(Back at the Edge of the Universe @ Sintra, Portugal, 2015/3/19)

Proto-clusters at high-z (z>1.5): structures and stellar populations

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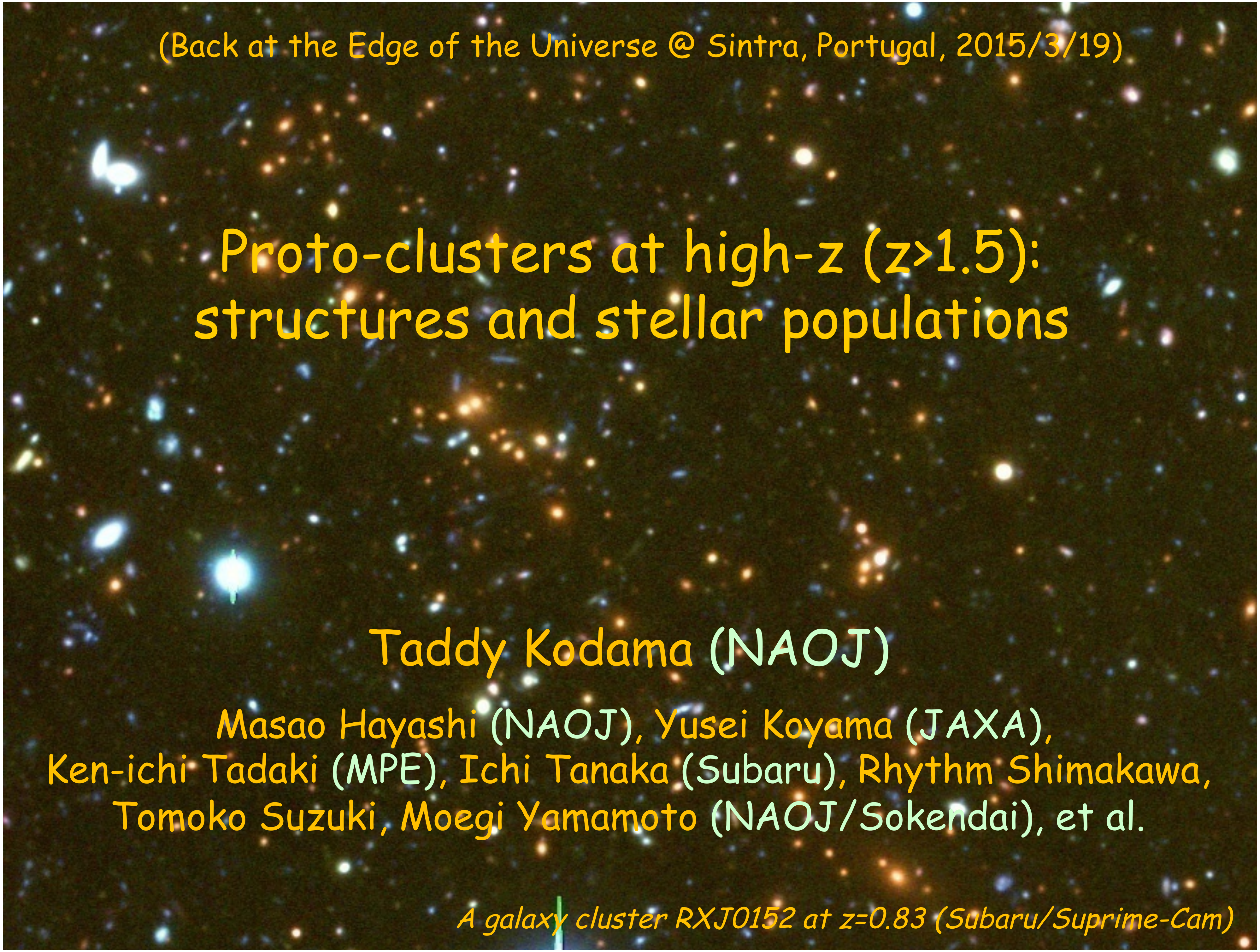
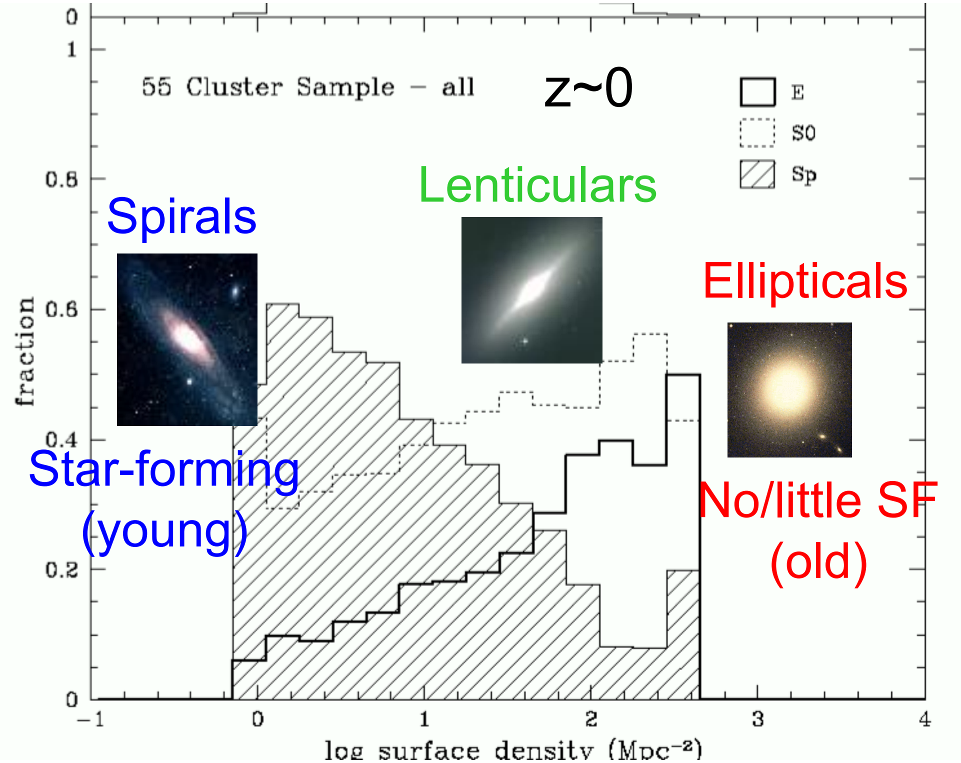
Ken-ichi Tadaki (MPE), Ichi Tanaka (Subaru), Rhythm Shimakawa,
Tomoko Suzuki, Moegi Yamamoto (NAOJ/Sokendai), et al.



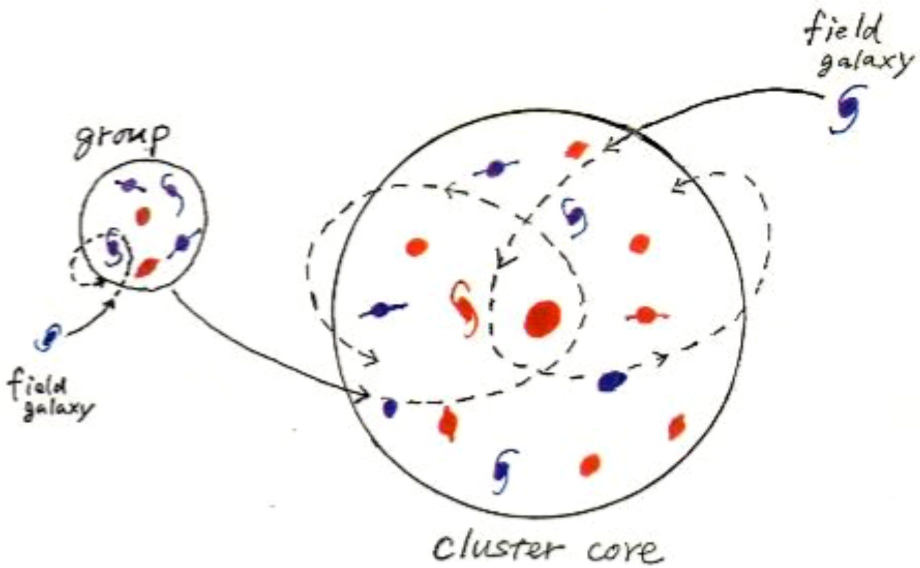
A galaxy cluster RXJ0152 at z=0.83 (Subaru/Suprime-Cam)

What is the origin of the cosmic habitat segregation?

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



log surface density (Mpc^{-2})



Nature? (intrinsic)

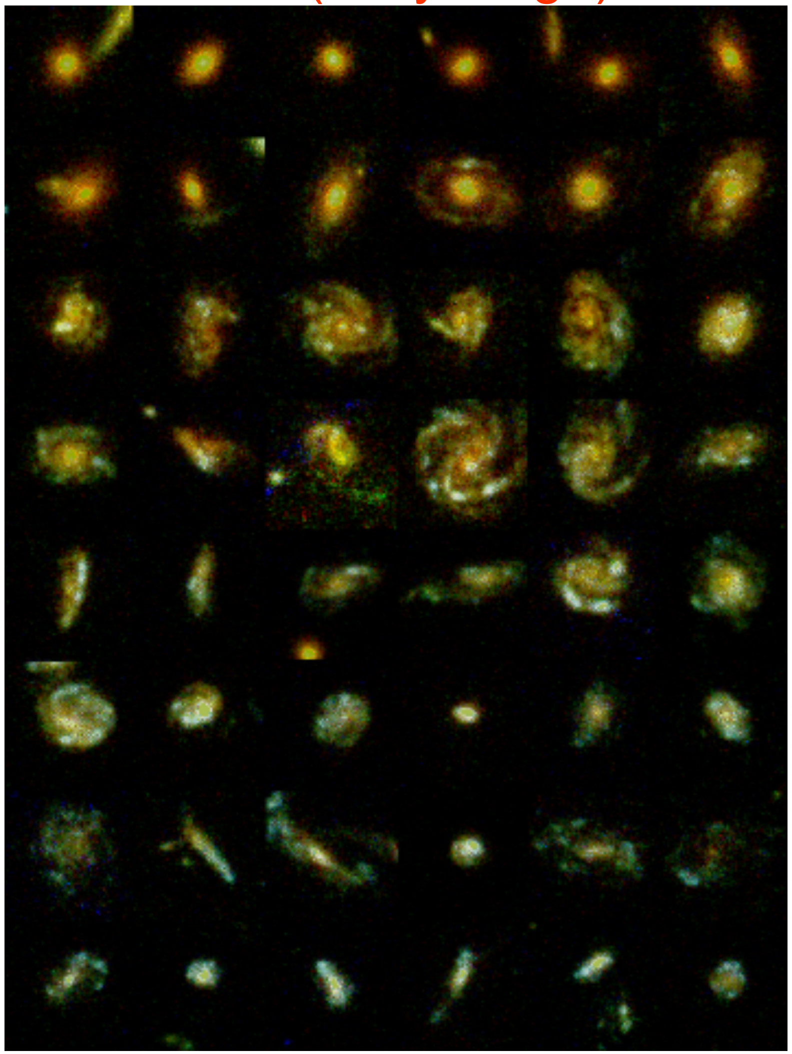
Biased, earlier galaxy formation in high density regions

Nurture? (external)

Galaxy-galaxy interaction/mergers, gas-stripping

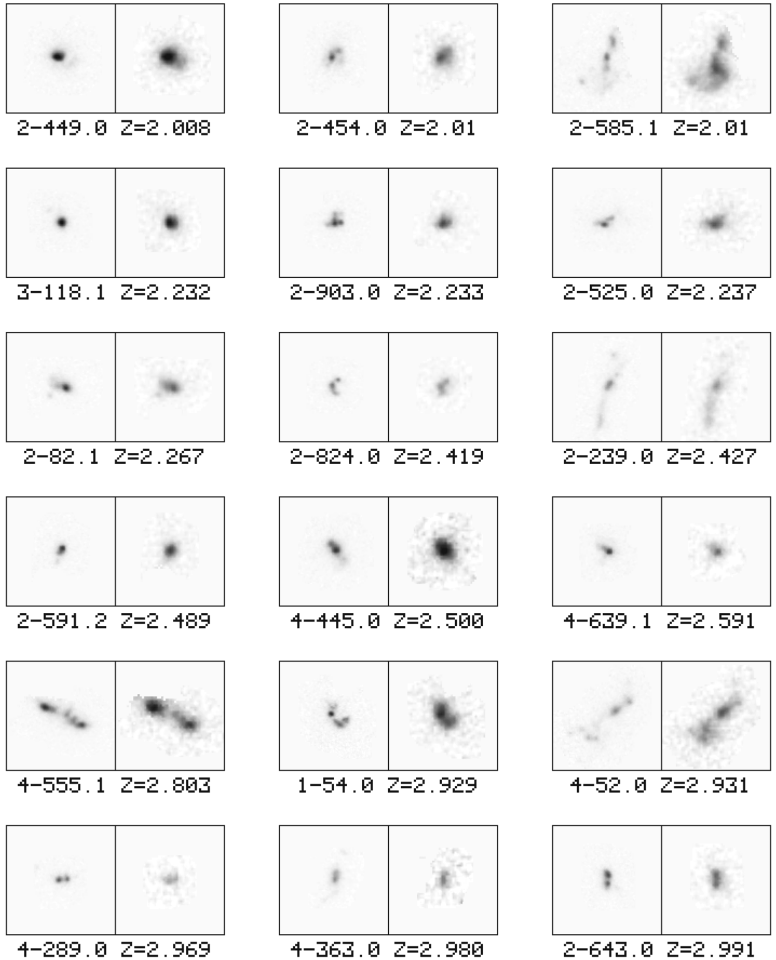
Emergence of the Hubble sequence between z=3 and 1

z~1 (8 Gyrs ago)



z~2-3 (10-11 Gyrs ago)

