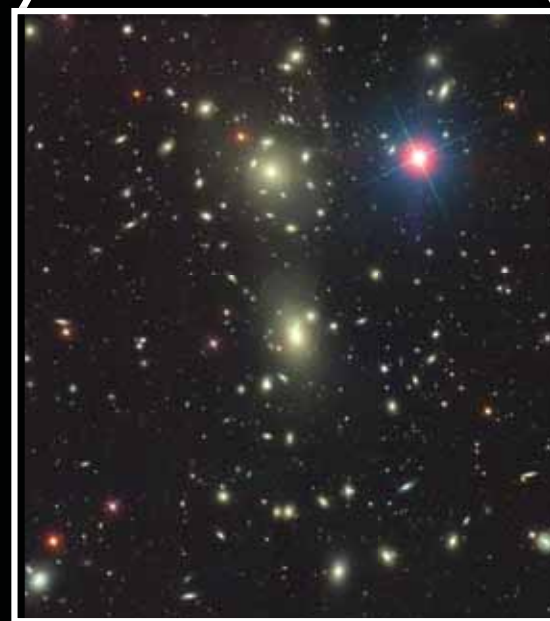
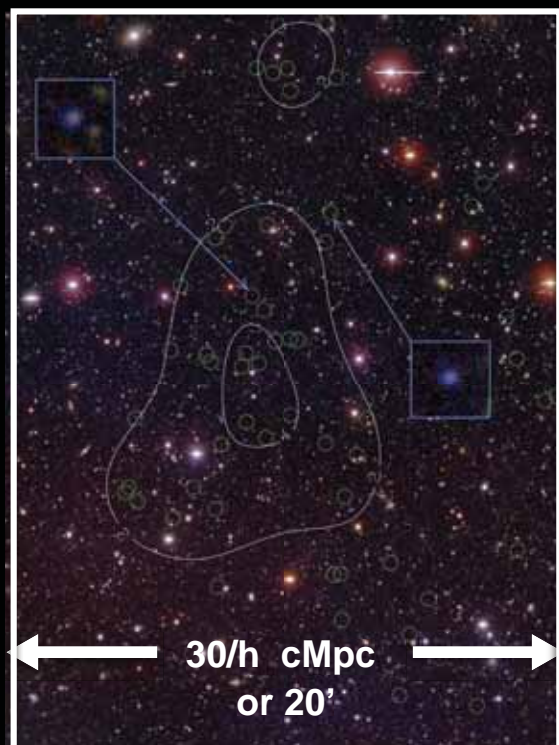
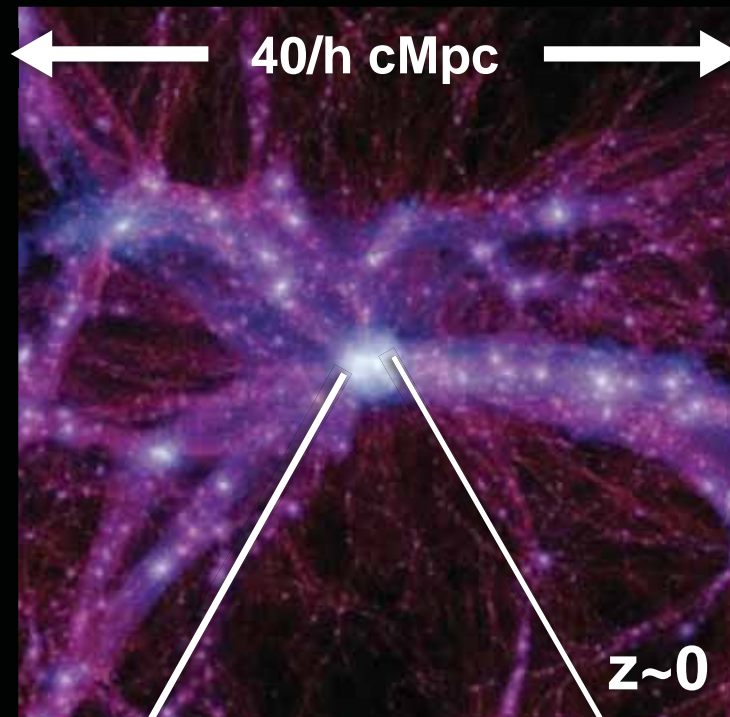
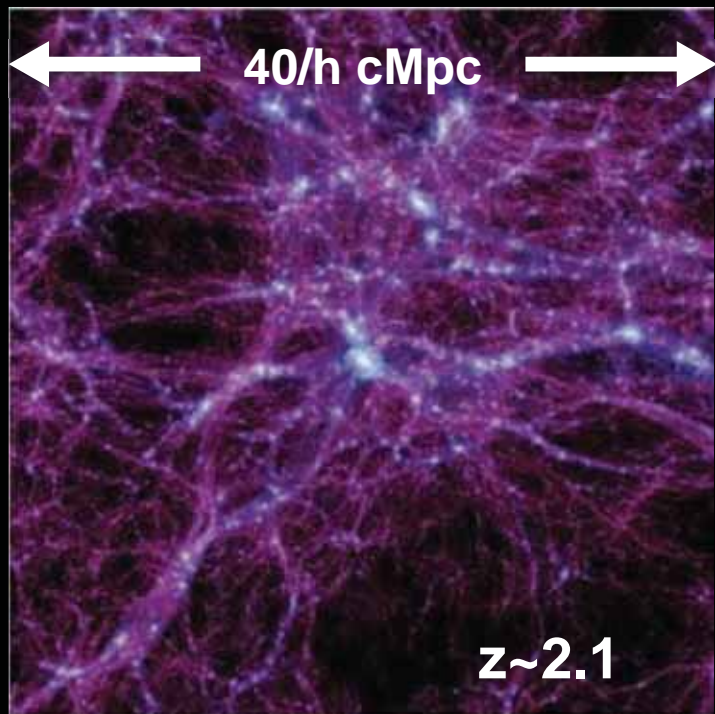




Diverse Constituents of a Massive Protocluster at $z=3.78$

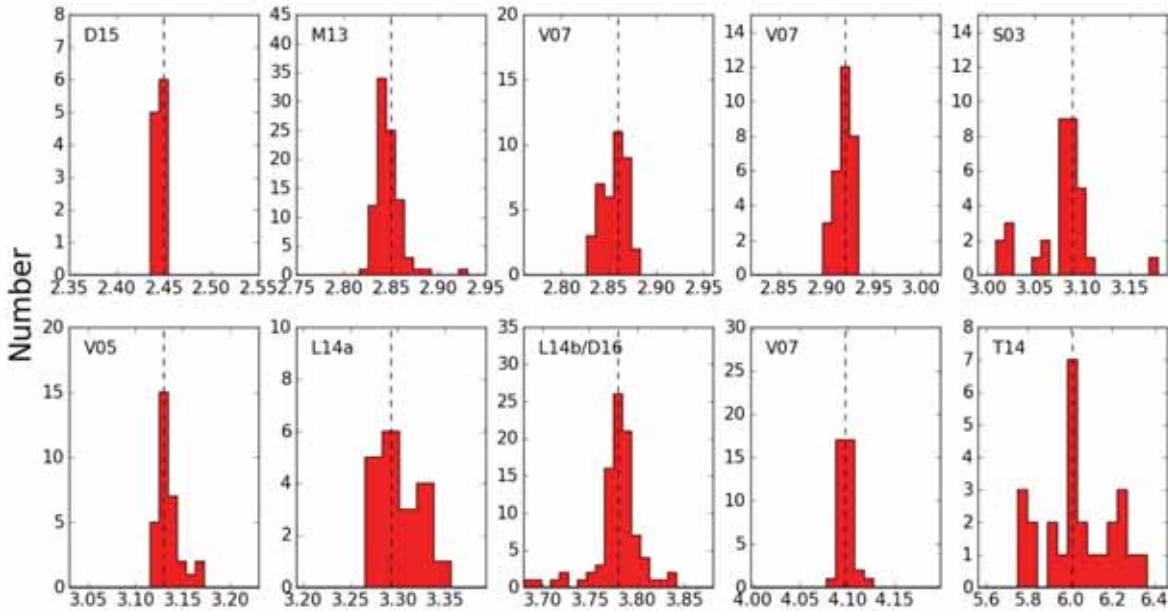
June 28 2018

Kyoung-Soo Lee (Purdue University)

