ESA-ESO workshop: Euclid Galaxy Evolution (25-28/Oct/2022; Madrid)

Rise and Fall of Star Formation in Clusters/Proto-clusters

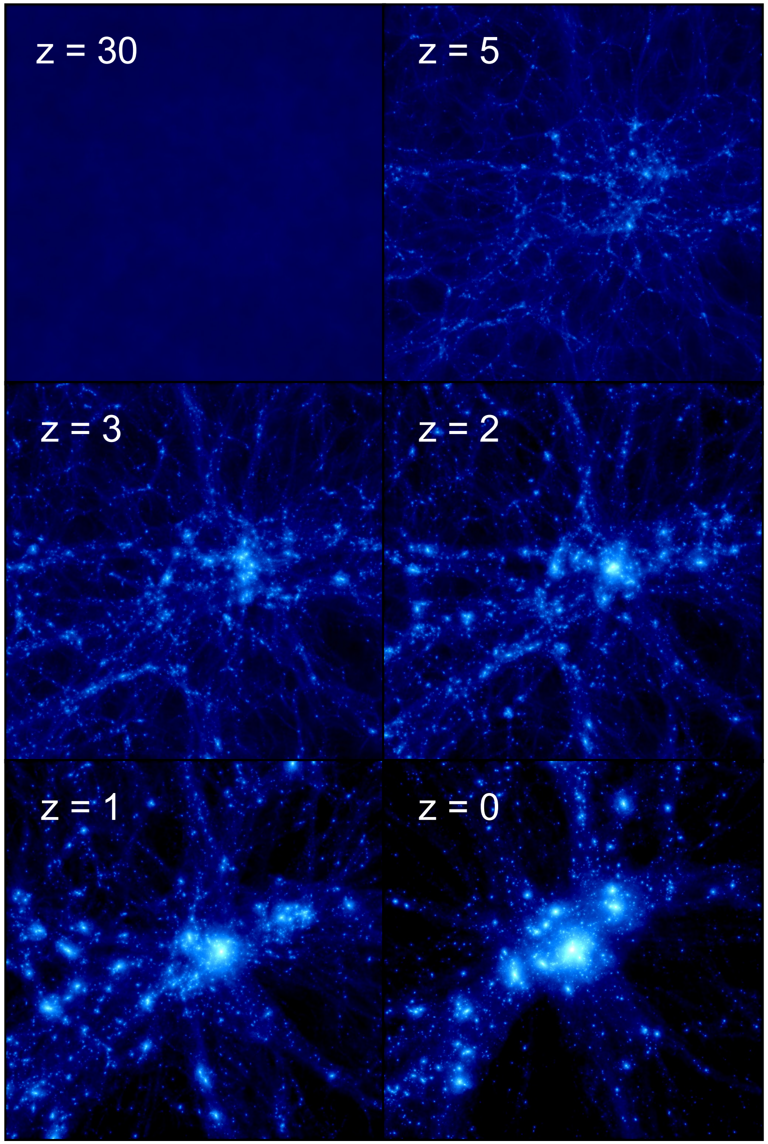
Taddy Kodama (Tohoku Univ., Sendai)

JWST image
SMACS J0723.3-7327 (z=0.39)
4.6 Gyrs ago

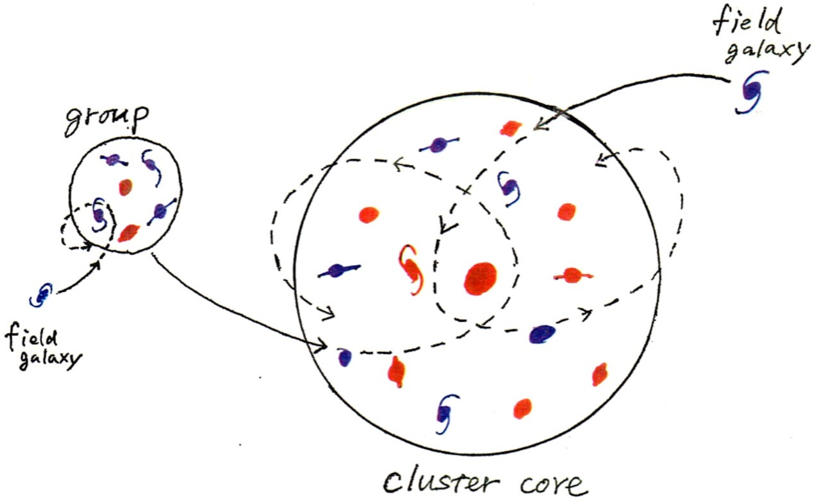
Credits: NASA, ESA, CSA, STScI

Environment matters in acceleration of galaxy formation and its quenching!

N-body cosmological simulation (Yahagi+05)



M=6 × 10^{14} $M_\odot$ 20 × $20 Mpc^2$ (co-moving)



Nature? (internal)

earlier (biased) galaxy formation and evolution in high density regions

Nurture? (external)

galaxy-galaxy interaction/mergers, gas-stripping

Key questions on galaxy clusters

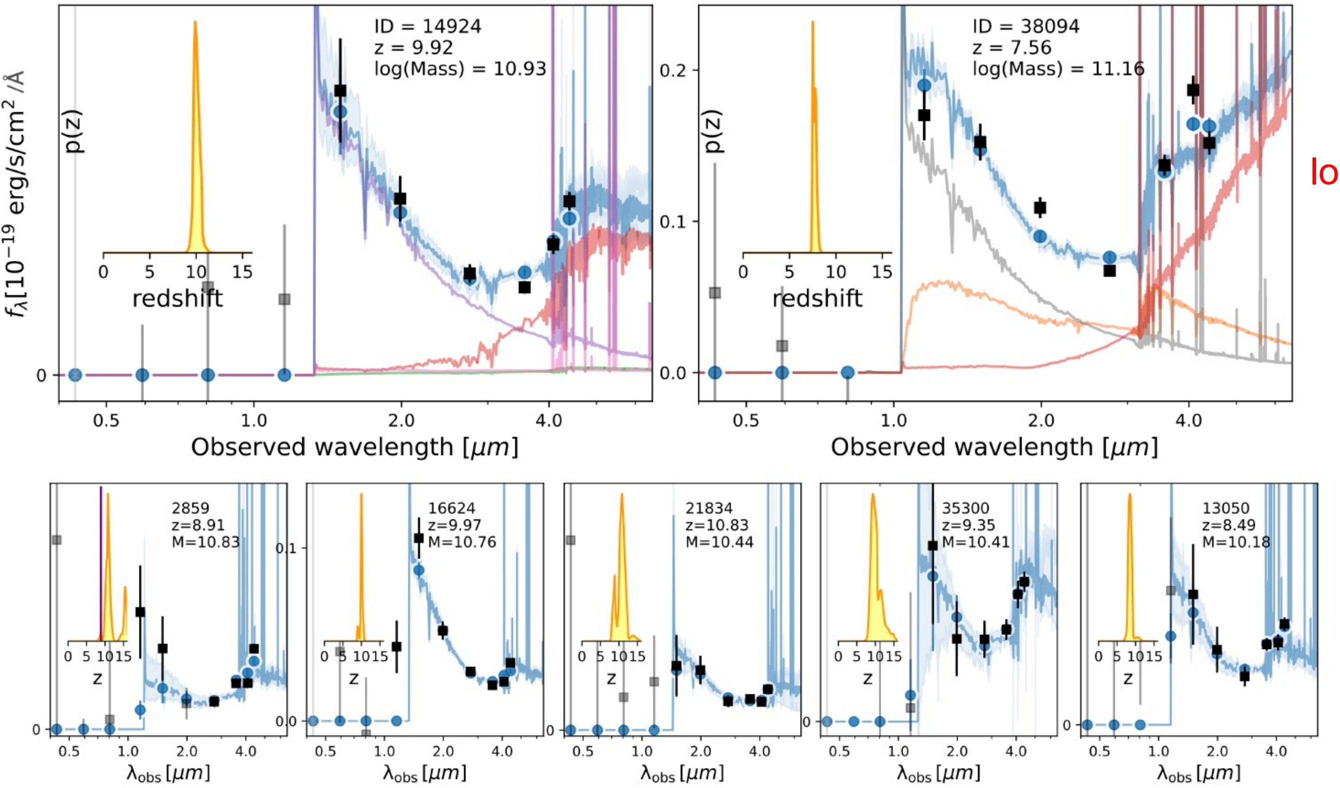
1. How much are (proto-)clusters ***biased (earlier/faster) in*** (massive) ***galaxy assembly and quenching?***
2. Are the ***SF/AGN activities ever boosted in situ in cluster cores, or pre-processed in the outskirts and then accreted?*** How do the ***SF/AGN activities and quenching propagate*** within cluster galaxies?
3. How much of SF in clusters is ***hidden by dust?***
   Is there an ***environmental effect in dust extinction?***
4. When and how does the ***gas accretion*** to clusters become ***efficient*** and then ***inefficient?***
5. Where and how do the ***gas outflow or stripping*** affect the galaxies in clusters?

1. How much are proto-clusters biased (earlier/faster) in (massive) galaxy assembly and quenching?

JWST seems to be finding (too?) many candidates for massive monsters at 7<z<11 !

7 with $\log (M/M_\odot) > 10$, including 2 with $\log (M/M_\odot) \sim 11$

$\log(M/M_\odot) = 10.93$ at z=9.92



$\log(M/M_\odot) = 11.16$ at z=7.56

Figure 3: Spectral energy distributions (SEDs) and photometric redshift probability distributions $P(z)$ of the 7 galaxies with $\log(M_*/M_\odot) > 10.0$. The flux density units are in $F\lambda$ versus wavelength in μm. All galaxies show a characteristic V-shaped SEDs, with a clear upturn at $3-4\,\mu$m and a double break. The redshifts are well-constrained owing to the presence of two breaks. The two most massive galaxies are highlighted on the top row. Shown are the contribution of each template in the fit, where the fit produces a prominent contribution of an older stellar population (left) or dusty stellar population (right) shown in red. Emission lines contribute clearly to the F356W and F444W bands, with the narrower F410M band providing a powerful diagnostic, improving both the redshift and the SED fit.

Labbe et al. 2022, arXiv:2207.12446

Flux calibration issue?

What causes the quenching of star formation in high-z massive monsters (z~4)?

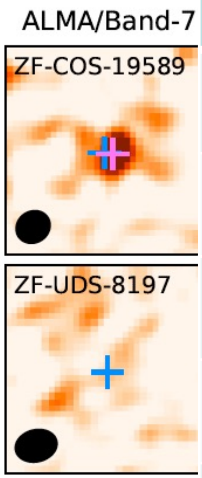
Whether f_{gas} is low, or t_{dep} is long (*SFE* is low) ?

→ ALMA observations of $[\mathrm{C\ I}](^3\mathrm{P}_1 - ^3\mathrm{P}_0)$ line and dust@870μm

4(+1) massive (log M/M$_\odot$~11) galaxies at z=3.5~4 (ZFOURGE)

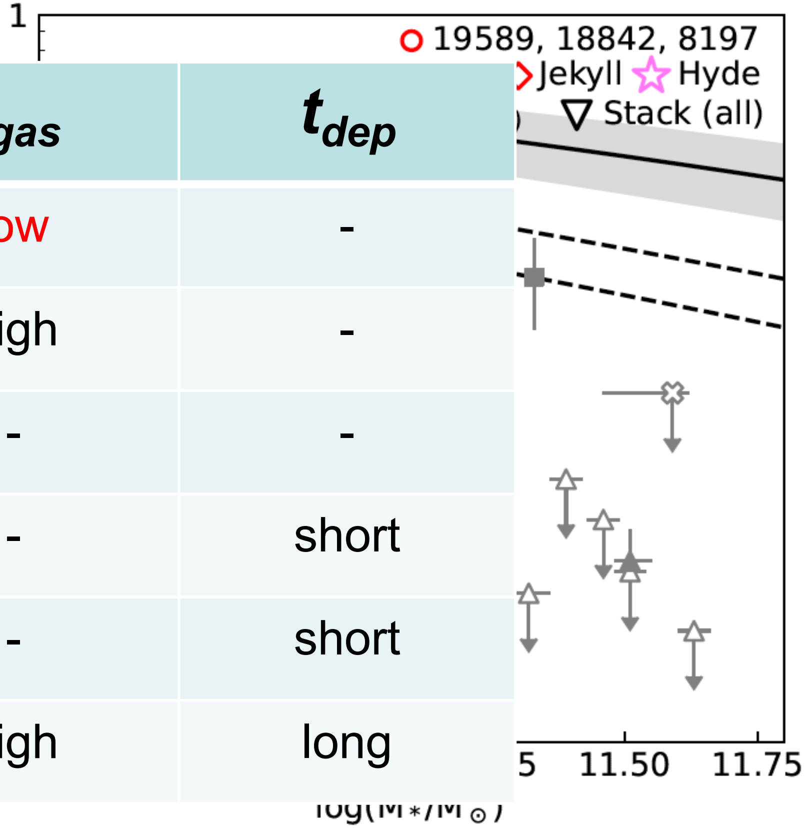
Already gas poor ! f_{gas} < 0.1-0.2

Glazebroo



Non

(Ba



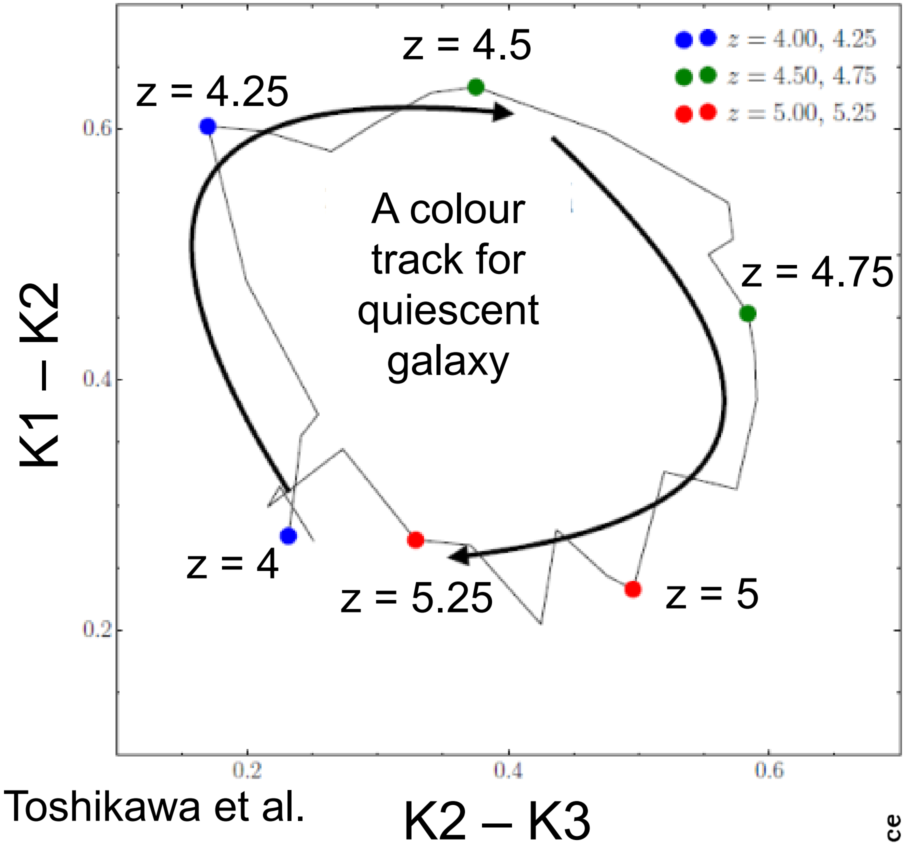
mechanisms	f_{gas}	t_{dep}
AGN feedback	low	-
Virial shock heating	high	-
Halo gas stripping	-	-
Gas-rich major mergers	-	short
Violent disk instabilities	-	short
Morphological (bulge) q.	high	long

