Simulations of Cosmic Chemical Enrichment

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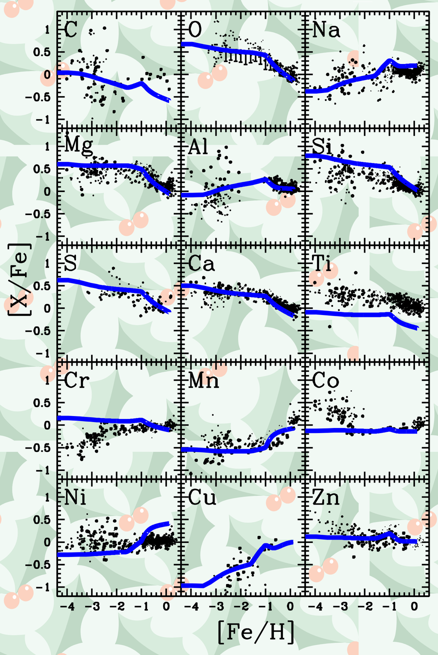
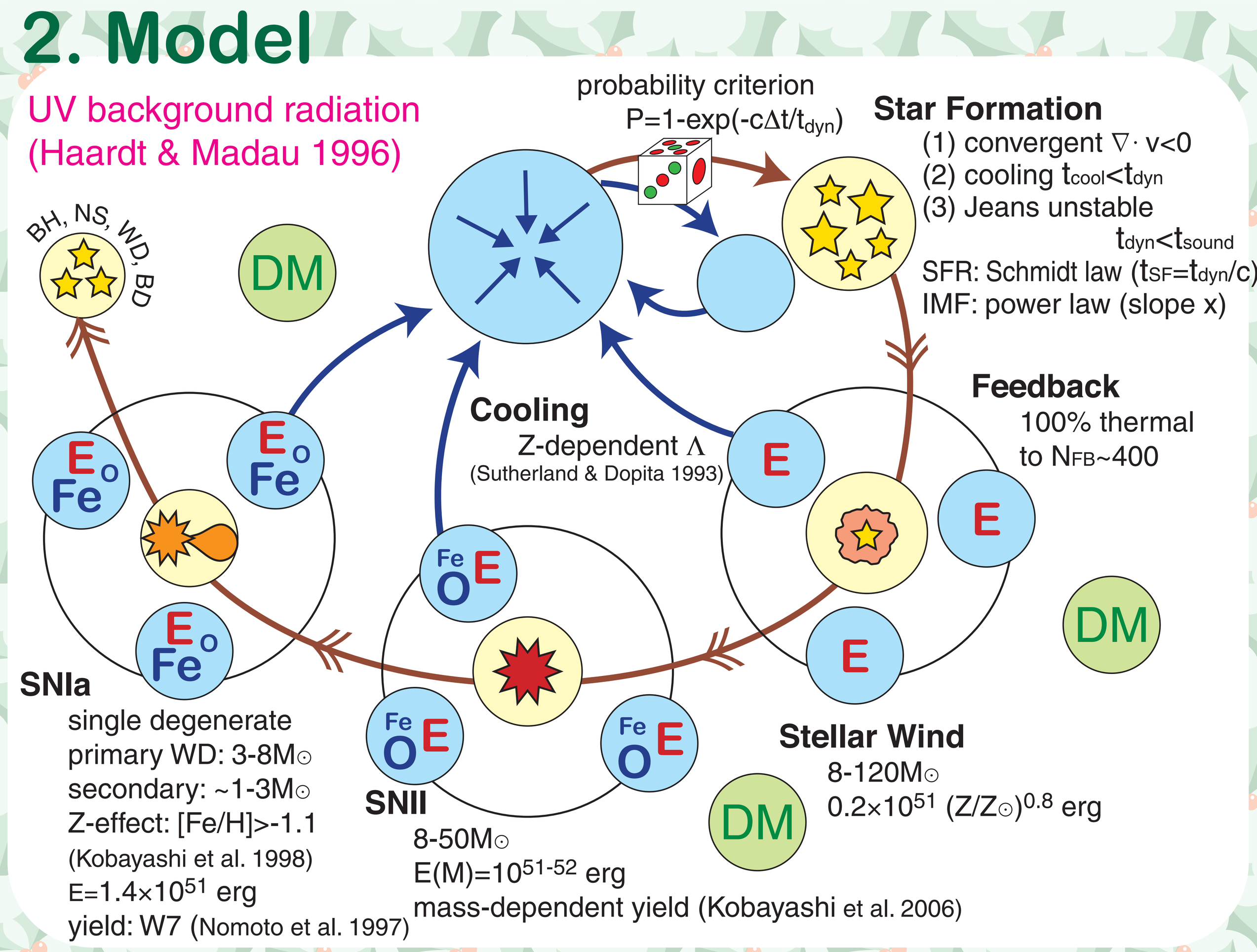
1. Abstract

