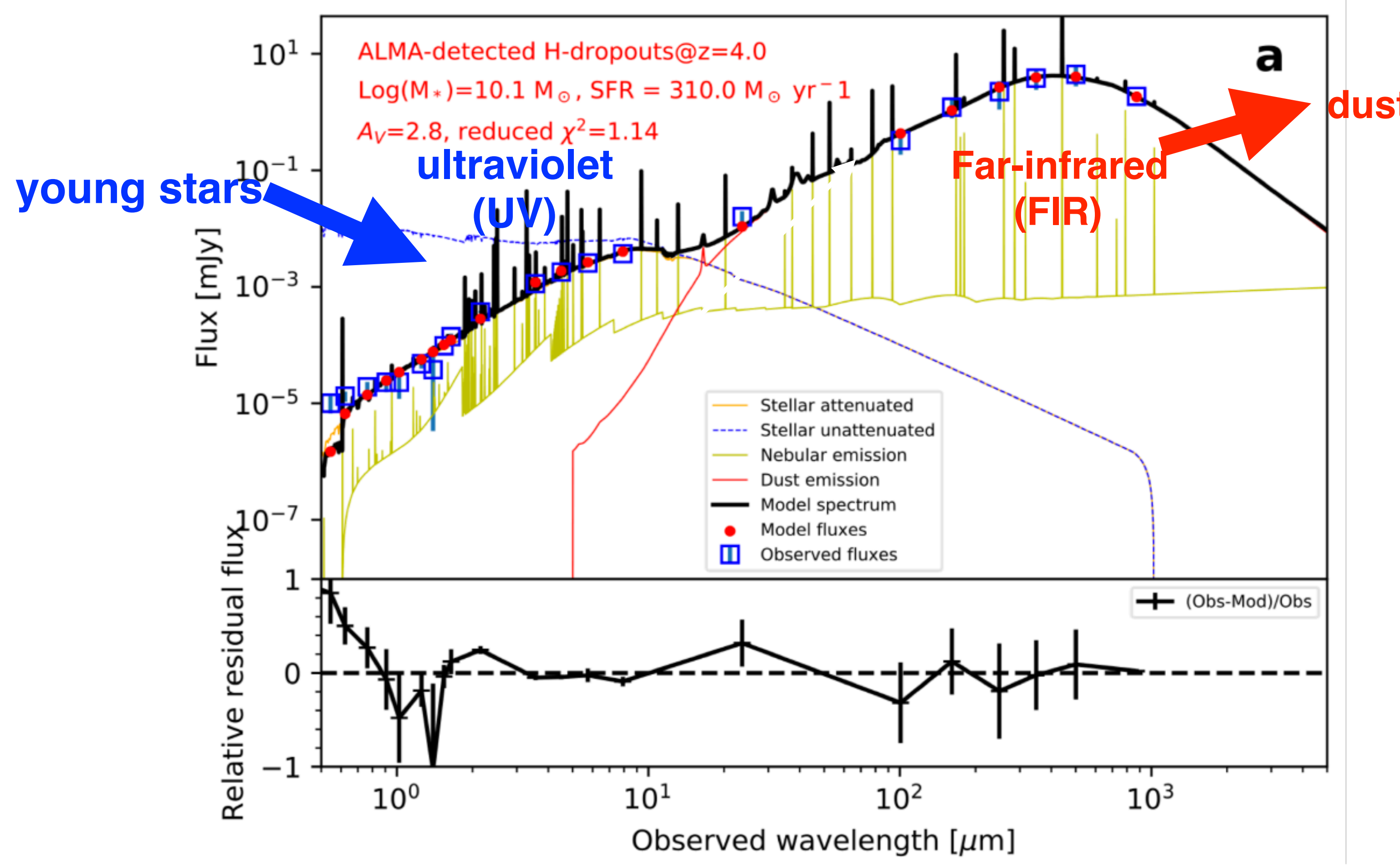
New frontiers in galaxy and structure formation in the early universe

Tao Wang (U. Tokyo and NAOJ)

Wang, Schreiber, Elbaz, et al. 2019, Nature, 572, 211
Yamaguchi, Kohno, Hatsukade, Wang, et al. 2018, ApJ,878,73
Franco, Elbaz, Bethermin, et al. 2018, A&A, 620, 152
Wang, Elbaz, Daddi, et al. 2016, ApJ, 828,56
Wang, Eblaz, Schreiber, et al. 2016, ApJ, 816,84

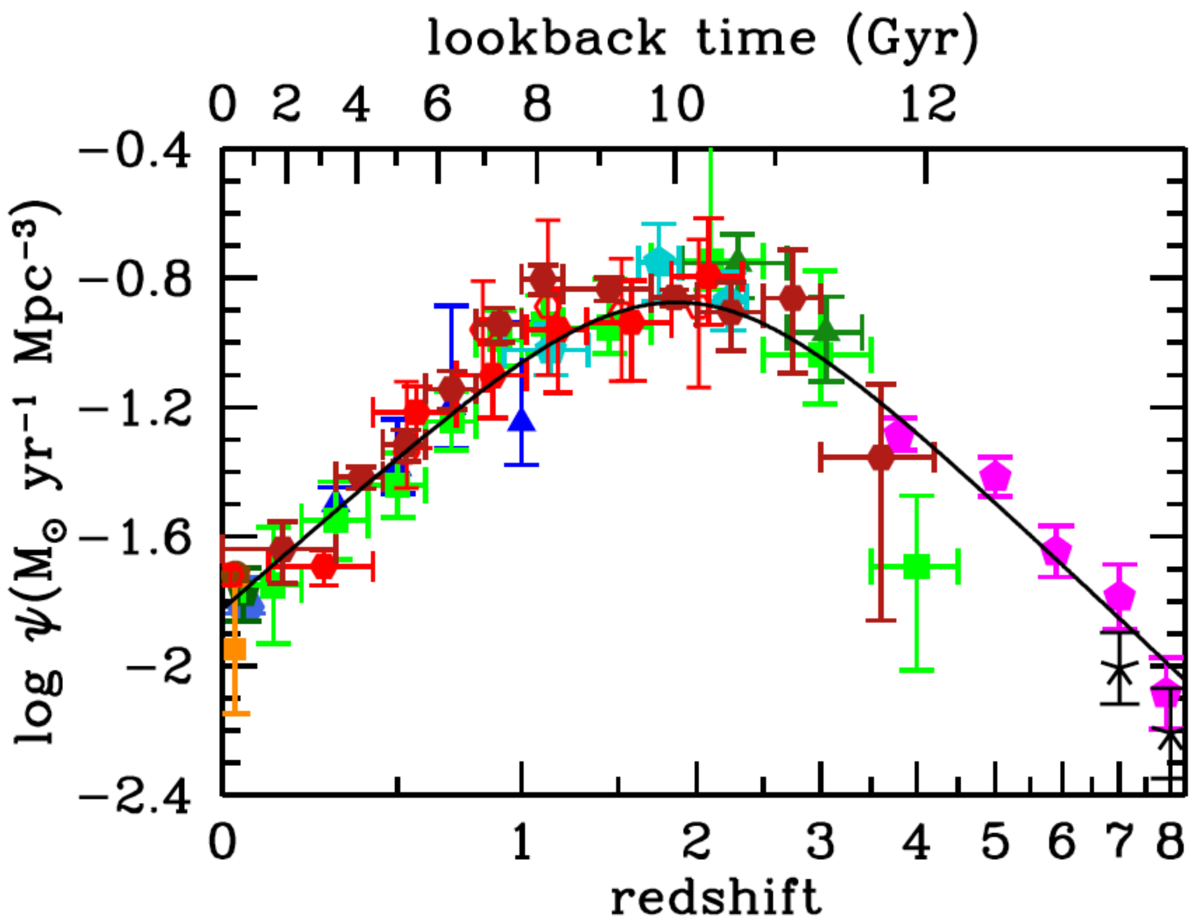
IPMU, Feb 20, 2020

Background:
Spectral Energy Distribution (SED) of Galaxies

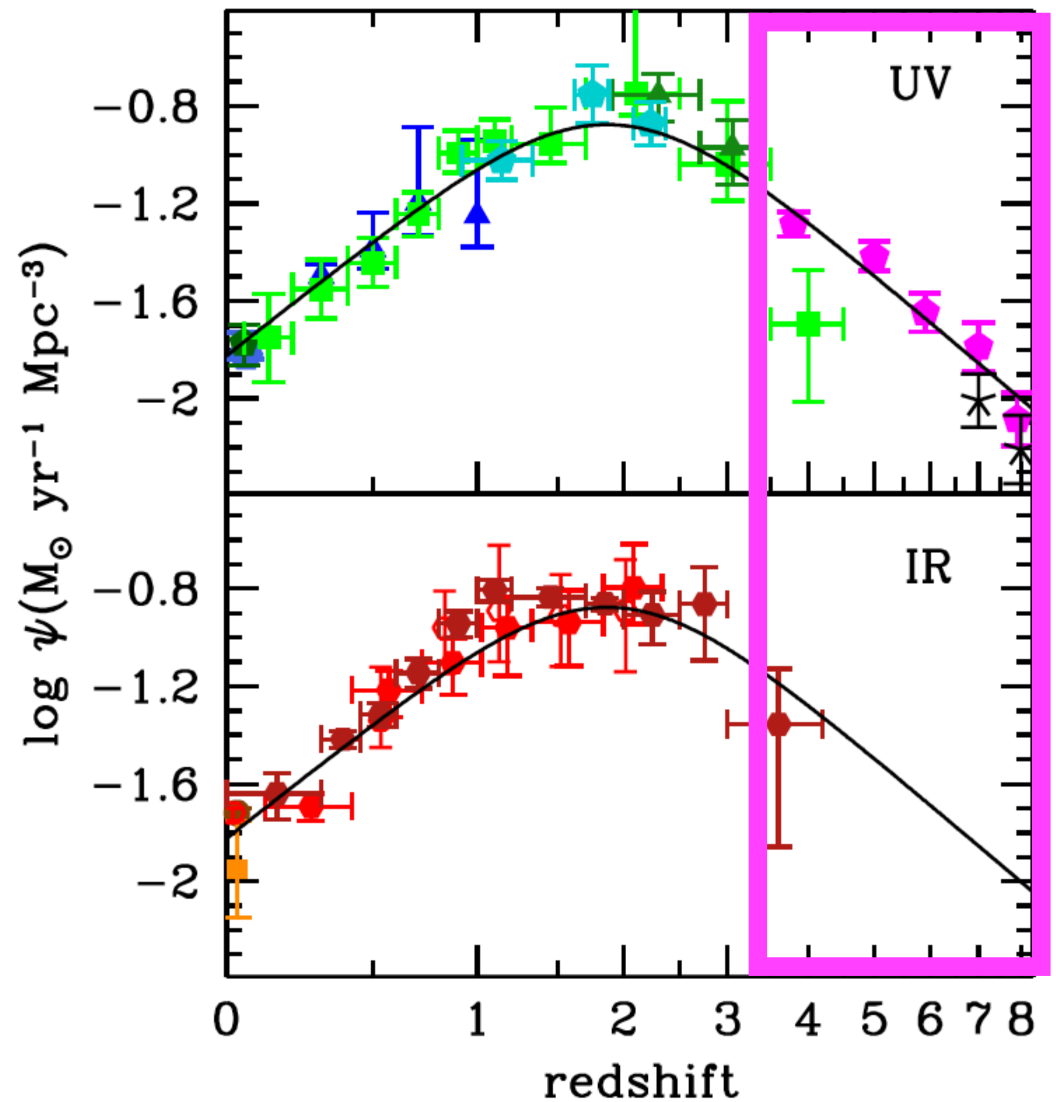


multi-wavelength observations of galaxies

Cosmic Star Formation History



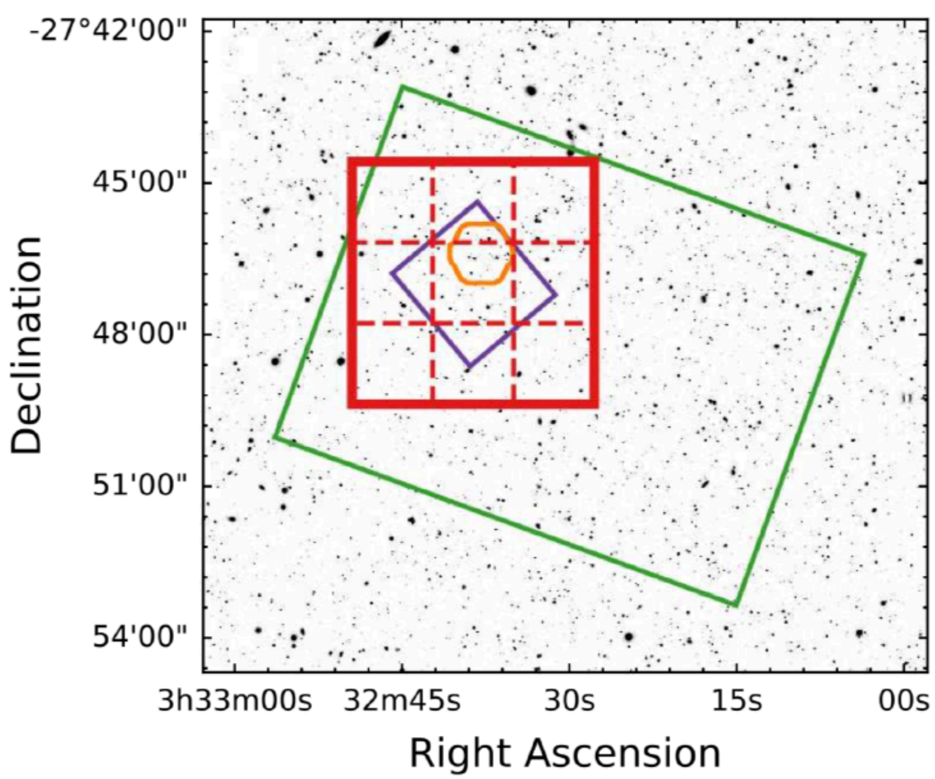
Madau & Dickinson, 2014

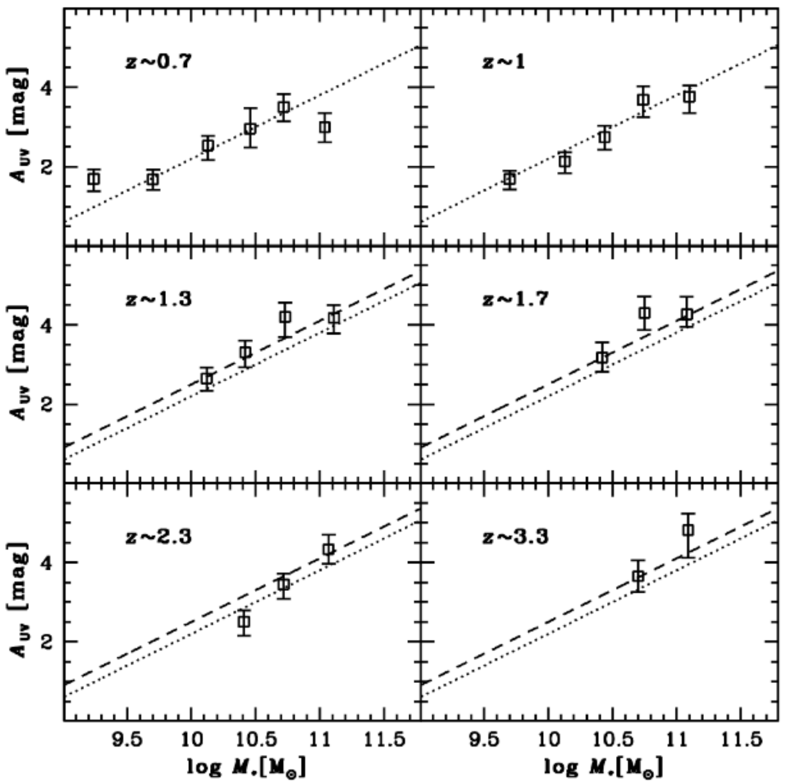


Current challenges:
SFR based on **UV+IR** for **mass-limited** sample at $z<3$;
SFR based on **(extinction-corrected) UV** for **UV-selected** (Lyman-break galaxies) sample at $z>3$

Towards a complete census of the cosmic SFR density at z>3

(1): IR measurements of SFR for typical Lyman-break galaxies:
ALPINE, HUDF, ASPECS, ASAGAO, GOODS-ALMA, ALMA Lensing Cluster Survey





ALMA deep surveys in GOODS-South

Dunlop+2016,Franco+2018,Hatsukade+2018

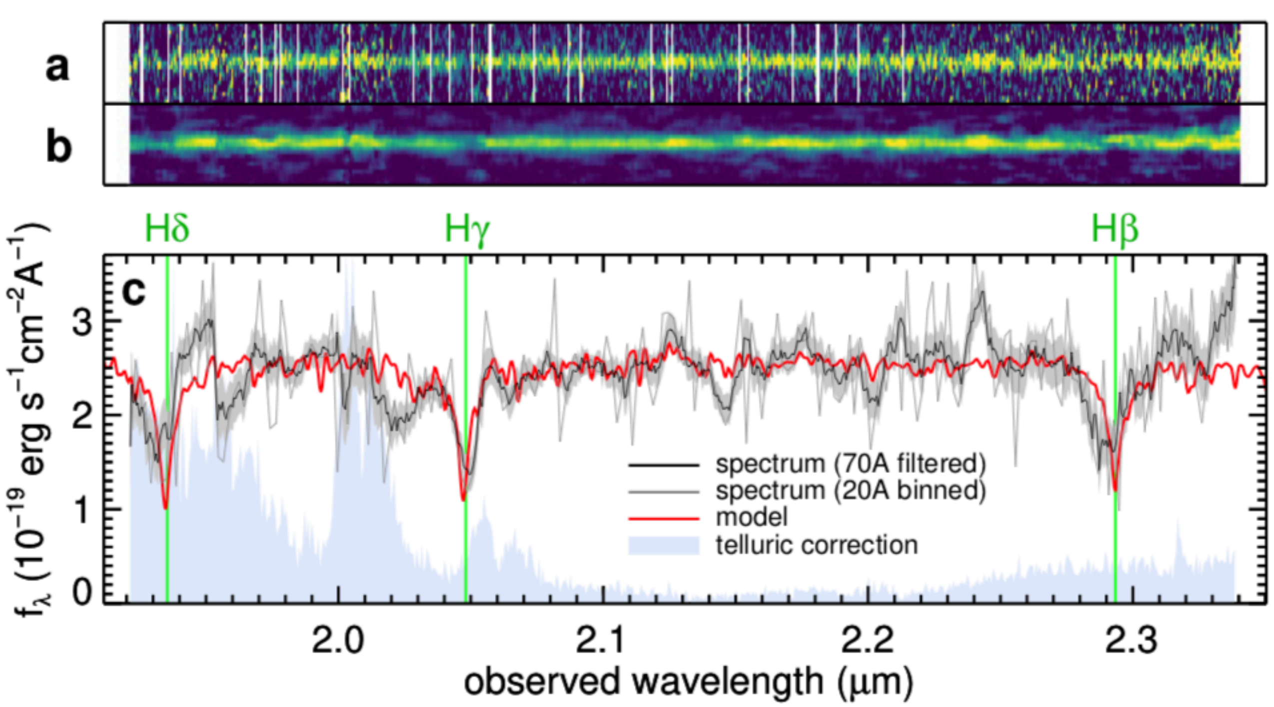
More massive galaxies suffer more severe extinction

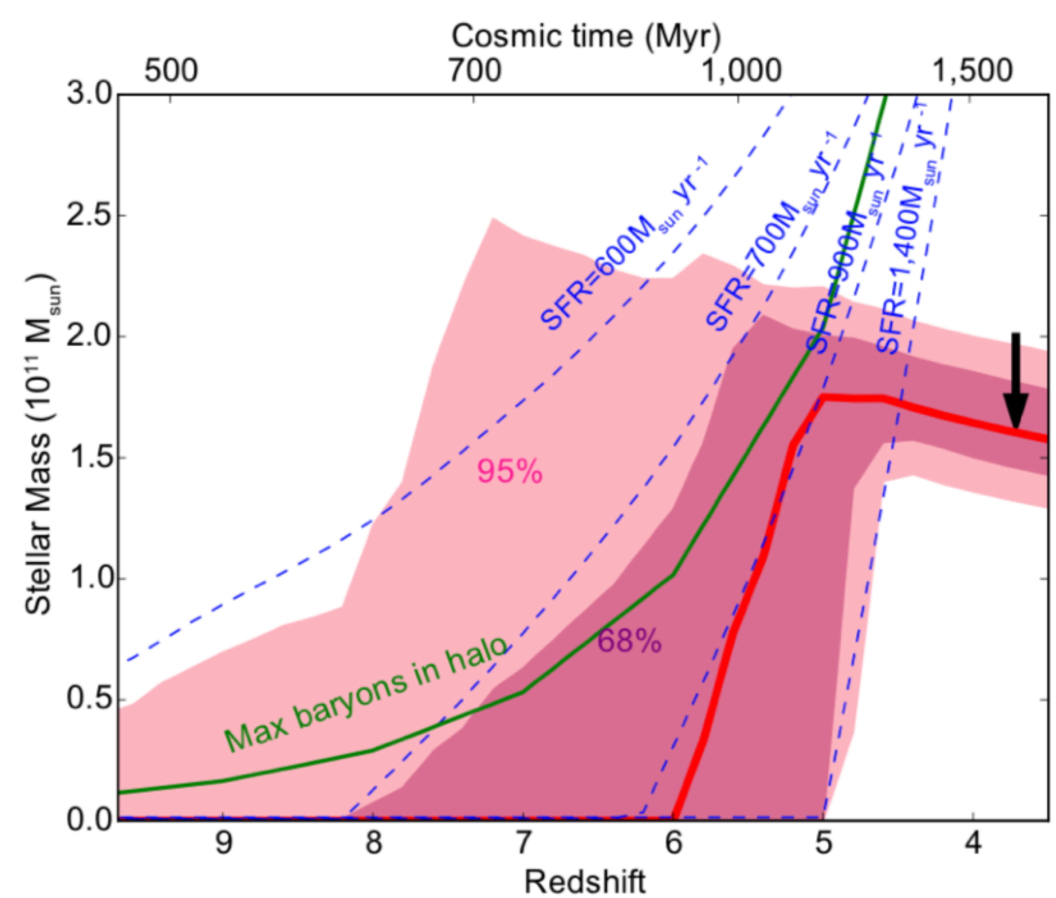
Pannella+2015

(2): An unbiased selection of massive (UV-faint) galaxies: ?

