Galaxies in 3D across the Universe (IAUS 309) @ Vienna, 2014/7/10

Mapping and resolving galaxy formation at its peak epoch with Mahalo-Subaru and Gracias-ALMA

Taddy Kodama (NAOJ)

Masao Hayashi, Ken-ichi Tadaki (NAOJ), Ichi Tanaka (Subaru),
Yusei Koyama (JAXA/ISAS),
Rhythm Shimakawa, Tomoko Suzuki, Moegi Yamamoto (NAOJ/GUAS),
and Mahalo-Subaru and Gracias-ALMA collaborations

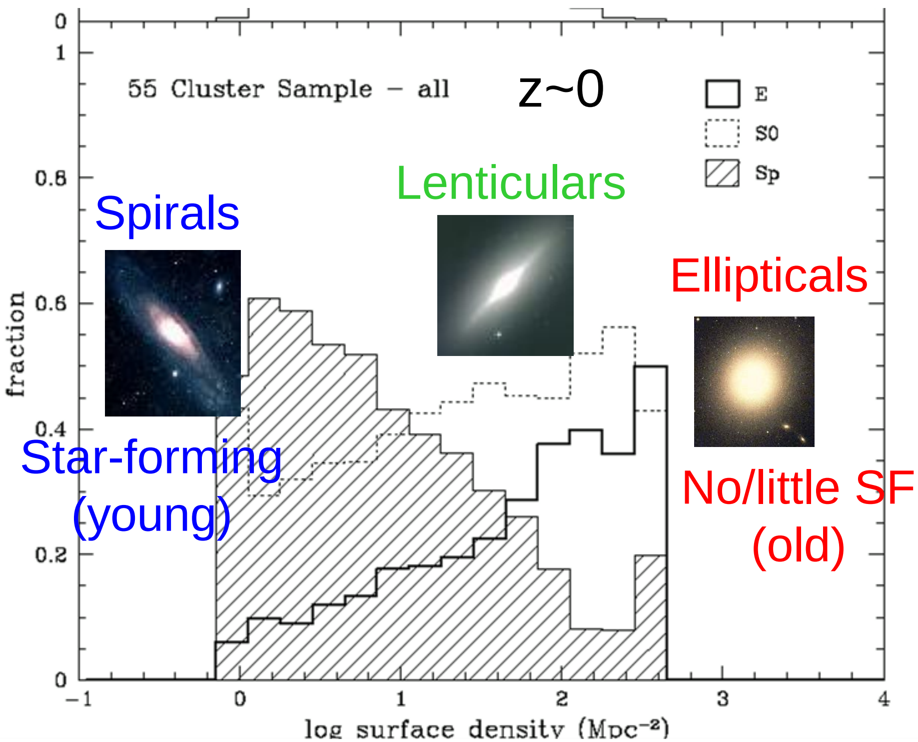
A galaxy cluster RXJ0152 at z=0.83 (Subaru/Suprime-Cam)

Outline

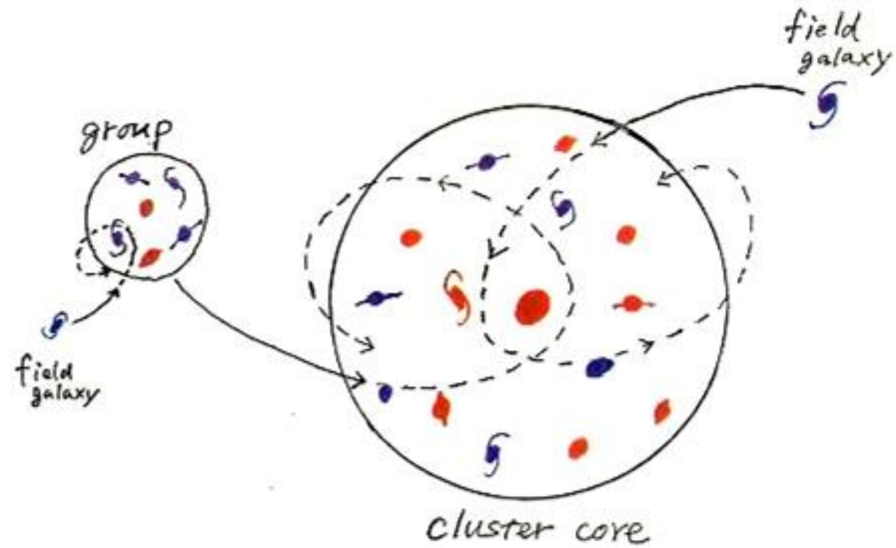
- Cosmic evolution of star forming activities in clusters since $z \sim 2.5$
- Environmental dependence of chemical evolution at $z>2$
- Spatially resolved views of "red" emitters and clumps at $z>2$

What is the origin of the cosmic habitat segregation?

