# Chemical Evolution of Galaxies in the High Redshift Universe

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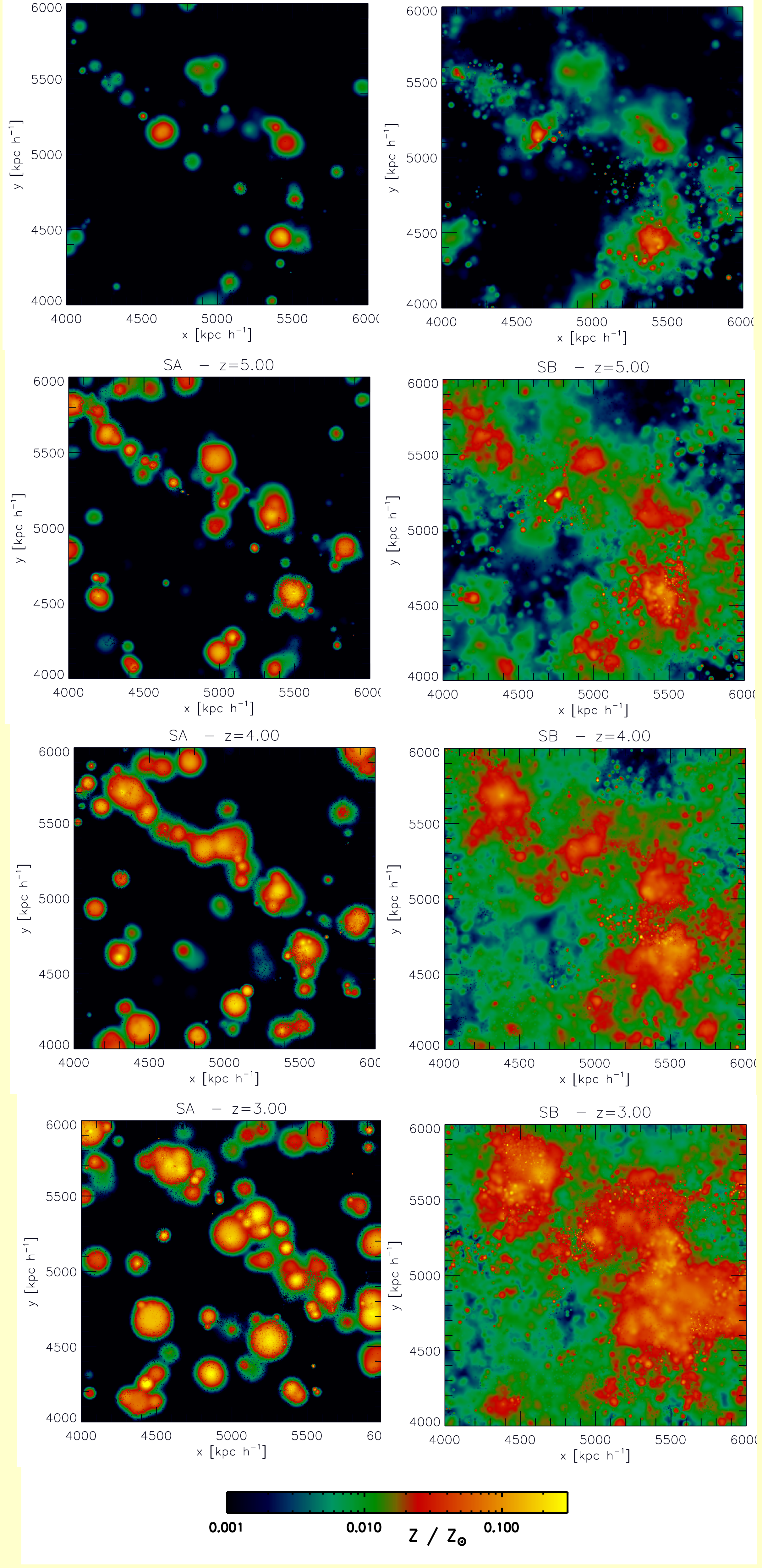
## *INTRODUCTION*

The **chemical abundances of galaxies** constitute fossils from the action of several astrophysical processes such as Supernova feedback, active galactic nuclei, gas infall, mergers and interactions, among others. Therefore, the study of the chemical enrichment of galaxies as a function of their mass could reveal important clues about the evolutionary history of the structure in the Universe (e.g. Tissera et al. 2005; De Rossi et al. 2007).

