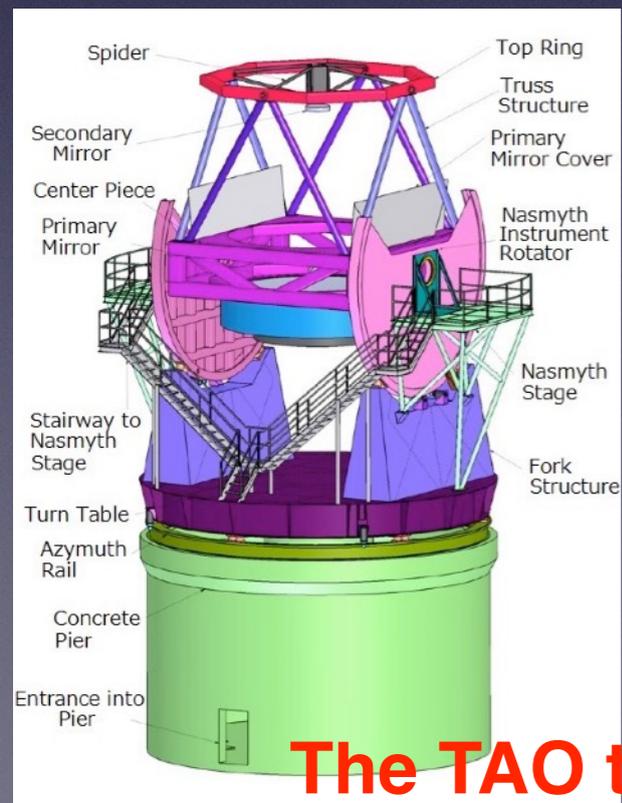


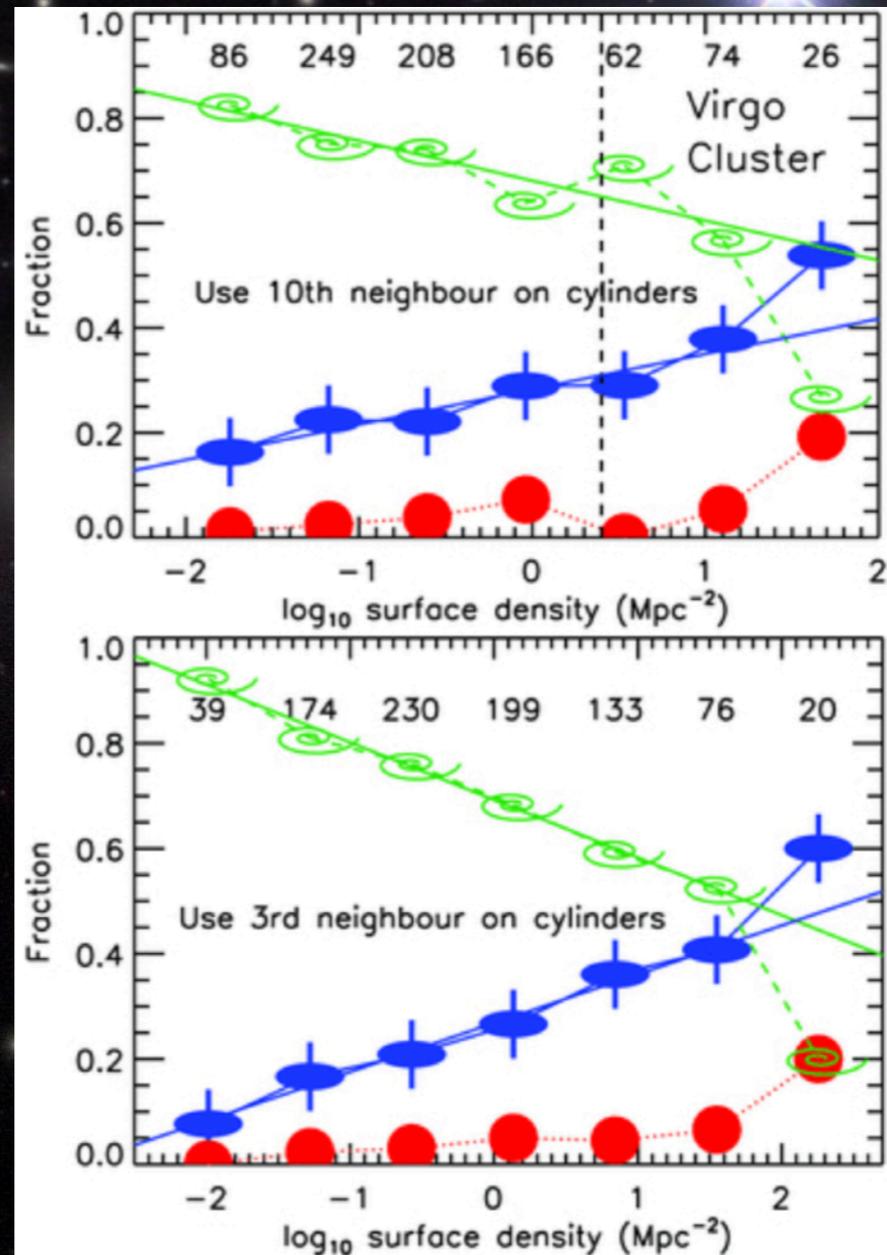
Environmental effects on massive galaxy formation in a distant X-ray cluster at $z=2.51$

Tao Wang (U. Tokyo/NAOJ)



