Panoramas of the Evolving Cosmos (Hiroshima; 2016/11/29)

Panoramic Mapping of Star Formation Activities across Environments since z~3

Taddy Kodama (NAOJ)

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Moegi Yamamoto (NAOJ/Sokendai), Minju Lee (NAOJ/U.Tokyo),

and Mahalo-Subaru, Ganba-Subaru, Gracias-ALMA teams

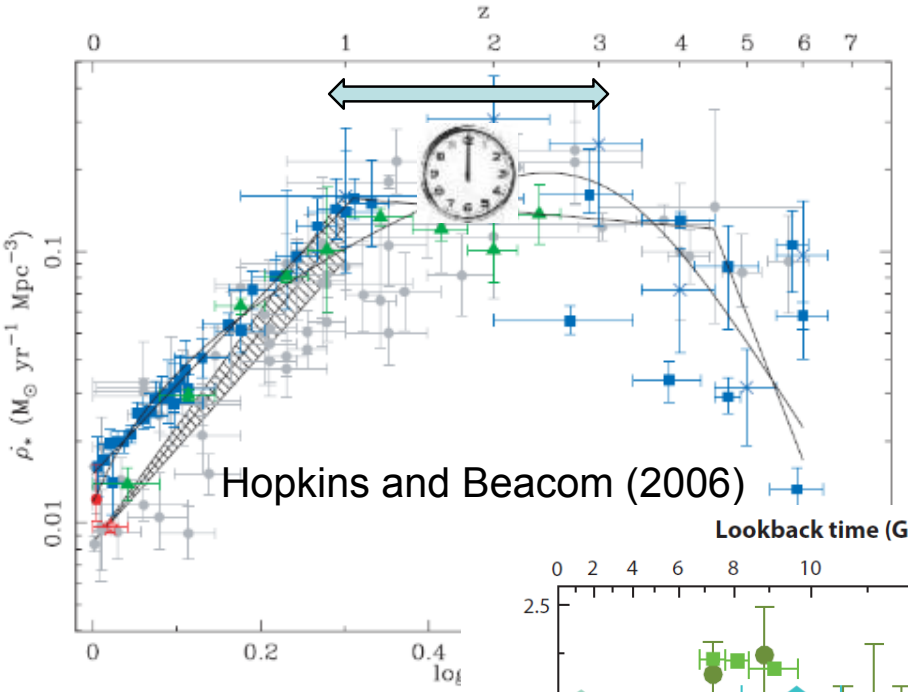
A galaxy cluster RXJ0152 at z=0.83 (Subaru/Suprime-Cam)

Outline

- **MAHALO**: Mapping star formation in clusters/fields at 0.4<z<3.6 with narrow-band imaging (Ha, [OII]) with Subaru
- **MAHALO−DEEP**: Towards lower masses (<$10^{9.5}M_{\odot}$)
- **MAHALO−LYA**: Environmental dependence of Lya emissivity from Ha emitters.
- MAHALO−FAR: Towards higher redshifts (3<z<3.6) with [OIII]
- **MAHALO−SHARP**: Towards higher spatial resolution (<0.2") with AO imaging and ALMA

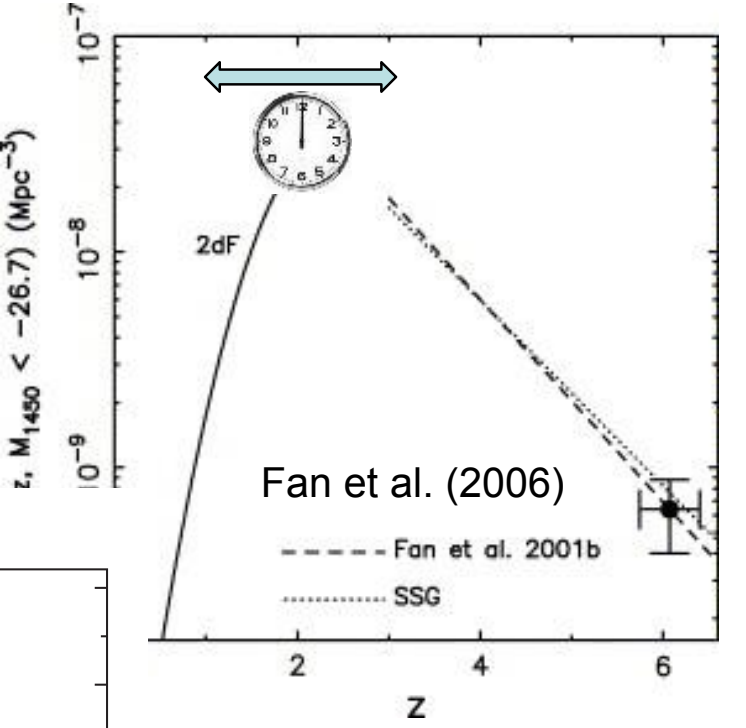
GANBA−Subaru
GRACIAS−ALMA

Why 1<z<3 ? and Why Ha and [OIII] ?



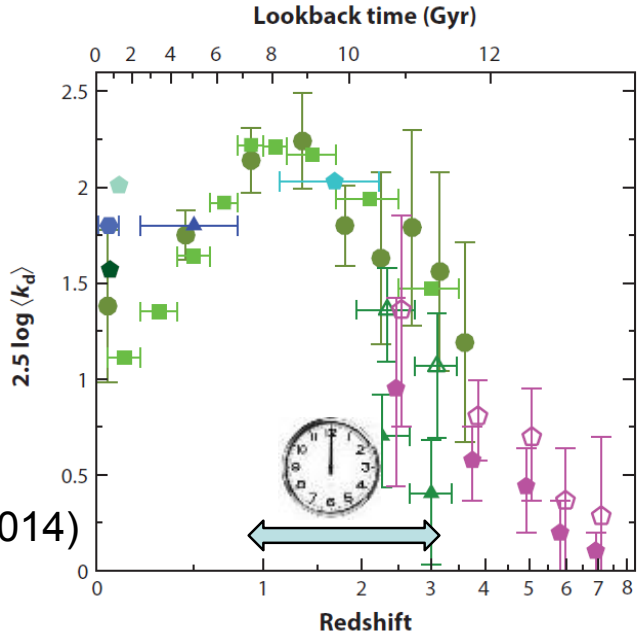
Hopkins and Beacom (2006)

Star formation



Fan et al. (2006)

BH accretion (AGN/QSO)



Madau & Dickinson (2014)

"Largely hidden by dust!"

Dust extinction

Rest-UV is NOT a good tracer of SF in this critical era → Go for Ha and [OIII] at NIR!

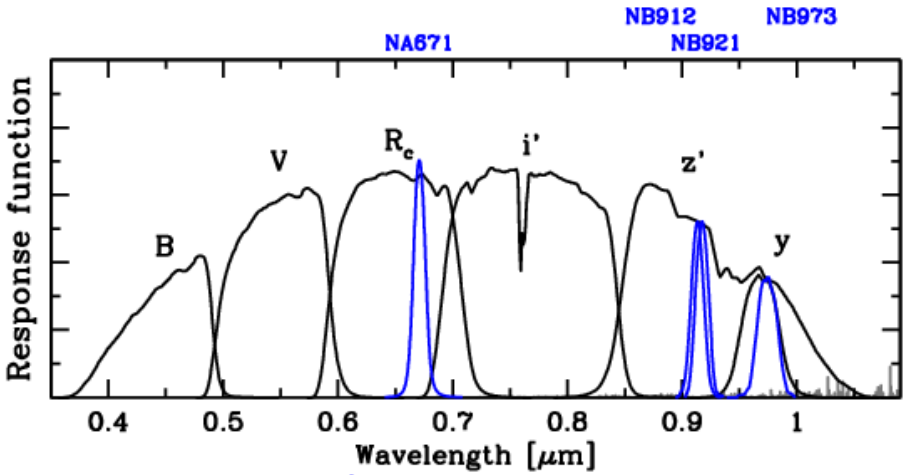
MAHALO-Subaru

MApping **HA**lpha and **L**ines of **O**xygen with Subaru

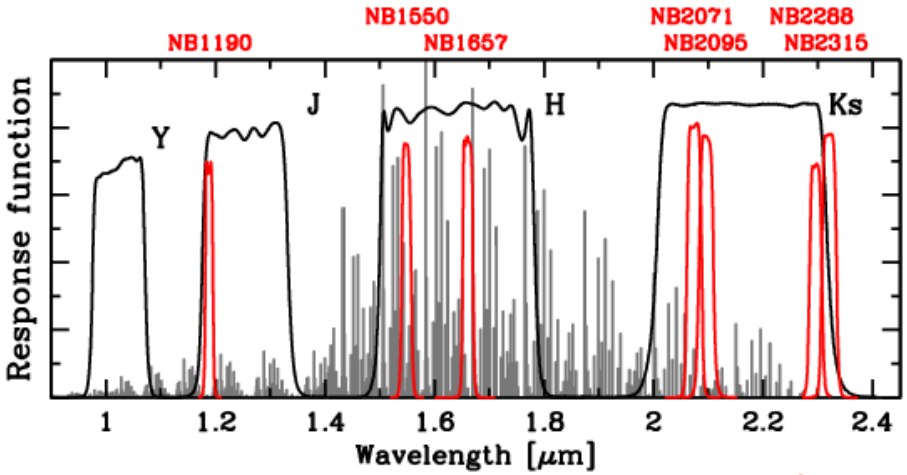
(PI: Kodama, T.)

Wide-Field Survey of Line Emitters ([OII], [OIII], Ha) of
14 known clusters at 0.4<z<3.6 and major general fields (CANDELS)

Suprime-Cam (optical; 34′x27′)



MOIRCS (NIR; 7′x4′)



4 narrow-band filters FWHMs correspond to ±1500-2000km/s 7 narrow-band filters

Advantages of NB-selected SFGs

1. Nearly a complete sample of SFGs down to a certain line flux limit. (no pre-selection)
2. Redshifts are accurately known only with imaging (the same within a narrow slice).
3. Lower dust extinction compared to UV-selected SFGs such as LBGs.
4. Known redshifts/line fluxes deserve excellent targets for follow-up observations, such as NIR spectroscopy and ALMA line observations.

