Importance of Dust in the Evolution of Galaxies: Prospect for SPICA

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On behalf of the Sub Working Group for the Evolution of Galaxies and Black Holes, SPICA Science Working Group

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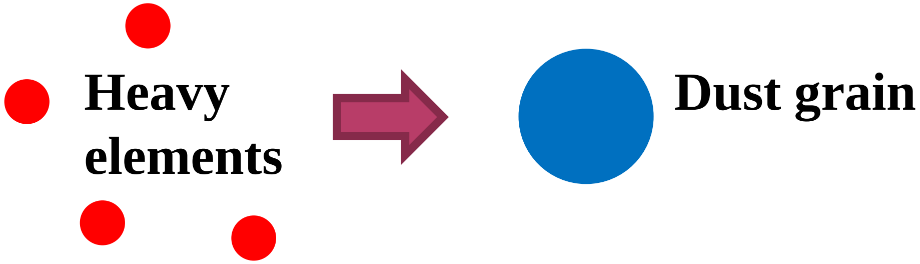
1. Introduction

What are dust grains?

Dust grains are

- **formed by condensation of heavy elements.**



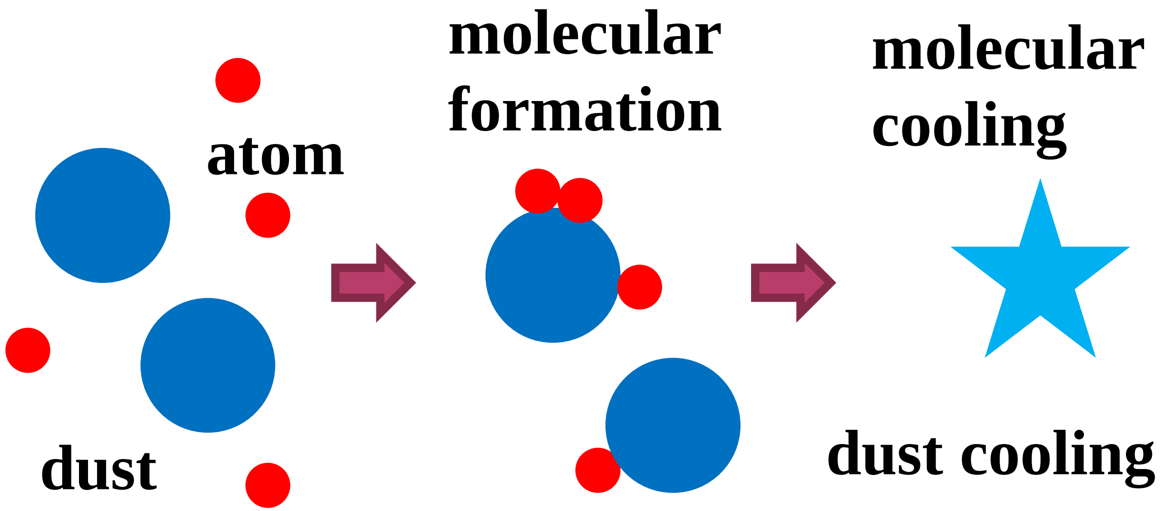
Heavy elements are supplied only by stars.

- **tightly connected to galaxy evolution**

There are many important physical quantities affected by dust.

Role of dust for the first star formation

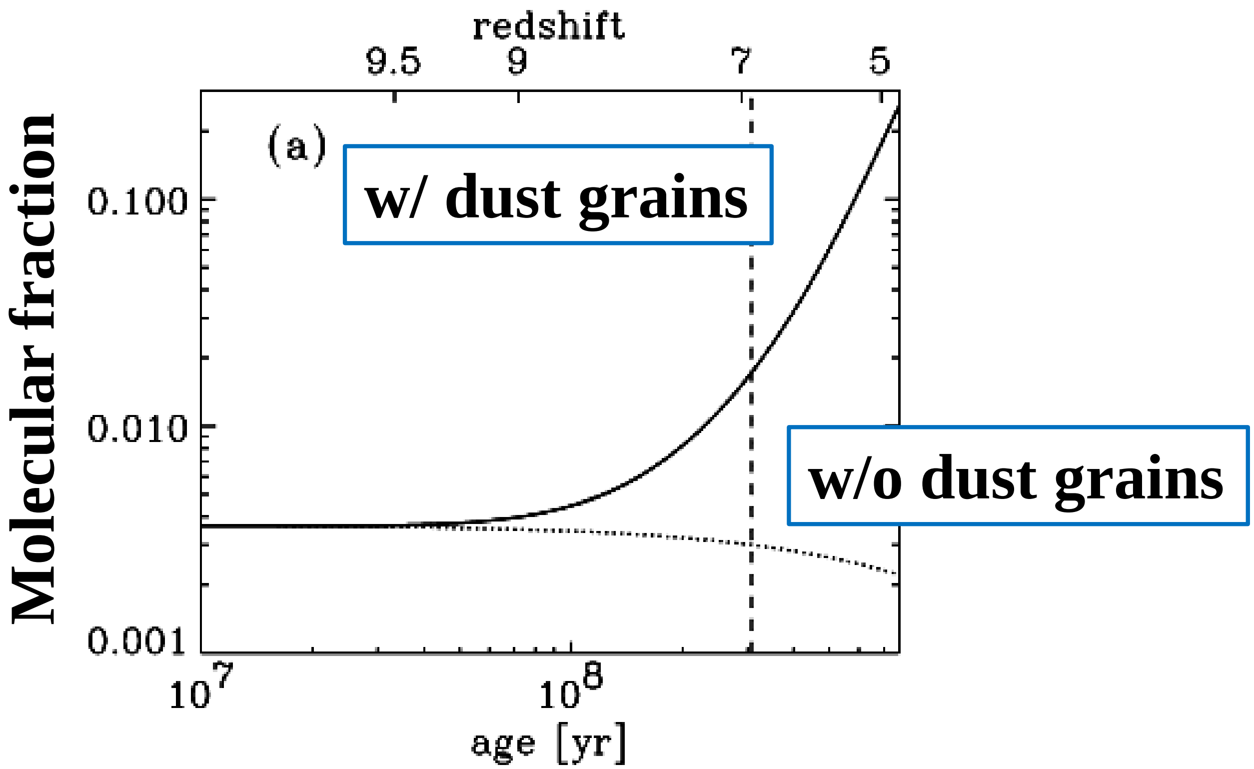
Surface of dust grains



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

Role of dust for the first star formation

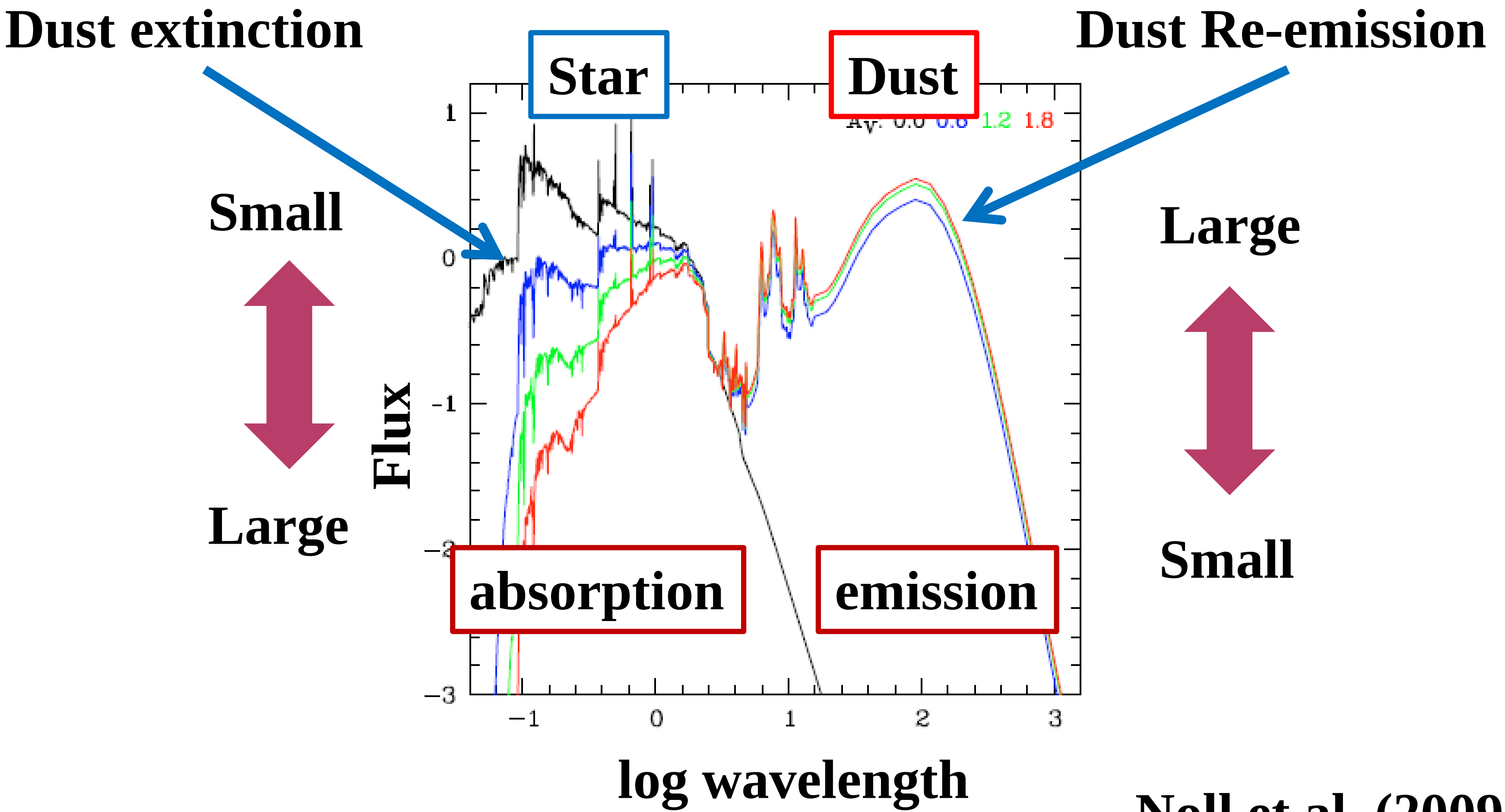
Surface of dust grains



Hirashita & Ferrara (2002)

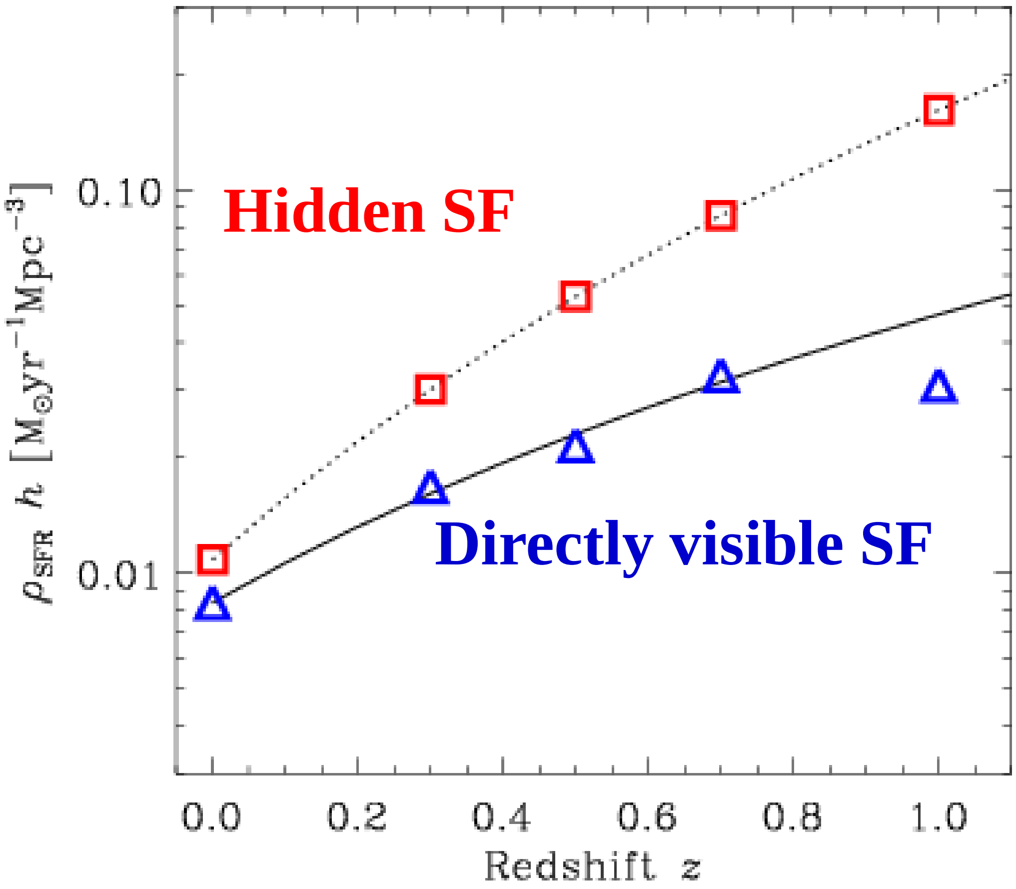
Dust grains drive the star formation.

Spectral energy distribution (SED)



Noll et al. (2009)

The hidden star formation in the Cosmic history

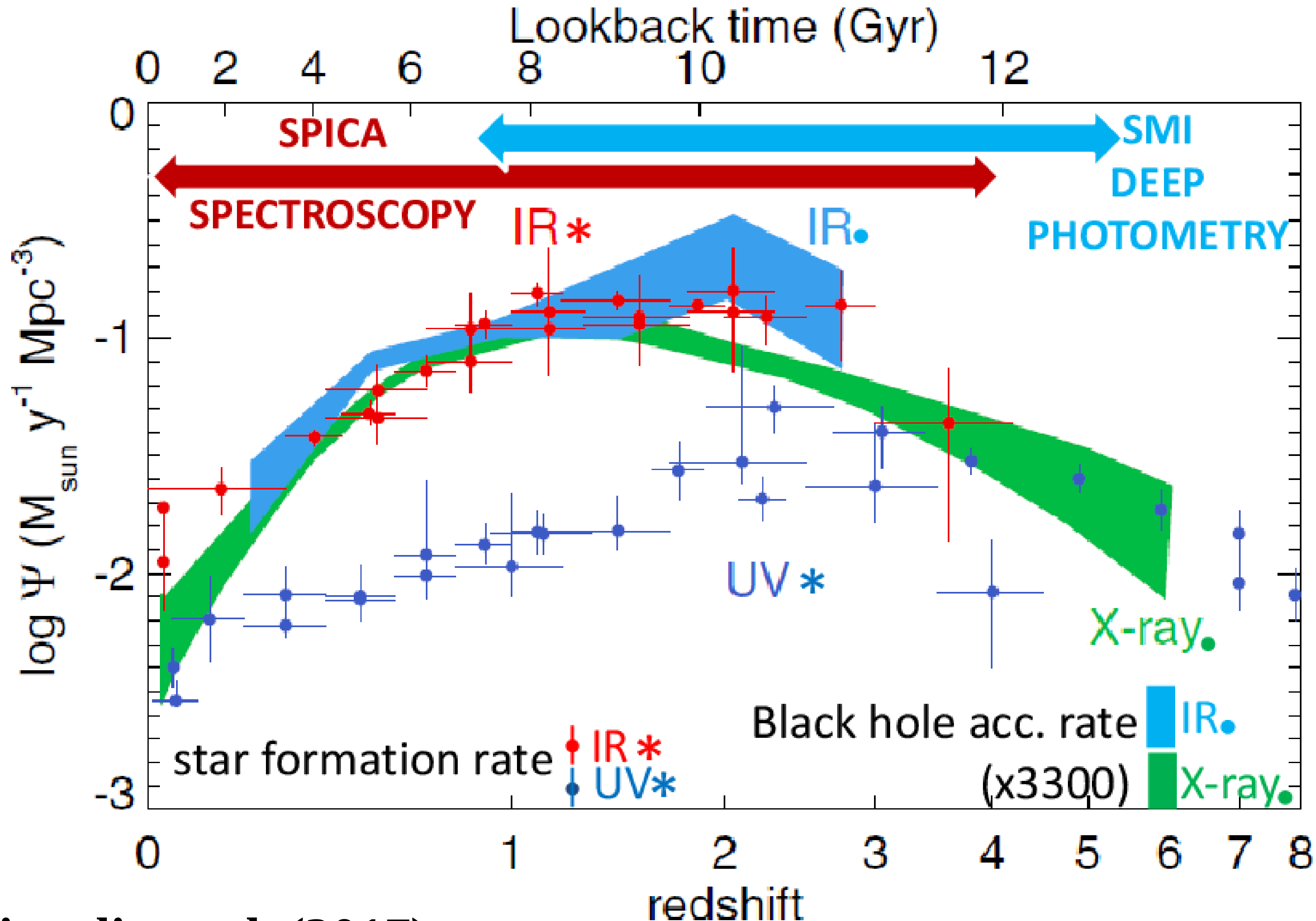


Takeuchi et al. (2005)

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.**

The hidden star formation in the Cosmic history



Spinoglio et al. (2017)

Understanding of dust so far

1. **Dust exists?**

2. **Does it play any role?**

3. **Is the role in galaxy evolution fundamental?**

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   Yes, at almost all redshifts.

2. **Does it play any role?**

3. **Is the role in galaxy evolution fundamental?**

Understanding of dust so far

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   Yes, at almost all redshifts.

2. **Does it play any role?**

   Yes, molecular formation, extinction, thermal processes in the ISM, etc.

3. **Is the role in galaxy evolution fundamental?**

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3. **Is the role in galaxy evolution fundamental?**

   Yes, dust is rather a leading player in galaxy evolution.

Understanding of dust so far

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   Yes, at almost all redshifts.

2. **Does it play any role?**

   Yes, molecular formation, extinction, thermal processes in the ISM, etc.

3. **Is the role in galaxy evolution fundamental?**

   Yes, dust is rather a leading player in galaxy evolution.

Qualitatively, these questions are already answered.