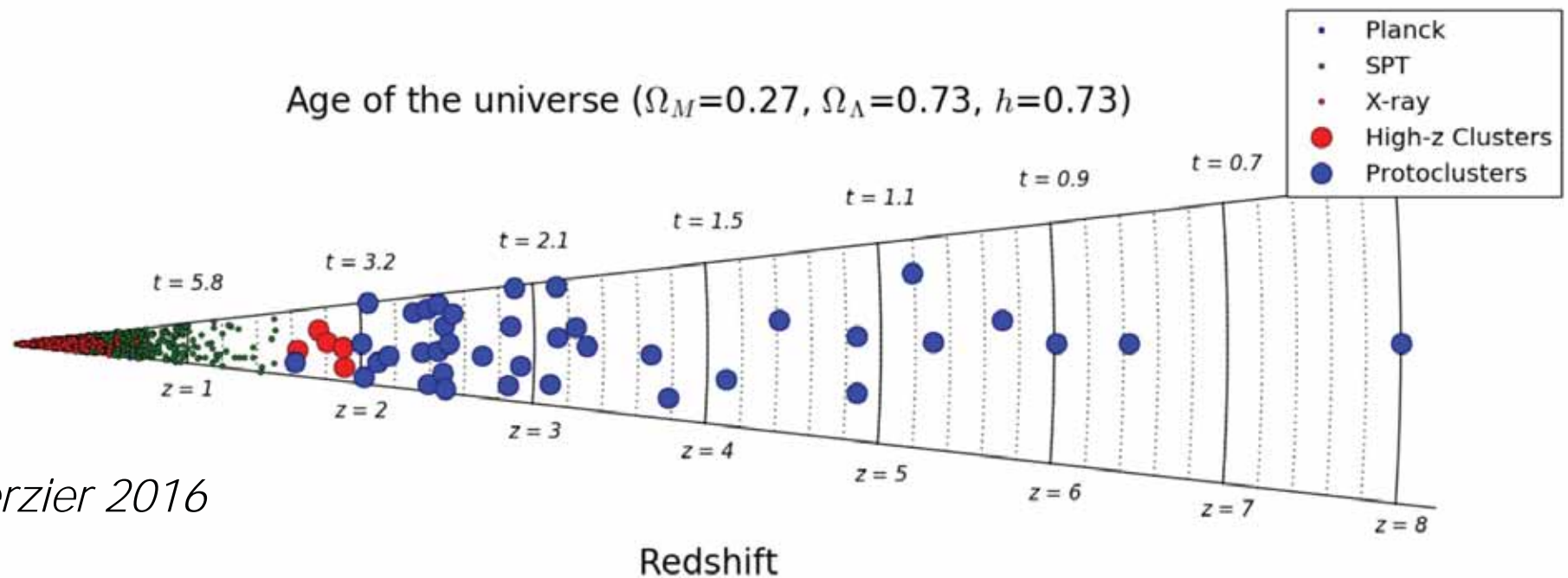


Boylan-Kolchin+2009

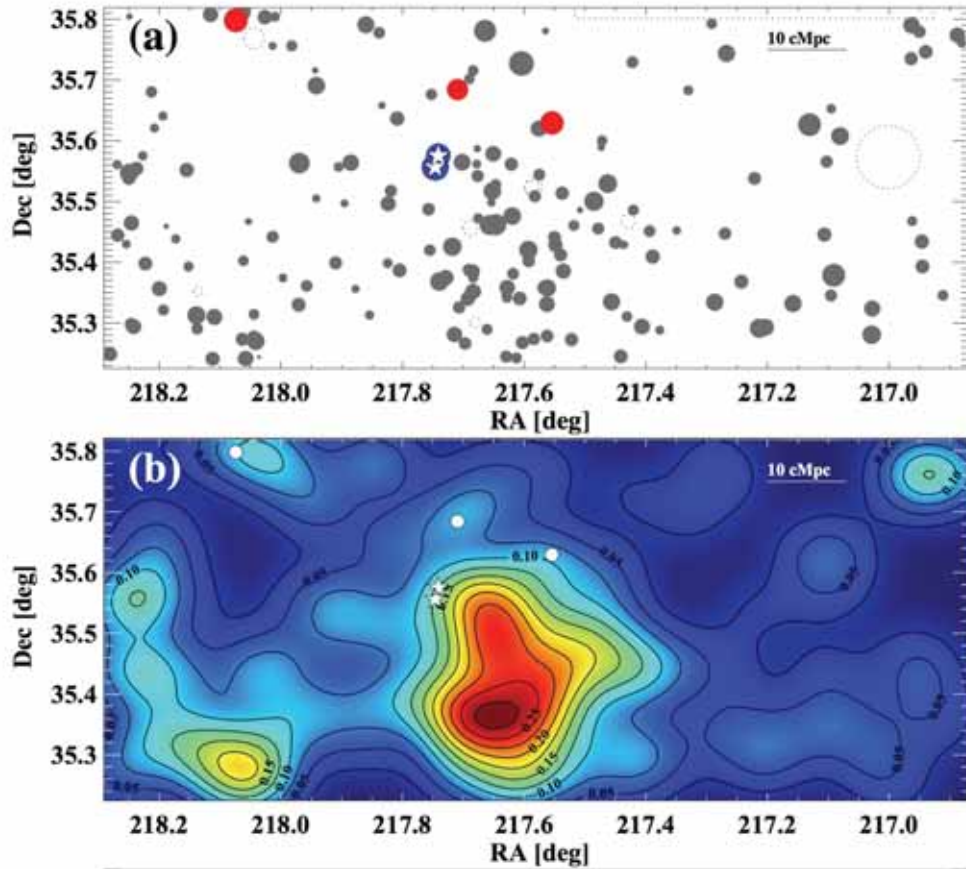
What is a protocluster?



