Discs in Galaxies (2016/7/13, ESO Garching)

MAHALO-Subaru

The nature of star-forming disc galaxies in proto-clusters

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A galaxy cluster RXJ0152 at z=0.83 (Subaru/Suprime-Cam)

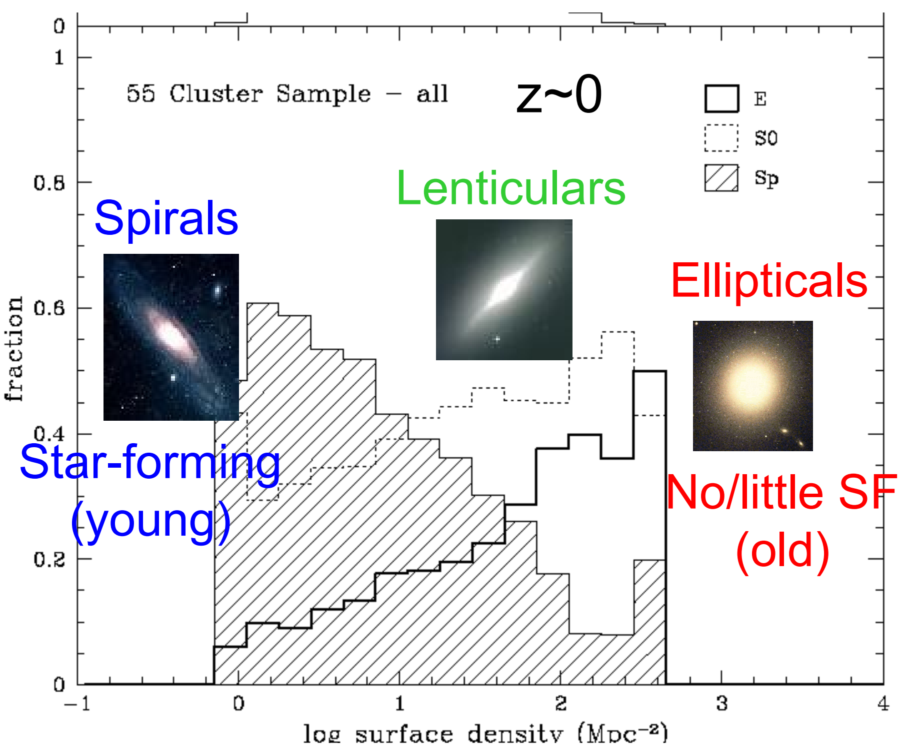
Outline

- MAHALO: Mapping star formation in clusters/ fields at $0.4<z<2.5$ with narrow-band imaging (Hα, [OII])
- MAHALO-Deep: Towards lower mass ($<10^{9.5}M_{\odot}$)
- MAHALO-Far: Towards higher redshift ($3<z<3.6$) with [OIII]
- MAHALO-Sharp: Towards higher spatial resolution (<0.2″) with AO imaging and ALMA

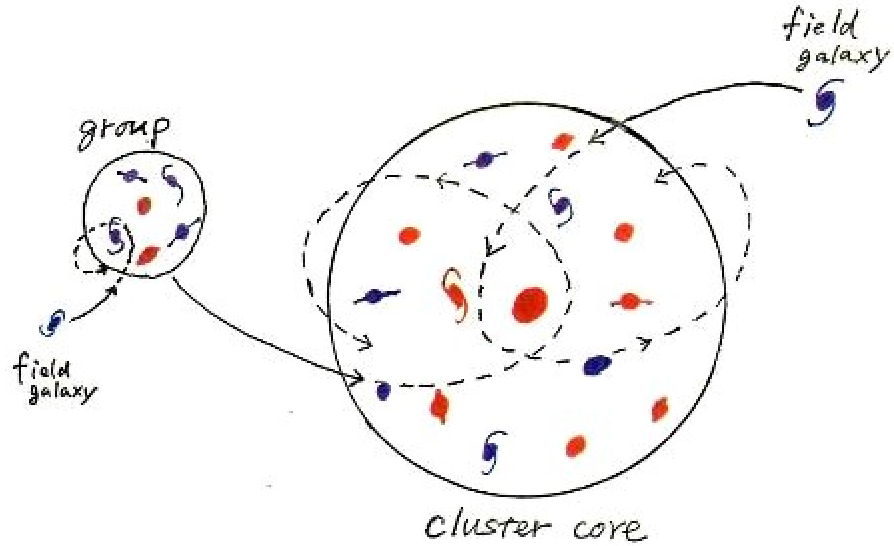
What is the origin of the cosmic habitat segregation?

Explore the initial stage of environmental effects by studying proto-clusters at z>1.5

Morphology- (SFR-) density relation
(Dressler 1980)



log surface density (Mpc^{-2})



Nature? (intrinsic)

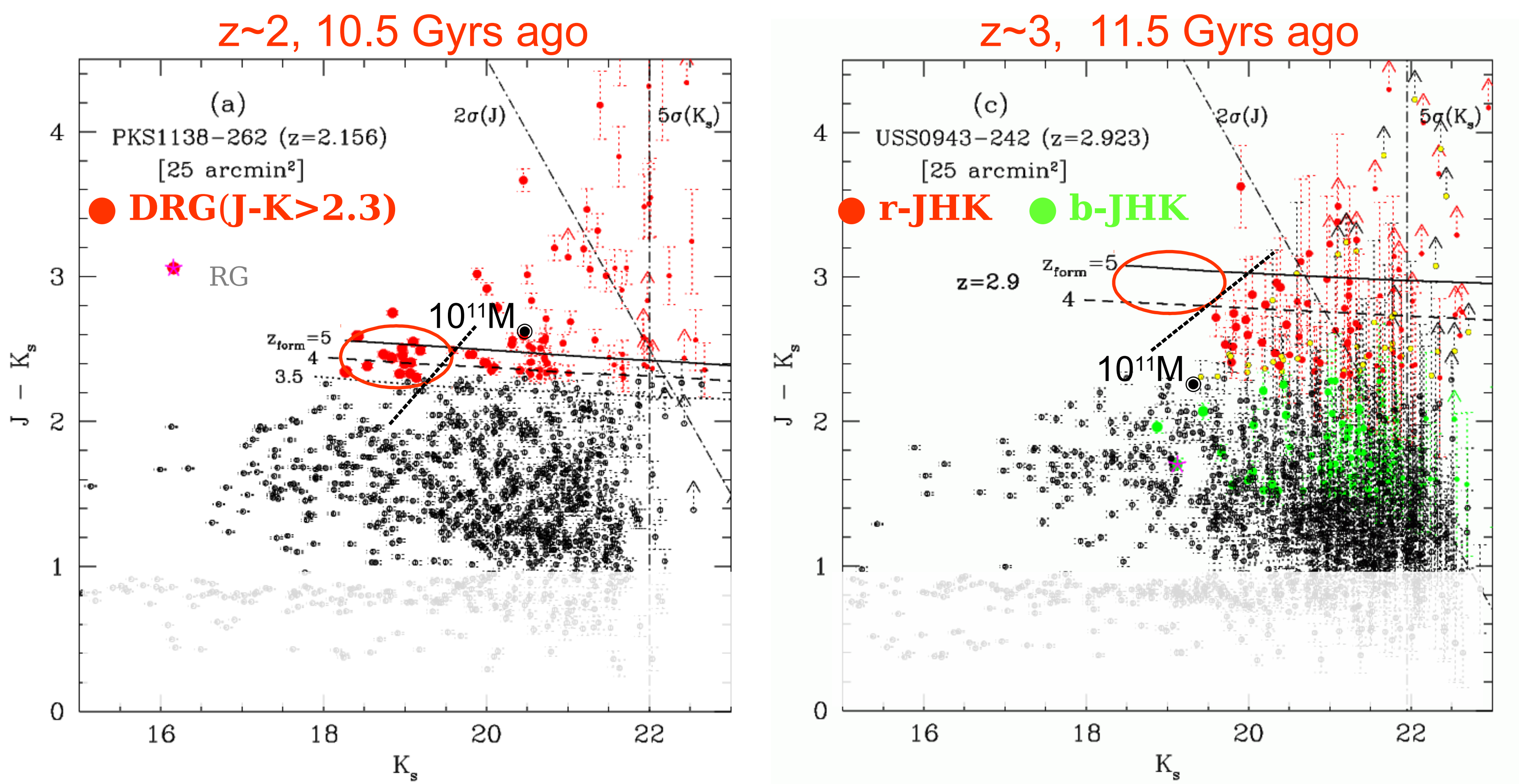
Biased, earlier galaxy formation
in high density regions

Nurture? (external)

Galaxy-galaxy interaction/mergers,
gas-stripping

Emergence of the red sequence in clusters at z~2

Note that they are not always quiescent



Massive, red galaxies grow rapidly during 2-3 Gyrs after the Big-Bang.