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

"MAHALO-Subaru"

MApping HAlpha and Lines of Oxygen with Subaru

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

	environ-ment	target	z	line	λ (μm)	camera	NB-filter	conti-nuum	status
z<1 clusters	Low-z cluster	CL0024+1652	0.40	Hα	0.916	S-Cam	NB912	z'	Kodama+'04
		CL0939+4713	0.41	Hα	0.923	S-Cam	NB921	z'	Koyama+'11
		RXJ1716.4+6708	0.81	Hα	1.190	MOIRCS	NB1190	J	Koyama+'10
				[OII]	0.676	S-Cam	NA671	R	observed
z~1.5 clusters	High-z cluster	XCSJ2215–1738	1.46	[OII]	0.916	S-Cam	NB912,921	z'	Hayashi+'10,'11
		4C65.22	1.52	Hα	1.651	MOIRCS	NB1657	H	Koyama+'14
		CL0332–2742	1.61	[OII]	0.973	S-Cam	NB973	y	Hayashi+'13
		CIGJ0218.3–0510	1.62	[OII]	0.977	S-Cam	NB973	y	Tadaki+'12
z>2 clusters	Proto-cluster	PKS1138–262	2.16	Hα	2.071	MOIRCS	NB2071	K_s	Koyama+'12
		4C23.56	2.48	Hα	2.286	MOIRCS	NB2288	K_s	Tanaka+'11
		USS1558–003	2.53	Hα	2.315	MOIRCS	NB2315	K_s	Hayashi+'12
z>2 field	General field	GOODS-N	2.19	Hα	2.094	MOIRCS	NB2095	K_s	Tadaki+'11
		(70 arcmin^2)		Hβ	1.551	MOIRCS	NB1550	H	not yet
				[OII]	1.189	MOIRCS	NB1190	J	observed
		SXDF-CANDELS	2.19	Hα	2.094	MOIRCS	NB2095	K	Tadaki+'13
		(92 arcmin^2)		Hβ	1.551	MOIRCS	NB1550	H	not yet
				[OII]	1.189	MOIRCS	NB1190	J	not yet
			2.53	Hα	2.315	MOIRCS	NB2315	K_s	Tadaki+'13

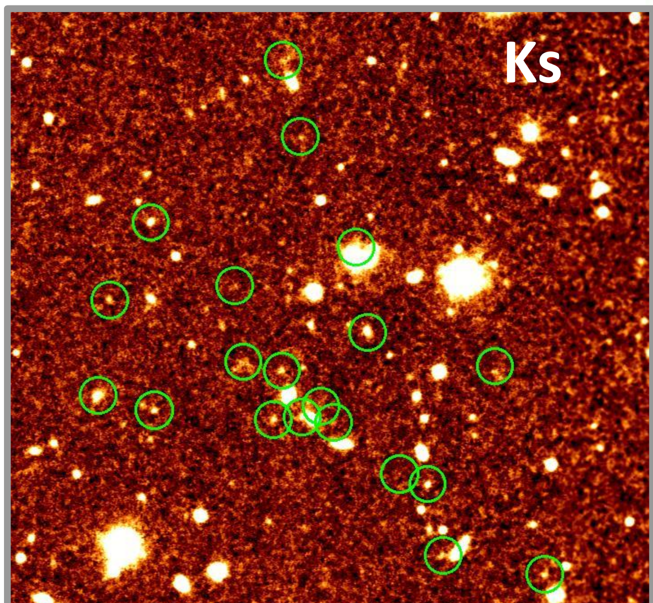
18 nights for imaging, >15 nights for spectroscopy

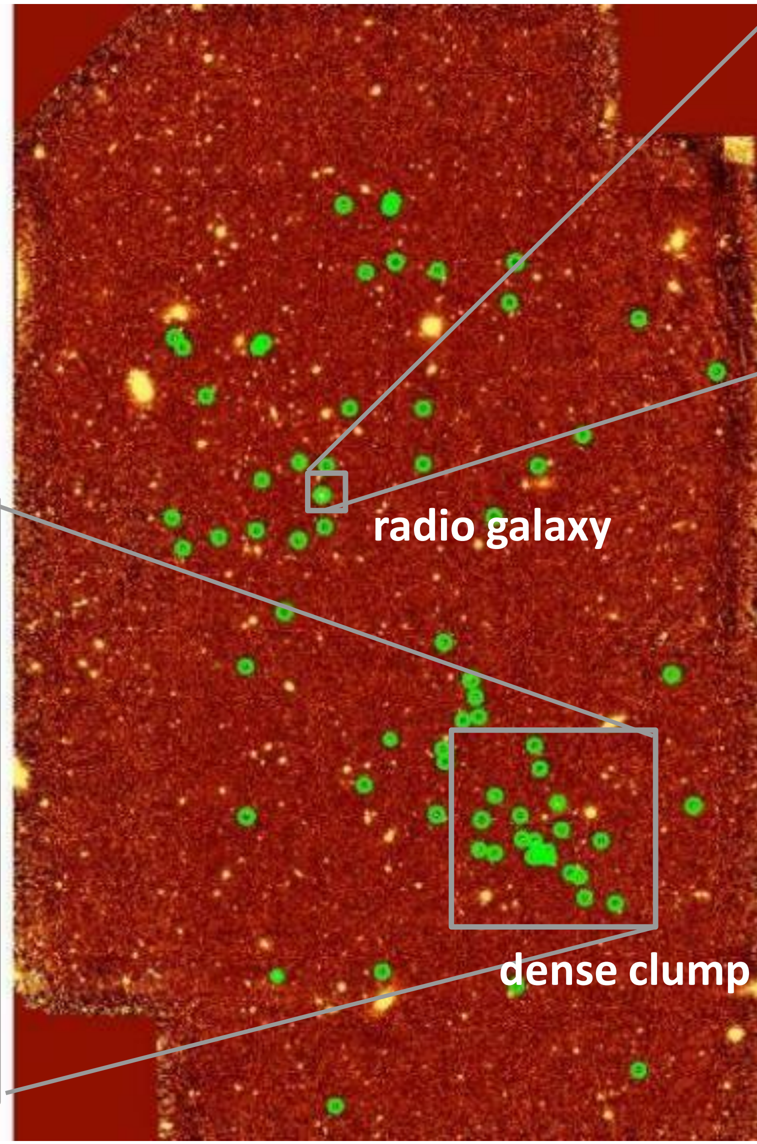
A Prominent Star-Bursting Proto-Cluster at z~2.5