In the **Local Universe,** there is a clear **correlation between mass and metallicity** in such a way that more massive systems tend to be more metal enriched. This correlation extends about five decades in stellar mass and two dex in metallicity (Tremonti et al. 2004; Lee et al. 2006). The important progress in observational techniques in the last decade allows the exploration of the **chemical enrichment of galaxies at higher redshifts.** Savaglio et al. (2005), for example, studied the MZR at z~0.7 estimating a relative evolution of 0.10-0.15 dex with respect to the local MZR of Tremonti et al. (2004), while Erb et al. (2006) found a relative evolution of ~0.30 dex for the MZR of galaxies since z~2.5. Moreover, recent obsrvational works suggest that the MZR is already in place at z~3, exhibiting a much stronger evolution than that observed at lower redshifts (Maiolino et al. 2008; Mannucci et al. 2009).

In this work, we present **preliminary results** of the study of the chemical evolution of baryons at high z by performing numerical simulations which includes chemical and energy Supernova (SN) feedback in a cosmological framework. We explore these simulations as a first step to build up a more complex model of the high redshift universe.

**FIGURE 1**



## *CHEMICAL ENRICHMENT IN THE HIGH REDSHIFT UNIVERSE*

In **FIGURE 1,** we show the chemical evolution of a typical simulated region of the Universe from z~7 towards z~3. Left panels correspond to a model without SN feedback (SA) while, in right panels, this mechanism has been turned on (SB). The color code indicates the projected mean metallicity onto the x-y plane.

We can appreciate the gradual enrichment of the gas component around star forming regions as a function of time. The more impressive result is the influence of SN winds on the distribution of metals. In the case of SA, metals tend to be highly concentrated forming bubbles surrounded by a metal-depleted intergalactic medium (IGM), even at z=0 (see **FIGURE 2**), which is in contradiction with observations. On the other hand, SB predicts an important chemical evolution of the IGM in the range 7<z<3. At z~7, the metal distributions obtained in SA and SB are similar but ~1.5 Gyr later the IGM in SB is a factor of ten more metal-enriched than in SA as a consequence of Supernova-driven galactic outflows (De Rossi et al. 2010, in preparation).