Kodama et al. (2007)

MAHALO-Subaru

MApping HAlpha and Lines of Oxygen with Subaru

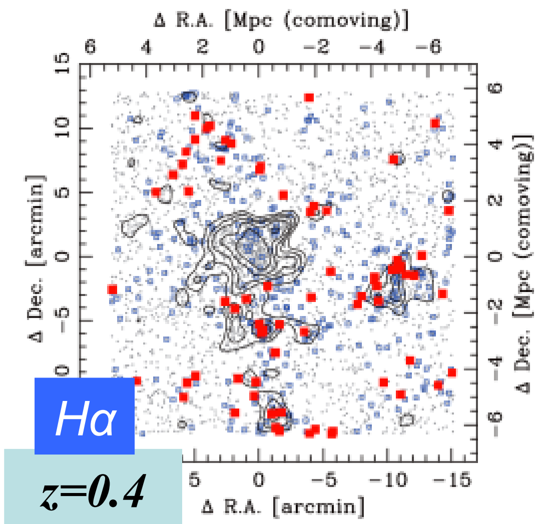
Unique sample of NB-selected SF galaxies across environments and cosmic times

	environment	target	z	line	λ (μm)	camera	NB-filter	continuum	status (as of Apr 2015)
z<1 clusters	Low-z clusters	CL0024+1652	0.395	Hα	0.916	Suprime-Cam	NB912	z'	Kodama+'04
		CL0939+4713	0.407	Hα	0.923	Suprime-Cam	NB921	z'	Koyama+'11
		CL0016+1609	0.541	Hα	1.011	Suprime-Cam	NB1006	z'	not yet
		RXJ1716.4+6708	0.813	Hα	1.190	MOIRCS	NB1190	J	Koyama+'10
				[OII]	0.676	Suprime-Cam	NA671	R	observed
		RXJ0152.7–1357	0.837	[OIII]	0.920	Suprime-Cam	NB921	z'	not yet
z~1.5 clusters	High-z clusters	XCSJ2215–1738	1.457	[OII]	0.916	Suprime-Cam	NB912, NB921	z'	Hayashi+'10, '12
		4C65.22	1.516	Hα	1.651	MOIRCS	NB1657	H	Koyama+'14
		CL0332–2742	1.61	[OII]	0.973	Suprime-Cam	NB973	y	observed
		ClGJ0218.3–0510	1.62	[OII]	0.977	Suprime-Cam	NB973	y	Tadaki+'12
z>2 clusters	Proto-clusters	PKS1138–262	2.156	Hα	2.071	MOIRCS	NB2071	K_s	Koyama+'12
		HS1700+64	2.30	Hα	2.156	MOIRCS	BrG	K_s	observed
				[OIII]	1.652	MOIRCS	[Fe II]	H	not yet
		4C23.56	2.483	Hα	2.286	MOIRCS	CO	K_s	Tanaka+'11
		USS1558–003	2.527	Hα	2.315	MOIRCS	NB2315	K_s	Hayashi+'12
		MRC0316–257	3.130	[OII]	2.539	MOIRCS	NB1550	H	not yet
				[OIII]	2.068	MOIRCS	NB2071	K_s	observed
z>2 field	General fields	SXDF-CANDELS	2.16	Hα	2.071	MOIRCS	NB2071	K_s	observed
		(90 arcmin^2)	2.19	Hα	2.094	MOIRCS	NB2095	K_s	Tadaki+'13
			2.53	Hα	2.315	MOIRCS	NB2315	K_s	Tadaki+'13
			3.17	[OIII]	2.093	MOIRCS	NB2095	K_s	Suzuki+'14
			3.63	[OIII]	2.317	MOIRCS	NB2315	K_s	Suzuki+'14
		COSMOS-CANDELS	2.16	Hα	2.071	MOIRCS	NB2071	K_s	partly observed
		(90 arcmin^2)	2.19	Hα	2.094	MOIRCS	NB2095	K_s	partly observed
		GOODS-N	2.19	Hα	2.094	MOIRCS	NB2095	K_s	Tadaki+'11
		(70 arcmin^2)		[OII]	1.189	MOIRCS	NB1190	J	observed

~20 nights for imaging, >15 nights for spectroscopy

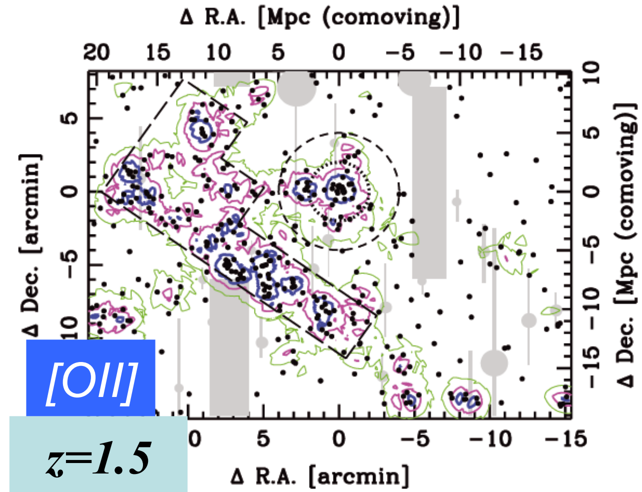
Kodama et al. (2013)

High-z structures revealed by MAHALO

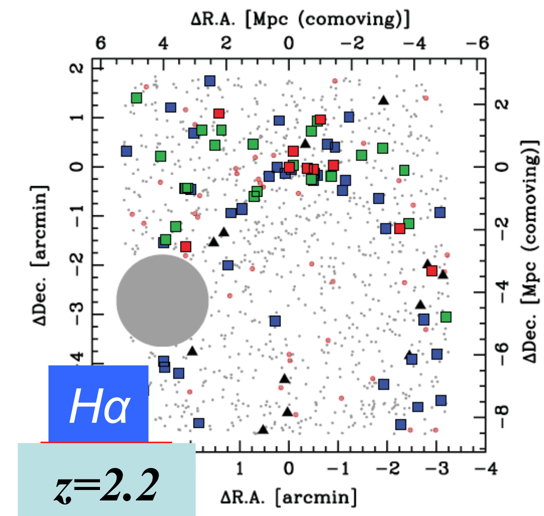


CL0939 *(Koyama+11)*

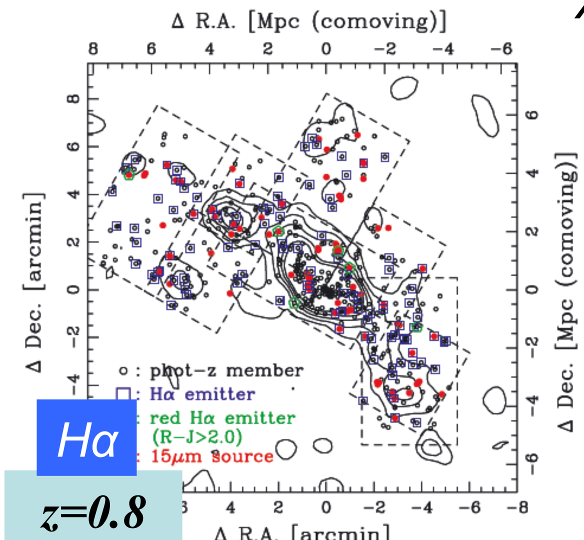
(Hayashi+10, 11)



XCSJ2215

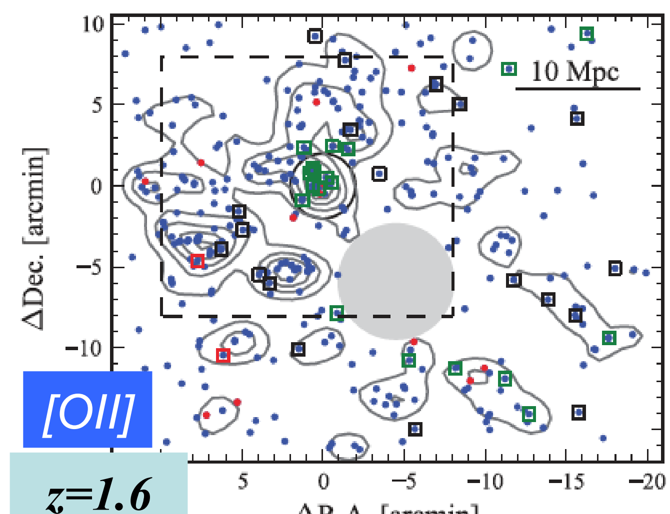


PKS1138 *(Koyama+13)*

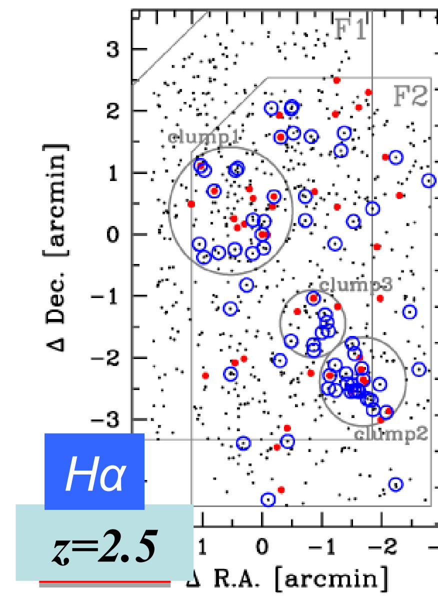


RXJ1716 *(Koyama+10)*

(Tadaki+12)