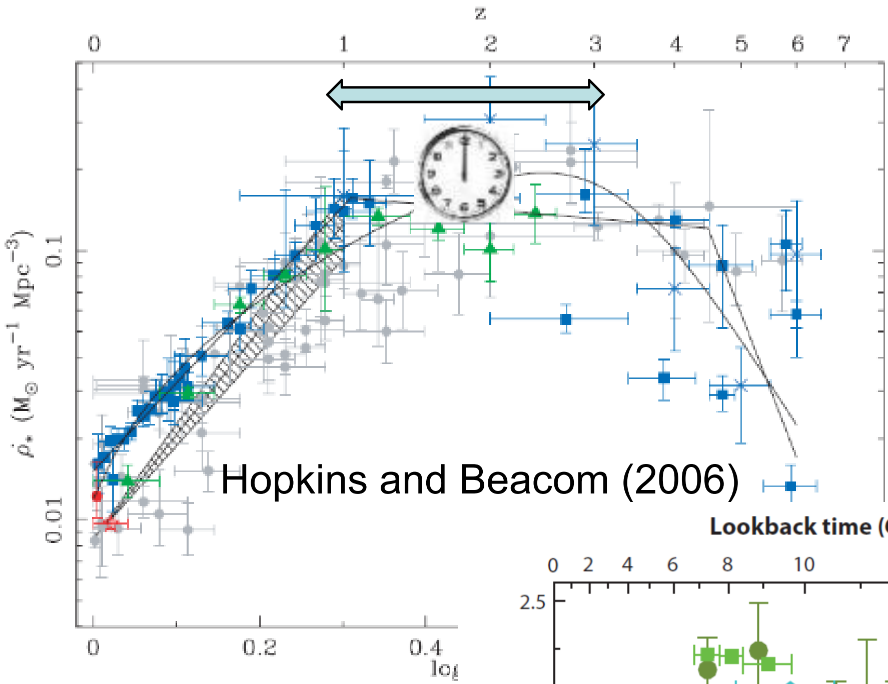
λ_{rest}=1700Å, 4300Å LBGs



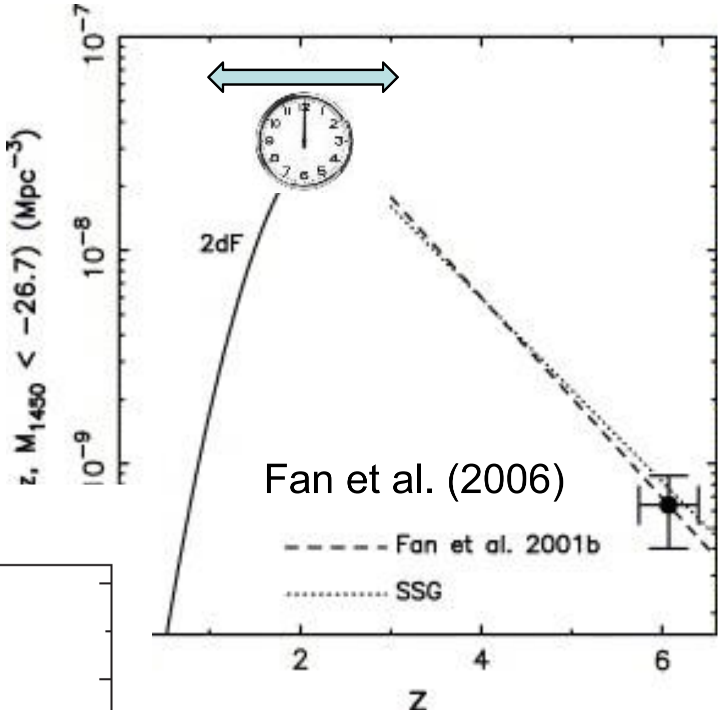
Hubble Space Telescope Dickinson (2000), ….many!

"COSMIC HIGH NOON"

The peak epoch of galaxy/SMBH formation/dust extinction: 1<z<3 (6>T_{cos}(Gyr)>2)

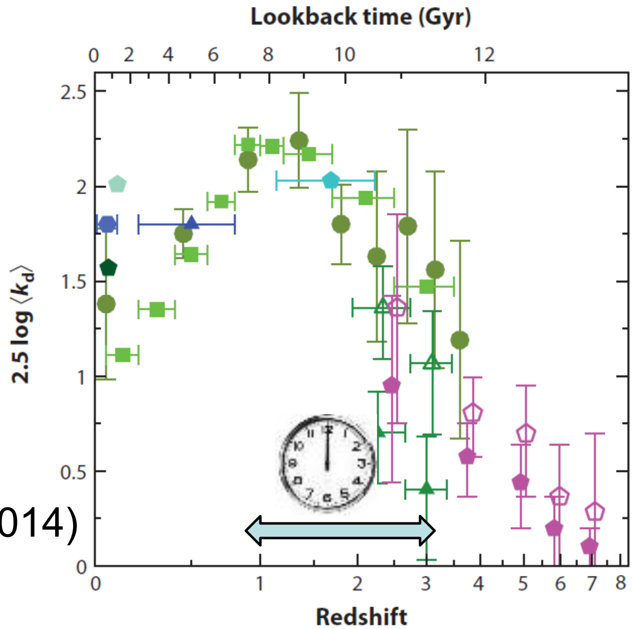


Star formation



BH accretion (AGN/QSO)

Madau & Dickinson (2014)



Dust extinction

Hα and [OIII] are better tracers of SF activities than the UV-light at this epoch, because they are less affected by dust extinction.

Outline

- How can we find proto-clusters ($z>1.5$)?
- Structures and growth of proto-clusters
- Environmental dependence of galaxy properties in proto-clusters

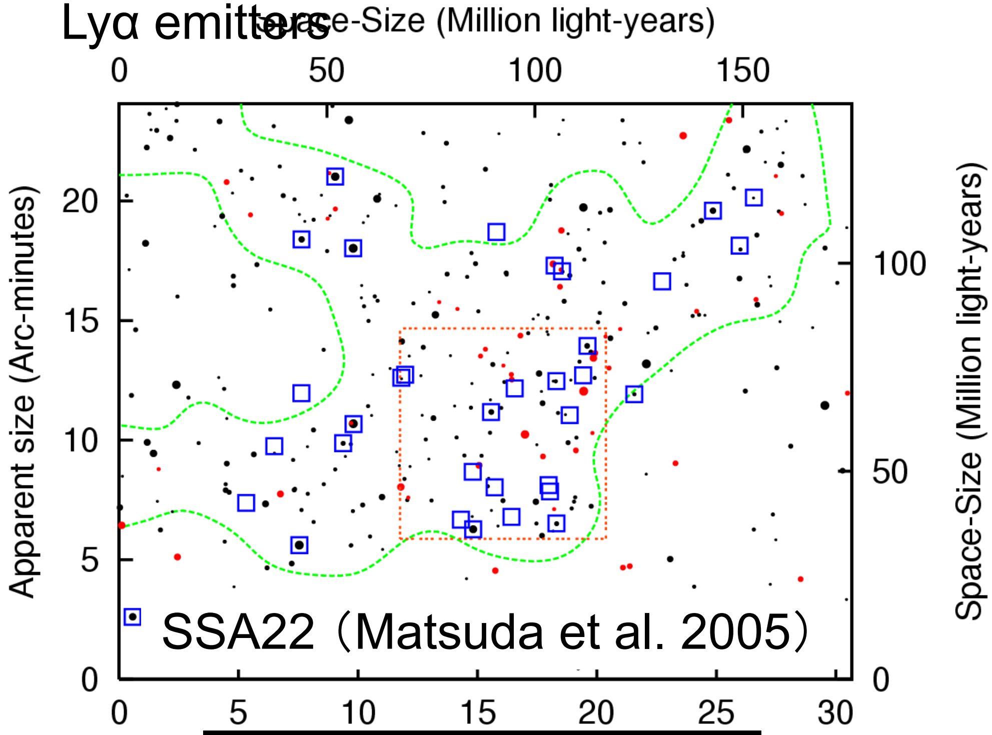
primarily based on our results

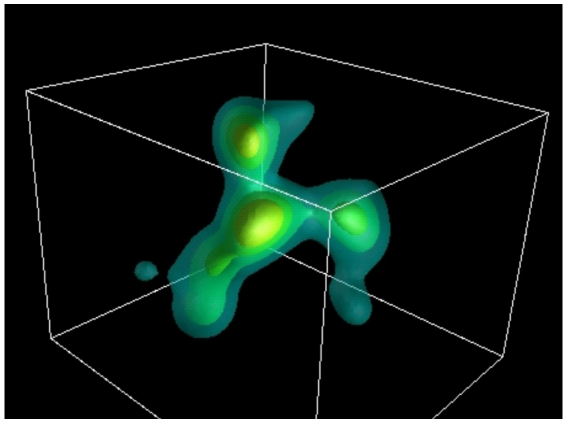
How can we find proto-clusters ($z>1.5$)?