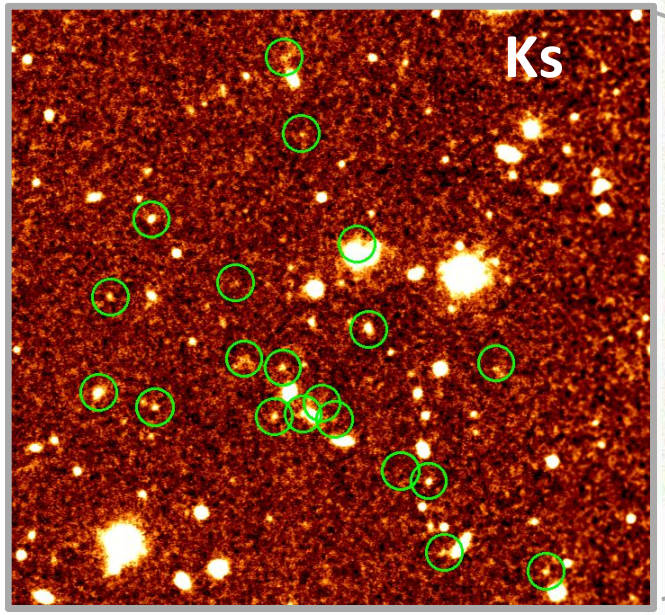
The most prominent star-bursting proto-cluster at z~2.5

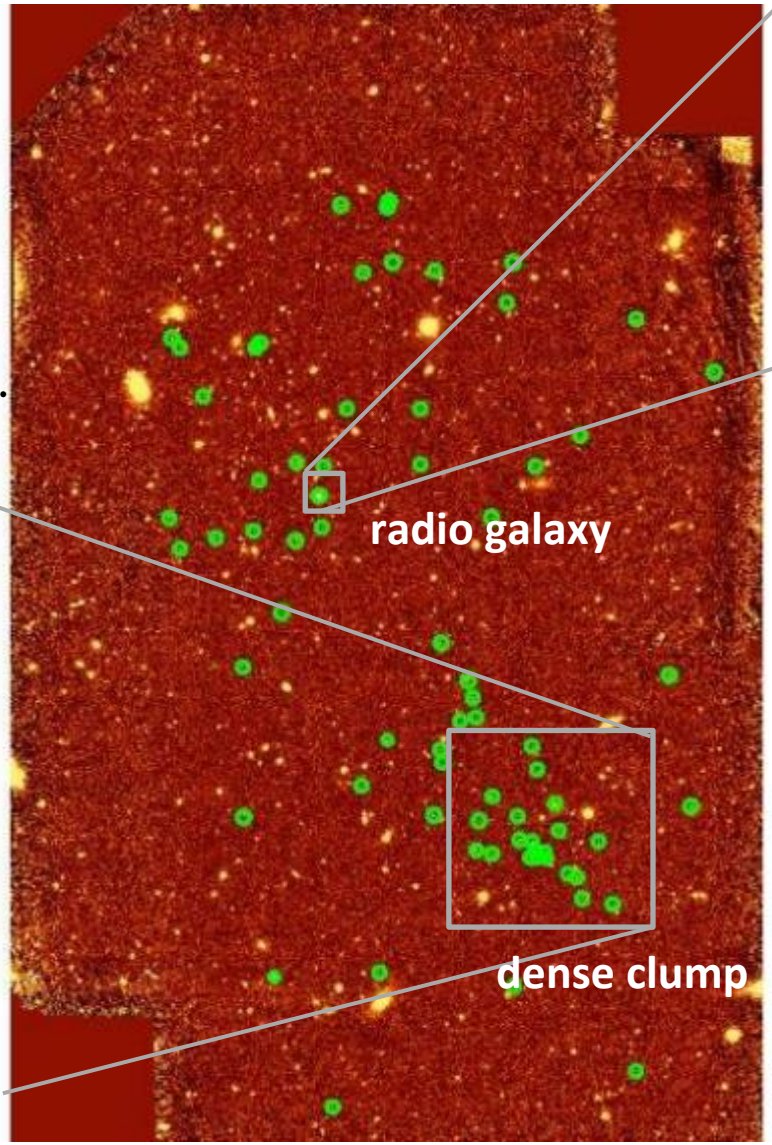
USS1558-003 (z=2.53)

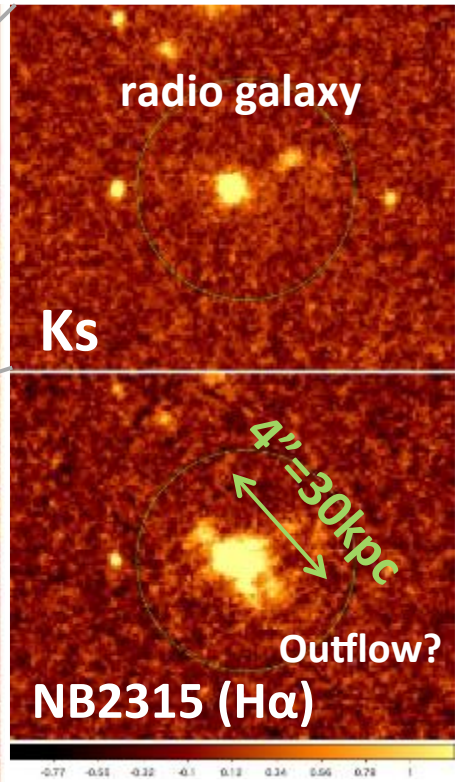
Ha imaging
with MOIRCS/NB2315

FoV=4' x 7'

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







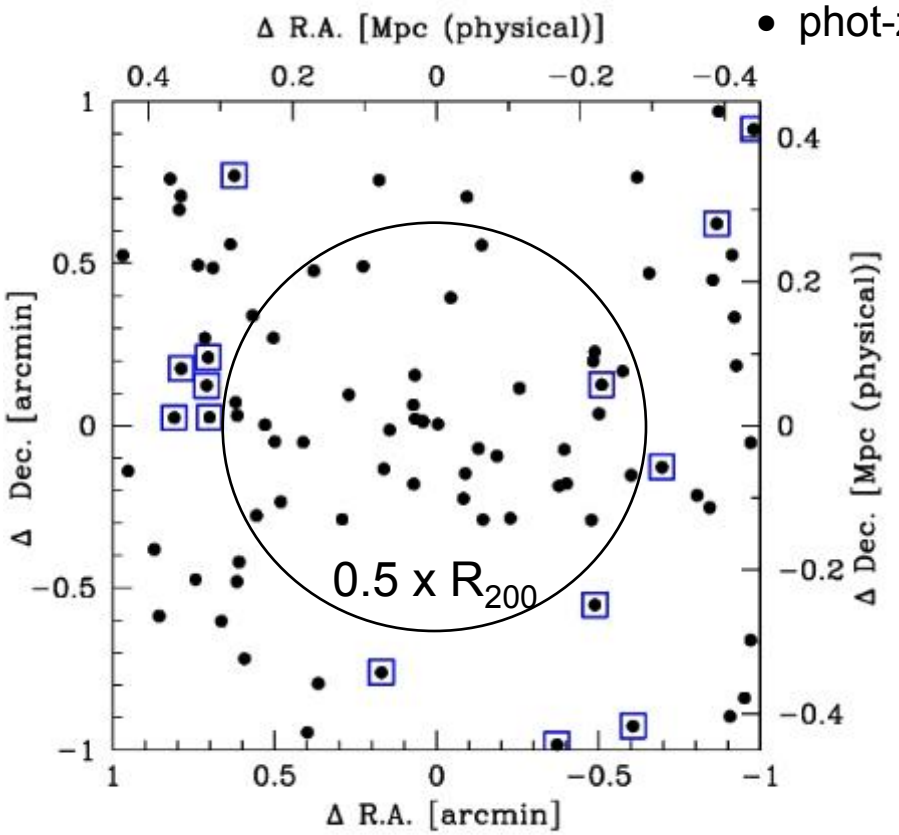
1.5Mpc away
from the RG

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

Hayashi et al. (2012)

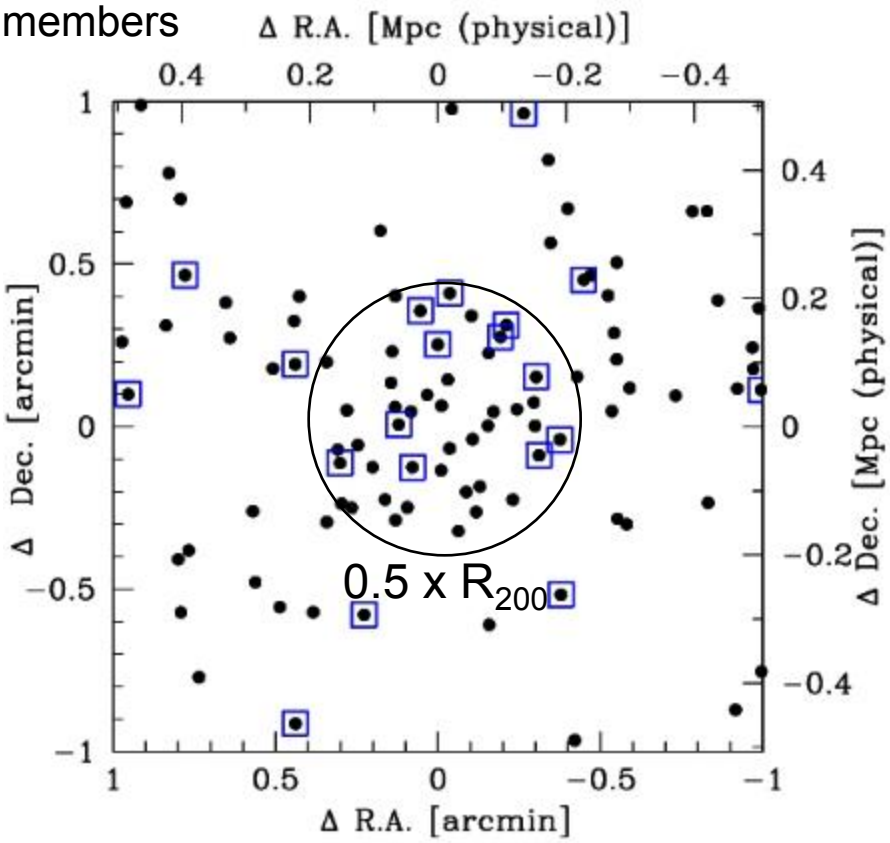
Spatial distribution of star-forming galaxies in clusters at z<1.5

