Atomic Gas, Molecular Gas, and Dust in Galaxy Evolution

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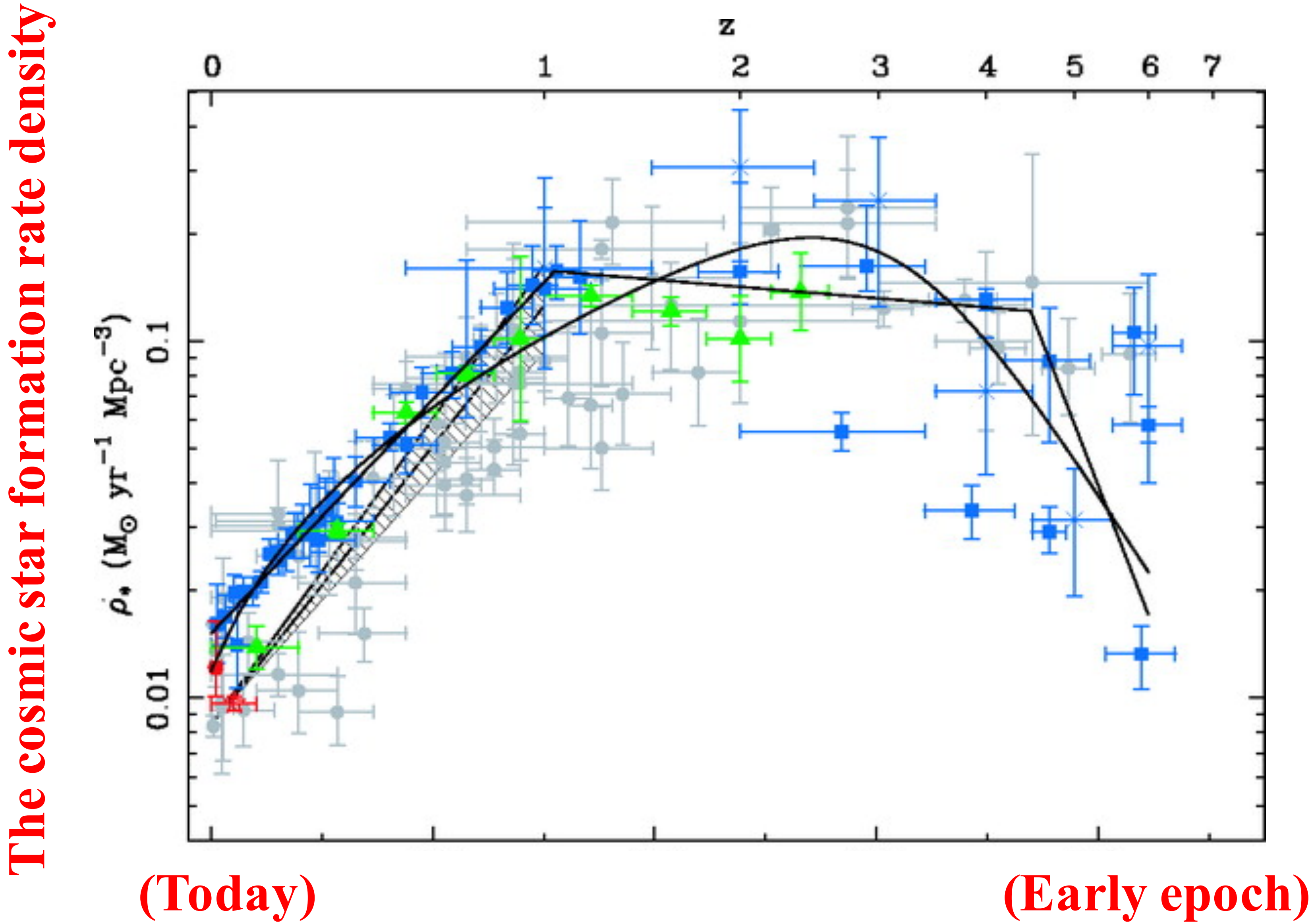
1 Interesting epochs of galaxy evolution



(Hopkins & Beacom 2006)

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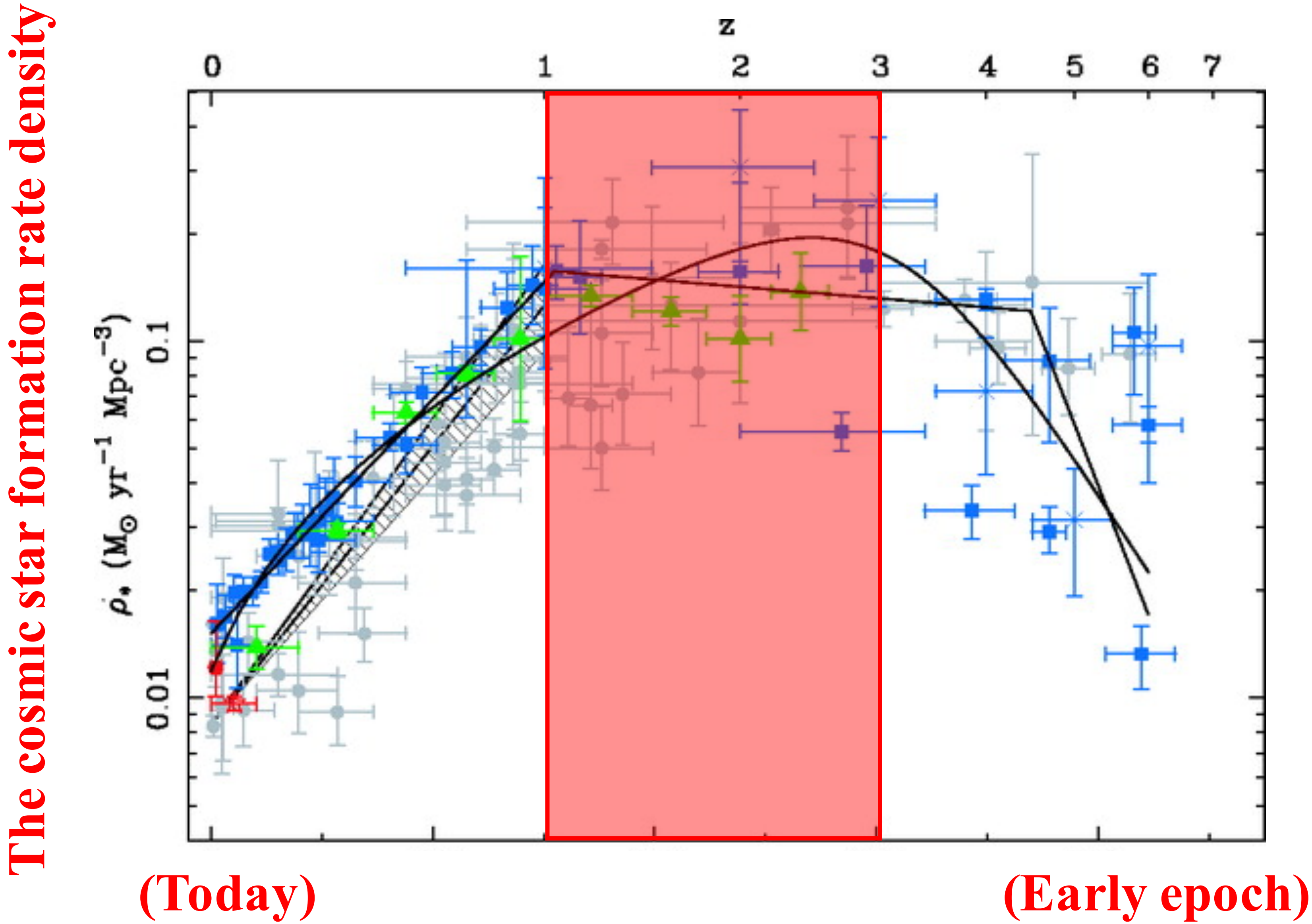


(Hopkins & Beacom 2006)

The cosmic star formation history

Focused property in previous studies on galaxy evolution: star formation rate (SFR)

Observational indicator of SFR

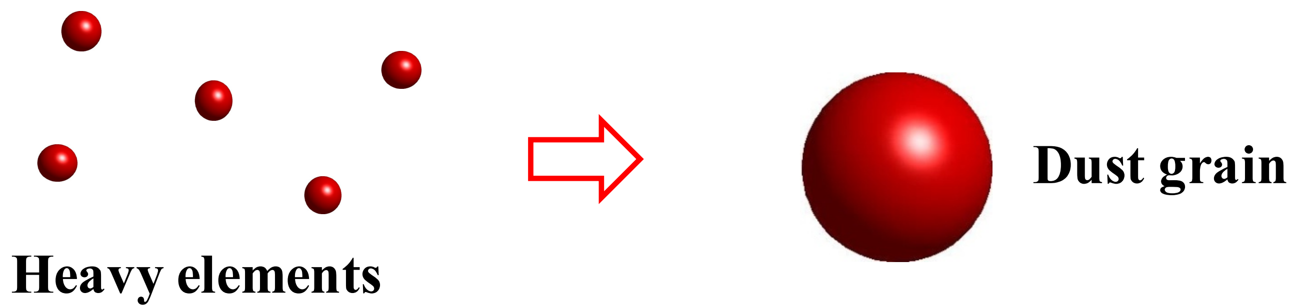
- **Ionizing UV photons from OB stars**
- **Recombination lines from HII regions**
- **Forbidden lines from HII regions**
- **Non-ionizing UV photons**
- **IR re-emission from dust**
- **PAH band emission from photodissociation regions**
- **Synchrotron radiation, etc.**

Though they give information on the SFR, but does not provide more fundamental information on the transformation from gas to stars.

