

# Galaxy luminosity function and its cosmological evolution: testing a new feedback model depending on galaxy-scale dust opacity

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## ABSTRACT

We present a new version of a semi-analytic model of cosmological galaxy formation, incorporating a star formation law with a feedback depending on the galaxy-scale mean dust opacity and metallicity, motivated by recent observations of star formation in nearby galaxies and theoretical considerations. This new model is used to investigate the effect of such a feedback on shaping the galaxy luminosity function and its evolution. Star formation activity is significantly suppressed in dwarf galaxies by the new feedback effect, and the faint-end slope of local luminosity functions can be reproduced with a reasonable strength of supernova feedback, which is in contrast to the previous models that require a rather extreme strength of supernova feedback. Our model can also reproduce the early appearance of massive galaxies manifested in the bright-end of high-redshift *K*-band luminosity functions. Though some of the previous models also succeeded in reproducing this, they assumed a star formation law depending on the galaxy-scale dynamical time, which is not supported by observations. We argue that the feedback depending on dust opacity (or metal column density) is essential, rather than that simply depending on gas column density, to get these results.

**Key words:** galaxies: evolution – galaxies: formation – cosmology: theory.

## 1 INTRODUCTION

The basic picture of galaxy formation and evolution in the cosmological context can be explained in the standard  $\Lambda$  cold dark matter ( $\Lambda$ CDM) cosmology. Particularly, large-scale clustering properties and formation and evolution of dark matter (DM) haloes can reliably be predicted by the theory of gravity. However, in order to obtain the full picture of cosmological galaxy formation, we must solve complicated processes of baryonic physics, such as gas cooling, star formation, feedback, galaxy mergers, and so on. One of the key observables about galaxies that must be explained by the theory of cosmological galaxy formation is the luminosity functions (LFs) and their evolution. Compared with the shape of DM halo mass function predicted by the  $\Lambda$ CDM cosmology, the observed galaxy LFs have two remarkable features: flatter faint-end slopes and sharp exponential cut-off at the luminous/massive end (see Benson et al. 2003, and references therein), which must be explained by some baryonic processes.

A widely accepted solution to achieve a flat faint-end is supernova (SN) feedback, i.e. energy input into the interstellar medium by SN explosions to suppress star formation in small galaxies. However, the problem is not yet completely solved at the quantitative level. In fact, unreasonably high efficiency of SN feedback to remove cold interstellar gas in dwarf galaxies is necessary in many existing theoretical models to reproduce the observed flat faint-ends, and such an extreme SN feedback tends to produce discrepancies with observations other than LF shapes (Nagashima & Yoshii 2004, hereafter NY04; Nagashima et al. 2005; Bower et al. 2006; Guo et al. 2011; Bower, Benson & Crain 2012; Wang, Weinmann & Neistein 2012; Hopkins et al. 2013; Mutch, Poole & Croton 2013; Puchwein & Springel 2013). These results imply that another physical effect may also be taking an important role to produce the observed flat faint-end slopes.

For the massive end, a popular solution to suppress the formation of too massive galaxies is the feedback by active galactic nuclei (AGNs; e.g. Bower et al. 2006; Croton et al. 2006; Menci et al. 2008; Somerville et al. 2008; Guo et al. 2011). The AGN feedback can also explain the observed trends of the early appearance of massive and quiescent galaxies at high redshifts, and downsizing of star-forming galaxies from high to low redshifts, which are

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apparently in contradiction with the simple expectation in the  $\Lambda$ CDM universe (e.g. Bower et al. 2006; Somerville et al. 2008). However, there are large uncertainties about the physics of AGN feedback both in theoretically and observationally. The current success in explaining the observed trends by this process is based on rather phenomenological modellings including highly uncertain parameters, and further studies are required to confirm the quantitative influence of this process on galaxy evolution.

Therefore, it is still worth to explore yet other physical effects working to shape galaxy LFs, which is the aim of this paper. It is reasonable to expect that such an effect would be manifested in the scaling laws about star formation efficiency (SFE). The relation between the surface densities of star formation rate (SFR) and gas ( $\Sigma_{\text{SFR}} - \Sigma_{\text{gas}}$ ) has been a subject of intensive research. It is popular to fit this relation by a power law (so-called Kennicutt–Schmidt law; Kennicutt 1998), but recent observations indicate a cut-off around the total (i.e.  $\text{H I} + \text{H}_2$ ) gas density of  $\Sigma_{\text{gas}} \sim 10 \text{ M}_{\odot} \text{ pc}^{-2}$ , under which SFR is suppressed and not well correlated with gas density. This threshold gas density for SFR can be interpreted as a result of less efficient formation of cold molecular gas under the threshold, while the SFE from molecular gas is rather universal in many different environments (Wong & Blitz 2002; Kennicutt et al. 2007; Bigiel et al. 2008, 2010; Leroy et al. 2008; Blanc et al. 2009; Heiderman et al. 2010; Lada, Lombardi & Alves 2010; Schrubba et al. 2011; see Kennicutt & Evans 2012; Schrubba 2013, for reviews).

A likely physical origin of the suppression of  $\text{H}_2$  formation under the threshold is radiative feedback by UV photons produced by young massive stars (Schaye 2004; Krumholz, McKee & Tumlinson 2008, 2009; McKee & Krumholz 2010; Hopkins et al. 2013). The formation of  $\text{H}_2$  is driven by collisionally excited metal line cooling and molecule formation on dust grain surfaces, which should be balanced with molecule dissociations by UV photons and grain photoelectric heating, both of which are energetically supplied by UV radiation field. If a region in a galaxy is optically thick to UV radiation field by dust grains, self-shielding of UV radiation would accelerate  $\text{H}_2$  formation. This implies that the more fundamental threshold about star formation is not the total gas surface density but dust opacity. For a typical dust-to-gas ratio, the observationally indicated threshold in  $\Sigma_{\text{gas}}$  is close to the value at which the effective dust opacity  $\tau_{\text{d}}^{\text{eff}}$  becomes of order unity, where  $\tau_{\text{d}}^{\text{eff}}$  is averaged over wavelength with a weight of the heating radiation energy spectrum (Totani et al. 2011).

Therefore, it is physically reasonable to expect that a galaxy-scale mean value of  $\tau_{\text{d}}^{\text{eff}}$  has an important role in galaxy formation and evolution. A further observational support to this picture comes from infrared observations. The relations between dust temperature, galaxy size and infrared luminosity of  $\sim 1000$  nearby star-forming galaxies indicate that almost all of them are in the optically thick regime, and the distribution of dust opacity estimated by gas-phase metal column density suddenly drops around  $\tau_{\text{d}}^{\text{eff}} \sim 1$ , indicating less efficient formation of galaxies at  $\tau_{\text{d}}^{\text{eff}} \lesssim 1$  (Totani et al. 2011).

The purpose of this paper is to investigate the effect of the radiative feedback depend on dust opacity, on cosmological galaxy formation and evolution particularly about the shape of galaxy LFs. The theory of structure formation in the universe predicts that the mean surface density  $M/r^2$  of dark haloes with mass  $M$  and size  $r$  nearly scales as  $\propto M^{1/3}(1+z)^2$ , indicating higher gas surface density and dust opacity at higher redshifts in more massive objects, and hence more efficient star formation. This may have a favourable effect to explain observations, in a similar way to the feedbacks by SN and AGNs.

To investigate the effect quantitatively, we use a semi-analytic model (SAM) of cosmological galaxy formation, the *Mitaka model* (NY04). This is a model similar to general SAMs, in which formation and evolution of DM haloes are solved analytically or calculated by  $N$ -body simulations, while complicated baryonic processes are treated phenomenologically (for reviews, see Baugh 2006; Benson 2010). In general, SAMs have many adjustable parameters and the effects of complicated physical processes on the LFs are degenerate (e.g. Neistein & Weinmann 2010); therefore a set of best-fitting parameters may not be a quantitatively correct description of real galaxy formation. It should be noted that the most important aim of this work is to examine the qualitative effects of the new feedback on LFs.