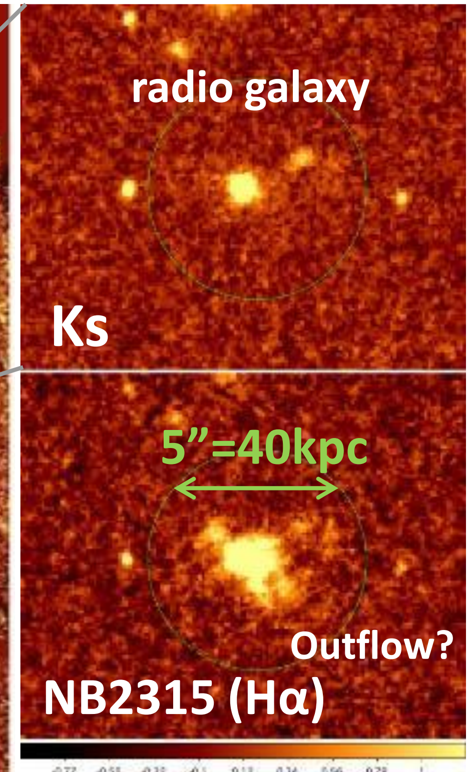
USS1558-003 (z=2.53)

Hα imaging
with MOIRCS/NB2315

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







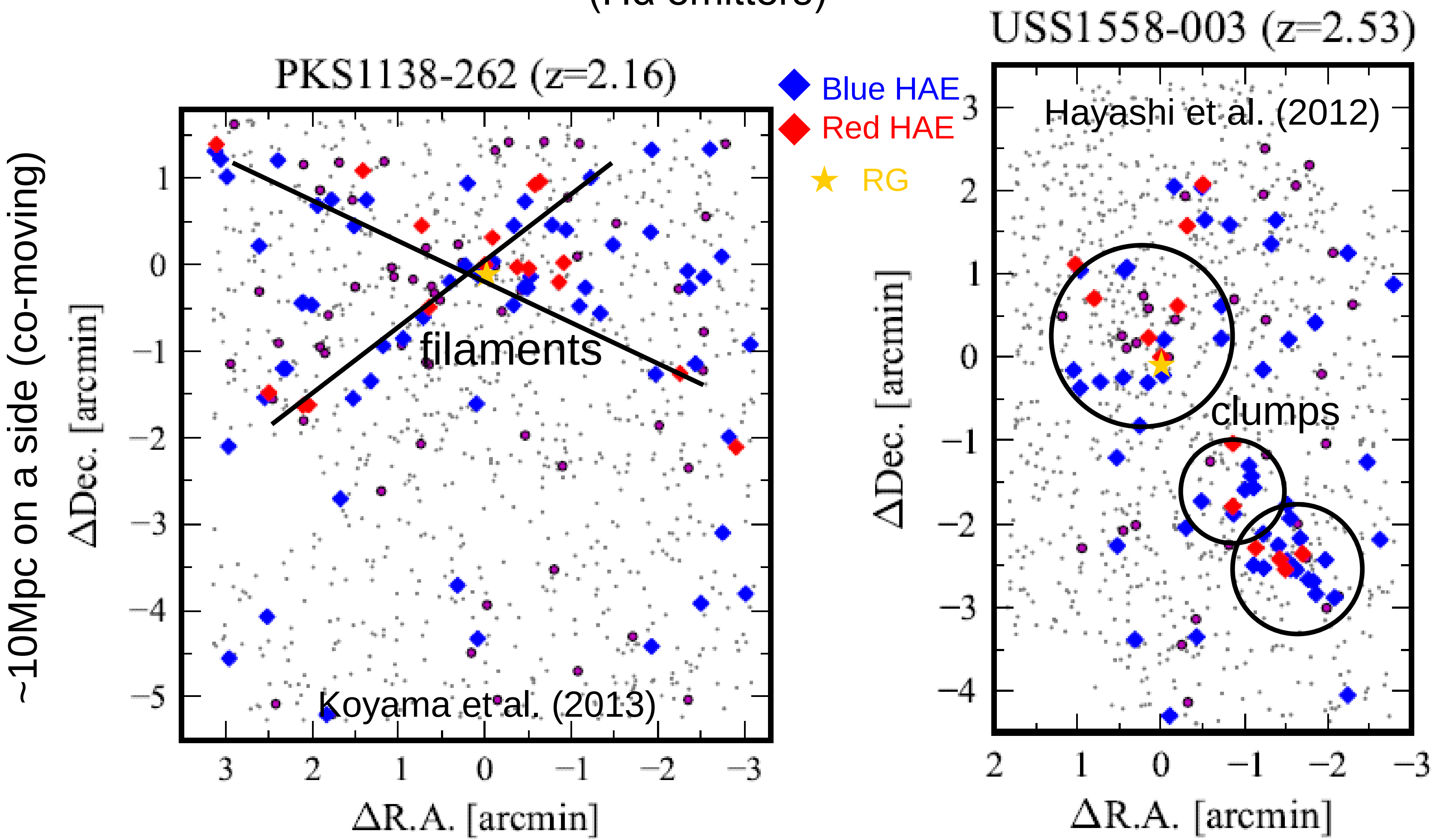
1.5Mpc away
from the RG

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

Hayashi et al. (2012)