2 Transition from atomic to molecular gas on dust

What are dust grains?

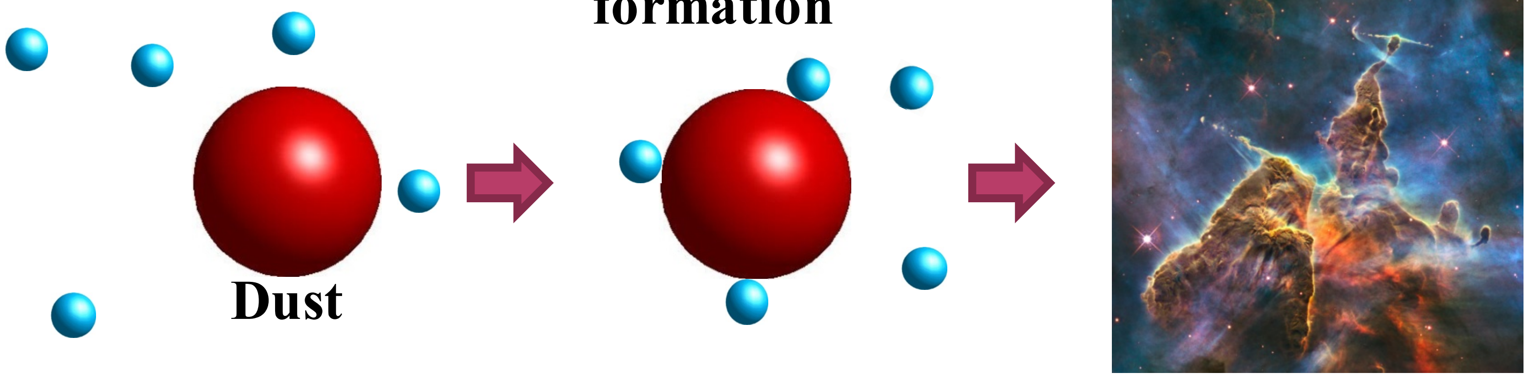
Dust grains are formed by condensation of heavy elements.



Heavy elements are supplied only by stars, hence tightly connected to galaxy evolution.
However, the formation and evolution of dust has been fully theoretically formulated only recently (Asano et al. 2013a, b, 2014; Nozawa et al. 2015), and more observational examinations are still needed.

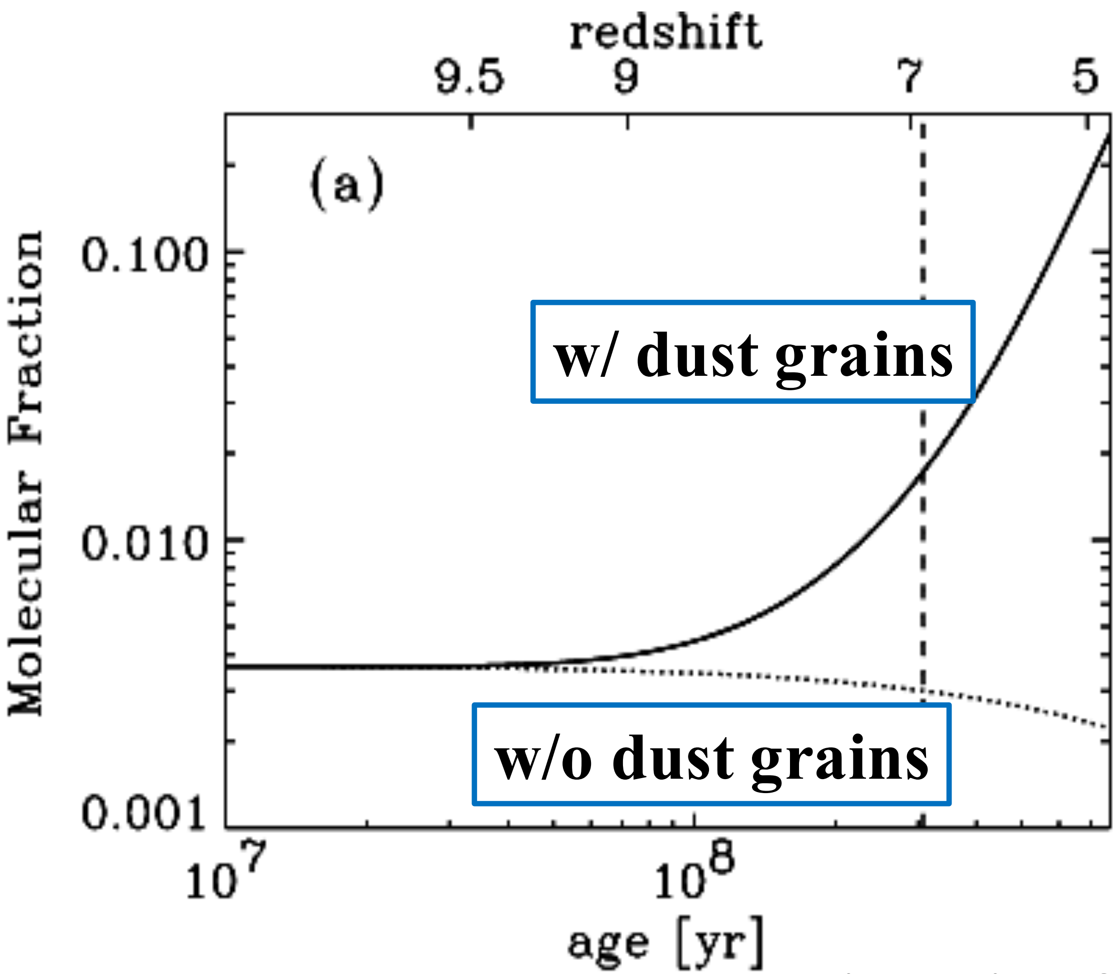
Role of dust for the star formation

Molecular formation is the key process for star formation, and molecules are predominantly formed on surface of dust grains (e.g., Gould & Salpeter 1963).



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

Role of dust for the star formation



Hirashita & Ferrara (2002)

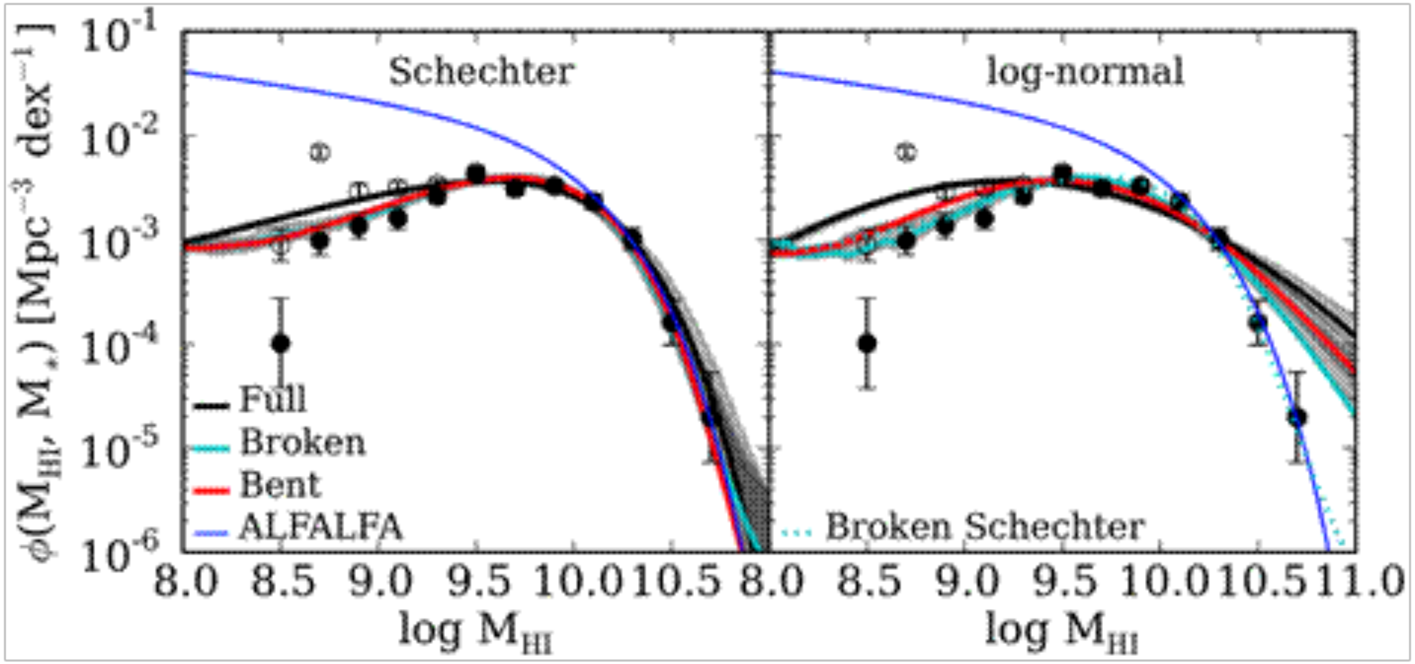
Dust grains drive the star formation, and actually this is the trigger of the initial starburst, i.e., galaxy formation.

3 Gas mass function of galaxies

Gas mass function of galaxies

Gas mass function of galaxies describes how much HI and H_2 gas exists in galaxies, i.e., the raw materials to form stars.

⇒ It provides complementary information to stellar mass and SFR functions.

