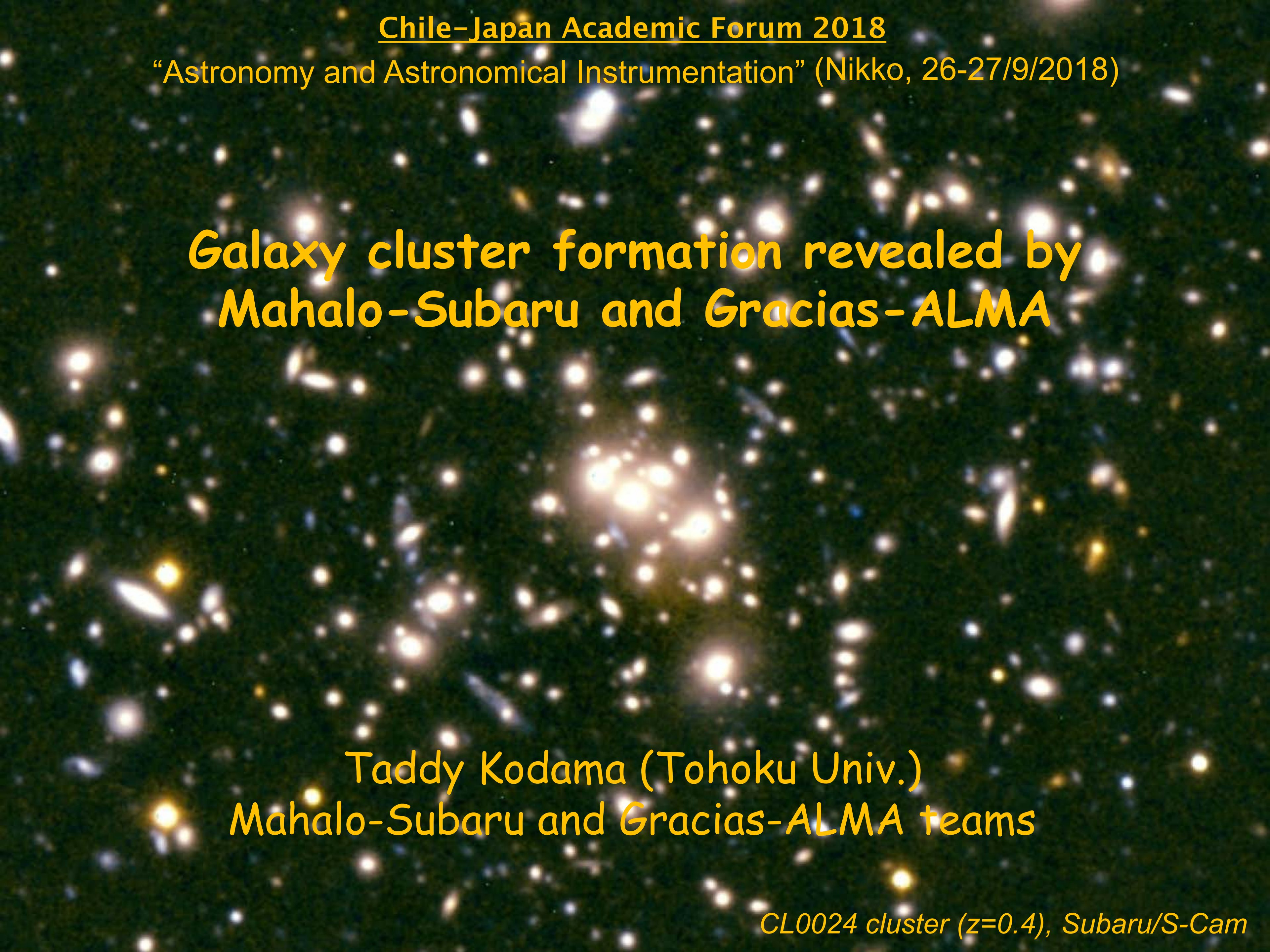
<u>**Chile–Japan Academic Forum 2018**</u>

"Astronomy and Astronomical Instrumentation" (Nikko, 26-27/9/2018)

Galaxy cluster formation revealed by Mahalo-Subaru and Gracias-ALMA

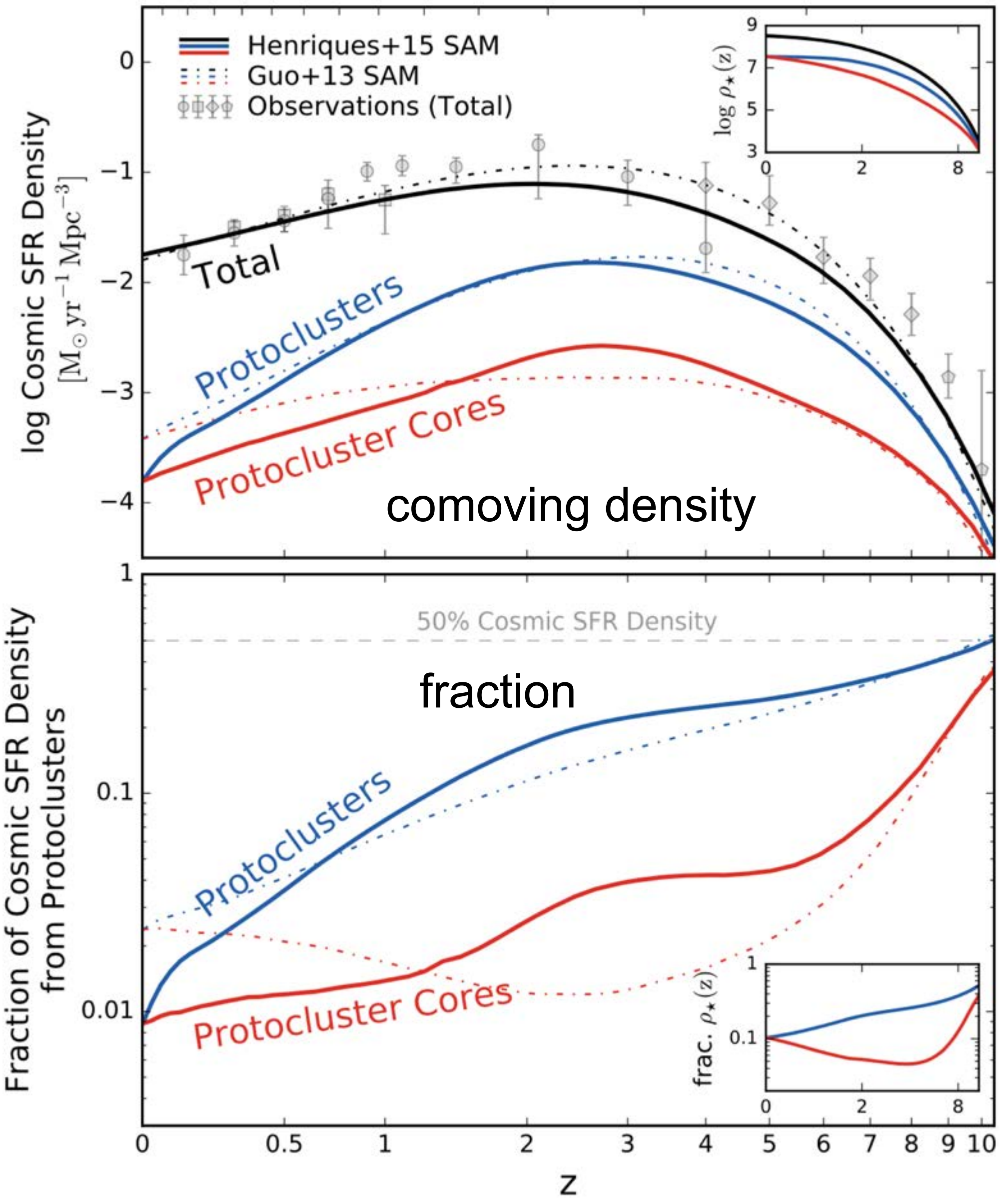
Taddy Kodama (Tohoku Univ.)
Mahalo-Subaru and Gracias-ALMA teams



CL0024 cluster (z=0.4), Subaru/S-Cam

Importance of proto-clusters in the cosmological context

Cosmic star formation rate density (CSFRD)



Chiang et al. (2017)

N-body + SAM

In the cosmic noon (1<z<4), the universe and clusters form 50% and 75% of their total stellar masses, respectively.

The fractional contribution of (proto-)cluster progenitors to the total CSFRD is only 1% at z=0 but it increases to 20% at z=2 and 50% at z=10.

Proto-clusters are increasingly more important at higher redshifts.

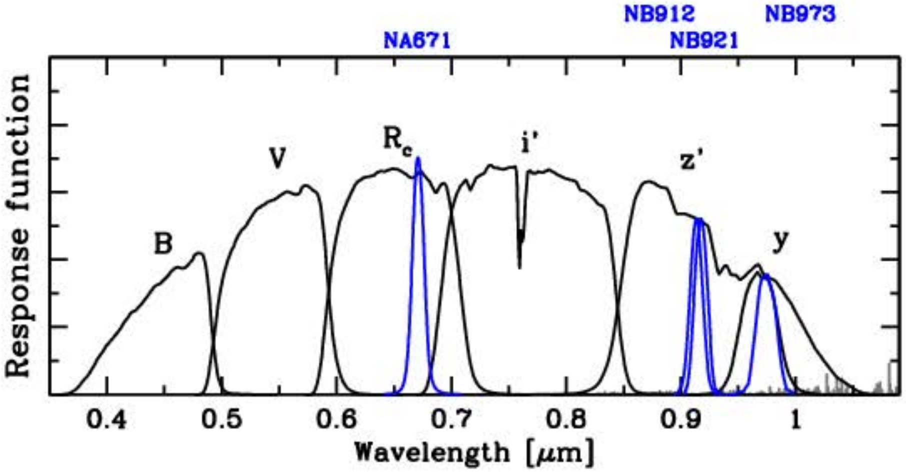
MAHALO–Subaru

MApping HAlpha and Lines of Oxygen with Subaru

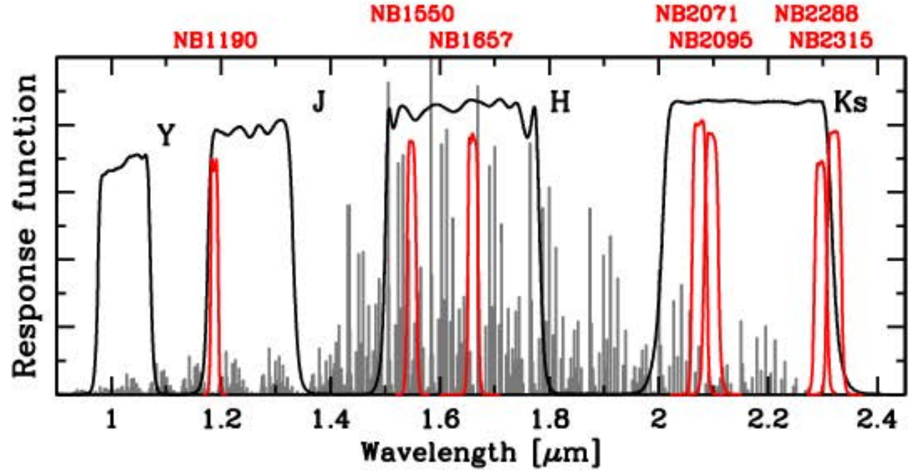
(PI: Kodama, T.) ~20 ninghts for imaging

Wide-Field Survey of Line Emitters ([OII], [OIII], Hα) 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 (HAEs, O3Es)

1. Nearly a complete sample of SFGs down to a certain line flux limit. (no pre-selection)
2. Redshifts are determined within a narrow slice only by imaging.
3. Less affected by dust extinction compared to UV-selected SFGs such as LAEs/LBGs.
4. Known redshifts/line fluxes are extremely useful for follow-up observations, such as NIR spectroscopy and ALMA line observations.