Suzuki et al. (2022)

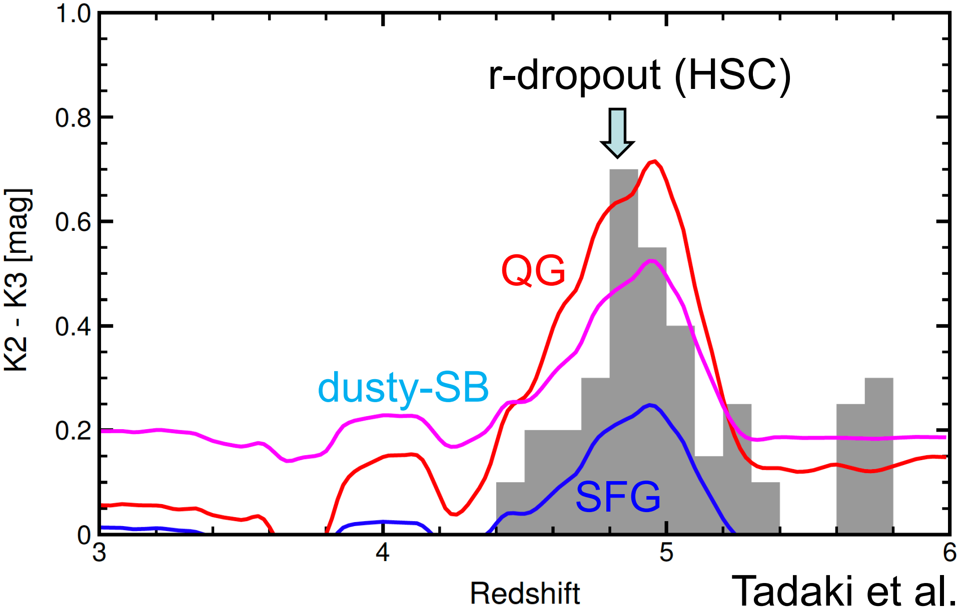
> 3-6 times lower than the MS !

Extending the survey of massive monsters back to z~5−5.4

Medium-band filters (K1~K4) can capture Balmer break at 4 < z < 5.4



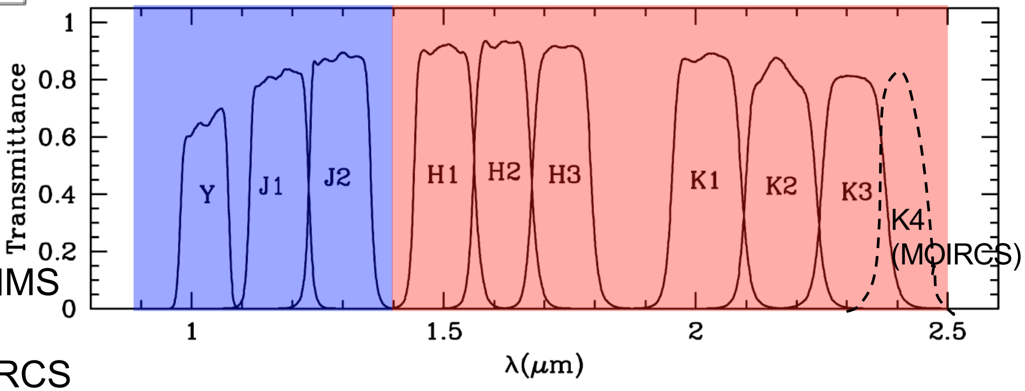
Toshikawa et al.



Tadaki et al.

K2−K3 becomes very red for quiescent or dusty SB galaxies at 4.6<z<5.1

MB filter	λ_c (μm)	FWHM (μm)	z(Bal.break) 3645Å	
K_1	2.03	0.14	4.38	
K_2	2.17	0.14	4.76	on SWIMS
K_3	2.31	0.14	5.14	
K_4	2.41	0.12	5.45	on MOIRCS

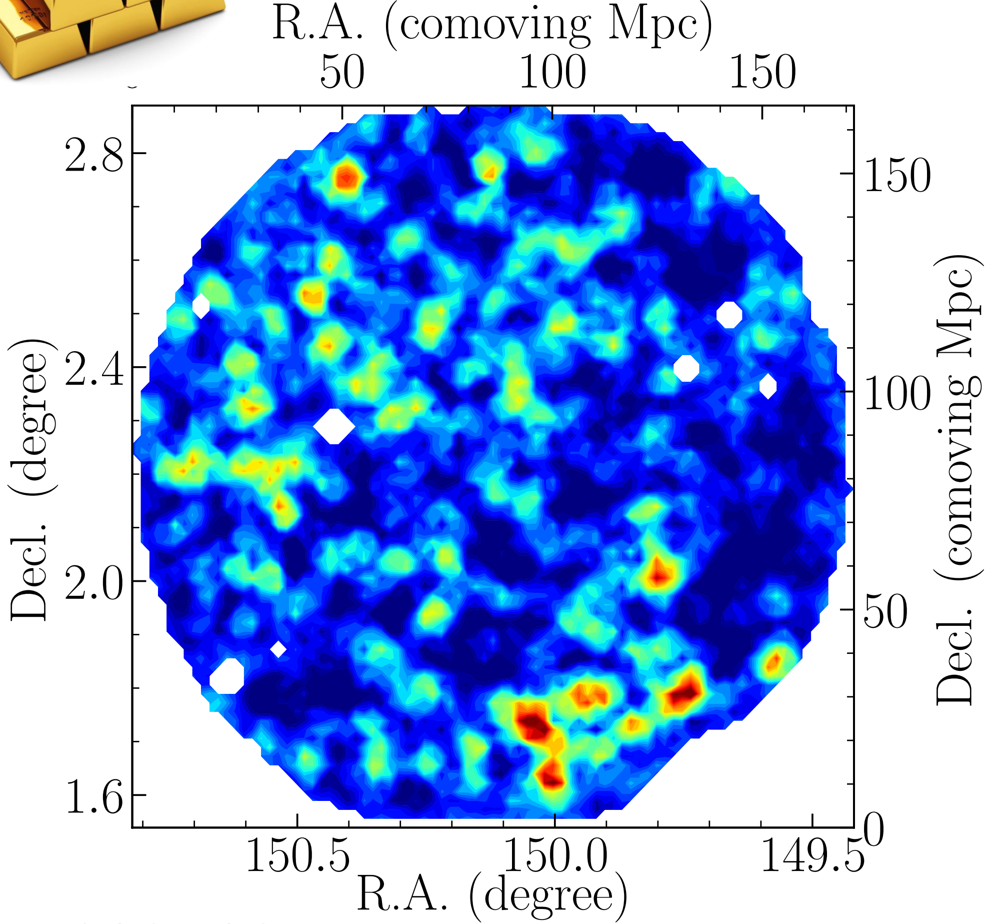


We search for massive monsters back to z~5.4 with K-MBF with SWIMS/MOIRCS and ULTIMATE.

Hunting massive (quiescent) galaxies at z~5 in proto-clusters

GOLD-RUSH

LBG (r-drop) selected protoclusters at z~5
with HSC on Subaru



UD-COSMOS, etc
Toshikawa et al.

RUBY-RUSH

Red Ultra-massive
Billion-YeaR-Universe SHiners

Search for massive galaxies in
GOLD-RUSH mines at z~5
with SWIMS/MOIRCS on Subaru

Comparison with a general field survey can quantify the galaxy formation bias.

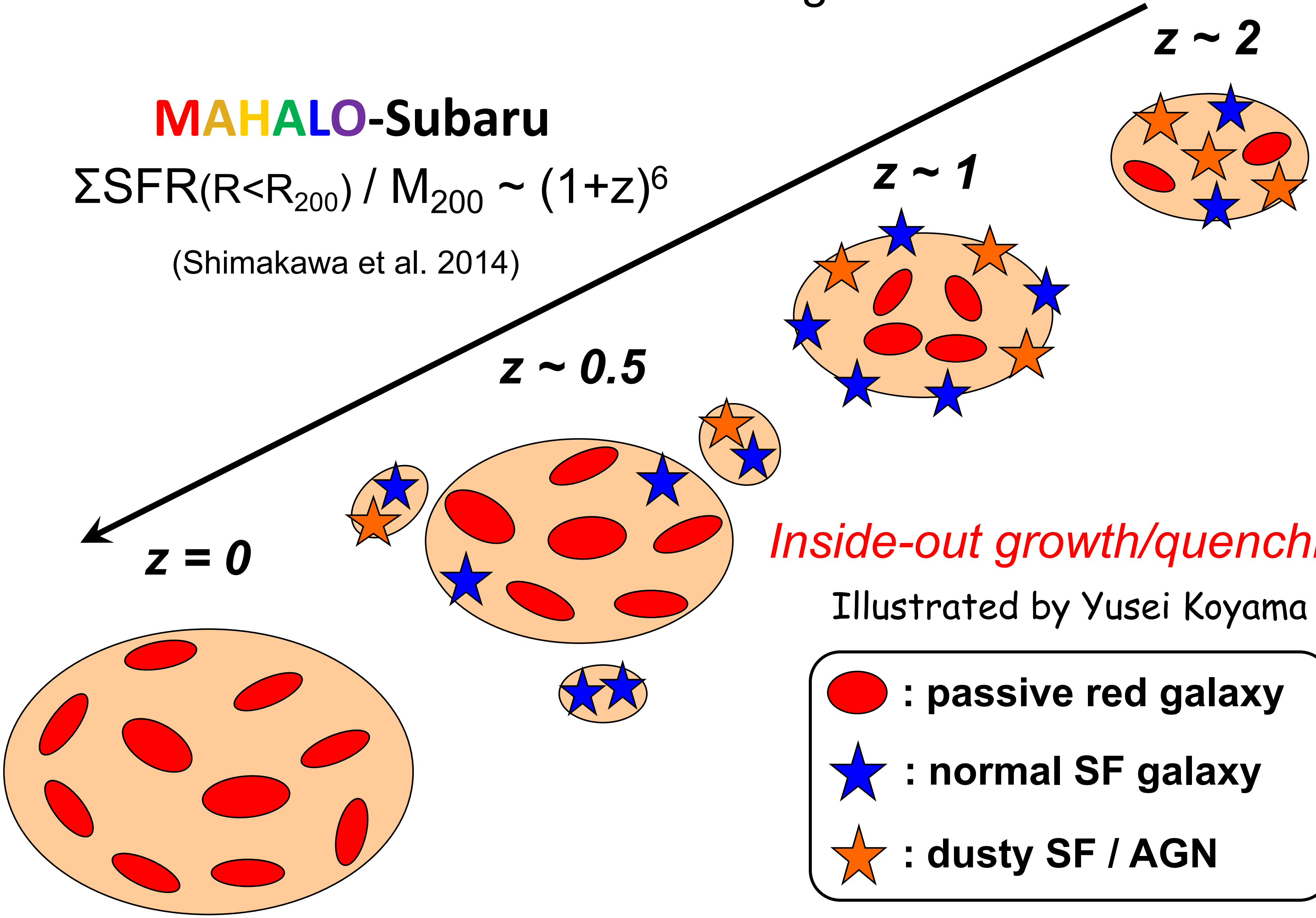
Subaru/SWIMS data were obtained (partly)
in S21A-S22A .

2. How do the *star formation* and its *quenching propagate* in and around clusters and within galaxies?

MAHALO-Subaru

$\Sigma\mathrm{SFR}(\mathrm{R}<\mathrm{R}_{200}) / \mathrm{M}_{200} \sim (1+z)^6$

(Shimakawa et al. 2014)



Inside-out growth/quenching?

Illustrated by Yusei Koyama

● **: passive red galaxy**

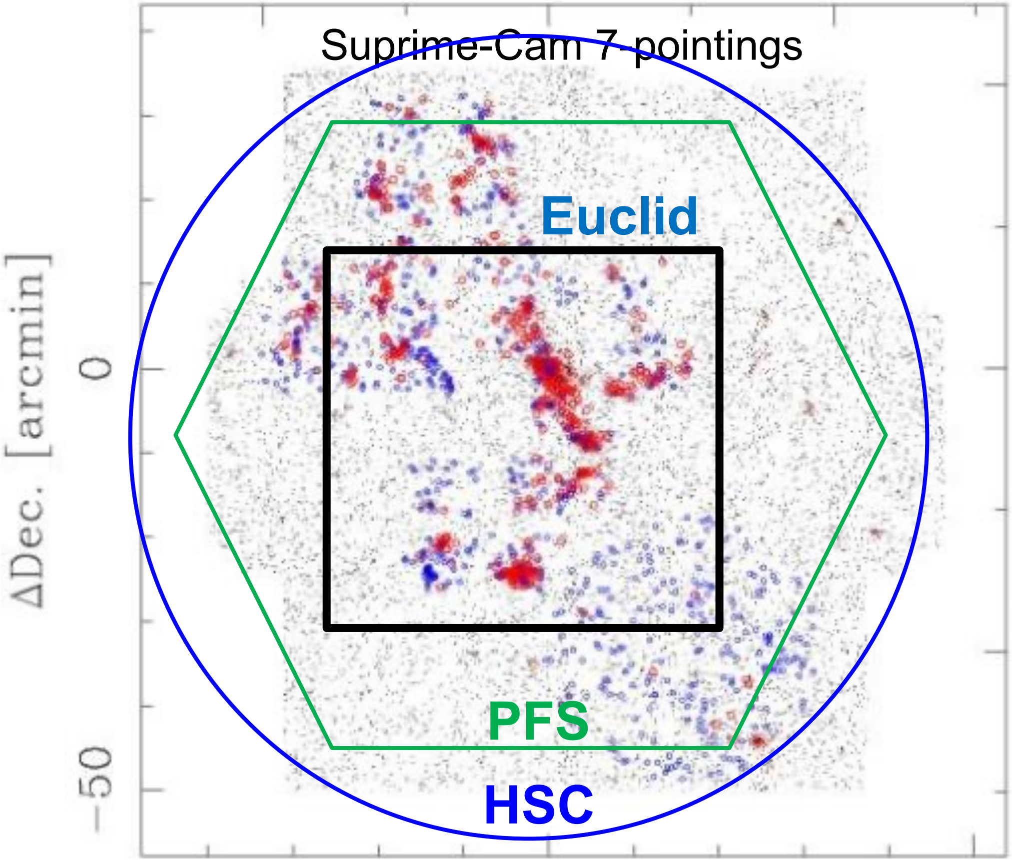
★ **: normal SF galaxy**

★ **: dusty SF / AGN**

HSC+PFS and Euclid are extremely powerful to probe LSSs

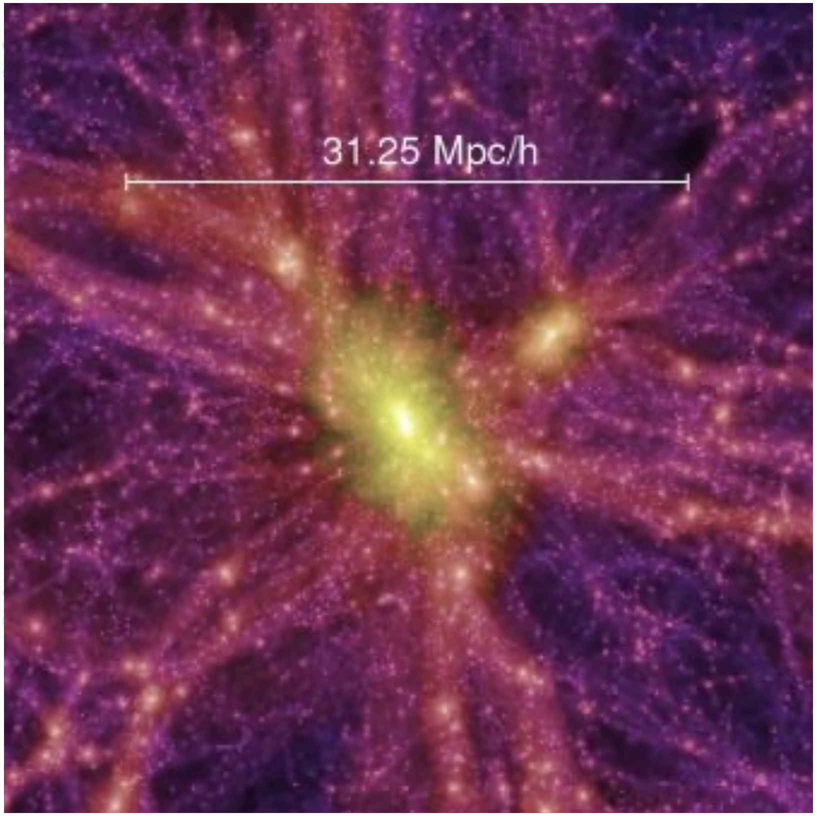
1.3° = 75 Mpc (z=1), 100 Mpc (z=1.5), 118 Mpc (z=2) in co-moving