In most of the SAMs, the SFR is simply proportional to cold gas mass, and the star formation time-scale is modelled as a simple function of the dynamical time-scale of galaxy discs or DM haloes (e.g. Cole et al. 2000; NY04). Some models (e.g. Kauffmann 1996; Croton et al. 2006; Somerville et al. 2008; Lagos et al. 2011; Wang et al. 2012) incorporated the threshold of gas surface density below which star formation activity is significantly suppressed. In the models of Kauffmann (1996), Croton et al. (2006) and Lagos et al. (2011), they introduced the threshold of gas surface density motivated by the Toomre stability criterion on a galactic scale (Toomre 1964). In this scenario, the threshold of gas surface density increases with redshift, and hence, the threshold effect should be systematically different in the cosmological context from the threshold by dust opacity considered in this paper. Furthermore, some recent observations indicate that star formation are controlled by the physical state of local interstellar gas, rather than the dynamical state of an entire galaxy (e.g. Leroy et al. 2008; Lada et al. 2010).

In other models, such as Somerville et al. (2008), a critical gas surface density threshold for star formation is introduced motivated from the observations of the  $\Sigma_{\text{SFR}} - \Sigma_{\text{gas}}$  relation; however, to our knowledge there are no SAMs that consider a feedback depending on dust surface density rather than gas density. Recently Krumholz & Dekel (2012) incorporated a star formation law which depends on gas surface density and gas metallicity, and discussed average evolution of typical galaxies without calculating detailed merger histories of dark haloes. The relation between the LF shapes and the dust opacity threshold of star formation has not yet been discussed in previous studies.

This paper is organized as follows. In Section 2, we will describe our model particularly focusing on the modellings of star formation and feedback. In Section 3, we show the results of our model, and Section 4 is devoted for discussion. We will summarize our work in Section 5. In this work, the cosmological parameters of  $\Omega_0 = 0.3$ ,  $\Omega_{\Lambda} = 0.7$  and  $H_0 = 70 \text{ Mpc}^{-1} \text{ km s}^{-1}$  are adopted, and all magnitudes are expressed in the AB system.

## 2 MODEL DESCRIPTION

The detailed description of the basic model, the *Mitaka model* is given by NY04. Here, we focus on the extension made in this work.

### 2.1 Star formation recipe

There are two modes of star formation in our model: quiescent star formation in galaxy discs and starbursts in major mergers. We follow the same modelling as NY04 for the starburst mode, where all the cold gas is converted into stars and hot gas instantaneously. Since the amount of stars formed during major mergers is rather

minor compared with that in disc galaxies at low redshift, modelling of the starburst mode does not significantly change the local luminosity/mass functions. We change the star formation recipe for the quiescent mode as follows. The SFR is expressed as

$$\psi = M_{\text{cold}}/\tau_{\text{SF}}, \quad (1)$$

where  $M_{\text{cold}}$  is the cold gas mass, and  $\tau_{\text{SF}}$  is star formation time-scale. In the NY04 model, two models for  $\tau_{\text{SF}}$  were considered: constant star formation model (CSF) and dynamical star formation model (DSF). In the CSF model, star formation time-scale ( $\tau_{\text{SF}}$ ) is constant against redshift, while in the DSF model  $\tau_{\text{SF}}$  is proportional to the dynamical time-scale of the host DM halo. These models were expressed as

$$\tau_{\text{SF}} = \begin{cases} \tau_{\text{SF}}^0 [1 + \beta(V_{\text{circ}})] & \text{(CSF),} \\ \tau_{\text{SF}}^0 [1 + \beta(V_{\text{circ}})] \left[ \frac{\tau_{\text{dyn}}(z)}{\tau_{\text{dyn}}(0)} \right] & \text{(DSF),} \end{cases} \quad (2)$$

where  $\tau_{\text{SF}}^0$  is a free parameter,  $\beta$  is the ratio of the SF time-scale to the reheating time-scale by the SN feedback defined by equation (7) (see below), and  $\tau_{\text{dyn}}(z)$ , which is nearly scales as  $\propto(1+z)^{-3/2}$ , is the dynamical time-scale of DM halo at each redshift.

The DSF model is based on an idea that the star formation time-scale is controlled by the dynamical state of an entire galaxy or DM halo, and star formation activity is highly enhanced at high redshifts because of the redshift dependence of the dynamical time. It is often stated that the AGN feedback is helpful to explain the early appearance of massive and quiescent galaxies and to suppress the formation of too massive galaxies, but we will later (Section 3.2) show that enhanced star formation at high redshifts is also essential, and it is incorporated by DSF in previous models (e.g. Bower et al. 2006).<sup>1</sup> However, recent observations suggest that the physics of star formation is determined by the physical state of local interstellar gas, rather than the dynamical state of entire galaxy (e.g. Leroy et al. 2008; Lada et al. 2010). Furthermore, the CSF model is more favourable than the DSF model to explain the observations of local dwarf spheroidal galaxies (NY04). In this work, we adopt a star formation law that is determined by the local gas/dust column density, independent of the galaxy-scale dynamical time.

The local LFs can be reproduced well by both of the CSF and DSF models of NY04, but the observed cut-off in the  $\Sigma_{\text{SFR}} - \Sigma_{\text{gas}}$  relation is not reproduced in these models, indicating a necessity of including another feedback working at low gas surface density. Following the discussion in Section 1, we introduce the radiative feedback depending on dust surface density by adopting the following form of star formation efficiency (SFE,  $\varepsilon \equiv 1/\tau_{\text{SF}}$ ),

$$\varepsilon = \varepsilon_{\text{max}} \exp(-\tau_{\text{d,th}}/\tau_{\text{dust}}) + \varepsilon_{\text{min}}, \quad (3)$$

where  $\tau_{\text{dust}}$  is the wavelength-averaged dust opacity. In the limit of high dust surface density, SFE becomes constant at  $\varepsilon_{\text{max}}$ , i.e.  $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}$ , which is consistent with the observation of nearby starburst galaxies (Kennicutt 1998; Kennicutt & Evans 2012). The parameter  $\varepsilon_{\text{min}}$  controls the strength of the feedback below the critical dust opacity  $\tau_{\text{d,th}}$ . We assume that the dust mass is proportional

to the metal mass in the cold gas phase, and hence,  $\tau_{\text{dust}}$  is given by

$$\tau_{\text{dust}} = \frac{1}{2} \frac{\kappa_{\text{d,eff}} M_{\text{dust}}}{\pi r_{\text{eff}}^2} = 2 \times 10^{-3} \left[ \frac{M_{\text{cold}} Z_{\text{cold}} / r_{\text{eff}}^2}{M_{\odot} Z_{\odot} \text{pc}^{-2}} \right], \quad (4)$$

where  $M_{\text{dust}}$  is the interstellar dust mass,  $\kappa_{\text{d,eff}} = 2.1 \text{ pc}^2 M_{\odot}^{-1}$  is the frequency-integrated effective dust mass opacity weighted by the local interstellar radiation field (Totani et al. 2011),  $r_{\text{eff}}$  is the effective radius of a galaxy disc, and  $Z_{\text{cold}}$  is the metallicity of cold gas. We assume that the solar metallicity gas has local dust-to-gas mass ratio, 0.006 (Zubko, Dwek & Arendt 2004). We follow the typical prescription of SAMs in our model by assuming that the disc size is proportional to the virial radius of host DM haloes, and therefore, it nearly scales as  $r_{\text{eff}} \propto 1/(1+z)$  for a fixed halo mass.