MAHALO–Subaru

MApping HAlpha and Lines of Oxygen with Subaru

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

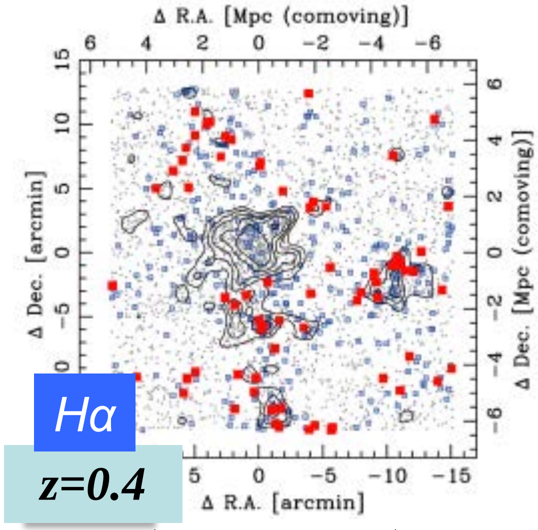
	environment	target	z	line	λ (μm)	camera	NB-filter	continuum	status (as of Apr 2015)
z<1 clusters	Low-z clusters	CL0024+1652	0.395	Hα	0.916	Suprime-Cam	NB912	z'	Kodama+'04
		CL0939+4713	0.407	Hα	0.923	Suprime-Cam	NB921	z'	Koyama+'11
		CL0016+1609	0.541	Hα	1.011	Suprime-Cam	NB1006	z'	not yet
		RXJ1716.4+6708	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

~23 nights for imaging, ~15 nights for spectroscopy

Kodama et al. (2013)

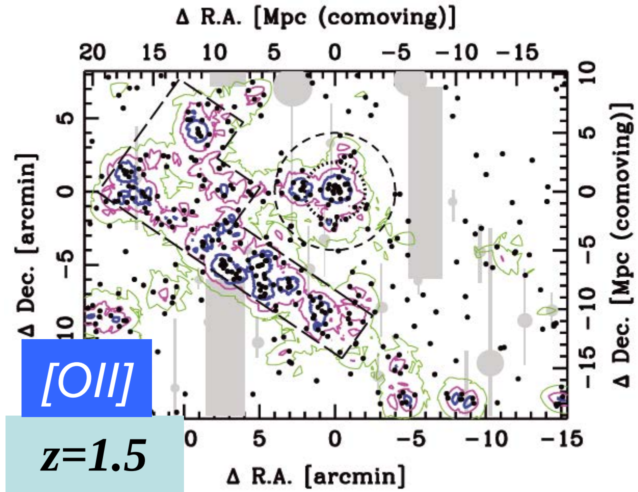
Panoramic narrow-band imaging by MAHALO-Subaru

MApping HAlpha and Lines of Oxygen with Subaru

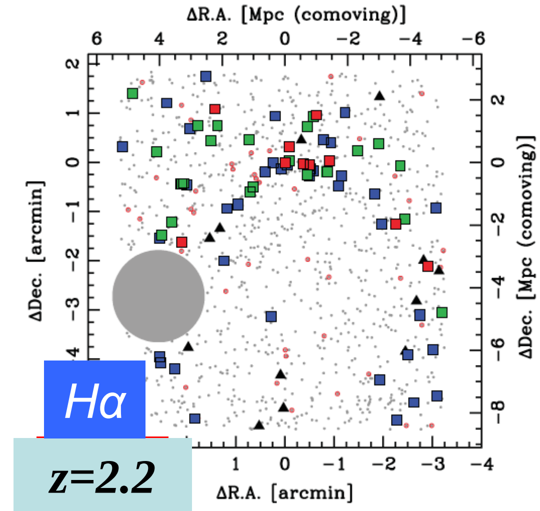


CL0939 *(Koyama+11)*

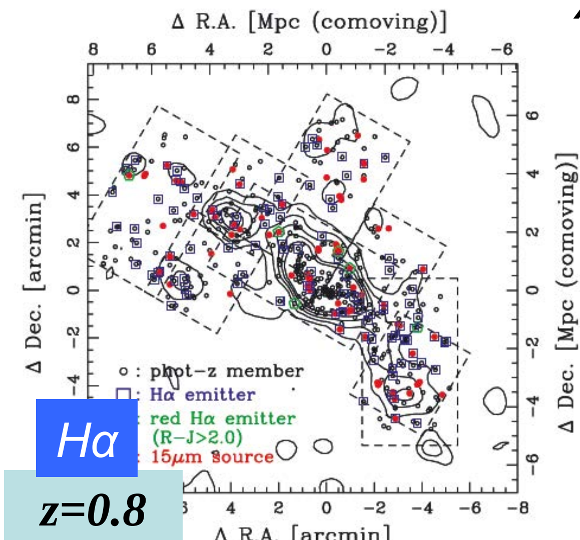
(Hayashi+10, 11)



XCSJ2215

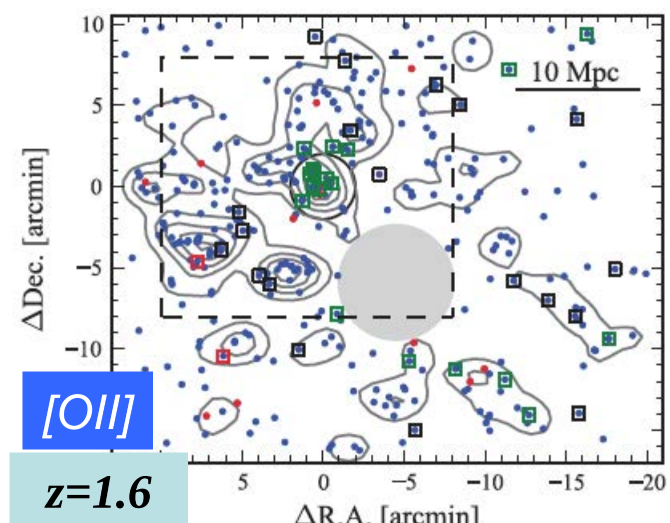


PKS1138 *(Koyama+13)*

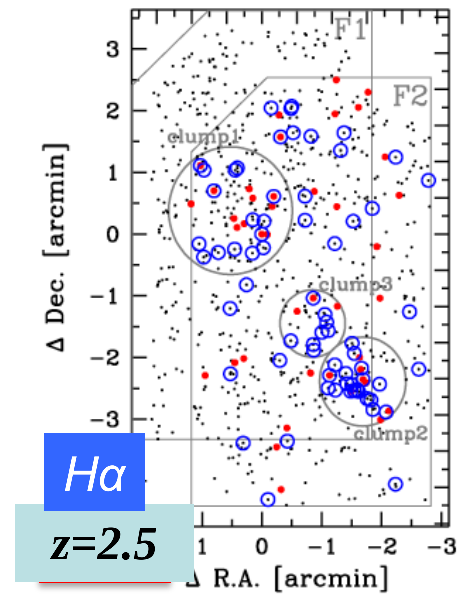


RXJ1716 *(Koyama+10)*

(Tadaki+12)