While the evolution of the dark matter in the Universe is reasonably well understood, the evolution of the baryonic component is much less certain because of the complexity of the relevant physical processes, such as star formation and feedback. We have simulated cosmic chemodynamical evolution with a **tree-SPH code** Gadget-2, including star formation, supernova and hypernova feedback, and a detailed chemical enrichment model (Kobayashi 2004) that does not rely on the instantaneous recycling approximation. We have also investigated the role hypernova may play for regulating star formation and for enriching the Universe.

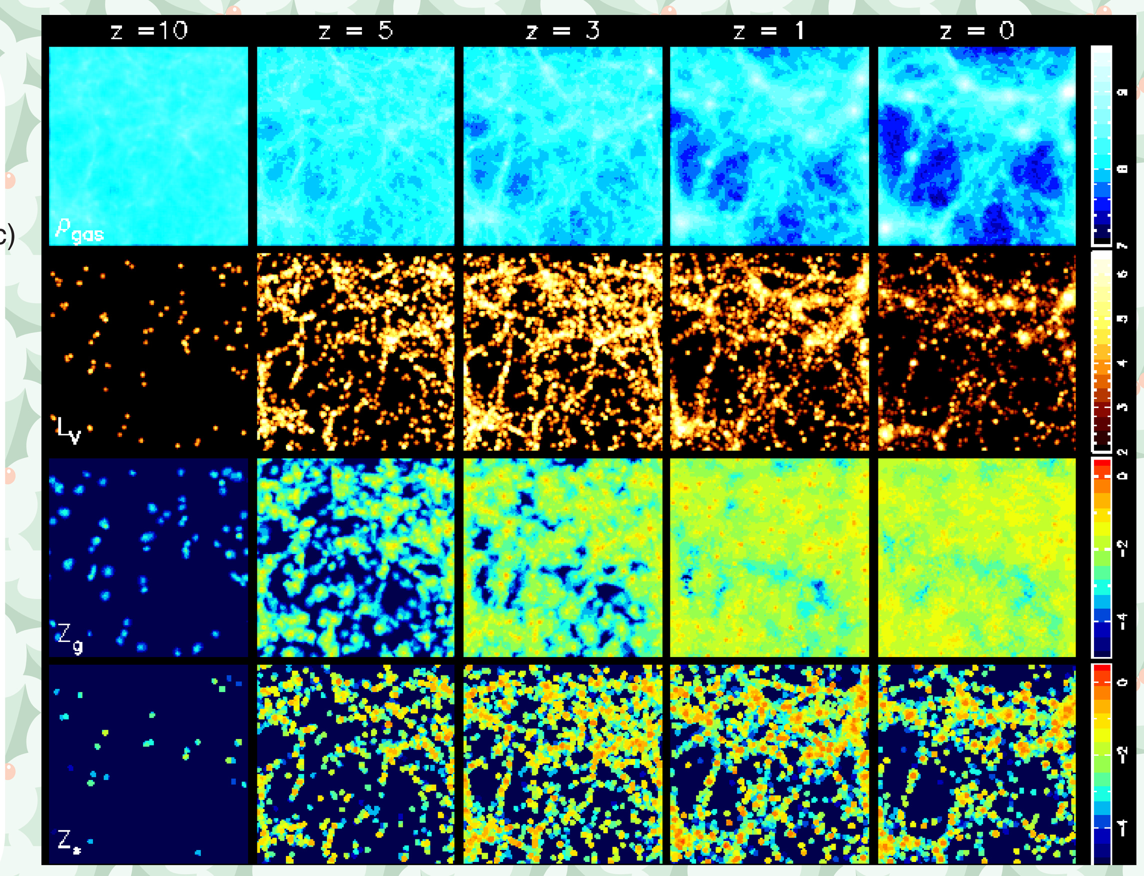


From the light curve and spectral fitting, it has been found that **hypernovae** (HNe) produce ten times more iron and kinetic energy than Type II Supernovae (SNe II). We adopt the mass/metallicity/energy-dependent yields (Kobayashi et al. 2006). A large fraction of HN is required from the elemental abundance ratios in the Milky Way Galaxy.