We treat  $\varepsilon_{\text{max}}$  as a constant, but introduce the following two modellings of  $\varepsilon_{\text{min}}$  for galaxies that are transparent to UV radiation. One is simply to assume that  $\varepsilon_{\text{min}}$  is also a universal constant. We cannot assume  $\varepsilon_{\text{min}} = 0$  in this case, because SFR becomes zero in metal-free galaxies, and hence galaxies cannot form in the universe. There is a physical motivation to expect that  $\varepsilon_{\text{min}}$  evolves with metallicity. There are two physical processes that would suppress star formation when UV radiation field is prevalent throughout a galaxy:  $\text{H}_2$  dissociation and photoelectric heating by dust grains (Schaye 2004; Krumholz et al. 2008, 2009; McKee & Krumholz 2010). The  $\text{H}_2$  dissociation should not depend on metallicity, but the efficiency of photoelectric heating should become larger with increasing amount of dust, which is assumed here to be proportional to the metallicity. If the photoelectric heating is relatively important, we expect that  $\varepsilon_{\text{min}}$  decreases with metallicity. Therefore, we consider two models (the constant and evolving  $\varepsilon_{\text{min}}$  models, hereafter) for the minimum SFE:

$$\varepsilon_{\text{min}} = \begin{cases} \varepsilon_{\text{min}}^0 & \text{(constant } \varepsilon_{\text{min}}), \\ \varepsilon_{\text{min}}^0 \exp(-Z_{\text{cold}}/Z_{\text{ch}}) & \text{(evolving } \varepsilon_{\text{min}}), \end{cases} \quad (5)$$

where  $\varepsilon_{\text{min}}^0$  and  $Z_{\text{ch}}$  are constant model parameters.

## 2.2 SN and AGN feedback

In this section, we describe the model of SN feedback and AGN feedback since they are highly relevant to star formation process.

(i) *SN feedback.* Following the original Mitaka model, we assumed that part of cold gas is reheated and ejected from galaxies as a consequence of SN feedback at a rate

$$\dot{M}_{\text{reheat}} = \psi \beta(V_{\text{circ}}), \quad (6)$$

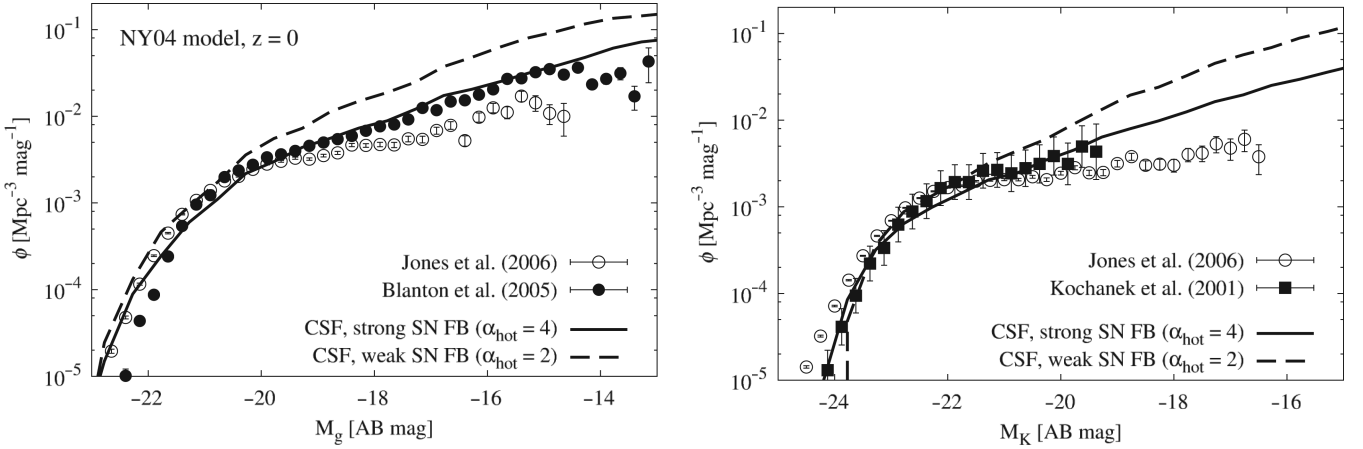
where

$$\beta(V_{\text{circ}}) = \left( \frac{V_{\text{circ}}}{V_{\text{hot}}} \right)^{-\alpha_{\text{hot}}}, \quad (7)$$

where  $\dot{M}_{\text{reheat}}$  is reheated gas mass per unit time, and  $V_{\text{circ}}$  is the circular velocity of a DM halo. The free parameters  $\alpha_{\text{hot}}$  and  $V_{\text{hot}}$  are determined by the fits to the local LFs, because the faint-end slope and characteristic luminosity of LF are sensitively dependent on  $\alpha_{\text{hot}}$  and  $V_{\text{hot}}$ , respectively.

In our model, reheated materials are assumed to be ejected from a galactic disc into its hot halo gas, with a kinetic energy production rate of  $\sim \dot{M}_{\text{reheat}} V_{\text{wind}}^2/2$ . It is reasonable to assume that the velocity is determined by the halo circular velocity, i.e.  $V_{\text{wind}} \sim V_{\text{circ}}$ , and the energy production rate by the SN feedback is proportional to SFR  $\psi$ . In this case, we expect  $\alpha_{\text{hot}} \sim 2$ . If the scaling is determined by momentum rather than energy, we expect  $\alpha_{\text{hot}} \sim 1$ . However,

<sup>1</sup> Note that Granato et al. (2004) also pointed out the importance of AGN feedback combined with enhanced star formation at high redshifts by using a simplified SAM, in a different context of reproducing high- $z$  elliptical galaxies rather than solving the problem of formation of too massive galaxies at the local universe.



**Figure 1.** Left: the local  $g$ -band LF compared with the NY04 model. The solid and dashed lines represent the NY04 model with strong SN feedback ( $\alpha_{\text{hot}} = 4$ ) and weak (reasonable) SN feedback ( $\alpha_{\text{hot}} = 2$ ), respectively. We only show the results of CSF model, since the DSF model gives the almost same results. Filled circles indicate the SDSS  $g$ -band LF obtained by Blanton et al. (2005), and open circles are the 6dF  $b_j$ -band LF obtained by Jones et al. (2006). We have transformed the 6dF  $b_j$ -band LF to match  $g$ , by subtracting 0.25 mag (Blanton et al. 2005). Right: the same as the left-hand panel but for the local  $K$ -band LF. Data points are the 6dF galaxy survey (Jones et al. 2006) and 2MASS (Kochanek et al. 2001).

it has been known that a much stronger feedback efficiency at low velocities than these reasonable values is required (i.e.  $\alpha_{\text{hot}} = 3\text{--}4$ ; NY04; Bower et al. 2006) to reproduce the faint-end slope of the local LFs. In Fig. 1, we show this for the local  $g$ - and  $K$ -band LFs using the NY04 model with the two different model predictions of  $\alpha_{\text{hot}} = 2$  and 4.

As already mentioned above, star formation activity in dwarf galaxies would be suppressed if we adopt the dust opacity-dependent star formation recipe. Therefore, our new model may reproduce the faint-end LF slopes with a more reasonable efficiency of SN feedback. We adopt a reasonable value of  $\alpha_{\text{hot}} = 2$  for all of our new models presented in our work, and will show that the new model can indeed reproduce the observed faint-end LF slopes.

(ii) *AGN feedback.* In the original Mitaka model, in order to avoid the formation of extremely massive galaxies the cooling process is applied only to DM haloes with circular velocity  $V_{\text{circ}} \leq V_{\text{cut}}$ , where  $V_{\text{cut}}$  is a free parameter which is determined to reproduce the local LFs. In the new model, we introduce the AGN feedback process to make the bright-end of LF consistent with observations, following the formulation of Bower et al. (2006).