Unbiased wide-field surveys

z∼3

Lyα emitters

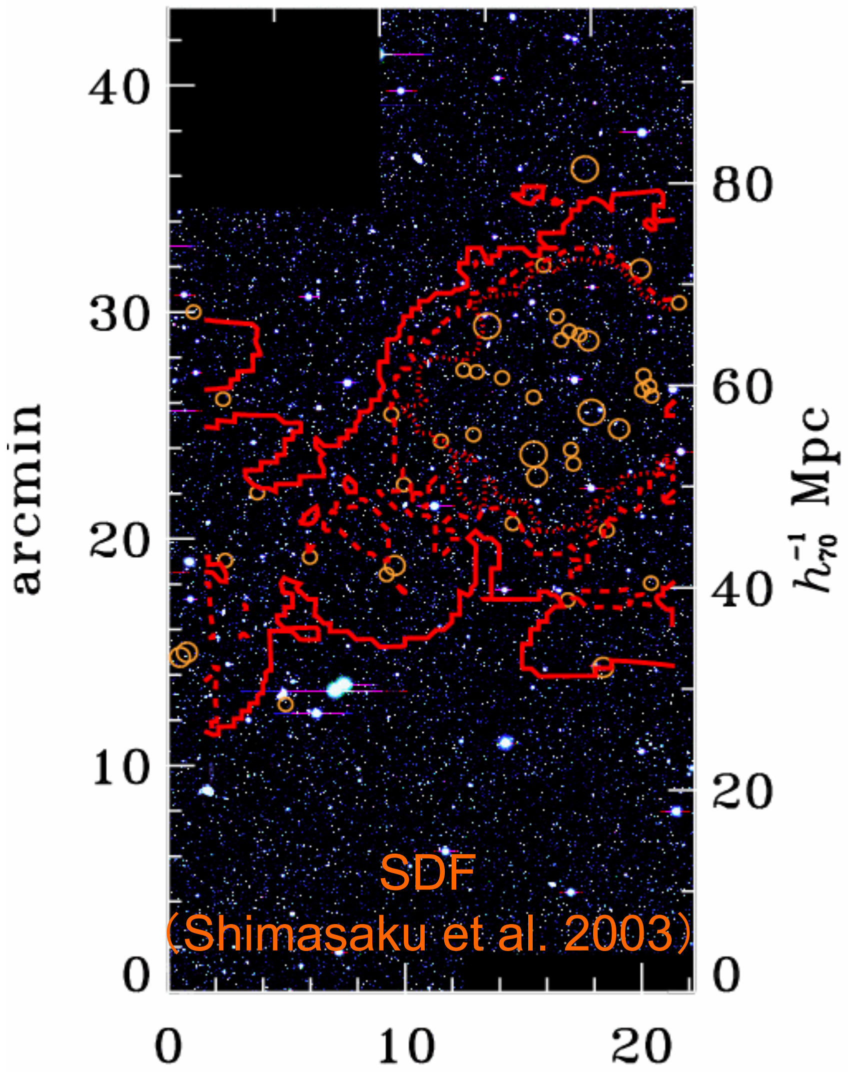




LAEs, LBGs, colour-selections, X-ray, S-Z, etc…

z∼5

Lyα emitters

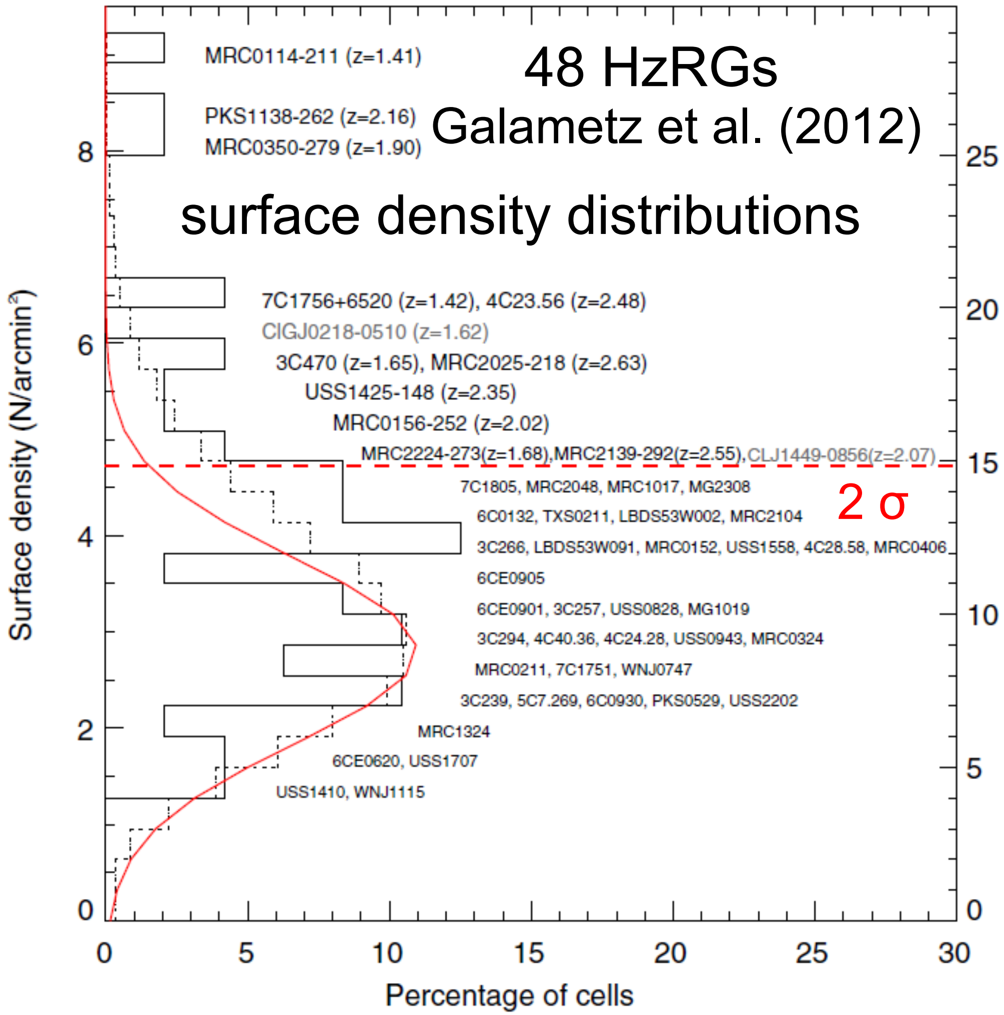


See Jun Toshikawa's talk.

Searching for proto-clusters around HzRGs

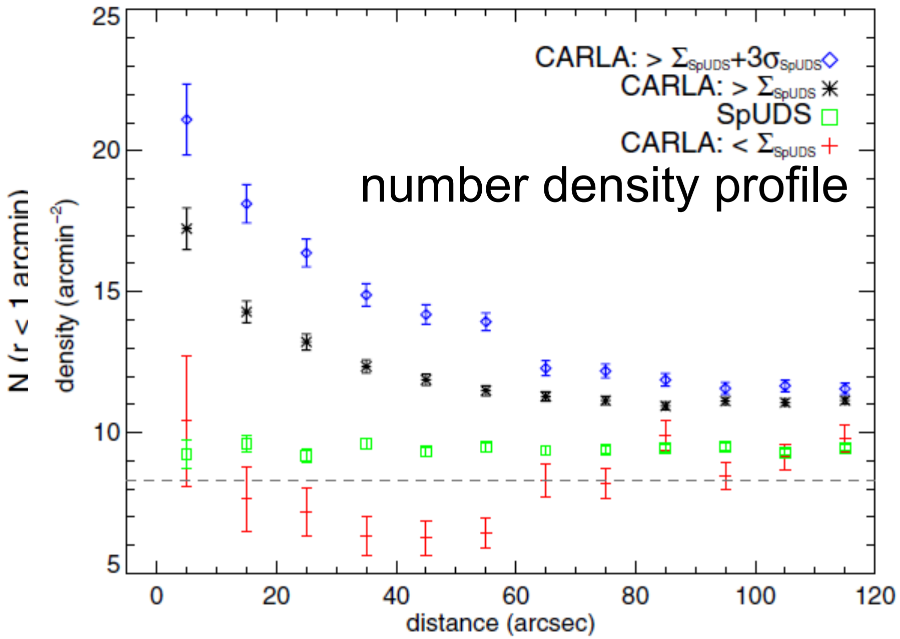
(may introduce unknown bias…)

Spitzer/IRAC colour-selected galaxies with $[3.6] - [4.5] > -0.1$ (AB)



CARLA: ~400 RL-AGNs

Wylezalek et al. (2013)



See Dominika Wylezalek's talk.

Lyα emitters: e.g. Venemans+ 07

Hα emitters: e.g. Matsuda+ 11, Mahalo…

Colour-selections: e.g. Best+ 03, Kajisawa+ 06, Kodama+ 07, Hatch+ 11,…

"MAHALO-Subaru"

MApping HAlpha and Lines of Oxygen with Subaru

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

Targeted observations of rich clusters are necessary to cover the whole range of environments.

	environ-ment	target		z	line	λ (μm)	camera	NB-filter	conti-nuum	status (as of Oct 2014)
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
z~1.5 clusters	High-z clusters	XCSJ2215–1738		1.457	[OII]	0.916	Suprime-Cam	NB912, NB921	z'	Hayashi+'10, '12
		4C65.22	RG	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	RG	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	RG	2.483	Hα	2.286	MOIRCS	CO	K_s	Tanaka+'11
		USS1558–003	RG	2.527	Hα	2.315	MOIRCS	NB2315	K_s	Hayashi+'12
		~~MRC0316–257~~	RG	~~3.130~~	[OII]	2.539	MOIRCS	NB1550	H	not yet
					[OIII]	2.068	MOIRCS	NB2071	K_s	observed
z>2 field	General	GOODS-N		2.19	Hα	2.094	MOIRCS	NB2095	K_s	Tadaki+'11
		(70 arcmin^2)			[OII]	1.189	MOIRCS	NB1190	J	observed
		SXDF-CANDELS		2.19	Hα	2.094	MOIRCS	NB2095	K	Tadaki+'13
		(92 arcmin^2)		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

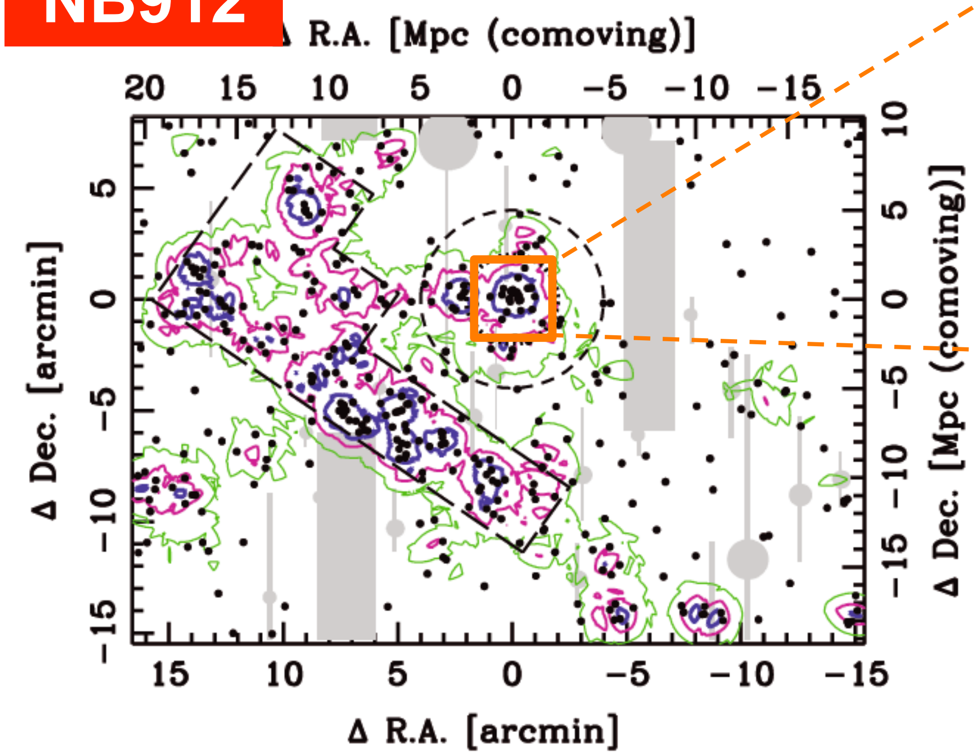
20 nights for imaging, >15 nights for spectroscopy

Kodama et al. (2013)

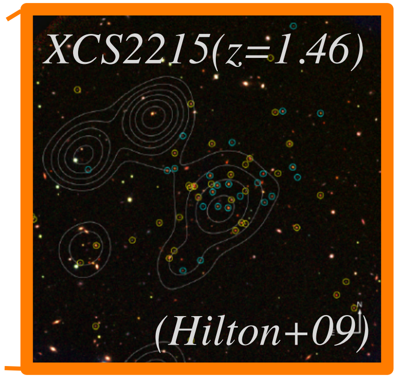
Structures and growth of proto-clusters

LSSs (~20Mpc) around two x-ray clusters at z~1.5 traced with [OII] emitters by *MAHALO-Subaru*

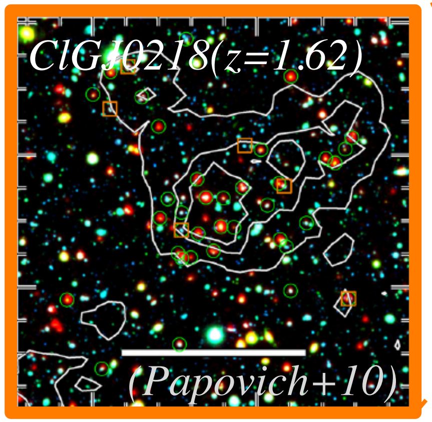
NB912



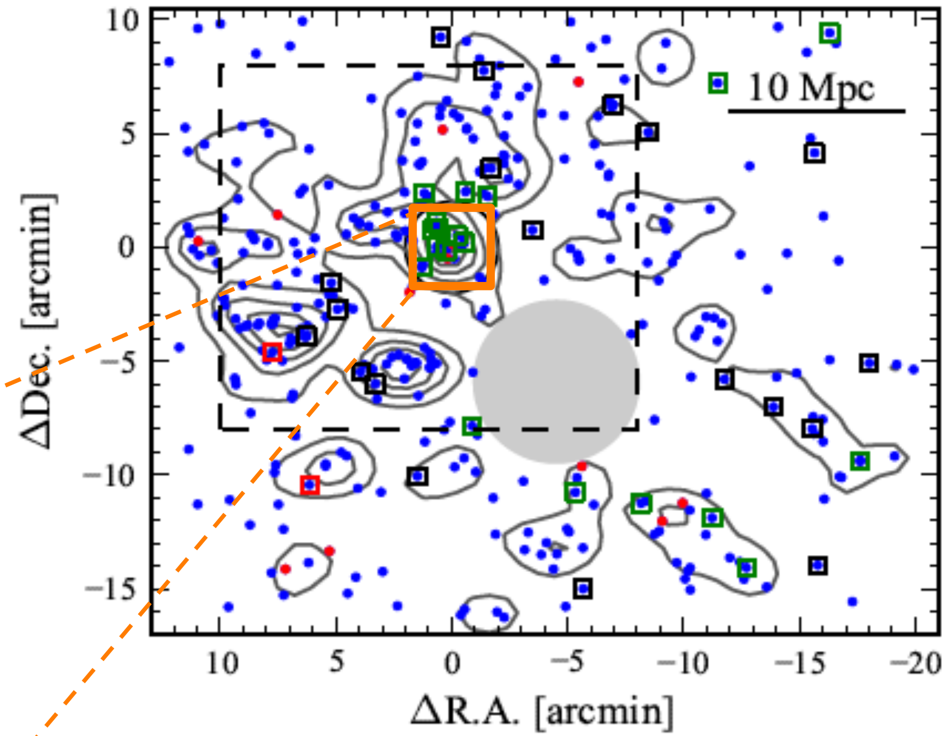
Hayashi et al. (2011)



