(銀河団の物理@東京理科大学, 2013/12/28)

光赤外で探る銀河団銀河の形成と進化

Optical-IR Views of Formation and Evolution of Galaxy Clusters

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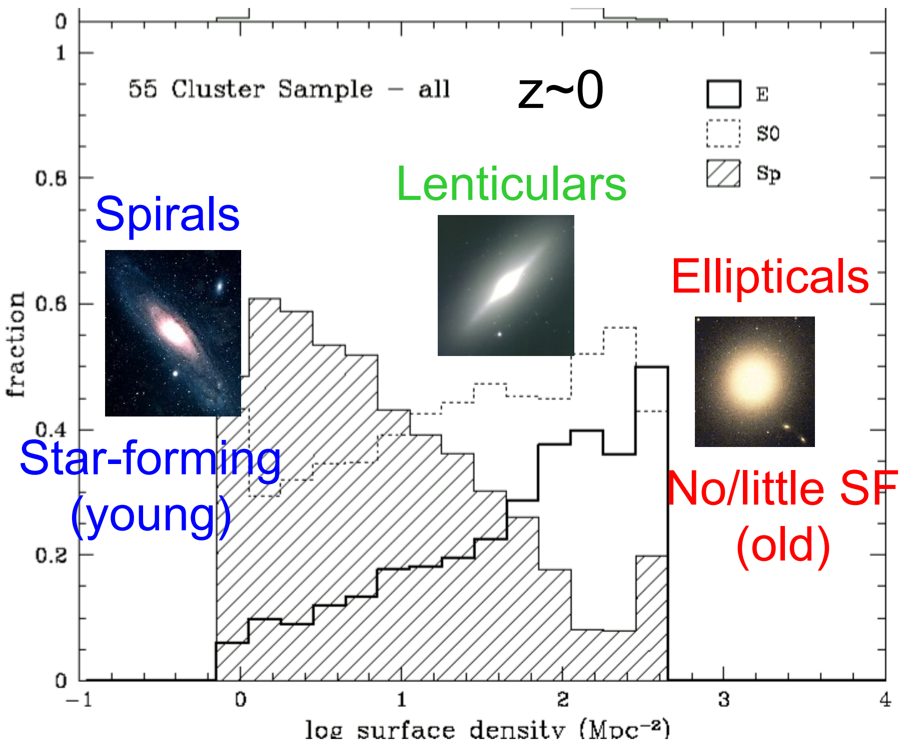
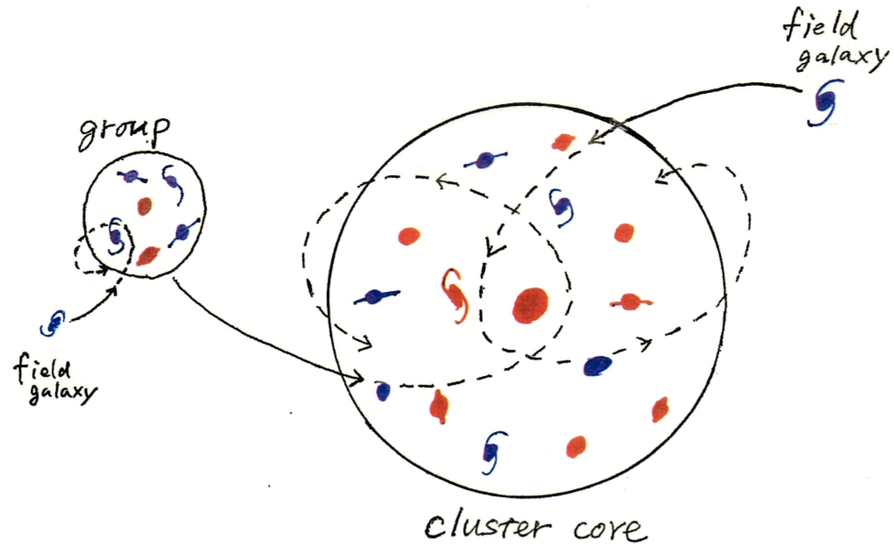
A galaxy cluster RXJ0152 at z=0.83 (Subaru/Suprime-Cam)

Origin of the cosmic habitat segregation

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



log surface density (Mpc^{-2})



Nature? (intrinsic)

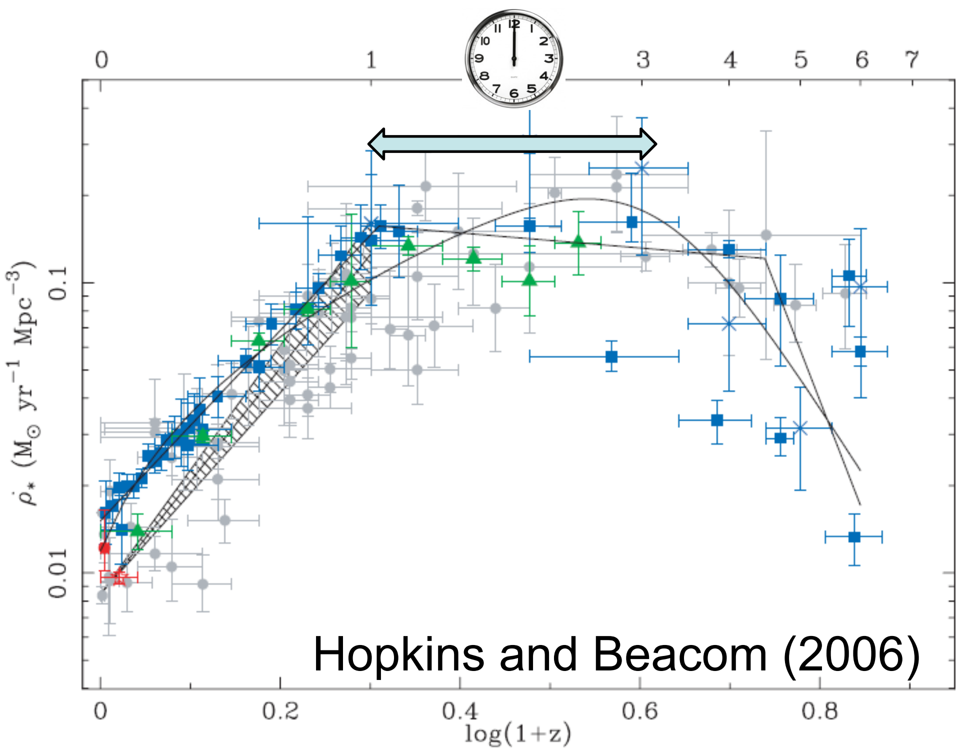
earlier galaxy formation and evolution in high density regions

Nurture? (external)

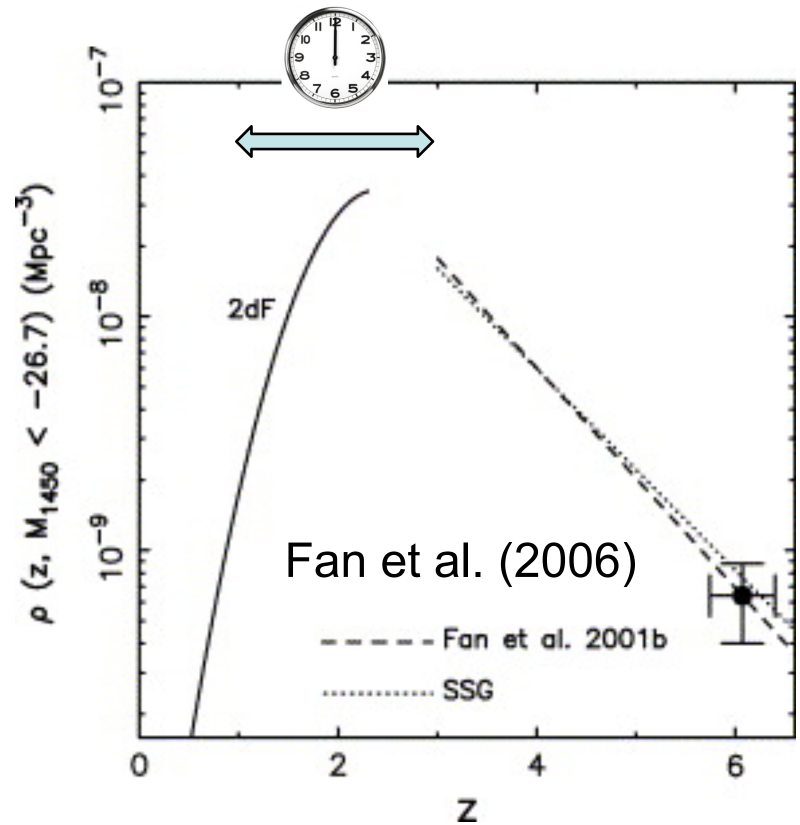
galaxy-galaxy interaction/mergers, gas-stripping

"COSMIC NOON"

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



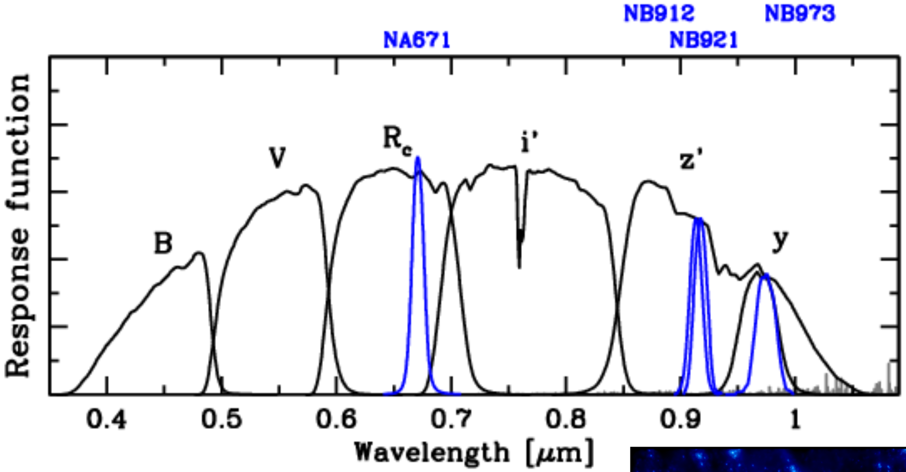
Star formation



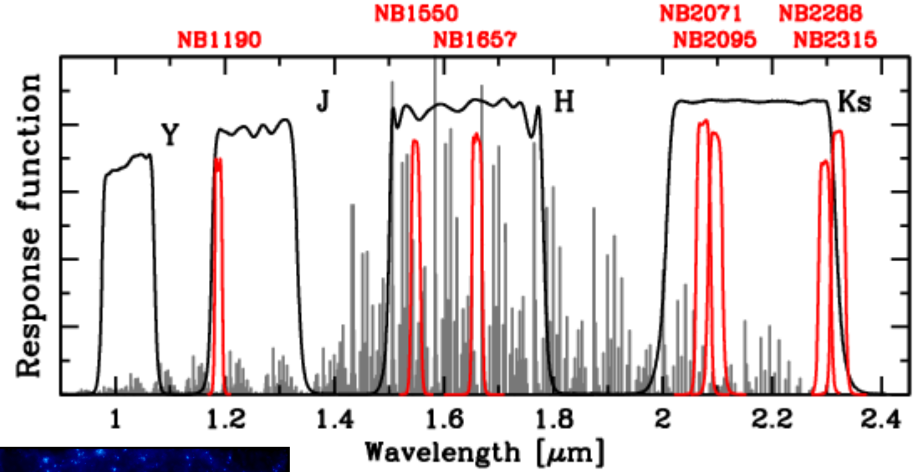
AGN (QSO)