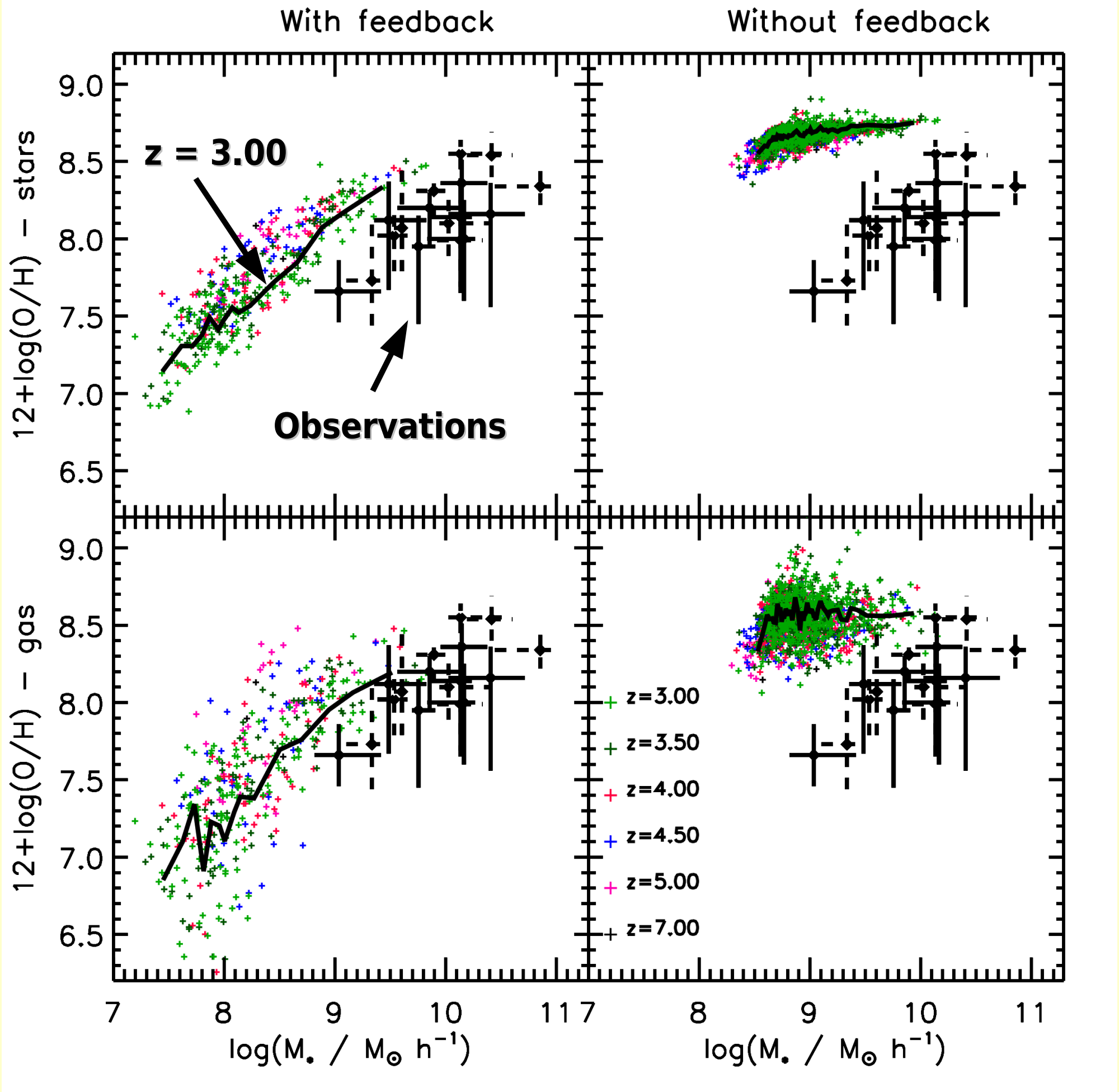
## *NUMERICAL SIMULATIONS*

We perform **numerical simulations** consistent with the the concordance **Λ-CDM Universe** with $\Omega_m$=0.3, $\Omega_\Lambda$=0.7, $\Omega_b$=0.04 and $H_0$=100 $h^{-1}$km $s^{-1}$ $Mpc^{-1}$, with h=0.7. These simulations were performed by using the **chemical code GADGET-3** (Scannapieco et al. 2008), which includes treatments for metal-dependent radiative cooling, stochastic star formation, chemical enrichment and Supernovae feedback. The chemical model includes the element production by Type II and Type Ia SN following 13 individual elements (Mosconi et al. 2001).

We adopted a **Salpeter Initial Mass Function** with lower and upper mass cut-off of 0.1 $M_O$ and 40 $M_O$, respectively. The simulated volume corresponds to a **cubic box of a comoving 10 Mpc $h^{-1}$ side length**. The masses of dark matter and initial gas-phase particles are $5.93\times10^6$ $M_O$ $h^{-1}$ and $9.12\times10^5$ $M_O$ $h^{-1}$, respectively.