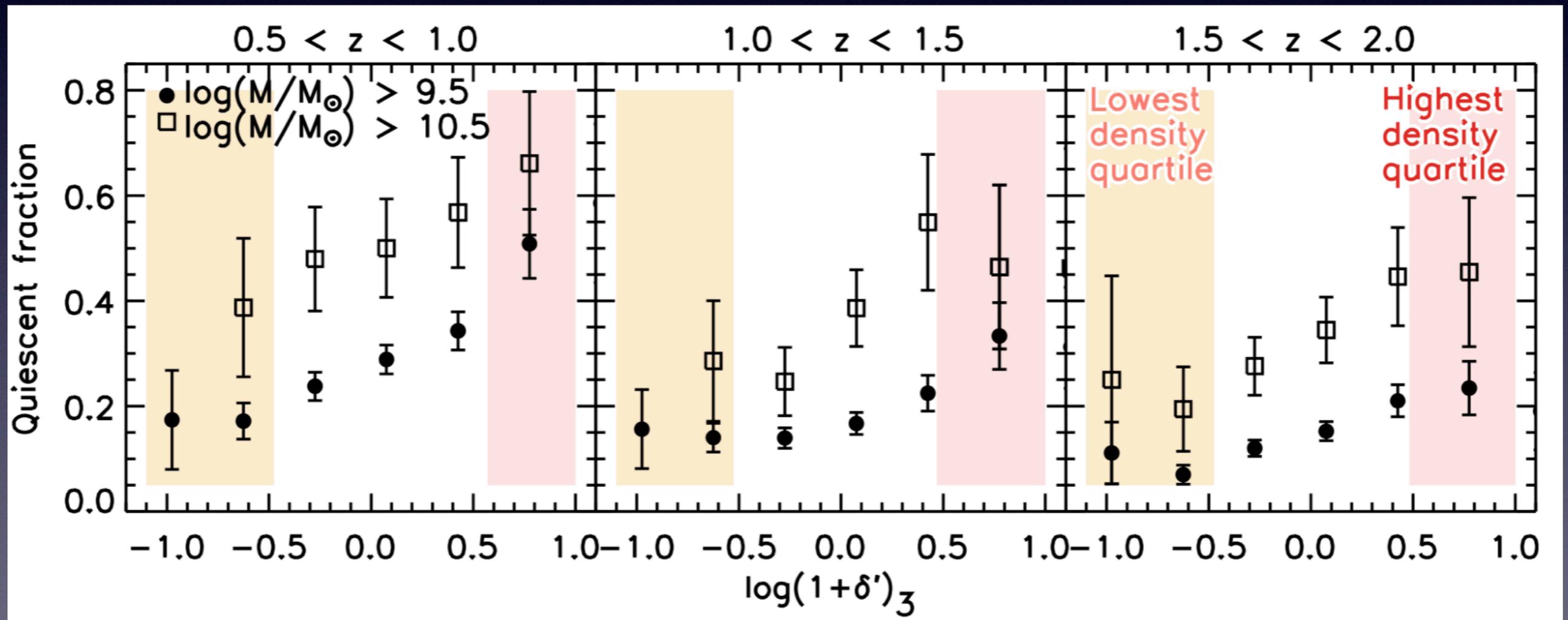
The TAO telescope

Environmental effects on galaxy formation and evolution

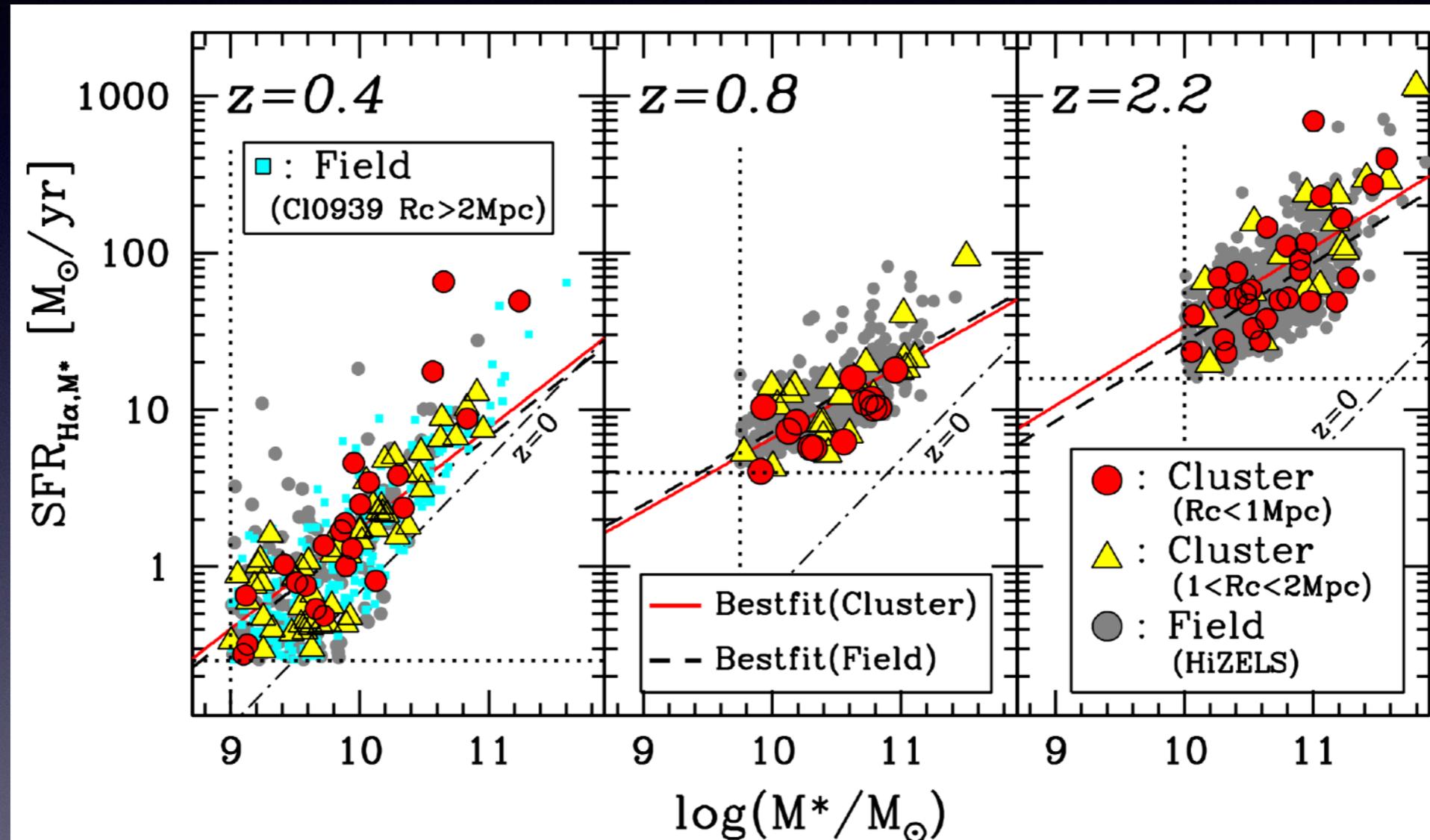


Morphology-density relation (Cappellari+2011)

Increasing quiescent fraction as increasing local density up to $z \sim 2$



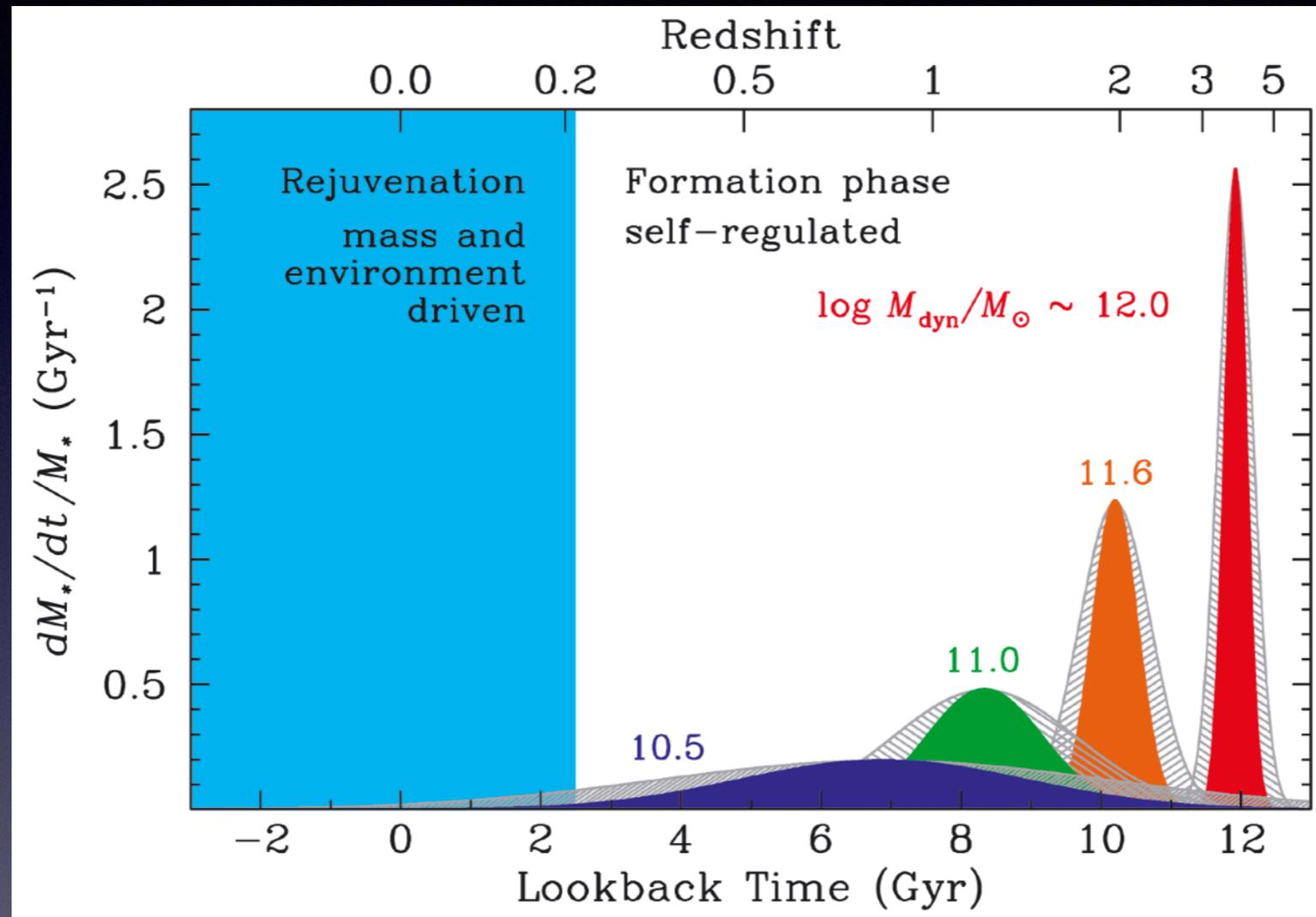
(Minor) Environmental effects on star formation properties of galaxies up to $z \sim 2$



“MAHALO-Subaru” ,Koyama+2013

Indications: the quenching processes must be quite **rapid** in clusters.

Star formation history of massive galaxies



Thomas+2010

The more massive galaxies assembled their masses at earlier times.
Large galaxies die early.