In our new model, if the following conditions are satisfied the halo is prevented from gas cooling;

$$\alpha_{\text{cool}} t_{\text{dyn}} < t_{\text{cool}} \quad (8)$$

and

$$\epsilon_{\text{SMBH}} L_{\text{edd}} > L_{\text{cool}}, \quad (9)$$

where  $t_{\text{dyn}}$  is dynamical time-scale of the halo,  $t_{\text{cool}}$  is the time-scale of gas cooling,  $L_{\text{edd}}$  is the Eddington luminosity of the AGN,  $L_{\text{cool}}$  is the cooling luminosity of gas and  $\alpha_{\text{cool}}$  and  $\epsilon_{\text{SMBH}}$  are the free parameters which are tuned to reproduce the observation. The cooling time and dynamical time are calculated at cooling radius, which is the radius where cooling time-scale is equal to the age of halo. Since our model does not include the formation and evolution of supermassive black holes, we simply estimated the black hole mass from the bulge stellar mass, using the observed bulge mass–black hole mass relation (Marconi & Hunt 2003). It is unclear whether the bulge mass–black hole mass relation evolves with redshift or not, but no evolution hypothesis is consistent with observations. The

AGN feedbacks are important for relatively low-redshift galaxies satisfying the condition of equation (8), and the possible evolution of the relation would not have a significant effect. For the results when an SMBH formation model is incorporated into the original Mitaka model, see Enoki, Nagashima & Gouda (2003), Enoki et al. (2004) and Enoki & Nagashima (2007).

The condition of equation (8) means that the AGN feedback works only in quasi-hydrostatically cooling haloes (the so-called radio mode feedback; Croton et al. 2006). In several SAMs, another mode of AGN feedback is also considered, namely the ‘quasar mode’ or ‘bright mode’ feedback (Somerville et al. 2008; Bower et al. 2012). This feedback mode is considered to be induced by rapid gas accretion on to supermassive black holes during the major merger phase. Our model does not include this feedback mode; however, this feedback mode is only acting in the starburst phase, and therefore, it would not strongly affect the total star formation history or luminosity/mass function shapes. Indeed, Bower et al. (2012) showed that the quasar-mode feedback has only a modest effect on the shape of the galaxy stellar mass function.

### 2.3 Parameter determination

In summary, there are four new free parameters related to the feedback depending on dust opacity ( $\epsilon_{\text{max}}$ ,  $\tau_{\text{d,th}}$ ,  $\epsilon_{\text{min}}^0$  and  $Z_{\text{ch}}$ ), in addition to the four SN and AGN feedback parameters in previous models ( $\alpha_{\text{hot}}$ ,  $V_{\text{hot}}$ ,  $\alpha_{\text{cool}}$  and  $\epsilon_{\text{SMBH}}$ ). These parameter values of our two models (constant and evolving  $\epsilon_{\text{min}}$  models) are determined by fitting to the local LFs with the following procedures. Throughout this paper, we adopt the Salpeter IMF (Salpeter 1955) with a mass range of 0.1–60  $M_{\odot}$ . The absolute luminosity and colours of individual galaxies are calculated using a population synthesis code by Kodama & Arimoto (1997), assuming the Galactic extinction curve.

As mentioned above, we fix the SN feedback parameters to the reasonable values of  $\alpha_{\text{hot}} = 2$  and  $V_{\text{hot}} = 150 \text{ km s}^{-1}$ . (The  $V_{\text{hot}}$  value is the same as that in NY04.) We then find best-fitting values of the new parameters introduced in this work ( $\epsilon_{\text{max}}$ ,  $\tau_{\text{th}}$ ,  $\epsilon_{\text{min}}^0$  and  $Z_{\text{ch}}$ ) by fitting to the local LFs in relatively faint luminosity range. Then, the AGN feedback parameters are determined by fitting the bright-end of LFs;  $\alpha_{\text{cool}}$  and  $\epsilon_{\text{SMBH}}$  control the cut-off luminosity



**Table 1.** The model parameters in the constant  $\epsilon_{\min}$  and evolving  $\epsilon_{\min}$  model. All of the other parameters are fixed at the same value with the NY04 model. See Sections 2.1 and 2.2 for parameter descriptions and Section 2.3 for the parameter determination procedures.

Parameter	Description	Constant $\epsilon_{\min}$	Evolving $\epsilon_{\min}$
$\epsilon_{\max}$ ( $\text{Gyr}^{-1}$ )	Maximum SFE	10.0	10.0
$\tau_{d, \text{th}}$	Threshold dust opacity	1.0	1.0
$\epsilon_{\min}^0$ ( $\text{Gyr}^{-1}$ )	Minimum SFE	$1.5 \times 10^{-4}$	$5.0 \times 10^{-3}$
$Z_{\text{ch}} (Z_{\odot})$	characteristic metallicity for $\epsilon_{\min}$ evolution	–	0.02
$\alpha_{\text{hot}}$	SN feedback controlling parameter	2.0 (fixed)	2.0 (fixed)
$V_{\text{hot}} (\text{kms}^{-1})$	SN feedback controlling parameter	150 (fixed)	150 (fixed)
$\alpha_{\text{cool}}$	AGN feedback controlling parameter	2.6	2.6
$\epsilon_{\text{SMBH}}$	AGN feedback controlling parameter	1.0	1.0

and the shape of the cut-off, respectively. For both the constant and evolving  $\epsilon_{\min}$  models, we found that the bright-end of local LFs are well reproduced with  $\alpha_{\text{cool}} = 2.6$  and  $\epsilon_{\text{SMBH}} = 1.0$ . Theoretically,  $\alpha_{\text{cool}} \sim 1$  and  $\epsilon_{\text{SMBH}} \leq 1$  are required, and the adopted parameter values are not unreasonable, considering uncertainties in detailed physical processes. The determined parameters are summarized in Table 1. All of the other parameters are fixed at the same value with the NY04 model.

### 3 RESULTS

#### 3.1 Local LFs

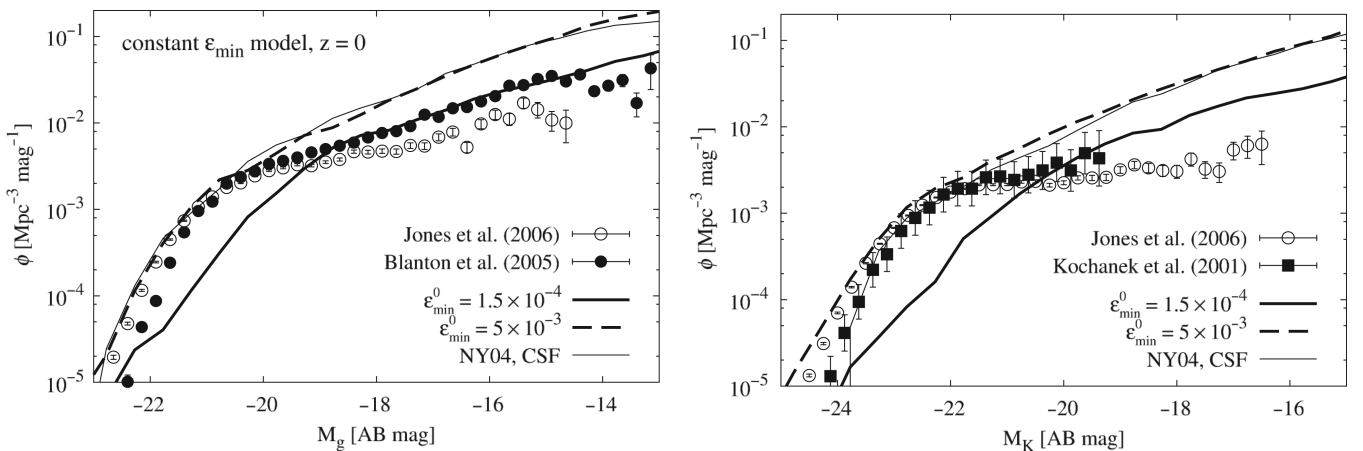
In Fig. 2, we show the local  $g$ - and  $K$ -band LFs for the constant  $\epsilon_{\min}$  model. The result of NY04 model with CSF model and weak SN feedback (i.e.  $\alpha_{\text{hot}} = 2.0$ ) is also shown for comparison. Since there is not much differences between the results of CSF and DSF model at the local universe, we only plot the result of CSF model. The data points are the SDSS, 6dF and 2MASS measurements of the local LFs (Kochanek et al. 2001; Blanton et al. 2005; Jones et al. 2006). We have transformed the 6dF  $b_j$ -band LF to match  $g$ -band LF, by subtracting 0.25 mag (Blanton et al. 2005). It can be seen that the faint-end slope of LF obtained by Jones et al. (2006) is flatter than that obtained by Blanton et al. (2005). One of the reasons of this discrepancy would be a local fluctuation of galaxy abundances. The data of Blanton et al. (2005) is deduced from deeper but narrower

survey, while the data of Jones et al. (2006) is based on the shallower but wider surveys.