Are we missing a significant population of UV-faint galaxies at high-z?

The large population of massive quiescent galaxies with $M_* \sim 10^{11} M_\odot$ at z~3-4 ($\sim 2 \times 10^{-5} Mpc^{-3}$) requires a significant population of massive star-forming galaxies at z>4, which are not found in UV-selected samples (Glazebrook+2017, Schreiber+2018).

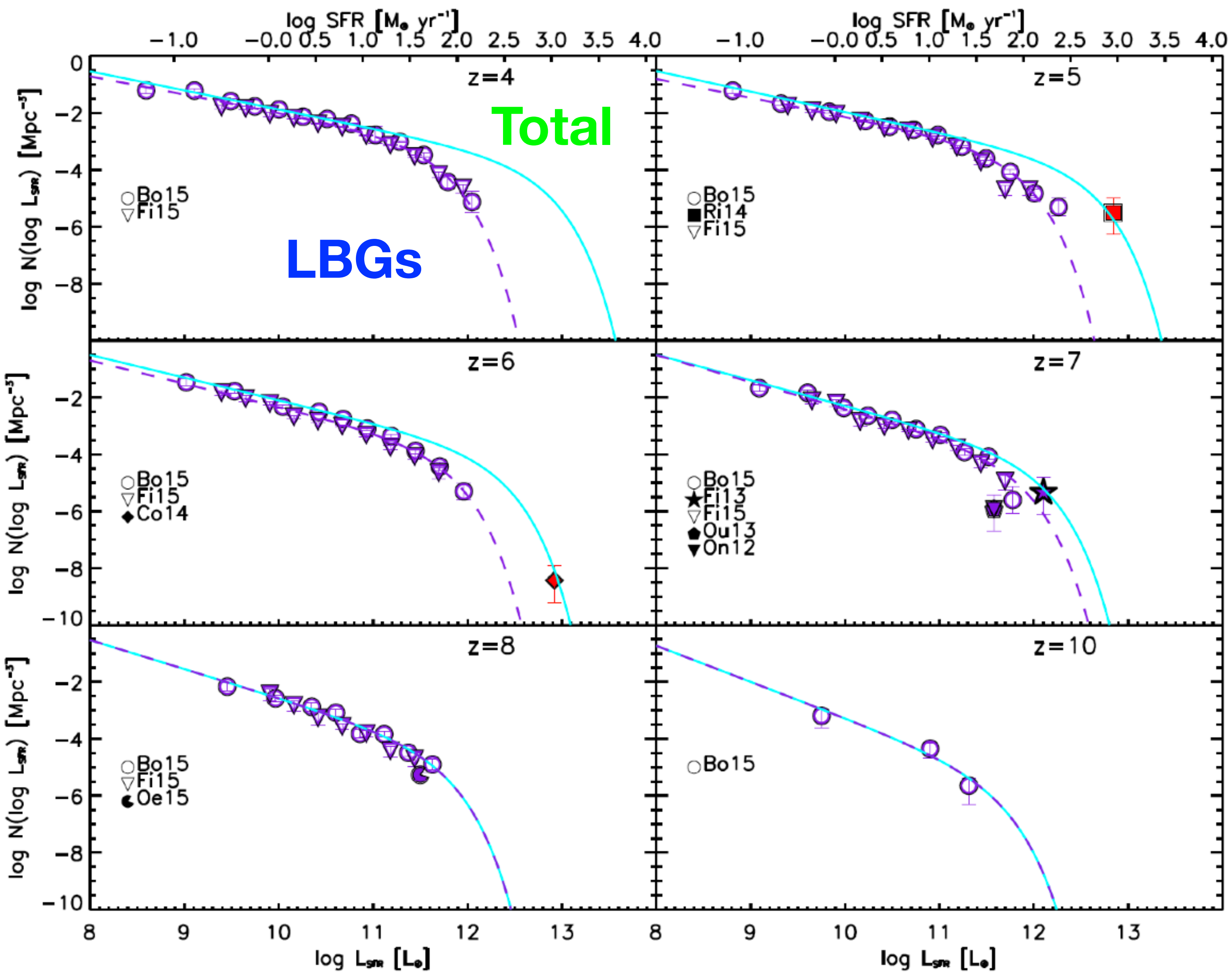




"A mass, quiescent galaxy at z=3.717" Glazebrook+2017, Nature

The quest for a significant population of massive (UV-faint) galaxies at z>3: the evolution of infrared luminosity functions

The inferred infrared luminosity functions at z>3 based on continuity equation suggest a large population of infrared-luminous galaxies that remain to be found.



Mancuso+2016

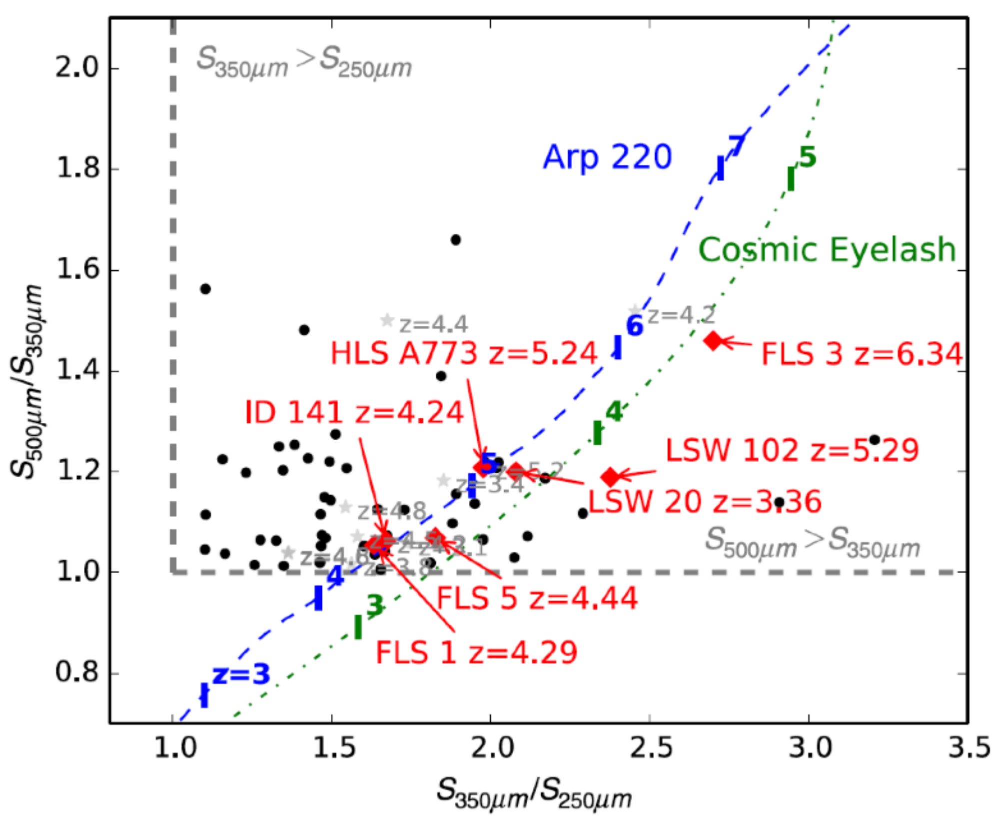
Searching for massive (UV-faint) galaxies at z>3: most confirmed cases are bright SMGs or quasars

bright SMGs

Summary of currently known highest redshift DSFGs at $z > 5$.

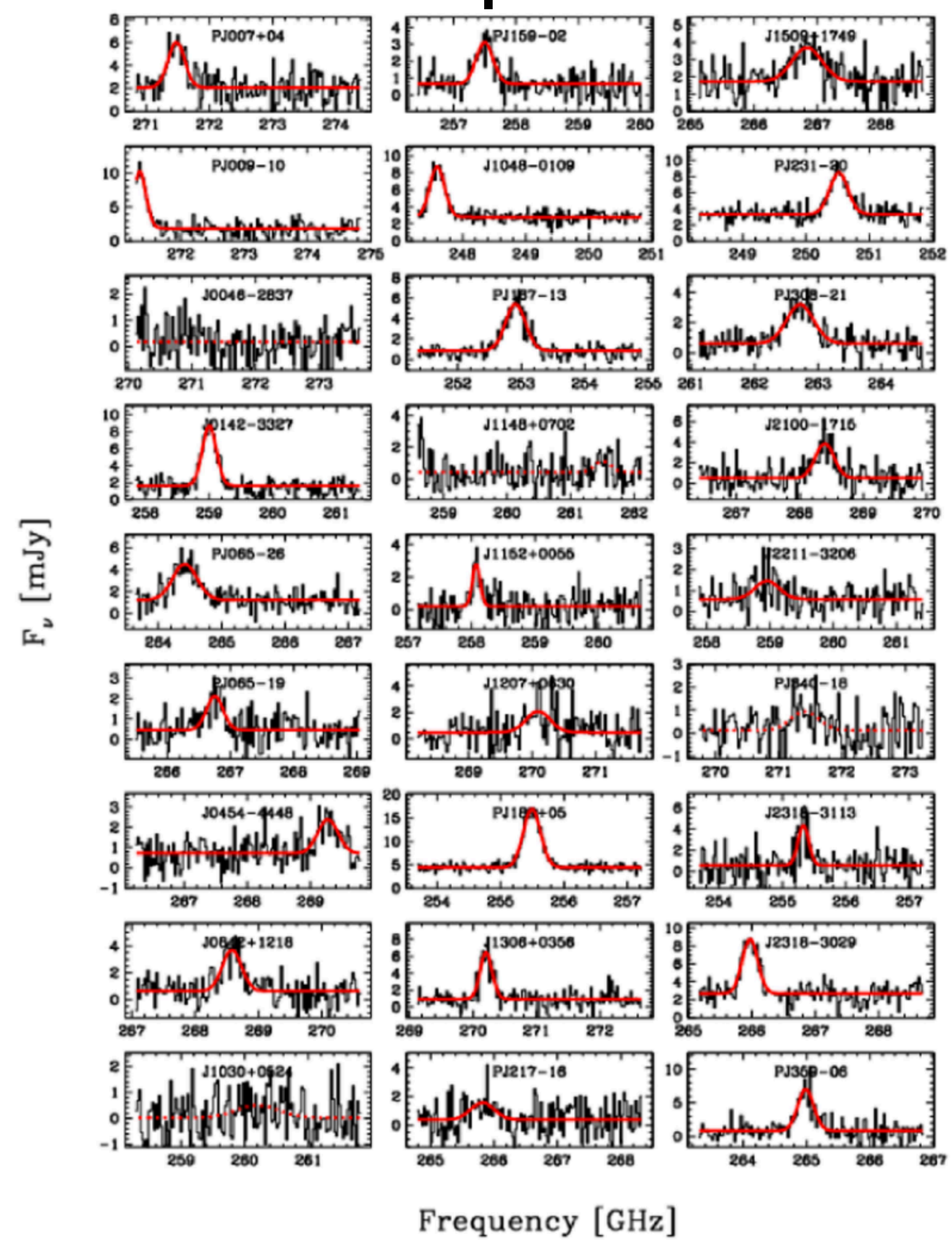
Name	Redshift	S_{850}^{obs} (mJy)	Ref.
J1148+5251[a]	6.42	7.8 ± 0.7	Wang et al. (2007)
HFLS3	6.34	33 ± 2	Riechers et al. (2013b)
SPT0243-49	5.69	73 ± 12	Vieira et al. (2013)
SPT0346-52	5.65	138 ± 24	Vieira et al. (2013)
AzTEC-3	5.30	8.7 ± 1.5	Capak et al. (2011)
HLS J0918+5142	5.24	125 ± 8	Combes et al. (2012)
HDF850.1	5.18	7.0 ± 0.5	Walter et al. (2012)

[a] J1148+5251 is a QSO which happens also to be a bright SMG.



Casey, Narayanan,Cooray, 2014, also see Jin+2019 for a sample of cold dust SMGs

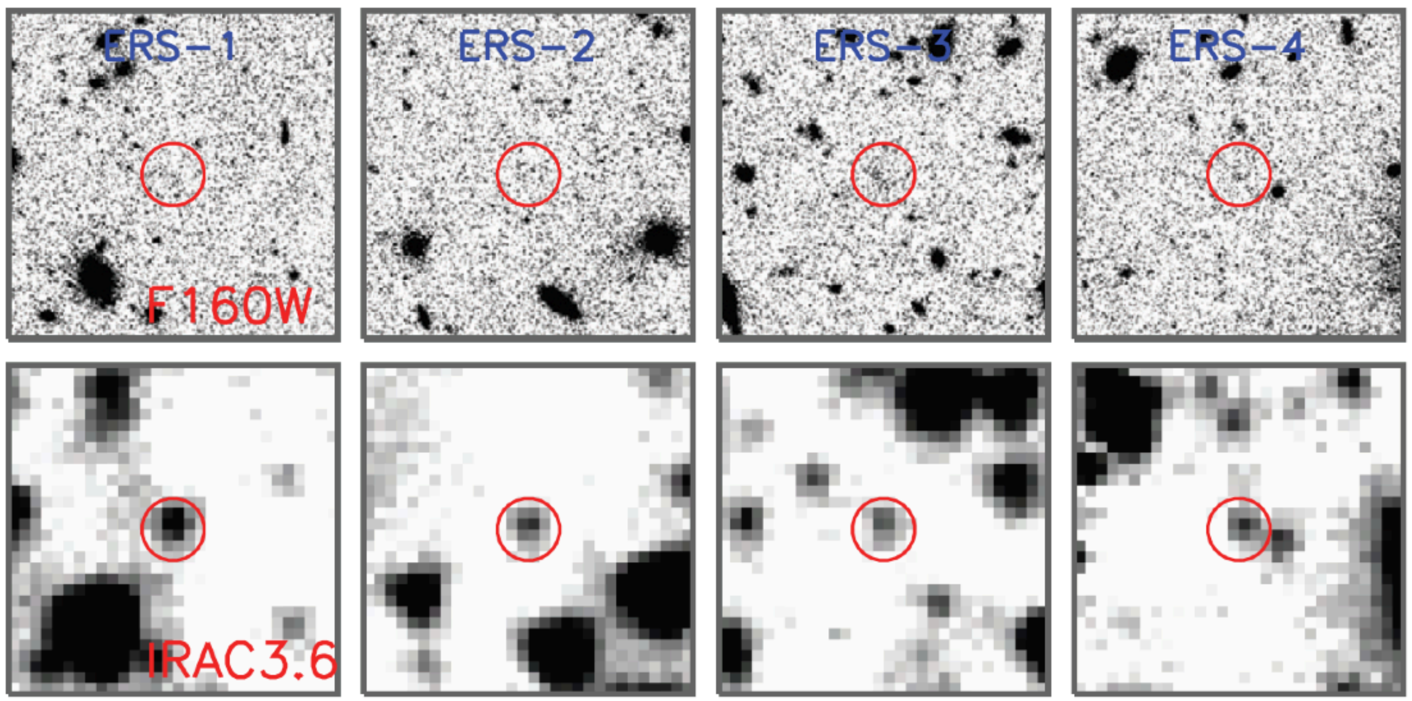
quasars



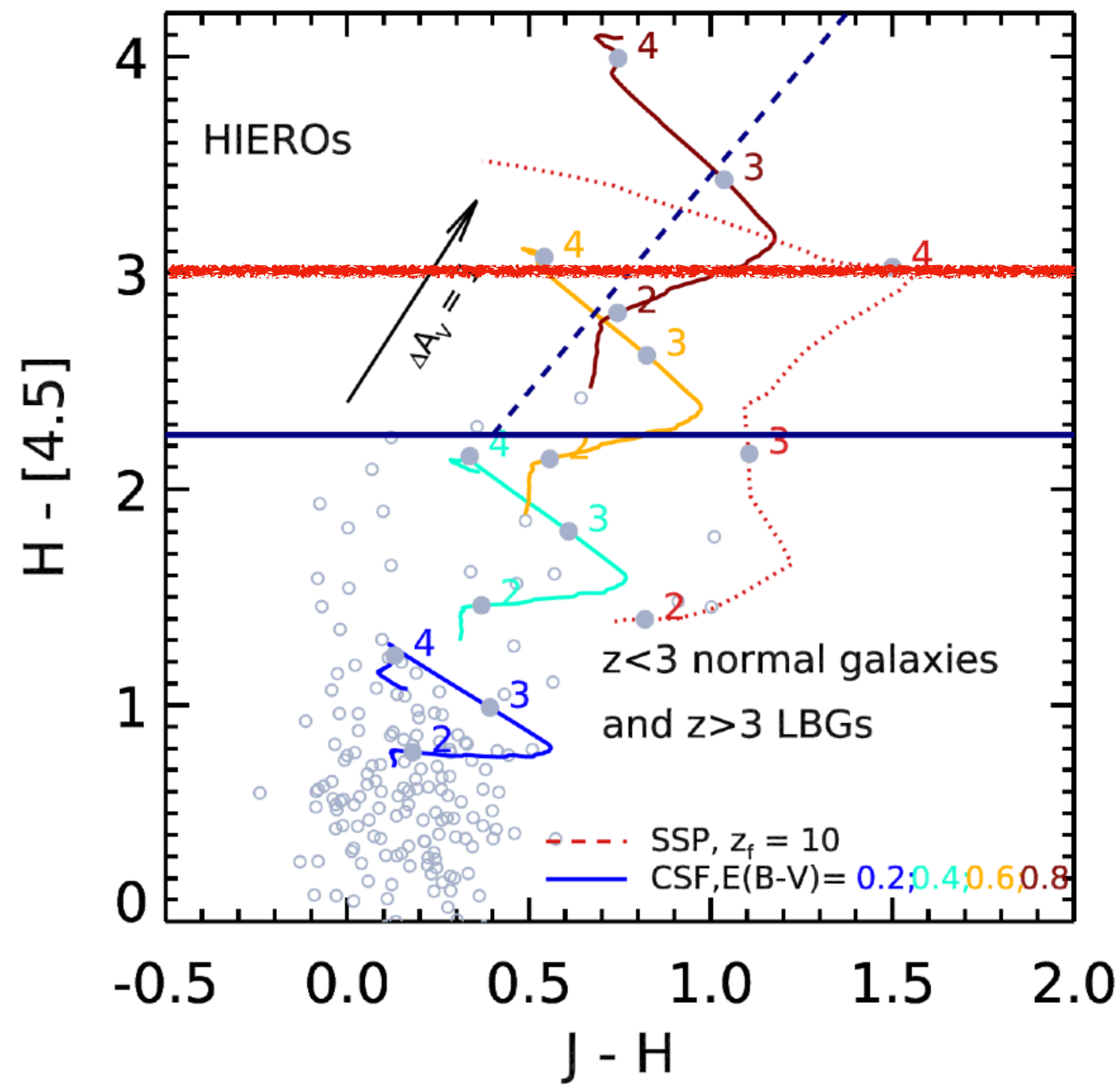
Decarli+2018

A systematic search for massive galaxies missed from UV surveys at z>3:

H-dropouts (IRAC-bright ([4.5] < 24), H-band undetected (H > 27))



Huang (incl Wang)+2011

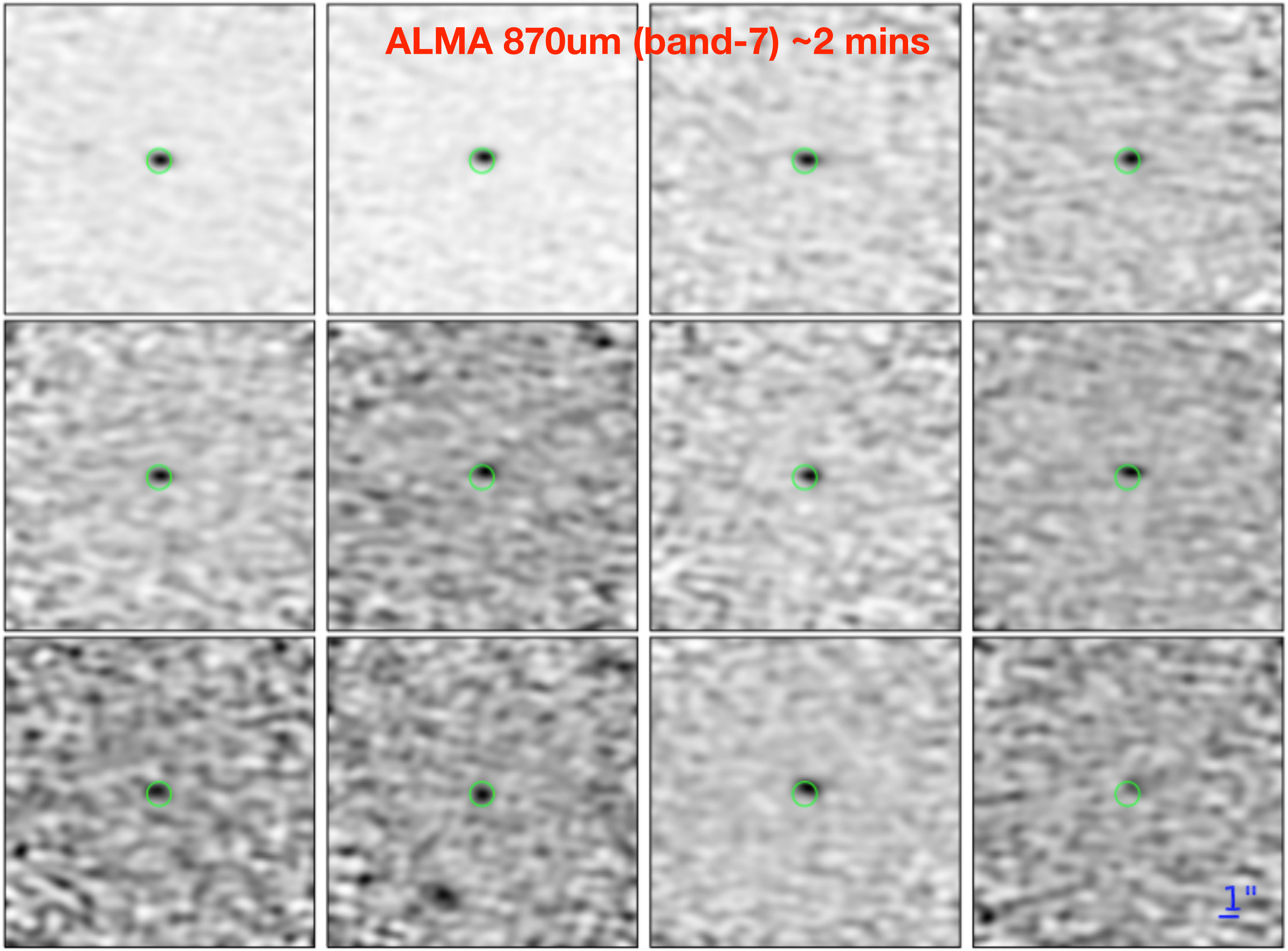


Wang+2016, ApJ, 816, 84

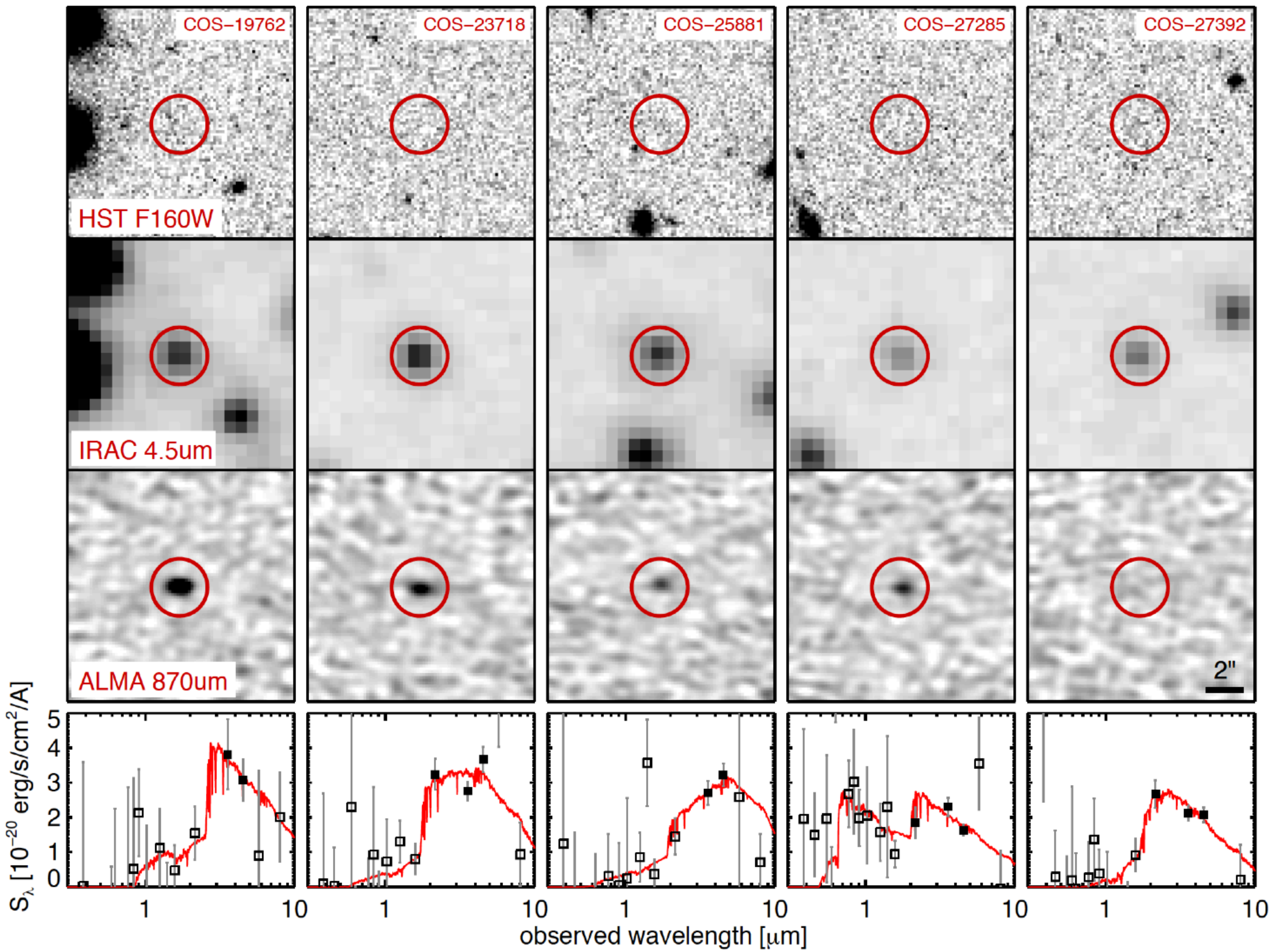
H-dropout sample selection: Crossmatch between 4.5um-selected sample ([4.5] < 24 mag, **complete at $M_* > 10^{10.3} M_\odot$ up to z=6**) and H-selected sample (H < 27 mag) in the three CANDELS fields (GOODS-South, UDS, COSMOS)

Are the most massive z>4 galaxies missed by HST?

(ALMA Cy3, PI: Tao Wang)



“A dominant population of optically invisible massive galaxies in the early universe”

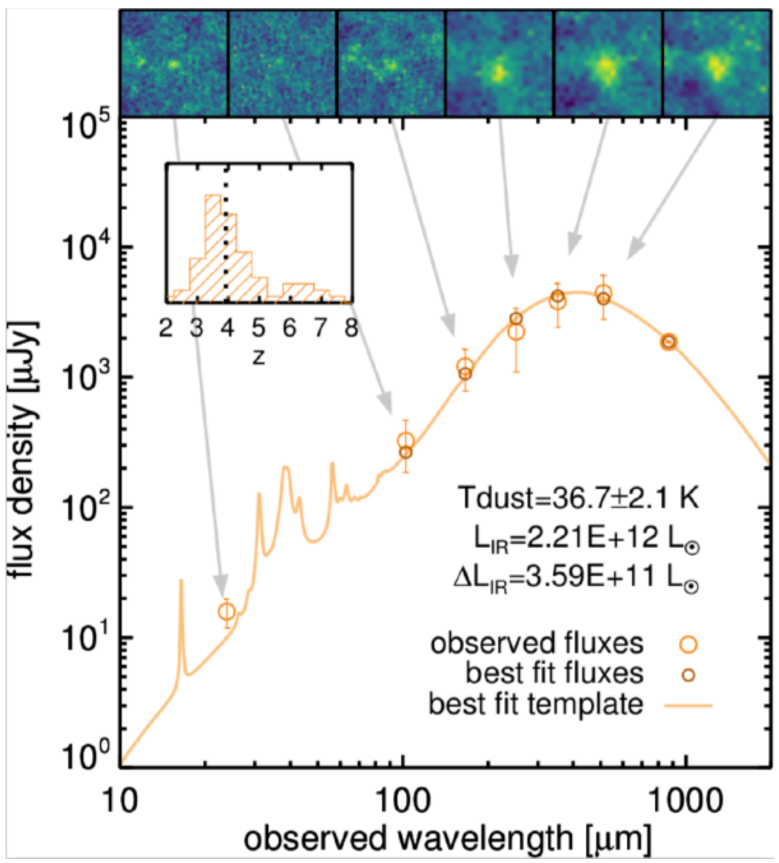


Wang, Schreiber, Elbaz+2019, Nature, 572, 211

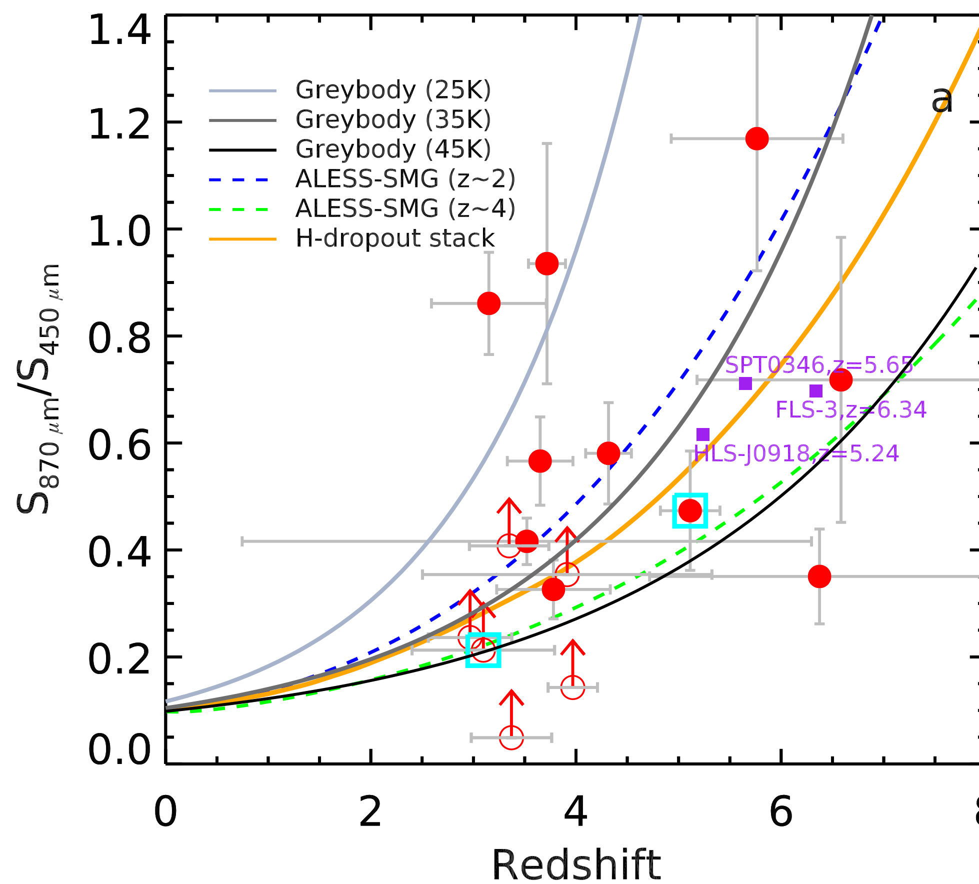
Confirming the redshifts of H-dropouts

- photometric redshifts based on UV-to-NIR SED fitting
- Stacked far-infrared SED
- Far-infrared photometric redshifts estimation based on submillimeter colors, radio-FIR relations
- Cross-correlation between H-dropouts and known UV-bright galaxies at z~4
- Spectroscopic confirmation

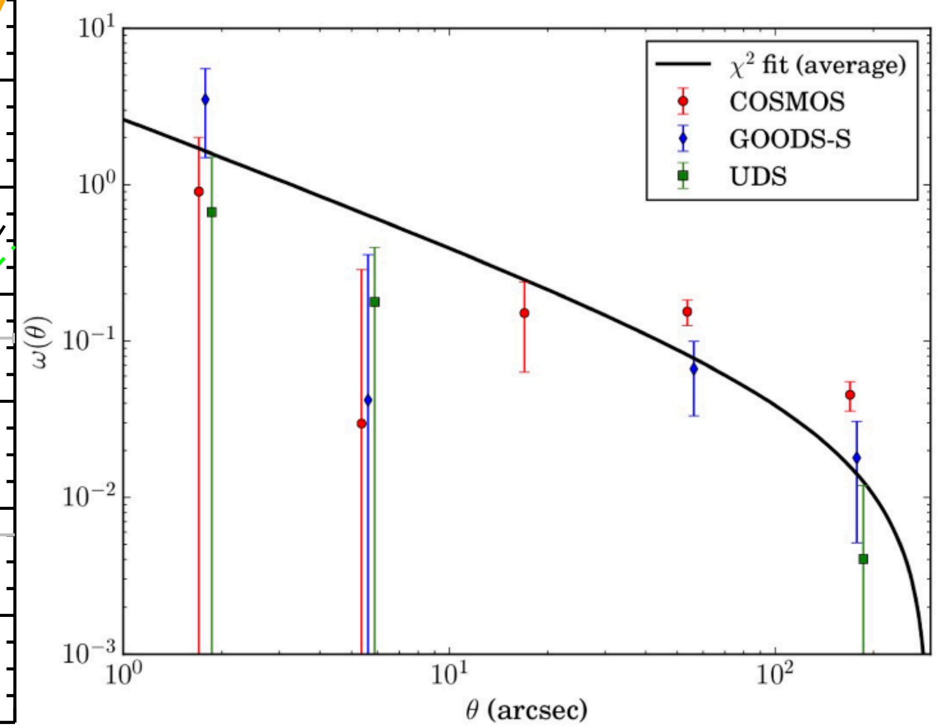
Confirming the redshifts of H-dropouts



Stacked far-infrared SED peaking at ~400um



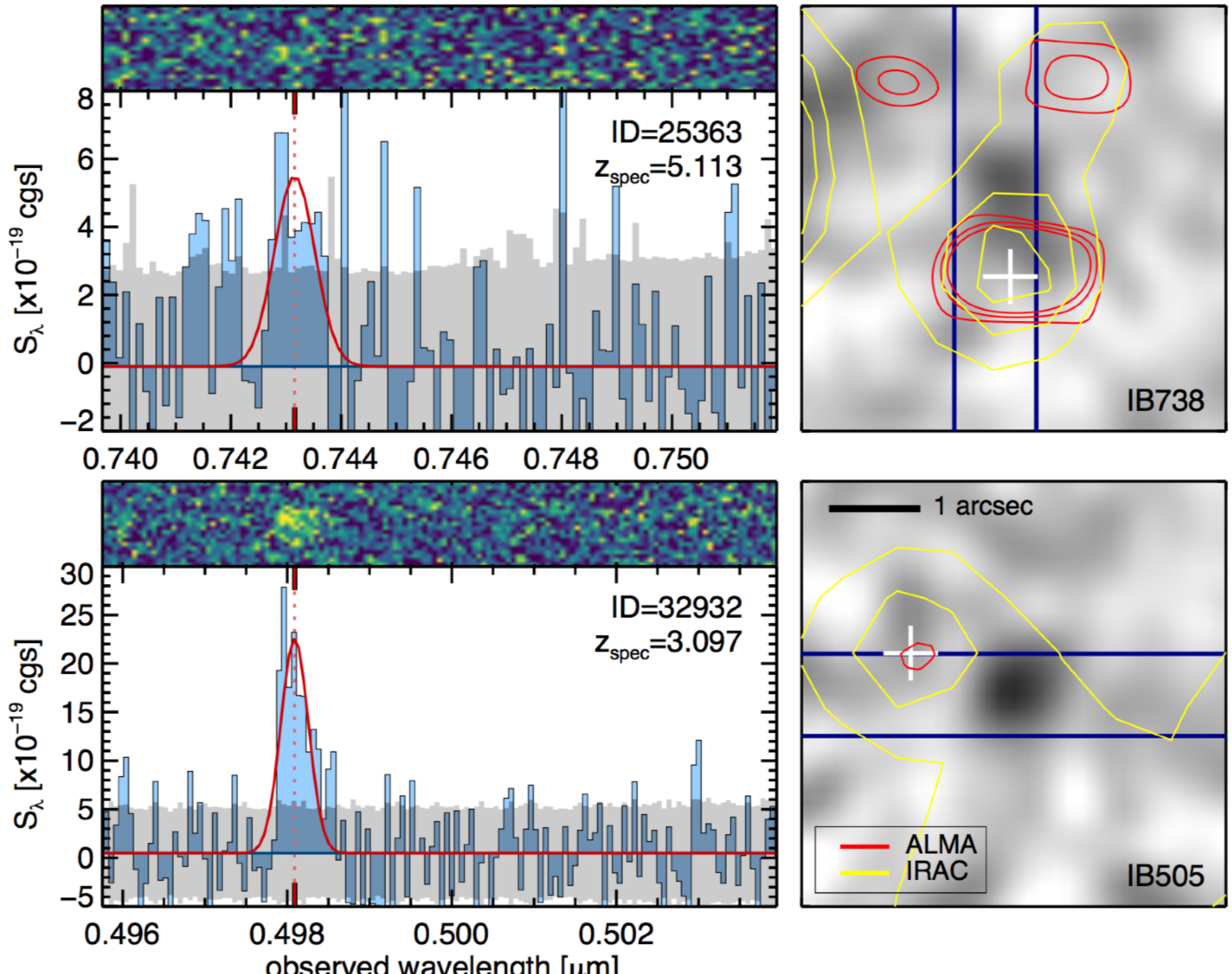
Extremely red 870um/450um colors: half of the sample are likely at z>4