We identified galactic systems by combining a **friends-of-friends technique** and the **algorithm SUBFIND** (Springel et al. 2001). **Only substructures with more than 2000 particles were considered for analysis.**

**FIGURE 3**



## *FIGURE 3: THE MASS-METALLICITY RELATION*

In this figure, we can appreciate the simulated **mass-metallicity relation** (MZR) in the high redshift Universe for the gas (lower panels) and stellar (upper panel) phases at different redshifts (small crosses). We compare the results from the simulations with (SB) and without (SA) SN feedback. The symbols with error bars correspond to the observations of the gas-phase MZR by Maiolino et al. (2008, dashed lines) and Mannucci et al. (2009, solid lines) at z~3. The solid black line over the crosses denotes the mean simulated MZR at z=3.

We see that the model which does not include galactic winds (SA) is not able to reproduce the observed trends and predicts a much larger dispersion than that reported by observations, in the case of the gas component. The treatment of Supernova feedback in the simulation SB generates a more important decrease of the metal content of smaller systems and leads to a smaller dispersion in the gas-phase MZR, in agreement with observations.

**FIGURE 2**

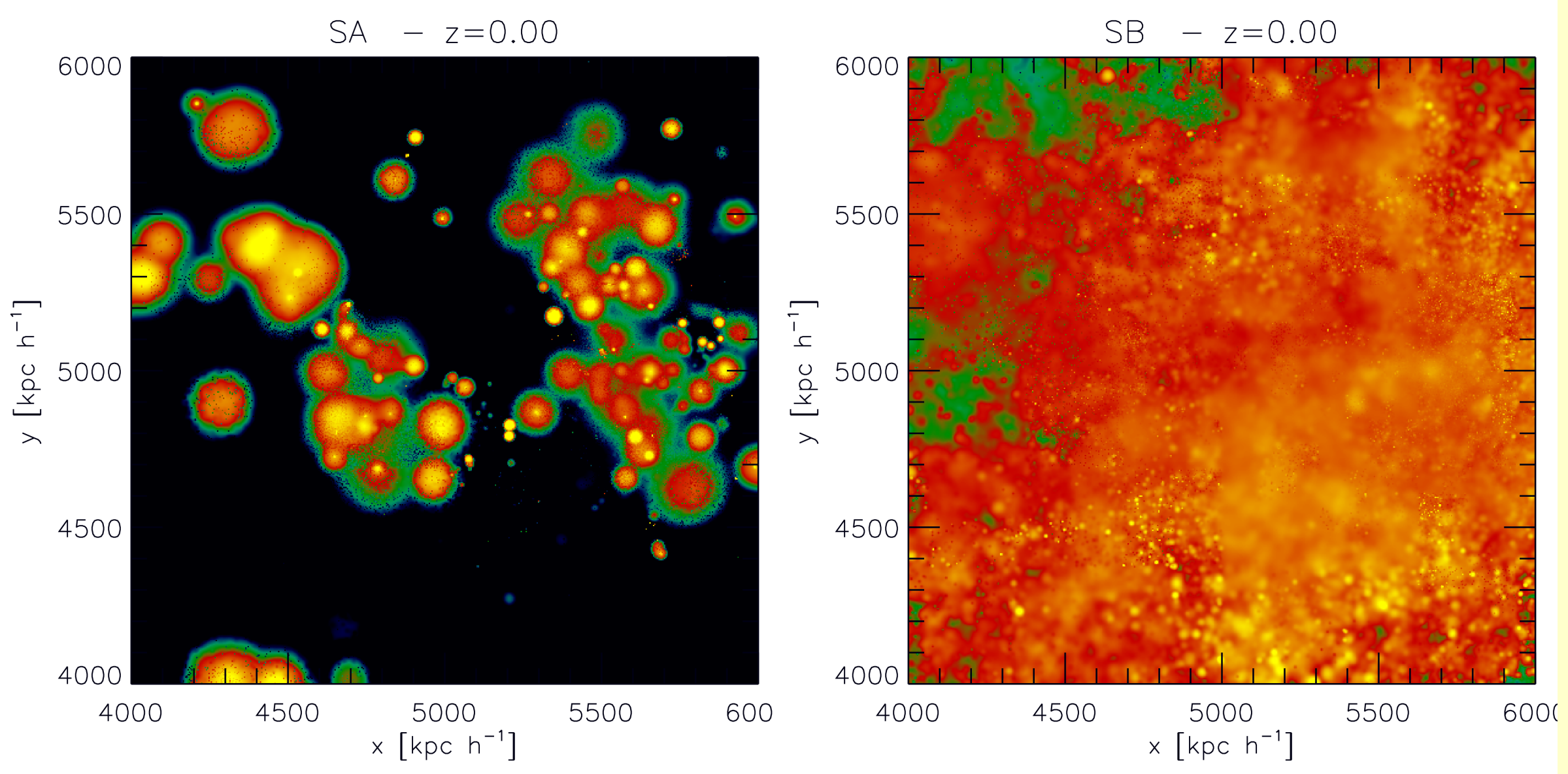


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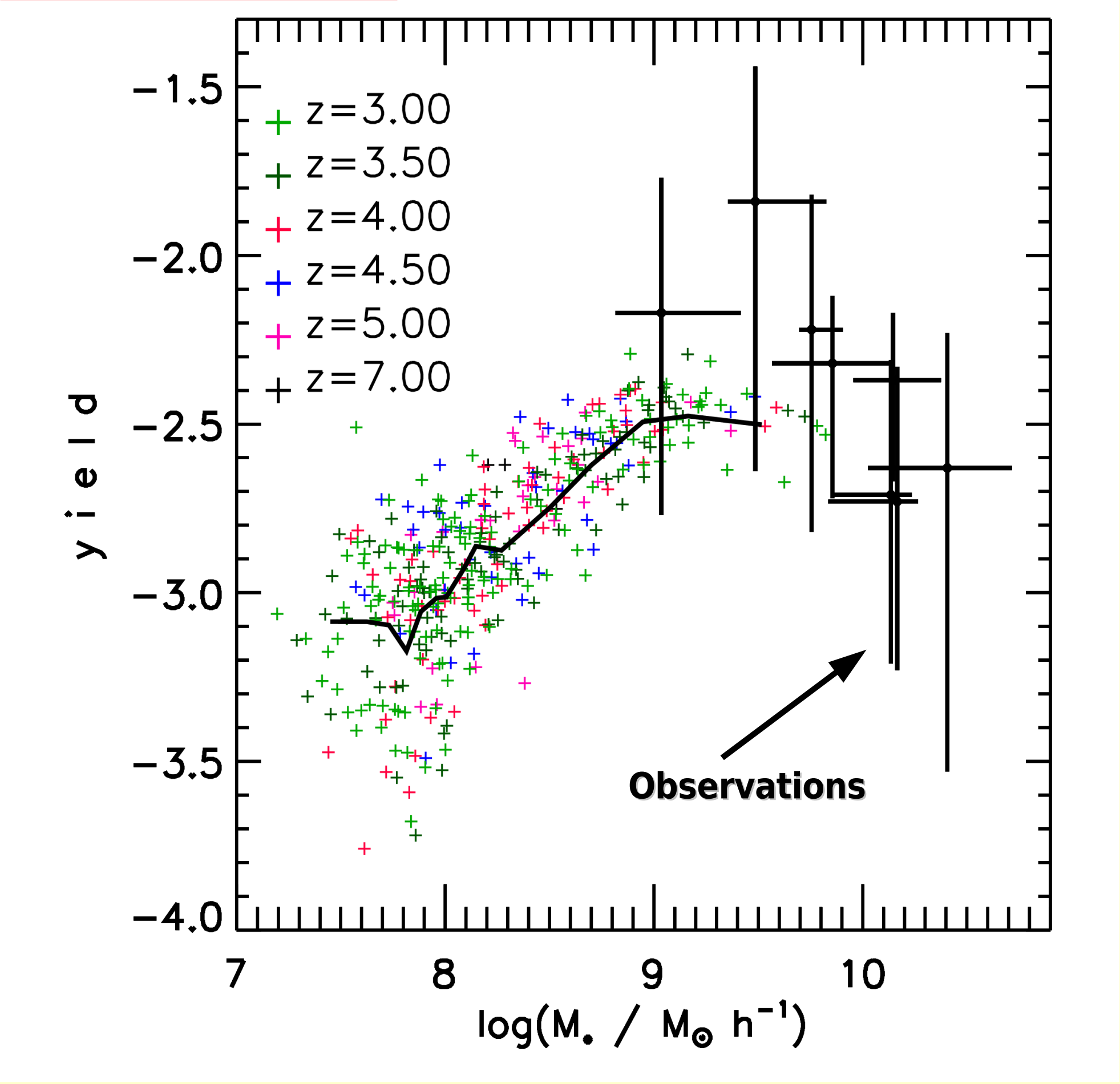
**FIGURE 4**