□ Hα emitters at z=0.81 (RXJ1716) □ [OII] emitters at z=1.46 (XCS2215)



Lx=2.7×10^{44} erg/s

Koyama, et al. (2011)



Lx=4.4×10^{44} erg/s

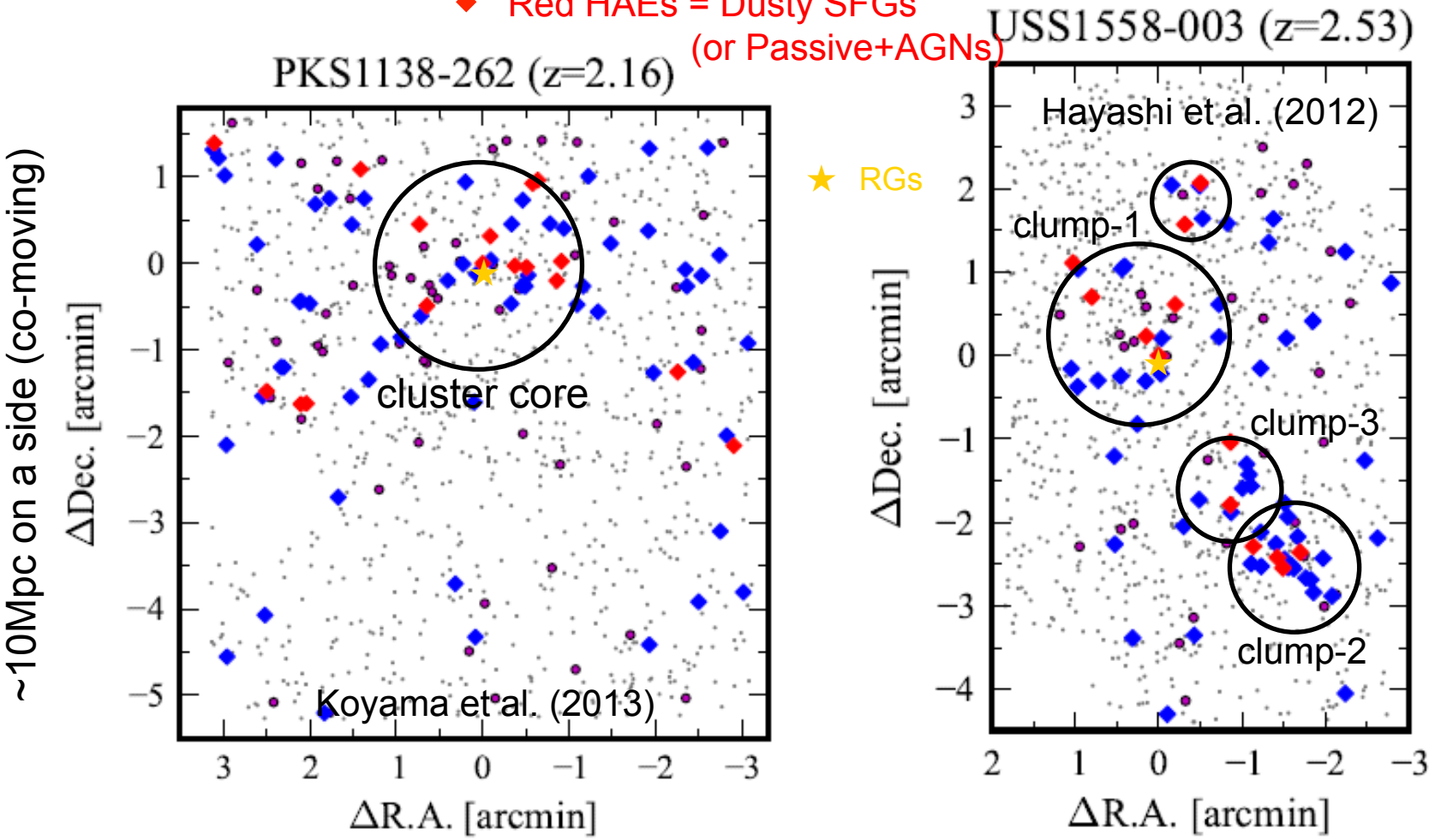
Hayashi, et al. (2010)

Clusters Grow (Quench) Inside-Out !

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

◆ Blue HAEs = Normal SFGs

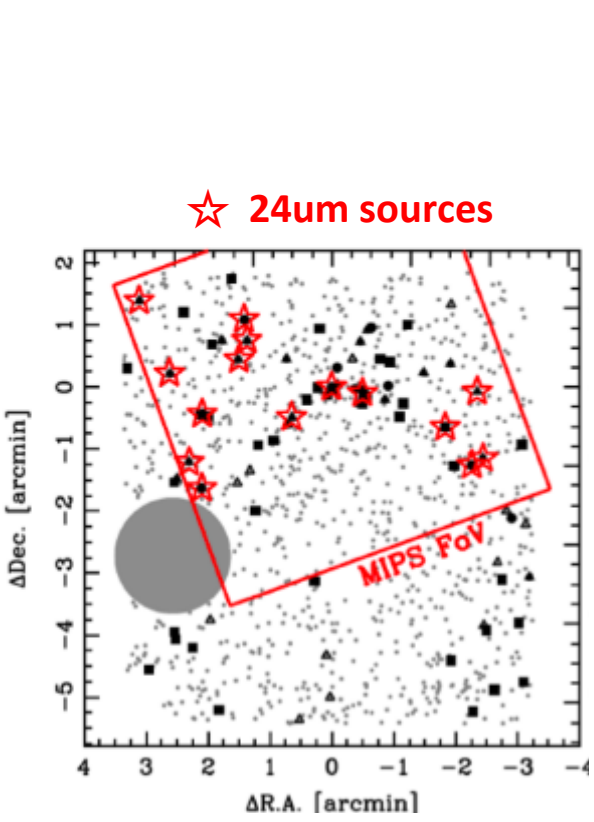
◆ Red HAEs = Dusty SFGs (or Passive+AGNs)

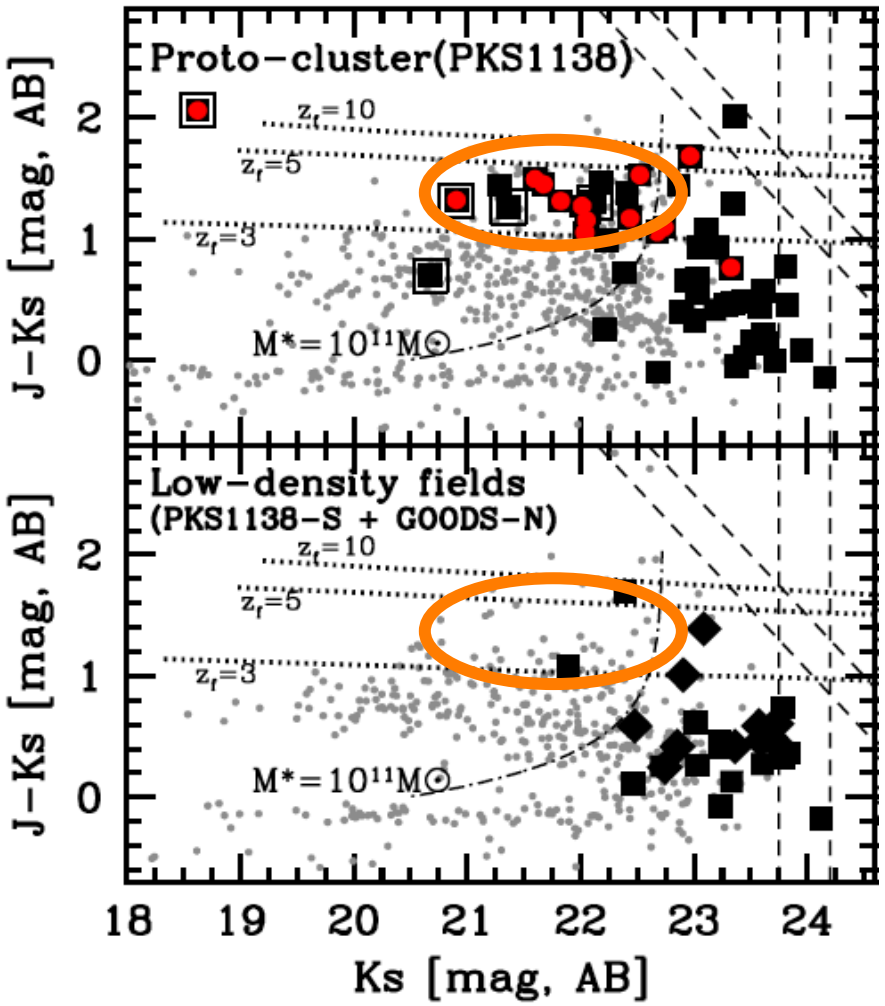


1. Lots of HAEs in proto-cluster cores unlike lower-z clusters (quenched center). Clusters grow (quench) inside-out!

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

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





High density

■ ◆ Hα emitters

● 24um sources

Low density

Koyama et al. (2013a)