Spatial Correlation between H-dropouts and H-detected galaxies at z=3.5-5.5

Wang+2019, Nature

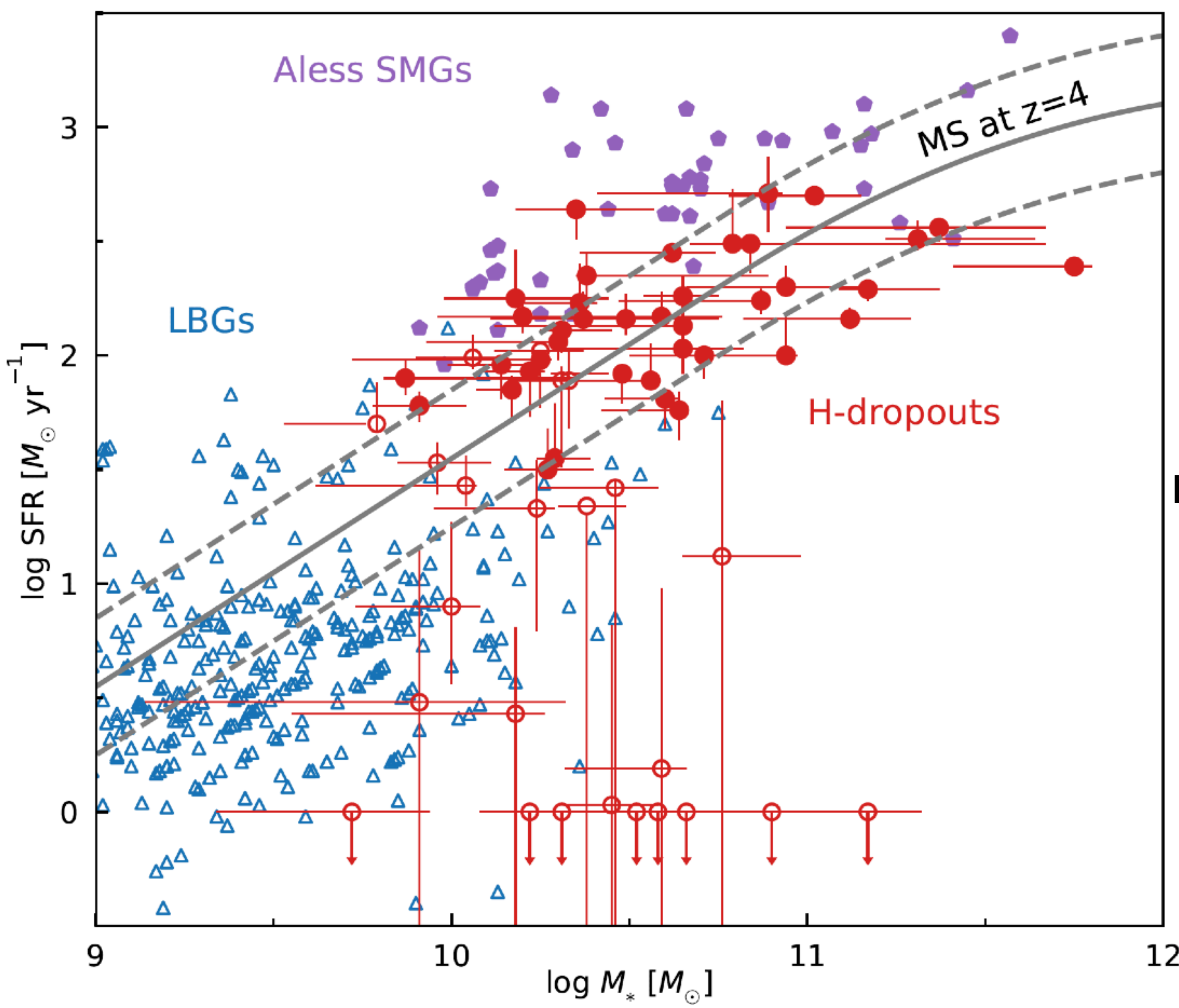
Spectroscopic confirmation: optical-NIR spectroscopy



Wang+2019, Nature

>20% of the sample show Lyman-alpha emission, despite their faintness in the UV continuum.

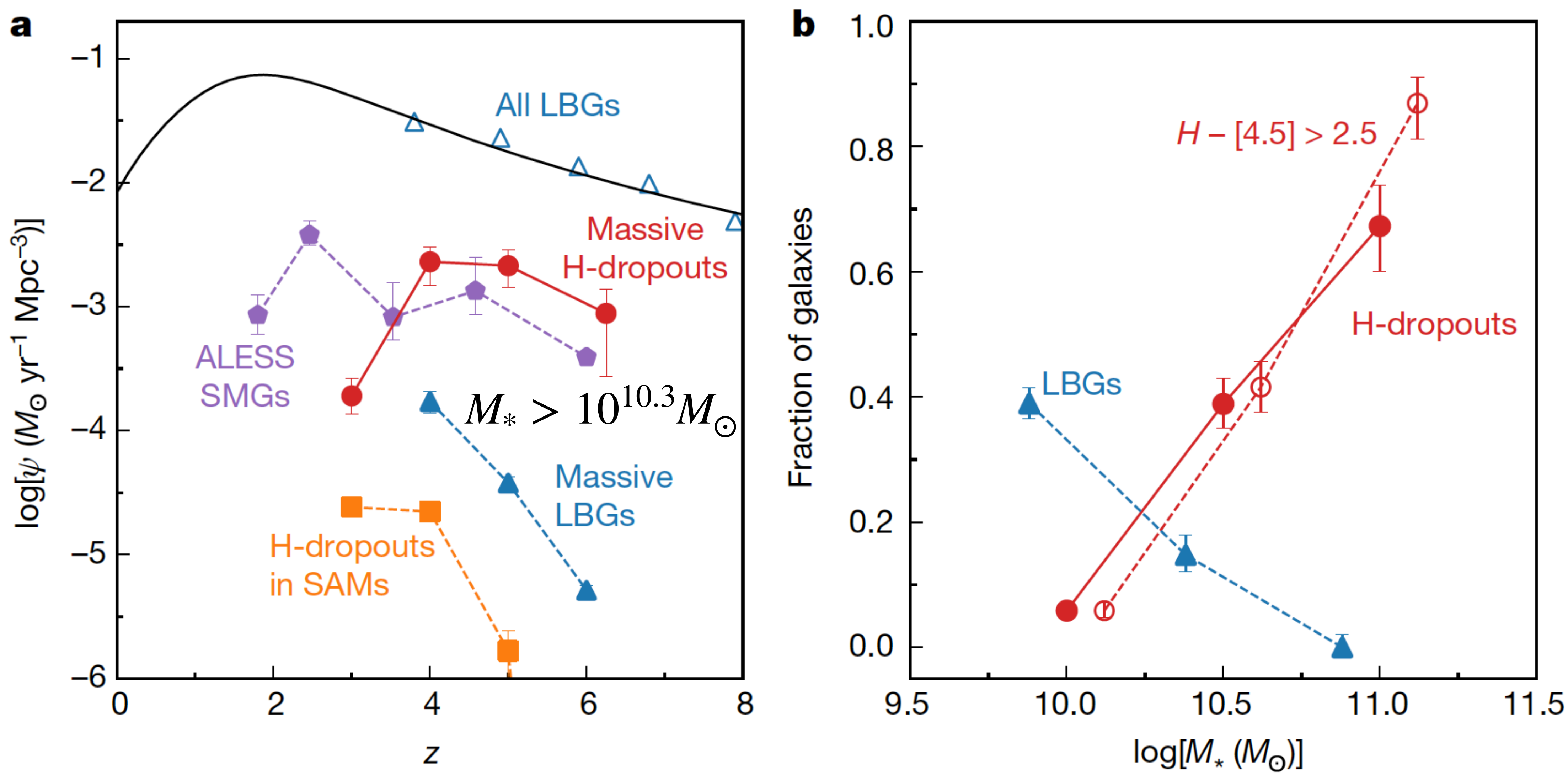
Star-formation: H-dropouts represent massive main-sequence (normal) galaxies at z~4



median S_870=1.6 mJy

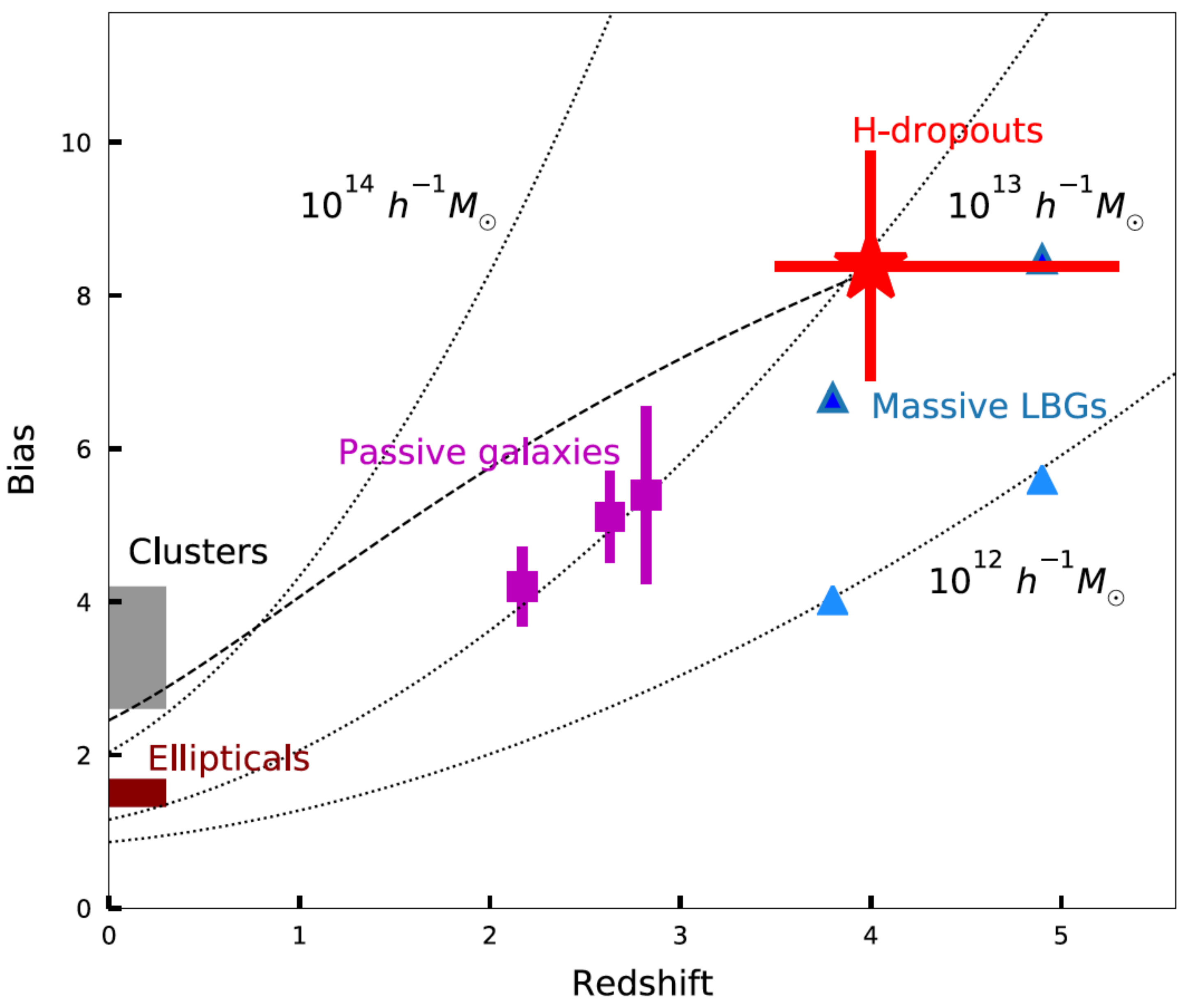
H-dropouts bridge the gap between LBGs and bright SMGs, and represent the bulk population of massive galaxies at z>4 ($n \sim 2 \times 10^{-5} Mpc^{-3}$), which are completely missed by LBGs

H-dropouts dominate the cosmic SFR density from massive galaxies and the high mass end of the stellar mass function at z>3

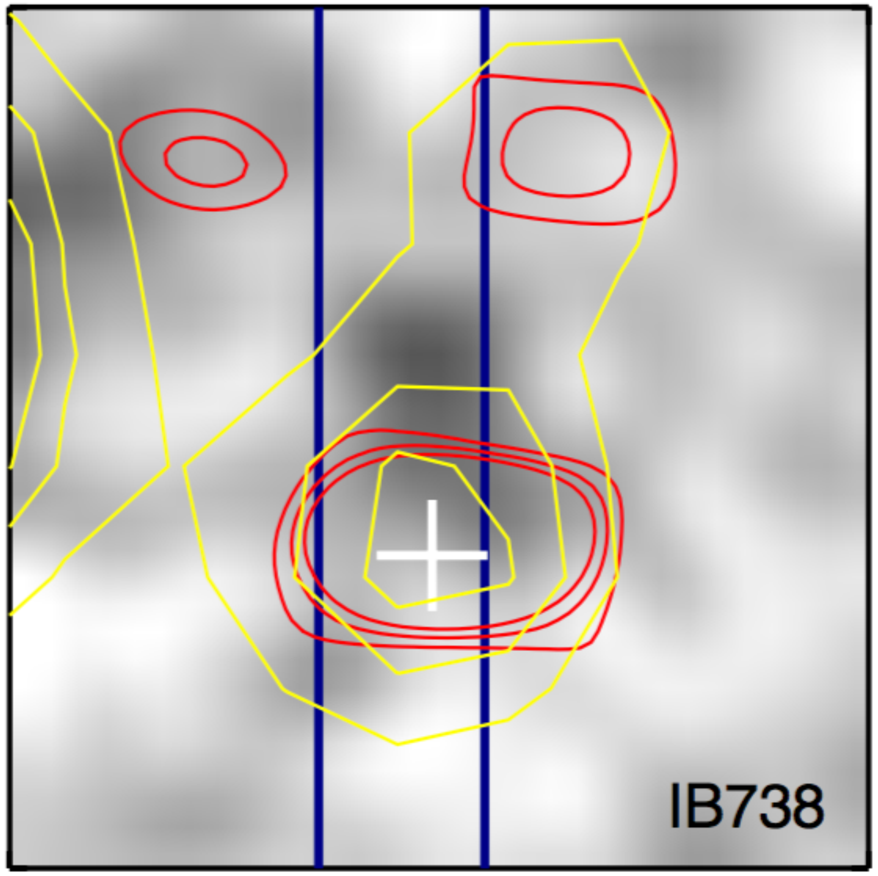


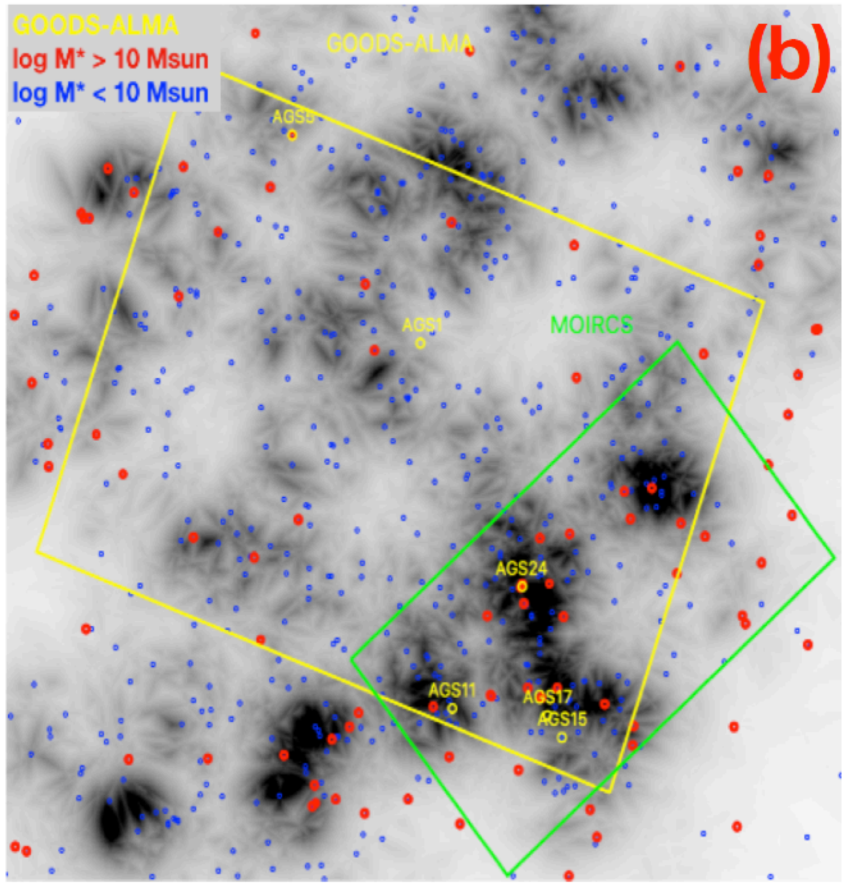
The number density of H-dropouts is orders of magnitudes higher than that in SAMs/Hydro simulations.