- A structure that will collapse and virialize by $z=0$ into a galaxy cluster ($> \sim 10^{14} M_{\text{sun}}$)
- Observationally, the definition of a protocluster is more nebulous
- Galaxy overdensity (in angular or redshift space)

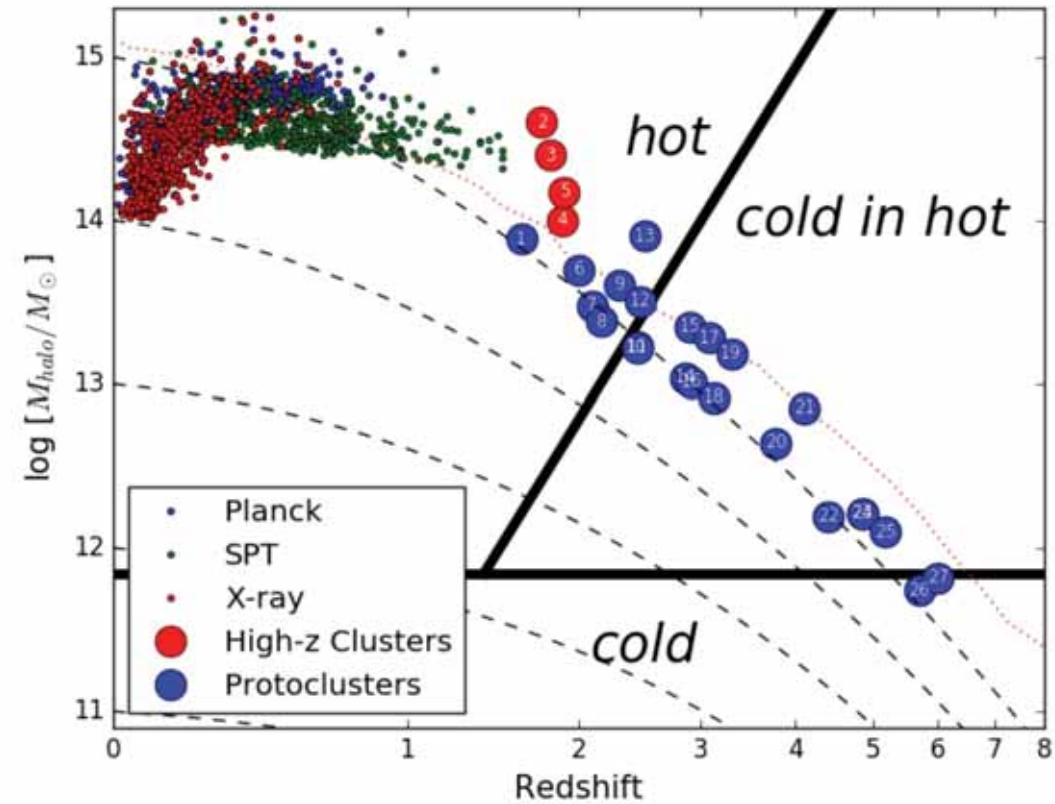


Mapping out the LSS



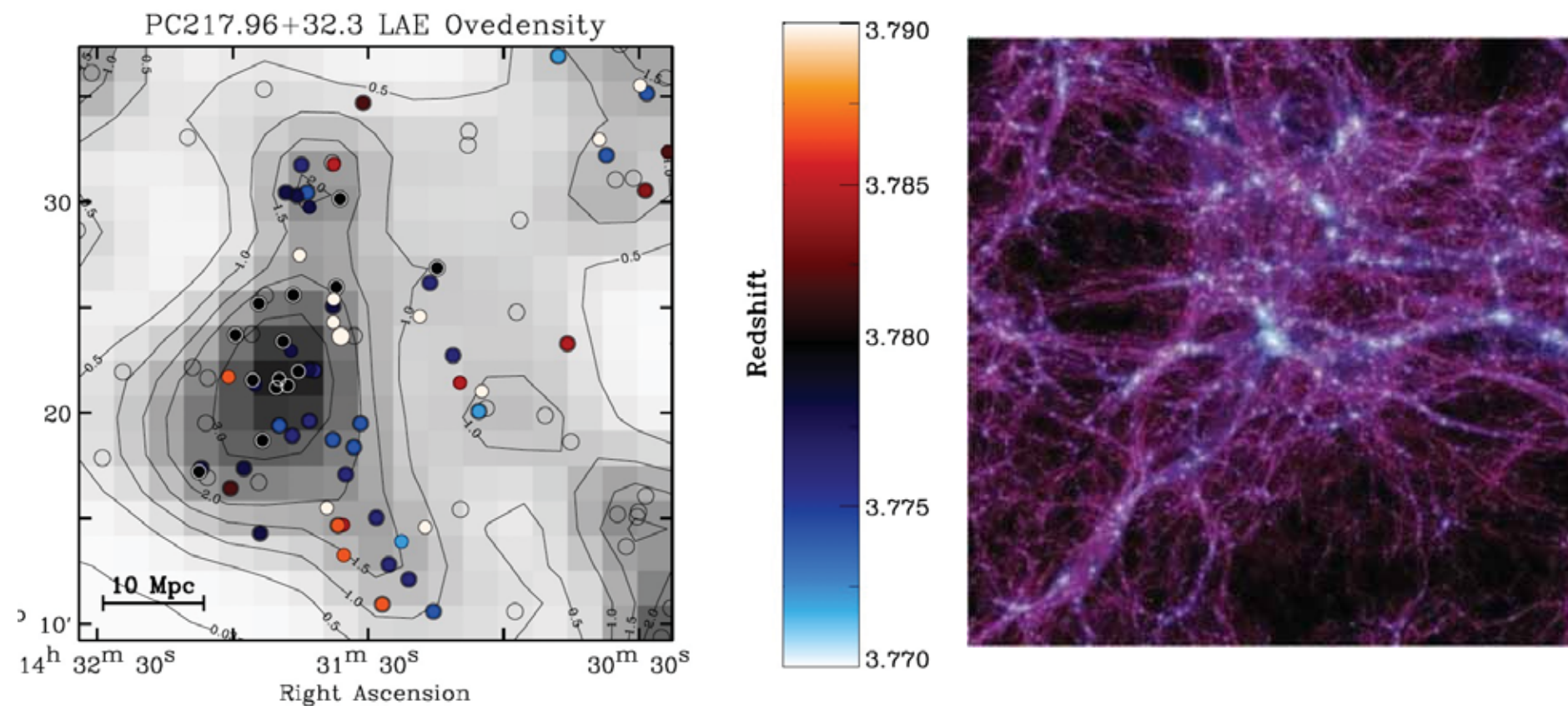
Badescu+2017

Overzier 2016



Well-measured size and level of galaxy overdensity, and galaxy bias can yield robust estimates of total mass (i.e., present-day cluster mass).

