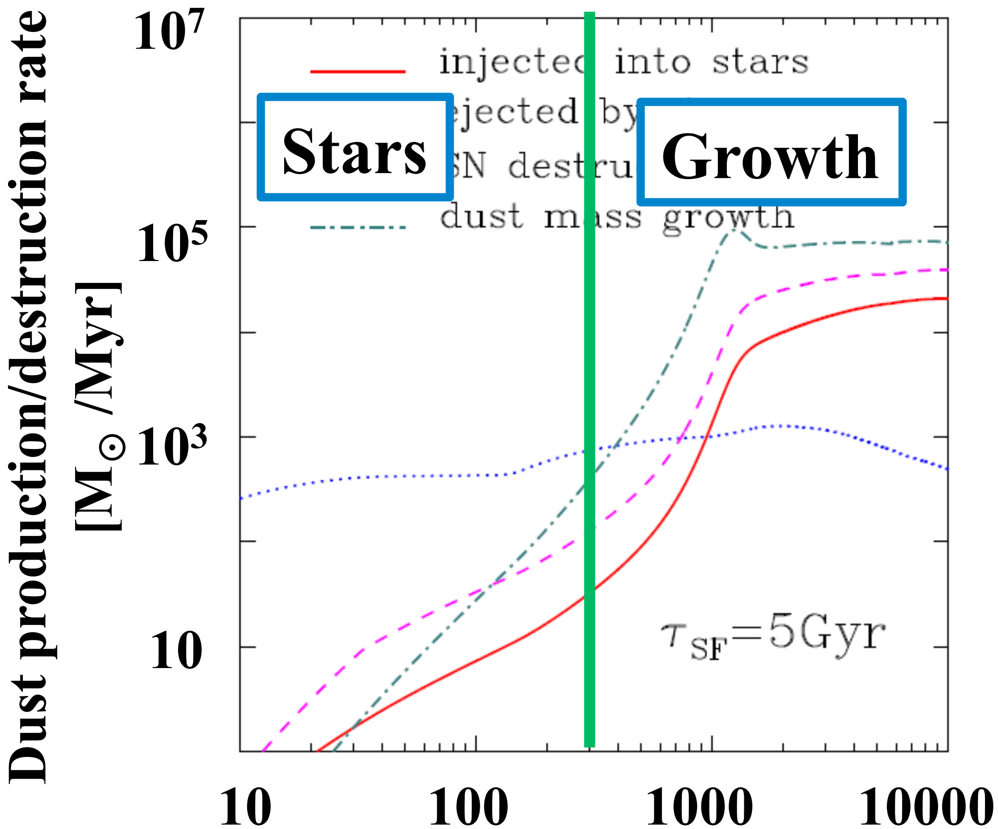


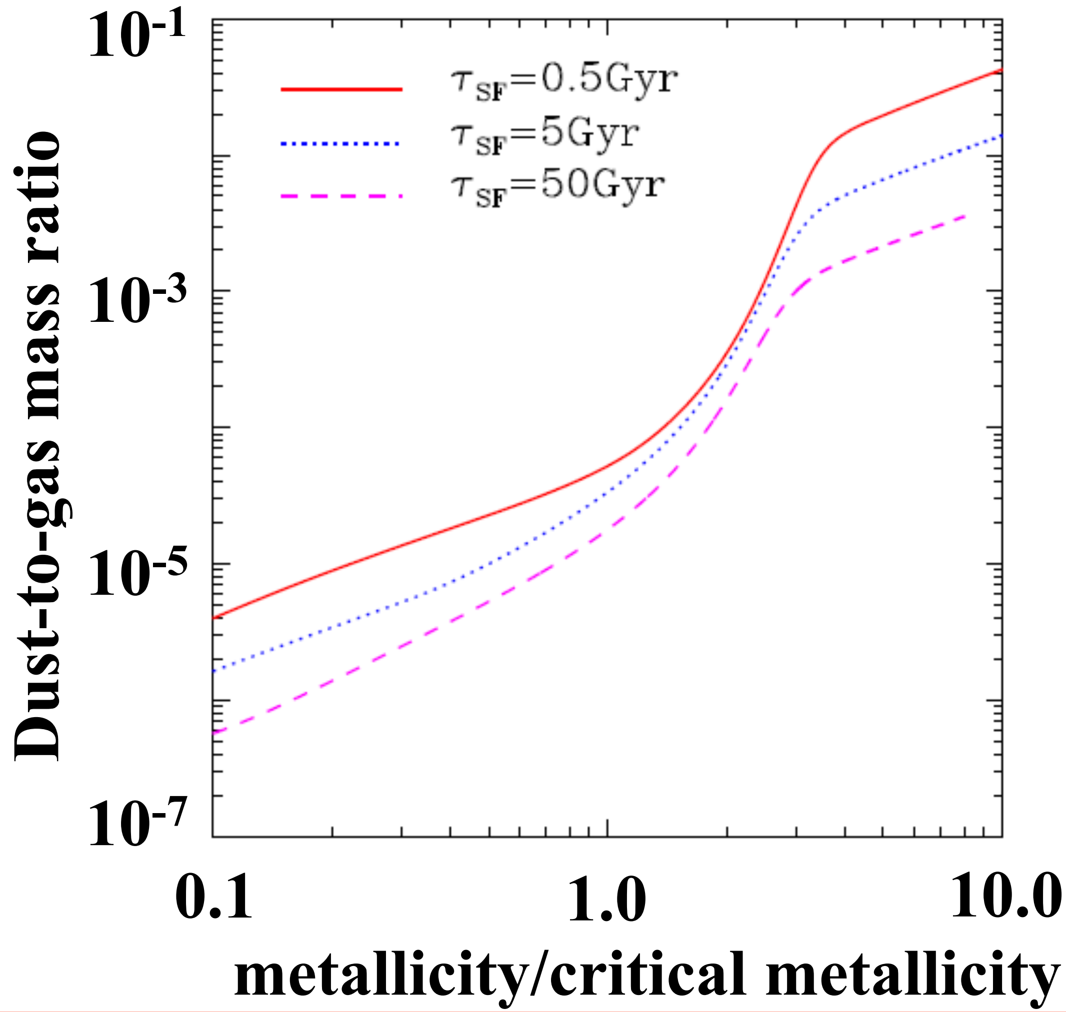
Growth is expected to explain the total dust mass of the Milky Way and high-*z* QSOs.

Critical metallicity for grain growth

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

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

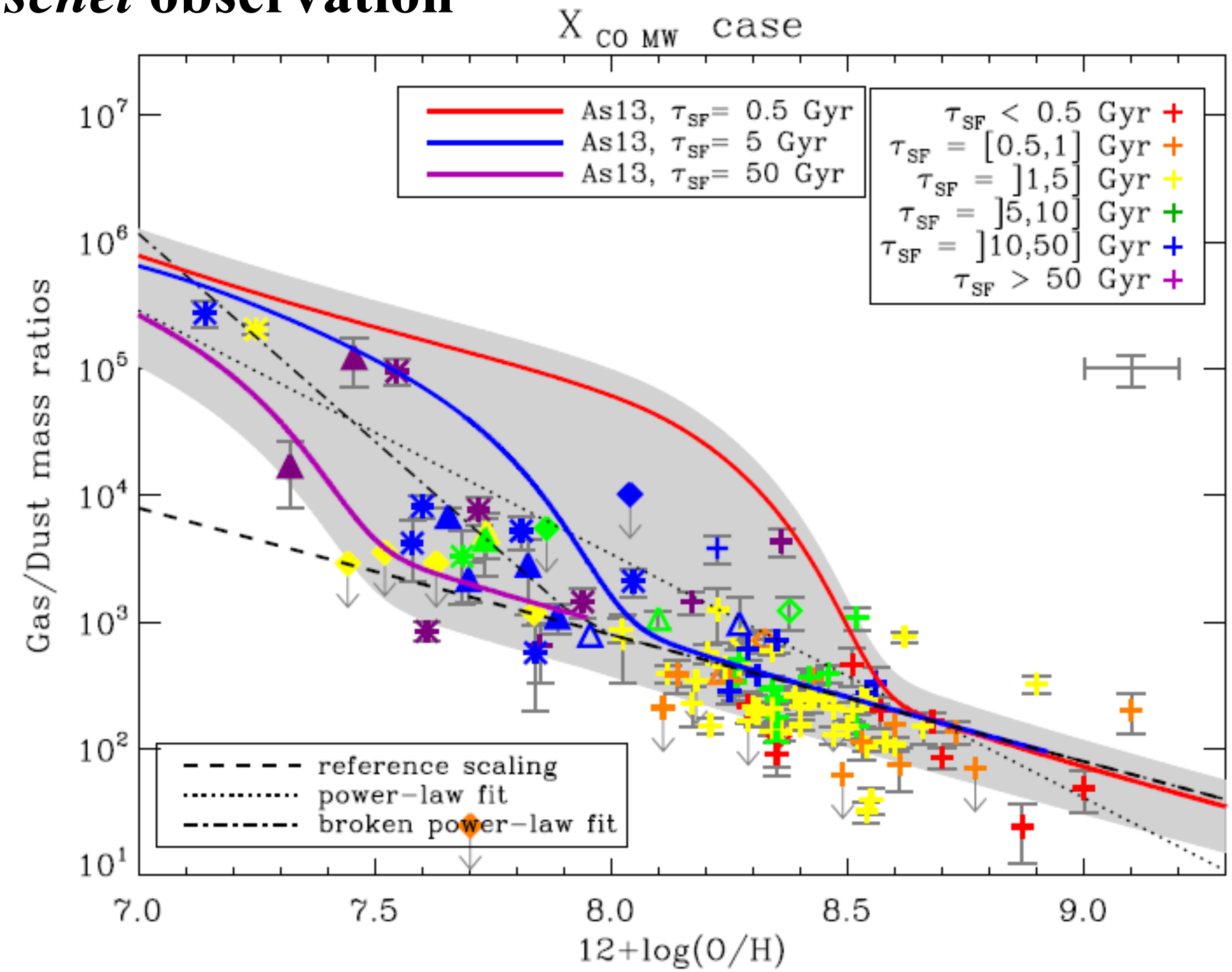
Critical metallicity for grain growth



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 the observed data

Herschel observation



Rémy-Ruyer et al. (2014) (cf. Suzanne's talk)

