Probing the Early Epoch of Massive Cluster Formation

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collaborators

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- Rui Xue (Purdue)
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galaxy clusters

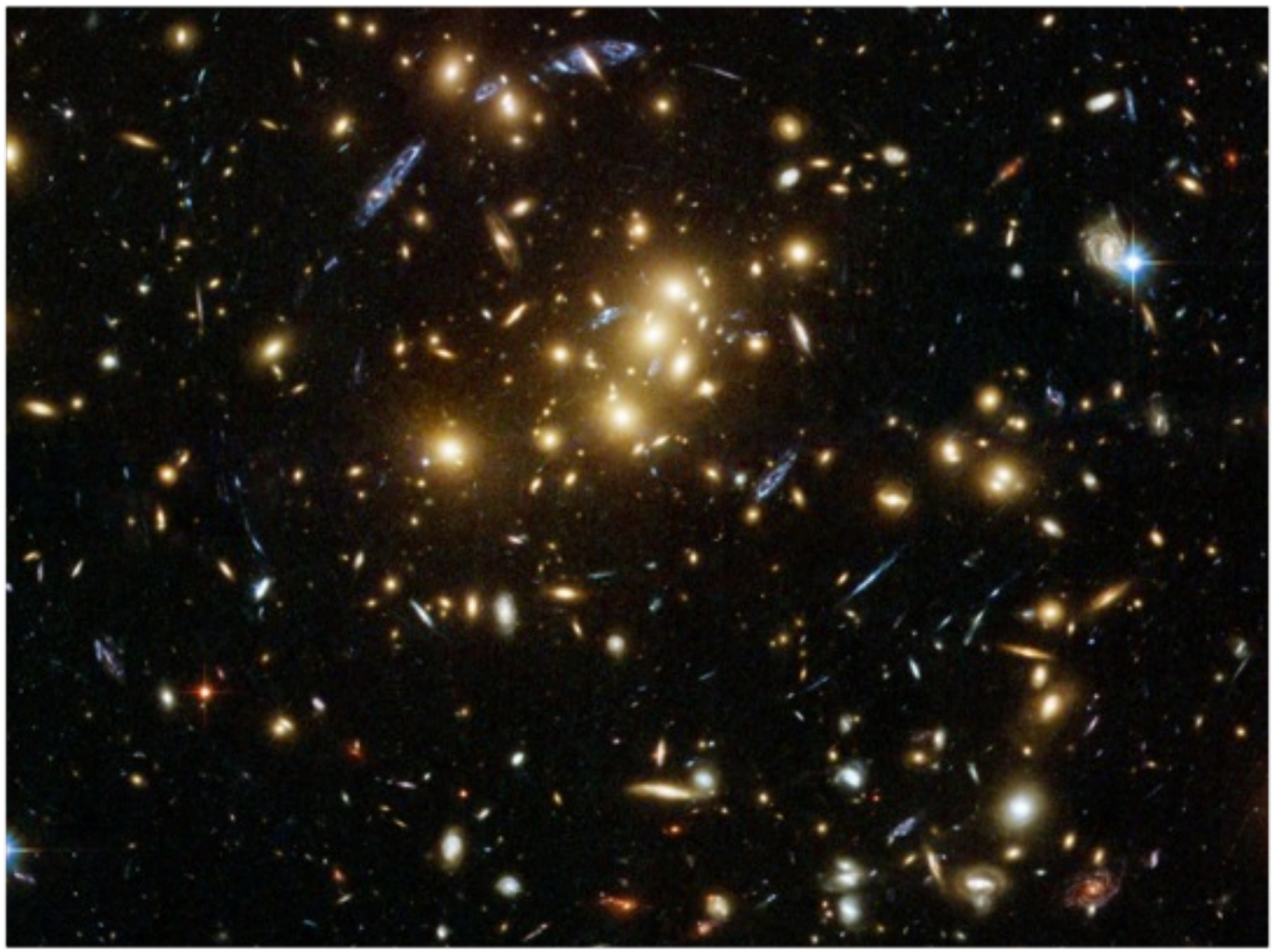
- The most massive gravitationally bound systems in the Universe

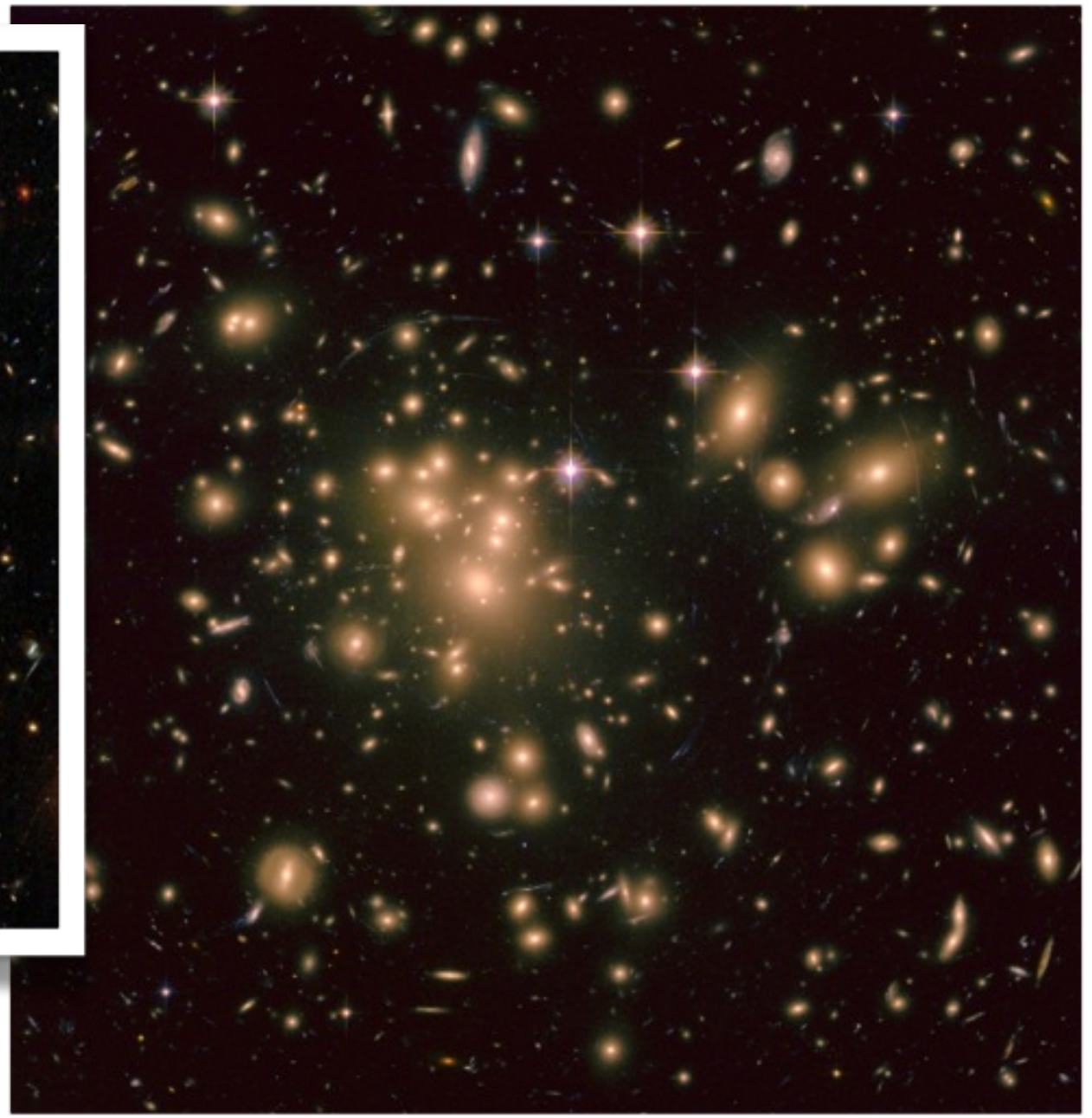
- a cosmological tool to measure matter content Ω and normalization of the power spectrum σ_8

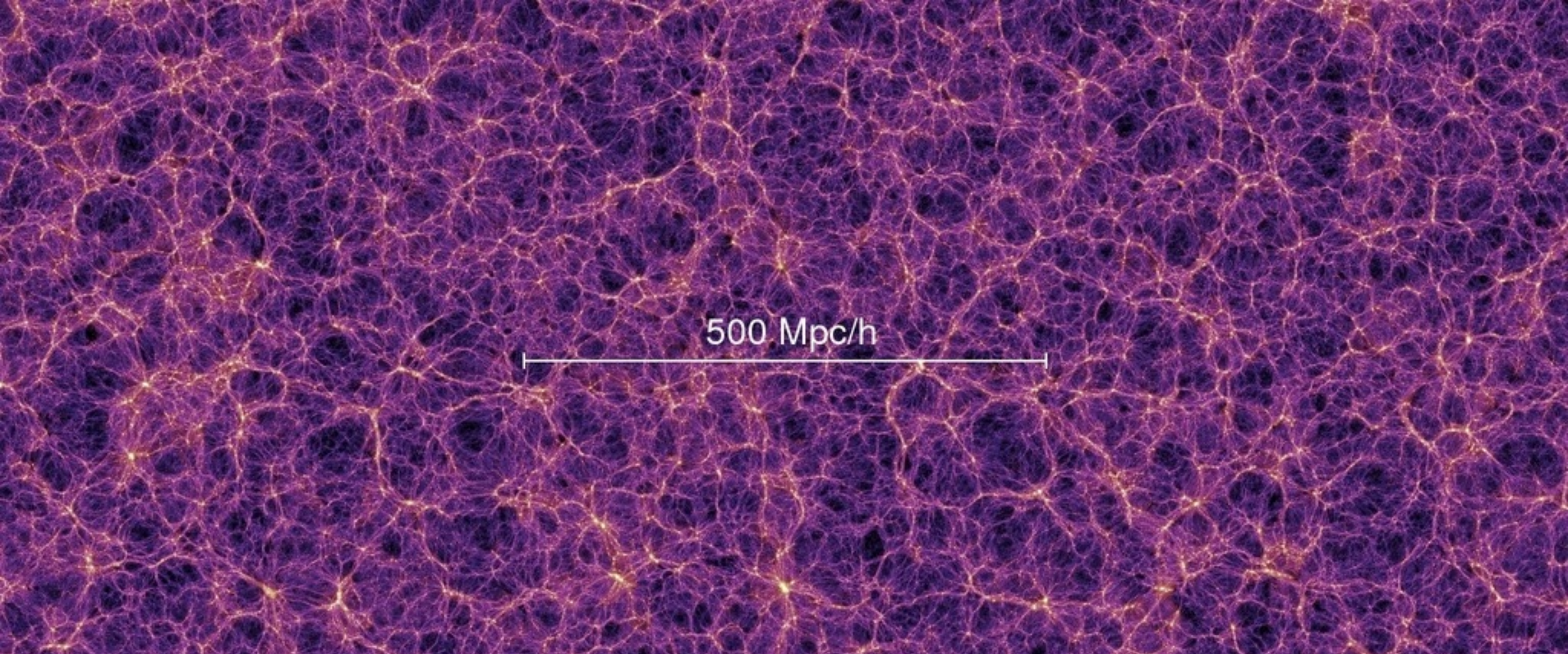
- unique laboratories to study environmental effects on galaxy formation