CL0218



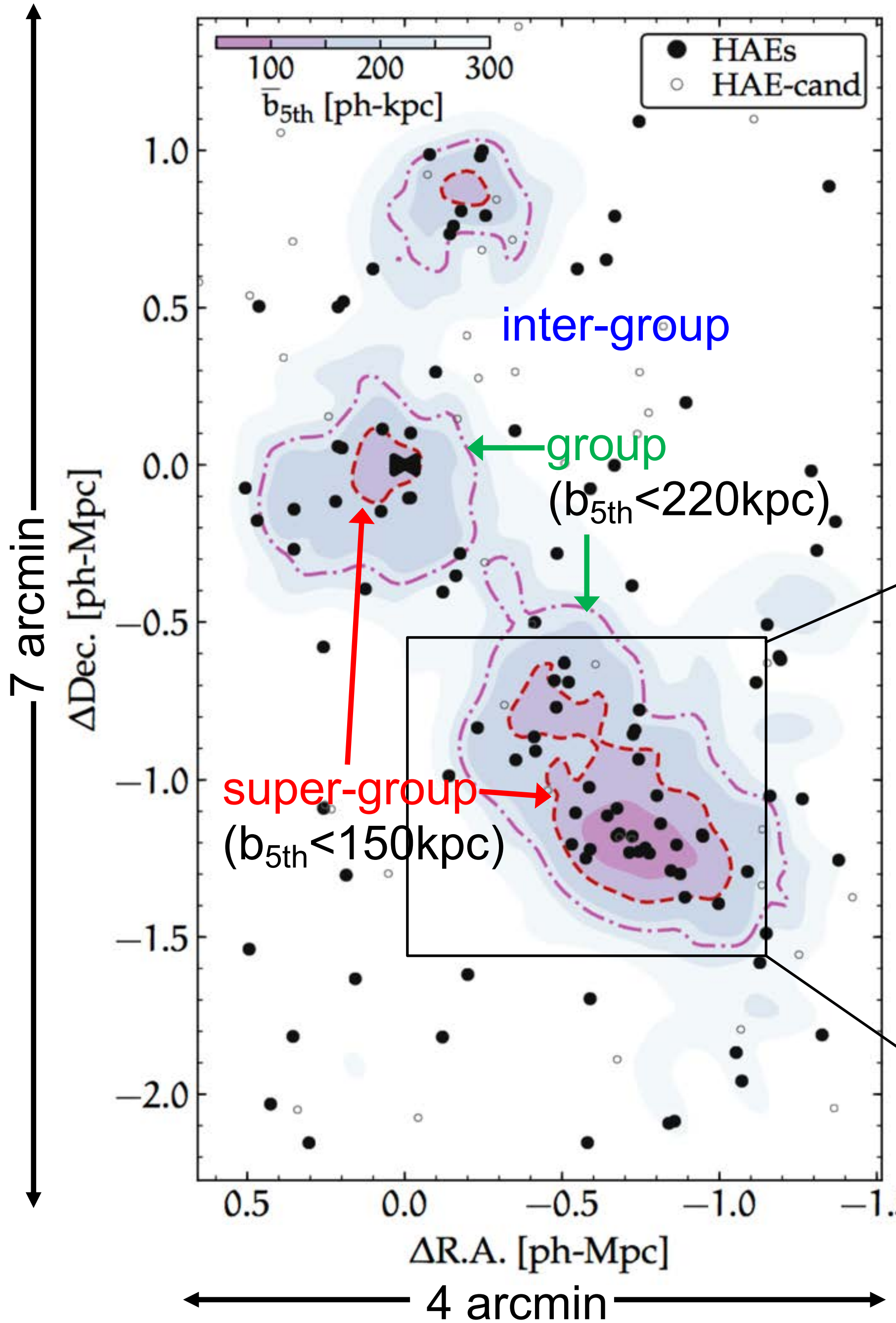
USS1558 *(Hayashi+12)*

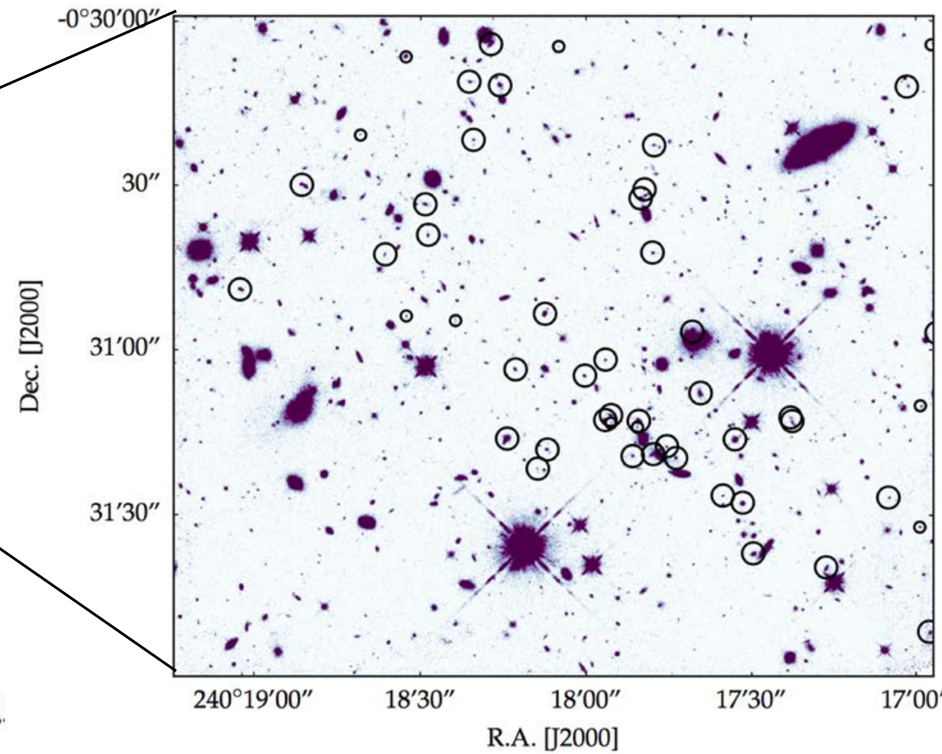
A Rich Proto-Cluster USS1558-003 at z=2.53

Subaru/MOIRCS, NB2315 (Hα) imaging

107 Hα emitters across the 4'x7' field

densest "super-group"
$M_{dyn}=10^{14}\ M_{sun}$

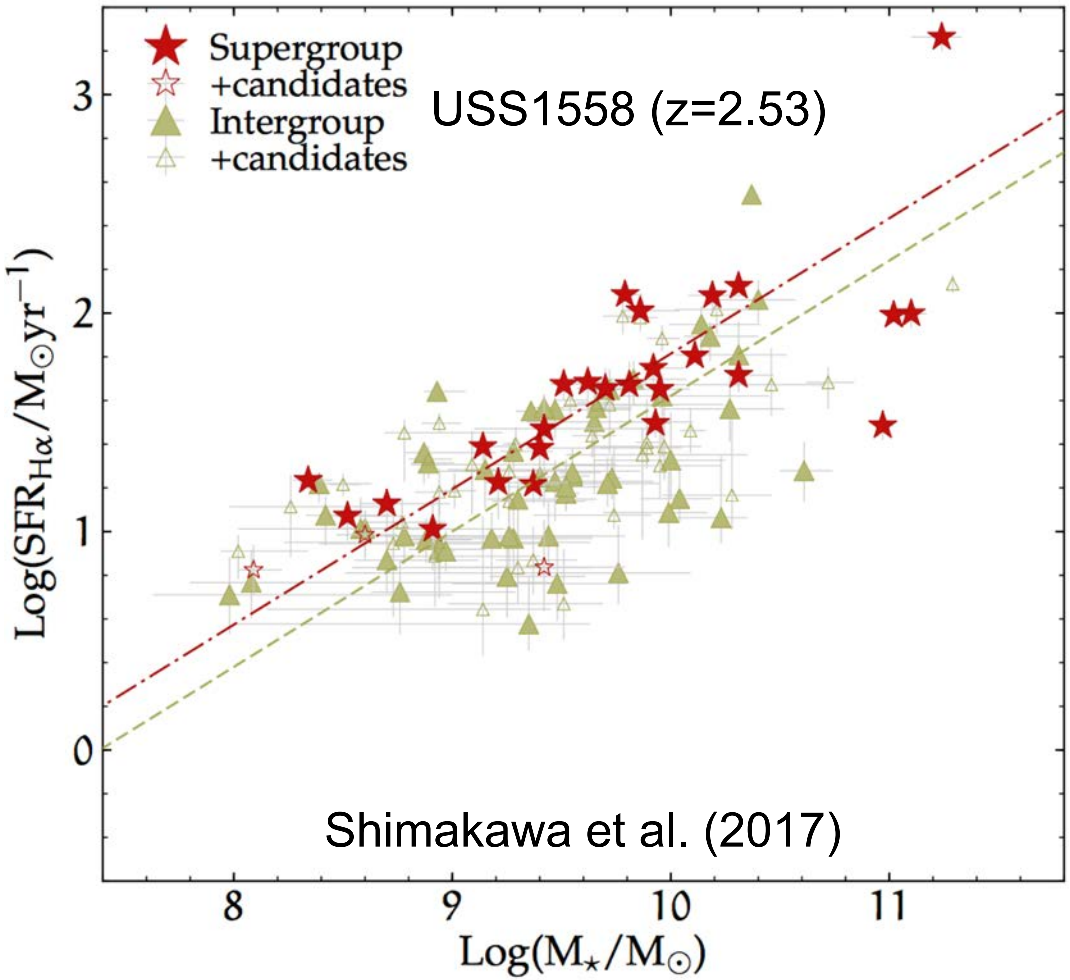


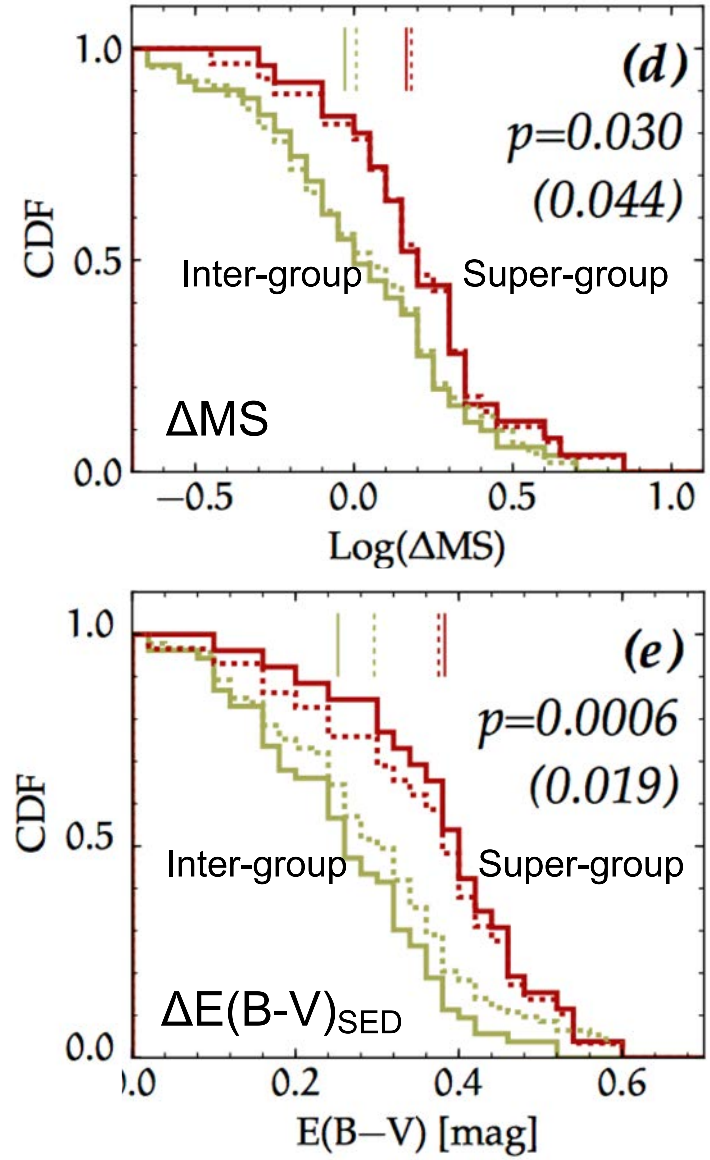


Shimakawa et al. (2017)

Enhanced SF (/AGN) activity in the densest "super-group" of the proto-cluster USS1558 at z=2.53