3. Evolution of Dust Grain Size Distribution

Model settings

- **Closed-box model**
(total baryon mass is a constant)
- Two-phase ISM (WNM and CNM)
- Schmidt law : SFR(t) = $M_{\mathrm{ISM}}(t)/\tau_{\mathrm{SF}}$

- 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 (mass-preserving processes)**

Formulation of the grain-size dependent evolution of dust mass

$M_d\,(a, t) = m(a)f(a, t)\mathrm{d}a$: 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} \quad = \quad & -\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}} \\
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Asano, TTT, Hirashita, Nozawa (2013)

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Stellar effects

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

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

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Destruction by SN shocks

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Grain growth

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\end{aligned}
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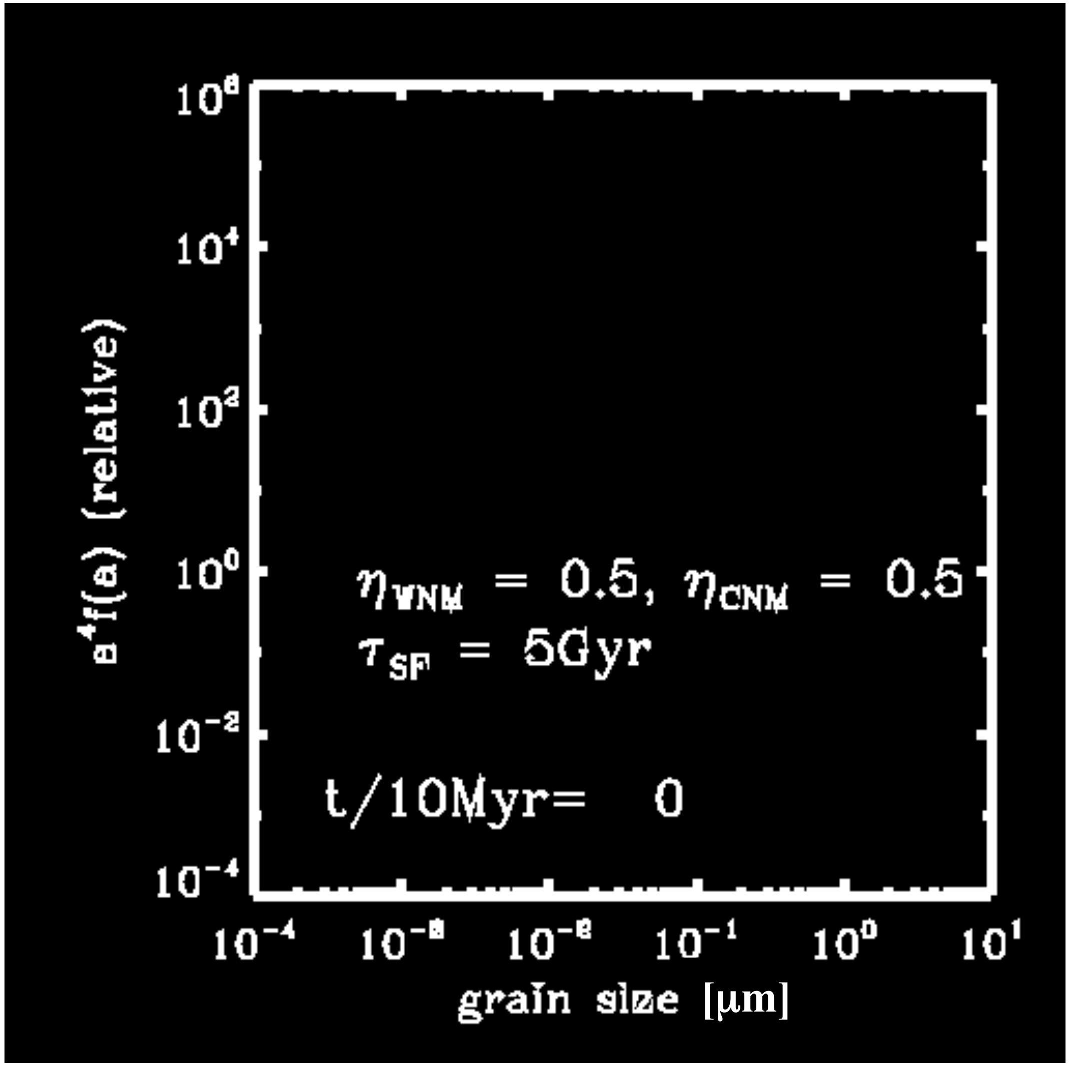
Coagulation

Evolution of the grain size distribution



4. Evolution of Extinction Curve

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**

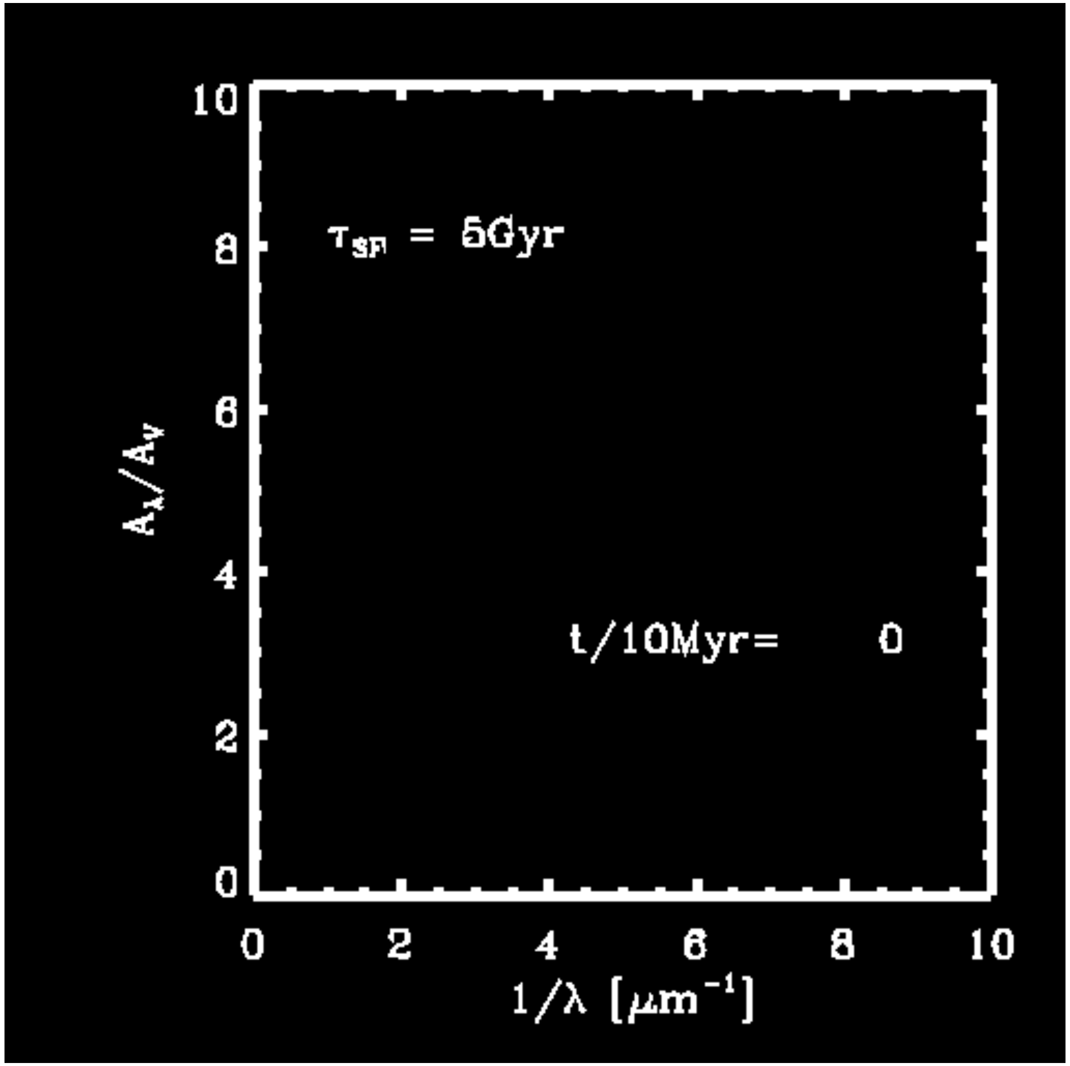
Optical constant:
graphite and astronomical silicate **($Mg_{1.}Fe_{0.9}SiO_4$)**
Draine & Lee (1984)