Mapping out the LSS



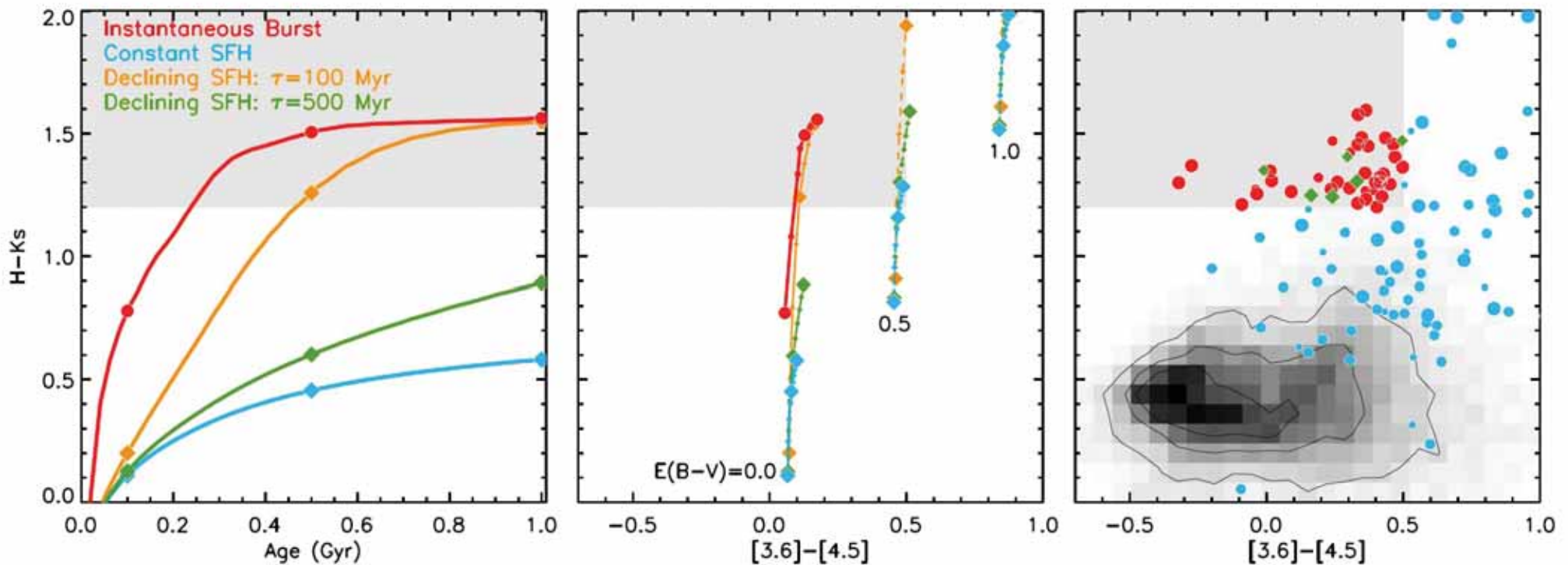
Dey, KSL+2016

Detailed knowledge of the large-scale structure (LSS) around the protocluster can reveal the regions of interest, e.g., the densest core, cosmic filaments, outskirts, etc.

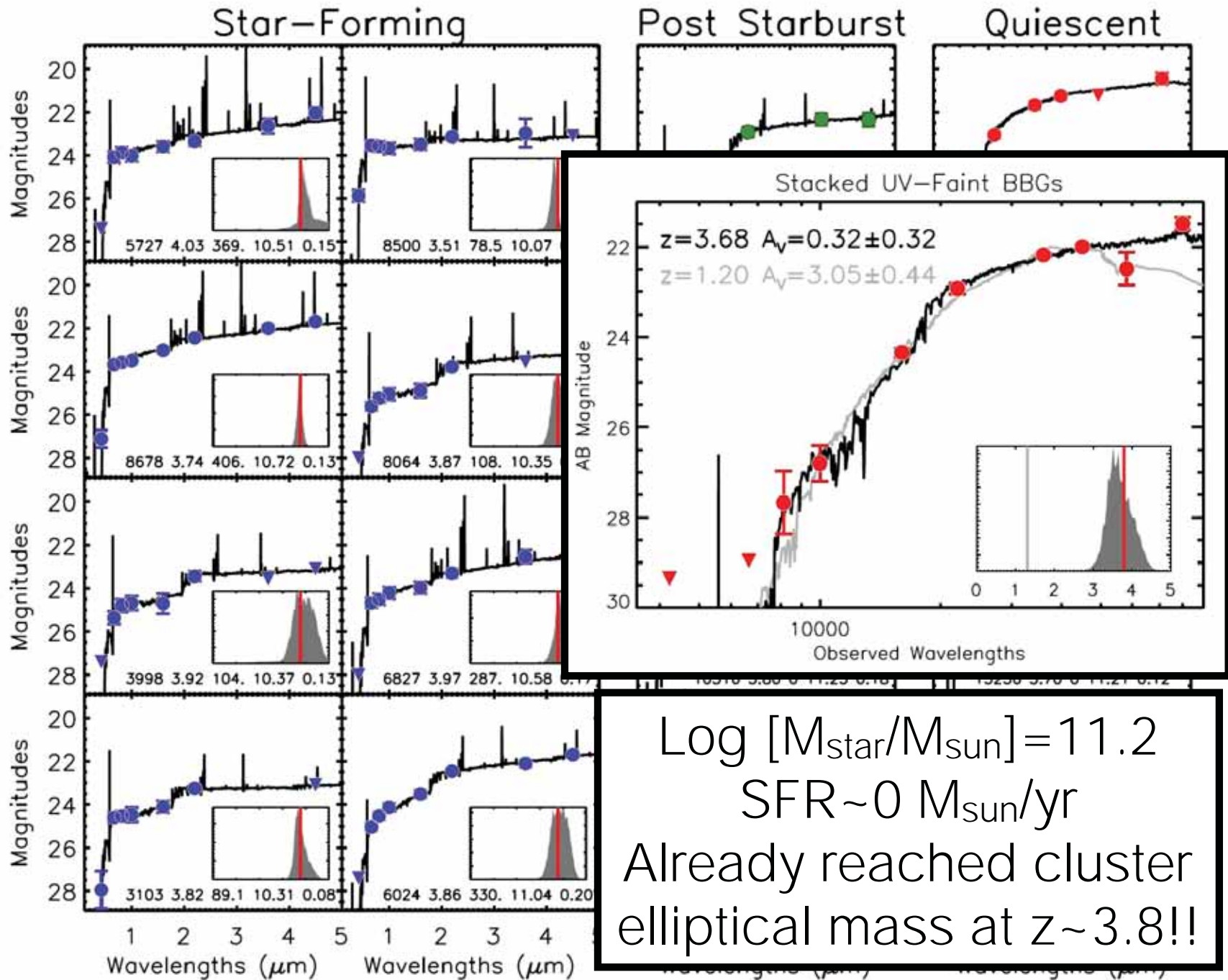
Search for protocluster constituents

We conducted a careful search of diverse types of galaxies around a known massive structure at $z=3.78$, which will evolve into a Coma like structure by $z=0$.