CL0218



USS1558 *(Hayashi+12)*

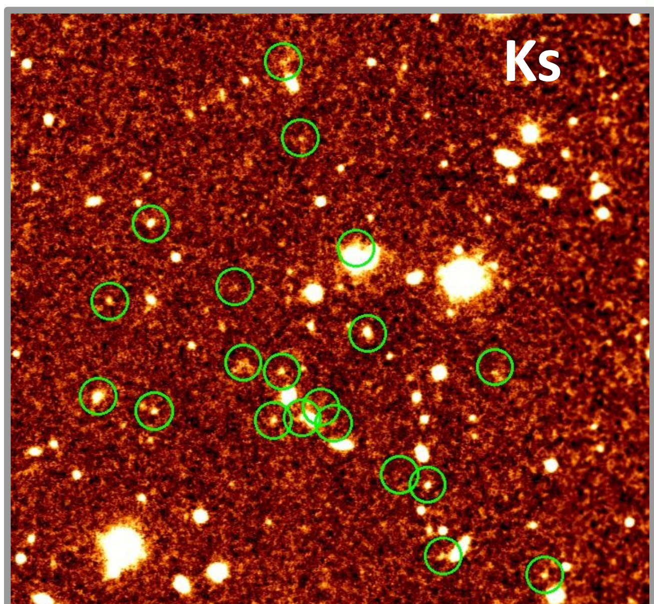
The most prominent star-bursting proto-cluster at z~2.5

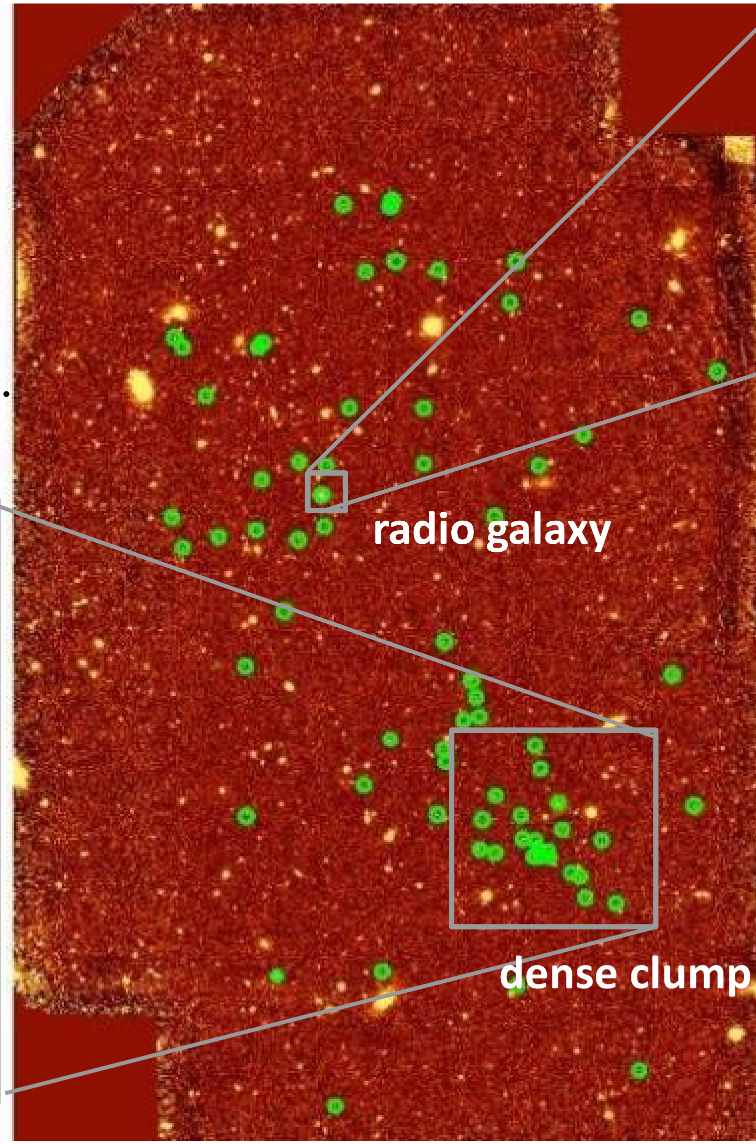
USS1558-003 (z=2.53)

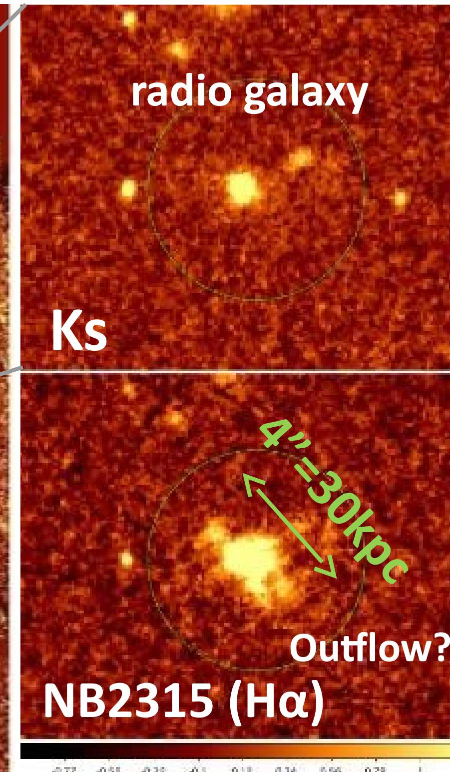
Hα imaging
with MOIRCS/NB2315

FoV=4' x 7'

68 Hα emitters are detected.
~40 are spec. confirmed.





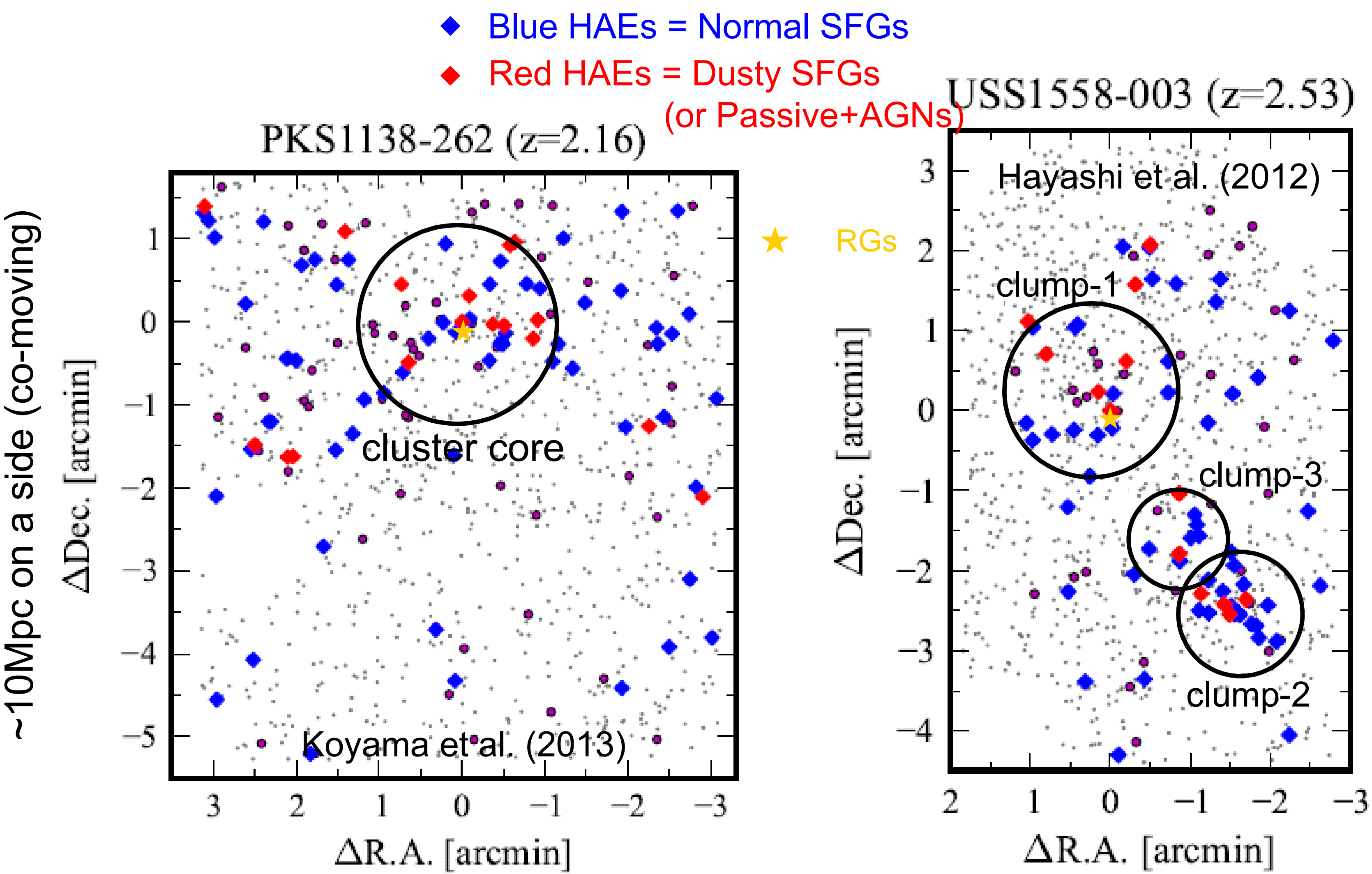


1.5Mpc away
from the RG

~20x denser than the general field.
Mean separation between galaxies is ~150kpc in 3D.

