(Subaru Winter School 2014 @KASI, Korea, 2014/2/25-27)

Galaxies and Clusters at the Cosmic Noon

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in collaborations with

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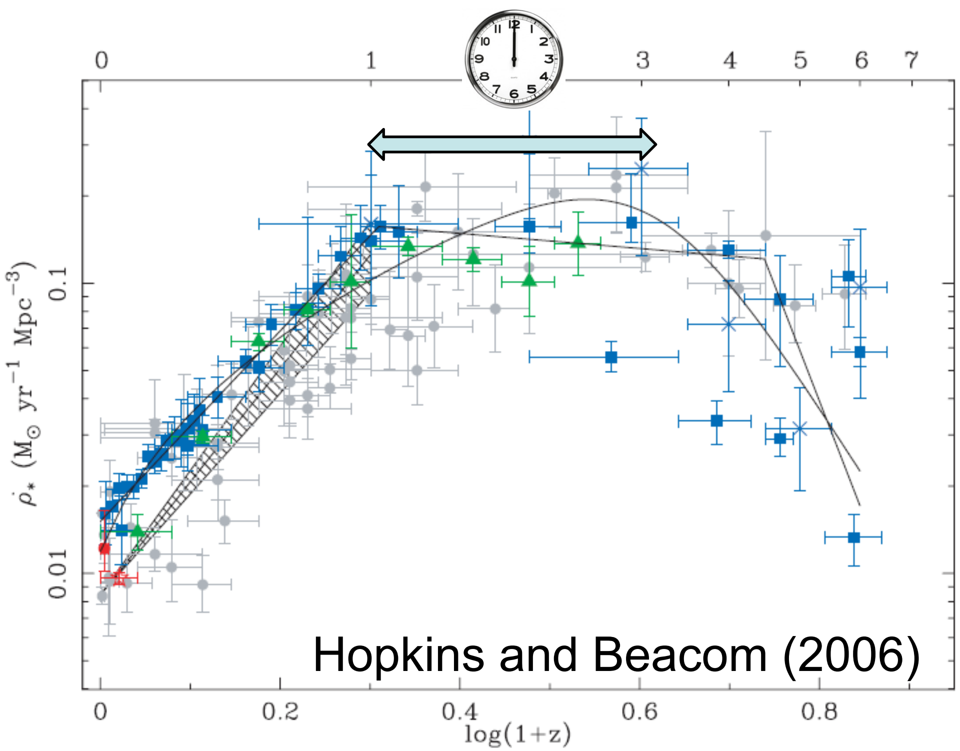
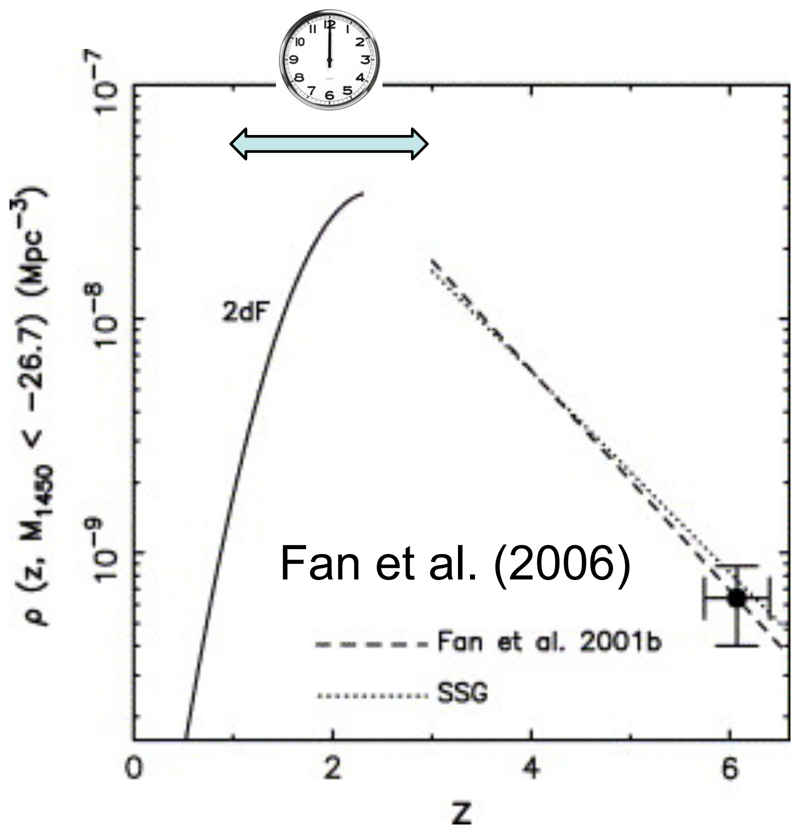
Rhythm Shimakawa (Sokendai), Tomoko Suzuki (Nagoya Univ.), et al.

"COSMIC NOON"

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



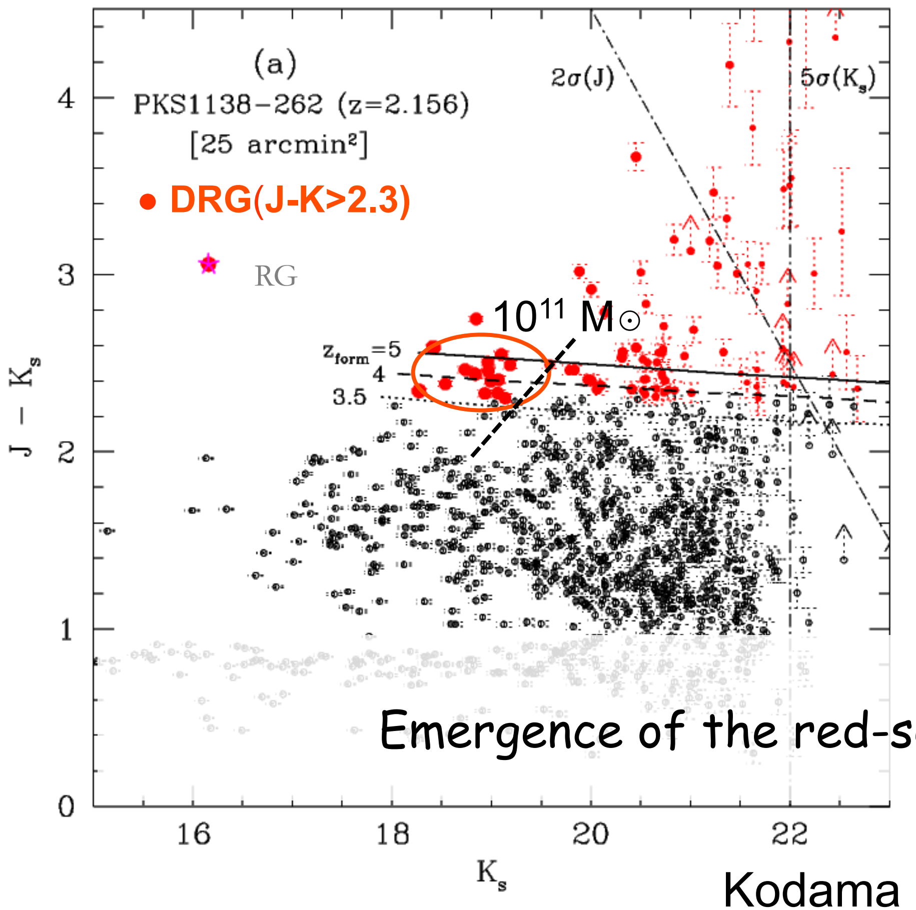
Star formation



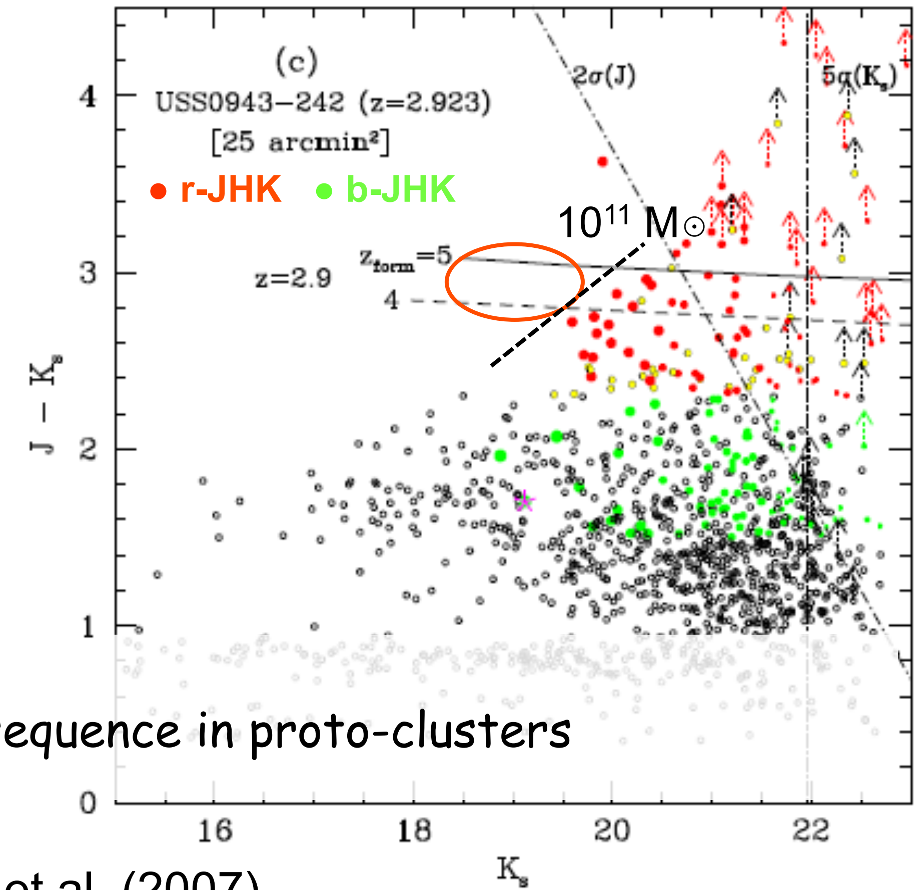
AGN (QSO)

The peak epoch of massive galaxy formation in clusters

PKS1138 (z=2.16)



USS0943 (z=2.93)



Emergence of the red-sequence in proto-clusters

Kodama et al. (2007)

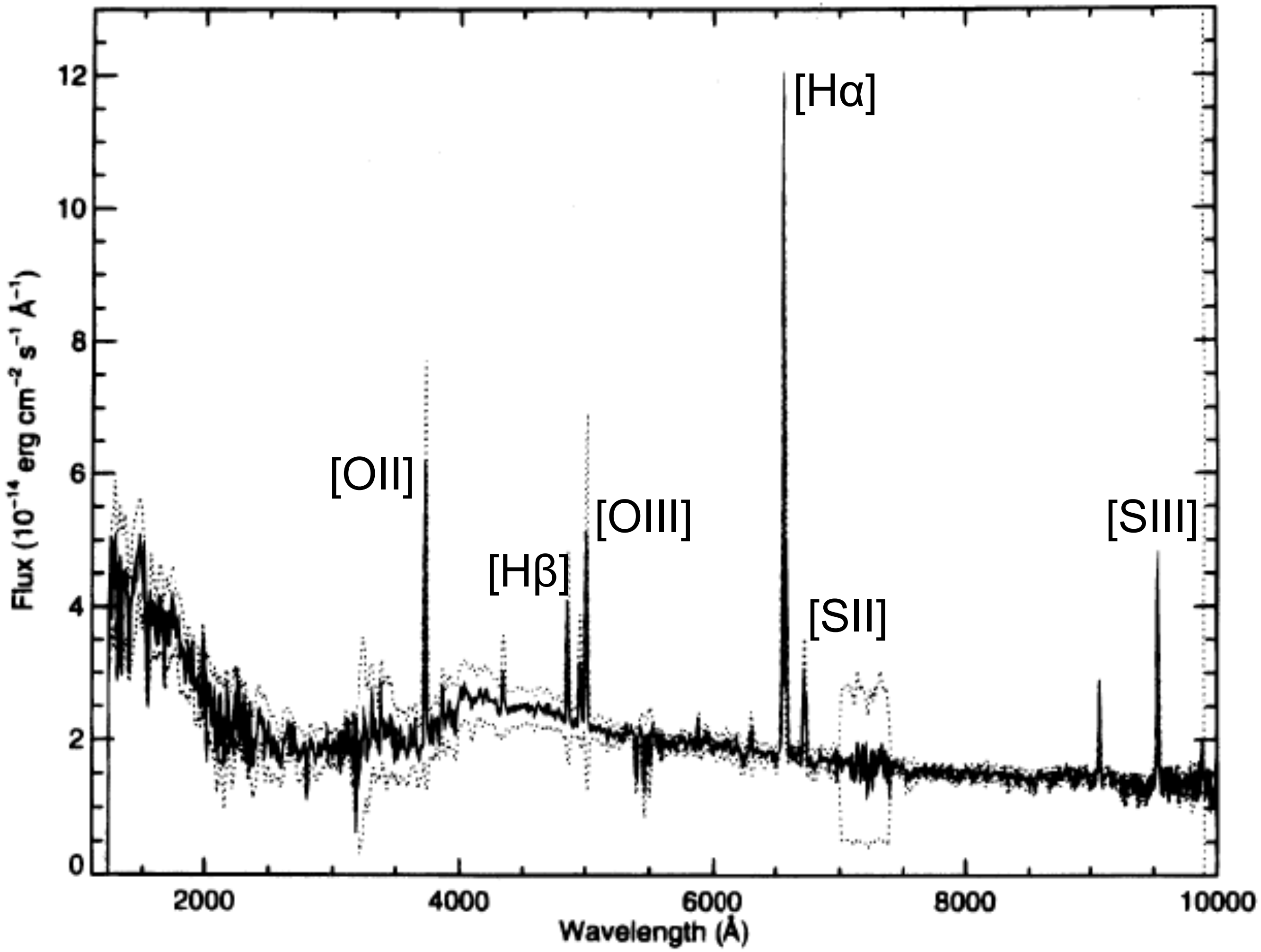
Direct progenitors of "some" of the present-day massive early-type galaxies.
The ideal laboratories to see any environmental effect at their "formation phase"

Recent Remarkable Achievements in the Cosmic Noon Era

- Presence of Dusty Starbursts (SMGs, red HAEs)
- Rapid Decline of Stellar Mass Density
- Emergence of Red Sequence
- Main Sequence of Star Forming Galaxies
- Fundamental Metallicity Relation
- Massive Compact Spheroids (red nuggets)
- Cold Streams (in theory)
- Turbulent, Clumpy, but Rotational Disk
- Gas Outflow (feedback)
- High Ionization State Galaxies (strong [OIII] line)
- etc…

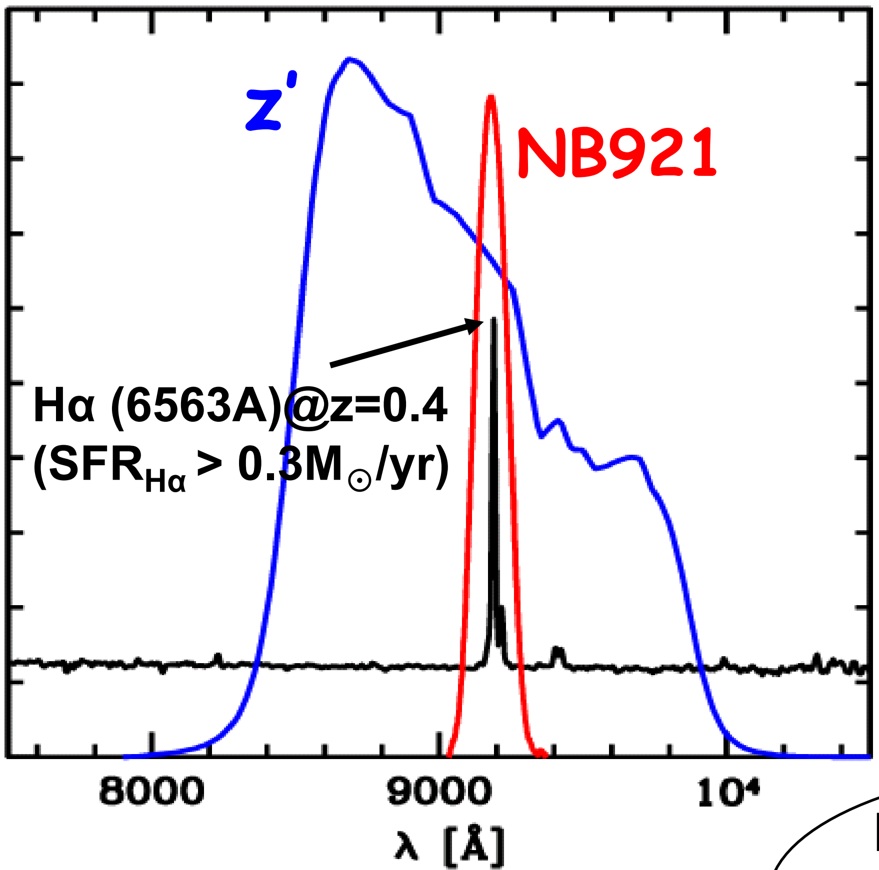
A typical spectrum of star forming galaxy