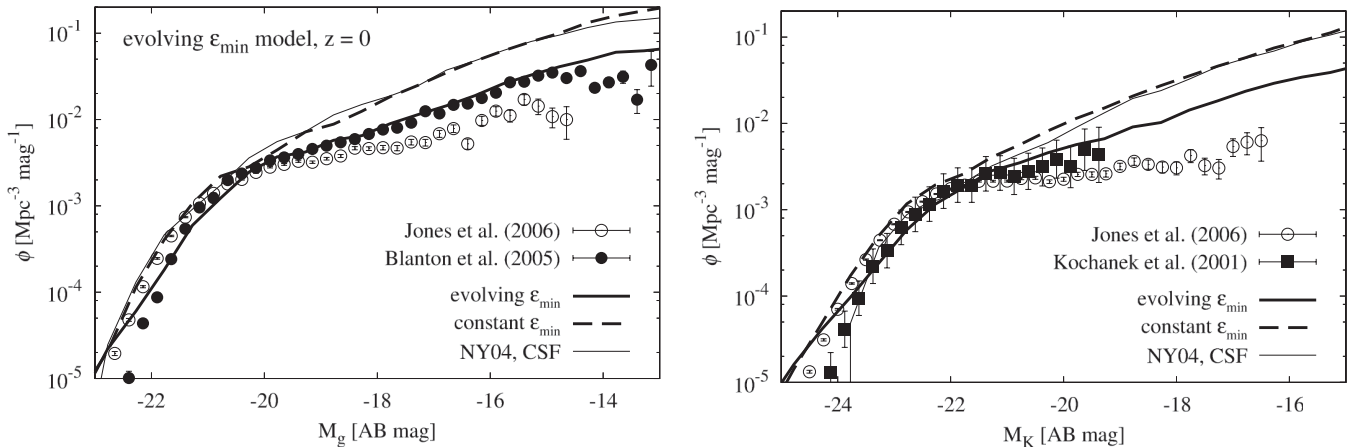
Two new model curves with the different values of  $\epsilon_{\min}^0 = 1.5 \times 10^{-4}$  and  $5 \times 10^{-3}$  are also shown, and it can be seen that the change of  $\epsilon_{\min}^0$  results in just a change of normalization of LF, keeping the LF shape roughly unchanged; steeper faint-end of the model compared with the data still remains. Since the constant  $\epsilon_{\min}$  model cannot reproduce the local LFs, we will focus on the evolving  $\epsilon_{\min}$  in the following of this paper.

In Fig. 3, we show the local  $g$ - and  $K$ -band LFs for the evolving  $\epsilon_{\min}$  model. The results of the constant  $\epsilon_{\min}$  model and the NY04 model with weak SN feedback are also plotted for comparison. In the evolving  $\epsilon_{\min}$  model, the formation of dwarf galaxies are significantly suppressed and the model well reproduces the observed LFs at overall magnitudes. Note that we used the same value of  $\epsilon_{\min}^0$ ,  $5 \times 10^{-3}$ , for the constant  $\epsilon_{\min}$  and evolving  $\epsilon_{\min}$  models in this plot, and therefore, the difference of two models are only due to the metallicity dependence of  $\epsilon_{\min}$ .

The LF faint-end is suppressed in the evolving  $\epsilon_{\min}$  model because the star formation in small galaxies at  $z \sim 0$  is suppressed by the feedback introduced to the model. This feedback is stronger at smaller galaxies by the condition for dust opacity, because more massive galaxies generally have higher metallicity and higher mass surface density when the ratio of gas mass to DM is fixed ( $\Sigma_{\text{DM}} \propto M^{1/3}$  at a fixed redshift). However, the success of the evolving  $\epsilon_{\min}$  model against the constant model indicates that the



**Figure 2.** Local  $g$ - (left) and  $K$ -band (right) LFs for the constant  $\epsilon_{\min}$  model. Data points are the same as Fig. 1. The thick solid line represents the result with the adopted parameter values listed in Table 1. We also plotted the result of NY04 with CSF model for comparison (thin solid line). The dashed line shows the same model but with a different value of  $\epsilon_{\min}^0 = 5 \times 10^{-3} \text{ Gyr}^{-1}$ . The weak SN feedback mode ( $\alpha_{\text{hot}} = 2$ ) is adopted in all models.



**Figure 3.** Local  $g$ - (left) and  $K$ -band (right) LFs for the evolving  $\epsilon_{\min}$  model. Data points are the same as Fig. 1. The thick solid line represents the result with the adopted parameter values listed in Table 1. The dashed line represents the result of constant  $\epsilon_{\min}$  model, with the same value of  $\epsilon_{\min}^0$  as the evolving  $\epsilon_{\min}$  model,  $5.0 \times 10^{-3}$ ; therefore, the difference of the evolving and constant  $\epsilon_{\min}$  in this figure is only due to the metallicity dependence of the minimum SFE,  $\epsilon_{\min}$ . We also plotted the NY04 model for comparison (thin solid line). The weak SN feedback ( $\alpha_{\text{hot}} = 2$ ) is adopted in all models.

feedback depending only on dust opacity is not sufficient. In such a model, the number of massive galaxies is also reduced when the feedback is strong enough to suppress the LF faint-end, as seen in Fig. 2. This is because star formation in the early phase of massive galaxies is suppressed by low dust opacity when their metallicity is still low. Therefore, another dependence of the feedback on metallicity, which is motivated by the dust photoelectric heating process, is essential to allow formation of massive galaxies at  $z \sim 0$ .

### 3.2 LF at high redshift

In Fig. 4, we show the  $K$ -band LFs at  $z = 0.5, 1, 1.5$  and 2 for the evolving  $\epsilon_{\min}$  model, in comparison with the observed data of Cirasuolo et al. (2010). To see the effect of star formation recipe and AGN feedback, we also show some variations of NY04 models: CSF with  $V_{\text{cut}}$  model, CSF with AGN feedback model, and DSF with AGN feedback model. In the evolving  $\epsilon_{\min}$  model, weak SN feedback model ( $\alpha_{\text{hot}} = 2$ ) is adopted, while in the other models adopted strong SN feedback model ( $\alpha_{\text{hot}} = 4$ ). The parameters of AGN feedback model are fixed as the same value in all models.

It can be seen that the CSF with  $V_{\text{cut}}$  model significantly underestimates the bright-end of LFs, especially at high redshift. If we introduced AGN feedback into the CSF model, the situation is slightly improved since AGN feedback does not efficiently work at high redshift; however, the model still underestimates the bright-end of LFs. By contrast, the DSF + AGN feedback model well reproduces the observations at all redshift range. This is because the DSF model has shorter star formation time-scale than CSF model at high redshift.