- environments one of the key parameters of galaxy formation; i) galaxy-galaxy interaction (tidal stripping, merger); ii) galaxy-ICM interaction (ram pressure); iii) surplus of gas accretion

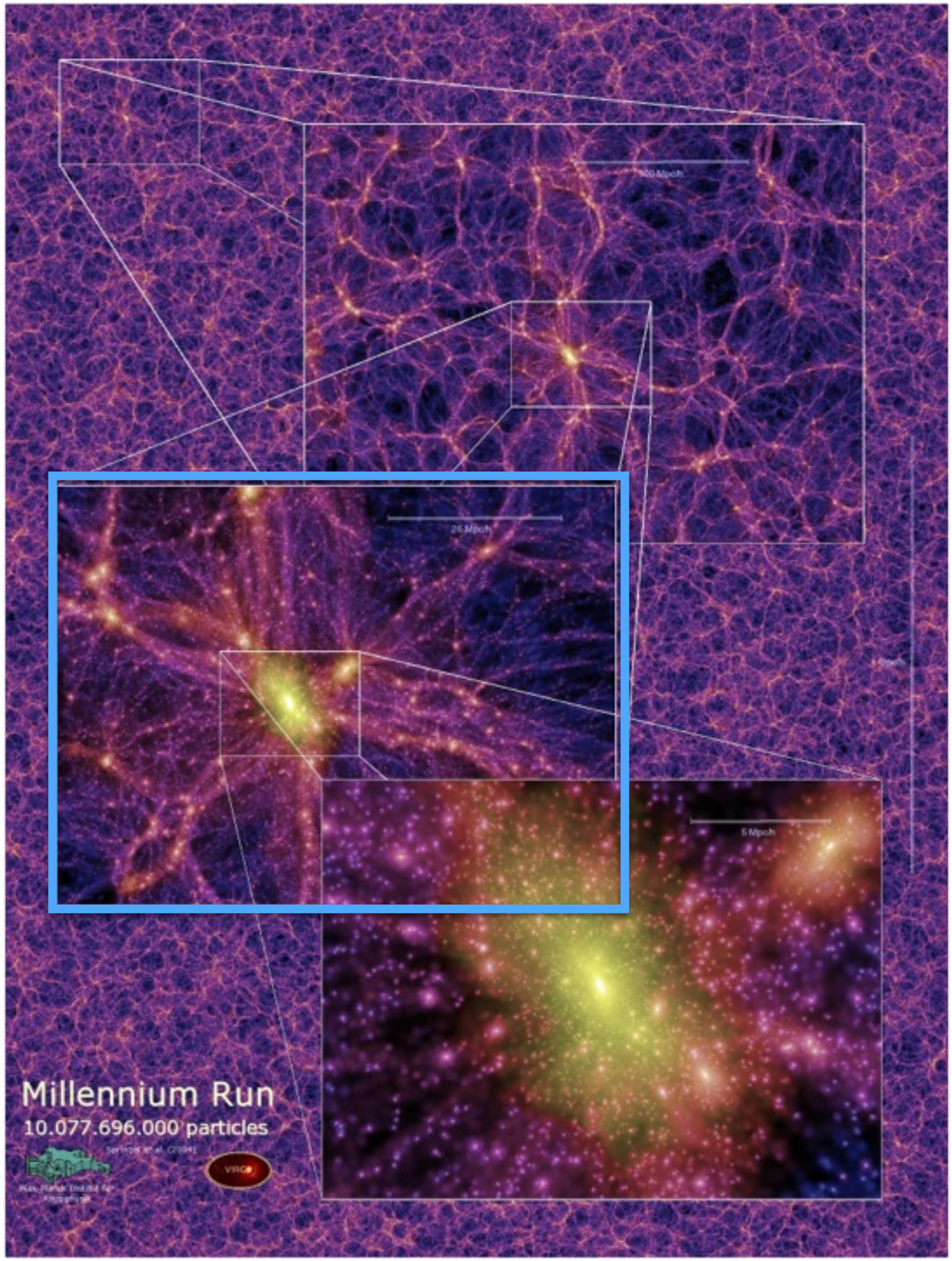
galaxy clusters







Clusters mark the largest, most massive dark matter structures (“halos”) in the universe, like the one in the center here



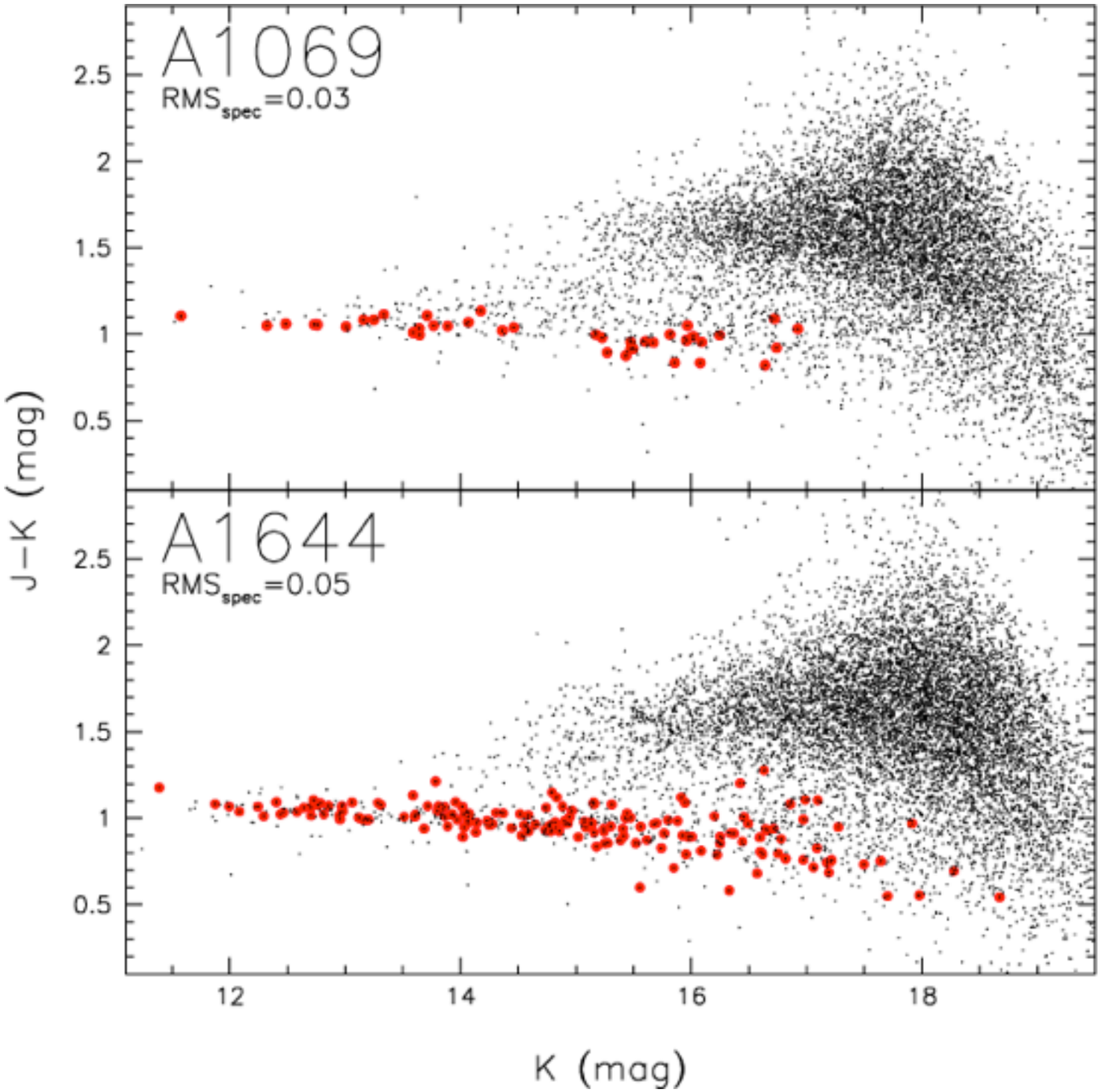
Zooming in on one cluster-sized halos, substructures and filamentary streams are evident. Clusters are not isolated systems, but rather a sink-hole where everything continuously falls in.

galaxy clusters

- a large concentration of massive, red galaxies in clusters = “cluster red sequence”

- red sequence is the outcome of environmental “quenching” of star formation in dense environments