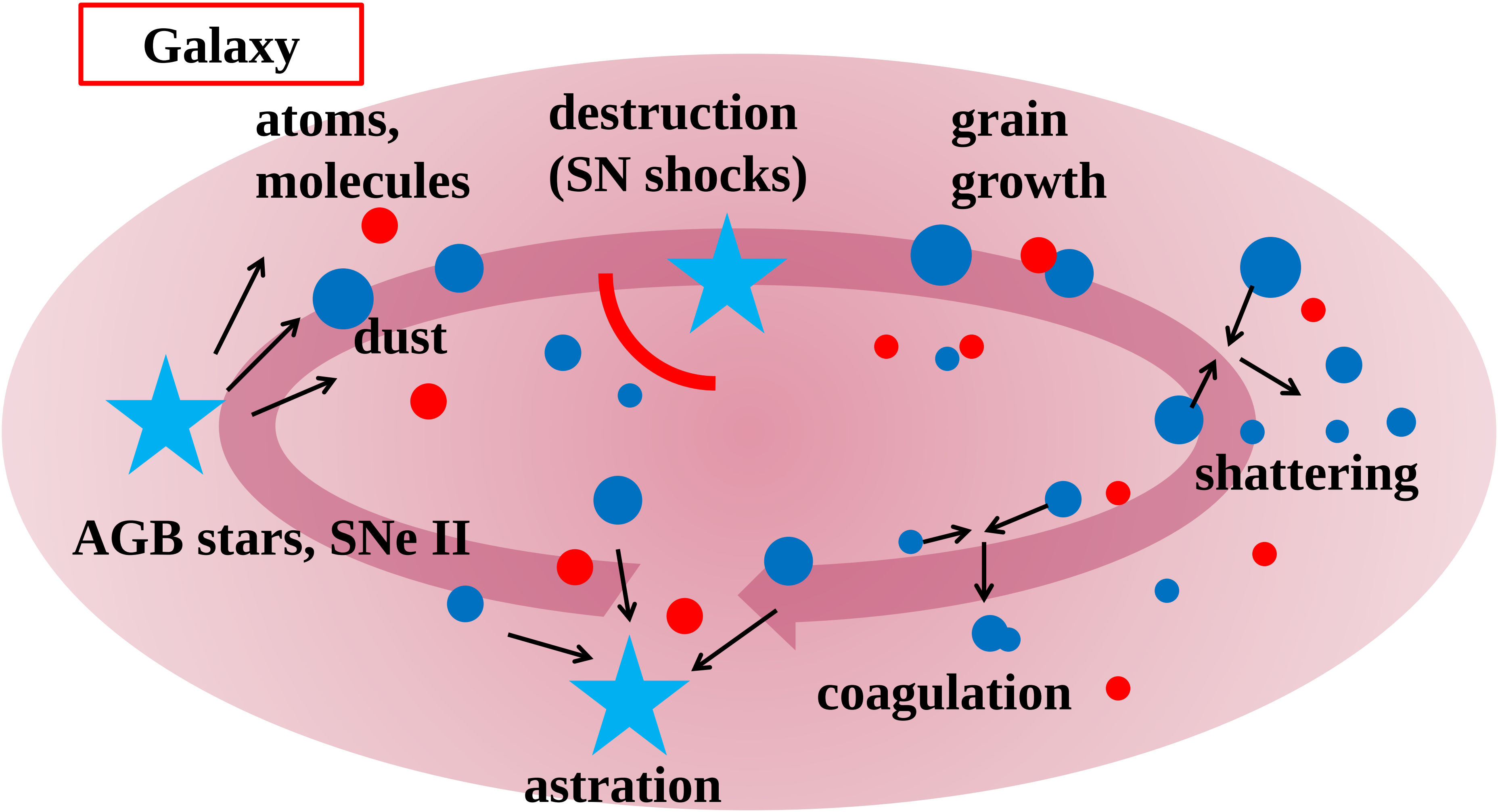
What is next?

5W1H

about dust.

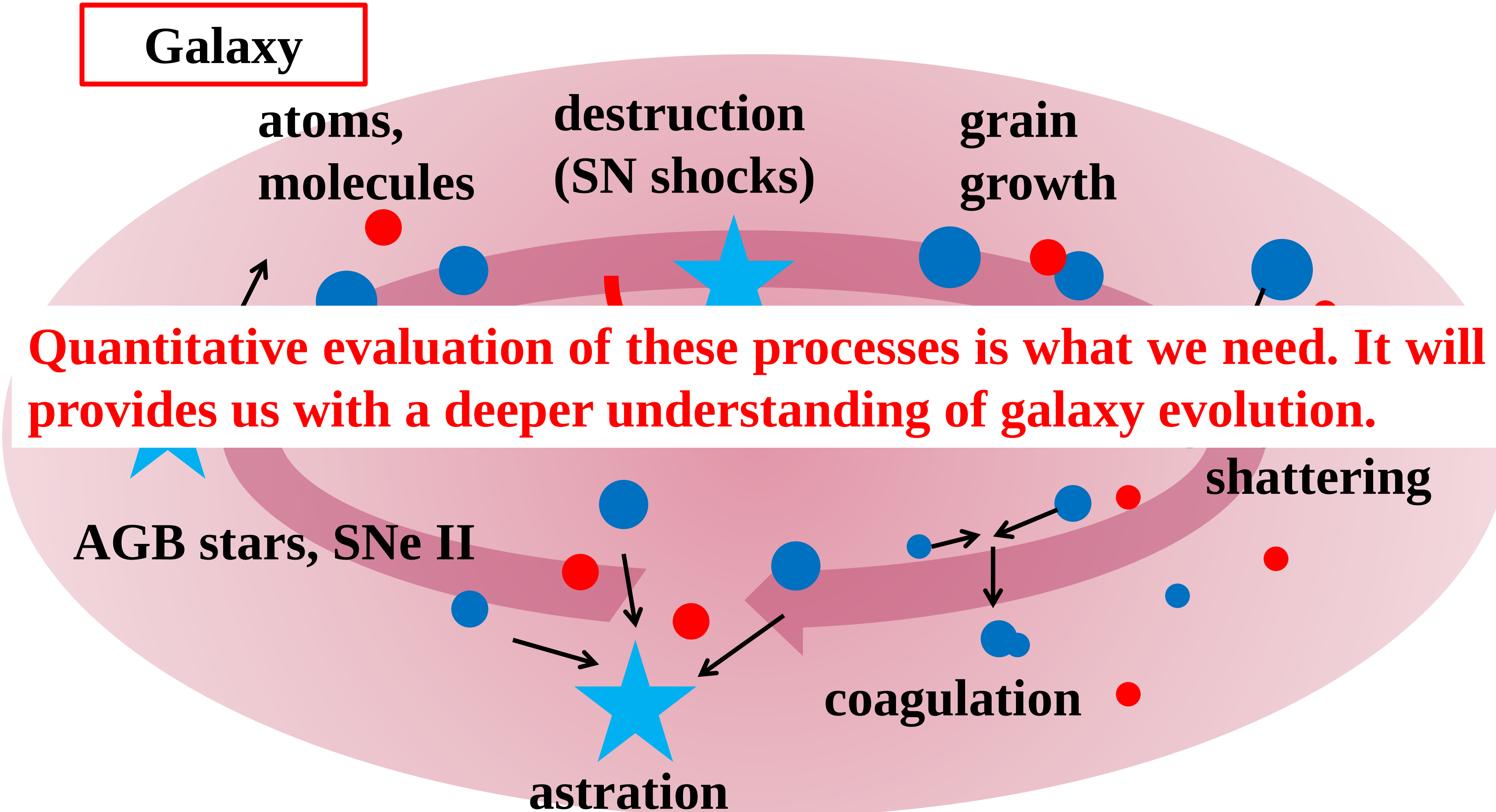
We should answer these questions quantitatively with SPICA.

Dust and matter circulation in a galaxy



Asano (2014) PhD Thesis

Dust and matter circulation in a galaxy



Quantitative evaluation of these processes is what we need. It will provides us with a deeper understanding of galaxy evolution.

Asano (2014) PhD Thesis

3. Evolution of the Total Dust Amount

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

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

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

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

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

$$Z \equiv M_Z/M_{\mathrm{ISM}}$$

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

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

3. Evolution of the Total Dust Amount

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

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

3. Evolution of the Total Dust Amount

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Closed-box model is assumed. For the extension to include infall, we discuss later.

Star formation law

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

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

This determines the SFH. This gives a simple picture on the star formation.

Timescales of dust destruction and grain growth

Dust destruction by SN shocks in the ISM

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

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

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

$\bar{a}$: mean grain size

$n_{\rm H}$: number density of the ISM

T : ISM temperature

Timescales of dust destruction and grain growth

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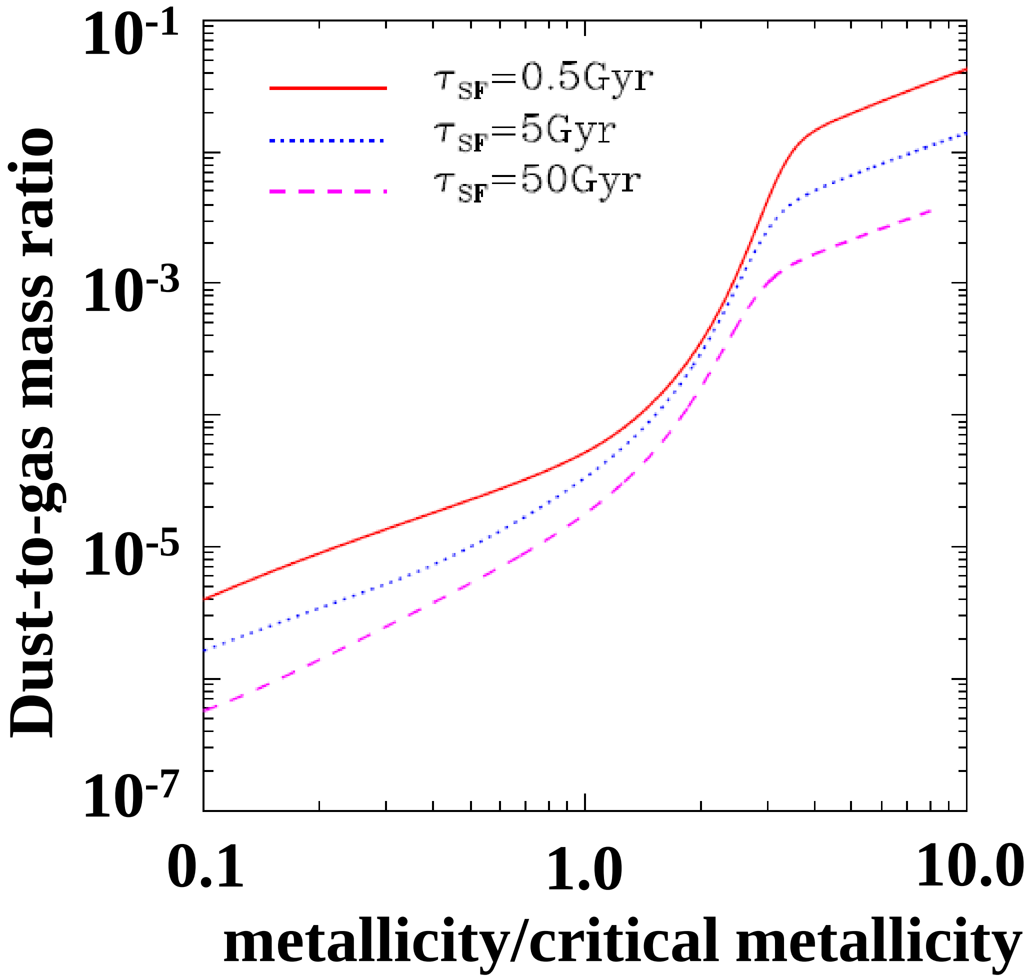
Critical metallicity for grain growth



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.

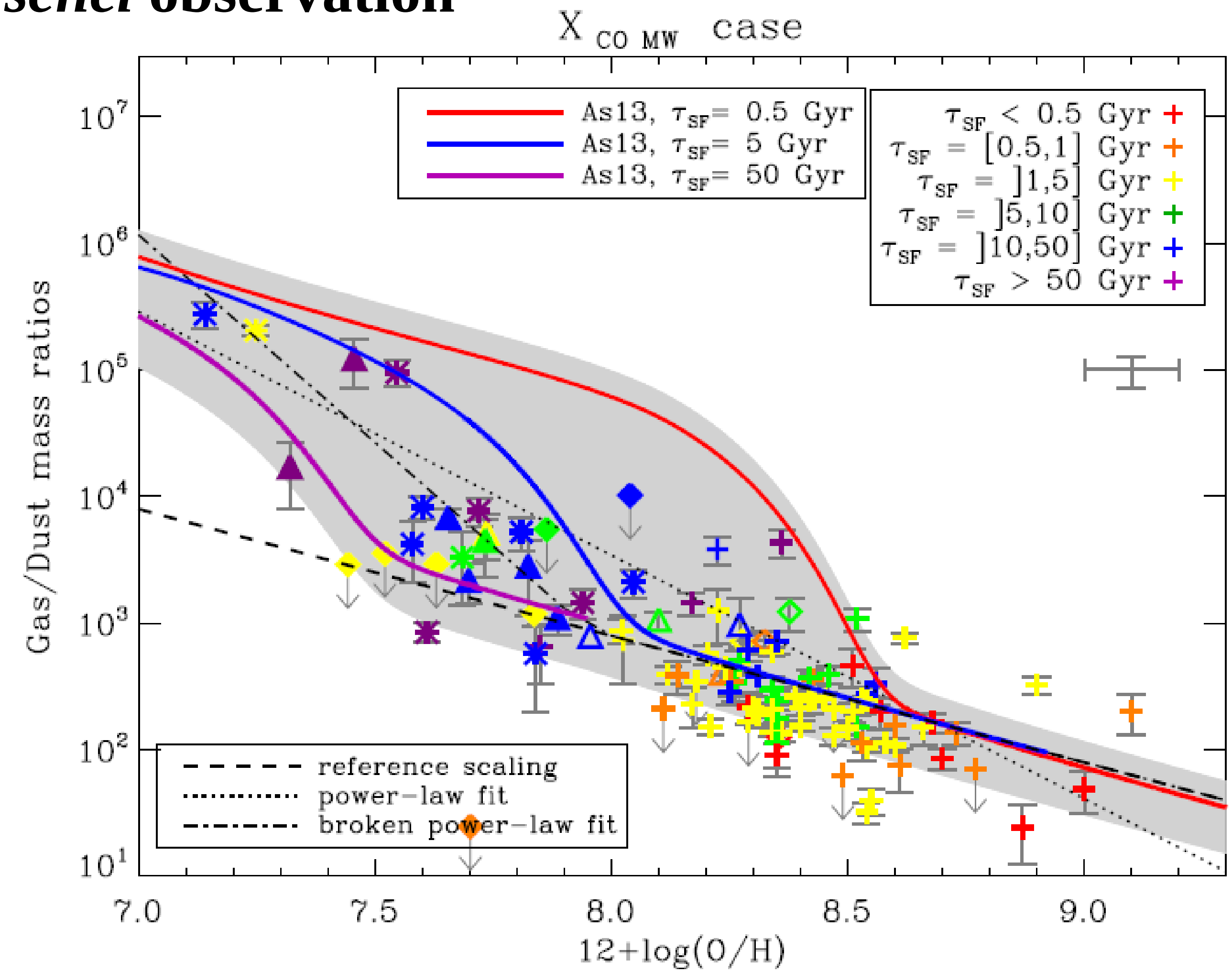
Critical metallicity for grain growth

$$Z_{\rm cr} = \left[\frac{\mathcal{D}}{\eta\delta(1-\delta)}\right]^{\frac{1}{2}} \left(\frac{\tau_{\rm acc}}{\tau_{\rm SF}}\right)^{\frac{1}{2}}$$

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

Application to the observed data

Herschel observation



Rémy-Ruyer et al. (2014)

4. 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**

- **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 $[a, a+\mathrm{d}a]$ at a galactic age t

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

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

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

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

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

Asano et al. (2013b)

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

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

Stellar effects

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

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

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

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Destruction by SN shocks

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

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Asano et al. (2013b)

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

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

Grain growth

Asano et al. (2013b)

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\end{aligned}
$$

Shattering

Asano et al. (2013b)

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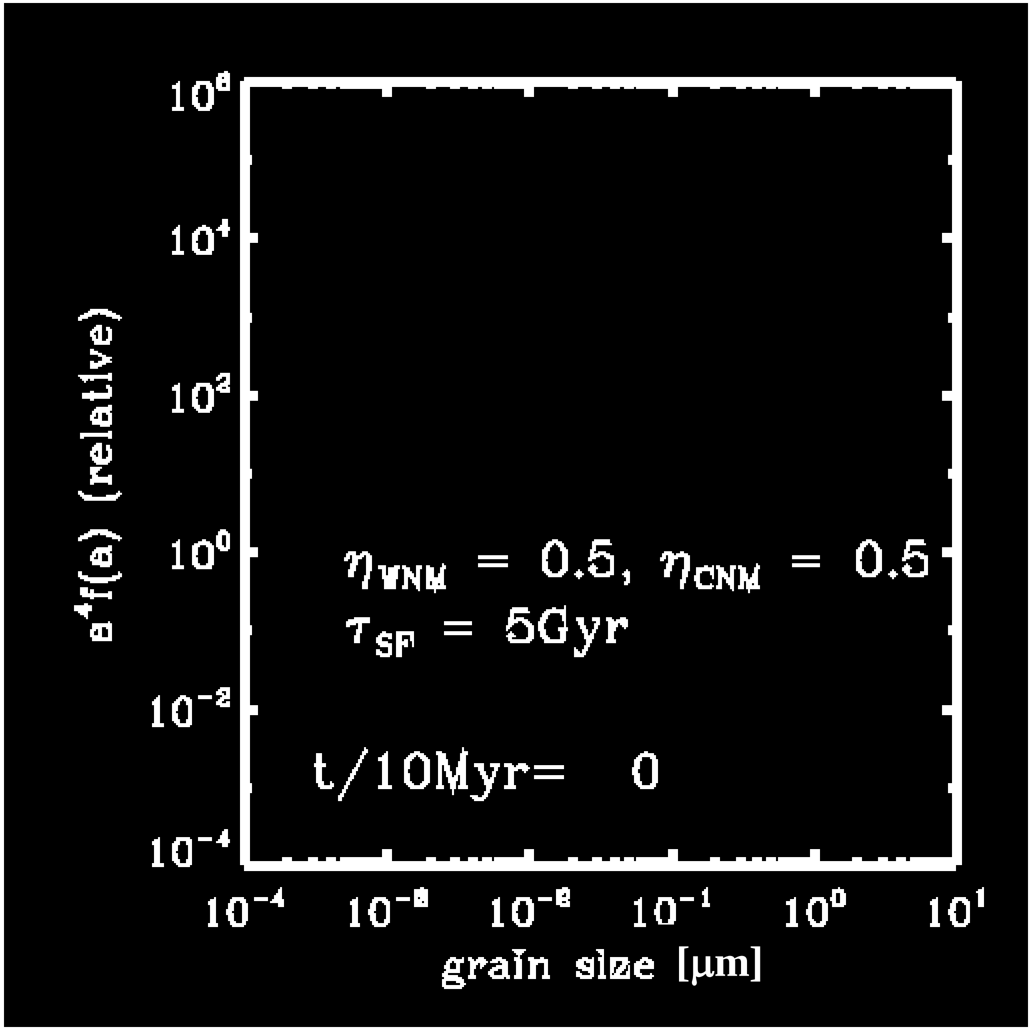
\end{aligned}
$$