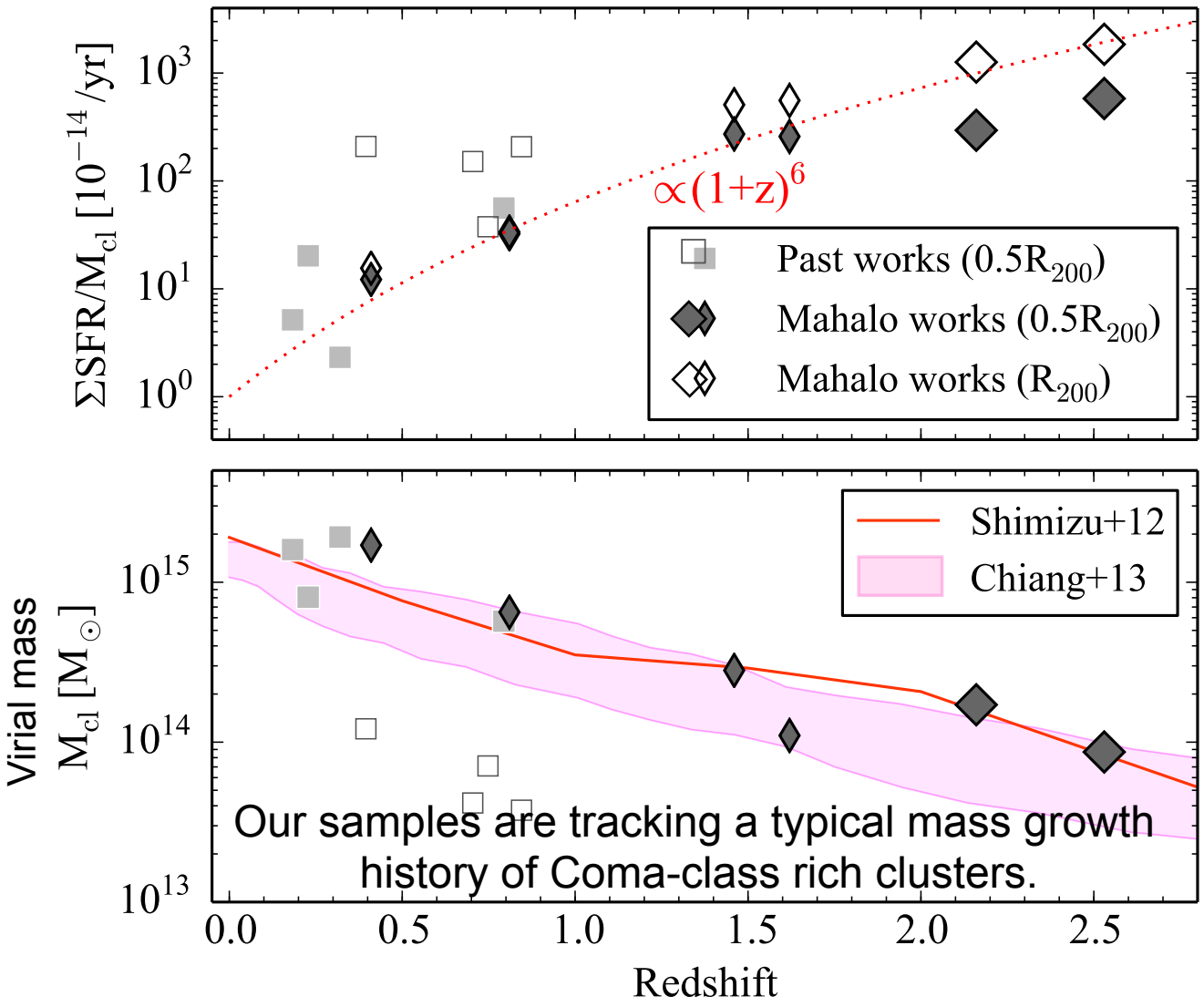
Red Hα emitters in PKS1138 are massive ($M_\star > 10^{11} M_\odot$) and dusty star-forming galaxies. Many are detected at 24μm with MIPS, but not in X-ray.

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

Red galaxies can be very active!

Hiroshima CARP

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



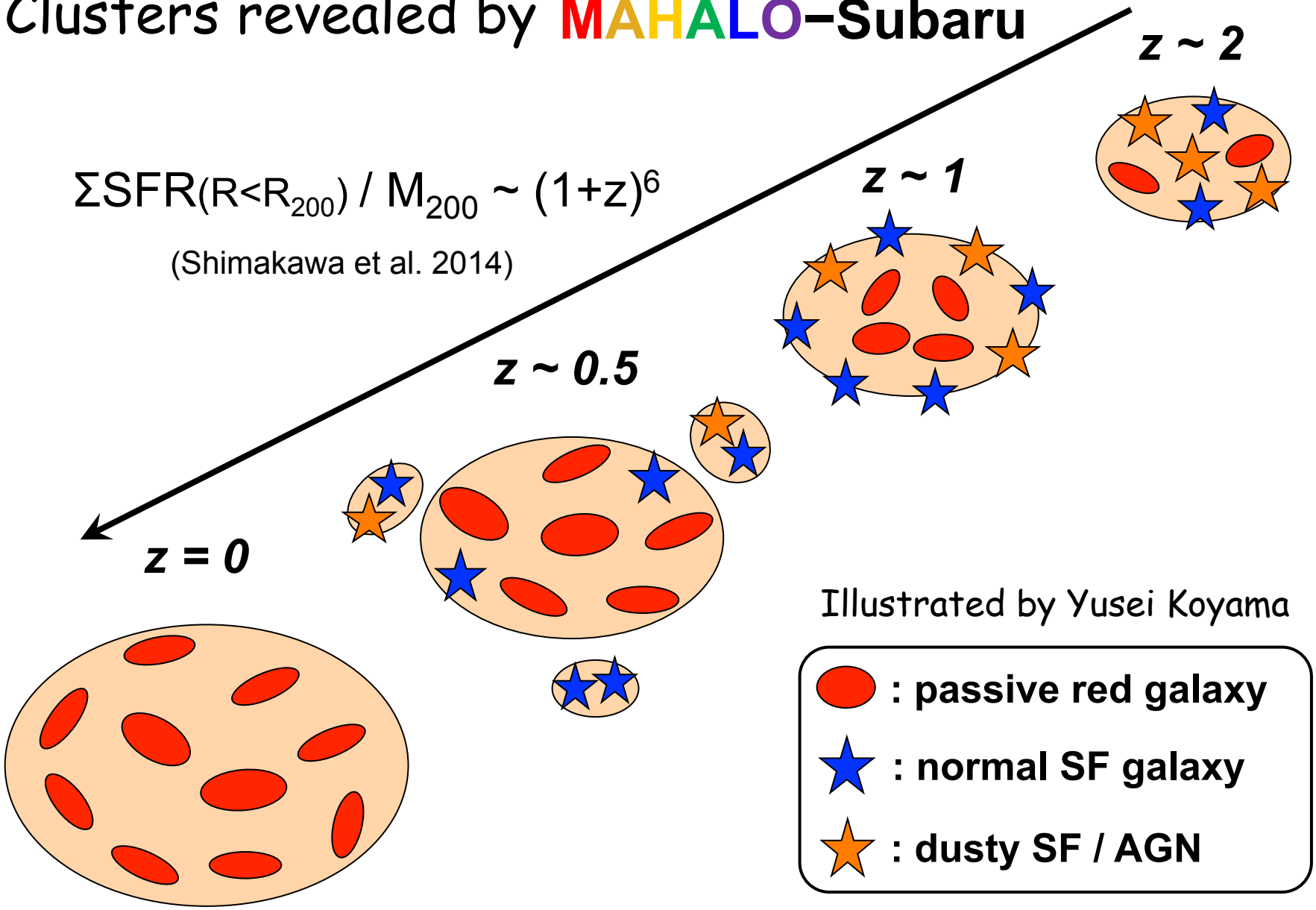
Rapid increase of integrated SFR per unit cluster mass with increasing z

cf.) Field $\rho_{SFR} \sim (1+z)^3$

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

Shimakawa et al. (2014)

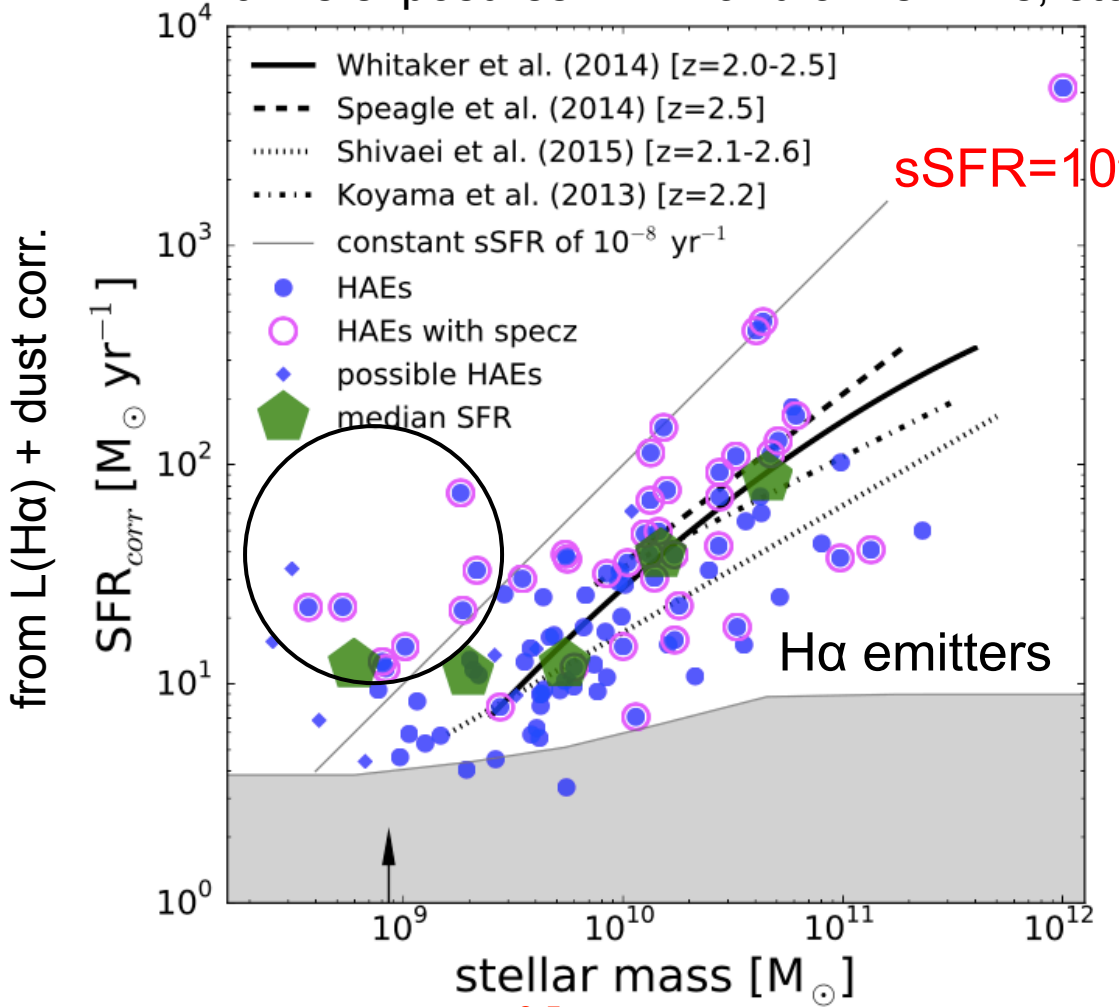
The Inside-Out Quenching of Galaxy Clusters revealed by MAHALO-Subaru



MAHALO−DEEP : towards lower mass galaxies

USS1558-003 (z=2.53) and PKS1138-262 (z=2.16) proto-clusters

10 hrs exposures in NB and 3 hrs in Ks, etc.