Grain size distribution:

Evolution model of grain size distribution

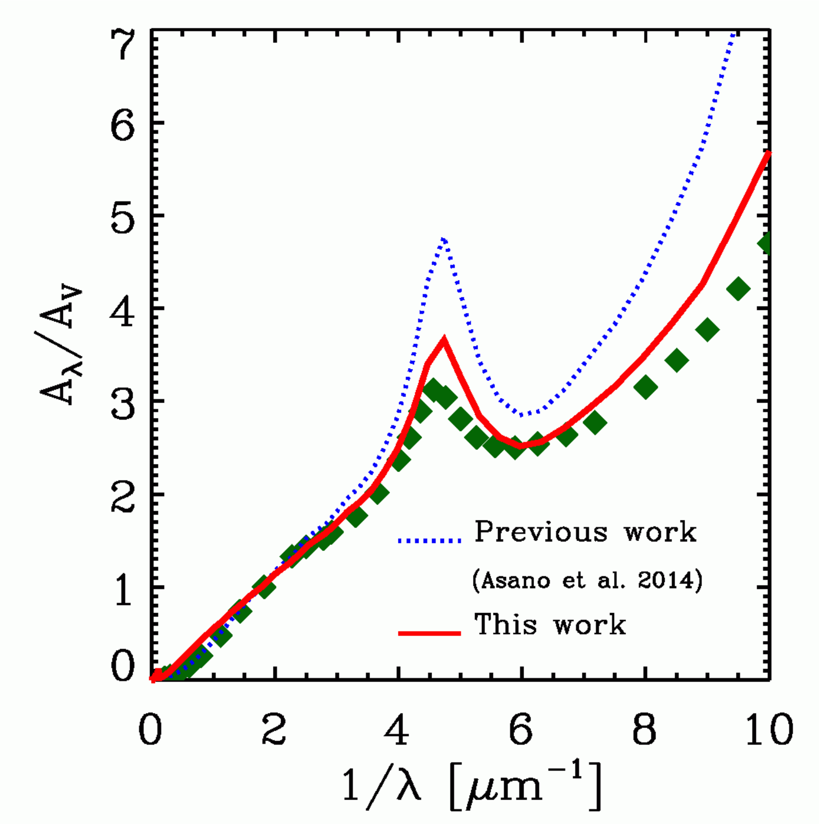
Asano et al. (2013)

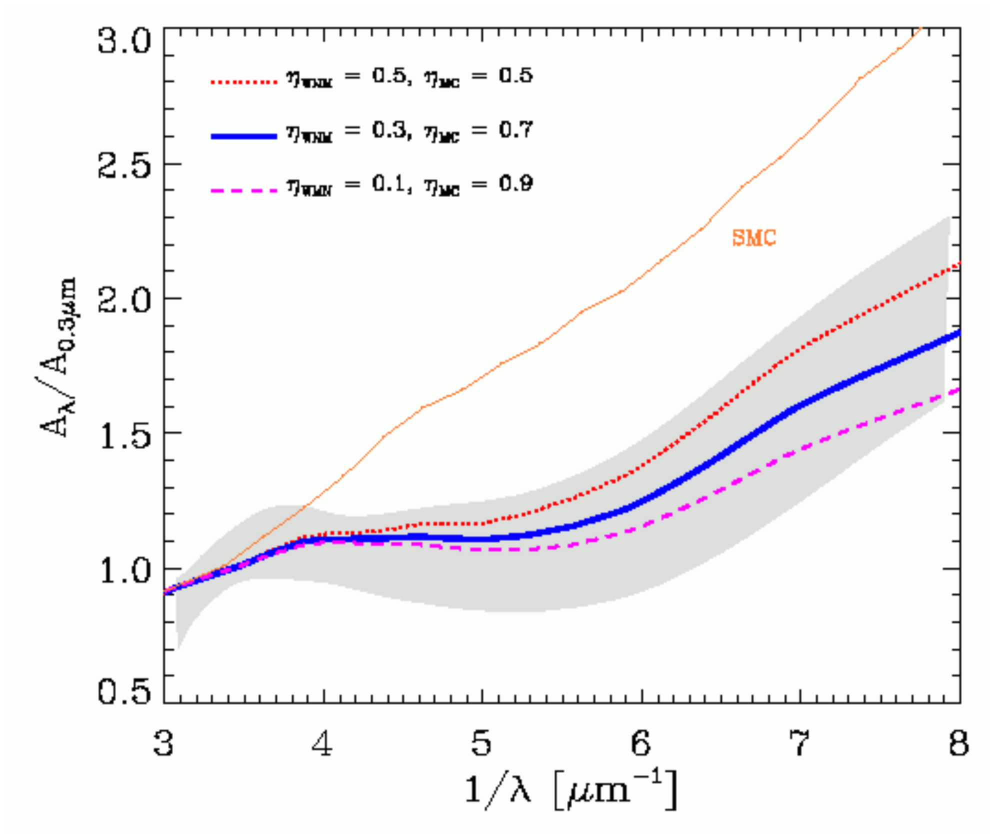
Evolution of the extinction curve in galaxies



Asano, TTT, Hirashita, Nozawa (2014)

Application to the Milky Way and a distant quasar





This model could reproduce the extinction curves of both the Milky Way and a distant quasar at once.

Nozawa, Asano, Hirashita, TTT (2014)

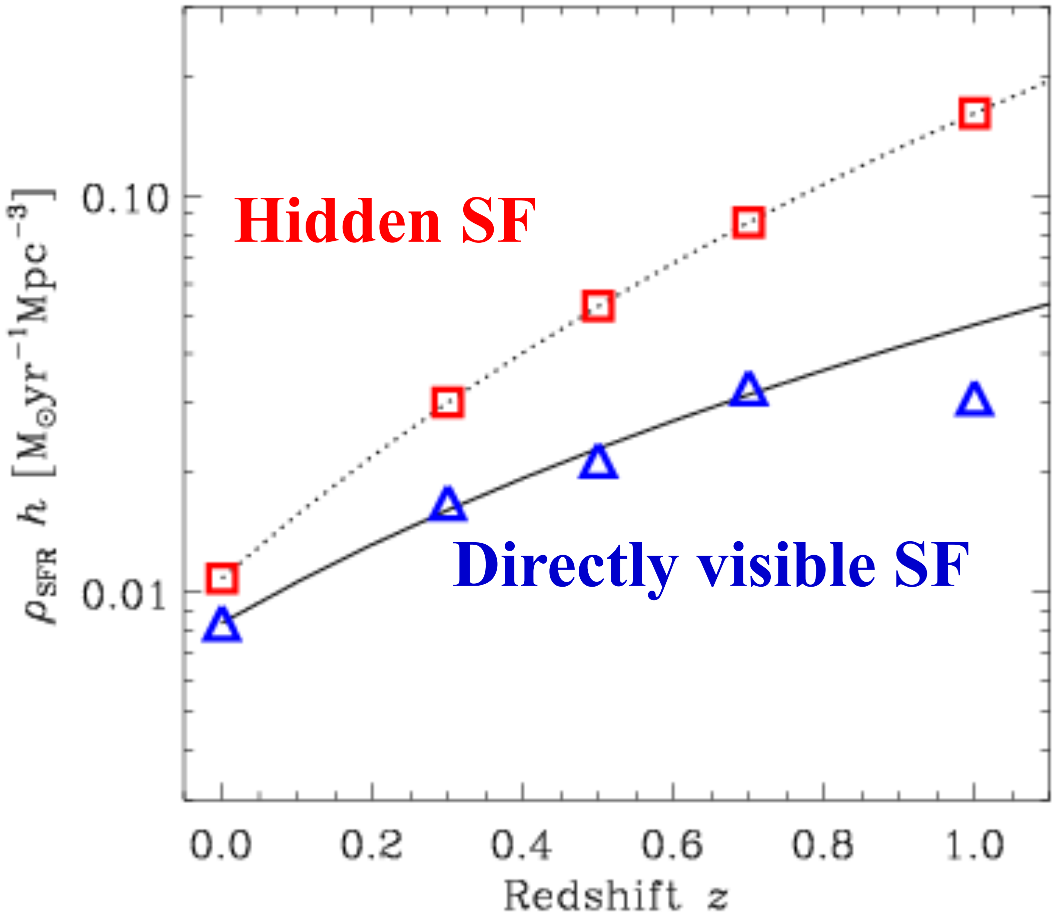
5. Conclusions

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).
4. **This model reproduced the extinction curves of both the MW and a distant quasar at once.**

We provide a coherent and convenient framework to treat the dust properties, which is valid for the whole lifetime of galaxies.