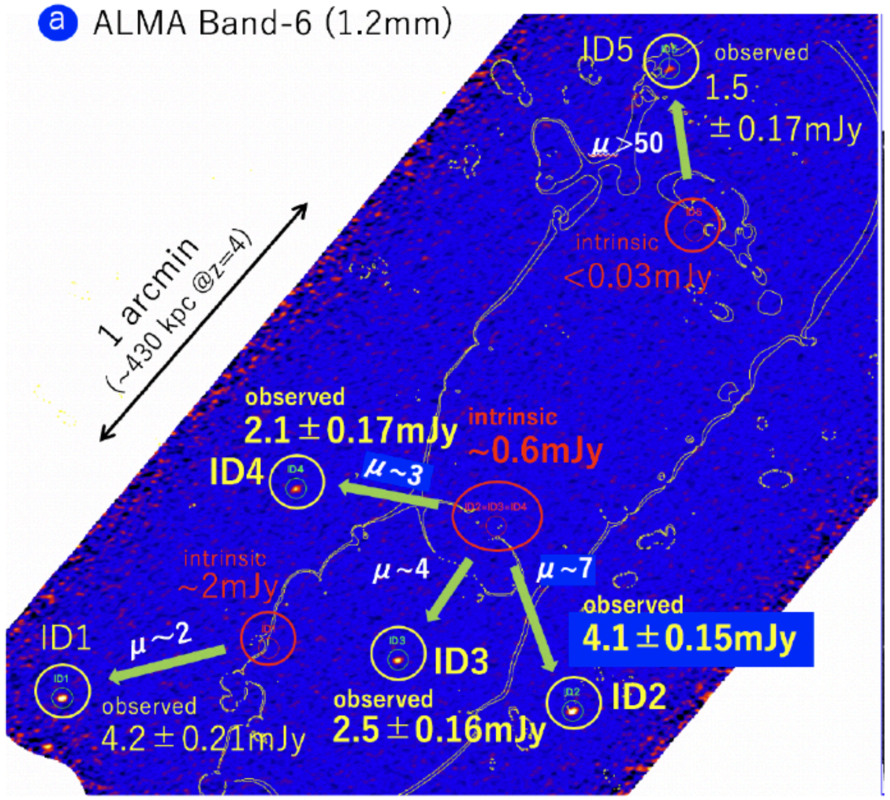
Environment: H-dropouts probe the most massive halos



Environment: H-dropouts trace proto-cluster cores



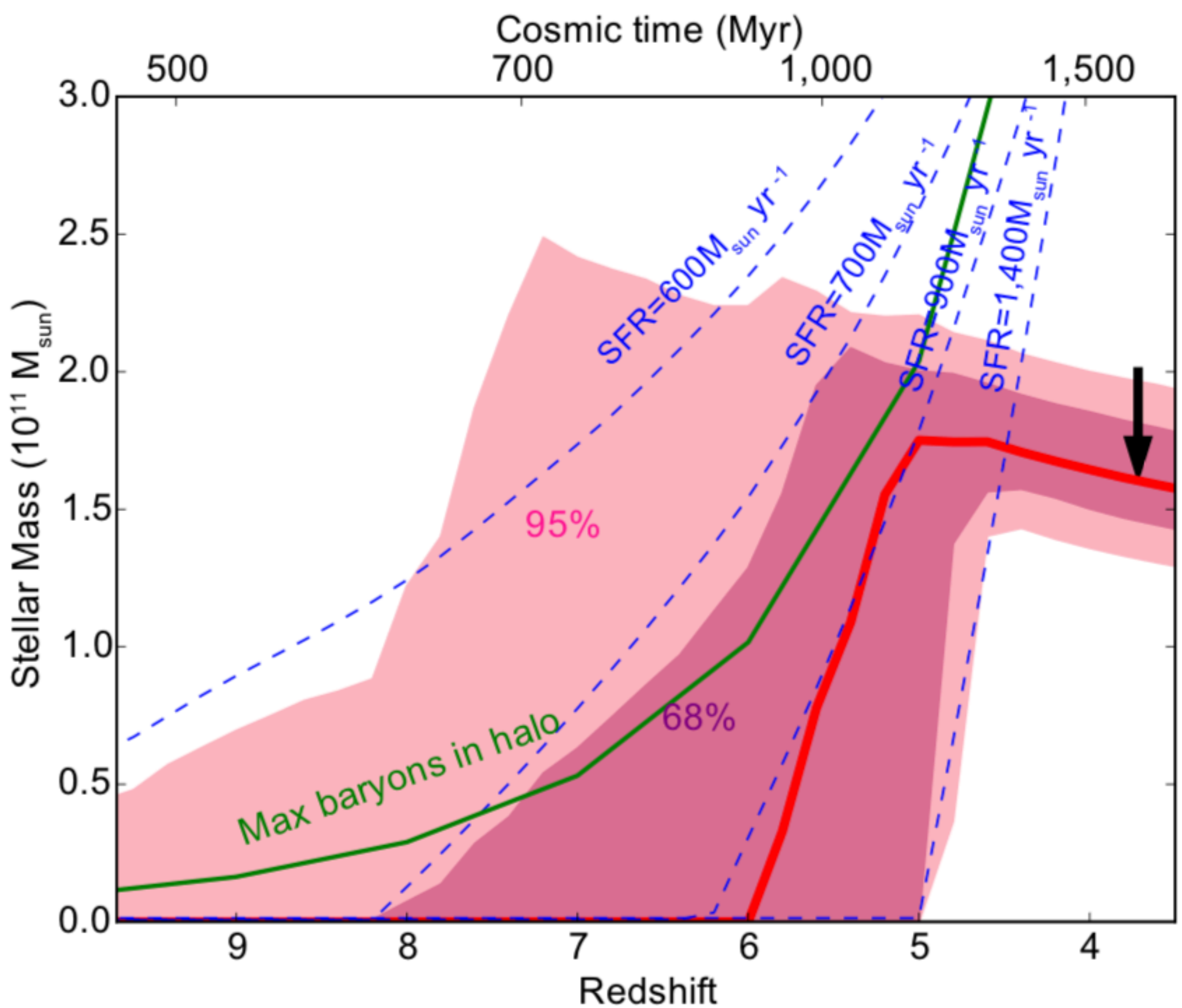




Zhou+2020 (to be submitted)
and GOODS-ALMA (PI: D. Elbaz)

ALMA Lensing Cluster Survey
(PI: K. Kohno)

Future: Prospects for JWST observations



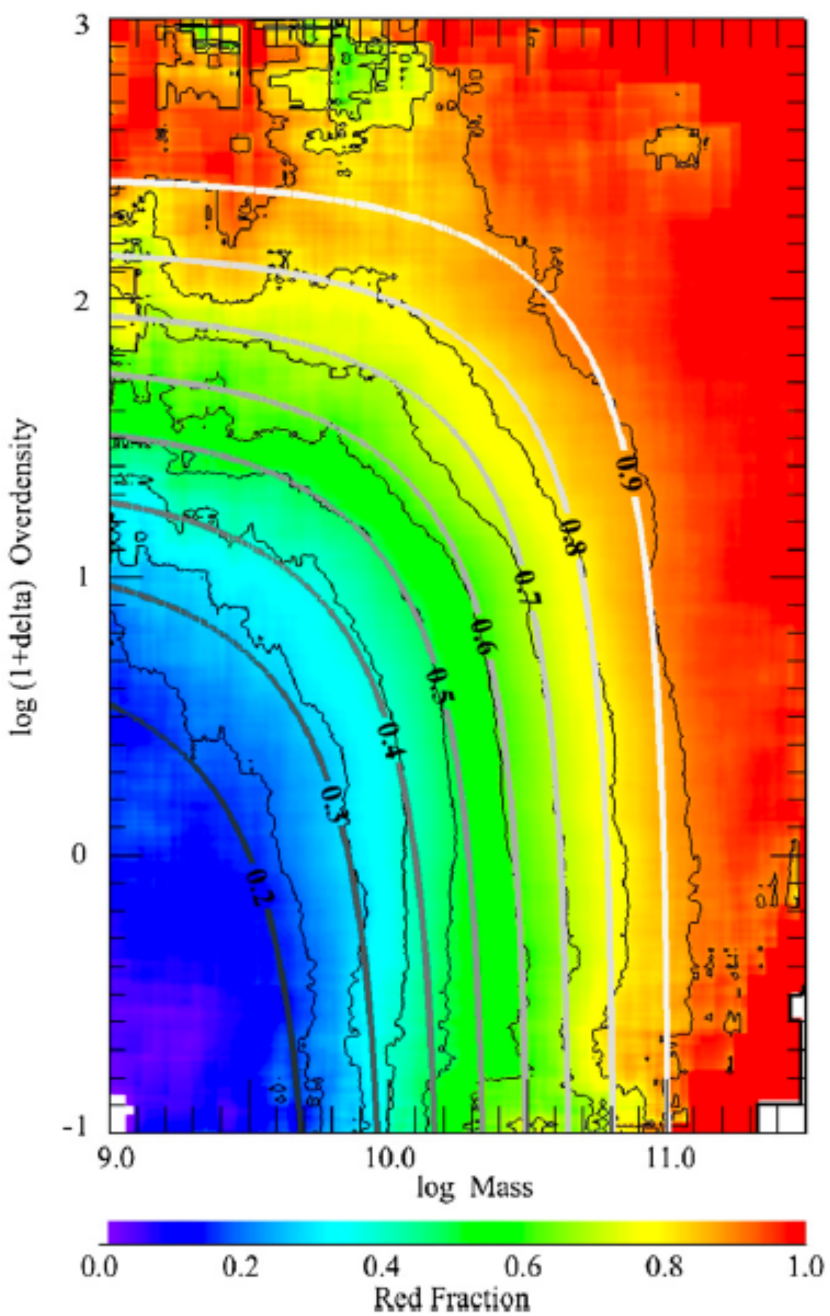
The first (massive) galaxies may never appear to be LBGs.

Star formation histories of a distant massive quiescent galaxies at z=3.717

Glazebrook+2017, Nature

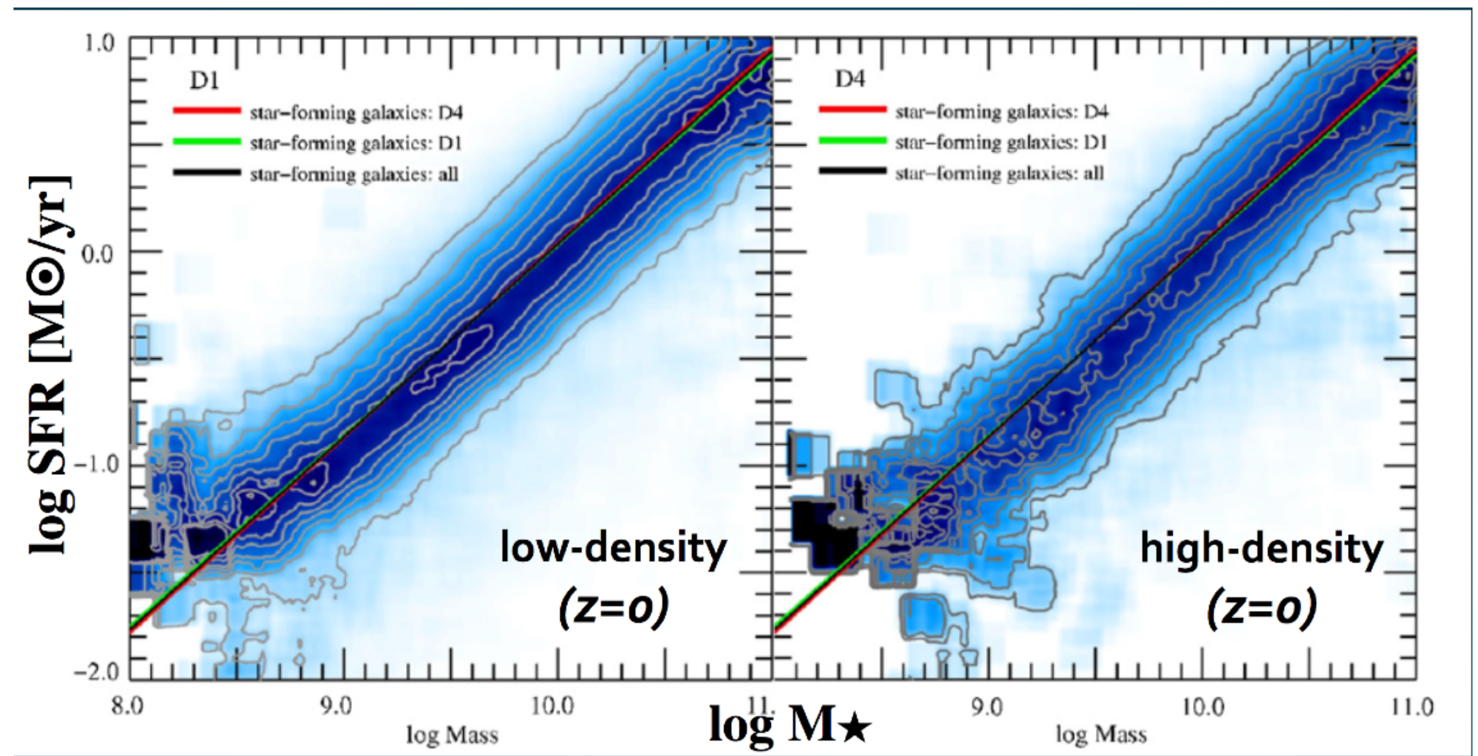

A distant, novel type of galaxy cluster at z=2.51
credit: HST

Environmental effects on massive galaxy formation



Peng+2010

Invariant star forming main-sequence

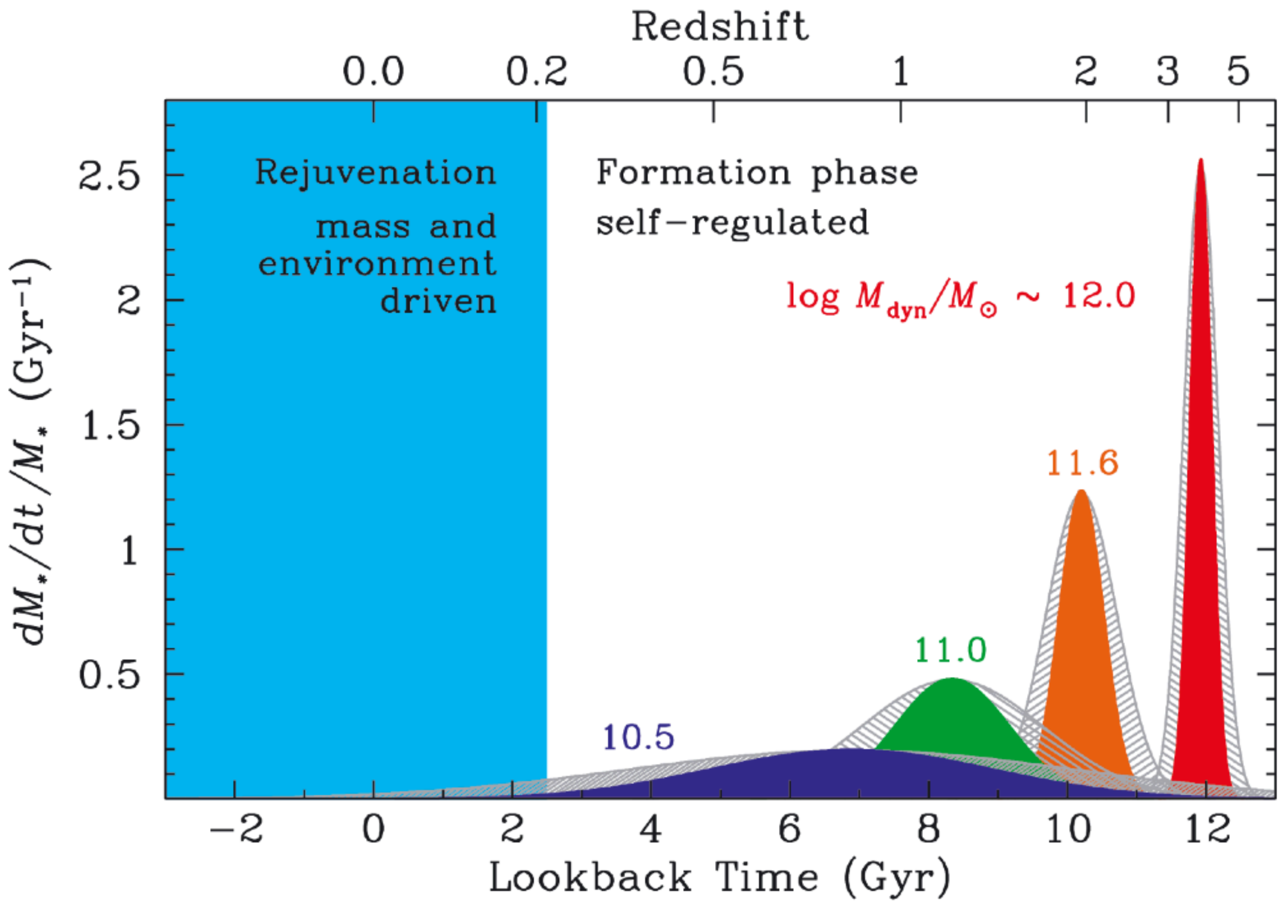


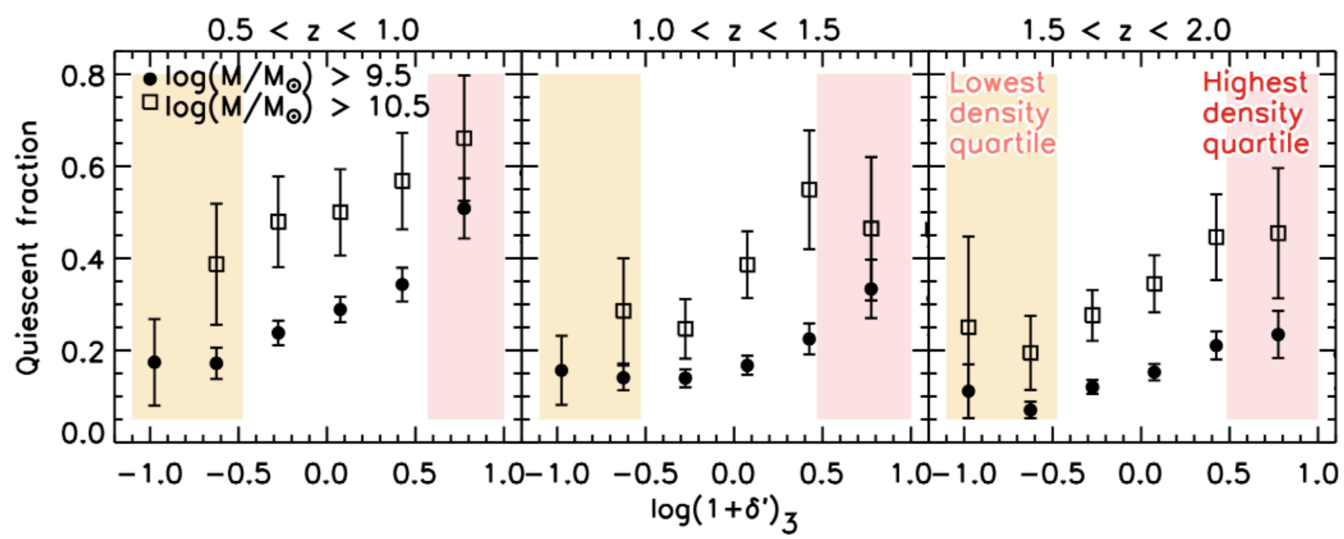
Baldry+2006

also see Koyama+2013 for high-z

The role of environment in massive galaxy formation/quenching remains unclear.