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

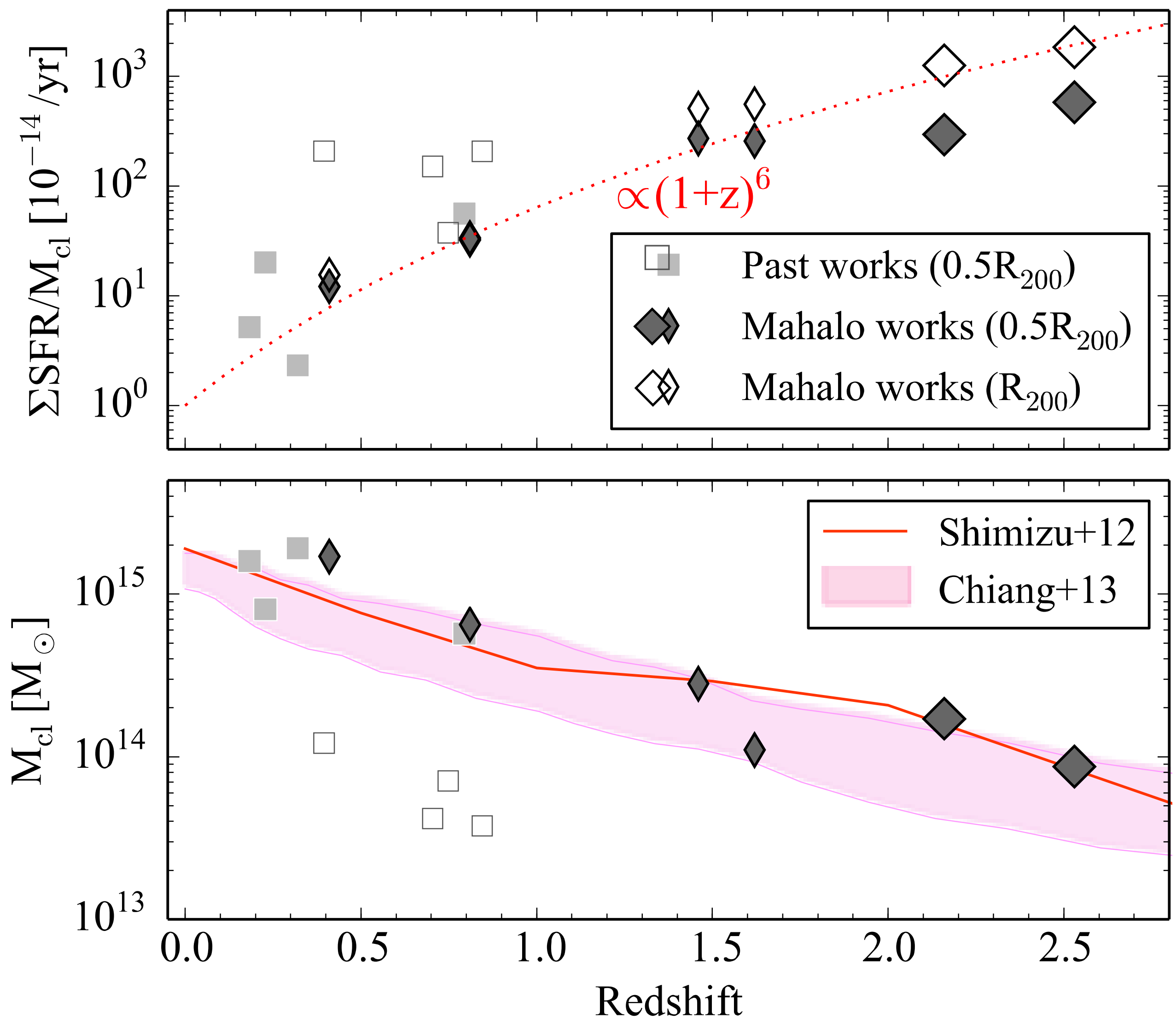
(Hα emitters)



Proto-clusters are filamentary/clumpy, in the mid of vigorous assembly!

Red Ha emitters (dusty starbursts?) tend to favor higher density regions!
(=key populations under the influence of environmental effects)