Suprime-Cam/Subaru
30’ ~ 30-40 Mpc
(co-moving) on a side



NB973



Tadaki et al. (2012)

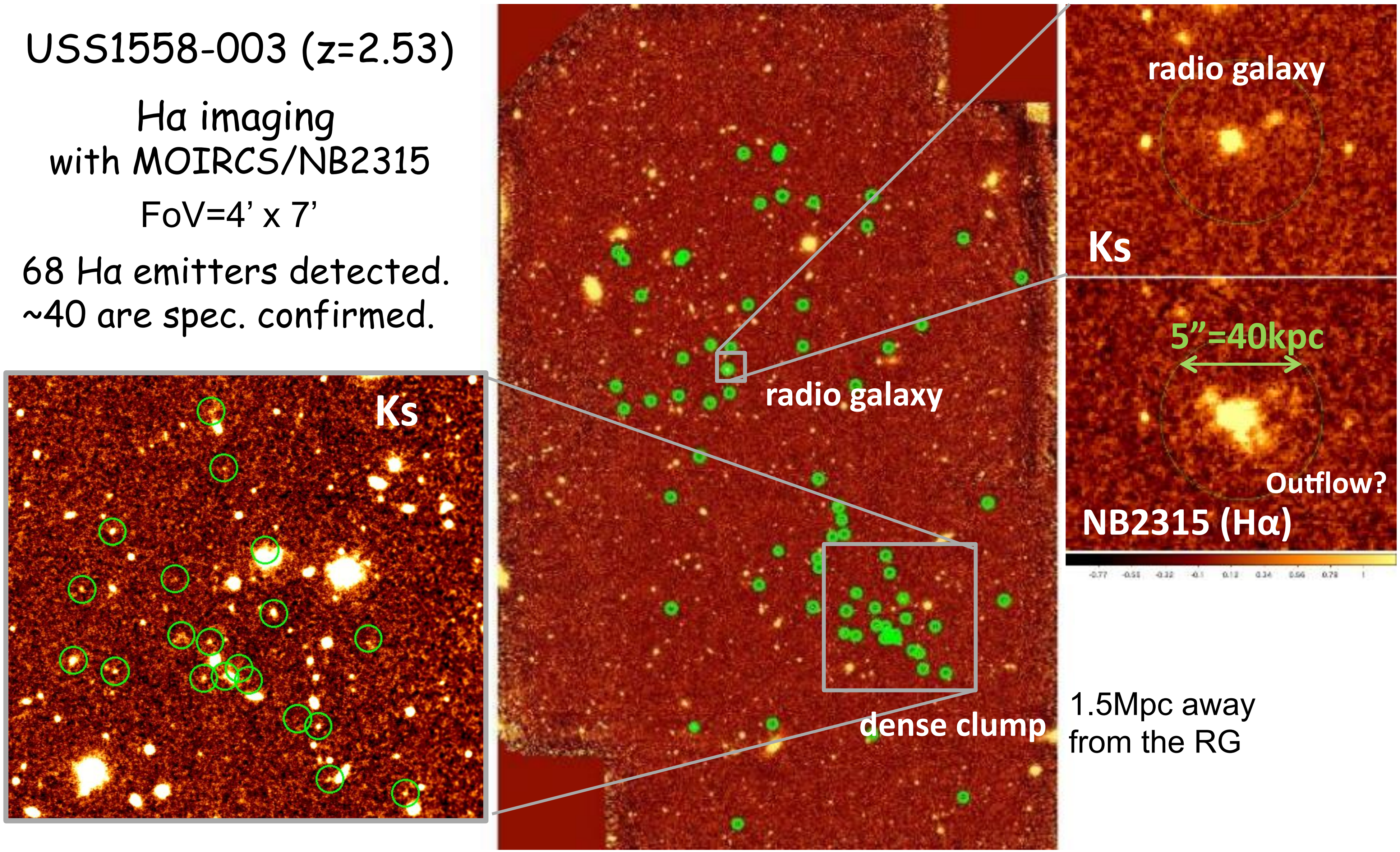
The most prominent star-bursting proto-cluster at z~2.5

USS1558-003 (z=2.53)

Hα imaging
with MOIRCS/NB2315

FoV=4' x 7'

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



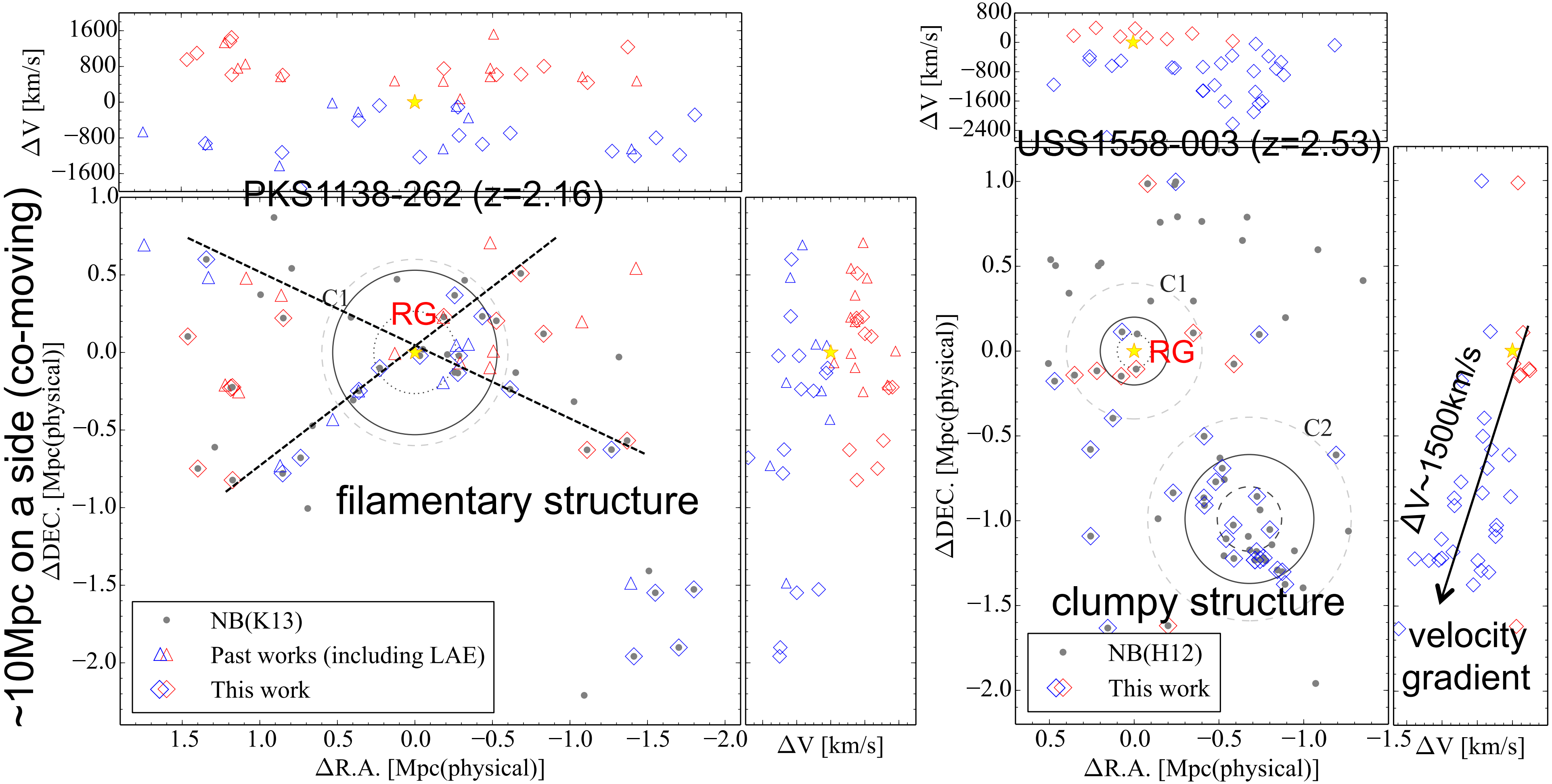
1.5Mpc away
from the RG

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

Hayashi et al. (2012)

2D/3D Views of Proto-Clusters at z>2

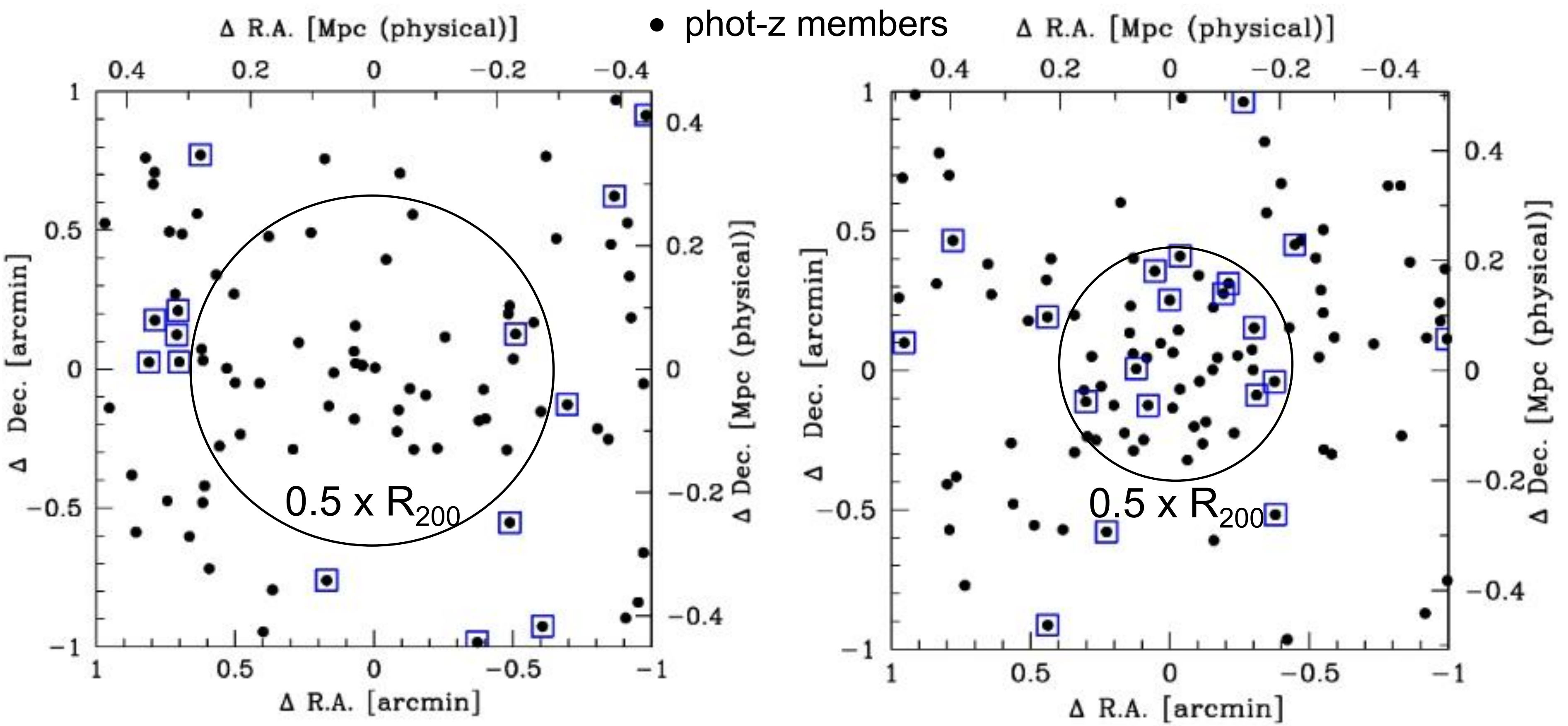
They are a mid of vigorous assembly!
HzRGs are not always located at the centers (densest regions).