The early assembly of massive (cluster) galaxies



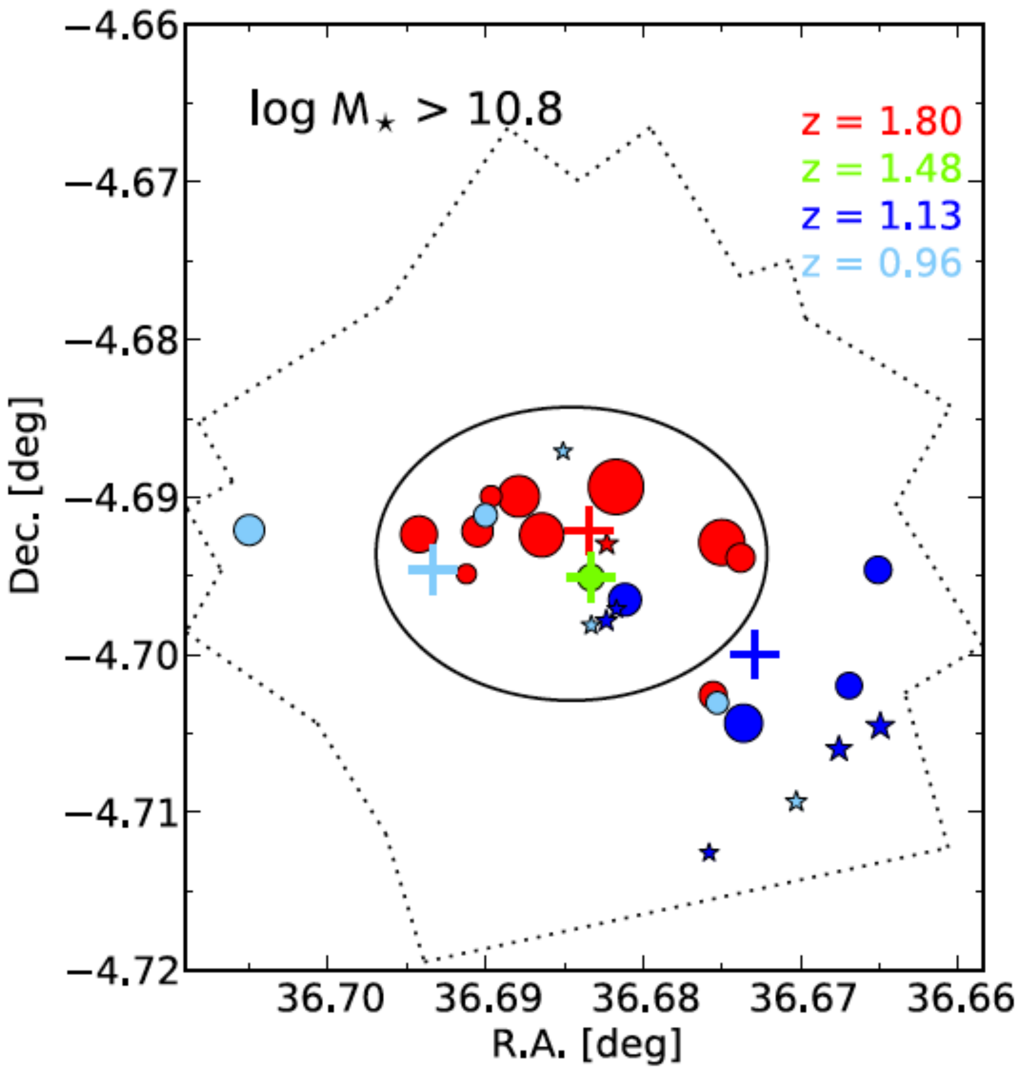


Thomas+2010

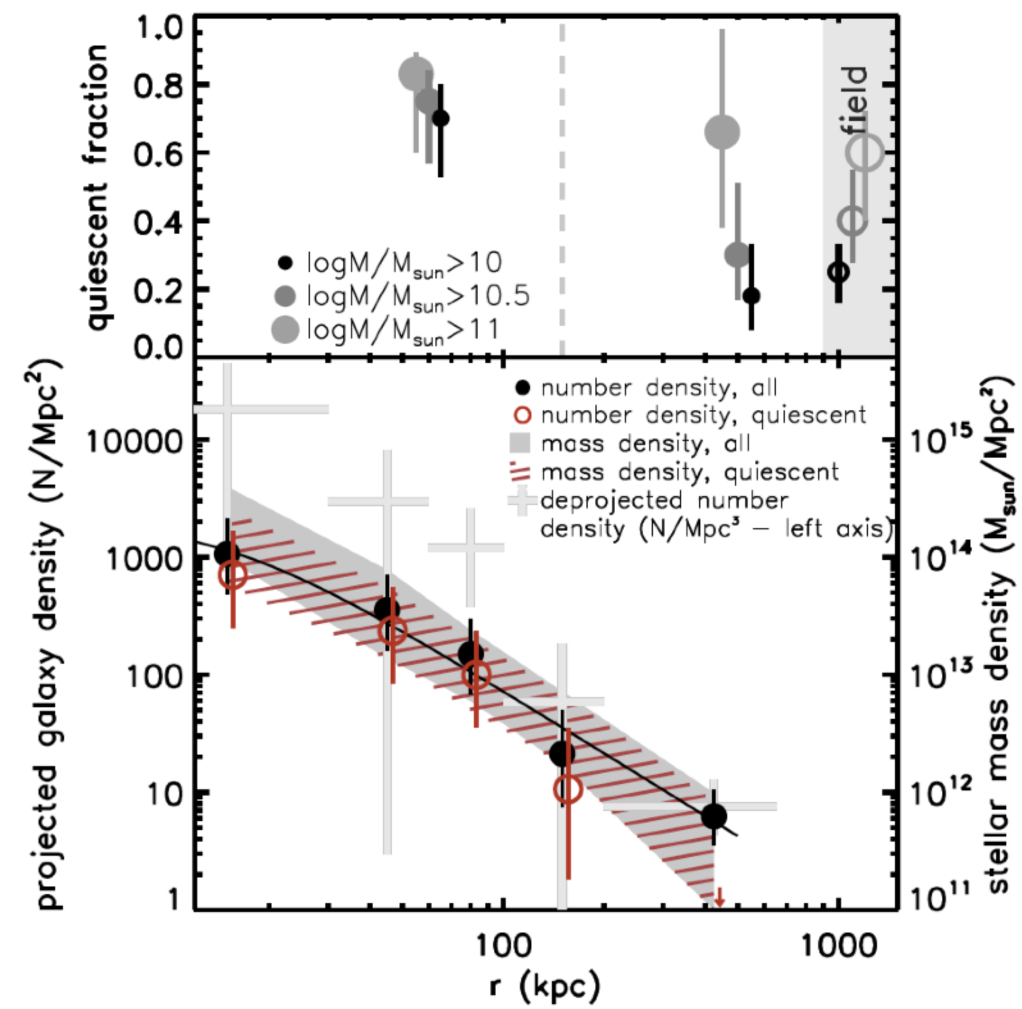
Kawinwanichakij+2017

The early assembly of massive cluster galaxies:

The core of the most massive clusters are already dominated by quiescent galaxies at z~2

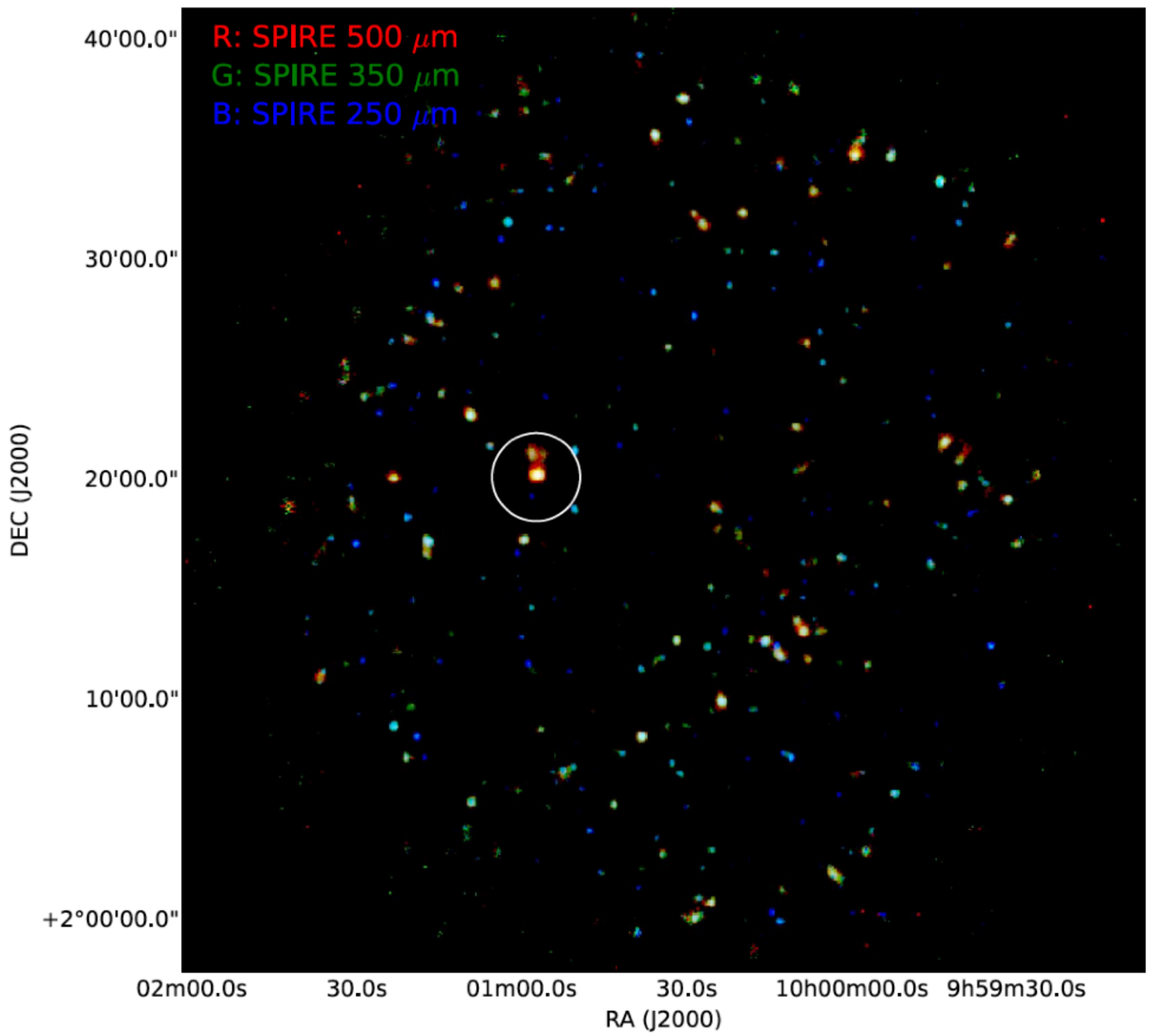


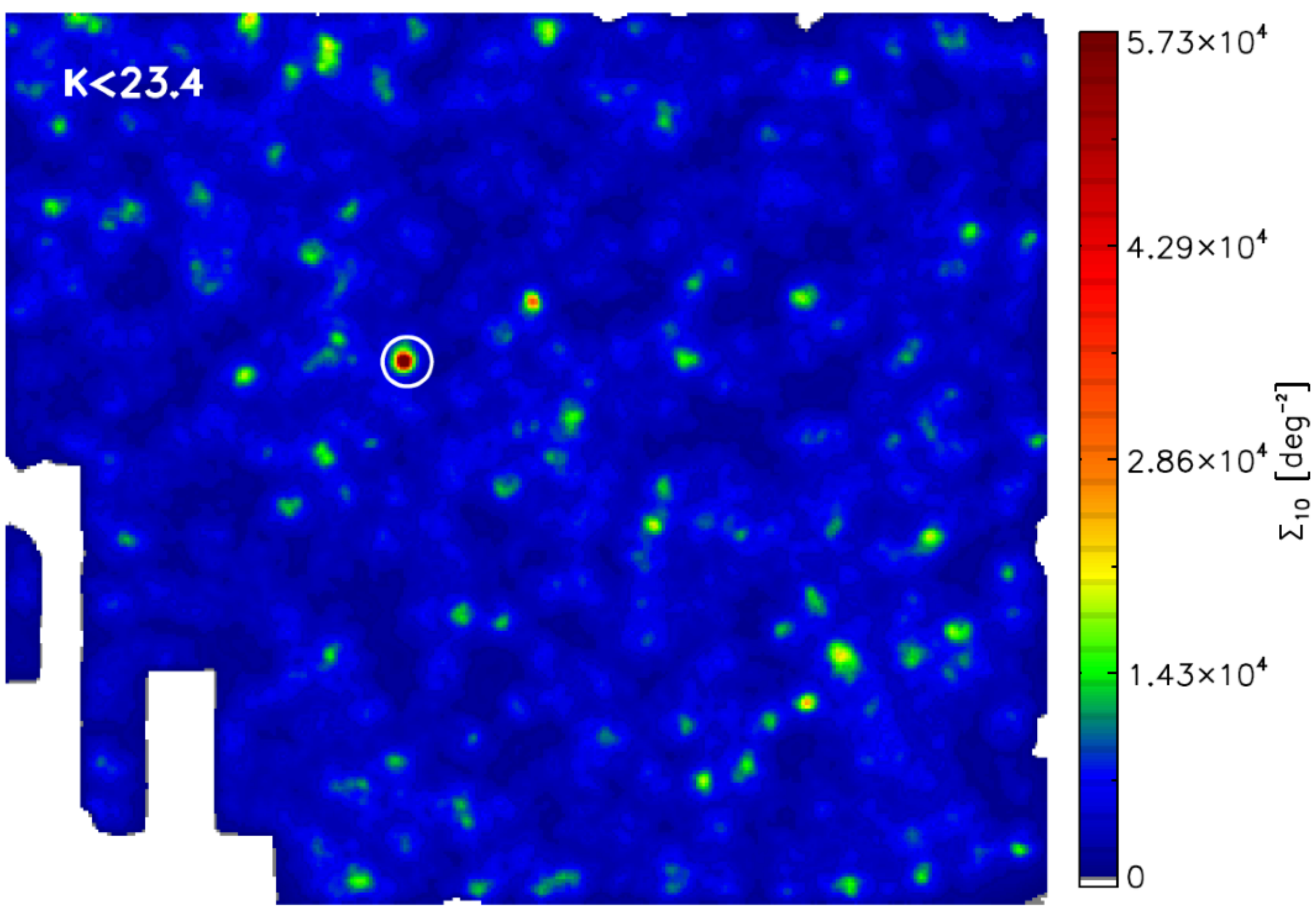
Newman+2014



Strazzullo+2013

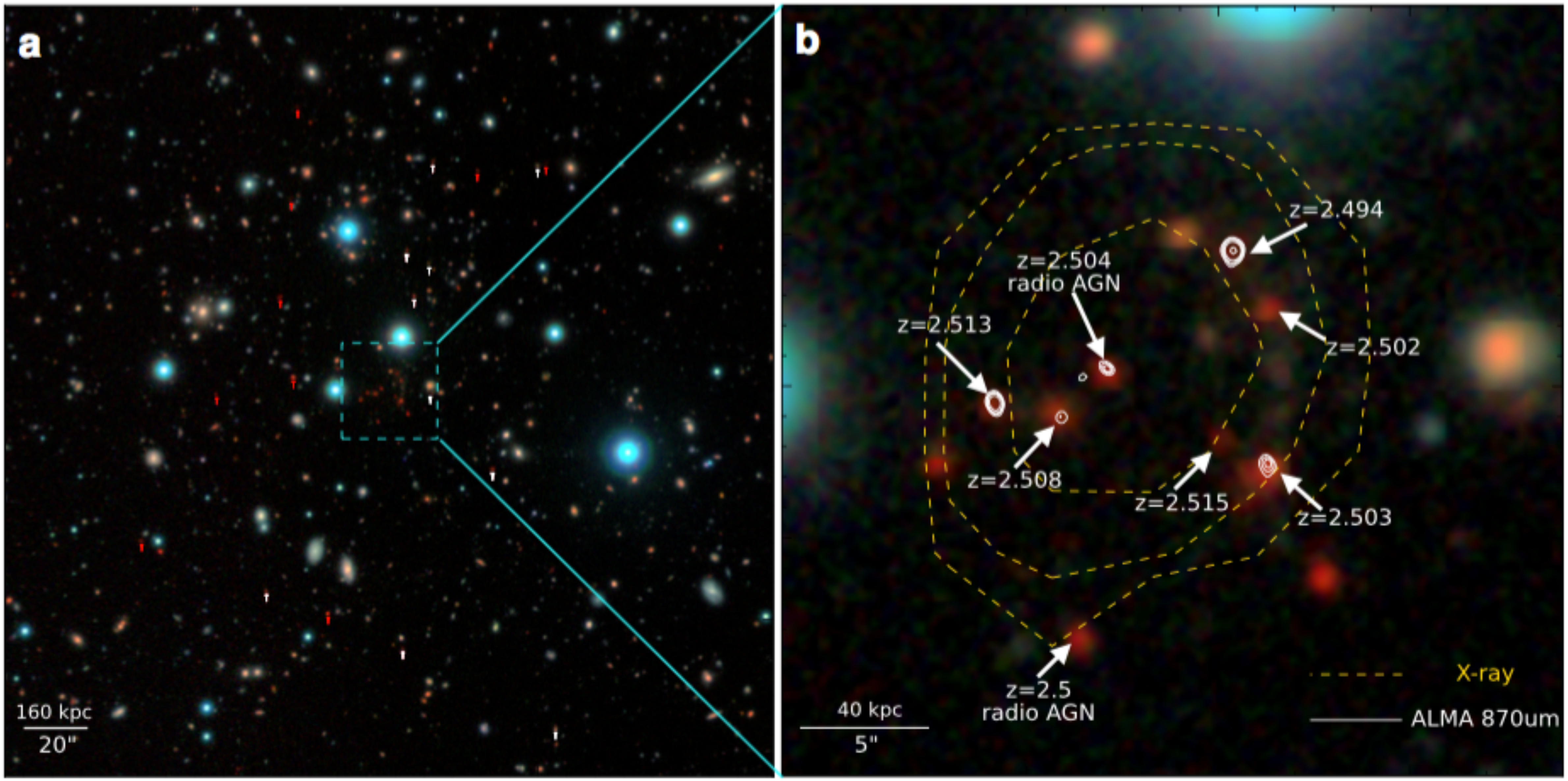
Hunting for massive galaxy clusters in formation (starbursting galaxy clusters) with far-infrared observations





Herschel/SPIRE-selected extremely luminous infrared sources

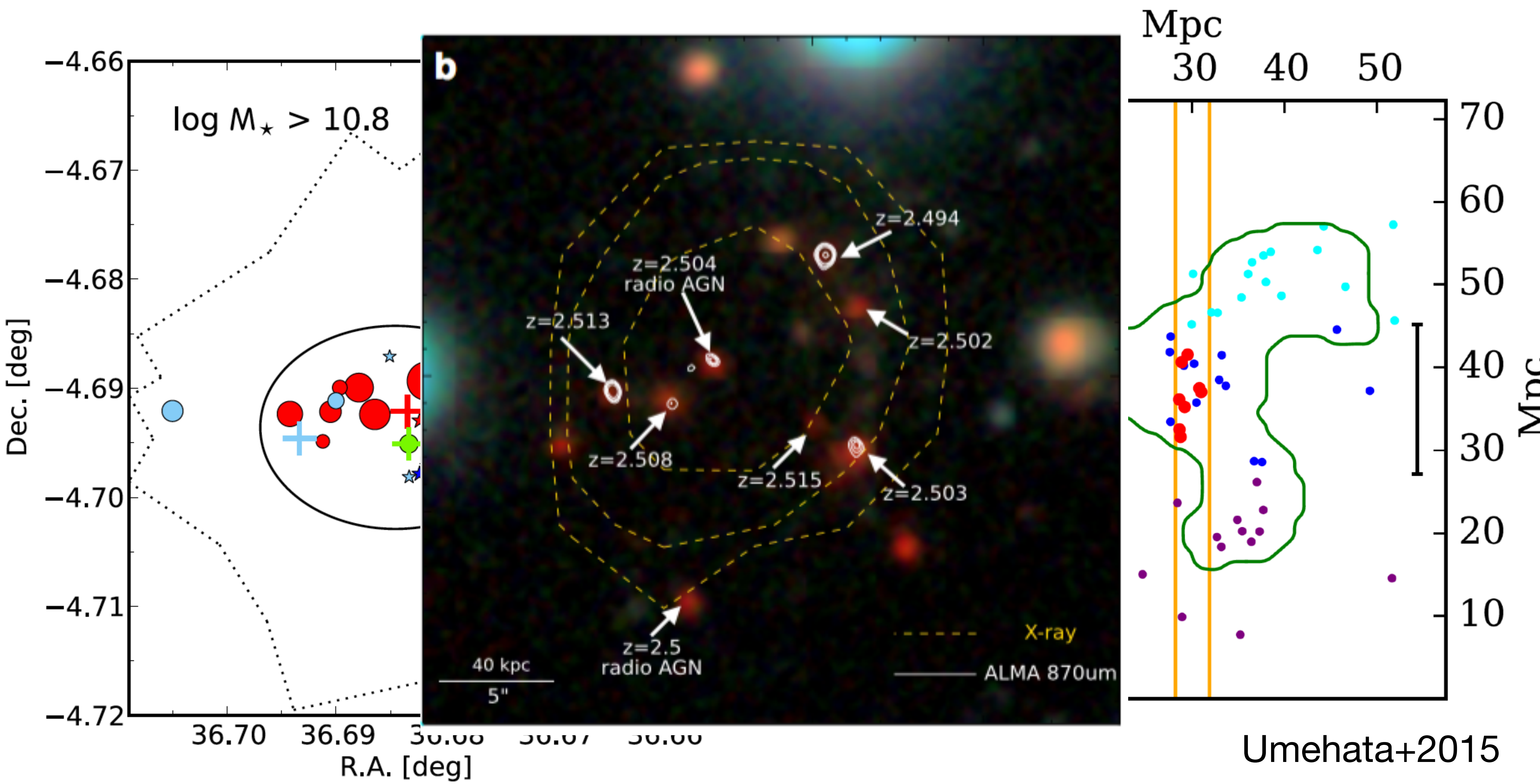
“Discovery of a Galaxy Cluster with a Violently Starbursting Core at z=2.506”



Presence of both **extended X-ray emission** and a **dominant population of massive SFGs**

