# The early phase of environmental effects on galaxy properties unveiled by near-infrared spectroscopy of protocluster galaxies at z > 2

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**Abstract** We present the results of near-infrared spectroscopy of Hα emitters (HAEs) associated with two protoclusters around radio galaxies (PKS 1138–262 at z=2.2 and USS 1558–003 at z=2.5) with the Multi-Object Infrared Camera and Spectrograph (MOIRCS) on the Subaru telescope. Among the HAE candidates constructed from our narrow-band imaging, we have confirmed membership of 27 and 36 HAEs for the respective protoclusters. The clusters show prominent substructures, suggesting that they are still in the midst of rapid building. We calculate the dynamical masses of the clusters and substructures, assuming their local virialization. The inferred masses (~1E14 M⊙) of the protocluster cores are consistent with their being typical progenitors of the present-day most massive class of clusters (~1E15 M⊙) if we take into account the typical mass growth history of clusters. We then estimate the integrated star formation rates (SFRs) of the protocluster cores normalized by their dynamical masses and compare these with lower redshift descendants. We see a marked increase of star-forming activities in the cluster cores as we go back in time to 11 billion years ago.

Also, the identified HAEs show very high excitation levels as characterized by much higher [OIII]/ Hβ line ratios than those of low-z galaxies. Such a high excitation level is qualitatively driven by their high specific SFRs (sSFRs) and lower gaseous metallicities. Furthermore, we investigate the environmental dependence of gaseous metallicities by comparing the HAEs in the protoclustrers with those in the general field at similar redshifts. We find that the gaseous metallicities of protocluster galaxies are more chemically enriched than those of field galaxies at a given stellar mass in the range of $M_{star} \lesssim$1E11M⊙. This can be attributed to many processes, such as intrinsic (or nature) effects, external (or nurture) effects, and some systematic effects (sampling bias). Although, none of the interpretation is perfect, the external effects such as gas recycling or stripping seem to be favored.

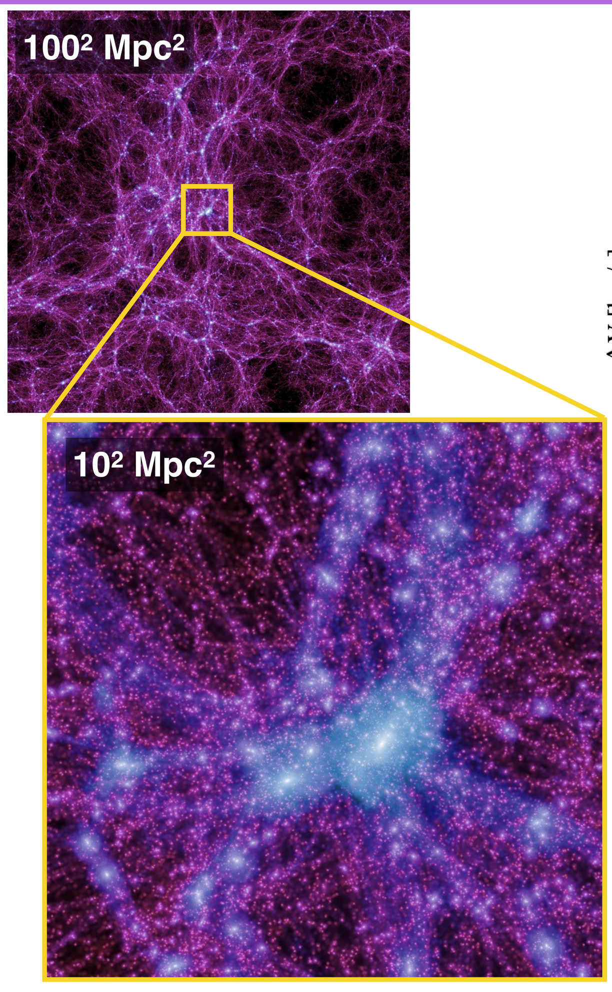
## MOIRCS spectroscopy (Apr. 2013)