- a convenient observable for systematic searches *e.g., Gladders & Yee 2000*

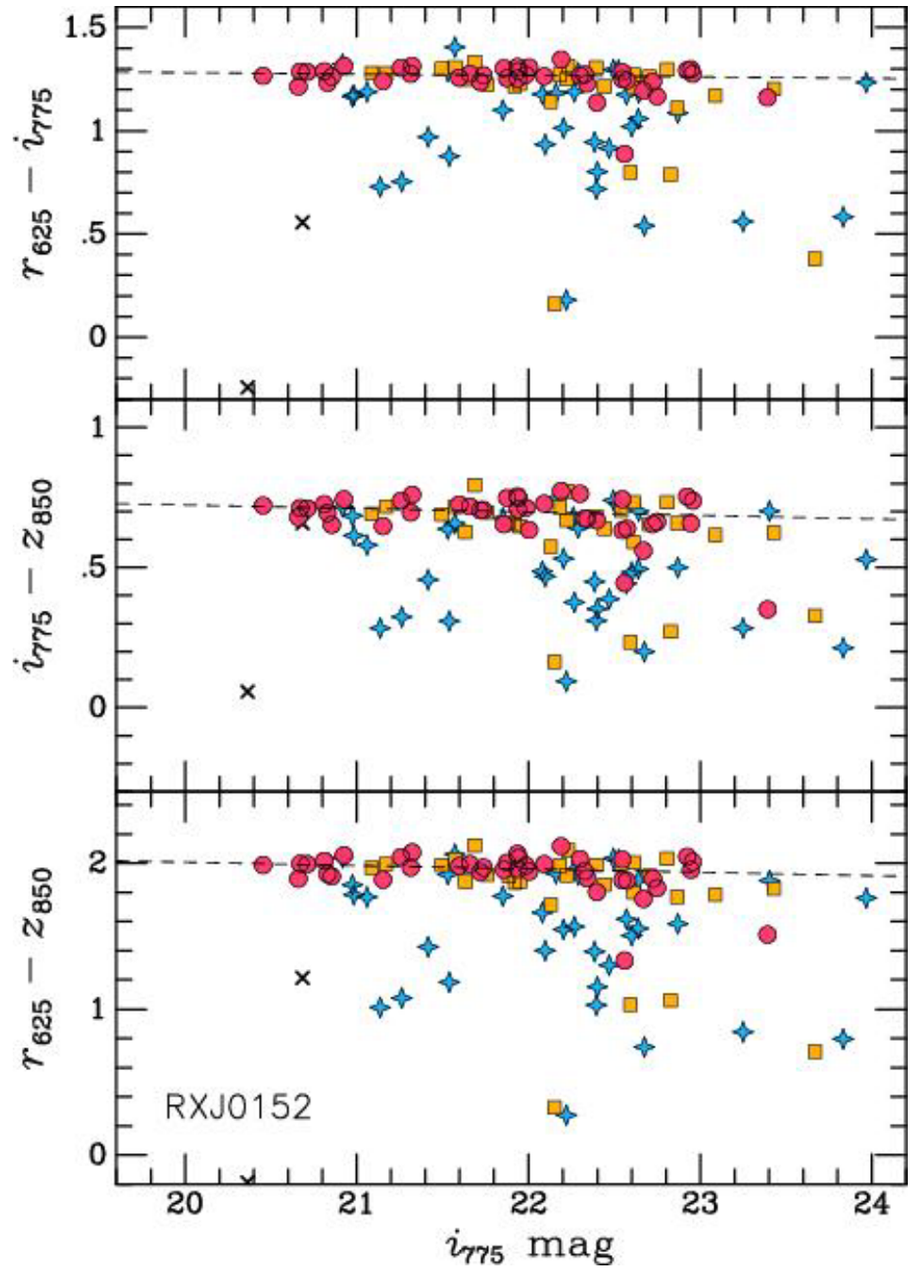


galaxy clusters

- cluster red sequence observed as early as z~2 ($t_{universe}$~3 Gyr)
  Kurk+ 06, Papovich+ 10

- The tightness of red sequence in distant clusters puts the formation epoch at z>~2-3
  Stanford+ 98, Blakeslee+ 06, Mei+ 09

- archeological studies (absorption lines indices to measure α/Fe peak ratio) also suggest that mass assembly complete by z>~2-3 *Thomas+ 05*



MS1054-03 @ z=0.83

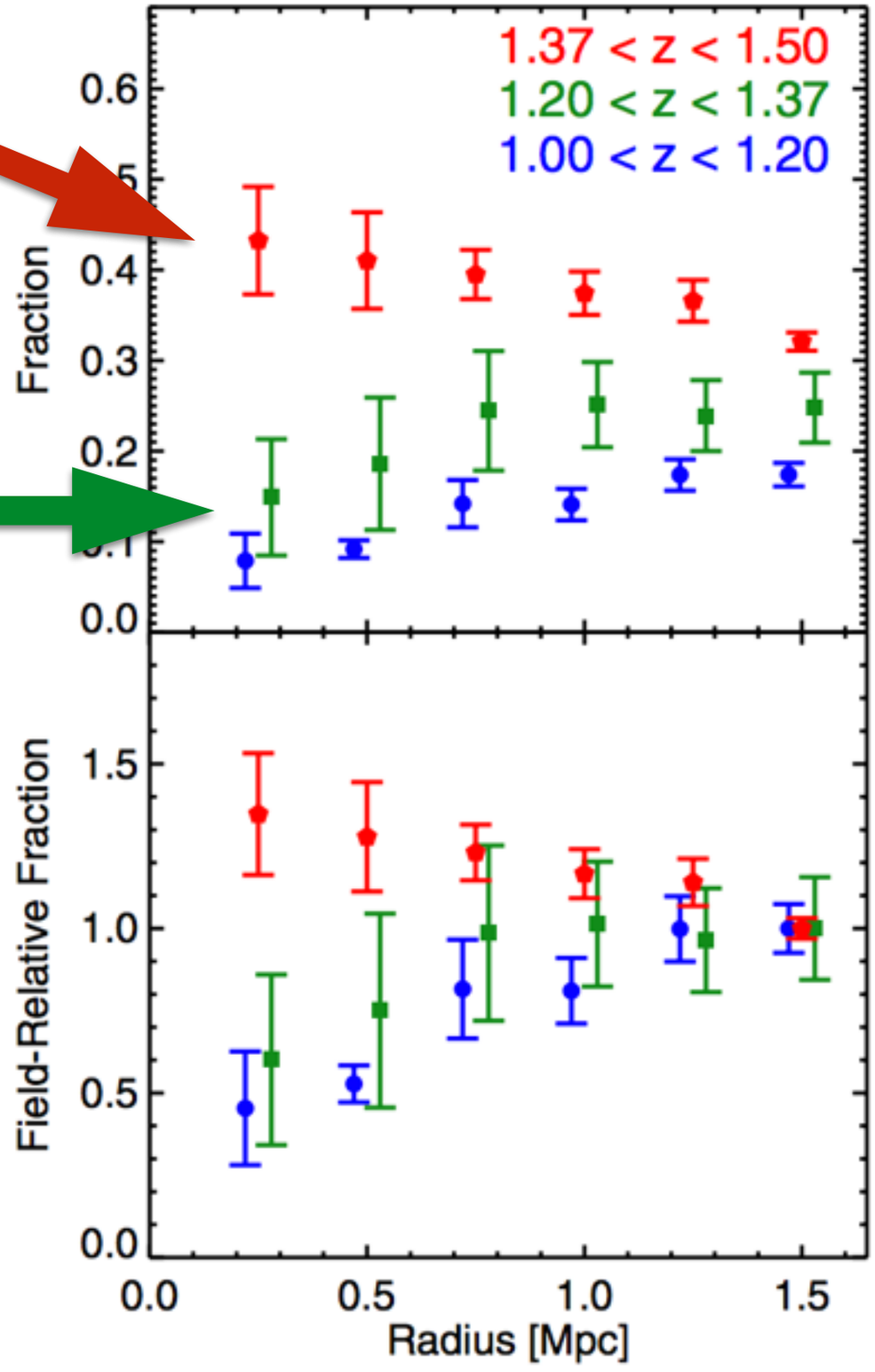
galaxy clusters at intermediate redshift

- Reversal of star-formation-density relation observed in z~1-2 clusters *Tran+ 09, Brodwin + 13, Koyama+ 13*

- approaching the epoch in which star formation is promoted in dense environments?

- Identifying cluster progenitors at z>~3 is key to determining early phase of cluster formation, and when environmental quenching becomes important

- **Complications**: no readily observable signatures — not enough time to form red-sequence, not relaxed (no X-ray emitting hot intracluster gas)



Brodwin+ 2013

Scarcity of high-redshift proto-clusters

- ~20 candidates at z>2, ~10 at z>3
- roughly half of them around high-z radio galaxies and quasars, and the other half mostly serendipitous discoveries from “field” surveys
- the latter typically from 0.1-1.0 deg^2 deep fields

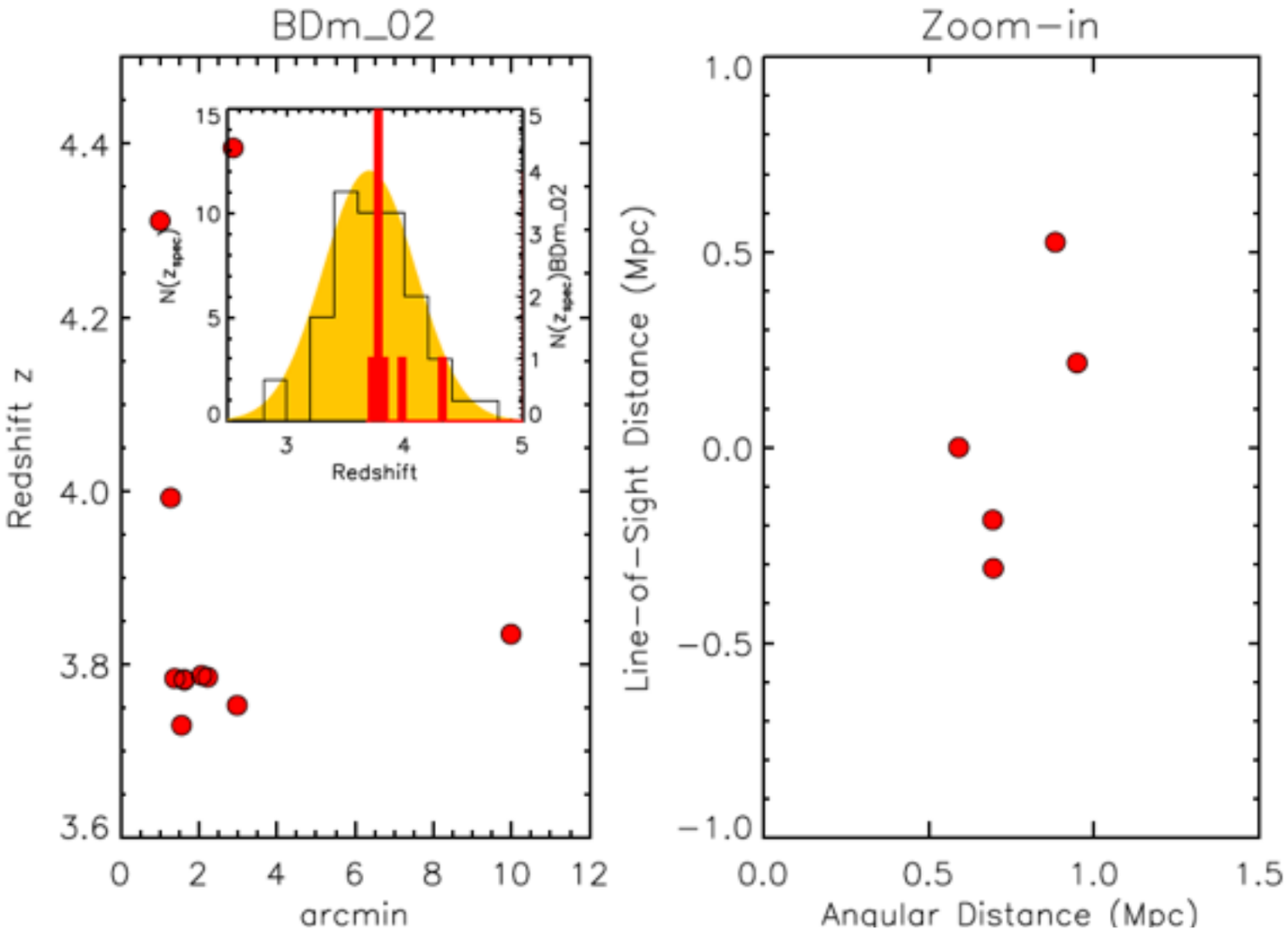
- 1 deg = 114 (130) Mpc at z=3 (4)
- distance for galaxies Δz=+/-0.3 corresponds to 600 (440) at z=3 (4)
- distance for galaxies Δz=+/-0.03 corresponds to 60 (44) at z=3 (4)
- A deep survey covering 1 deg^2 with Δz=+/-0.3 contains **1.6** massive (Coma-like) clusters — in other words, don’t count on serendipity to find many!