Coagulation

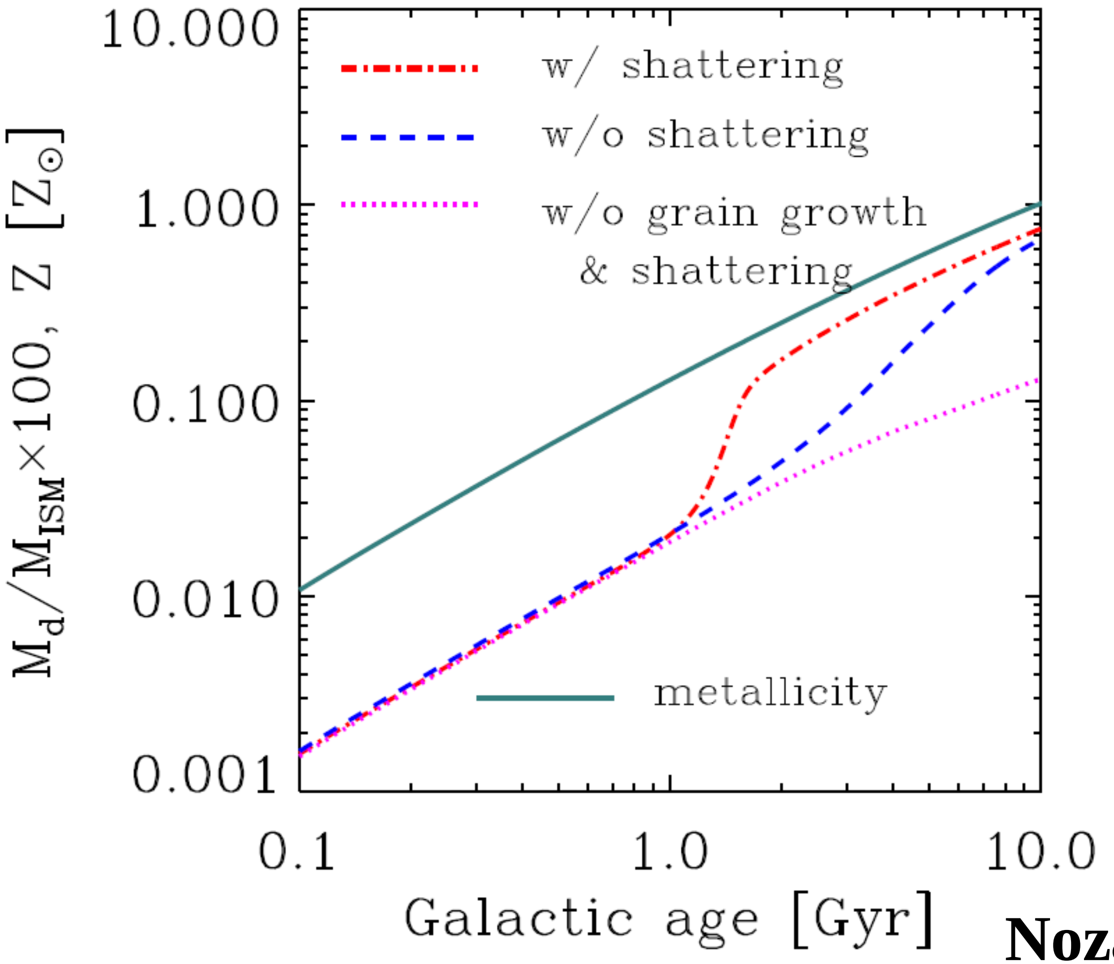
Asano et al. (2013b)

Evolution of the grain size distribution



Asano et al. (2013b)

Effect of the evolution of the grain size distribution in galaxies

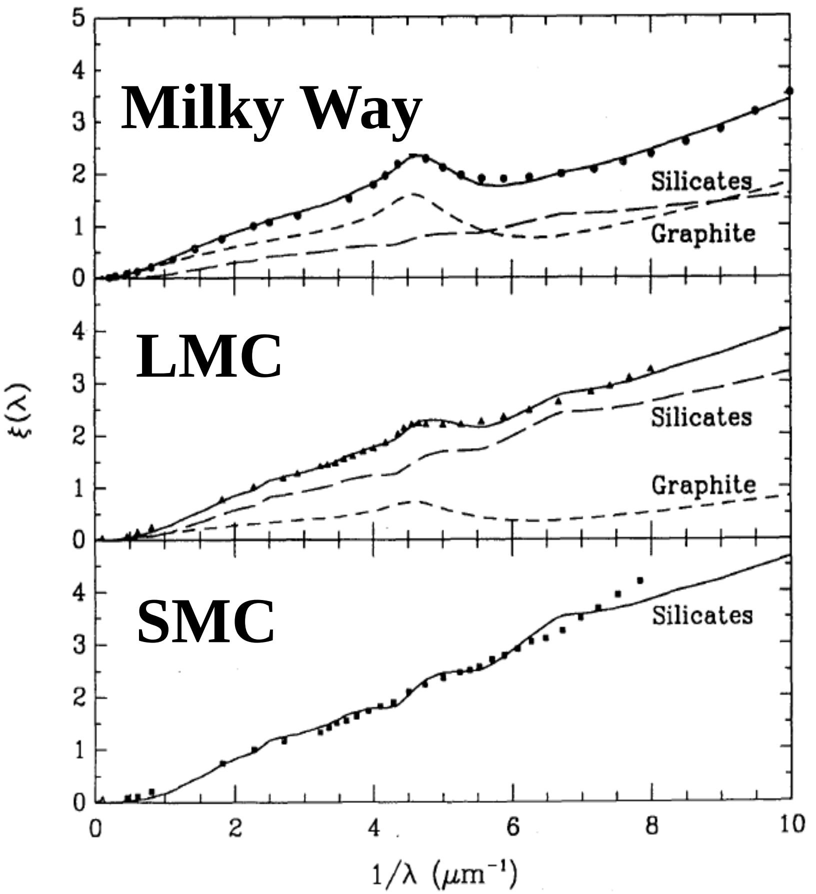


Nozawa et al. (2015)

Small grains production by shattering activates grain growth.

5. Evolution of Extinction Curve

Nearby galaxies



Pei (1992)

By fitting:

Grain size distribution

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

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

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

Mathis et al., (1977)

Feature

2175 Å bump

UV slope

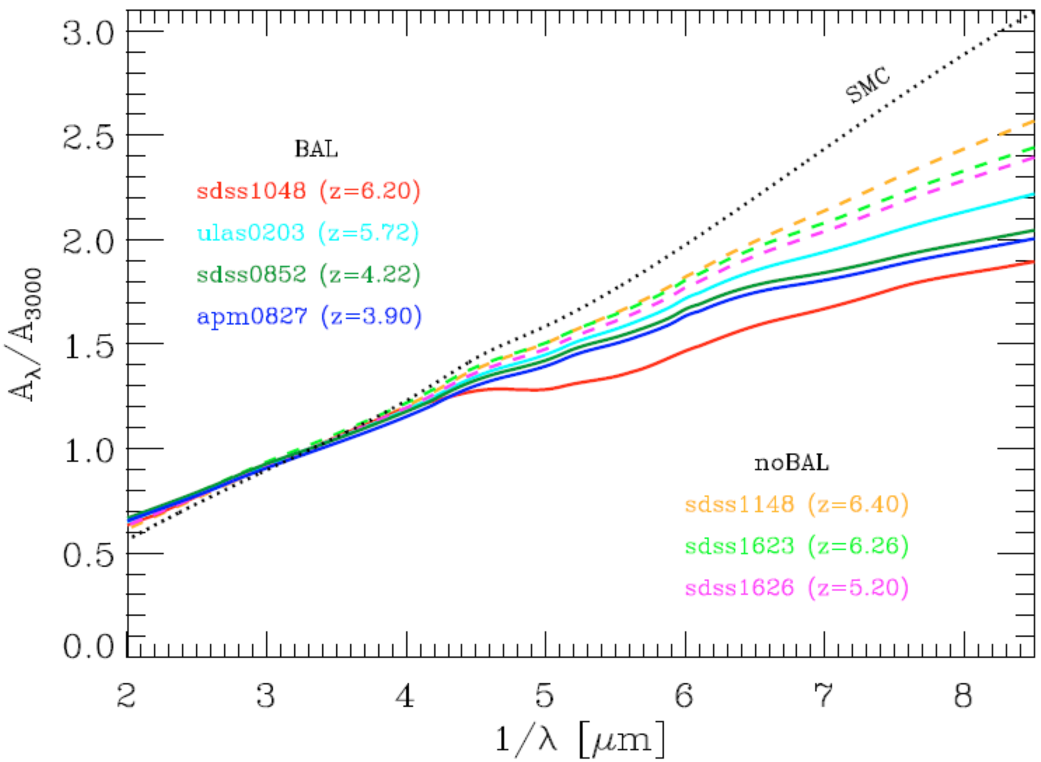
Component

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)

Setting for the calculation of the extinction curve

Extinction in unit of magnitude at a wavelength: A_λ

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

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

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

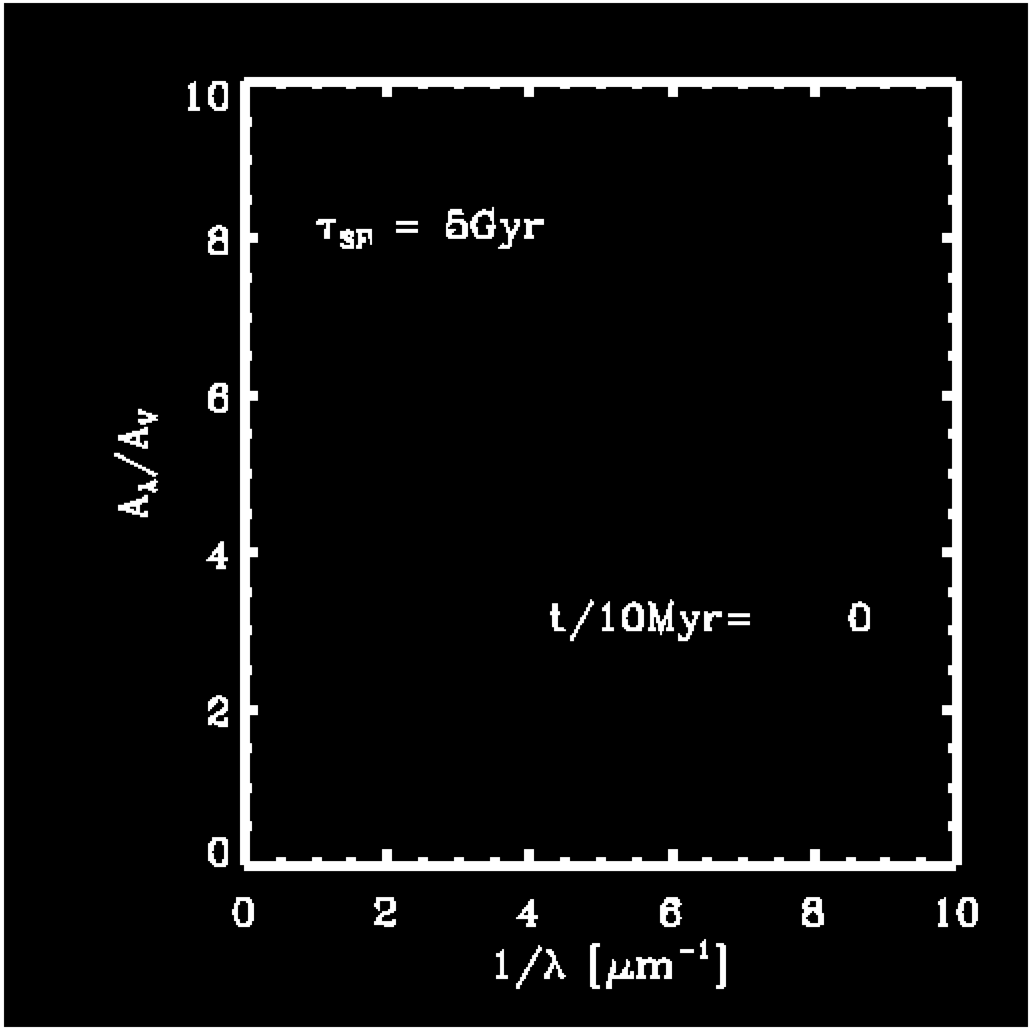
Optical constant:
graphite and astronomical silicate **($Mg_{1.}Fe_{0.9}SiO_4$)**
Draine & Lee (1984)

Grain size distribution:

Evolution model of grain size distribution

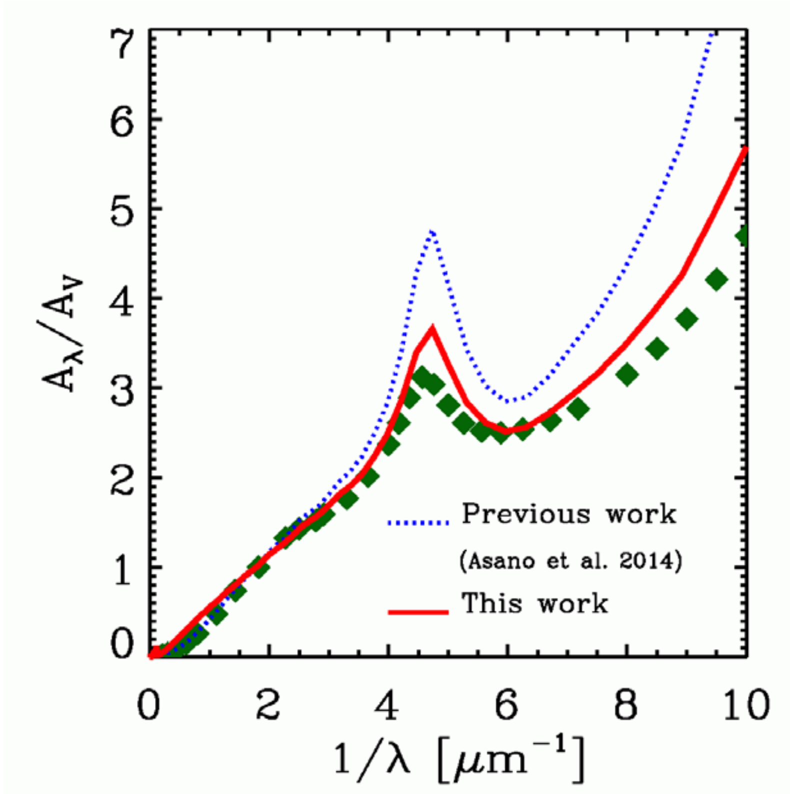
Asano et al. (2013a)

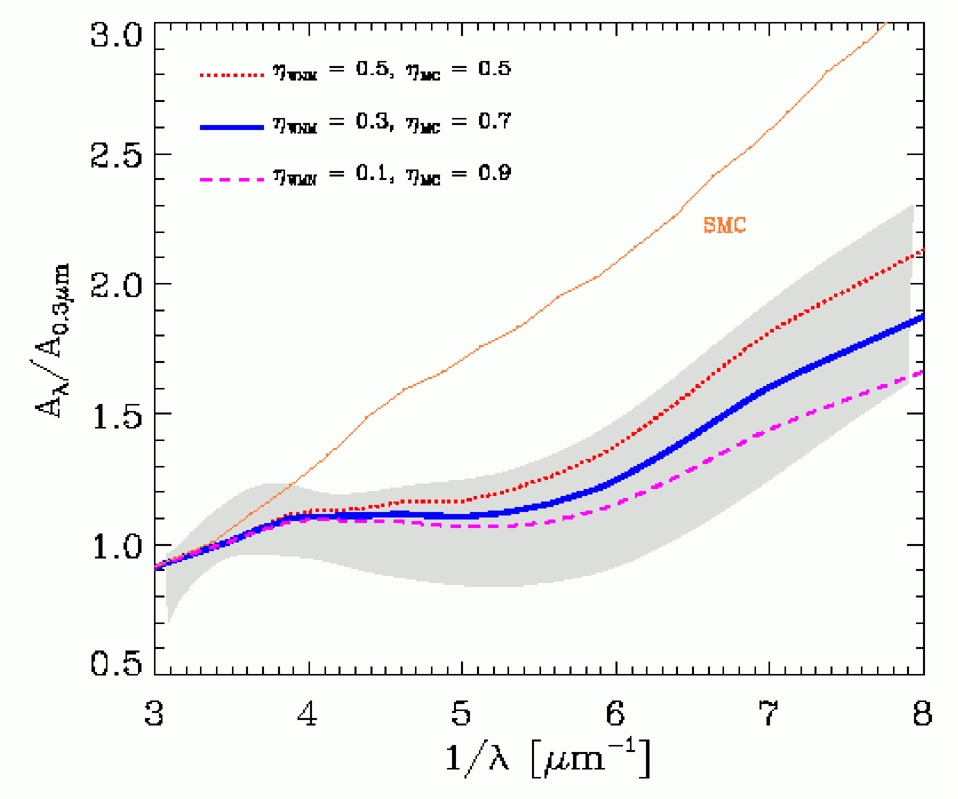
Evolution of the extinction curve in galaxies



Asano et al. (2014)

Application to the Milky Way and a distant quasar





Nozawa et al. (2015)

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

6. Dust Evolution with Infall Model

To treat the chemical evolution of galaxies more realistically, we should consider the effect of infall.

$$M = M_* + M_{\rm ISM}$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \mathcal{F}(t)$$

$\mathcal{F}(t)$ **: Infalling mass**

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

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

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

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

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$$M = M_* + M_{\rm ISM}$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \mathcal{F}(t)$$

$$\mathcal{F}(t) = \frac{M_{\rm in}}{\tau_{\rm in}} e^{-\frac{t}{\tau_{\rm in}}}$$

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

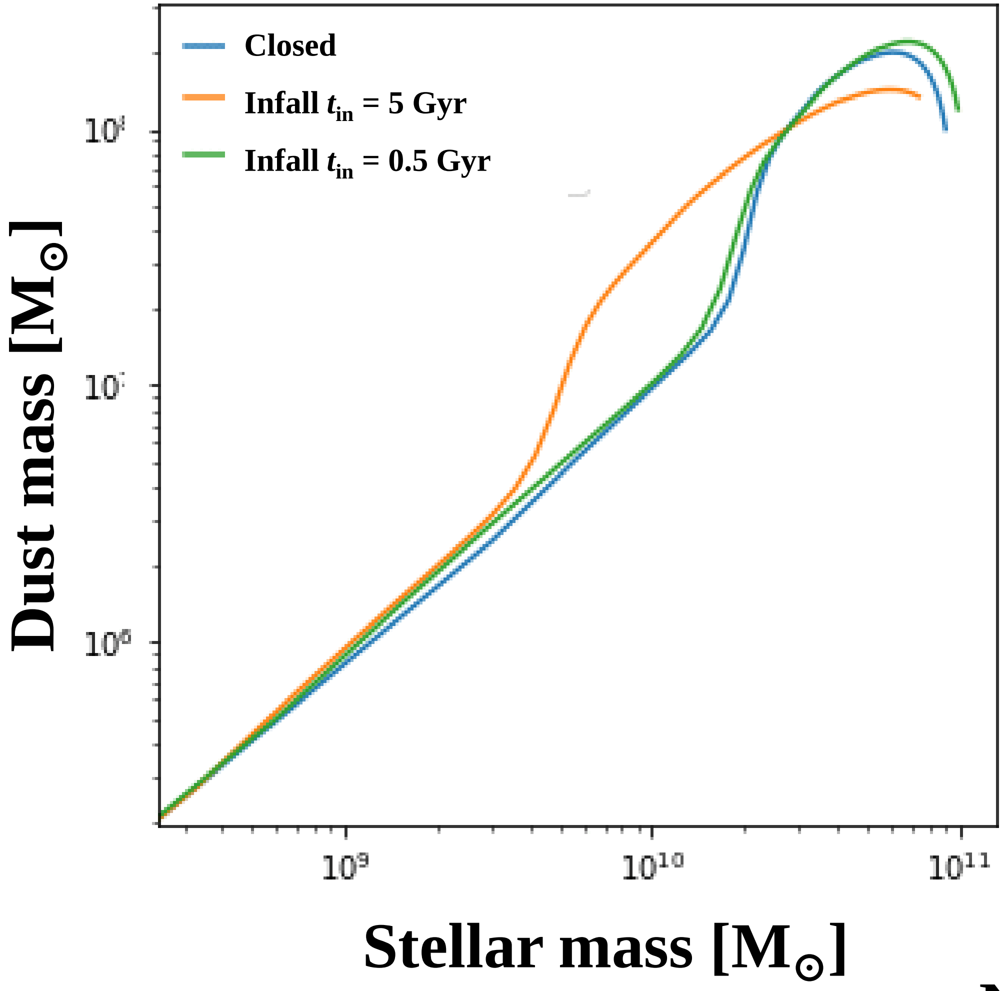
$$\frac{\mathrm{d}M_{\rm ISM}}{\mathrm{d}t} = -\mathrm{SFR}(t) + R(t) + \mathcal{F}(t)$$

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

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

Pristine gas

Evolution of stellar and dust mass



Nagasaki et al. (2019)

With respect to the stellar mass, dust mass is larger than the closed box model for a while.