HK500: 1.3–2.5μm, R≈500, VPH-K: 1.9–2.5μm, R≈1700

| Cluster Name (1) | Grism (2) | R (3) | Integ. time (4) | Targets (5) |
|---|---|---|---|---|
| PKS 1138−262 | HK500 | 513 | 120 min | 23 |
| (11:40:48,−26:29:08) | HK500 | 513 | 161 min | 19 |
| $z = 2.16$ | VPH-K | 1675 | 225 min | 18 |
| USS 1558−003 | HK500 | 513 | 180 min | 25 |
| (16:01:17,+00:28:48) | HK500 | 513 | 276 min | 19 |
| $z = 2.53$ | HK500 | 513 | 175 min | 15 |

➡48 and 68 HAE candidates in PKS1138 and USS1558 are selected by NB technique *(Koyama et al. 2013a; Hayashi et al. 2012)*

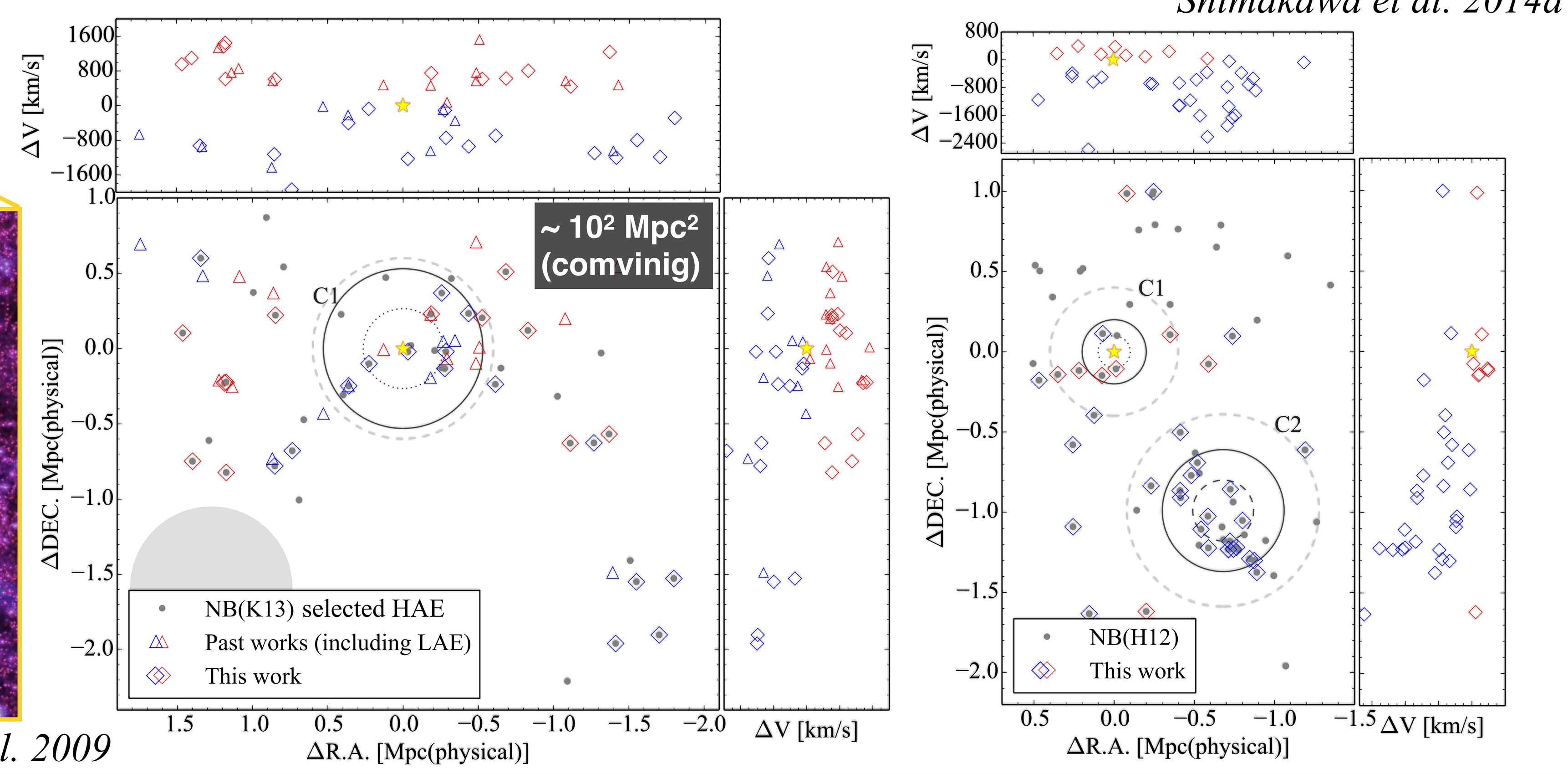
➡New confirmation of 27 and 36 HAEs in PKS1138 and USS1558, respectively




