Spatially resolved star formation of galaxies and its environmental dependence

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Outline

I. Our studies with Suprime-Cam, MOIRCS, and IRCS at the Subaru Telescope (MAHALO-Subaru and GANBA-Subaru projects)
II. Proposal of observations with ULTIMATE-Subaru
III. Answers to the questions to speakers

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

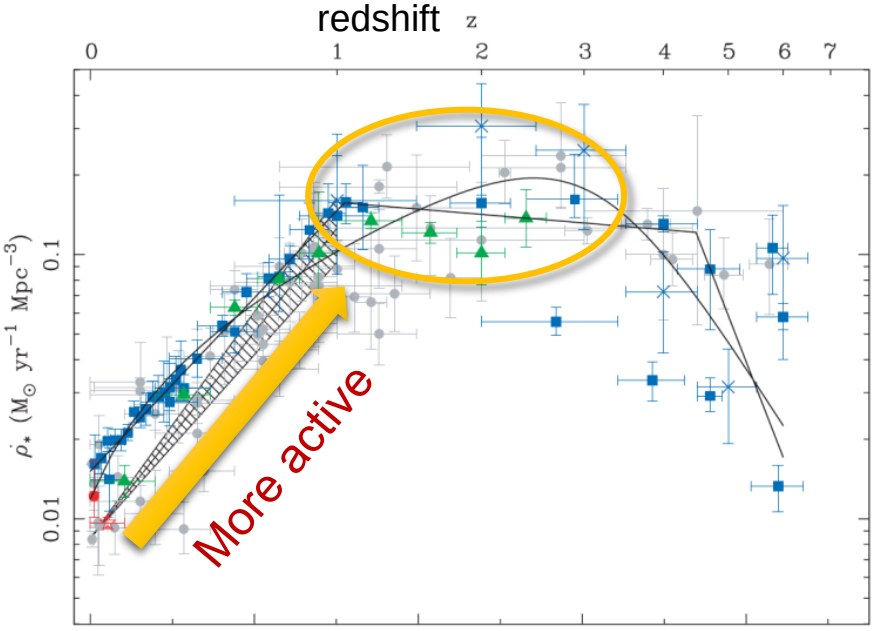
~20 nights for imaging, >15 nights for spectroscopy Kodama et al. (2013)

[core members] T. Kodama (PI), I. Tanaka, Y. Minowa, M. Hayashi, Y. Koyama, K. Tadaki, R. Shimakawa, T. Suzuki, M. Yamamoto

The critical epoch of formation of massive early-type galaxies: z=1.5-2.5

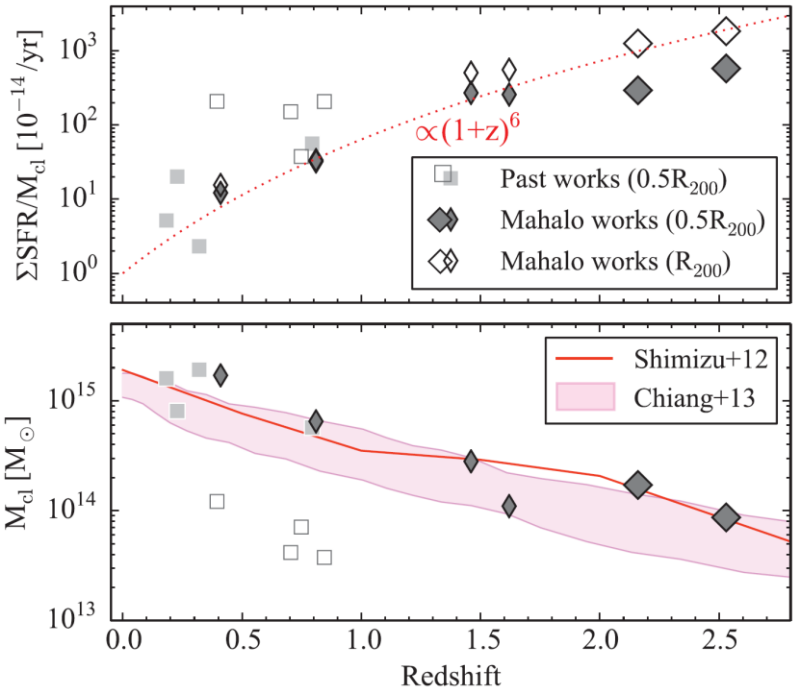
- Formation redshift of quiescent galaxies in clusters is z~3-4 (Tanaka+13)
- Appearance of massive red-sequence galaxies at z~ 2-3 (Kodama+07)

Cosmic star formation rate density



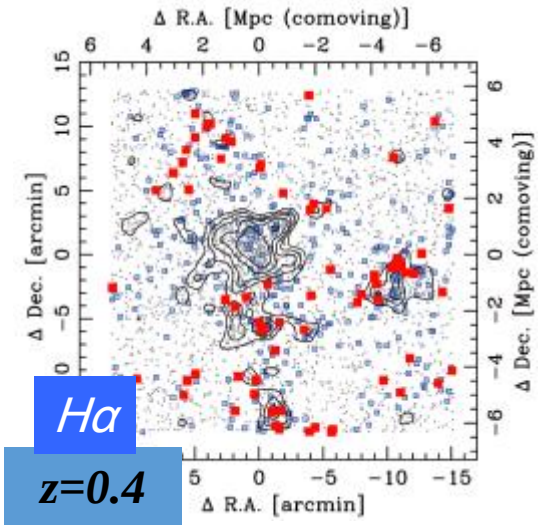
Hopkins & Beacom 2006

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



Shimakawa et al. (2014b)

High-z structures revealed by MAHALO

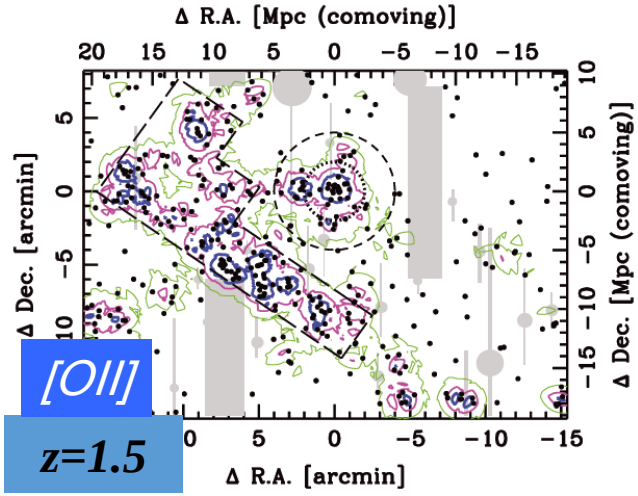


Hα

z=0.4

CL0939(*Koyama+11*)

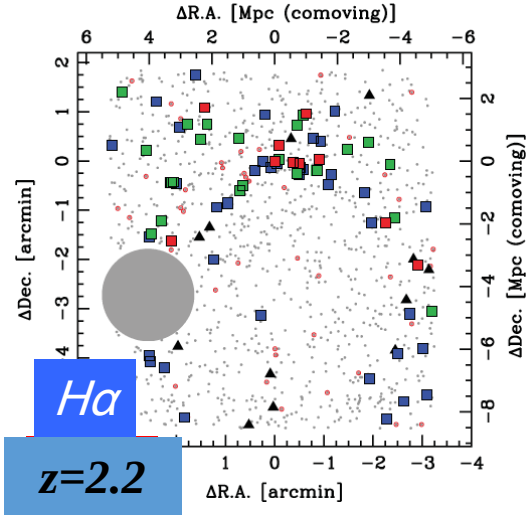
(Hayashi+10, 11)