CL0016 cluster (z=0.55)
(Tanaka, M. et al. 2009)



LSS around the richest cluster at z=0.55
~1,200 redshifts from spectroscopy
red are cluster members, while blue are non-members

Millenium Simulation
(Springel et al. 2005)



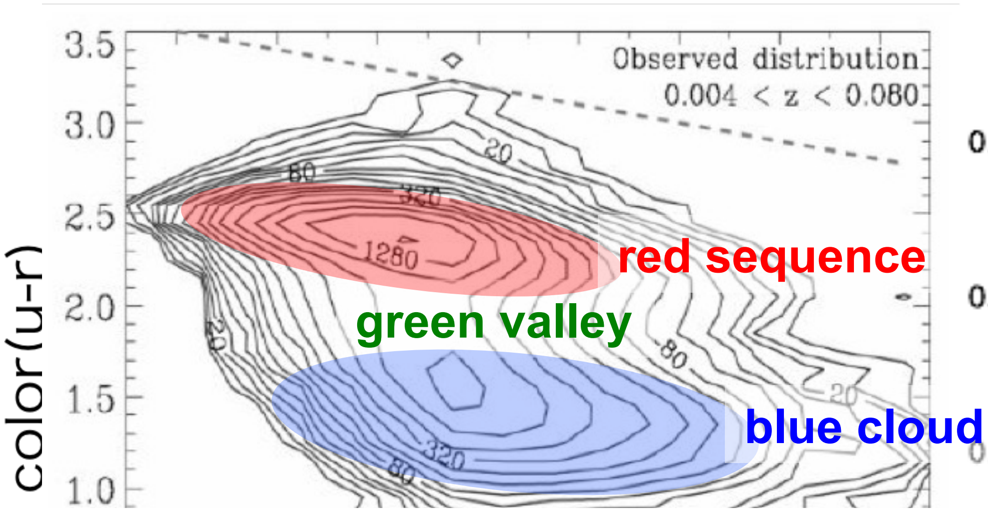
HSC^2

Hybrid Search for Clusters with HSC

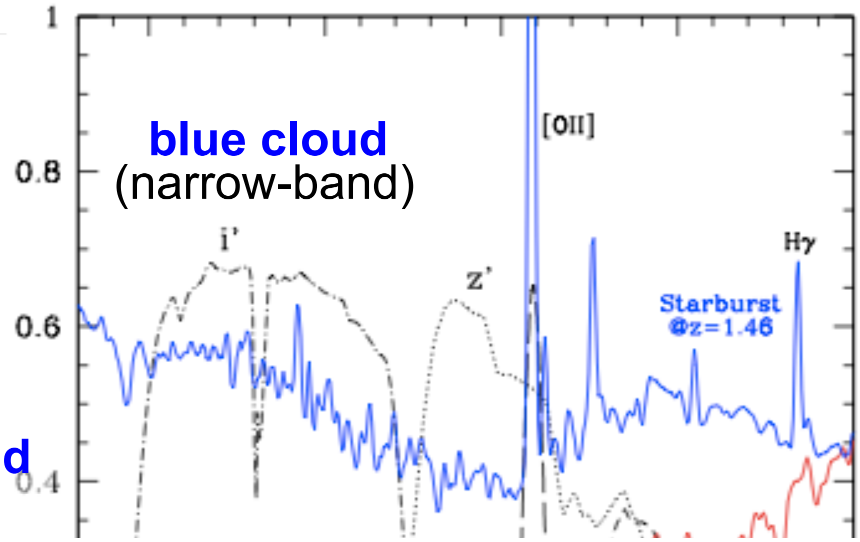
0.4<z<1.7

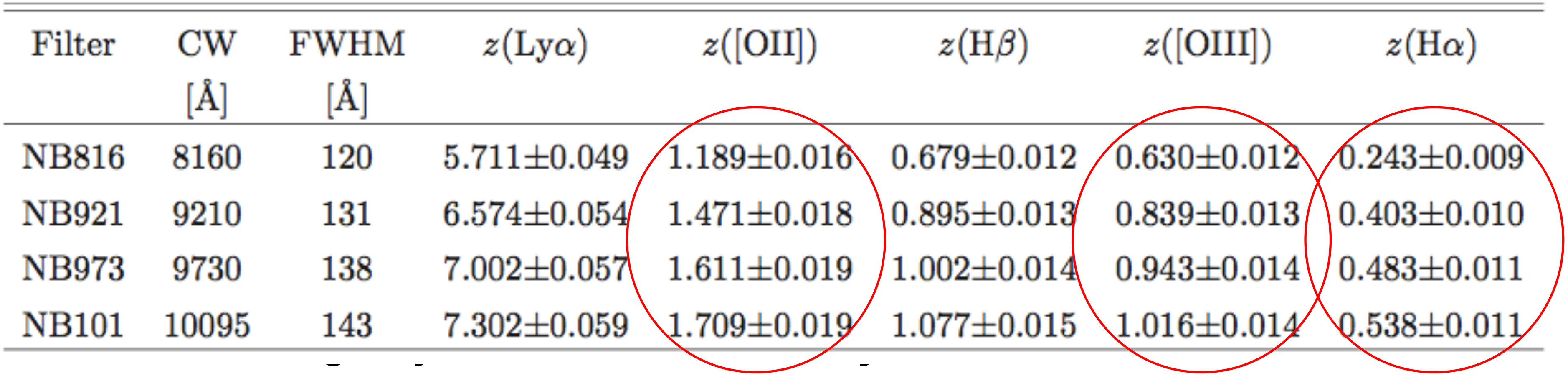
HSC-SSP (Deep and Ultra-Deep layers; 27 deg^2)

Two galaxy populations



Hybrid cluster finder

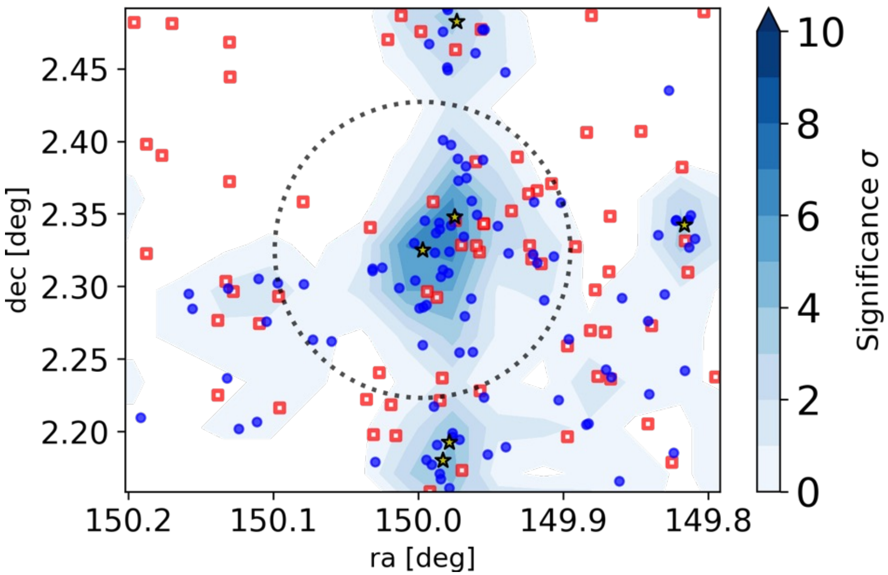




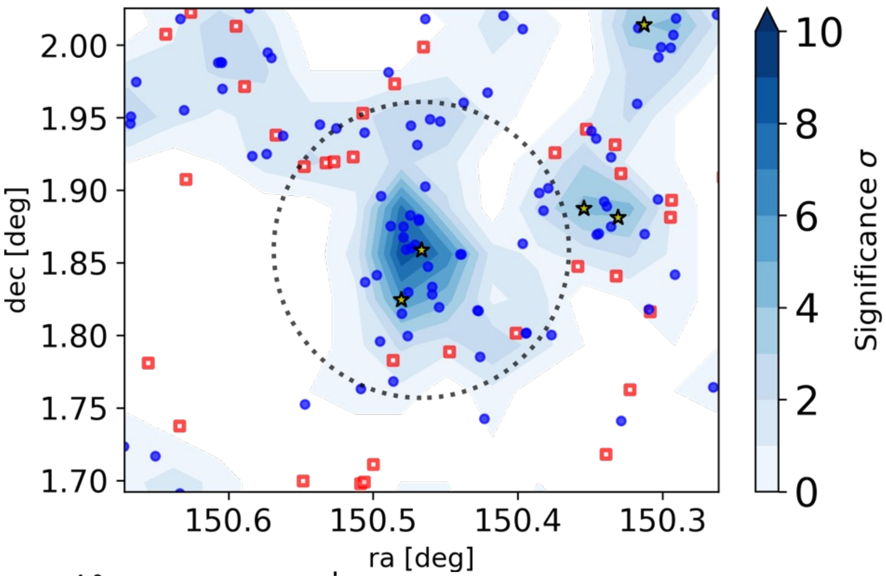
Filter	CW [Å]	FWHM [Å]	$z(\mathrm{Ly}\alpha)$	$z([\mathrm{OII}])$	$z(\mathrm{H}\beta)$	$z([\mathrm{OIII}])$	$z(\mathrm{H}\alpha)$
NB816	8160	120	5.711±0.049	1.189±0.016	0.679±0.012	0.630±0.012	0.243±0.009
NB921	9210	131	6.574±0.054	1.471±0.018	0.895±0.013	0.839±0.013	0.403±0.010
NB973	9730	138	7.002±0.057	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

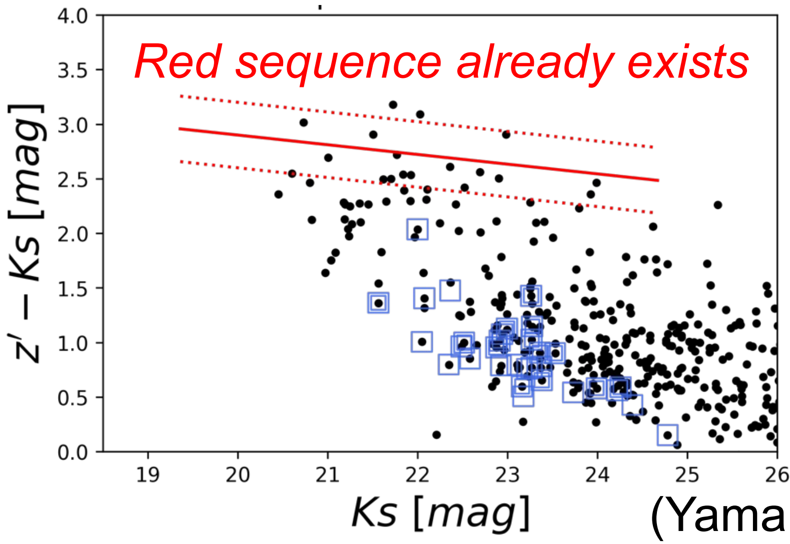
Hybrid Search for Clusters with HSC (HSC^2)

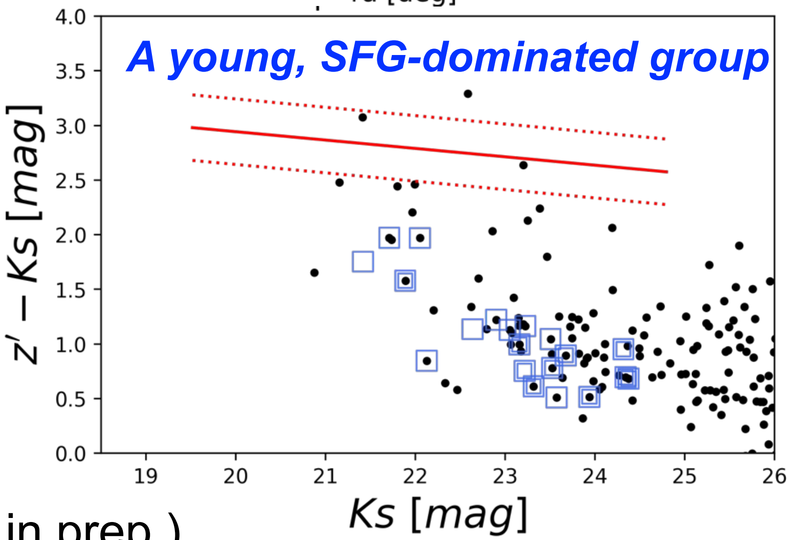
Dual (red + blue) cluster
CL1 @ z=1.47



Blue dominated cluster/group
CL2 @ z=1.61





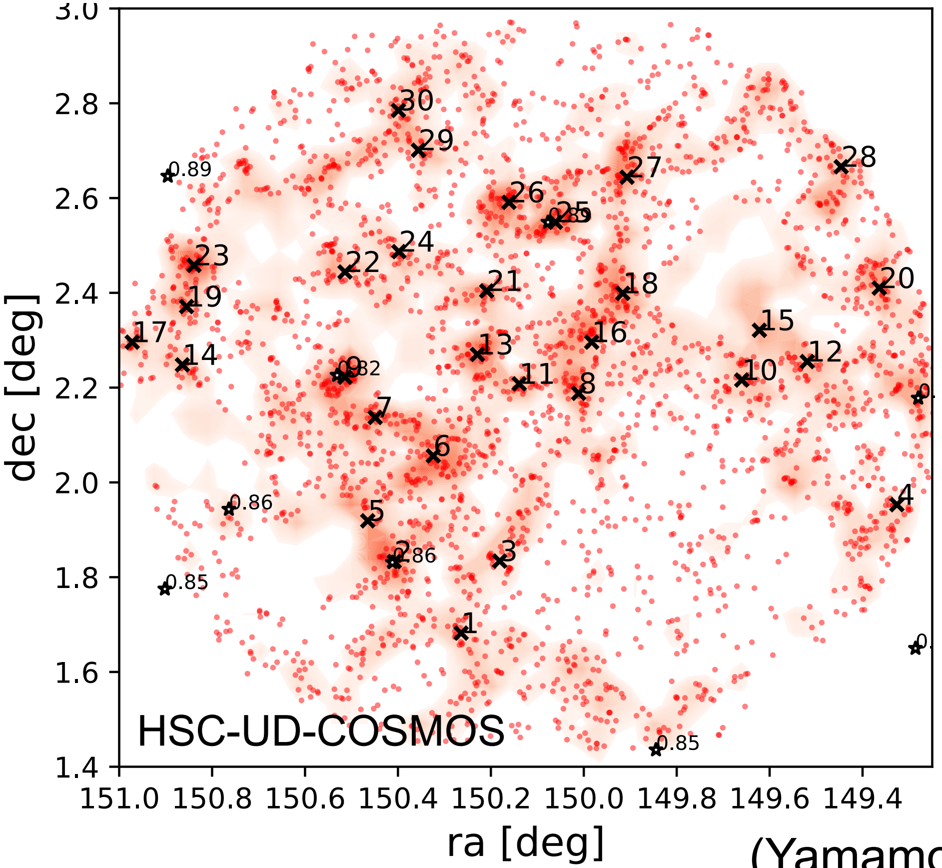


(Yamamoto+ in prep.)