7. Radiative Transfer with Dust Evolution

Based on the Asano model, we constructed an SED model with radiative transfer.

Step1 Attenuation curve

Stellar spectrum (PÉGASE: Fioc & Rocca-Volmerange 1999)

+

Dust attenuation (Asano et al. 2013b) and the Mega-Grain Approximation (Városi & Dwek 1999; Inoue 2005)

Step2 Stochastic dust heating

Monte-Carlo calculation

Step3 Dust emission

Thermal radiation

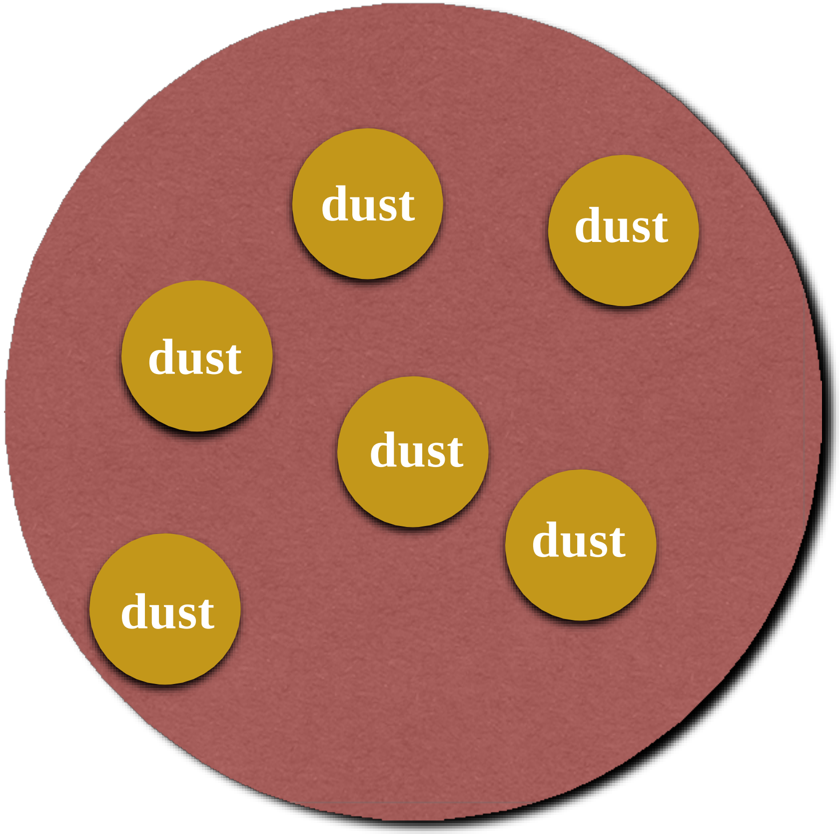
Step4 Construction of SED

Stellar + dust SED

Mega-Grain Approximation

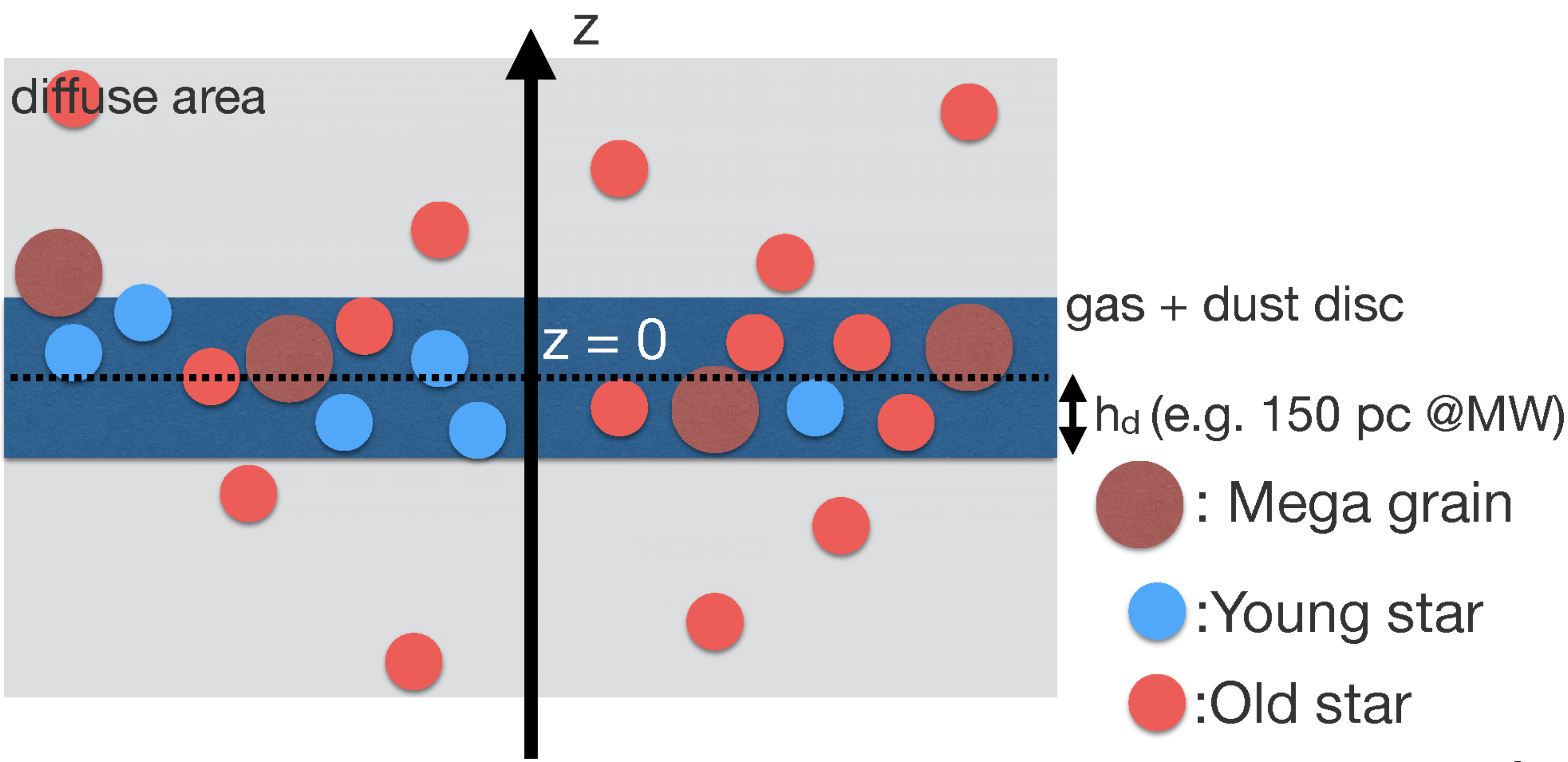
Absorption and scattering by each grain is treated with the Mega-Grain Approximation, i.e., we treat the clump of dense dust regions as a huge single dust grain.

This approximation drastically simplifies the radiative transfer in the SED calculation.

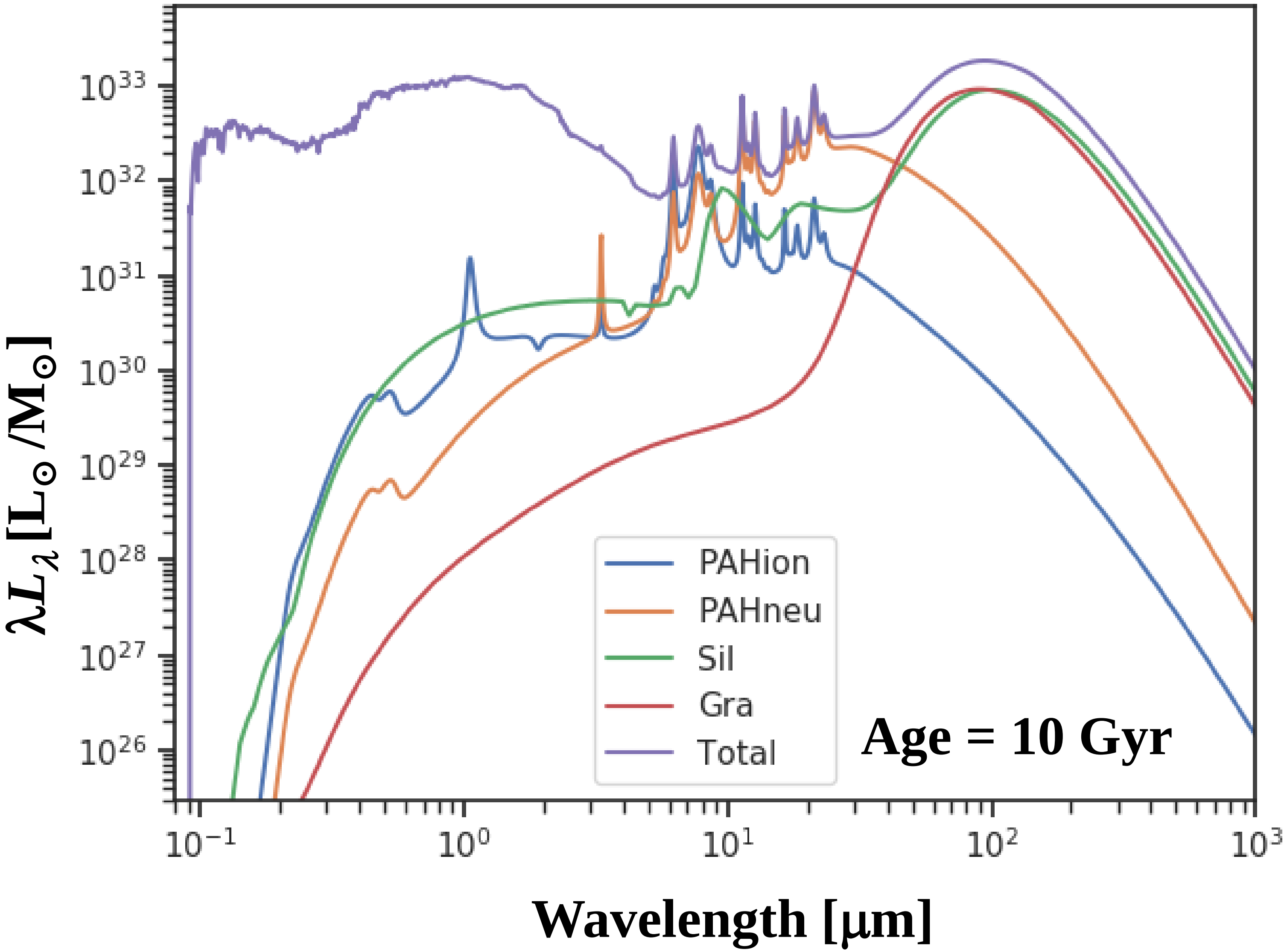


Geometry of galaxy disk

The Galactic disk is treated as a one-dimensional plane-parallel structure. We assume a young star-dust layer in a thin disk around *z* ~ 0, and much thicker layer of old stellar population.



SED of a Milky Way like galaxy



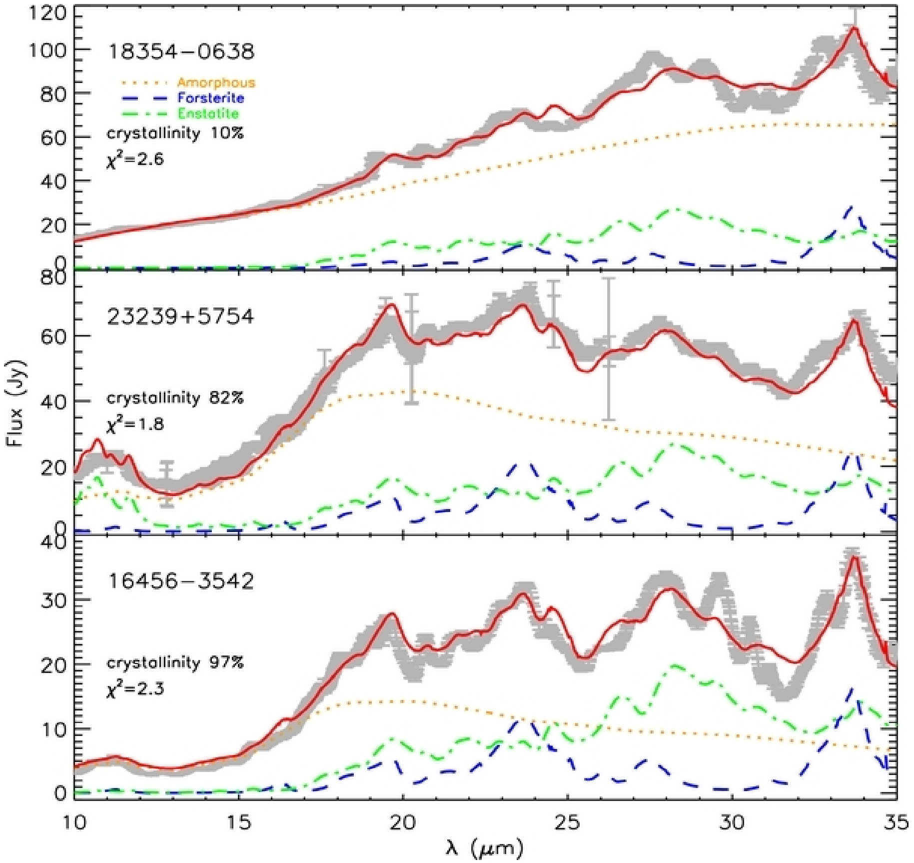
Nishida (2020) PhD Thesis

8. Unsolved Problems on Dust in Galaxies

Galactic astromineralogy

Based on the framework of theoretical SED model, we can further explore the composition and even structure of dust grains in galaxies.

Observed MIR spectra of stars. We can decompose the spectra into silicate and carbonaceous species of dust.



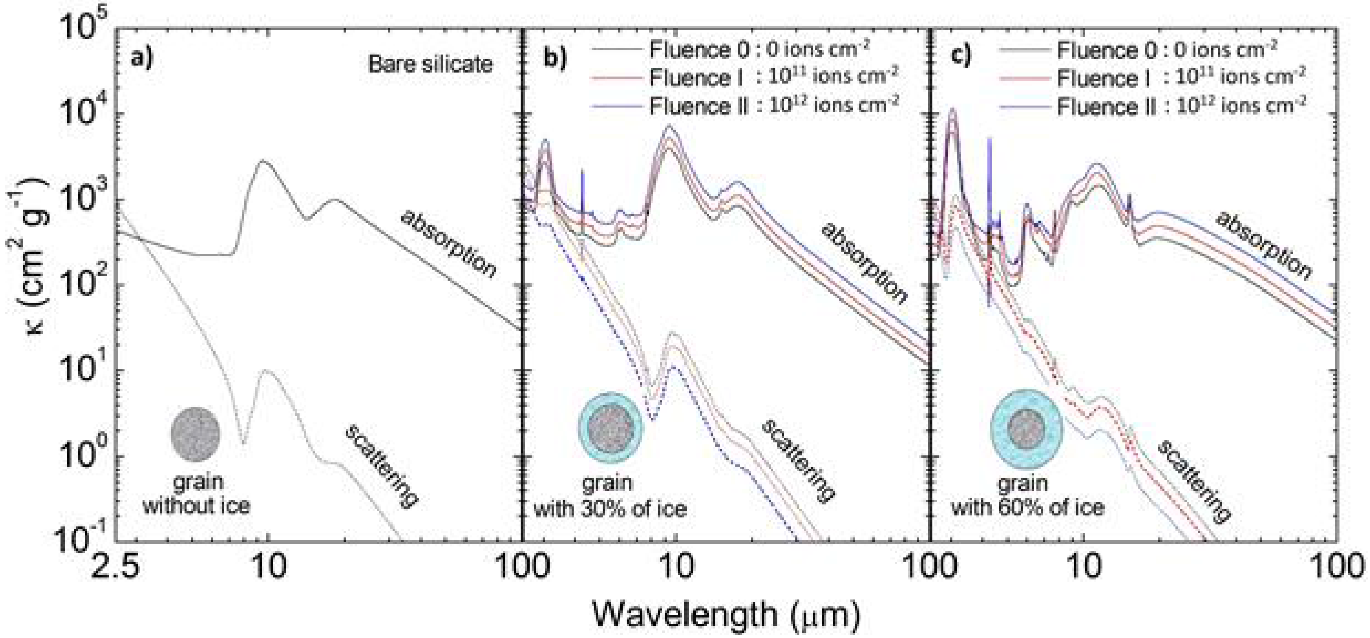
Jiang et al. (2013)

8. Unsolved Problems on Dust in Galaxies

Galactic astromineralogy

Based on the framework of theoretical SED model, we can further explore the composition and even structure of dust grains in galaxies.