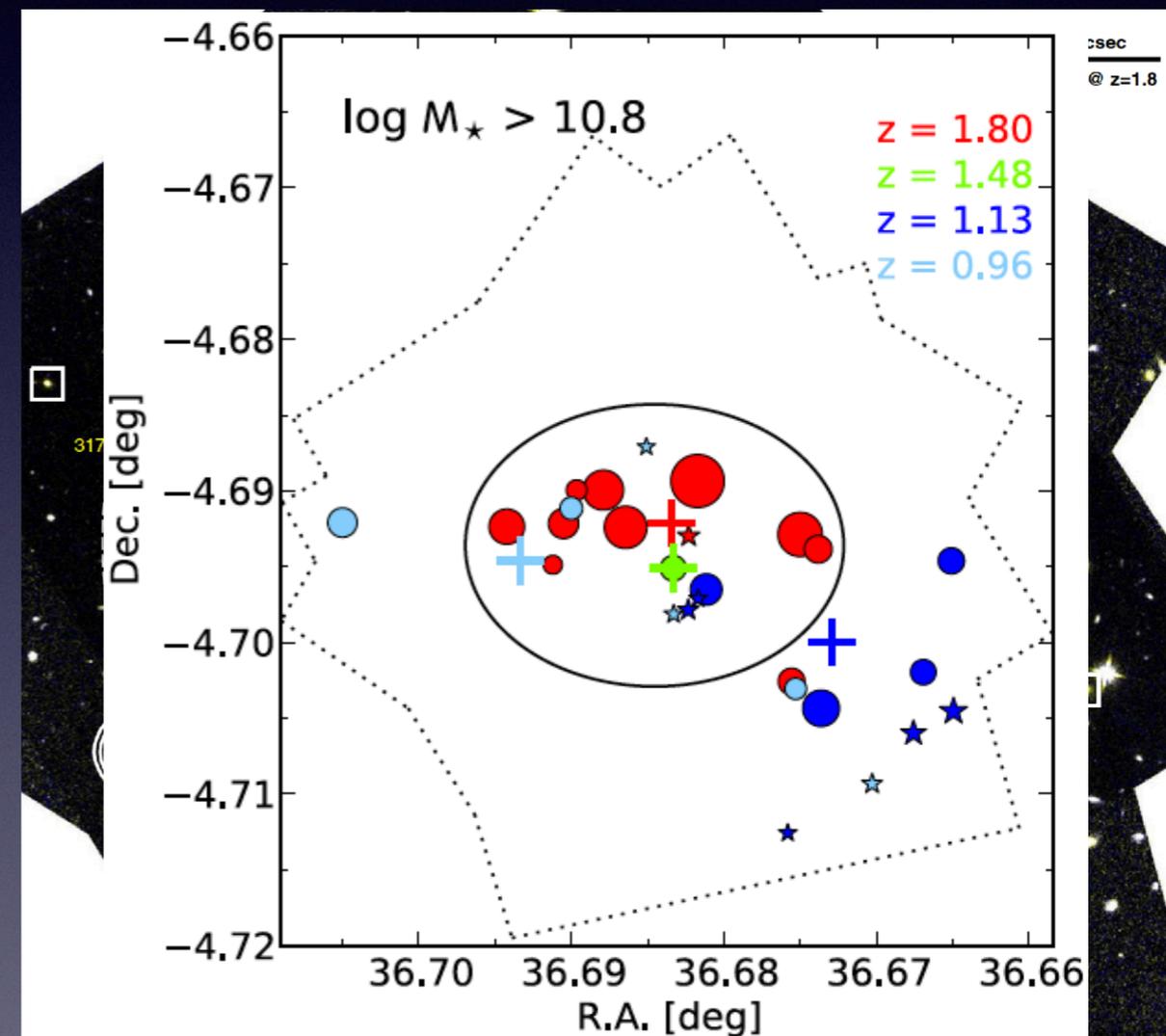
To uncover the role of (densest) environment
in shaping galaxies:
hunting for high-z clusters

$z \sim 0$



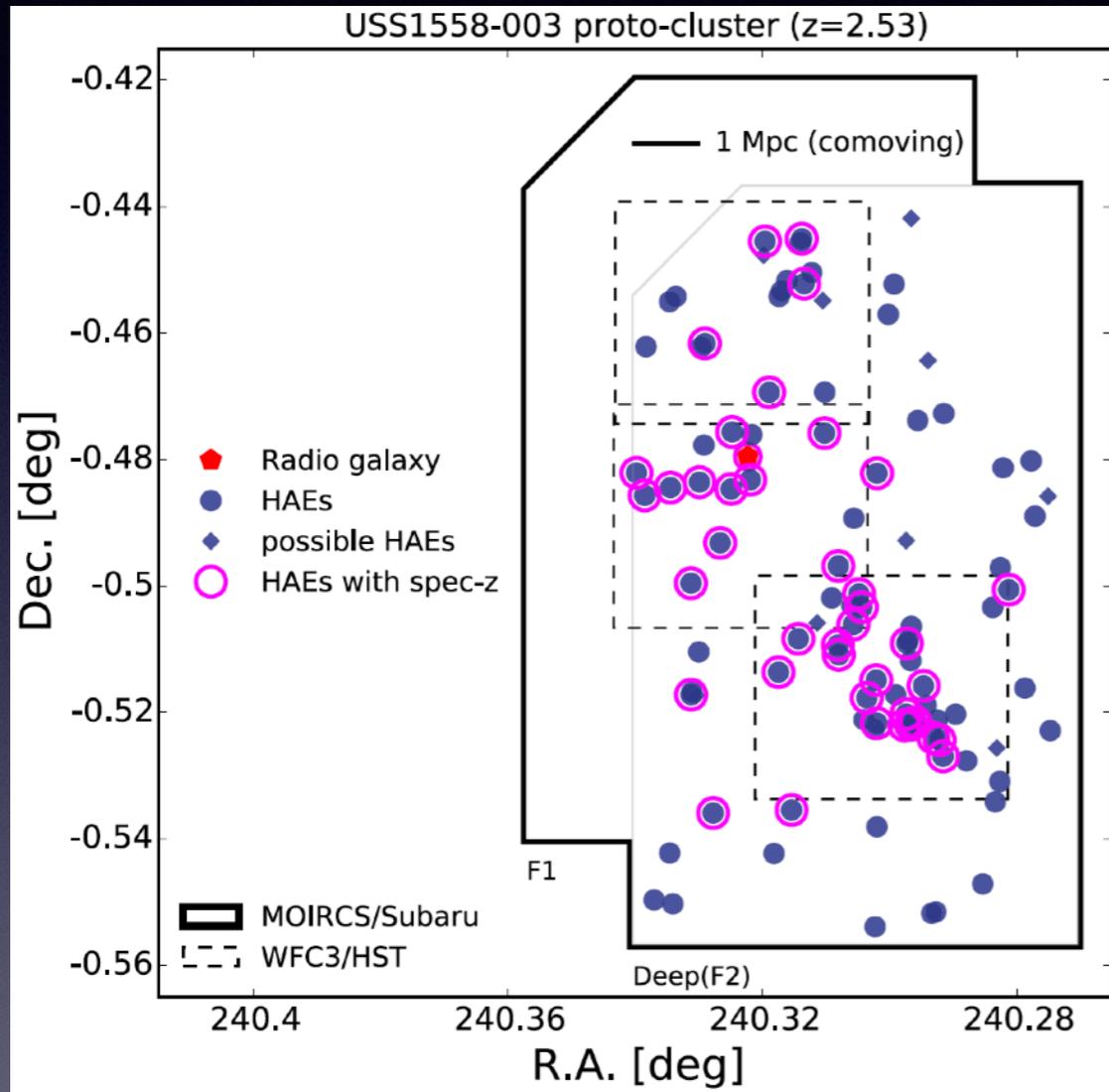
The Hubble Space Telescope Treasury
Survey of the Coma Cluster of Galaxies