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

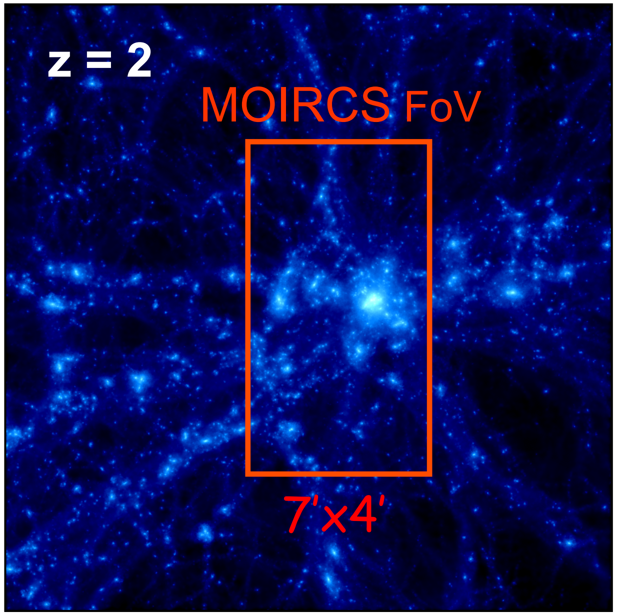
Suprime-Cam (optical; 34'x27')



MOIRCS (NIR; 7'x4')



4 narrow-band filters



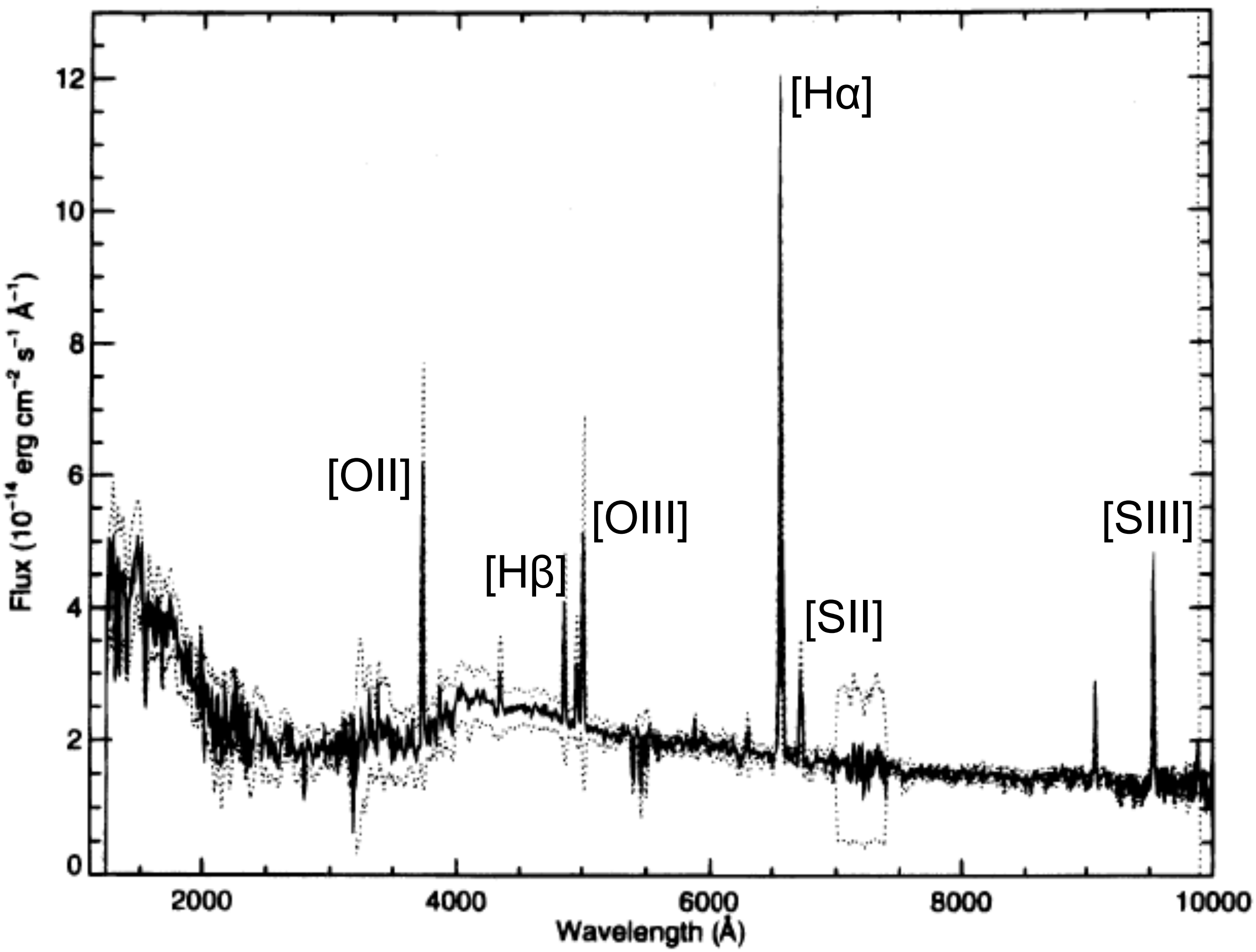
7 narrow-band filters

FWHMs correspond to ±1500-2000km/s

Cluster N-body+SAM simulation (Yahagi et al. 2005; ν GC)
20×20 Mpc^2 box (co-moving)

A typical spectrum of star forming galaxy

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



Kinney et al. (1996)

"MAHALO-Subaru"

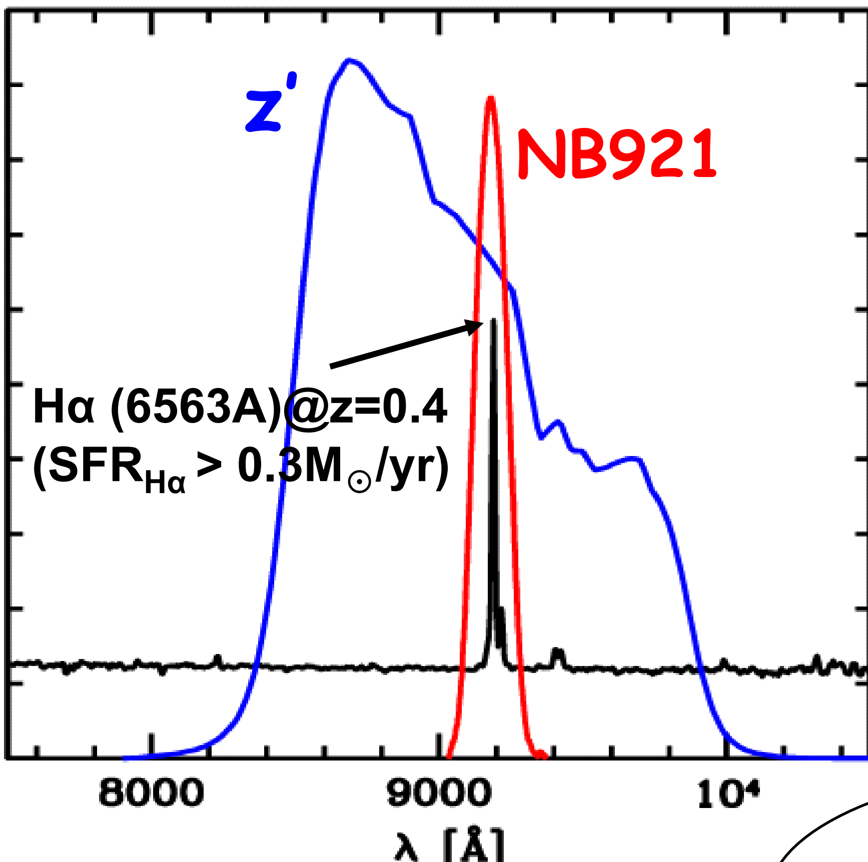
MApping **HA**lpha and **L**ines of **O**xygen with **Subaru**