[OII]

z=1.5

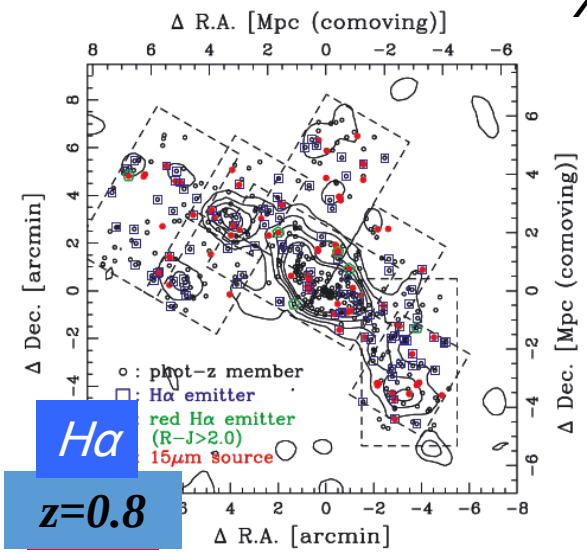
XCSJ2215 *(Tadaki+12)*



Hα

z=2.2

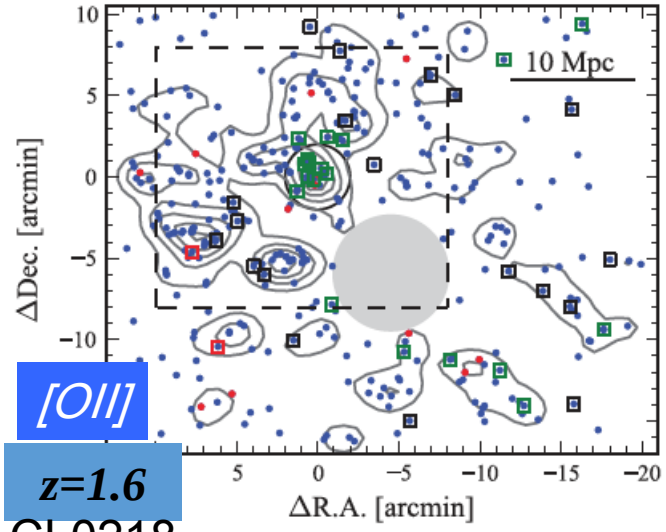
PKS1138 *(Koyama+13)*



Hα

z=0.8

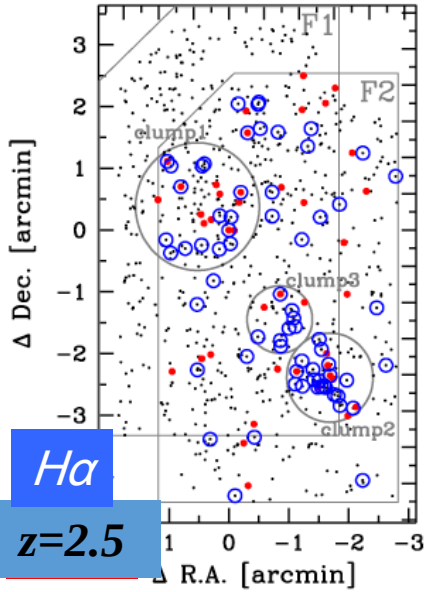
RXJ1716(*Koyama+10*)



[OII]

z=1.6

CL0218



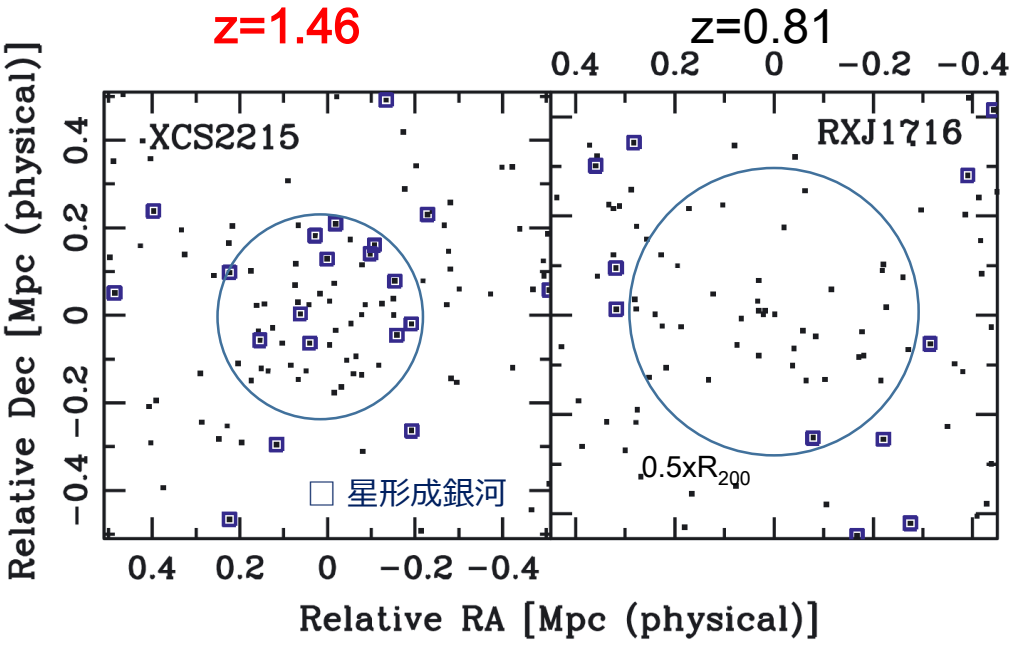
Hα

z=2.5

USS1558 *(Hayashi+12)*

Active star formation in the center of high-z galaxy clusters at z>1.5

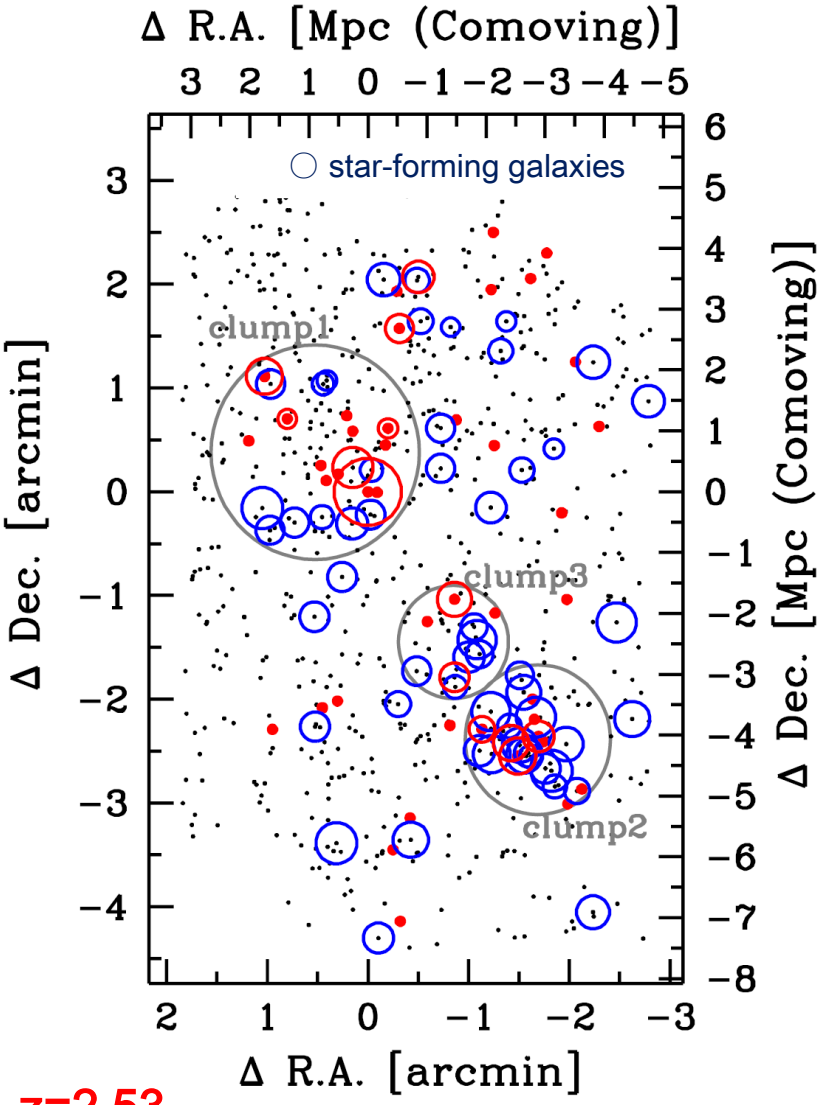
NB imaging with Subaru/Suprime-Cam, MOIRCS