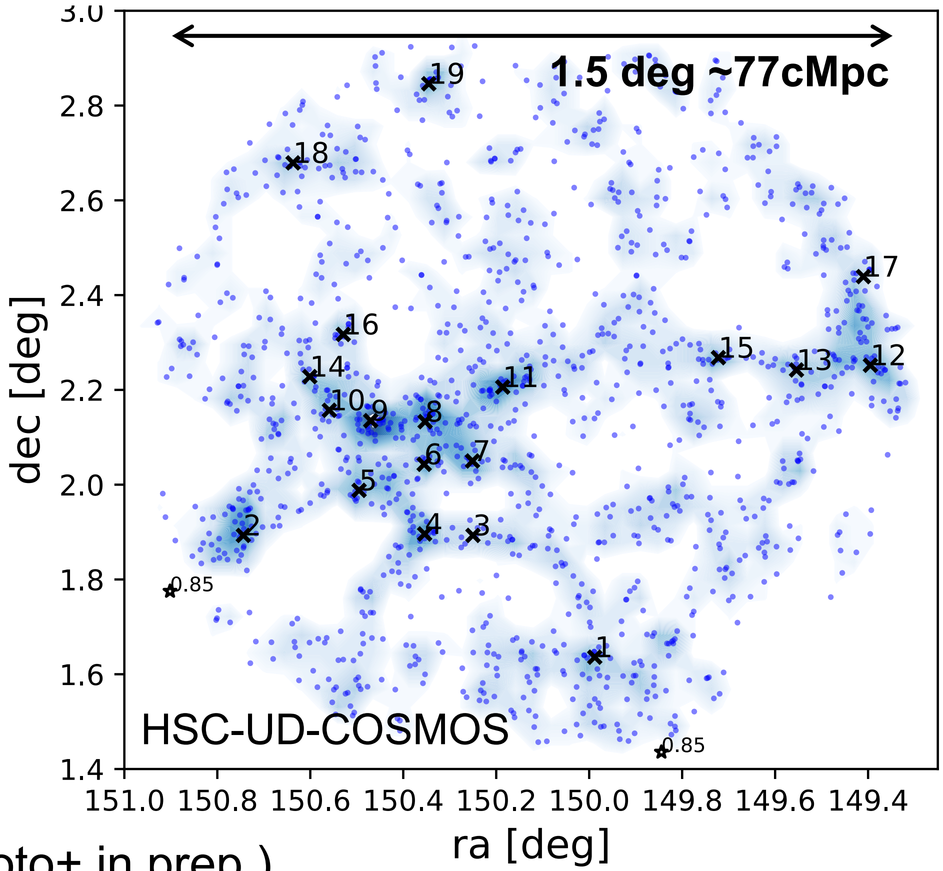
Panoramic Follow-up Spectroscopy with PFS (**PFS^2**)

Spectroscopic follow-up of **HSC^2** selected clusters and LSSs with **PFS**

Red sequence galaxies at $0.8<z<0.9$



[OIII] line emitters at $0.82<z<0.86$



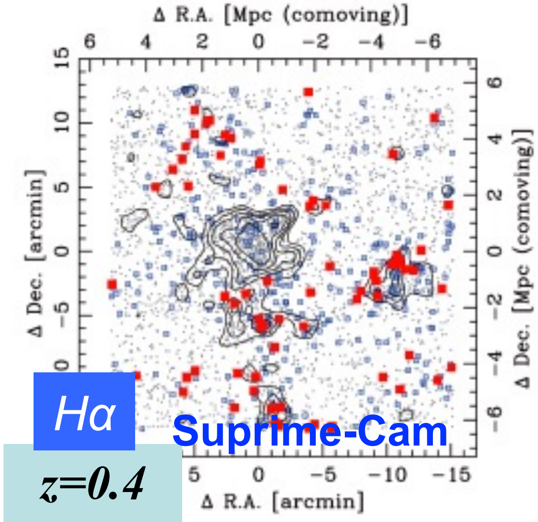
(Yamamoto+ in prep.)

We have ~100s of cluster candidates, and systematic and intensive spectroscopic confirmation with PFS is critical (cluster mass functions can also be compared with cosmological models).

PFS: 0.35-1.26μm, 2,400 fibers over a 1.3 deg^2 FoV, but the min fiber separation is 30”

Panoramic narrow-band imaging by MAHALO-Subaru

MApping HAlpha and Lines of Oxygen with Subaru

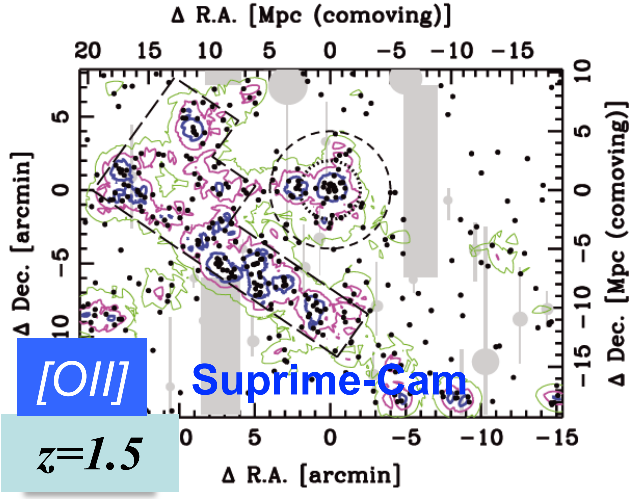


Hα Suprime-Cam

z=0.4

CL0939 *(Koyama+11)*

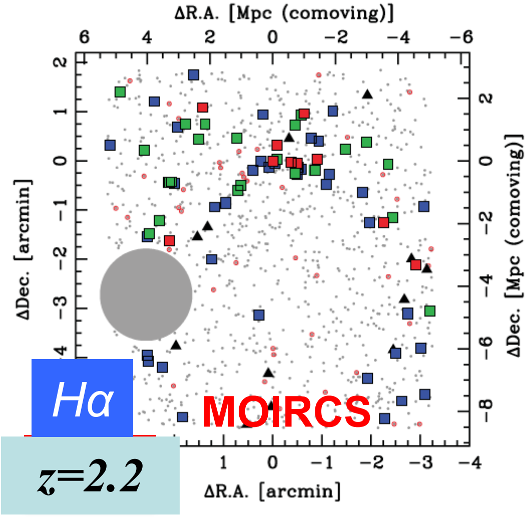
(Hayashi+10, 11)



[OII] Suprime-Cam

z=1.5

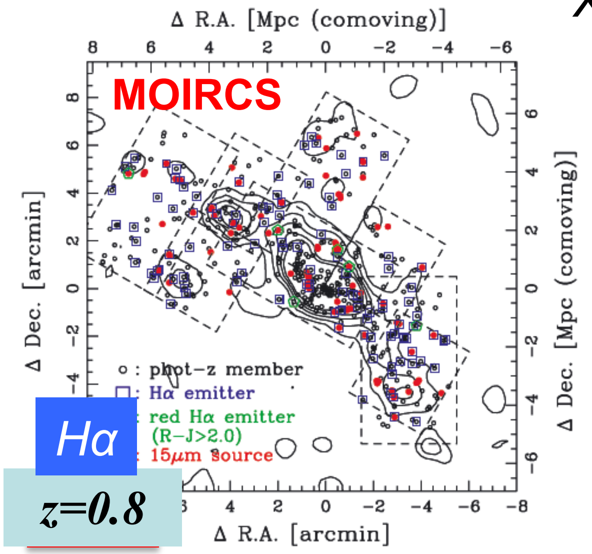
XCSJ2215



Hα MOIRCS

z=2.2

PKS1138 *(Koyama+13)*



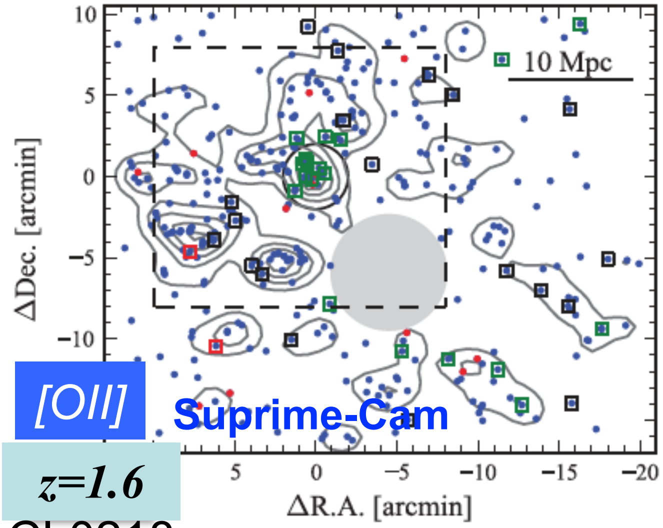
MOIRCS

Hα

z=0.8

RXJ1716 *(Koyama+10)*

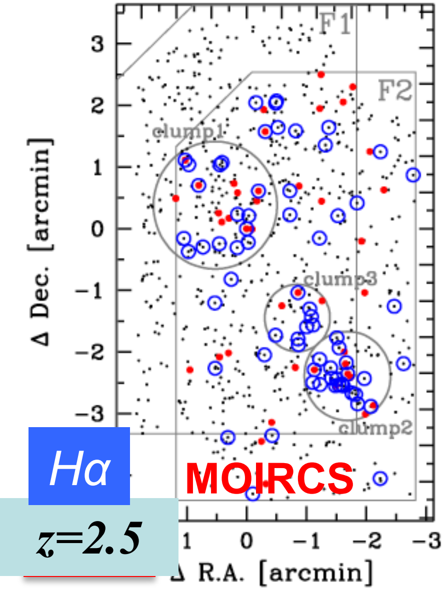
(Tadaki+12)