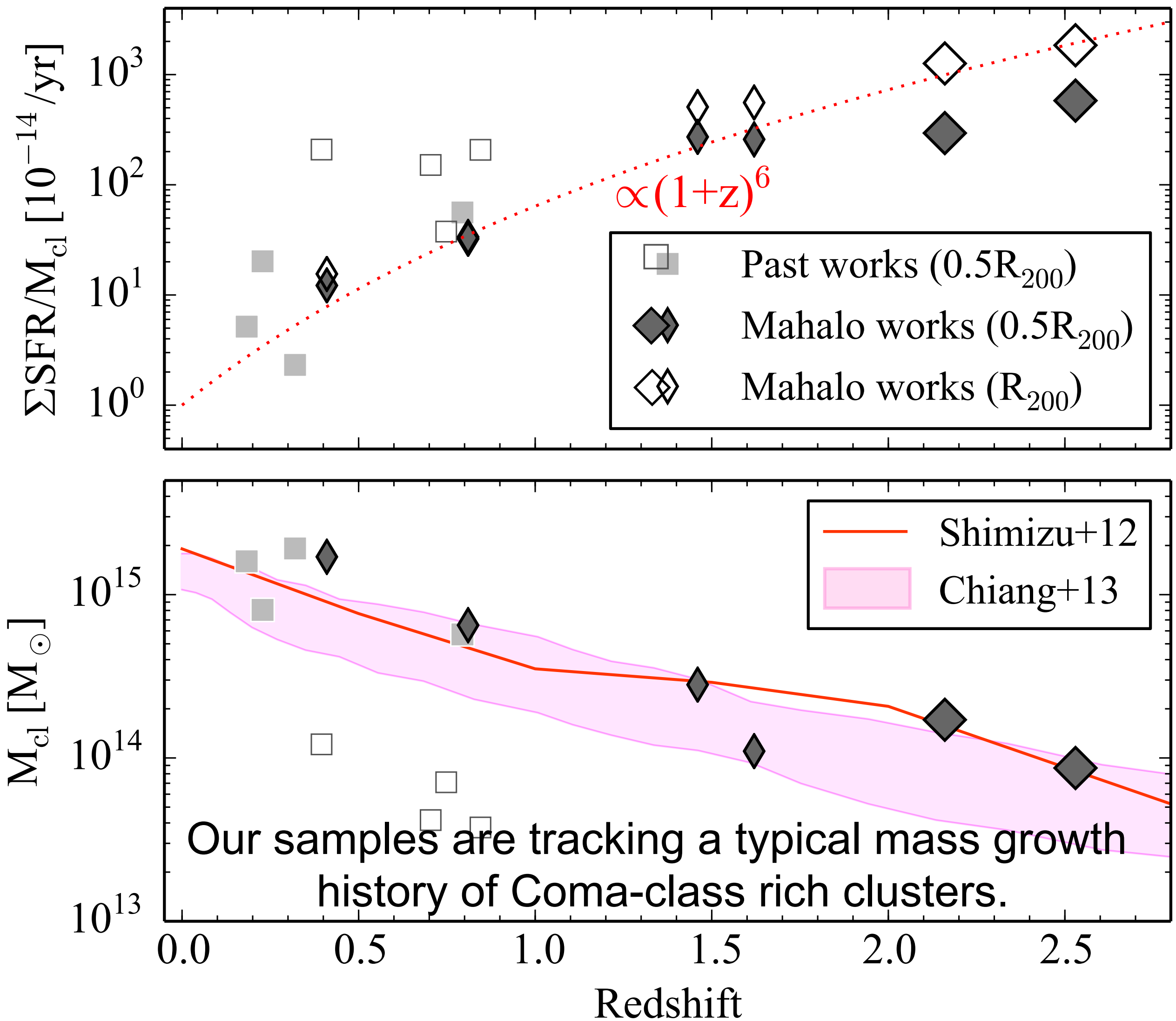
(b_{5th}<150kpc)





※There are some other works which do not see any environmental dependence on the MS diagram.

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

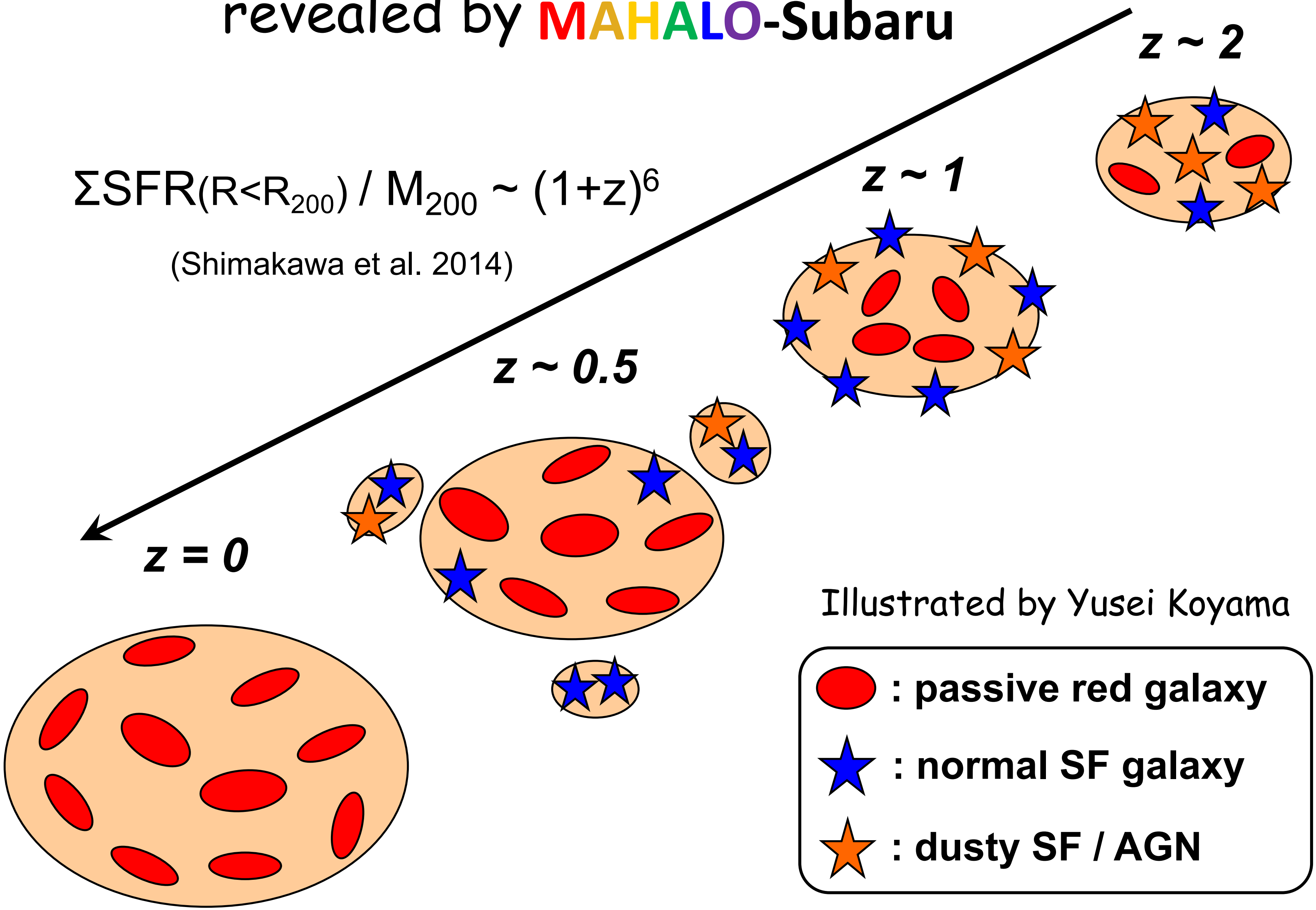


Rapid increase of integrated SFR per unit cluster mass with increasing z

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



GRACIAS–ALMA

Galaxy **R**esolved **A**natomy with **C**O **I**nterferometry **A**nd **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~50M$_\odot$/yr (~3hrs, 5σ)

Dust continuum@ Band-6,7,9 (450 μm–1.1 mm) SFR~15M$_\odot$/yr (~0.5hr, 5σ)

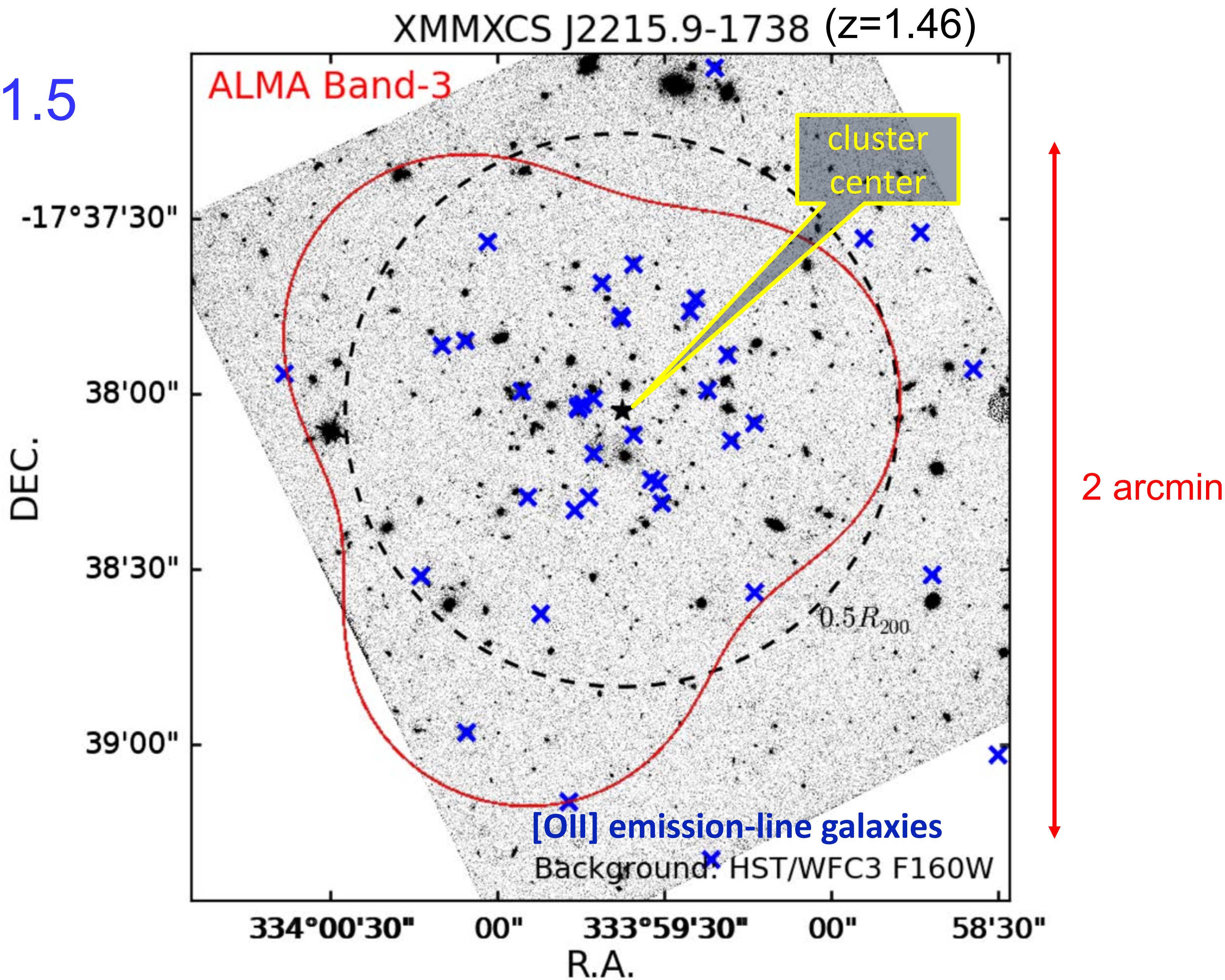
@1<z<3

Spatial resolution: 0.2~1.5” (~1.5-12 kpc)