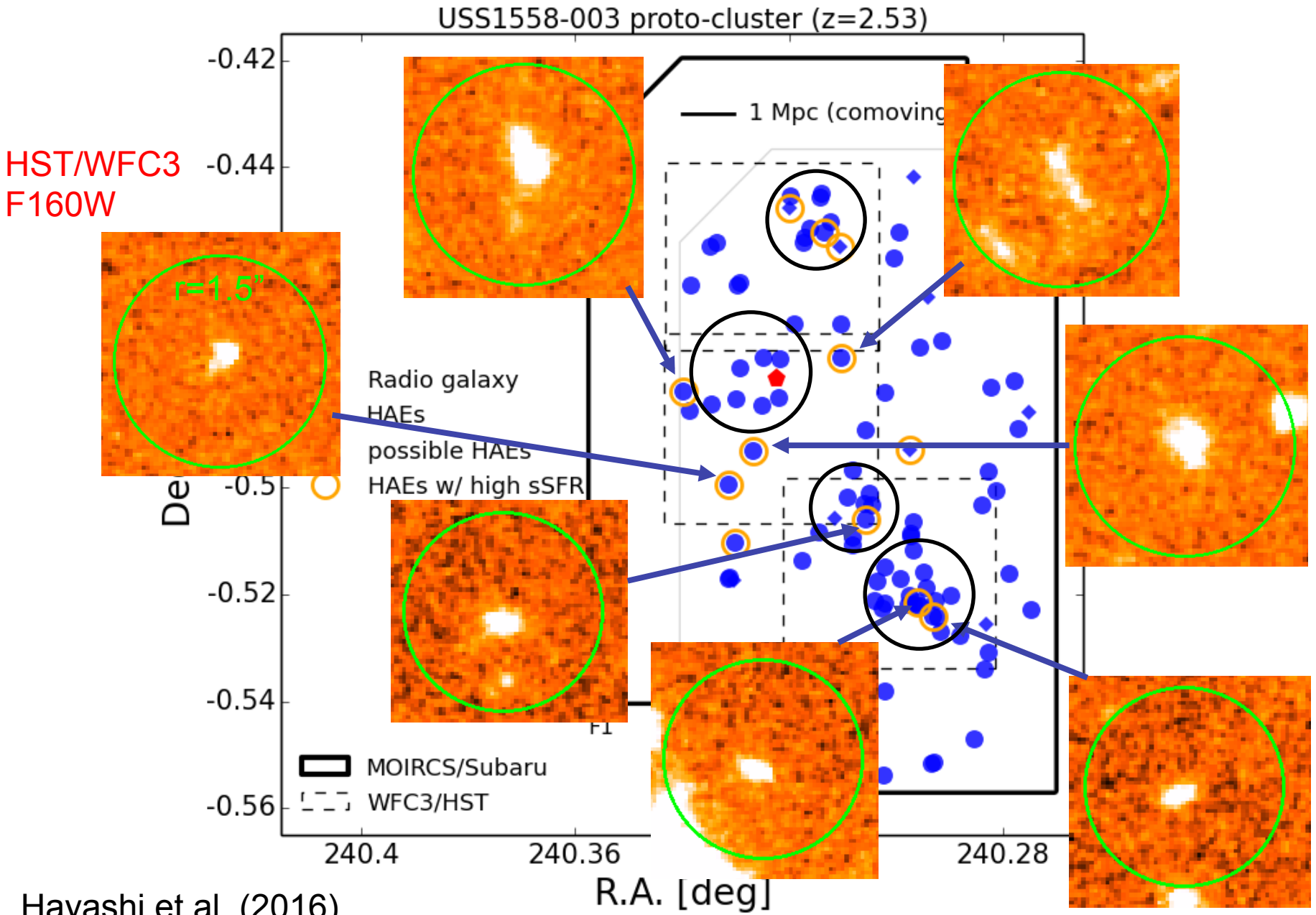
USS1558-003 (z=2.53)

Hayashi et al. (2016)

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

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

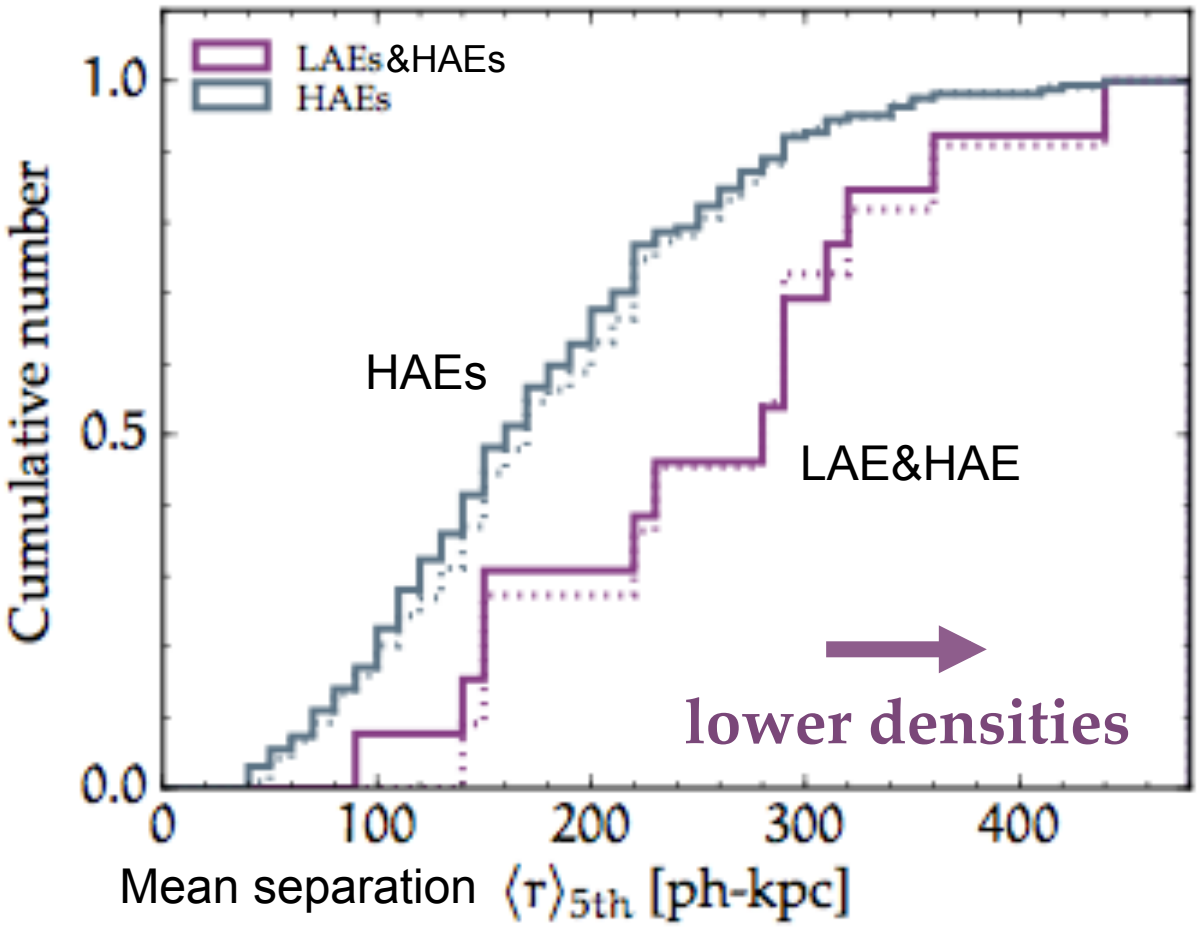
A half of them are located in the dense clumps, but the other half are in the outskirts.