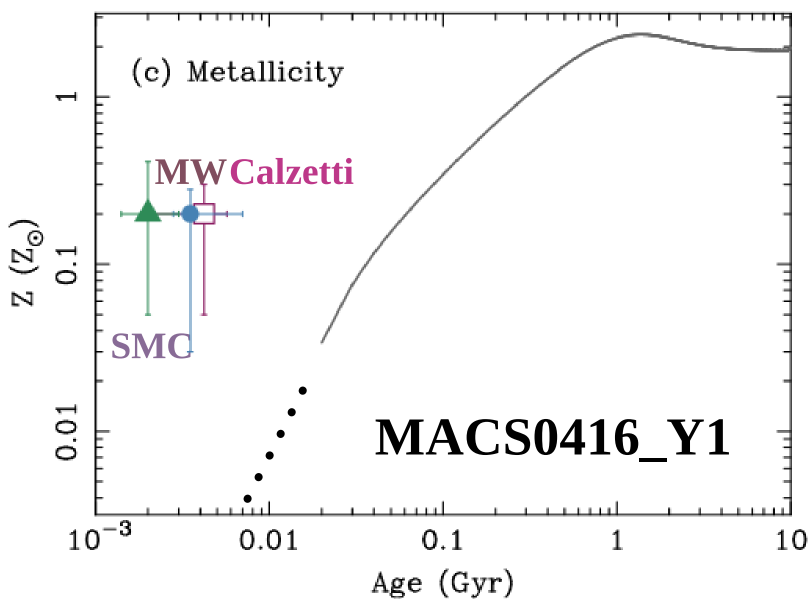
Experimental spectra of silicate grains coated by ice.

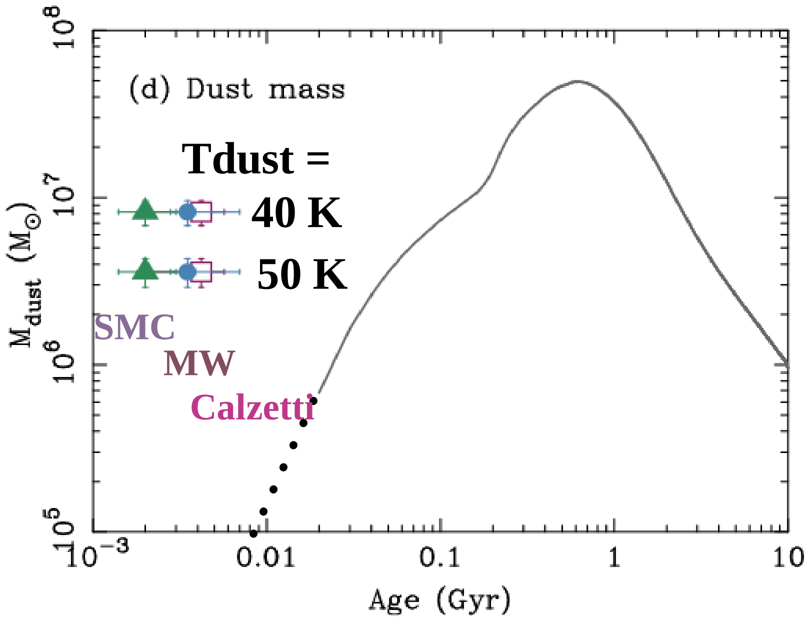


Rocha et al. (2017)

Dust budget crisis

Ultra-high-z galaxies tend to have too much metal and dust. So far it cannot be reproduced by theoretical models.



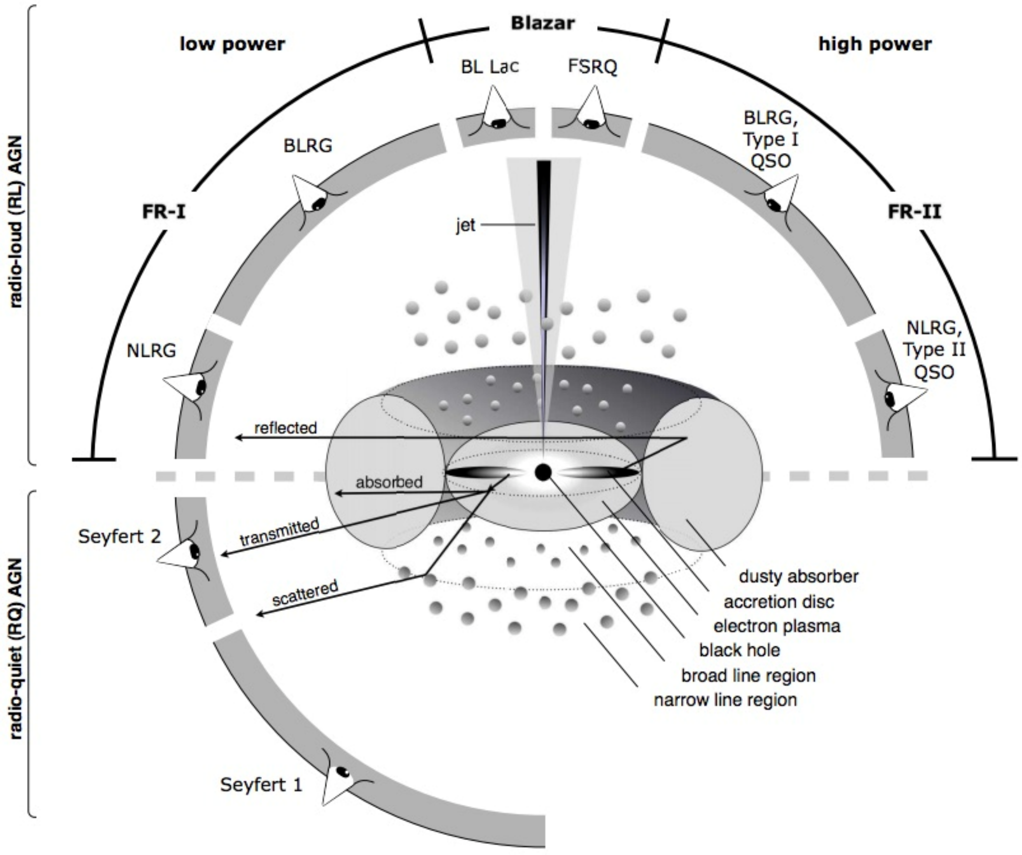


Tamura et al. (2019)

We have to clarify what is wrong in it.

Dust formation in AGN

Dust torus is, even though it is putative, a fundamental component of the AGN structure.



https://aasnova.org/2016/09/13/making-of-an-active-galactic-nucleus/

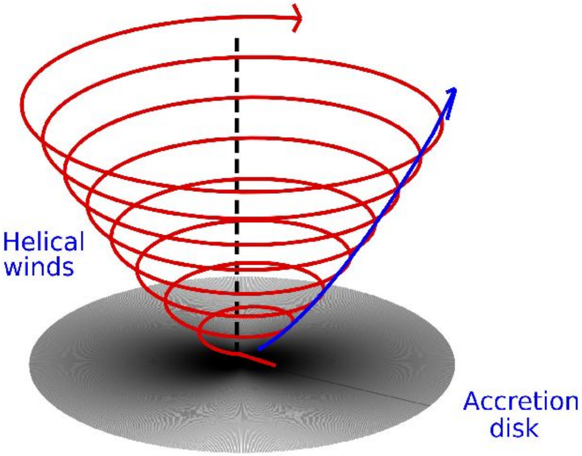
Dust formation in AGN

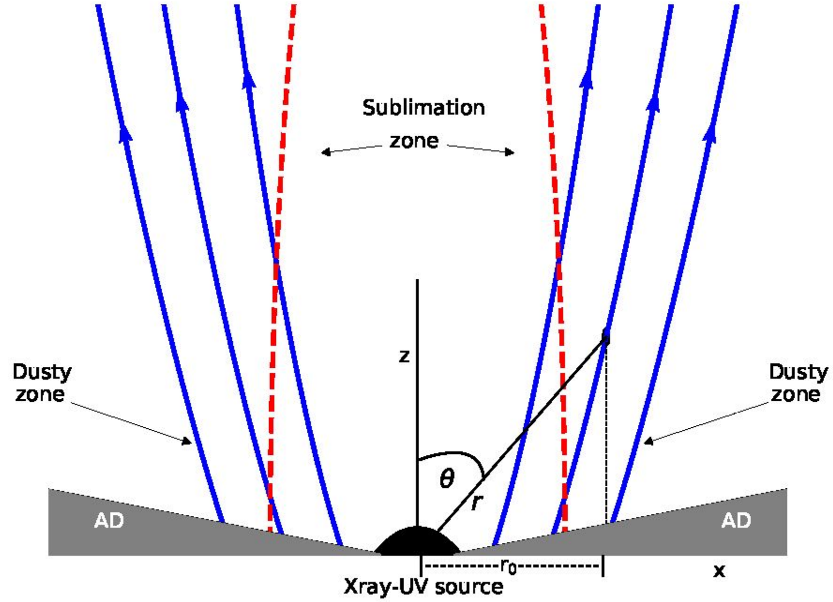
Dust torus is, even though it is putative, a fundamental component of the AGN structure.

Where does this dust come from?

Dust formation in AGN

Recently, a production of dust on the AGN accretion disk wind was proposed (Sarangi et al. 2019). The wind can form significant amounts of dust, especially for objects accreting close to their Eddington limit.





Sarangi et al. (2019)

⇒ AGN can be a significant source of dust in the universe, especially for luminous quasars.

9. Conclusions

1. **Dust amount:**
   Dust supply alters from stars to grain growth in the ISM when the metallicity exceeds the critical metallicity. This behavior does not depend on the SF history, but simply *Z*.

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 successfully reproduced the extinction curves of both the MW and a distant quasar at once.

9. Conclusions

4. **Infall**:
   Infall changes the history of dust. When the infall timescale is comparable to τ_{SF}, M_{dust}/M_* increases more quickly than the case for the closed box.

5. **Radiative transfer**:
   We built a radiative transfer SED model with Asano model with the aid of the Mega-Grain Approximation. It will be a convenient tool for the interpretation of the SEDs of galaxies at various *z*.

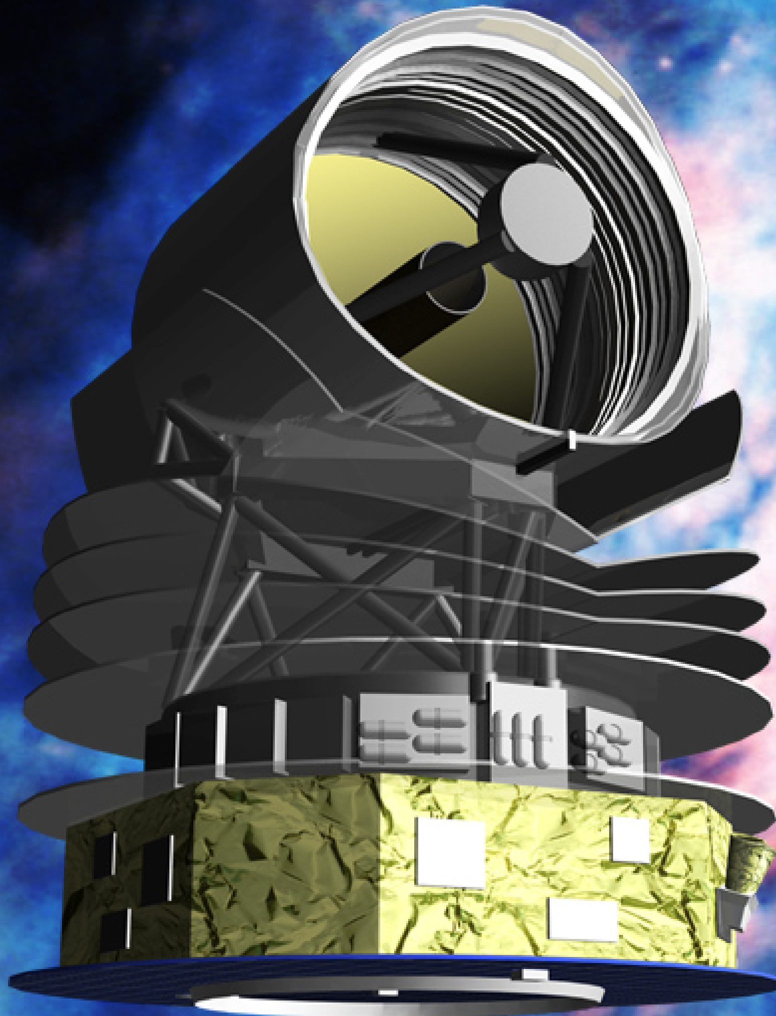
6. **Astromineralogy**:
   With SPICA, Galactic astromineralogy will be feasible. This will give strong constraints on the production process of dust along with the galaxy evolution.

9. Conclusions

7. **Dust budget crisis:**
   Ultra-high-z galaxies tend to have too much metal and dust. So far it cannot be reproduced by theoretical models.

8. **Dust production by AGN:**
   We built a radiative transfer SED model with Asano model with the aid of the Mega-Grain Approximation. It will be a convenient tool for the interpretation of the SEDs of galaxies at various z.

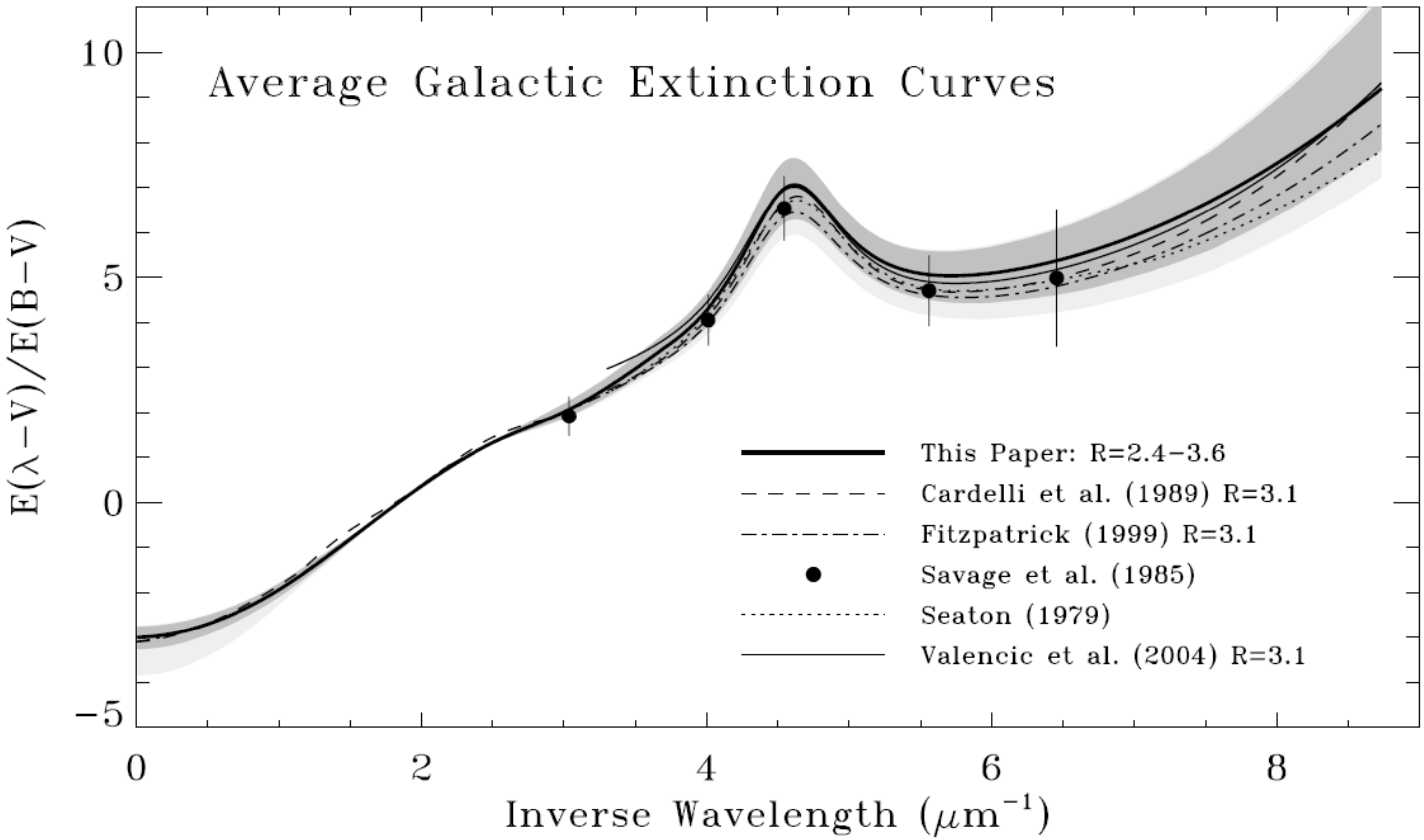
SPICA is a promise!