[OII] Suprime-Cam

z=1.6

CL0218

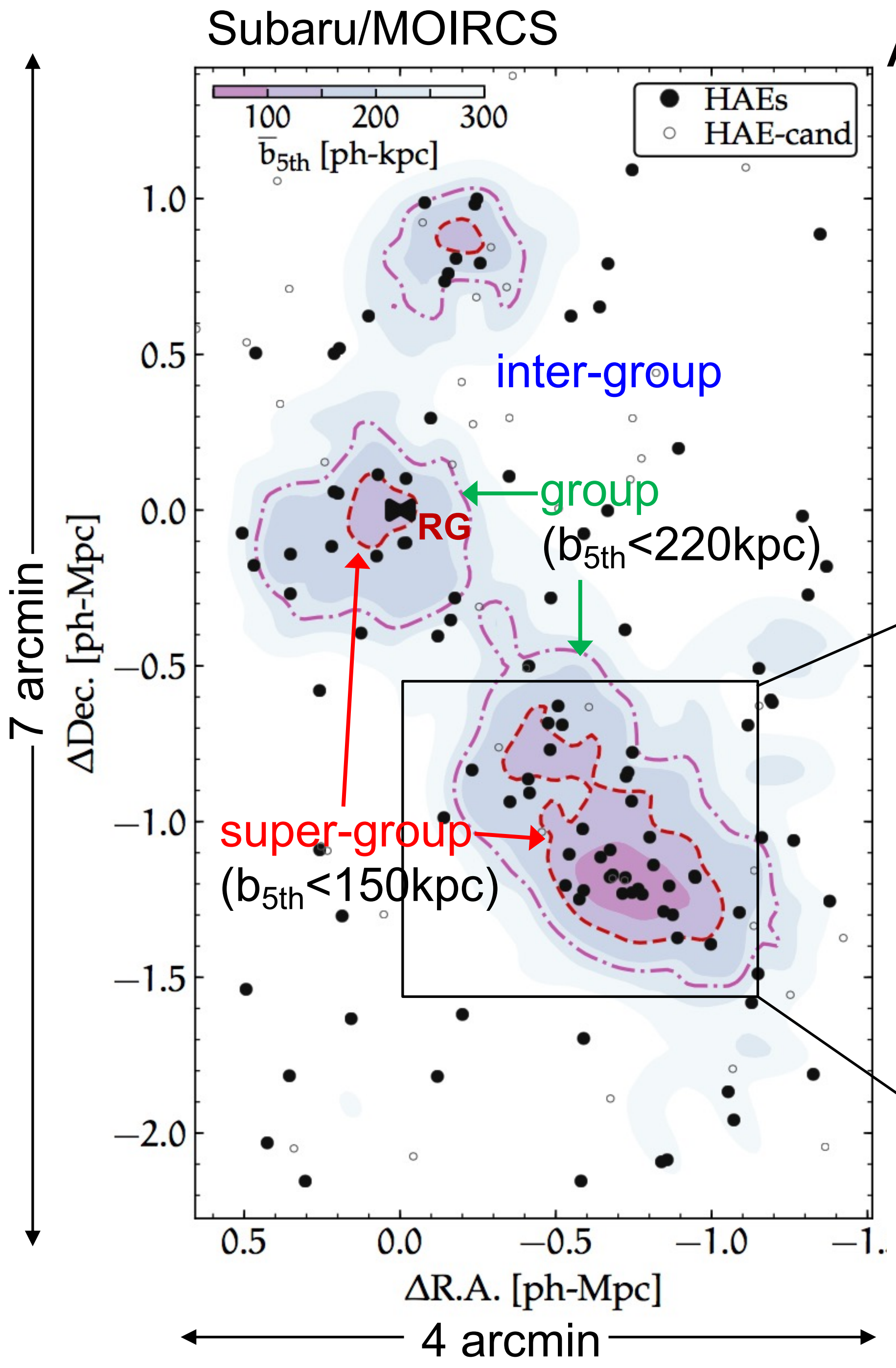


Hα MOIRCS

z=2.5

USS1558 *(Hayashi+12)*

A dense proto-cluster in assembly USS1558-003 at z=2.53

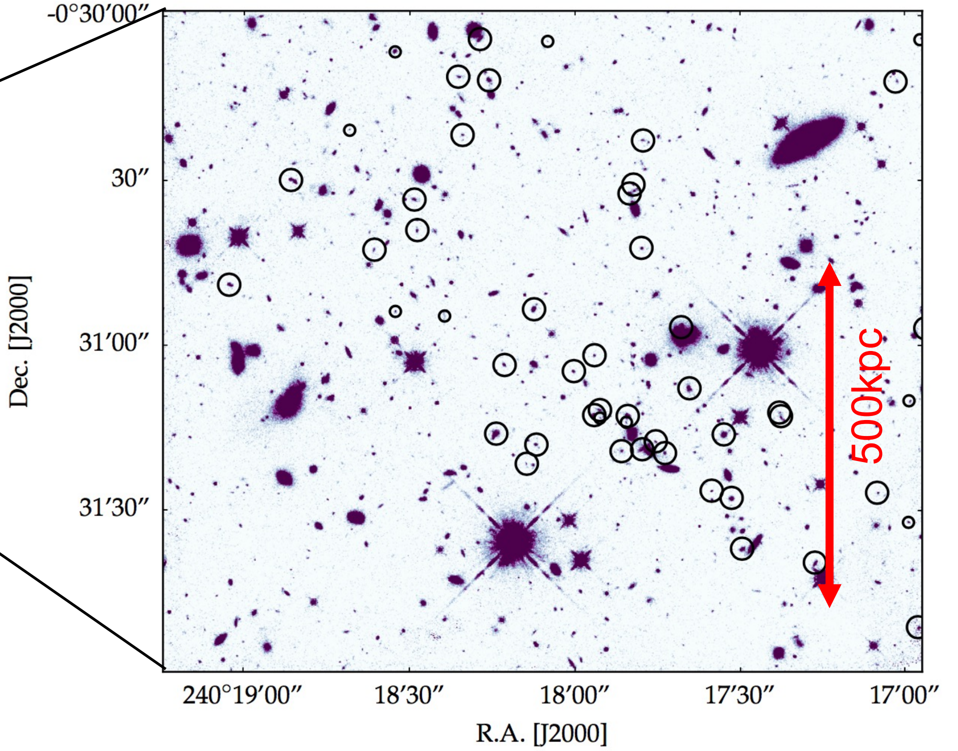


NB2315 (Hα) imaging on Subaru/MOIRCS

107 Hα emitters across the 4’x7’ field.
36 are spectroscopically confirmed.

Densest “super-group”(~20x) $M_{dyn}=10^{14}\,M_\odot$

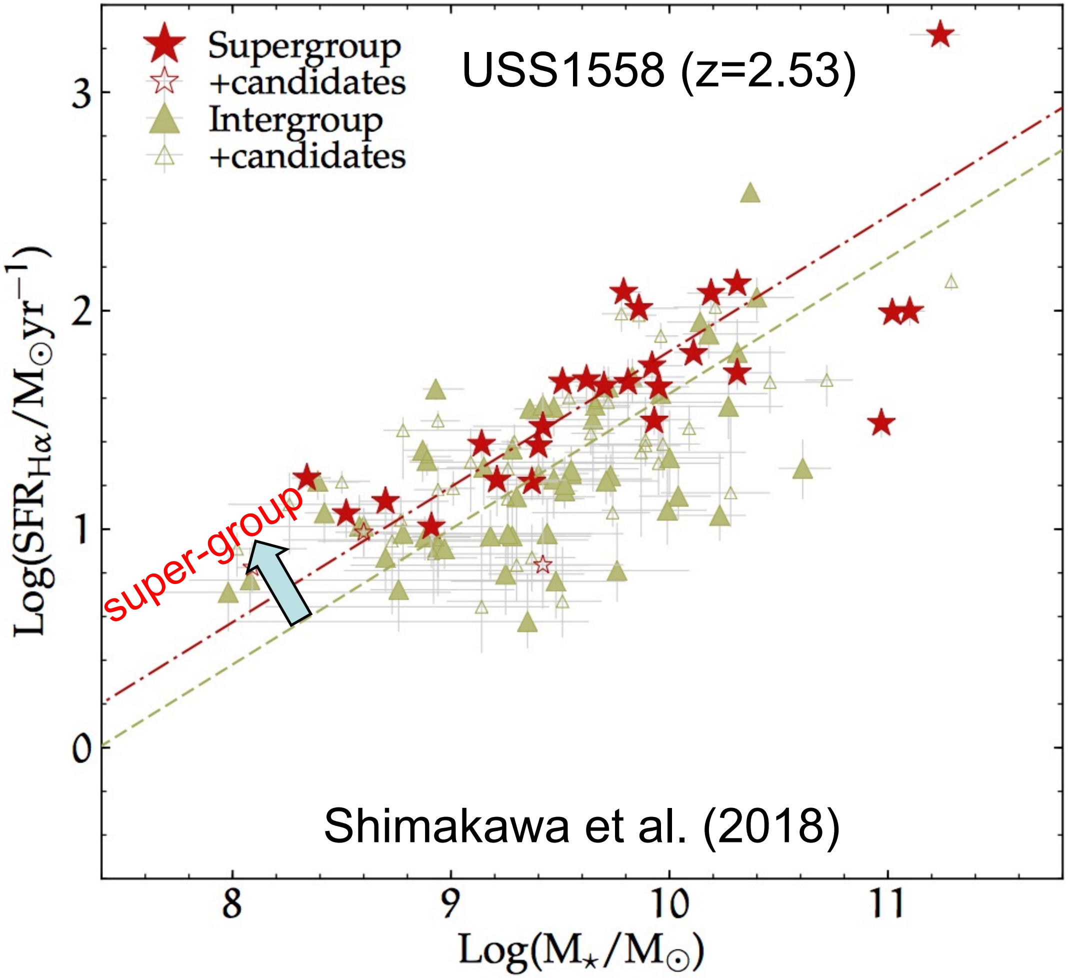
Galaxy haloes are likely to be overlapping.

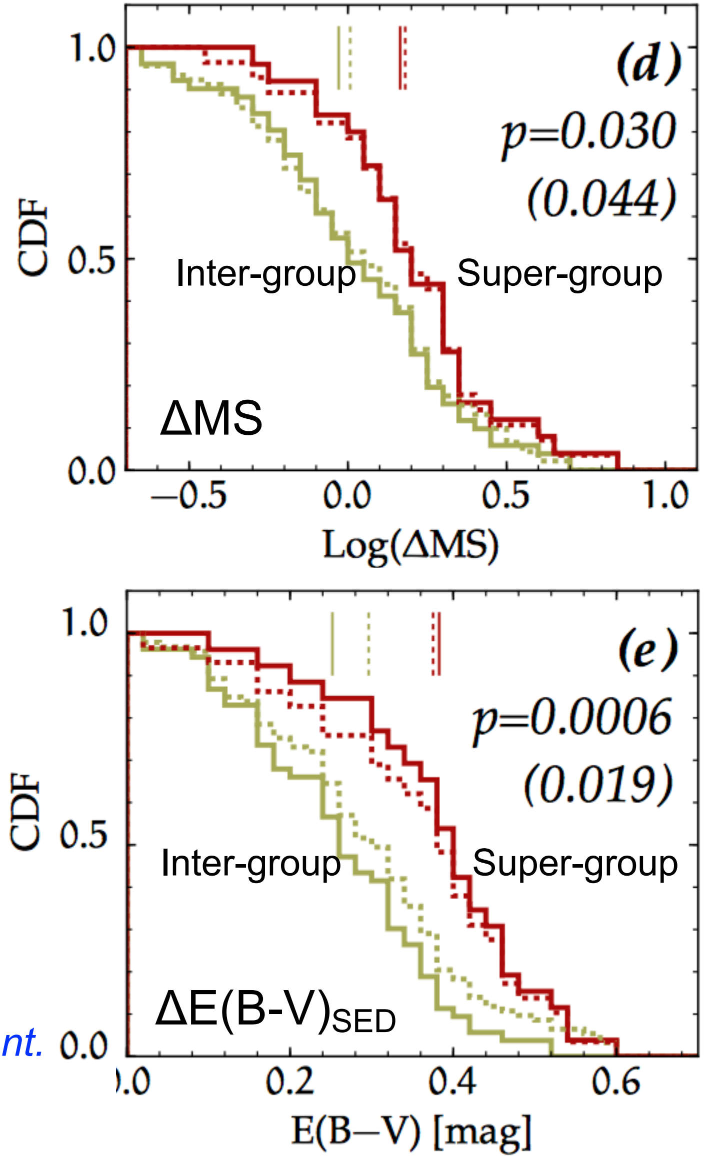


Shimakawa et al. (2017)

2. Is the star formation ever boosted in-situ in cluster cores?

Enhancement of SF activity and molecular gas fraction in the densest “super-group” of the proto-cluster USS1558 at z=2.53





Spiderweb (PKS1138 @z=2.16) does not show such enhancement.

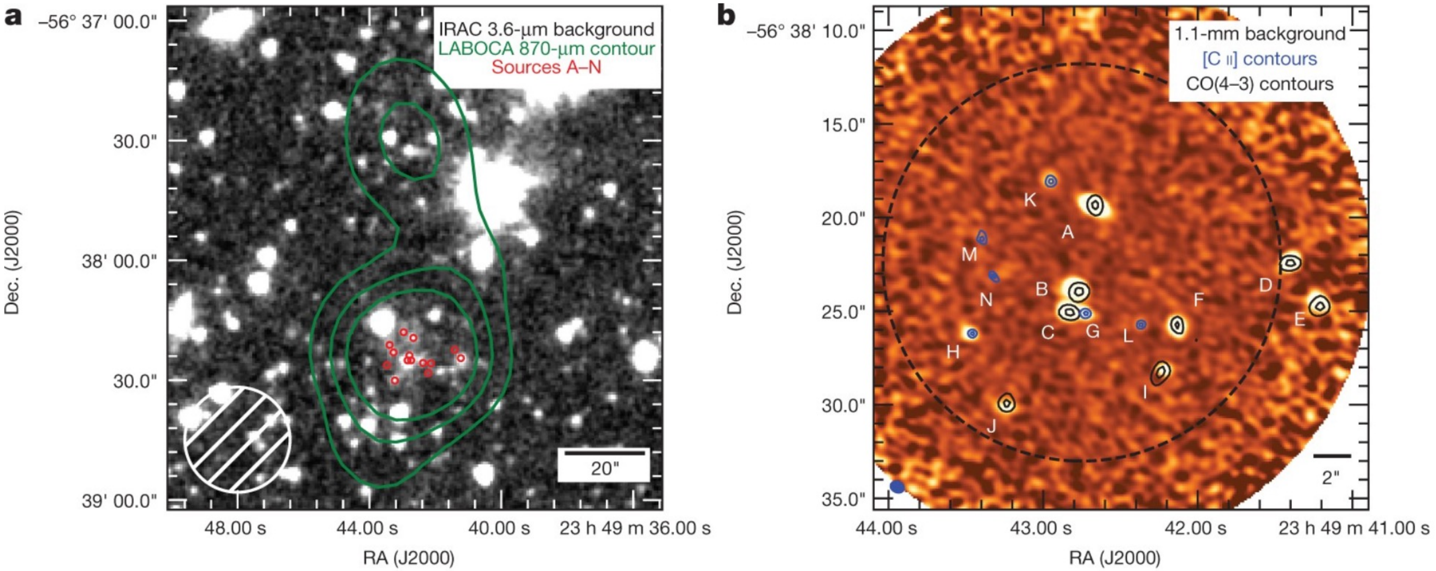
There are also some other works which do not see any environmental dependence on the MS diagram.

3. How much of star formation is hidden by dust?

Submm selected proto-clusters

SPT (South Pole Telescope) millimeter-wave survey ($S_{1.4mm}$=23.3mJy)
+ ALMA follow-up (CO43, [CII], dust)

SPT2349-56 at z=4.3 Miller et al. (2018), Nature



14 SMGs within 130kpc ! $M_{cl} = 9 \times 10^{12}\ M_\odot$

Total SFR > 10,000 $M_\odot$ /yr, Total SFR density ~ 40,000 $M_\odot$ /yr/Mpc^3 !?

No current simulations can reproduce such high SFR density!

We may be still missing ***a lot*** of SFR by dust??

Unveiling the propagation of “intrinsic” SF activities across the proto-cluster and within individual galaxies

JWST cycle-1 GO program (Dannerbauer, Koyama, et al.)

Resolving and penetrating into the dusty Spiderweb and its surrounding protocluster with Pa-beta imaging

Dust-free SF tracer down to SFR=3.5 $M_\odot$ /yr (rest-frame 1.28μm)

Scientific Category: Galaxies

Scientific Keywords: Galaxy Environments, High-Redshift Galaxies, Starburst Galaxies, Ultraluminous Infrared Galaxies

Instruments: NIRCAM

Proposal Size: SMALL

Exclusive Access Period: 12 months

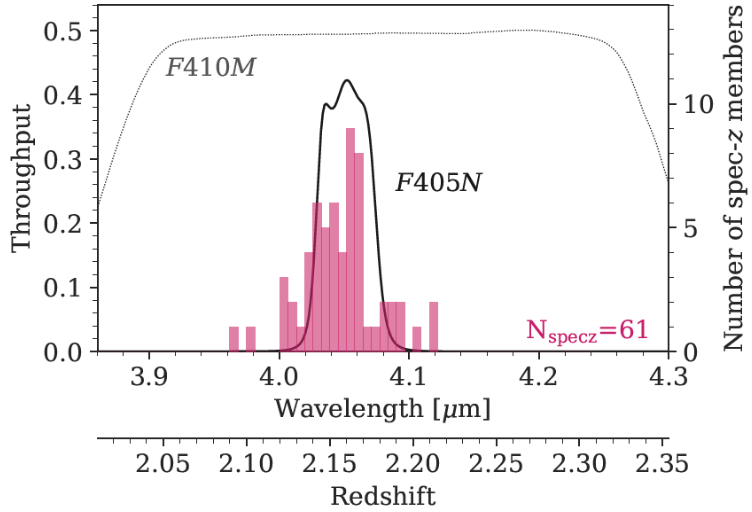
Allocation Information (in hours):

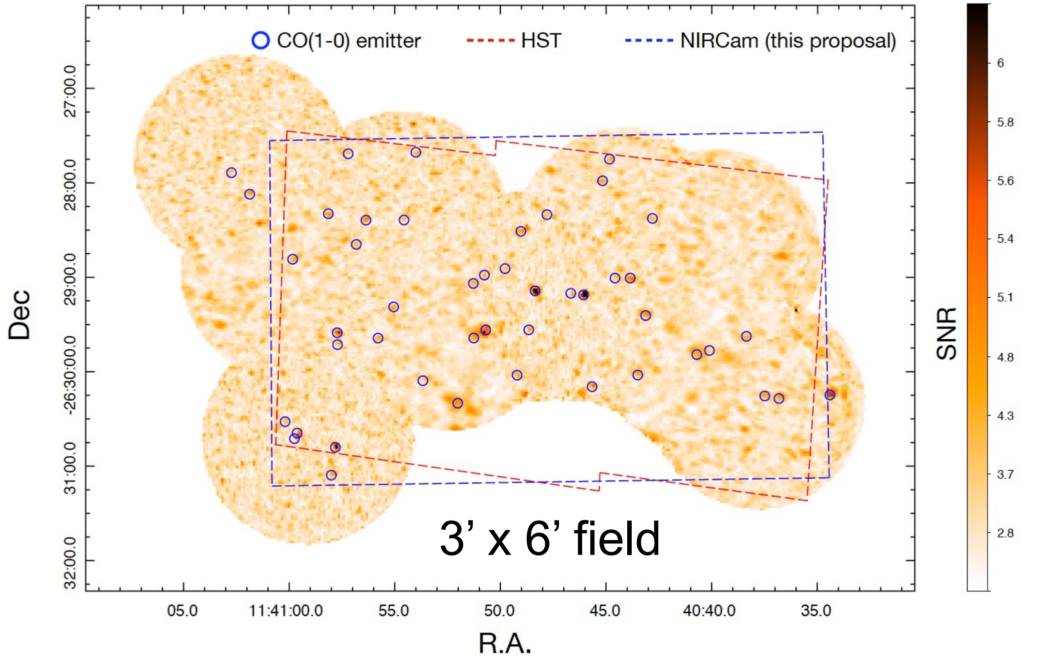
Science Time: 1.4

Charged Time: 3.6

Data will be delivered in May-Jun 2023.