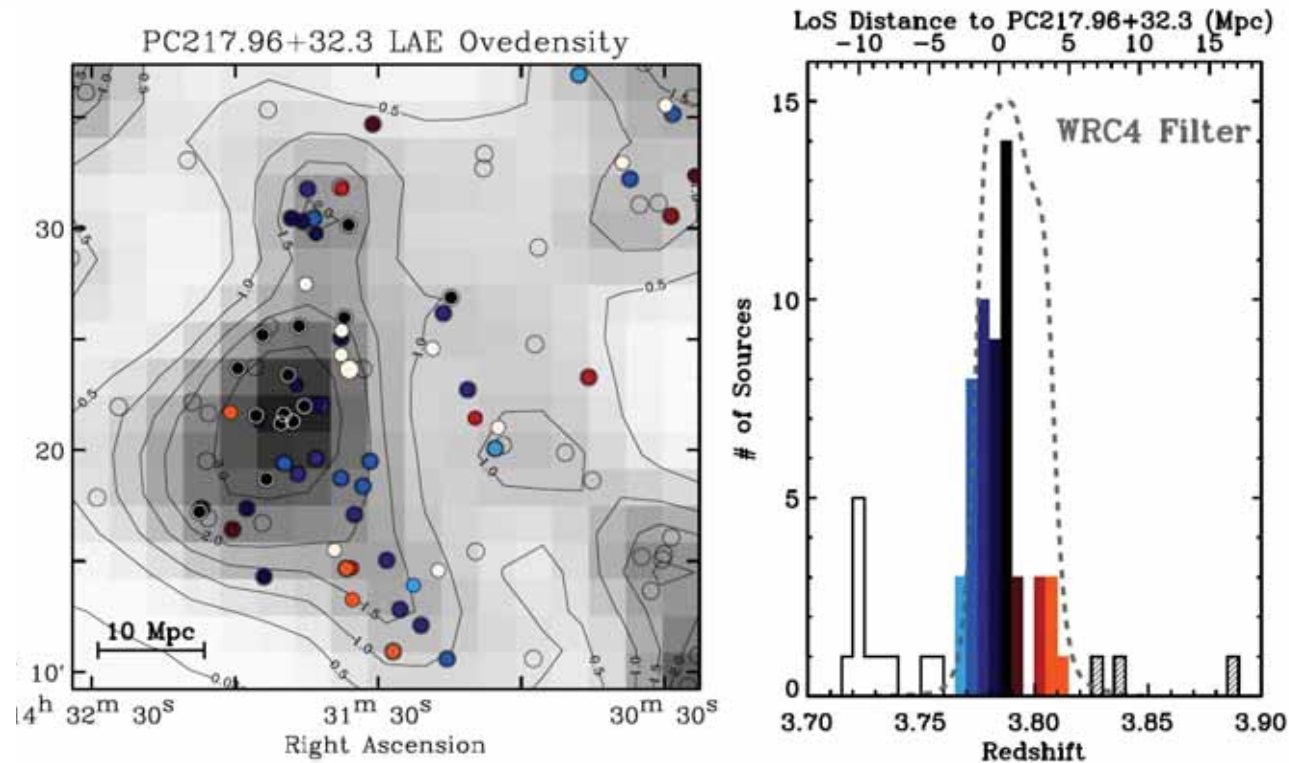
- a mass-limited sample of star-forming galaxies (via photo-z)
- galaxies with old stellar populations (strong Balmer/4000Å break)
- spectroscopically confirmed Ly α emitters ($z=3.775\pm 0.015$)



SEDs of protocluster member candidates



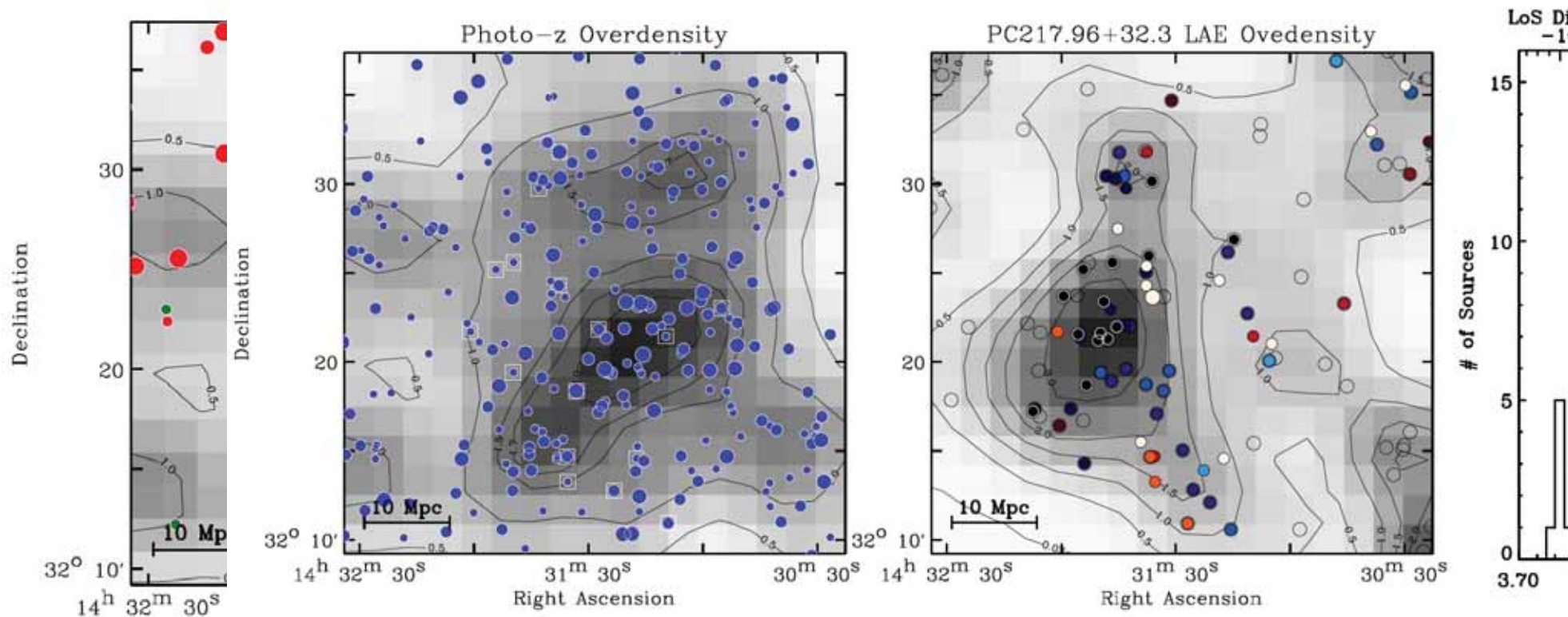
A tale of two galaxy overdensities



- Photo-z overdensity only partially overlaps with the confirmed members;
- photo-z overdensity consistent with $\delta_g=8\pm 2$ and the present-day mass of $(8\pm 1)\times 10^{14}M_{\text{sun}}$; the previously known extent has the estimated mass of $> \sim 10^{15}M_{\text{sun}}$
- Superposition of two unrelated Coma analogs, or a single very extended structure? Both equally unlikely but not impossible.

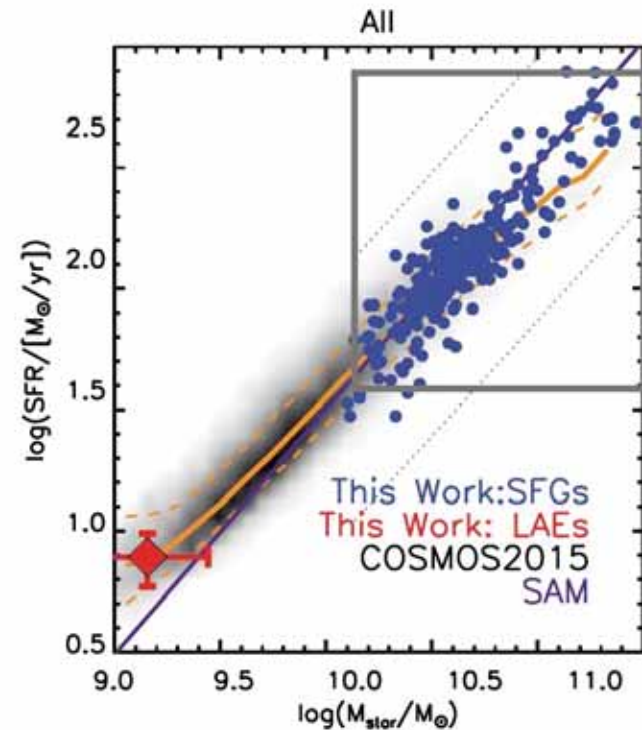
Shi, KSL+2018

Meantime, quiescent galaxies...