$z \sim 2$

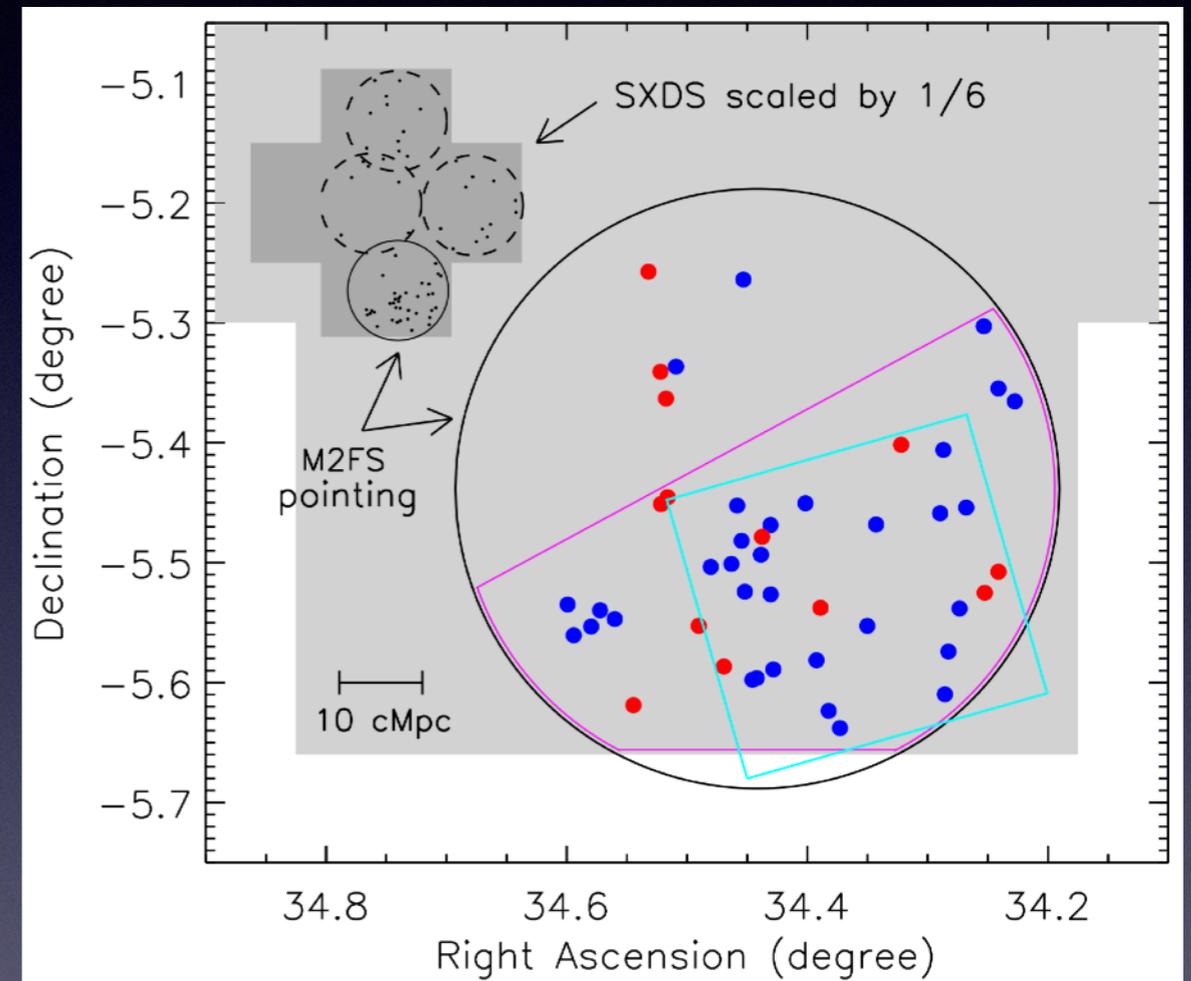


JKCS 041@ $z = 1.803$
Newman+2014

A large number of protoclusters at high redshift



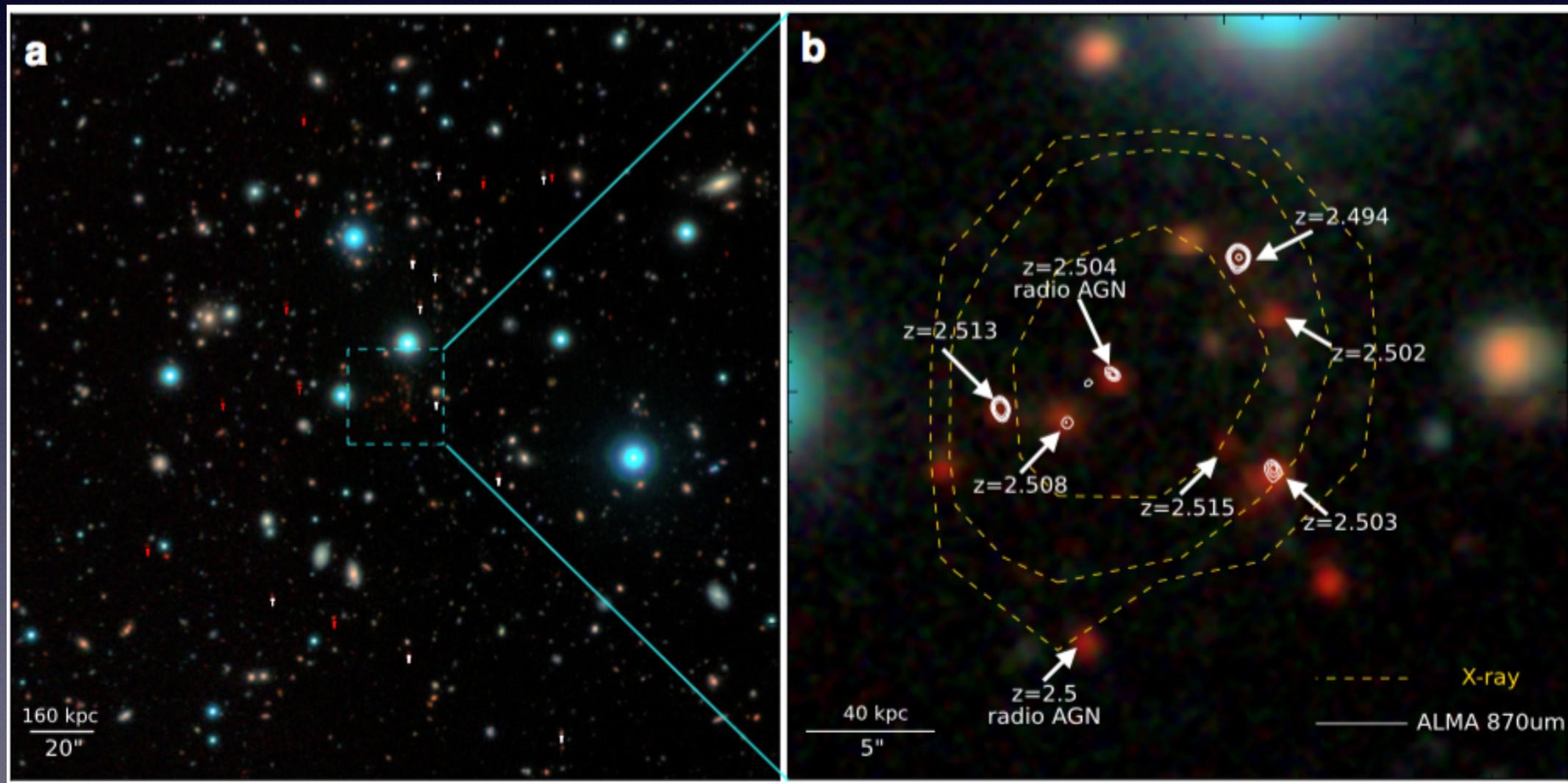
$z=2.53$, Hayashi+2016



$z=5.7$, Jiang+2018, Nature astronomy

low galaxy densities;
extended structure; not yet collapsed

J1001: A starbursting, X-ray cluster at $z=2.51$, the furthest ever known



J1001: A starbursting, X-ray cluster at $z=2.51$, the furthest ever known

The image is a screenshot of a NASA website page. At the top left is the NASA logo. A navigation bar contains links for Missions, Galleries, NASA TV, Follow NASA, Downloads, About, and NASA Audiences. Below this is a secondary navigation bar with links for International Space Station, Journey to Mars, Earth, Technology, Aeronautics, Solar System and Beyond, Education, History, and Benefits to You. The main content area features a large, vibrant image of a galaxy cluster with a purple and blue glow. Overlaid on this image is a blue box with the text "Solar System and Beyond" and a white box with the headline "Record-Breaking Galaxy Cluster Discovered". Below the main image is a "NASA Events" section with a small video thumbnail. At the bottom of the screenshot are two smaller images: the left one shows a wide field of galaxies with a scale bar of 160 kpc and 20"; the right one is a zoomed-in view of a specific galaxy with a scale bar of 40 kpc and 5", featuring a red dot labeled "z=2.5 radio AGN" and a legend for "X-ray" (dashed line) and "ALMA 870um" (solid line).