It has been thought that the AGN feedback plays an important role in reproducing the downsizing trend of cosmological galaxy formation (e.g. Bower et al. 2006); however, these results suggest that the dependence of star formation time-scale on the halo or galaxy dynamical scale is also essential, as well as the AGN feedback. In most of SAMs, star formation time-scale is simply proportional to the dynamical time-scale of host DM halo or galaxy disc (e.g. Cole et al. 2000; NY04; Bower et al. 2006). However, recent observations suggest that star formation time-scale seems to be determined by local physical condition in a galaxy, rather than the dynamical time-scale of an entire galaxy (see section 1).

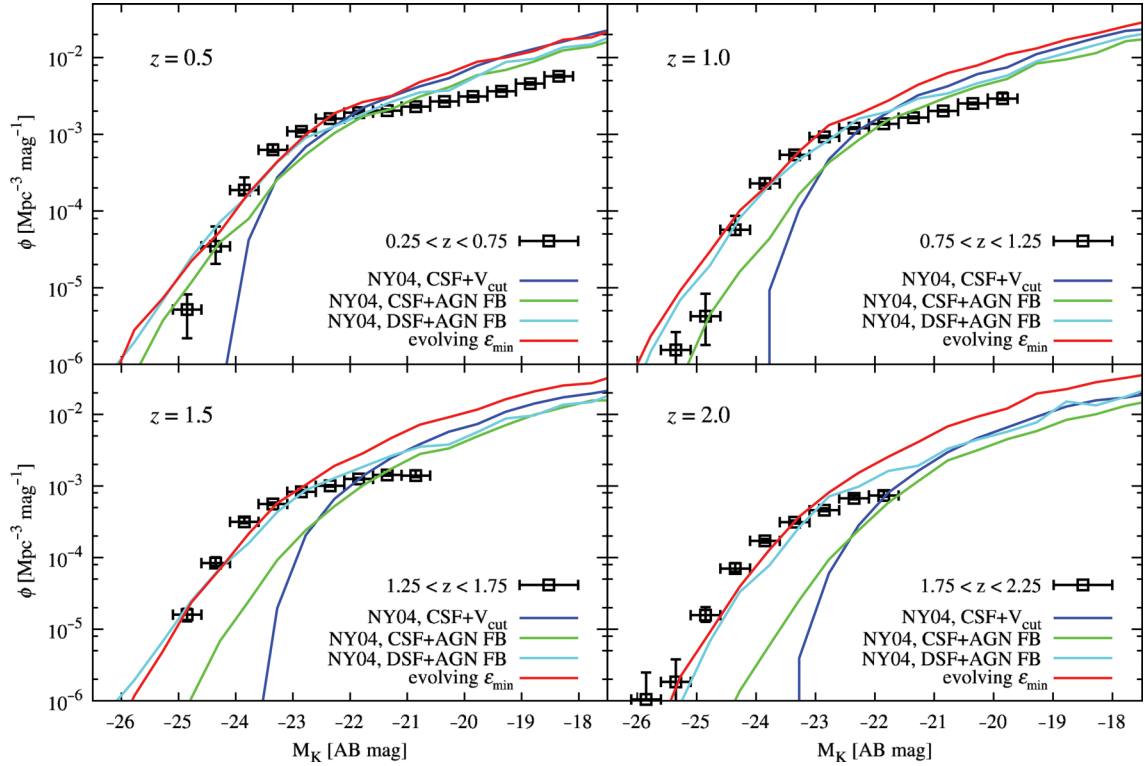
By contrast, our new model successfully reproduces the high- $z$   $K$ -band LFs, without introducing the dependence of star formation on the dynamical time-scale of a DM halo or galaxy. Star formation time-scale is shorter in massive galaxies at higher redshift also in our new model, but it is because of the newly introduced feedback depending on metallicity and dust opacity, and the general trend that high-redshift star-forming massive galaxies have high dust opacity. It should be noted that the baseline star formation time-scale  $\epsilon_{\text{max}}$ , which determines SFR when the feedback is not effective, is a universal constant in our model.

Our models overestimate the abundance of dwarf galaxies, especially at high redshift. This is not only for the new feedback model, but also for the conventional models with the AGN feedback. It might suggest that there are some missing physical processes in the presented models; however, there may also be a large uncertainty on the measurement of the faint-end high- $z$   $K$ -band LFs, by e.g. detection efficiency around the detection limit, errors on determination of the rest-frame luminosities, or cosmic variance. Therefore, we do not discuss this issue further in this paper.

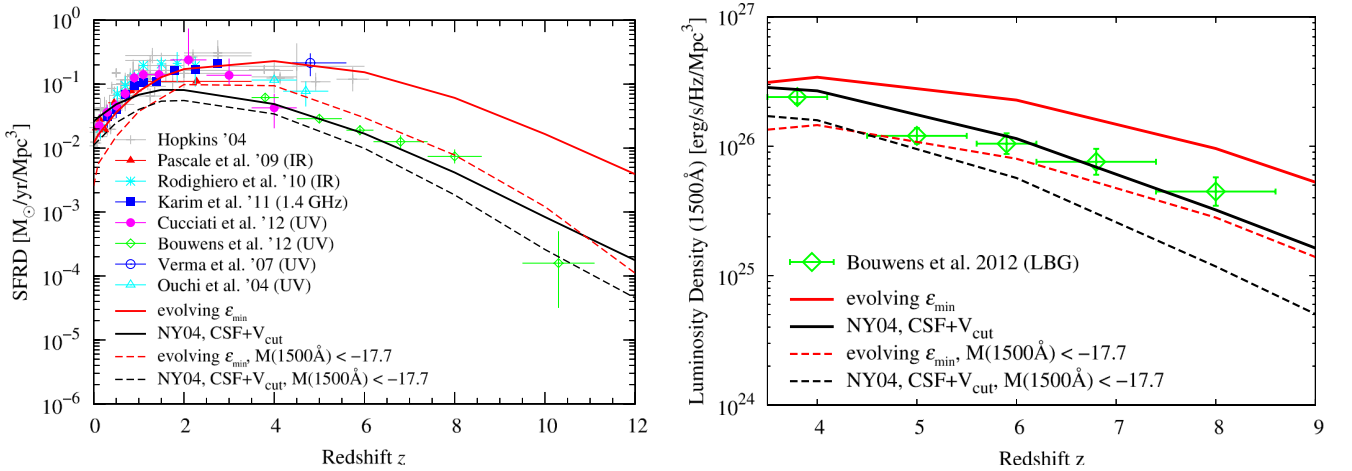
### 3.3 The cosmic star formation history

In Fig. 5, we compare the cosmic star formation history (i.e. SFR per unit comoving volume as a function of redshift) of our theoretical models with the observed data. In the new evolving  $\epsilon_{\min}$  model, star formation activity is significantly enhanced at high redshifts, and it becomes about an order of magnitude higher than the old NY04 model with CSF and  $V_{\text{cut}}$  at  $z \gtrsim 6$ . This enhancement is caused by galaxies having high dust opacity or low metallicity in which the feedback is not strongly working.