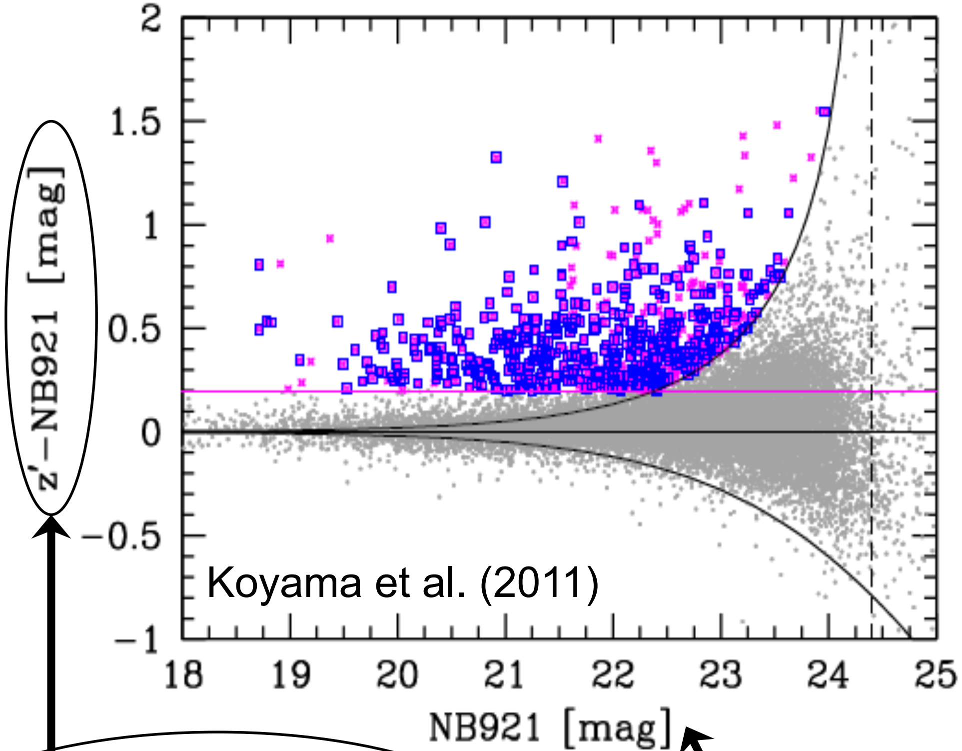
It consists of blue stellar continuum and many emission lines from ionized gas.



Kinney et al. (1996)

How narrow-band imaging survey works to sample star forming galaxies at high-z



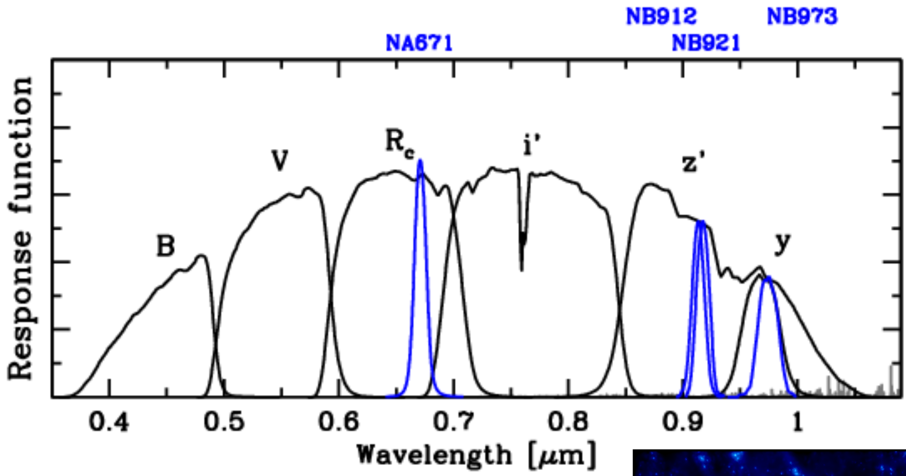


Flux ratio between narrow-band (NB921) and broad-band (z')

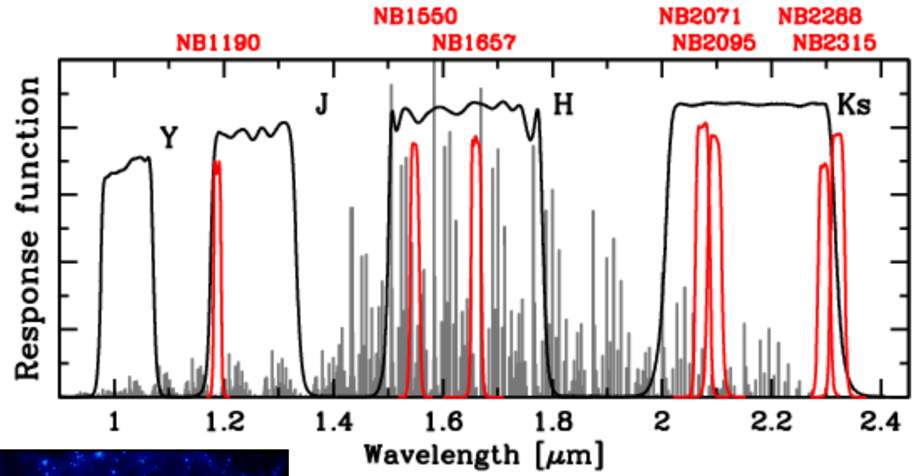
Magnitudes in NB

Subaru Wide-Field Survey of Narrow-Band Emitters ([OII], [OIII] and Hα) at 0.4<z<2.5

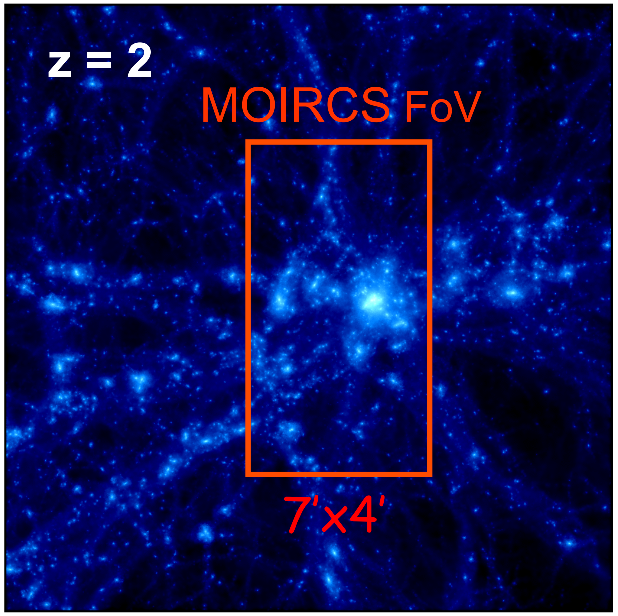
Suprime-Cam (optical; 34'x27')



MOIRCS (NIR; 7'x4')



4 narrow-band filters



7 narrow-band filters

FWHMs correspond to ±1500-2000km/s

Cluster N-body+SAM simulation (Yahagi et al. 2005; ν GC)

20×20 Mpc^2 box (co-moving)

"MAHALO-Subaru"

MApping HAlpha and Lines of Oxygen with Subaru

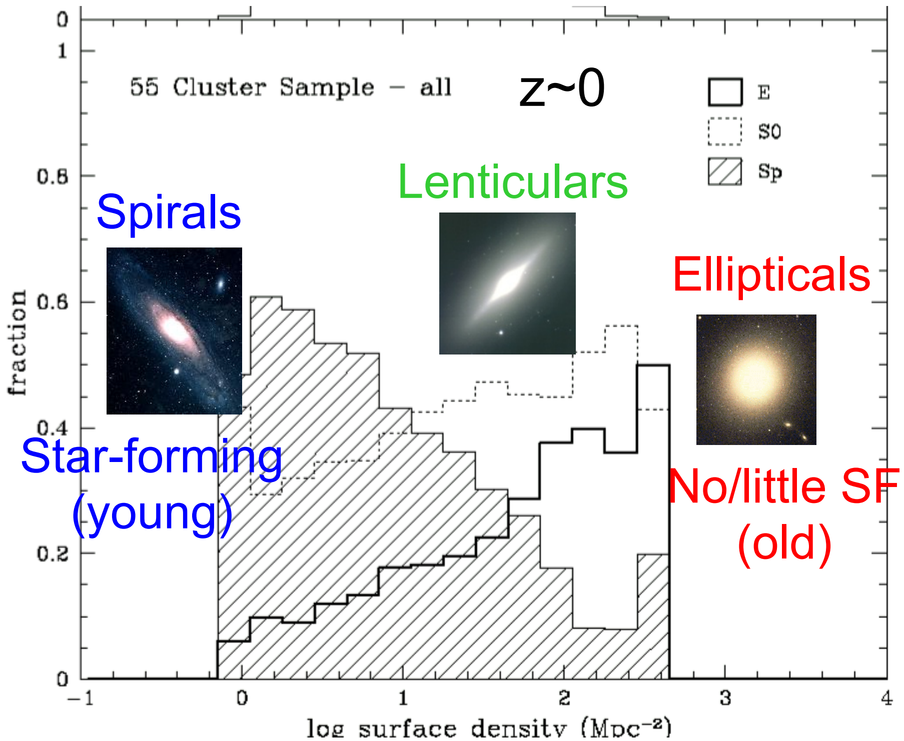
Unique sample of NB selected SF galaxies across environments and cosmic times

	environ-ment	target	z	line	λ (μm)	camera	NB-filter	conti-nuum	status as of Oct '12
z<1 cluster	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 cluster	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	observed
		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 cluster	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

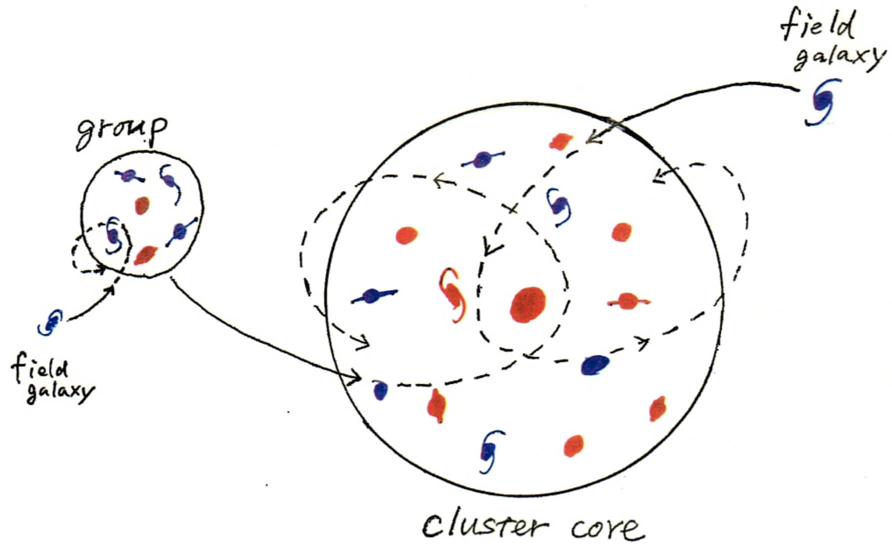
18 nights for imaging, >15 nights for spectroscopy

Origin of the cosmic habitat segregation

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



log surface density (Mpc^{-2})



Nature? (intrinsic)

earlier galaxy formation and evolution in high density regions

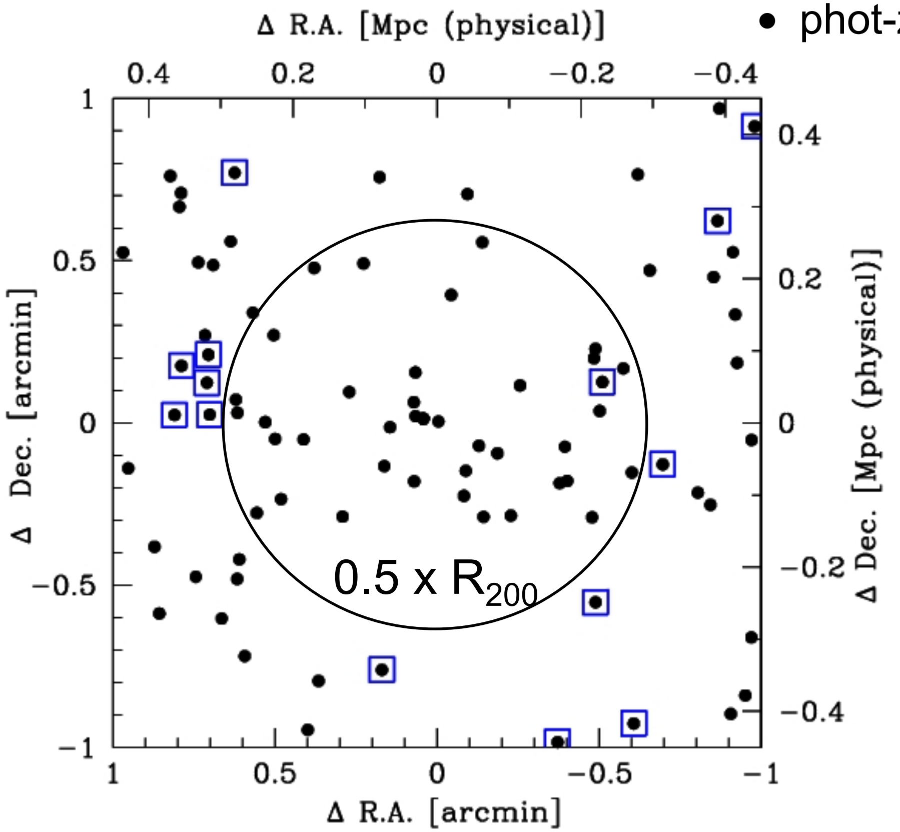
Nurture? (external)

galaxy-galaxy interaction/mergers, gas-stripping

Spatial distribution of star-forming galaxies in clusters

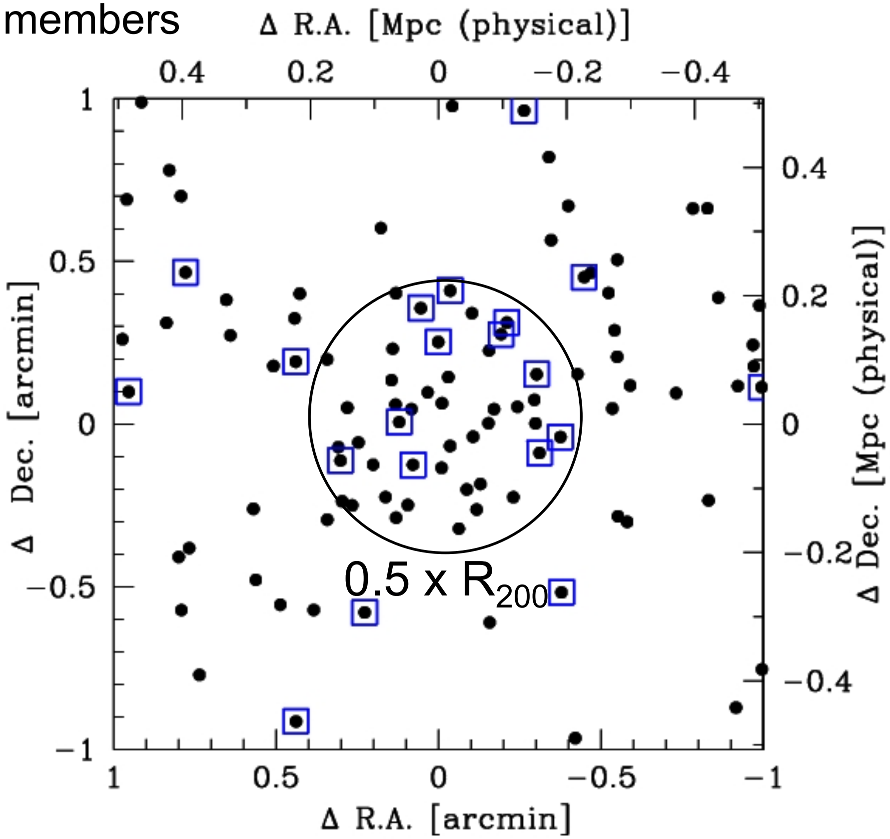
□ Hα emitters at z=0.81 (RXJ1716) □ [OII] emitters at z=1.46 (XCS2215)

● phot-z members



Lx=2.7×10^{44} erg/s

Koyama, et al. (2011)



Lx=4.4×10^{44} erg/s

Hayashi, et al. (2010)

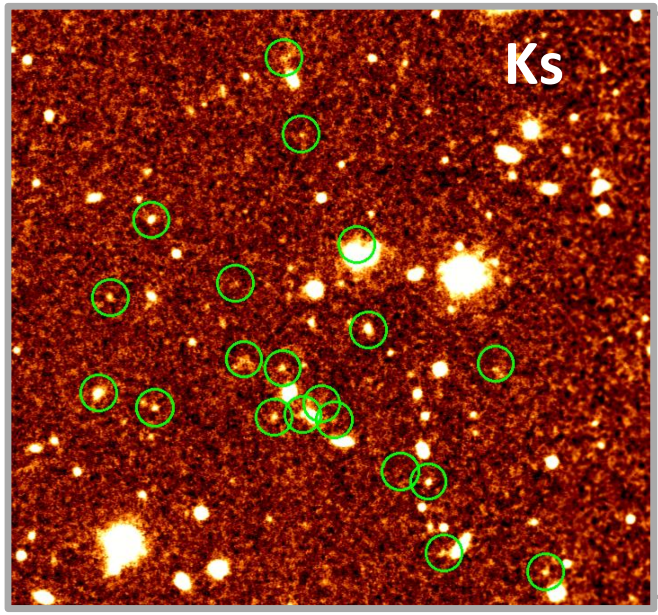
Clusters Grow Inside-Out !