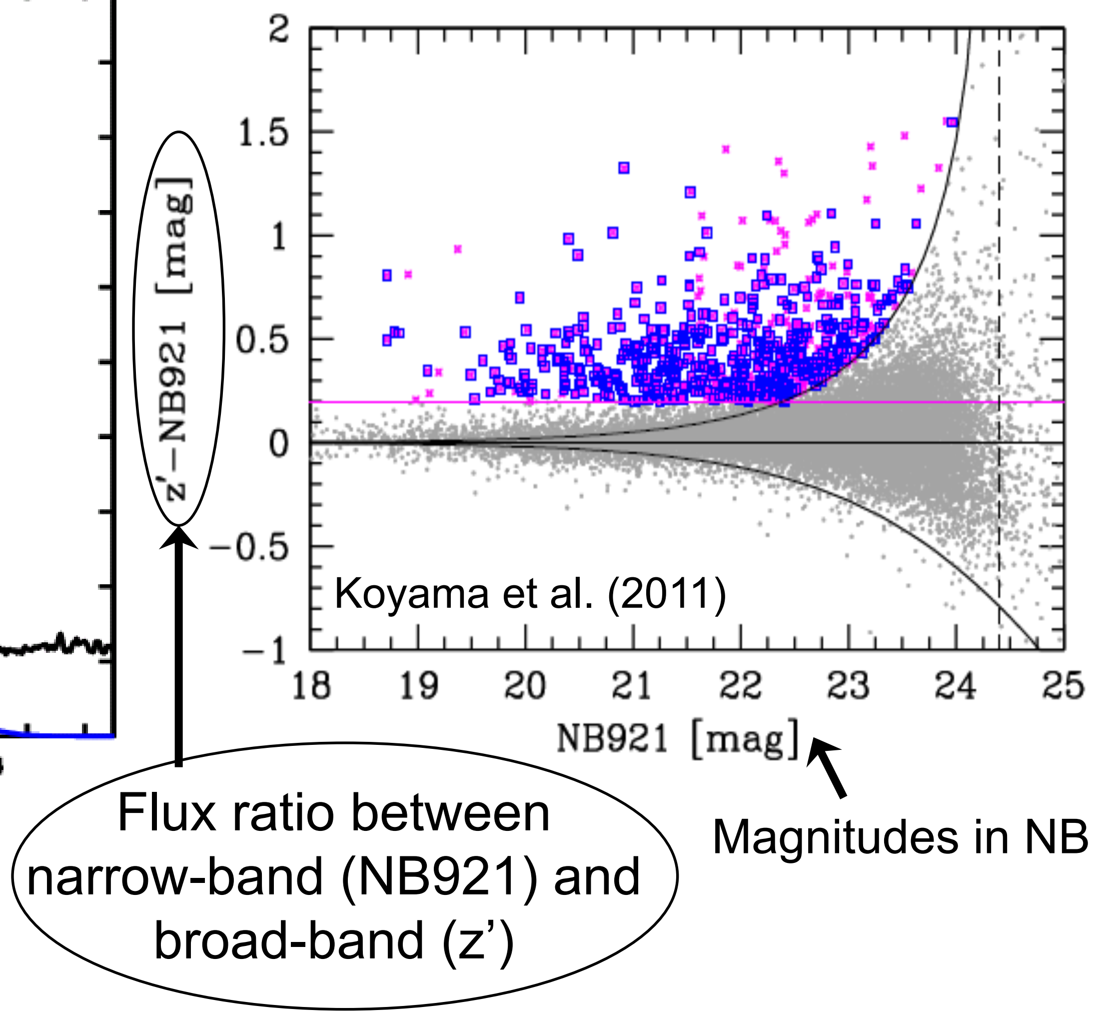
Unique sample of NB selected SF galaxies across environments and cosmic times

	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

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



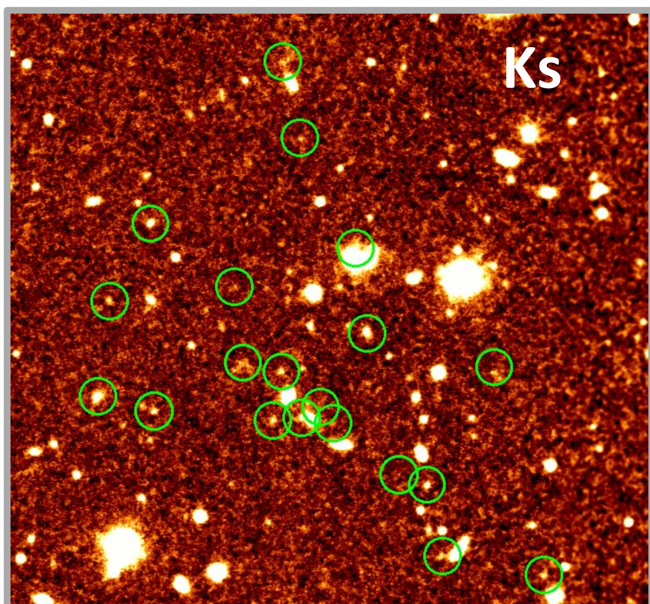


Discovery of a Prominent Star-Bursting Proto-Cluster at z~2.5

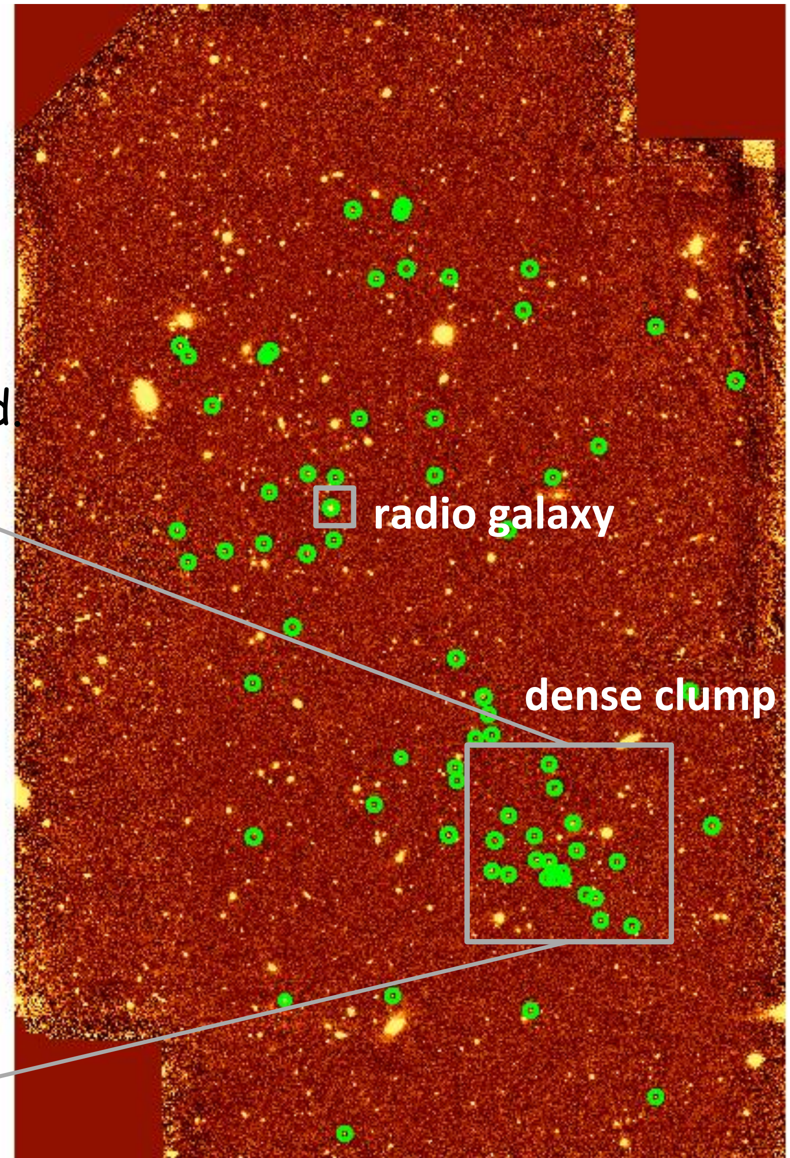
USS1558-003 (z=2.53)

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

68 Ha emitters (HAEs) are detected.



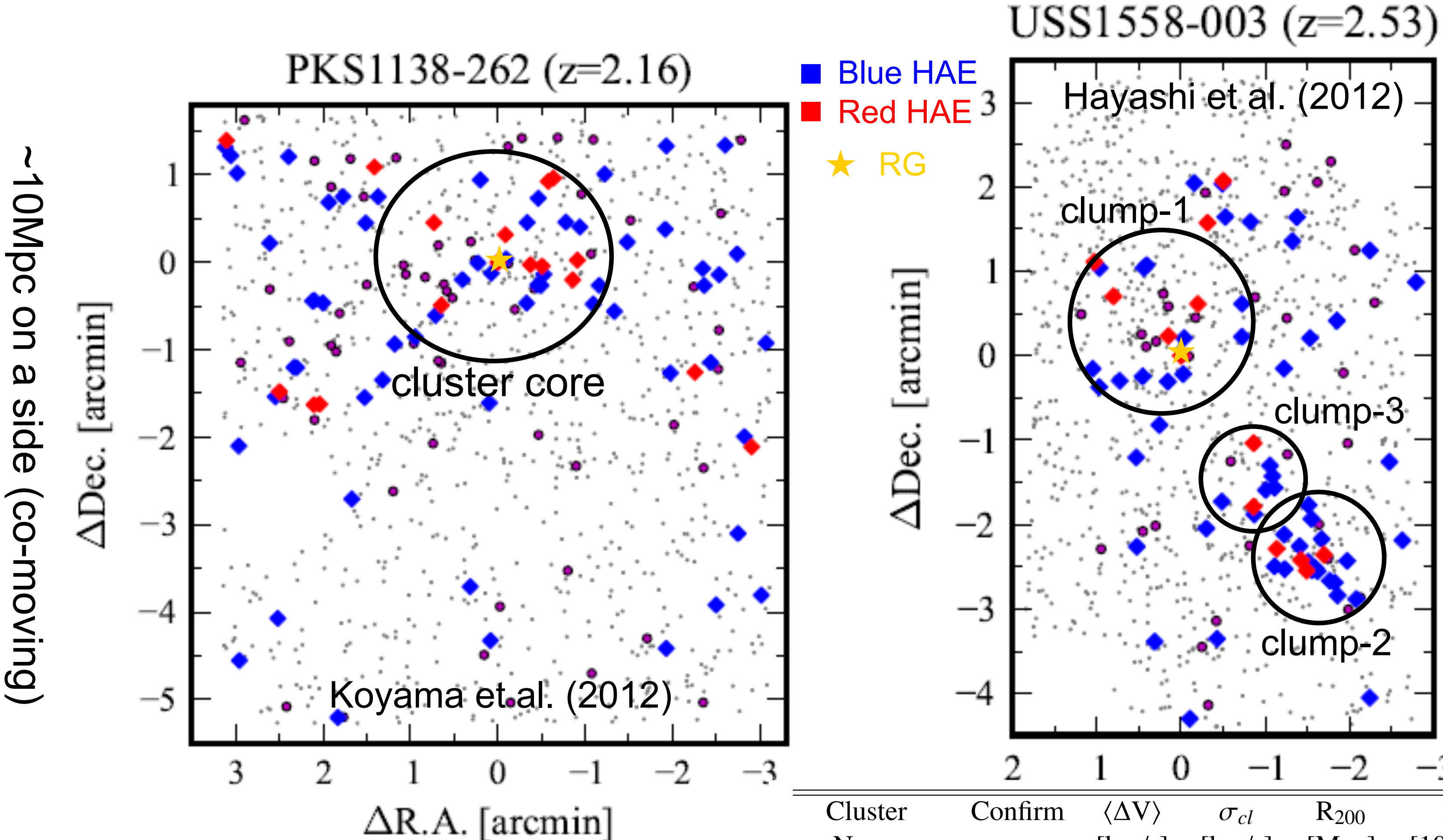
~20x denser than the general field.
Mean separation between galaxies is ~150kpc.