Dynamical masses and Integrated SFRs in cluster cores



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

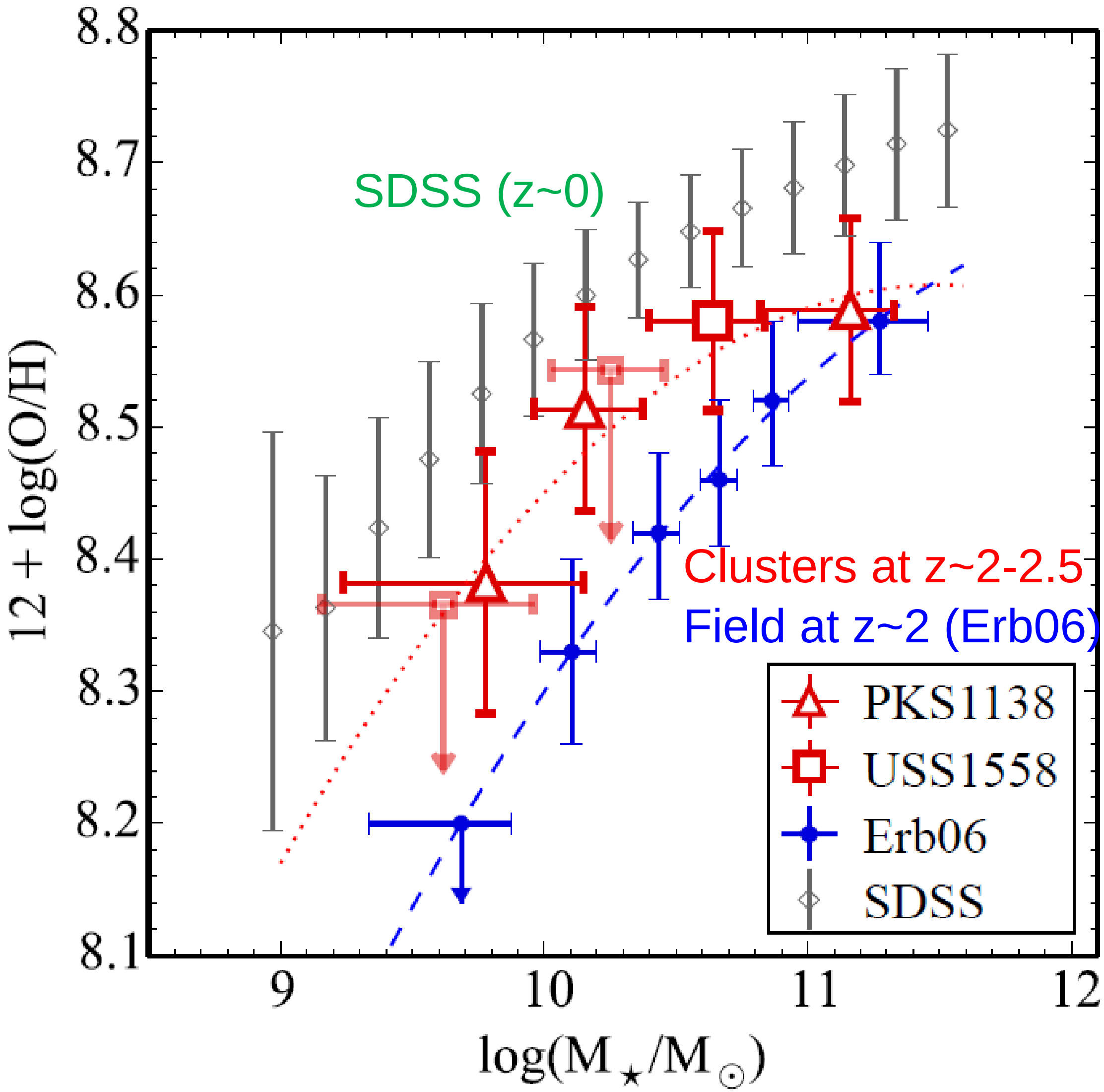
Numerical simulations suggest that these proto-clusters will grow to ~$10^{15}M_{\odot}$ clusters by the present-day

Shimakawa et al. (2014a)

Poster #76 Shimakawa et al.

Environmental Dependence of Gaseous Metallicity at z>2

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



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)?

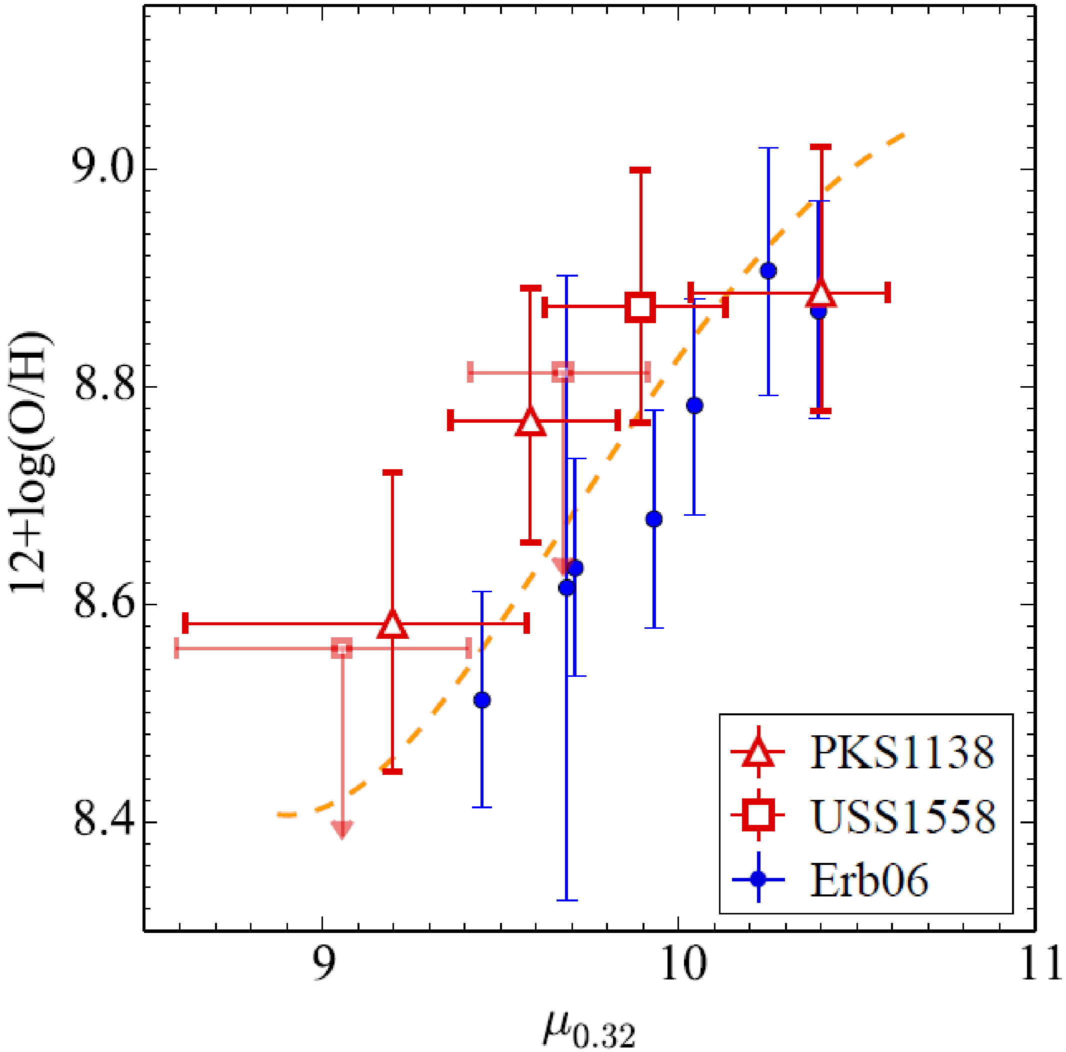
③ Stripping of metal poor gas from the reservoir, and stopping dilution of metals.