Spectroscopic confirmation of 40-50 members in each cluster
with Subaru/MOIRCS Shimakawa et al. (2014)

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)



$L_X = 2.7\times10^{44}$ erg/s

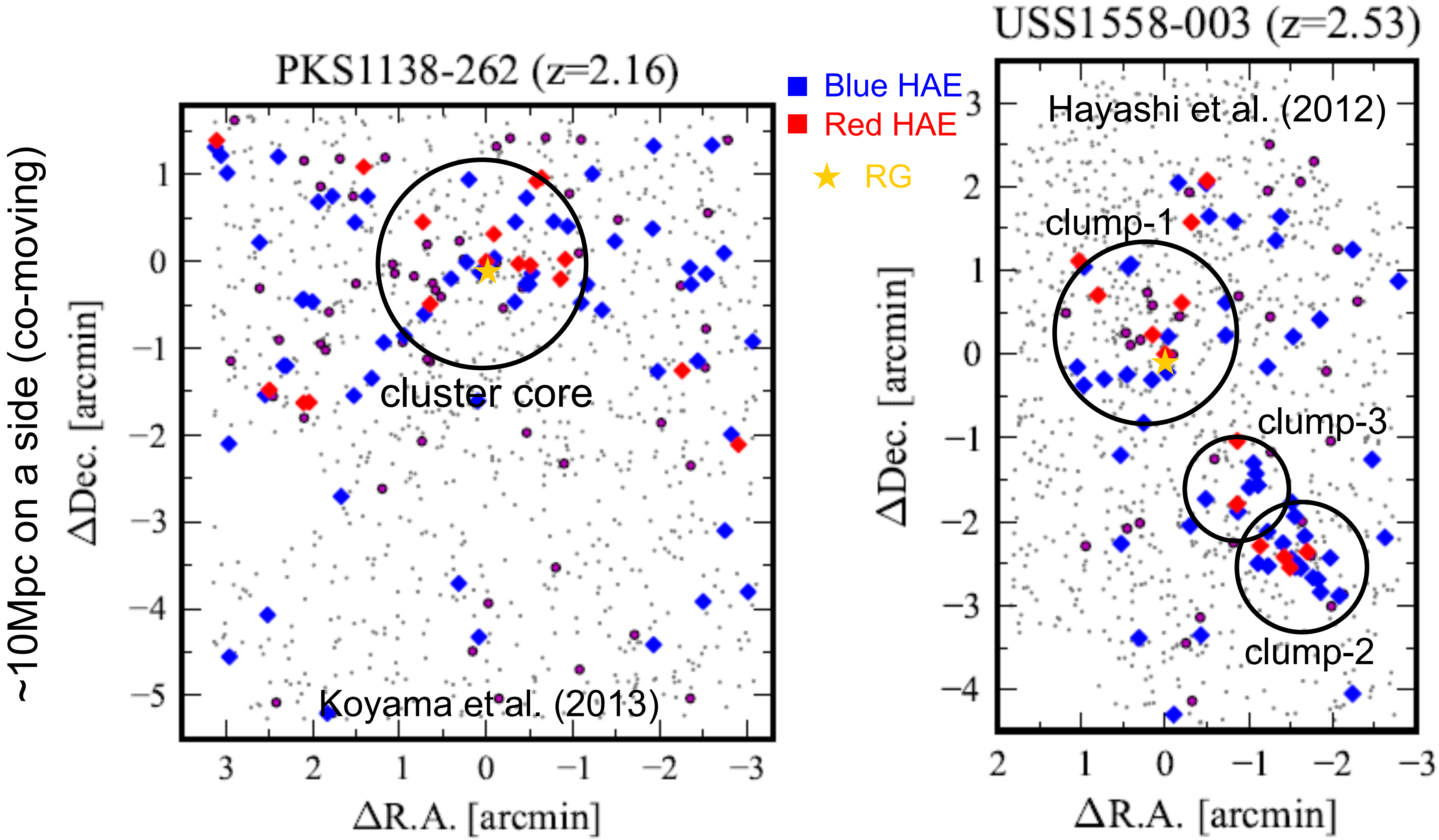
Koyama, et al. (2011)

$L_X = 4.4\times10^{44}$ erg/s

Hayashi, et al. (2010)

Clusters Grow Inside-Out !

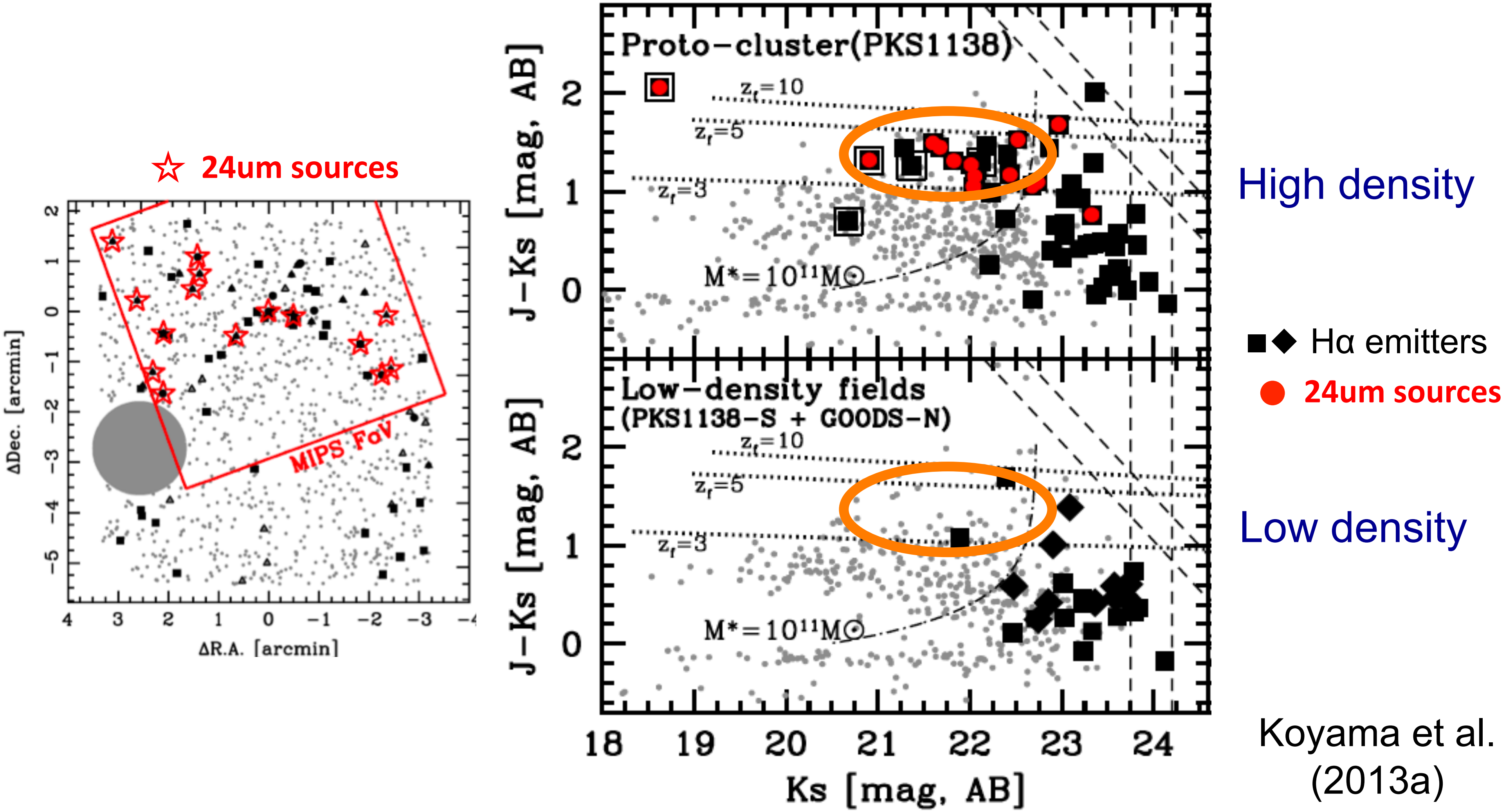
Spatial distributions of HAEs in two proto-clusters at z>2



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

Red HAEs (dusty starbursts) tend to favor even denser cores/clumps!

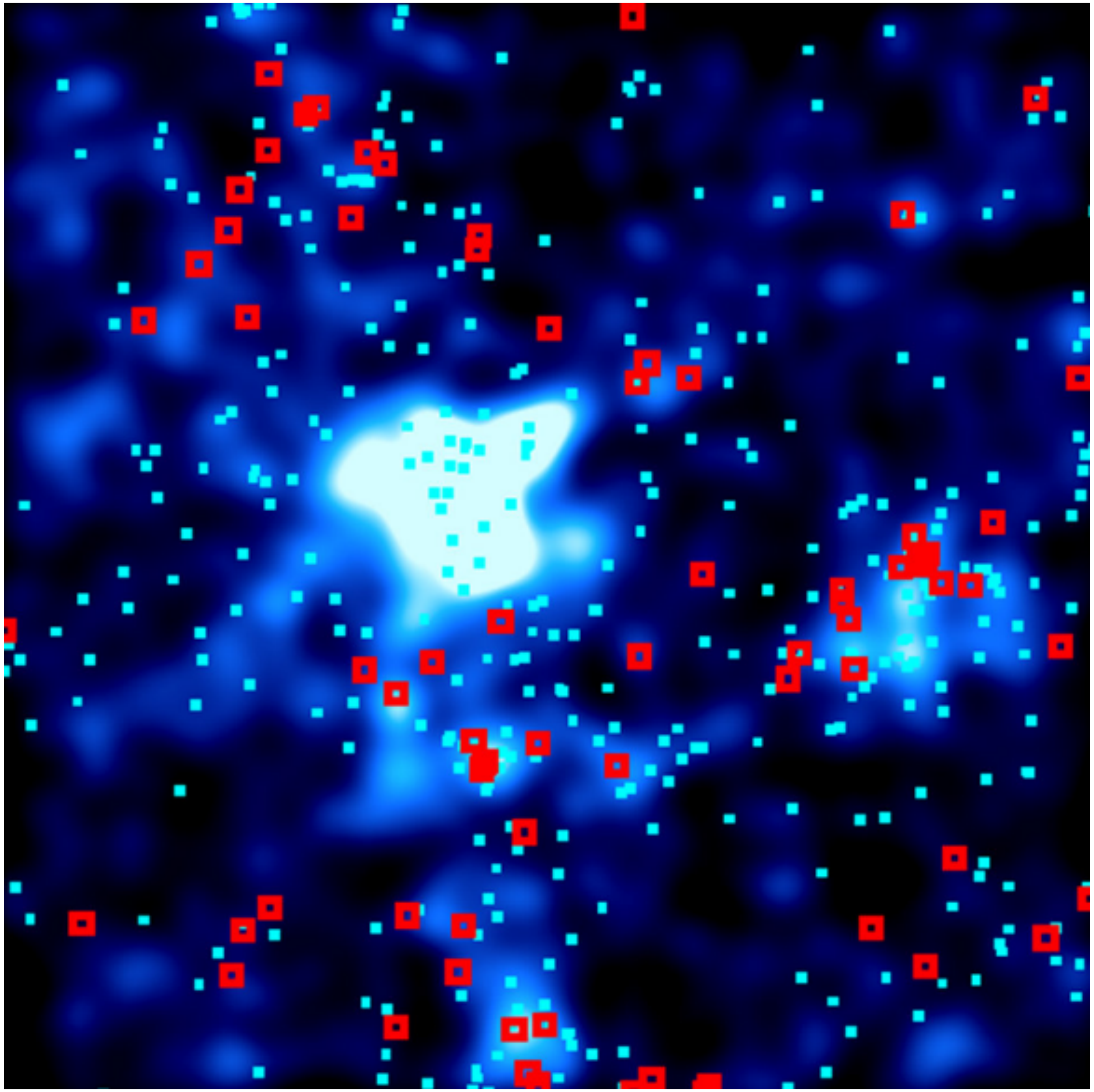
Massive + dusty galaxies in the proto-cluster core



Koyama et al. (2013a)

Red Ha emitters are very massive ($M_\star > 10^{11} M_\odot$) and dusty star-forming galaxies.
Many are actually detected at 24μm with MIPS.
→ Cluster specific/preferred phenomena at high-z,
holding a key to understanding the environmental effects.