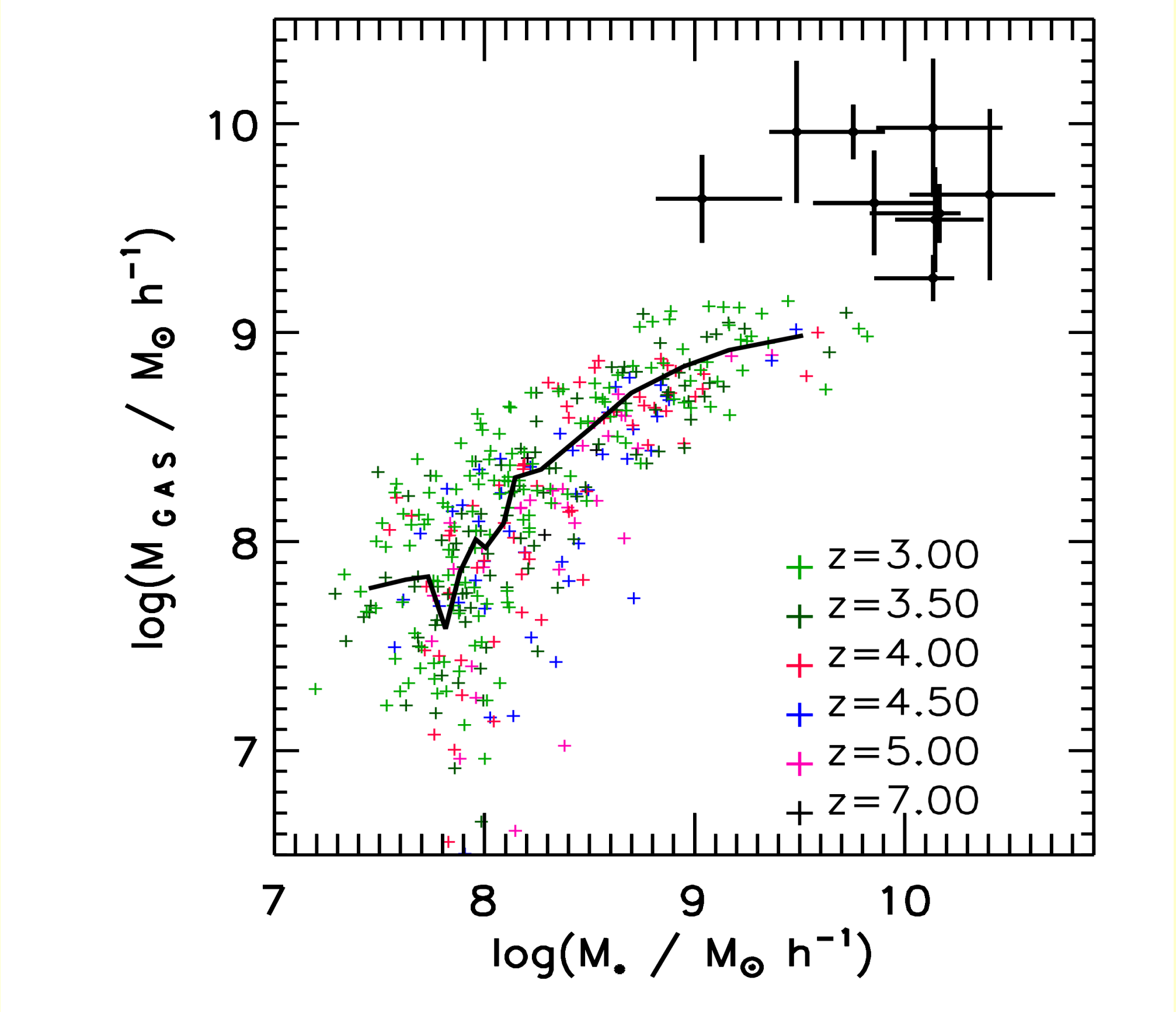


## *FIGURE 4: THE EFFECTIVE YIELDS*

In **FIGURE 4**, we show the **correlation between the effective yields and stellar masses** for simulated galaxies in SB at different redshifts (small crosses). The solid black line over the crosses denotes the mean simulated relation at z=3. We compare our results with those reported by Mannucci et al. (2009, symbols with error bars) at z~3.

We see that simulations map a range of stellar masses not covered by current observations. SB simulations predict an increase of the yield values with mass, similar to the behaviour of galaxies in local Universe (Tremonti et al. 2004). However, we can appreciate that, at a given stellar mass, simulated effective yields lay within the error bars corresponding to the observed values. These findings would indicate the presence of a turn-over in the yield-mass relation at high redshift. Nevertheless, the range of masses covered by the SB simulation is not large enough to test this hypothesis.

**FIGURE 5**



## *FIGURE 5: GAS FRACTIONS*

With respect to the **gas fractions**, simulated galaxies in SB exhibit smaller values than those expected from observations (**FIGURE 5,** the symbol and line codes are similar to FIGURE 4). This suggests that the SN feedback parameters adopted for this simulation leads to an important ejection of the gas component into the intergalactic medium, indicating the need for a revision of the parameters which regulate the feedback efficiency in these simulations. However, since the stellar mass range covered by simulations and observations are different, we also need to increase our simulated volume or to have observations of smaller systems in order to make a robust prediction.