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

Shimakawa et al. (2014b)

Poster #76 Shimakawa et al.

Fundamental Metallicity Relation



$\mu_{0.32} \equiv \log(M_\star) - 0.32 \log(SFR)$

Cluster > Field
at low-mid mass?

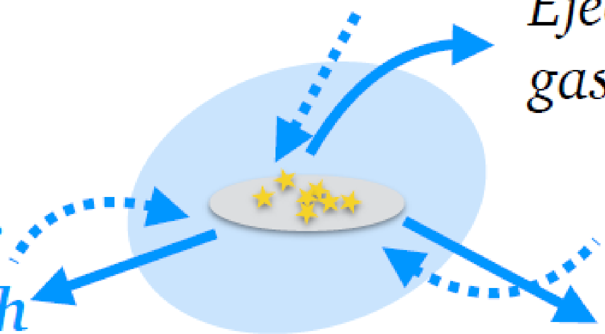
It is not just because the evolutionary stages of cluster SFGs are more advanced (=gas fraction is smaller), but their effective yield must be higher due to some external effects!

either
③ stripping of metal poor gas
or
④ recycling of metal rich gas
in proto-clusters

Shimakawa et al. (2014b)

Inflow and outflow processes may well depend on environment !

General field



(Proto)cluster

Recycling of metal enriched gas

Stripping of metal poor gas from the reservoir

(Dave+ ’11; Kulas+ ’13)

Clumpy structures are common in HAEs at z~2 (Field)

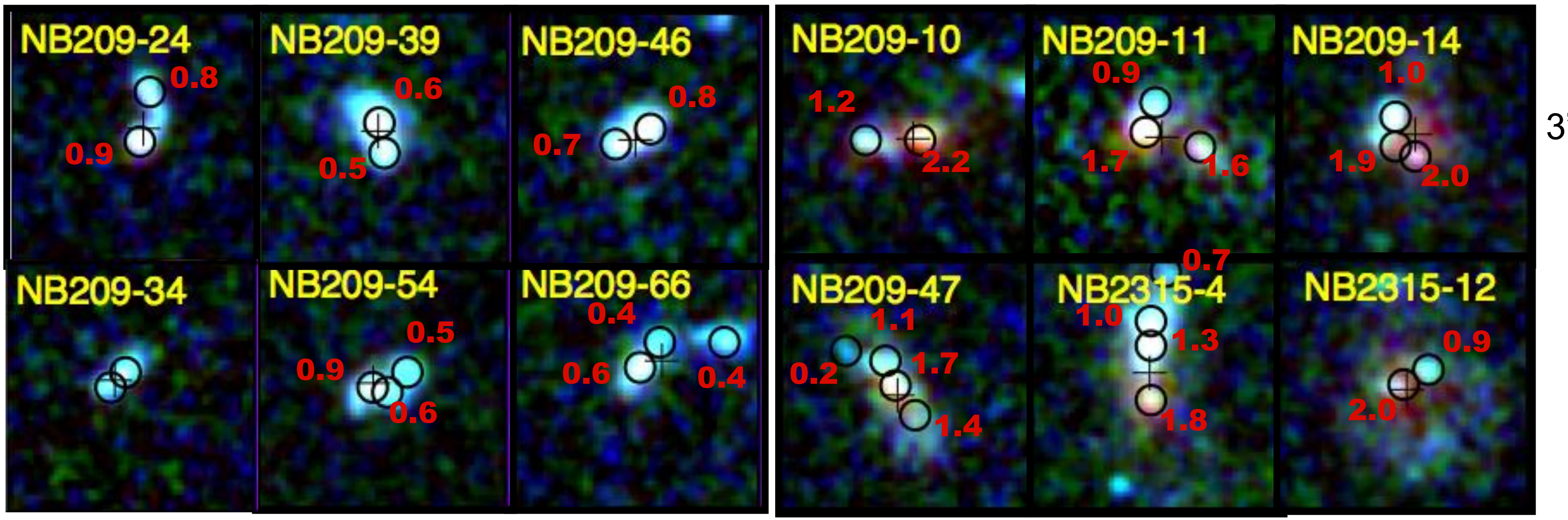
~40% of HAEs at z~2 show clumpy (or merger) structures

HST images (V_{606},I_{814},H_{160}) from the CANDELS survey

less massive clumpy galaxies
(M_{star}<$10^{10}M_{\odot}$)

massive clumpy galaxies
(M_{star}=$10^{10\text{-}11}M_{\odot}$)

3” (~25kpc)