However, the difference between the new model and NY04 is rather modest when galaxies are limited into those with  $M_{\text{UV}}(1500 \text{ \AA}) < -17.7$ . This is because the enhancement of SFR in the new model is mainly by dusty galaxies, and such galaxies are faint in UV. Even if UV luminosity is brighter than the observational limiting magnitude, dusty and hence red galaxies may be missed in the selection criteria of Lyman break galaxies (Bouwens et al. 2012). As a result, both models are roughly consistent with the observed data when the limiting magnitudes are appropriately taken into account, also considering various sources of uncertainties in the estimation of cosmic SFR density, such as the faint-end slope



**Figure 4.** The evolution of  $K$ -band LFs at  $z = 0.5, 1.0, 1.5$  and  $2.0$ . The solid lines represent the results of NY04 with CSF and  $V_{\text{cut}}$  model (blue), NY04 with CSF and AGN feedback model (green), NY04 with DSF and AGN feedback model (cyan), and our new model (the evolving  $\epsilon_{\text{min}}$  model with AGN feedback, red). Open squares are the observed data obtained by Cirasuolo et al. (2010). In the evolving  $\epsilon_{\text{min}}$  model, weak SN feedback model ( $\alpha_{\text{hot}} = 2$ ) is adopted, while in the other models adopted strong SN feedback model ( $\alpha_{\text{hot}} = 4$ ). The parameters of AGN feedback model are fixed as the same value in all models.



**Figure 5.** Left: The cosmic SFR density evolution. The solid lines show the total SFR (i.e. integrated over all luminosity range) per unit comoving volume in the evolving  $\epsilon_{\text{min}}$  model (red) and the NY04 with CSF and  $V_{\text{cut}}$  model (black). The dashed red and black lines are the same as the solid lines, but integrated only for galaxies brighter than  $M_{\text{AB}}(1500\text{\AA}) < -17.7$  (extinction uncorrected magnitude). We also plot the observed data estimated by dust continuum emission from FIR to radio band (Pascale et al. 2009; Rodighiero et al. 2010; Karim et al. 2011) and UV continuum (Ouchi et al. 2004; Verma et al. 2007; Bouwens et al. 2012; Cucciati et al. 2012). The data points of Hopkins (2004) are the compilation of observations in several wavelengths and methods. All the data points are corrected for extinction, by the methods adopted in individual references. The open symbols for UV continuum-based estimates at  $z > 4$  are obtained by integrating LF down to the limiting magnitudes of each survey; the limiting magnitude of  $M_{\text{AB}}(1500\text{\AA}) < -17.7$  adopted by Bouwens et al. (2012) is the same as that for the dashed model curves. The other filled symbol data points are integration of LFs in the entire magnitude range. Right: the redshift evolution of luminosity density at rest-frame  $1500\text{\AA}$ , without correction about extinction. The model curves are the same as the left-hand panel. The data points are integrations in the range of  $M(1500\text{\AA}) < -17.7$ .

of the LF, correction of dust extinction, contamination from old stellar populations to the IR luminosity, assumed stellar spectra and IMF. Recently, Kobayashi, Inoue & Inoue (2013) have shown that a discrepancy by a factor of 2–3 can indeed arise from overcorrection for dust obscuration and luminosity-to-SFR conversion.

Comparison in the rest-frame UV luminosity density would suffer from less uncertainties than that in SFR density, and this is shown in the right-hand panel of Fig. 5. Interestingly, the new model gives a quantitatively better fit to the data than the old NY04 model, though the discrepancy between the NY04 model and the data may still be within the systematic uncertainties. The new model shows a flatter evolutionary trend towards higher redshift than the NY04 model, which is also in good agreement with the data.

It would be interesting to search for the UV-faint, dusty star-forming galaxies at high redshifts predicted by the new model, by future observations in other wavelengths, e.g. submillimetre surveys by Atacama Large Millimeter/submillimeter Array. They are below the magnitude limit in the current surveys in UV but significantly contributing to the total cosmic SFR.

#### 4 RADIATIVE FEEDBACK DEPENDING ON GAS SURFACE DENSITY

In this paper, we have examined a new feedback process depending on galaxy-scale dust surface density. Although observations and theoretical considerations suggest that a dust surface density plays an important role in determining the galaxy-scale SFR, the original Kennicutt–Schmidt relation is the scaling relation between SFR surface density and gas surface density, not dust surface density. Therefore, it is interesting to compare our new model with another one assuming a star formation law depending on gas surface density, and examine whether the dust opacity dependence is essential or not in our new model.

Here, we adopt the following simple formula of SFE,

$$\varepsilon = \varepsilon_{\max} \exp(-\Sigma_{\text{gas,th}}/\Sigma_{\text{gas}}), \quad (10)$$

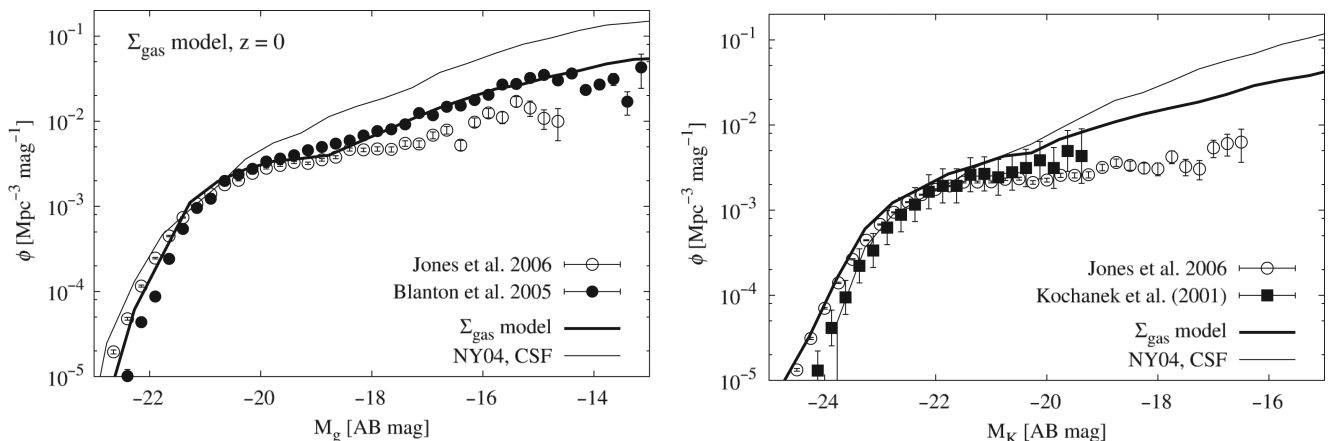
where  $\Sigma_{\text{gas}} = M_{\text{cold}}/\pi r^2$  is the gas surface density, and  $\Sigma_{\text{gas,th}}$  is the threshold of gas surface density below which SFE rapidly decreases. In what follows, we will refer to this model as ‘the  $\Sigma_{\text{gas}}$  model’. In the  $\Sigma_{\text{gas}}$  model, we do not introduce the lower limit of SFE,  $\varepsilon_{\min}$ , since  $\varepsilon$  has a finite value in this model even in galaxies without any metal or dust, provided that  $\Sigma_{\text{gas}}$  is higher than the threshold value.

In Fig. 6, we show the local  $g$ - and  $K$ -band LFs for the  $\Sigma_{\text{gas}}$  model. We also show the result of NY04 model (CSF and weak SN feedback is adopted) for comparison. The adopted parameters are  $\varepsilon_{\max} = 10 \text{ Gyr}^{-1}$  and  $\Sigma_{\text{gas,th}} = 50 M_{\odot} \text{ pc}^{-2}$ . This  $\Sigma_{\text{gas,th}}$  roughly corresponds to  $\tau_{\text{dust}} \sim 0.3$  when  $Z \sim Z_{\odot}$ . In this model, we also adopted the weak SN feedback parameter ( $\alpha_{\text{hot}} = 2$ ). Other parameters are fixed at the same with the adopted values of the evolving  $\varepsilon_{\min}$  model (see Table 1). Procedures of the parameter determination is the same with the dust-opacity dependent feedback models (see Section 2.3). We can see that the formation of dwarf galaxies is significantly suppressed, and the  $\Sigma_{\text{gas}}$  model also well reproduces the observed LFs. Thus, the dependence on dust opacity or gas surface density cannot be discriminated only in local LFs.