1.5Mpc away
from the RG

Hayashi et al. (2012)

Spatial distributions of HAEs in proto-clusters at z~2



Cluster Name (1)	Confirm (2)	⟨ΔV⟩ [km/s] (3)	σ_{cl} [km/s] (4)	R_{200} [Mpc] (5)	M_{cl} [$10^{14} M_\odot$] (6)
PKS1138 all	27	−41	882[4]	—	—
PKS1138 C1	9	+9	683[2]	0.371[2]	1.20
USS1558 all	37	−164	841	—	—
USS1558 C1	7	+426	508	0.236	0.42
USS1558 C2	13	−1134	660	0.306	0.92
USS1558 C3	6	−956	319	0.148	0.10

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

Environmental dependence in the formation phase of early-type galaxies?

- Mode of star formation? (starburst, dusty)

  Location on the SFR-M* diagram

  SFE=SFR / f(gas)

  SFR(IR) / SFR(UV) or SFR(Hα) / SFR(UV)

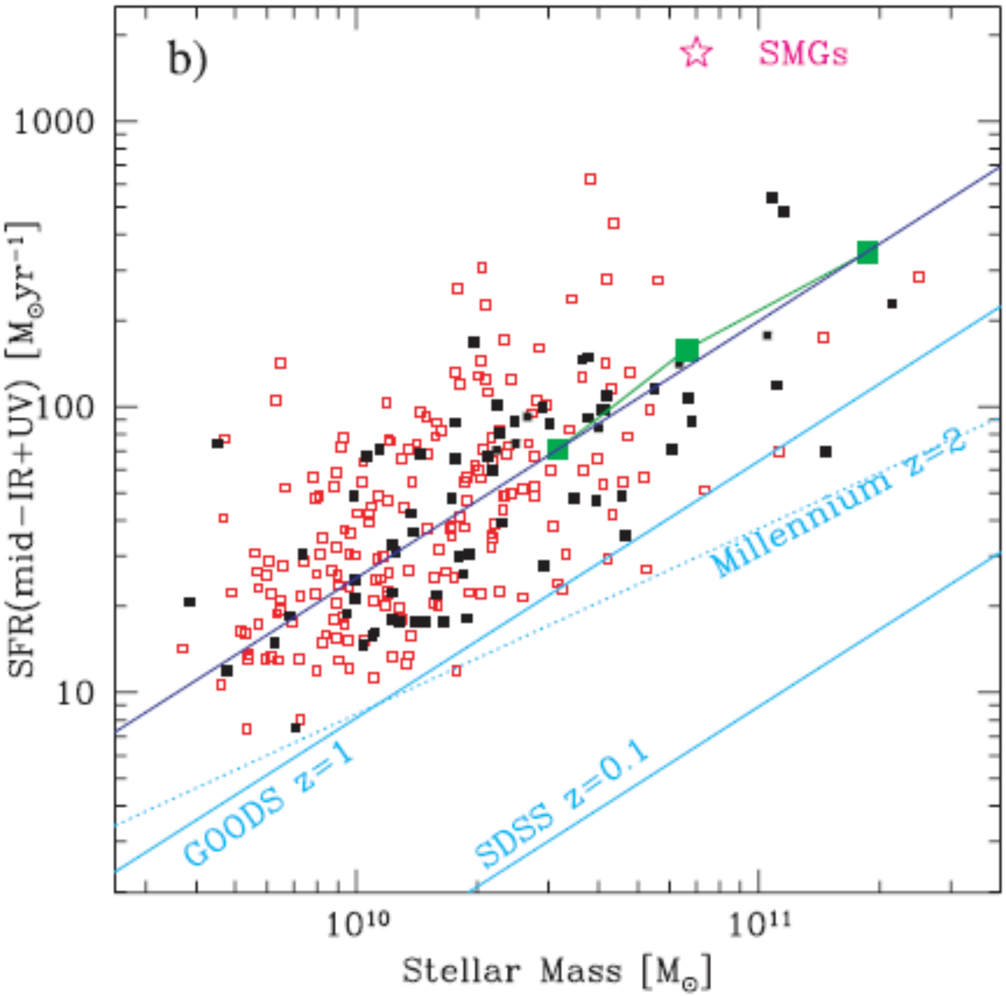
- Internal structure? (clumpy, central burst)

  HST images of USS1558 proto-cluster (z=2.53)

  Hα imaging w/ AO, IFU spectroscopy, ALMA

"Main Sequence" of Star Forming Galaxies at z~2

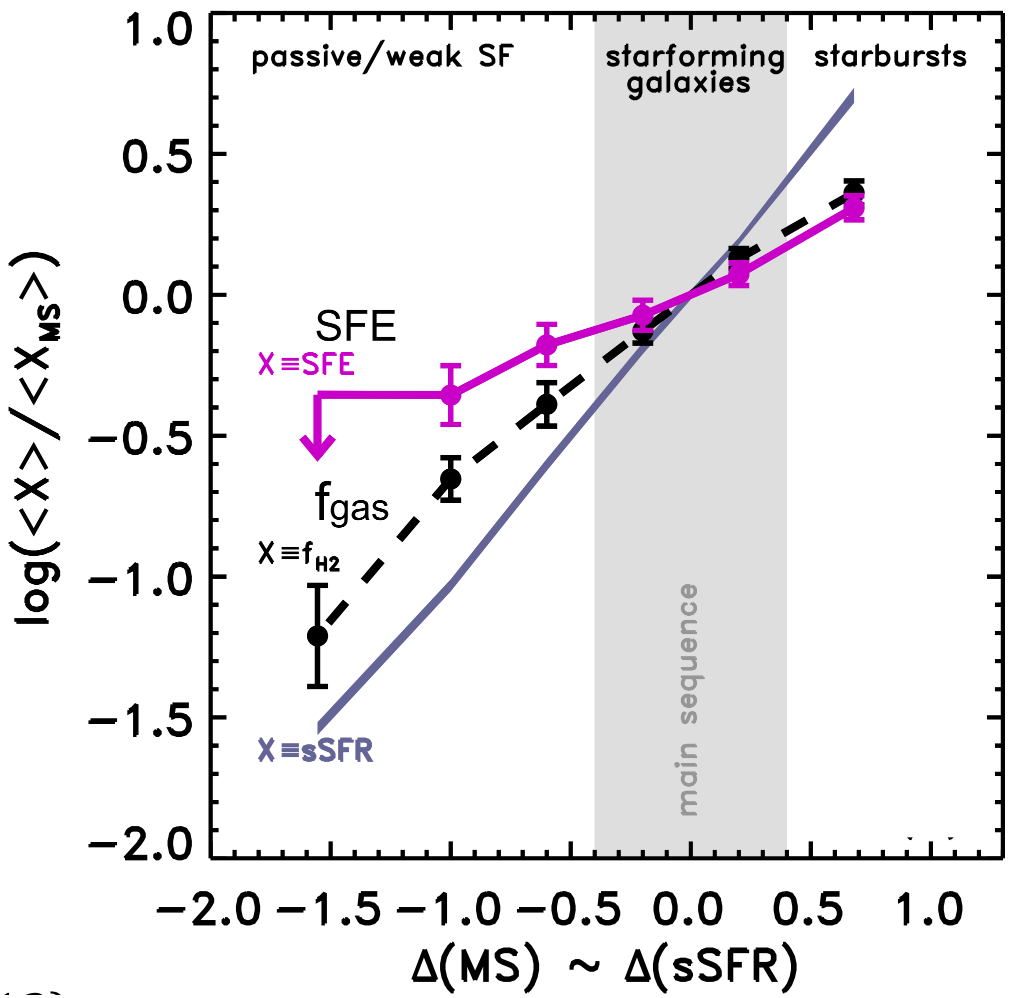
SFR vs. M* (~proportional). Large scatter. SMG is up-scattered by ~×10.
There are two modes of star formation: Normal mode and Burst mode



Good relation,
but a considerable scatter!

Daddi et al. (2007)

Star formation efficiency (SFE) and molecular gas fraction (f_{gas}) as a function of deviation from the main sequence (ΔMS)



COLDGASS project

SDSS galaxies
IRAM 30-m

Saintonge et al. (2012)