Red/green HAEs are seen in the outskirts/clumps at z=0.4



"Octopus" cluster (CL0939@z=0.41)

□ **red/green HAEs**

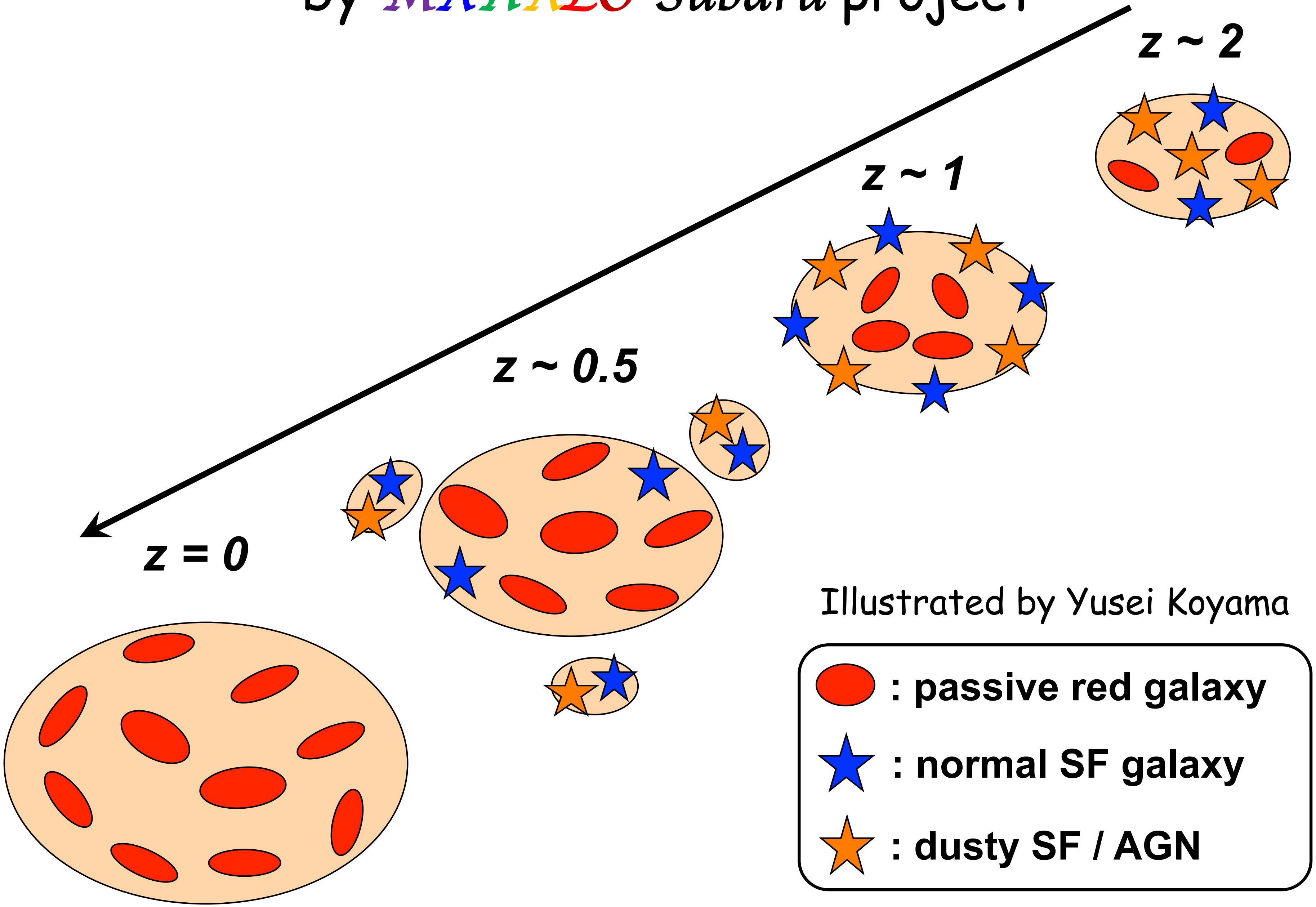
■ **blue HAEs**

SFR>0.75$M_{\odot}$/yr

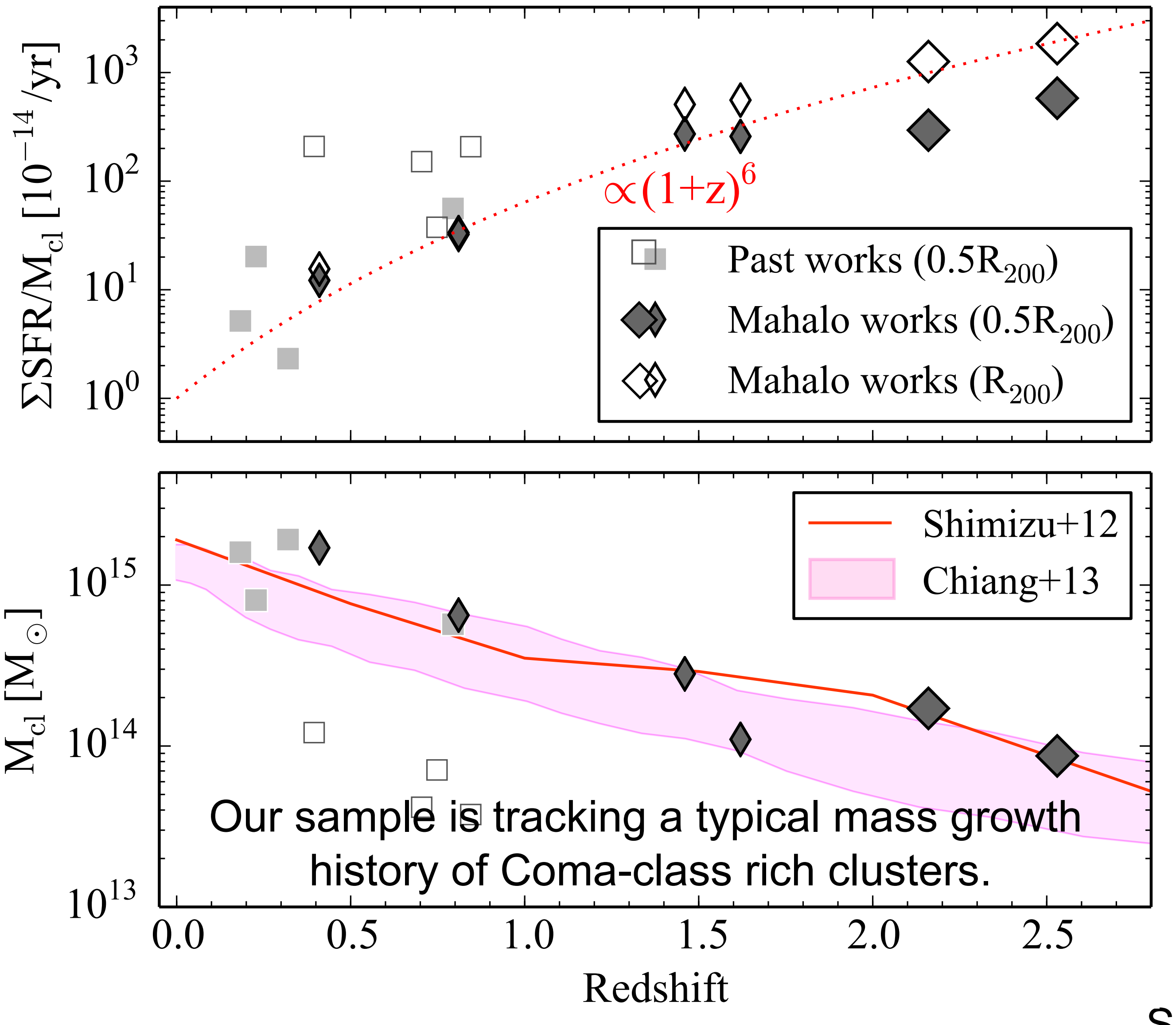
Red/green HAEs always reside in the most active environment at any epoch!

Koyama et al. (2011)

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



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. (2014)

Environmental dependence of galaxy properties in proto-clusters

Environmental effects at high-z

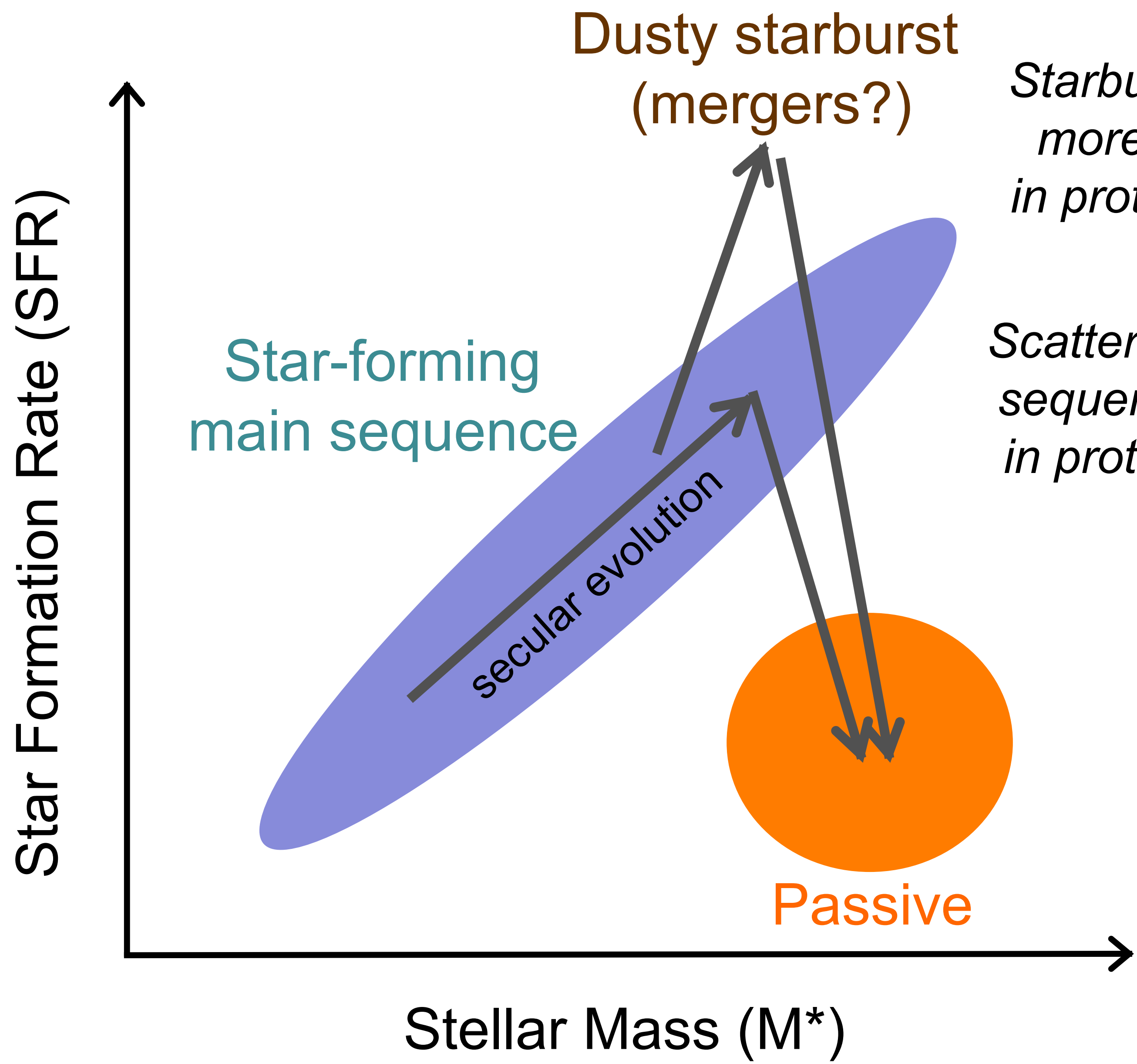
(Physical Processes)

- Merger, Interaction
  Frequency, Mode of SF (starburst)
- Gas inflow
  Filamentary cold streams vs. spherical accretion
- Gas outflow, stripping
  IGM pressure confinement, R-P/Tidal Stripping

(Consequences)

- Star formation activity
  Scatter of the SF main sequence (boost/truncation)
- AGN activity
  Frequency, Co-activation with star formation
- Internal structure
  Location/Compactness/Dustiness of SF, Clumpiness

Hypothetical galaxy evolution on the SFR vs. M* diagram

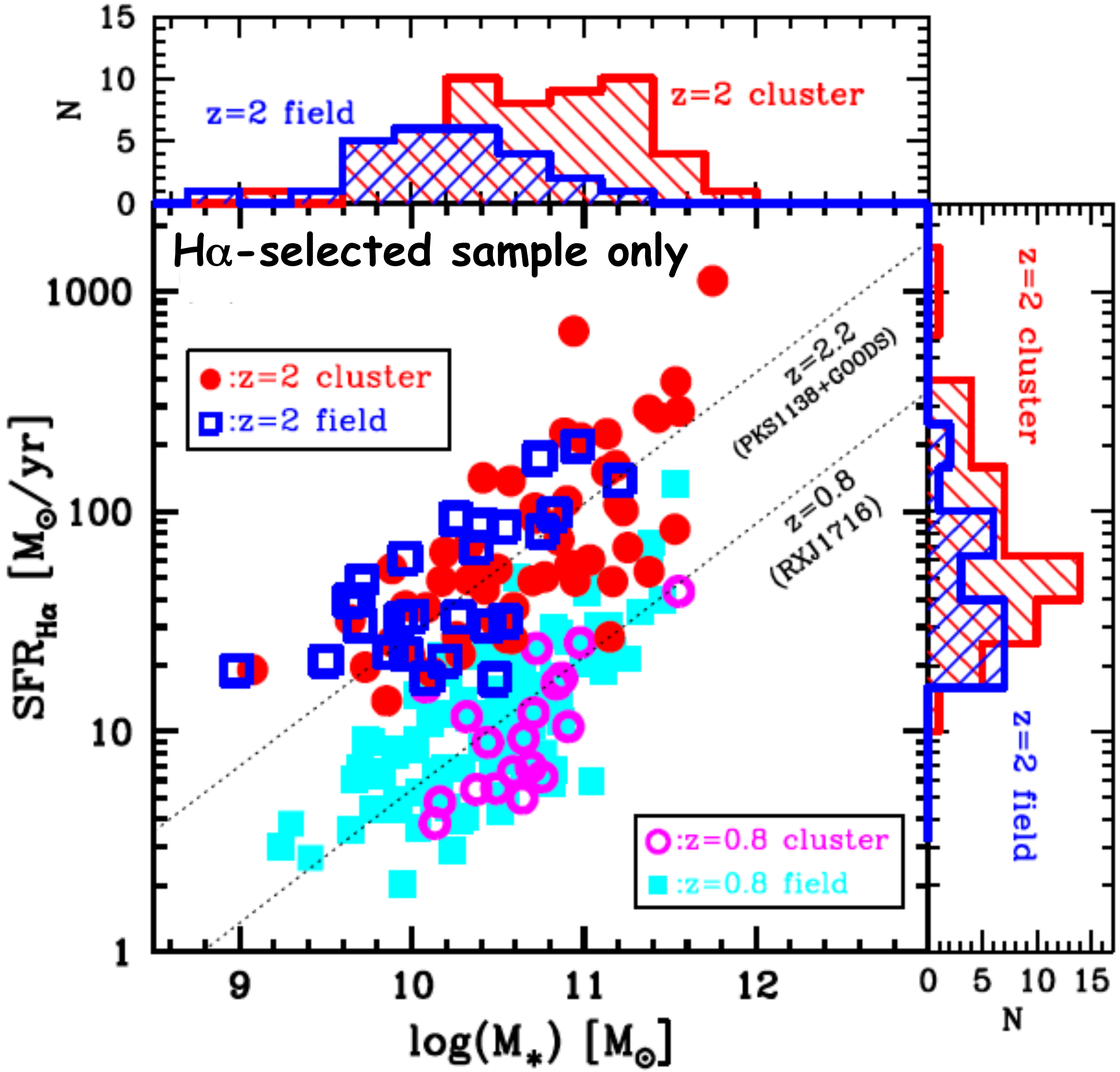


Starburst mode is more prevalent in proto-clusters?