However, they show different redshift evolution of  $K$ -band LFs as shown in Fig. 7. In this figure, we also show the results of the evolving  $\varepsilon_{\min}$  model for comparison. It can be seen that the  $\Sigma_{\text{gas}}$  model predicts more dwarf galaxies and less massive galaxies than the evolving  $\varepsilon_{\min}$  model, especially at high redshift. This difference can be explained as follows. There is a well-known trend of higher metallicity for more massive galaxies, i.e. the so-called stellar mass–metallicity relation (e.g. Tremonti et al. 2004). Therefore, the model depending on dust opacity should have a stronger trend of higher SFE for more massive galaxies than the  $\Sigma_{\text{gas}}$  model at a fixed redshift. The  $\Sigma_{\text{gas}}$  model predicts high SFE for dwarf galaxies at high redshifts because of high gas density, and the result of Fig. 7 indicates that the predicted efficiency is too high compared with observations. The new model presented here depending on dust opacity gives a better fit about this observation.

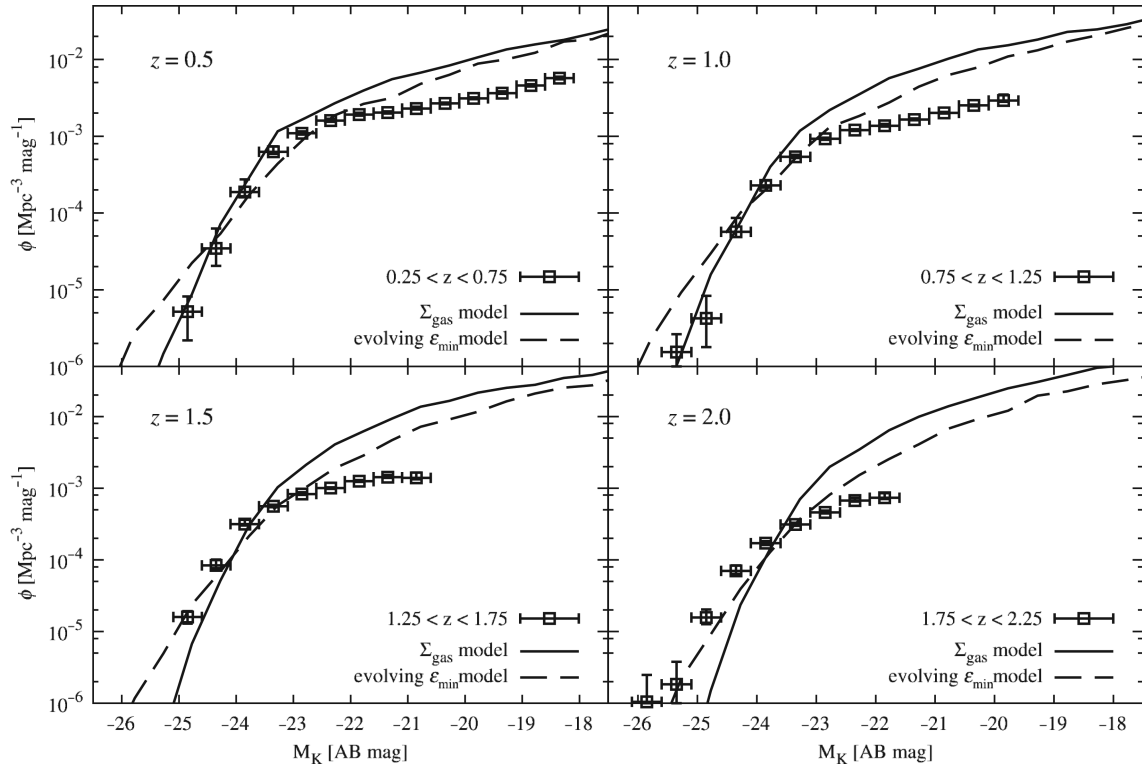
#### 5 SUMMARY

In this paper, we have considered a new feedback mechanism on star formation depending on galaxy-scale mean optical depth to absorption by dust grains, and examined the effect on galaxy LFs and their cosmological evolution, making use of an SAM of galaxy formation. The introduction of such feedback process is motivated not only by theoretical considerations but also by recent observations, which indicate that star formation activity is significantly suppressed in galaxies that are transparent to UV radiation. The structure formation theory predicts that the dust-opacity becomes higher in massive objects and at higher redshifts for a fixed dust-to-gas ratio; therefore, it is expected that the faint-end of local LFs would be suppressed, which is required for the current galaxy



**Figure 6.** Local  $g$ - (left) and  $K$ -band (right) LFs for the  $\Sigma_{\text{gas}}$  model (thick solid line). We also plotted the results of the NY04 model (thin solid line) for comparison. The weak SN feedback mode ( $\alpha_{\text{hot}} = 2$ ) is adopted in all models. The observed data points are the same as Fig. 1.





**Figure 7.** The evolution of  $K$ -band LFs at  $z = 0.5, 1.0, 1.5$  and  $2.0$  for the  $\Sigma_{\text{gas}}$  model. We also plotted the results of the evolving  $\epsilon_{\text{min}}$  model for comparison. Open squares are the observed LFs obtained by Cirasuolo et al. (2010).

formation models to match the observations. Note that extremely strong SN feedback was required in the conventional models to reproduce the observed faint-end of local LFs. Such feedback process would also accelerate the formation of massive galaxies at high redshifts.

We have tested a few models about star formation feedback, and the best fit with observations is found with the model in which star formation is suppressed when the galaxy-scale dust opacity is low and metallicity is higher than a critical value (the evolving  $\epsilon_{\text{min}}$  model). The latter condition is introduced phenomenologically, but theoretically motivated by the process of photoelectric heating by dust grains. In this model, formation of dwarf galaxies at  $z \sim 0$  is significantly suppressed, and the model successfully reproduces the faint-end slope of local LFs with a physically natural strength of the SN feedback.

The new model also succeeded in reproducing the number density of high- $z$  massive galaxies. The early appearance of massive galaxies have been explained by the AGN feedback process; however, we have found that the star formation model is also important as well as the AGN feedback. In most of SAMs, star formation time-scale is assumed to be proportional to the dynamical time-scale of a host DM halo or galaxy disc (e.g. Cole et al. 2000; Bower et al. 2006; NY04). This is essential to explain the early appearance of massive galaxies, because the model with a CSF time-scale cannot reproduce it even if the AGN feedback is incorporated. However, recent observations suggest that the SFE is closely related to the gas or dust surface density, rather than the dynamical time-scale of an entire galaxy or halo (see Section 1). Our new model incorporating the AGN feedback can explain the number density of high- $z$  massive galaxies with the observationally suggested star formation

law. The new model is also consistent with the observed cosmic star formation history.

We also tested a star formation feedback model depending simply on the gas surface density (the  $\Sigma_{\text{gas}}$  model), rather than the dust opacity, to examine whether the dust opacity is essential or not. Although this model can also reproduce the shape of the local LFs, the difference from the evolving  $\epsilon_{\text{min}}$  model appears in the mass function (or  $K$ -band LF) at high redshifts. The evolving  $\epsilon_{\text{min}}$  model predicts more galaxies than the  $\Sigma_{\text{gas}}$  model at the bright-end of  $K$ -band LFs at  $z \sim 2$ , which is in better agreement with the observed data.

To conclude, we have found that the feedback depending on galaxy-scale dust opacity has significant effects on the cosmological galaxy formation, and has good properties to solve some of the problems found in the previous theoretical models. However, it should also be noted that there are still various uncertainties in our model. For example, we determined the value of SFE under the dust opacity threshold phenomenologically from fits to the LF data, but these results should be examined in light of theoretical studies of star formation. We assumed that dust mass is simply proportional to the metal mass, but it is not obvious that this proportionality is valid for all galaxies. More observational and theoretical studies on formation/evolution of dust grains are desirable to establish a better star formation modelling for cosmological galaxy formation.

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