*Millenium Run II: Boylan-Kolchin et al. 2009*

## Identification of prominent substructures (clumps, filaments and velocity gradients)

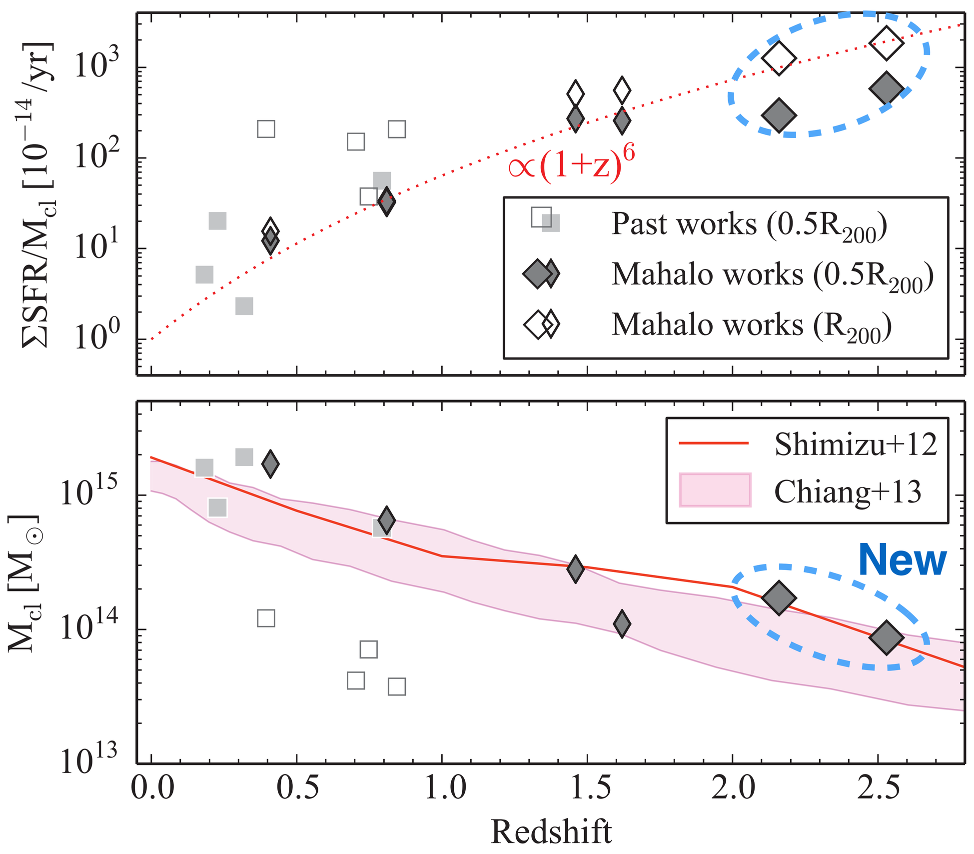
Left: PKS 1138-262 (z=2.2)
Right: USS 1558-003 (z=2.5)
Solid & dotted line: $R_{200}$, $0.5R_{200}$




*Shimakawa et al. 2014a*

## We find the progenitors of rich clusters like 'Coma' in rapid formation at z>2

Mahalo: *Koyama+10,11, Hayashi+11, Tadaki+12*
Past works: compilation by *Finn+05*




*Shimakawa et al. 2014a*

### $M_{cl}$ and $\Sigma SFR/M_{cl}$ histories

➡Comparing cluster masses with those by numerical simulations *(Shimizu et a. 2012; Chiang et al. 2013)*