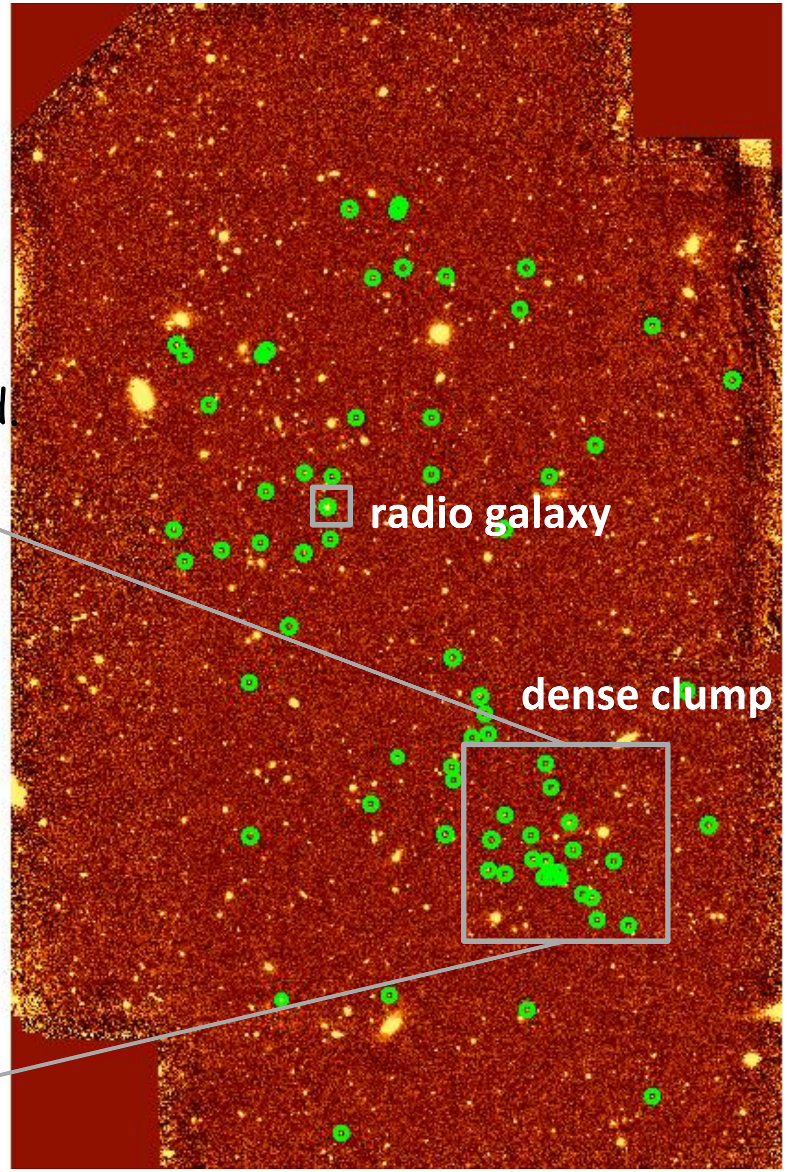
Discovery of a Prominent Star-Bursting Proto-Cluster at z~2.5

USS1558-003 (z=2.53)

Ha imaging
with MOIRCS/NB2315
3.4 hrs, 0.3-0.4" seeing

68 Ha emitters (HAEs) are detected.



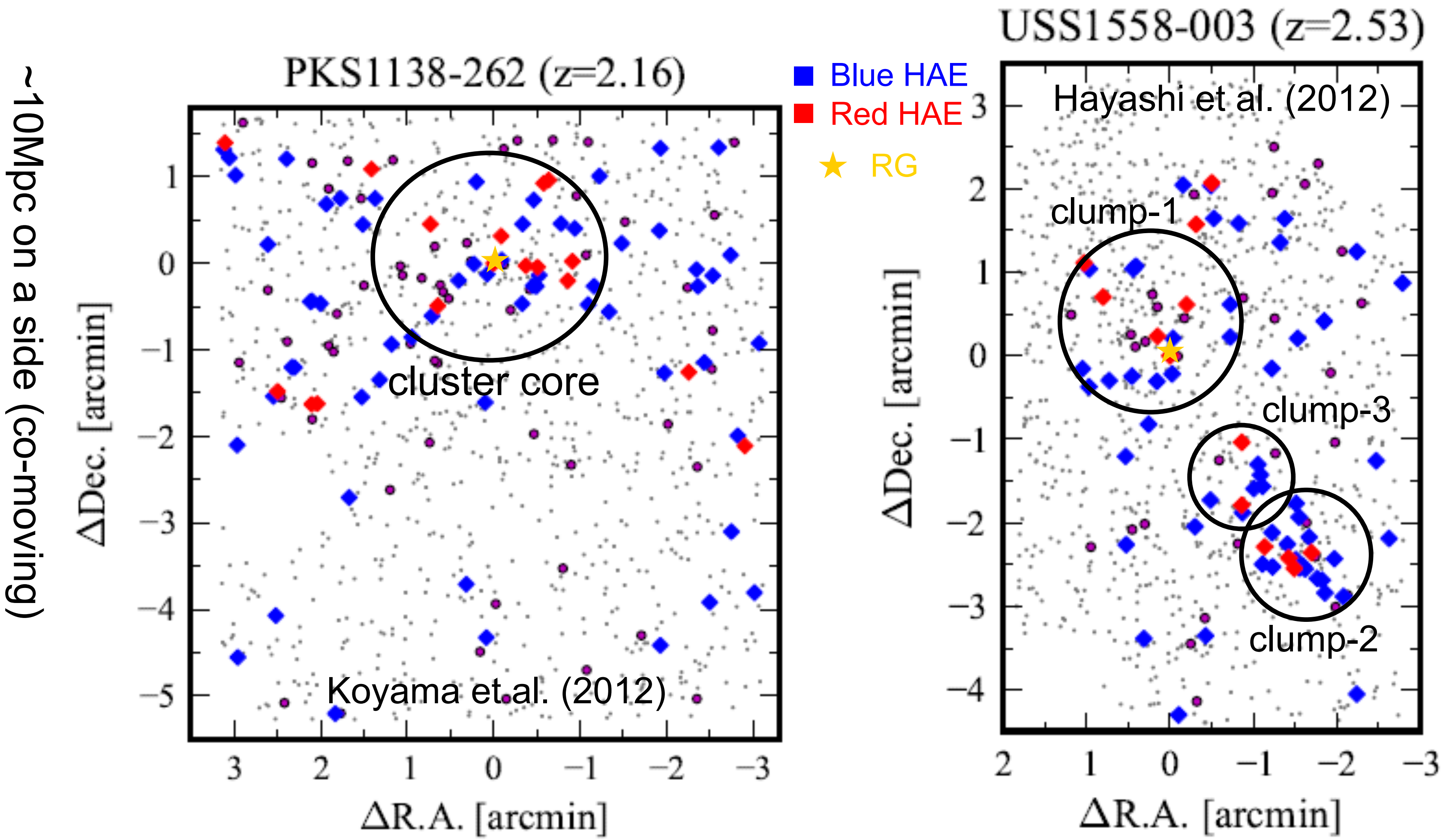


1.5Mpc away
from the RG

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

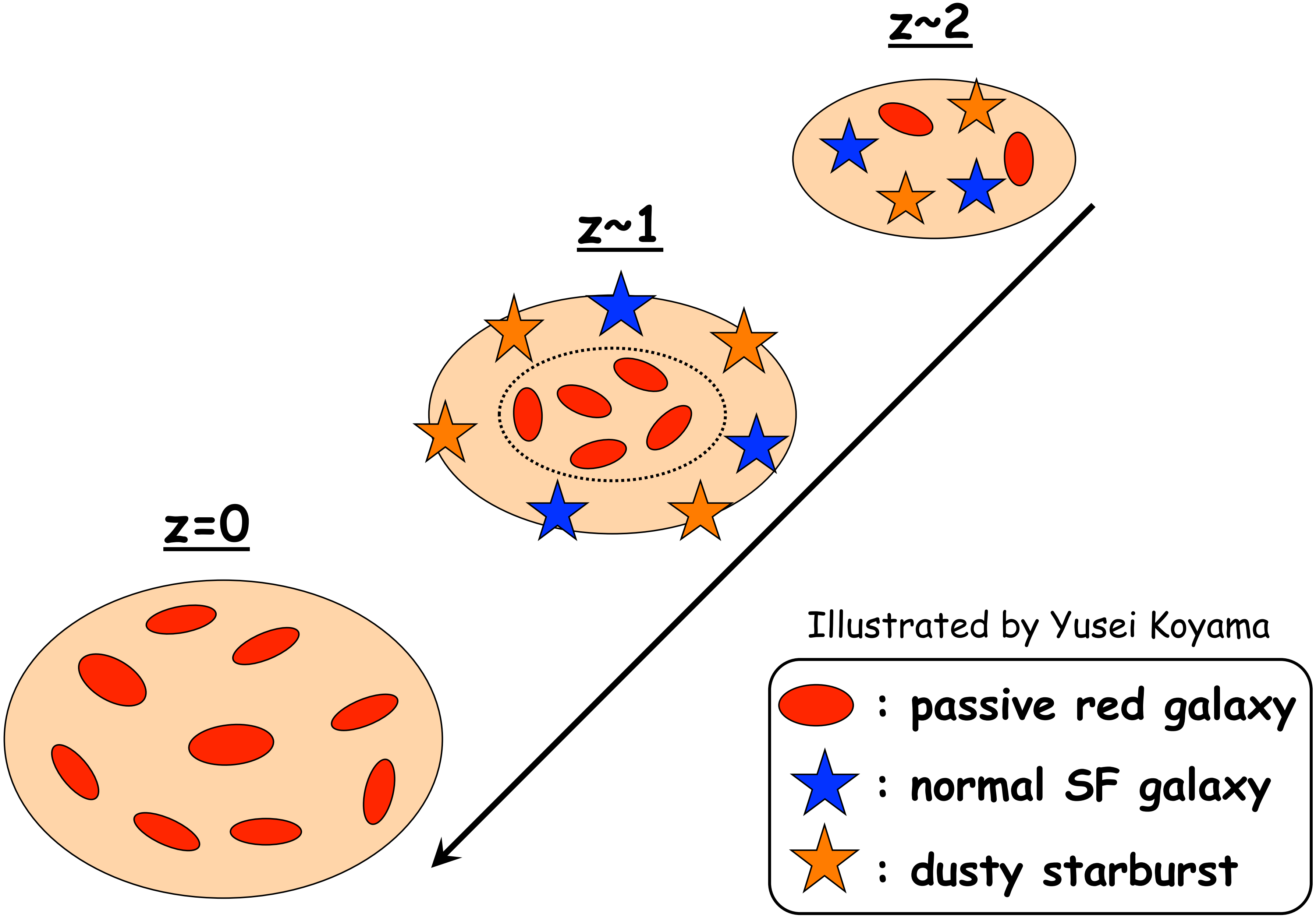
Hayashi et al. (2012)

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



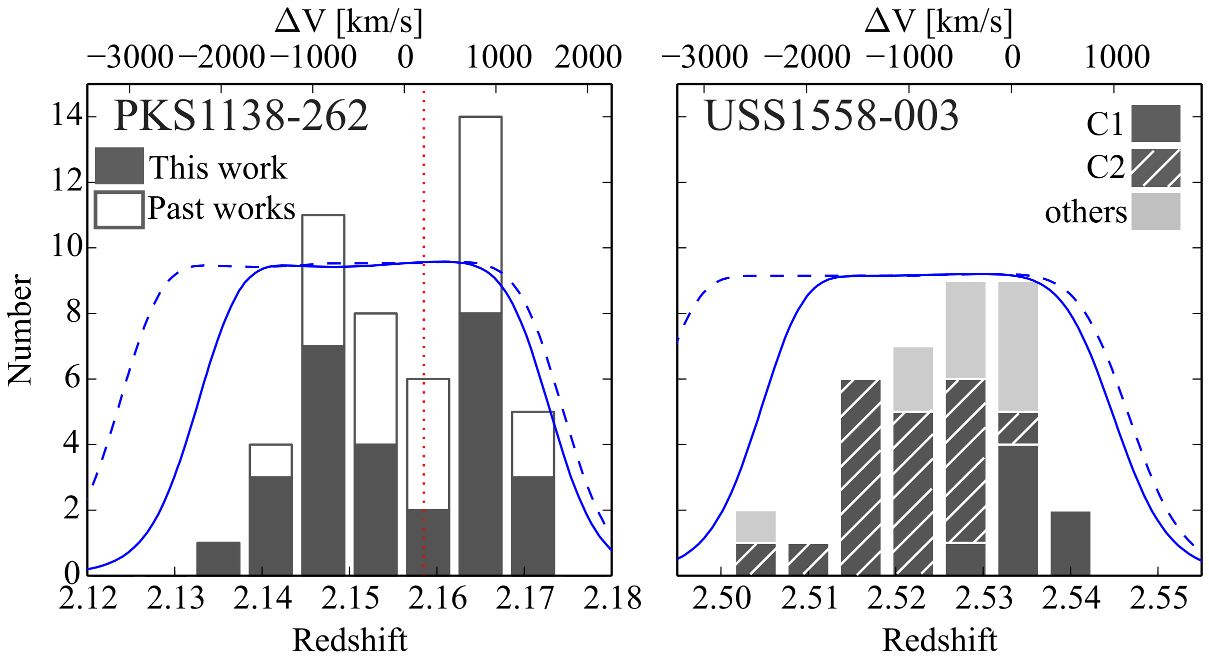
Red Ha emitters (dusty starbursts) tend to favor higher density regions!

Clusters Grow Inside-Out !



