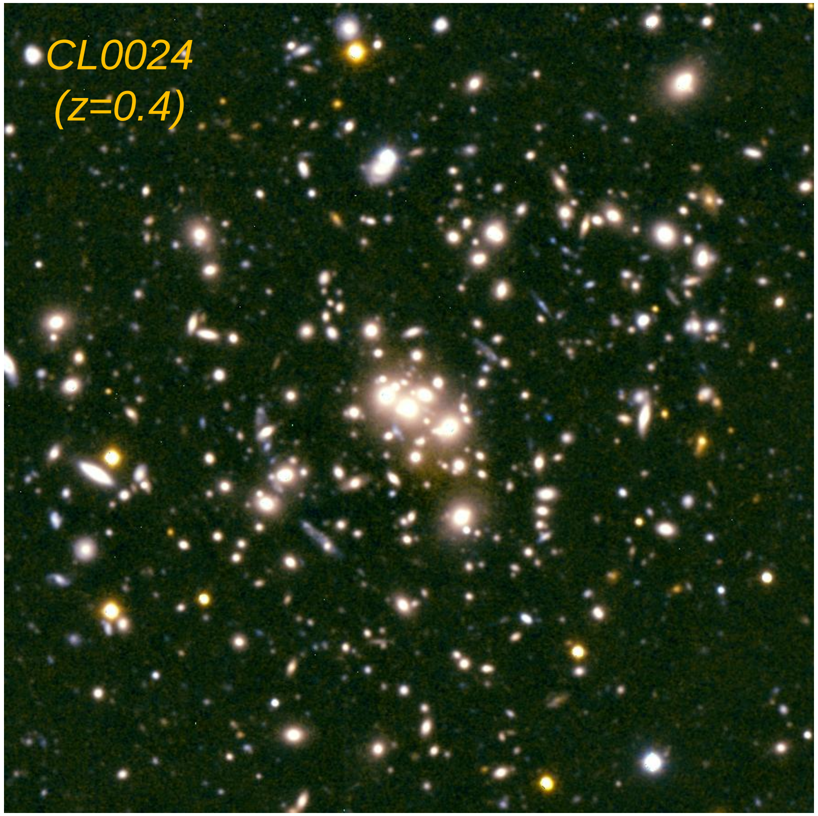
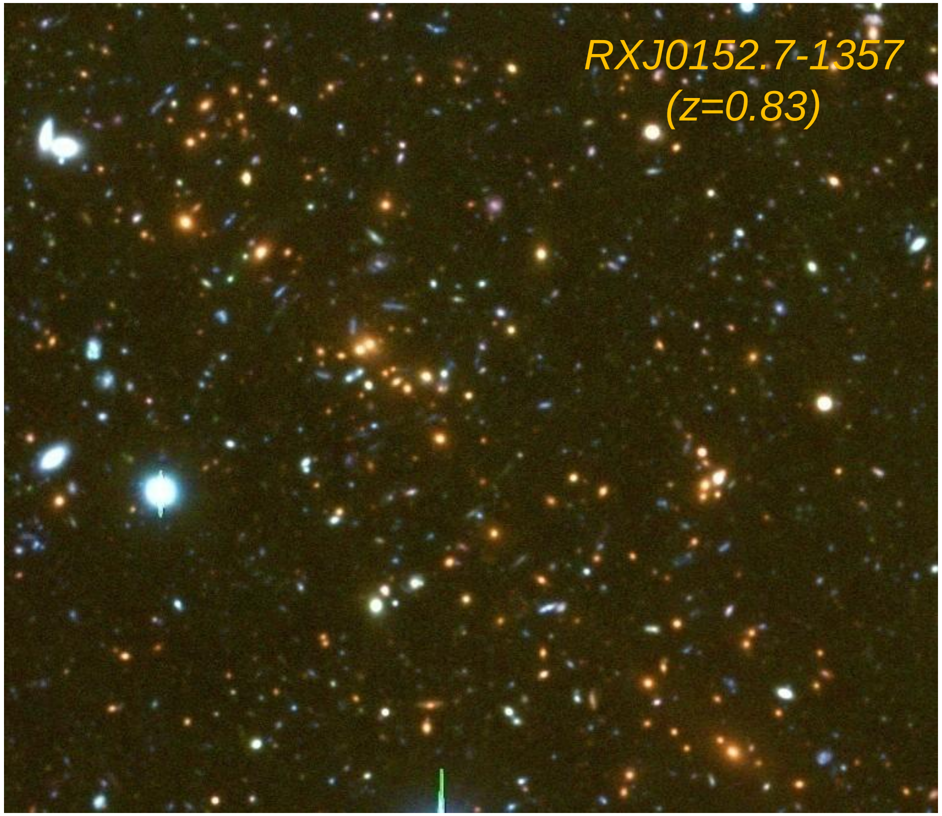
Galaxy Clusters in the Early Universe (Pucon, Chile, 12/11/2009)

Panoramic Views of Cluster Evolution since z=3 with Subaru





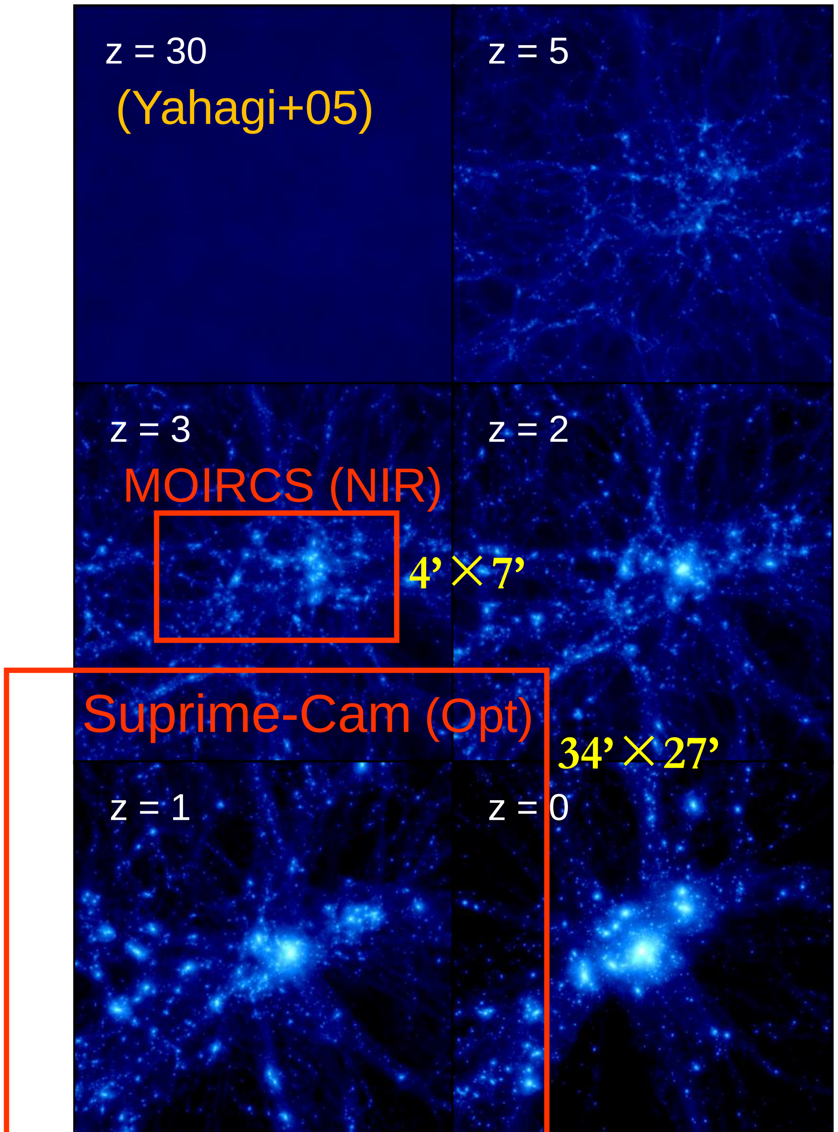
Taddy Kodama (NAOJ),
Yusei Koyama (Tokyo), Masao Hayashi (Tokyo), Masayuki Tanaka (ESO),
Ichi Tanaka (Subaru), Masaru Kajisawa (Tohoku), Carlos de Breuck (ESO),
and the PISCES/HzRG teams

Outline (Summary)

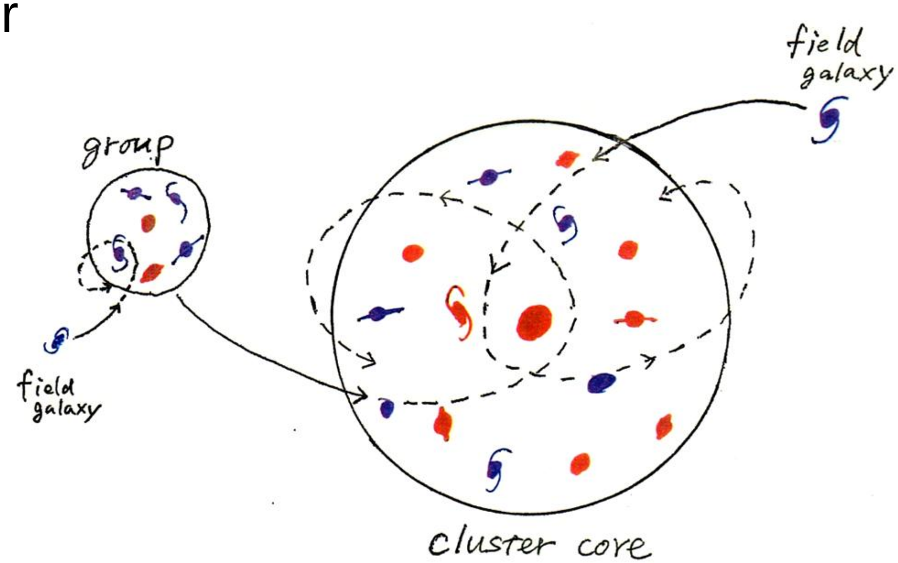
- Large scale structures in and around clusters at all redshifts ($0.4<z<3$)
- Starbursts and truncation in groups/outskirts at $z<1$
- High SF activity in the cluster core at $z\sim1.5$
- Disappearance of the red sequence at $z>2.2$

Origin of Environmental Dependence

N-body simulation of a massive cluster



$M_{cl}=6\times10^{14}\ M_{\odot}$, $20\times20\mathrm{Mpc}^2$ (co-moving)



Nature? (intrinsic)

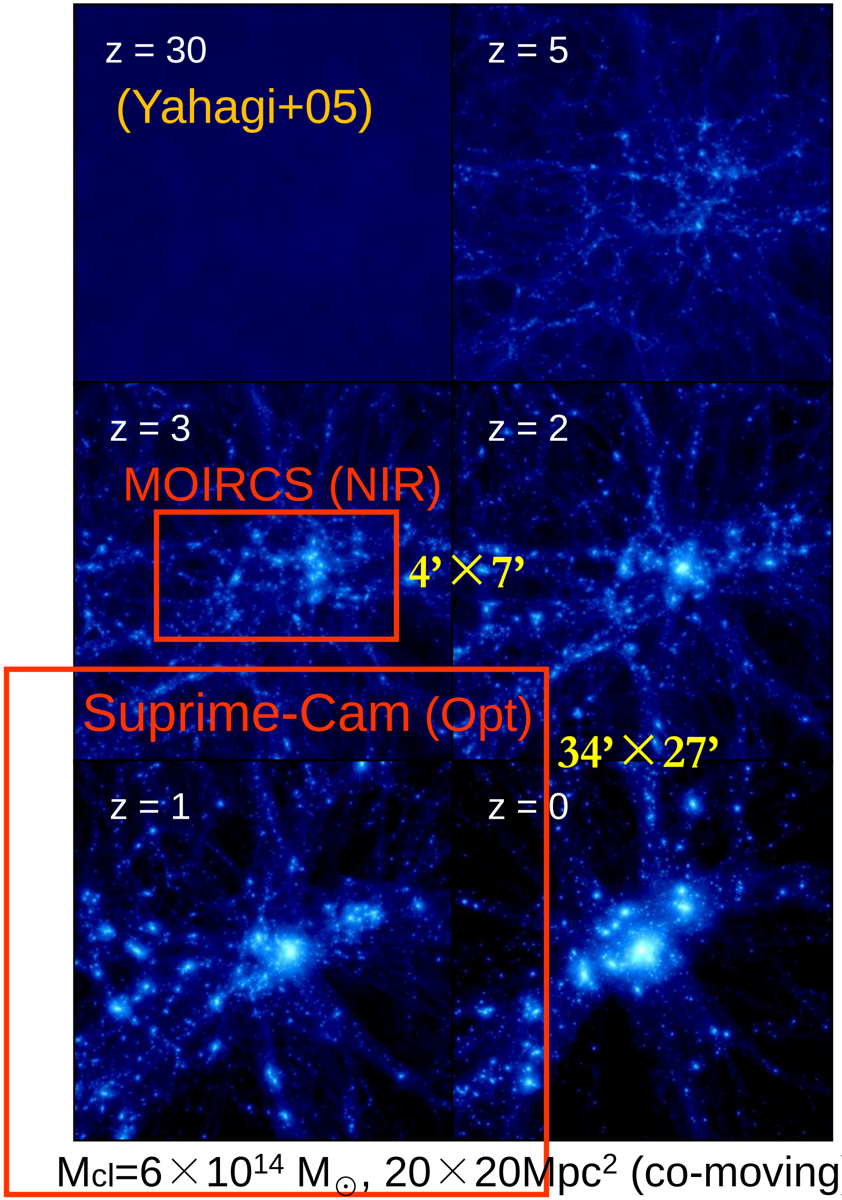
earlier galaxy formation and evolution in high density regions

Nurture? (external)

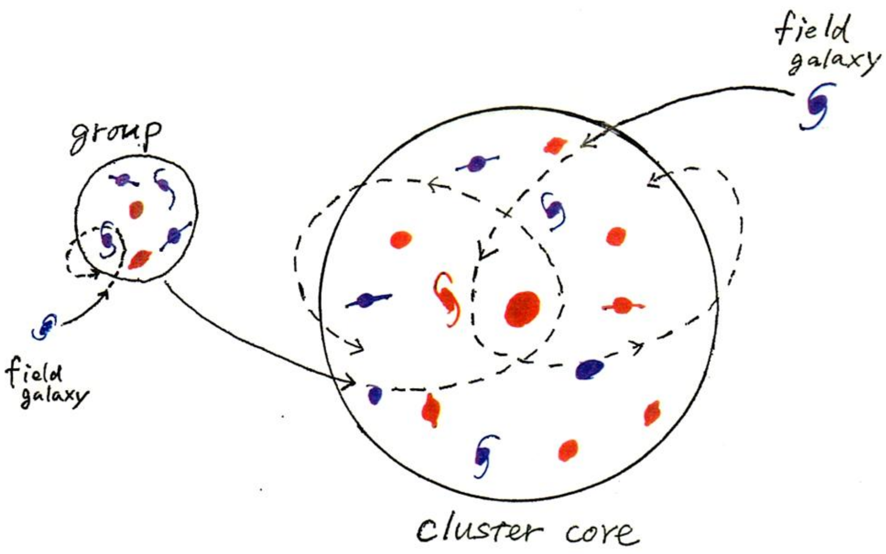
galaxy-galaxy interaction/mergers, gas-stripping

Origin of Environmental Dependence

N-body simulation of a massive cluster



$M_{cl}=6\times10^{14}\ M_\odot$, $20\times20\text{Mpc}^2$ (co-moving)



Nature? (intrinsic)

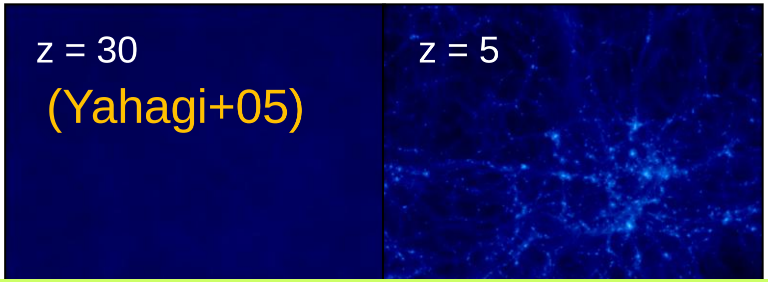
Need to go higher redshifts as it becomes more relevant.

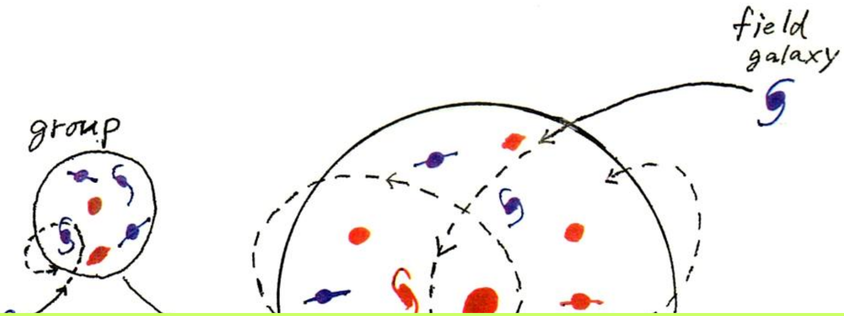
Nurture? (external)

Need to go outer infall regions to see directly what’s happening there.

Origin of Environmental Dependence

N-body simulation of a massive cluster



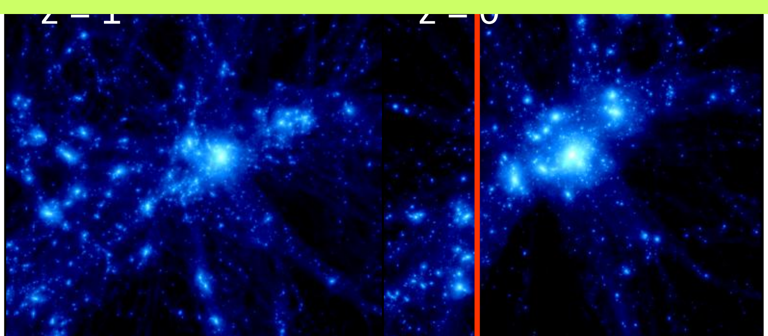


★Distant X-ray clusters (0.4<z<1.5): Suprime-Cam, MOIRCS

Kodama, M.Tanaka, Koyama, Hayashi, et al. (PISCES team)

★Proto clusters around RGs/QSOs (2<z<5.2): MOIRCS

Kodama, I.Tanaka, Kajisawa, De Breuck, Miley, Kurk, et al. (HzRG team)



$M_{cl}=6\times10^{14}\ M_{\odot}$, $20\times20\mathrm{Mpc}^2$ (co-moving)

becomes more relevant.

Nurture? (external)

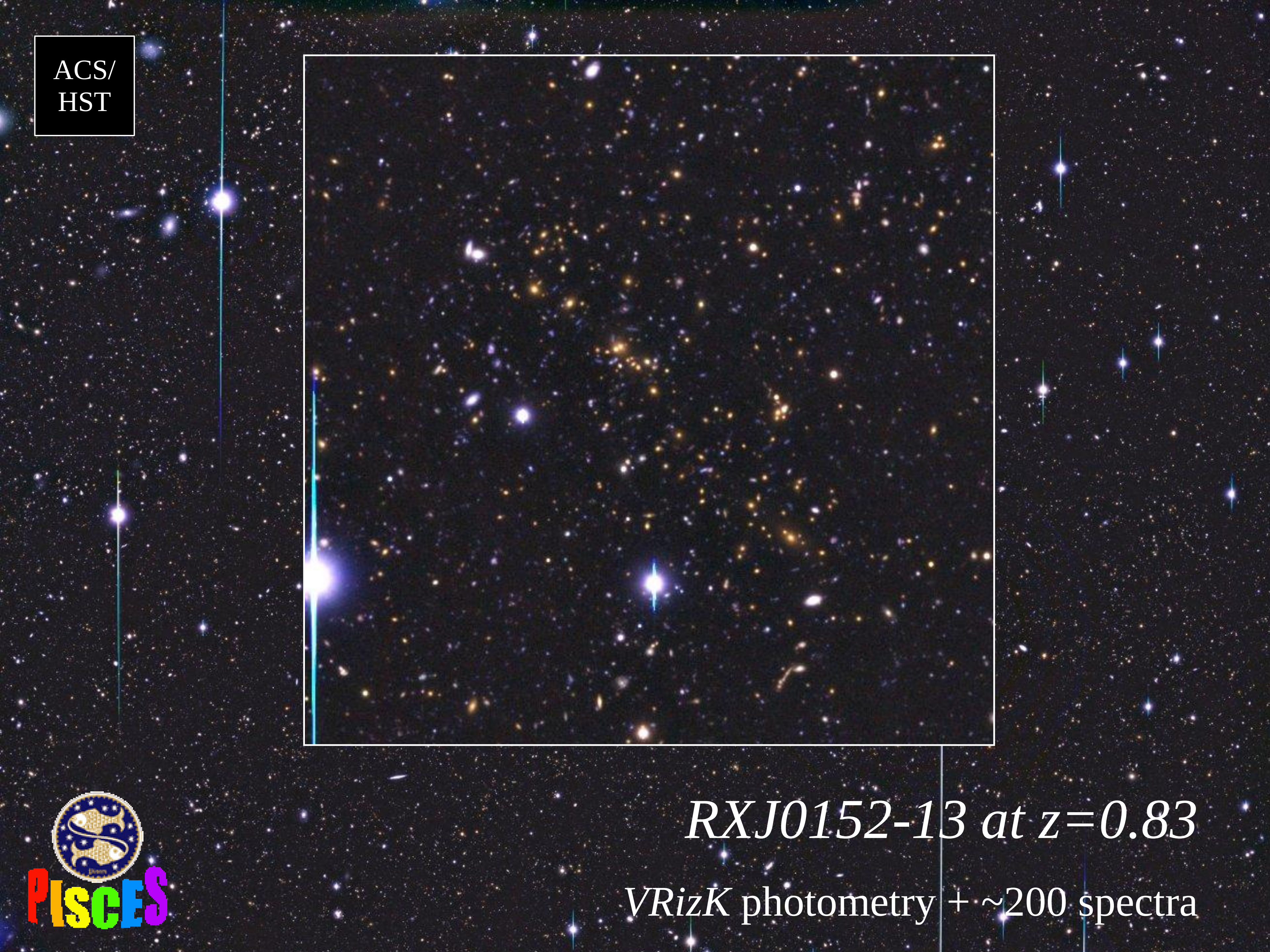
Need to go outer infall regions to see directly what's happening there.