↓

Scatter of the main sequence is larger in proto-clusters?

Environmental (In-)dependence of the Star-Forming Main-Sequence at z>2?



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

SF galaxies in the proto-cluster at z~2 follow the same "main sequence" as the field one.

However, the galaxy distributions on the sequence are different in the sense that the proto-cluster contains more massive, higher-SFR, and probably dustier galaxies.

Also, a caveat is that the M* -scaled dust correction may not be applied for cluster galaxies.

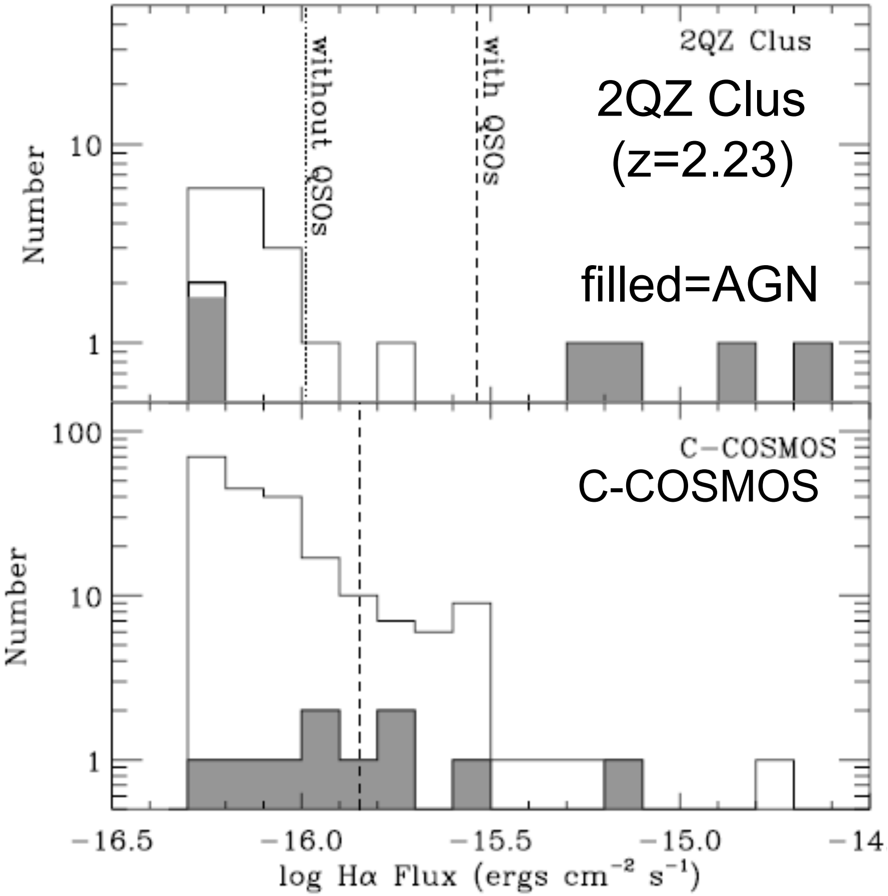
Koyama et al. (2013a)

see also Hatch et al. (2011) and Cooke et al. (2014)

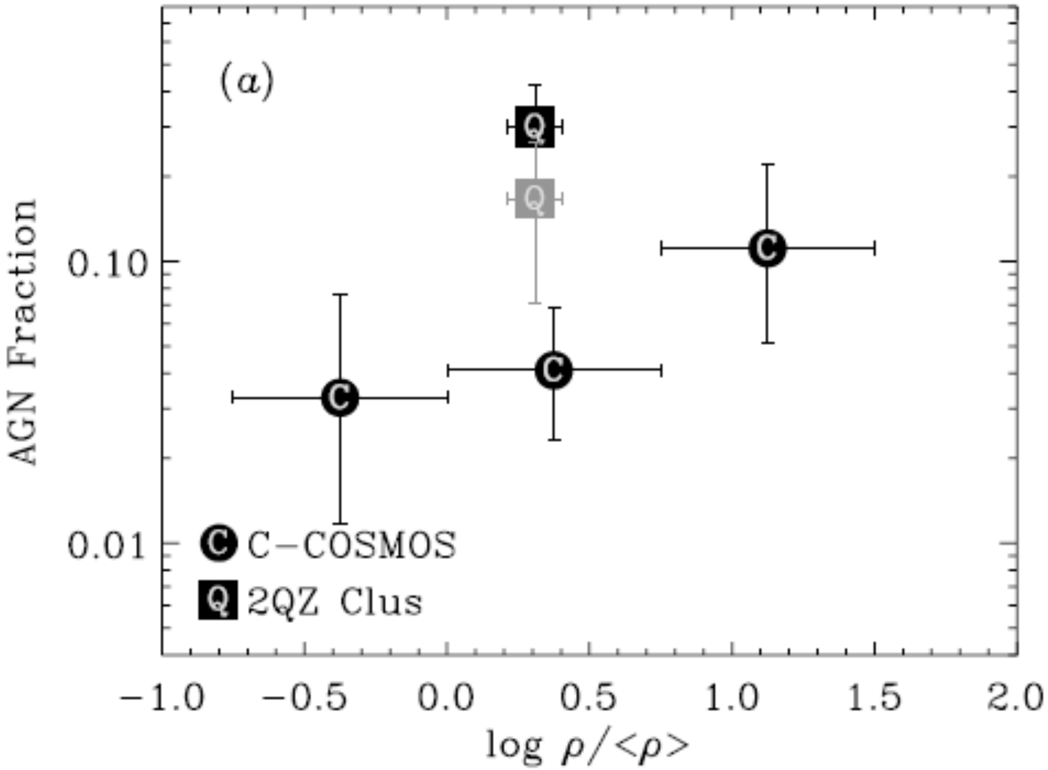
Environmental dependence of AGN fraction at z~2

Controversial issue!

(X-ray AGNs with Chandra)



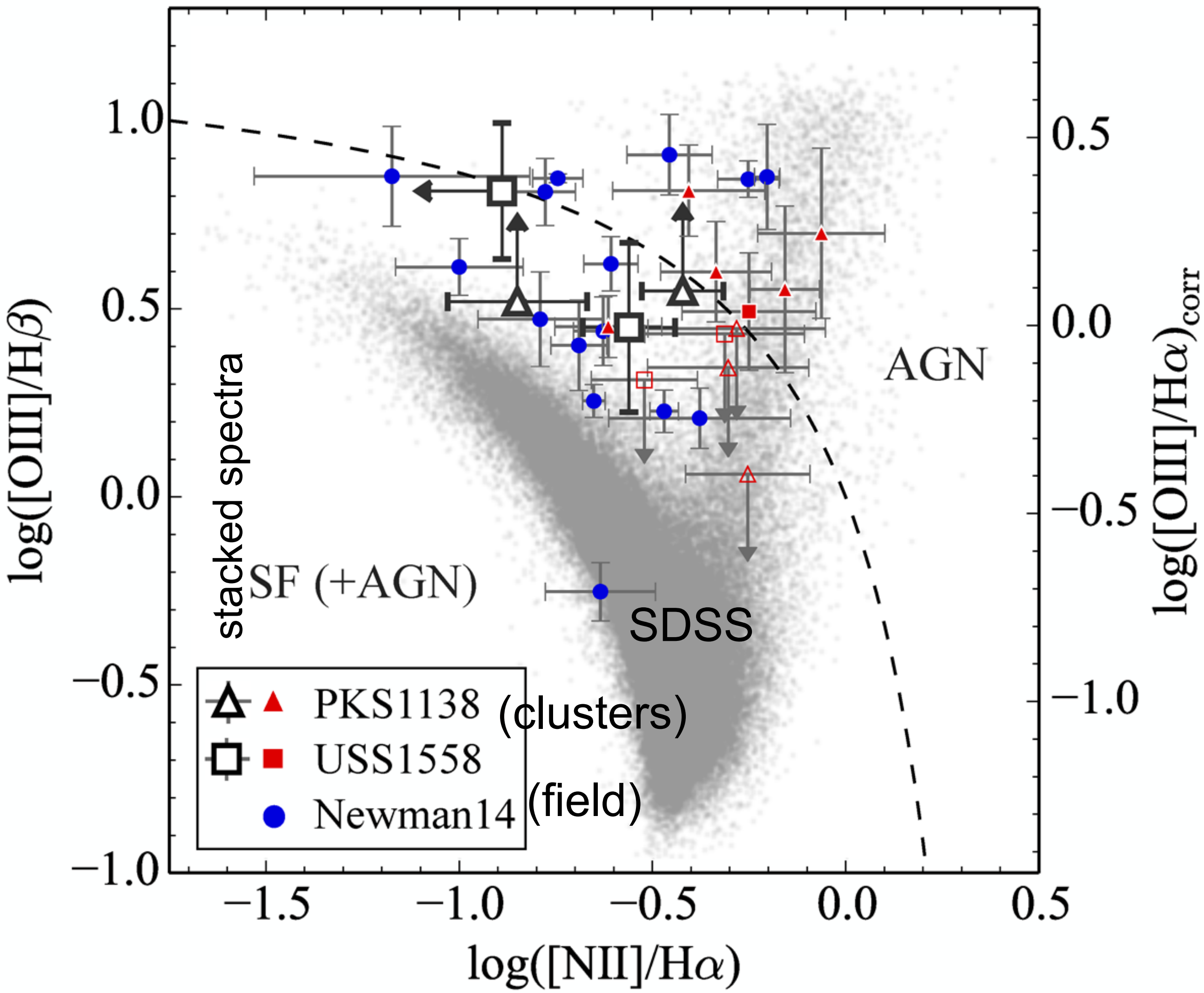
f_{AGN}=10-30% in proto-clusters at z~2



Higher AGN fraction in proto-clusters. Lehmer et al. (2014)

But see also Philip Best's talk (Sobater+ '15) which shows NO env. dependence!