We adopt a new progenitor model of **Type Ia Supernova** (SNe Ia), based on the single degenerate scenario, including the metallicity and and mass-stripping effects (Kobayashi et al. 1998; Kobayashi & Nomoto 2007).
The hypernova feedback drives **galactic winds** efficiently in low mass galaxies, and these winds eject heavy elements into the intergalactic medium. The mass-dependent galactic winds result in the observed **mass-metallicity relation.**
The resulting enrichment history is broadly consistent with the observed abundances of Lyman break galaxies (LBGs), of damped Lyman α (DLA) systems, and of the intergalactic medium (IGM).
We also predict the **cosmic SNIa/SNII/GRB rate history** and the properties of the host galaxies in our cosmological simulation.

2. Model



Kobayashi, Springel & White 2007, MNRAS, 376, 1465

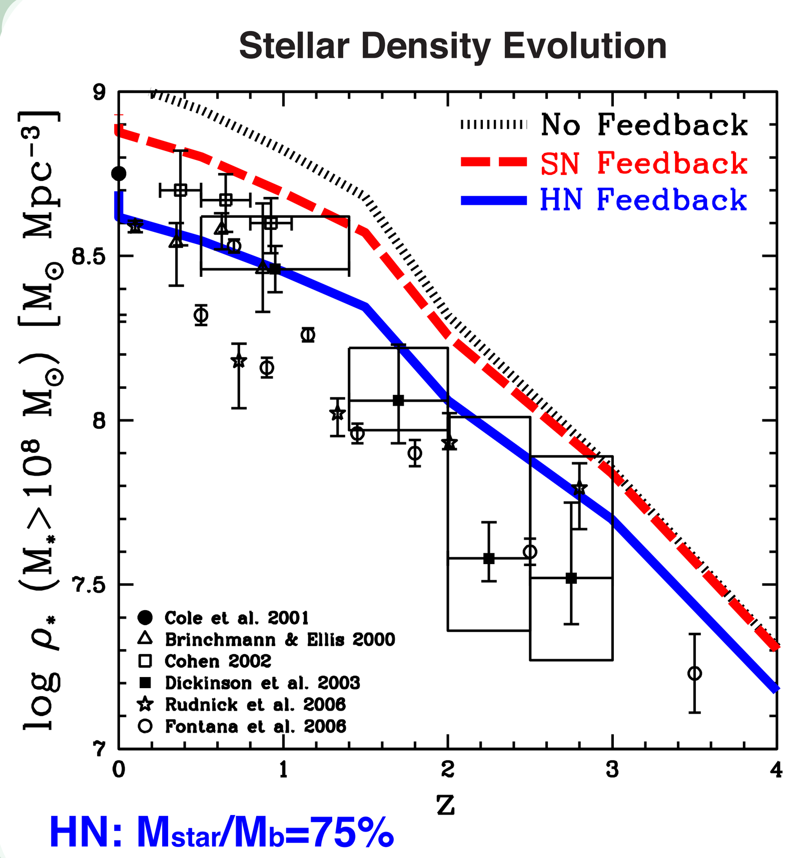


10Mpc; N~2×96^3; $m_{gas}\sim10^7$ M⊙; H_0=70, Ω_m=0.3, Ω_λ=0.7, Ω_b=0.04, n=1, σ_8=0.9

3. When & Where Stars Formed?

--- In dwarf galaxies, before they merge to massive galaxies.
Massive galaxies form later, but their stars are old.