Panoramic Imaging and Spectroscopy of Cluster Evolution with Subaru

10 X-ray clusters (0.4 < z < 1.45) are completed

Class	Cluster	RA (J2000)	Dec (J2000)	z	L_X 10^{44}	Bands	Coordination
z~0.4	CL 0024+1654	00 26 35.7	+17 09 43.1	0.39	3.2	BRz',NB	ACS, XMM, Chandra
	CL 0939+4713	09 42 56.2	+46 59 12	0.41	9.2	$BVRI$,NB	XMM
	(RX J2228+2037)	22 28 36	+20 37 12	0.42	16.5	$BVRi'$	Chandra, S-Z
z~0.55	MS 0451.6−0305	04 54 10.9	−02 58 07	0.54	12.0	$BVRI$	ACS (3.5′), Chandra, S-Z
	CL 0016+1609	00 18 33.5	+16 26 13.4	0.546	26.0†	$BVRi'z'$	ACS (3.5′), XMM, Chandra, S-Z
	(MS 2053.7−0449)	20 56 21.8	−04 37 51.4	0.583	5.0	$BVRi'z'$	ACS (3.5′), XMM, Chandra, S-Z
z~0.85	RX J1716.4+6708	17 16 49.6	+67 08 30	0.813	2.7‡	$VRi'z'$,NB	Chandra, Astro-F target
	(MS 1054.4−0321)	10 56 59.5	−03 37 28.4	0.83	20.0	$VRi'z'$	ACS (6′), XMM, Chandra, S-Z
	RX J0152.7−1357	01 52 42.0	−13 57 52.9	0.831	16.0	$VRi'z'$	ACS (6′), XMM, Chandra, S-Z
	(RX J1226.9+3332)	12 26 58.2	+33 32 49	0.9	53.0	$VRi'z'$	XMM, Chandra, S-Z
	(CL 1604+43)	16 04 28.3	+43 16 24.0	0.9	2.0	$VRi'z'$	ACS (6′), XMM
z~1.2	RDCS J0910+5422	09 10 44.9	+54 22 08.9	1.11	2.1	$VRi'z'$	Chandra ACS(3.5')
	CL 1252−2927	12 52 54.4	−29 27 17.0	1.23	6.6	$VRi'z'$	ACS (6′), XMM, Chandra
	(RX J1053.7+5735)	10 53 43.4	+57 35 21	1.14	2.0‡	$VRi'z'$	ACS (6′) XMM
	RX J0848.9+4452	08 48 46.9	+44 56 22	1.26	2.8	$BVRi'z'$	ACS (6′), XMM, Chandra
z~1.4	(XMMU2235.3-2557)	22 35 20.6	-25 57 42.0	1.39	3.0	$VRi'z'$	XMM
	XMMJ2215.9-1738	22 15 58.5	-17 38 02.5	1.45	4.4	$VRi'z'$,NB	XMM

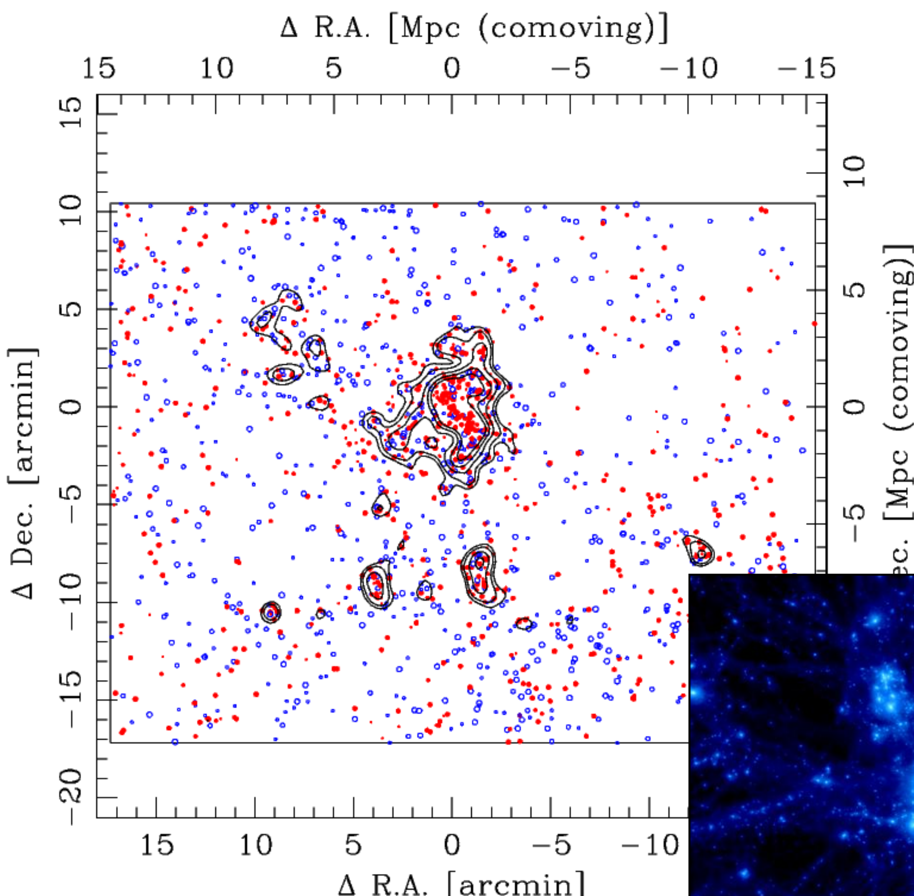
Kodama et al. (2005)


ACS/
HST
RXJ0152-13 at z=0.83
VRizK photometry + ~200 spectra
PISCES

Panoramic Views of Cluster Assembly

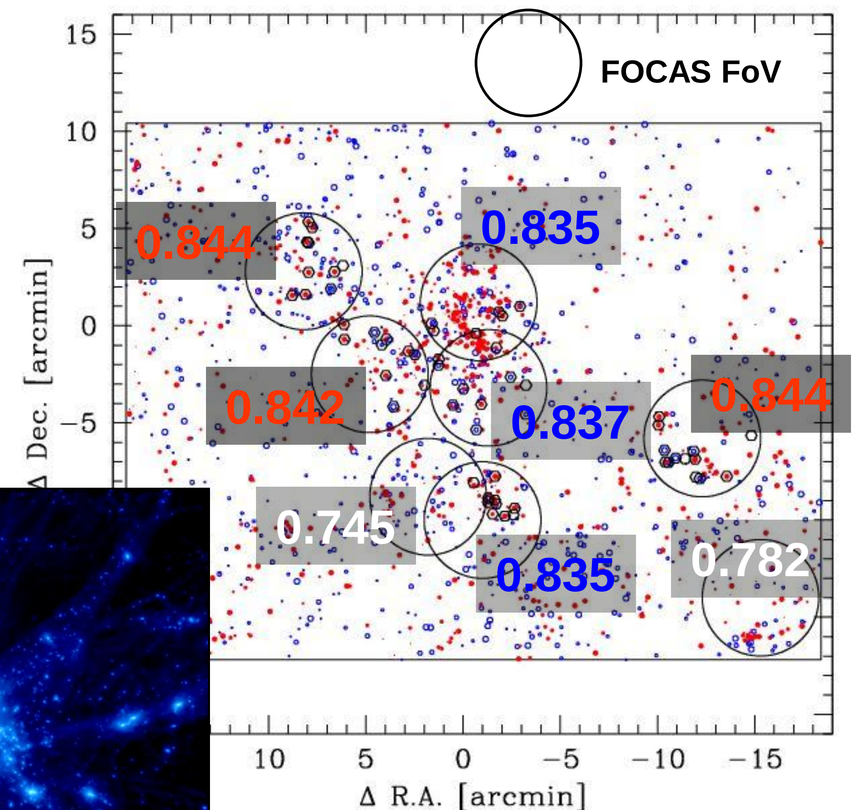
RXJ 0152.7-1357 cluster (z=0.83; ~7Gyrs ago)

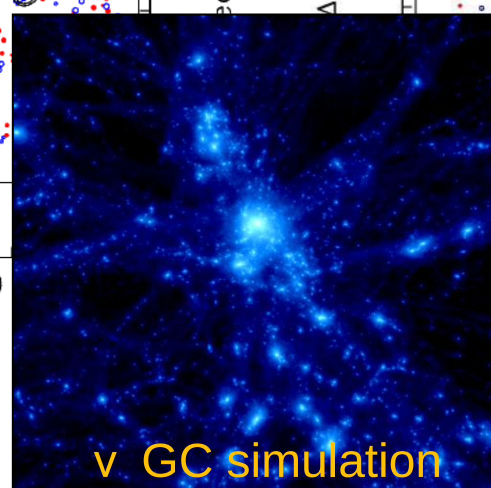
phot-z members (Δz =−0.05~+0.03; Vri'z')



Kodama, et al. (2005)

spec-z members (~200 redshifts)

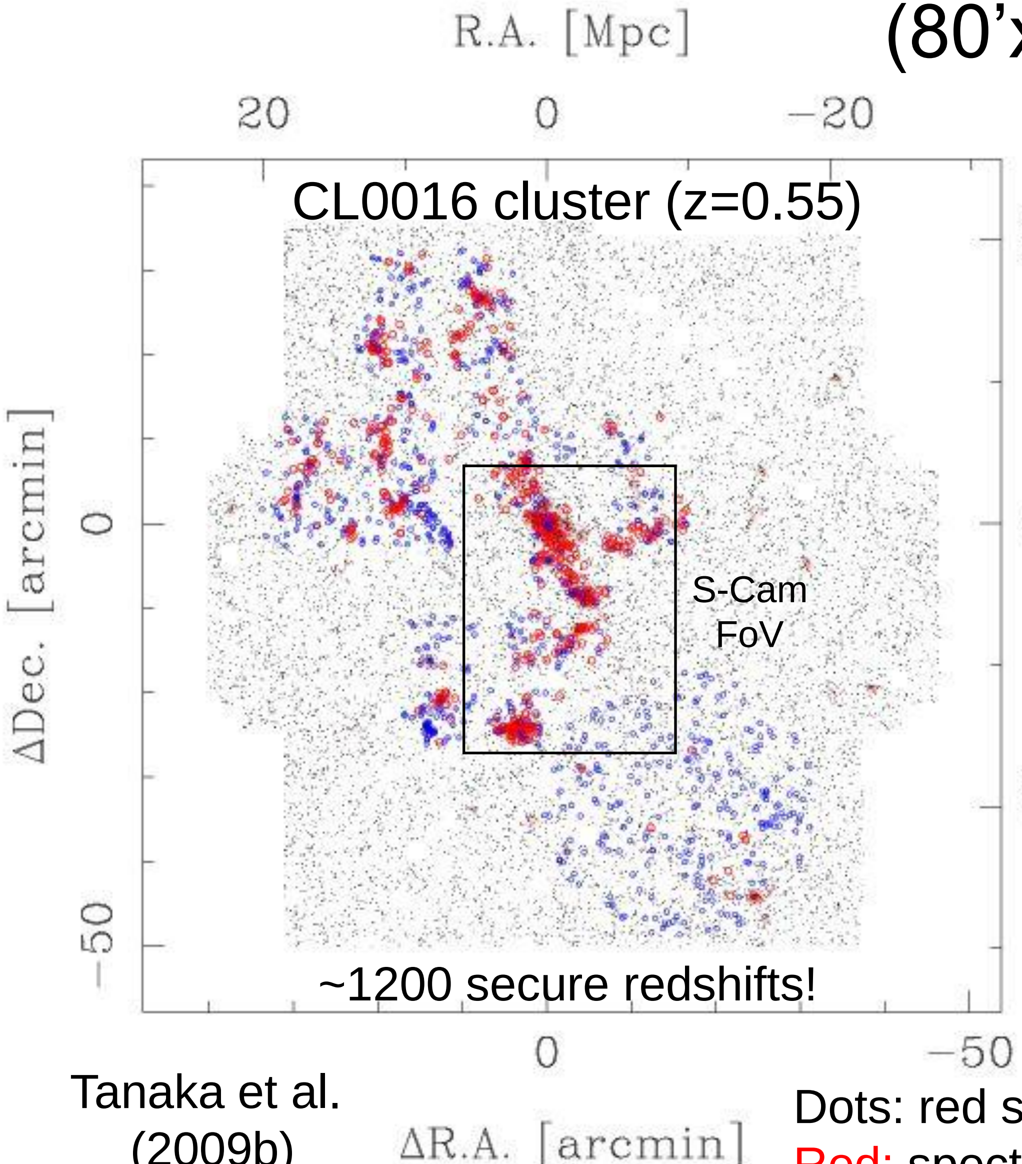


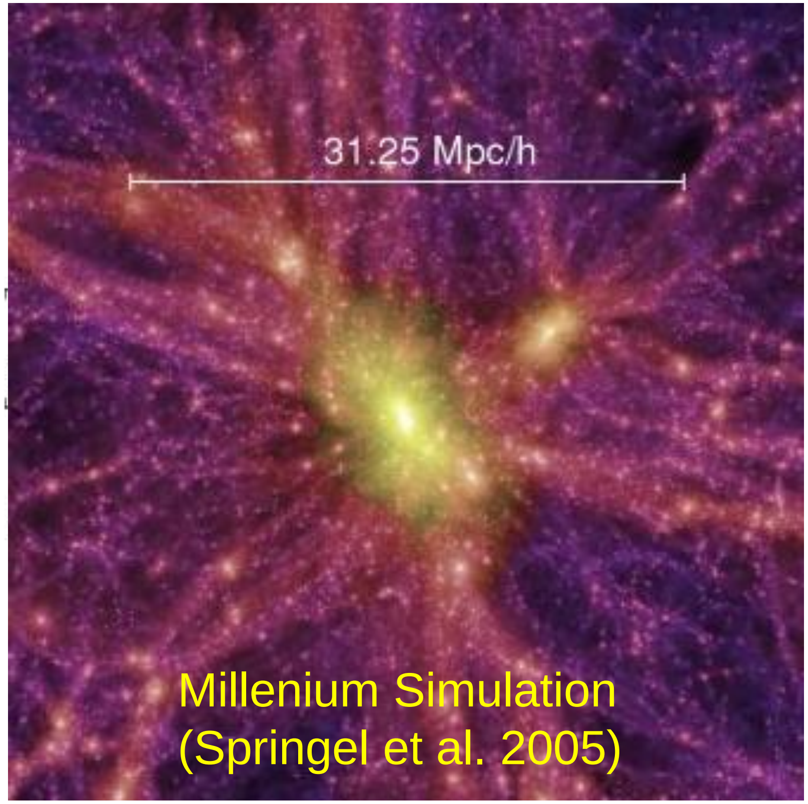


Tanaka, TK, et al. (2007)

A Huge Cosmic Web at z=0.55 over 50 Mpc

(80'x80' by 7 S-Cam ptgs.)





Tanaka et al. (2009b)

ESO 41/09 - Science Release

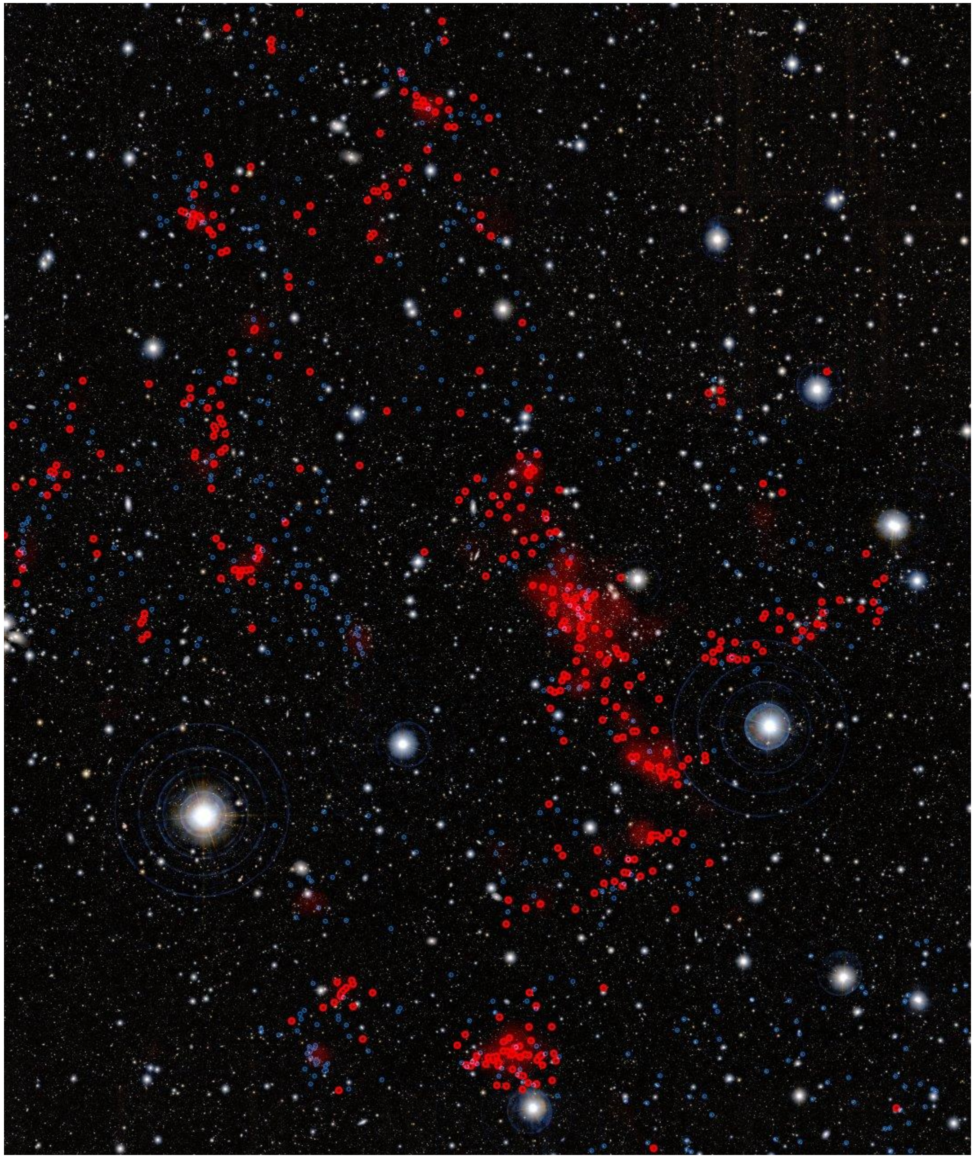
Dots: red sequence galaxies in V-I

Red: spectroscopically confirmed members

Blue: spectroscopically confirmed non-members

ESO 41/09 - Science Release **03 November 2009**

Shedding Light on the Cosmic Skeleton



Masayuki Tanaka,
et al.