MOIRCS spectroscopy of two proto-clusters at z>2

27 new members

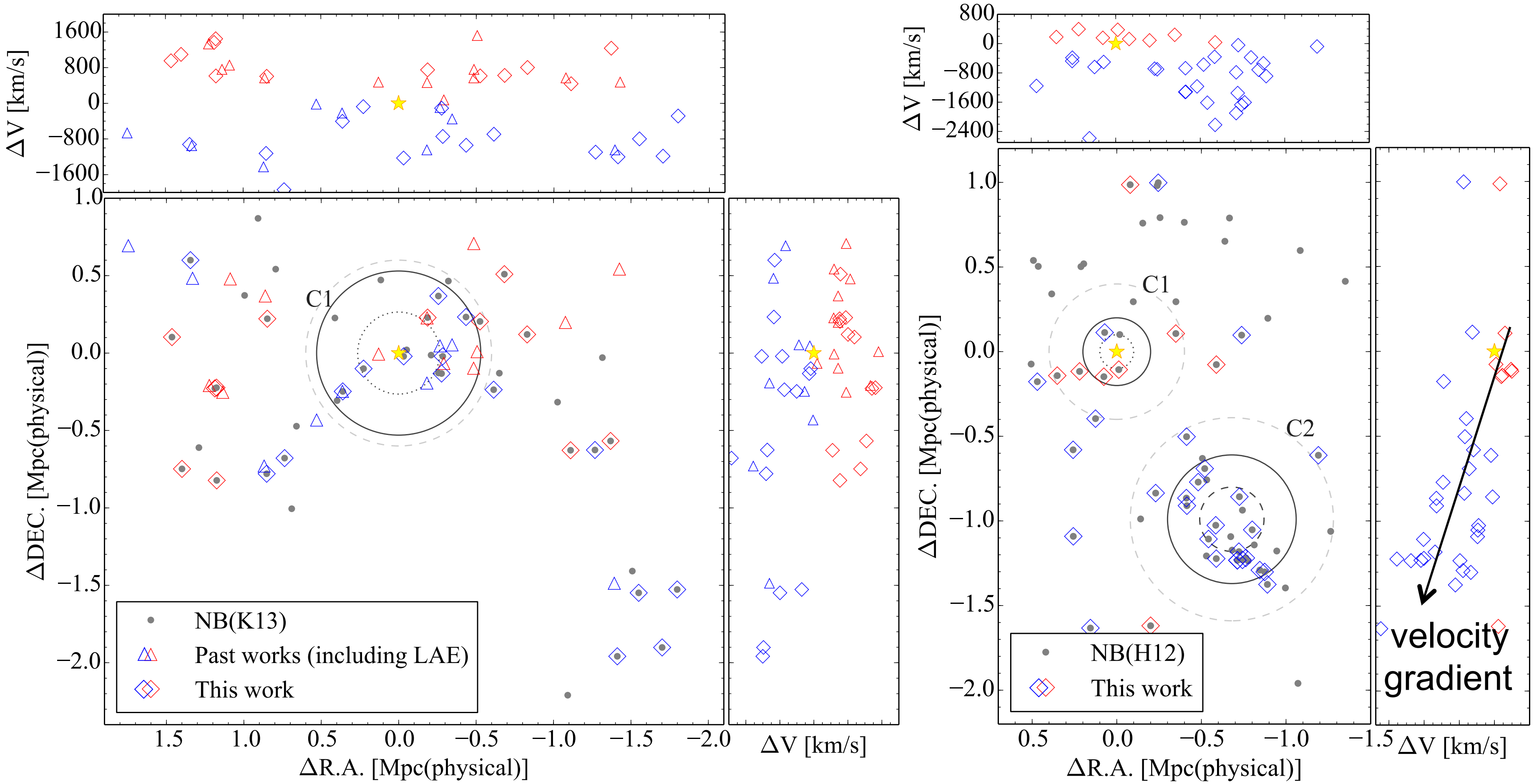


36 new members

cluster name (1)	new members (2)	$\langle\Delta V\rangle$ [km/s] (3)	σ_{cl} [km/s] (4)	R_{200} [Mpc] (5)	M_{cl} $[10^{14}M_\odot]$ (6)
PKS1138 all	27	−41	882^5	—	—
PKS1138 C1	9	+9	683^5	0.53^5	1.71^5
USS1558 all	36	−717	756	—	—
USS1558 C1	7	+121	284	0.19	0.10
USS1558 C2	19	−1042	574	0.38	0.87

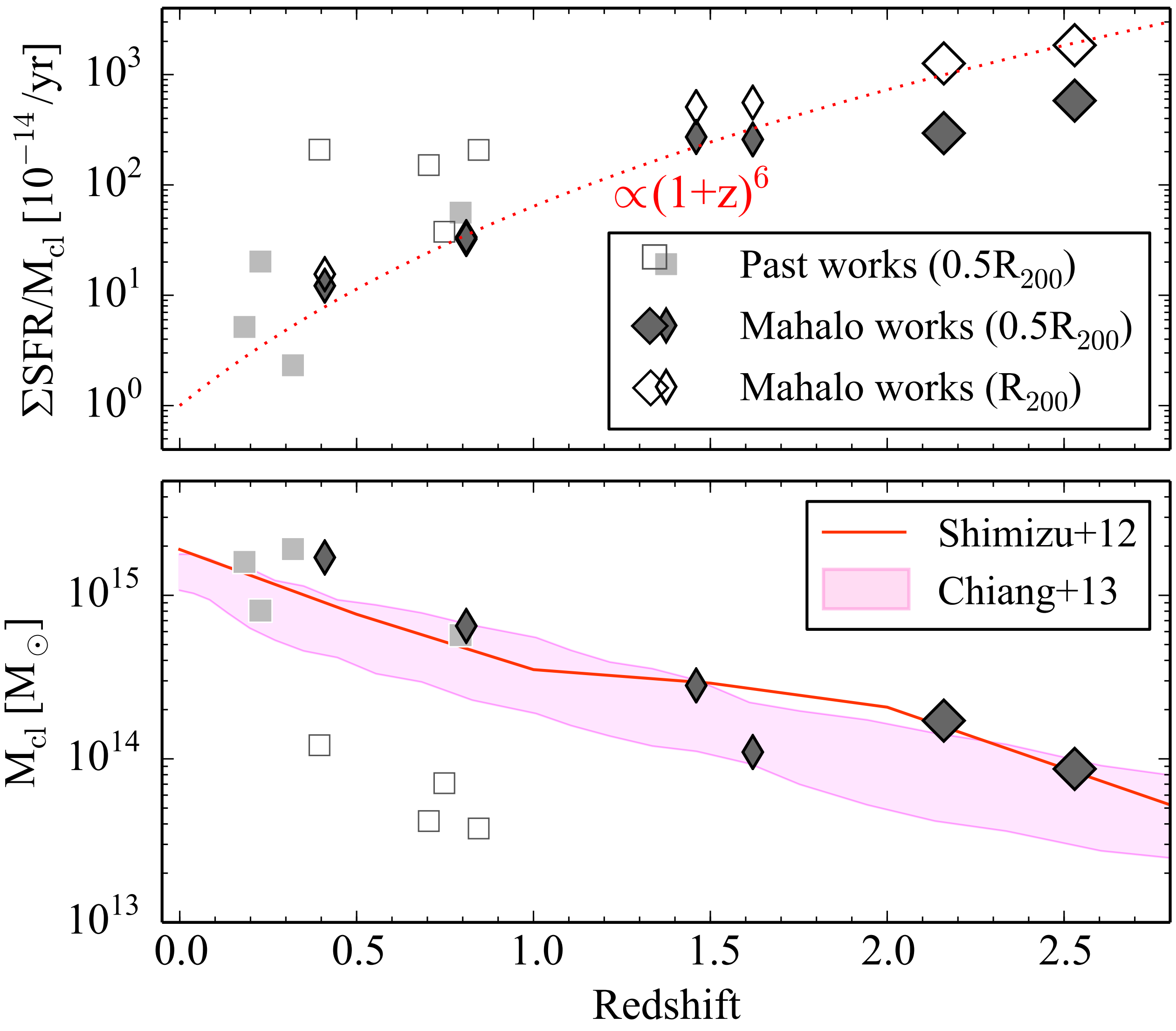
Shimakawa et al. (2014a)

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



Shimakawa et al. (2014a)

Integrated Star Formation Rates in Cluster Cores

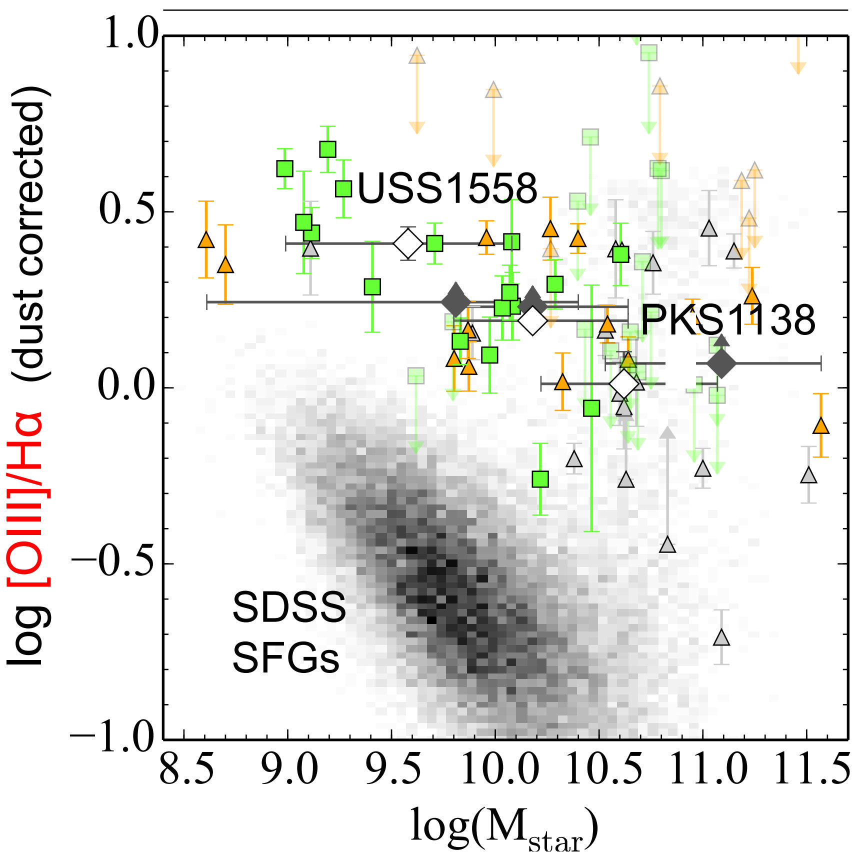


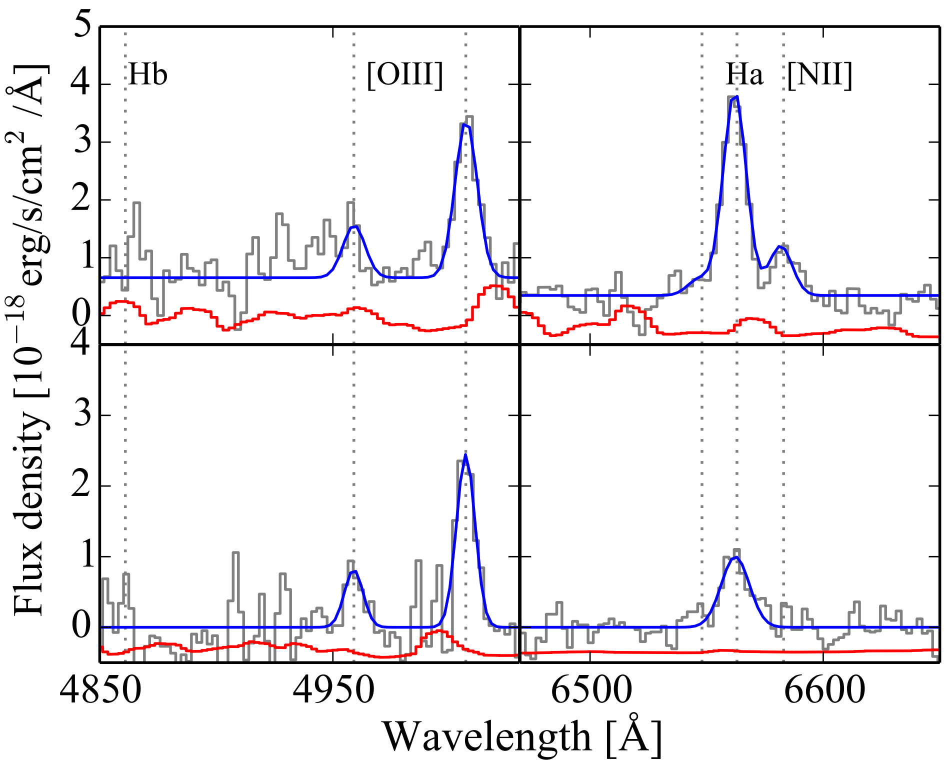
Rapid increase of integrated SFR with z

Our proto-clusters will grow to ~$10^{15}M_{\odot}$ clusters by the present-day

Shimakawa et al. (2014a)

[OIII] strong galaxies at high-z (proto-clusters at z>2)





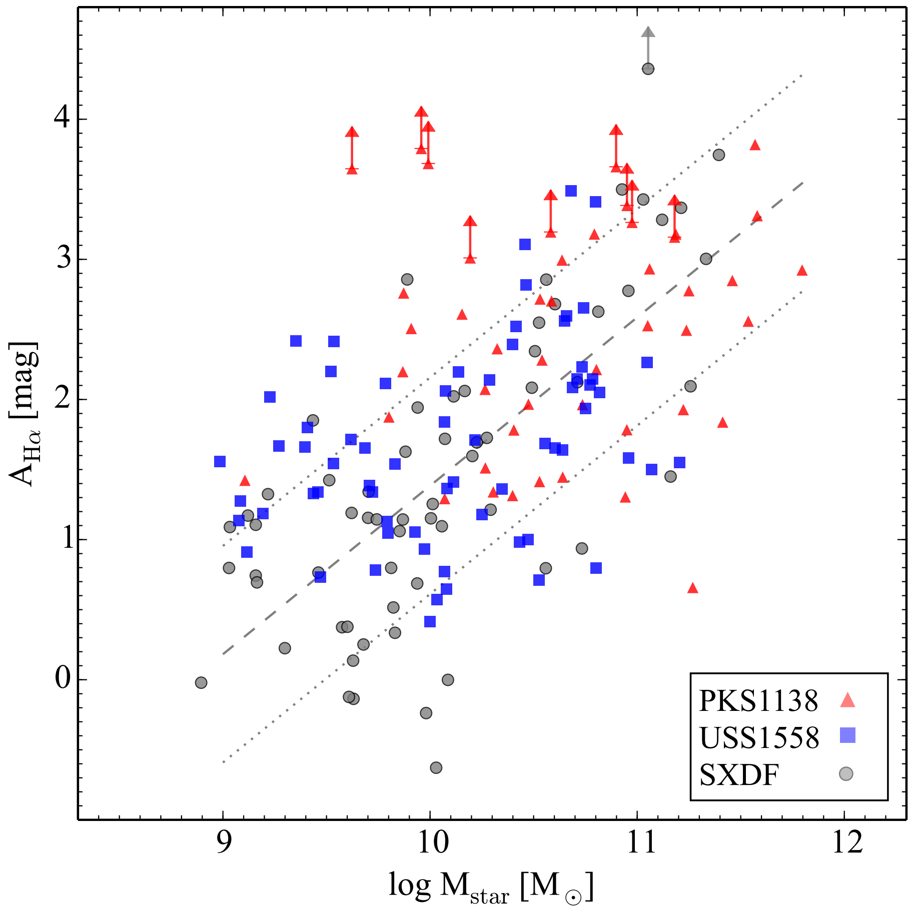
Kewley's recent model (2013) suggests:

low metallicity and/or large sSFR and/or large density?