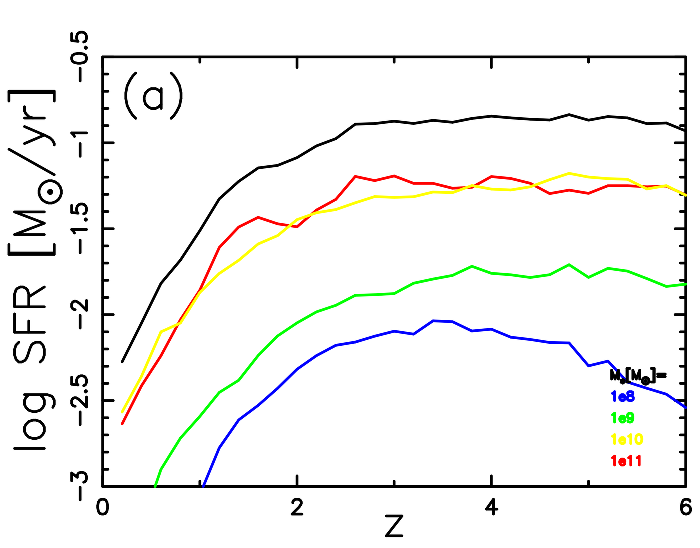
Hypernova feedback can efficiently suppress star formation, and the **cosmic star formation rate** (SFR) shows a peak at z~4, with ~10% of baryons turning into stars, which are consistent with the observational estimates.
In the right figure, to avoid uncertainties in the completeness from the faint end, we show the time evolution of the stellar mass density measured in the galaxies with $M_* > 10^8$ M⊙. The HN feedback gives better agreement with these observations.

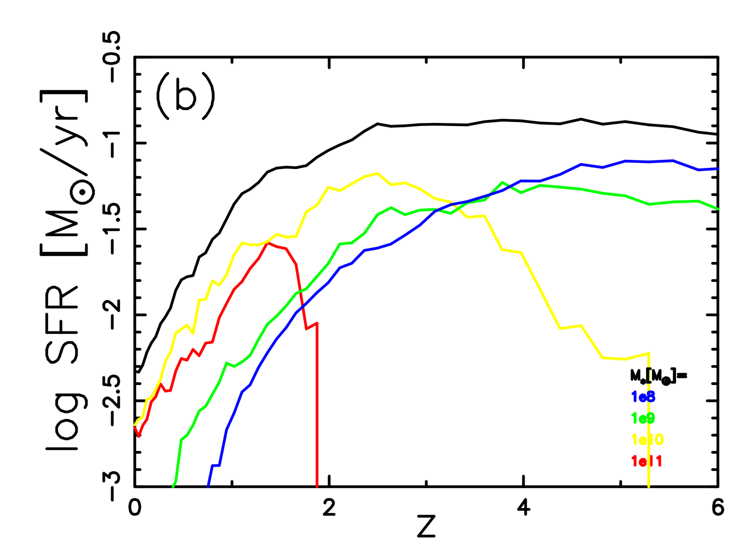


HN: M_{star}/M_b=75%
SN: M_{star}/M_b=94%

We break up the cosmic SFR history according to stellar mass of galaxies. (a) The galaxies are identified by FOF **at z=0**, and thus these SFRs correspond to the age distribution of stars in the galaxies. For all galaxy masses, the SFRs show a peak around z~3-4, and the majority of stars are as old as ~10 Gyr. The ages of low-mass galaxies span a wide range of 1-10 Gyr.

(b) The galaxies are identified at each redshift and split up the SFRs according to the current stellar mass measured at the redshift, which are comparable to the observations of high redshift galaxies. This shows that most stars have formed in low-mass galaxies with $10^{8\text{-}9}$ M⊙ at z>3. 10^{10} M⊙ galaxies exist at z<5, but 10^{11} M⊙ galaxies appear only after z~2.





From these two figures we conclude that most stars have formed in dwarf galaxies before they merge to massive galaxies in our simulation. As a result of the hierarchical clustering of dark matter halos, such old stars belong to massive galaxies at low redshifts.