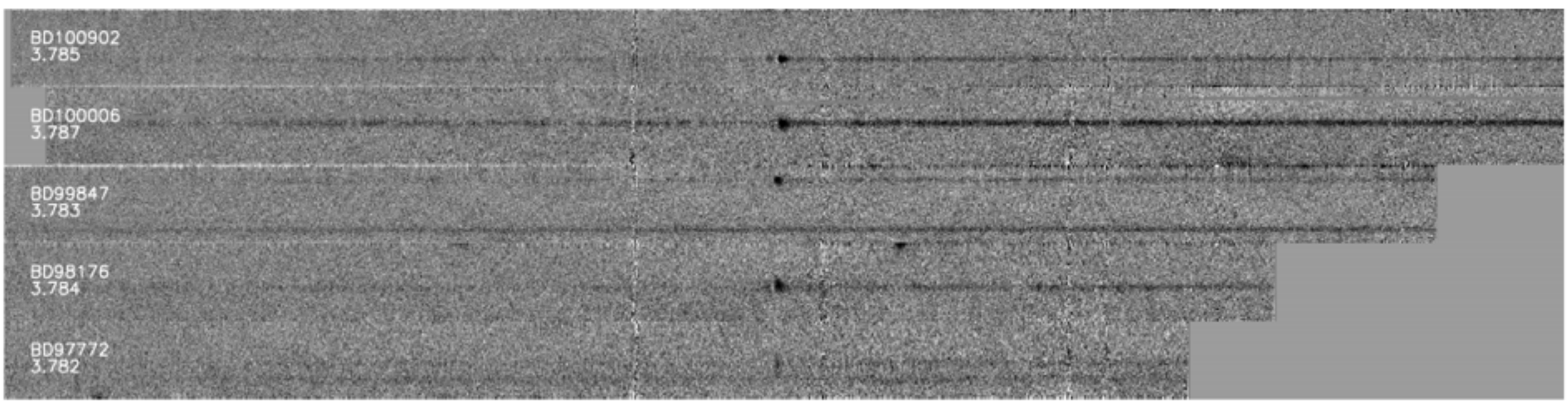
Discovery of a z=3.78 proto-cluster

Lee+ 2013

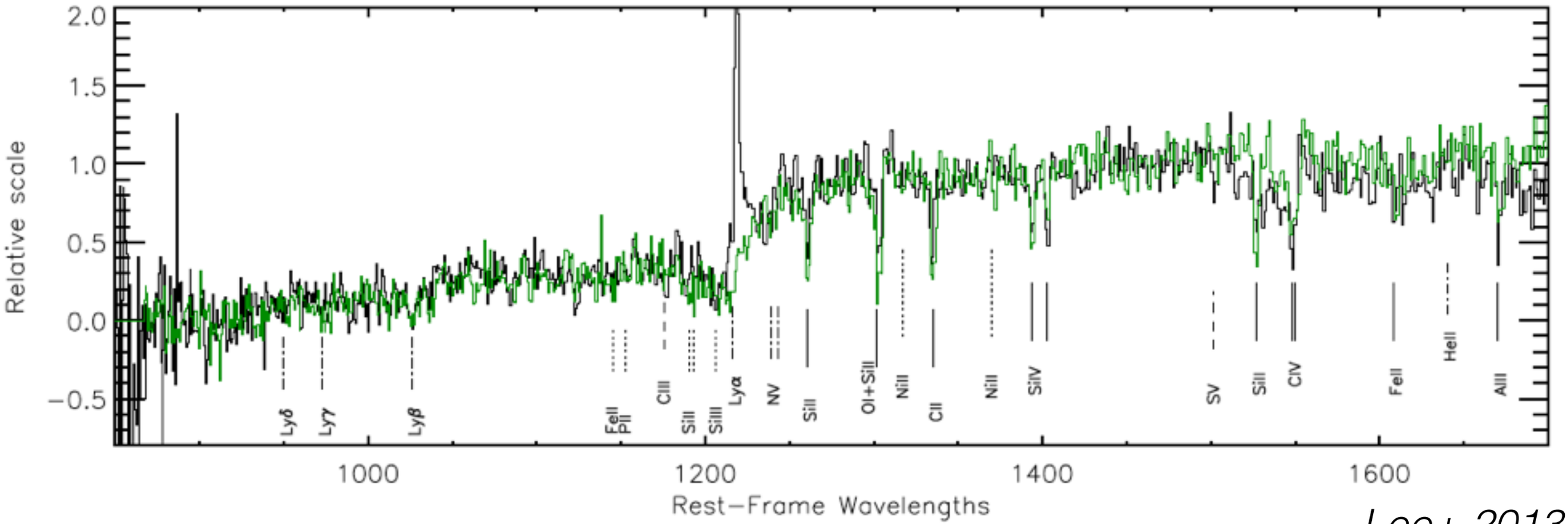
- Spectroscopic followup of field galaxies yielded a discovery of a localized redshift spike at z=3.785

- All 5 galaxies with prominent Lyman alpha in emission





Lyman alpha line

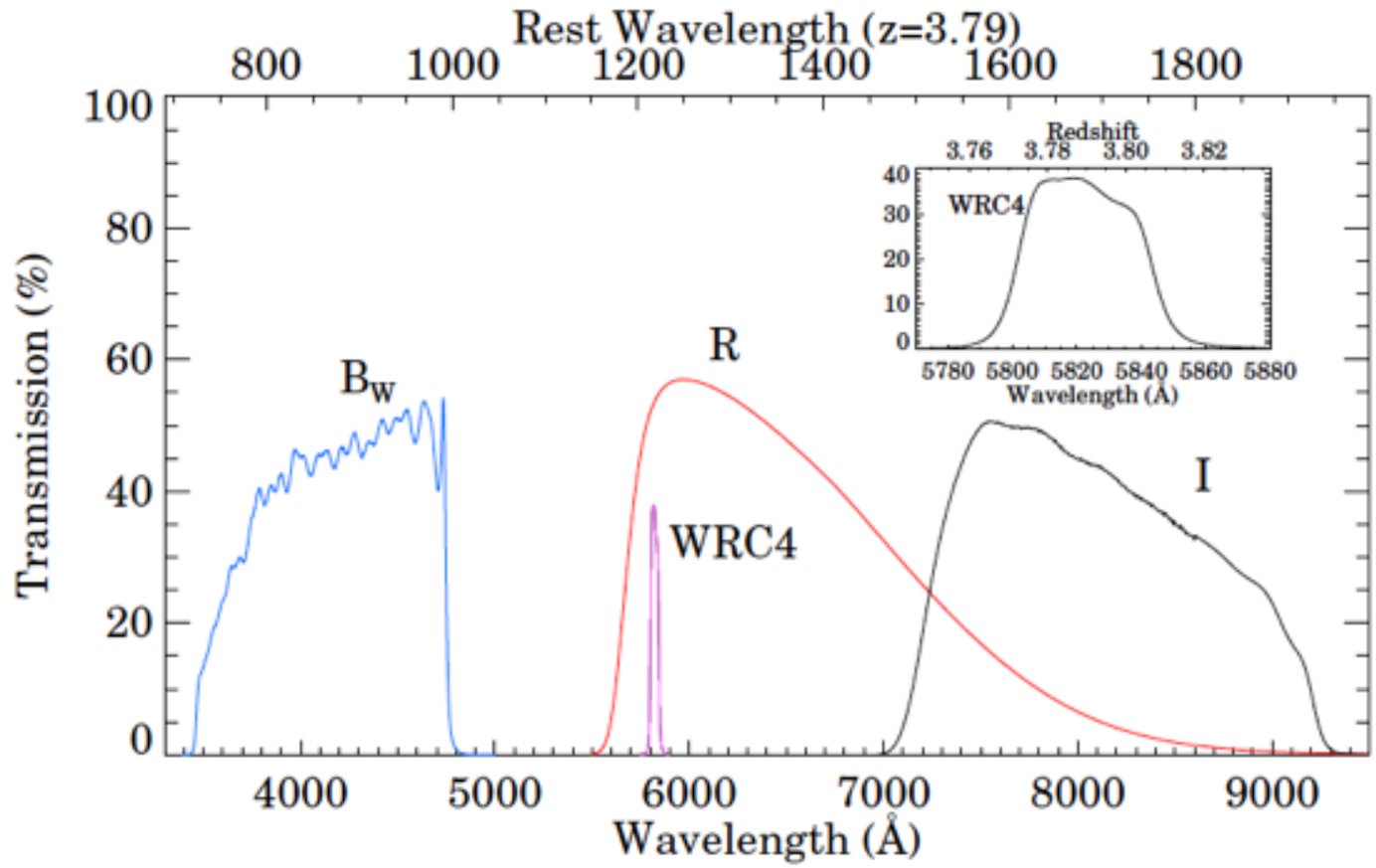


Lee+ 2013

- A recombination line of ionizing radiation in HII region, and thus is related to “instantaneous” star formation rates of the galaxy, when observed