Hayashi+2010

- There are a lot of star-forming galaxies in the center of galaxy (proto-)clusters at z>1.5
- No strong environmental dependence of star formation activity

We are witnessing the high-z star-forming galaxies that will grow to be massive early-type galaxies in galaxy clusters



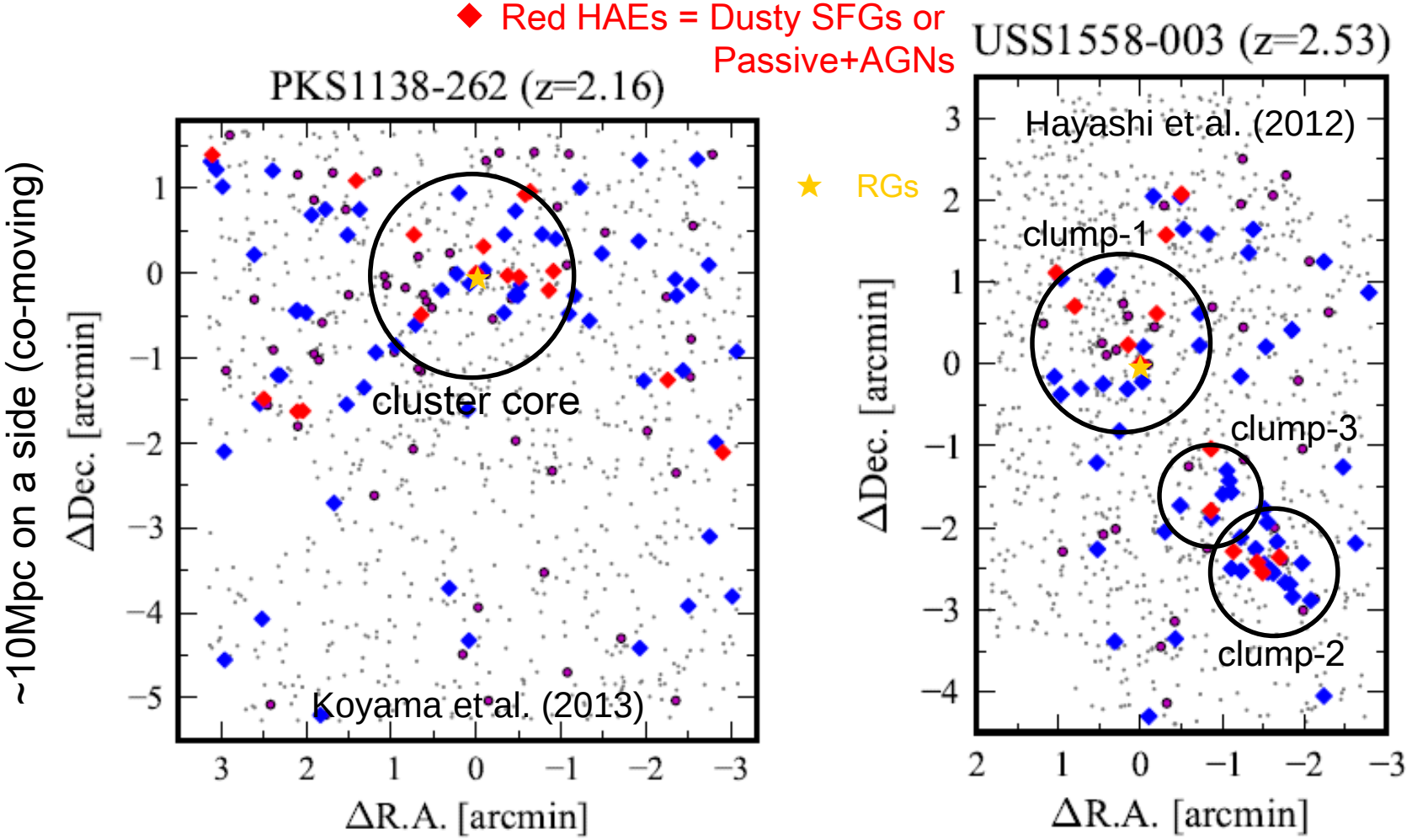