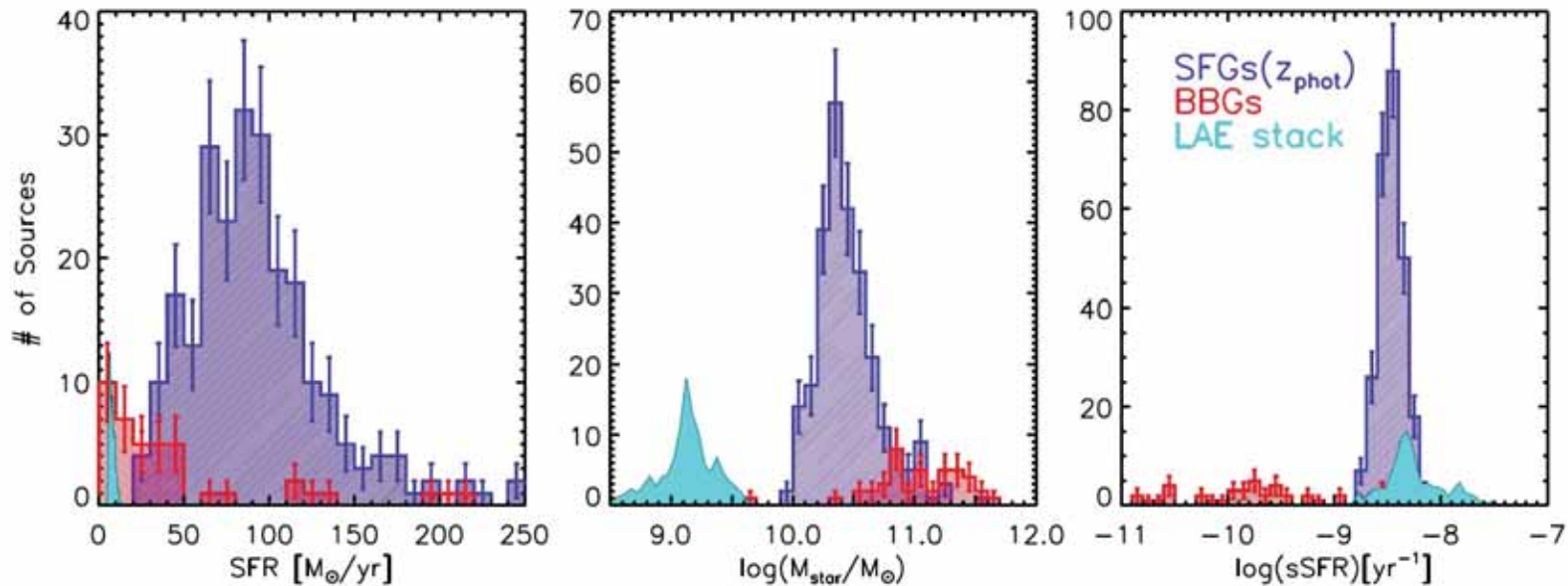
- A large surface overdensity (9-16x) of quiescent galaxies relative to the field.
- Quiescent galaxies found *in the outskirts*, but not at the core (Ly α blobs are often found in the outskirts of a protocluster: *Erb+2011, Mawatari+2012, Badescu+18*)
- Quiescence comes well before virialization, perhaps marking the most massive inhabitants of merging dark matter halos (no environmental quenching yet). *Shi, KSL+2018*

environmental dependence of galaxy formation (or lack thereof)



- the same scaling law obeyed by protocluster galaxies and average-field galaxies
- most of the cluster galaxy assembly hidden from view by dust? (*e.g.*, *Umehata+2015*, *Casey+2015*); deeper mid/far-IR data needed to test this scenario.

To make progress....

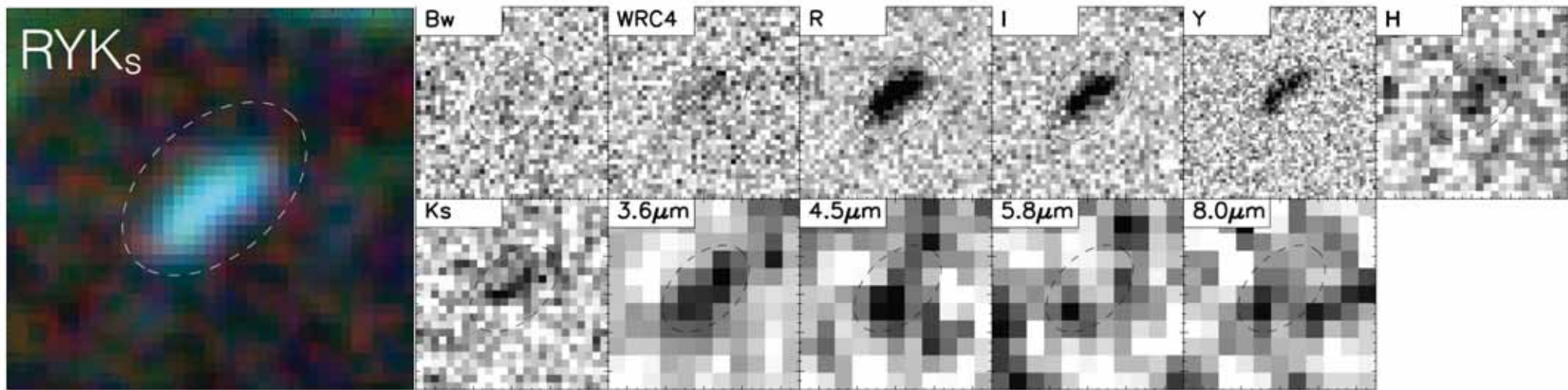


- Finding more protoclusters important, but not enough. Targeted searches for line-emitting galaxies perhaps the most efficient way to map out the large-scale structure (e.g., HETDEX, narrowband-driven searches?)
- Identify common trends in protocluster environments to better inform future searches (Ly α blobs, sub-mm galaxies, radio galaxies, Planck cold sources?)
- Detailed census of protocluster constituents needed to make the much needed evolutionary connection to lower-z galaxy clusters.

summary

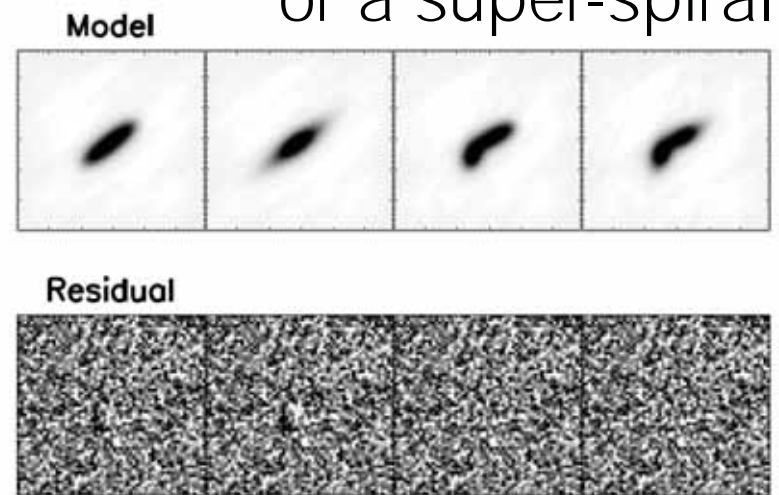
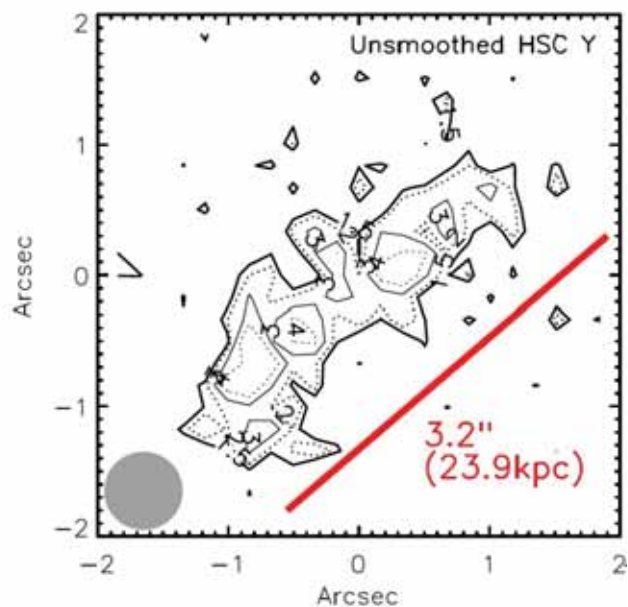
- A large population of very diverse galaxy types inhabit in and around the protocluster PC217.96+32.3 @ $z=3.78$.
- A slight offset between the confirmed LAE members and those of photo-z's raise the possibility of a very extended, very massive ($M_{\text{tot}} > 1.5 \times 10^{15} M_{\text{sun}}$) protocluster.
- Alternatively, we are witnessing a formation of proto-superclusters.
- A significant excess of ultramassive ($M_{\text{star}} > 10^{11} M_{\text{sun}}$) quiescent galaxies (and a handful of galaxies with post-starburst-like SEDs) in the field; cluster red sequence already in place as early as 1.5 Gyr after the Big Bang.
- No clear enhancement of star formation in cluster members, but cannot rule out the possibility that the main beneficiaries are obscured from view (submillimeter galaxies, obscured AGN, etc.).