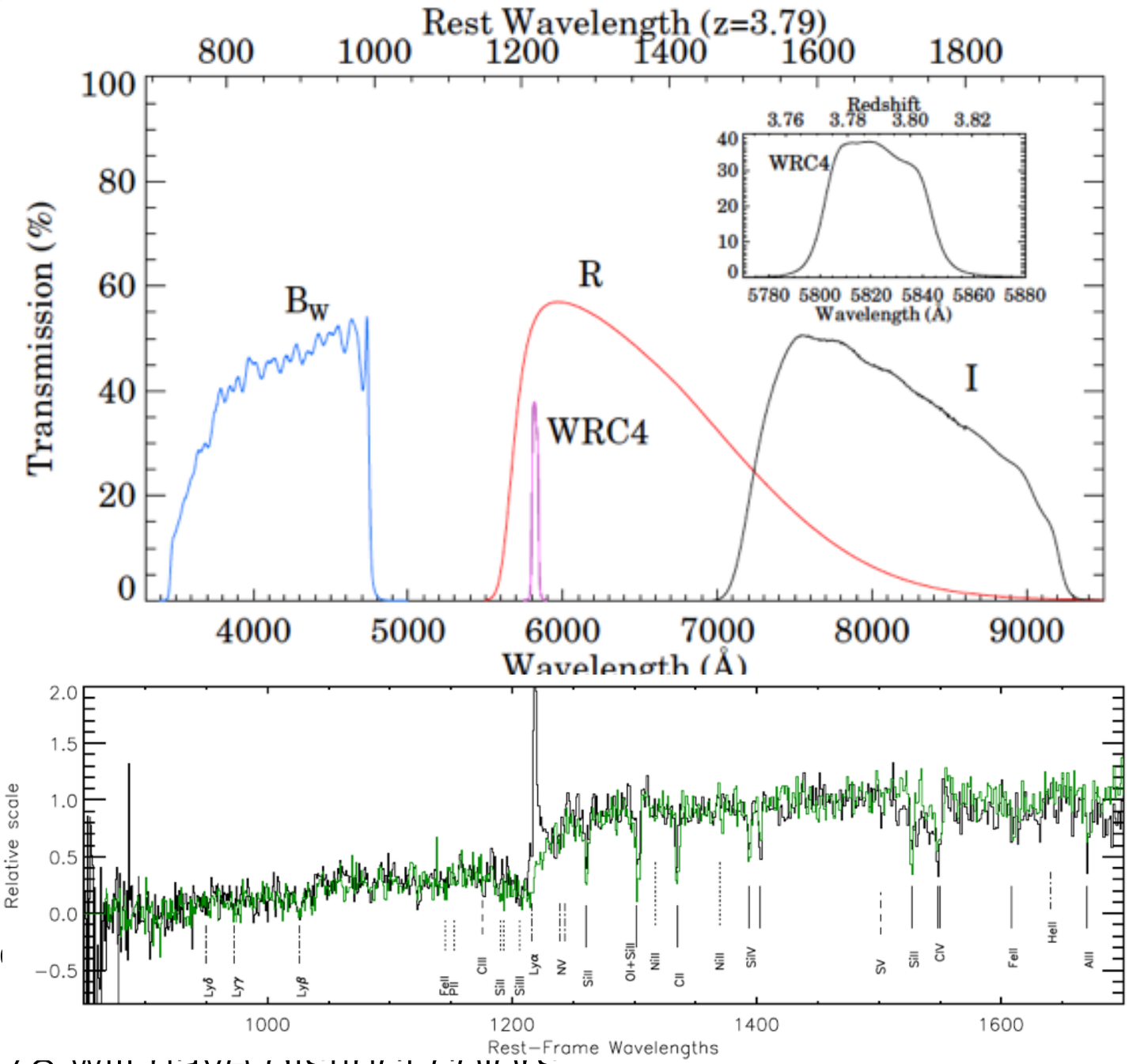
- seen in either emission or absorption (sensitive to kinematics, column density, and geometry of the gas and dust in the medium)

A z=3.78 proto-cluster



- At z=3.785, Lya line redshifts to the optical window, at 5820 A *Lee+ 2014*
- Strong Lya emitters (LAEs) at z=3.78 will have distinct colors
- We had just the filter! NOAO WRC4 (5820A/42A)
- Deep imaging with three broad-band filters (B_wRI) and a narrow-band filter (WRC4)

A z=3.78 proto-cluster



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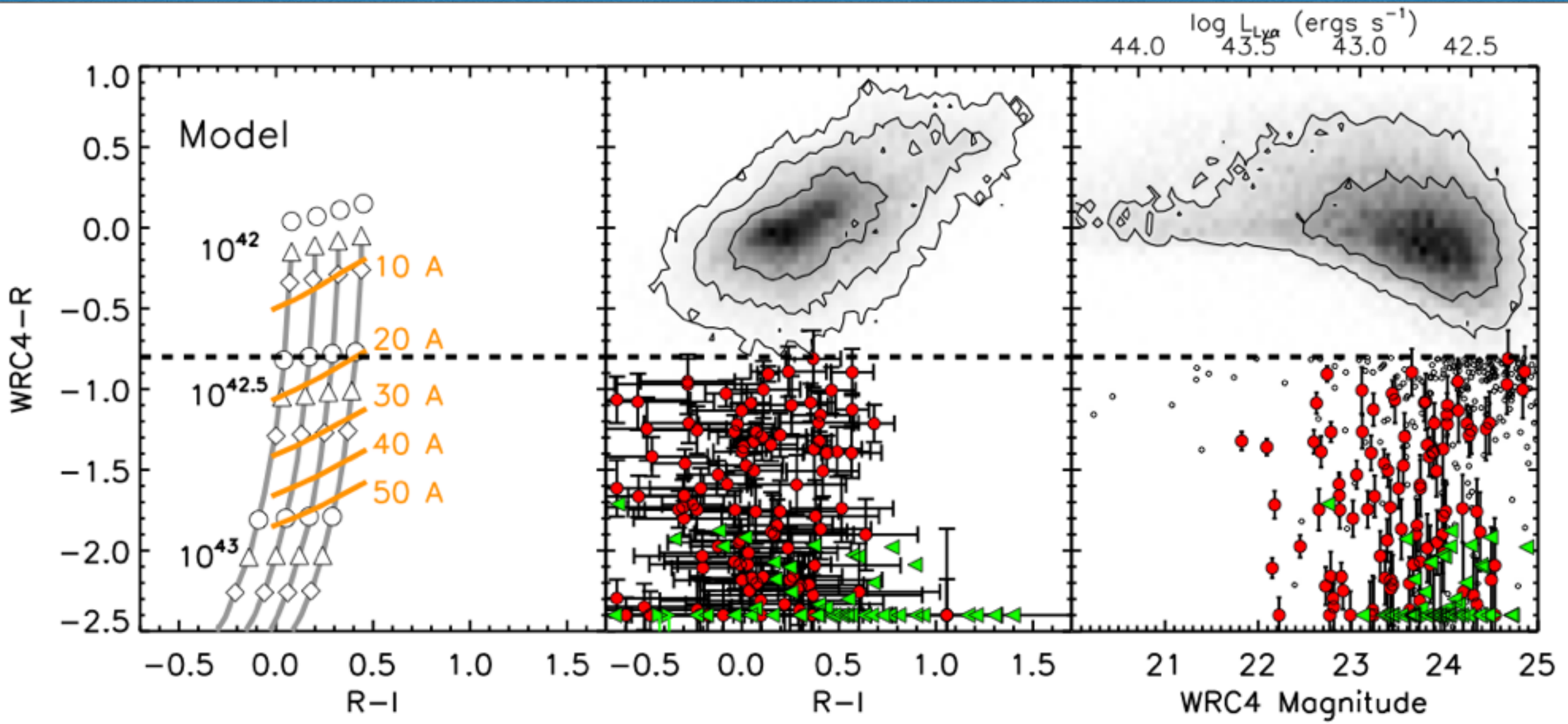

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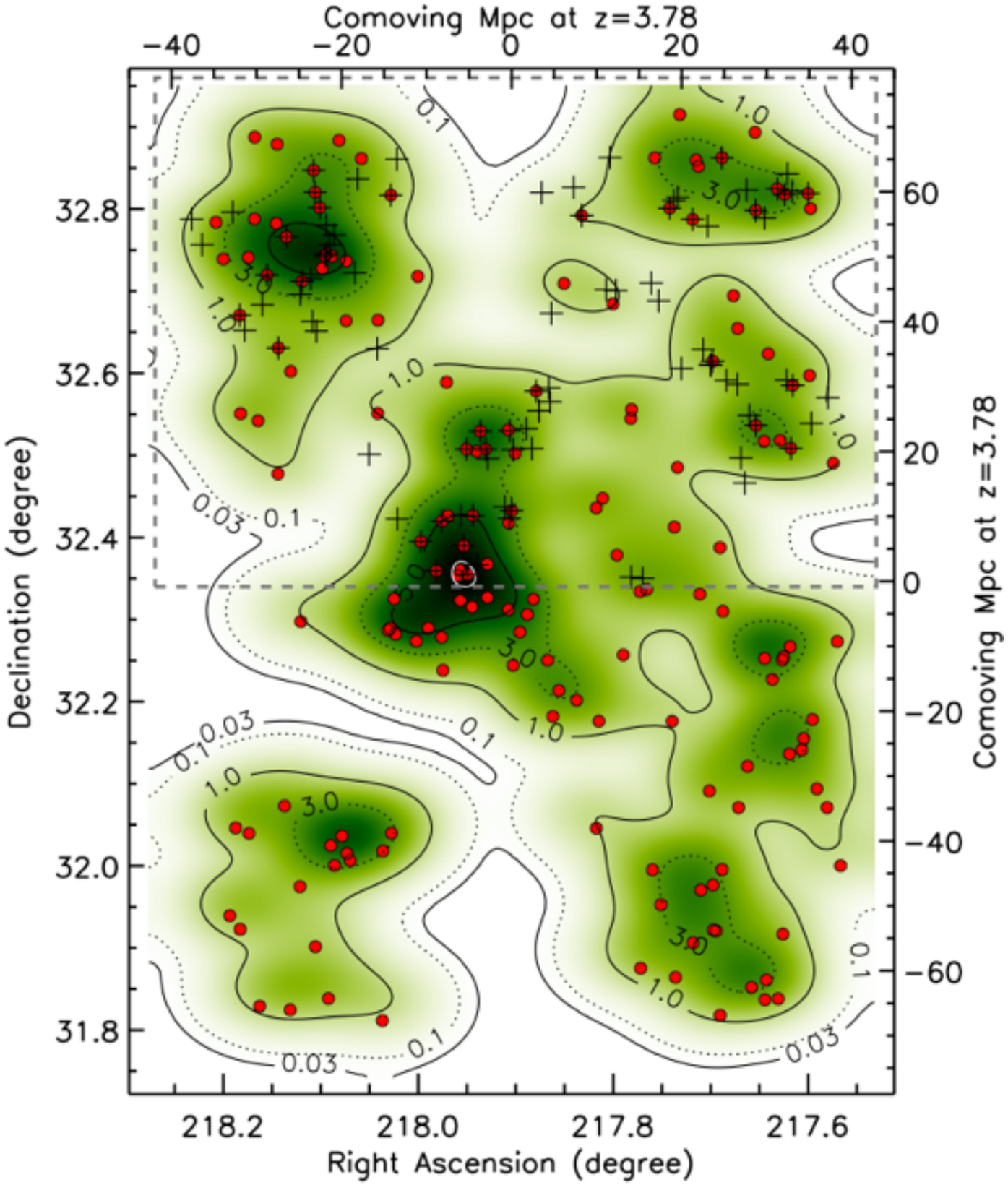
A z=3.78 proto-cluster