SFE = SFR / M_{gas}

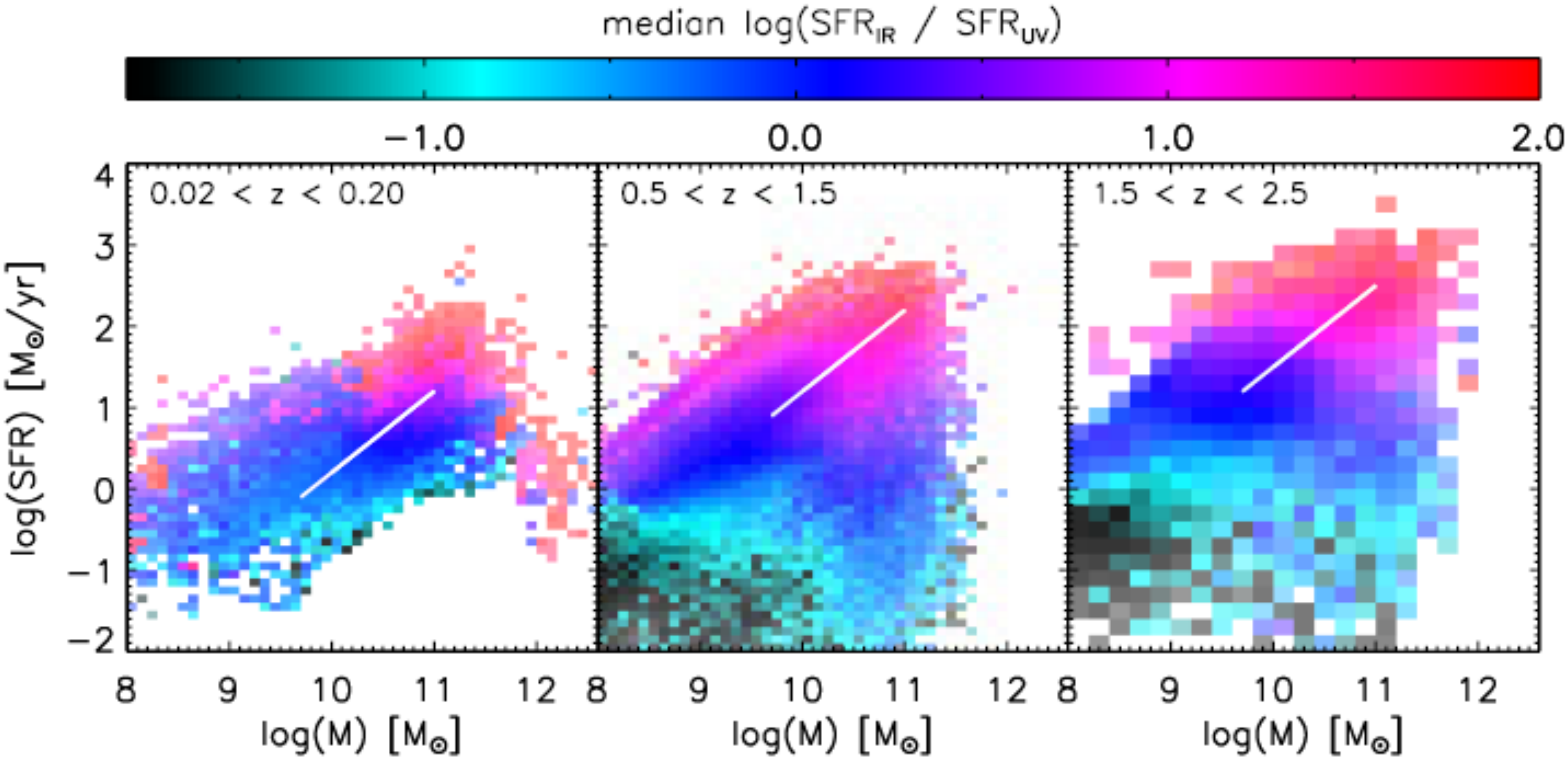
$f_{gas}=M_{gas}/(M_{gas}+M_{star})$

(sSFR = SFR / M_{star})

SFE and f_{gas} both go up with Δ(MS) !

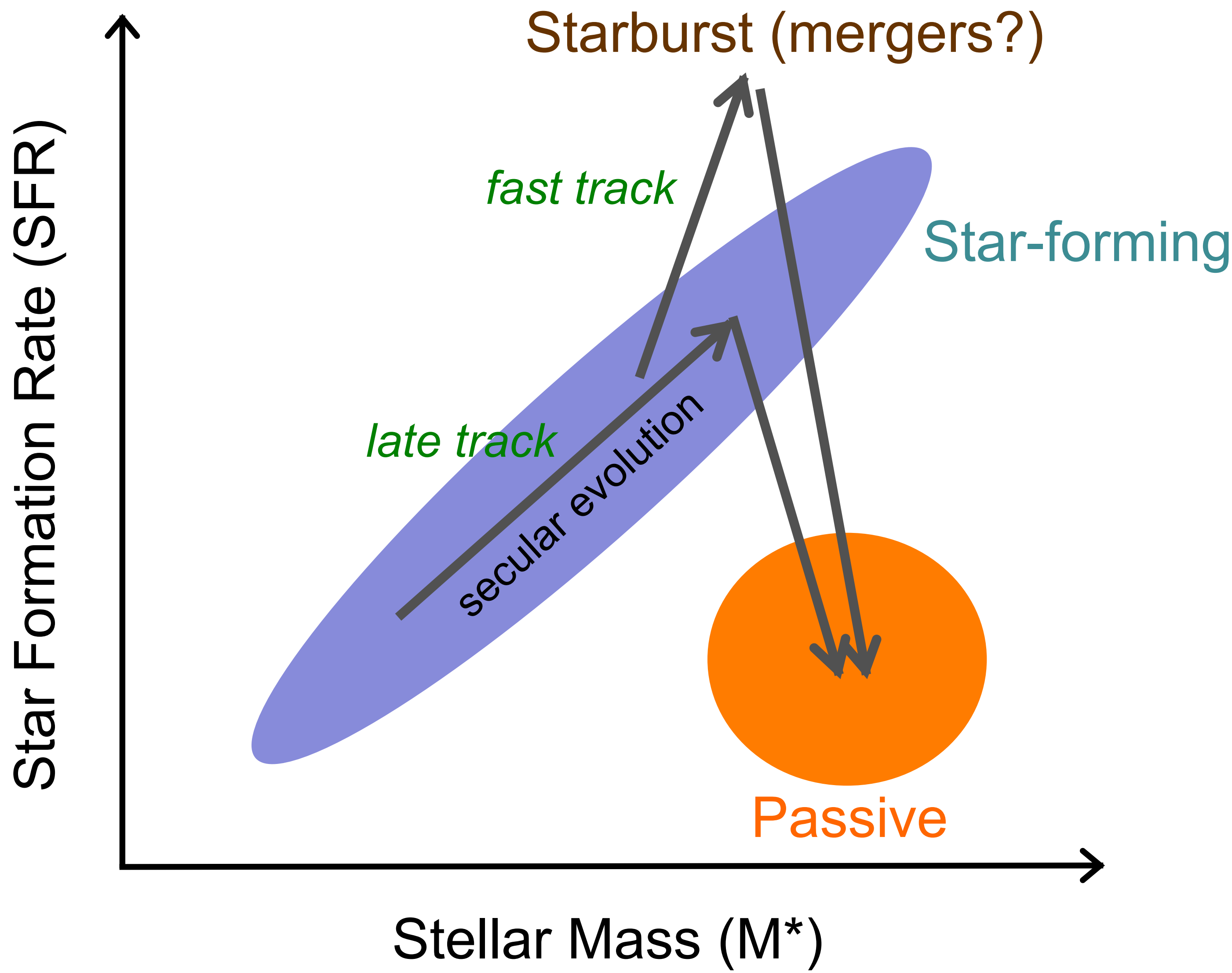
Starburst galaxies (high-sSFR; up-scattered from the MS) are dustier (higher SFR(IR) / SFR(UV) ratios)

Nucleated starburst regions are compact and hence have large dust extinction, probably as a result of gas inflow due to galaxy-galaxy interactions/mergers.

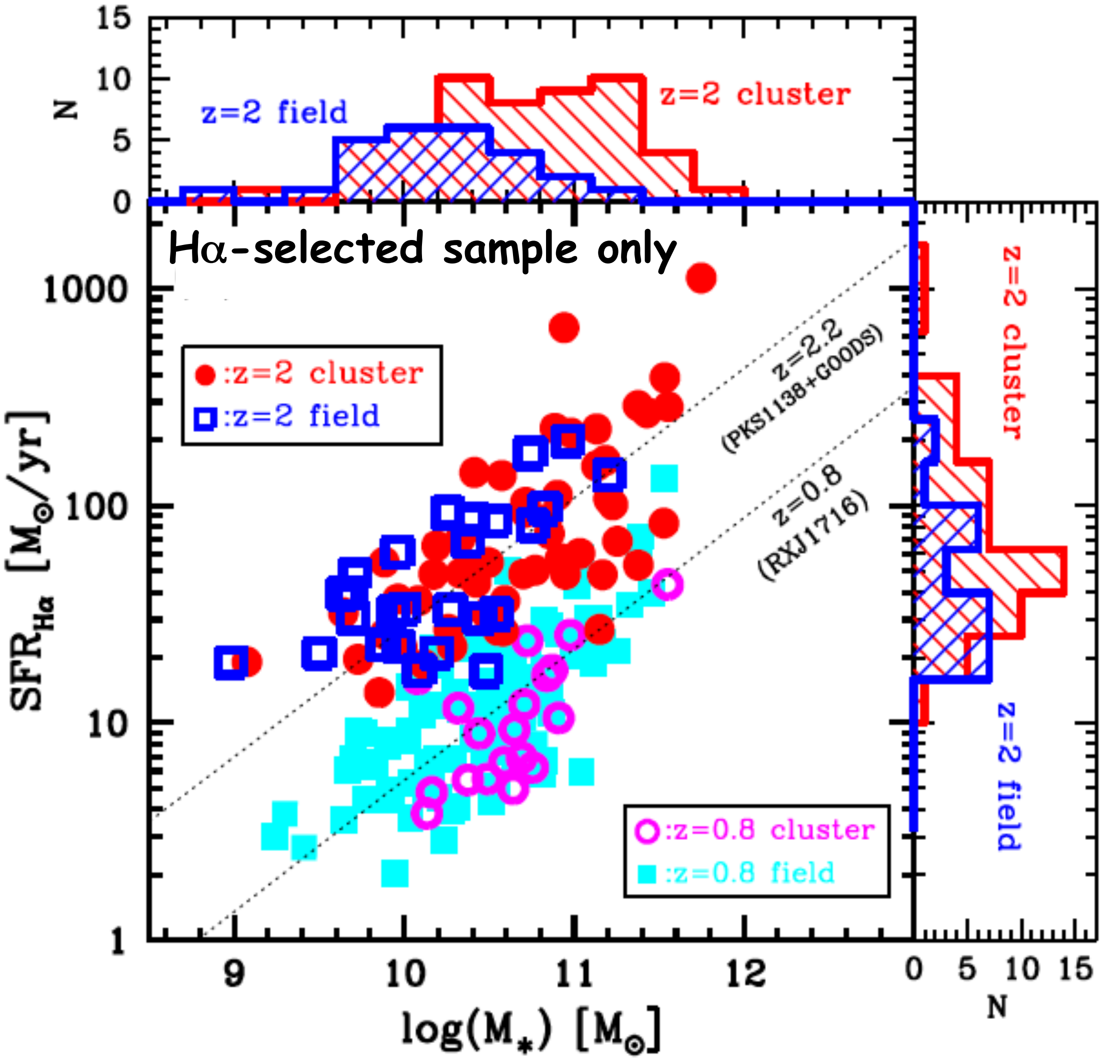


Wuyts et al. (2011)

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



Environmental Dependence of the Main-Sequence?
→ accelerated galaxy formation in proto-cluster (PKS1138) at z~2



M*-dependent dust correction for Ha 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 distribution on the sequence depends on environment in a sense that the proto-cluster tends to contain more massive/high-SFR galaxies than the field.