Shimakawa et al. (2014b)

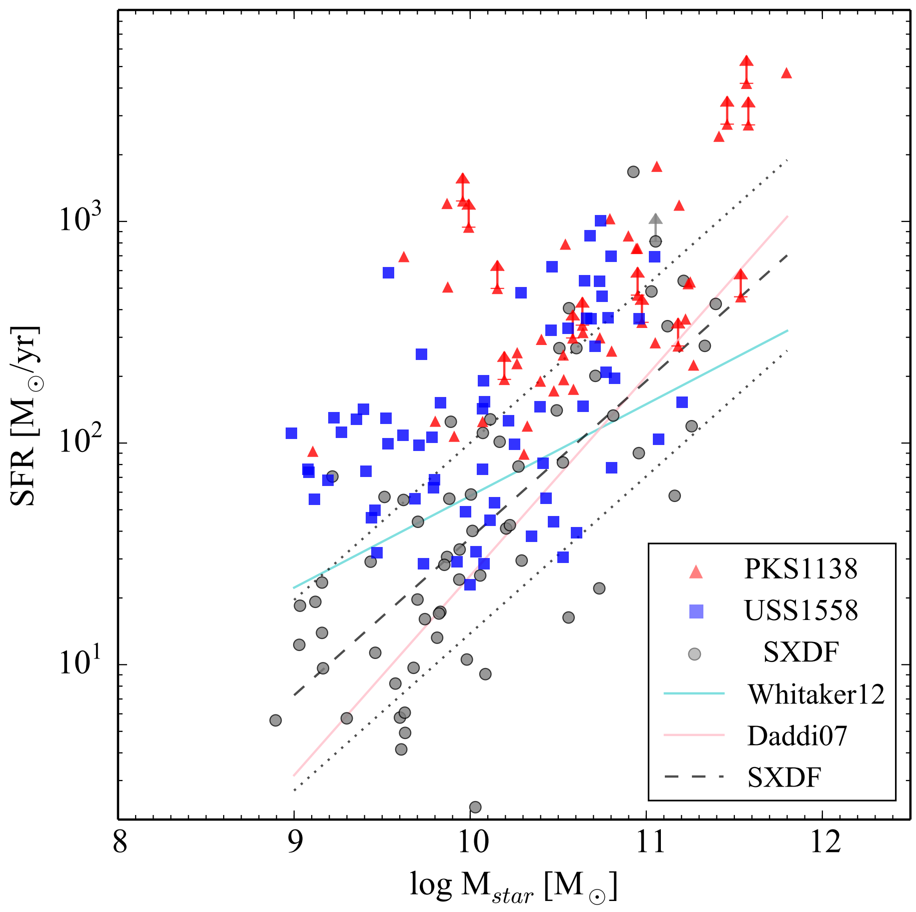
Environmental Dependence

Dust extinction vs. log M(star)



Cluster > Field

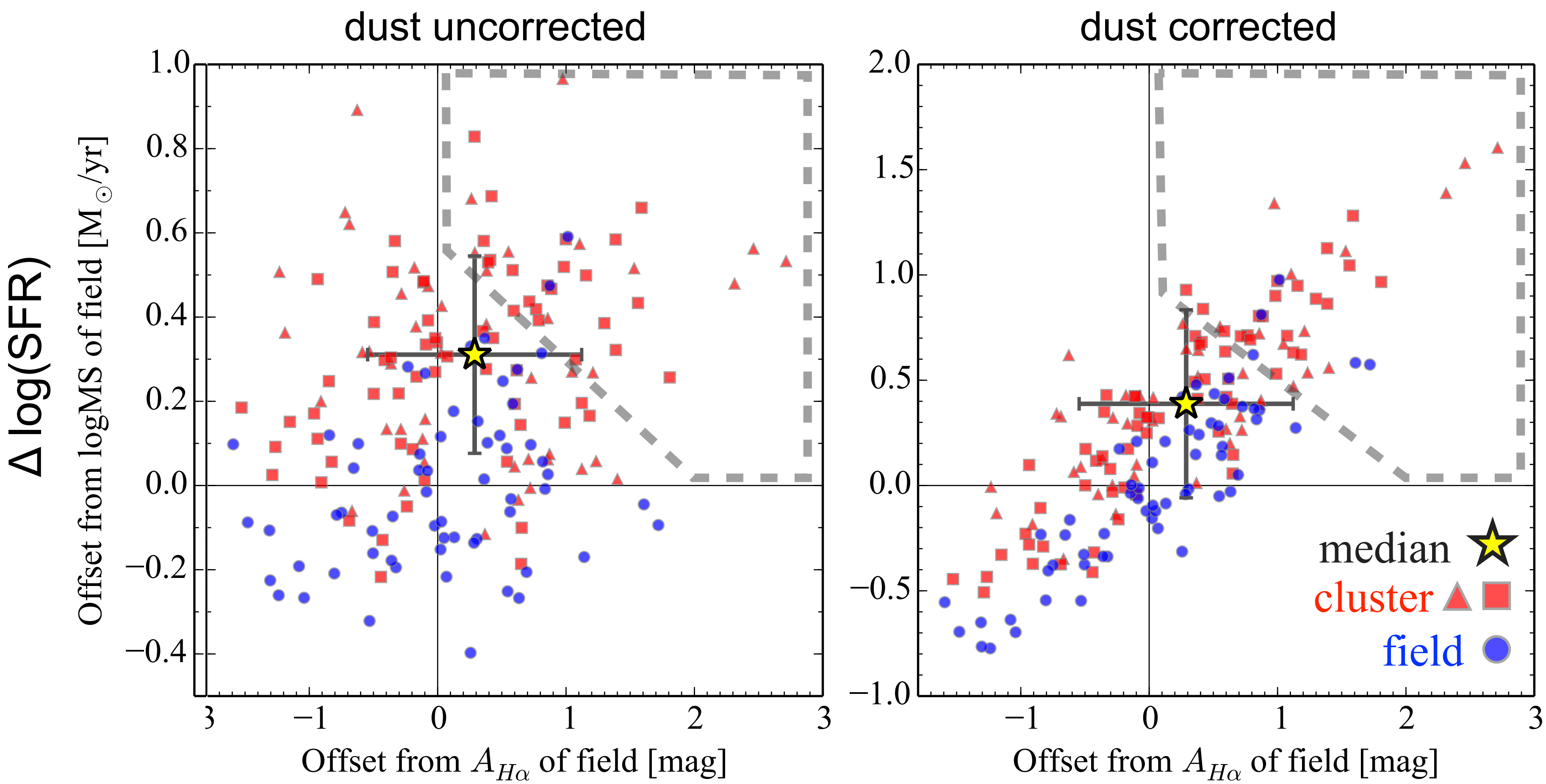
SFR vs. log M(star)



Cluster > Field

Shimakawa et al. (2014b)

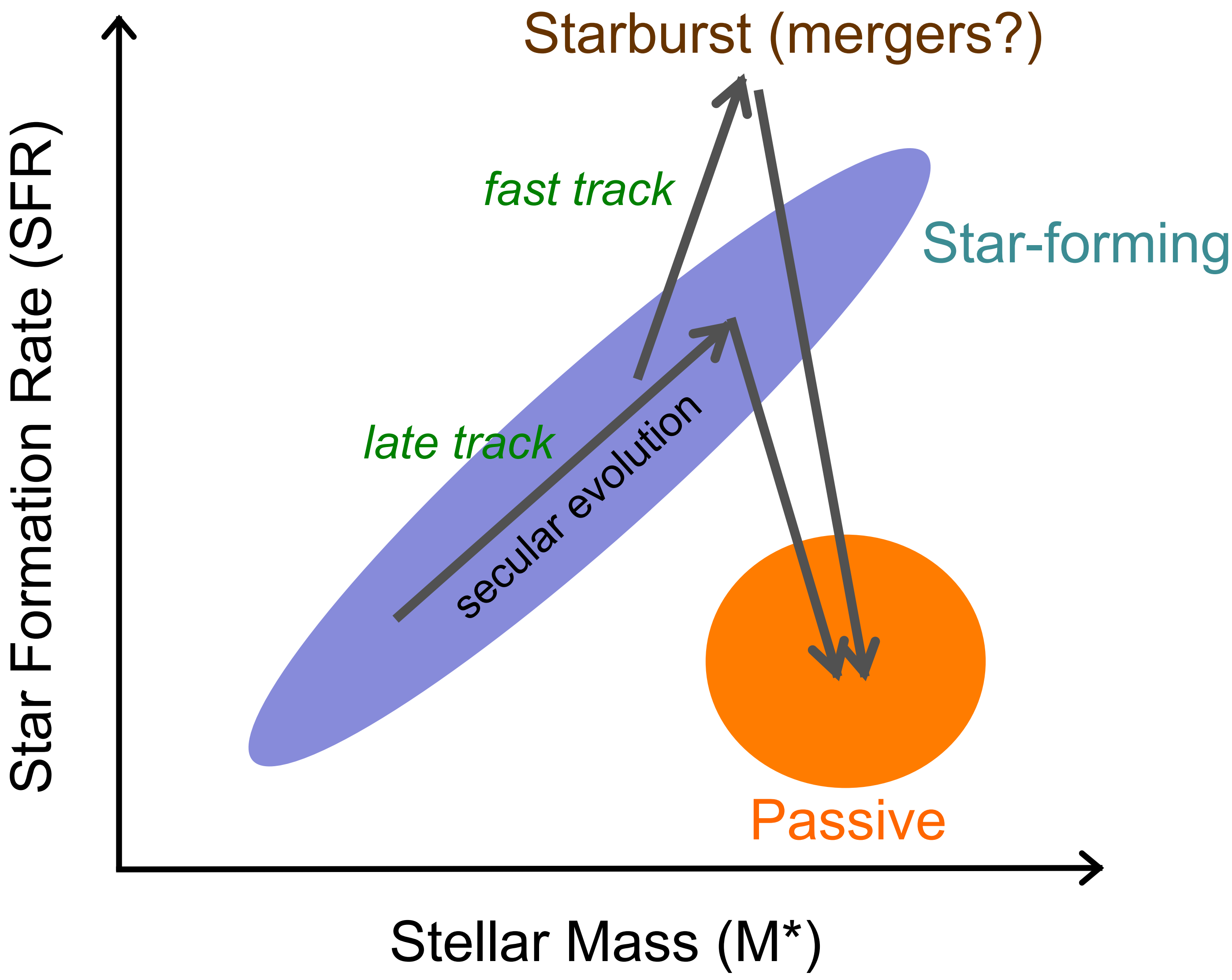
Δ log(SFR) and Δ $A_{H\alpha}$ from the Field are correlated !



Dusty starburst activities in proto-clusters, due to interactions/mergers?

Shimakawa et al. (2014b)

Schematic diagram of evolution on SFR-M* (Main Sequence)



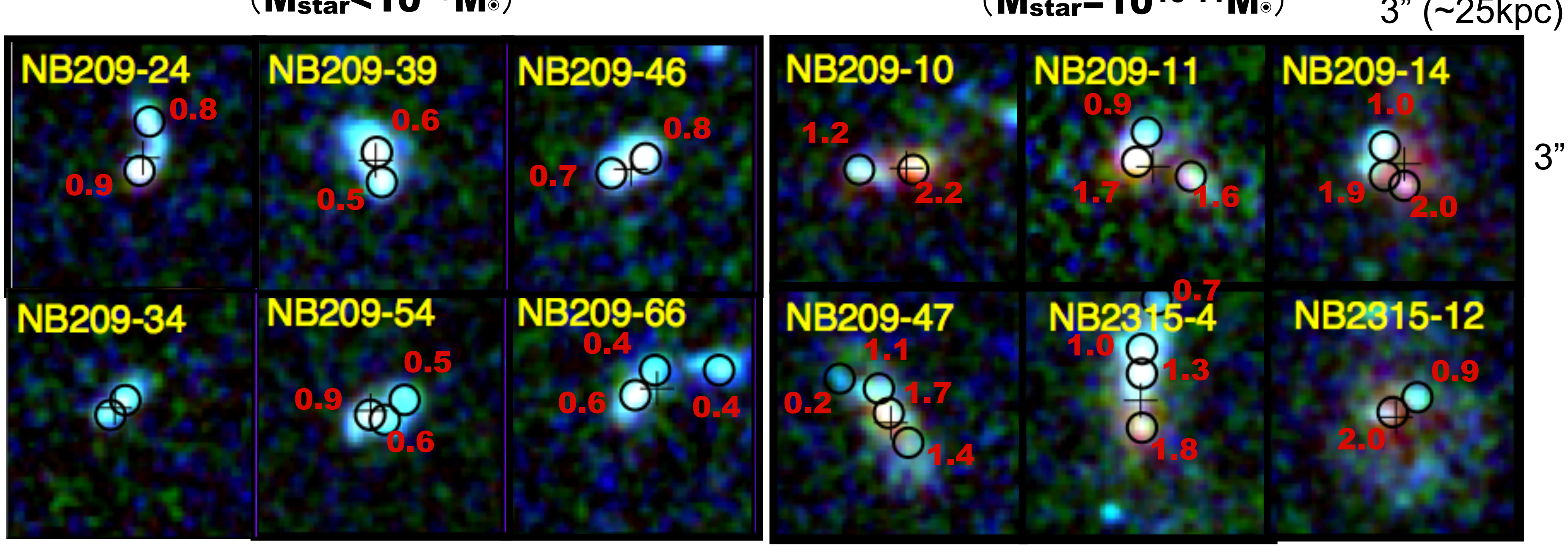
Clumpy structure is common in high-z SFGs (Field)

~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 ($M_{star}=10^{10\text{-}11}M_{\odot}$)



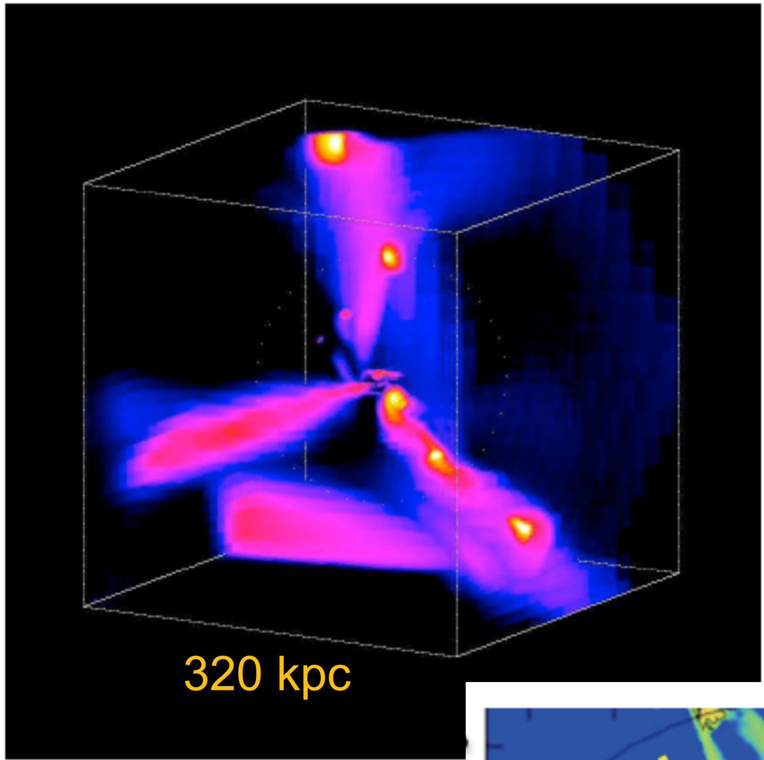
colours (I_{814}-H_{160}) of individual clumps are shown with red numbers

Tadaki et al. (2013b)

Massive galaxies tend to have a red clump near the mass center, which may be hosting a central dusty starburst and forming a bulge eventually !

Environmental dependence of the clumpiness and the clump colours is expected, and should be tested with up-coming HST imaging of the USS1558 proto-cluster.

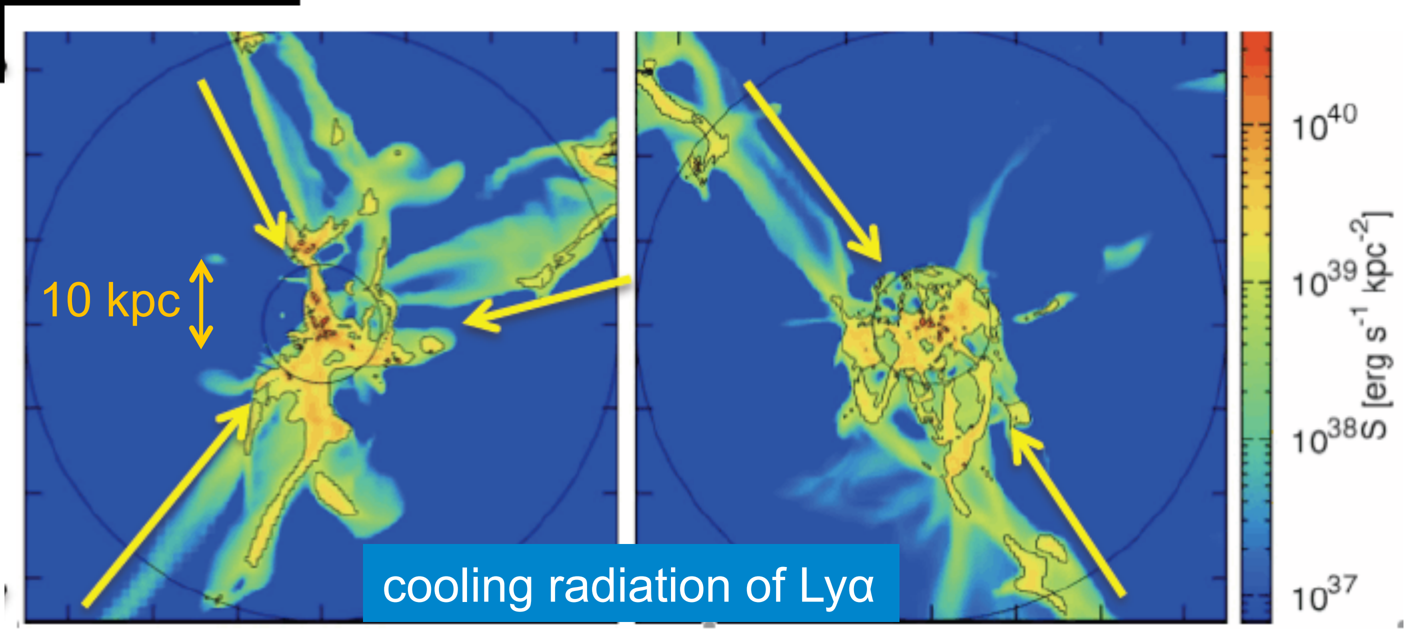
“Cold Streams” along filaments (Inflow)



Dekel et al. (2009, Nature)

Efficient gas supply to form a massive galaxy on a short time scale at high-z.