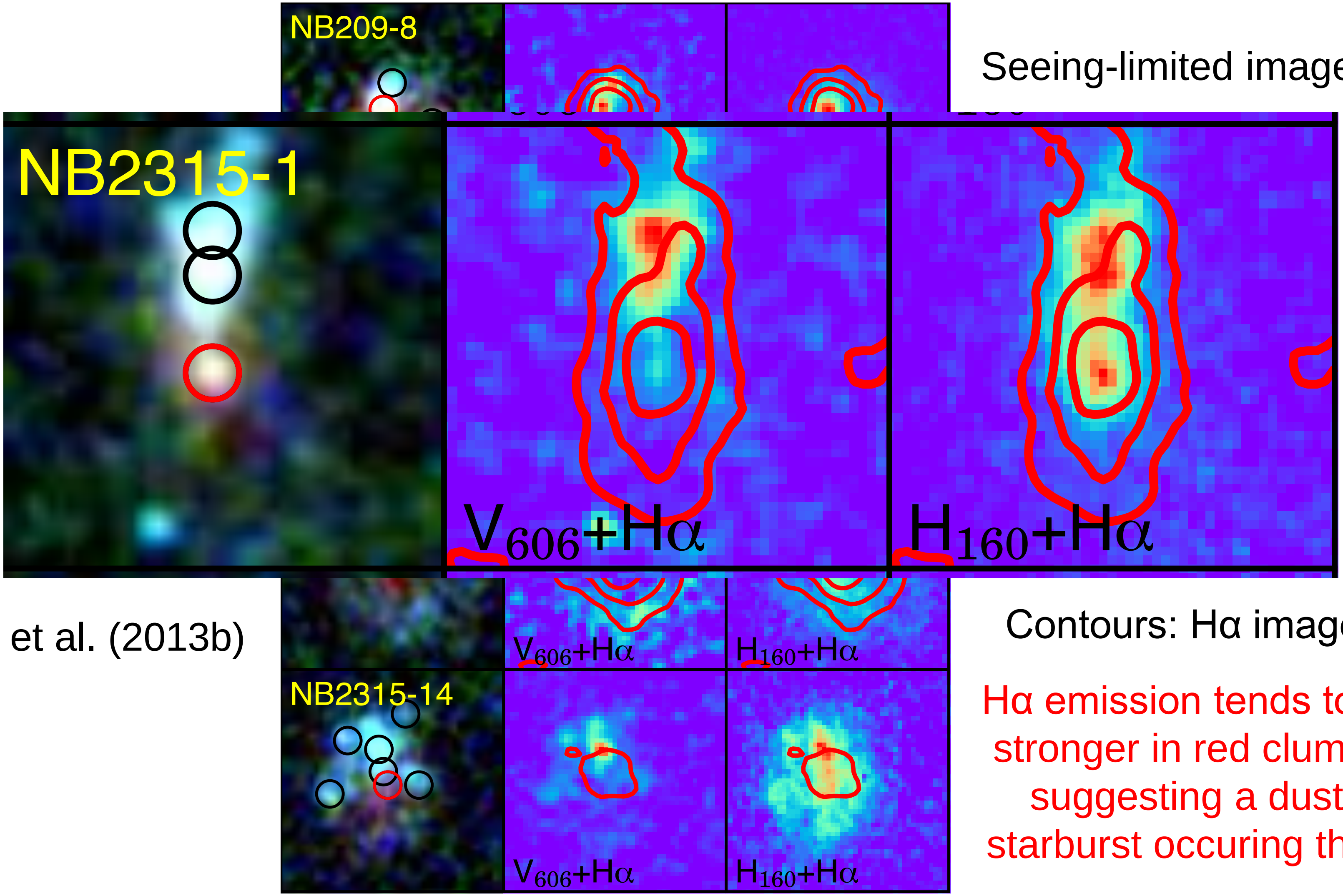


colours (I_{814}-H_{160}) of individual clumps are shown with red numbers

Tadaki et al. (2013b)

Massive galaxies tend to have a red clump near the stellar mass center,
And they tend to be detected with MIPS 24μm.
→ The red clumps may be the site of nucleated dusty starburst to form a bulge!
We need to spatially resolve star forming activities within galaxies.

Spatially resolved Hα line emission in clumpy galaxies



Seeing-limited images

Tadaki et al. (2013b)

Contours: Hα images

Hα emission tends to be stronger in red clumps, suggesting a dusty starburst occuring there

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

"GRACIAS-ALMA"

GRAphing CO Intensity And Submm with ALMA

Mapping/resolving molecular gas and dust contents of high-z SF galaxies

cycle-2 sensitivities

CO line @ Band-3 (~100GHz) SFR~50$M_\odot$/yr (2.7hrs, 5σ)

Dust continuum@ Band-6-9 (450 μm–1.1 mm) SFR~15$M_\odot$/yr (50min, 5σ)

@1<z<3

Spatial resolution: 0.01-0.1" (←→ 0.1-1kpc) (0.18-0.4" in cycle-2)

		Mahalo-Subaru				Gracias-ALMA		cycle-1	
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+	**1st**
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+	**2nd**
4C23.56	2.48	Hα	2.286	NB2288	MCS	B6,7,9	CO(3-2)@99 (B3)	Suzuki+	**1st**
1558–003	2.53	Hα	2.315	NB2315	MCS	B6,7,9	CO(3-2)@98 (B3)	Kodama+	**2nd**
SXDF	2.19	Hα	2.094	NB2095	MCS	B6,7,9	CO(3-2)@108 (B3)	Tadaki+	**1st**
-CANDELS	2.53	Hα	2.315	NB2315	MCS	B6,7,9	CO(3-2)@98 (B3)	Tadaki+	**1st**