Wang, T., et al. 2016, ApJ, 828, 56

J1001 bridges the gap between mature clusters and protoclusters

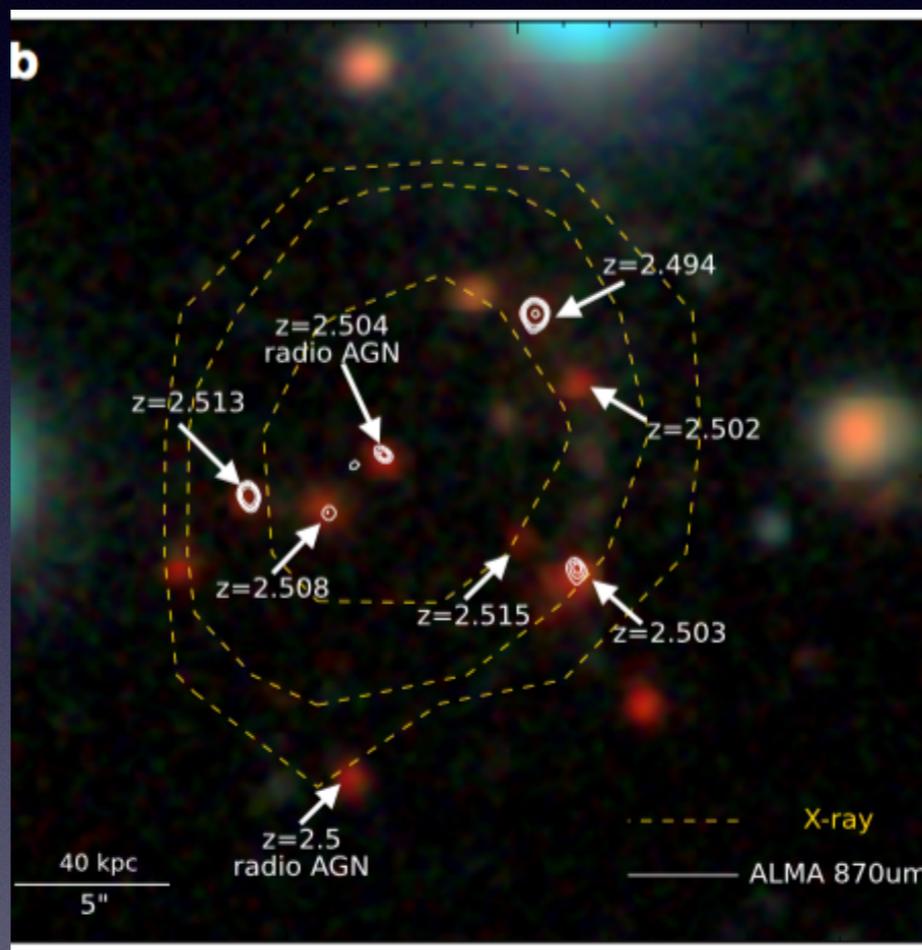
$z=0$

J1001@ $z=2.5$

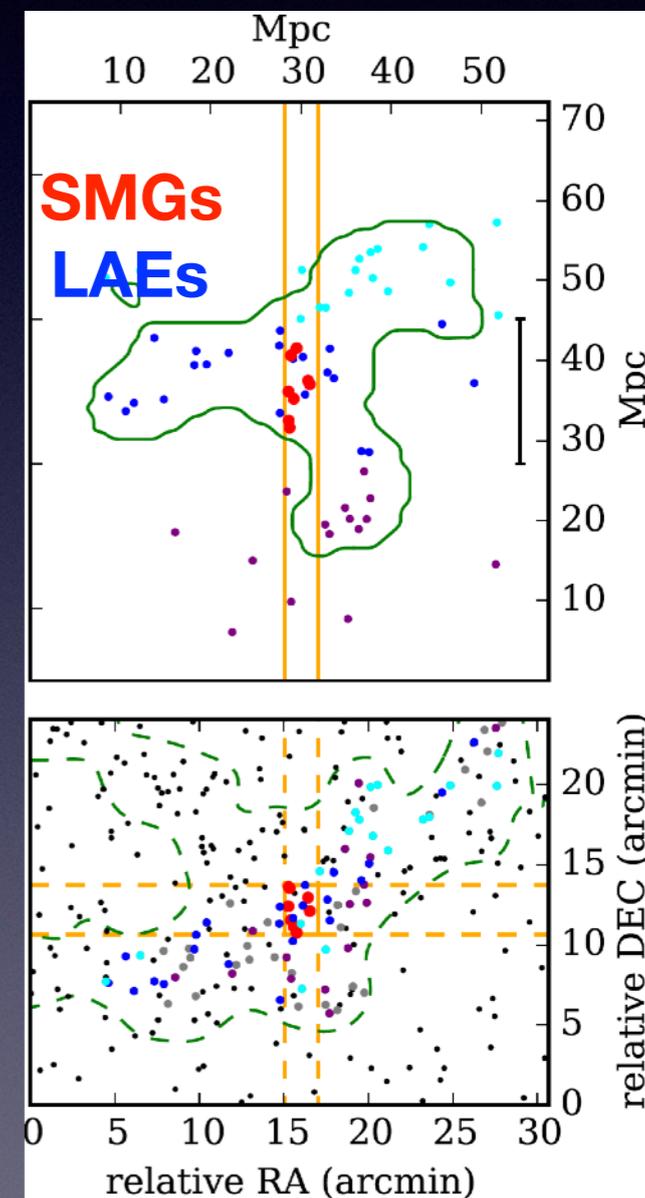
$z=3.1$



Coma Cluster

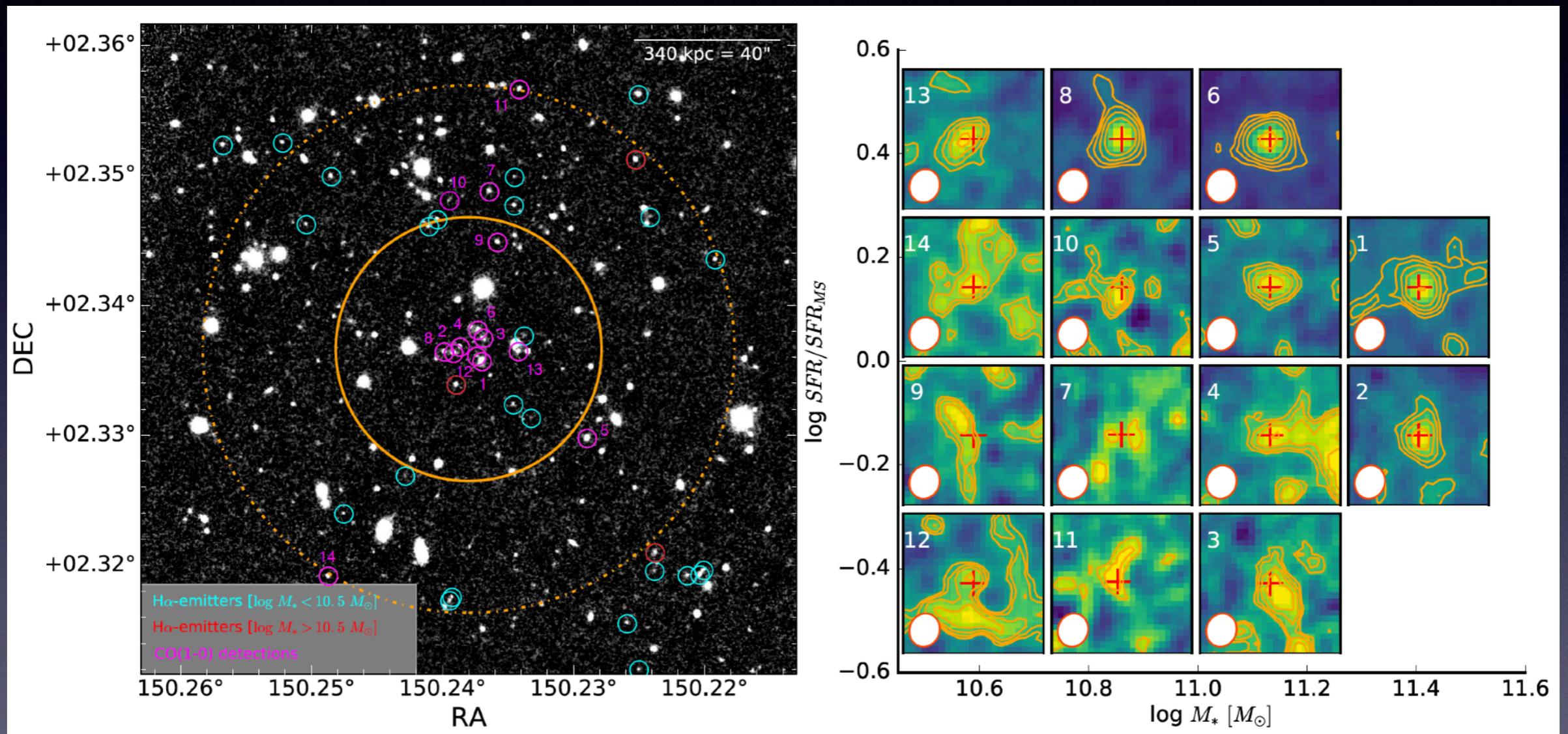


J1001: presence of both an X-ray halo and a starbursting core, ideal laboratory for studying environmental effects on massive galaxy formation