Hayashi et al. (2012)

Spatial distributions of Hα emitters in two proto-clusters at z>2

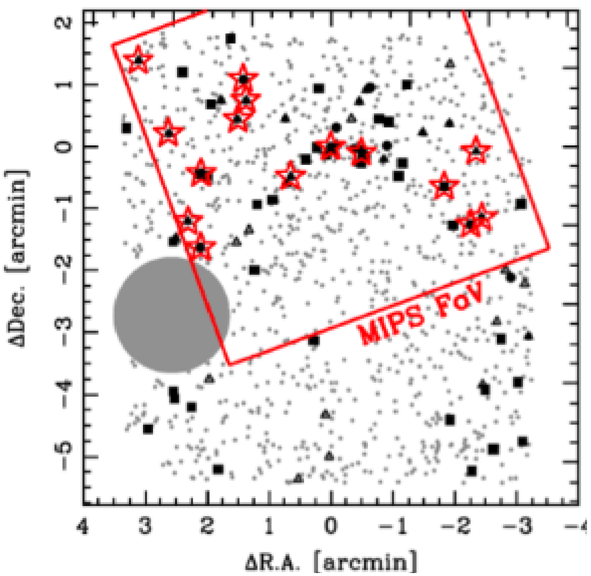


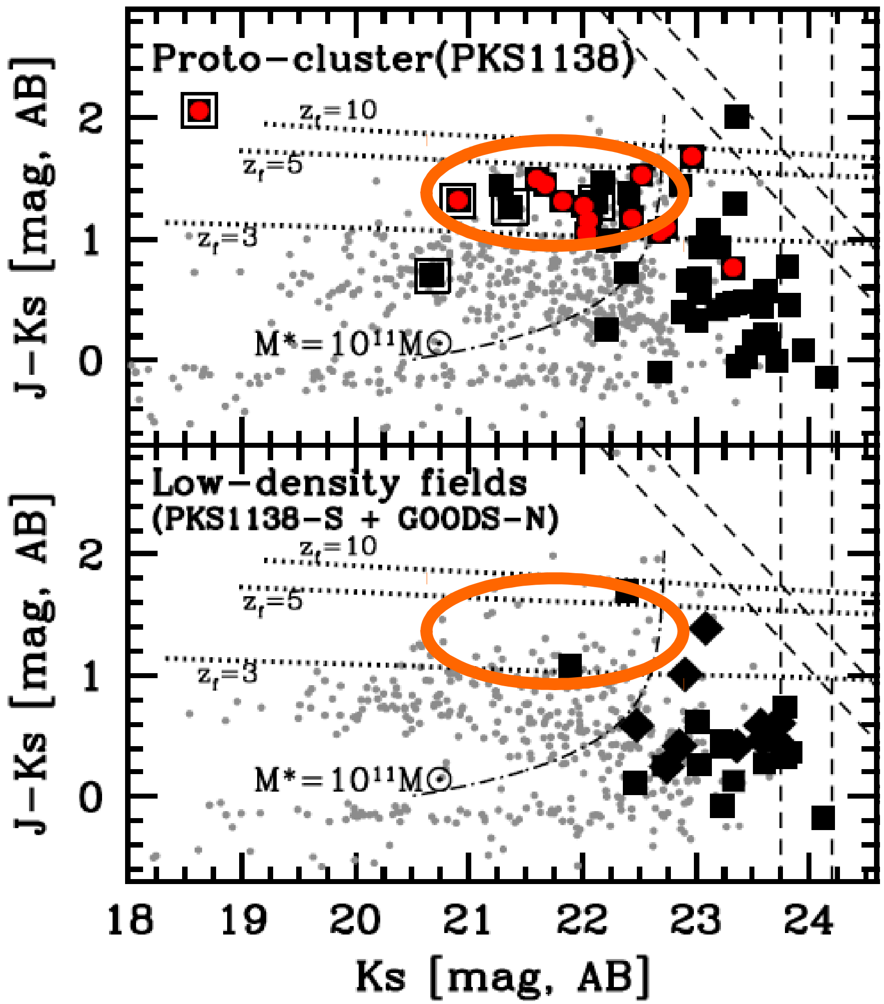
Lots of HAEs live in proto-cluster, indicating strong SF activities there.

Red HAEs (J-Ks >1.38; dusty starbursts) tend to favor even denser cores/clumps!

Massive + dusty galaxies in the proto-cluster core at z~2

☆ 24um sources





High density

■ ◆ Hα emitters

● 24um sources

Low density

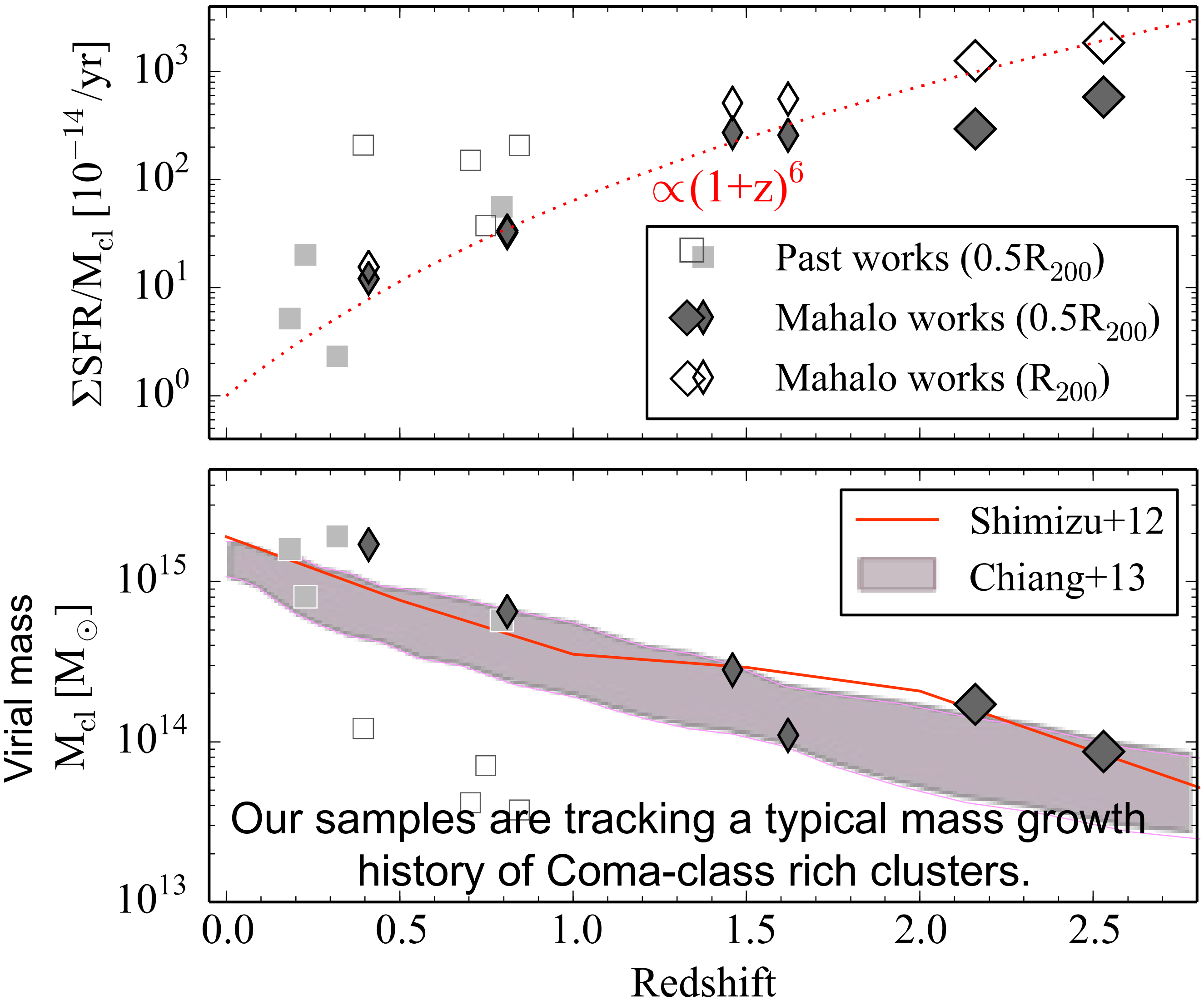
Koyama et al. (2013a)

Red Ha emitters are massive ($M_\star > 10^{11} M_\odot$) and dusty star-forming galaxies.