z=2.53

Hayashi+2012

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

◆ Blue HAEs = Normal SFGs

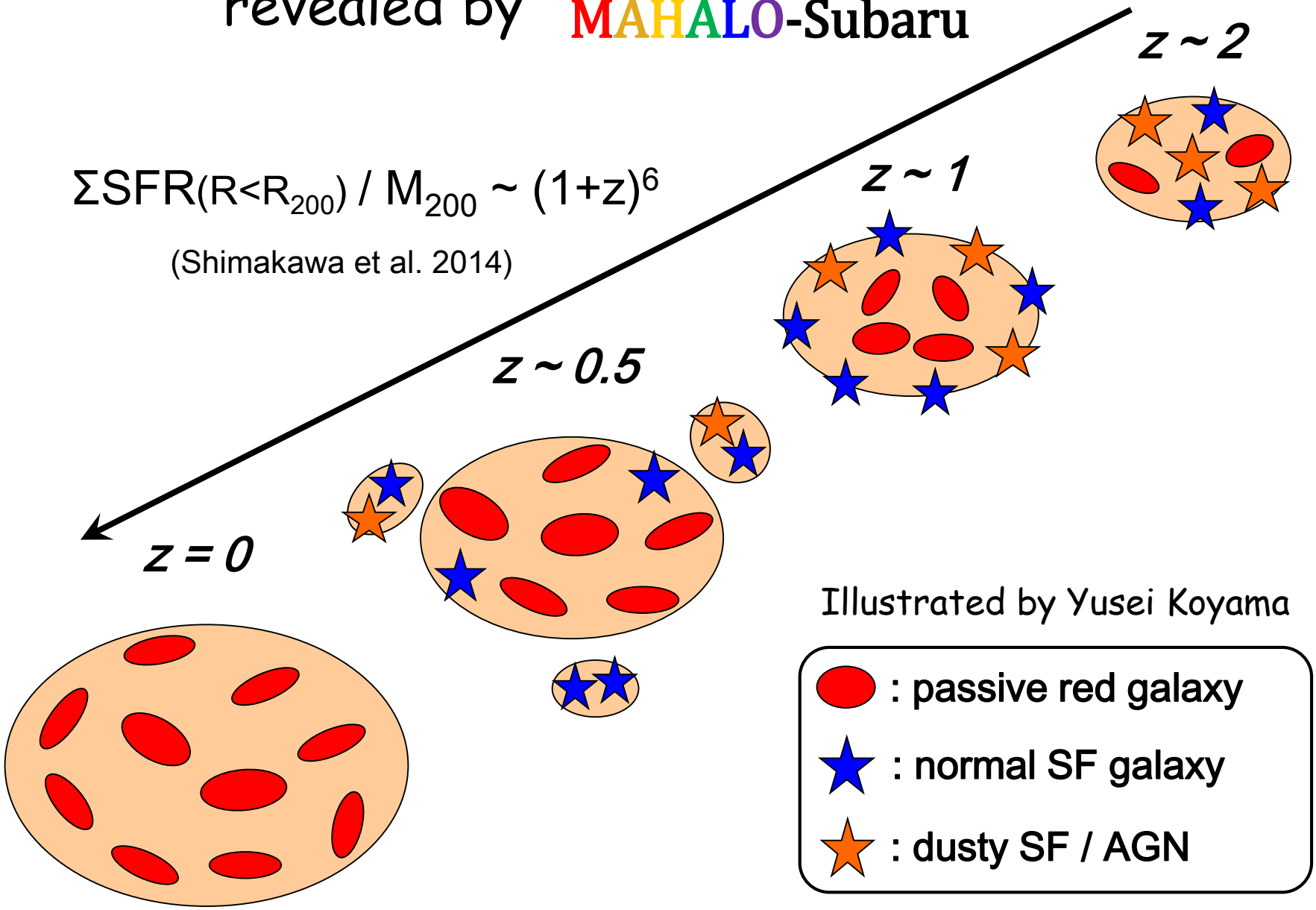
◆ Red HAEs = Dusty SFGs or Passive+AGNs



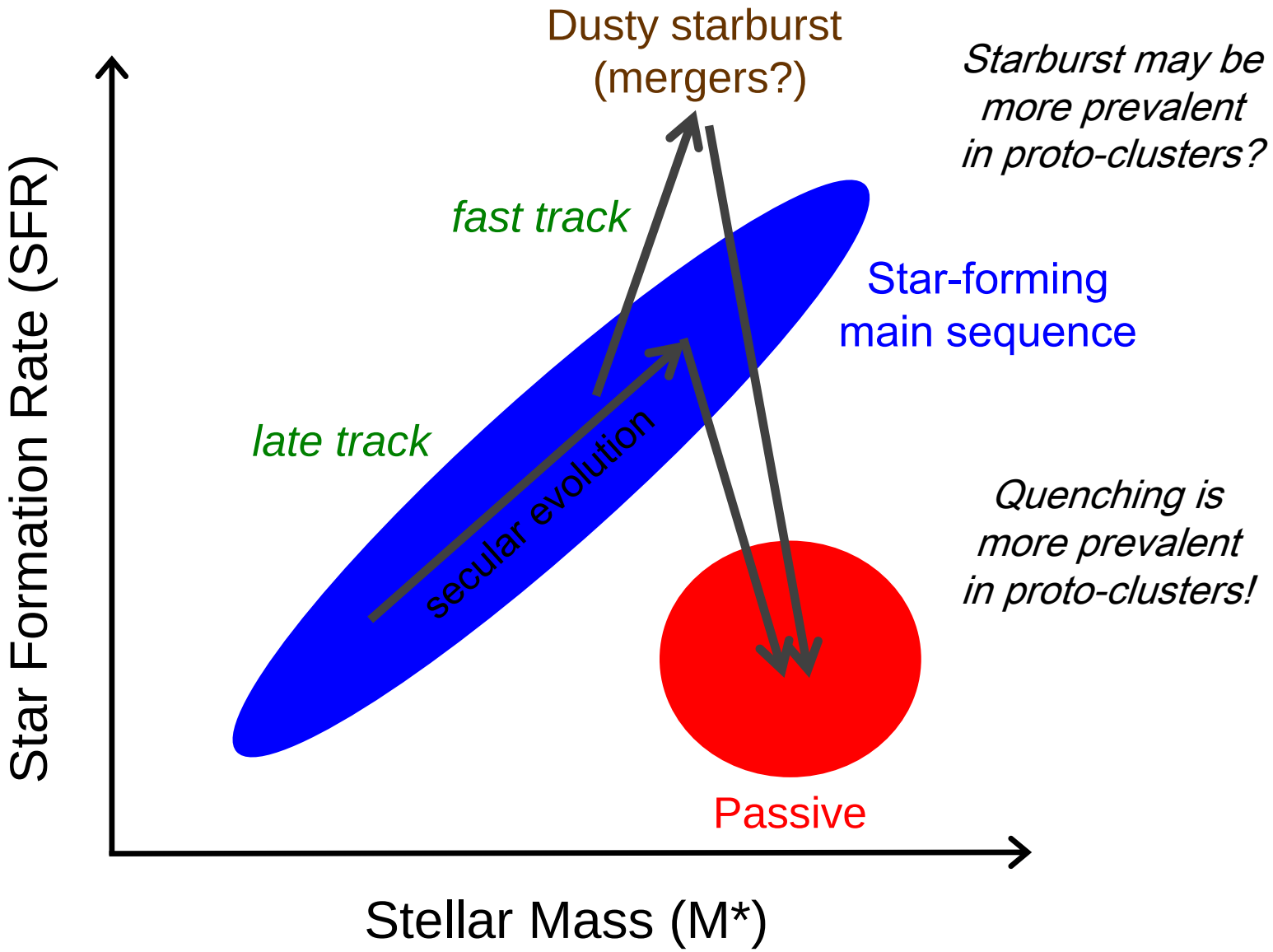
Lots of HAEs live in proto-cluster cores, indicating strong SF activities there.