➡Identification of the progenitors of the most massive class of clusters

➡Redshift variation of the mass-normalized SFRs is roughly scaled as $(1+z)^6$

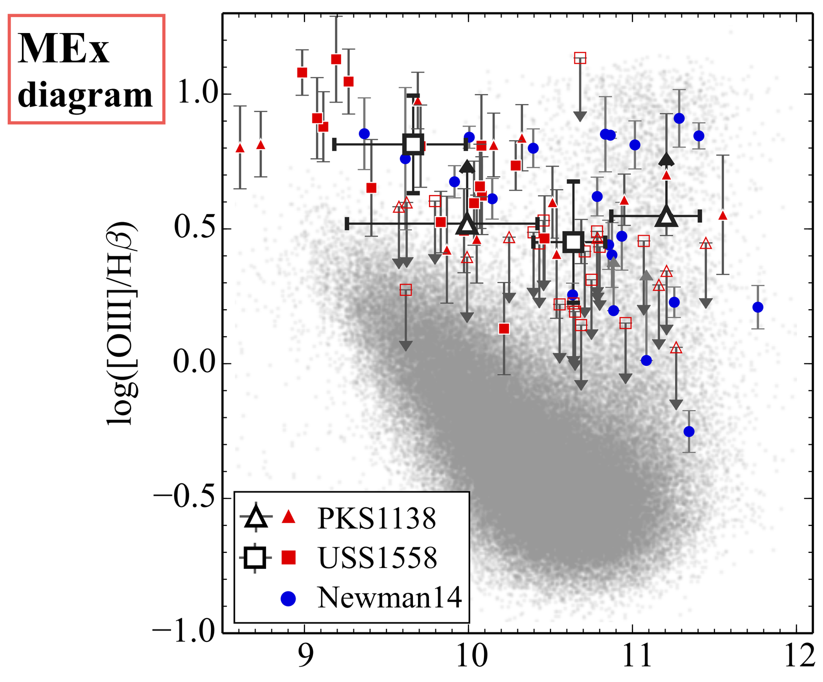
➡Their SFHs are compared between the right ancestors and the right descendants

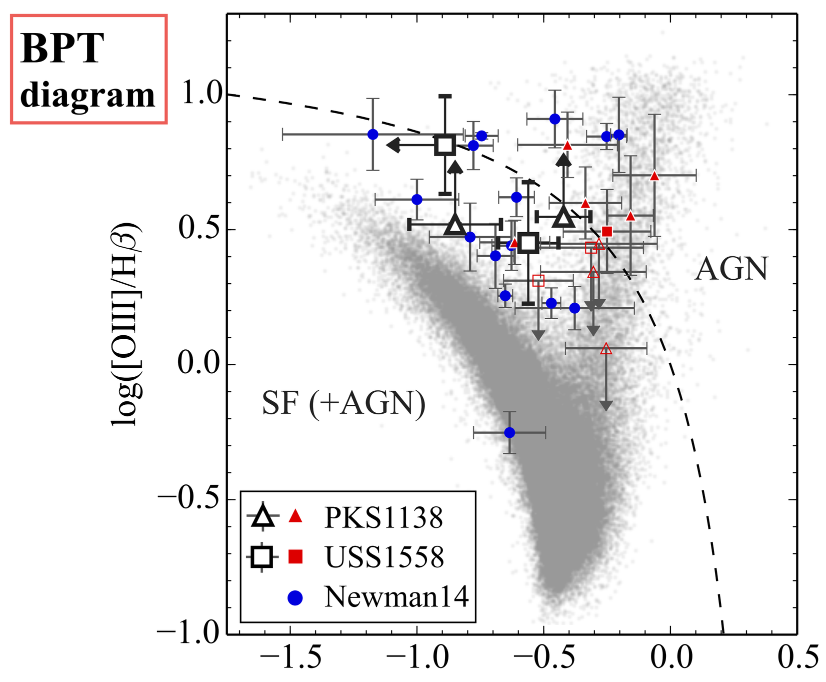
## ISM conditions of the protocluster galaxies at z>2