Many are detected at 24μm with MIPS.

→ Cluster specific/preferred phenomena at high-z,
holding a key to understanding the early environmental effects.

Evolution of integrated SFRs and growth of dynamical mass in cluster cores

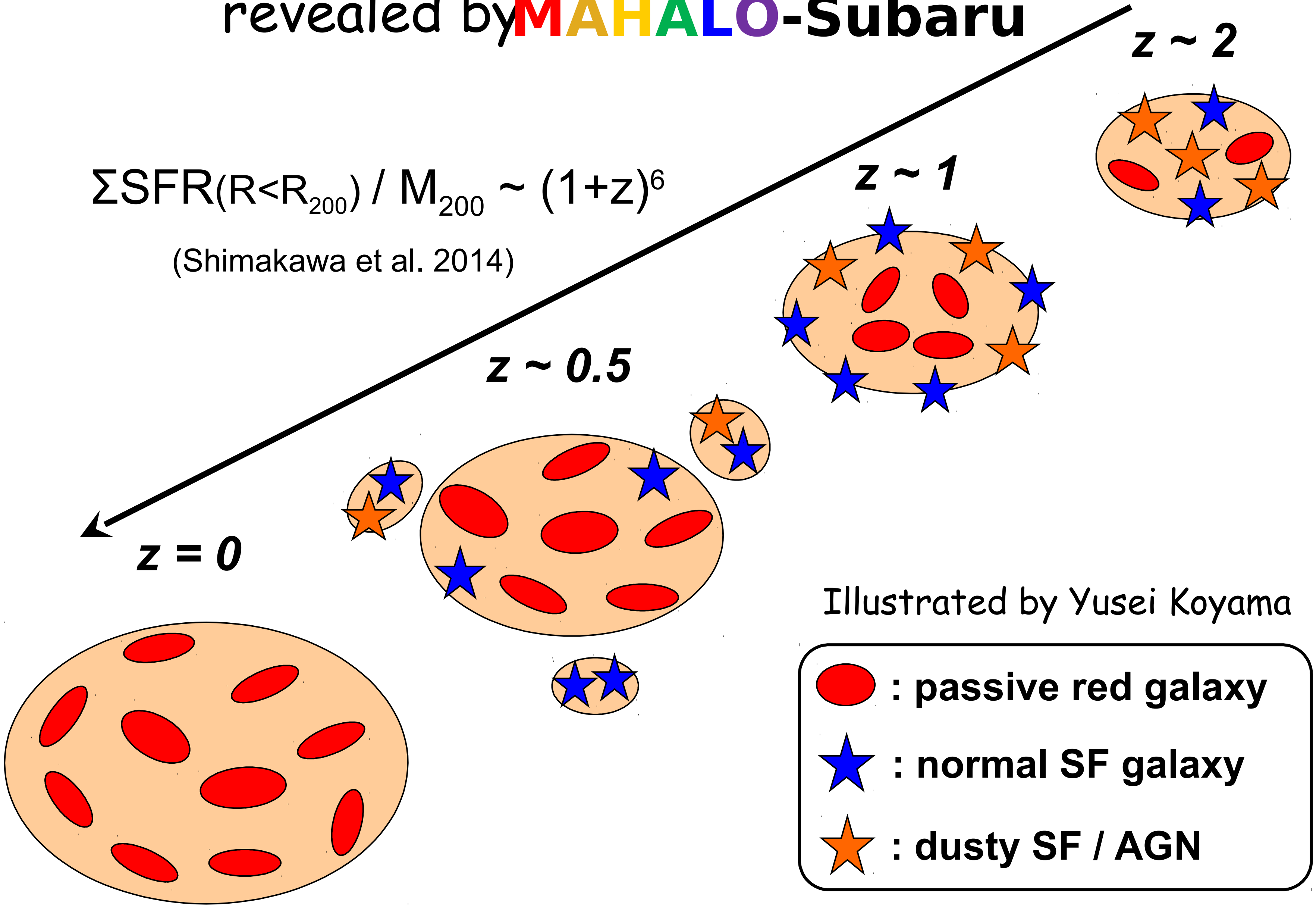


Rapid increase of integrated SFR per unit cluster mass with increasing z

Numerical simulations suggest that these proto-clusters will grow to ~$10^{15}M_\odot$ clusters by the present-day

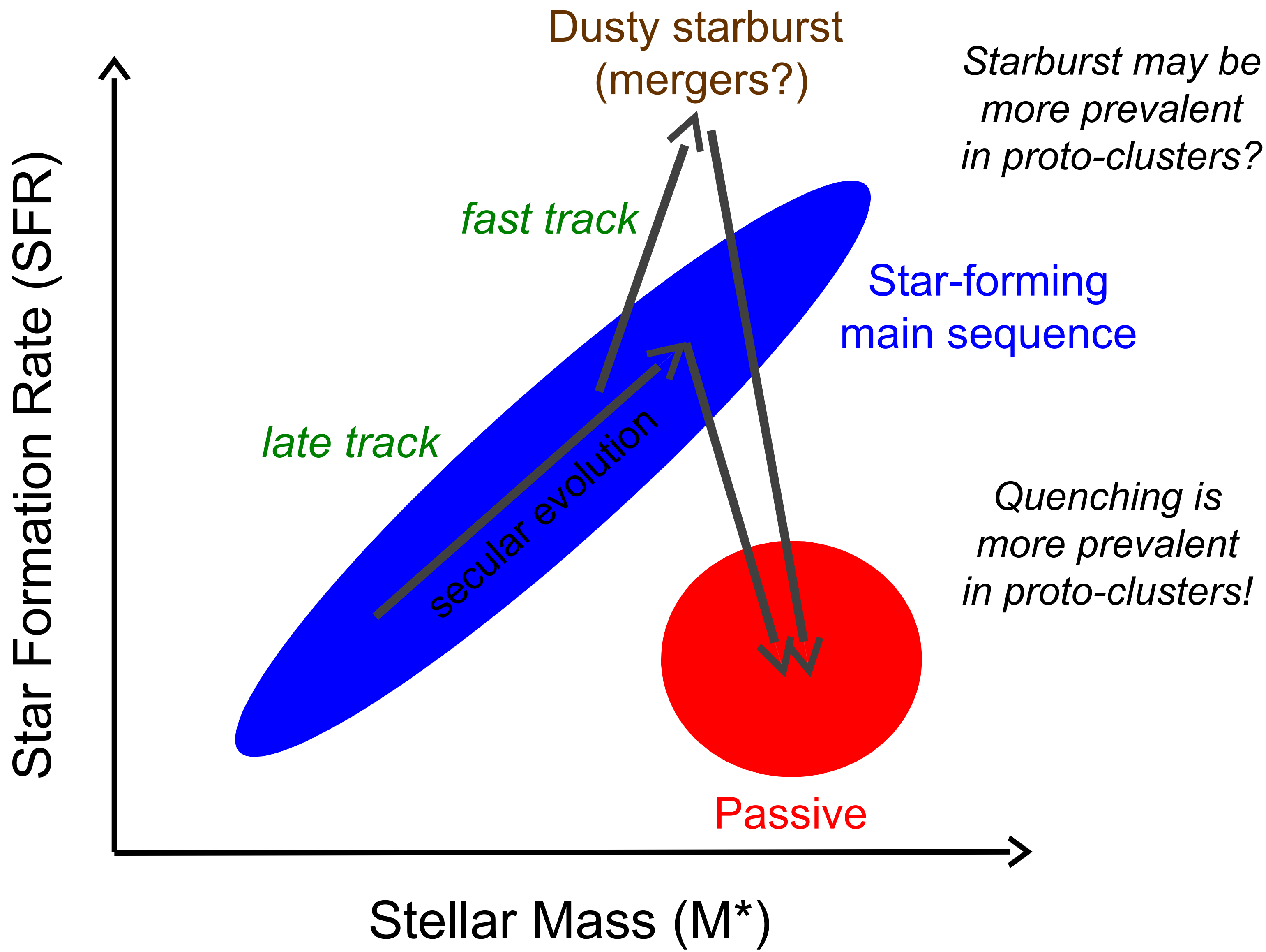
Shimakawa et al. (2014b)