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

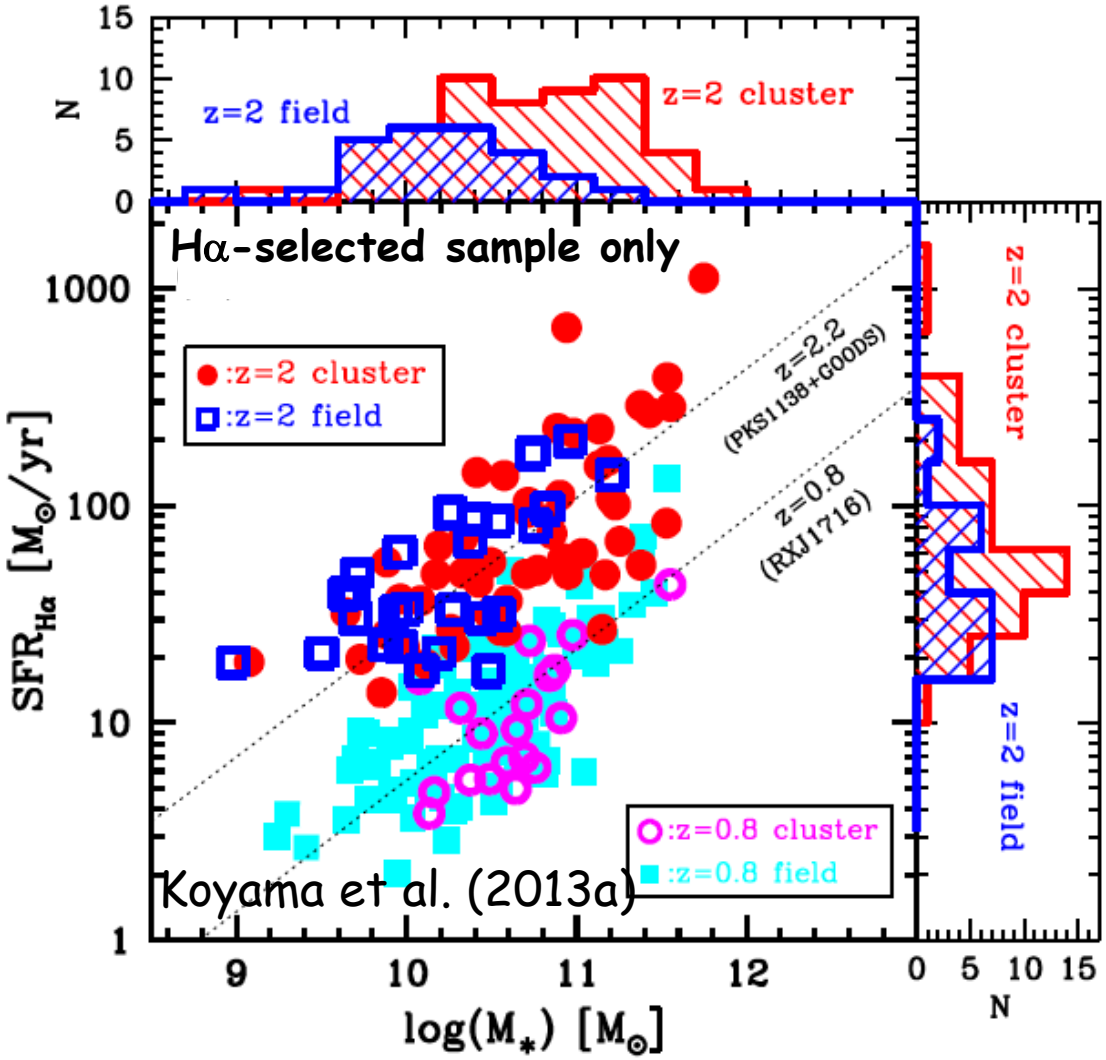
Inside-out growth of galaxy clusters revealed by MAHALO-Subaru



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



Environmental dependence of the Star-Forming Main-Sequence?



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

No environmental dependence in the location of the main sequence.

But cluster galaxies tend to be more massive.

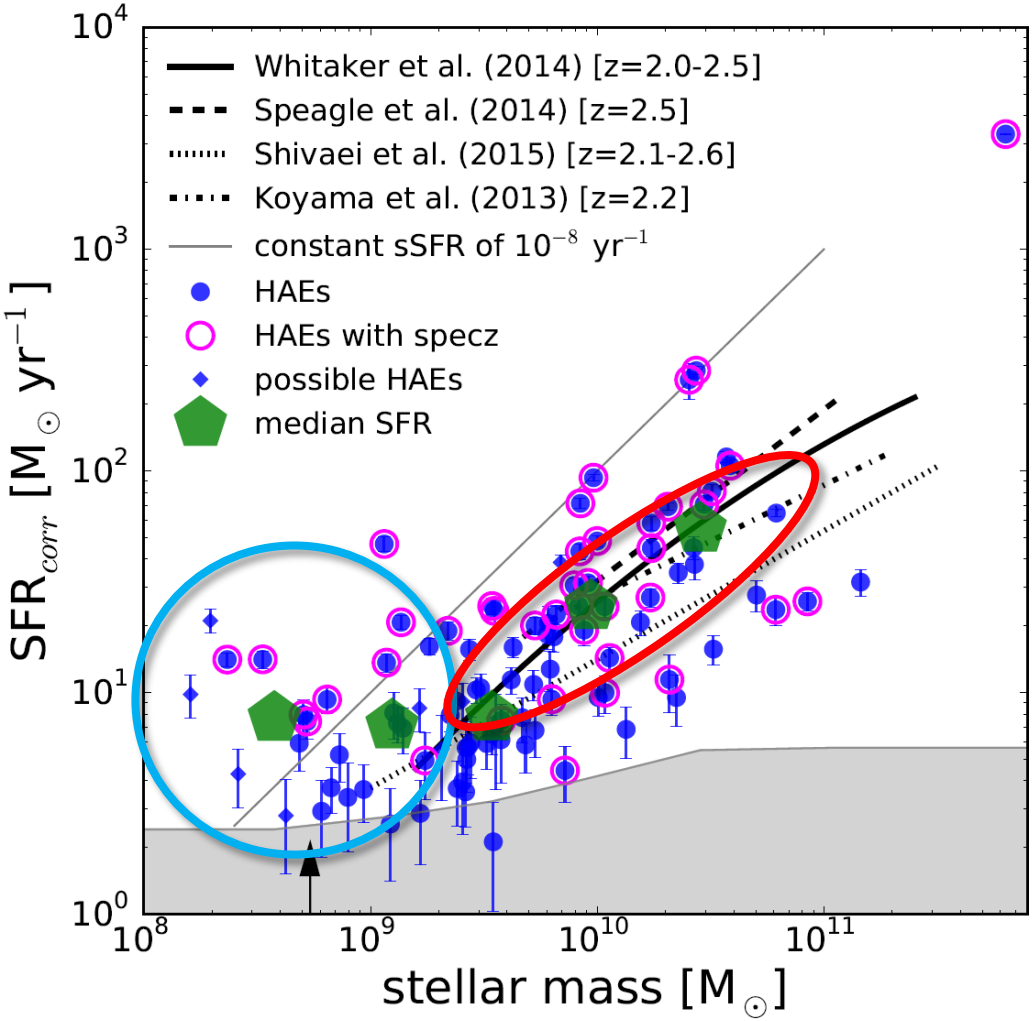
Scatter analysis is hard due to short timescale and uncertain dust correction.

→ *Great statistics and accurate dust correction are the keys.*

Alternatively, see the dusty starburst populations directly!

Enhanced star formation of less massive galaxies in a proto-cluster at z=2.5

Deep NB imaging with Subaru/MOIRCS: ~10 hours integration



Hayashi et al. submitted

At $M^*>10^{9.5}$ M_{sun}, star forming galaxies are on the universal main sequence irrespective of the environment.