Wang,T+2016, ApJ, 828,56

J1001 bridges the gap from protocluster to mature clusters

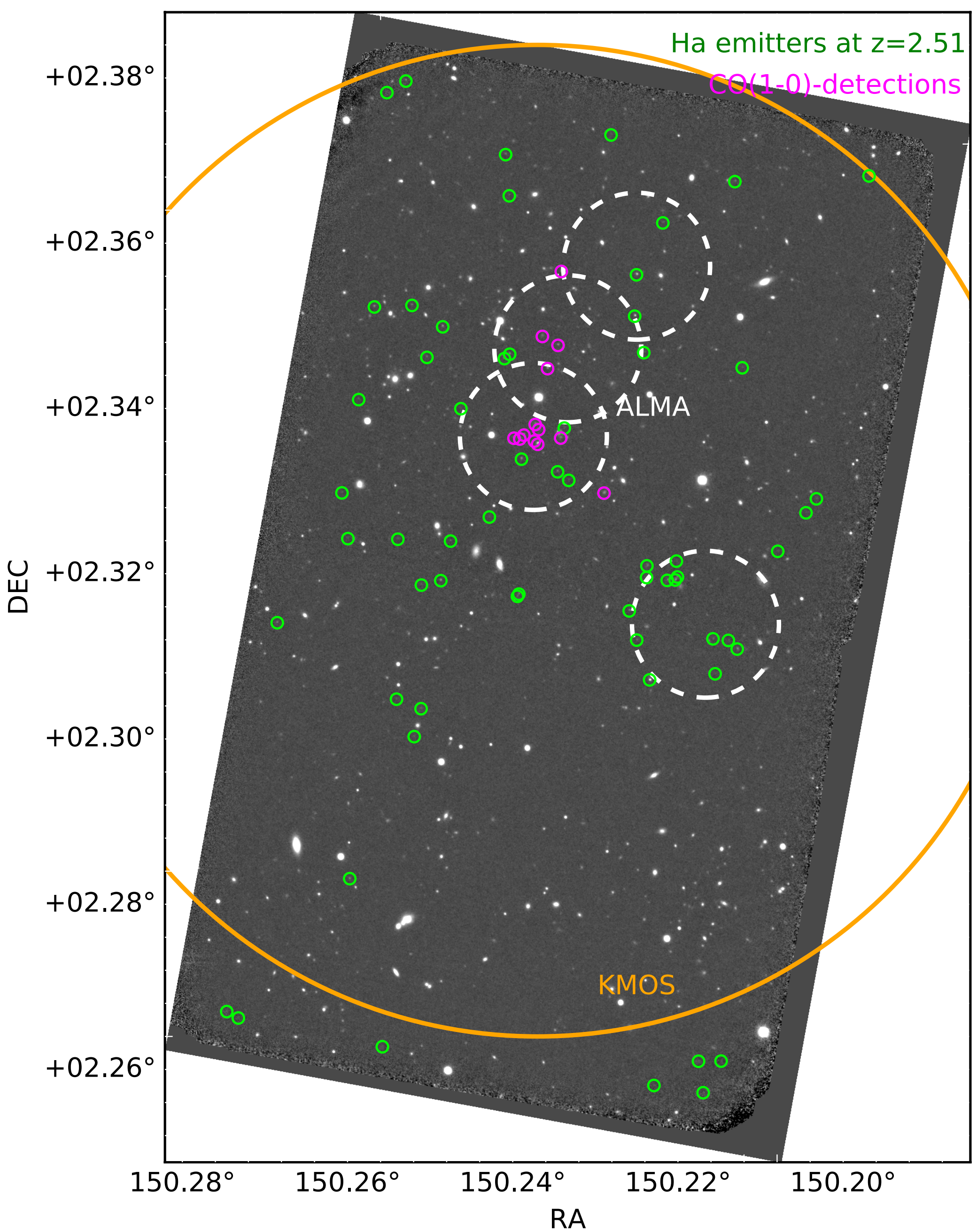


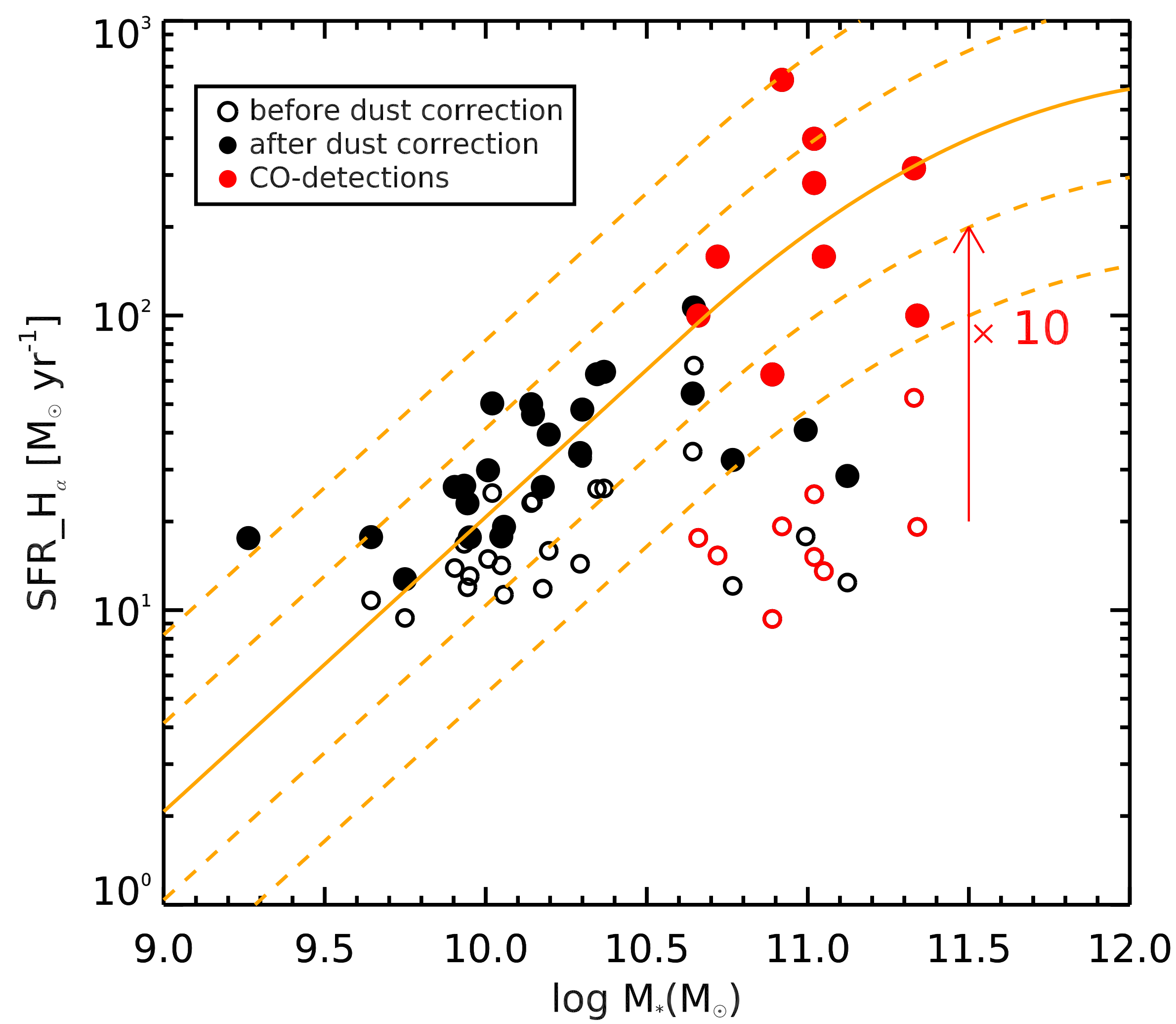
Umehata+2015

A cluster-size, virialized halo yet a dominant population of massive star-forming galaxies

Narrow-band imaging (Ha-emitters) of J1001 with Subaru/MOIRCS:

Towards a complete census of star-forming cluster members

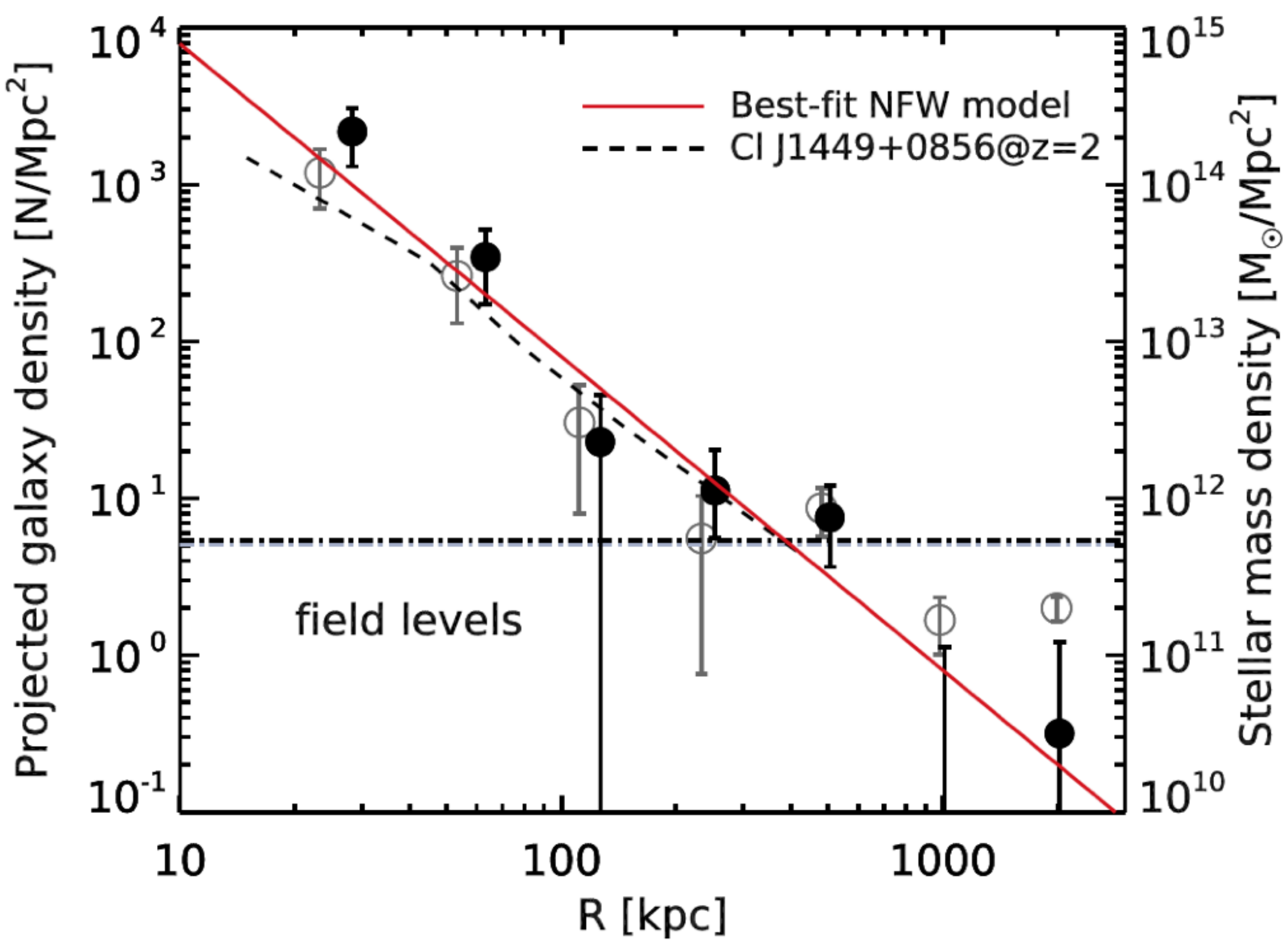




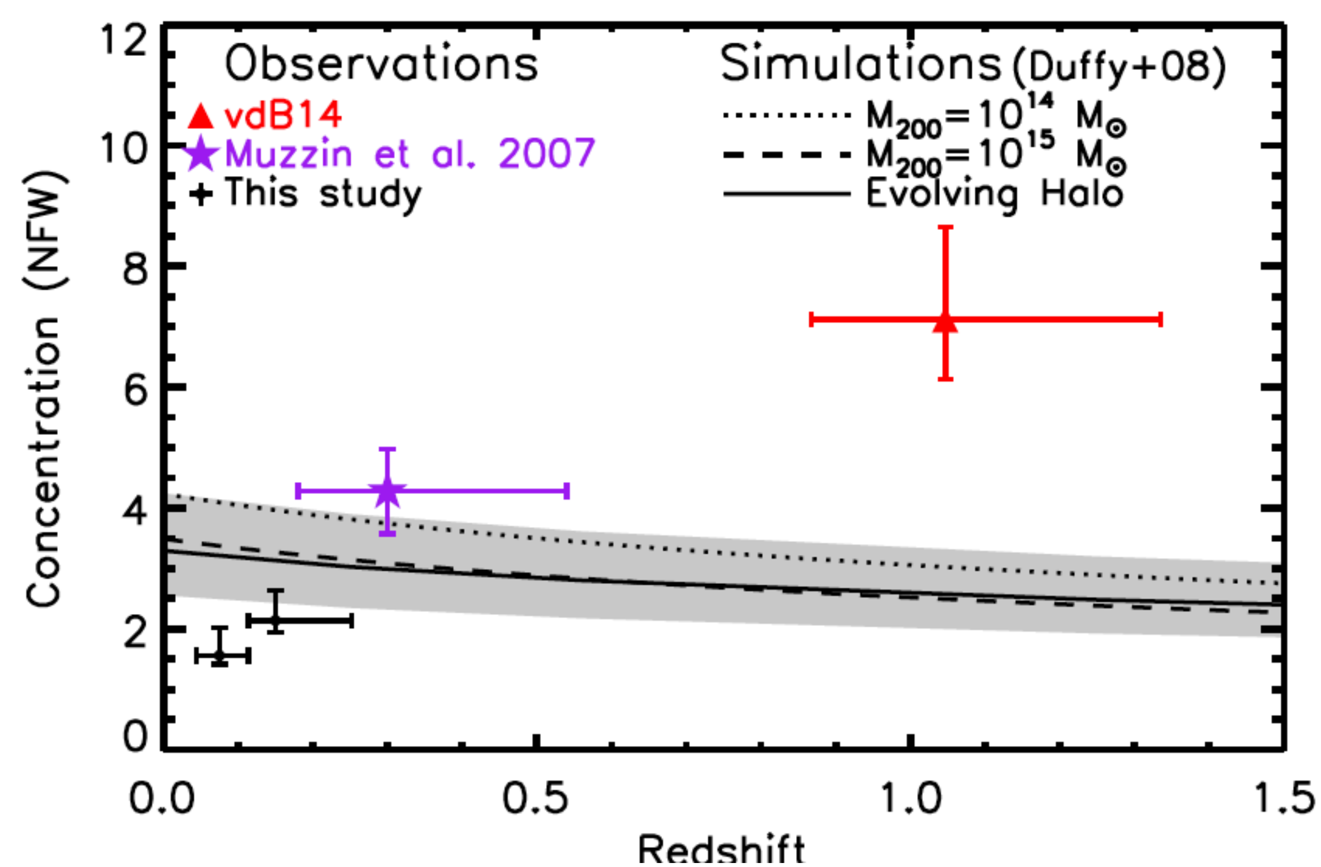
The massive cluster galaxies are heavily obscured.

Wang, Kodama, Tanaka, et al. in prep

A high stellar mass density concentration in high-z clusters?



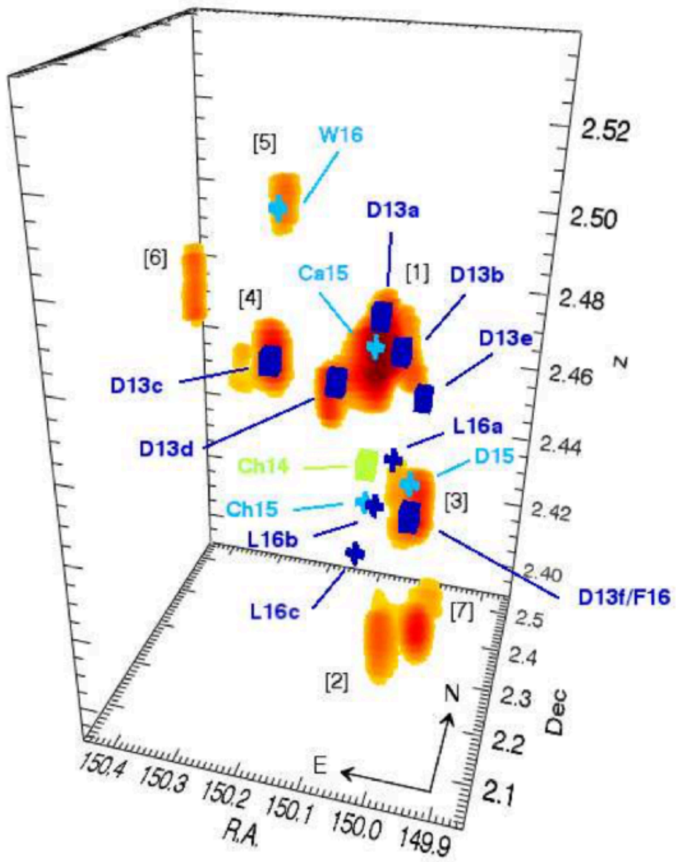
Wang+2016



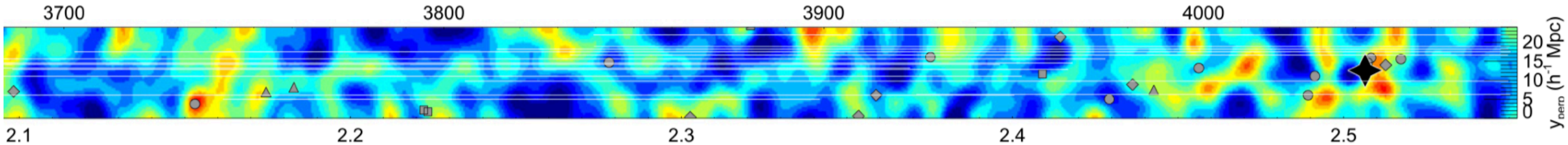
stellar mass density concentration

van der Burg+2015

A massive proto-supercluster in formation around J1001?