Inside-out growth (quenching) of galaxy clusters revealed by MAHALO-Subaru

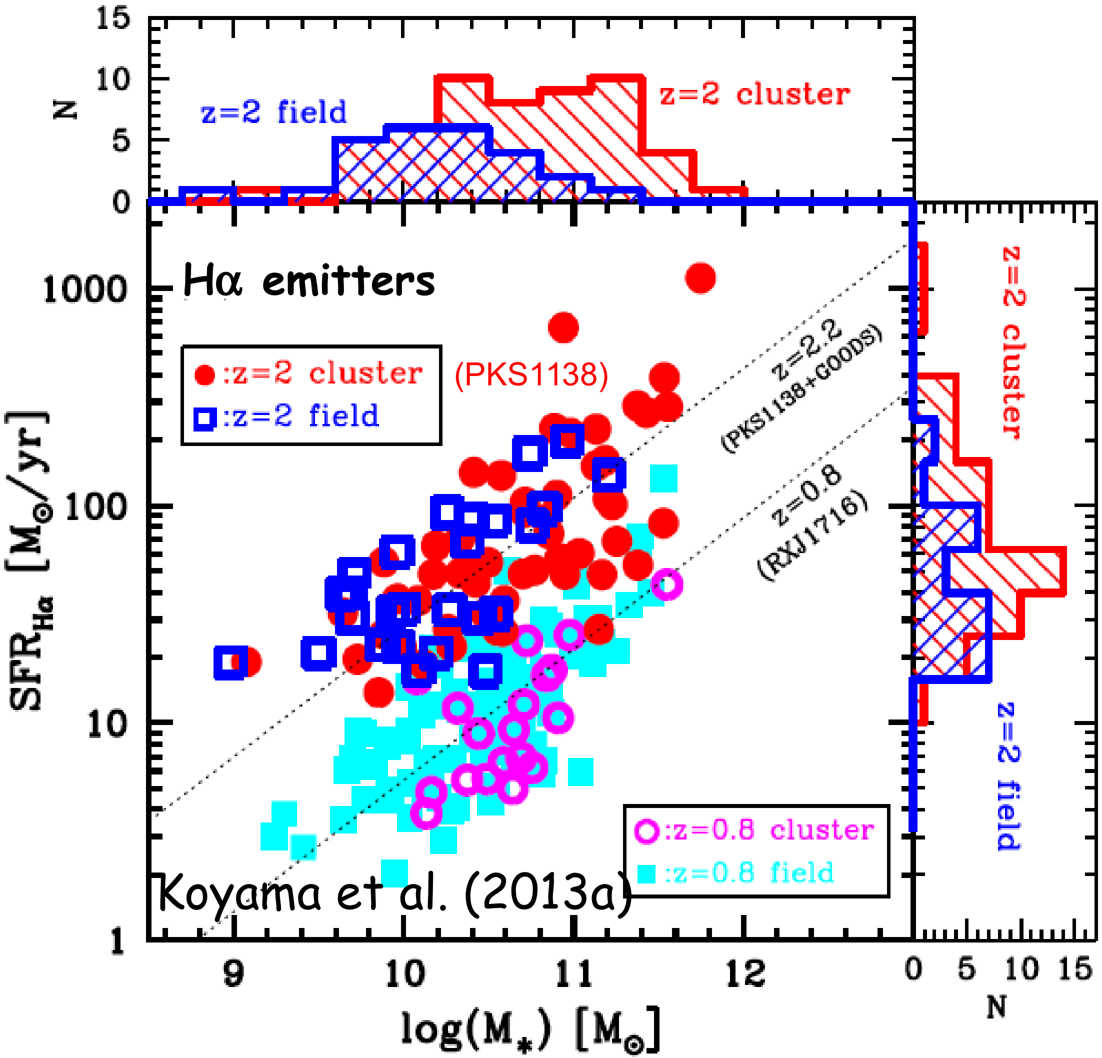


Galaxy evolution on the main seq. and its environ. dependence

▭ Large scatter around the MS for cluster galaxies?



Environmental dependence of the Star-Forming Main-Sequence?



M*-scaled dust correction for Hα is applied.
(Garn & Best 2010)

No clear environmental dependence in the location of the main sequence.

But cluster galaxies tend to be more massive.

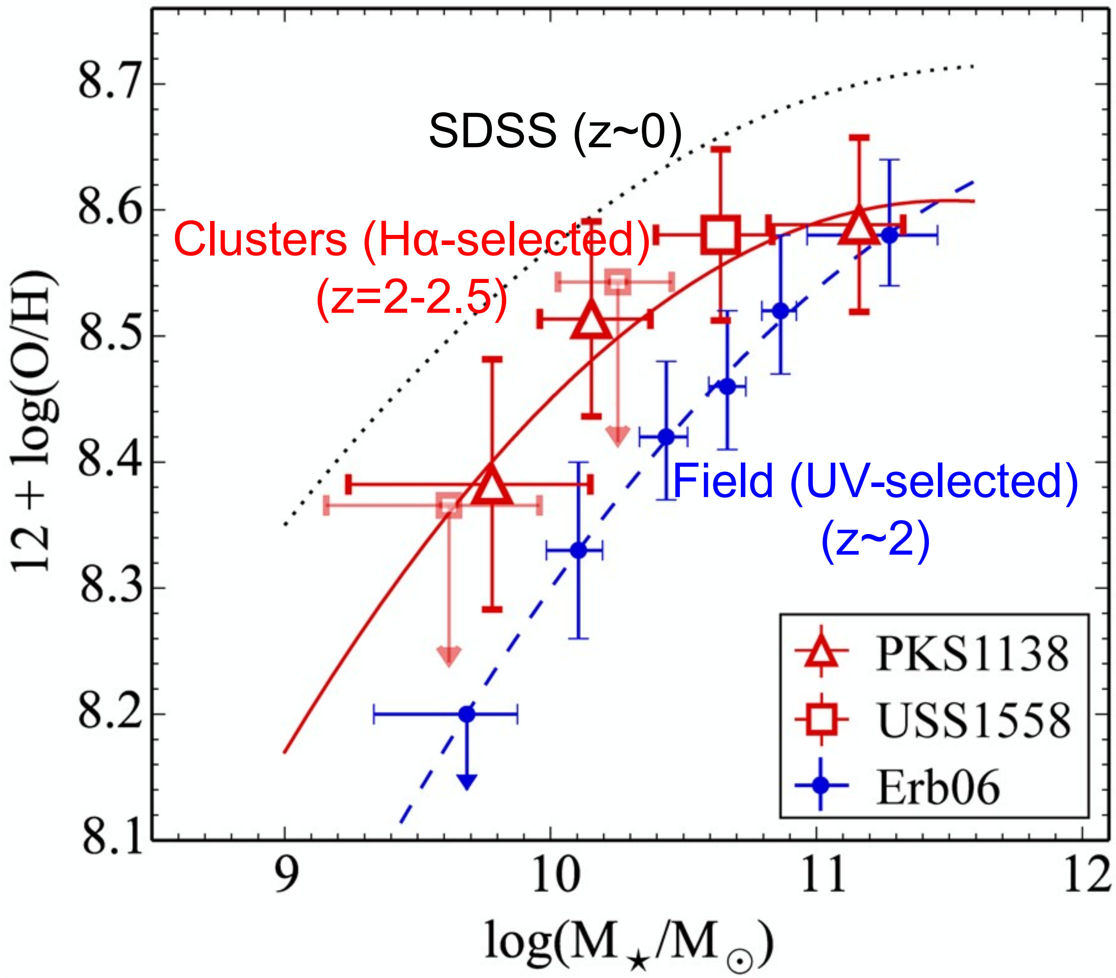
Scatter maybe a bit larger for the cluster galaxies but we suffer from small statistics due to short timescales of enhancement/quenching and uncertain dust correction.

Better statistics and accurate dust correction are required.

Environmental dependence of gaseous metallicity at z~2

Gas is harder to remove from galaxies in clusters?

Based on stacking analysis of N2=[NII]/Hα
with Subaru/MOIRCS



Shimakawa et al. (2015a)

High-z < Low-z

Cluster > Field
at low-mid mass

① Sample selections? HAEs in clusters tend to be more evolved than LBGs in the field.