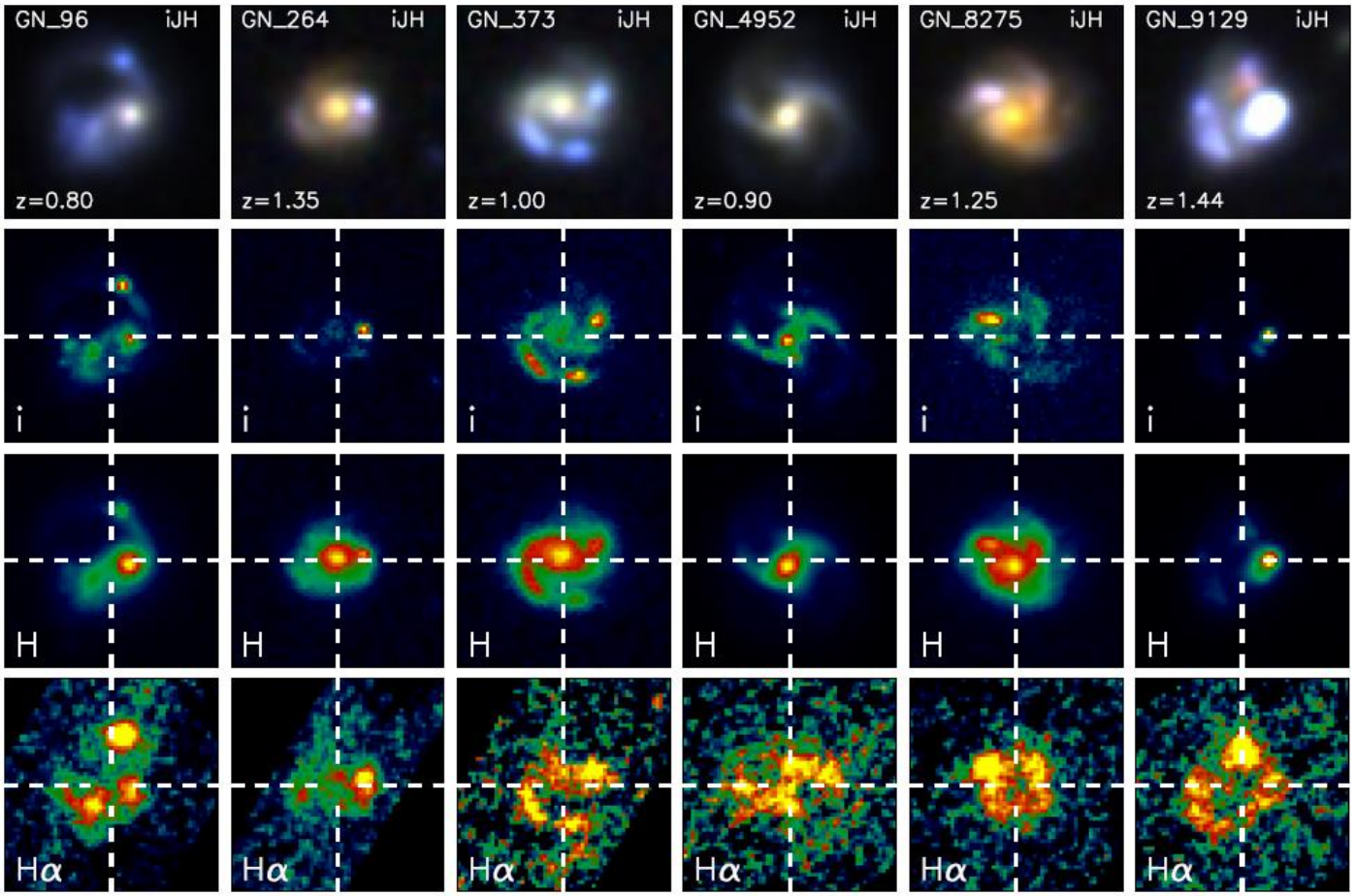
At $M^*<10^{9.0}$ M_{sun}, star forming galaxies in a proto-cluster at z=2.5 show a significant upward scatter from the main sequence.

Deep imaging is important. In addition, to better understand galaxy evolution, we have to reveal where the star-formation is occurred within a galaxy.

How does the internal structures of galaxy form?

Key is to spatially resolve individual galaxies at kpc scale.

- Distribution of star formation regions and stellar component
- Spatially resolved specific star formation



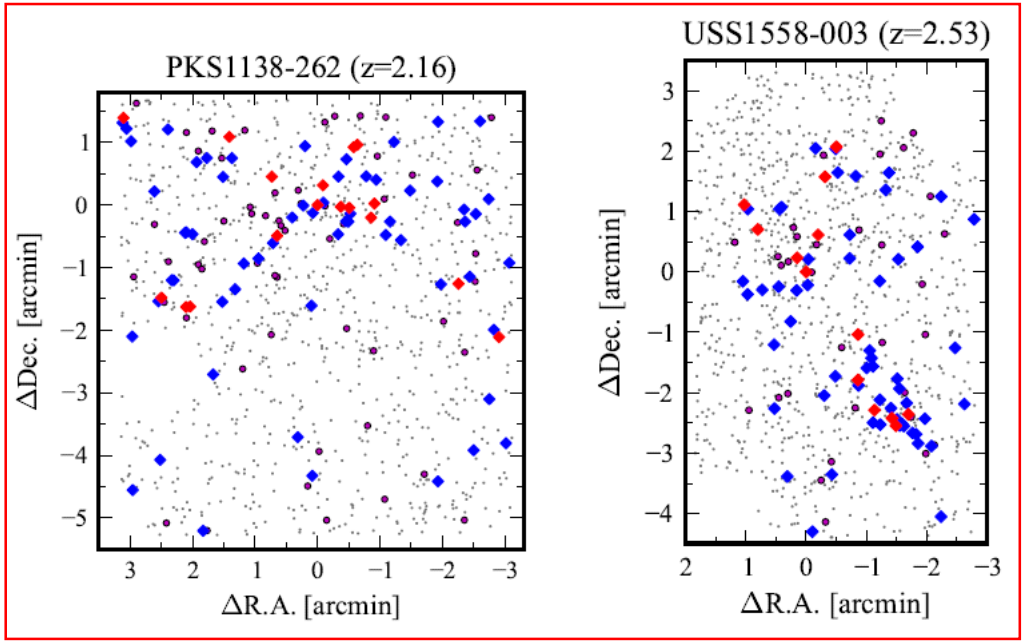
3D-HST survey Wuyts et al. (2013)

Proposal of observations with ULTIMATE-Subaru

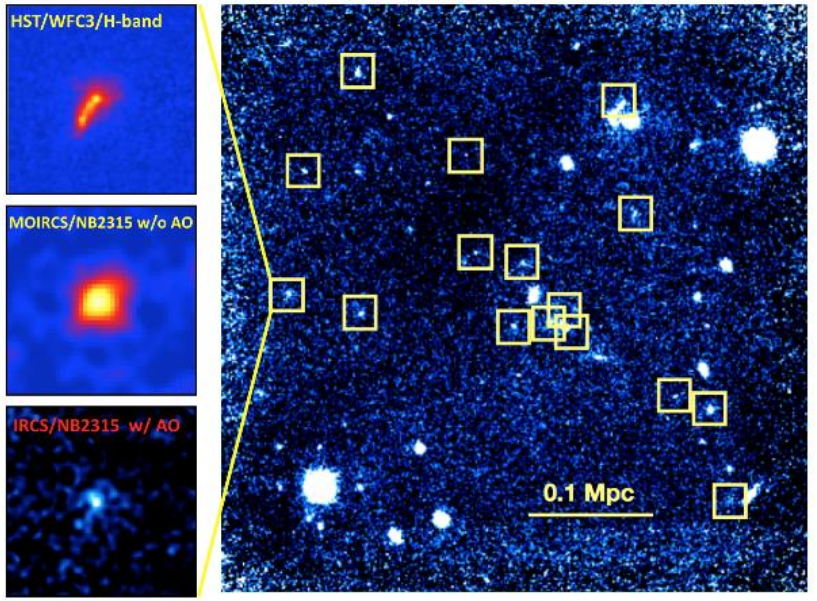
Proposal: Wide-field NB imaging with ULTIMATE-Subaru