Appendix

Extinction curve

Extinction = absorption + scattering by dust grains



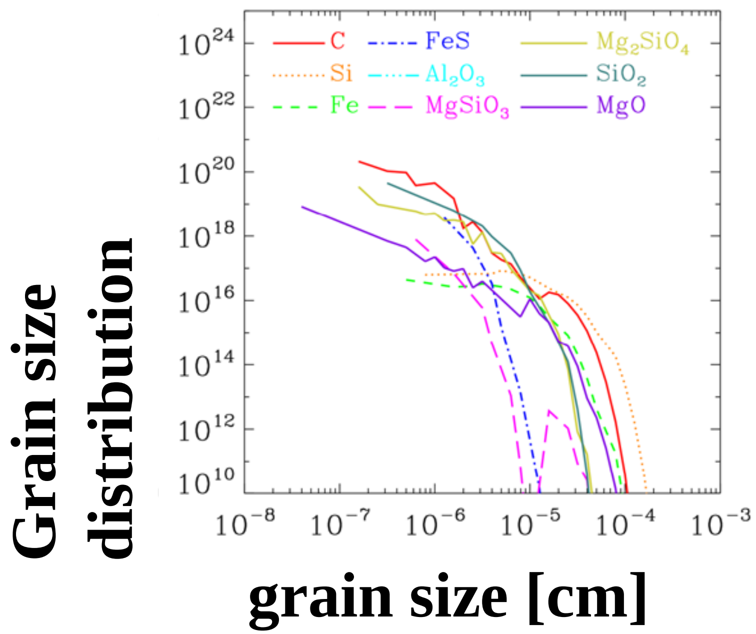
Fitzpatrick & Massa (2007)

Dust supply

Type II Supernovae (SNe II)

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

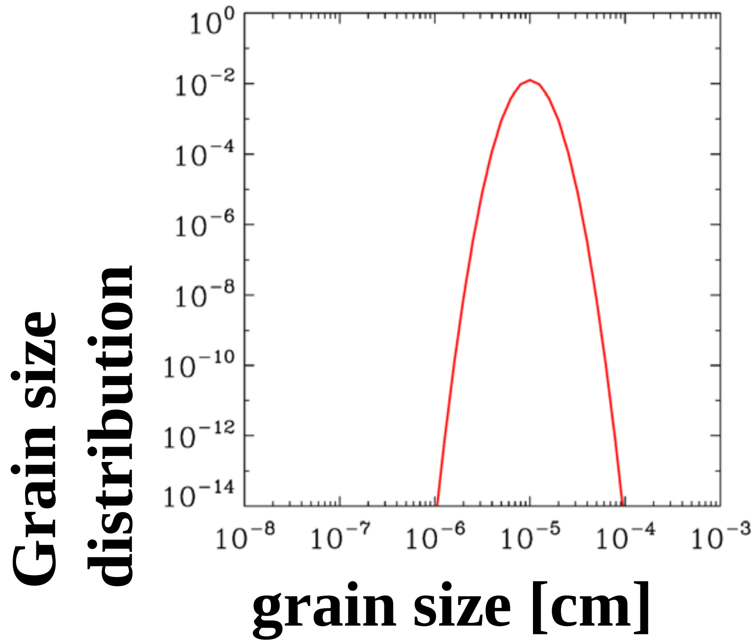
Dust mass data
Nozawa et al. (2007)



AGB stars

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

Dust mass data
Zhukovska et al. (2008)

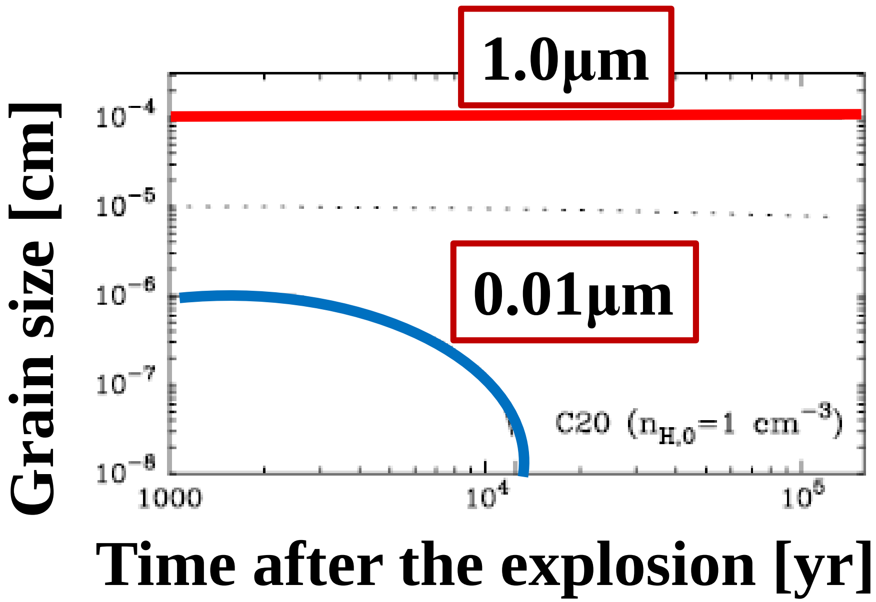


Dust destruction and grain growth

Dust destruction by SN shocks

Smaller grains are mainly destroyed by SN shocks.

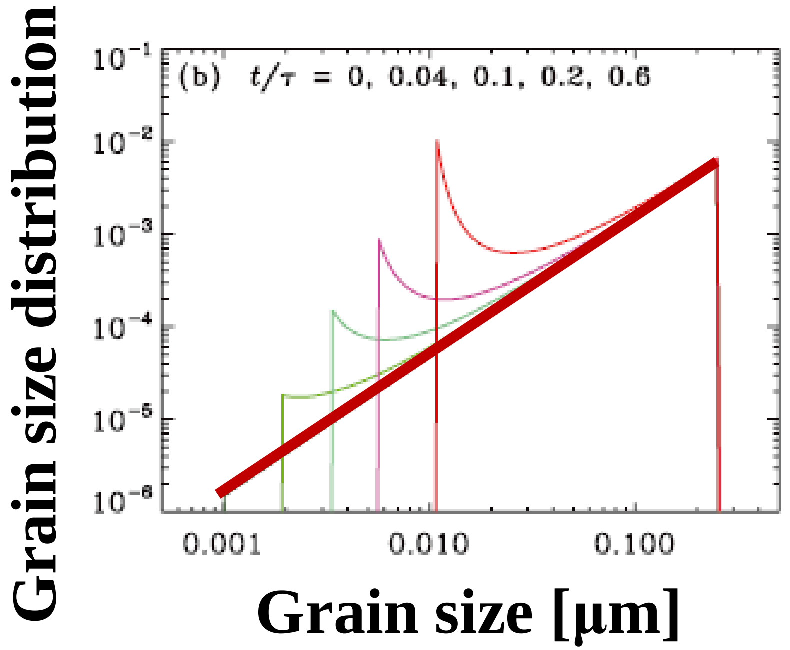
Nozawa et al. (2006)



Grain growth (metal accretion onto grains)

Smaller grains grow to larger grains.

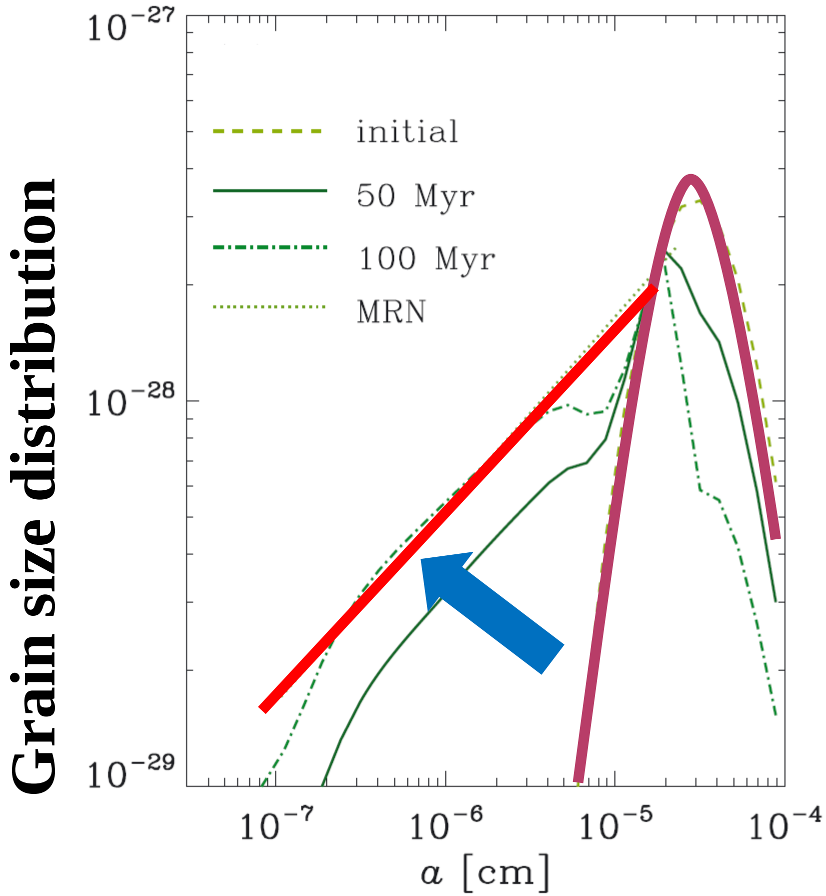
Hirashita & Kuo (2011)



Shattering and coagulation (driven by ISM turbulence)

Shattering

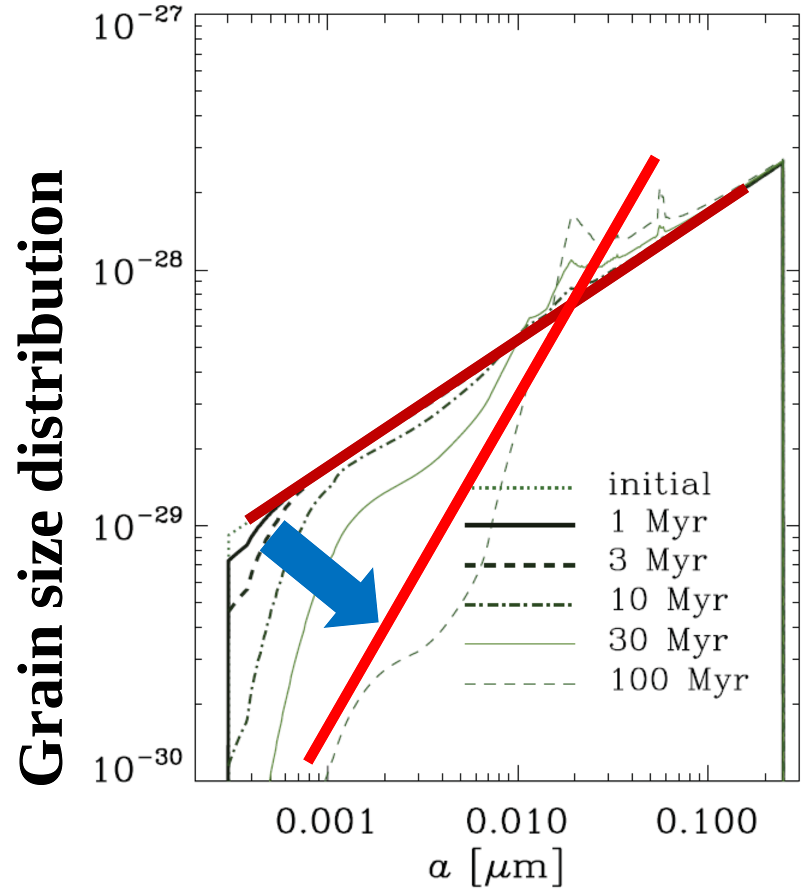
Smaller grains are produced by larger grains



Hirashita (2010)

Coagulation

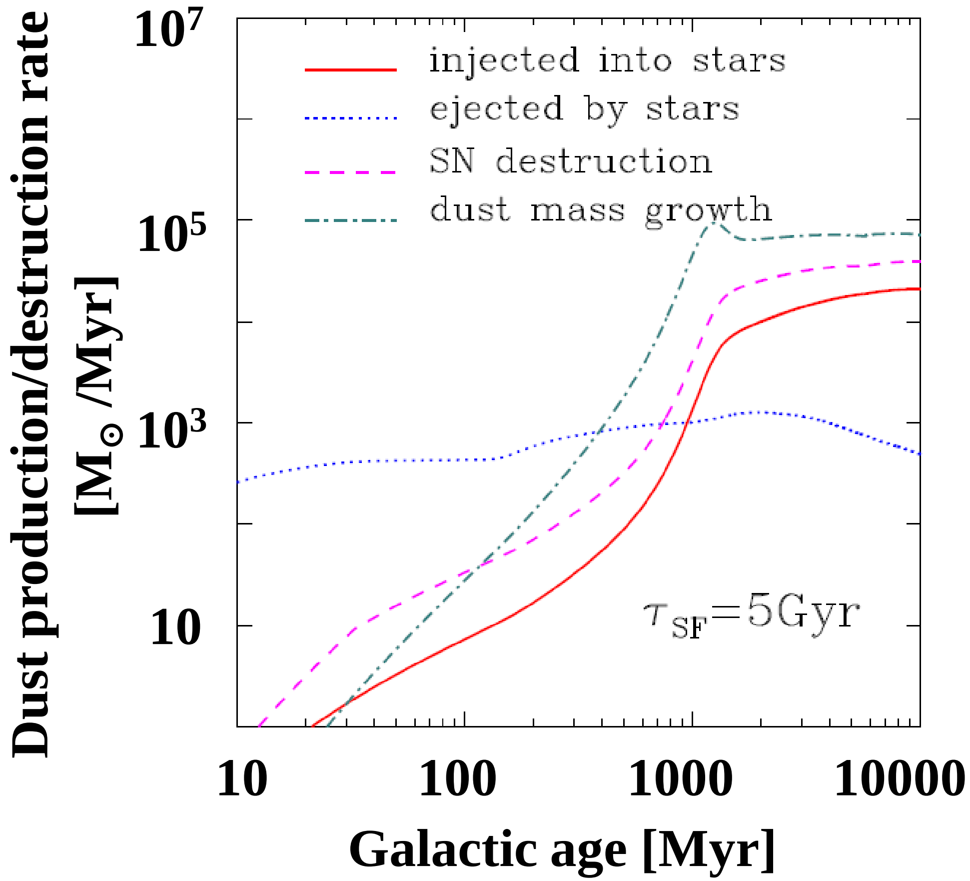
Larger grains are produced by smaller grains



Hirashita (2012)

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?

Parameter setting :
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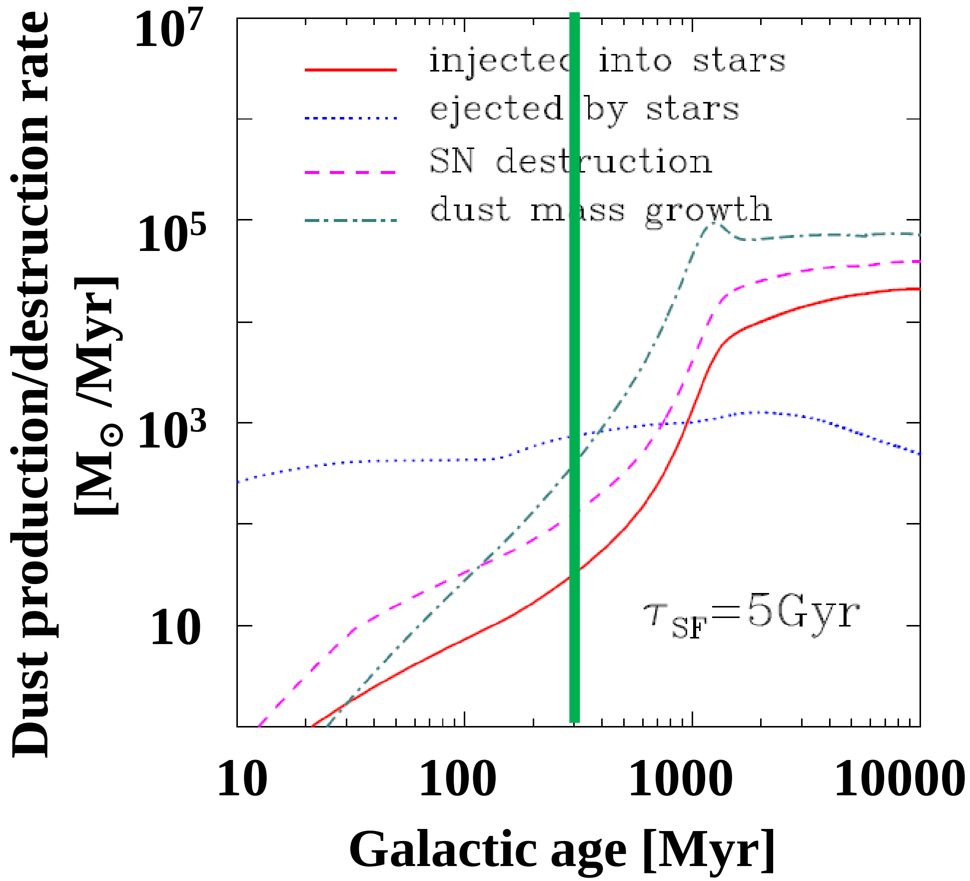