		Mahalo-Subaru				Gracias-ALMA		ALMA status	
target	z	line	μm	NB-filter	Camera	Continuum	Line@GHz(band)	proposals	results
z~1.5									
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	
z~2.5									
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/dust)
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.

z~1.5

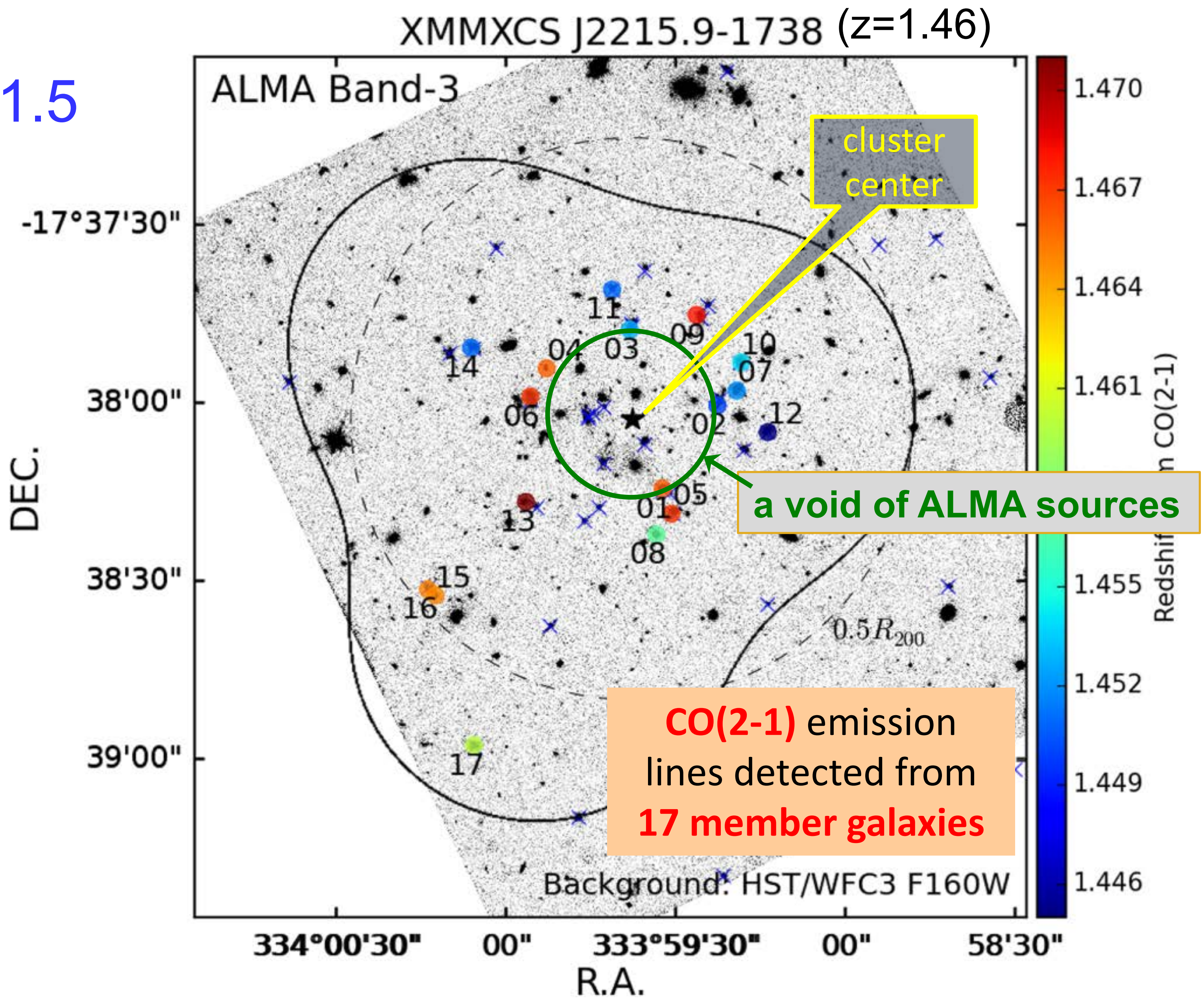


1 hour integration x 3 pointings, beam size=1.79” x 1.41”

Noise level ~ 0.11 mJy/beam (in Δv = 200 km/s)

Hayashi et al. (2017)

z~1.5



1 hour integration x 3 pointings, beam size=1.79" x 1.41"

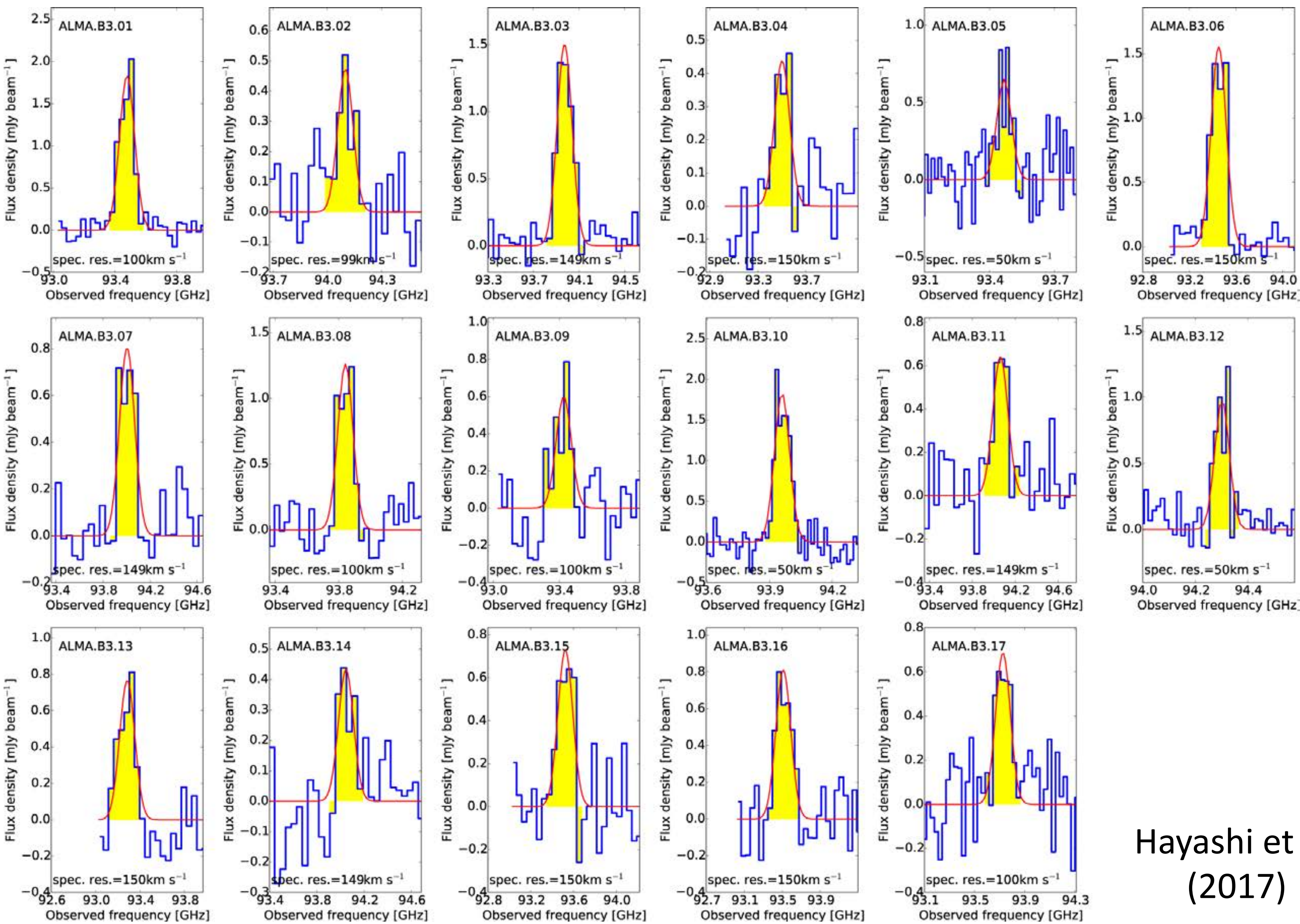
Noise level ~ 0.11 mJy/beam (in Δv = 200 km/s)

Hayashi et al. (2017)

CO(2-1) emission lines from 17 cluster members

XCS2215 cluster (z=1.46)

($>10^{10}$Msun)