We can reveal simultaneously
- the large-scale structures
- spatially resolved star formation in individual galaxies

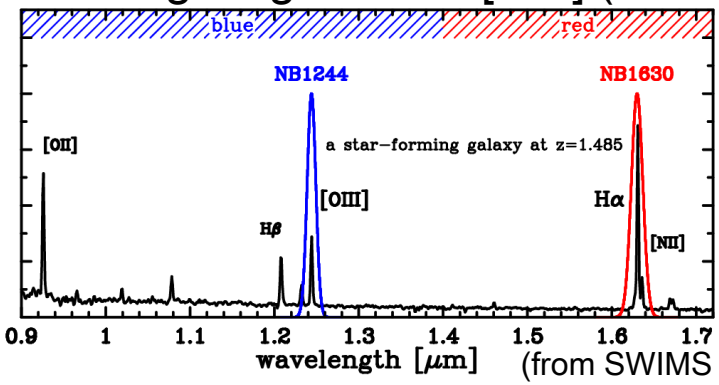
wide field of view



high spatial resolution



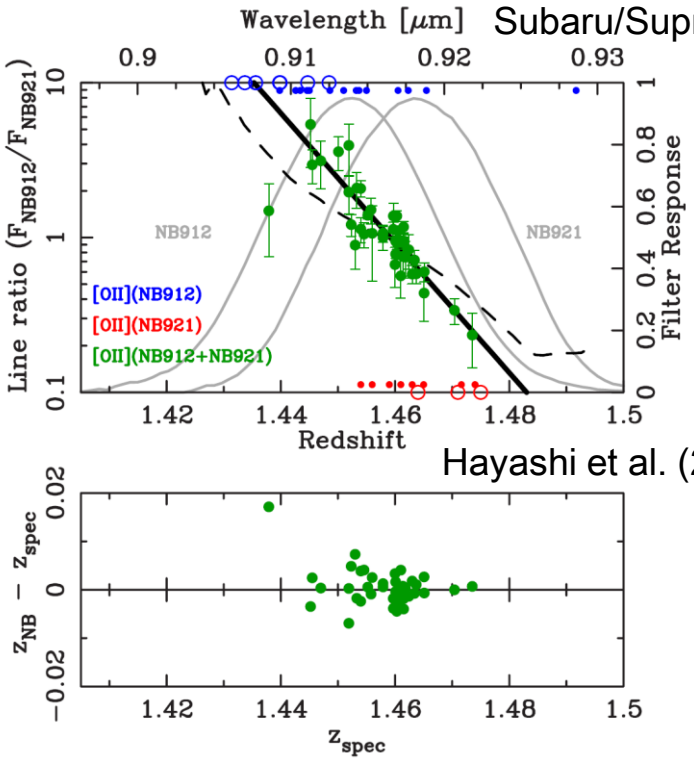
Pair filters targeting Hα and [OIII] (or Hα and Hβ)



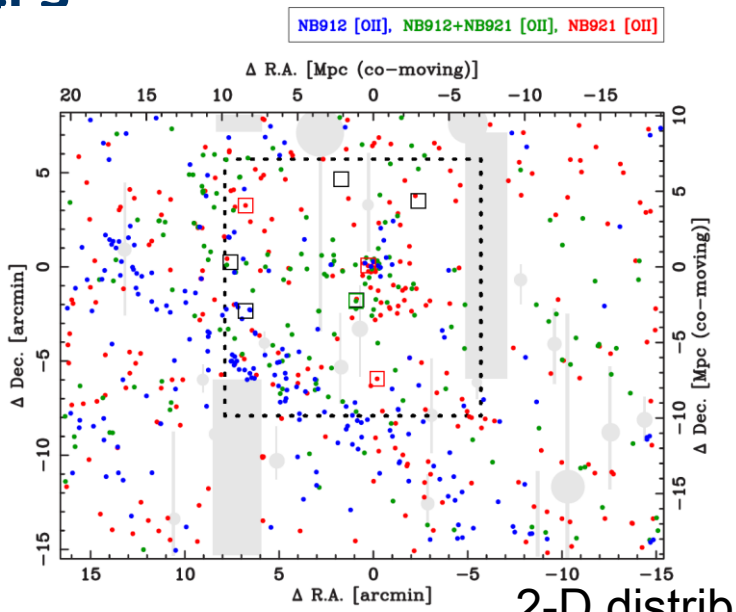
(from SWIMS filters)

Proposal: Two adjacent NB filters

Subaru/Suprime-Cam

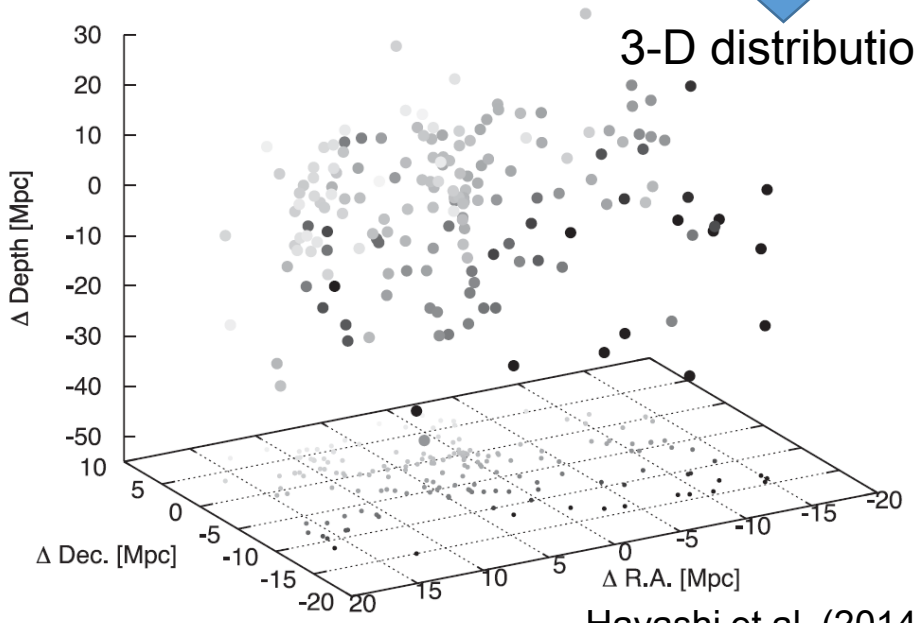


Hayashi et al. (2014)



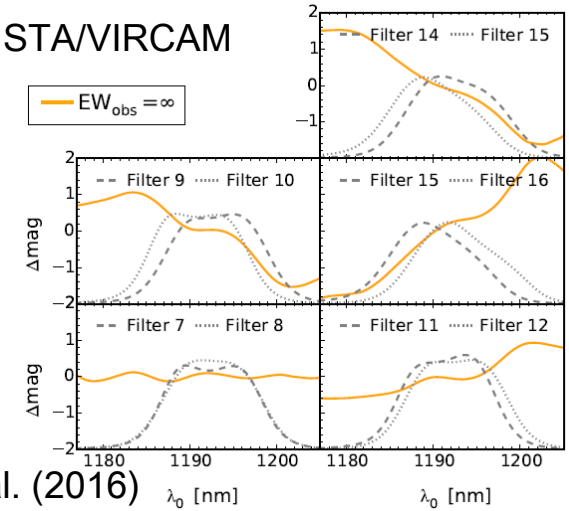
2-D distribution

3-D distribution



Hayashi et al. (2014)