Appendix

Importance of infrared galaxies in the cosmic star formation



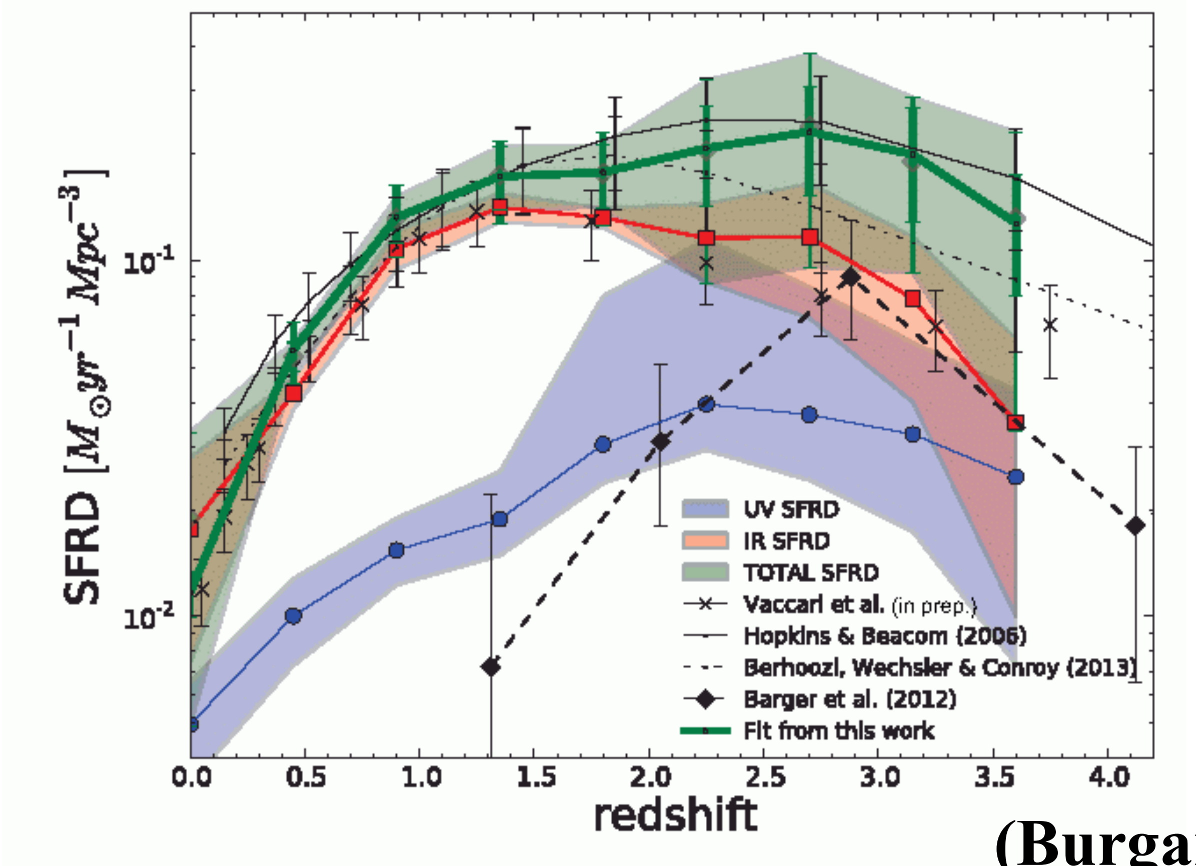
Infrared and ultraviolet-luminous galaxies, which of them are the major player of the star formation history?

⇒ At $z < 1$ (cosmic age < 6.1 Gyr), more than 90% of the star formation is hidden by dust and invisible through the UV window.

(Takeuchi et al. 2005)

Importance of infrared galaxies in the cosmic star formation

This trend was confirmed by *Herschel* and other facilities. Further, the hidden SF is found to be dominant up to $z \sim 3$ (e.g., Cucciati et al. 2011; Burgarella et al. 2013).

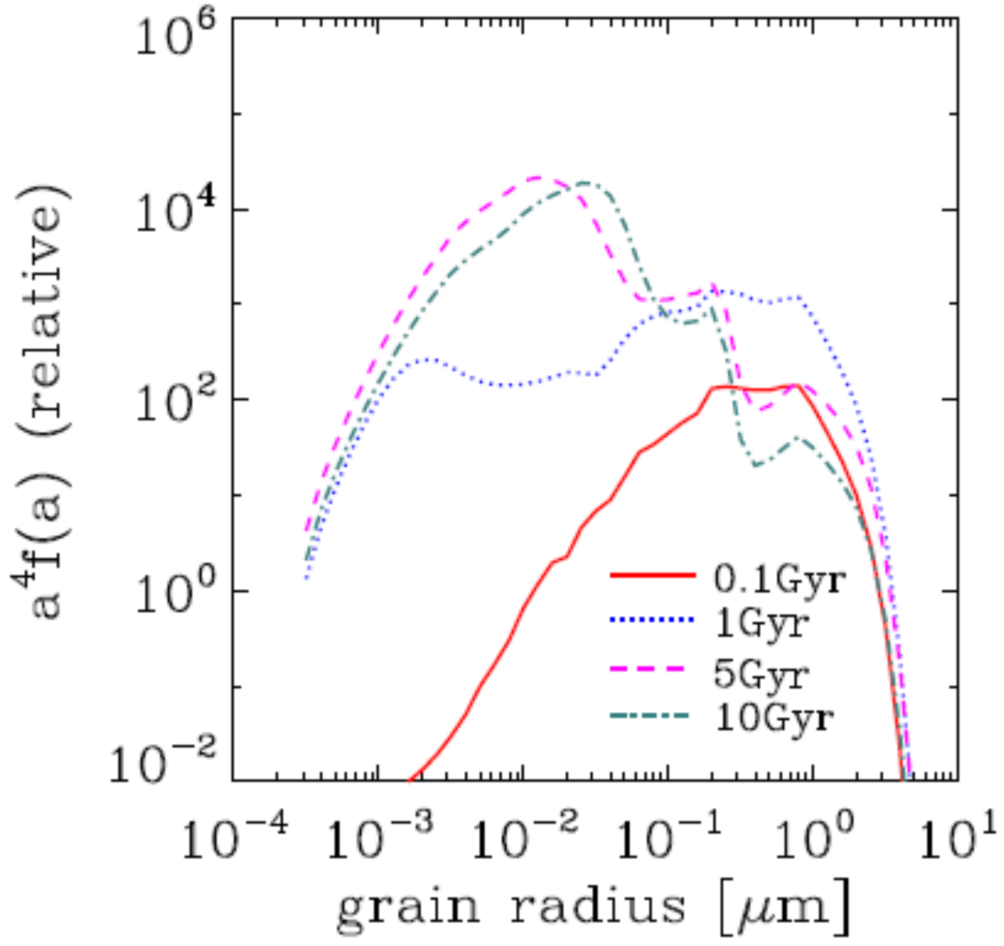


(Burgarella et al. 2013)

In most of the cosmic history, the hidden SF is a major player.