Rapid gas accretion forms a gas rich disk which becomes gravitationally unstable and fragmented.



Goerdt et al. (2010)

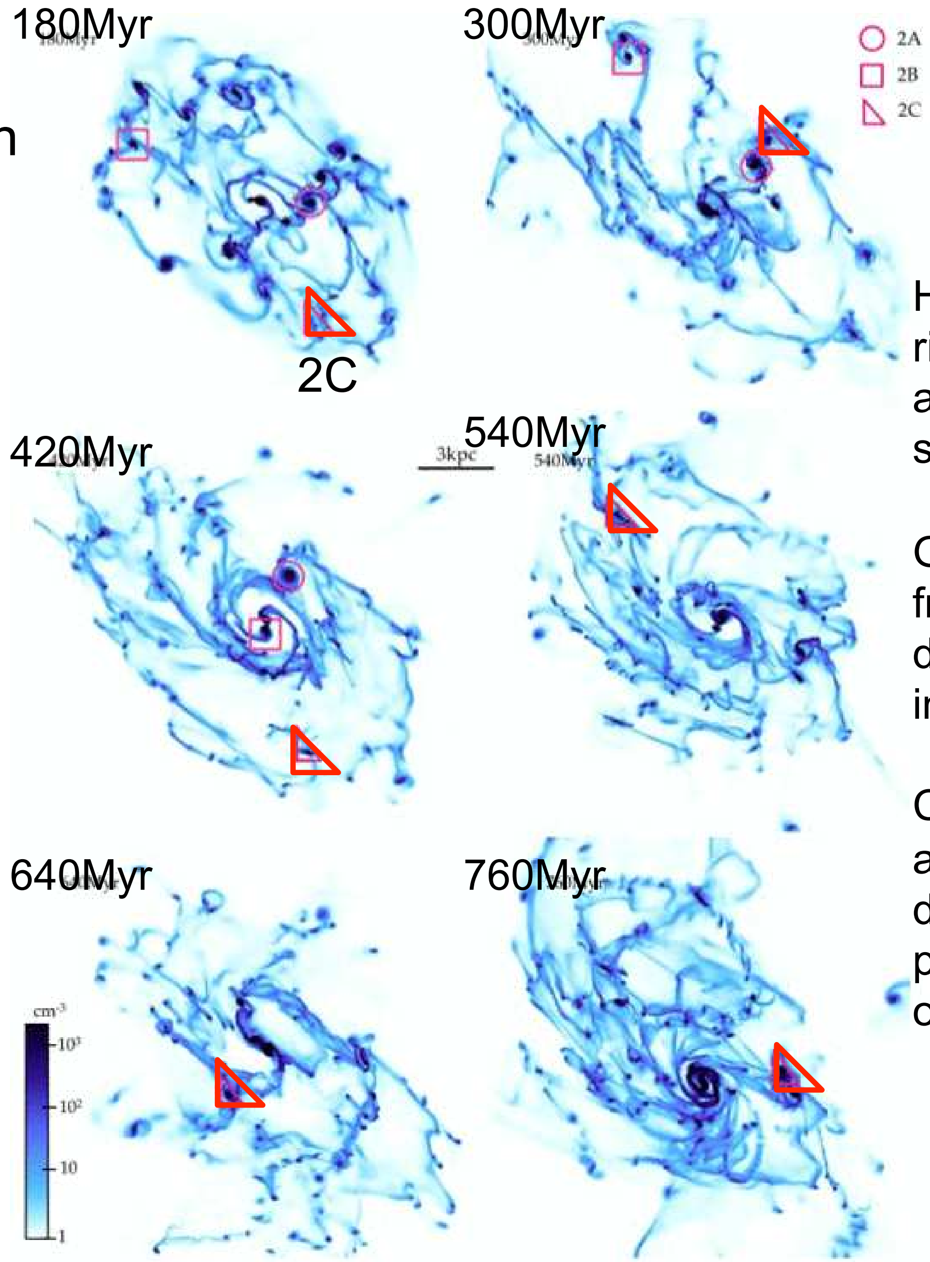
Numerical simulation of clumpy galaxies (N-body + SPH)

Bourmaud et al. (2013)

Stellar feedback (photo-ionization, radiation pressure, and supernova) are fully considered.

Medium-mass galaxy

$M_{dyn} = 3.5 \times 10^{10}\,M_{\odot}$



High-z galaxies are gas rich due to massive gas accretion through cold streams.

Gas rich disks are fragmented to clumps due to gravitational instability.

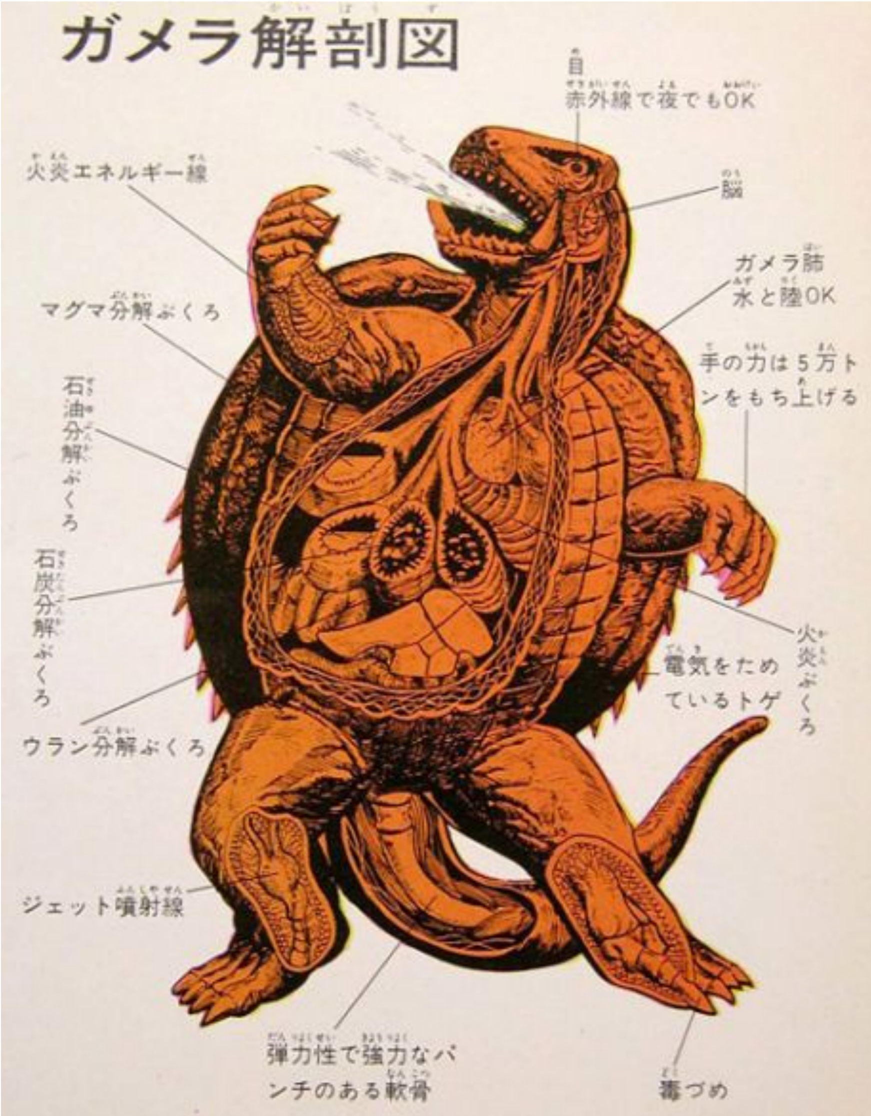
Clumps migrate towards a galactic center due to dynamical friction and probably make a bulge of a disk galaxy.

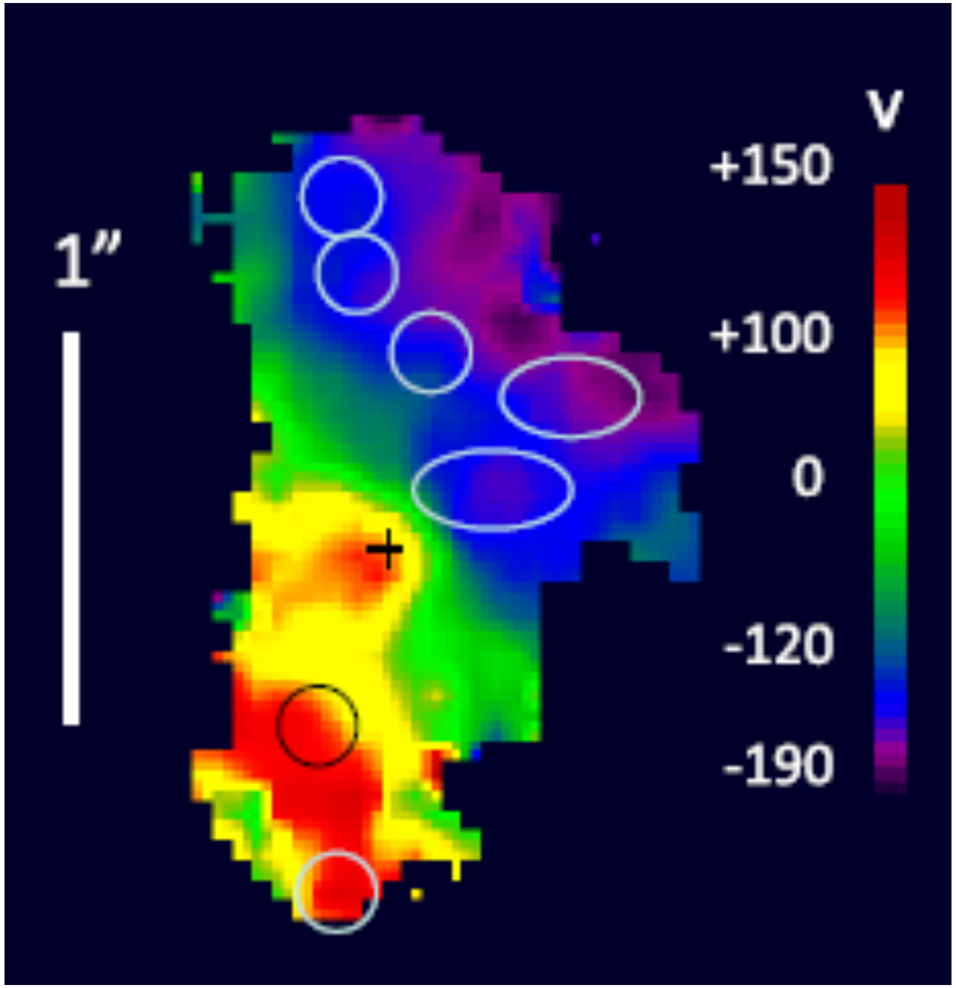
Bulge formation in disk galaxies through clump migration?

→ Necessity for spatially resolved studies of distant galaxies

High-z Galaxy Anatomy

IFU (3D spectroscopy) w/AO





Rotation of gas-rich clumpy disk of a SFG at z=2.4 resolved with IFU (SINFONI) on VLT

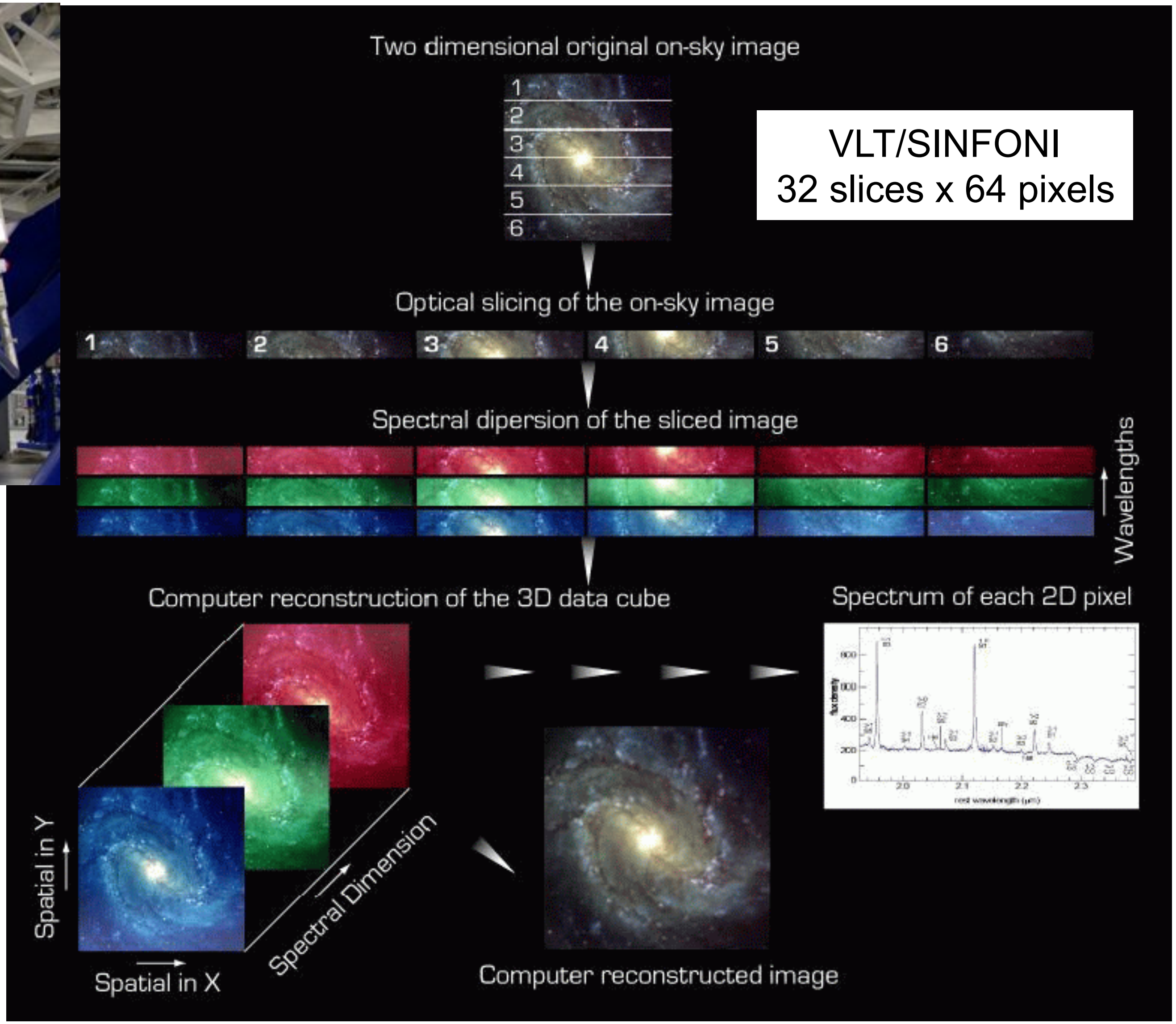
Genzel et al. (2011)