CL 1252-2927 (z=1.24)

Tanaka, et al. (2009a)

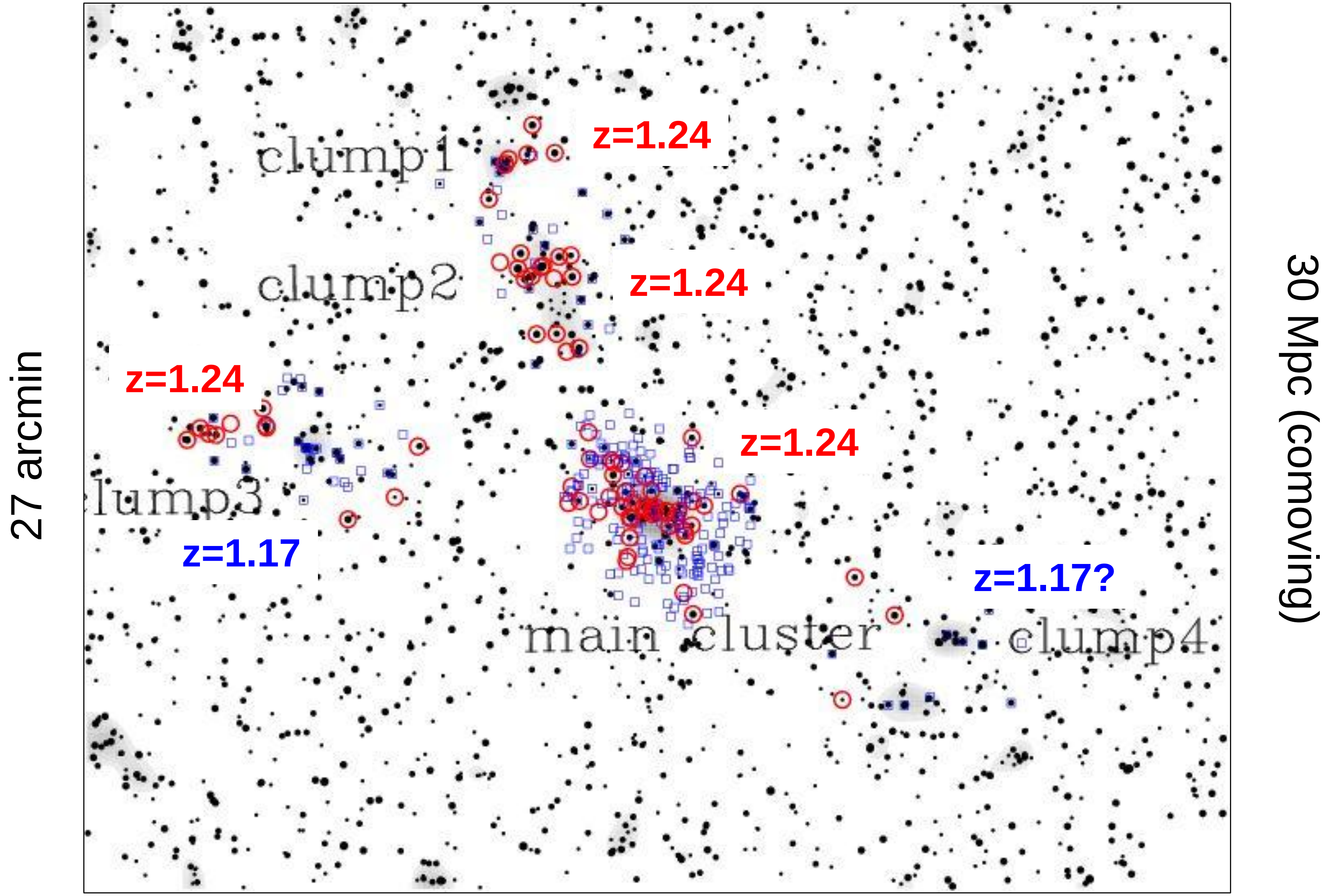
27 arcmin

30 Mpc (comoving)

Subaru/Suprime-Cam (V,R,I’,z’) + UKIRT/WFCAM (K’)

LSS around CL 1252-2927 (z=1.24)

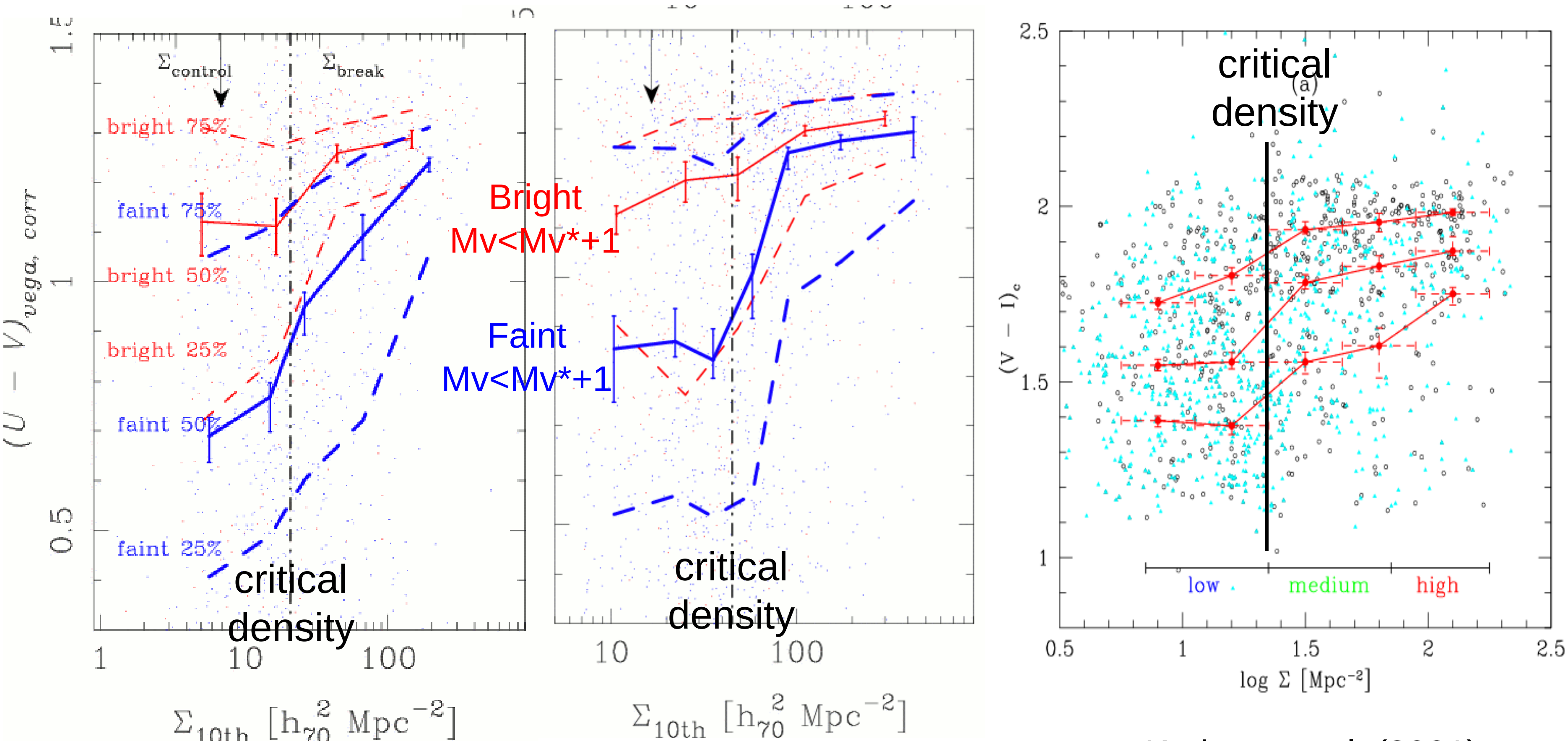
Tanaka, et al. (2009a)



Subaru/Suprime-Cam (V,R,I',z') + UKIRT/WFCAM (K') + VLT/FORS2 (spectroscopy)

Galaxy properties vs. environment in LSS

RXJ0152 @ z=0.83	CL0016 @ z=0.55	CL0939 @ z=41

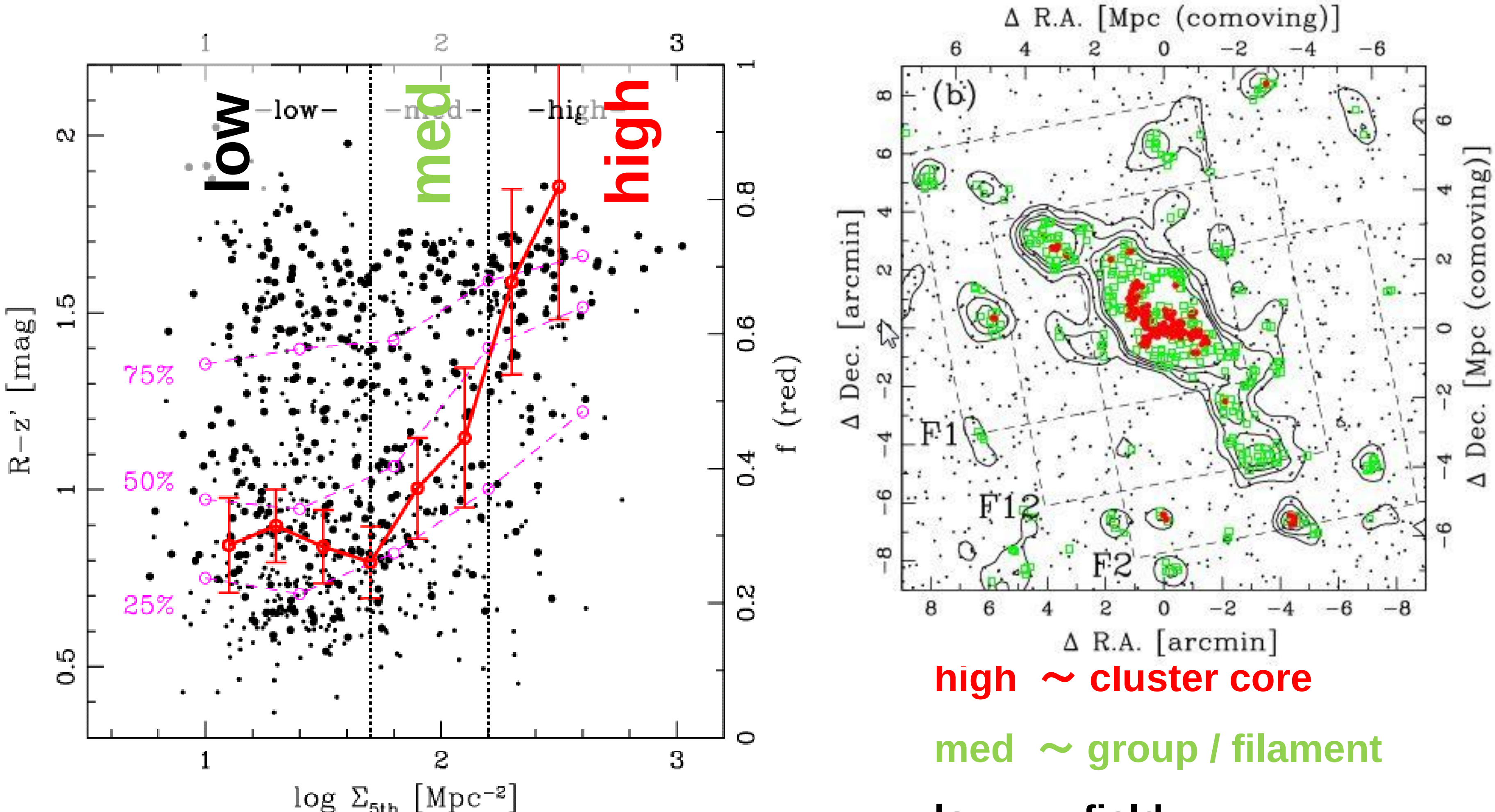


Tanaka, TK, et al. (2005) Tanaka, TK, et al. (2005) Kodama et al. (2001)

Sharp colour transition is seen at medium (“group”) density!

Sharp colour transition in groups/outskirts

RXJ1716 cluster (z=0.81)



high ～ cluster core

med ～ group / filament

low ～ field

Koyama, TK, et al. (2008)

Mapping star formation avtivities with narrow-band imaging (Hα, [OII]) with Suprime-Cam/MOIRCS

Targets	Redshift (z)	Filter	Instr.	CW (μm)	FWHM (μm)	Line	SFR (M/yr, 5σ)	Status
CL0024+1652	0.395	NB912	S-Cam	0.9139	0.0134	Hα	0.1	Kodama+04
CL0939+4713	0.407	NB921	S-Cam	0.9196	0.0132	Hα	0.1	Nakata+10
RXJ1716.4+6708	**0.813**	**NB119**	**MOIRCS**	**1.1885**	**0.0141**	**Hα**	**1.7**	**Koyama+09**
		NA671	S-Cam	0.6714	0.0130	[OII]	~2	Koyama+10
XCS2215.9-1738	**1.457**	**NB912**	**S-Cam**	**0.9139**	**0.0134**	**[OII]**	**4.3**	**Hayashi+09**

Advantages:

(1) Good indicators of SFR, especially Ha (low reddening, well calibrated)

(2) "Unbiased" sample (no pre-selection of targets is required).

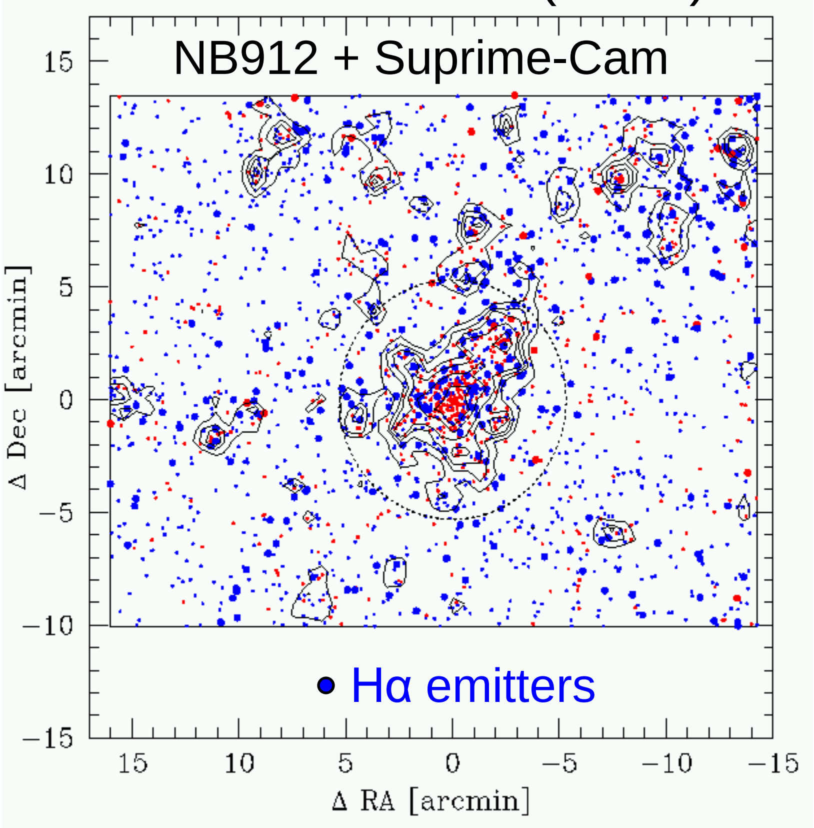
(3) "Complete" census of star forming galaxies to a certain limit in SFR.

(4) Membership can be confirmed by the presence of emitters in NB +colours.

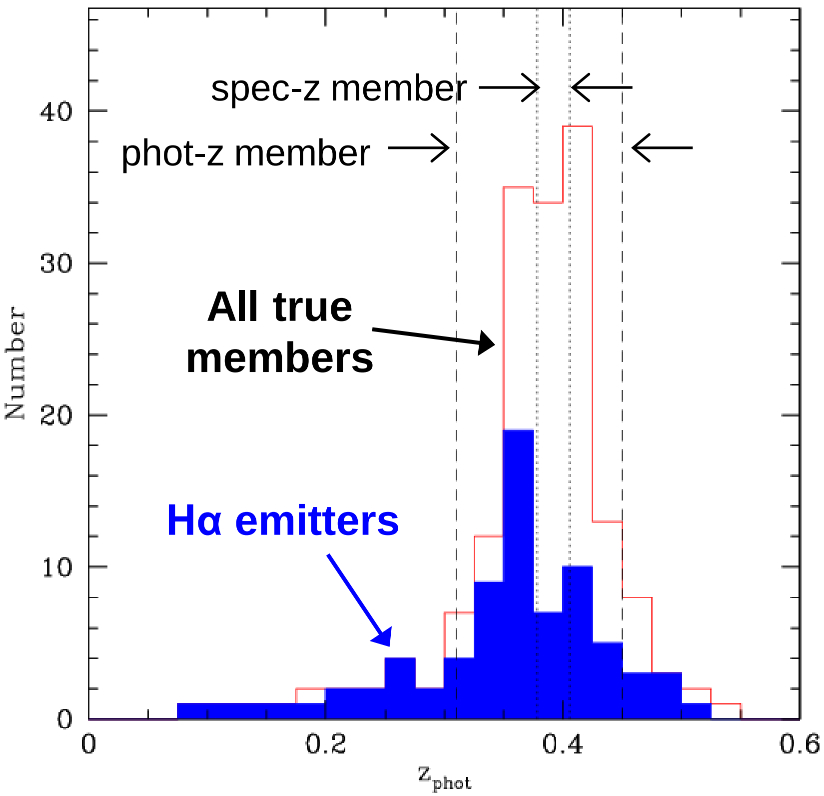
(5) On top of the phot-z selected members (e.g. "passive" galaxies), we can pick out "active" galaxies which tend to be missed by phot-z selection.

Combination of BB selection (passive galaxies) + NB emitters (active galaxies)

CL0024 cluster (z=0.4)



Phot-z distribution of true members

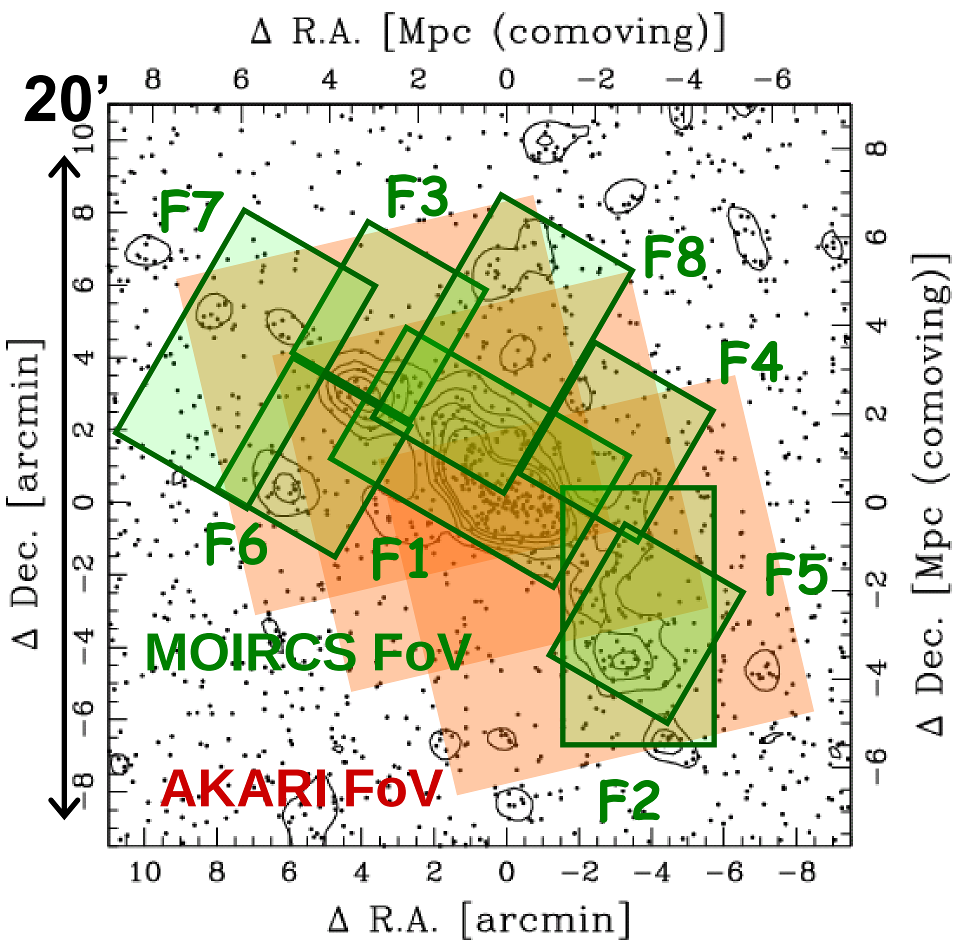


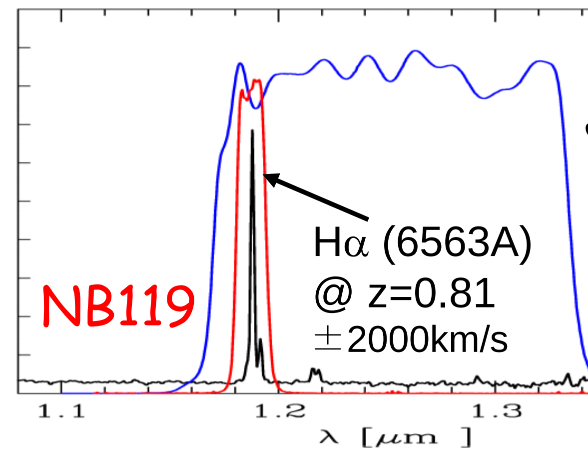
Kodama, Balogh, et al. (2004)

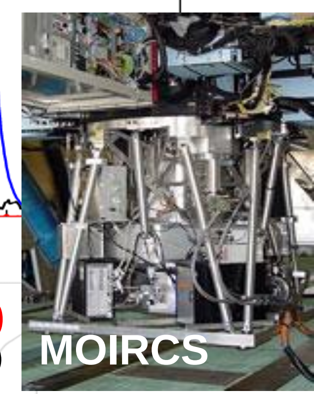
Combination of BB imaging (passive galaxies) & NB imaging (active galaxies) provides high-completeness sample of cluster members (even w/o spec-z)!