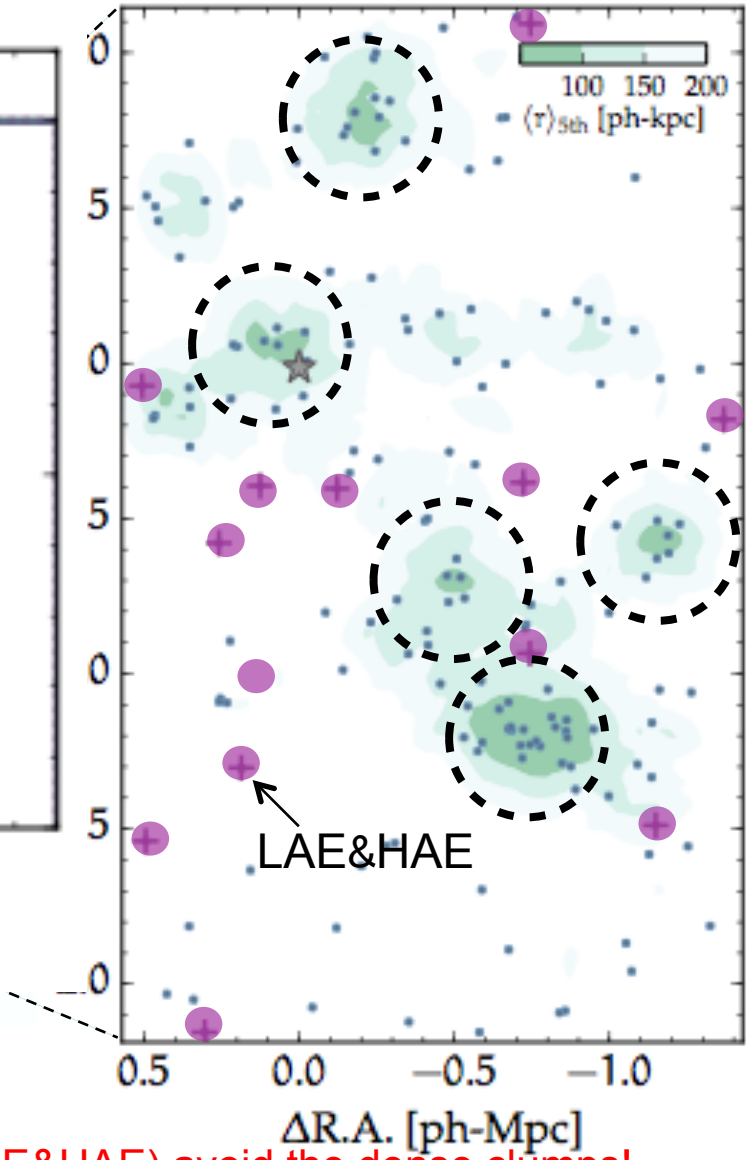
Hayashi et al. (2016)

Dual emitter (Lyα+Hα) survey in and around USS1558 (z=2.53)

MAHALO-LYA



MOIRCS (7' x 4') − NB2315 (Hα)

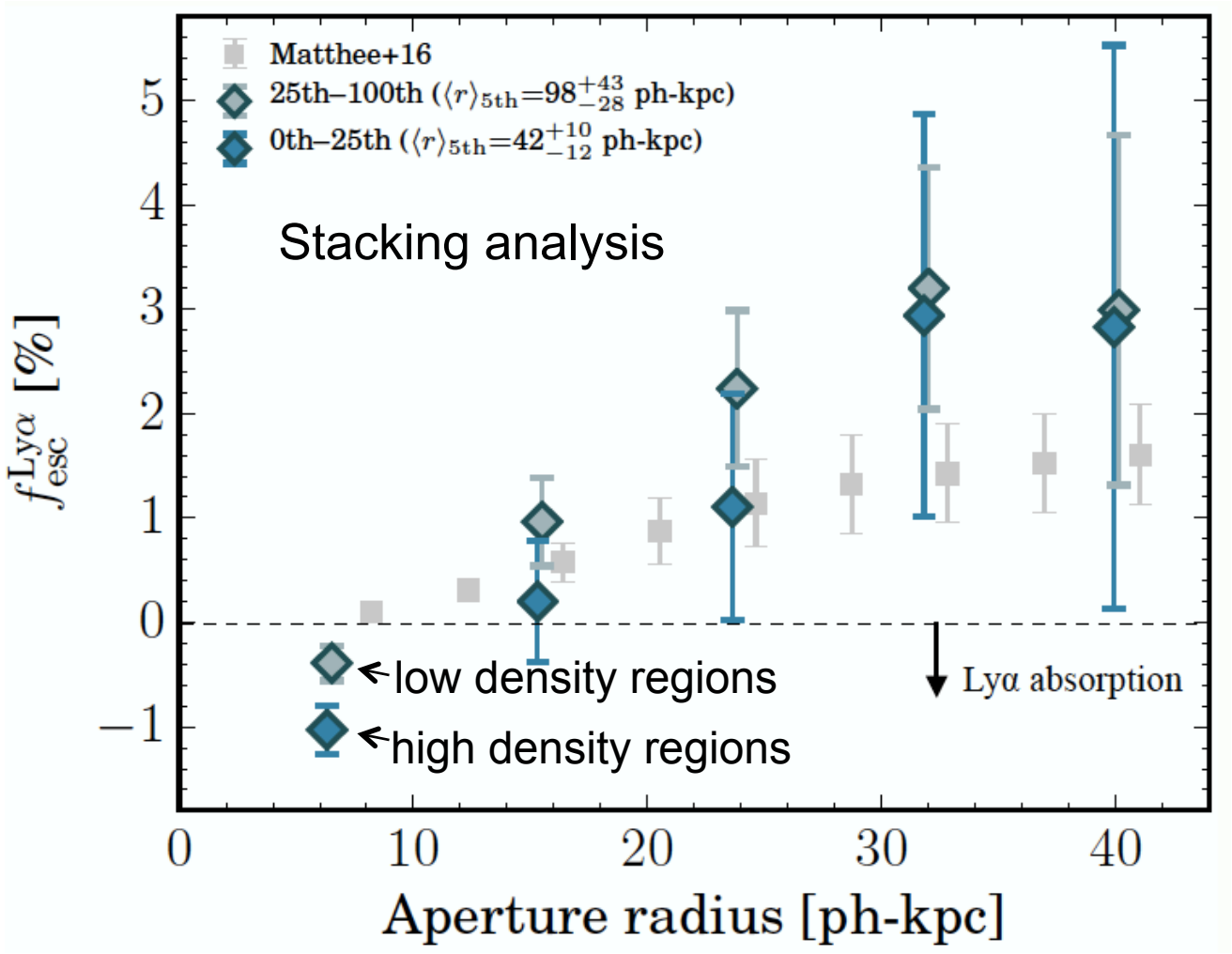


Shimakawa et al (in prep)
Hayashi et al. (2012; 2016)

Dual emitters (LAE&HAE) avoid the dense clumps!
HAEs in the high density clumps are often Lyα absorbers.

Low Lyα escape fraction in HAEs in the dense clumps

Integrated Lyα escape fraction: $f_{esc\ (Ly\alpha)}$ = $Flux_{obs.}(Ly\alpha)$ / $Flux_{dust\text{-}corr.}(H\alpha \rightarrow Ly\alpha)$

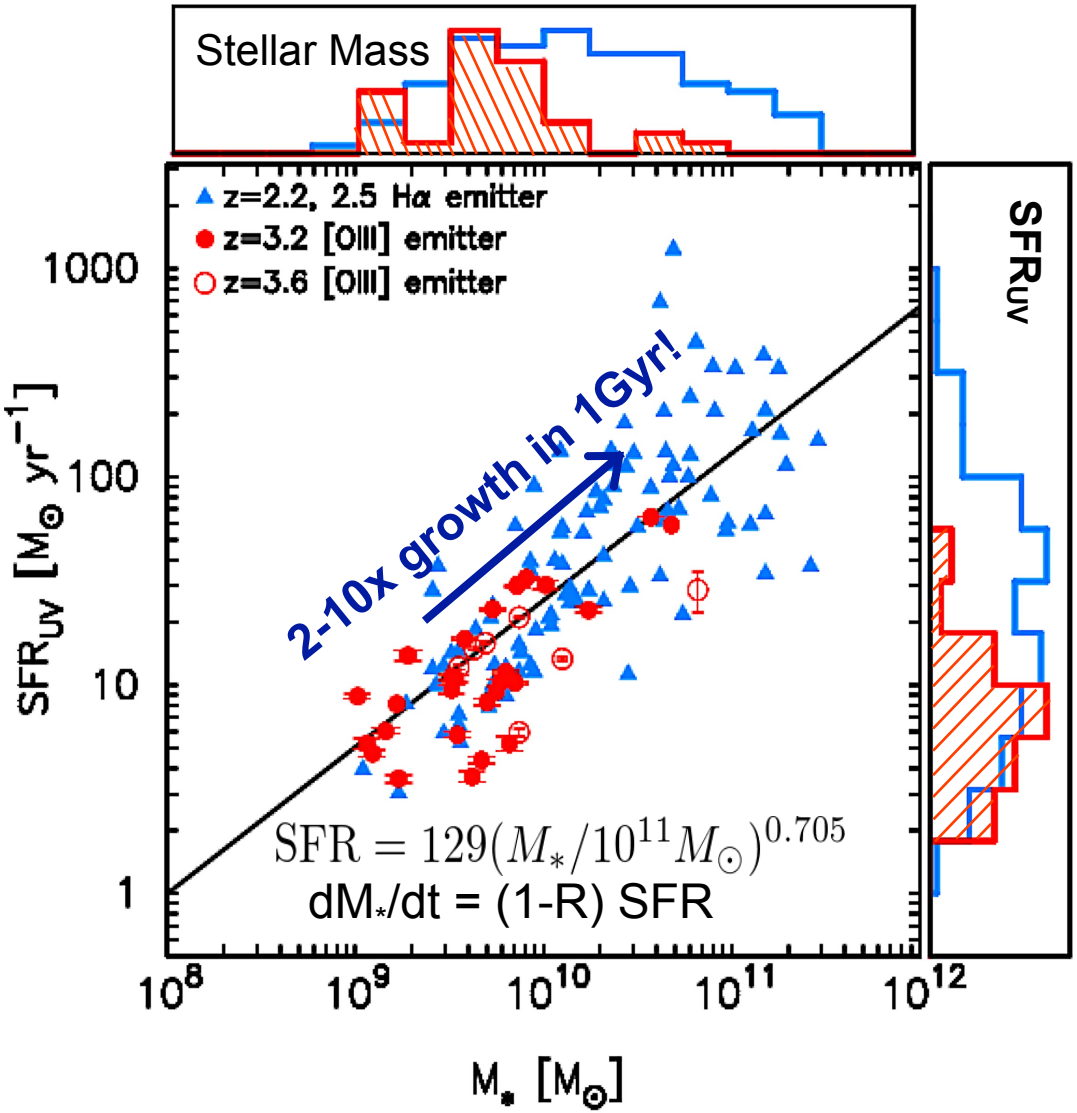


Radius within which we stack the images

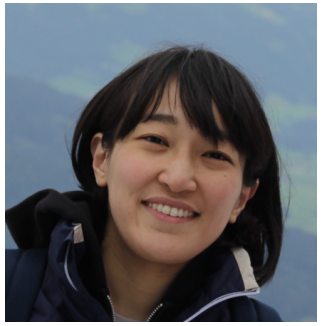
Shimakawa et al.
(in prep.)