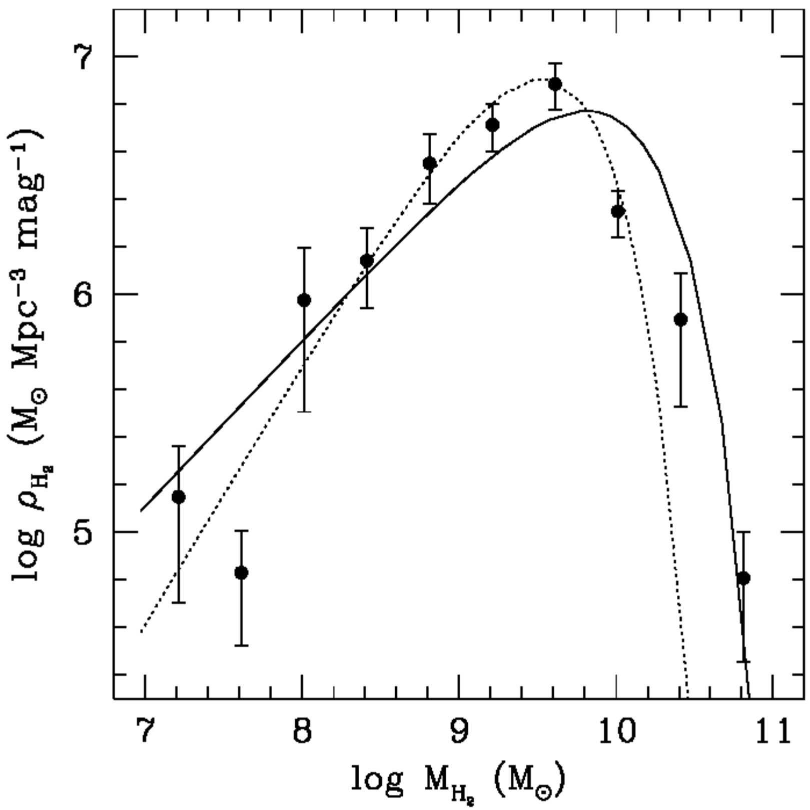


Local HI mass function (Lemonias et al. 2013)

Current status of the observational gas mass function

It is not a trivial task to estimate the gas mass function from observation, and currently both HI and H_2 mass functions are obtained only at $z \sim 0$ (Keres et al. 2003; Lemonias et al. 2013).

Local H_2 mass function (Keres et al. 2003)



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Problem:

- **No dedicated wide-area survey for H_2 (in practice, CO), and no ideal survey for HI (as for HI, wide-area survey exists but redshifts are taken from optical surveys).**
- **Statistical methods are inadequate: the method often adopted to obtain the gas mass function gives a biased result.**

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⇒ Many further investigations are necessary.

Gas mass estimate from dust emission

For high-*z* galaxies, it is fashionable to convert the dust continuum emission to the total gas (HI+H_2) mass (e.g., Groves et al. 2015).

If it can be used for all types of galaxies, it is extremely useful for statistical studies of gas mass at various redshifts.

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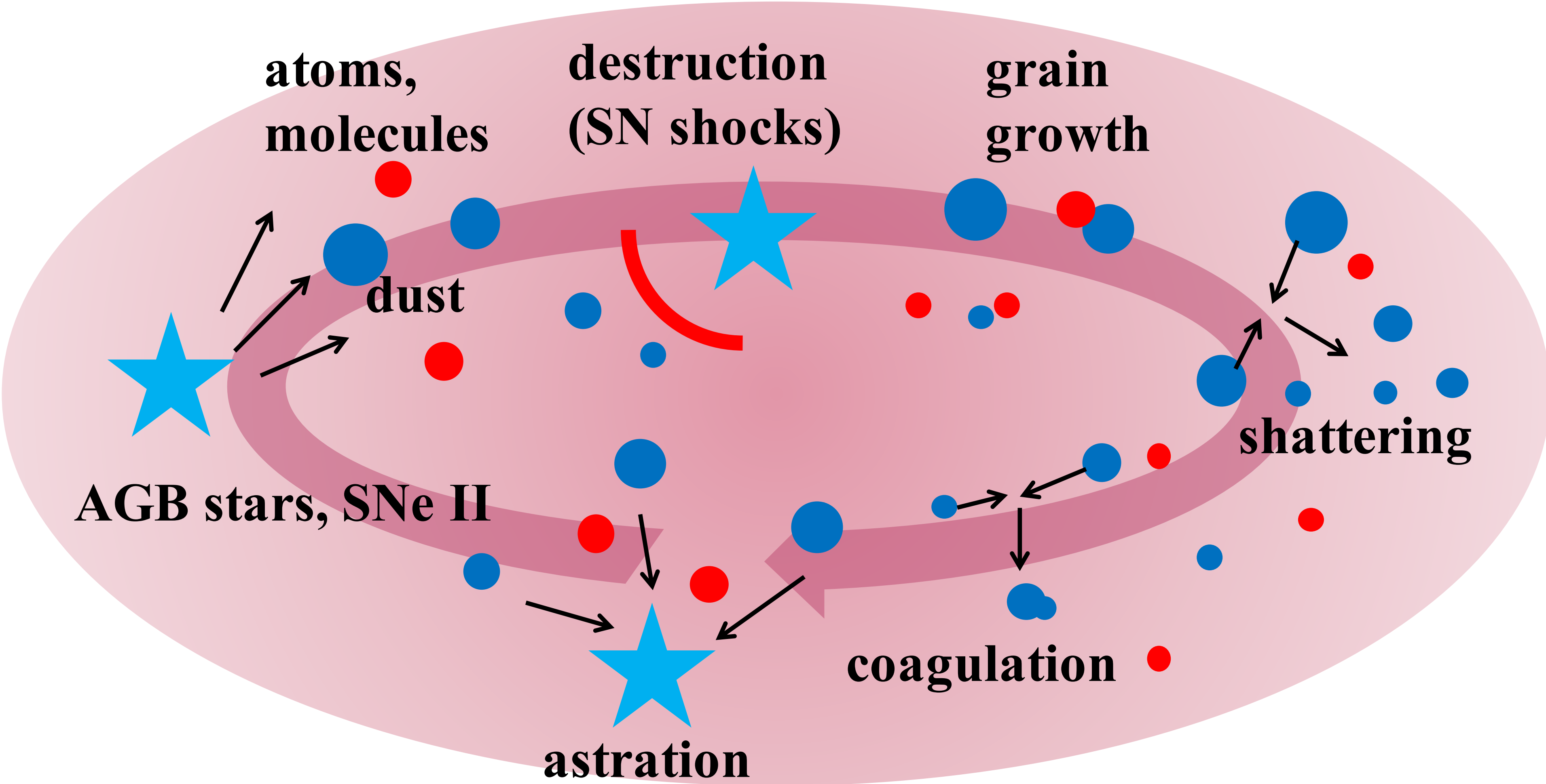
⇒ A better understanding is needed!

Dust and matter circulation in a galaxy



We have developed a theoretical framework to explain this relation (Asano et al. 2013a, b, 2014; Nozawa et al. 2015).

Model of galaxy evolution

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

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

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

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

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

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

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

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

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

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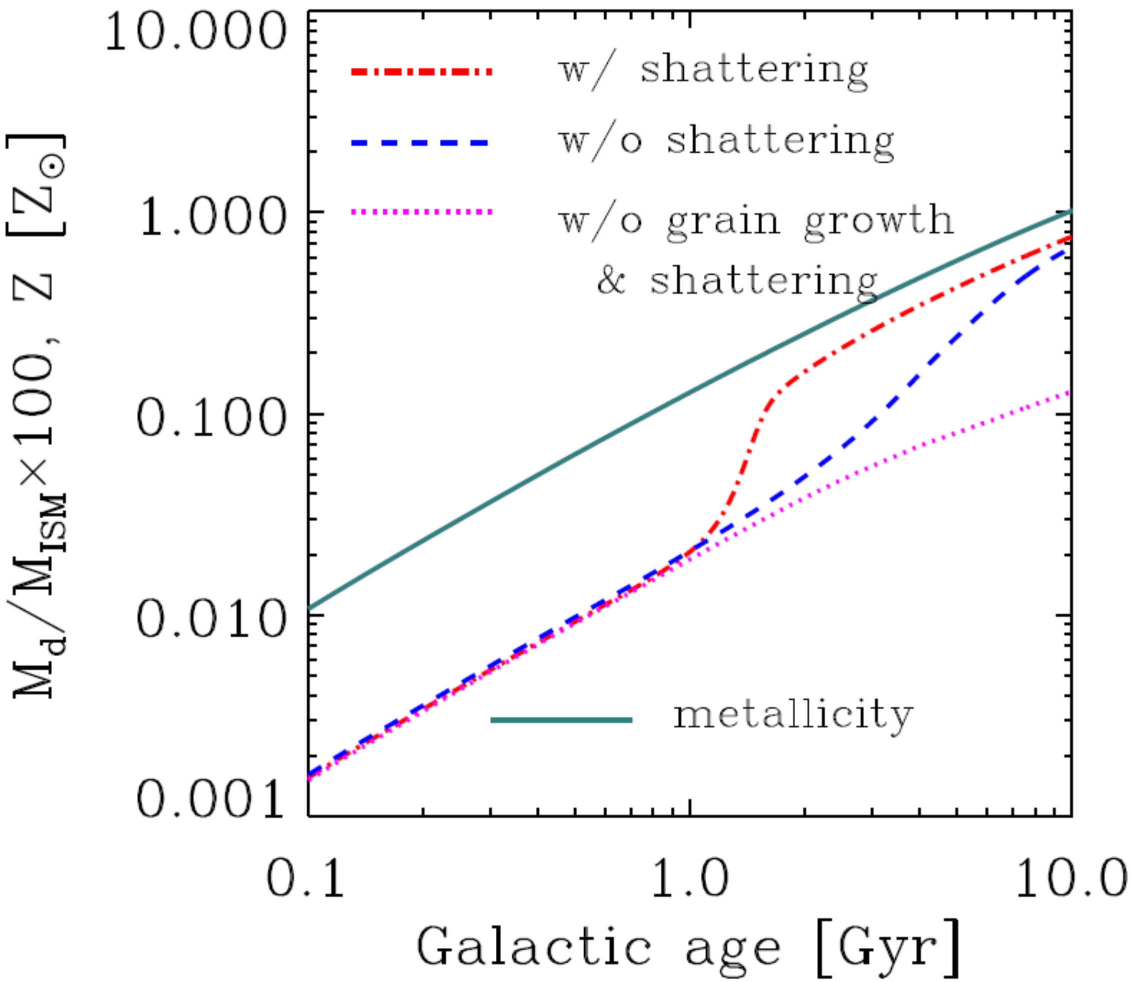
- **Injection/ejection from stars**
- **Destruction by SN shocks**
- **Grain growth in the ISM**