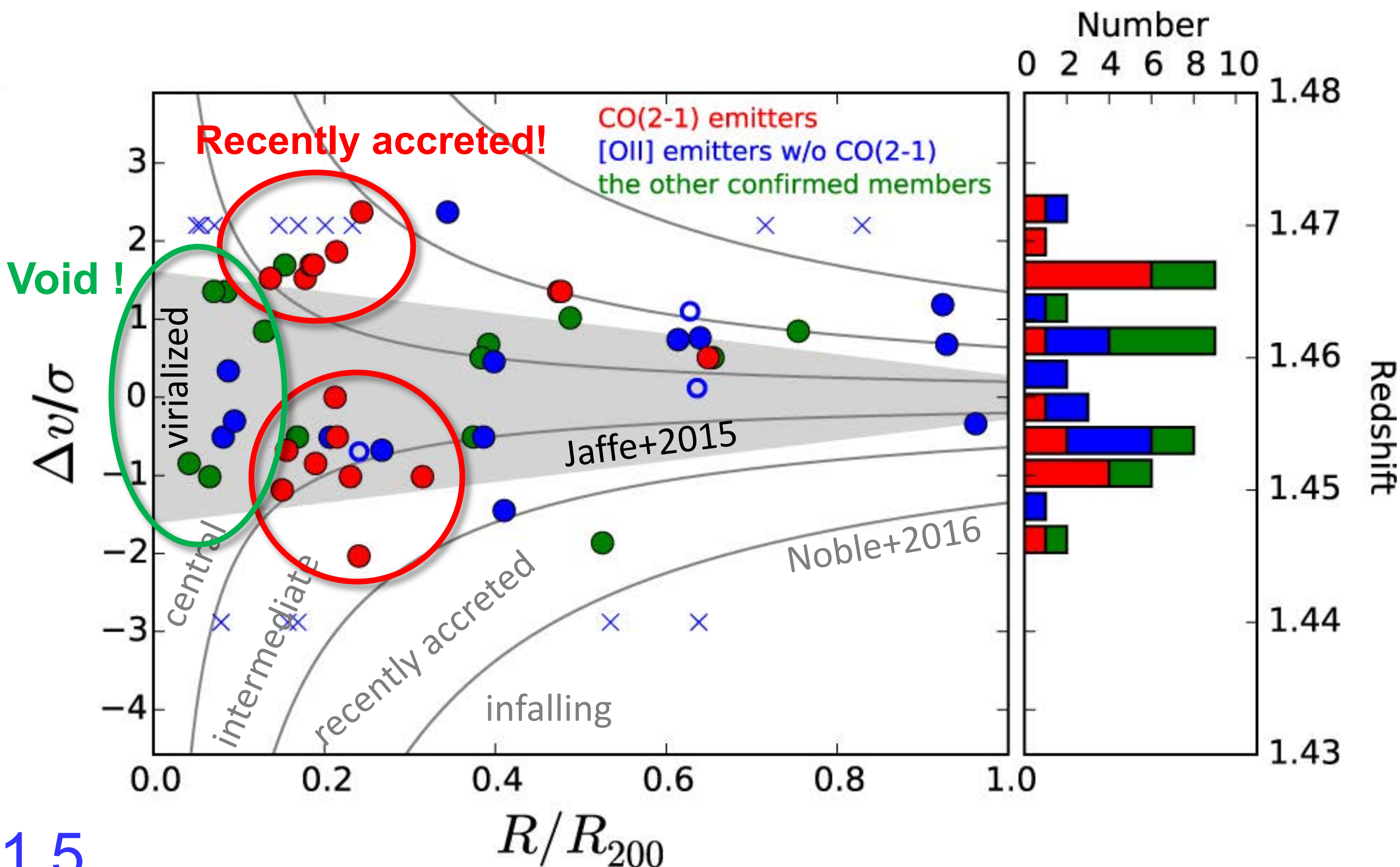


Hayashi et al. (2017)

Cluster phase space diagram

XCS2215 cluster (z=1.46)

Gas rich galaxies seem to be recently accreted galaxies.

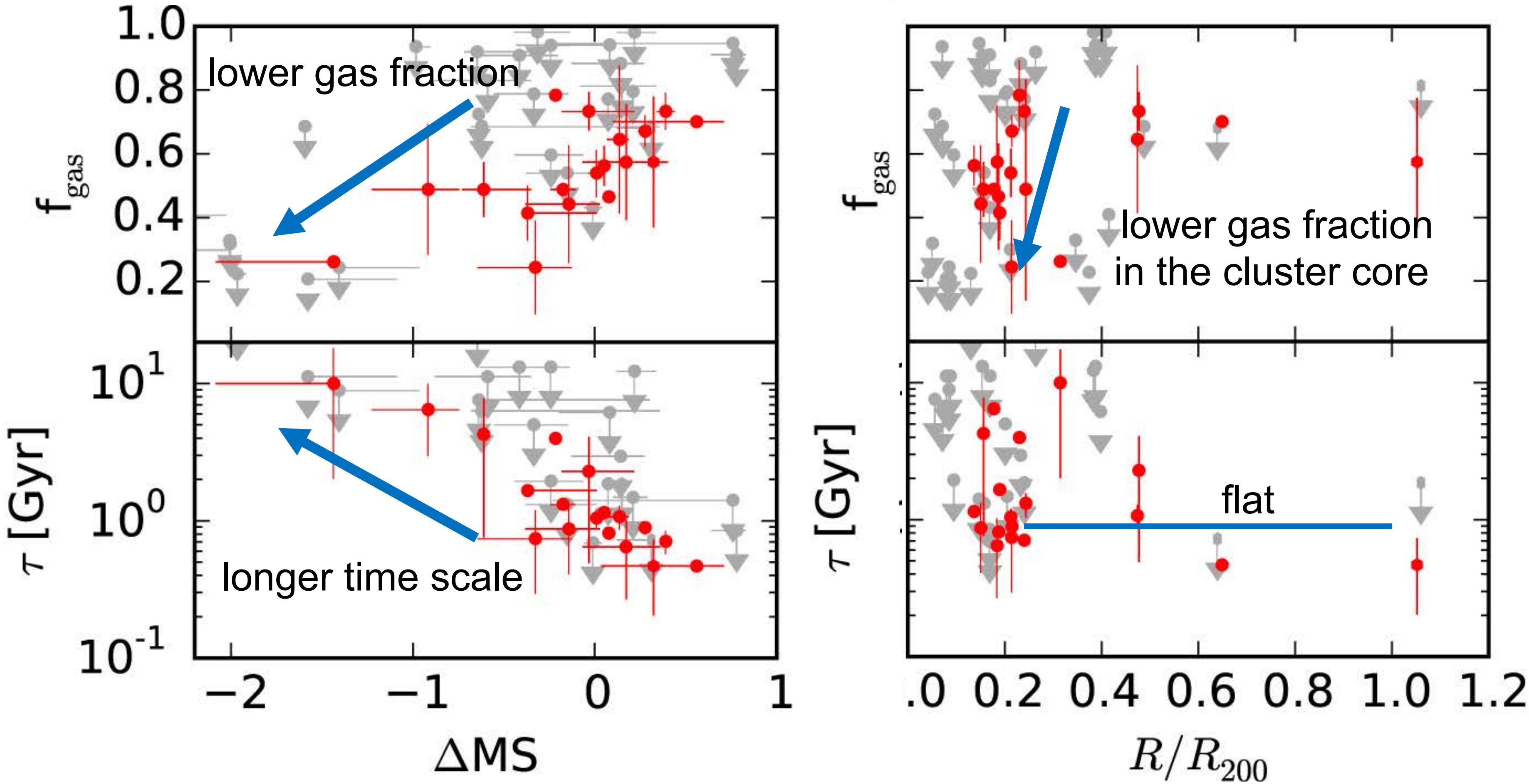


z~1.5

Hayashi et al. (2017)

Gas mass fraction (f_{gas}) and depletion time scale (τ)

z~1.5 XCS2215 cluster (z=1.46)



M_{gas} with Tacconi et al. (2018) recipe.

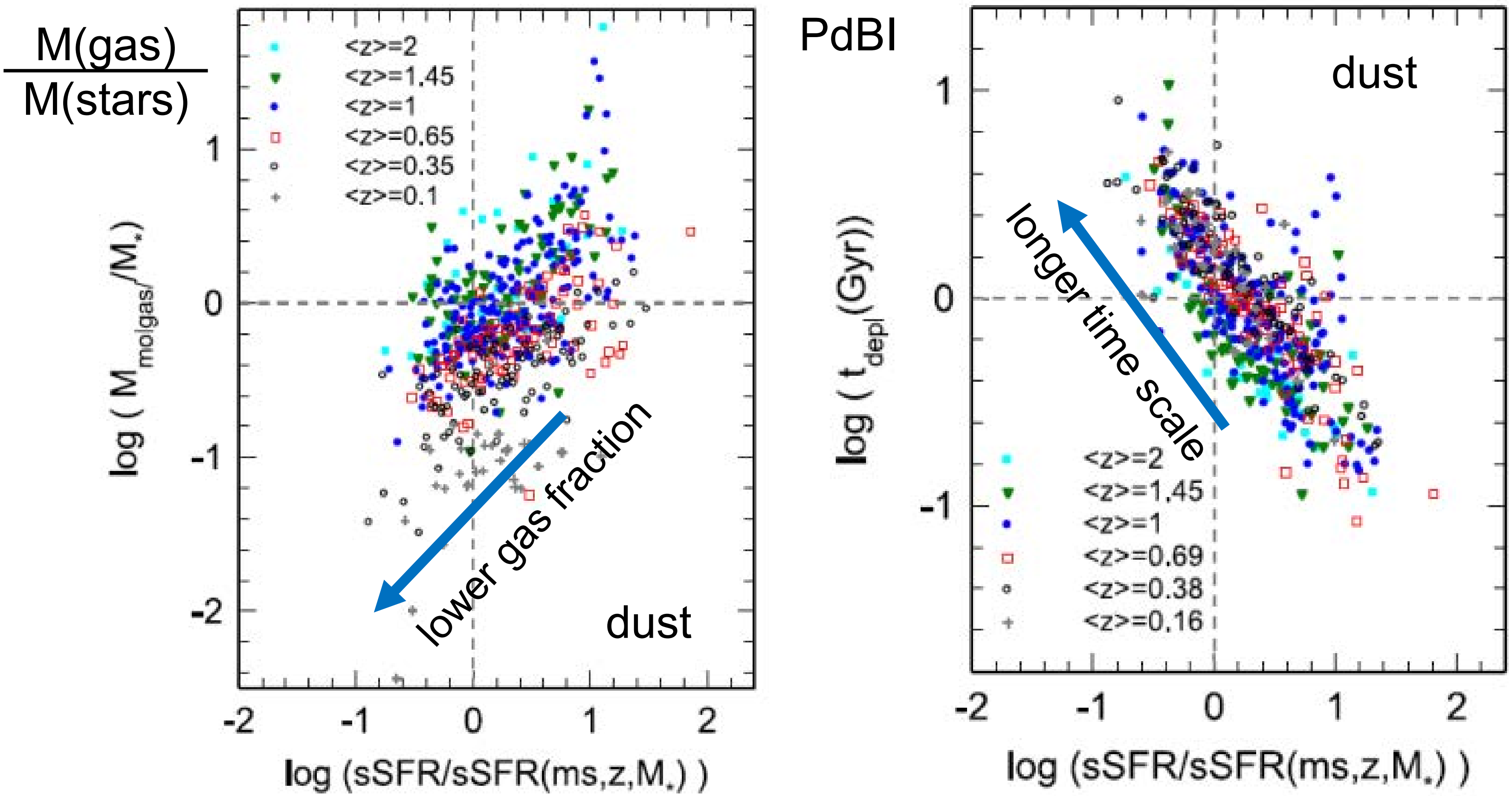
$f_{gas} = M_{gas} / (M_{star} + M_{gas})$ $\tau = M_{gas} / SFR$

Hayashi et al. (2017)

Field galaxies at 0.1<z<2:

f_{gas} and τ_{dep} (1/SFE) and as a function of Δ(MS)

Both are equally contributing to enhancement/quenching.