### Extremely high excitation of ISM condition of z>2 star-forming galaxies

➡Mass-excitation *(Juneau et al. 2011)* and BPT diagram *(Baldwin et al. 1981)*

➡We estimate [OIII]/Hβ ratio from [OIII]/Hα based on the dust correction

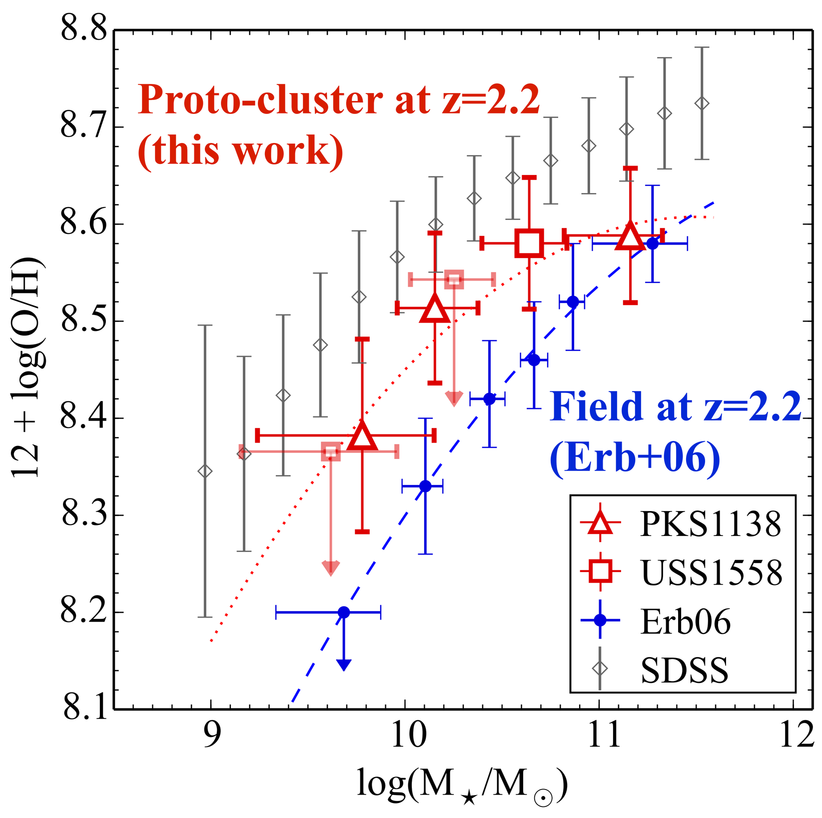



*Shimakawa et al. 2014b*

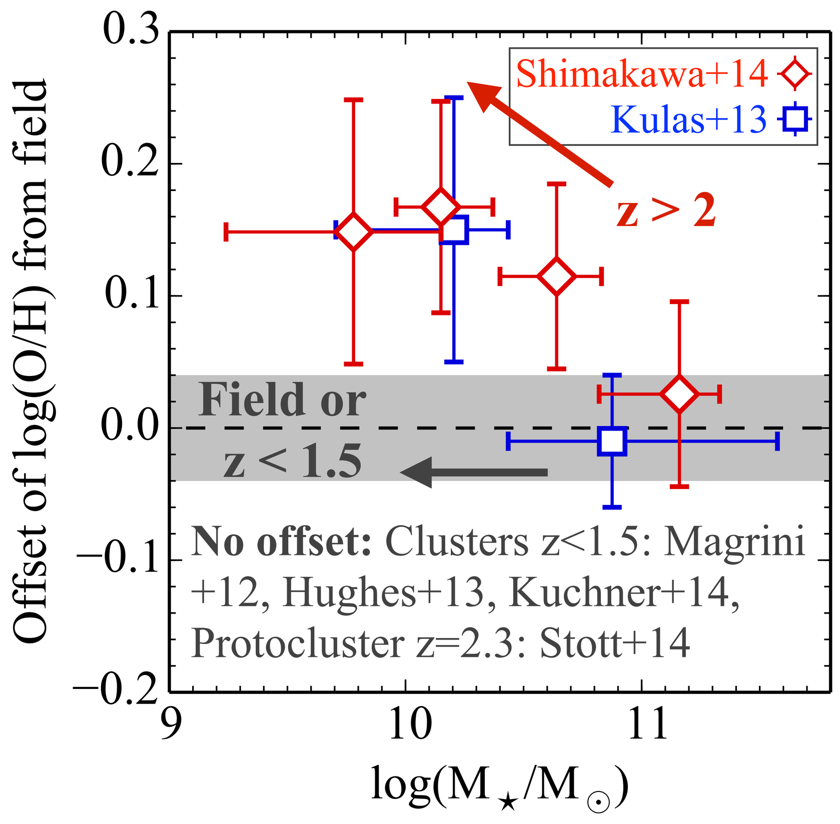
## Mass—metallicity (M-Z) relation in the protocluster at z>2