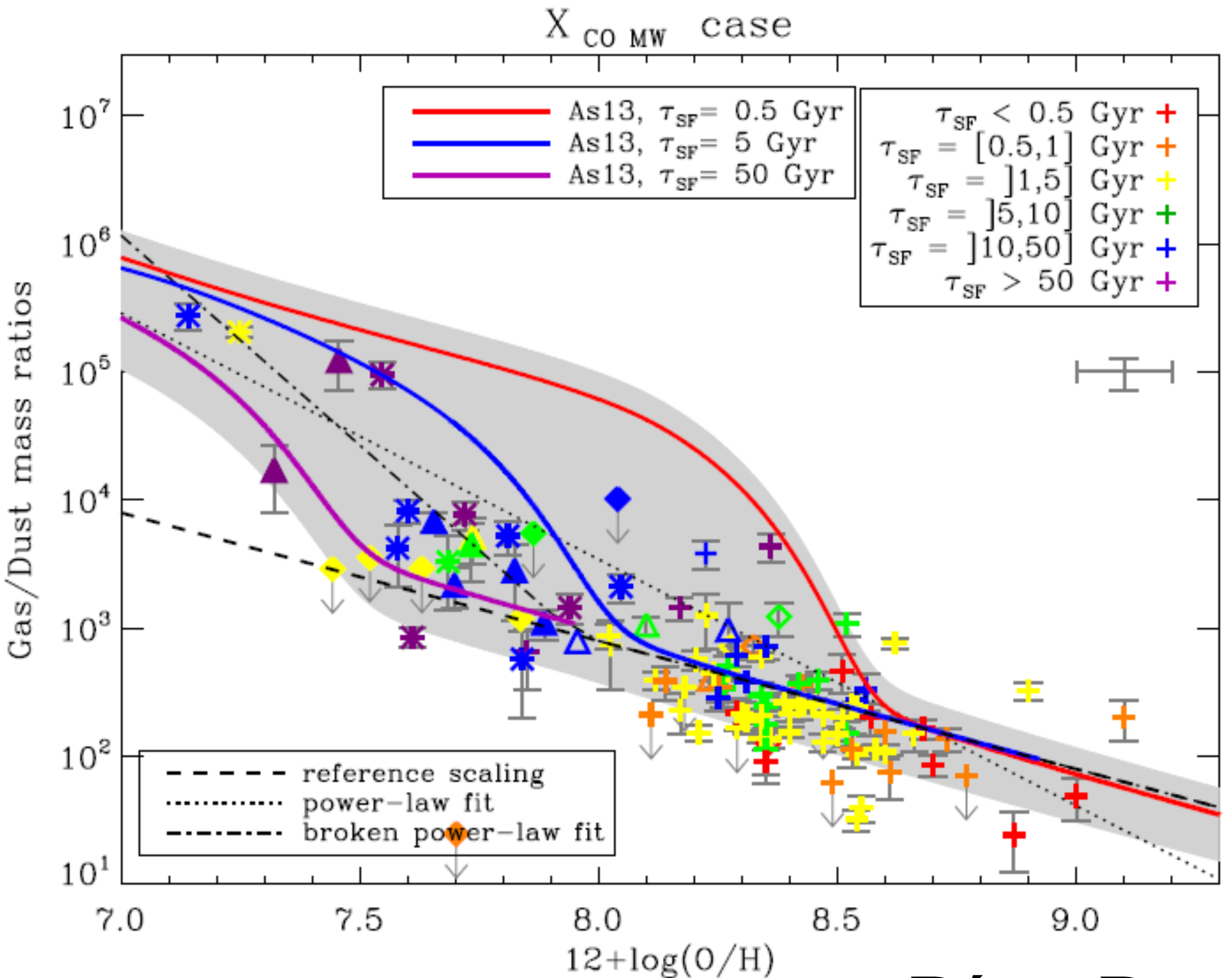
Result: evolution of gas-to-dust mass ratio



Small grain production by shattering activates the grain growth.

Application to the observed data

The model well reproduced the *Herschel* observation of the dust-to-gas mass ratio for local galaxies.



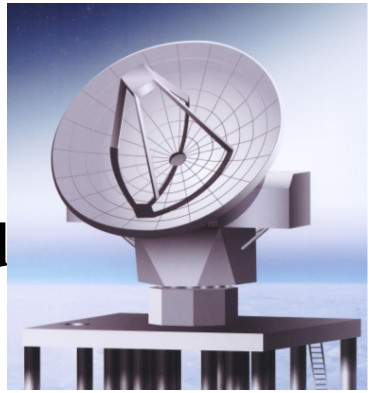
Rémy-Ruyer et al. (2014)

Need for the establishment of the gas-to-dust mass ratio

The empirical relation between metallicity and gas-to-dust mass ratio for local giant galaxies is not valid. For the estimation of gas mass for galaxies, we should replace it with the prediction of Asano model.

We should establish the gas-to-dust mass ratio and its evolution for the studies of gas in high-*z* galaxies.

⇒ A large dust continuum survey at various redshifts is desired.



The Antarctic terahertz telescope has a high survey efficiency for dust continuum, and we expect a good performance.

4 HI-H_2 bivariate mass function

HI-to-H_2 transition in star formation

Total gas mass-stellar mass relation carries significant information for the star formation process.

We, however, are interested in more detailed process in the star formation in galaxies at various redshifts. From a global point of view, star formation proceeds like:

neutral (HI) gas ⇒ molecular (H_2) gas ⇒ star formation

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Hence, HI-to-H_2 transition is fundamental to understand the physics of star formation.

The HI-H_2 bivariate mass function and its extension

If we have a bivariate distribution function of HI and H_2 in galaxies as a function of redshifts, it can work as a direct measure of the HI-H_2 transition and its evolution.

If we further incorporate it with the stellar mass and SFR distribution, it will give a complete picture of the (global) star formation in galaxies.

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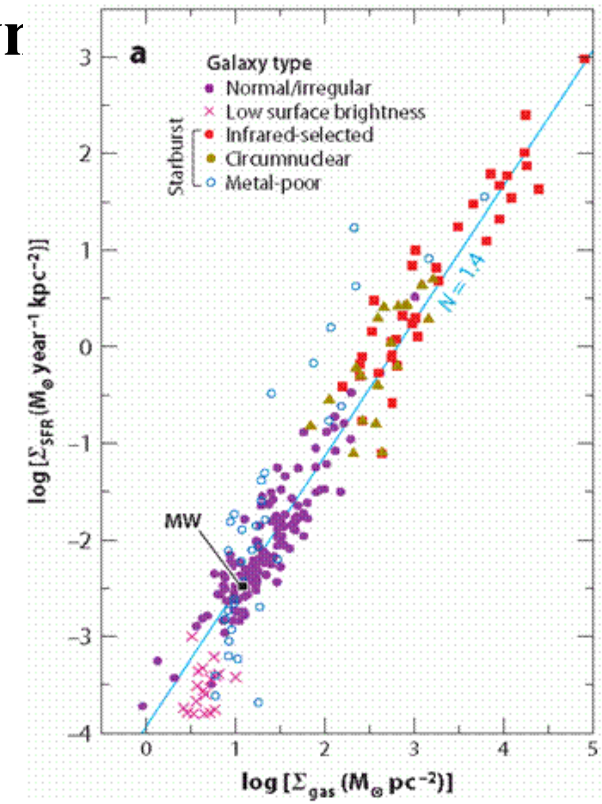
As a relation between (the density of) gas and SFR, the Kennicutt-Schmidt (KS) law is well known

The HI-H_2 bivariate mass function corresponds to a further analysis of the KS law.



Kennicutt & Evans (2012)

Construction of the HI-H_2 bivariate mass function

In general, construction of a bivariate distribution is not a trivial task because of complicated combination of selection effects.

This problem is particularly serious in astronomy!