- 165 Lyman alpha emitters (LAEs) at z=3.78 identified
- At least two significant overdensities found ~40-50 Mpc apart
- Large voids of comparable size found

Dey, Lee+ 2015



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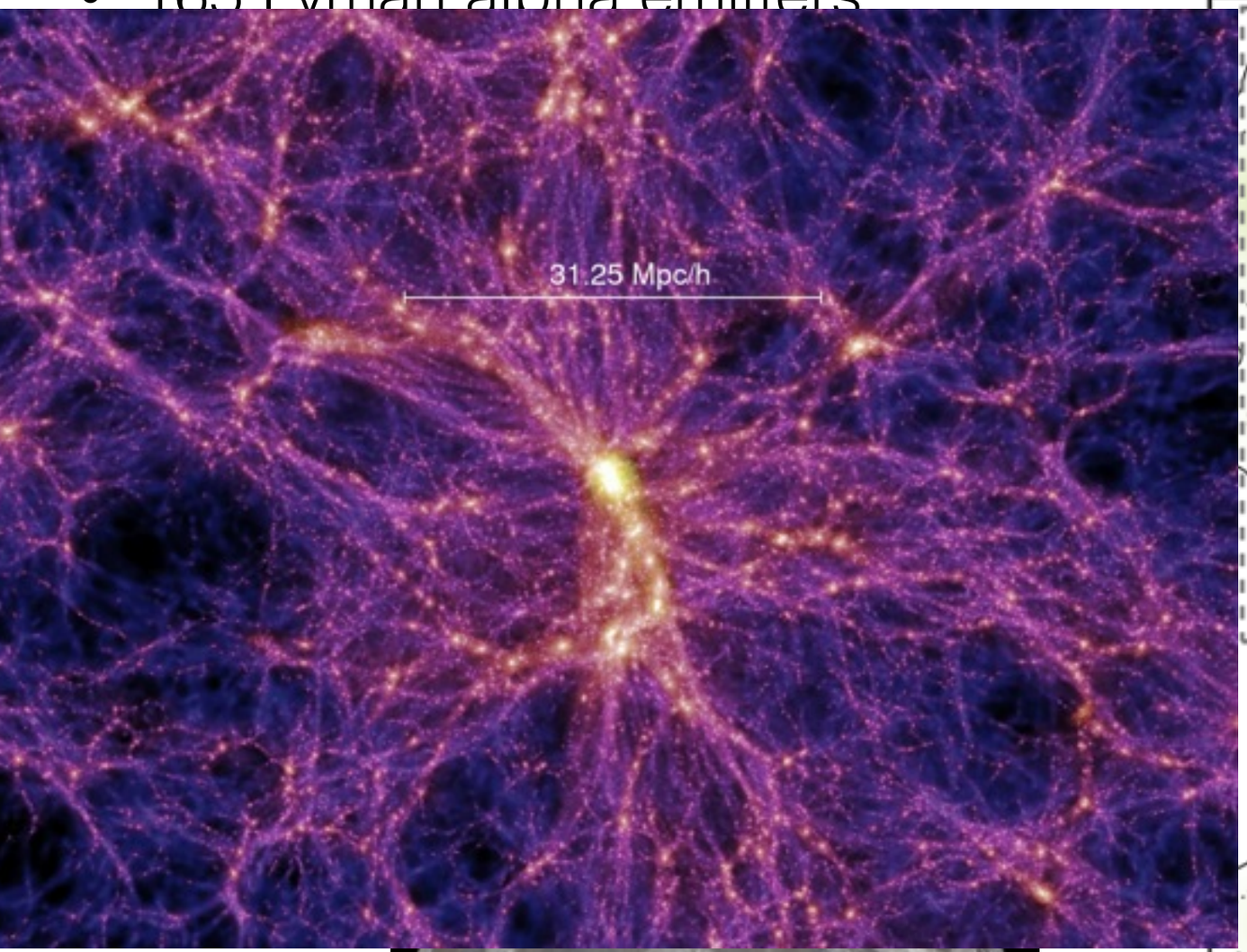
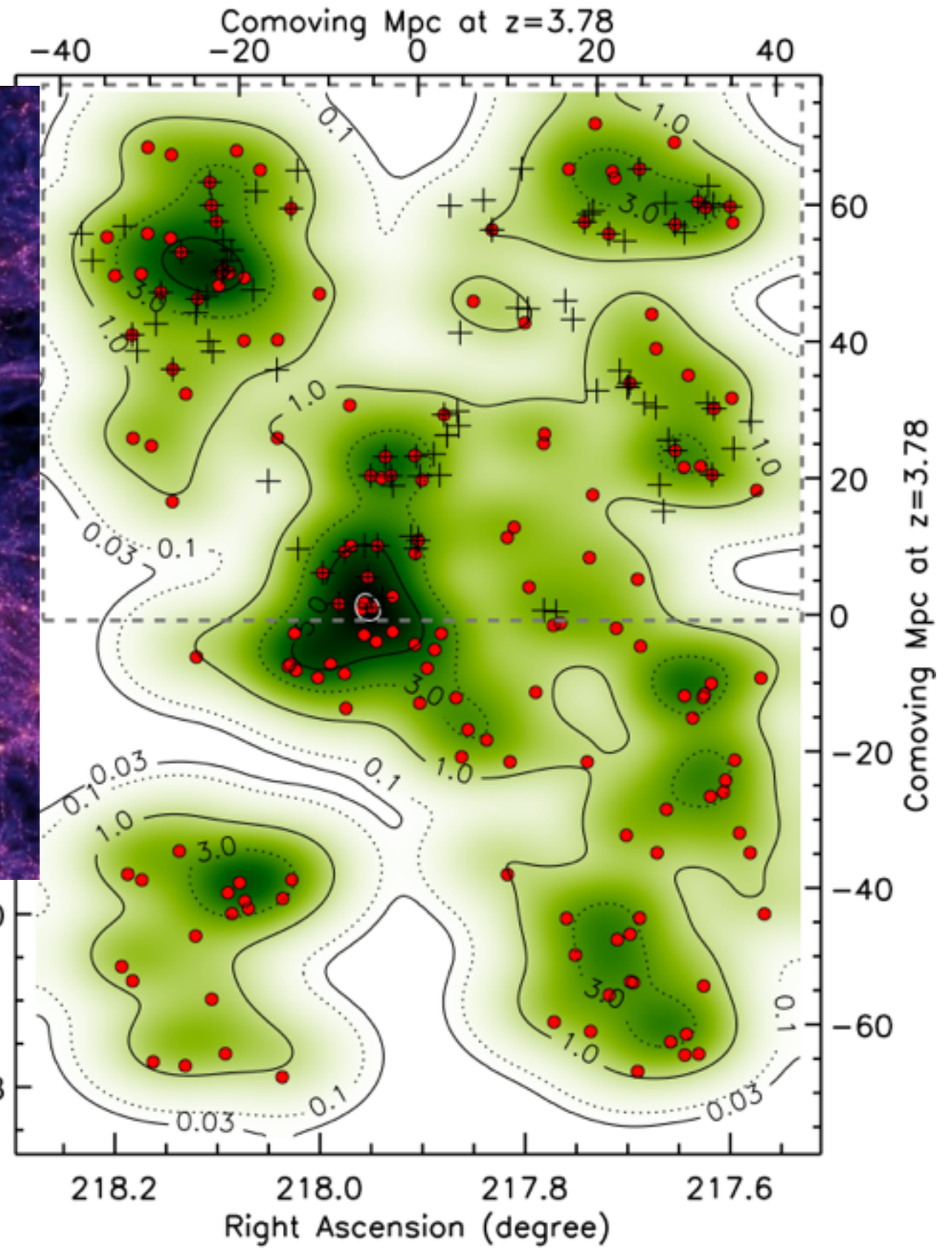
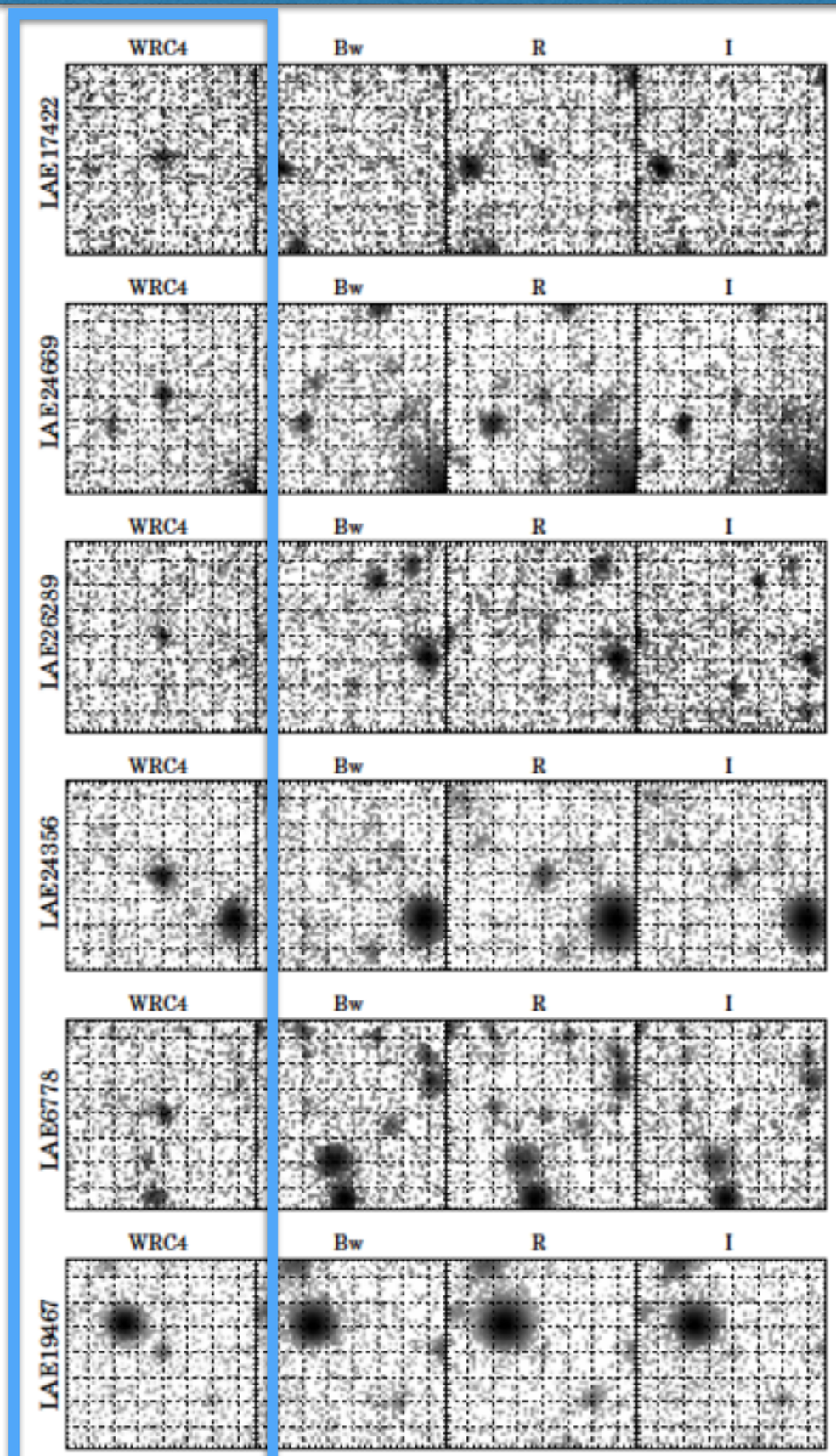
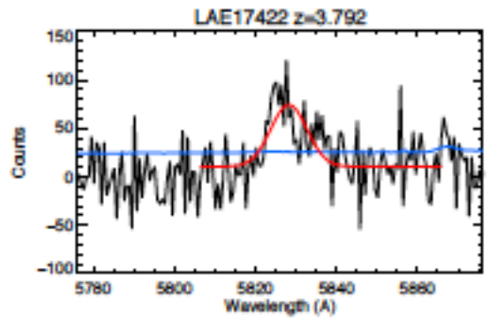
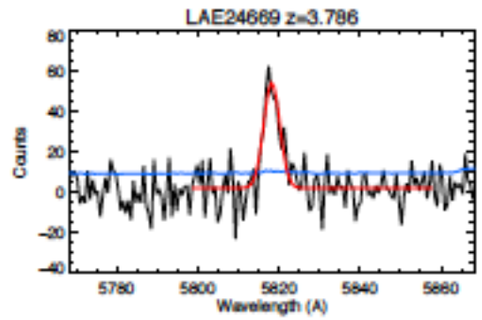