> ~20 kpc galaxy at $z=3.72$

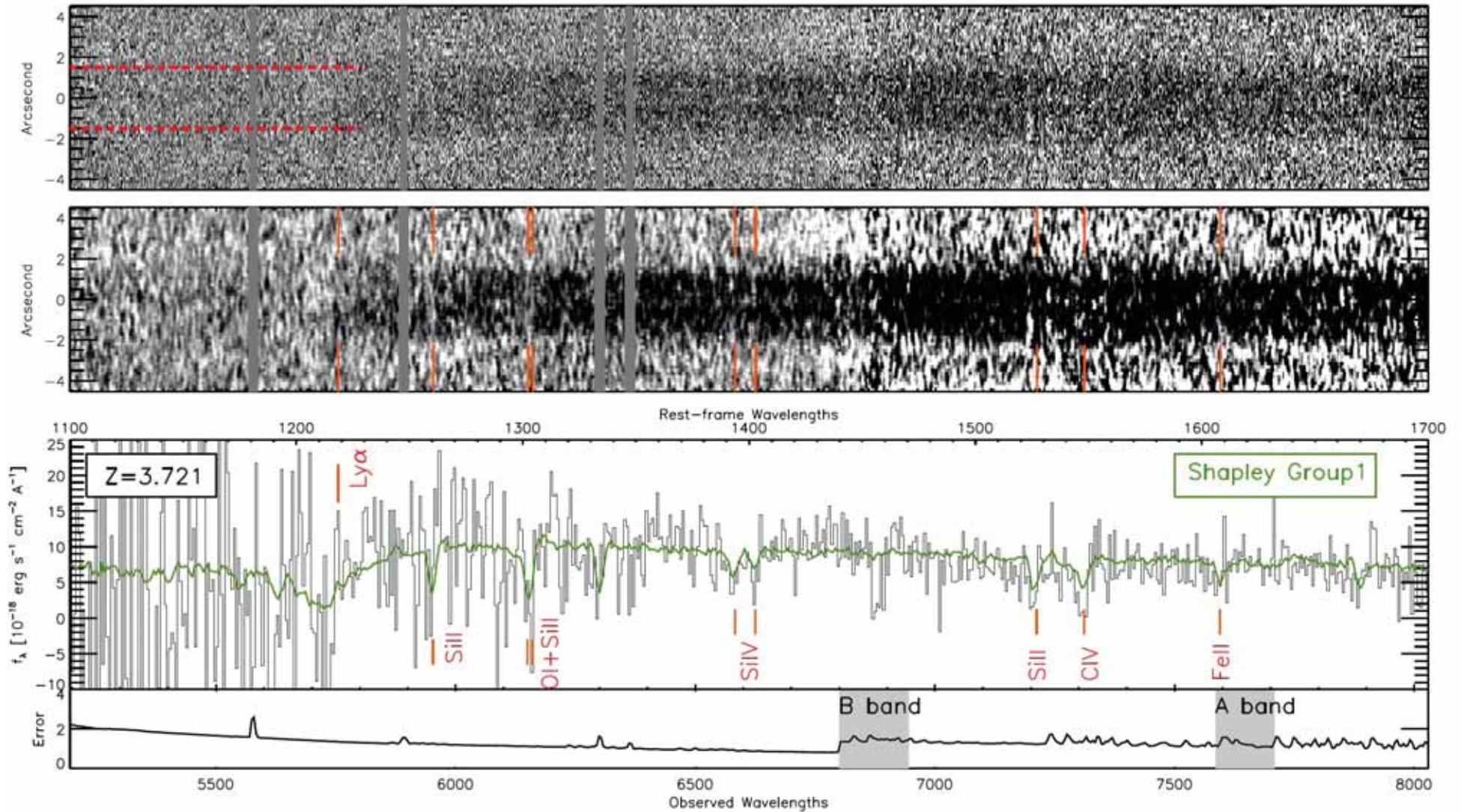


10"