Ionization/Excitation States



(individual Hβ are estimated from Hα with dust correction)

High-z > Low-z

Both higher sSFR and lower metallicity are contributing to much higher ionization states of high-z SF galaxies. (Kewley et al. 2013)

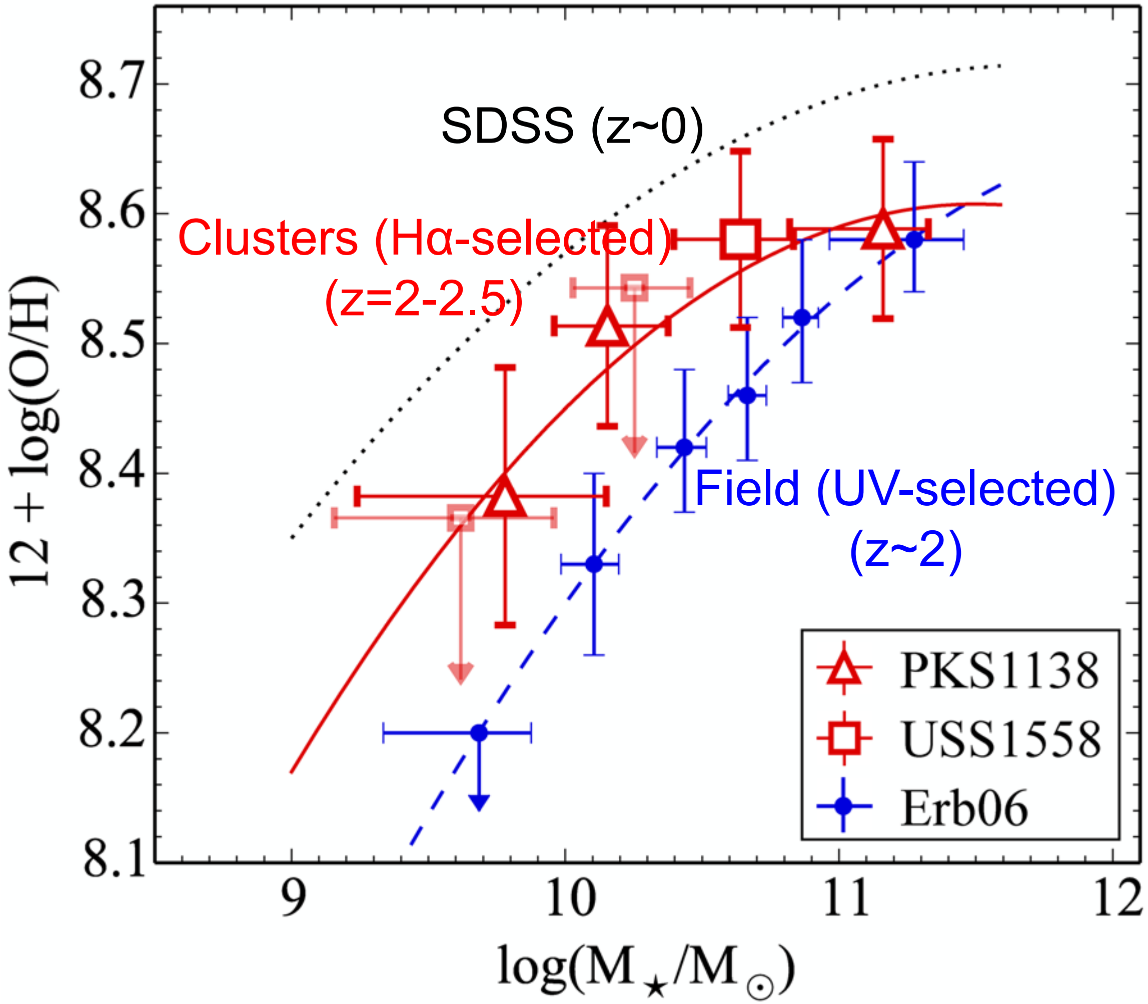
Cluster ~ Field

No environmental dependence? (low statistics!)

Shimakawa et al. (2015a)

Environmental dependence of gaseous metallicity at z>2

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)?

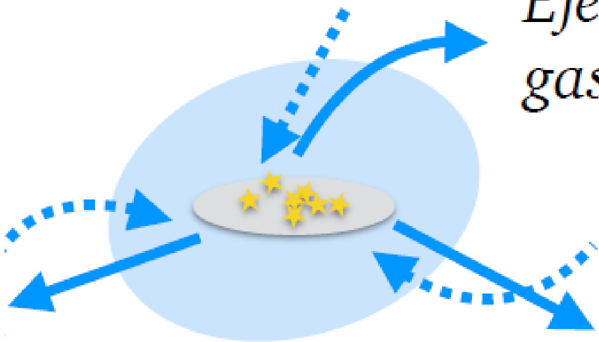
③ Stripping of metal poor gas from the reservoir, and stopping dilution of metals.

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

Inflow and outflow processes may well depend on environment !

General field

Stochastic, rapid, cold gas accretion through filaments



Ejecting enriched gas selectively

Metal dilution by primordial gas inflow

(Proto)cluster

Recycling of metal enriched gas

Stripping of metal poor gas from the reservoir

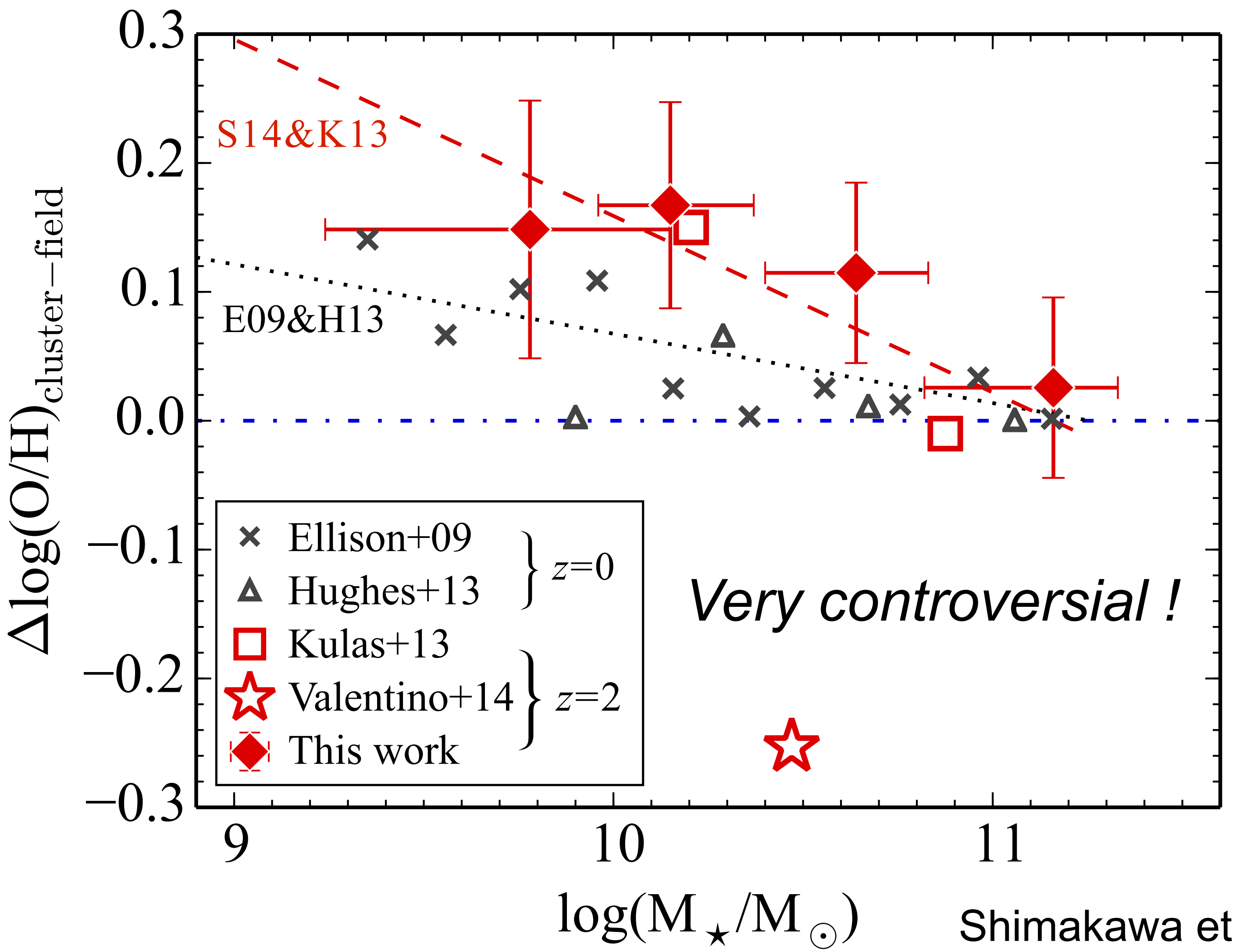
enriched gas falls back

Steady but slow(?) gas accretion from a common halo

Stripping outer metal-poor gas

(Dave+ '11; Kulas+ '13)

Environment and Mass Dependences of Gaseous Metallicity



Shimakawa et al. (2015a)

See also Lee Spitler's talk who briefly mentioned
no environmental dependence in z=2.09 proto-cluster

Environmental dependence of gas in-/out-flow processes is expected and should be explored!

→ another key aspect of the environmental effects on top of merger?

Inflow (cold streams):

- can be different between common haloes in clusters and isolated haloes in the field?
- may affect internal structures (clumpiness)?

Outflow:

- suppressed by IGM pressure?
- selective stripping of outer metal poor gas?

→ Gaseous metallicity (MOSFIRE spectroscopy),
Gas fraction and effective chemical yield (ALMA), and
Galaxy anatomy (AO+NB imaging, IFU) will tell us more.

"GANBA-Subaru" (our on-going project, but really struggling with terrible weather ☹)

Galaxy Anatomy with Narrow-Band AO imaging with Subaru

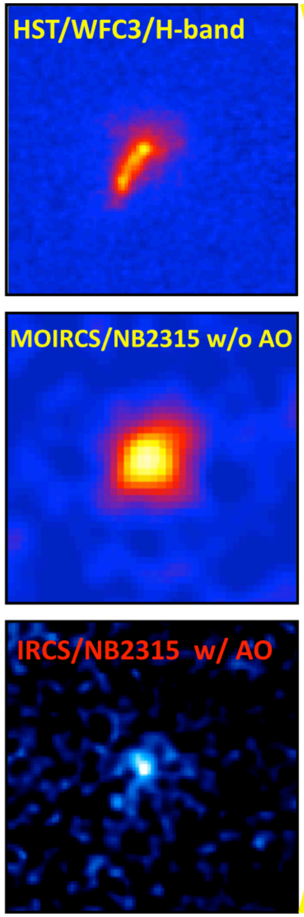
AO-assisted narrow-band Hα, [OIII] imaging with IRCS/Subaru

Any environmental dependence in internal structures?

HST/H-band
(0.16")
(Hayashi et al.
in prep)

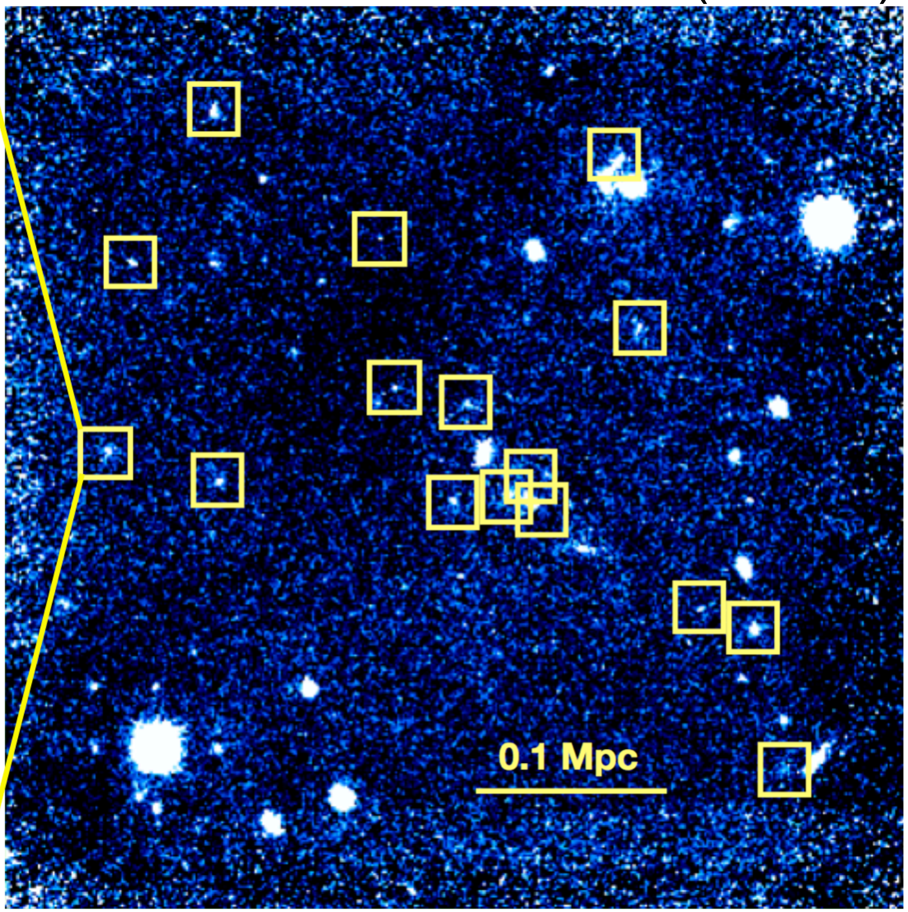
MOIRCS + NB (Hα)
(seeing~0.5")

IRCS + AO188
+NB (Hα)
(0.16" ~ 1.3 kpc)



Resolved star-forming clumps!

Proto-cluster USS1558-003 (z=2.53)



IRCS
1' x 1'

Suzuki et al., in prep.

Summary

- Filamentary/clumpy structures of proto-clusters, a mid of their assembly process.
- 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 they hold a key to understanding environmental effects.
- AGN fraction may be higher in clusters/groups at high-z?
- Gaseous metallicity is higher in proto-clusters at z>2 than in the field (controversial yet!).
- Environmental dependence of gas inflow/outflow may be another key factor (as well as galaxy mergers).


HAWAIIAN ISLAND
MAHALO
ALOHA STATE