VISTA/VIRCAM



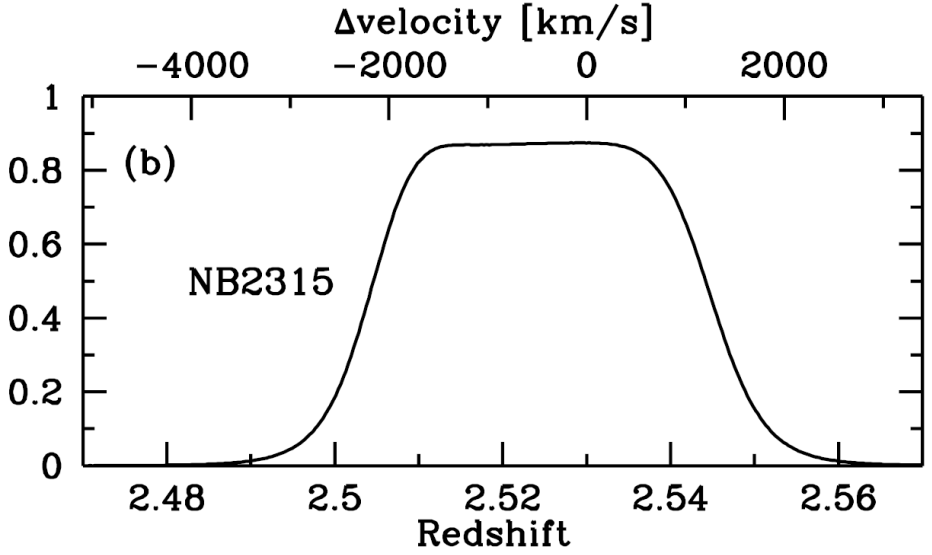
Zabl et al. (2016)

Proposal: Tunable filter is worth considering

- Pair NB filters
- Two adjacent NB filters
- Redshift distribution of high-z galaxy clusters

Even if we focus on galaxy (proto-)clusters at z~2.5, we cannot observe all of them with single NB filter

FWHM of NB => Δz~0.02-0.03



z=2.44 Lee+2016 (IGM)
z=2.45 Diener+2015 (zCOSMOS)
z=2.47 Casey+2015 (SCUBA-2)
z=2.49 Cooke+2014 (HzRG)
z=2.506 Wang+2016 (DRGs)
z=2.53 Hayashi+2012 (HzRG)

The increasing number of galaxy clusters at z>2 are found recently.


Questions to speakers
ULTIMATE-Subaru Working Group
SUBARU TELESCOPE
National Astronomical Observatory of Japan

Answers to the questions to speakers (1/3)

Q1: What do you think is the "KEY" science/observations for ULTIMATE in your research field? We hope to establish the very best science cases which are unique enough even in mid-late 2020s (i.e. post-JWST or WFIRST era!).

- Observations with a unique set of narrow-band filters
- Large-scale structures (i.e, environments) thanks to the wide field of view
- Spatial revolved SF and stellar components in K-band thanks to the high spatial resolution
- Galaxies at z=2.0-2.5 (Hα from these galaxies enters K-band)

Q2: Which instrument (WFC/MOS/IFU) do you think is 1st priority for ULTIMATE? We currently consider the wide-field imager (WFC) is 1st priority, but we want to have your opinion.

- Agree that the WFC is 1st priority.

Answers to the questions to speakers (2/3)

Q3: Our current plan is to (1) build GLAO first, and then to (2) build new NIR instrument(s). This means that we will start our ULTIMATE science with GLAO +MOIRCS at the first stage. Do you have good science cases to be done with GLAO+MOIRCS during the period of ~2020-2023?

- Since we have investigated the large-scale structures around proto-clusters and the SF activity there with MOIRCS, of course, we can develop the studies with GLAO+MOIRCS.

Q4: Which survey design sounds best for you (see *survey_design.pdf*)? Your comments/suggestions on the ULTIMATE survey design are very welcome.

(A) BB+MB+NB imaging survey over 2-deg^2

(B) "NB-only" survey over 2-deg^2

(C) "K-only" survey over ~20-deg^2

(D) MOS spectroscopic survey

(E) Multi-IFU spectroscopic survey

Answers to the questions to speakers (3/3)

Q5: For those who are interested in wide-field imager (WFC) : Are there any special requirements for the instrument specification (FoV, pixel scale, N. of NB filters)? Please note that FoV and pixel scale are trade-off (i.e. pix scale gets larger if we choose wider FoV).

WFC covers ~14'x14' FoV with ~0.1" pixel scale

- This current plan is acceptable.
- 14 arcmin => 21 co-moving Mpc @ z=2,
- 0.2 arcsec resolution => 1.7 physical kpc @ z=2

Q6: Also, are you interested in tunable filter on WFC if technically feasible? With tunable filter we can flexibly change central wavelength of the filter, but the tunable filter is expected to be ~25% less sensitive than NBs.

- Yes, but the conclusion may depend on the actual sensitivity and total throughput.
- To do the studies with two adjacent filters and/or pair filters, the shape of the transmission curve is also important. I'm concerned about how accurately the shape of the transmission curve can be produced.

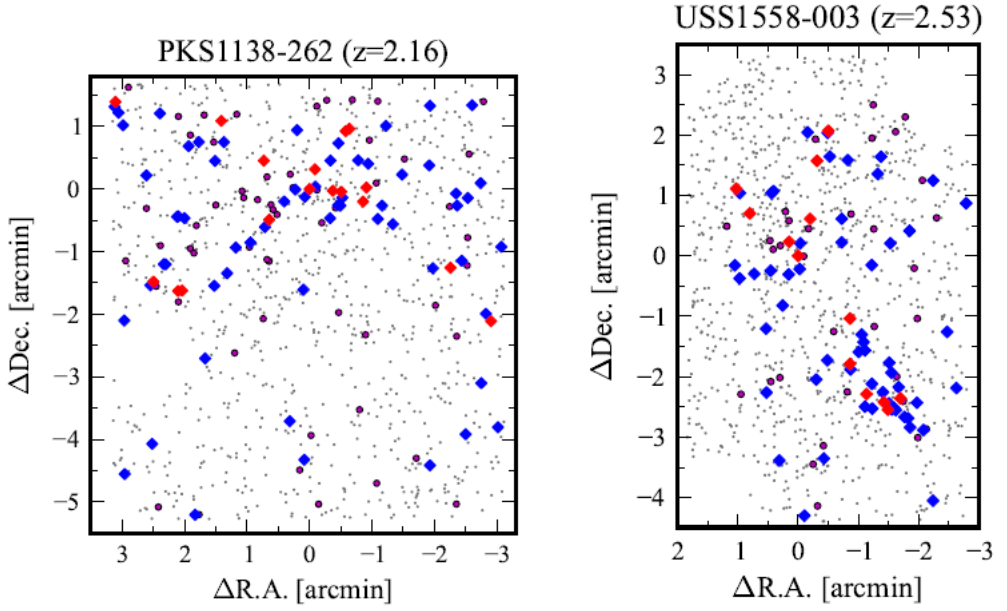
Summary of our proposal

- Wide field imager
- Pair NB filters or tunable filter

We can reveal **simultaneously**

- the large-scale structures of SF galaxies with Hα emission
- spatially resolved star formation in individual galaxies

wide field of view



high spatial resolution