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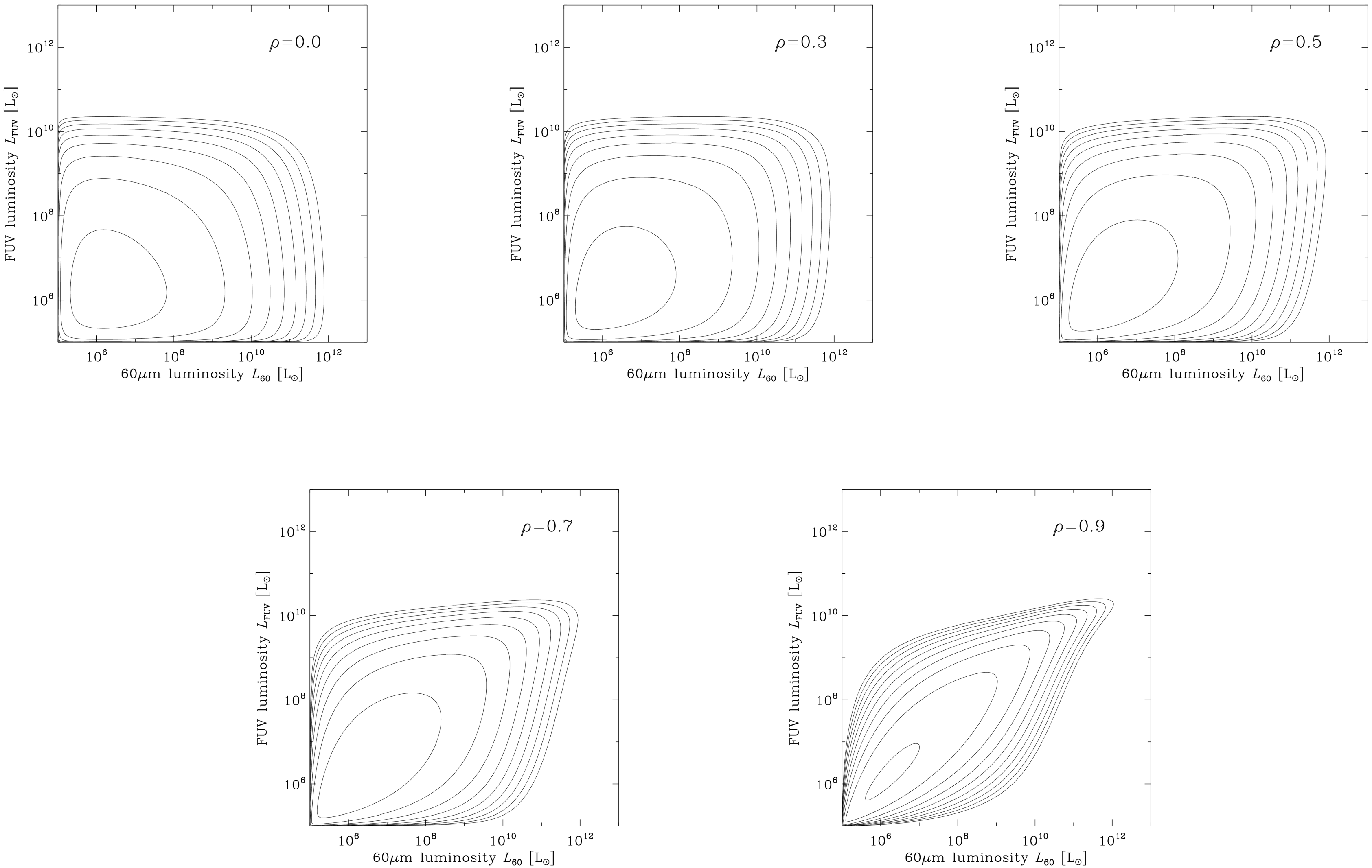
We developed a general method to construct a bivariate (and multivariate) distribution function with treating the sample selection effects appropriately (Takeuchi 2010; Takeuchi et al. 2013).

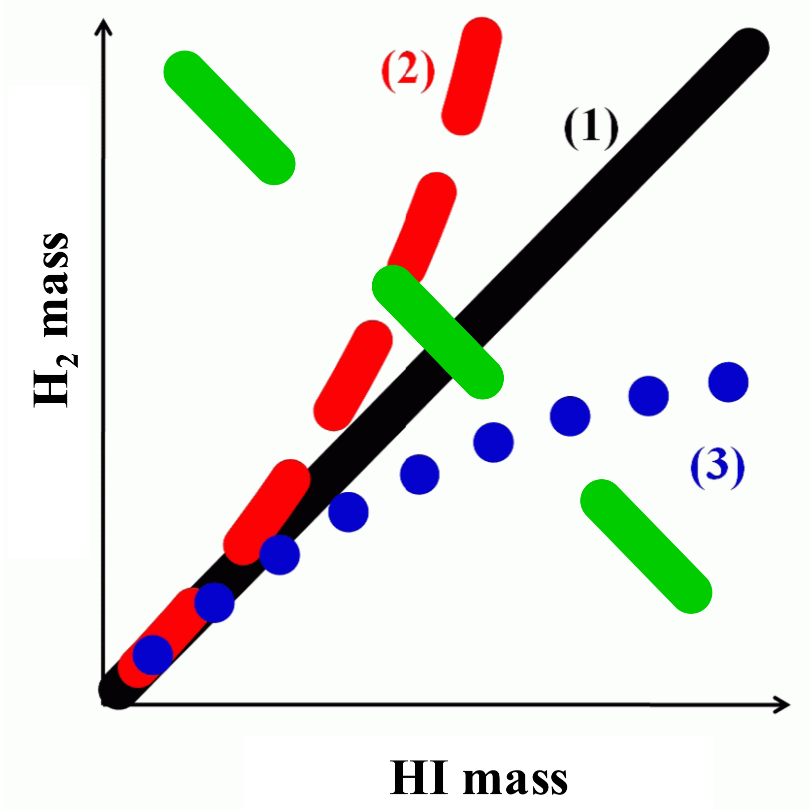
$$g(x_1, x_2) = \frac{\partial^2 C\left[F_1(x_1), F_2(x_2)\right]}{\partial x_1 \partial x_2} f_1(x_1) f_2(x_2)$$
$$\equiv c\left[F_1(x_1), F_2(x_2)\right] f_1(x_1) f_2(x_2)$$

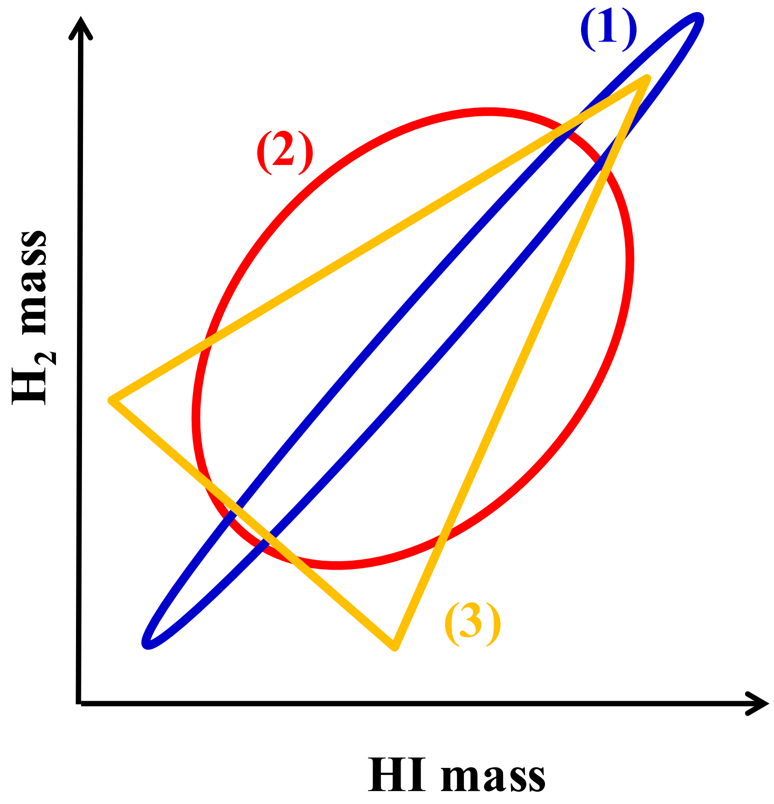
Construction of the HI-H_2 bivariate mass function



Example with various correlation (Takeuchi 2010)

What can we learn from the bivariate function?





(1) Proportional
(2) More HI, less H_2
(3) More HI, more H_2
(4) HI is consumed to form H_2

(1) Stochastic
(2) Deterministic
(3) Transitive

Construction of the HI-H_2 bivariate mass function

Data

HI: 21 cm line observation by Square Kilometre Array (SKA) Phase 1 (2023 ~)

H_2: Dust continuum/line observation by the Antarctic telescope (10 m) (2023 ~)

Benefit: both are highly efficient in surveys, and coherently obtain the data with simple selection.

⇒ Gas mass of galaxies up to $z \sim 1$.

We will be able to constrain the theoretical model with the HI-H_2 bivariate mass function.

5 Conclusions

1. To have a complete picture of star formation in galaxies, the transition from HI to H_2 is fundamental.
2. Gas mass function of galaxies is a useful statistical tool to explore the physics of galaxy evolution.
3. Currently dust emission is used to estimate the total gas mass in galaxies. But recently both from observational and theoretical sides, the empirical relation is not valid at low metallicity.
4. We developed a new theoretical model for the dust evolution, and it should be examined observationally with the Antarctic telescope.
5. HI-H_2 bivariate gas mass function gives more information than simple total mass function.
6. HI data will be provided by SKA, and H_2 at the same redshift range can be well covered by the Antarctic telescope.