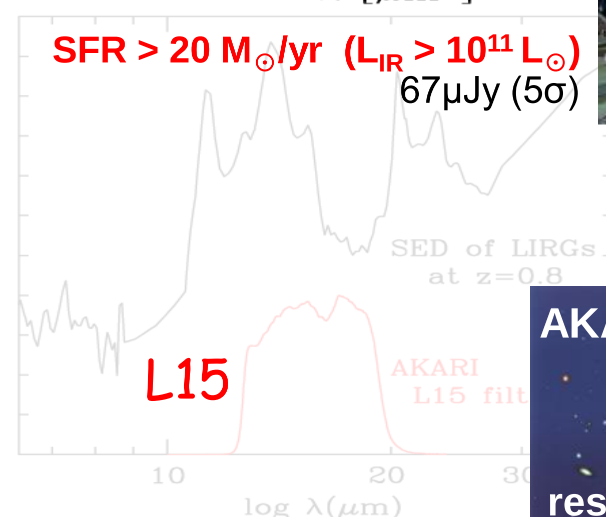
Mapping star formation in and around the RXJ1716 cluster at z=0.81 with Hα and MIR

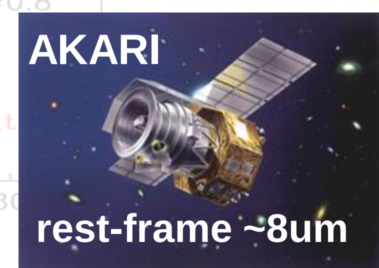
Subaru/S-Cam (*V R i' z'*) MOIRCS (*J, NB119*) AKARI / IRC (*3, 7, 15μm*)







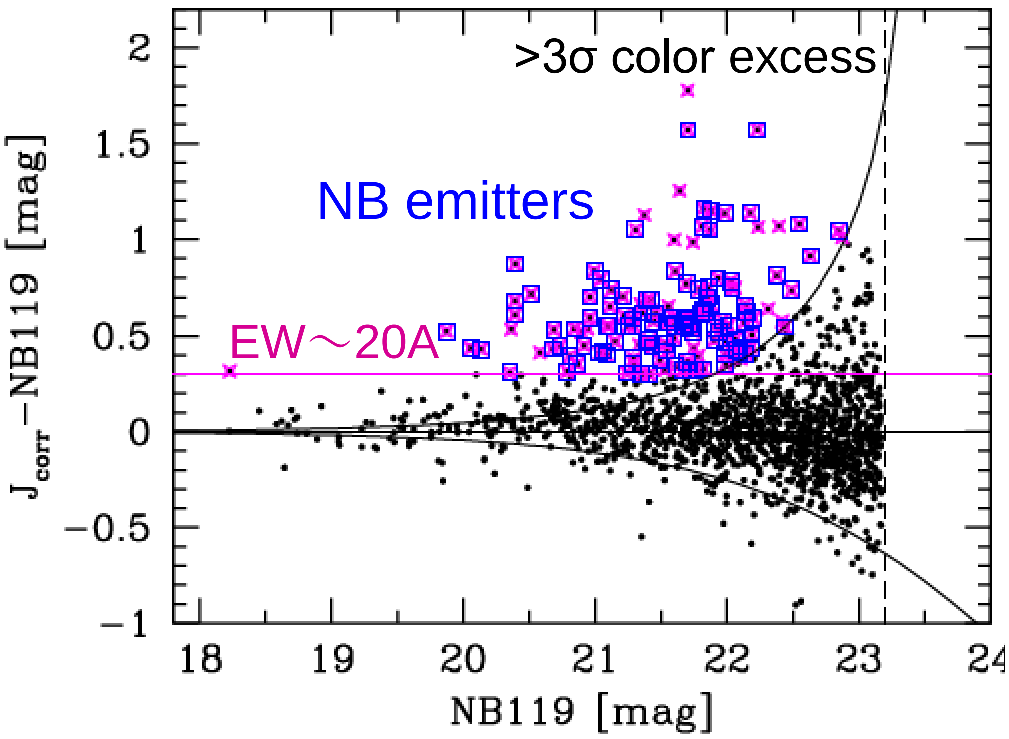


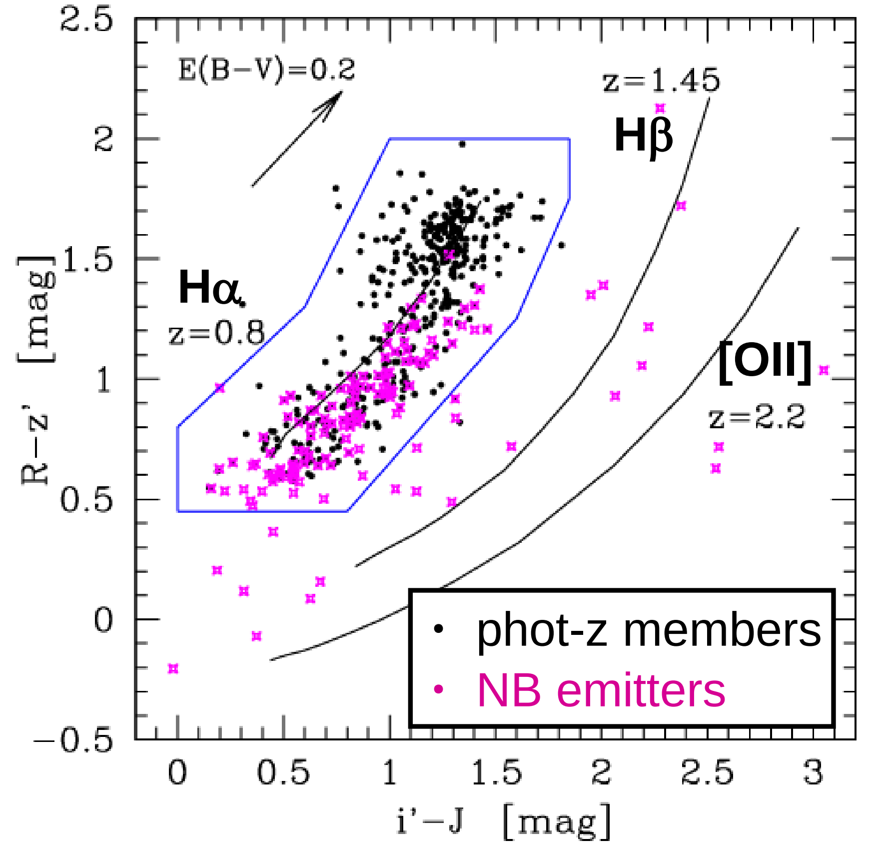


Selection of Hα emitters associated to the RXJ1716 cluster (z=0.81)

J-NB colour excesses + appropriate broad-band colours

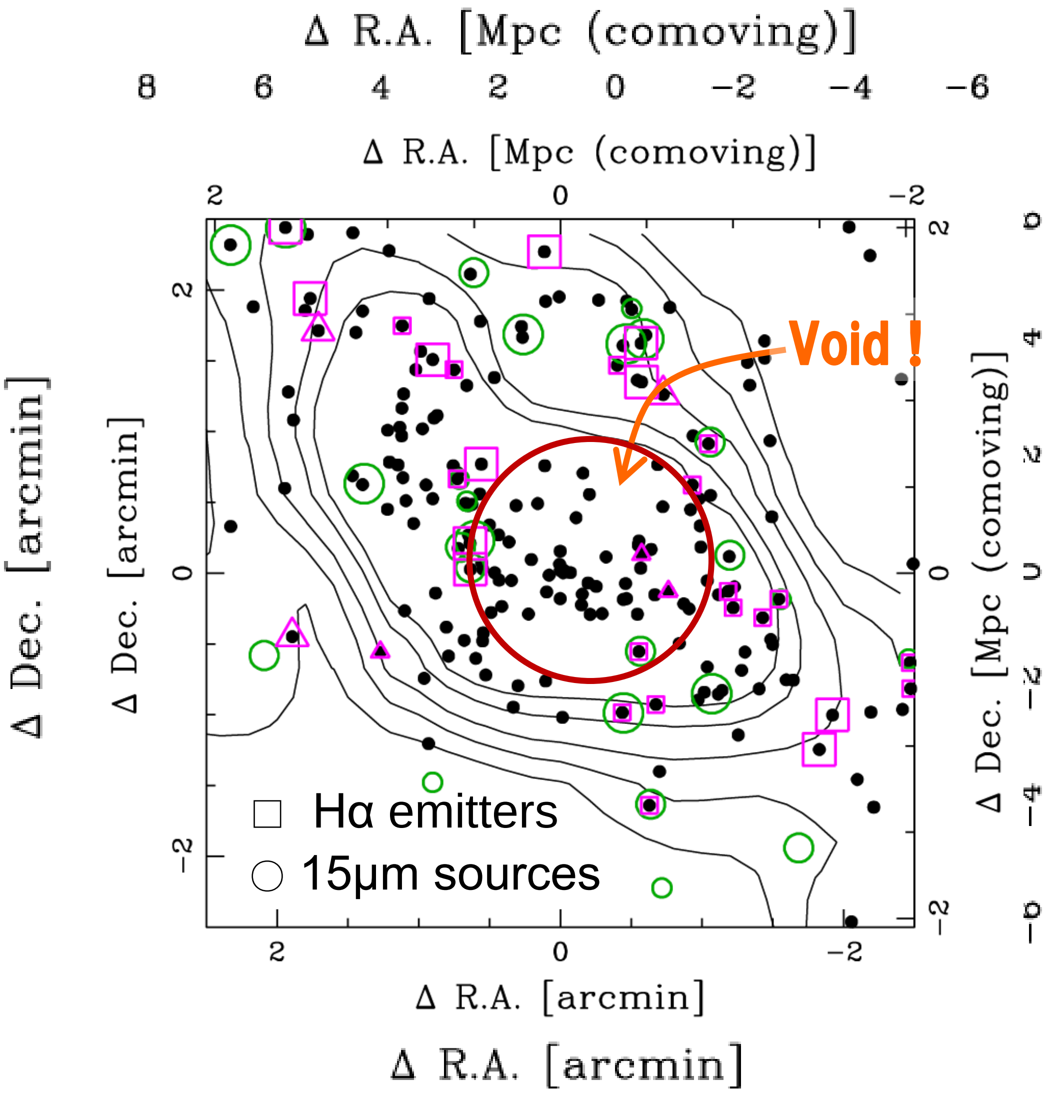
SFR (Hα) > 1.5 M⊙/yr

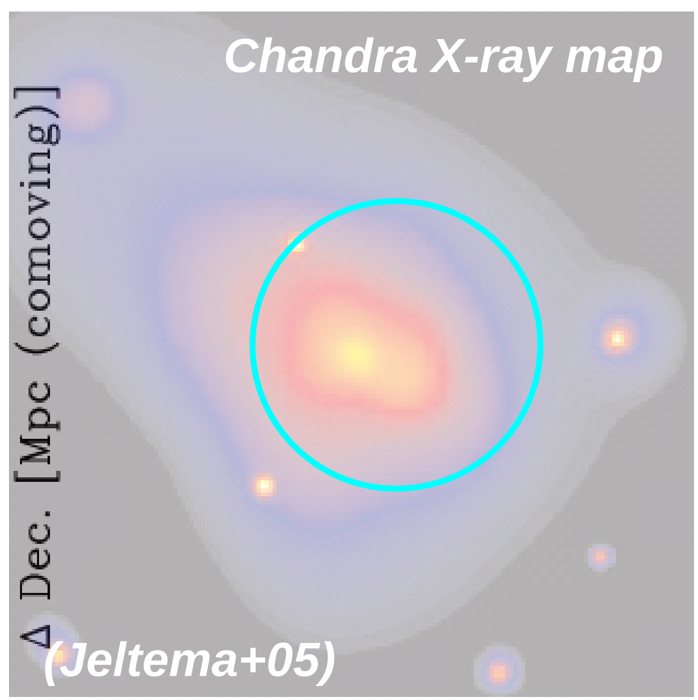




Koyama, TK, et al. (2009)

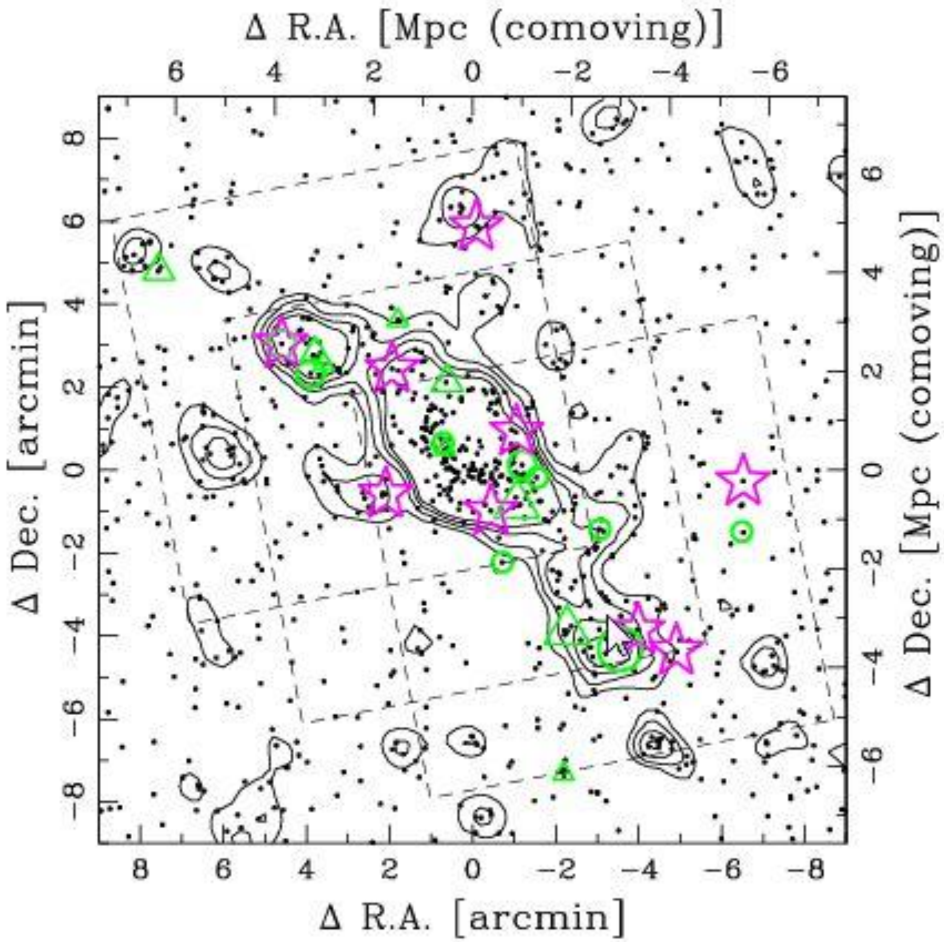
Avoidance of the 15μm sources and the Hα emitters in the cluster centre



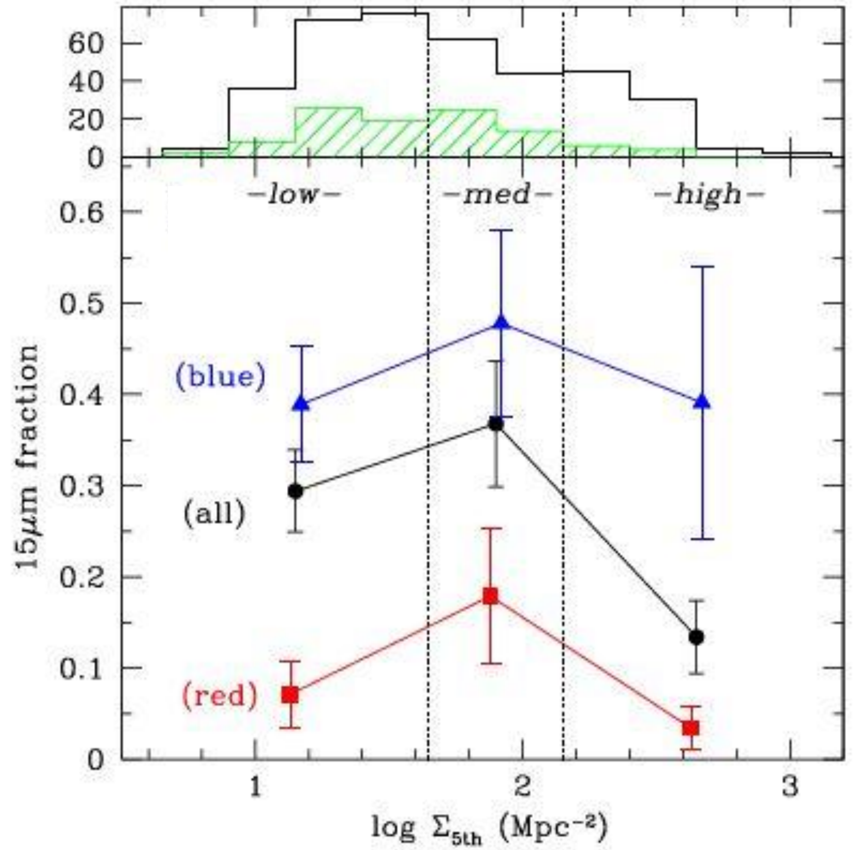


Koyama, TK, et al. (2009)

Spatial Distribution of the 15μm sources



f(15μm) > 67 μJy



○△ red15μm sources (dusty)

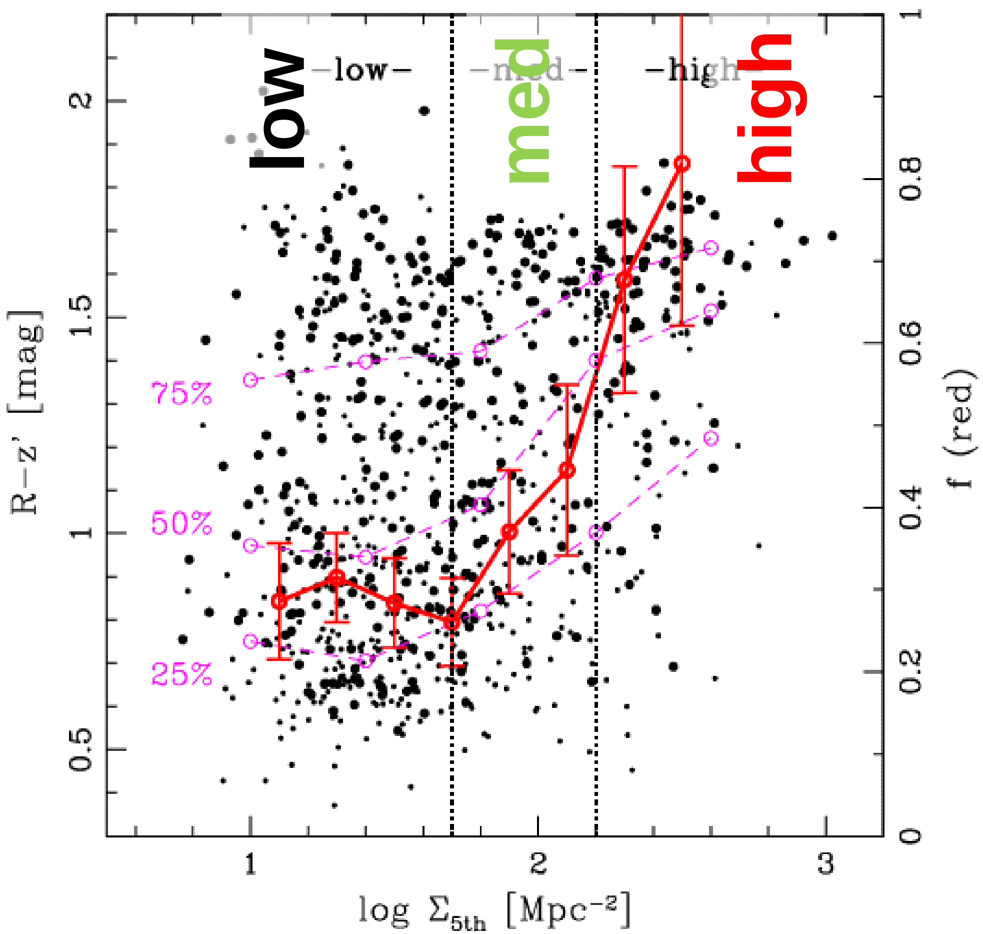
☆ high SSFR(IR) (starbursts)

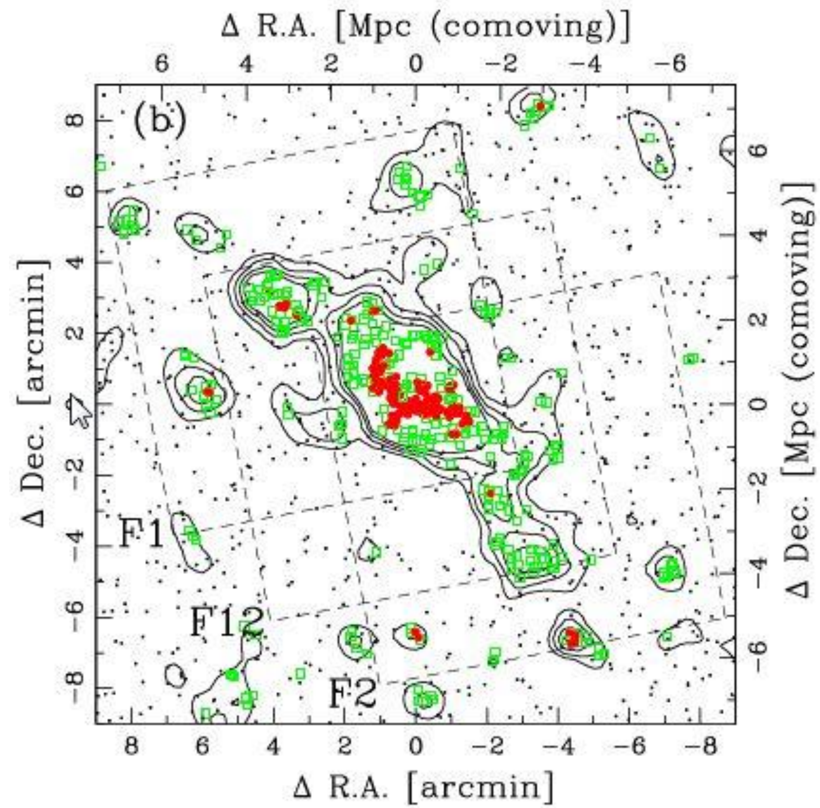
Optically red 15μm sources (dusty starbursts) are preferentially found in the medium density regions.

Koyama, TK, et al. (2008)

Sharp colour transition in groups/outskirts

RXJ1716 cluster (z=0.81)





high ～ cluster core

med ～ group / filament

low ～ field

Koyama, TK, et al. (2008)

What is responsible for truncation of star formation？

- Ram-Pressure Stripping (～10^7 yrs)

  Gas in galaxies is stripped off as they fall into cluster environment.

  This is not efficient in group environment where travelling velocities of galaxies are not very high (～200-300km/s)

- Galaxy-Galaxy Mergers (～10^8 yrs)

  Gas in galaxies is quickly consumed as a burst or stripped off due to galaxy-galaxy interaction/mergers.