(Koyama et al. 2013a)

Environmental dependence in the formation phase of early-type galaxies?

- Mode of star formation? (starburst, dusty)

  Location on the SFR-M* diagram

  SFE=SFR / f(gas)

  SFR(IR) / SFR(UV) or SFR(Hα) / SFR(UV)

- Internal structure? (clumpy, central burst)

  HST images of USS1558 proto-cluster (z=2.53)

  Hα imaging w/ AO, IFU spectroscopy, ALMA

Clumpy Structure is Common

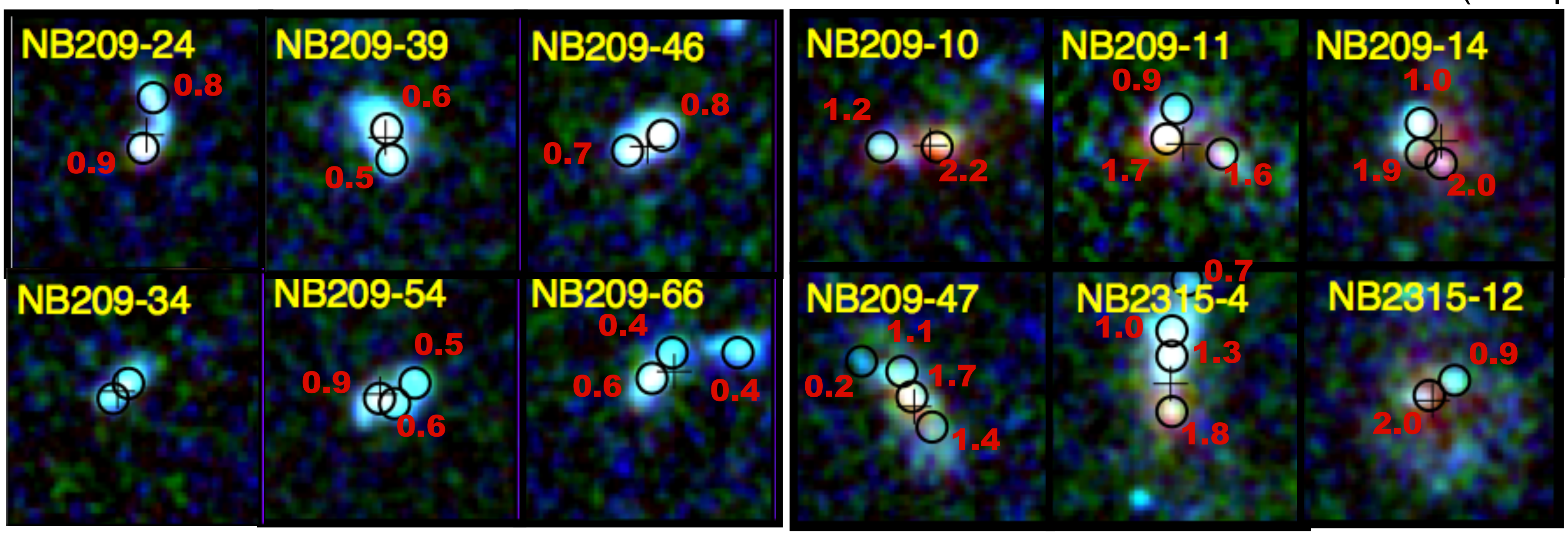
~40% of HAEs at z~2 show clumpy (or merger) structures

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)



3”

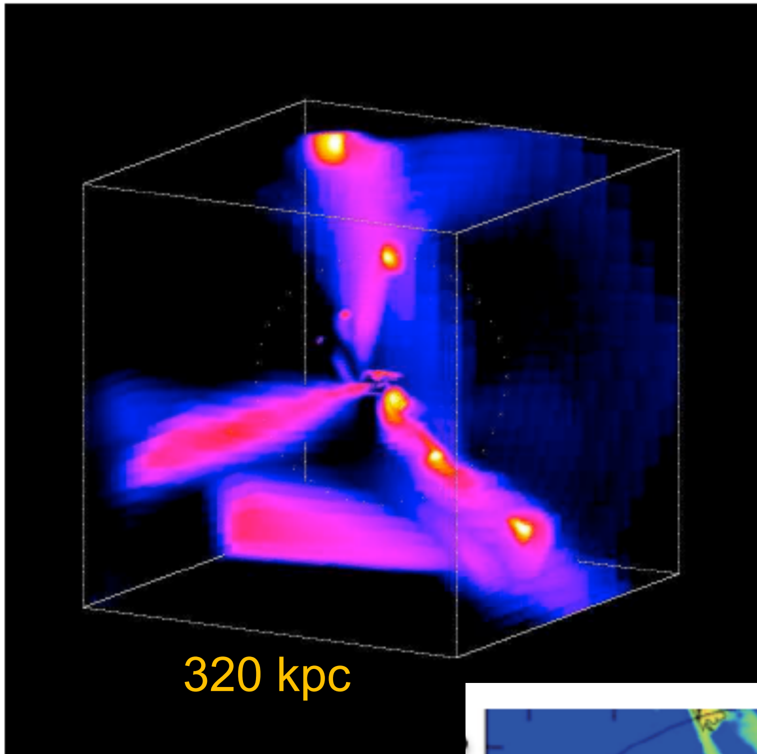
colours (I_{814}-H_{160}) of individual clumps are shown with red numbers

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.

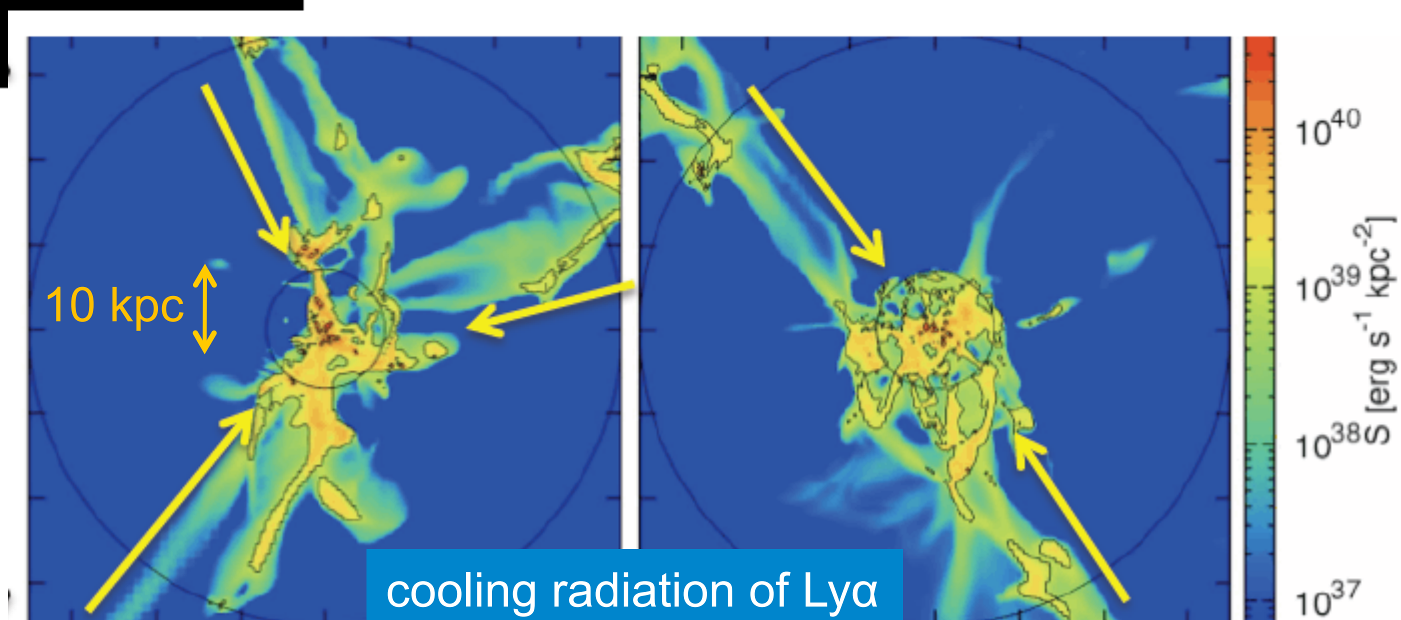
"Cold Streams" along filaments (Inflow)



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

Bournaud et al. (2013)