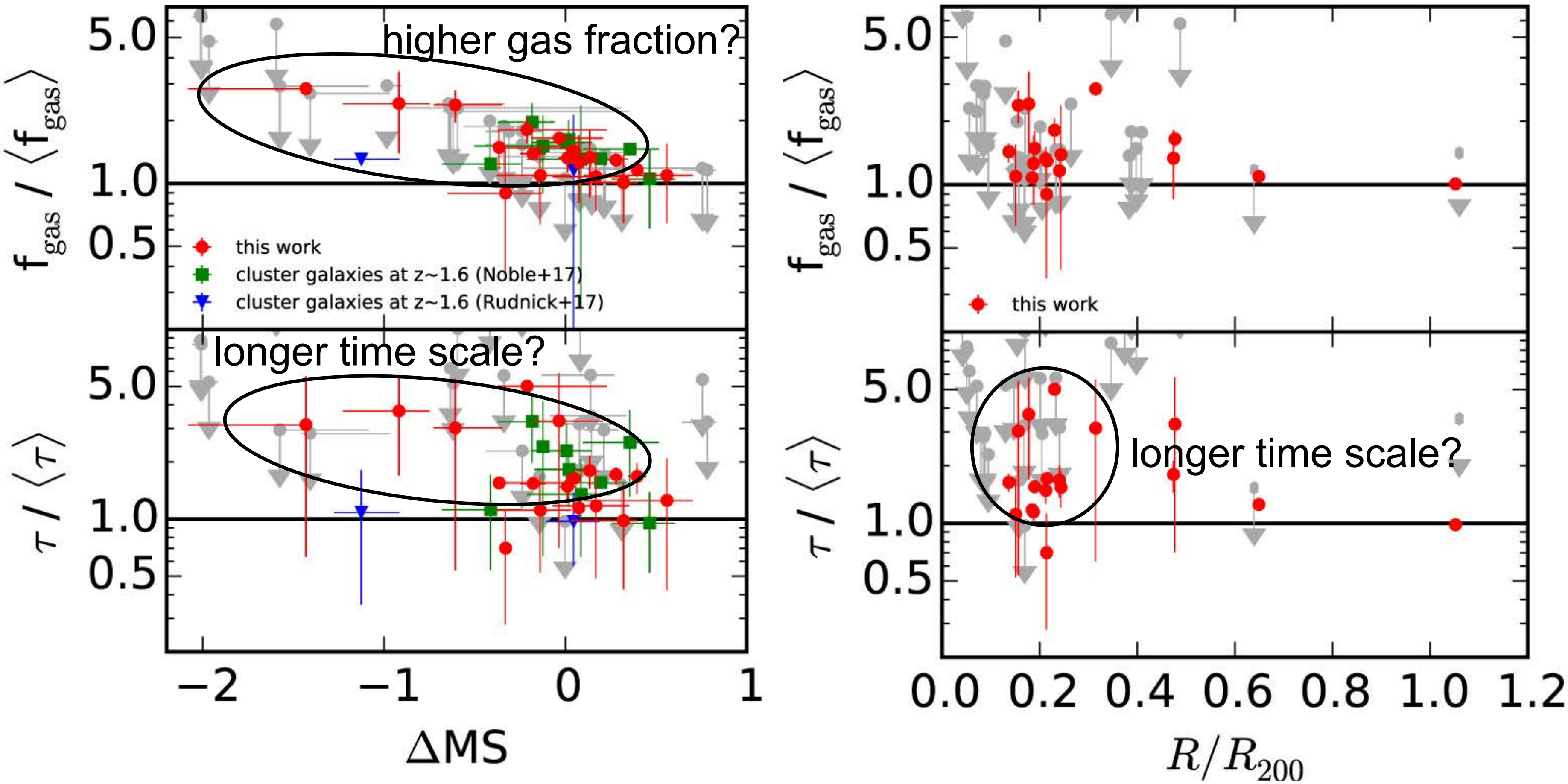


Genzel et al. (2015)

See also COLDGASS project (Saintonge et al. 2011) for similar trend at z~0

Environmental dependence?

z~1.5 XCS2215 cluster (z=1.46)



Horizontal lines: ***Scaling relation*** by Tacconi et al. (2018) for ***field galaxies (SFR, M*)***

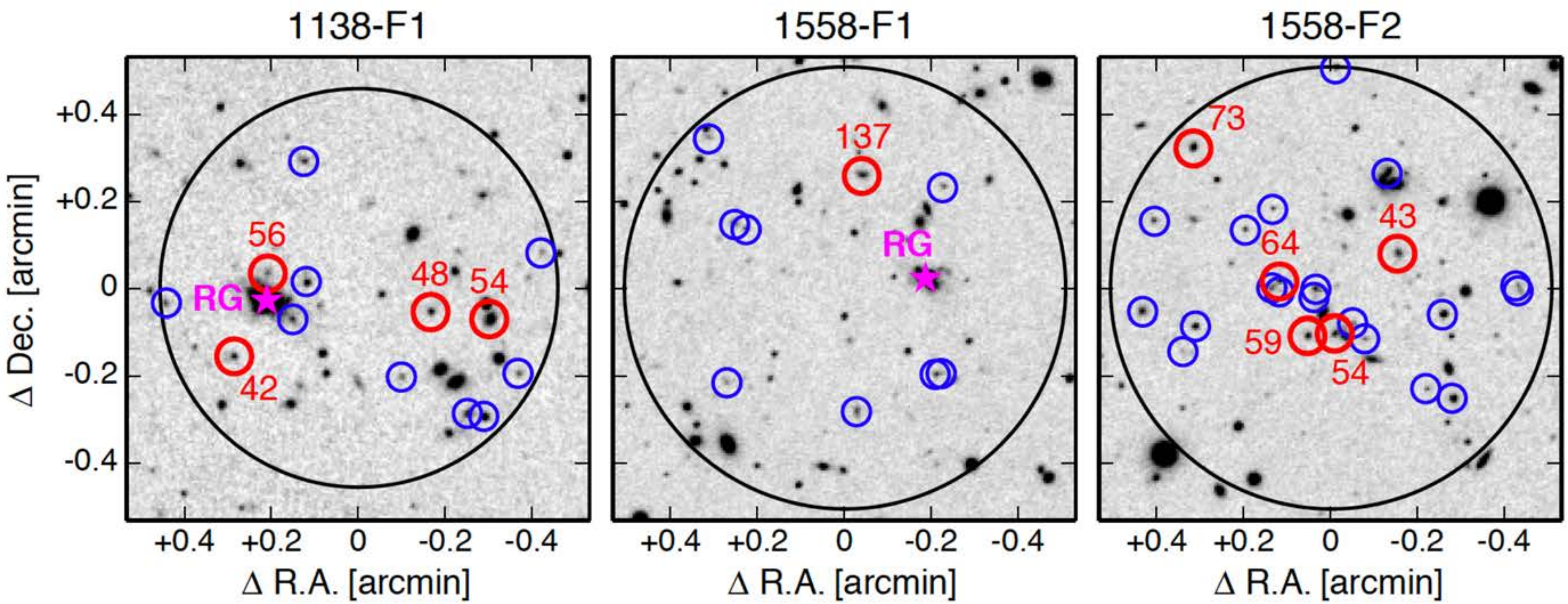
$f_{gas} = M_{gas} / (M_{star} + M_{gas})$ $\tau = M_{gas} / SFR$

Hayashi et al. (2017)

ALMA Band-3 observations of z=2-2.5 proto-clusters (all around HzRGs)

+ 4C23.56 (z=2.48)

PKS1138 (z=2.16) USS1558 (z=2.53)



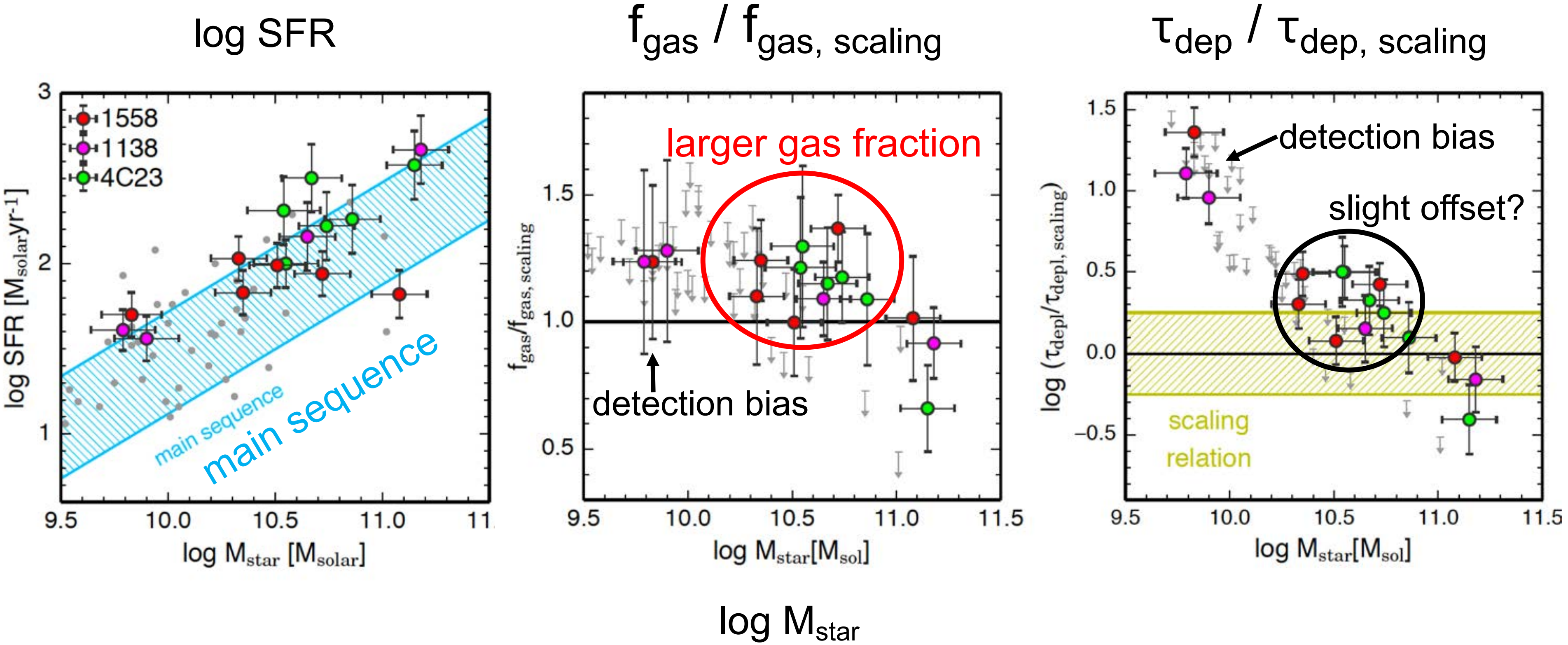
Beam size = 59" diameter

○ ALMA CO(3-2) detections
○ non detections

Tadaki et al. (2018)