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



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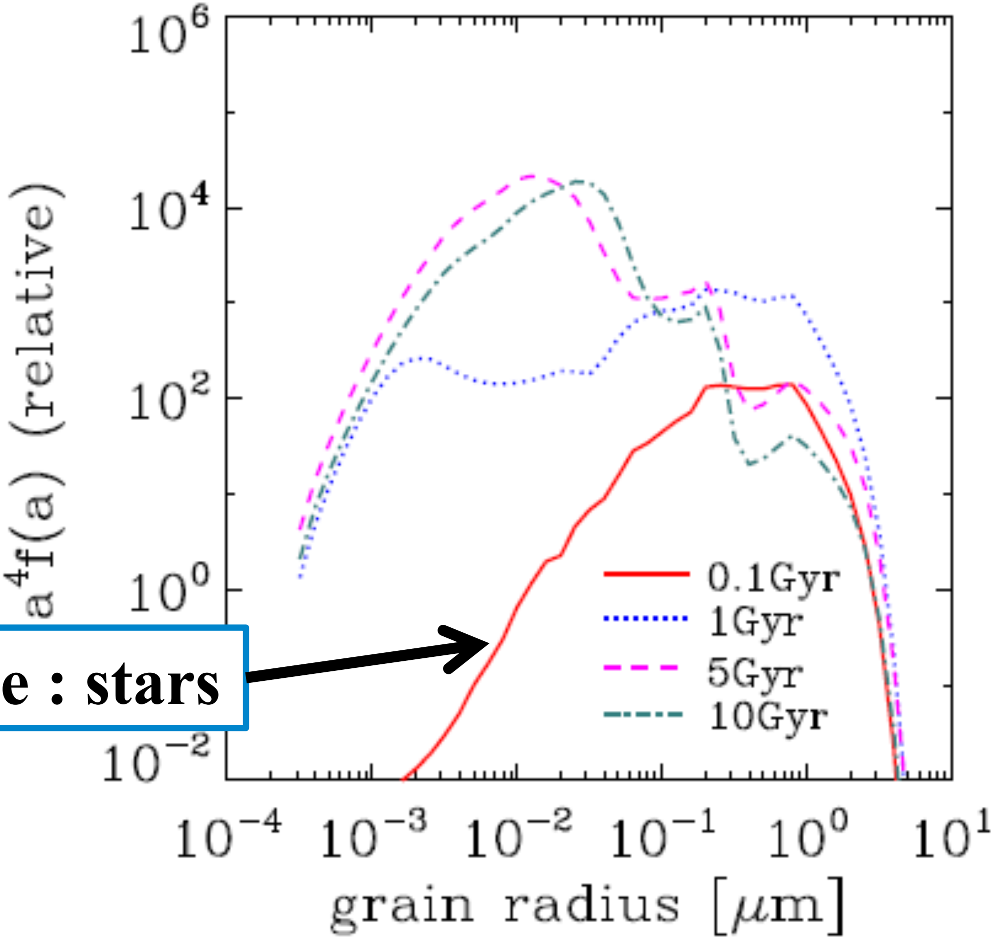
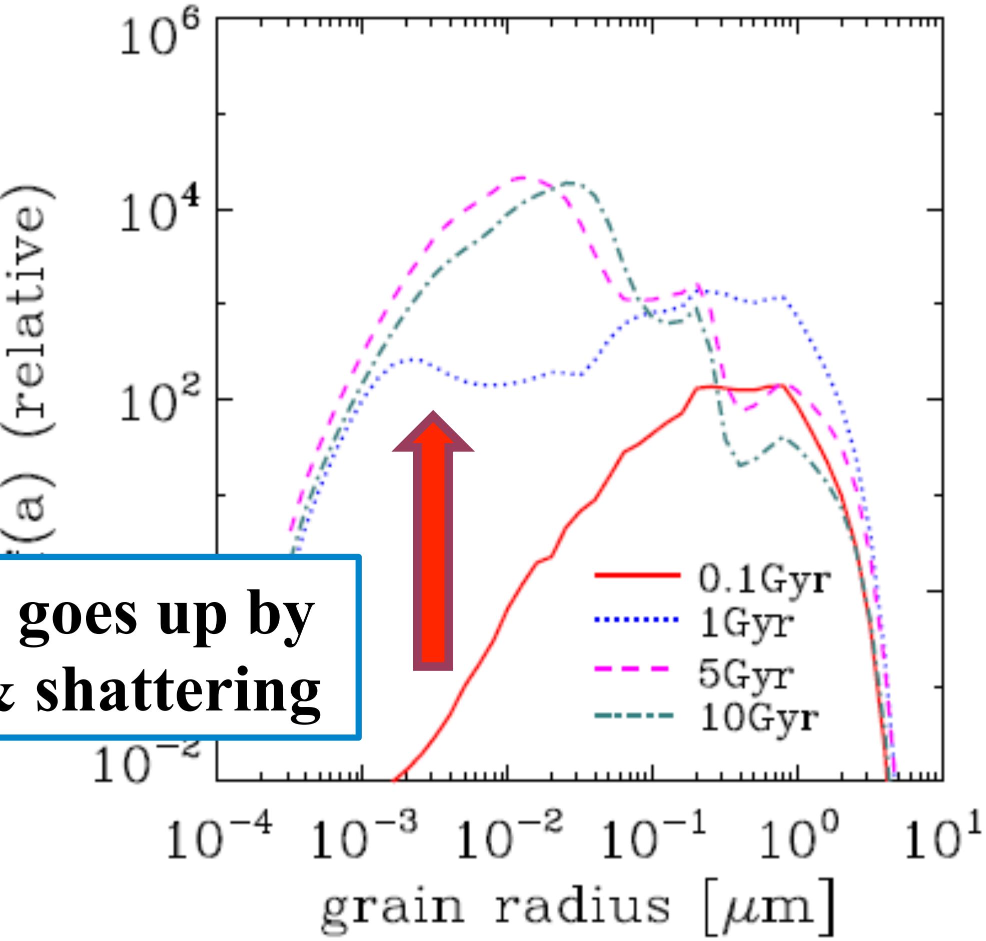


Early stage : stars

Evolution of the grain size distribution

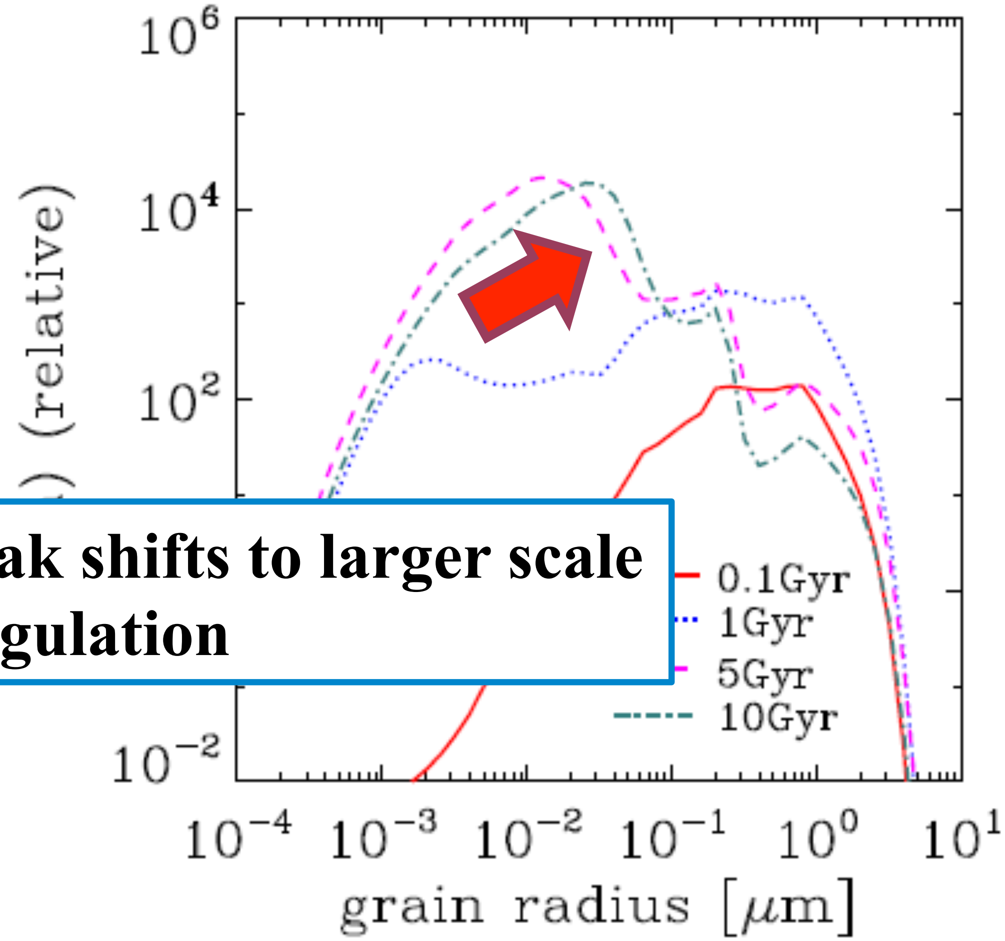
Parameter setting :
Total baryon mass : 10^{10} $M_{\odot}$
Star formation timescale :
5 Gyr
CNM mass fraction : 0.5
WNM mass fraction : 0.5



Small scale goes up by accretion & shattering

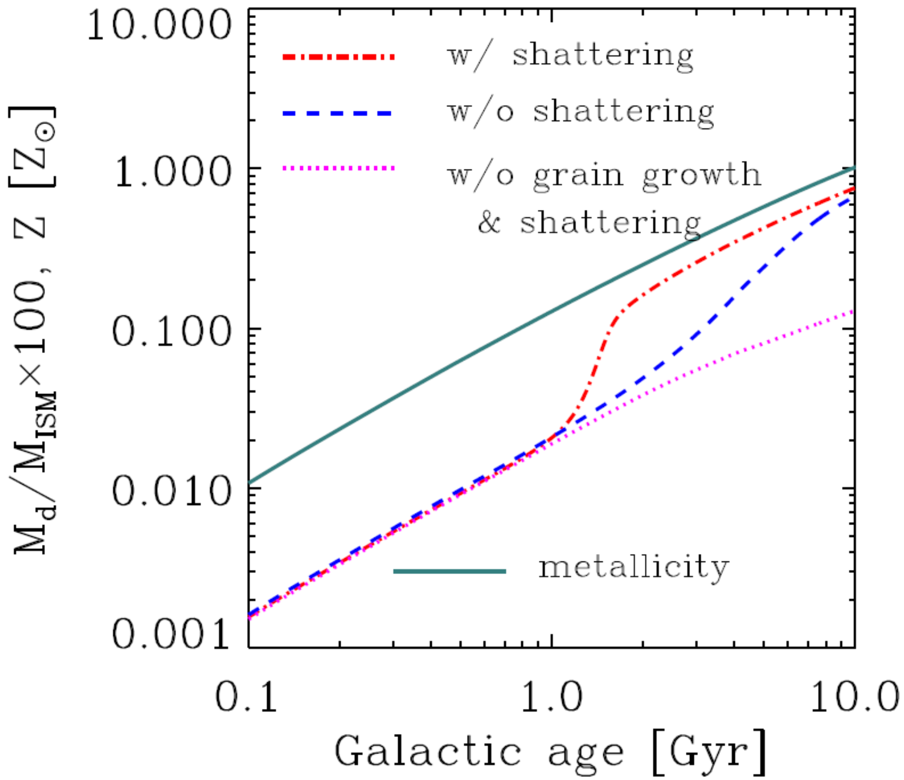
Evolution of the grain size distribution