Appendix

Formulation of the grain-size dependent evolution of dust mass

Model settings

- **Closed-box model**

(total baryon mass is a constant)

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

- **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

$M_{\mathrm{d}}(a, t) = m(a)f(a, t)\mathrm{d}a$: 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} \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}} \\
& +\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}}
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Stellar effects

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

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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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Grain growth

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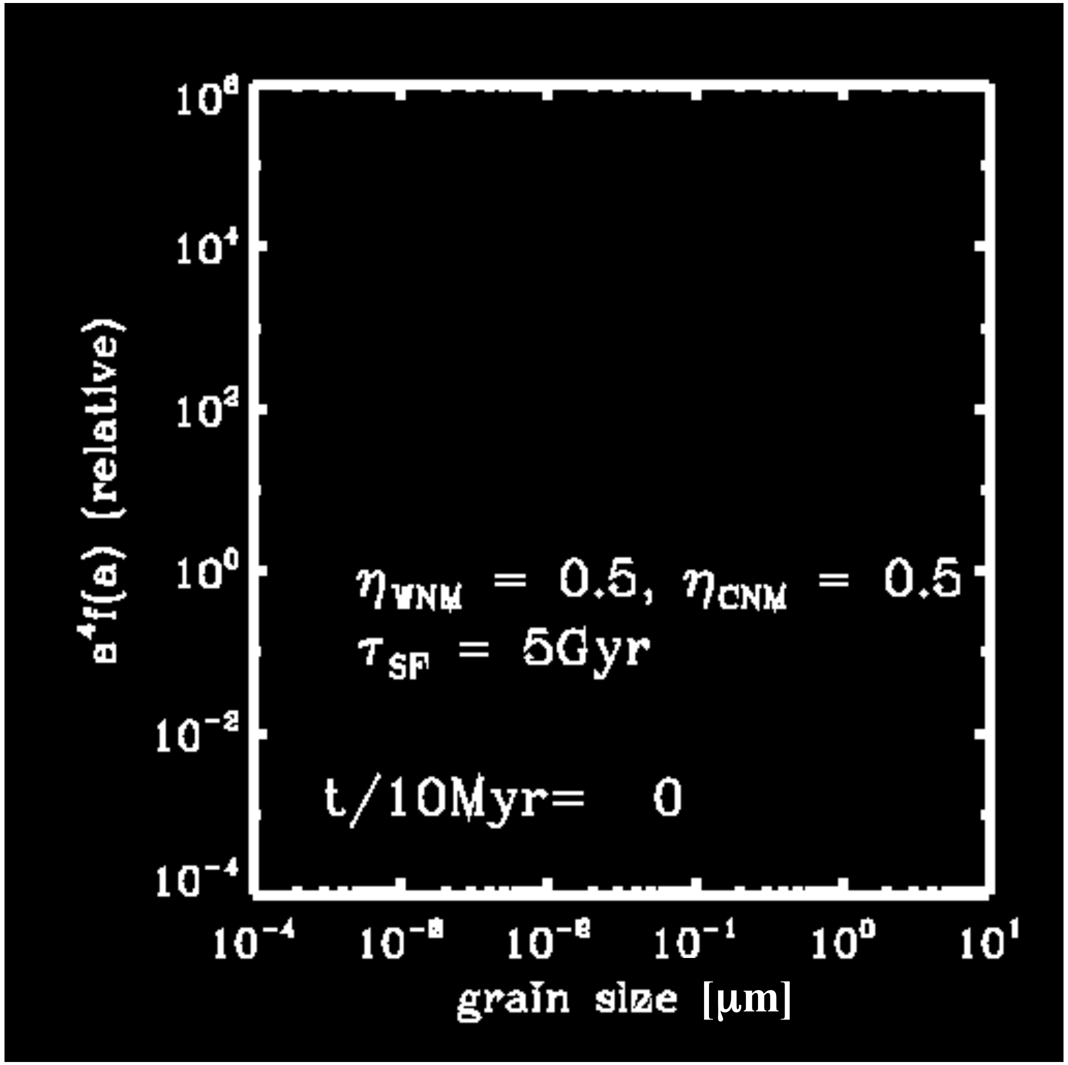
Coagulation

Evolution of the grain size distribution



Dust supply

AGB stars

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)

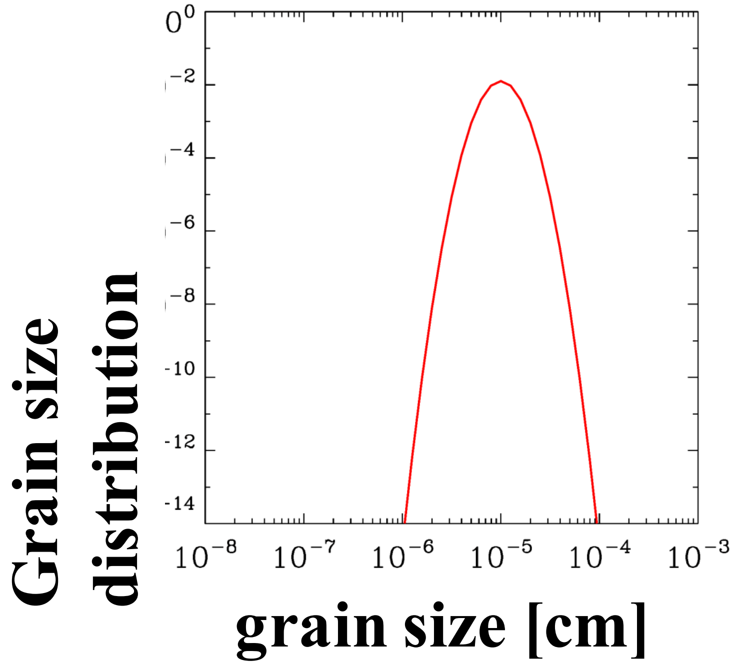
Broken power-law

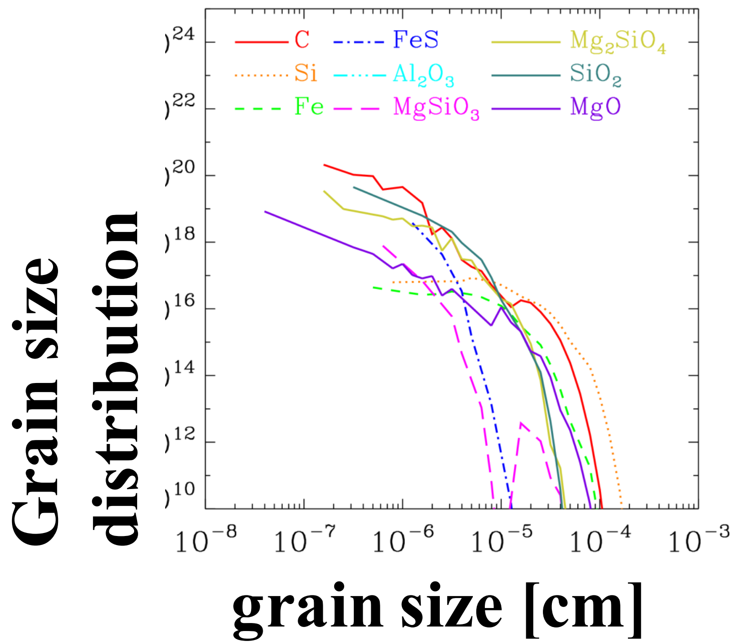
Biased to large grains

Nozawa et al. (2007)

Dust mass data

Nozawa et al. (2007)

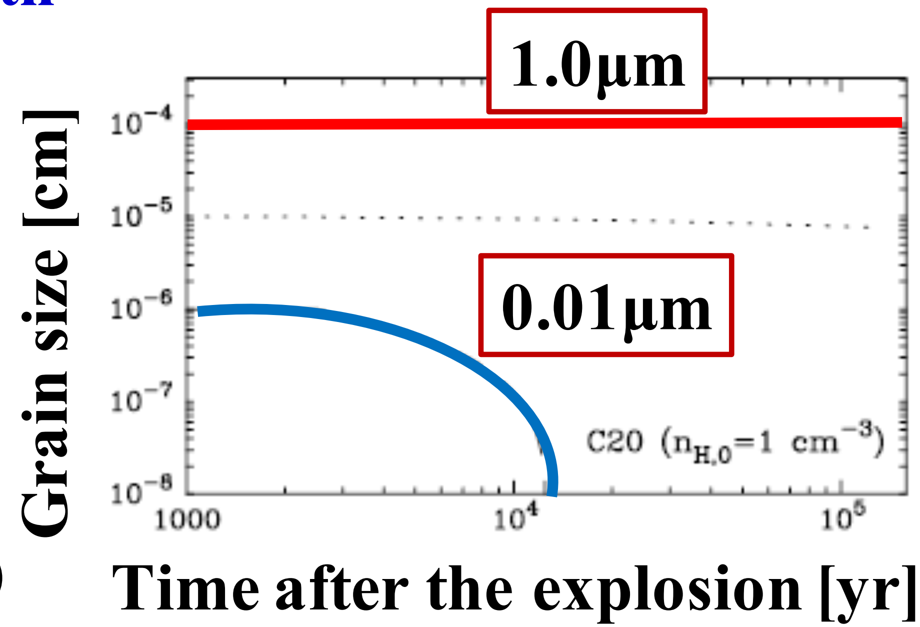




Dust destruction and grain growth

Dust destruction by SN shocks

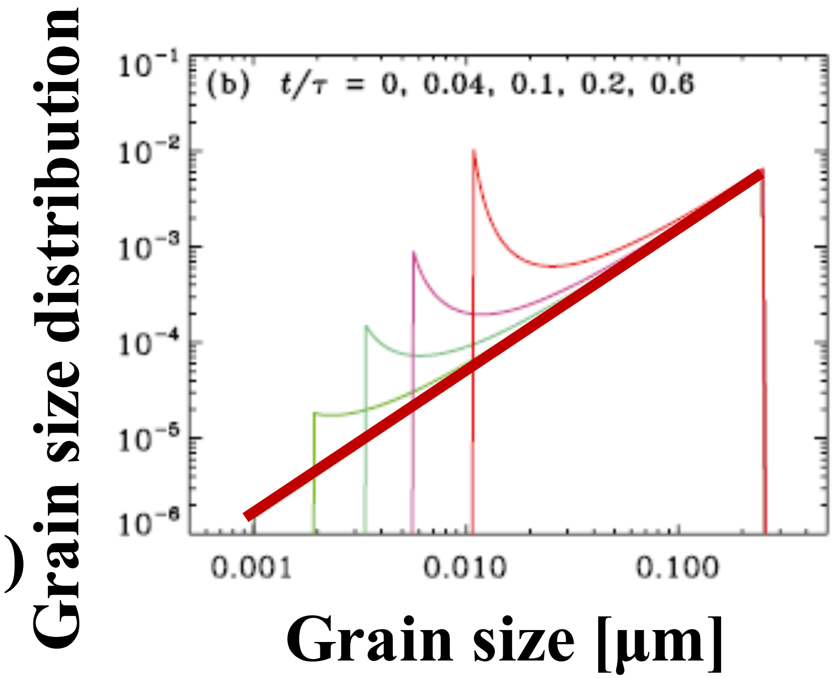
Smaller grains are mainly destroyed by SN shocks.