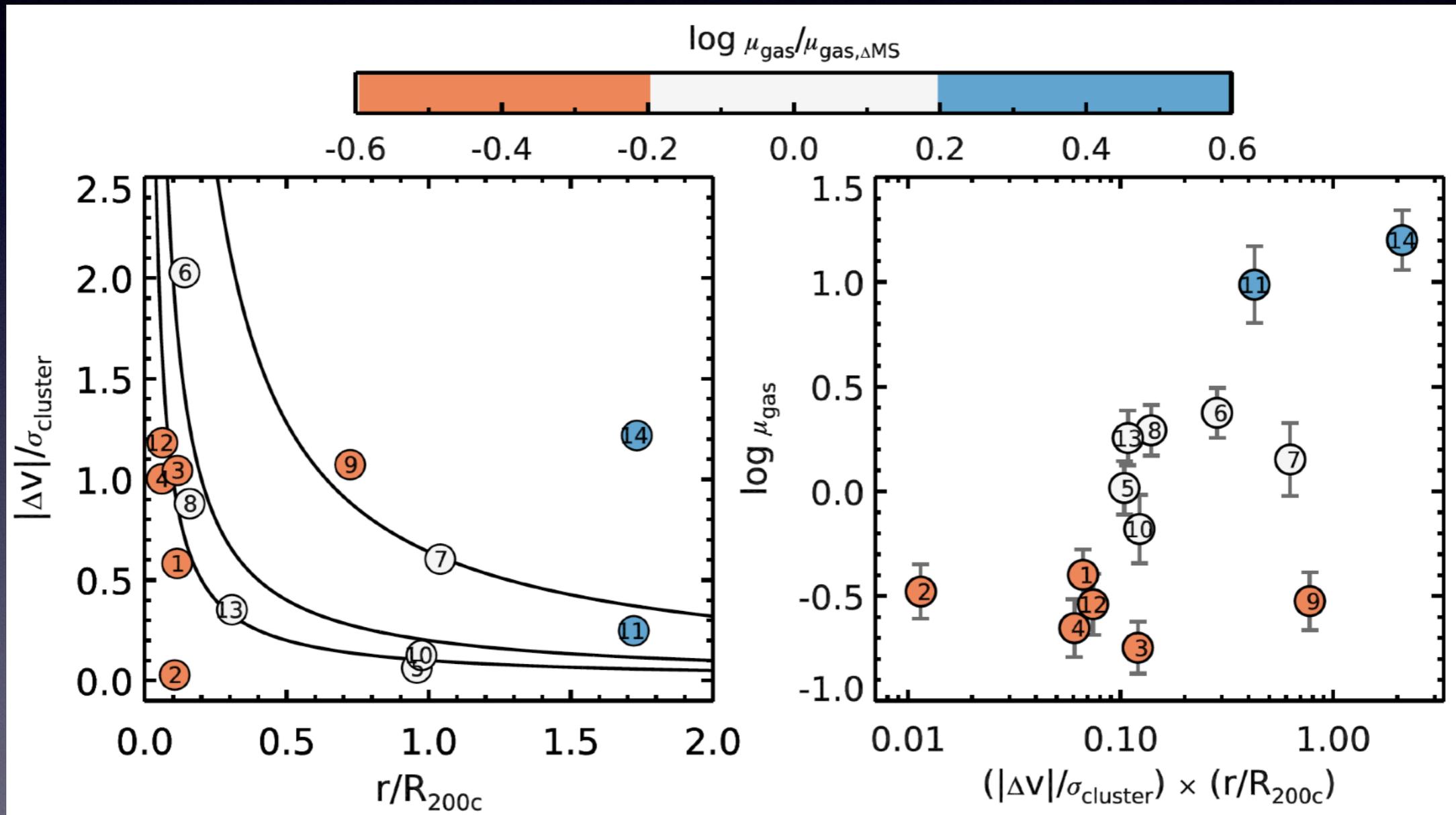
SSA22, Umehata+2015

A census of CO(1-0) in J1001 with JVLA



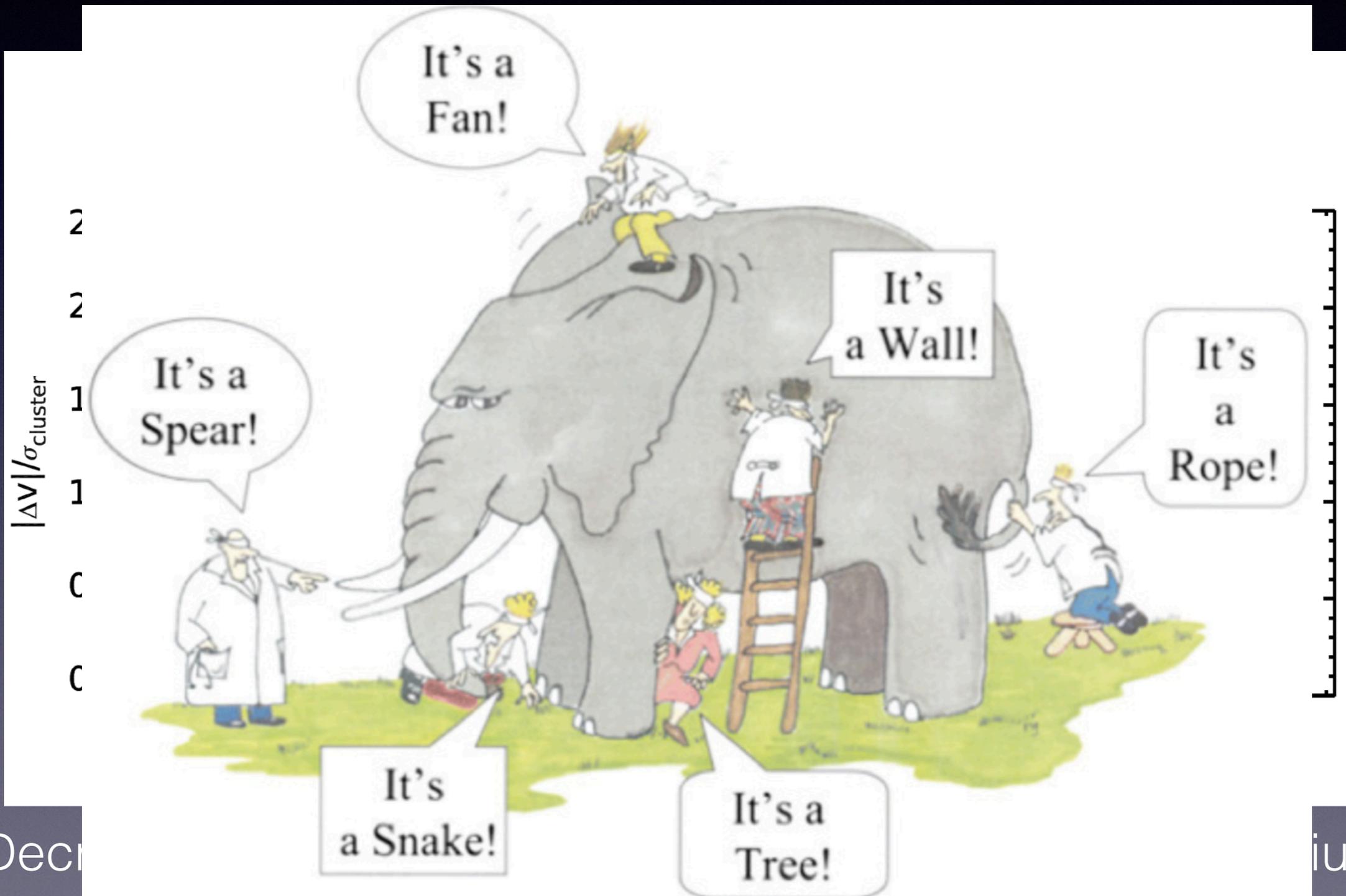
CO(1-0) detections towards a **mass-complete** sample of cluster galaxies