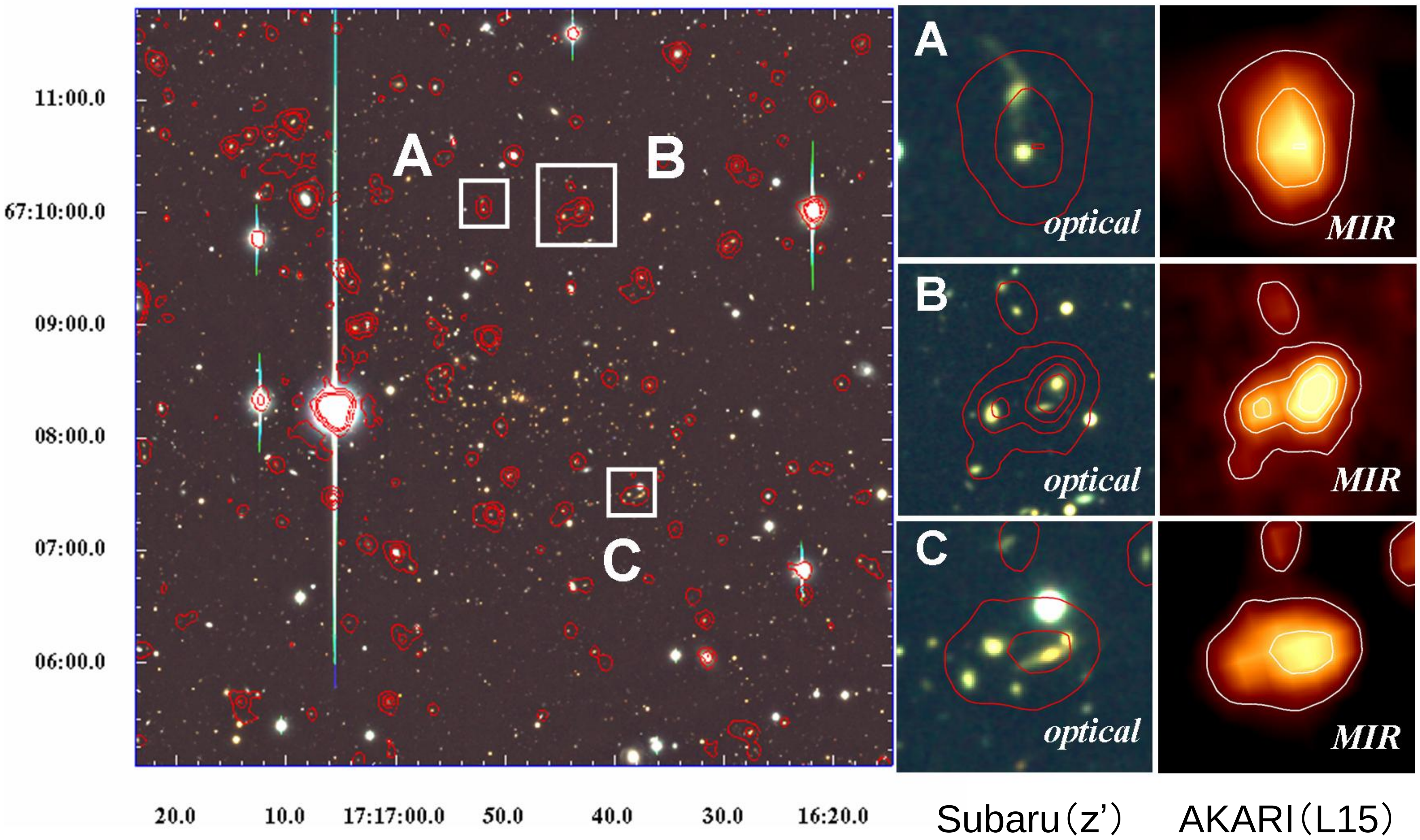
  Starburst is expected.

- Suffocation (hot gas stripping) (～10^9 yrs)

  Weak interaction/ram-pressure can still expel the loosely bound gas in the halos, and star formation in disks eventually terminates without any supply from the gas reservoir.

  No starburst is expected.

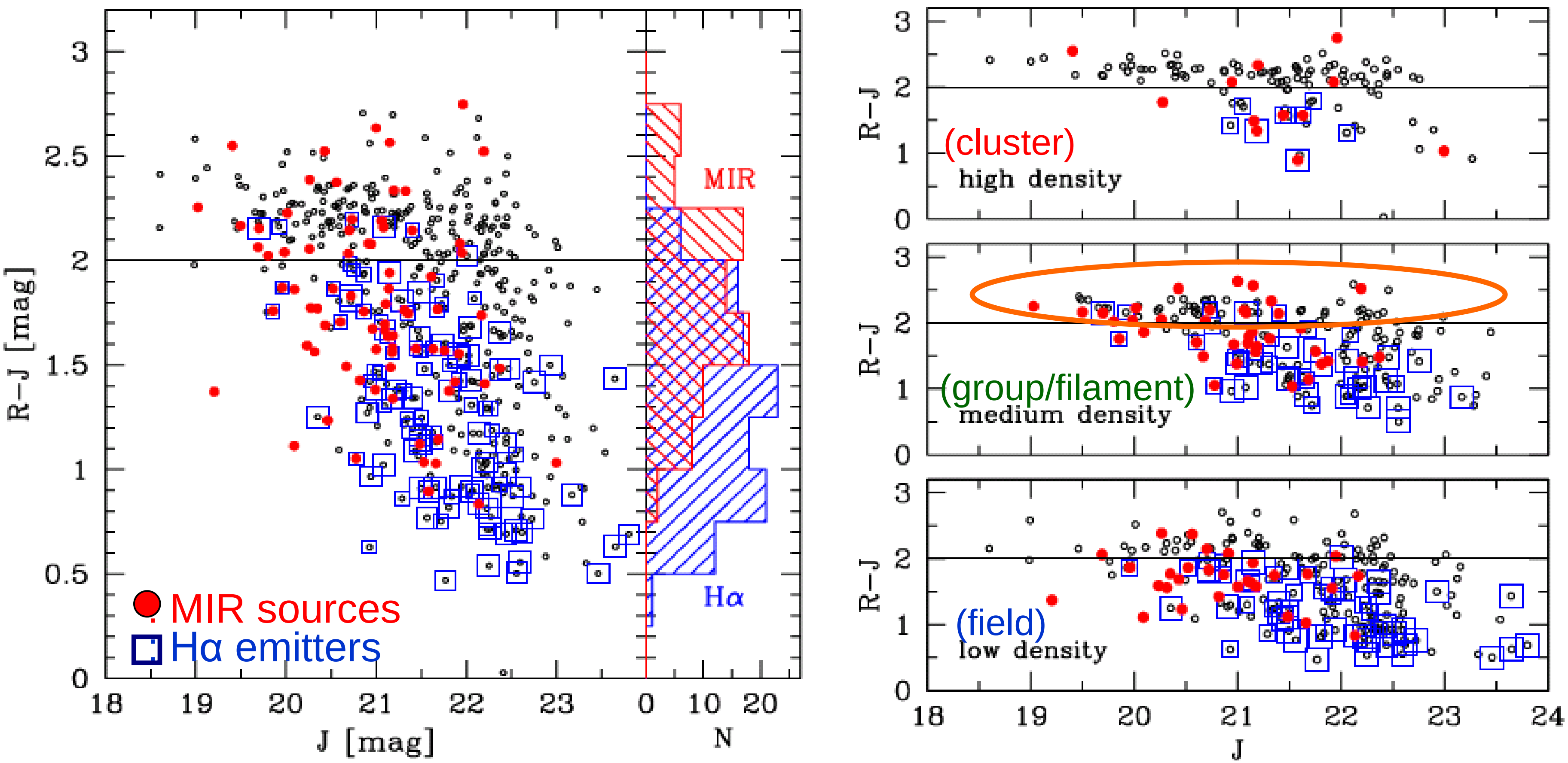
Interacting galaxies in the strong15μm sources



Koyama, TK, et al. (2008)

Hidden star formation in the red sequence?

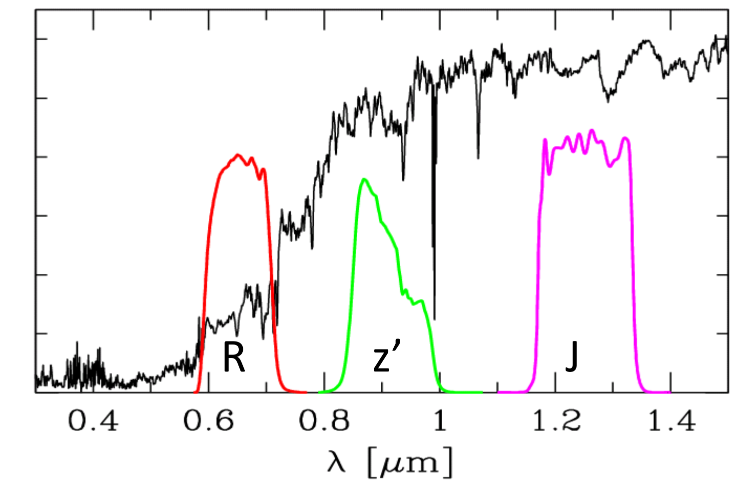
Hα emitters and 15μm sources on the red sequence!

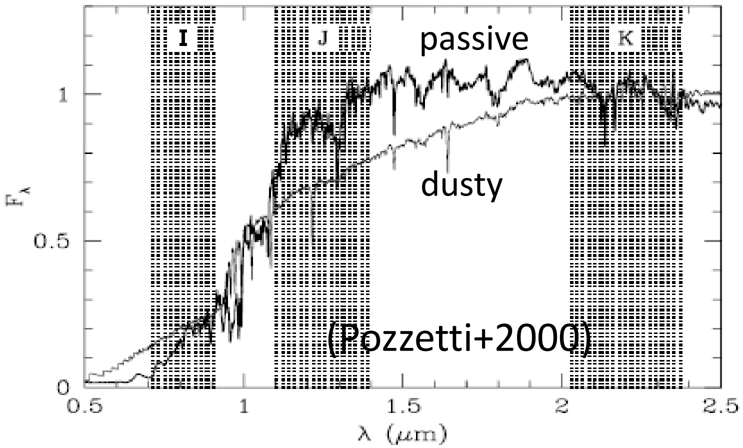


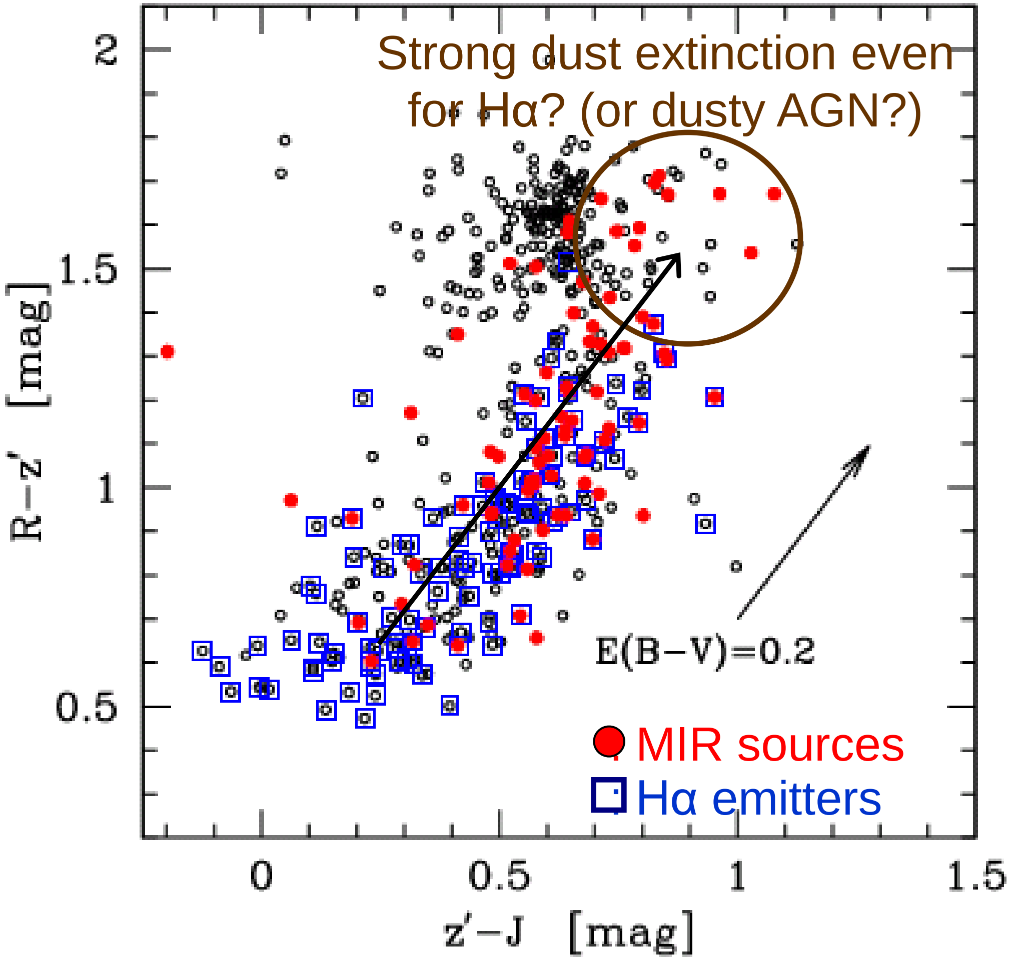
Lots of star formation is likely to be hidden in the optical (rest UV) surveys!

Koyama, TK, et al. (2009)

Dusty star forming galaxies on the red sequence!



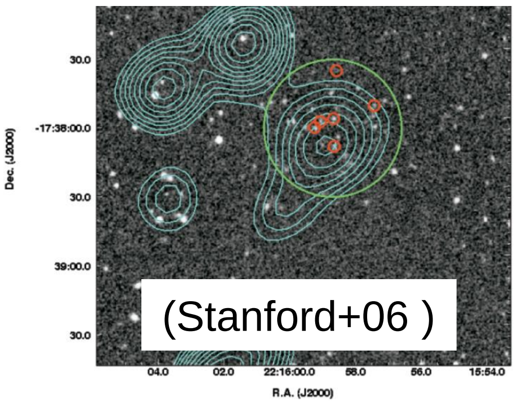


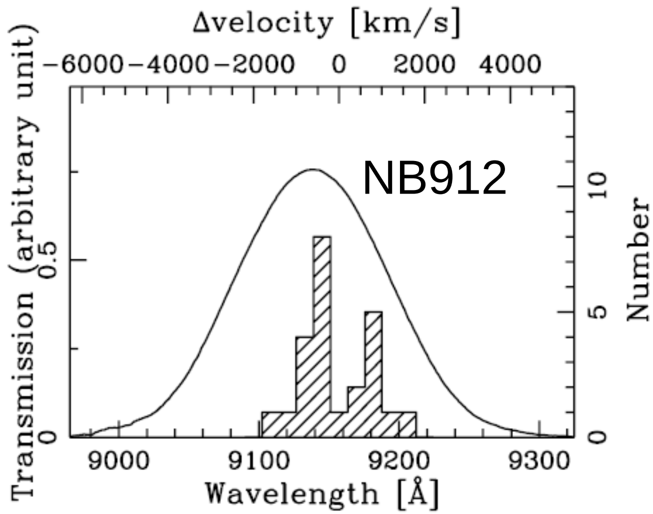


There may be a large amount of hidden star formation in IR which is not seen even with Hα??

A narrow-band [OII] imaging with Suprime-Cam/Subaru (XCS2215@z=1.457)

XMMXCS J2215.9-1738





Hayashi et al. (2009)
just accepted by MNRAS

[OII] @ z=1.46

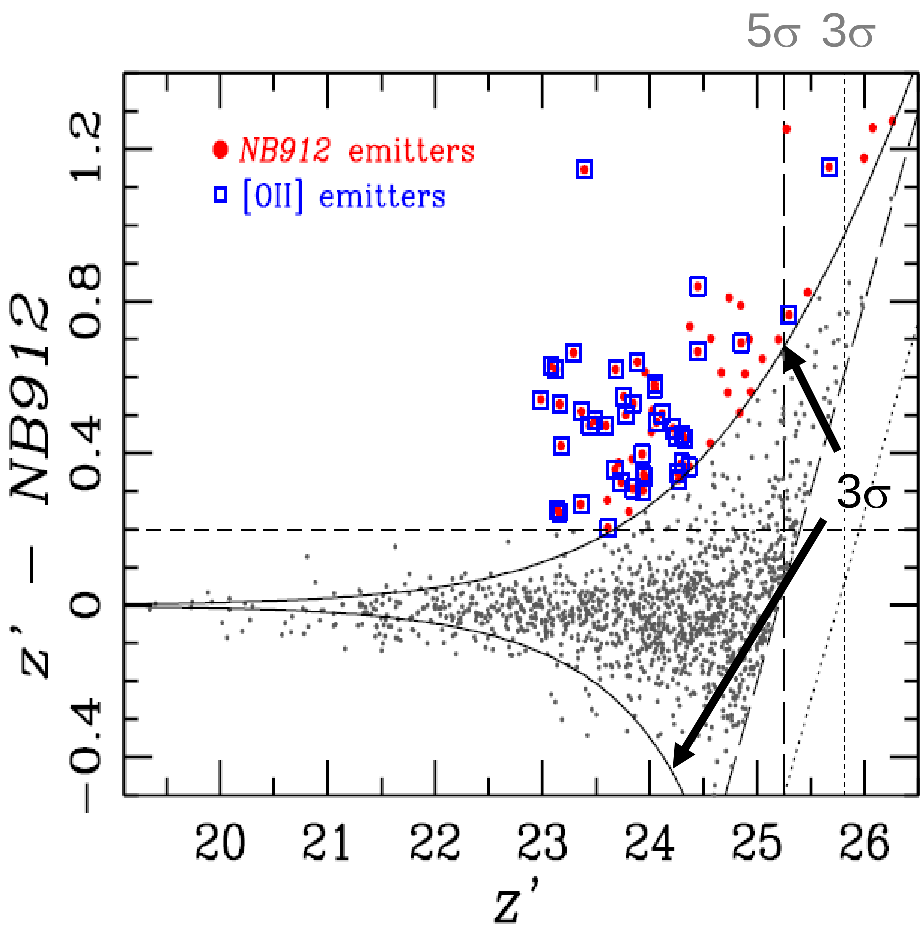
↓

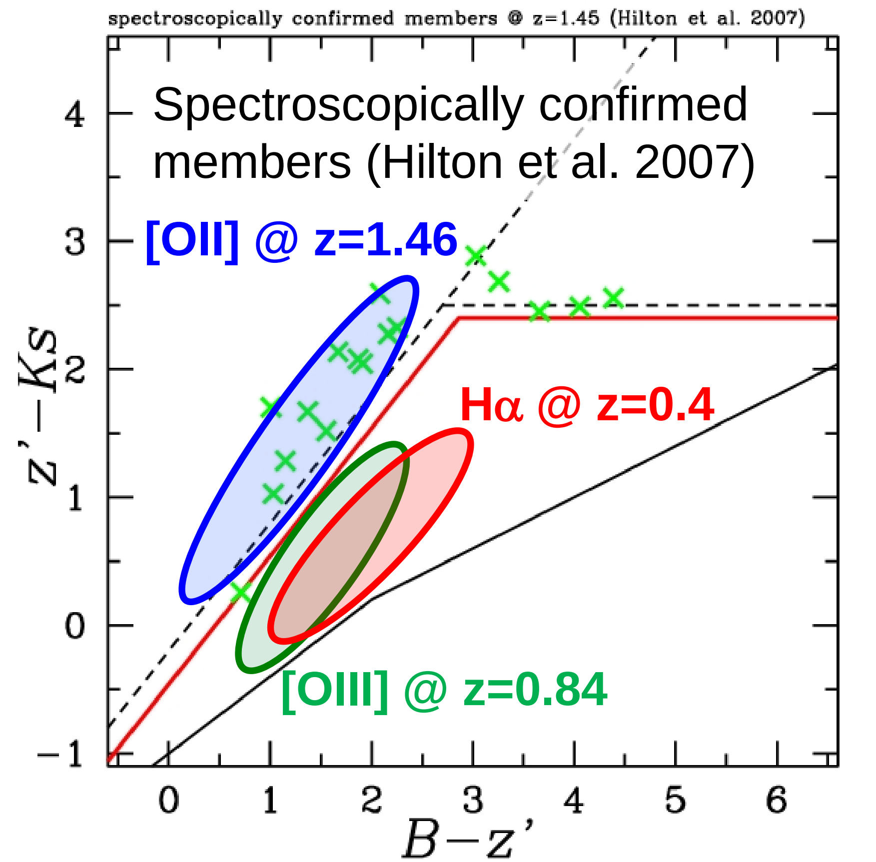
NB912 filter

(λ_c=9139A, $\Delta\lambda$=134A)

instruments	**Suprime-Cam**			**MOIRCS**	
passbands	**B**	**z'**	**NB912**	**J**	**Ks**
dates	2008. 07.30-31			2008. 06.30-07.01	
pointings	1			4	
FoV	32' x 23'			6.1' x 5.8'	
3σ mags	27.59	25.81	25.75	23.84-24.57	23.07-23.65
seeing	1.09"			1.09"	

Selection of [OII] emitters associated to the XCS2215 cluster (z=1.46)

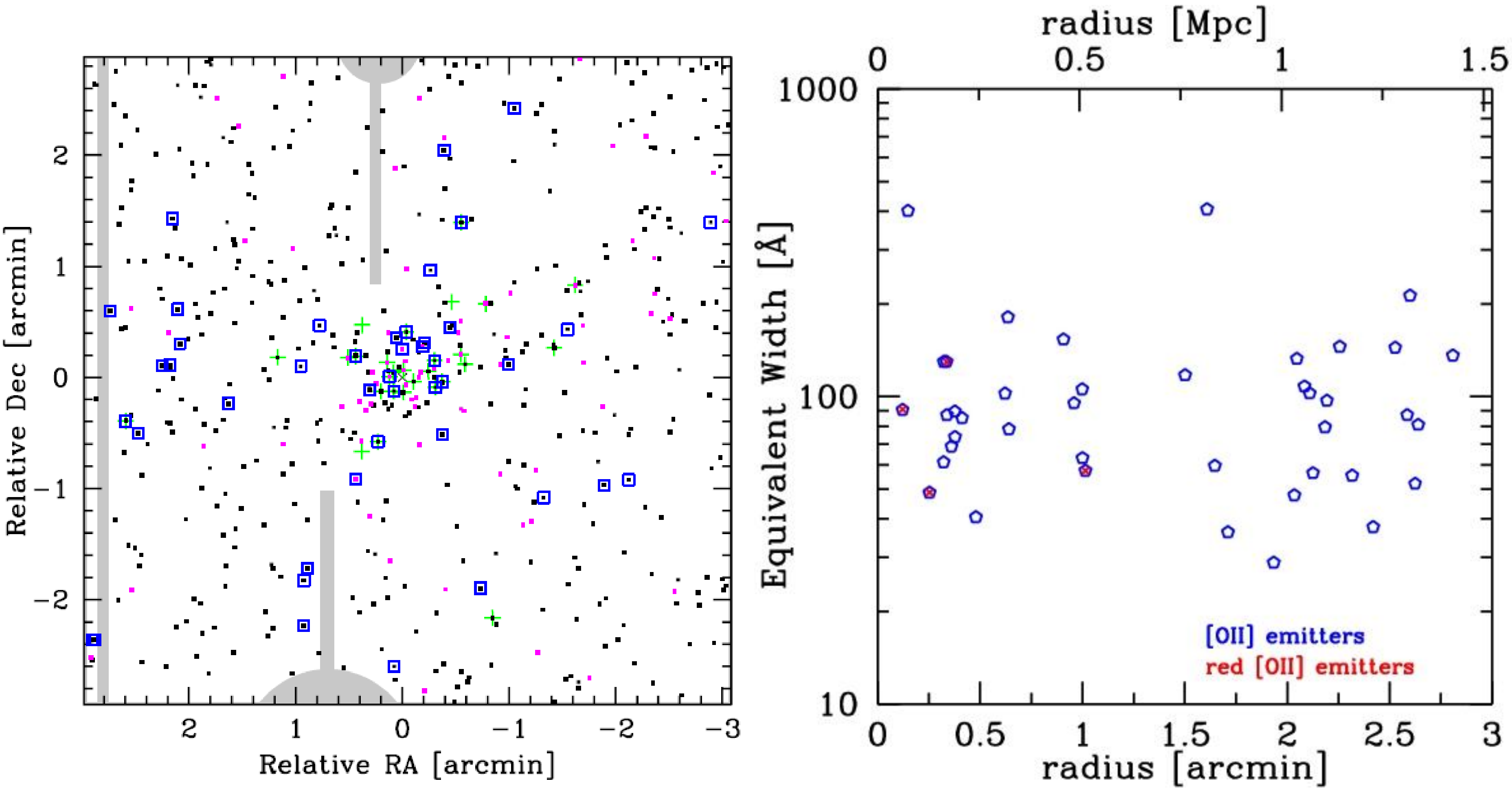




SFR ([OII]) > 2.6 M⊙/yr

Hayashi, TK, et al. (2009)