Rich CGM/IGM (HI) in the dense clumps fed by cold mode accretion?

MAHALO-FAR : Towards higher-z SFGs with [OIII]



[OIII] emitters at z~3.4
versus
Hα emitters at z~2.3
in SXDF-UDS-CANDELS



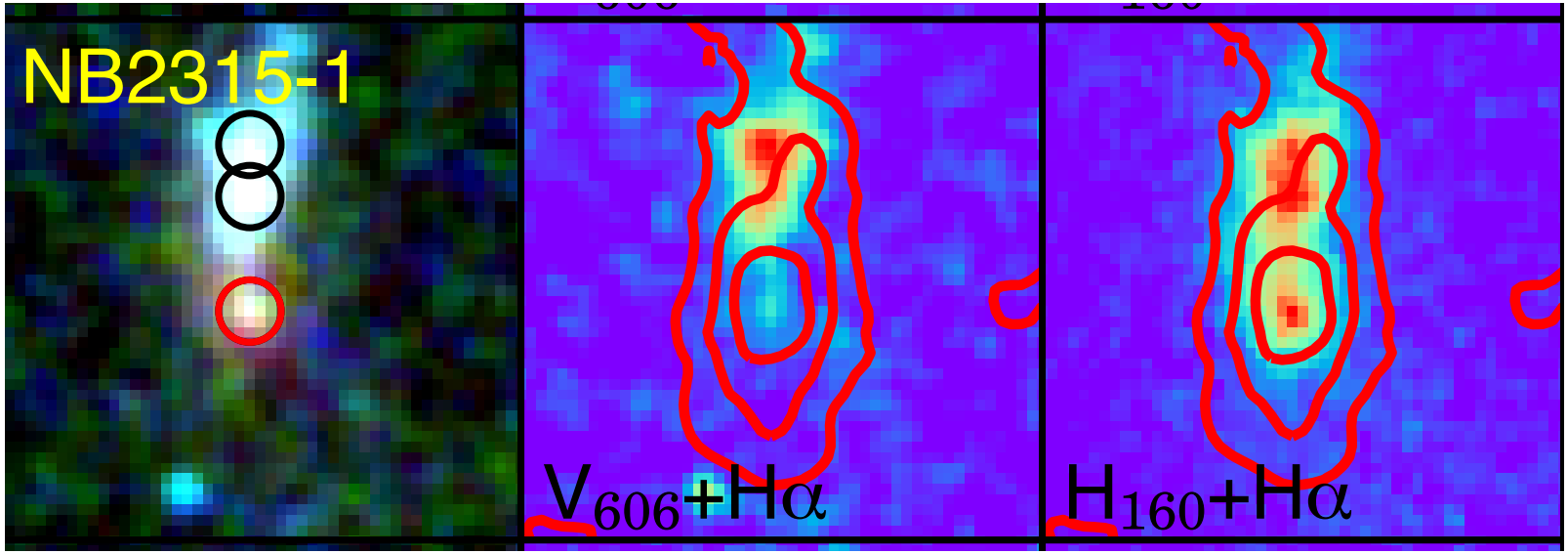
Suzuki et al. (2015)

Galaxies increase their M* and SFR by a large factor (2-10) in this 1Gyr interval!

MAHALO−SHARP : Towards higher spatial resolution

A clumpy, extended SFG (HAE) at z=2.53 from MAHALO

Seeing-limited Hα image in red contour



Hα tends to be stronger in the red clump, suggesting a dusty SB occurring there.

→ The site of bulge formation with a dusty starburst?

Tadaki et al. (2013b)

Some extended HAEs are resolved with natural seeing, but for the majority, we require better resolutions with AO+NB imaging, IFU and ALMA.

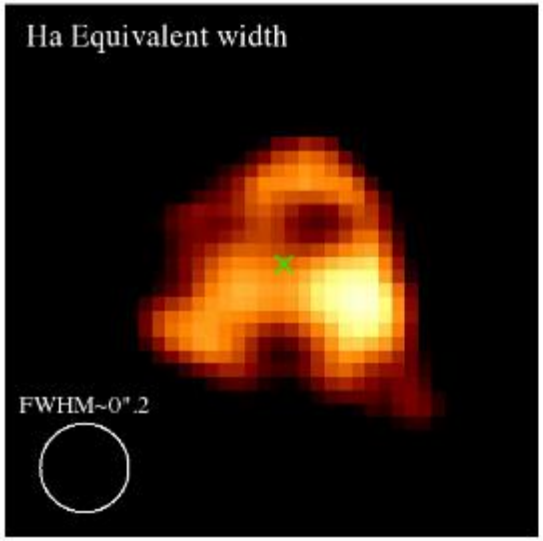
GANBA−Subaru

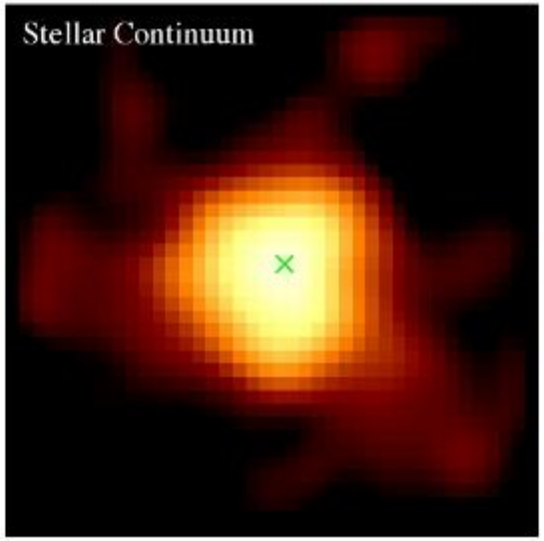
Struggling with terrible weather :<

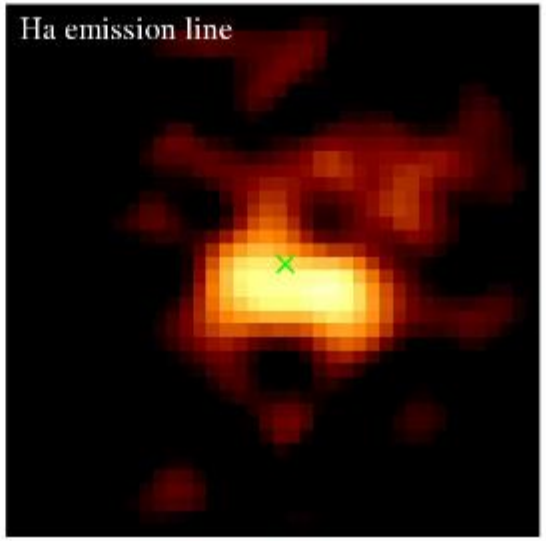
Galaxy Anatomy with Narrow-Band AO imaging with Subaru

AO-assisted narrow-band Hα or [OIII] imaging with IRCS on Subaru

EW(Hα) ~ sSFR Continuum ~ M_{stars} L(Hα) ~ SFR







A Hα emitter at z~2.19 (NB2095 + AO188) in SXDF-CANDELS

(0.2” ~ 1.6 kpc)

Being-truncated bulge + Off-center star-forming clump ?

Minowa et al., in prep.

GRACIAS–ALMA

Galaxy **R**esolved **A**natomy with **C**O **I**nterferometry
And **S**ubmm 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~50$M_\odot$/yr (~3hrs, 5σ)

Dust continuum@ Band-6-9 (450 μm–1.1 mm) SFR~15$M_\odot$/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/dust)
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.
Spatially resolved maps of these quantities are also the keys to understand the physics.

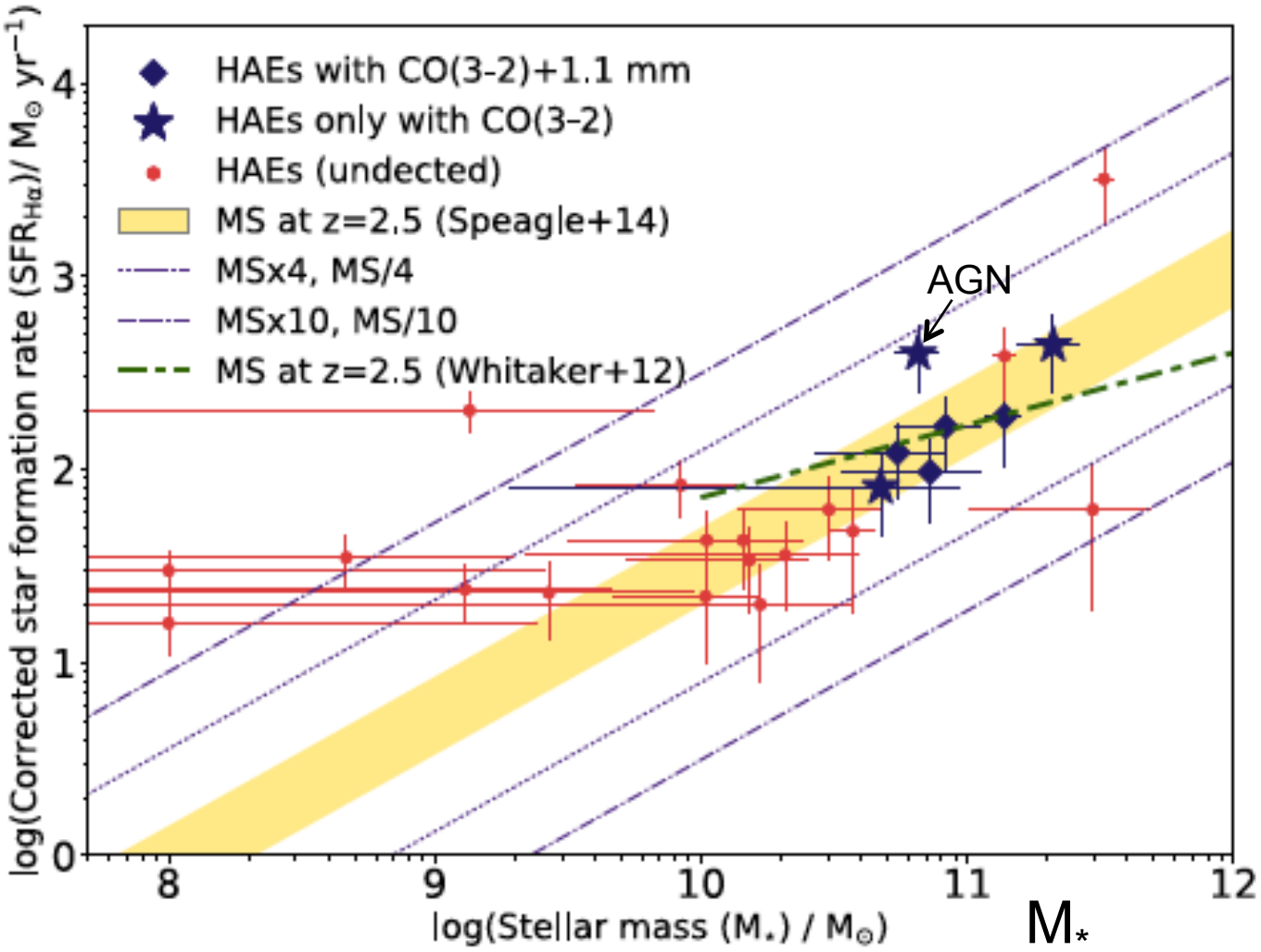
ALMA observations (Band-3, 6) of 4C23.56 proto-cluster at z=2.48