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

Medium-mass galaxy

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

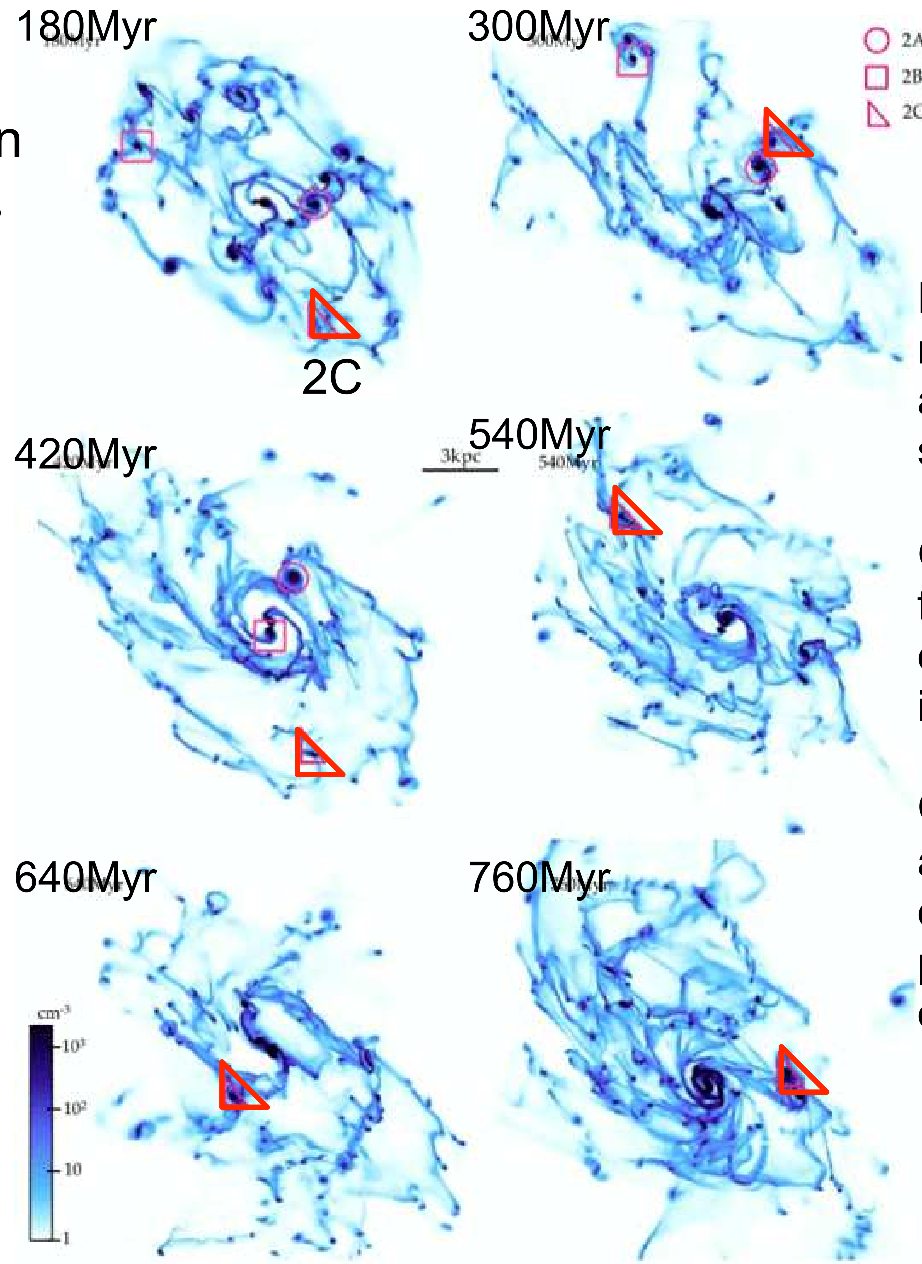


FIG. 2.— Same as Figure 1 for galaxy G2 (medium mass). Detailed sequences and movies of our fiducial models are available in Perret et al. (2013a).

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.

Environmental dependence?

Galaxy Anatomy at z~2 as a function of Environment

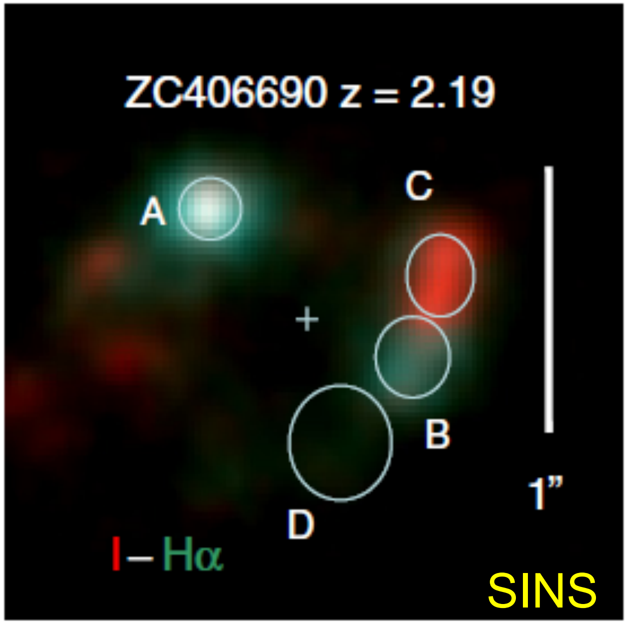
Galaxy mergers?	Tidal signatures? Nucleated dusty SB? AGN? Disordered kinematics? Central outflow?
Clump migration?	SF clumps? Ordinary rotating disk? Outflows from clumps?
Secular evolution?	Exponential disk-wide star formation? Well-ordered rotational disk?

HST imaging
size, morphology, clumpiness

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

ALMA
gas distribution, SF mode, kinematics

All these new exciting data
are up-coming within a year or so!



"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

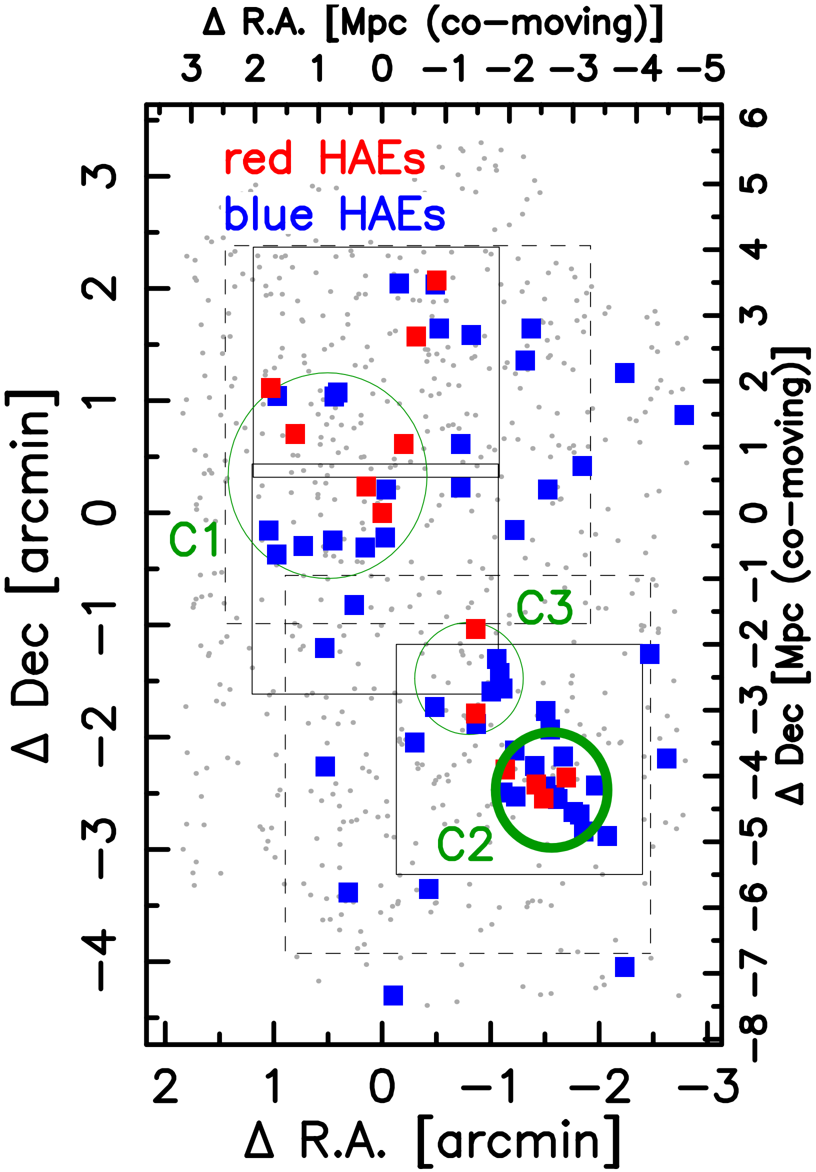
CO line @ Band-3 (~100GHz)	SFR~$50M_{\odot}$/yr (2.7hrs, 5σ)	@1<z<3
Dust continuum@ Band-6-9 (450 μm–1.1 mm)	SFR~$15M_{\odot}$/yr (50min, 5σ)	

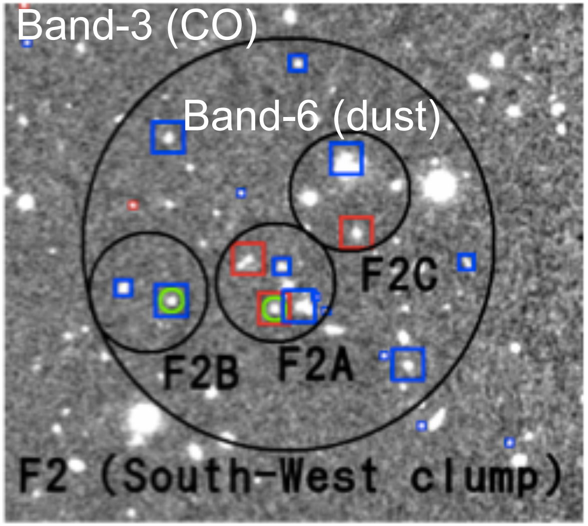
		Mahalo-Subaru				Gracias-ALMA		cycle-1	
target	z	line	μm	NB-filter	Camera	Continuum	Line@GHz(band)	proposals	results
2215–1738	1.46	[OII]	0.916	NB912	S-Cam	B7,9	CO(2-1)@94 (B3)	Hayashi+	**1st**
0332–2742	1.61	[OII]	0.973	NB973	S-Cam	B7,9	CO(2-1)@89 (B3)	not yet	
0218.3–0510	1.62	[OII]	0.977	NB973	S-Cam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

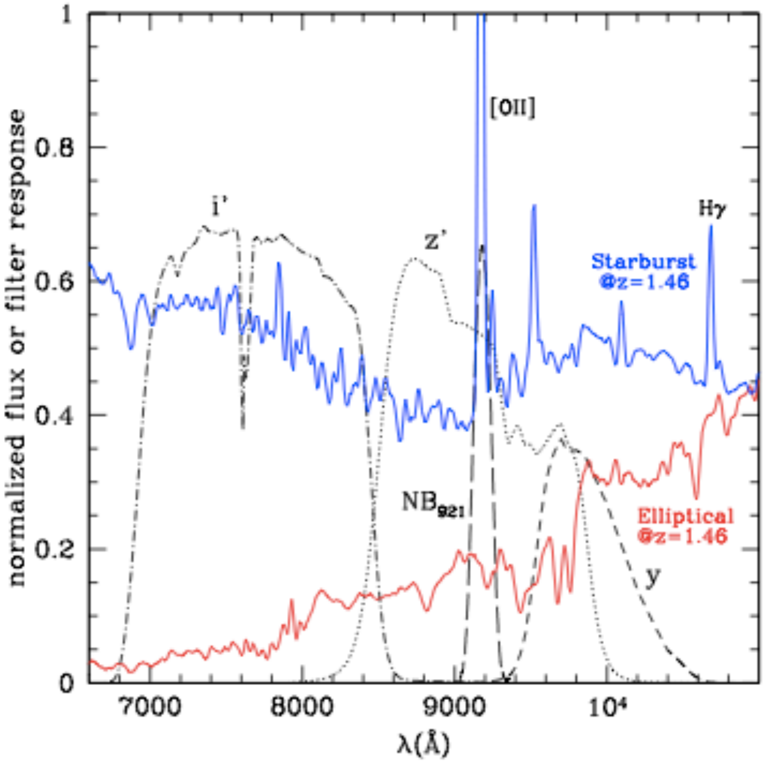
HSC-Deep (27 deg^2) Hybrid Cluster Survey to z~1.7