Evidence for strong environmental dependence of (molecular) gas content



Decreasing gas content as decreasing cluster-centric radius

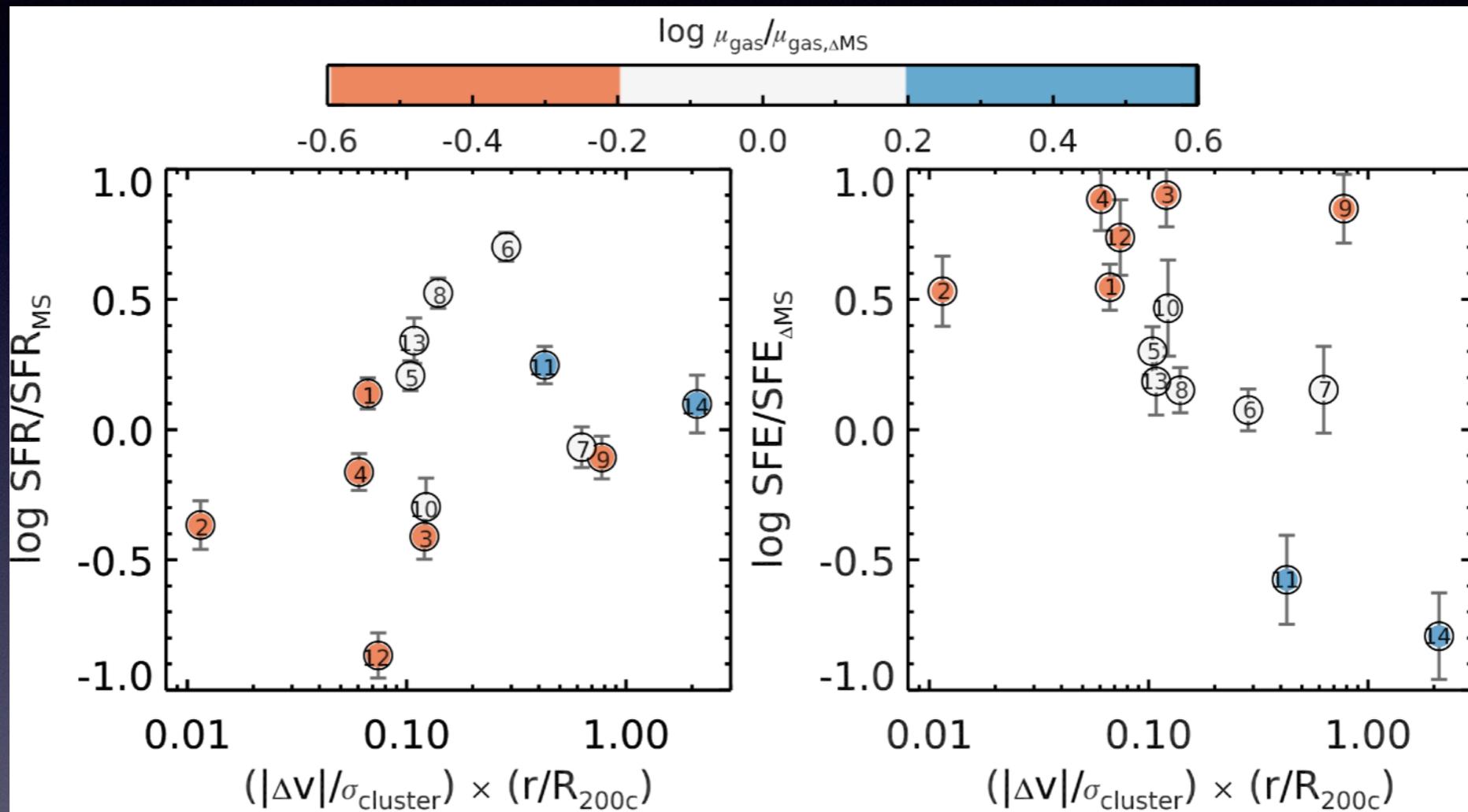
Evidence for strong environmental dependence of (molecular) gas content



Decr

ius

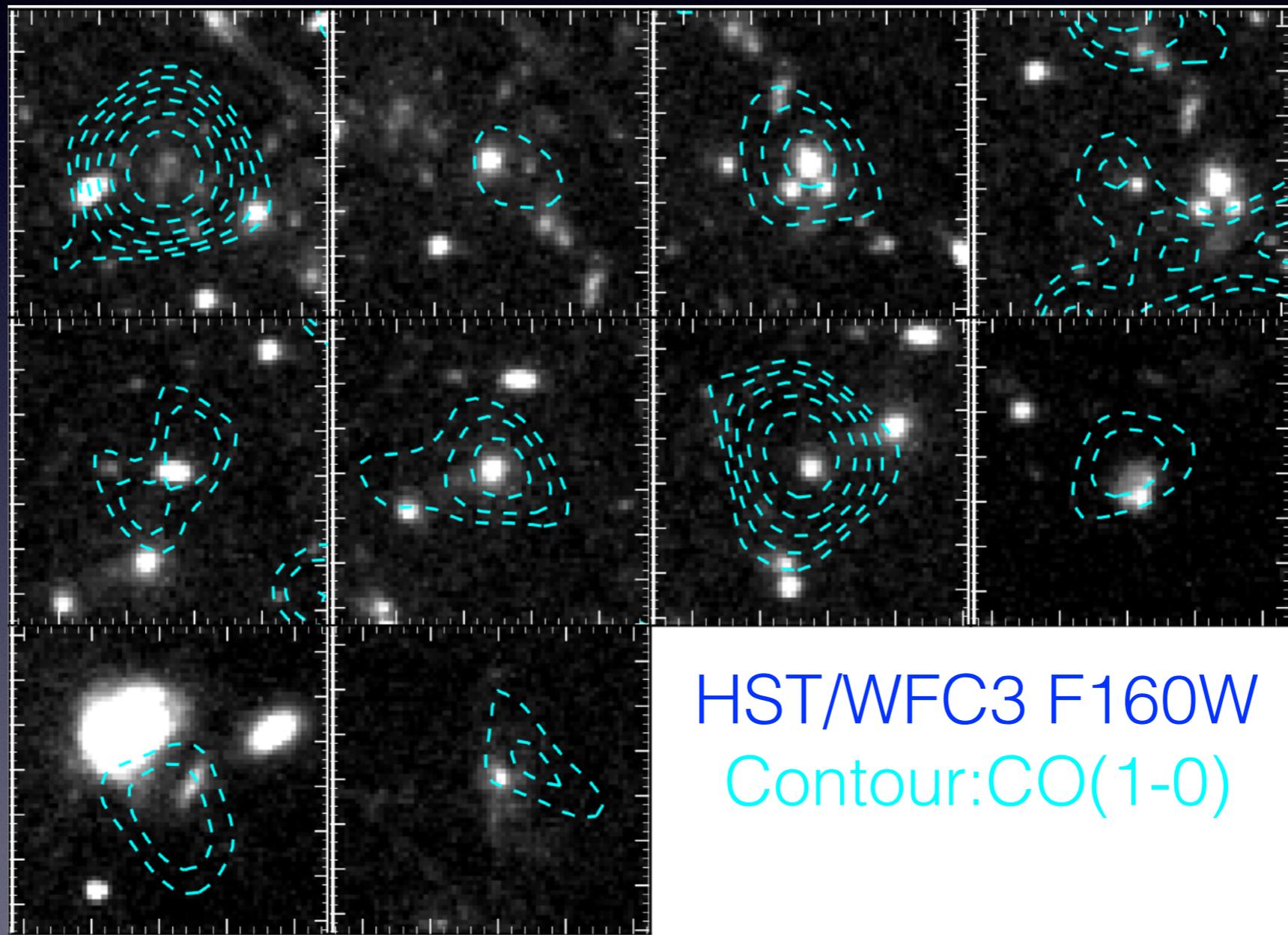
Elevated star formation efficiency (SFE=SFR/ M_gas) for galaxies in the cluster center