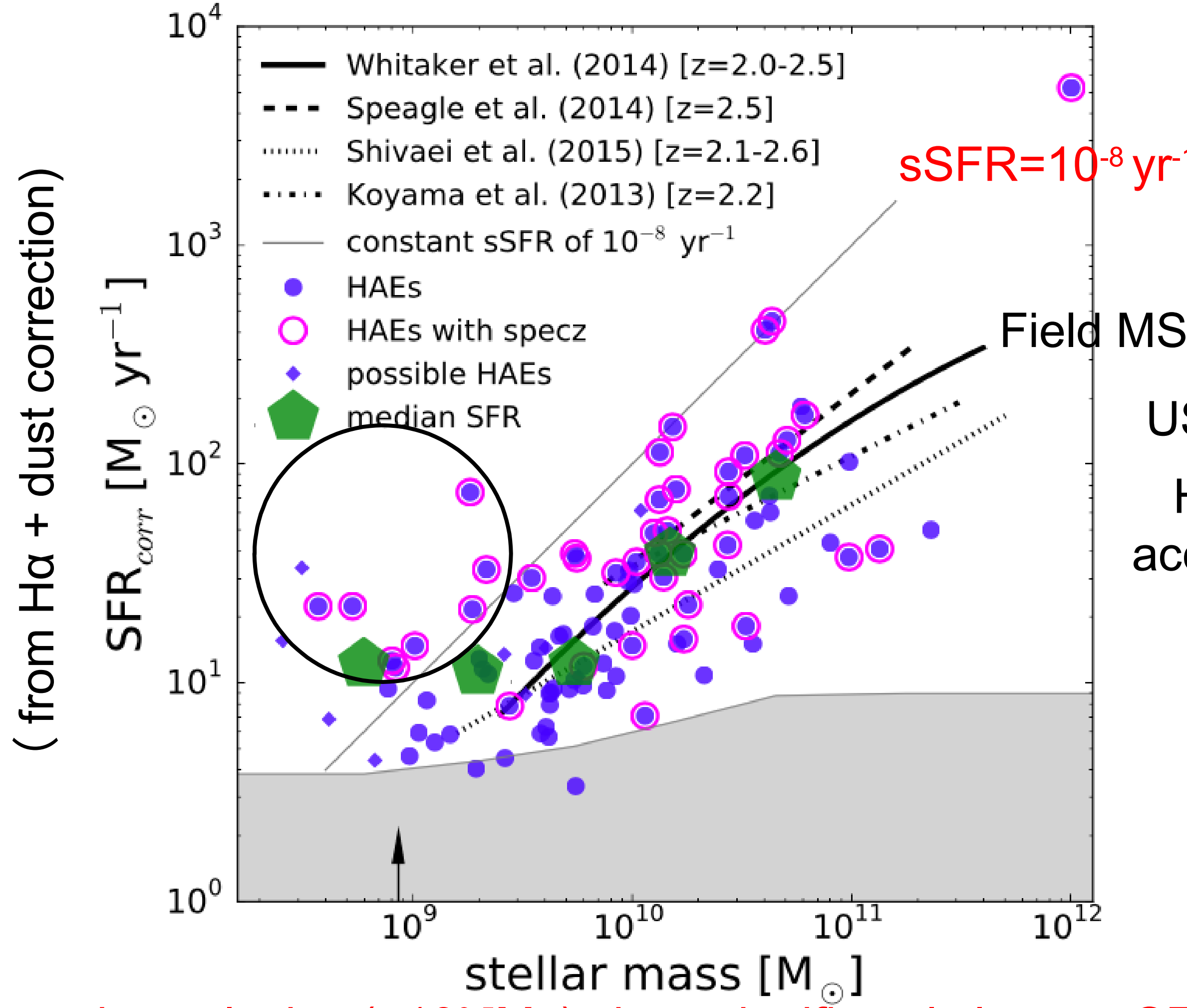
② Accelerated, hence more advanced chemical evolution in clusters, and smaller f(gas)?

③ Stripping of metal poor gas from the reservoir, and stopping dilution of metals.

④ Recycling of enriched and once ejected gas? (Dave+ '11; Kulas+ '13)

MAHALO-Deep

We went significantly deeper on two proto-clusters at z>2 by 10 hrs exposures in NB and 3 hrs in Ks with MOIRCS/Subaru under 0.3-0.4”



USS1558-003 (z=2.53)

Hayashi et al. (2016), accepted by ApJ TODAY!

Less massive galaxies (<$10^{9.5}M_\odot$) show significantly larger sSFR (bursty or younger)!

⇨ Is this due to an environmental effect in high-z proto-clusters?

Star forming galaxies in the general field @SXDF-UDS-CANDELS

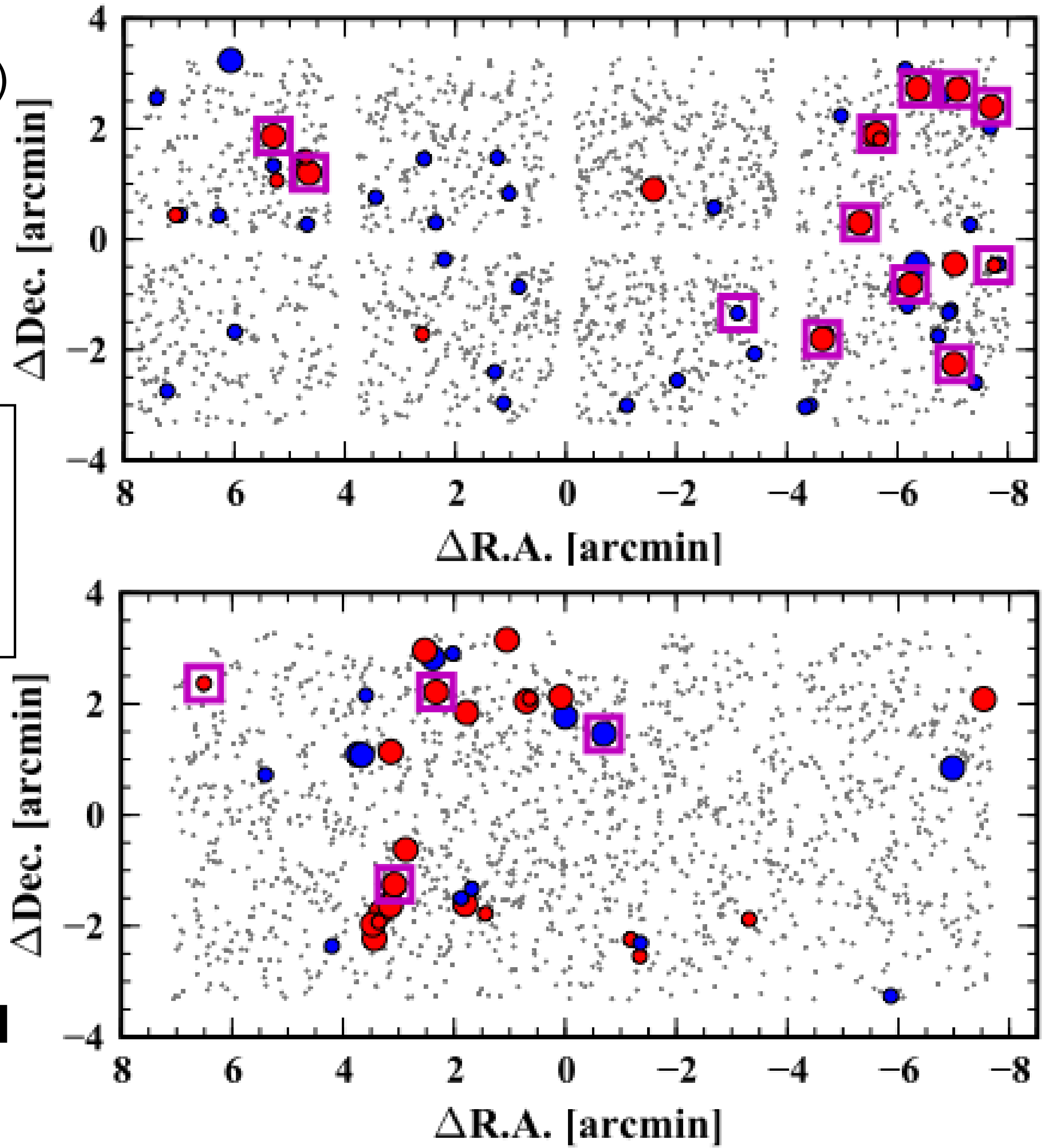
Tadaki+ (2013a), Suzuki+ (2015)

NB2095
Hα emitters at z=2.2
and [OIII] emitters at z=3.2

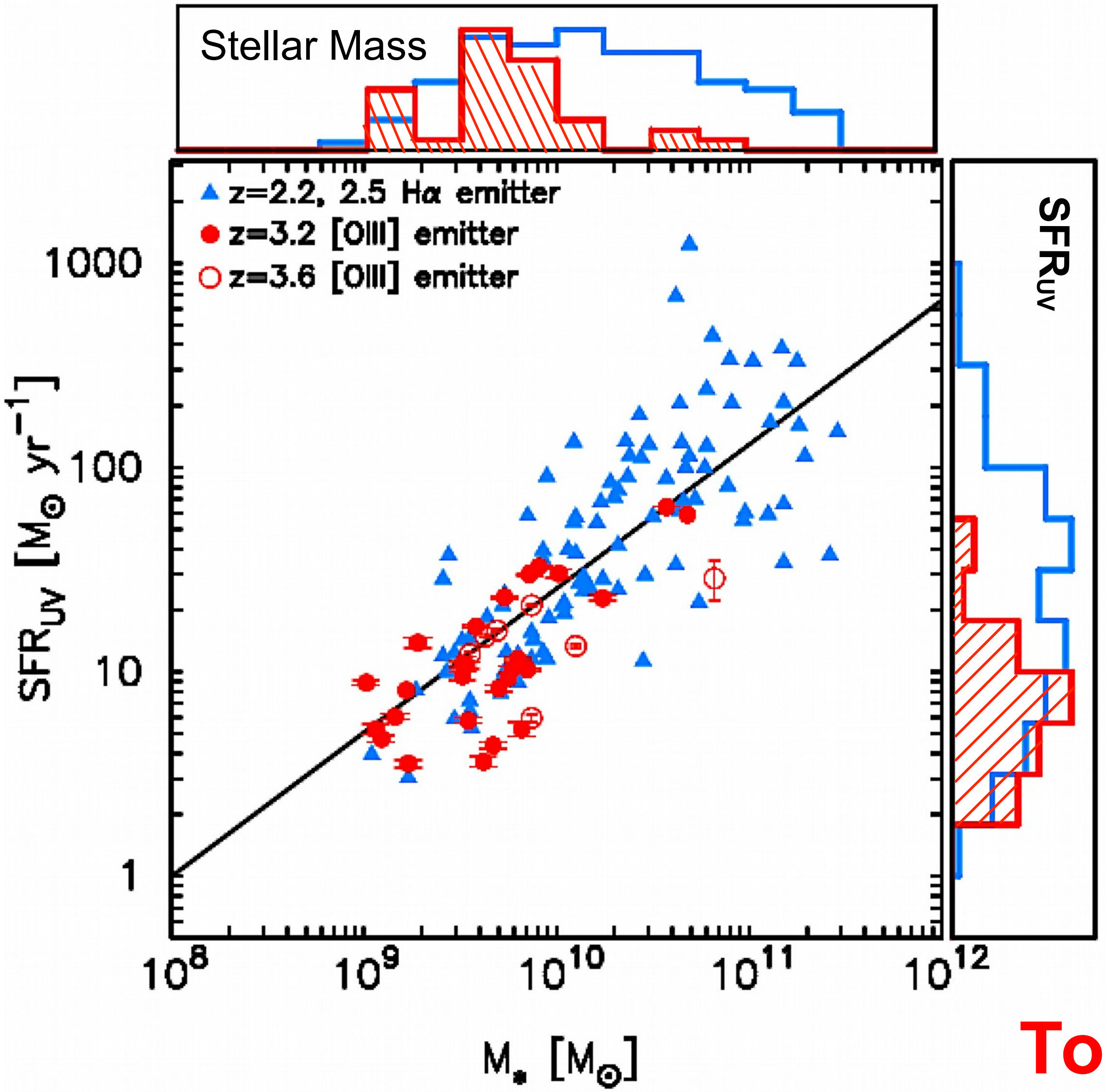
● : blue HAE (J-K<1)
● : red HAE (J-K>1)
□ : MIPS sources
(dusty star-bursting galaxies)