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

Effect of the evolution of the grain size distribution in galaxies

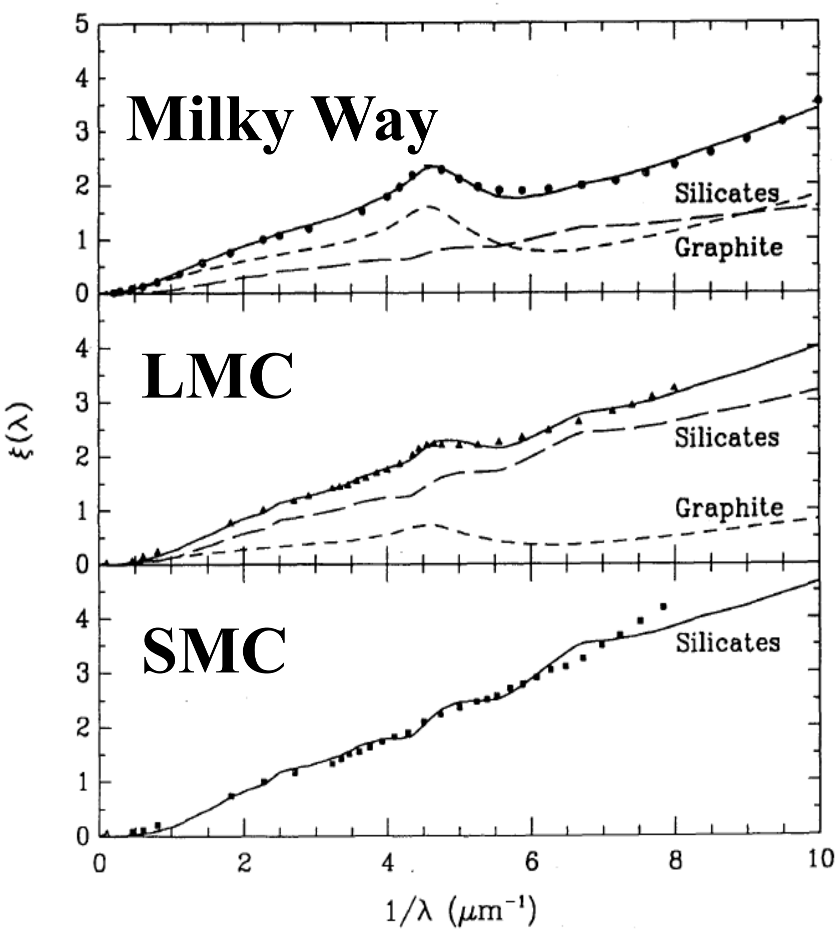


Small grains production by shattering activates grain growth

3.2 Evolution of the extinction curve in galaxies

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

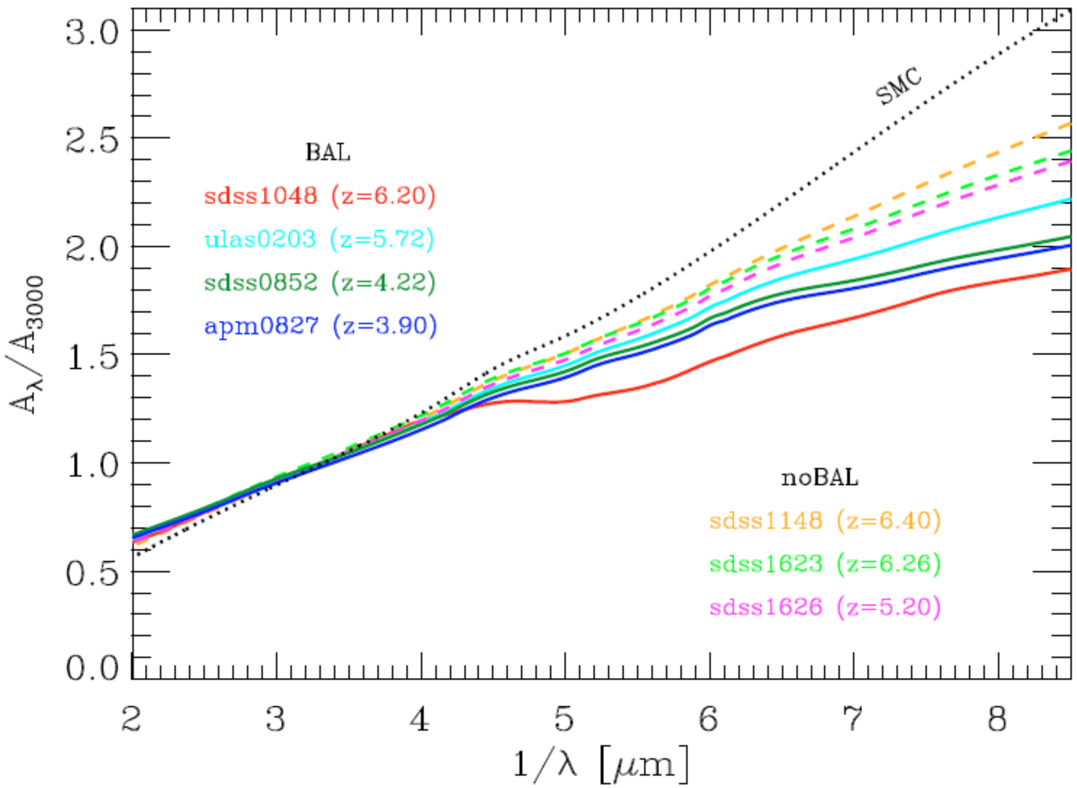
Component

Carbonaceous

Silicate

Extinction curve and dust properties

High-*z* quasars



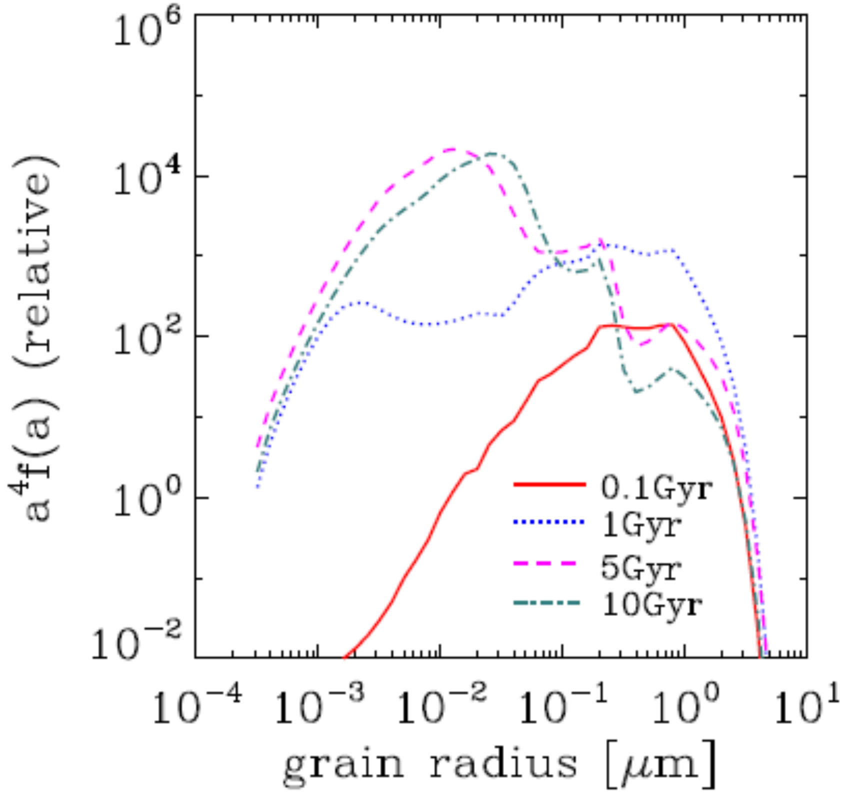
Different from nearby galaxies (no bump, flat)

Different origin of dust grains and processing mechanism

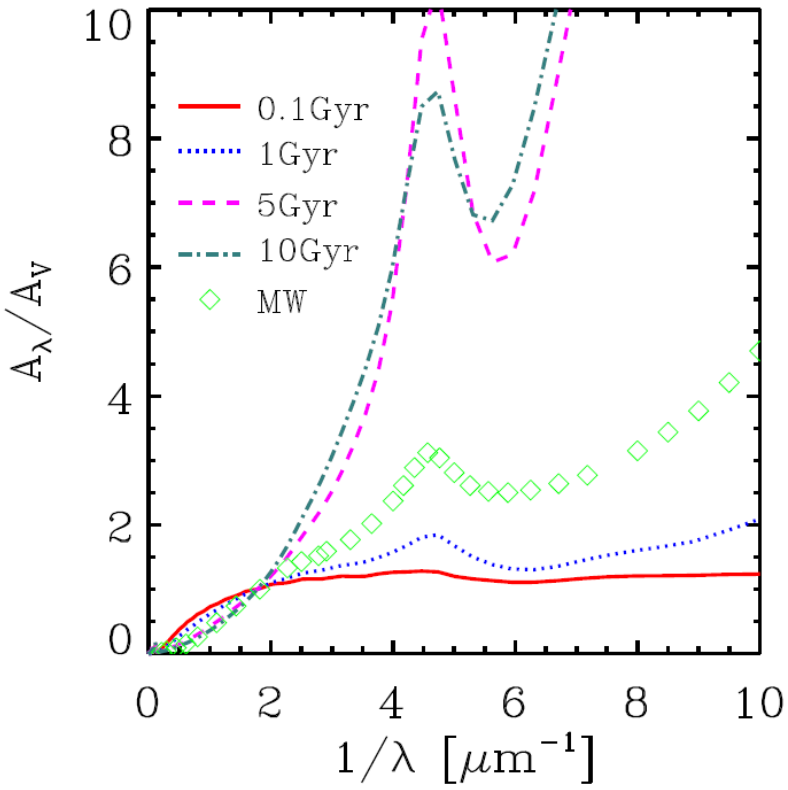
Gallerani et al. (2010)