Contribution of each physical process to the total dust mass

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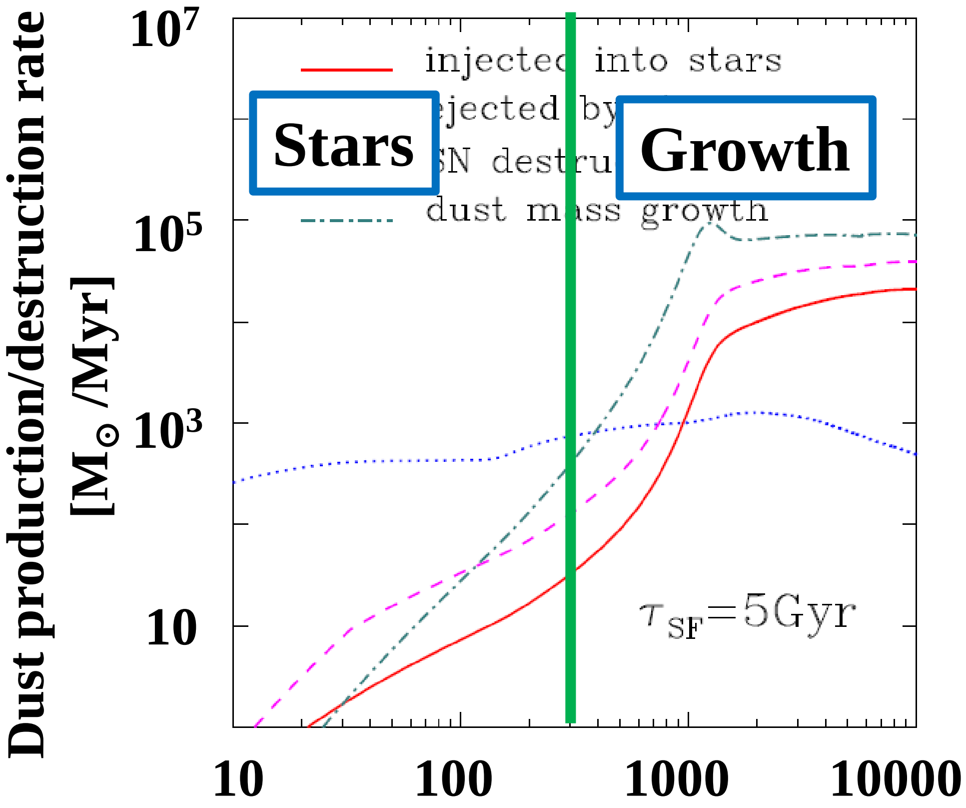
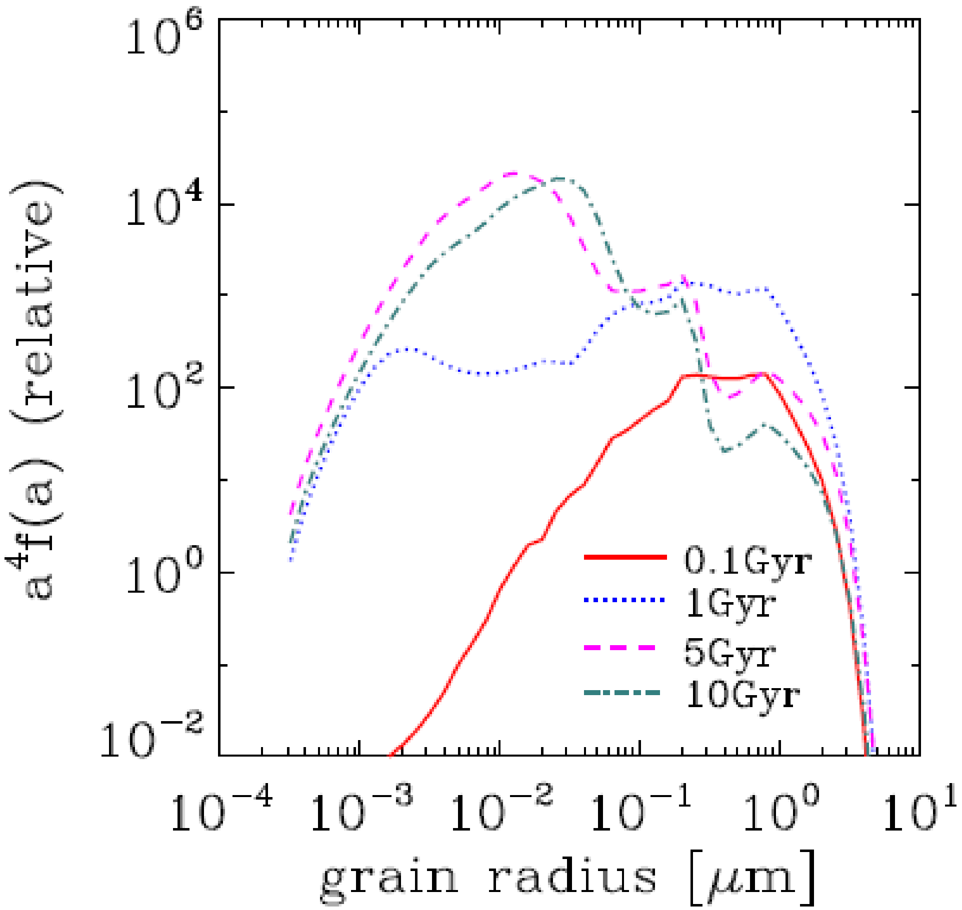
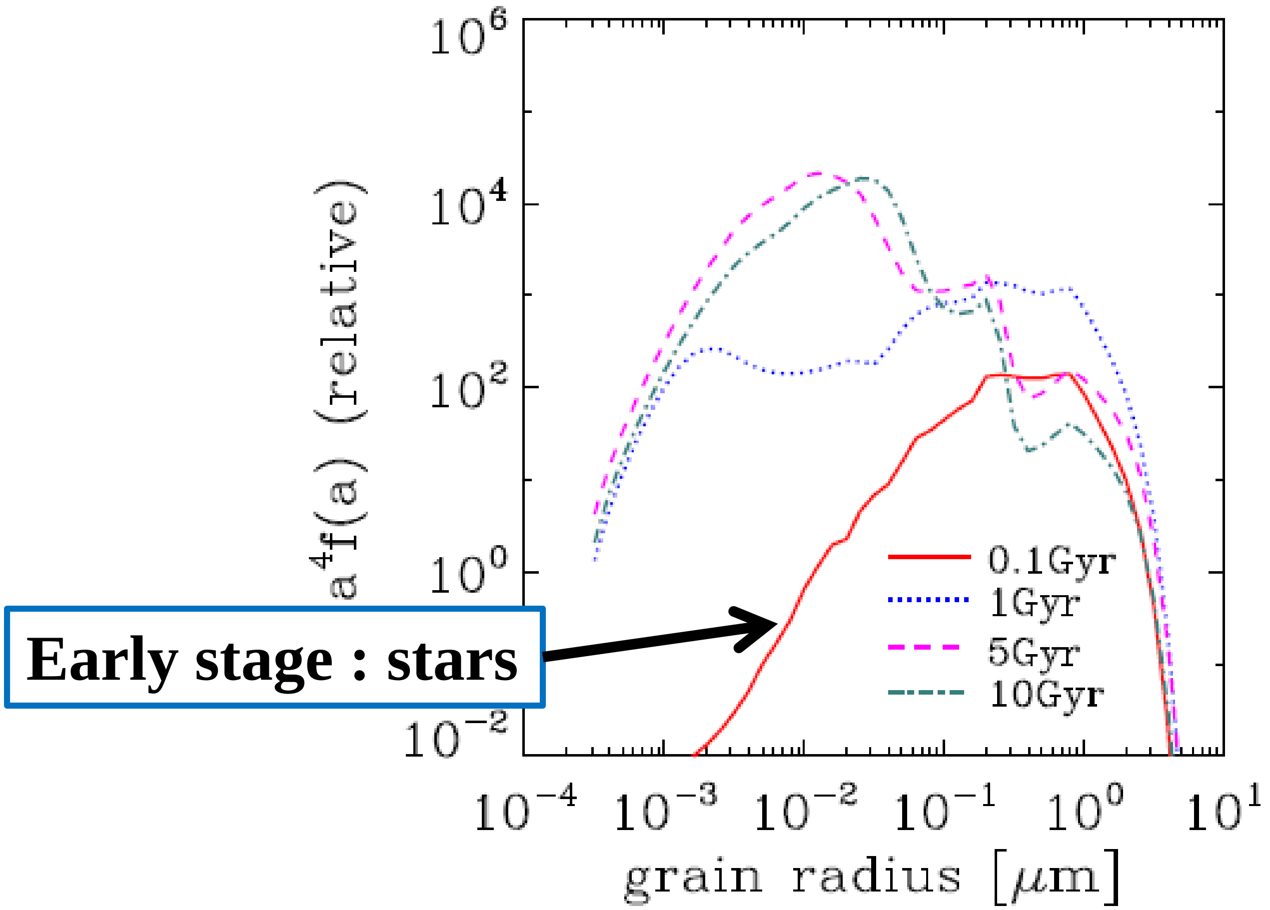


Growth is expected to explain the total dust mass of the Milky Way and high-*z* QSOs.

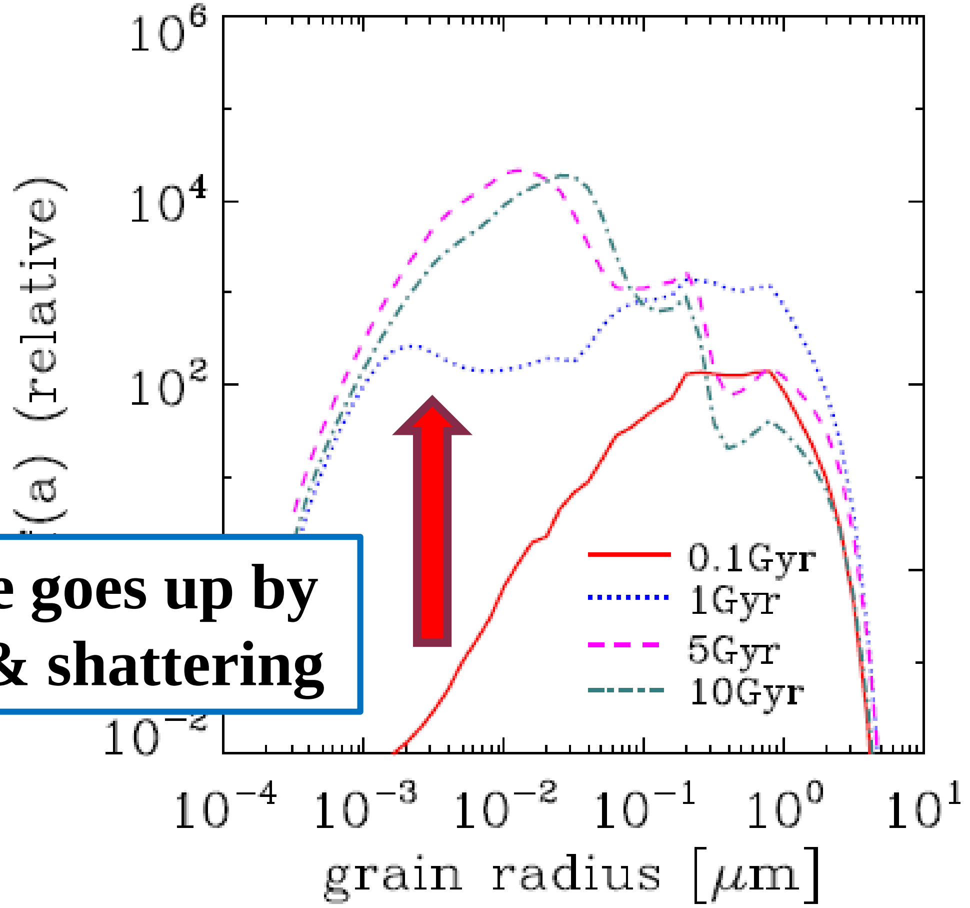
Evolution of the grain size distribution



Evolution of the grain size distribution

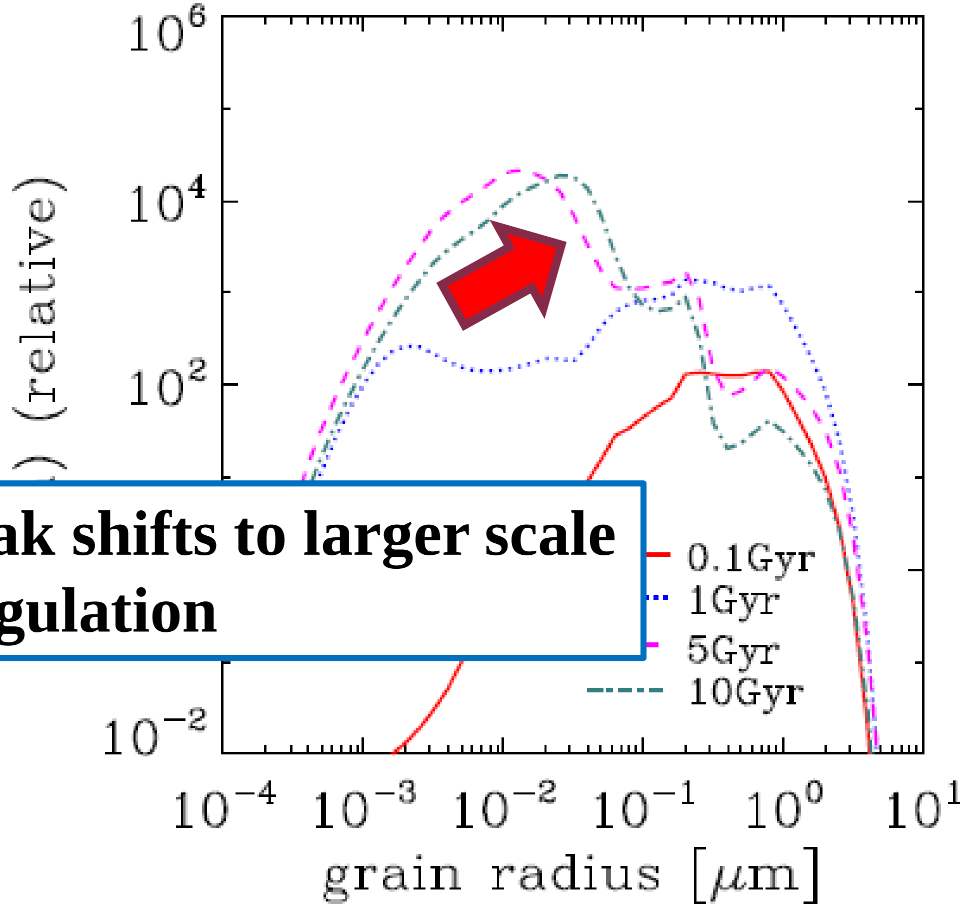


Evolution of the grain size distribution



Small scale goes up by accretion & shattering

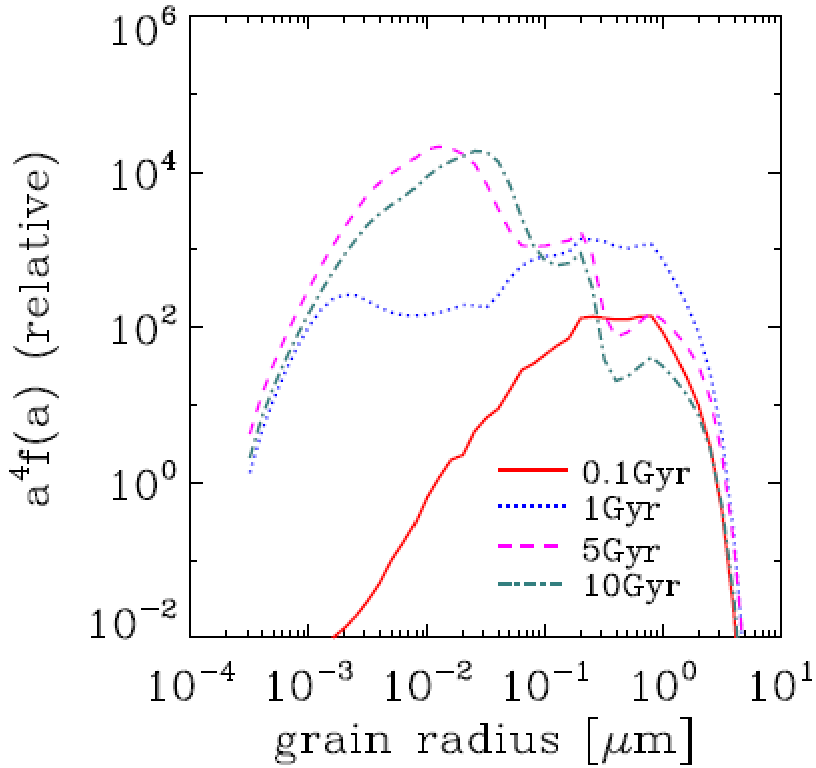
Evolution of the grain size distribution



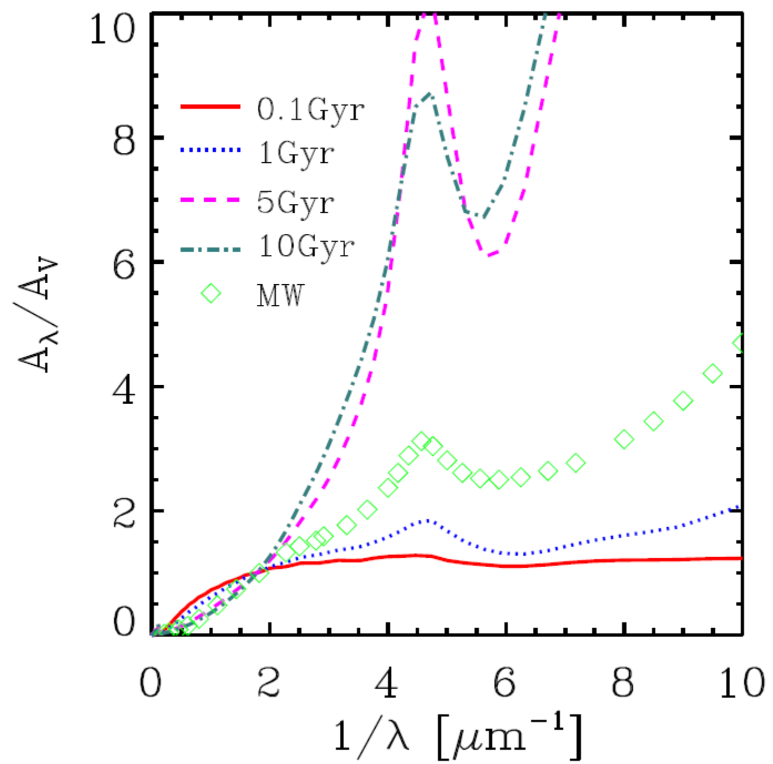
The peak shifts to larger scale by coagulation

Evolution of the extinction curve in galaxies

Size distribution



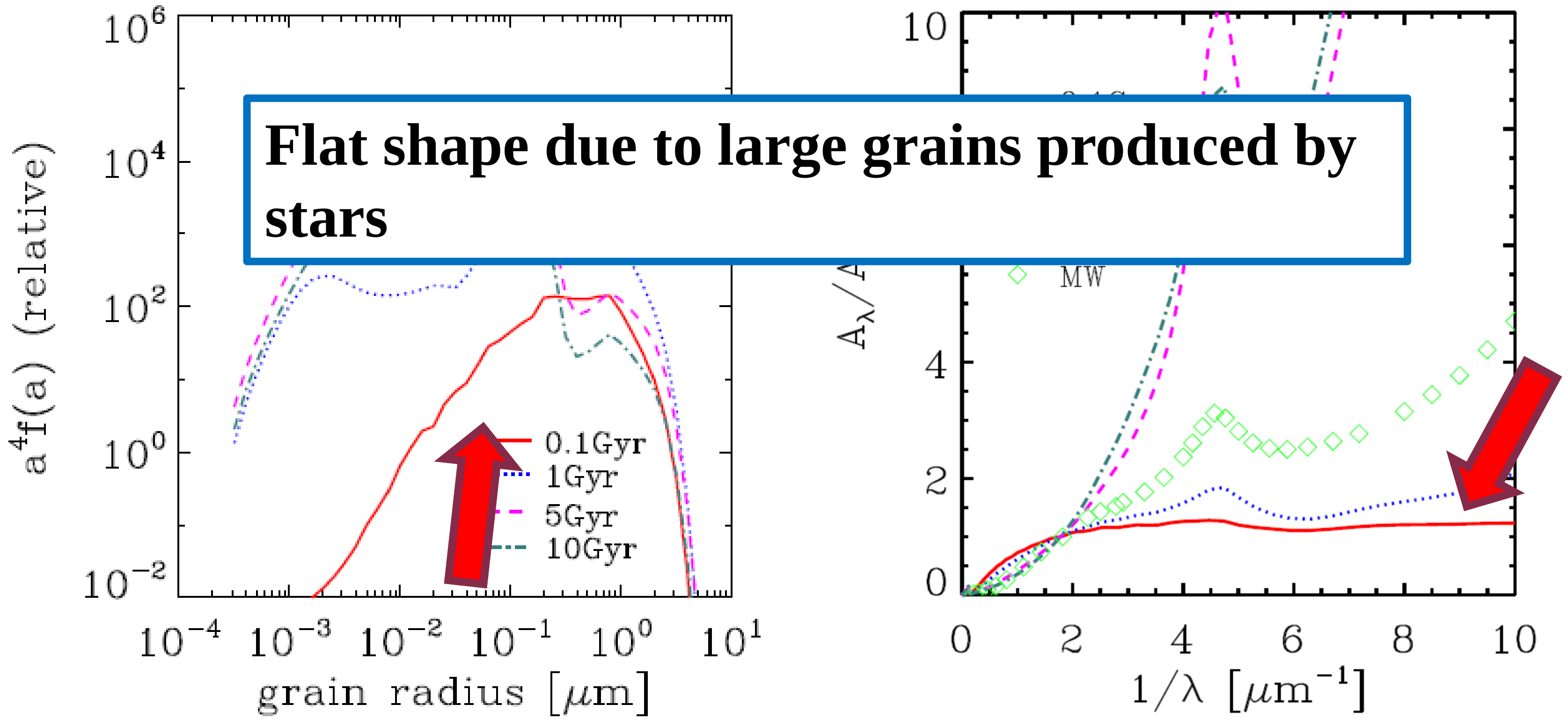
Extinction curve



The extinction curve drastically changes through the galaxy evolution!