Environmental dependence?

z~2.5

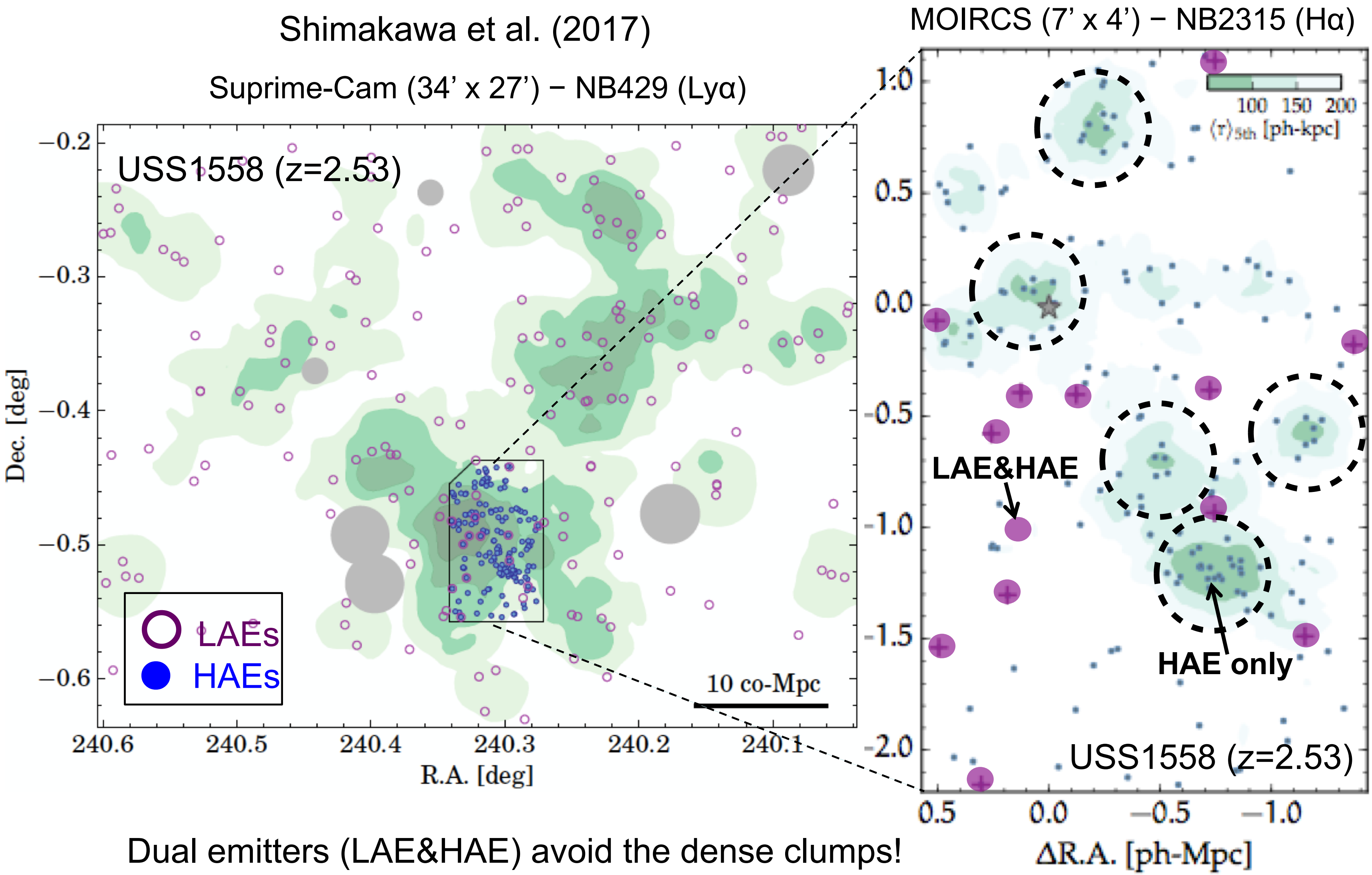


Horizontal lines: ***Scaling relation*** by Tacconi et al. (2018) for ***field galaxies (SFR, M*)***

Larger gas fraction in proto-cluster galaxies compared to the general field due to the efficient cold gas accretion towards the intersections of the filaments?

Tadaki et al. (2018)

Dual NB emitter survey (Lyα, Hα) of a proto-cluster at z=2.5



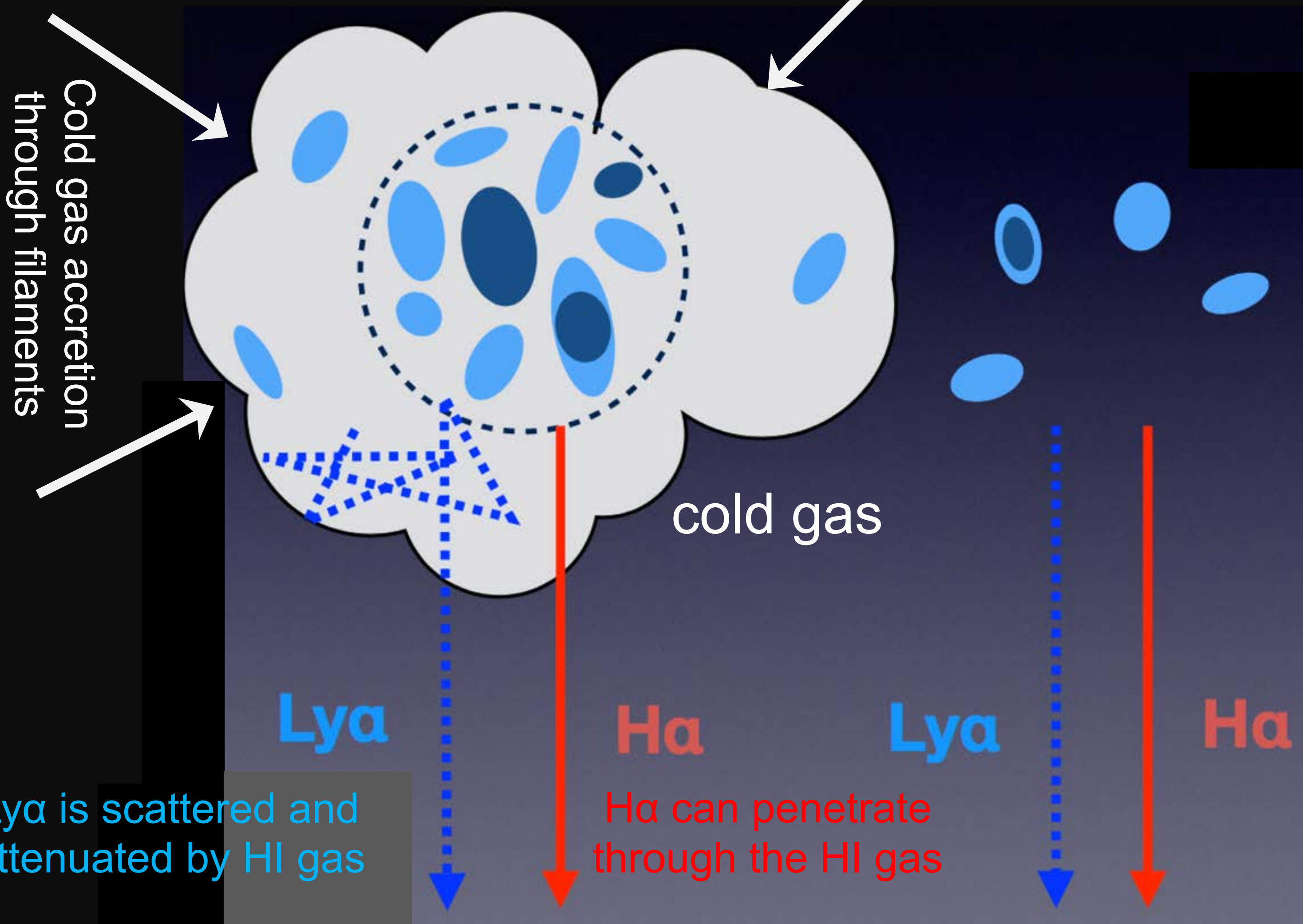
Dual emitters (LAE&HAE) avoid the dense clumps!

→ Dense cores are enshrouded by HI gas fed by cold streams?

USS1558 (z=2.5)

Proto-cluster core

Field



Shimakawa et al. (2017)

Dual NB Survey (Lyα + Hα)

Not **transparent** ✕ ◎ ○ ◎

Low Lyα/Hα ratios of galaxies in the cluster core → HI gas is associated

Summary

- **Mahalo-Subaru** has been mapping LSSs around distant clusters at high redshifts and revealing star formation histories in clusters, such as the boosting of SF in a proto-cluster core ($z\sim2.5$) and the inside-out quenching of SF at $z<2$.

- **Gracias-ALMA** is now detecting gas/ISM within the SFGs and its environmental dependence, such as higher gas fraction in proto-cluster cores ($z>1.5$), which may trigger high SF activities. Will resolve internal structures of galaxies and witness physical processes in action with high resolution observations.

- These results can be interpreted by abundant gas associated to proto-cluster core fed by cold streams.