NB2315
Hα emitters at z=2.5
and [OIII] emitters at
z=3.6

MAHALO-Subaru (field sample)



Dramatic Evolution of SFGs along the MS within a Gyr from z~3.4 [OIII] emitters to z~2.3 Hα emitters in UDS (Field)



Evolution
or
Selection effect?

Suzuki+ (2015)

Poster #40
Tomoko Suzuki +

They follow the same main sequence (MS), but a significant offset along the MS.

GANBA-Subaru

Galaxy Anatomy with Narrow-Band AO imaging with Subaru

IRCS (FoV=1’) + AO188 + Narrow-band filters

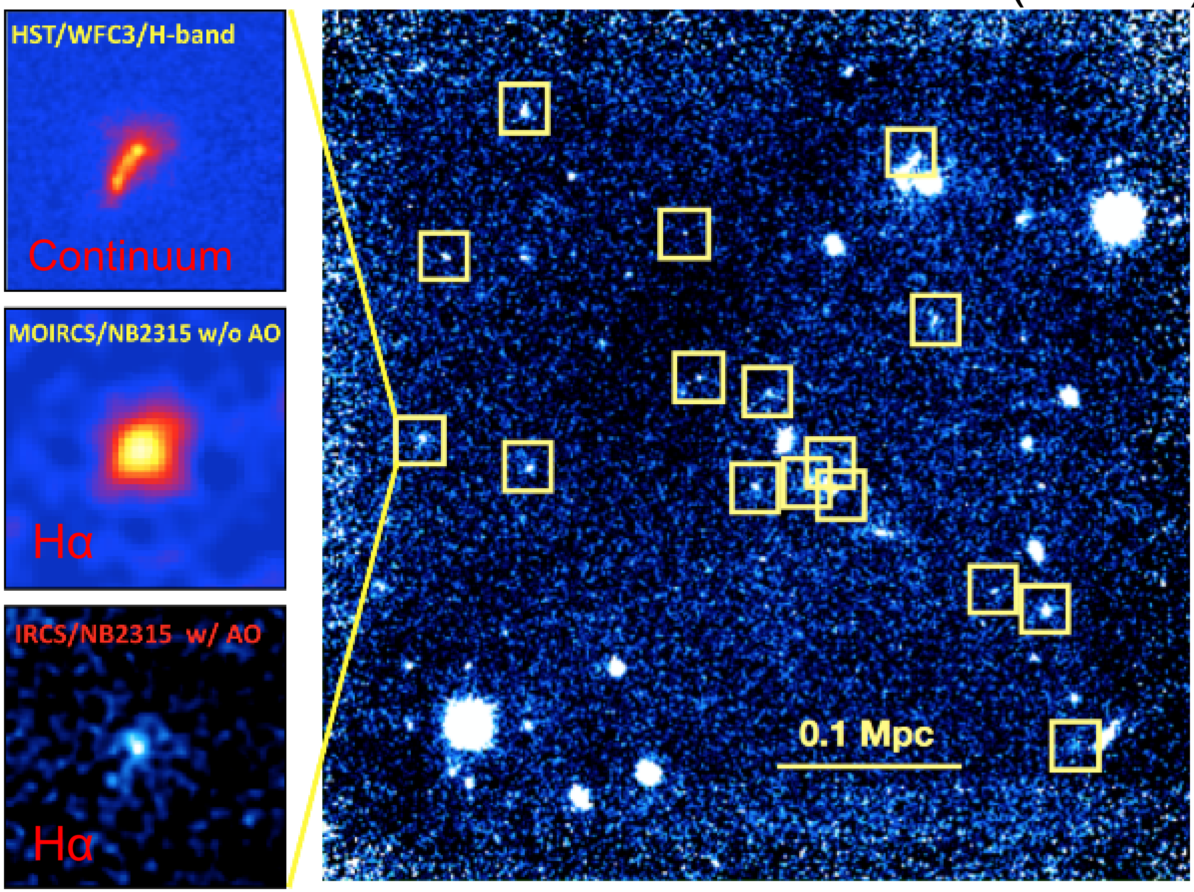
Any environmental dependence in internal structures (Ha map, clumpiness)?

Proto-cluster USS1558-003 (z=2.53)

HST/H-band
(0.16”)

MAHALO w/o AO
(seeing~0.5”)

GANBA w/ AO
(0.16” ~ 1.3 kpc)



IRCS
+NB2315
+AO188

FWHM=0.16”
FoV=1’ x 1’

Resolved star-forming clumps!

Suzuki et al., in prep.

GRACIAS-ALMA

Galaxy Resolved Anatomy with CO Interferometry And Submm observations with ALMA

Mapping/resolving molecular gas and dust contents of high-z SF galaxies at 1.5<z<2.5 across various environments

CO line @ Band-3 (~100GHz) SFR~50M$_\odot$/yr (~3hrs, 5σ)

Dust continuum@ Band-6-9 (450 μm–1.1 mm) SFR~15M$_\odot$/yr (~1hr, 5σ)

@1<z<3

Spatial resolution: 0.1-0.2” (~1kpc)

		Mahalo-Subaru				Gracias-ALMA		ALMA status	
target	z	line	μm	NB-filter	Camera	Continuum	Line@GHz(band)	proposals	results
2215–1738	1.46	[OII]	0.916	NB912	S-Cam	B7,9	CO(2-1)@94 (B3)	Hayashi	done (CO/dus
0332–2742	1.61	[OII]	0.973	NB973	S-Cam	B7,9	CO(2-1)@89 (B3)	not yet	
0218.3–0510	1.62	[OII]	0.977	NB973	S-Cam	B7,9	CO(2-1)@88 (B3)	not yet	
1138–262	2.16	Hα	2.071	NB2071	MCS	B6,7,9	CO(3-2)@110 (B3)	Koyama+	done (CO)
4C23.56	2.48	Hα	2.286	NB2288	MCS	B6,7,9	CO(3-2)@99 (B3)	Suzuki	done (CO/dust
1558–003	2.53	Hα	2.315	NB2315	MCS	B6,7,9	CO(3-2)@98 (B3)	Kodama+	done (CO)
SXDF	2.19	Hα	2.094	NB2095	MCS	B6,7,9	CO(3-2)@108 (B3)	Tadaki+	done
-CANDELS	2.53	Hα	2.315	NB2315	MCS	B6,7,9	CO(3-2)@98 (B3)	Tadaki+	(CO/dust)

f(gas) and SFE(=SFR/M$_{gas}$) are essential quantities to characterize the mode of SF.

Poster #34 Minju Lee +

Summary

- **MAHALO-Subaru** has revealed a rapid, inside-out quenching of galaxy clusters since z~2.5, and environmental dependence in mass and M-Z relation.
- **MAHALO-Deep** has revealed a new population of high-sSFR galaxies at the low mass end (~$10^9 M_\odot$).
- **MAHALO-Far** has sampled [OIII] emitters at z>3 which show the accelerated growth of SFGs along the MS towards the peak epoch z~2 by a factor of 2-10 !
- **GANBA-Subaru** and **GRACIAS-ALMA** are resolving internal structures of SFGs at z>2 and witnessing the physical processes of galaxy formation, depending also on environments.