## *DISCUSSION AND FUTURE WORK*

We explore the **chemical enrichment of galaxies in the high redshift Universe** by employing numerical hydrodynamical simulations in a cosmological scenario. Our model includes only chemical and energy feedback by SN II and SNIa, hence, it is only a first step towards building up a physical scheme which can describe more adequately the complexity of the galaxy formation at high redshifts.

From this first exploration we find that :

*1) SN feedback starts to enrich the intergalactic medium at z~7, leading to an important chemical evolution towards z~3.*
*2) The simulated MZR at z~3 is consistent with observational works at similar redshifts (Maiolino et al. 2008; Mannucci et al. 2009).*
*3) The simulated yield-mass relation at z~3 is also consistent with observations. Gas fractions in the simulated galaxies are lower than those reported by observations.*

*SN feedback in these simulations is very efficient generating important outflows of metal enriched material. This tends to accelerate the chemical enrichment of the intergalactic medium at the expense of quenching the chemical evolution of galaxies towards lower redshifts. The strong galactic outflows lead to a weaker evolution of the MZR and lower gas fractions than results reported by observations.*

FUTURE WORK:

1. We will intend to regulate better the SN feedback but observations of galaxies at high redshift are crucial to be able to confront our results and choose the best combination of parameters.
2. We will model other missing physical processes which are relevant to the high redshift Universe.
3. We plan to increase the simulated volume and the numerical resolution in future simulations.