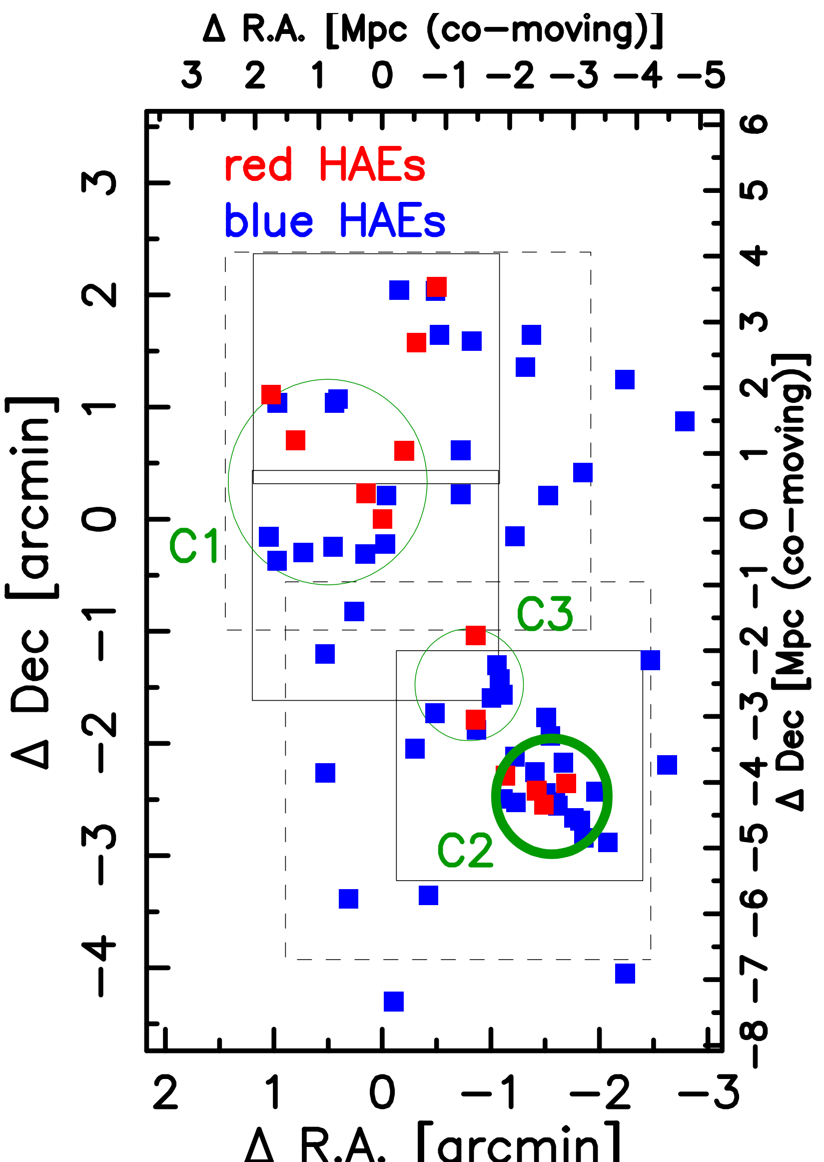
We can spatiall resolve dusty star formation directly within galaxies.

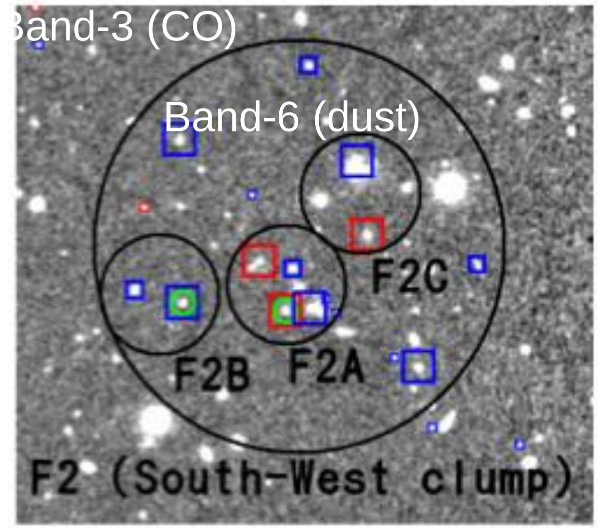
f(gas) and SFE(=SFR/M_{gas}) are essential quantities to characterize the mode of SF.

Relations between red clumps ~ dusty starbursts ~ bulge formation ~ environment

Unique targets to test the effects of environment on galaxy formation

USS1558 proto-cluster (z=2.53)





Clusters are efficient targets for ALMA especially at Band-3 as multiple targets can be observed by a single pointing (1').

HST images (Hayashi et al.) are being taken NOW! (Clumpy fraction, size evolution)

Chandra 100ks X-ray data (Martini et al.) have just been taken. (AGN fraction, distribution)

Summary

- Mahalo-Subaru has been mapping out star formation activities across cosmic times ($0.4<z<3$) and environments.
- Clusters grow inside-out, and the SF activity in cluster cores drops rapidly as $(1+z)^6$.
- Dusty starbursts are more prevalent in proto-clusters, and the key populations under the influence of environmental effects.
- Gaseous metallicities are higher in proto-clusters than in the field due to recycling of enriched gas or stripping of metal poor gas.
- Clumpy nature of SFGs at $z\sim2$ (in particular, red dusty clumps) maybe closely related to a bulge formation. We expect some environmental dependence, which should be tested with up-coming AO, HST and ALMA observations.