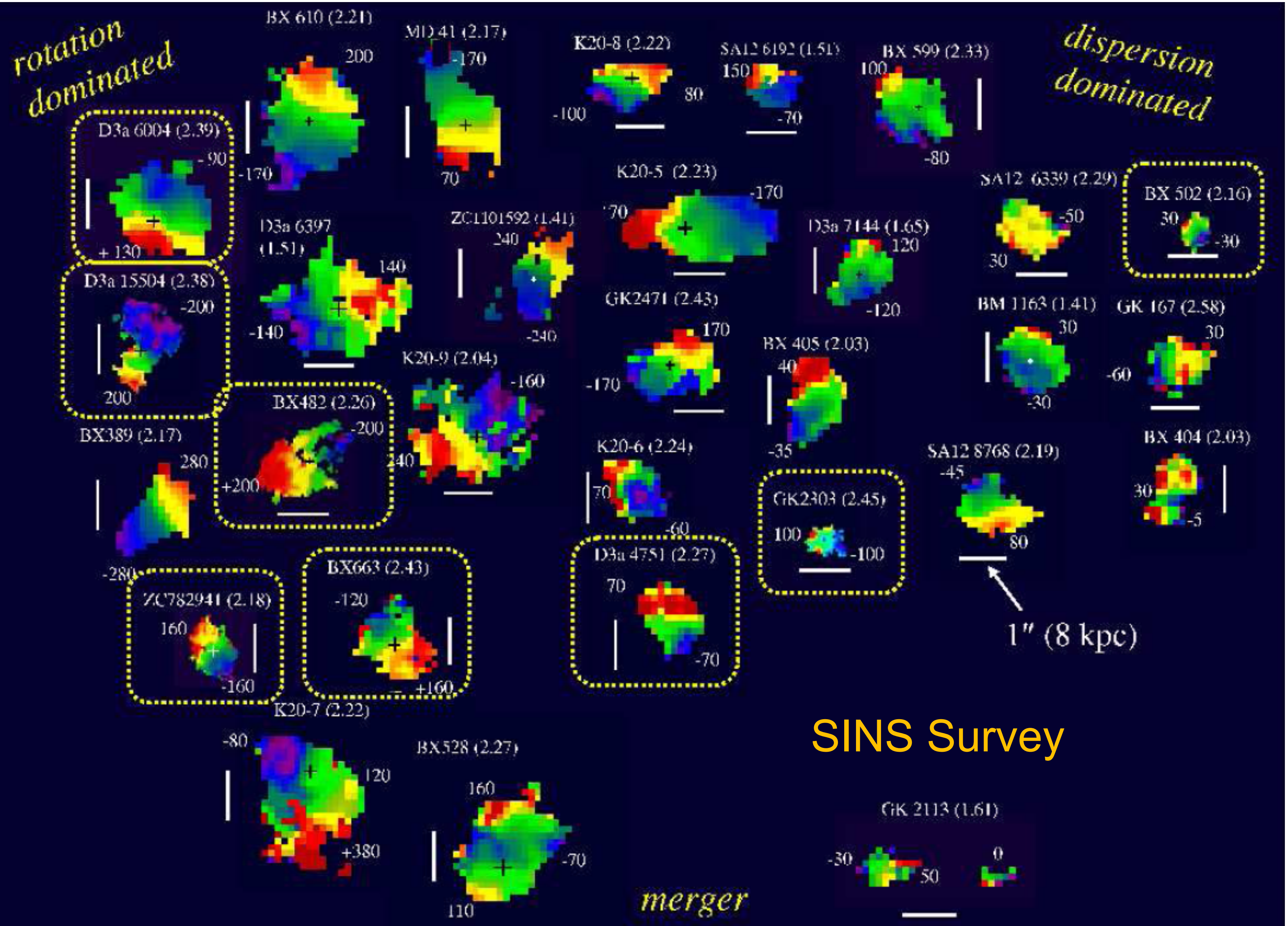
Galaxy Anatomy with 3D spectroscopy (Integral Field Unit)

VLT(UT4) / SINFONI

Keck/OSIRIS
Gemini/NIFS

No such NIR instrument
on Subaru unfortunately!

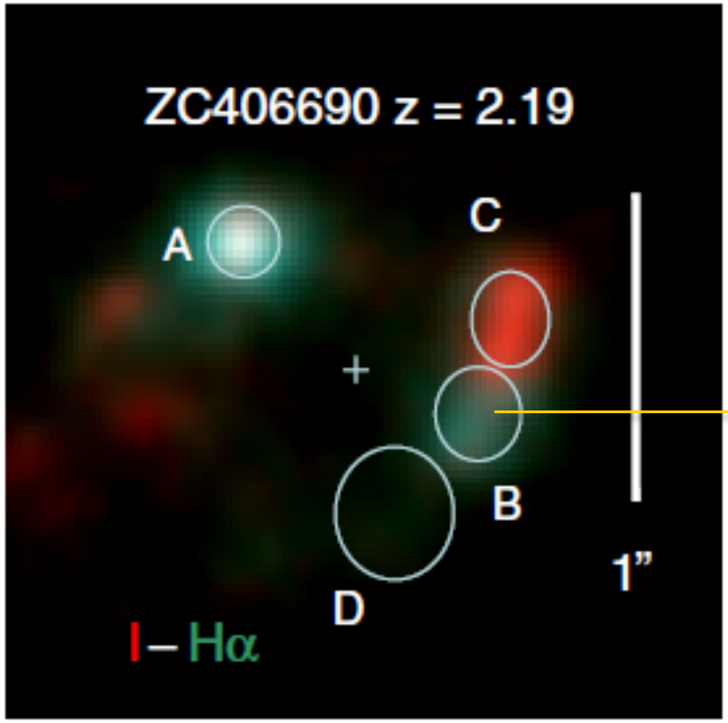




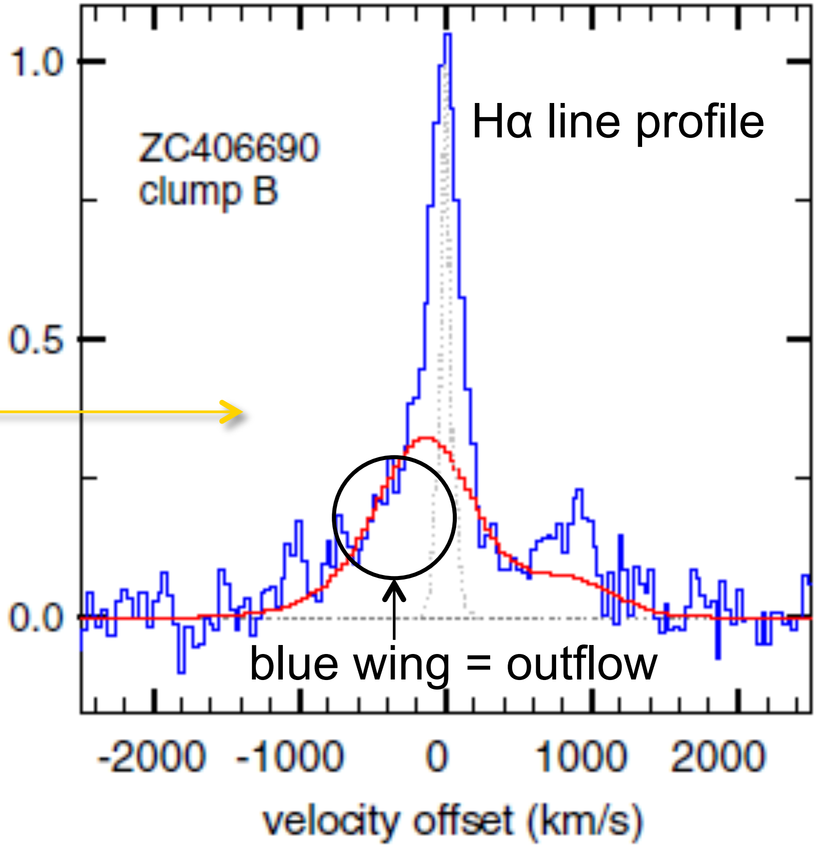
z~2 UV selected galaxies; VLT/SINFONI w/o AO; Vc/σ~2-4

Foerster-Schreiber et al. (2009)

Gas outflows from clumpy galaxies (feedback in action)



Genzel et al. (2011)



Gas outflow from the star-bursting clump-B (~500km/s)

F_{broad}/F_{narrow} (outflow strength) scales with SFR, suggesting "stellar" feedback.

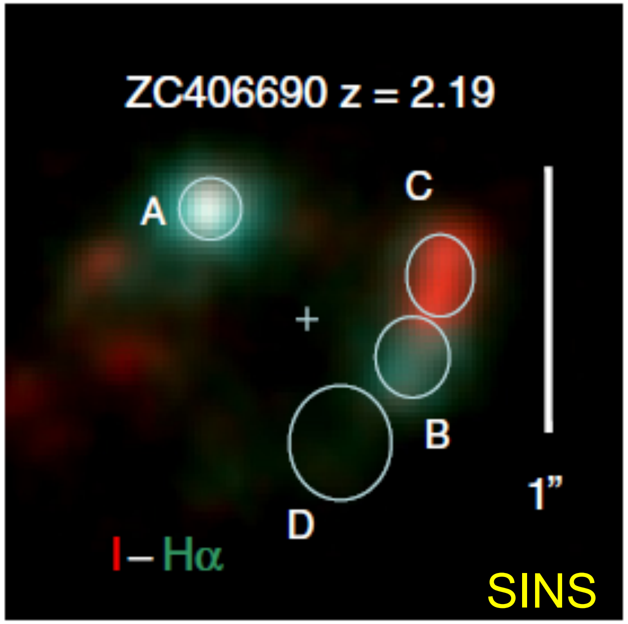
Galaxy Anatomy reveals internal physics of forming galaxies, and its environmental dependence.

Galaxy mergers?	Tidal signatures? Nucleated dusty SB? AGN? Disordered kinematics? Central outflow?
Clump migration?	SF clumps? Ordinary rotating disk? Outflows from clumps?
Secular evolution?	Exponential disk-wide star formation? Well-ordered rotational disk?

HST imaging
size, morphology, clumpiness

AO+NB imaging and IFU
SF regions, AGN, kinematics

ALMA
gas distribution, SF mode, kinematics



Existing/Upcoming instruments for galaxy anatomy

"Spatial Resolution" versus "Field of View"

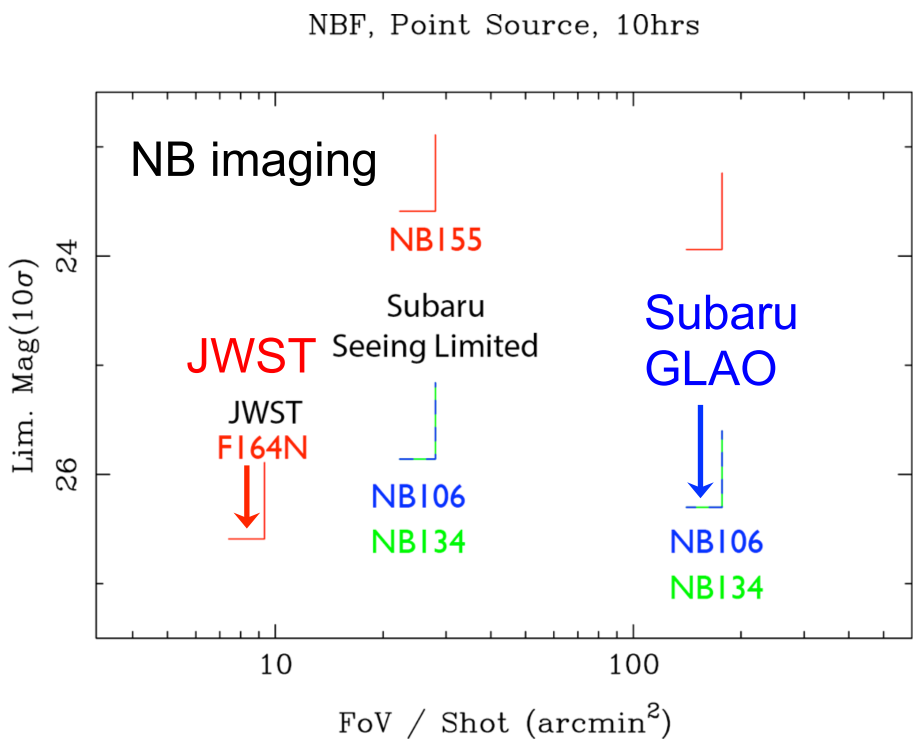
Subaru+AO		
	0.06-0.1"@2μm (~0.5-1kpc @z>1),	1 arcmin (FoV)
Subaru+GLAO		
	0.2" @2μm (~1.5kpc),	15 arcmin
HST		
	0.18" @1.6μm (~1.4kpc),	3.5 arcmin
JWST		
	0.05" @2μm (~0.5kpc),	3 arcmin
TMT+AO		
	0.015" @2μm (~0.1kpc),	15 arcsec
ALMA		
	0.01-0.1"@Submm-mm (0.1-1kpc),	10arcsec-1arcmin

"ULTIMATE-Subaru": GLAO + Wide-Field NIR Instr.

Ultra-wide Laser Tomographic Imager and MOS with AO for Transcendent Exploration

High resolution (0.2"~1.5kpc) and Wide-field (15')

NIR: Narrow-band imaging and Multi-object spectroscopy



NB imaging in between OH sky lines is competitive to JWST (wins by 20x FoV !)

Lyα emitters at z=8-10
and
spatially resolved
Hα, [OIII] emitters at 1<z<3.5

"ALOHA-TMT"

Anatomy with Lines of Oxygen and Hydrogen with AO on TMT

Resolving internal structures/kinematics within galaxies under construction

Huge light collecting power (13×Subaru), and
High spatial resolution (0.015"@2μm with AO)

~3 mag deeper (x 15) for point sources and
~1.5 mag deeper (x 4) for extended sources
compared to Subaru (8.2m diameter)

0.015"@2μm ⇔ ~0.1kpc @z>1

TMT can resolve stars and ionized gas with high resolution which is comparable to ALMA (molecular gas and dust)!

"GRACIAS-ALMA"

GRAphing CO Intensity And Submm with ALMA

Mapping/resolving gas and dust contents at the peak epoch of galaxy formation

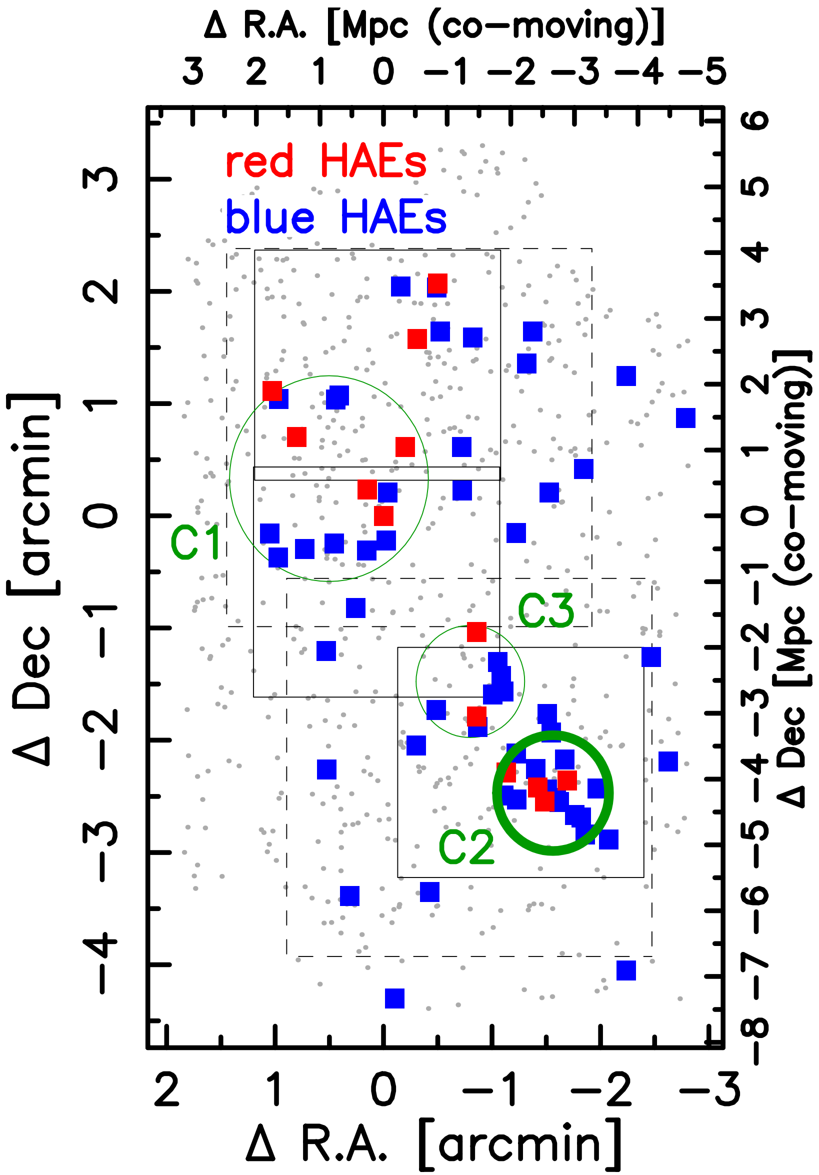
	Cycle-2 sensitivities	
CO line @ Band-3 (~100GHz)	SFR~50$M_\odot$/yr (2.7hrs, 5σ)	@1<z<3
Dust continuum@ Band-6-9 (450 μm–1.1 mm)	SFR~15$M_\odot$/yr (50min, 5σ)	