*Erb et al. 2006b; Shimakawa et al. 2014b*



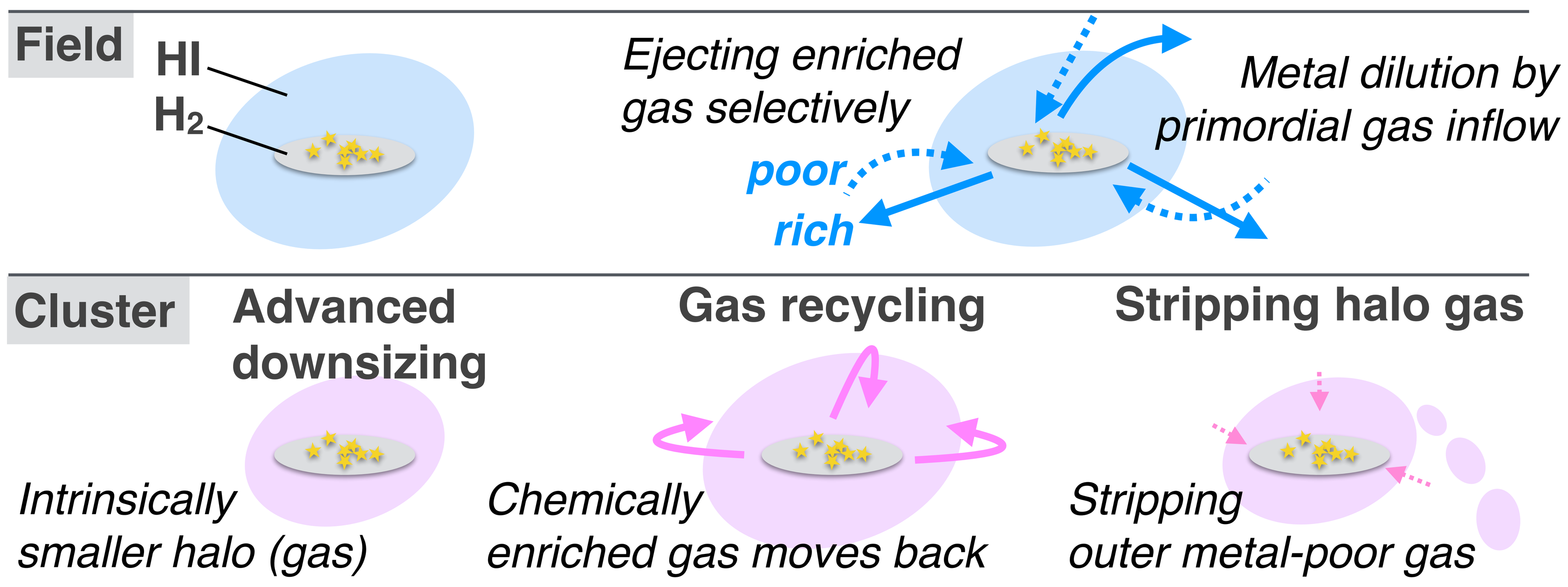

## Offsets from field at each z

*Hughes et al. 2013; Magrini et al. 2012; Kulas et al. 2013; Shimakawa et al. 2014b*




## Possibilities (see more detail in Shimakawa et al. 2014b)

### Mass-metallicity relation of (proto)cluster galaxies through cosmic times




➡The excess of M-Z relation for the protocluster galaxies with those of field galaxies *(Erb et al. 2006b)*, which is consistent with *Kulas et al. 2013*

➡We discuss many possibilities to coincide with our and past results

➡However, we have not yet reached to any fully consistent view

**Future work** We are now studying the characteristics of the 'individual' galaxies with MOSFIRE on Keck. It is essential towards understanding the environmental dependence of galaxy formation. However, these current works are limited with only the integrated or averaged features in each galaxy. As a next step, we need to know their spatially resolved physical properties. The 3D spectroscopy such as SINFONI and KMOS mounted on VLT will spatially resolve radial gradients of the gaseous metallicity and ionization states directly as well as dust extinctions and specific star-formation rates.