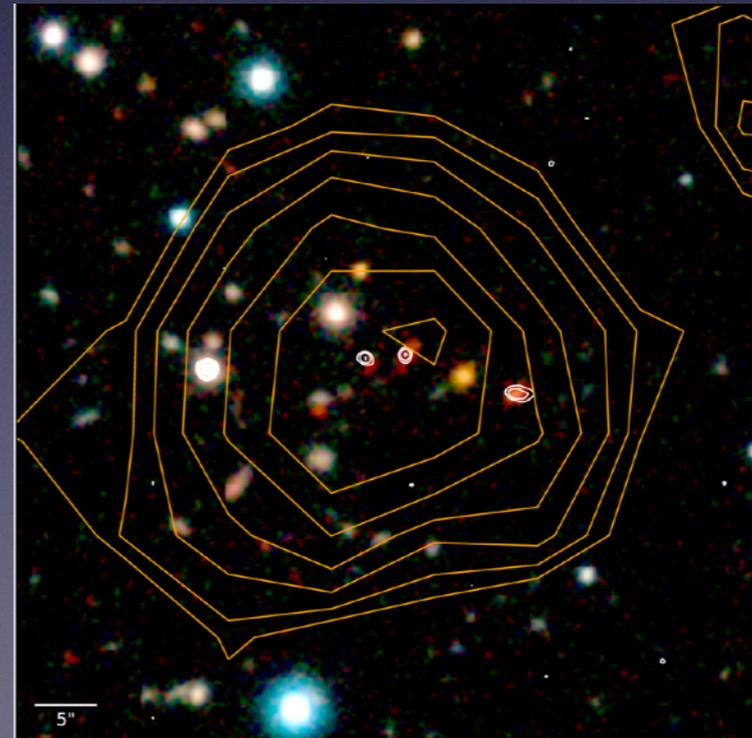
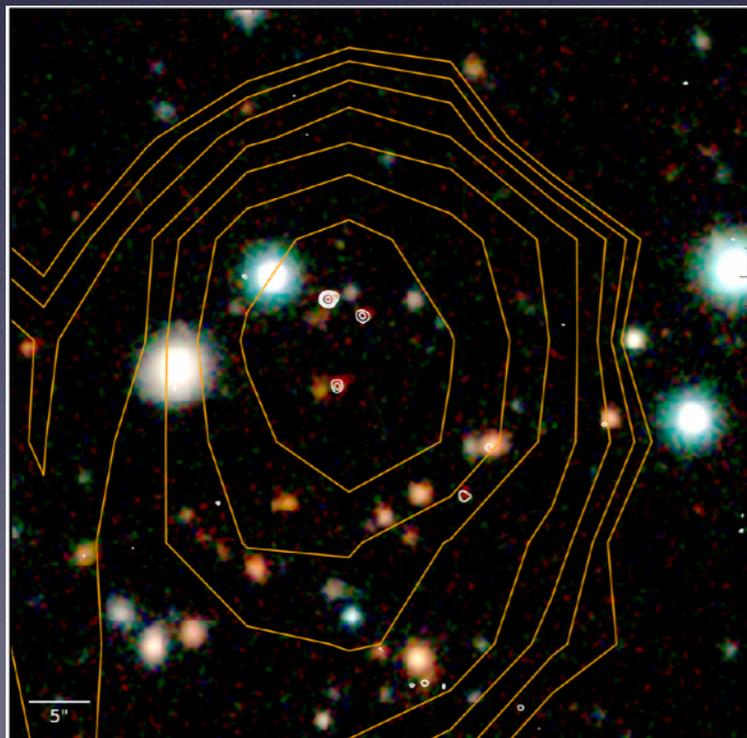
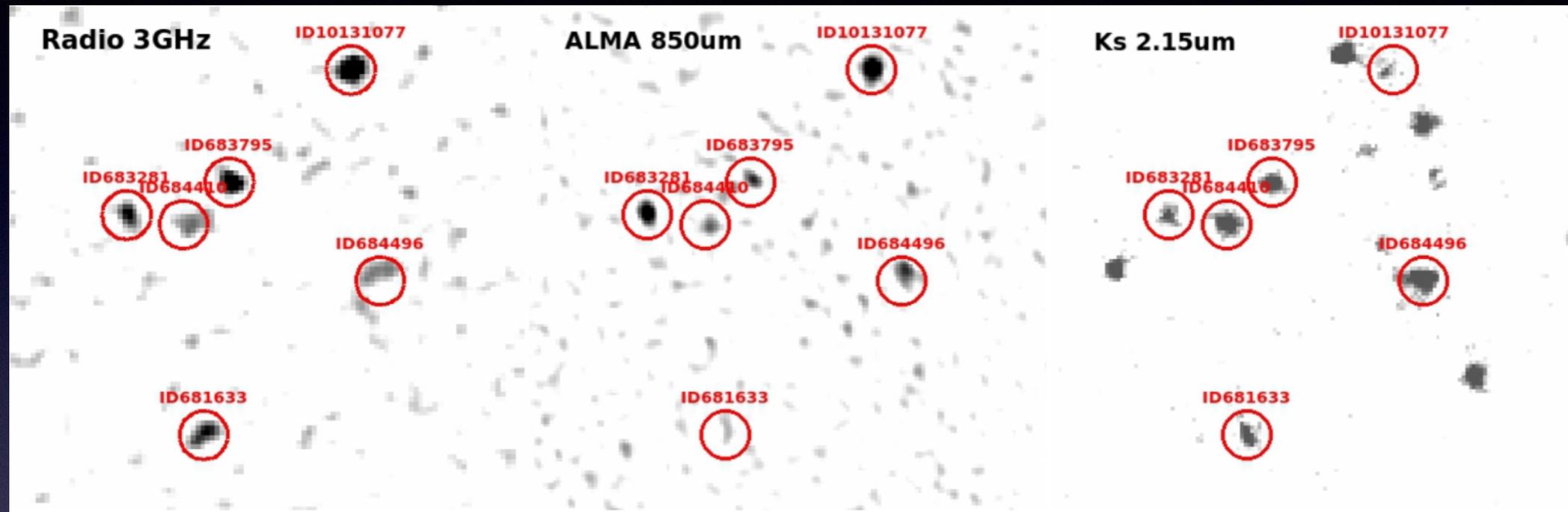
Environmental effects on the SFR of galaxies are likely delayed compared to that on the gas content.

The gas depletion time ranges 100 to 400 Myrs, comparable to the dynamical time of the cluster

The physical origin of the rapid quenching in cluster cores: tidal and ram pressure stripping at $z=2.5$?



Next: Radio selection of distant galaxy clusters



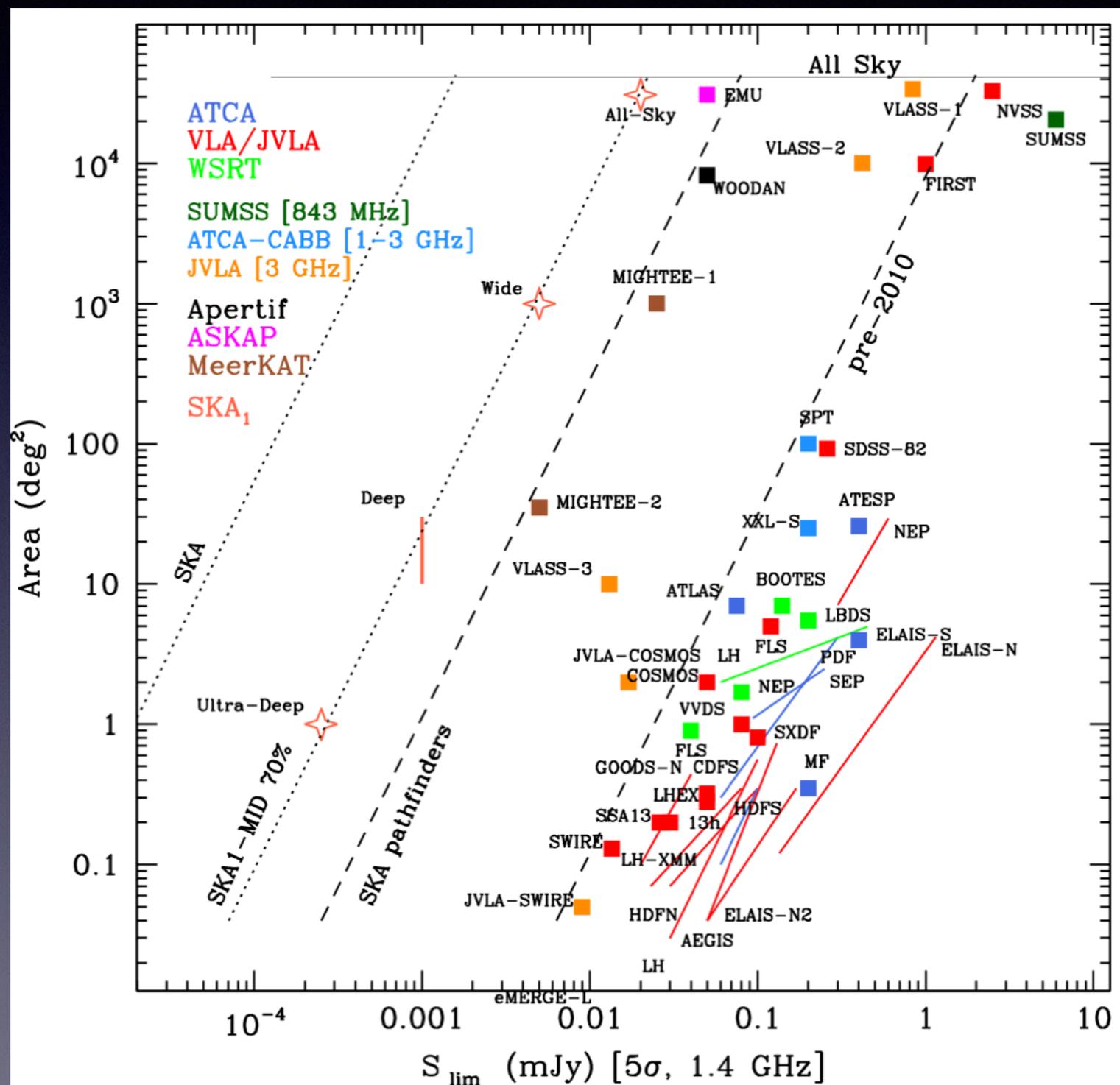
Great potential for SKA



Square Kilometer Array



Great potential for SKA: 200~2000 clusters like J1001



Summary

- We have discovered the most distant X-ray cluster J1001 at $z=2.51$ known to date. This structure is unique in the presence of both an X-ray emitting halo and a starbursting core, bridging the gap between mature clusters and protoclusters.
- Based on CO(1-0) detections towards a mass-complete sample of member galaxies in J1001, we have found a strong clustercentric radius dependence of molecular gas content, with galaxies closer to the cluster core being increasingly gas-poor.
- Despite their low gas content, galaxies in the cluster center suggest an elevated star formation efficiency, suggesting that the effects on the SFR are likely delayed compared to that on the gas content.
- Future wide-field, deep radio continuum surveys with SKA could help to reveal thousands of similar clusters at high redshifts, which will revolutionize the field on both galaxy formation and **cosmology**.