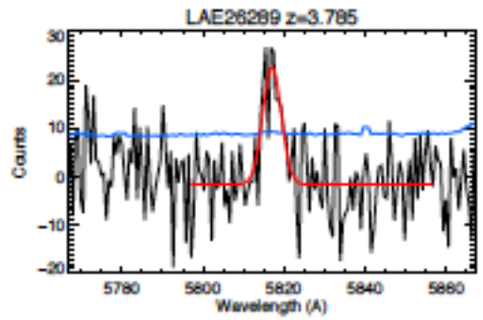


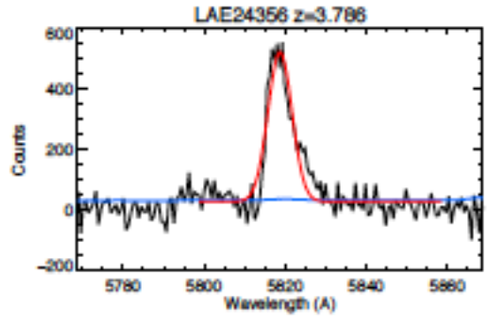
A z=3.78 proto-cluster

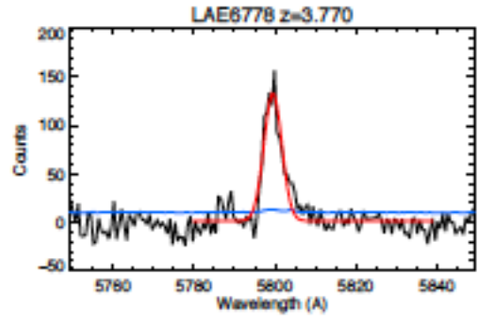


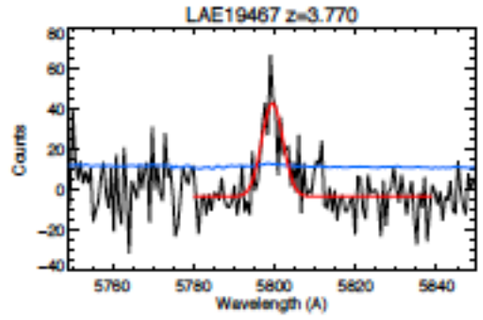






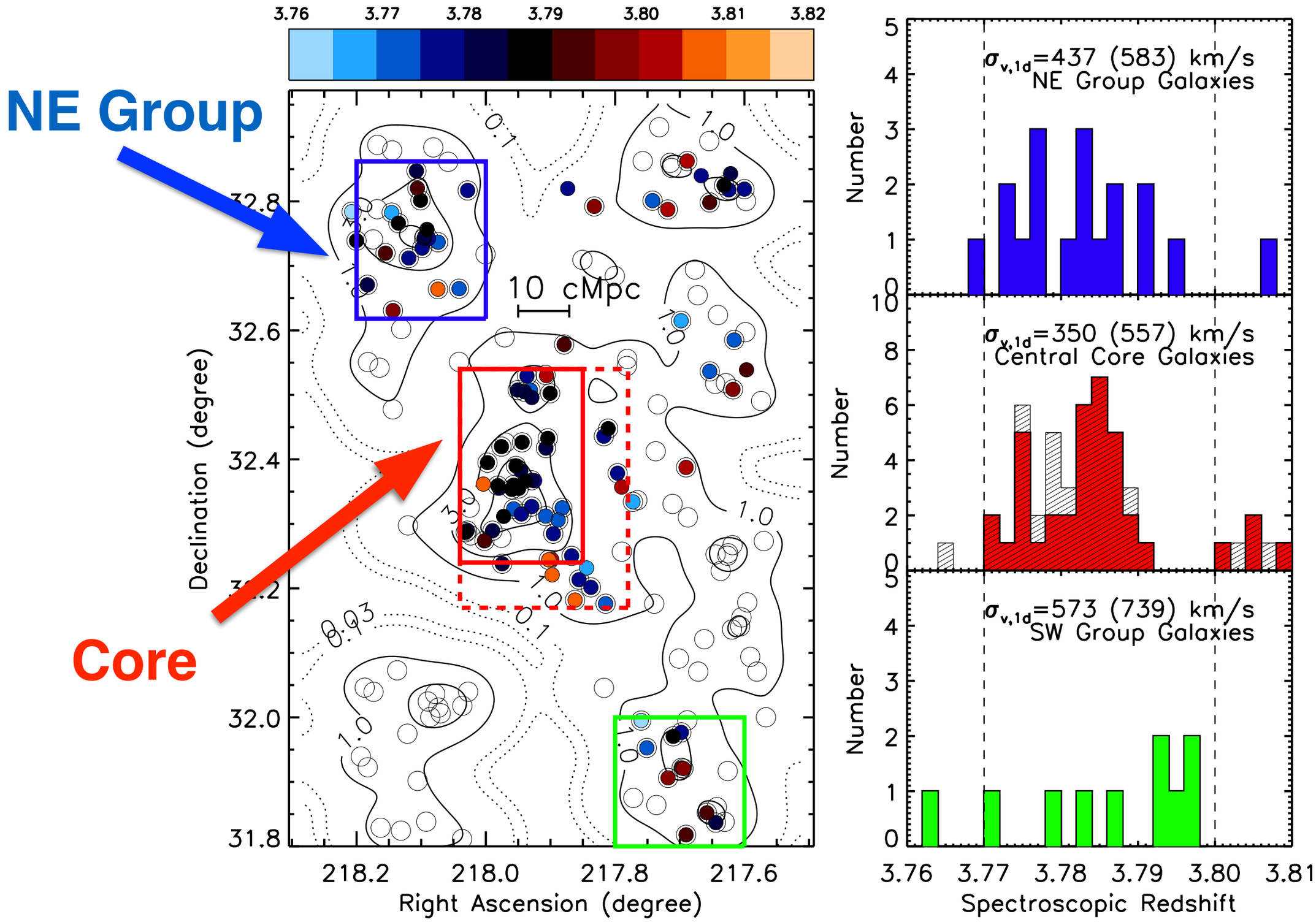






- 100 LAEs observed with Keck/DEIMOS, only 2 are [OII] or [OIII] emitters at low-z
- Roughly 12 non-LAEs (UV-bright star-forming galaxies) also identified within LAE overdensity regions
- **Two protoclusters confirmed**: 43 members in the Core, 16 members for the NE group