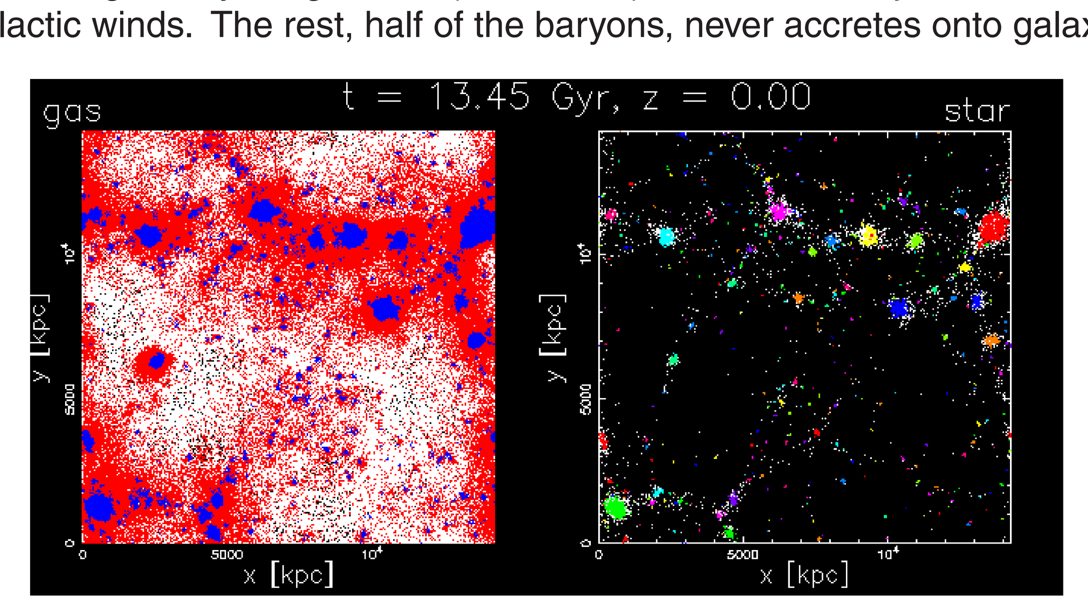
4. Where Metals Come From?

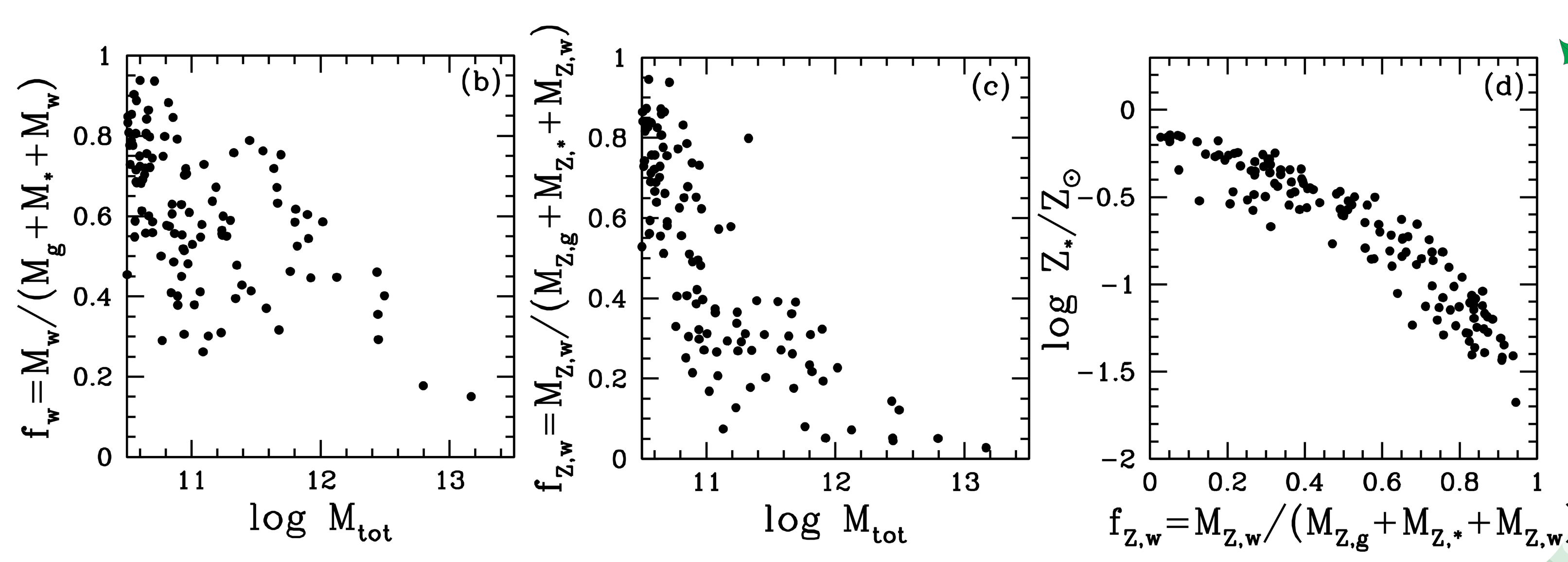
--- More effectively ejected from (present) dwarfs.
The origin of the mass-metallicity relation is the mass-dependent galactic winds.