Nozawa et al. (2006)

Grain growth (metal accretion onto grains)

Smaller grains grow to larger grains.

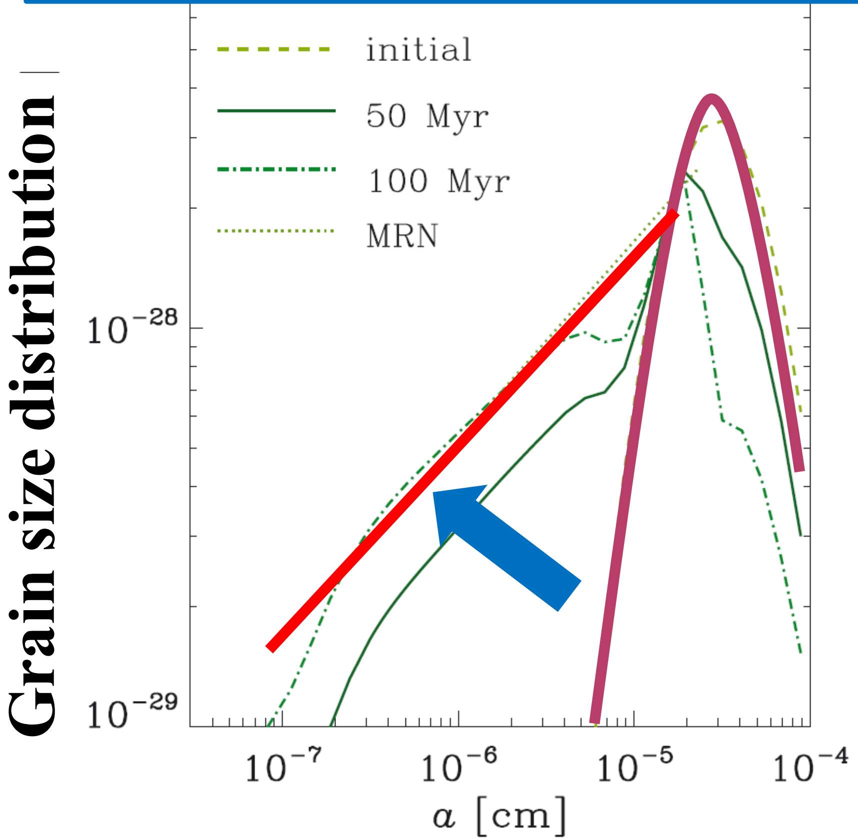


Hirashita & Kuo (2011)

Shattering and coagulation (driven by ISM turbulence)

Shattering

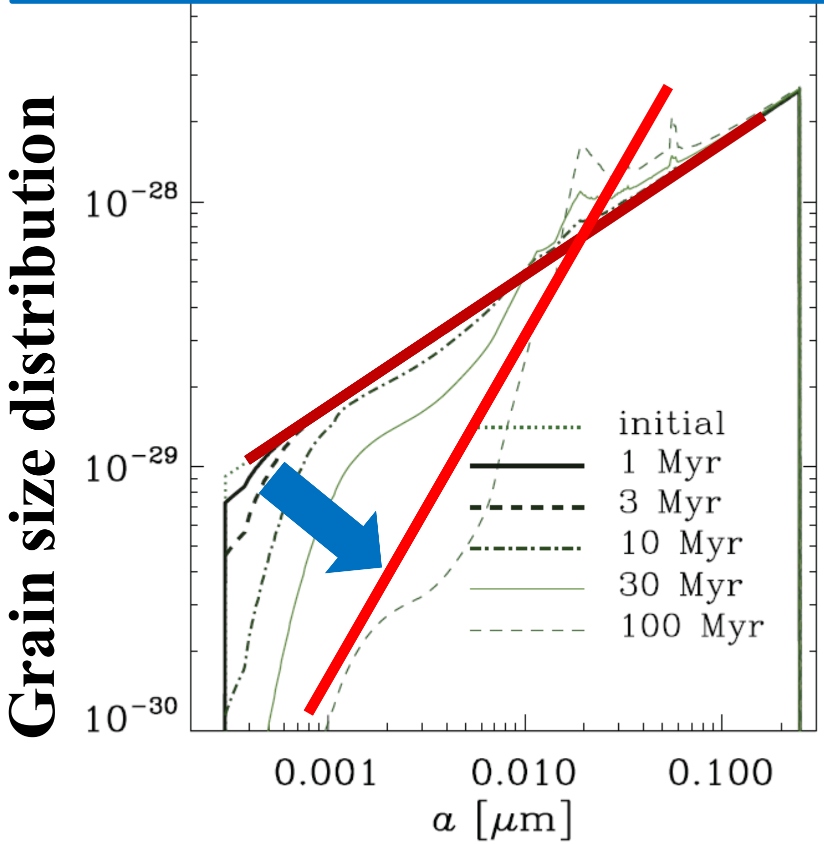
Smaller grains are produced by larger grains



Hirashita (2010)

Coagulation

Larger grains are produced by smaller grains



Hirashita (2012)

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

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

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)