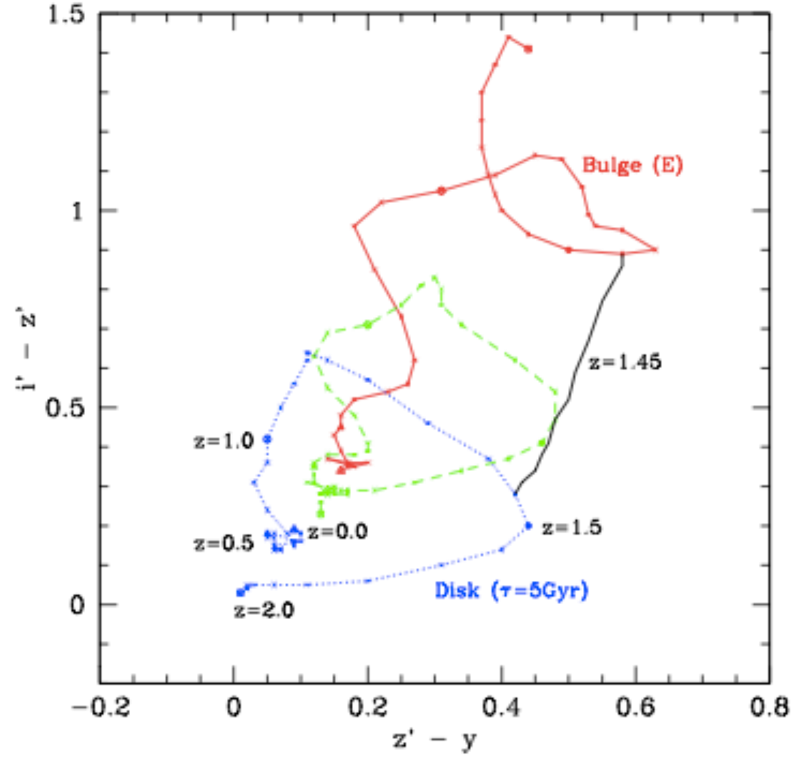
"blue sequence" survey (NB emitters)

~10 NB-selected clusters at z~1.5

(or "phot-z")
"red sequence" survey (passive galaxies)

~200 clusters (>$10^{14}M_\odot$) at z~1 (per Δz=1)

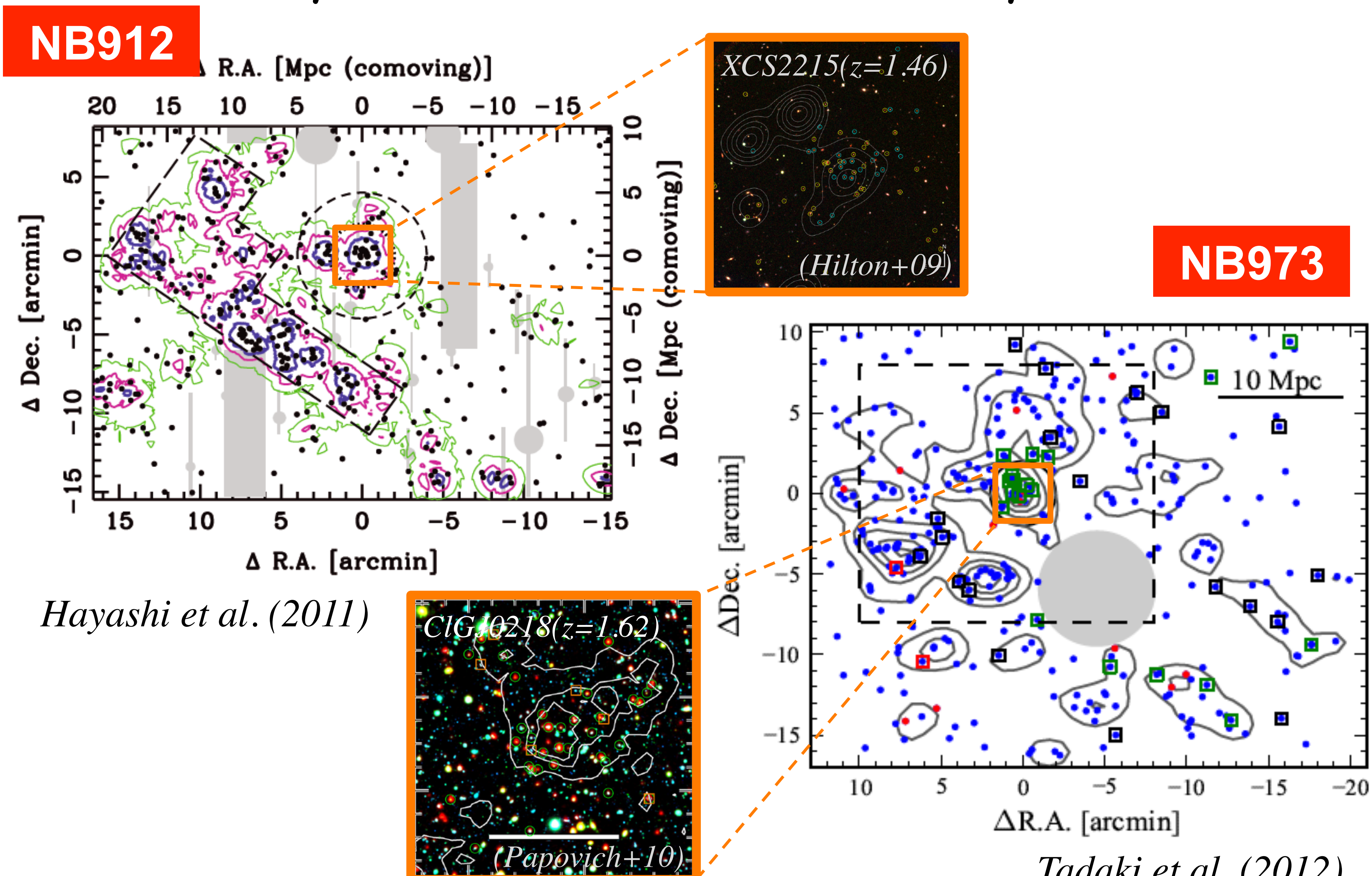




HSC NB filters

Filter	CW [Å]	FWHM [Å]	z(Lyα)	z([OII])	z(Hβ)	z([OIII])	z(Hα)
NB816	8160	120	5.711±0.049	1.189±0.016	0.679±0.012	0.630±0.012	0.243±0.009
NB921	9210	131	6.574±0.054	1.471±0.018	0.895±0.013	0.839±0.013	0.403±0.010
NB973	9730	138	7.002±0.057	1.611±0.019	1.002±0.014	0.943±0.014	0.483±0.011
NB101	10095	143	7.302±0.059	1.709±0.019	1.077±0.015	1.016±0.014	0.538±0.011

Large-scale (~20Mpc) structures at z~1.5 unveiled by [OII]λ3727 emitter survey with S-Cam



Hayashi et al. (2011)

Tadaki et al. (2012)

Expected number of galaxy clusters

survey	area	cluster number / ($\Delta z=1$)
HSC-Deep	27 deg^2	200 ($>10^{14}$ $M_\odot$) at z=1
(AB=27)		6 ($>10^{14.5}M_\odot$) at z=1
HSC-Wide	1400 deg^2	10,000 ($>10^{14}$ $M_\odot$) at z=1
(AB=26)		300 ($>10^{14.5}M_\odot$) at z=1
Euclid-Deep	20 deg^2	6 ($>10^{14}$ $M_\odot$) at z=2
(AB=26)		0.015 ($>10^{14.5}M_\odot$) at z=2
Euclid-Wide	6000 deg^2	1,800 ($>10^{14}$ $M_\odot$) at z=2
(AB=24)		4 ($>10^{14.5}M_\odot$) at z=2

Ref: HSC-SSP proposal

WISH Space Telescope

WISH
upon a first galaxy....

WISH is a 1.5m diameter space telescope
for 1-5μm (NIR) with a FoV of 0.24 sq. deg.

Proposing NB filters for WISH

6hrs exp. (5σ), 1mag extinction of Hα

NB Filter	**Wavelength (μm)**	**Redshift (Hα, OIII)**	**SFR (Msun/yr)**	**Number / FoV**
NB217 (same as SWIMS-18)	2.17	2.3, 3.3	7	~1500
NB284	2.84	3.3, 4.7	20	~200
NB335	3.35	4.1, 5.7	30	~150
NB441	4.41	5.7, 7.8	90	~20
NB497	4.97	6.6, 8.9	250	??

NB filters at 2.5 ~ 5 μm will be the key for WISH !

WISH-7 Survey

for $1.5<z<8$

- 「**7**」sq. deg.

  ~7×10^{7} Mpc^{3} / (Δz=1)

  ~10 progenitors of Coma class clusters at every z

  NB: 3.5-7×10^{6} Mpc^{3} / (Δz=0.05-0.1)

  ~ 1 progenitor of Coma class cluster per filter

  30 WISH pointings (0.24 sq. deg. / FoV)

- Exposure times needed

  BB: 1 hrs × 6 filters x 30 p = 180 hrs

  NB: 6 hrs × 4 filters x 30 p = 720 hrs

  900 hrs in total (or 1200 hrs including overheads)

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 $z\sim2$
- More massive SFGs in proto-clusters, indicating the biased, accelerated galaxy formation in clusters.
- 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.
- HSC will make a large, complete sample of 10K clusters to $z\sim1.7$. WISH will extend it to $z\sim6-8$.