Spatial Distribution of the [OII] emitters

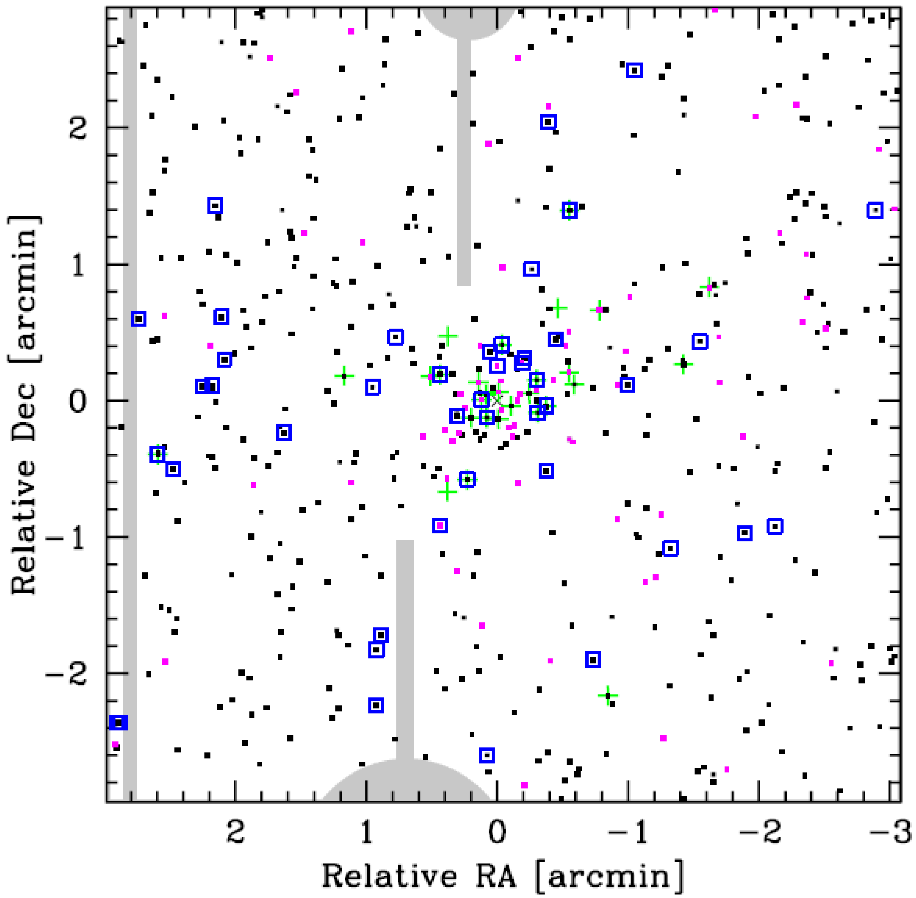


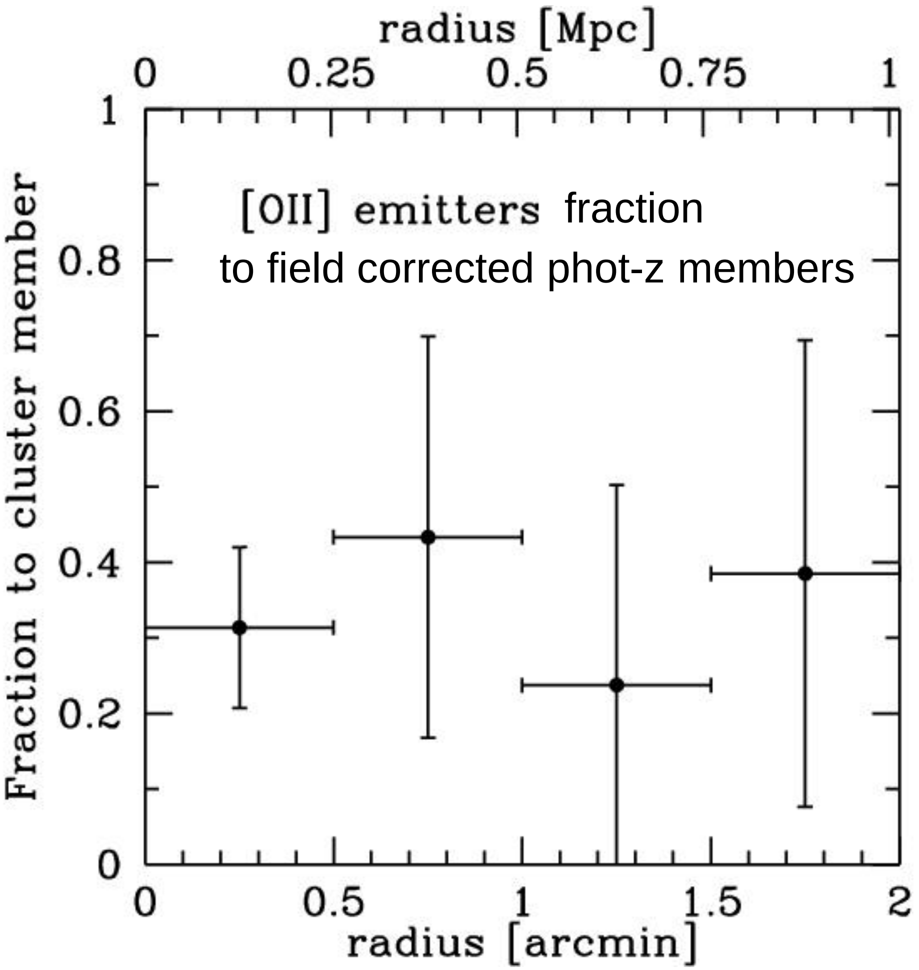
High star formation activity all the way to the very centre of the cluster!

(AGN contamination?)

Hayashi, TK, et al. (2009)

Spatial Distribution of the [OII] emitters





High star formation activity all the way to the very centre of the cluster!

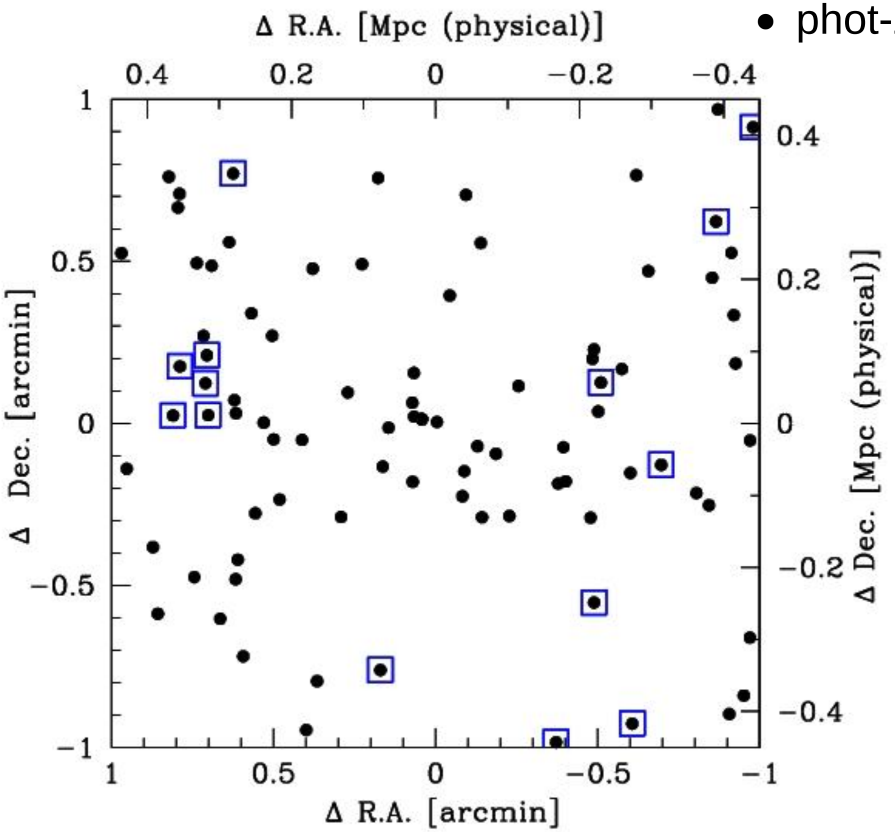
(AGN contamination?)

Hayashi, TK, et al. (2009)

Star forming activity in the cluster cores

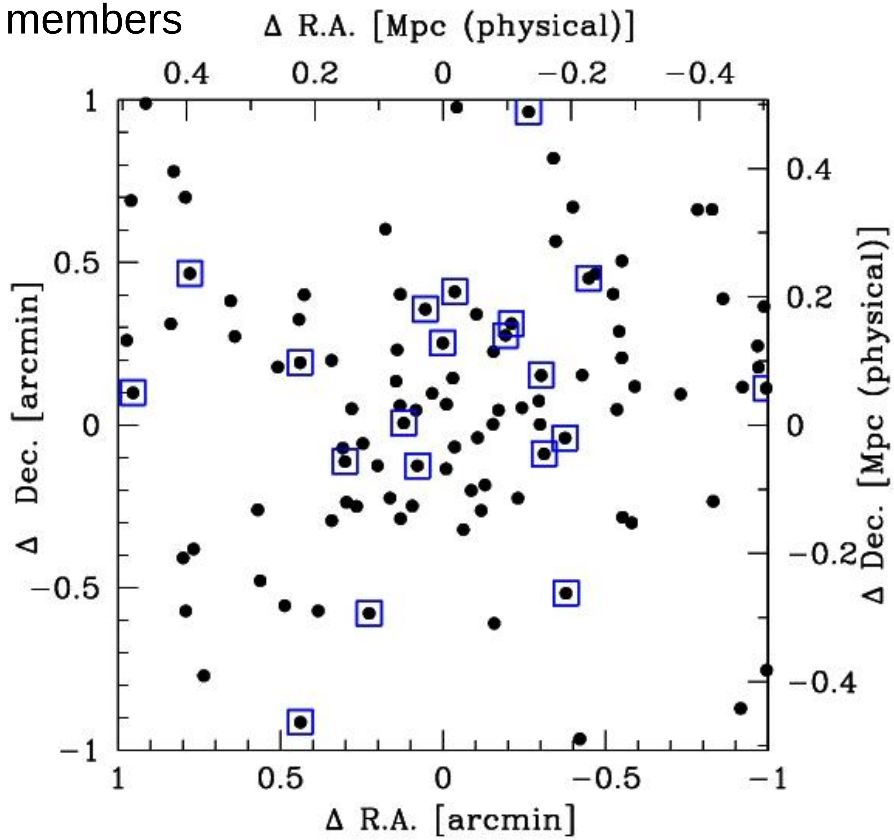
□ Hα emitters at z=0.81 (RXJ1716)　　□ [OII] emitters at z=1.46 (XCS2215)

• phot-z members



Lx=2.7×10[44] erg/s

Koyama, TK, et al. (2009)



Lx=4.4×10[44] erg/s

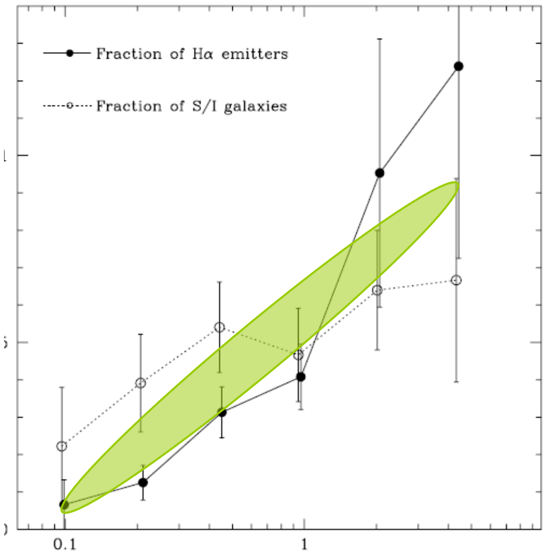
Hayashi, TK, et al. (2009)

Star forming activity in the core is much higher in the higher redshift cluster!

Inside-out propagation/truncation of star forming activity in clusters?

Fraction of emitters (star-forming galaxies)

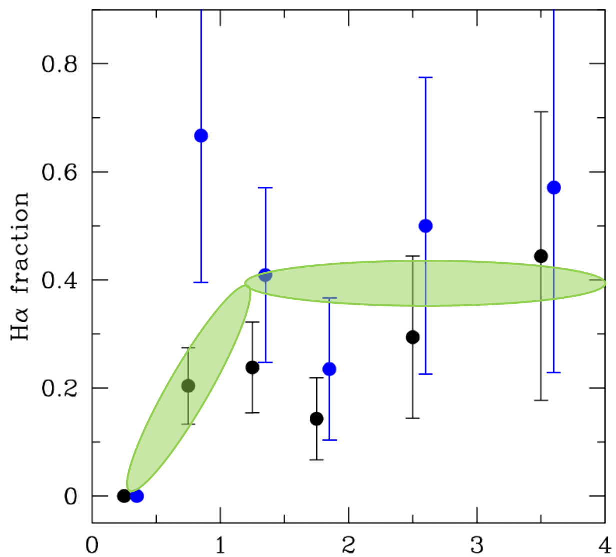
Hα @ z=0.4



Radius [Mpc]

(Kodama+ 04)

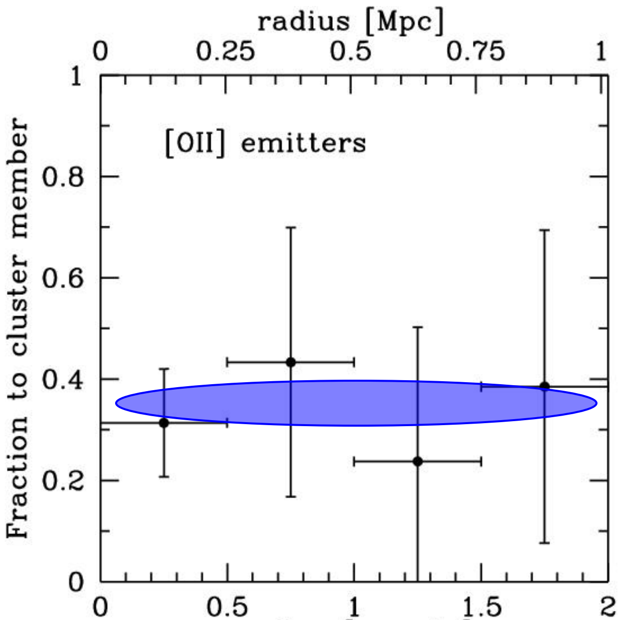
Hα @ z=0.8



Radius [arcmin]

(Koyama+ 09)

[OII] @ z=1.5



Radius [arcmin]

(Hayashi+ 09)

Do we eventually see a reversal of the SFR-Rc / SFR-density relations?
(galaxy formation bias)

High redshift(z) Radio Galaxies [HzRG] with Subaru, VLT, and Spitzer

7 confirmed proto-clusters at 2 < z < 5.2 associated to radio galaxies

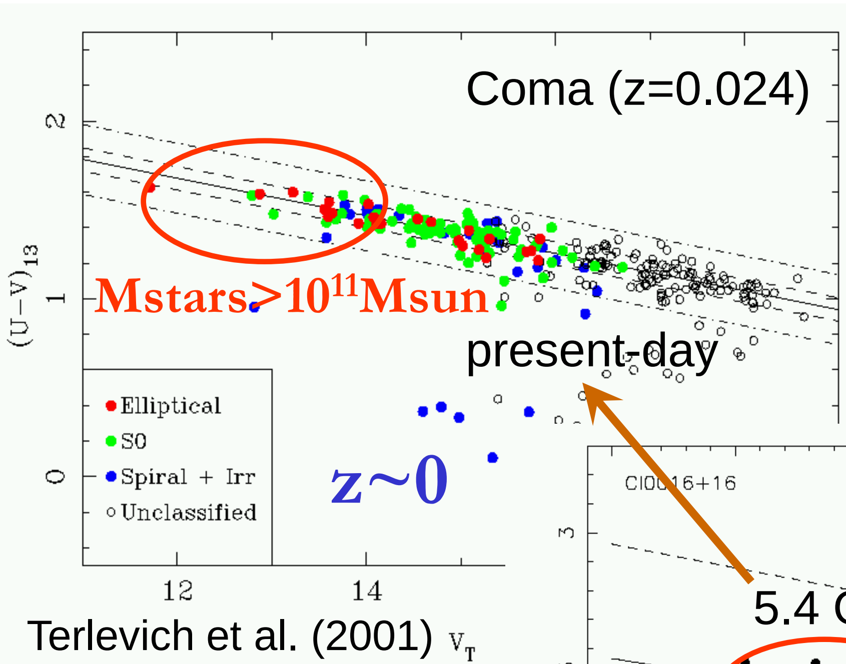
Overdense regions in Lyman-α emitters by a factor of 3—5.

Name	redshift	NIR	Spitzer	Lya	spectra	others
PKS 1138-262	2.16	JHKs	3.6--24.0	16	NIR/Opt	Ha, VLA, Chandra, SCUBA
4C 23.56	2.48	JHKs	3.6--8.0	--	NIR	Ha
USS 1558-003	2.53	JHKs	3.6--8.0	--		Ha planned
MRC 0052-241	2.86	JHKs	3.6--8.0	35		
USS 0943-242	2.92	JHKs	3.6--24.0	29	Opt	
MRC 0316-257	3.13	JHKs	3.6--8.0	32	NIR	
TNJ 1338-1942	4.11	JHKs	3.6--8.0	37		Suprime-Cam, VLA, MAMBO
TNJ 0924-2201	5.19	JHKs	3.6--24.0	6		Suprime-Cam/ACS (LBGs)

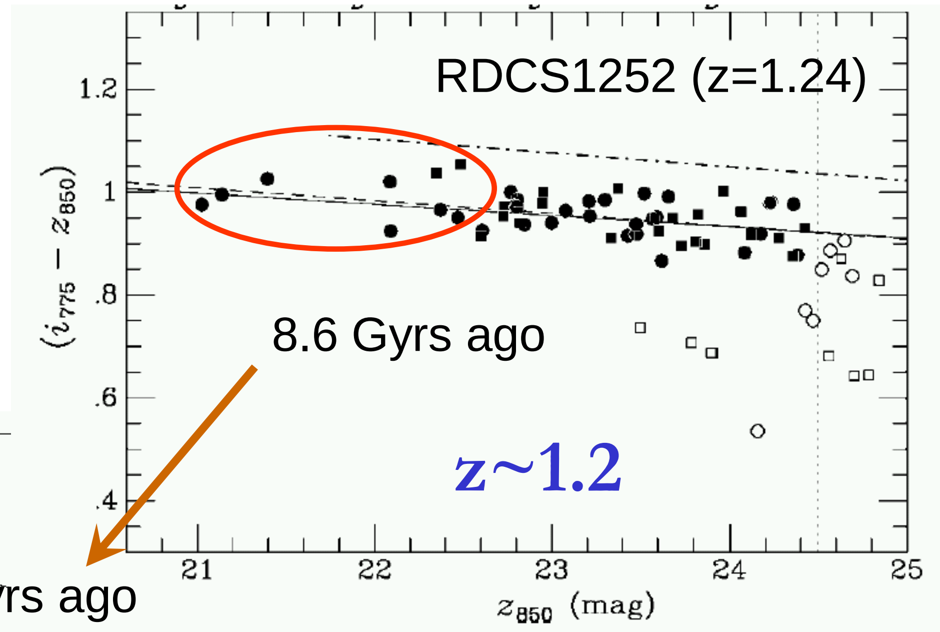
NIR imaging primarily using MOIRCS/Subaru and Hawk-I/VLT

Kodama et al. (2007), De Breuck et al. (Spitzer HzRGs)

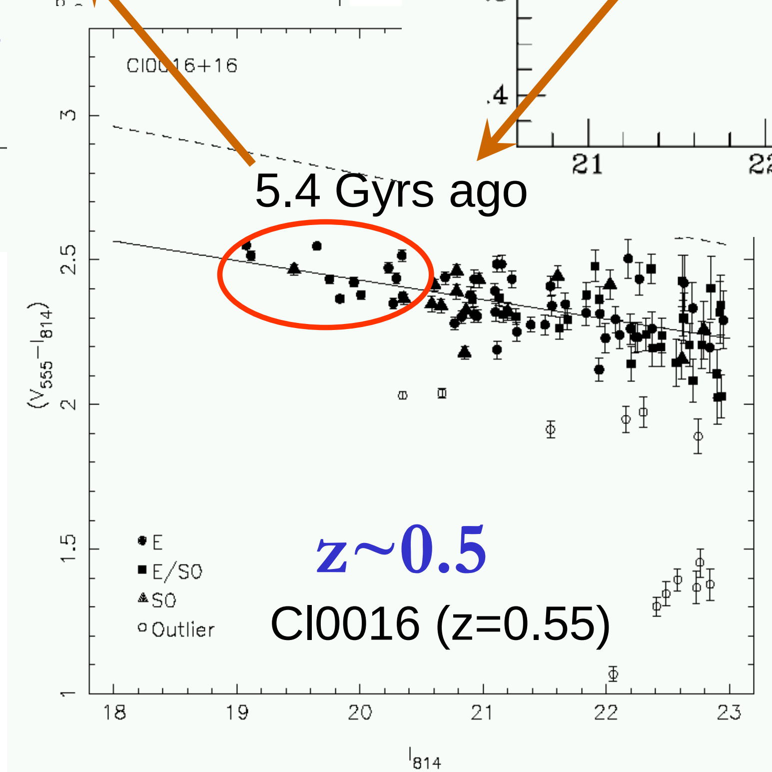
When does the red-sequence of galaxies eventually break down ?