The spiderweb protocluster PKS1138 @z=2.16





3’ x 6’ field

We can capture Paβ line (rest 1.28μm) from the cluster members with F405N narrow-band filter.

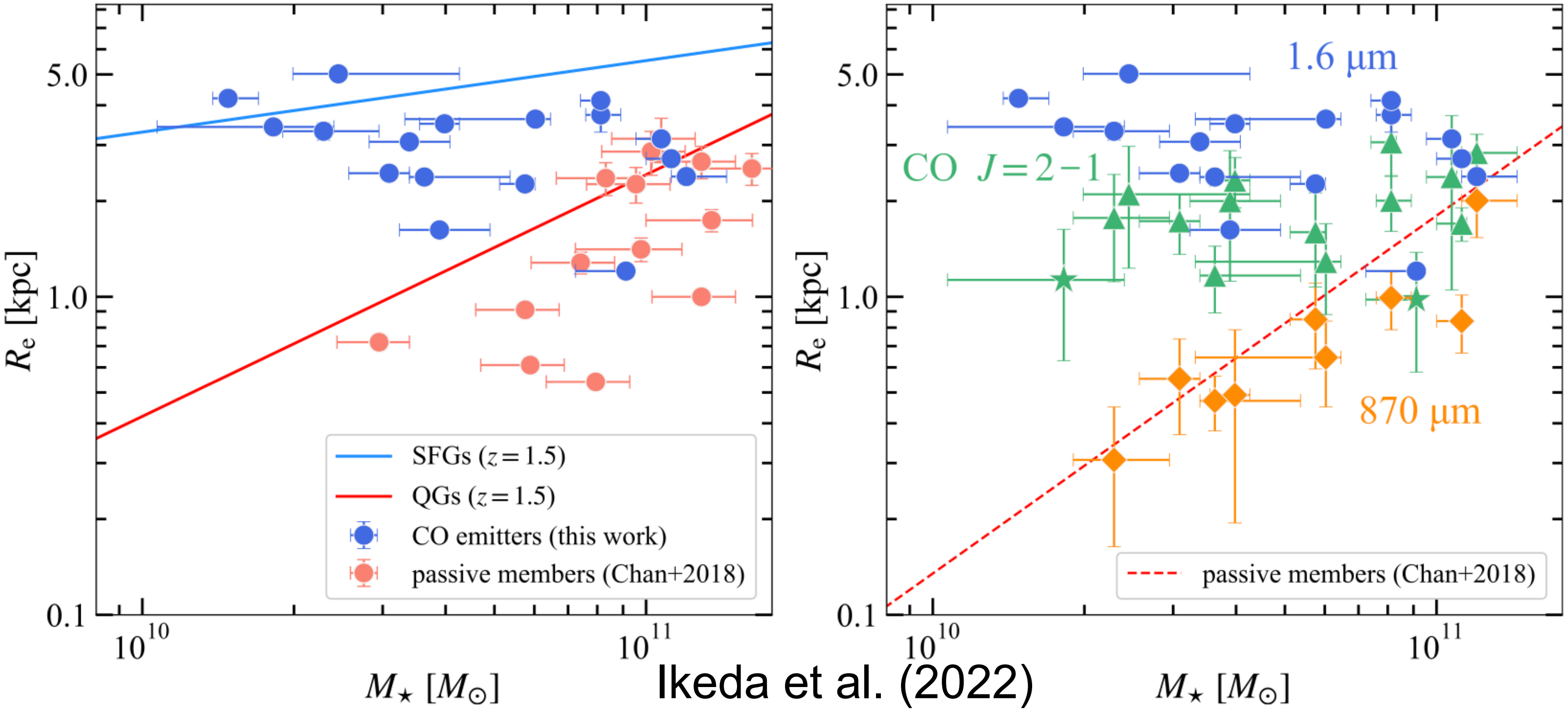
Size comparison of various galaxy components

dust continuum < molecular gas < stars

→ Formation of bulges with higher SFE in galaxy centers?

XCS2215 cluster (z~1.47)

ALMA high-R observations of CO(2-1) line and dust continuum (870μm)



Ikeda et al. (2022)

Figure 7. Stellar mass–size distribution of the galaxies in XCS J2215. Left: HST/1.6 μm sizes are shown for 17 CO emitters (blue circles) and 14 spectroscopically confirmed passive members (red circles; Chan et al. 2018). The solid lines correspond to the best-fit mass–size relation of star-forming (blue) and passive (red) galaxies at $z = 1.5$ (van der Wel et al. 2014). Right: comparison of the sizes of the CO emitters measured from different tracers. The blue circles, green triangles or stars, and orange diamonds indicate the effective radii of the HST/1.6 μm, CO $J = 2$–1 line, and 870 μm continuum, respectively. Two AGNs (ALMA.11 and ALMA.14) are shown with green stars for the CO size. The red dashed line is the best-fit mass–size relation of the passive members of XCS J2215 at 1.6 μm, as presented in the left panel.

We also see this trend for field galaxies at z~2 (Tadaki et al. 2017).

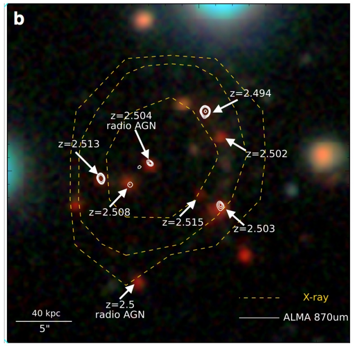
Any environmental dependence? → Need more data.

4. When and how does *gas accretion* to proto-clusters become *inefficient?*

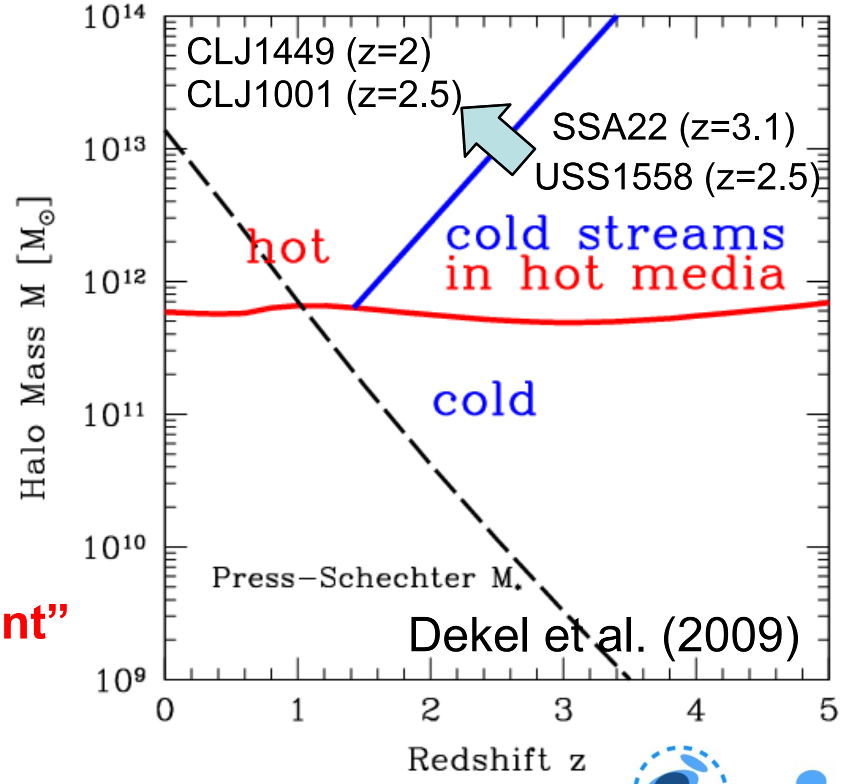
Transition of gas accretion mode in proto-clusters?

c.f., Valentino et al. (2015)

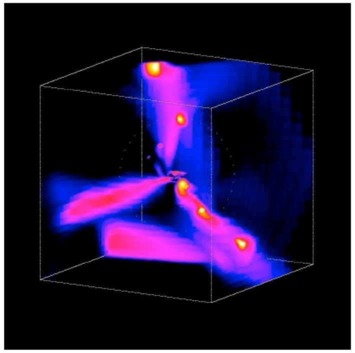
See also Raphael's talk



accretion "inefficient" phase



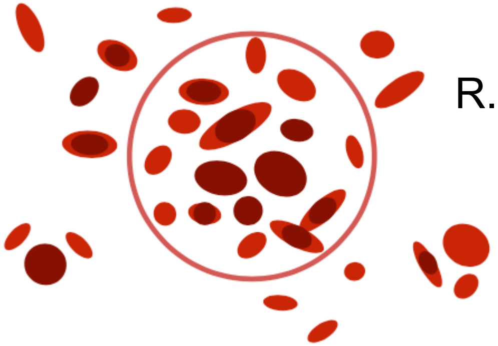
Dekel et al. (2009)



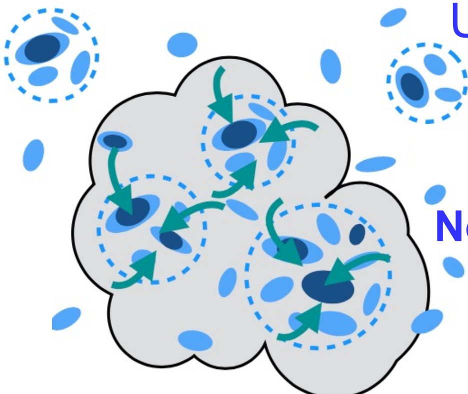
accretion "dominated" phase

CLJ1001 (z=2.5)
CLJ1449 (z=2)

X-ray clusters



Credit:
R. Shimakawa



USS1558 (z=2.5)
4C23.56 (z=2.5)
SSA22 (z=3.1)

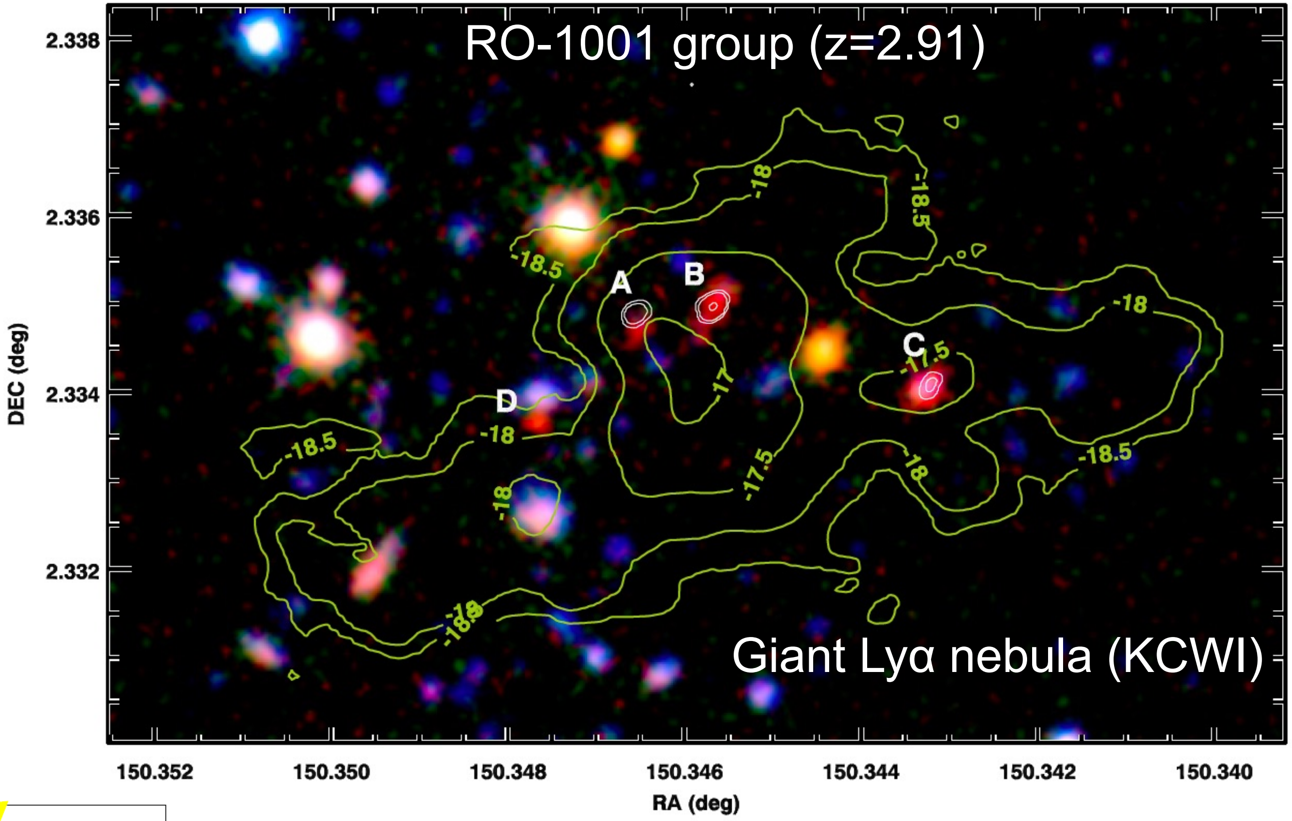
Non-X-ray clusters

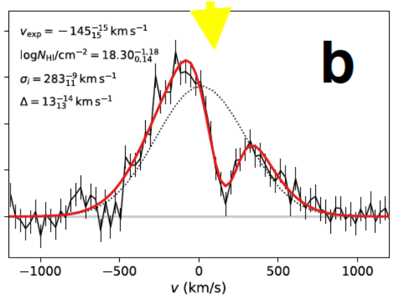
As cluster halos grow massive/dense, gas is heated up to high T, and X-ray is emitted.

Cold gas is efficiently supplied to proto-clusters with cold streams along filaments.