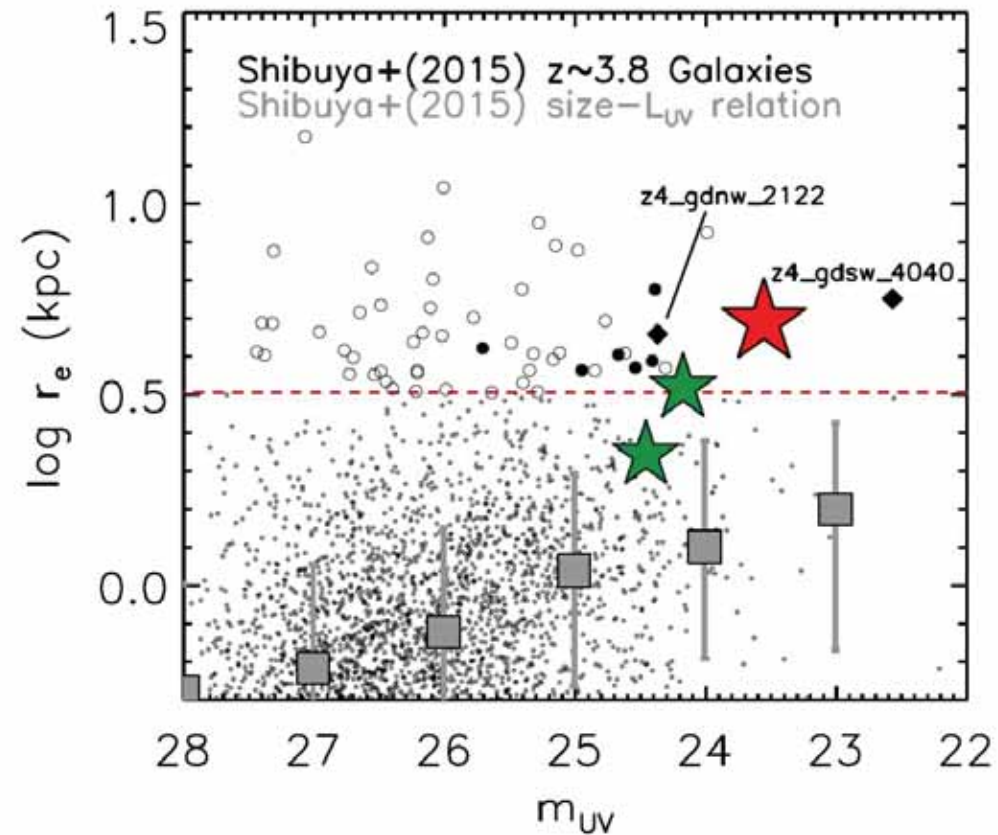
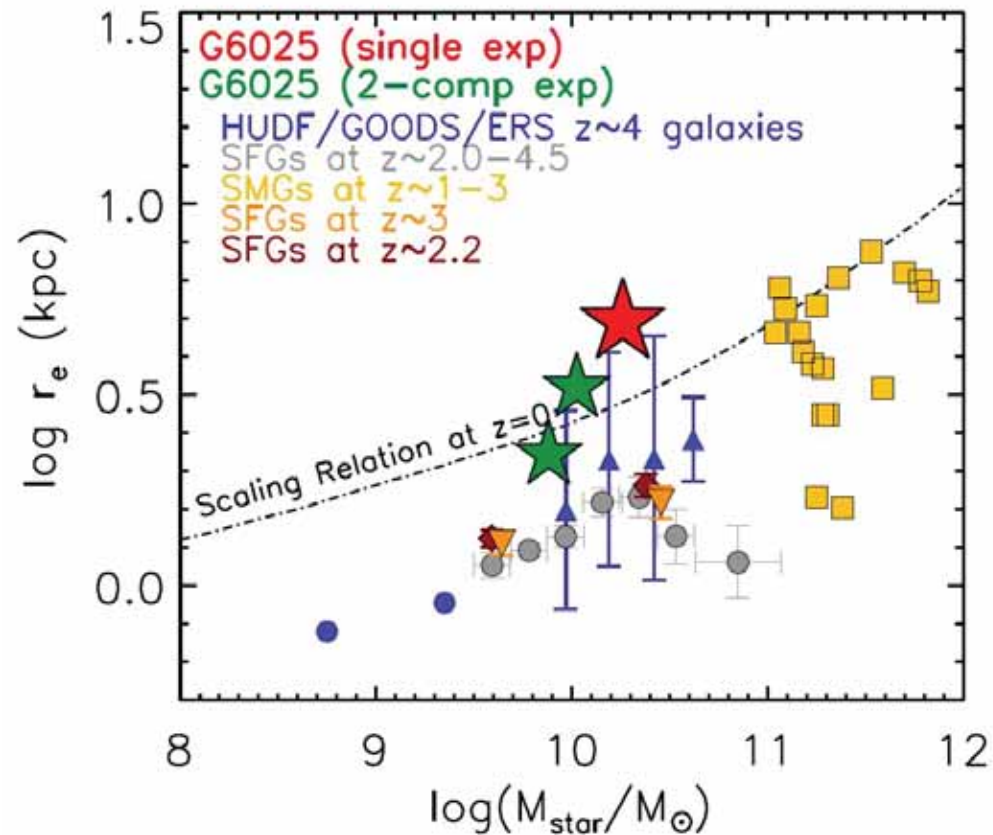
two overlapping galaxies, a giant chain galaxy, or a super-spiral?



$> \sim 20$ kpc galaxy at $z=3.72$

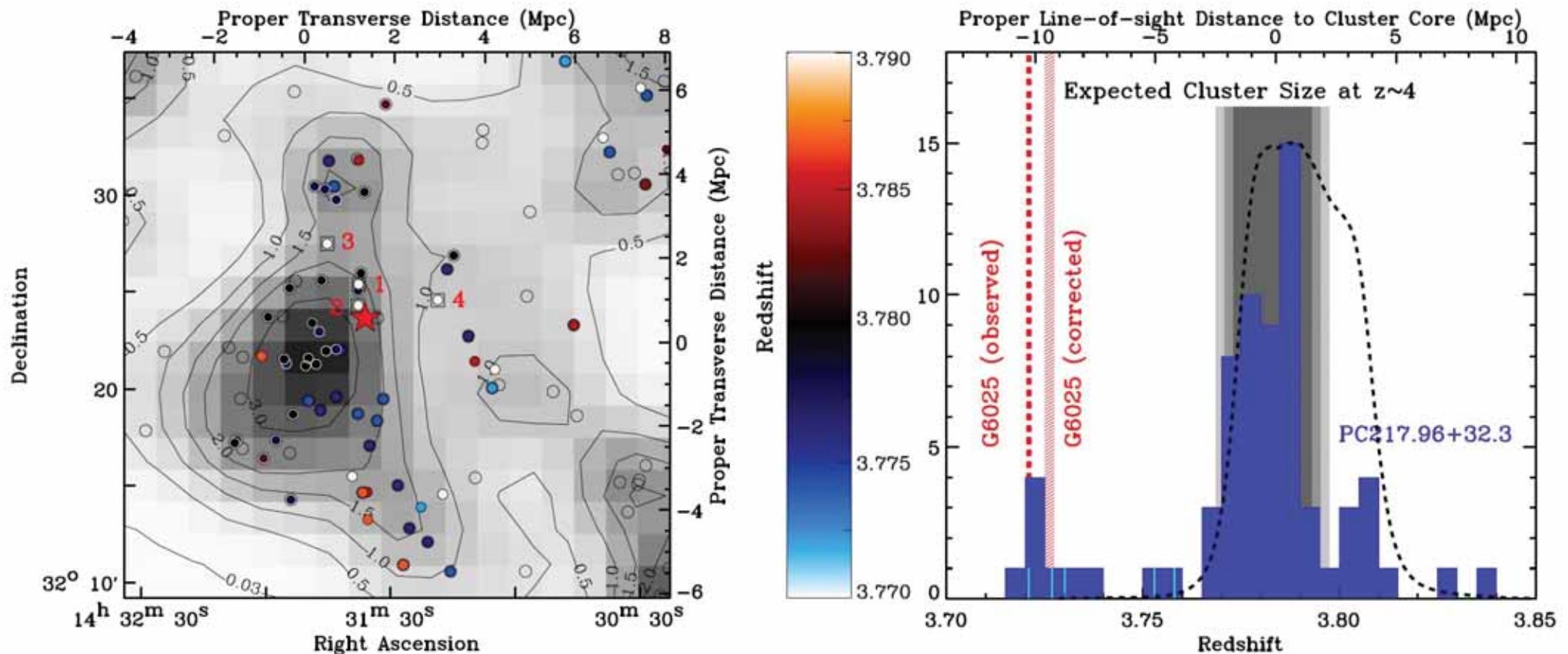


$> \sim 20$ kpc galaxy at $z=3.72$



A significant outlier in size-luminosity/mass relation.

> ~20 kpc galaxy at $z=3.72$



- Its position relative to the $z=3.78$ protocluster offers tantalizing evidence for a very extended structure (proto-super-cluster? Lee+2014, Cucciati+2018); spectroscopic followup just done in May 2018 (stay tuned!)
- Its unusual properties reflect that it represents an extremely short-lived phase of galaxy formation, or an entirely different pathway to form massive galaxies in dense environments.

Lee+2018, in press (arXiv:1803.07145)