Terlevich et al. (2001)



Blakeslee et al. (2003)



Ellis et al. (1997)

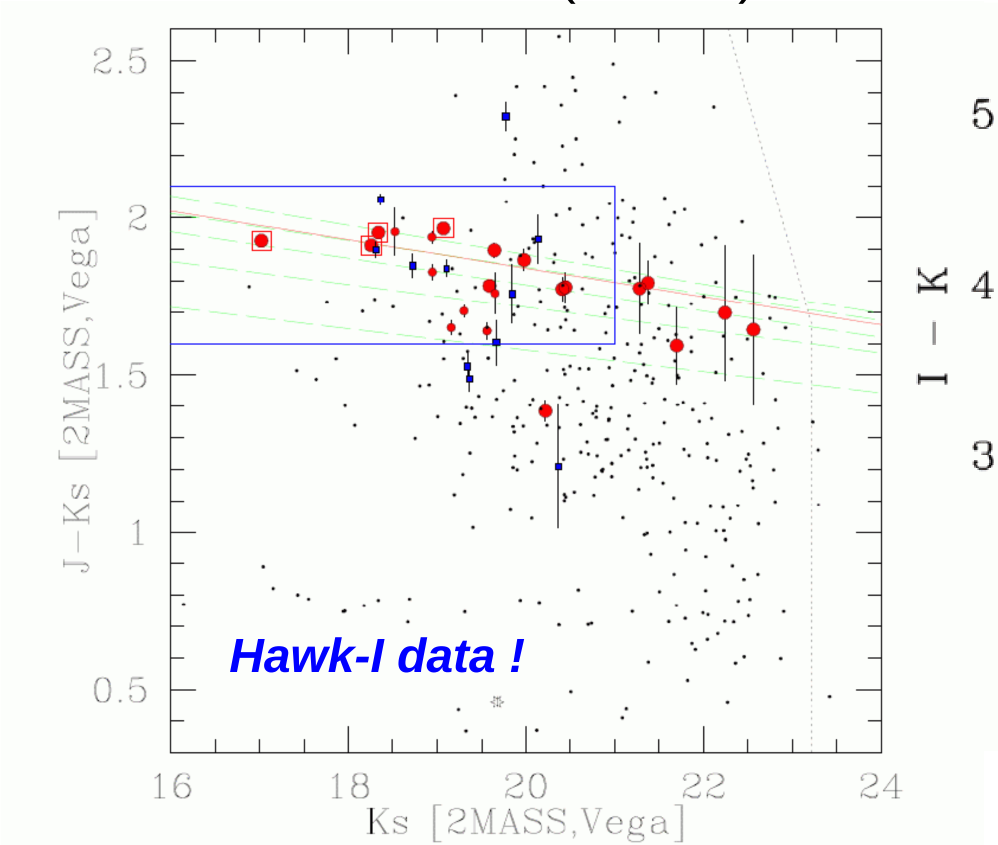
z(SF)>2

z(assembly)>1

When does the red-sequence eventually break down？

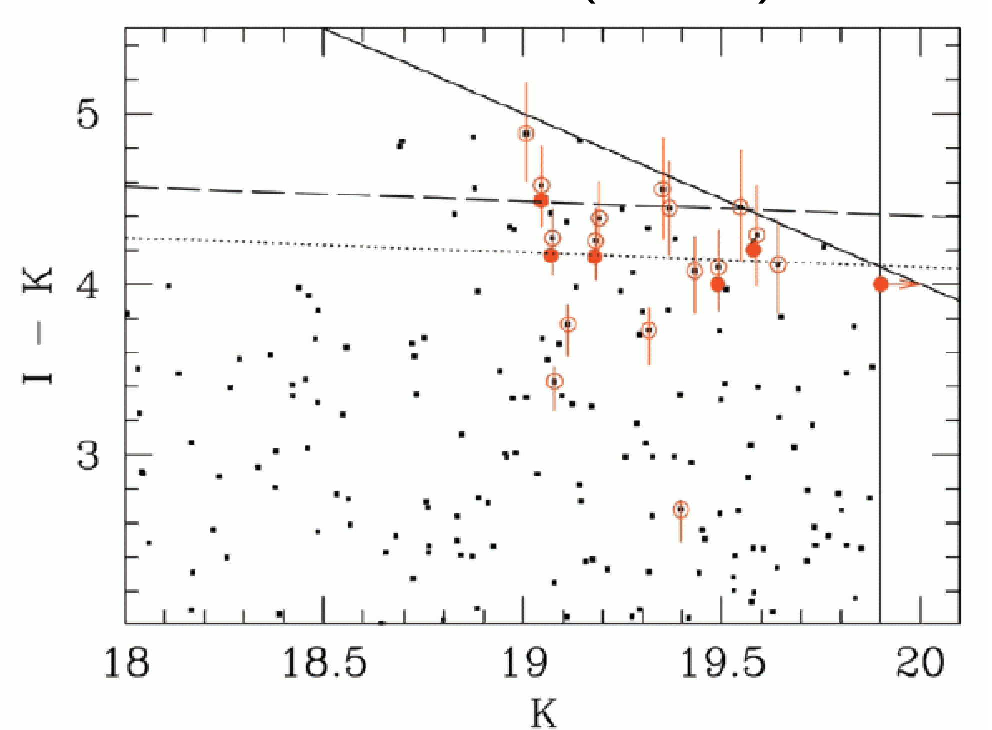
The most distant X-ray clusters to date

XMMJ2235 (z=1.39)



Lidman et al. (2008)

XMMJ2215 (z=1.45)

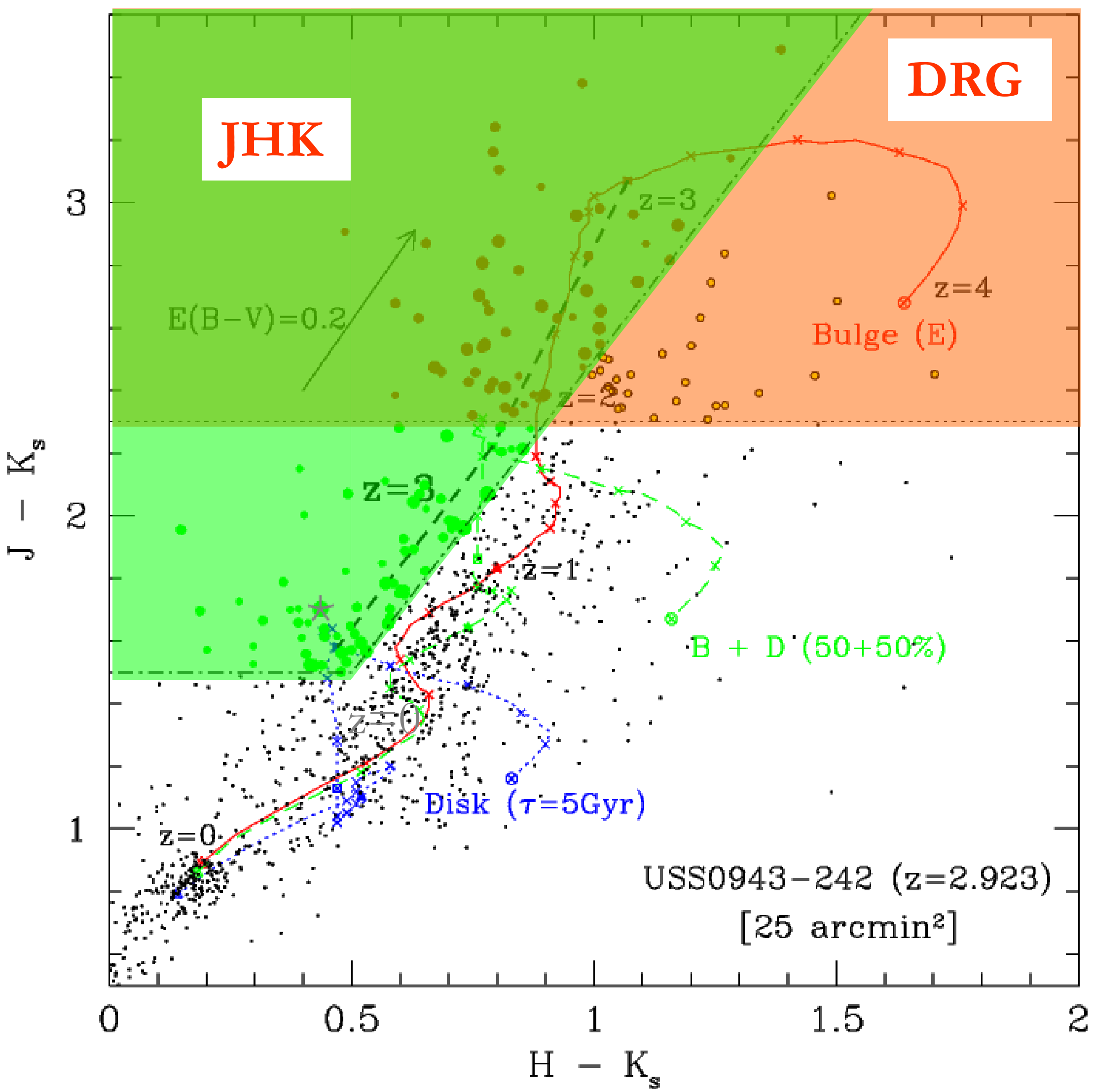


Stanford et al. (2006)

z(star formation)>2

z(assembly)>1.5

JHK selection of 2.3≲z≲3.1 galaxies



Kajisawa et al. (2006), Kodama et al. (2007)

Common criteria (DRG):

J-K>2.3

passive/dusty gals at z>2

↓

Our new criteria (JHK):

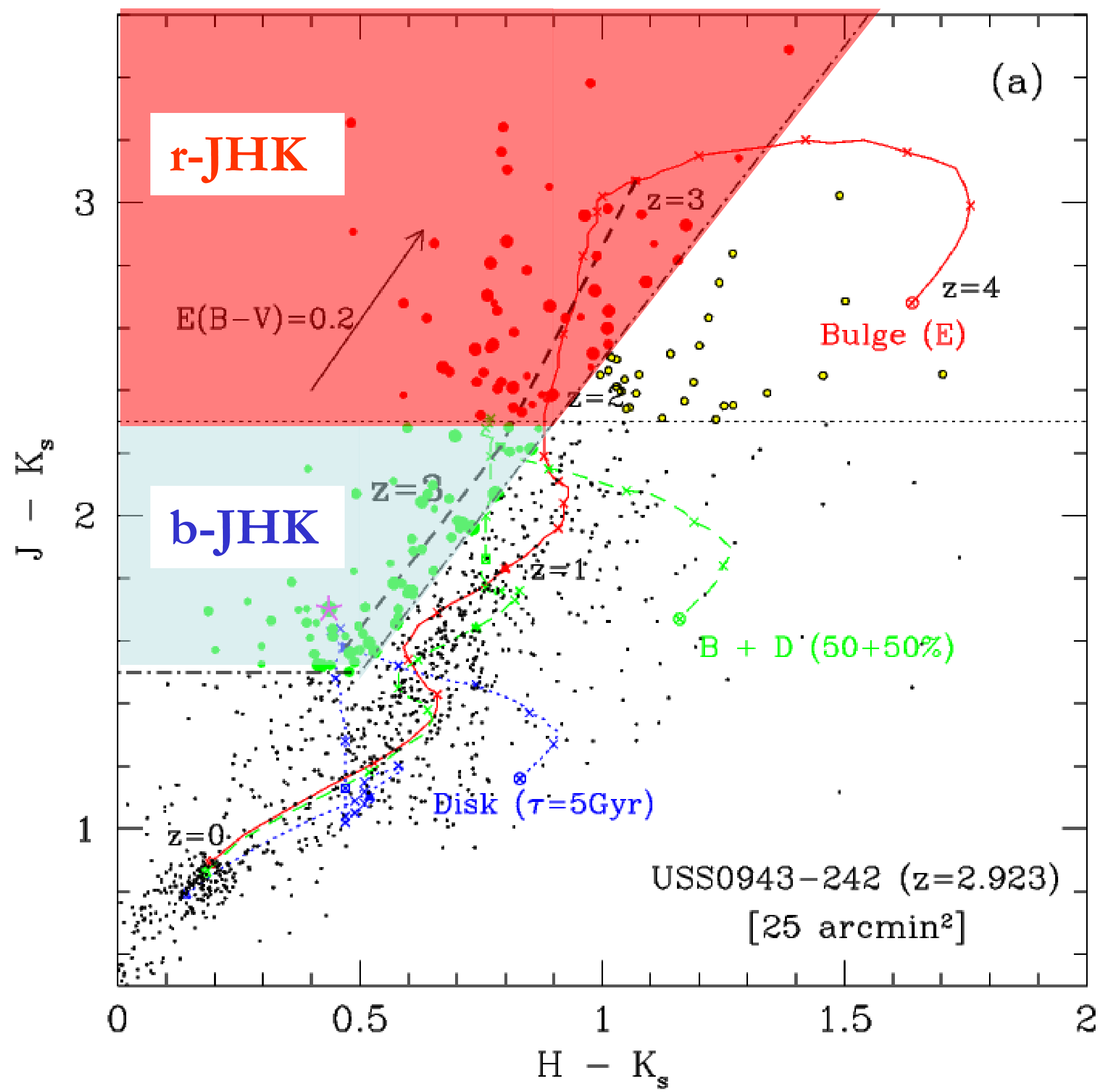
(J-K)> 2(H-K)+0.5

&& J-K>1.5

passive/dusty (2<z<3.3) +

star-forming (2.3<z<3.1)

JHK selection of 2.3≲z≲3.1 galaxies



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&& J-K>1.5
passive/dusty (2<z<3.3) +
star-forming (2.3<z<3.1)

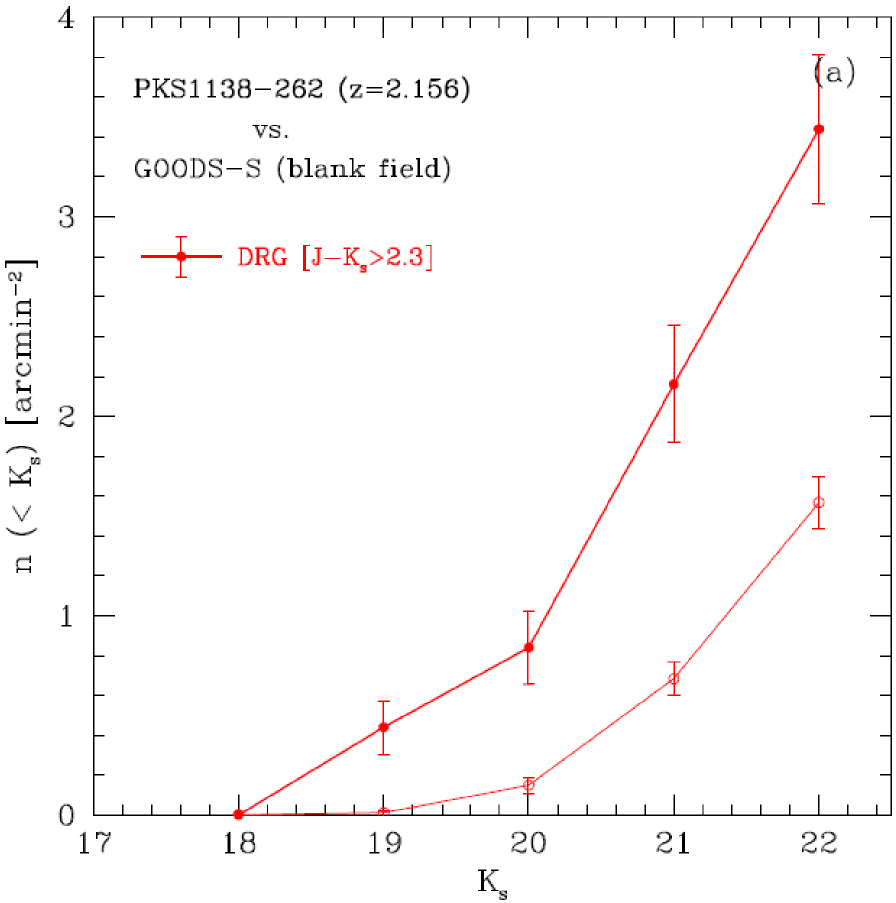
J-K>2.3 -- r-JHK

J-K<2.3 -- b-JHK

Overdensity of NIR selected galaxies in proto-clusters

Kodama, et al. (2007)

PKS1138 (z=2.16)

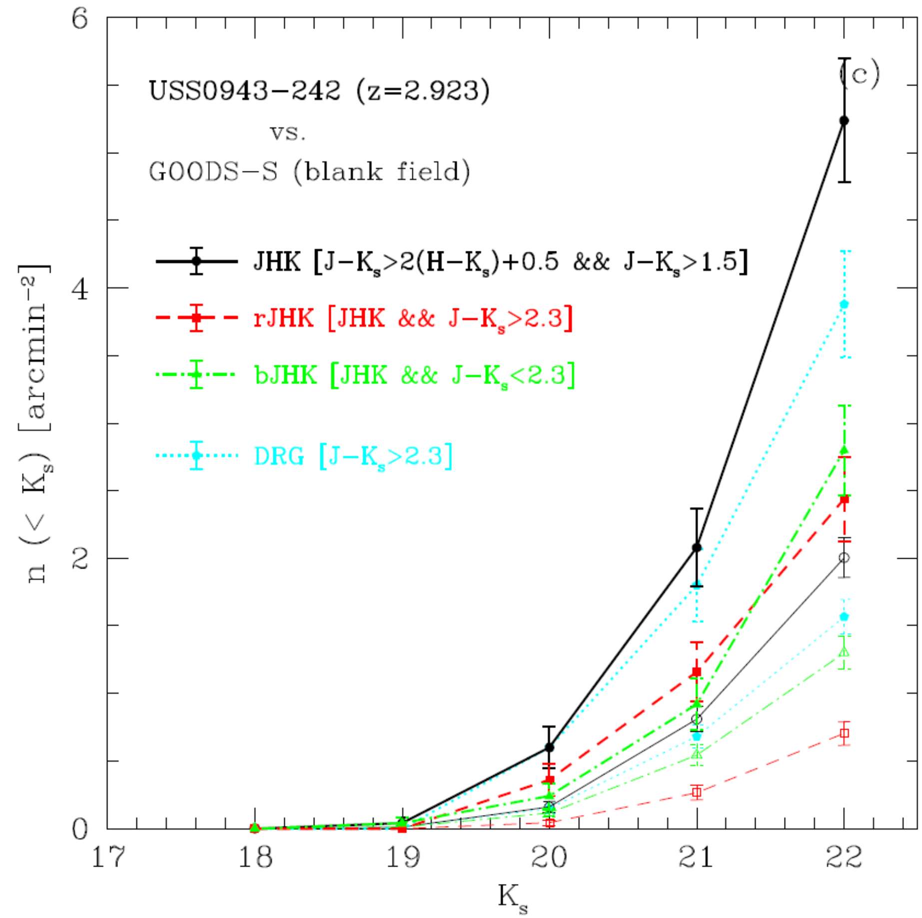


Overdensity of DRGs at Ks<20 is factor~5

Ks<22 2

See also Kurk et al. (2004) and Zirm et al. (2008)

USS0943 (z=2.93)



Overdensity of r-JHKs is factor~3

b-JHK 2

Spectroscopic follow-up in progress…

Incredibly unlucky with weather so far!
(10 out of 13 Subaru nights were clouded out !)
Nevertheless…

Subaru/MOIRCS (NIR, ~30 slits over 7’×4’, R=1300, 5 hrs)

Subaru/FOCAS (optical, ~30 slits over 6’φ, R=1000, 5 hrs)

VLT/FORS2 (optical, ~30 slits over 7’×7’, R=1000, 5 hrs)

PKS1138 (z=2.16) see Doherty et al. (2009)

- 30 out of 97 DRGs were targeted (31%)
- 4 redshifts could be measured out of 30 (13%)
- 2 out of 4 are confirmed to be at the RG redshift of z~2.16 (50%).