Evolution of the extinction curve in galaxies

Size distribution

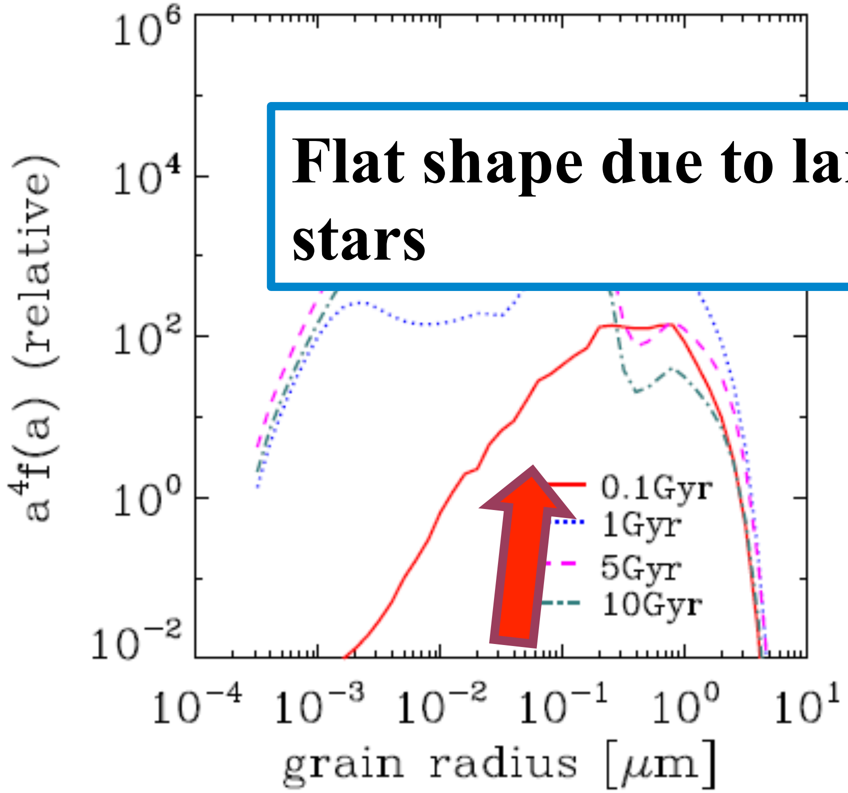


Extinction curve

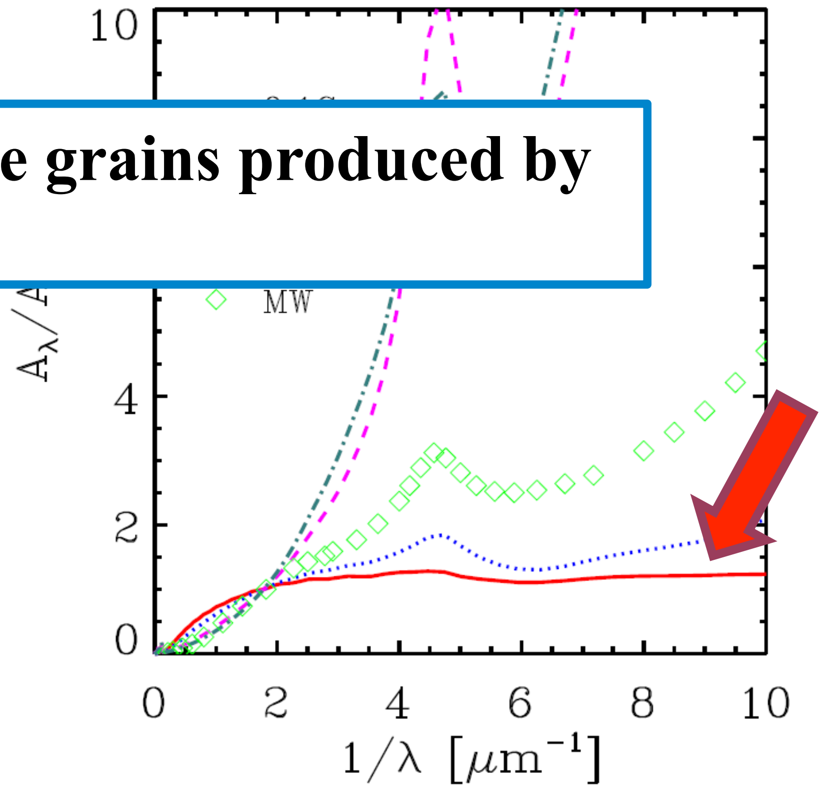


Evolution of the extinction curve in galaxies

Size distribution



Extinction curve

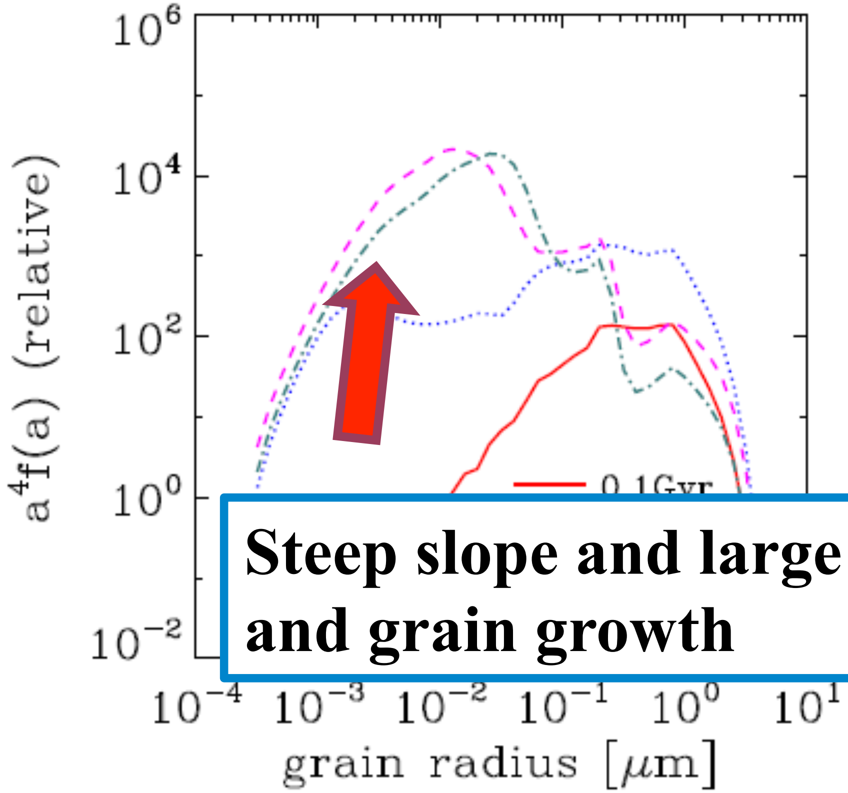


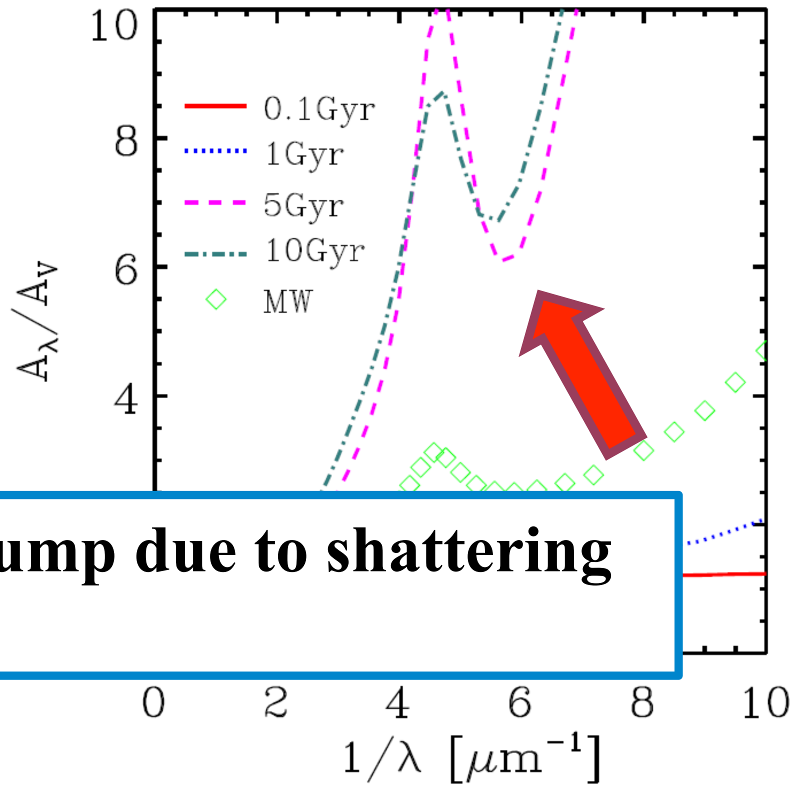
Flat shape due to large grains produced by stars