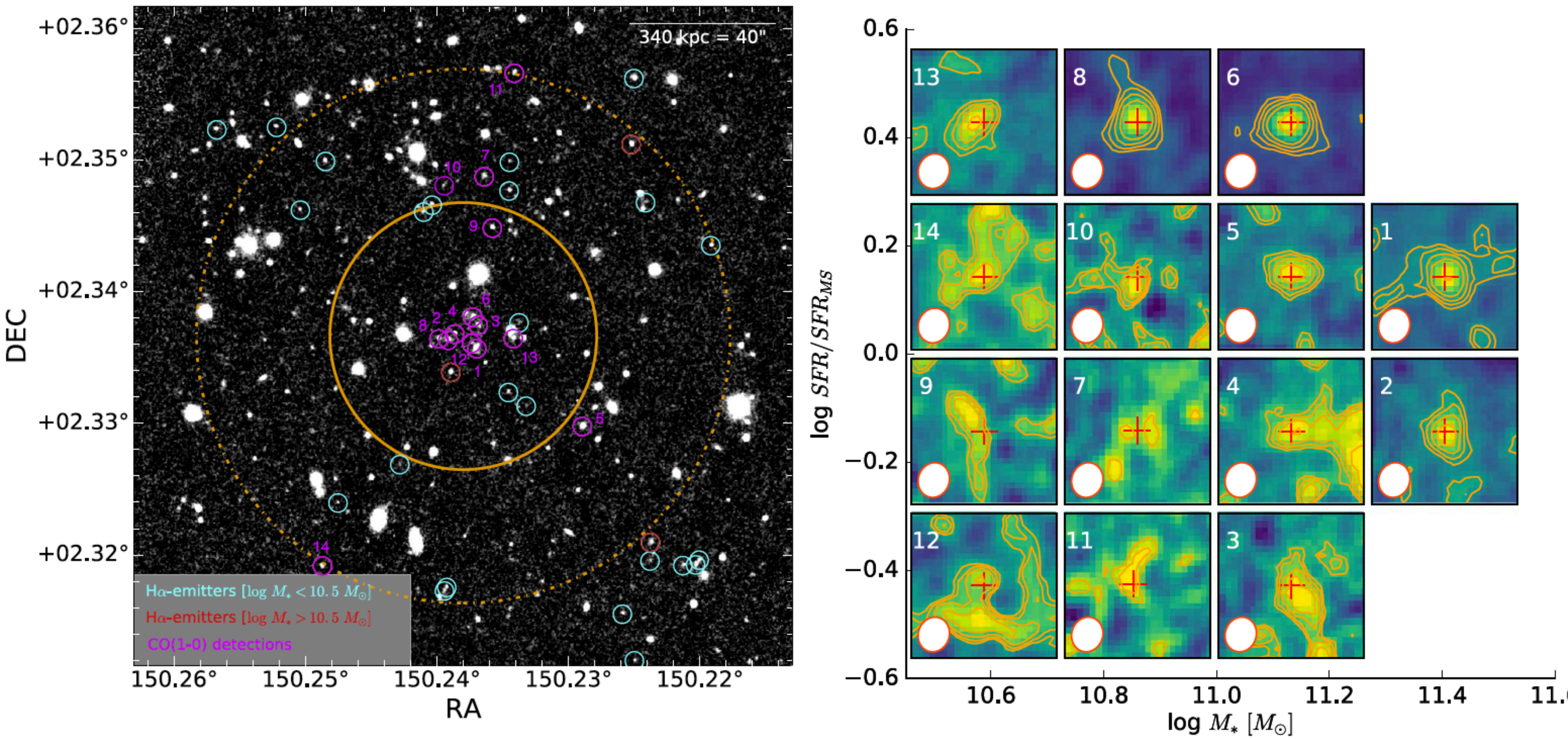


Cucciati+2018



3D Lya Forest Tomography: Khee-Gan Lee+2018

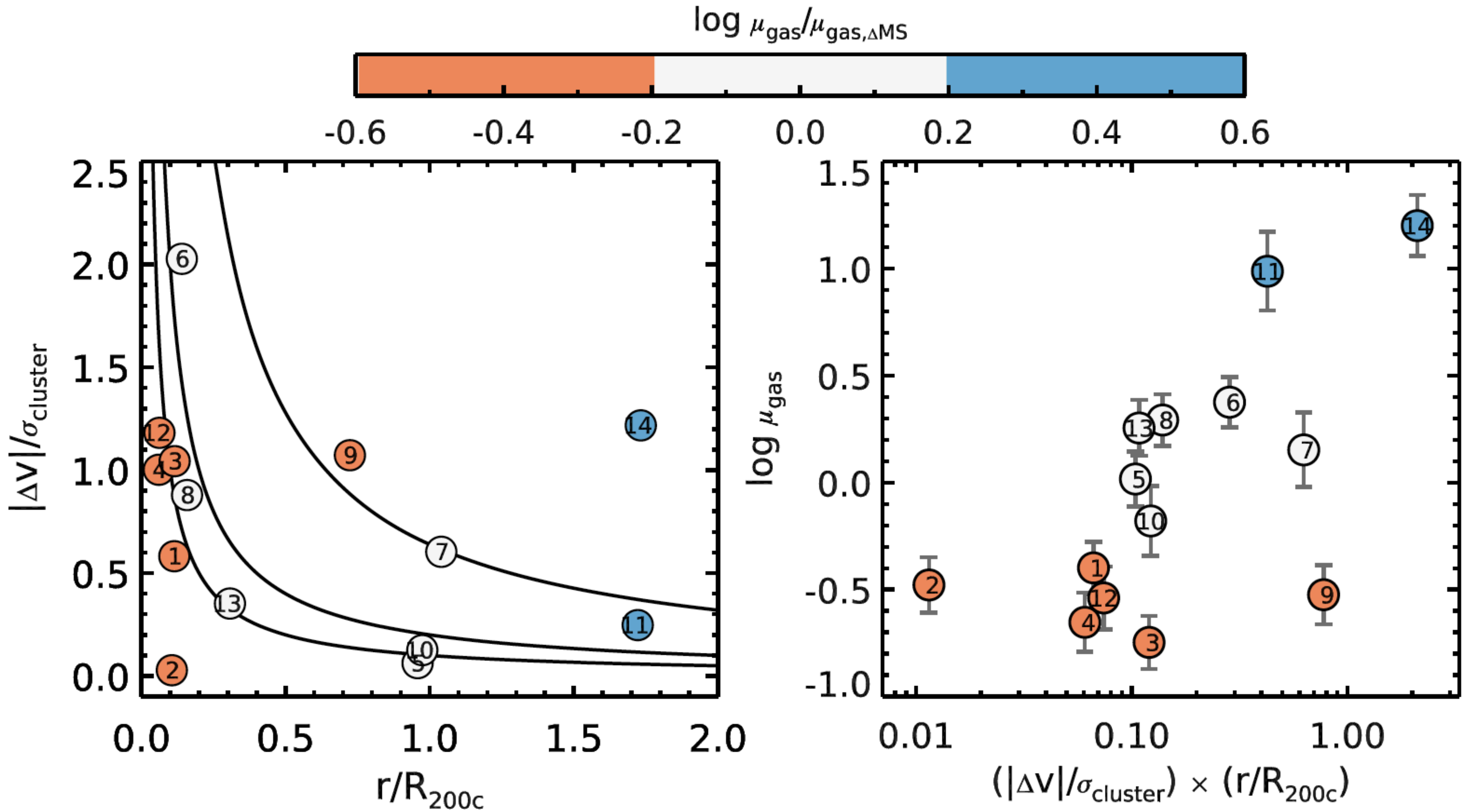
Galaxy Properties in J1001: CO(1-0) observations with VLA



With a single pointing from VLA, we detected 11 cluster members in CO(1-0), which nearly doubles the total number of CO(1-0)-detected normal galaxies at z>2

Wang+2018, ApJL,867, 29

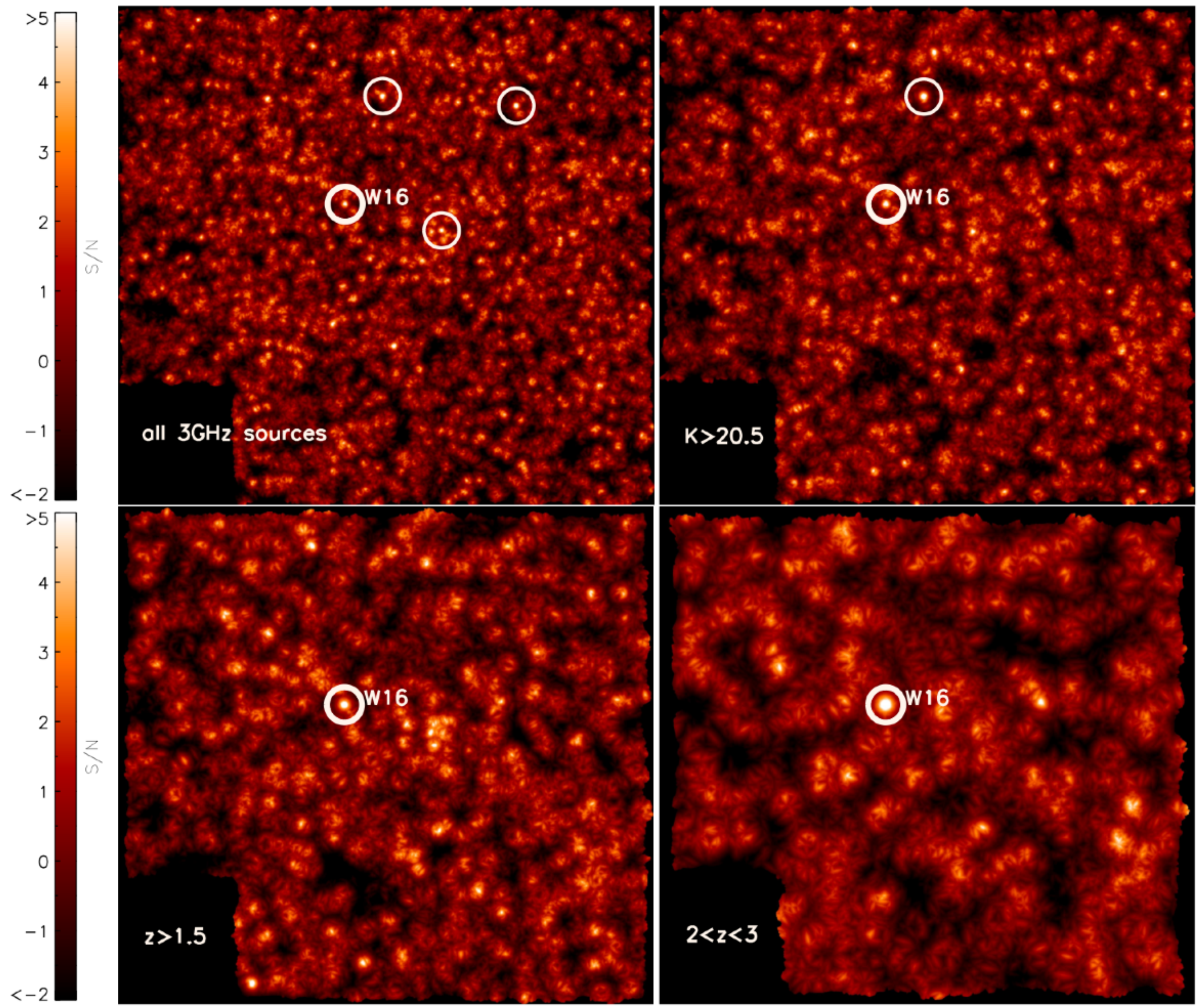
First evidence of environmental dependence of gas content at z>2:
Decreasing gas fraction towards the cluster core



Key: CO(1-0) observations of mass-complete samples of cluster members across different local environment!

also see Tadaki+2019

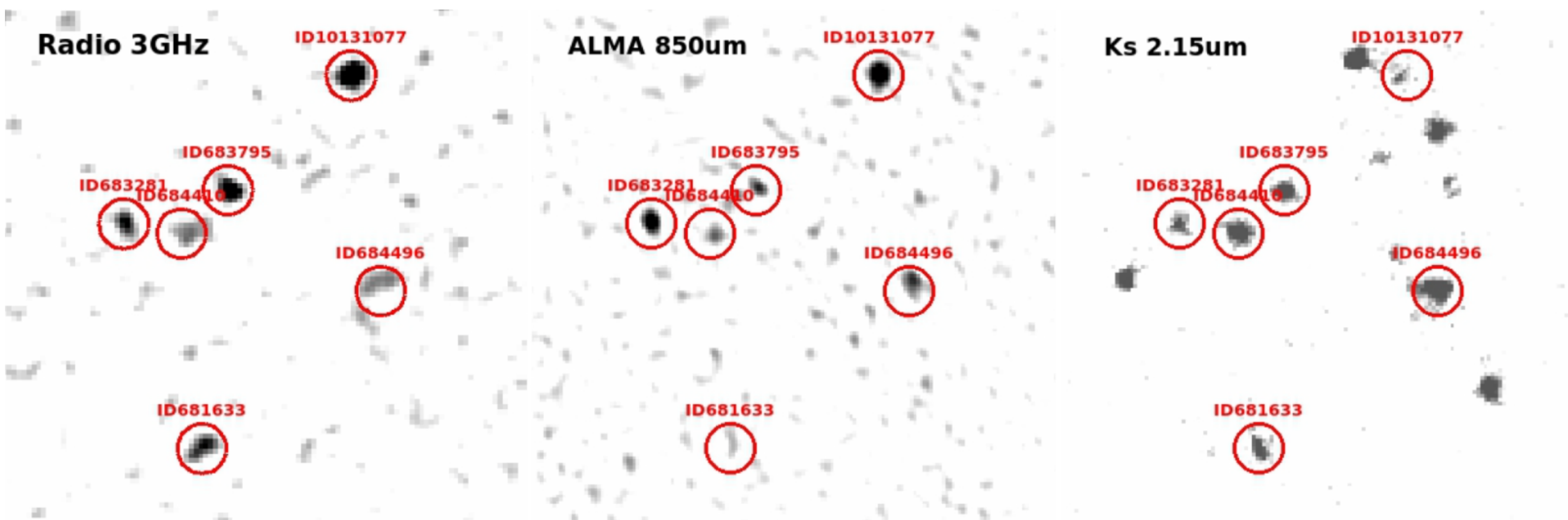
Future: Radio selection of distant (star-forming)galaxy clusters

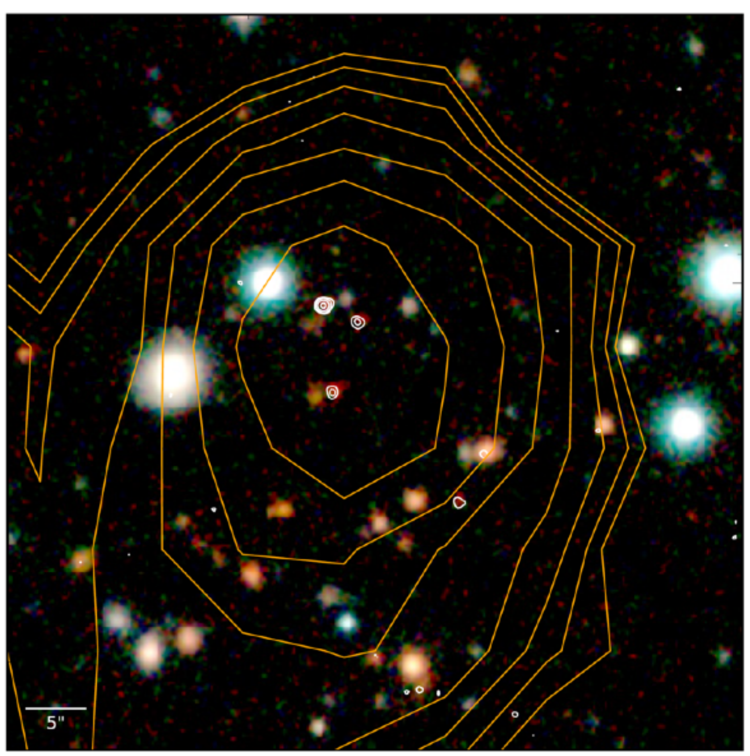


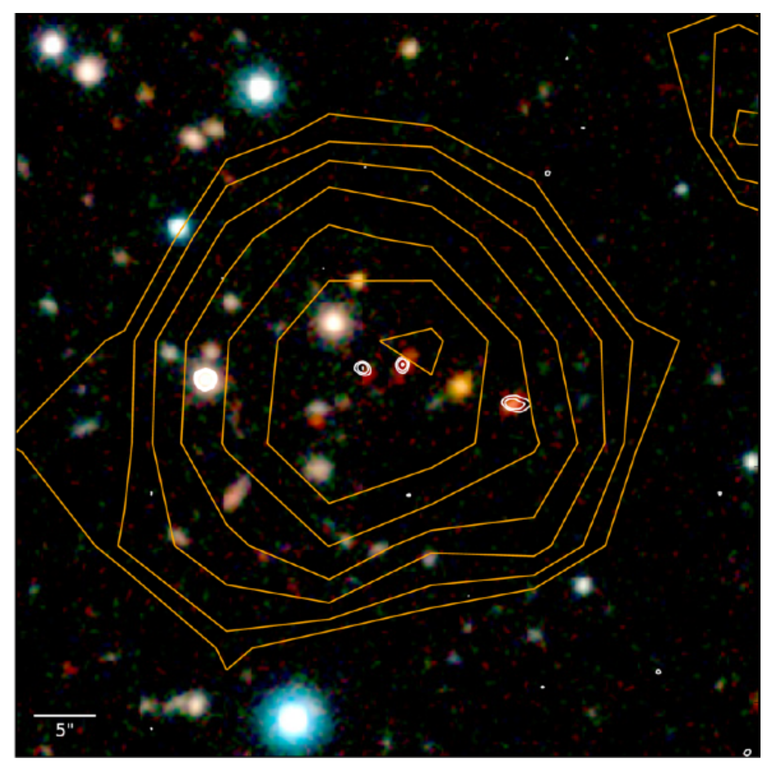
density map of radio sources

Daddi (incl **Wang)**+2017

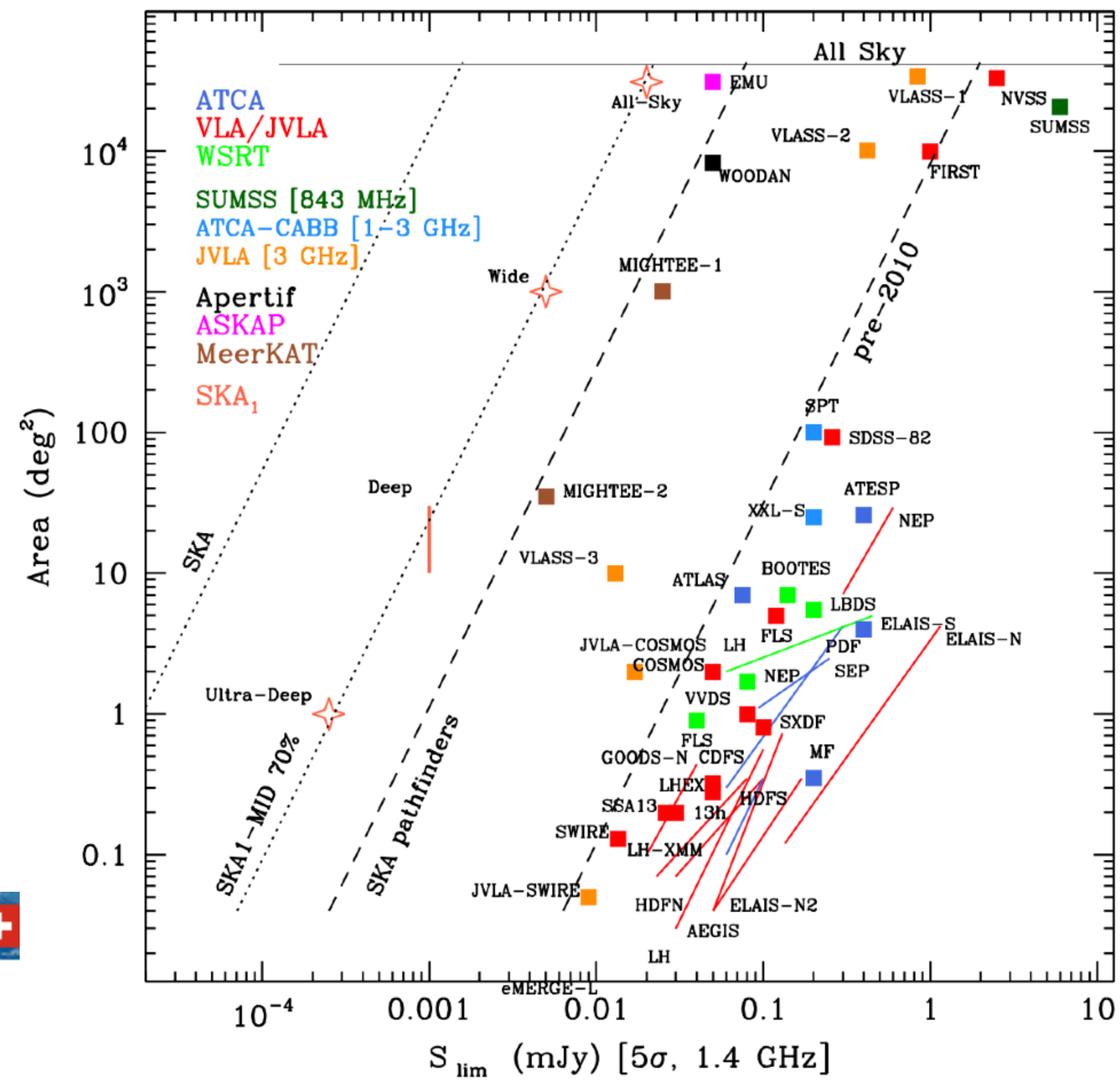
Larger samples of distant star-forming clusters







Great potential for Square Kilometer Array: 200~2000 clusters like J1001



Summary

- Towards a census of massive galaxies in the early universe: **ALMA unveils a dominant population of massive galaxies at z>3** that are invisible in the HST near-infrared imaging. These galaxies lie on the main-sequence of star-forming galaxies at z~4 and represent the bulk population of massive galaxies that have been missed from UV-selected samples.

- The large number density of H-dropouts ($n \sim 2 \times 10^{-5} Mpc^{-3}$) suggests that they are likely the main progenitors of the most massive quiescent galaxies formed at z~3. Current theoretical models and simulations do not predict such a large population of massive and dusty galaxies in the early universe.

- Towards a census of high-z clusters: We reveal **a novel population of young clusters with a dominate population of massive star-forming galaxies in the core**, which bridges the gap between mature clusters and protoclusters.

- While most of the massive cluster galaxies locate on the main-sequence, strong cluster-centric radius dependence of molecular gas content (and SFE) is revealed in J1001, providing direct evidence on environmental dependence of massive galaxy formation at z>2.