M_{star}/M_b ~ 10%
$M_{gas,gal}/M_b$ ~10%
M_{wind}/M_b ~20%

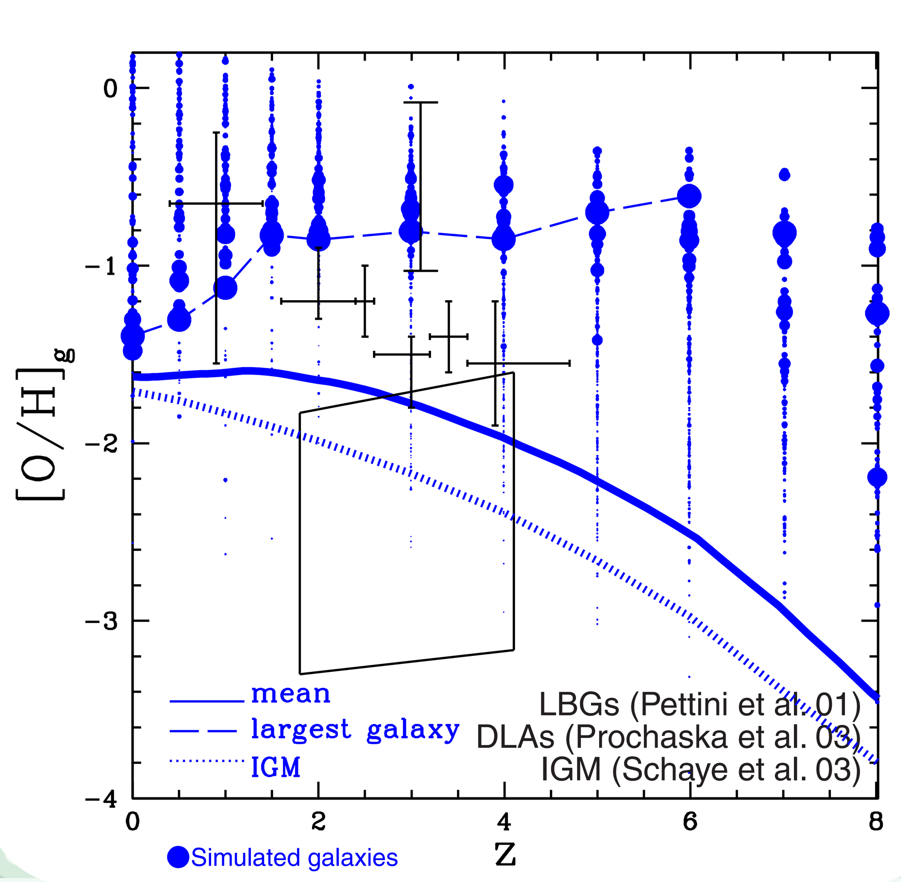
In the simulation, we can trace the orbit of gas particles over time. Exploiting this, we define as wind particles *those that are not in galaxies now, but have been in galaxies before.* In the figure, the blue and red points are for gas particles in galaxies and wind particles, respectively. The corresponding distribution of star particles is shown in the right panel. ~10% of gas stays in galaxies (~8% is hot), and ~20% is ejected as galactic winds. The rest, half of the baryons, never accretes onto galaxies.