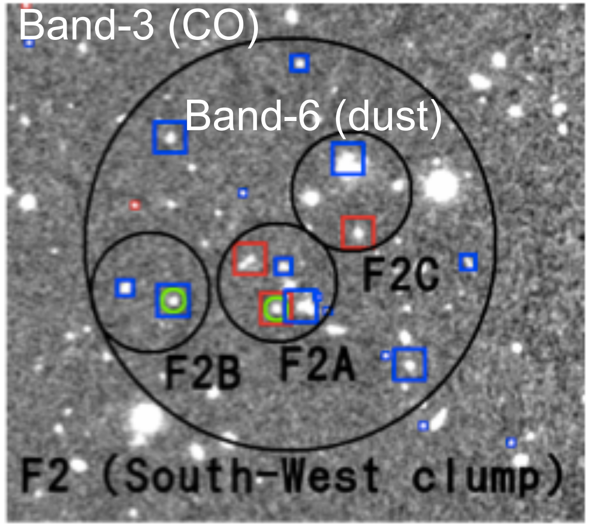
		Mahalo-Subaru				Gracias-ALMA		cycle-1	
target	z	line	μm	NB-filter	Camera	Continuum	Line@GHz(band)	proposals	results
2215–1738	1.46	[OII]	0.916	NB912	S-Cam	B7,9	CO(2-1)@94 (B3)	Hayashi+	**1st**
0332–2742	1.61	[OII]	0.973	NB973	S-Cam	B7,9	CO(2-1)@89 (B3)	not yet	
0218.3–0510	1.62	[OII]	0.977	NB973	S-Cam	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**

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

Internal structures: < 0.1" (<1kpc) : centralized, disturbed or disk-wide gas distribution?
< 50km/s: gas in-/out-flow, rotating disk or disturbed motions?

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.)
will be taken soon.
(Clumpy fraction, size evolution)

Chandra 100ks X-ray data (Martini et al.)
will also be taken soon.
(AGN fraction, distribution)

SWIMS-18 Survey (Kodama et al.)

Unique, comprehensive imaging survey of the Cosmic Noon

SWIMS is the new wide-field NIR camera and spectrograph to be installed on TAO 6.5m telescope in Chile, and will be mounted on Subaru for 2015-2017.

18 filters (6 NBs, 9 MBs, and 3 BBs) will be available !

Narrow-Band			Medium-Band				Broad-Band			
Band	λ_0 (μm)	FWHM (μm)	Band	λ (μm)	λ_0 (μm)	FWHM (μm)	Band	λ (μm)	λ_0 (μm)	FWHM (μm)
NB1244	1.244	0.012	Y	1.00-1.10	1.05	0.10	J	1.17-1.33	1.25	0.16
NB1261	1.261	0.012	J1	1.11-1.23	1.17	0.12	H	1.48-1.78	1.63	0.30
NB1630	1.630	0.016	J2	1.23-1.35	1.29	0.12	Ks	1.99-2.30	2.15	0.30
NB1653	1.653	0.016	H1	1.44-1.56	1.50	0.12				
NB2137	2.137	0.021	H2	1.56-1.68	1.62	0.12				
NB2167	2.167	0.021	H3	1.68-1.80	1.74	0.12				
			K1	1.96-2.10	2.03	0.14				
			K2	2.10-2.24	2.17	0.14				
			K3	2.24-2.38	2.31	0.14				

Simultaneous observations of blue (<1.4μm) and red (>1.4μm) channels !

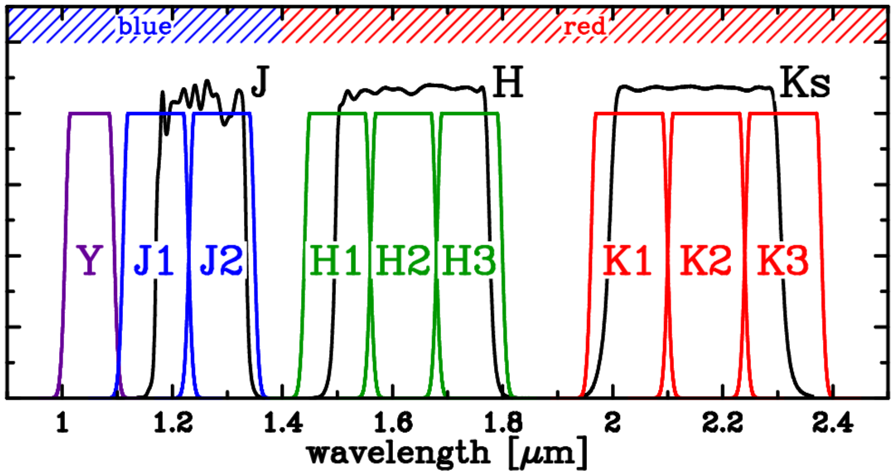
Blue	Red	
NB1244 (6h)	NB1630 (3h)	NB2137 (3h)
NB1261 (6h)	NB1653 (3h)	NB2167 (3h)
Y (3h)	H1 (2h)	K1 (1h)
J1 (3h)	H2 (2h)	K2 (1h)
J2 (3h)	H3 (2h)	K3 (1h)
J (1.5h)	H (1h)	K_s (0.5h)

SWIMS-18 Medium-Band Filters

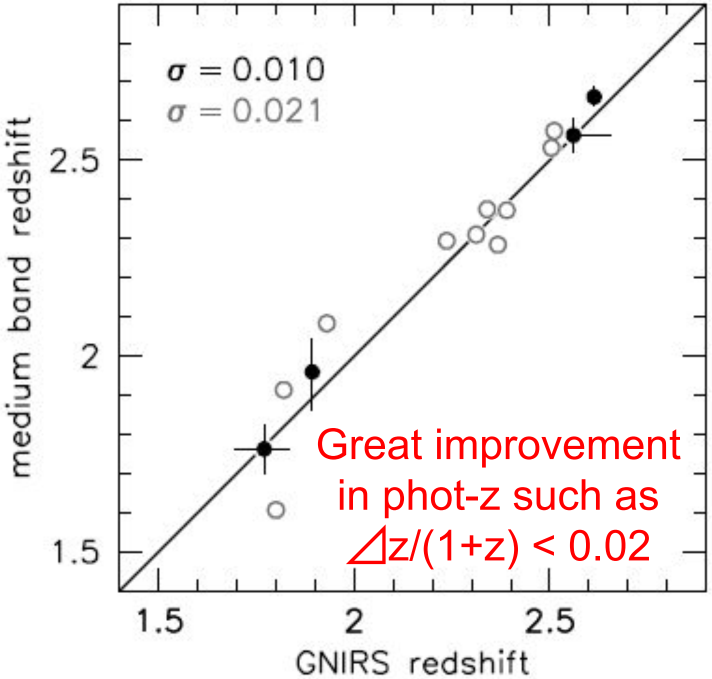
MB filters	λ_c (μm)	FWHM (μm)	z_s(Bal.Lim.) 3645Å	z_s(D4000) 4000Å
Y	1.05	0.10	1.74	1.50
J1	1.17	0.12	2.05	1.78
J2	1.29	0.12	2.37	2.08
H1	1.50	0.12	2.95	2.60
H2	1.62	0.12	3.28	2.90
H3	1.74	0.12	3.61	3.20
K1	2.03	0.14	4.38	3.90
K2	2.17	0.14	4.76	4.25
K3	2.31	0.14	5.14	5.60

BB filters	λ (μm)	λ_c (μm)	FWHM (μm)
J	1.17–1.33	1.25	0.16
H	1.48–1.78	1.63	0.30
K_s	1.99–2.30	2.15	0.30

Will open a new window to 3.5<z<5 with K1,K2,K3 !



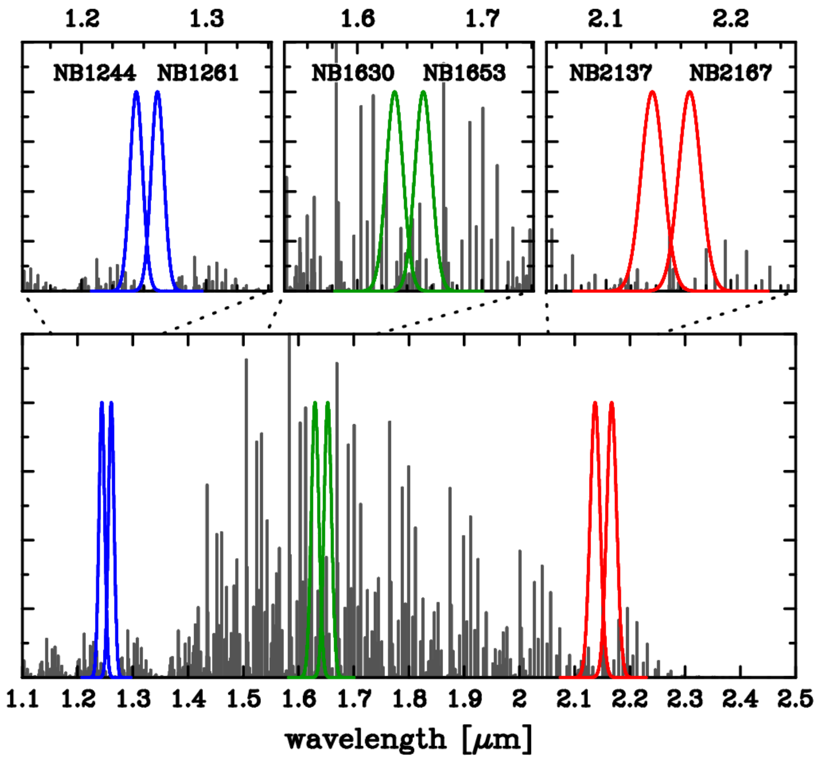
NEWFIRM survey (KPNO)



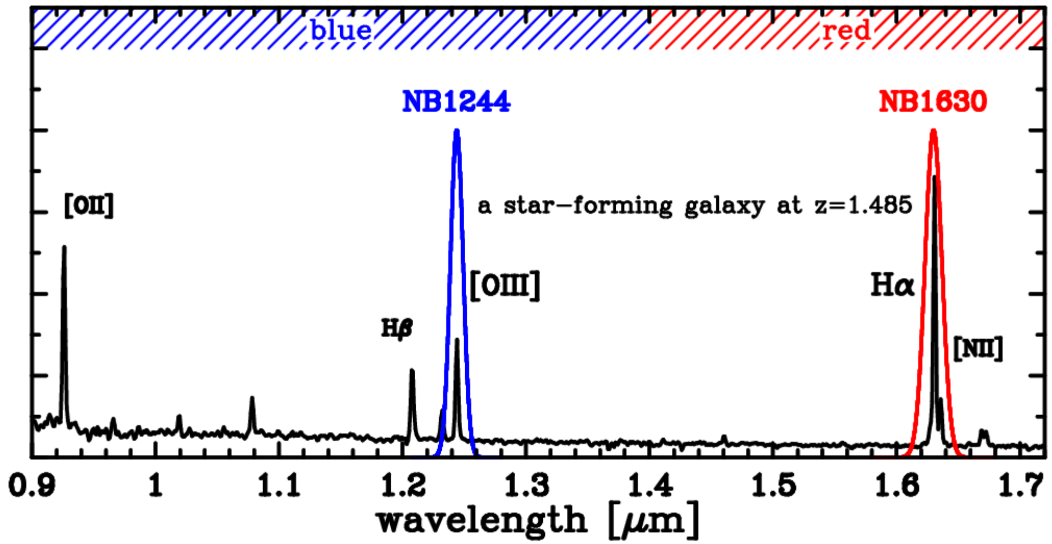
van Dokkum et al. (2009)

SWIMS-18 Narrow-Band Filters

NB filters	λ_c (μm)	FWHM (μm)	z(Hα) 6563Å	z([OIII]) 5007Å	z(Hβ) 4861Å	z([OII]) 3727Å	z(Paα) 1.875μm	note
NB1244	1.244	0.012	0.895	*1.484*	1.559	2.337	–	CL1604+4304(z=0.895)
NB1261	1.261	0.012	0.922	*1.519*	1.595	2.384	–	CL1604+4321(z=0.920)
NB1630	1.630	0.016	*1.484*	*2.256*	2.354	3.374	–	※ HST F126N 1.259 0.015
NB1653	1.653	0.016	*1.519*	*2.302*	2.401	3.436	–	
NB2137	2.137	0.021	*2.256*	3.268	3.396	4.734	0.140	
NB2167	2.167	0.021	*2.302*	3.328	3.458	4.814	0.156	



Dual Emitters ([OIII] and Hα) Survey with Pair NB filters



Why SWIMS-18 > Z-FOURGE ?

(TAO 6.5m) (Magellan 6.5m)

- More medium-band filters (from 6 to 9)
  J1(Y),J2,J3,Hs,Hl,Ks → Y,J1,J2,H1,H2,H3,K1,K2,K3
  → Improvement of phot-z accuracy (in particular at z>3), Balmer break up to z<5
- Existence of narrow-band filters
  6 narrow-band filters, 4 pairs (Hα and [OIII]), adjacent on/off bands
  → optimized to strong [OIII] emitters at high-z, no contamination
- Simultaneous observations of two passbands
  λ<1.4μm (blue channel) and λ>1.4μm (red channel) with a dichroic mirror
  → Survey efficiency doubled
- Large amount of time allocation to some dedicated programs
  → 0.7-1.5 yrs of observing time for 1 sq. deg. (×10 Z-FOURGE),
  optimal for environmental studies with clusters of $>10^{14}M_{\odot}$

Survey Design for SWIMS-18 (imaging)

survey layer	area (sq. deg.)	# of pointings	observing time (Subaru)	observing time (TAO)	total time for TAO
SWIMS-18-Wide	1	100	25hrs/FoV	40hrs/FoV	4,000 hrs
SWIMS-18-Deep	0.1	10	125hrs/FoV	200hrs/FoV	2,000 hrs

SFR-limit sample (HAEs) : 7.5×10^5 Mpc^3 at each redshift

SFR-limit ($M_\odot$/yr)	expected # of HAEs
10(z=1.5), 30(z=2.5)	8000(z=1.5), 4000(z=2.5)

M*-limit sample: 1.2×10^7 Mpc^3 (Δz=1)

M_*-limit ($M_\odot$)	expected # /(Δz=1)
10^{10}(z=1.5), 10^{11}(z=3)	3000(z=3), 300(z=4)

→ **Requires 0.7-1.5 yrs of observing time at TAO**

1/10-1/30 of the survey will be done with Subaru when SWIMS is mounted there for 3 yrs (2015-2017)

Summary

- Mahalo-Subaru is mapping out star formation activities across cosmic times and environment, covering the peak epoch of galaxy formation and evolution ($1<z<3$).
- Enhanced star forming activities in cluster cores at $z\sim2$
- The mode of star formation (e.g. dusty starburst) may depend on environment.
- Clumpy nature of SFGs at $z\sim2$ (especially the red clumps) maybe closely related to a bulge formation. We expect some environmental dependence in internal structures of SFGs.
- Galaxy Anatomy with IFU and Gracias-ALMA will reveal the physical processes of galaxy formation.
- HSC will make a large, complete sample of 10K clusters to $z\sim1.7$. SWIMS-18 will be sensitive up to $z\sim5$, WISH will extend the frontier of SFR- and Mass-limited samples to $z\sim6$-8.

Thank you very much for Korean's great hospitality!

Giant Makgeolli Telescope
&
Taddy Makgeolli Telescope