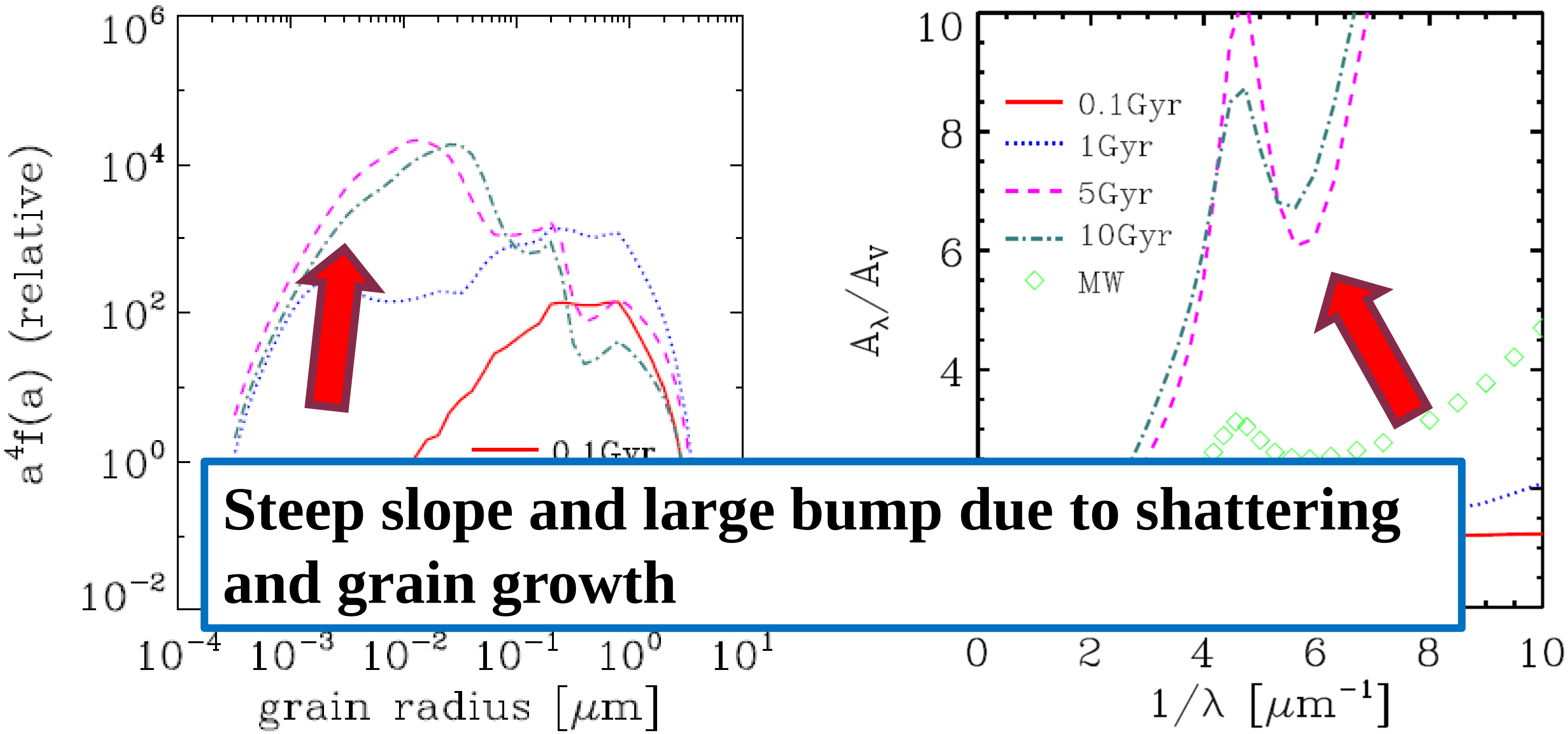
Evolution of the extinction curve in galaxies

Size distribution **Extinction curve**



Evolution of the extinction curve in galaxies

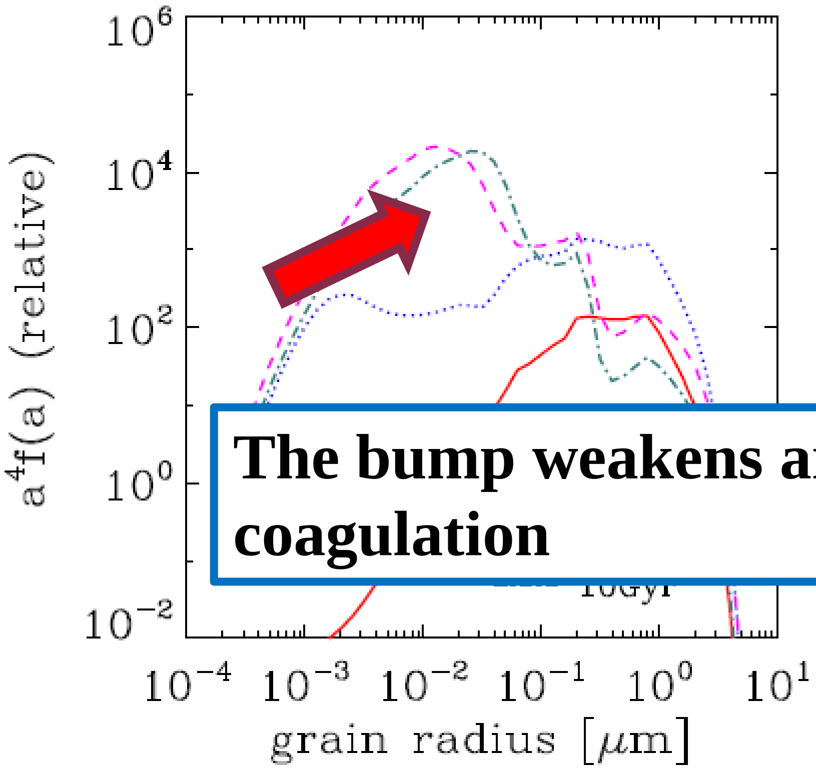
Size distribution **Extinction curve**



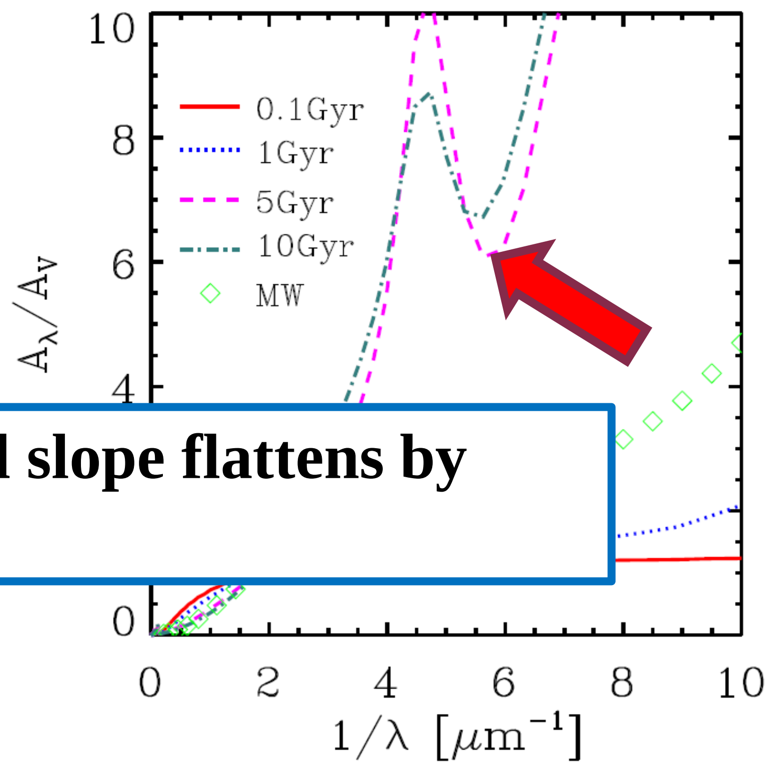
Steep slope and large bump due to shattering and grain growth

Evolution of the extinction curve in galaxies

Size distribution

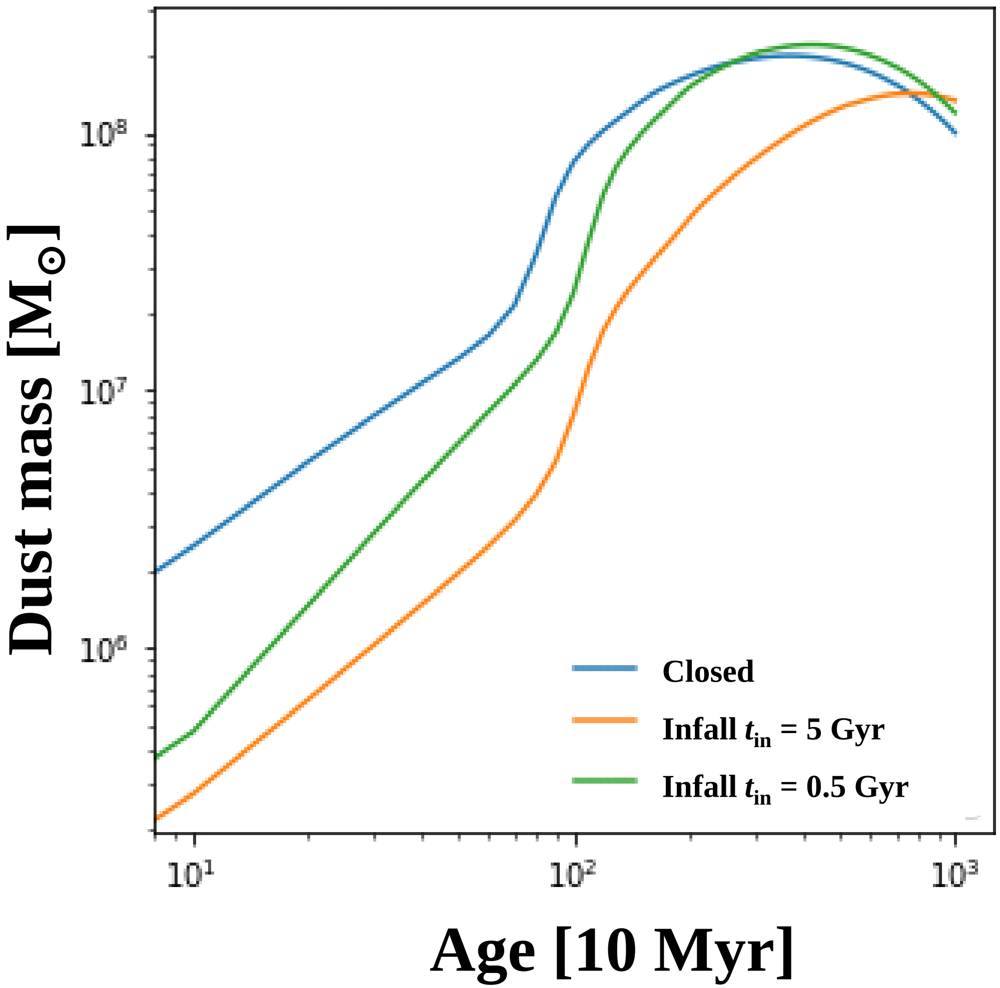


Extinction curve



The bump weakens and slope flattens by coagulation

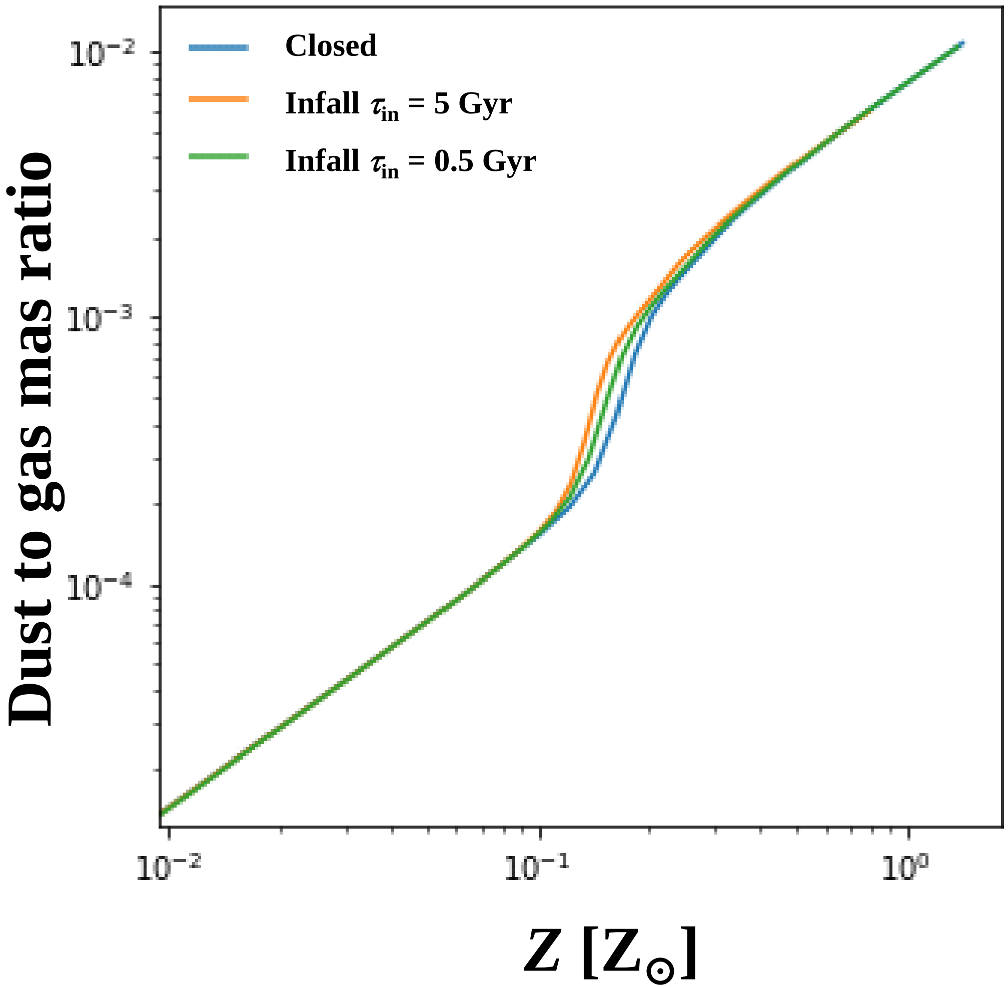
Evolution of dust mass



Dust accumulates gradually, and the onset of the grain growth is almost the same for all the cases.

Nagasaki et al. (2020)

Relation between metallicity and dust-to-gas mass ratio



The relation is strikingly unchanged!

Nagasaki et al. (2020)

Stochastic heating of dust grains

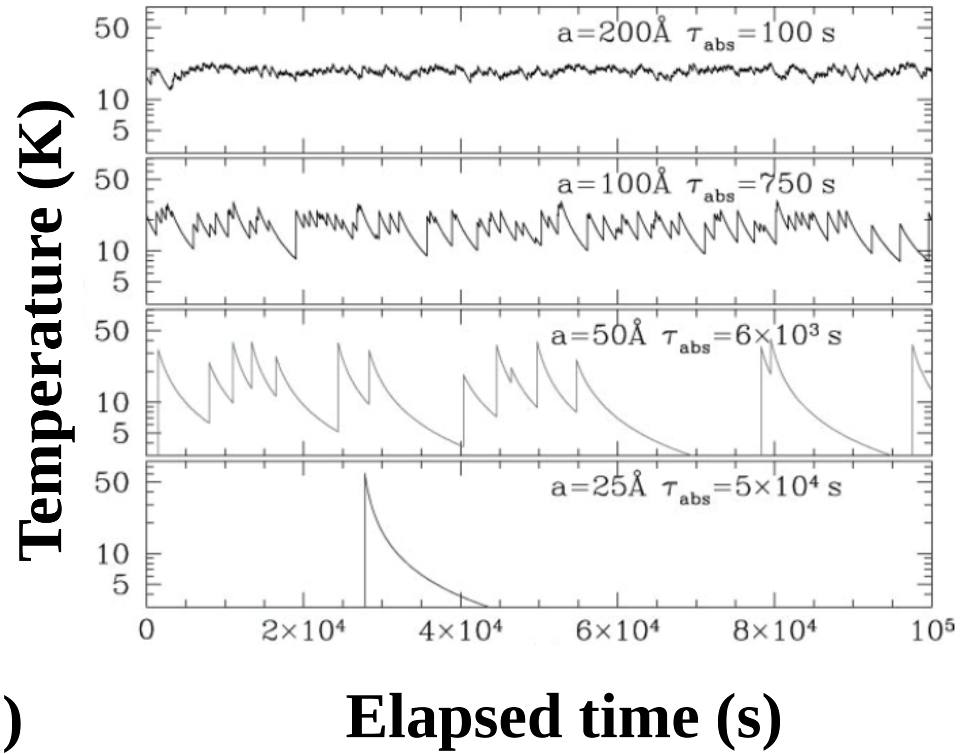
A small dust grain is stochastically heated by photons and cannot keep an equilibrium temperature with the ambient radiation field. We calculated the temperature distribution of small grains by Monte-Carlo method.

Absorption probability

$$\frac{d^2 p}{d\lambda dt} = \pi a^2 Q_{abs}(\lambda, a) u_\lambda \frac{\lambda}{h}$$

Dust heating

$$\frac{hc}{\lambda} = \frac{4\pi a^3}{3} \int_{T_0}^{T} C(T')dT'$$



Draine (2003)