When we follow the orbits of gas particles, we can also examine from which galaxies the wind gas particles are ejected. This allows a measurement of the ejected wind mass from each galaxy. (b) A clear relation is found between *the wind fraction and the total mass.* Winds are efficiently ejected from small galaxies. (c) A similar relation is also found for *the ejected metal fraction*, i.e. *the ratio between the wind metal mass to the total metal mass.* (d) These wind fraction and ejected metal fraction correlate well with the stellar metallicity. Therefore, the origin of the mass-metallicity relation can be explained with the galactic winds.

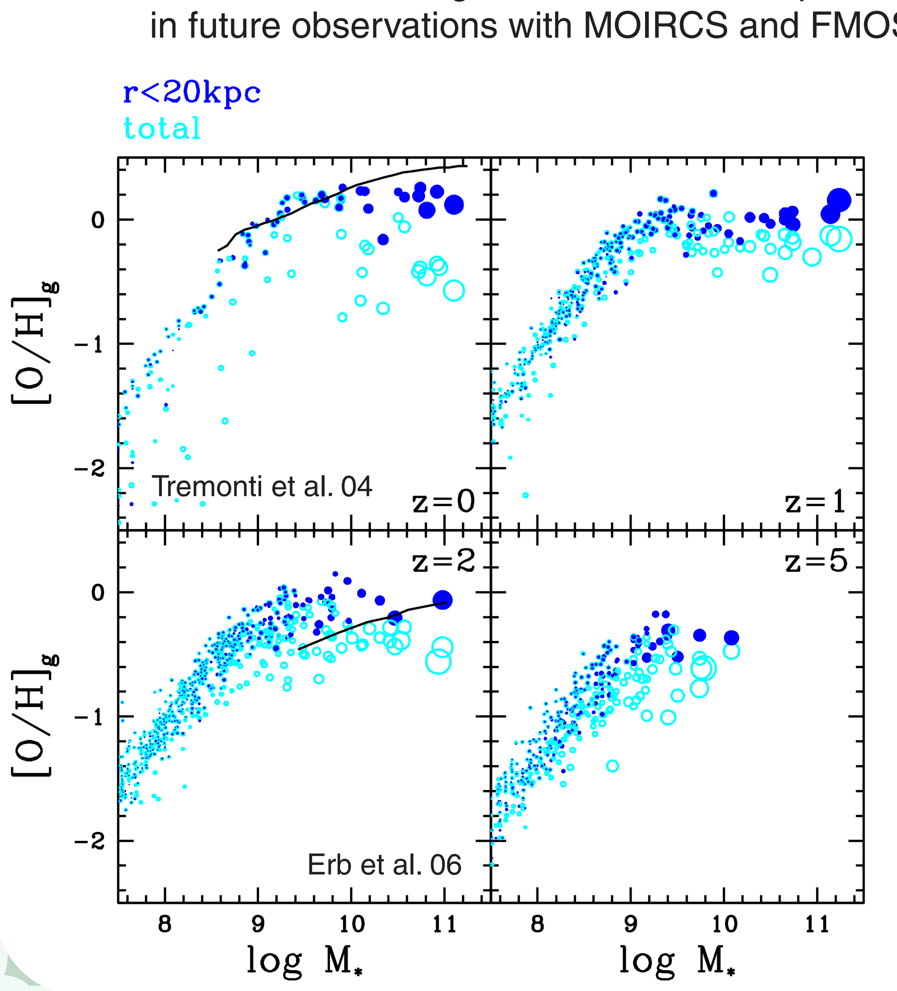


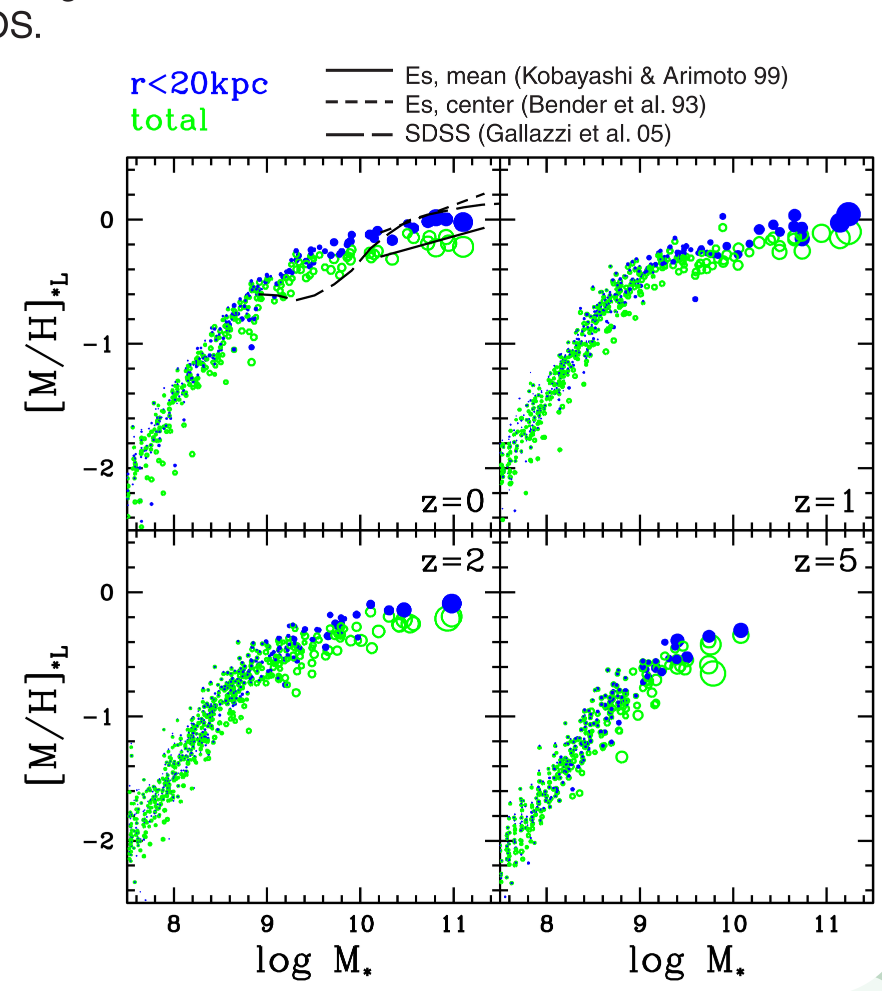


Chemical enrichment history depends on environment. In large galaxies, enrichment takes place so quickly that [O/H] reaches ~ -1 at z~7, which is consistent with the sub-solar metallicities of LBGs. The low metallicities of DLA systems are also consistent with our galaxies, provided these systems are dwarf galaxies or the outskirts of massive galaxies. The low [C/H] of the IGM can be explained if the IGM is enriched only by SNe II and HNe ([C/O]=-1). The average metallicity of the universe reaches [O/H] ~ -2 and [Fe/H] ~ -2.5 at z~4, but reaches the same values at z~3 in the IGM.



Mass-Metallicity relations:
(a) In galaxies, metallicity of the cold gas increases with galaxy mass, which is comparable to observations with a large scatter. The central cold gas shows a relation between galaxy mass and metallicity with a shallower slope than observed in SDSS emission-line galaxies at z=0.
(b) For the stellar population, tight relations are found between V-band luminosity-weighted metallicity and stellar mass at any redshift. The observed mass-metallicity relations are well reproduced for the mean stellar metallicity where the effect of metallicity gradients is taken into account, and for the central metallicity, which is two times higher than a global average.
These relations originate in the mass-dependent galactic winds, and will be found since z~5 in future observations with MOIRCS and FMOS.





5.Cosmic SN/GRB History

HN-GRB Connection

	HN	HN only (low-mass HN)
long GRB	1998bw/980425, 2003dh/030329, 2003lw/031203, ~10 photometry only: 980326, ...	1997ef (35M⊙), 2002ap (20M⊙), 2003jd (30M⊙?), ...
GRB only (dark HN?)	060505 (long?), 060614 (long?,high-z?)	
HN? & X-ray flash	2006aj/060218, 020903	

We assume
HNe ~ 50%-1% of SNe II (>20M⊙) for Z=0-0.02
GRBs ~ massive (>40M⊙) HNe.

SN Ia rate slightly increases to z~1, and sharply decreases from z~2 because of the lifetime and metallicity effects. SN II rate traces the SFR.
If GRBs are massive HNe, the GRB rate keeps on increasing toward higher redshift.
The host galaxy of GRBs tends to have low metallicity, while those of SNe Ia have high metallicity.