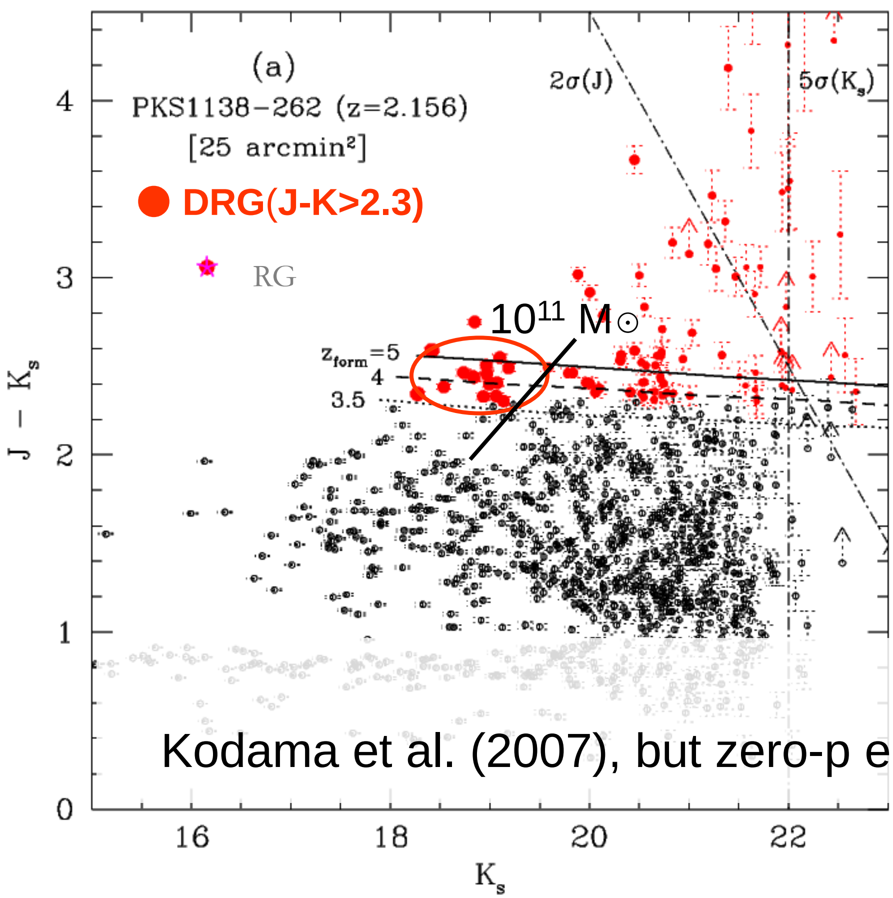
USS0943 (z=2.93)

- 38 out of 132 JHKs were targeted (28%).
- 18 redshifts could be measured out of 38 (47%).
- 10 out of 18 JHKs are confirmed to be at 2.3<z<3.1 as designed (58%).
- But none (out of 17), except the RG itself, is located at z~2.93 (0%).
- Instead, we found a foreground structure at z=2.6 consisting of 6 JHKs.

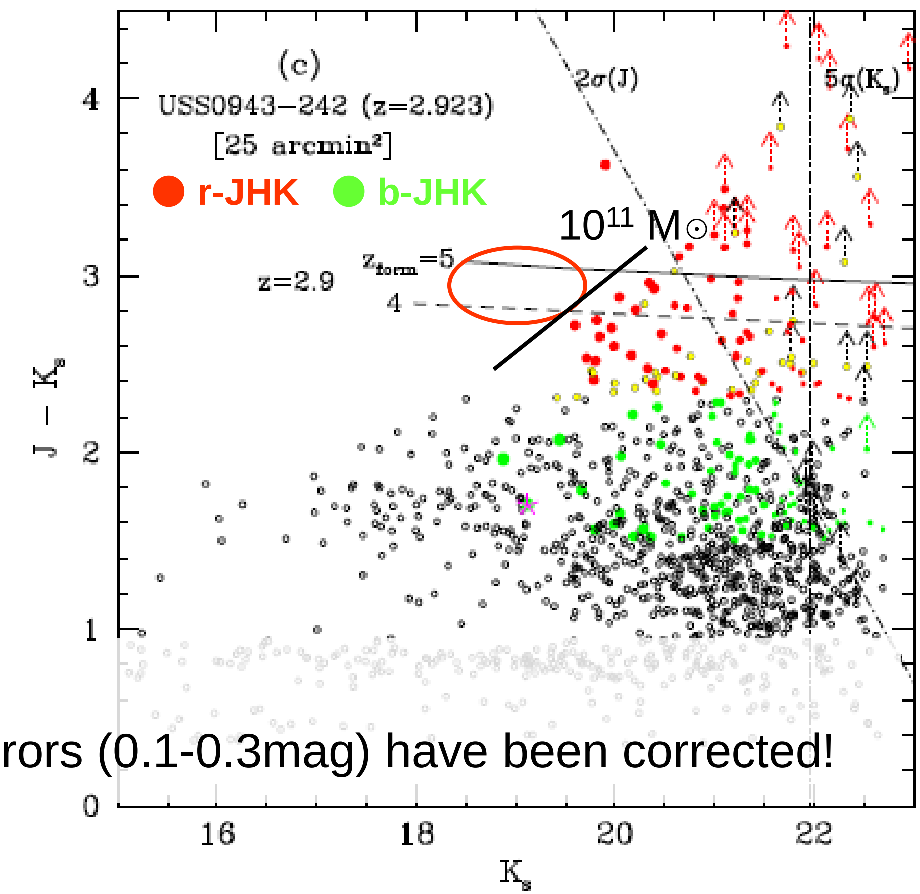
We should go much deeper under good conditions and also target more candidates.

Emergence of the red-sequence at z~2 in proto-clusters?

PKS1138 (z=2.16)



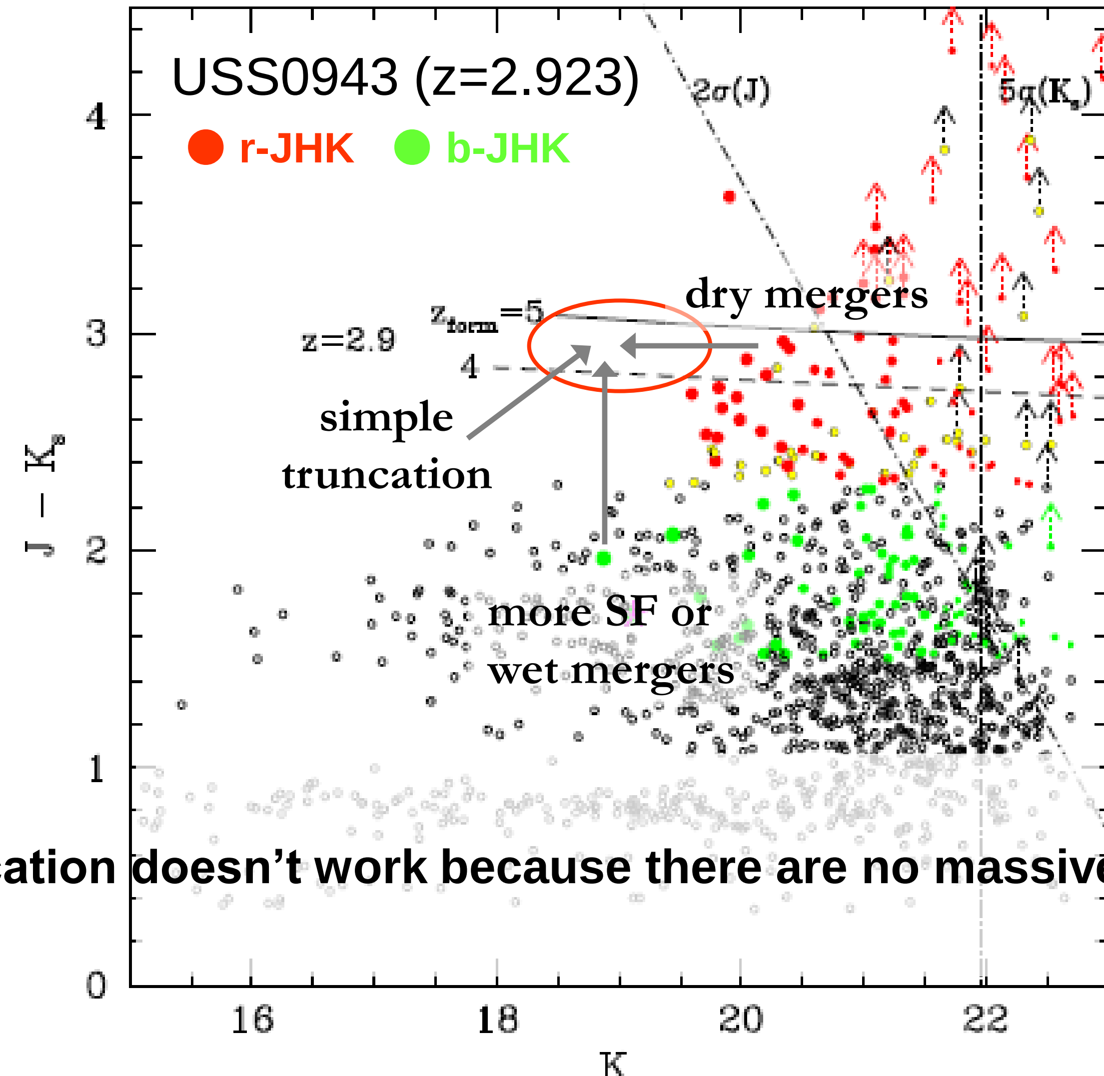
USS0943 (z=2.93)



Kodama et al. (2007), but zero-p errors (0.1-0.3mag) have been corrected!

The red sequence seems to be emerging between z=3 and 2 (2 < Tuniv[Gyr] < 3) !

Where are the progenitors of massive galaxies at z~3?

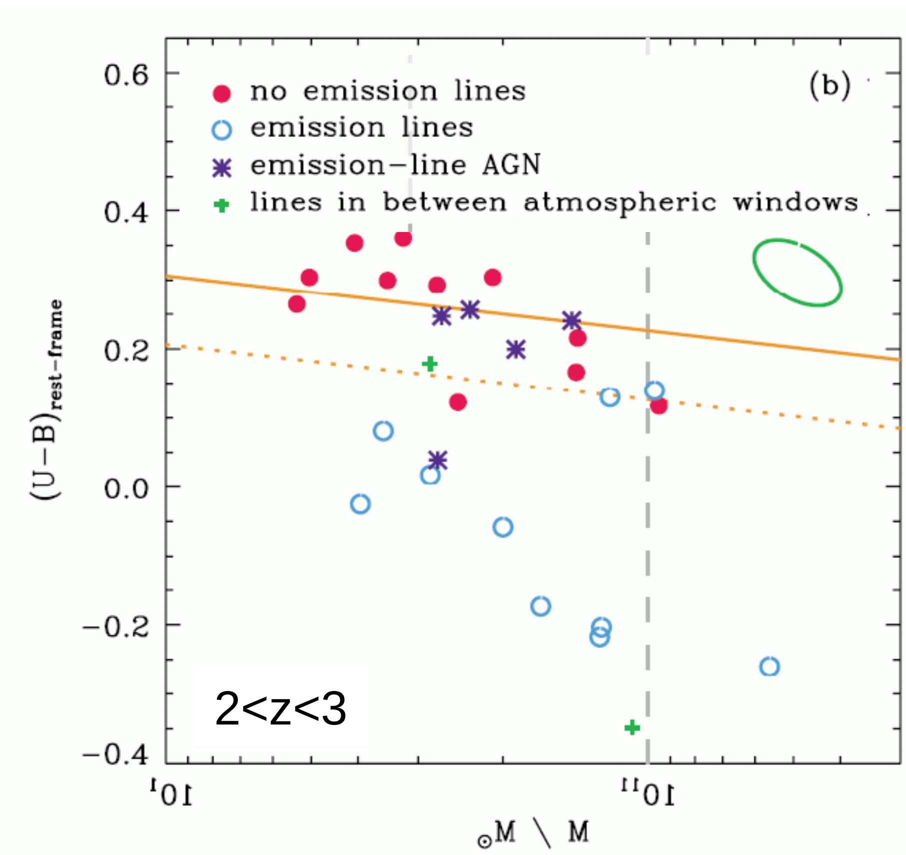


Simple truncation doesn't work because there are no massive blue counterparts!

100 $M_\odot$/yr (SFR) x 1 Gyr (z=3→2) = 10^{11} $M_\odot$

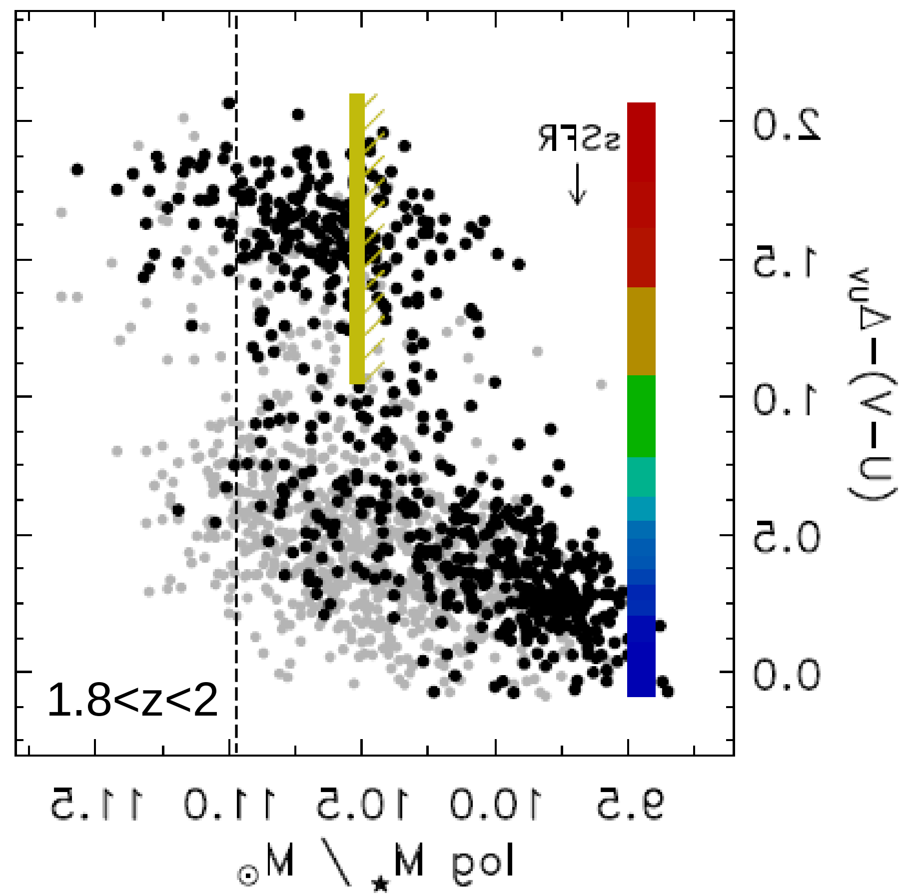
Red sequences in the field at z~2

Yale-Chile (MUSYC)



Kriek et al. (2008)

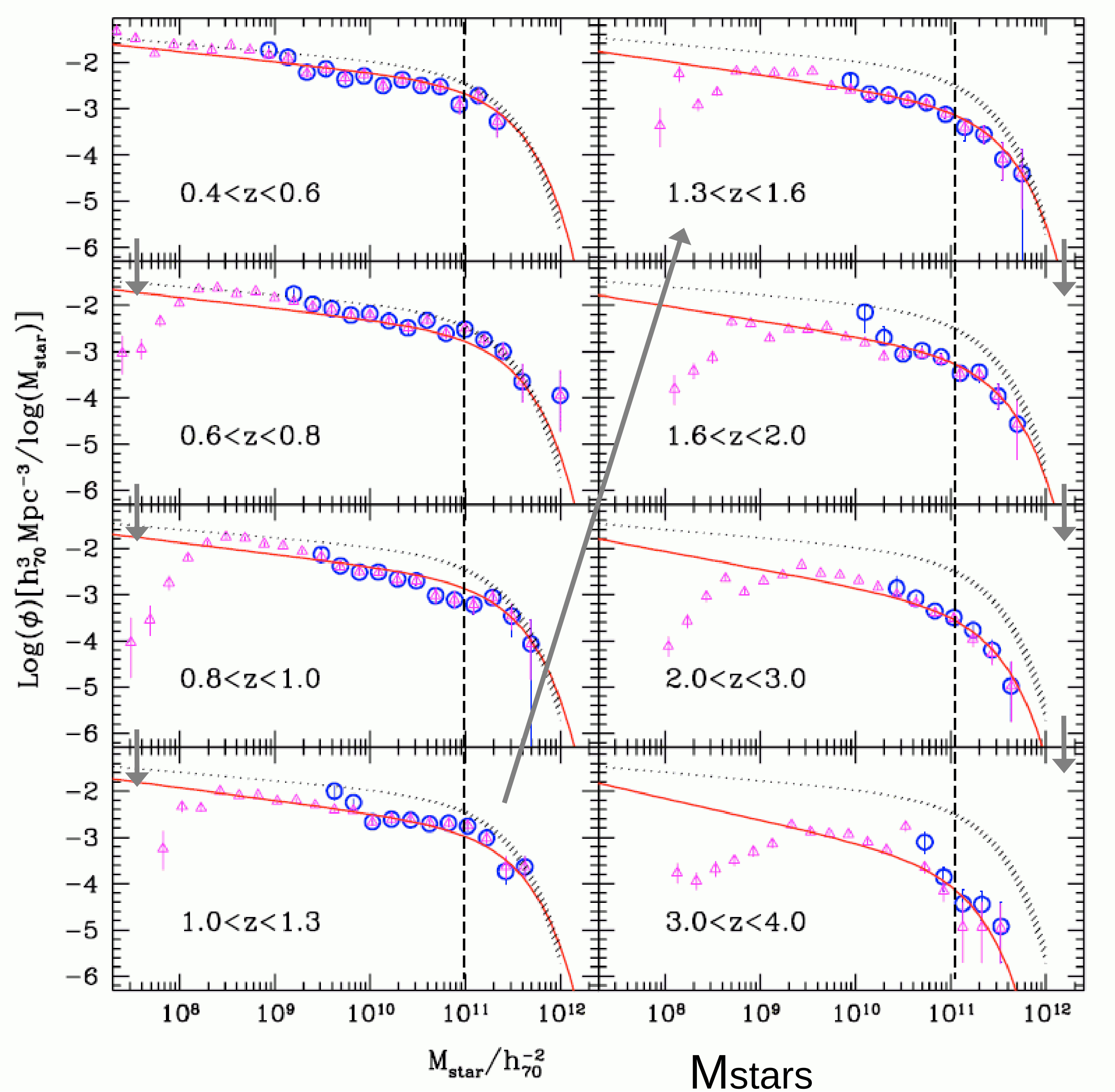
NEWFIRM, 0.5 sq. deg. (COSMOS, AEGIS)



Brammer et al. (2009)

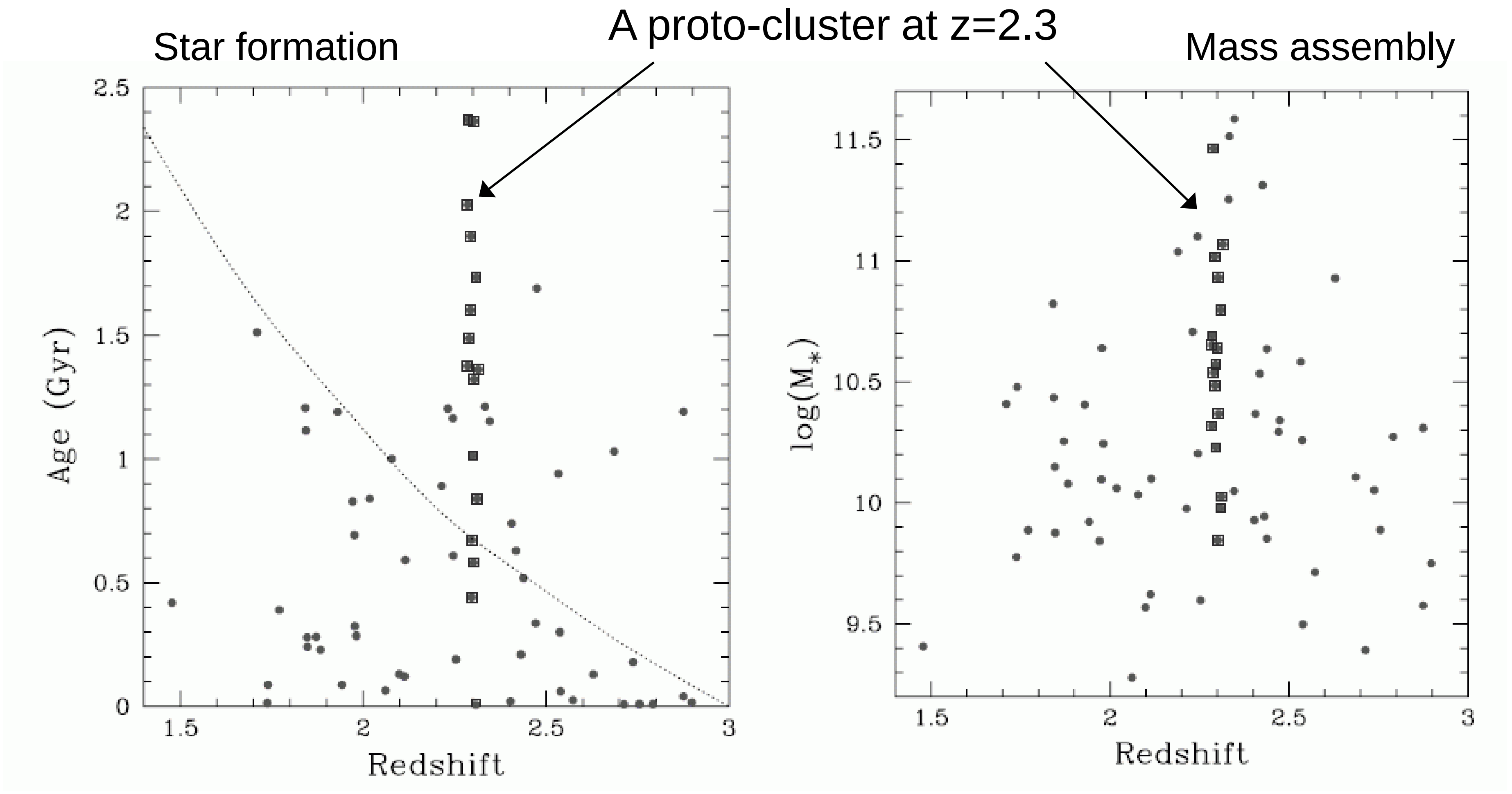
Evolution of stellar mass function

GOODS-MUSIC (160 arcmin^2) with Spitzer bands. Fontana et al. (2006)



dramatic decrease of massive galaxies at z>2

Environmental Dependence at z~2.3



Ages and stellar masses are larger by factor ~2 in the proto-cluster than outside.

Steidel et al. (2005)

Summary

- Starbursts/truncation of galaxies in groups/ outskirts of clusters at $z<1$

  → *External effects ("Nurture")*

  (galaxy-galaxy interaction?)

- Formation of massive galaxies in cluster cores at $z>1.5$-2

  → *Intrinsic effects ("Nature")*

  (galaxy formation bias?)

"Inside-out propagation/truncation of star formation in clusters?"

I thank the “real” organizers!