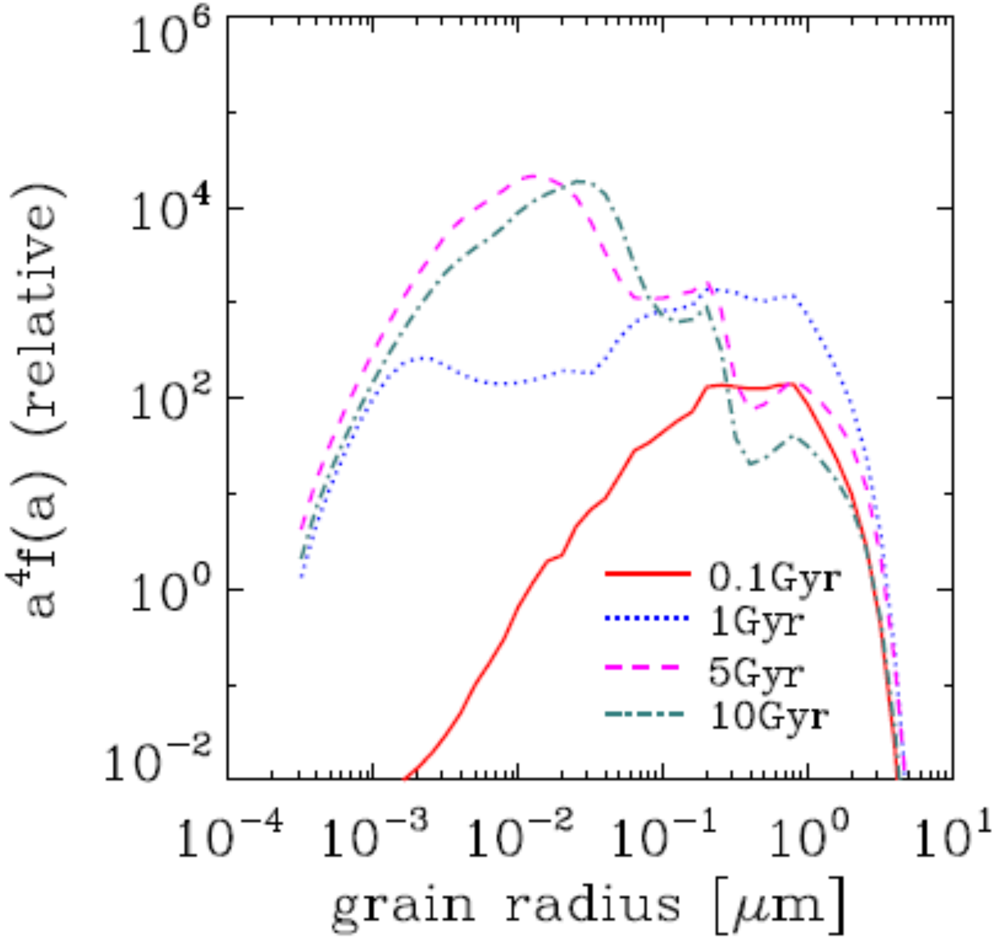
Grain growth by metal accretion

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

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

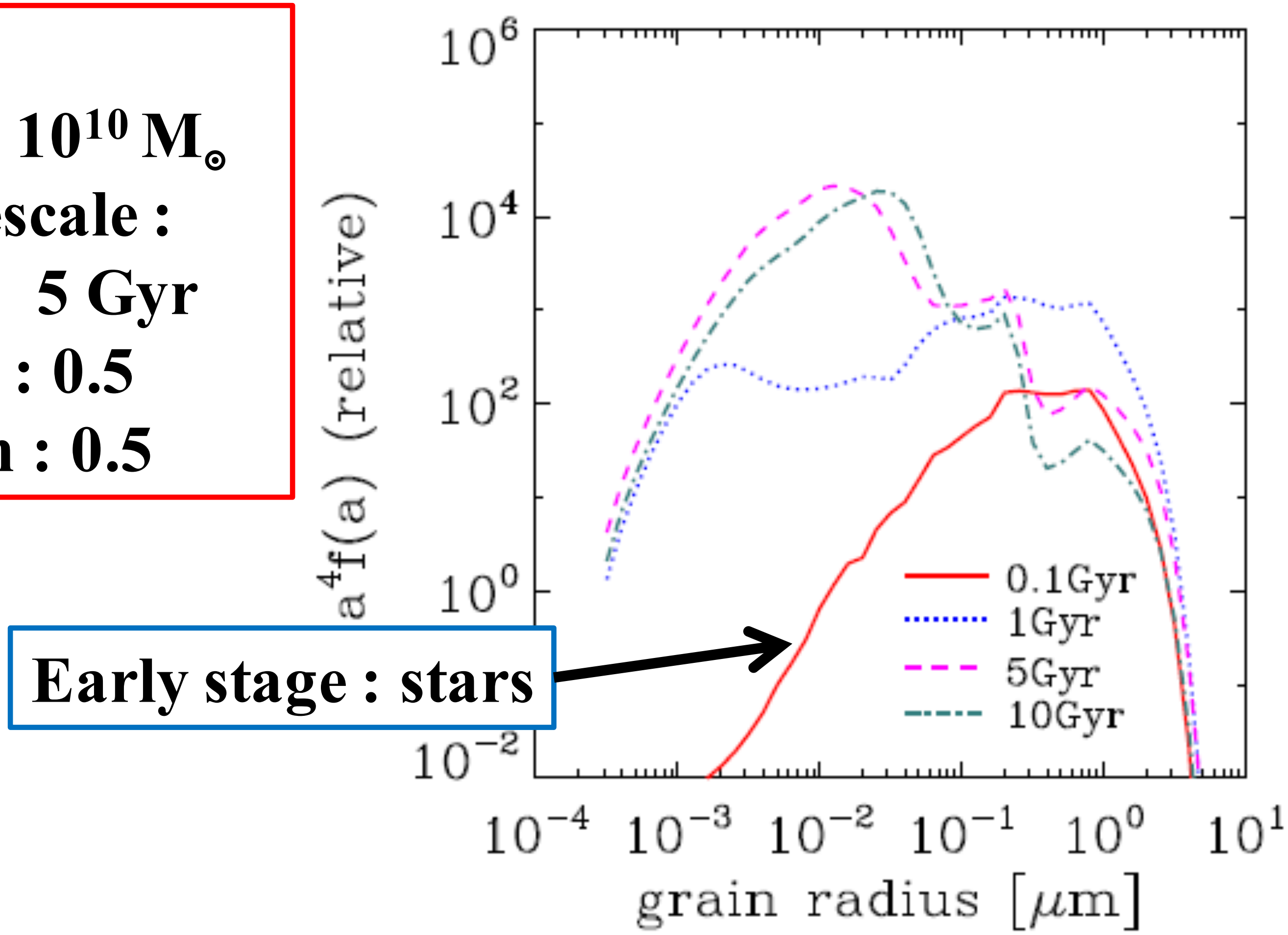
Evolution of the grain size distribution

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



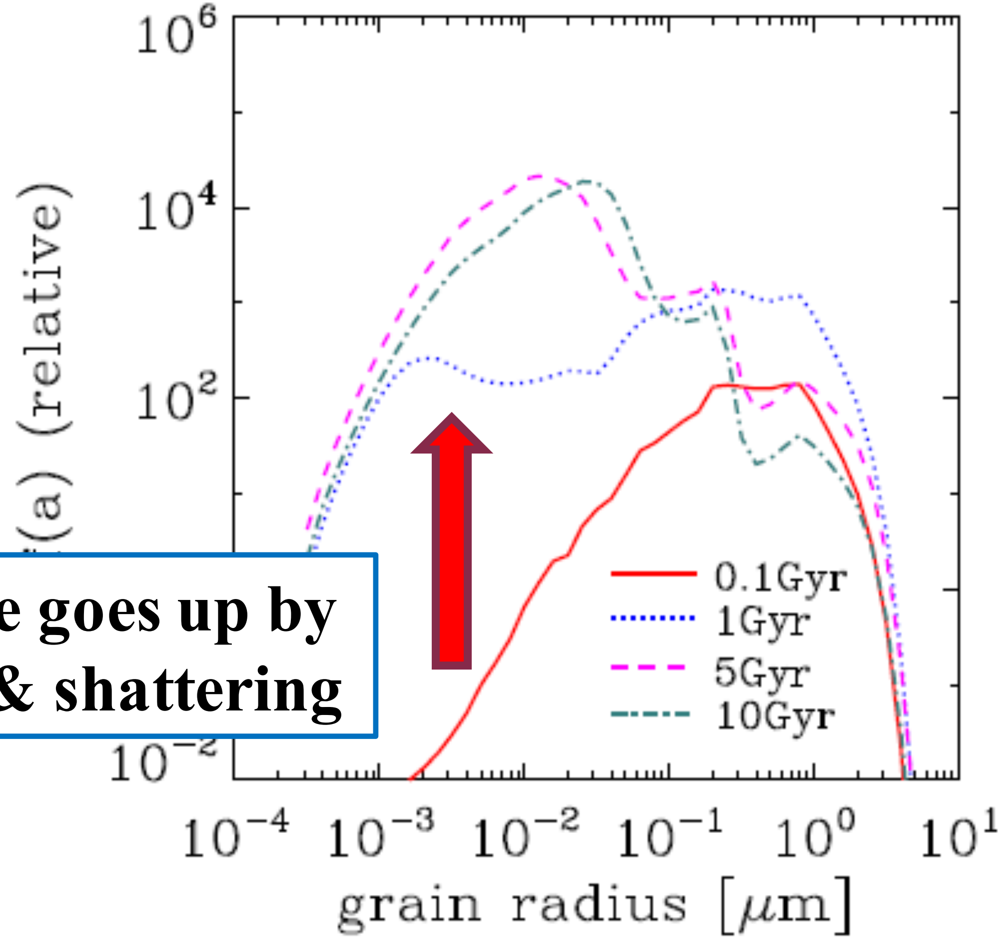
Evolution of the grain size distribution

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

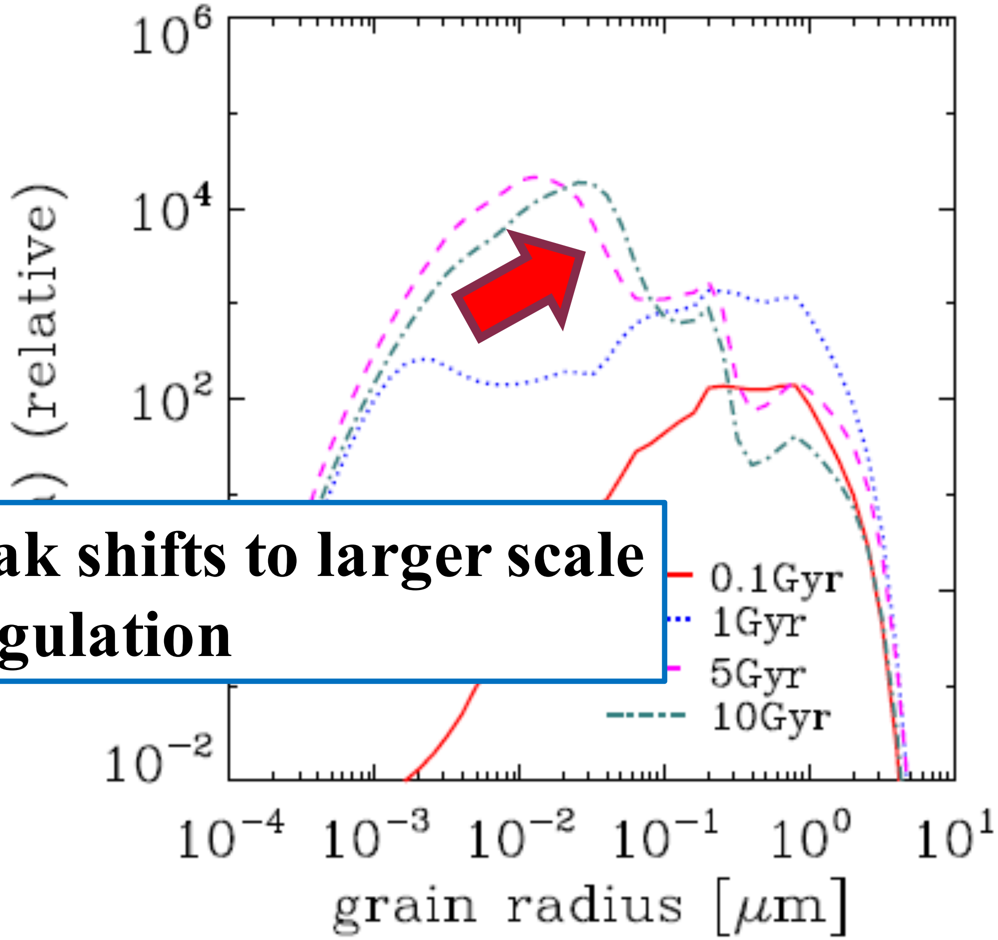
Parameter setting :
Total baryon mass : 10^{10} $M_{\odot}$
Star formation timescale :
5 Gyr
CNM mass fraction : 0.5
WNM mass fraction : 0.5



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