7 detections with CO(3-2) line and 4 detections with dust continuum at 1.1mm from HAEs

Lee et al., in prep.

ALMA observations of CO(3-2) and dust continuum of HAEs in 4C23.56 proto-cluster at z=2.48

SFR(Hα)



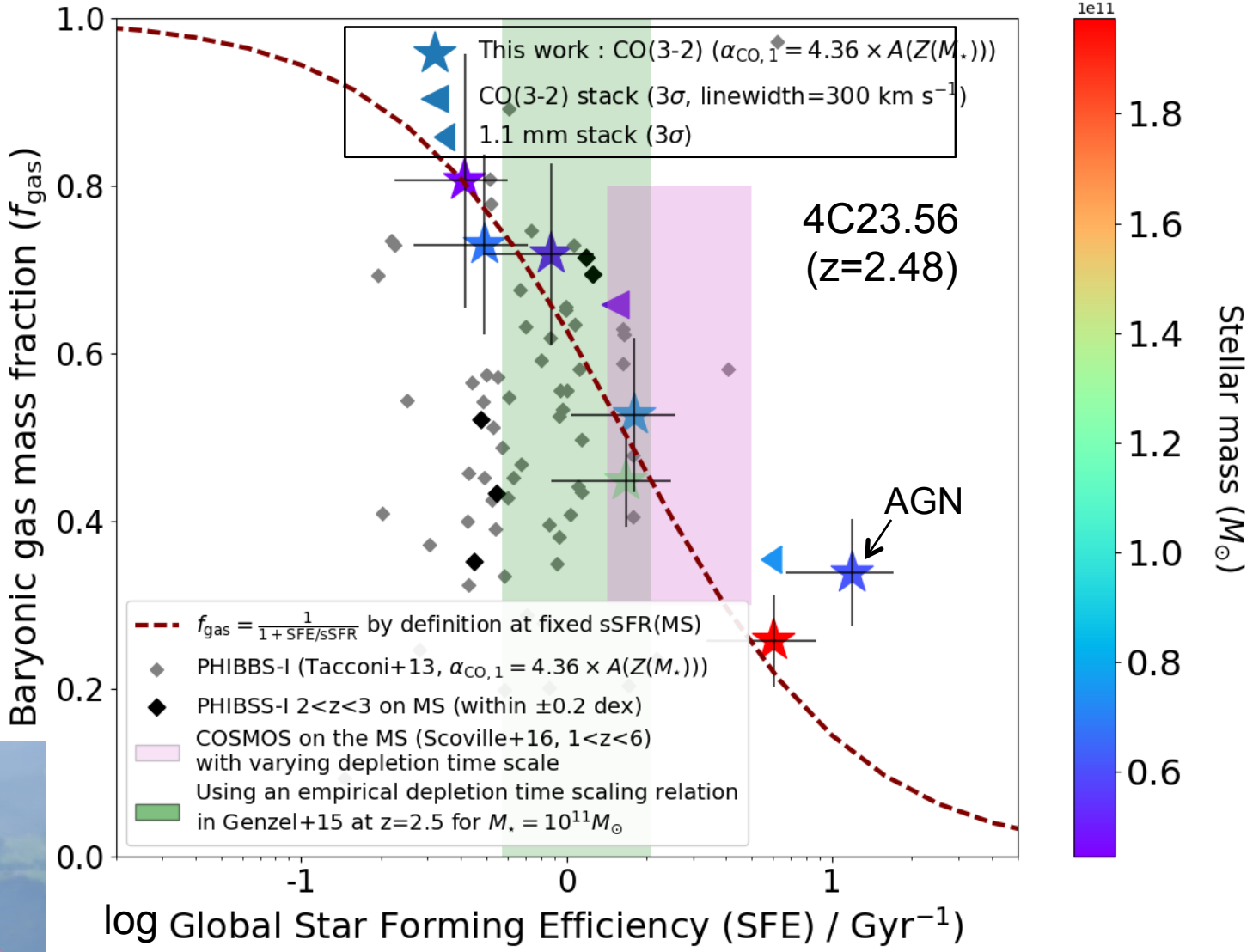
Our ALMA sources (SFGs) are located on the SF main sequence (similar in sSFR).

Lee et al., in prep.

Anti-correlation between f(gas) and SFE in the z~2.5 proto-cluster??

But WHY??

f(gas)



Lee, Minju et al., in prep.

SFE

Bulge/clump scale (~1kpc) anatomy of high-z SFGs across various environments with Subaru-AO + HST + ALMA (higher resolution)

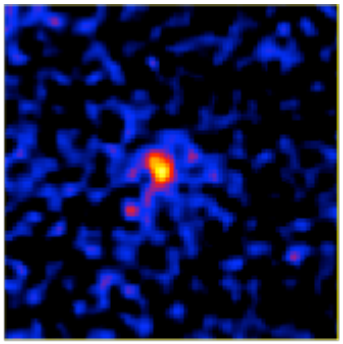
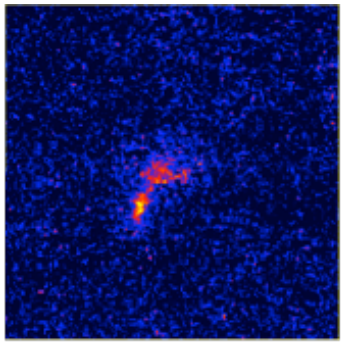
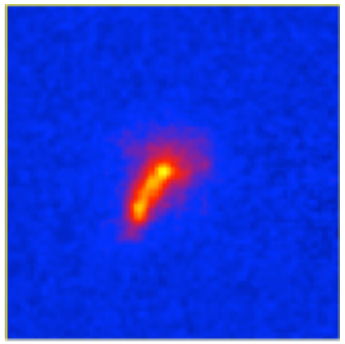
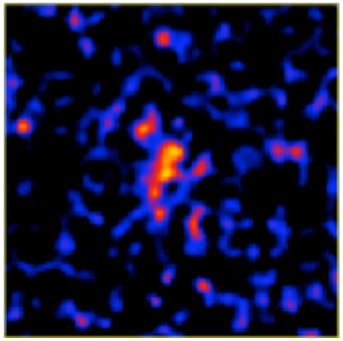
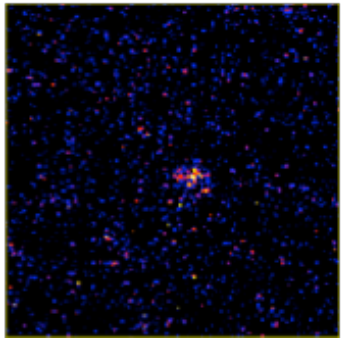
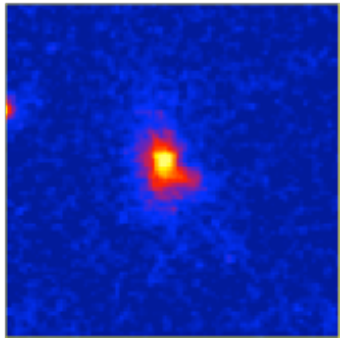
Subaru/IRCS NB+AO
SF traced by Hα
0.1”-0.15”

HST / ACS
SF traced by UV
0.1”

HST / WFC3
Stellar mass
0.16”

ALMA
Dust cont.
0.1”

ALMA
CO line
0.2”

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GANBA-Subaru

HST imaging

GRACIAS-ALMA

Summary

- **MAHALO-Subaru** has been mapping out SFGs in clusters and the general fields, and has revealed the inside-out quenching of galaxy clusters since z~2.5.
- **MAHALO-LYA** finds that LAEs are totally avoiding the dense clumps in the young proto-cluster at z=2.5 due probably to rich HI gas associated to the clumps fed by the cold-mode accretion.
- **MAHALO-DEEP** has revealed star-bursting galaxies with high-sSFR at the low mass end ($< 10^{9.5} M_{\odot}$) in z>2 proto-clusters. Environmental effects?
- **MAHALO-SHARP (GANBA-Subaru, GRACIAS-ALMA)** are resolving internal structures of SFGs at z>2 and witnessing the physical processes of galaxy formation, depending also on environments. Anti-correlation between f(gas) and SFE is seen in a proto-cluster at z~2.5 ?