Evolution of the extinction curve in galaxies

Size distribution

Extinction curve

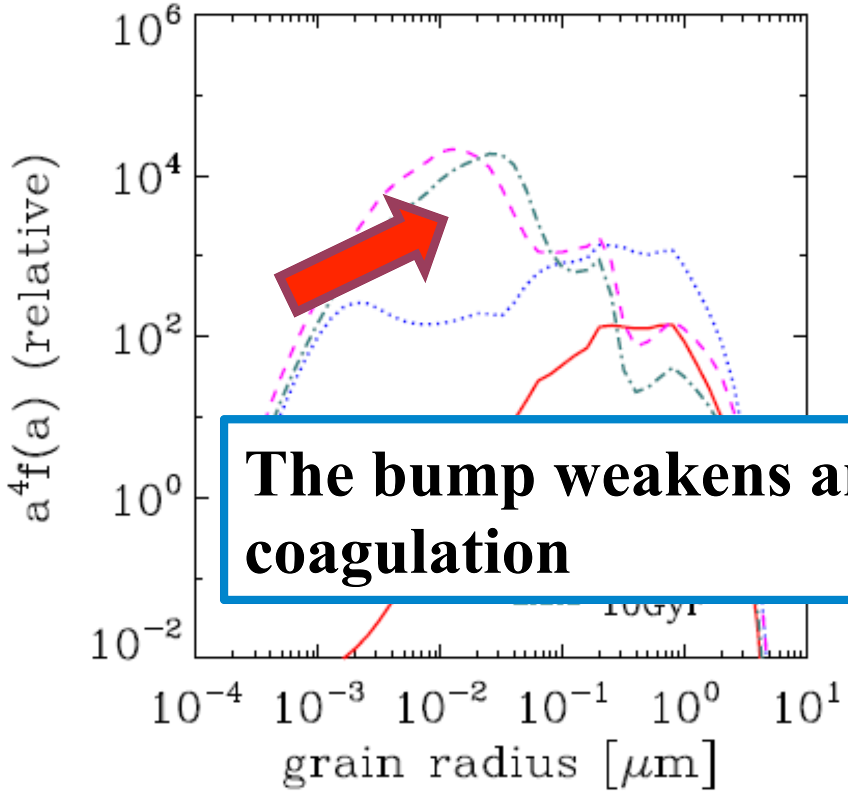




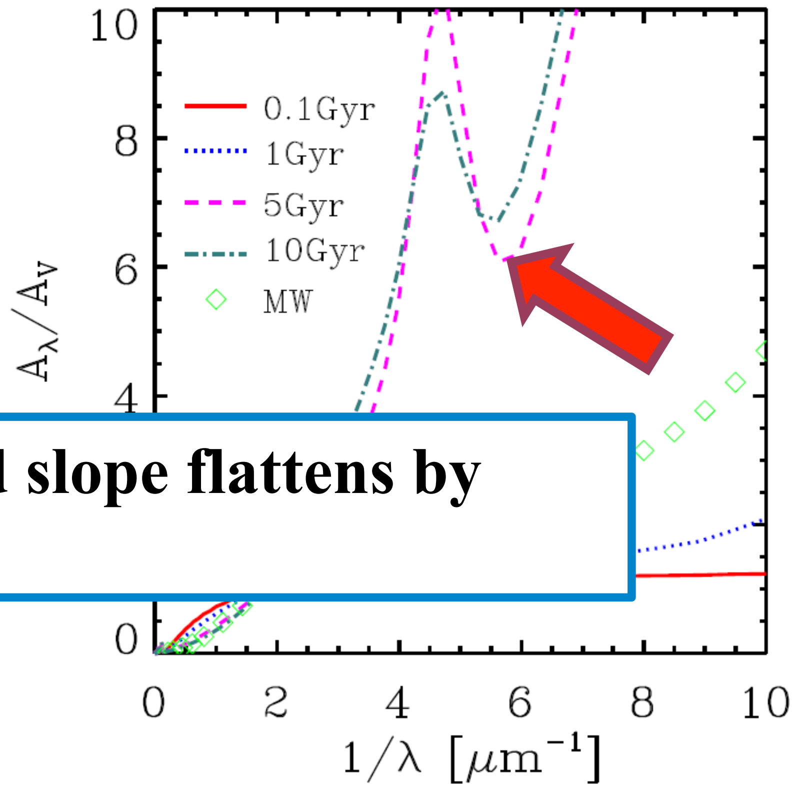
Steep slope and large bump due to shattering and grain growth

Evolution of the extinction curve in galaxies

Size distribution



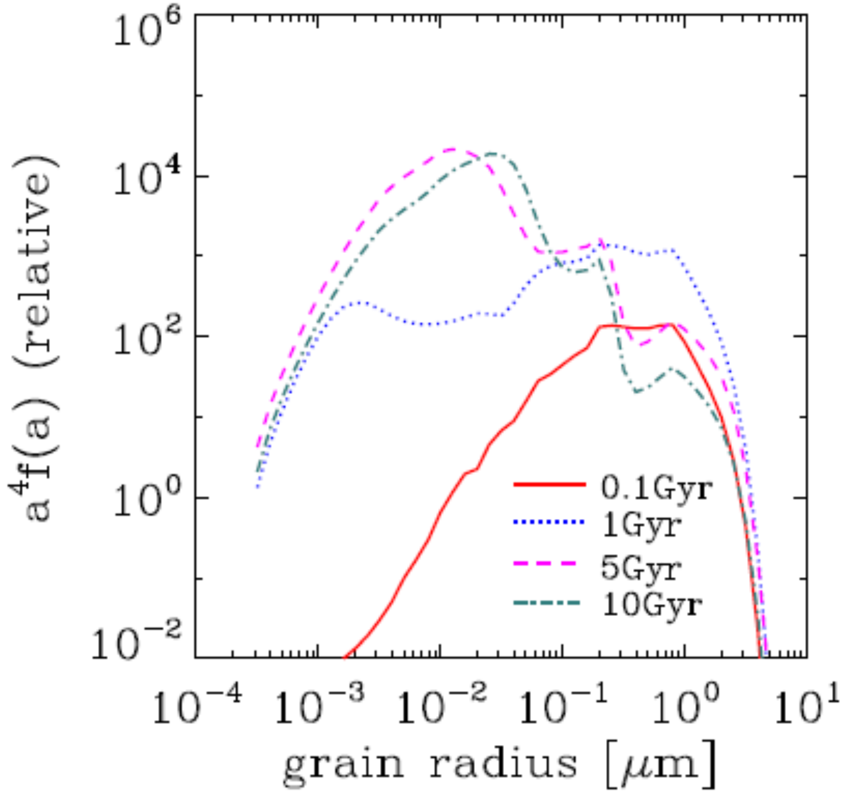
Extinction curve



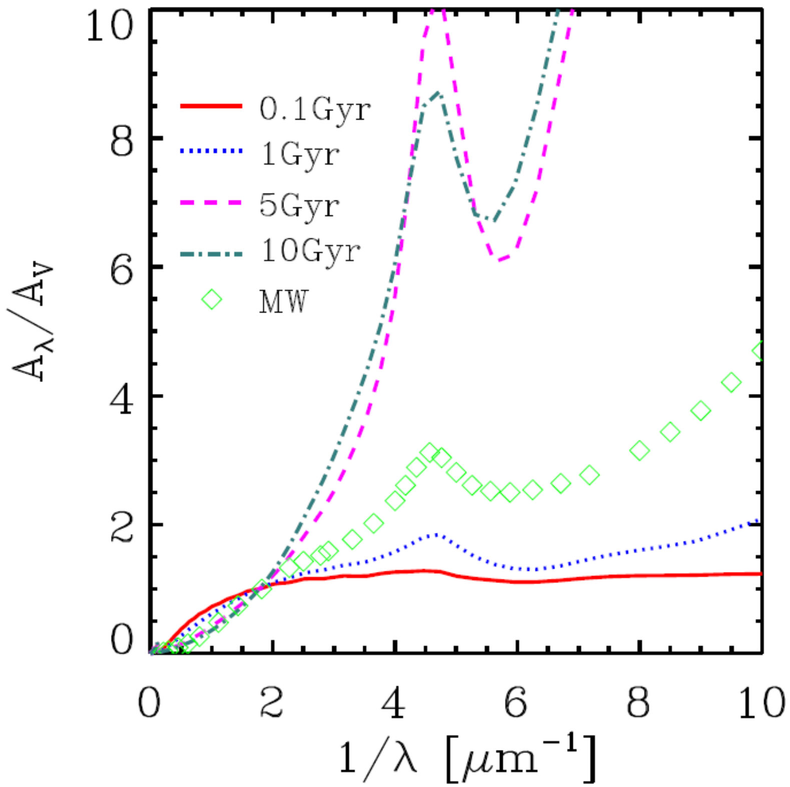
The bump weakens and slope flattens by coagulation

Evolution of the extinction curve in galaxies

Size distribution



Extinction curve



The extinction curve drastically changes through the galaxy evolution!