A 300 kpc-wide giant Lyα nebula centered on the massive galaxy group at z~3

$4 \times 10^{13}\ M_\odot$ dark matter halo, hosting 1,200 $M_\odot\ \mathrm{yr}^{-1}$ of star formation



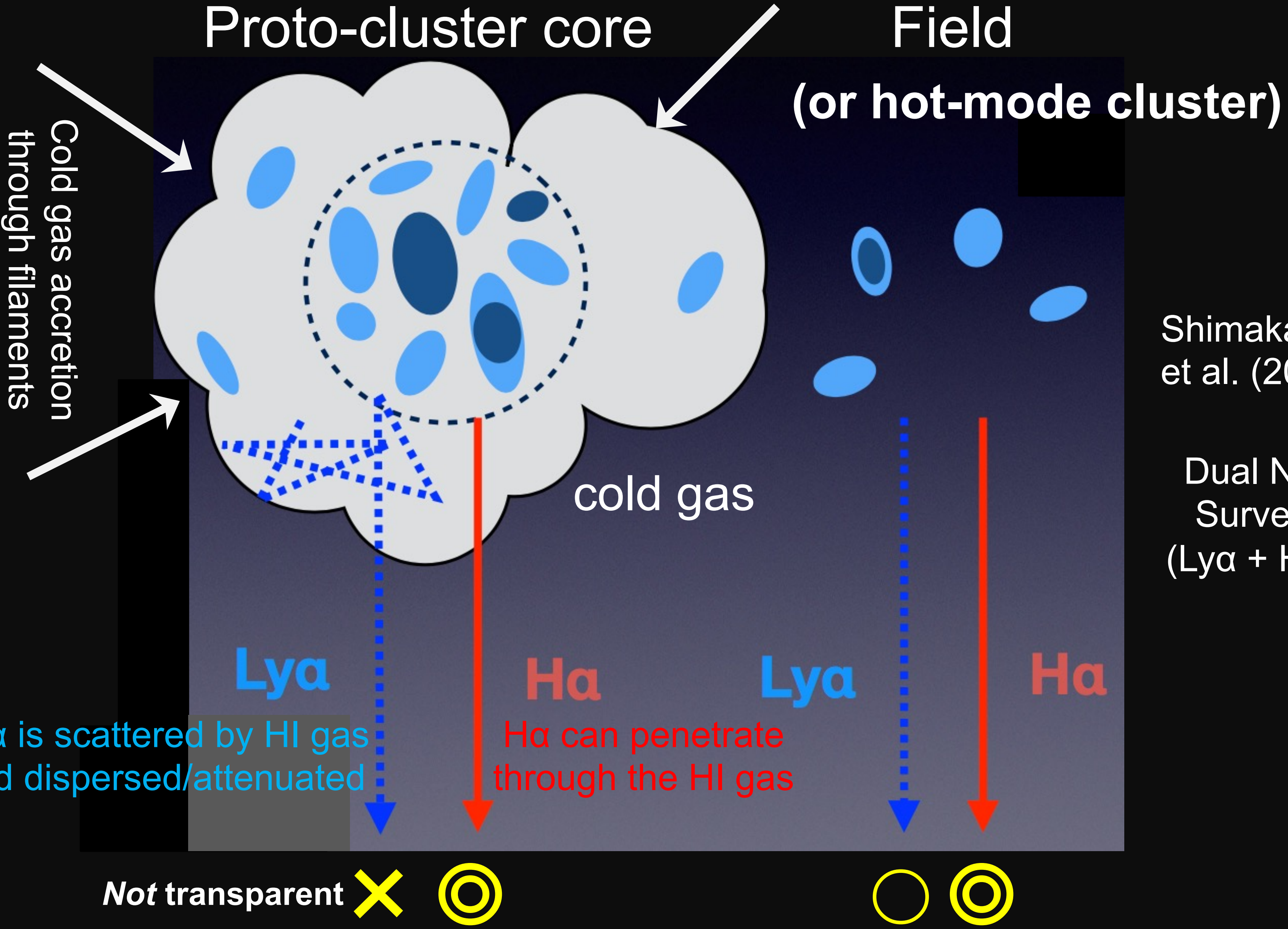


Daddi et al. (2021), see also Daddi+22

Red shifted Lyα absorption → inflow

Direct evidence for cold streams

But diffuse Lyα emission is hard to observe due to cosmological dimming of $SB=(1+z)^{-4}$



Shimakawa
et al. (2017)

Dual NB
Survey
(Lyα + Hα)

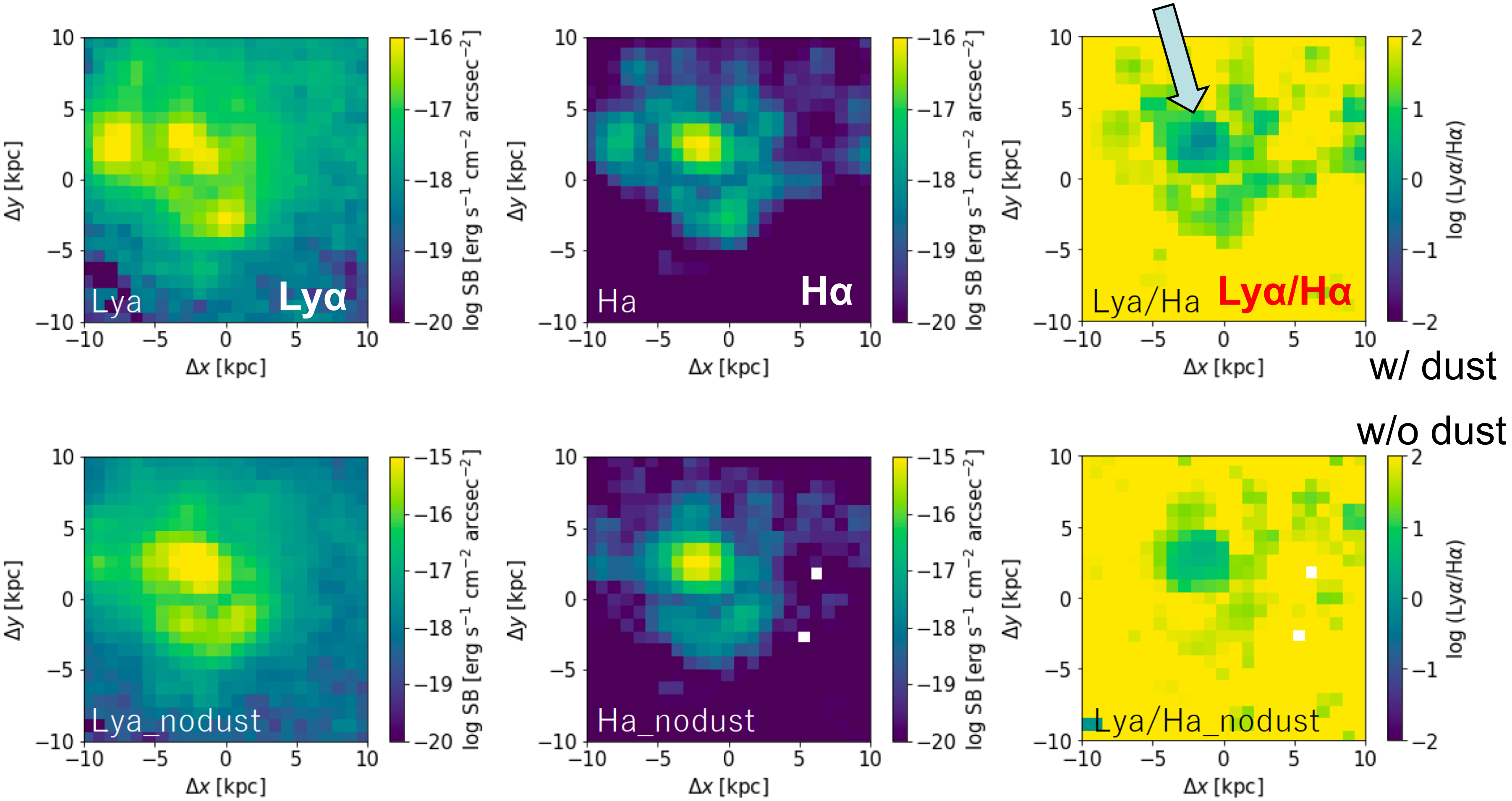
Lyα/Hα ratio within a certain aperture can trace the associated HI gas.

Lyα versus Hα in the simulation

Osaka zoom-in hydrodynamical-simulation with radiative transfer (post process)

A central dent in Lyα/Hα ratio is predicted due to Lyα resonant scattering (+dust)

More prominent in protoclusters due to more associated HI gas.

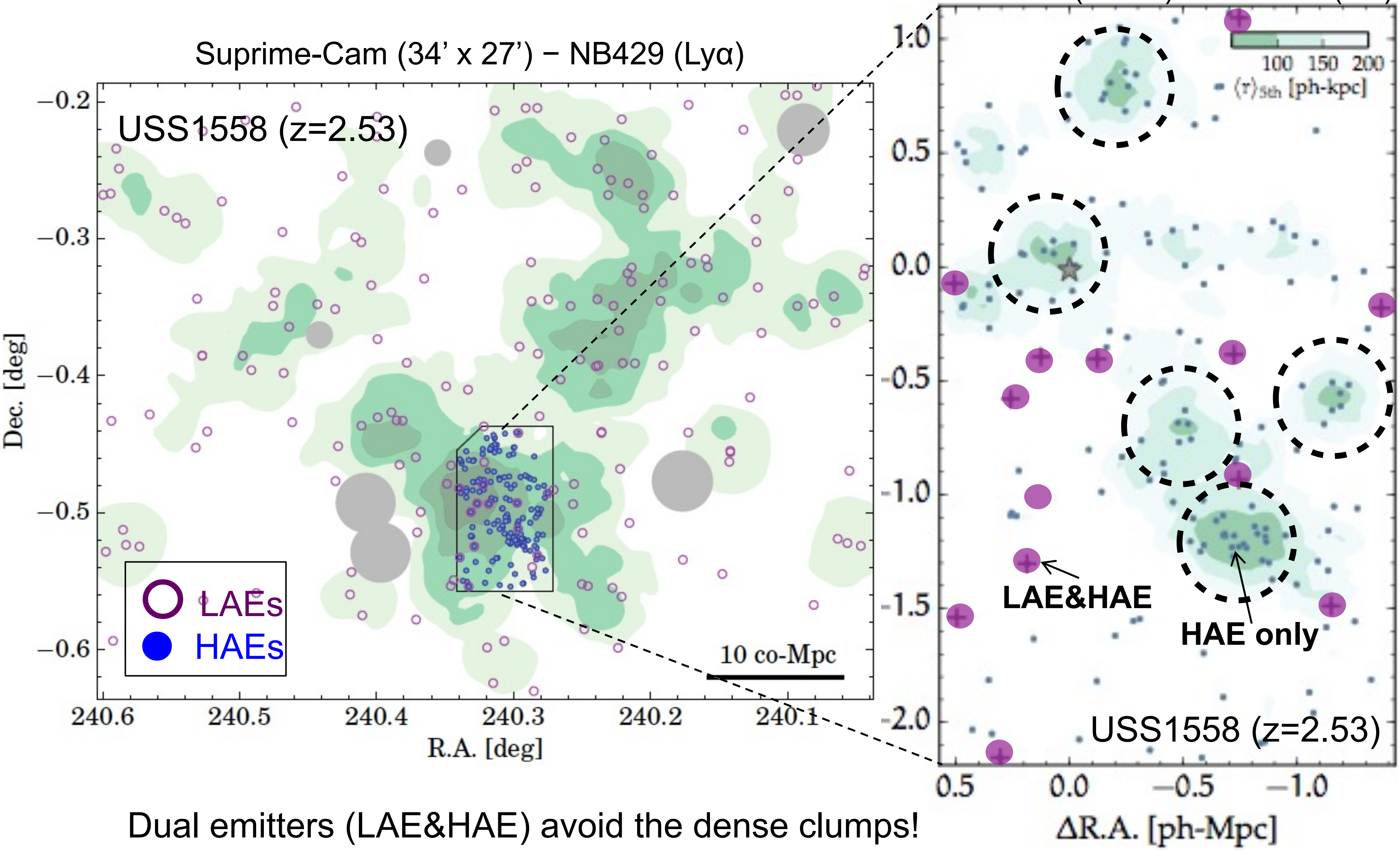


a simulated SFG at z~2

Nagamine et al., private communication

Dual NB emitter survey (Lyα, Hα) of USS1558 at z=2.53

Shimakawa et al. (2017)



Suprime-Cam (34’ x 27’) − NB429 (Lyα)

MOIRCS (7’ x 4’) − NB2315 (Hα)

Dual emitters (LAE&HAE) avoid the dense clumps!

→ Dense cores are enshrouded by HI gas fed by cold streams?

Triple NB imaging (Lyα+Hα+[OIII]) of HS1700+64 protocluster (z=2.30)

Just observed in S22A with SWIMS on Subaru (Kusakabe et al.)

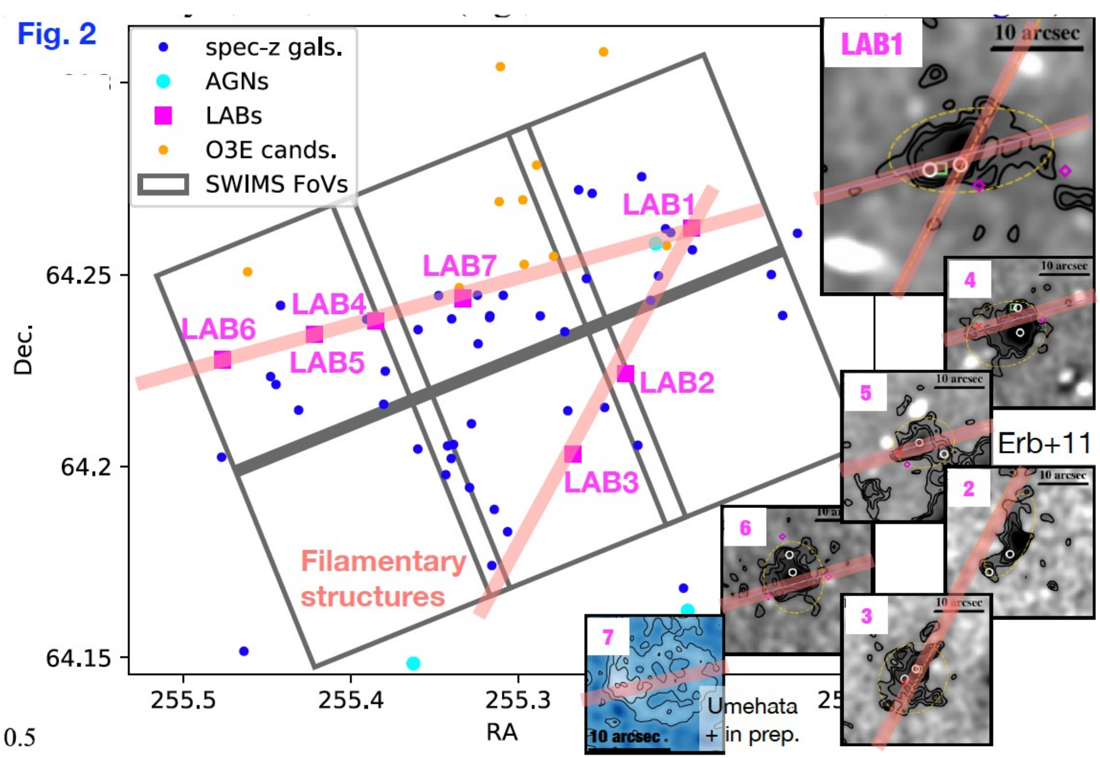
Lyα / Hα ratio → HI gas (resonant scattering) + dust attenuation

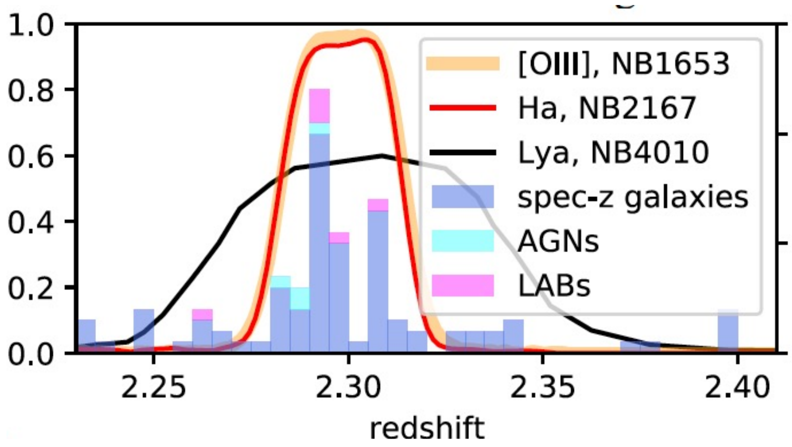
Do we see lower ratios towards the filaments?

[OIII] / Hα ratio → AGN

Is AGN fraction higher in protoclusters?

Fig. 2





SWIMS

NB1653: [OIII] emitters

NB2167: Hα emitters

Palomer/LFC

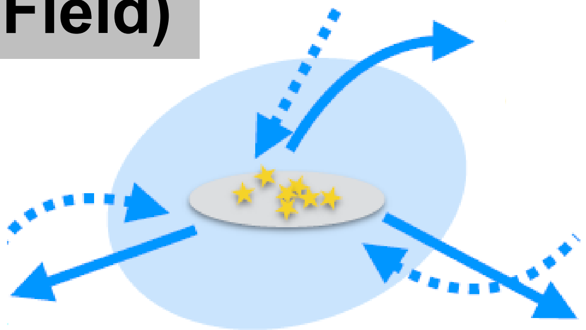
NB4010: Lyα emitters

7 Lyα blobs are aligned in 2 filaments!

Steidel (2005), Erb et al. (2011), Umehata et al. (2021), Bogosavljevic (2010)

5. Where and how do the *gas outflow or stripping* affect galaxies in clusters?

Isolated galaxies (Field)



(Inflow)

Stochastic, rapid, cold gas accretion through filaments

(Outflow)

Gas removal due to feedback (SN, AGN)

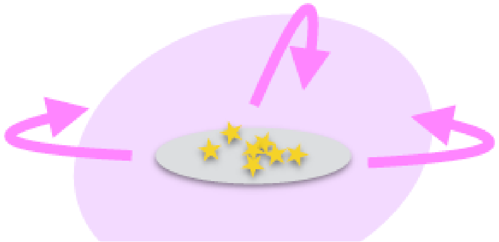
→ Selective ejection of metal rich gas

→ Metal dilution by accreting pristine gas

(Proto-)Cluster galaxies

(Inflow)

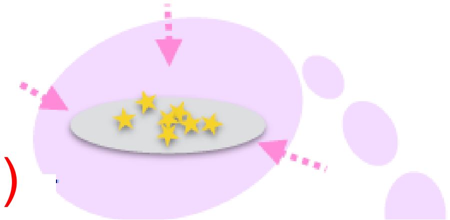
A common halo is formed and gas is shock heated to its virial temperature.
→ inefficient gas accretion compared to isolated galaxies.



(Outflow)

Fall back of gas due to deeper potential wells and surrounding gas pressure (Dave+11, Klus+13)

→ Recycling of gas (further enrichment)



(Stripping)

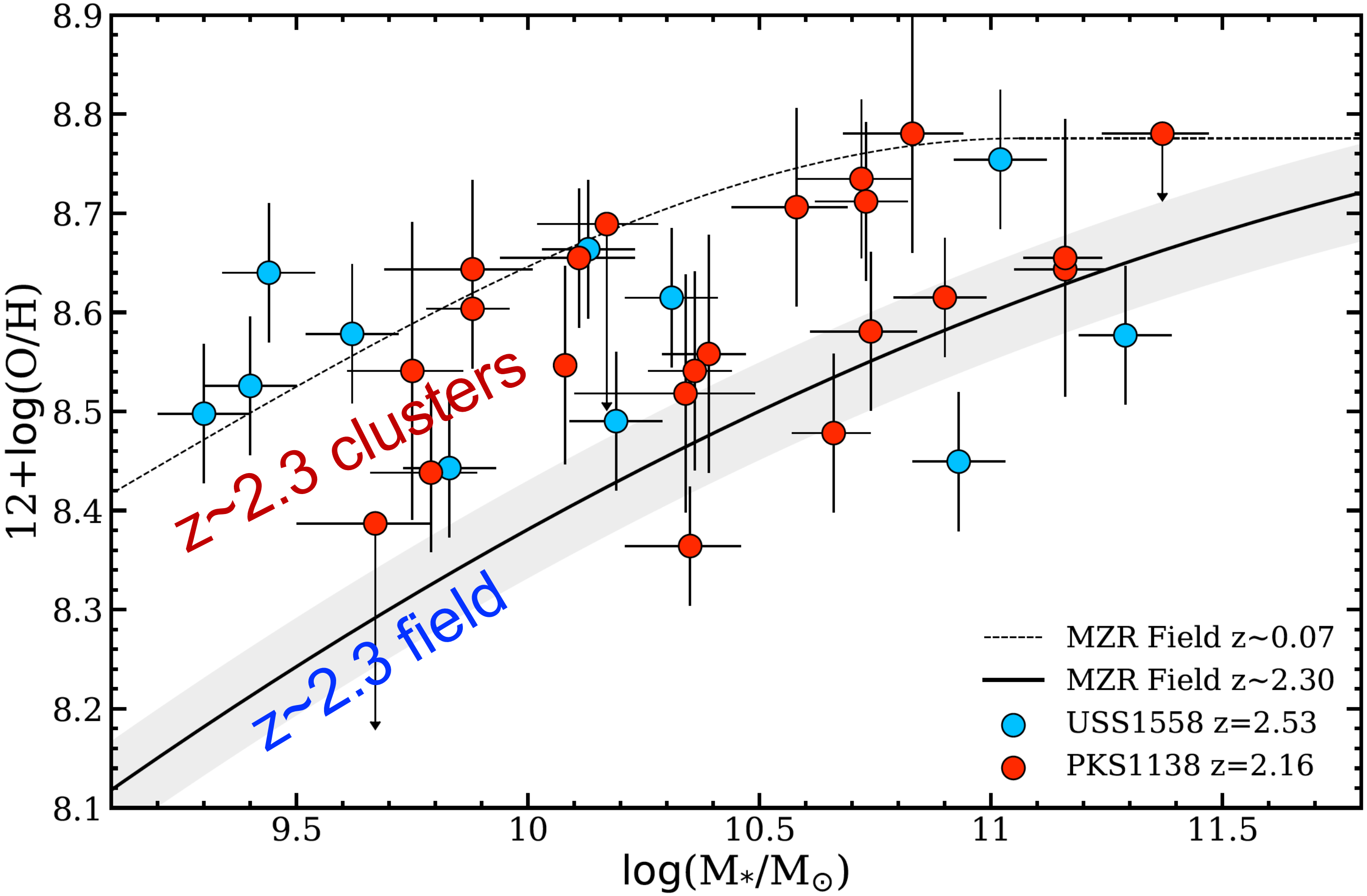
Gas stripping (tidal or ram-pressure)

→ Removal of outer metal poor gas

Mass-Metallicity Relation of Galaxies in Proto-Clusters

- Indirect investigation of gas inflow/outflow -

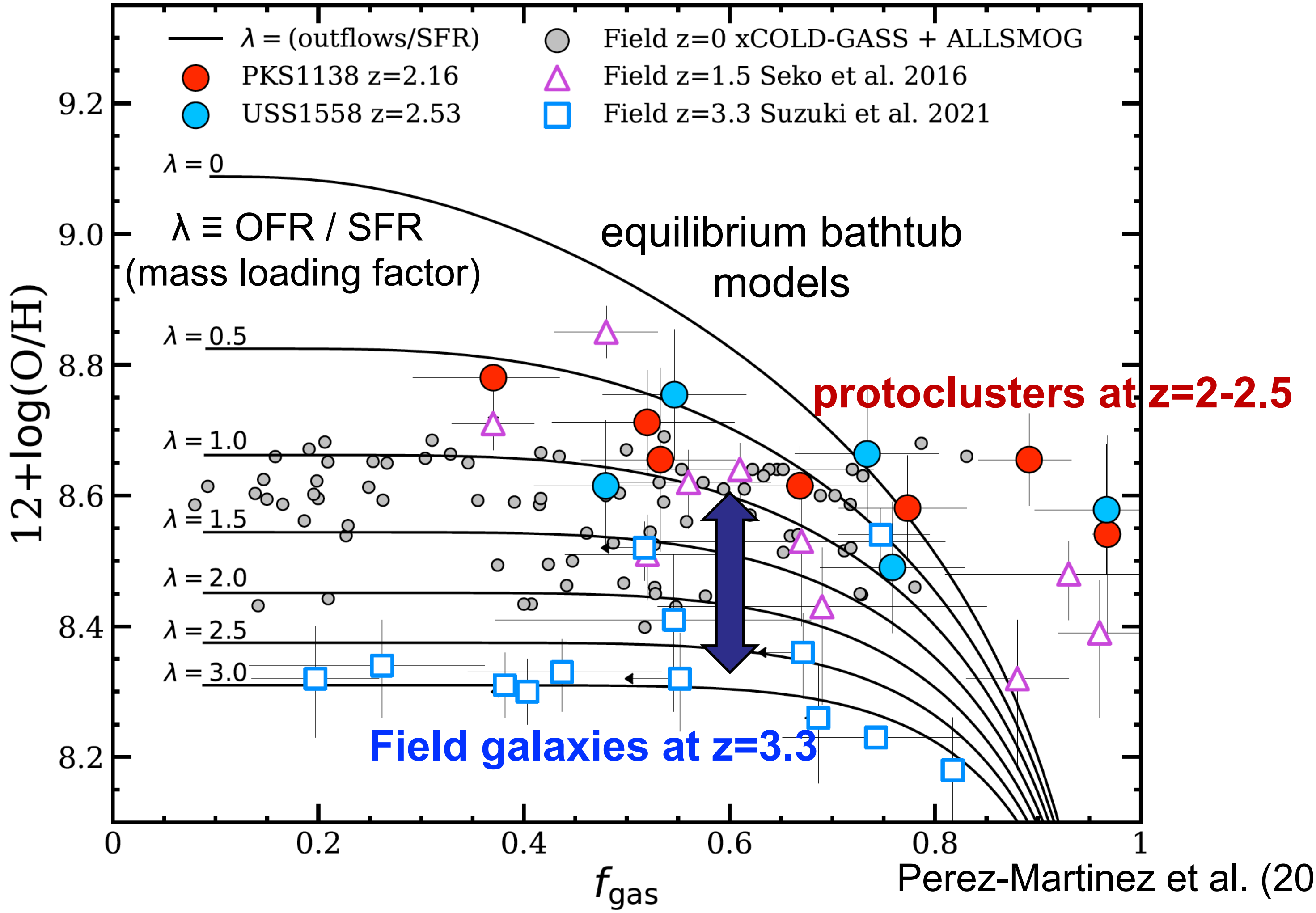
Slight enhancement with respect to the field relation?



Perez-Martinez et al. (2022a,b)

Gas Outflows constrained by Chemical Evolution

Gaseous metallicity (Z_{gas}) versus gas fraction (f_{gas}) diagram can constrain outflows (mass loading factor).



λ ≡ OFR / SFR
(mass loading factor)

equilibrium bathtub models

protoclusters at z=2-2.5

Field galaxies at z=3.3

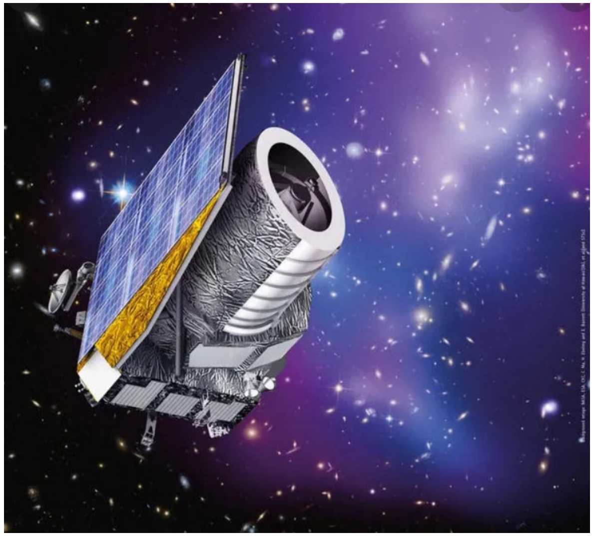
Perez-Martinez et al. (2022a,b)

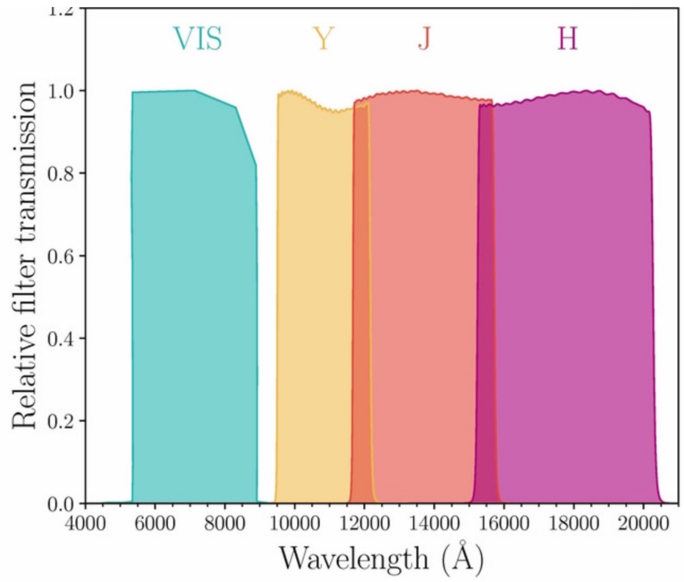
Gas is more confined in galaxies in protoclusters due to deeper potential wells and surrounding gas pressure?

Euclid

1.2m telescope to be launched in 2023

Japan is participating Euclid through the Subaru intensive program by Oguri et al.:
z-band imaging follow-up of the Euclid fields.
Wide Imaging with Subaru HSC of the Euclid Sky (WISHES)





Red sequence survey + **Grism emitter survey** (Euclid-Deep over 50 deg^2)

Similar to our HSC^2 concept (tracing both QGs and SFGs),
but not limited to NB redshift slices!

∗ **VIS, z, Y, J, H** can capture **4000Å/Balmer break** back to **z=3**

∗ **Grism** can capture **Hα** to **z=1.8**, **[OIII]** to **z=2.6**
(R=260)
(Also, spectroscopic confirmation with PFS and MOONS)

CH1=24.8 ↔ 6x10^9 $M_\odot$
H=26 ↔ 3x10^9 $M_\odot$
(5σ) @z~2

5 x 10^{-17} cgs ↔ 20 $M_\odot$/yr @ z~1.8
(3.5σ) ($A_{H\alpha}$=1mag) 5 $M_\odot$/yr @ z~1

Summary

1. How much are (proto-)clusters ***biased (earlier/faster) in*** (massive) ***galaxy assembly and quenching?***

2. Are the ***SF/AGN activities ever boosted in situ in cluster cores, or pre-processed in the outskirts and then accreted?*** How do the ***SF/AGN activities and quenching propagate*** within cluster galaxies?

3. How much of SF in clusters is ***hidden by dust?***
   Is there an ***environmental effect in dust extinction?***

4. When and how does the ***gas accretion*** to clusters become ***efficient*** and then ***inefficient?***

5. Where and how do the ***gas outflow or stripping*** affect the galaxies in clusters?