A z=3.78 proto-cluster



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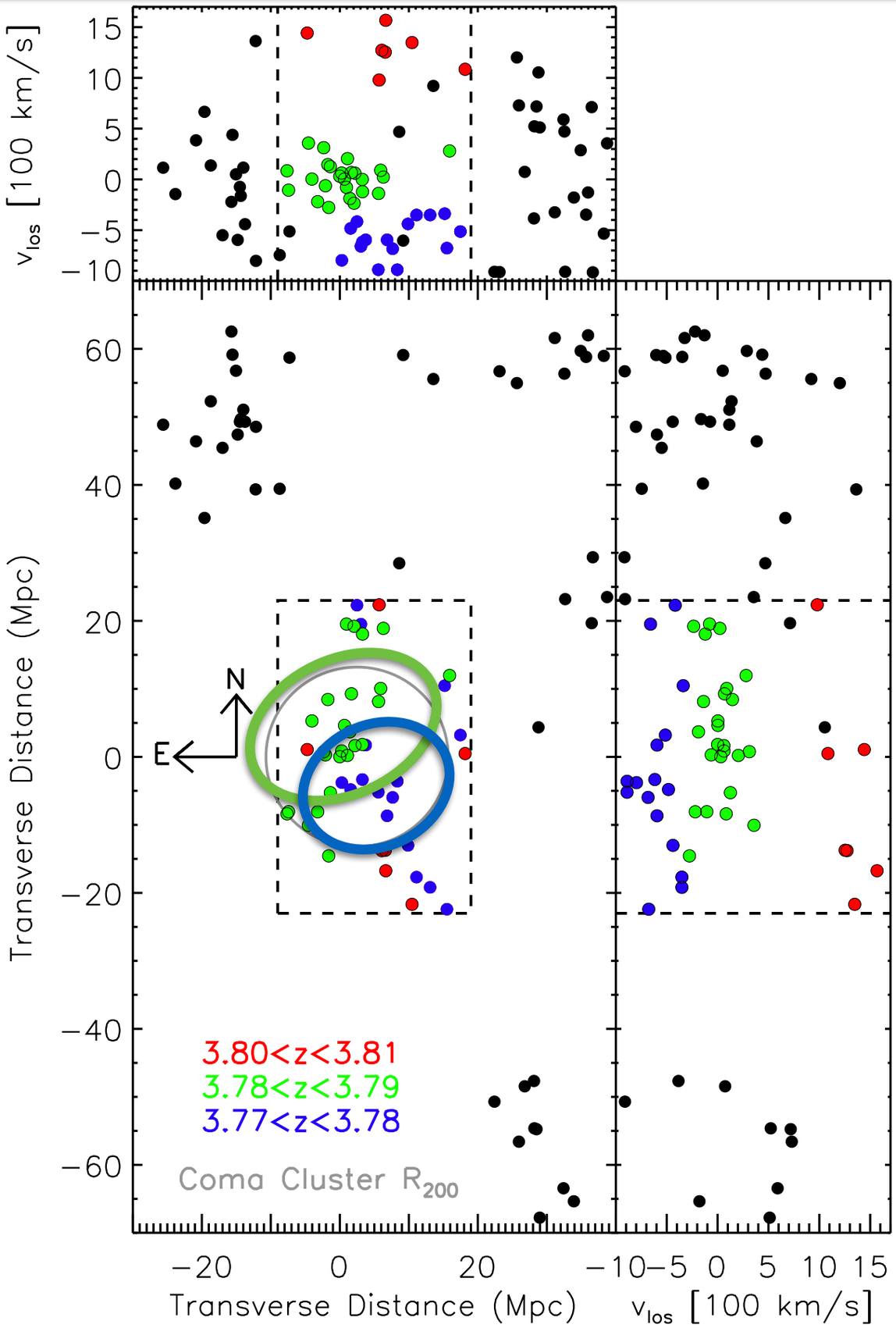
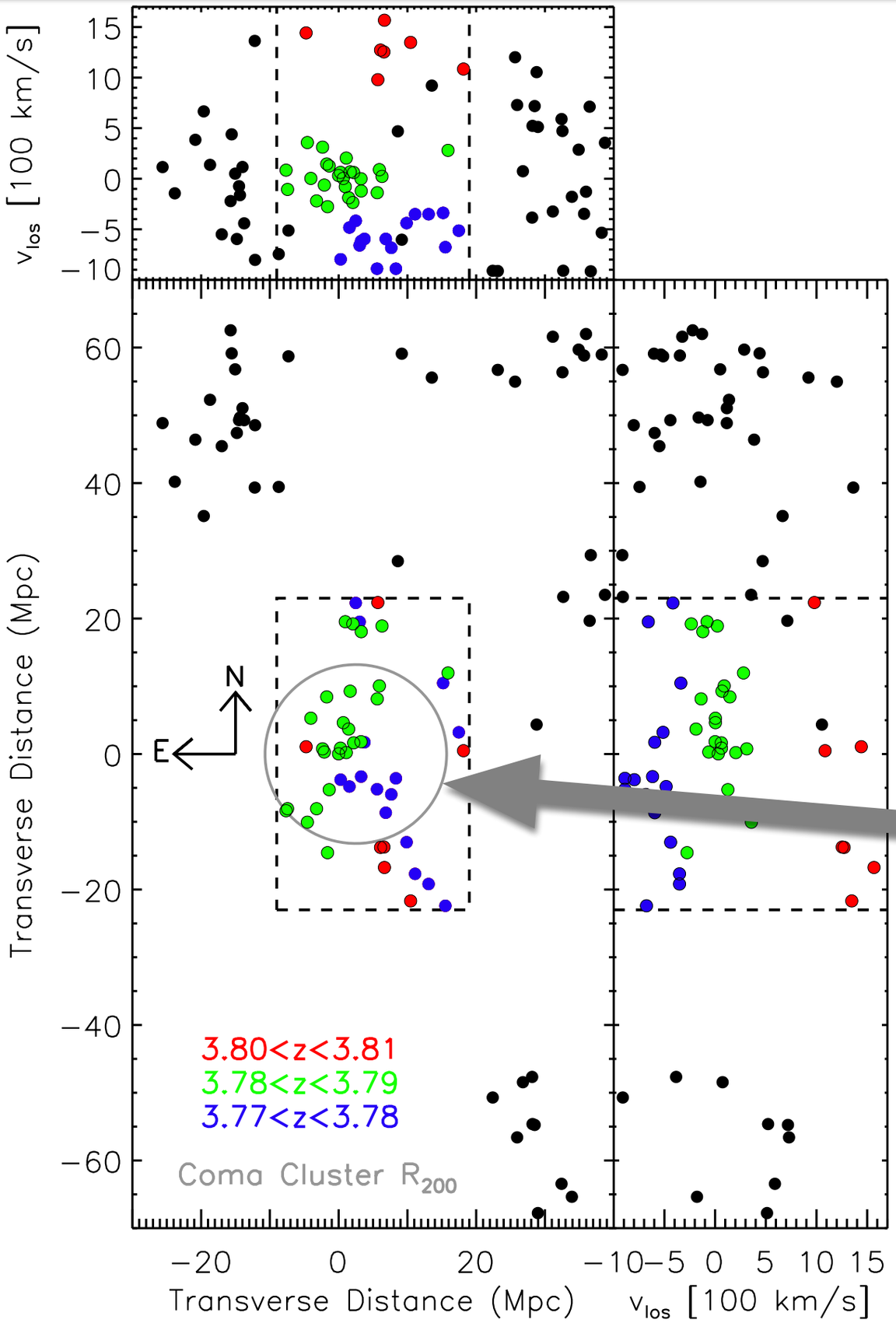


- velocity structure indicates two large groups (**green** and **blue**) falling into each other, while other galaxies fall in along filaments

- grey circle shows the physical size of the present-day Coma cluster

A z=3.78 proto-cluster



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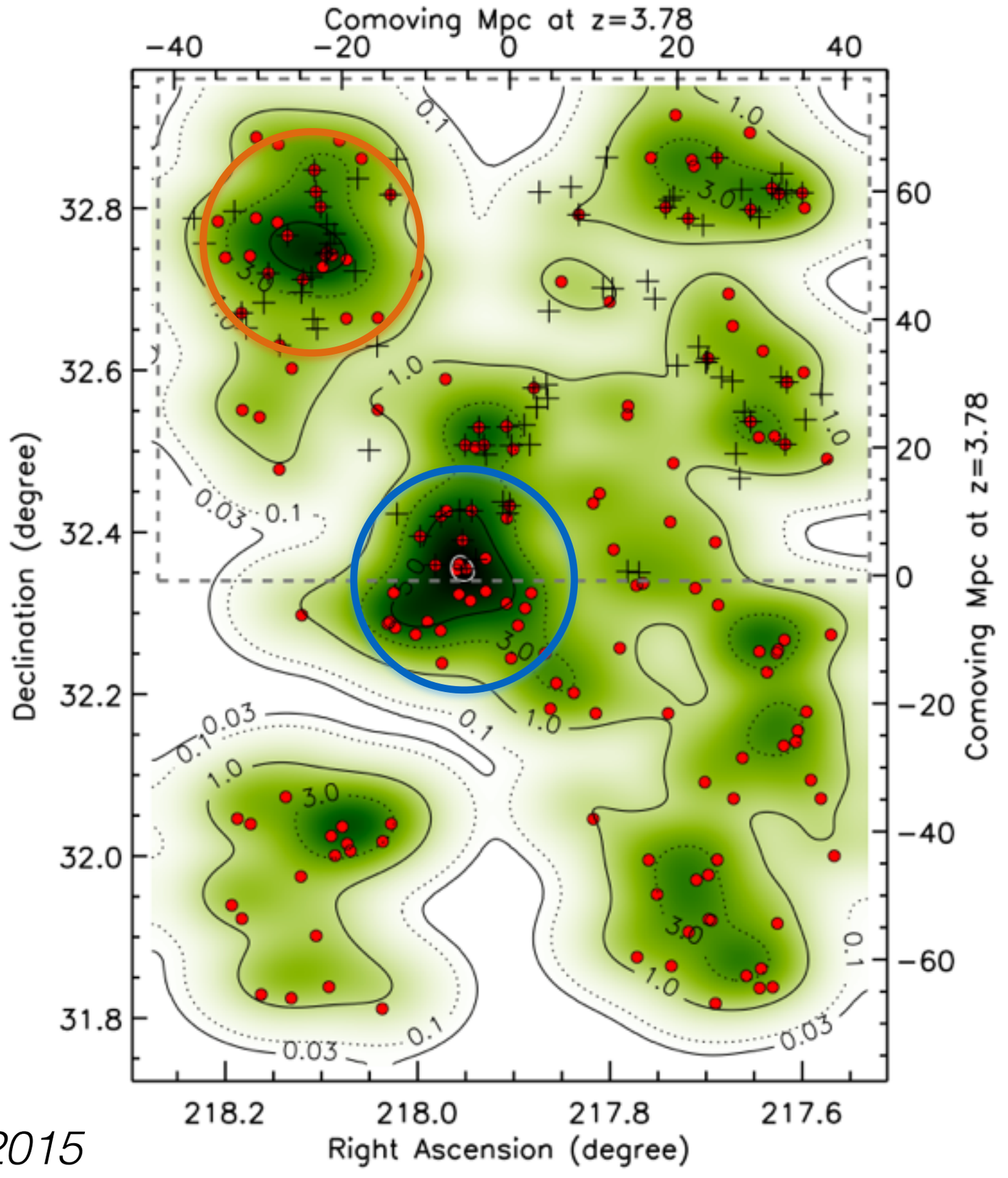
A z=3.78 proto-cluster

- Overdensity $\delta_{gal} = \Sigma_{group}/\Sigma_{field} - 1$
- "Core" δ_{gal} = 4-15
- "NE group" δ_{gal} = 3-5
- Possibly there are a few less significant structures within the field
- How do we determine the "significance" of any structure?



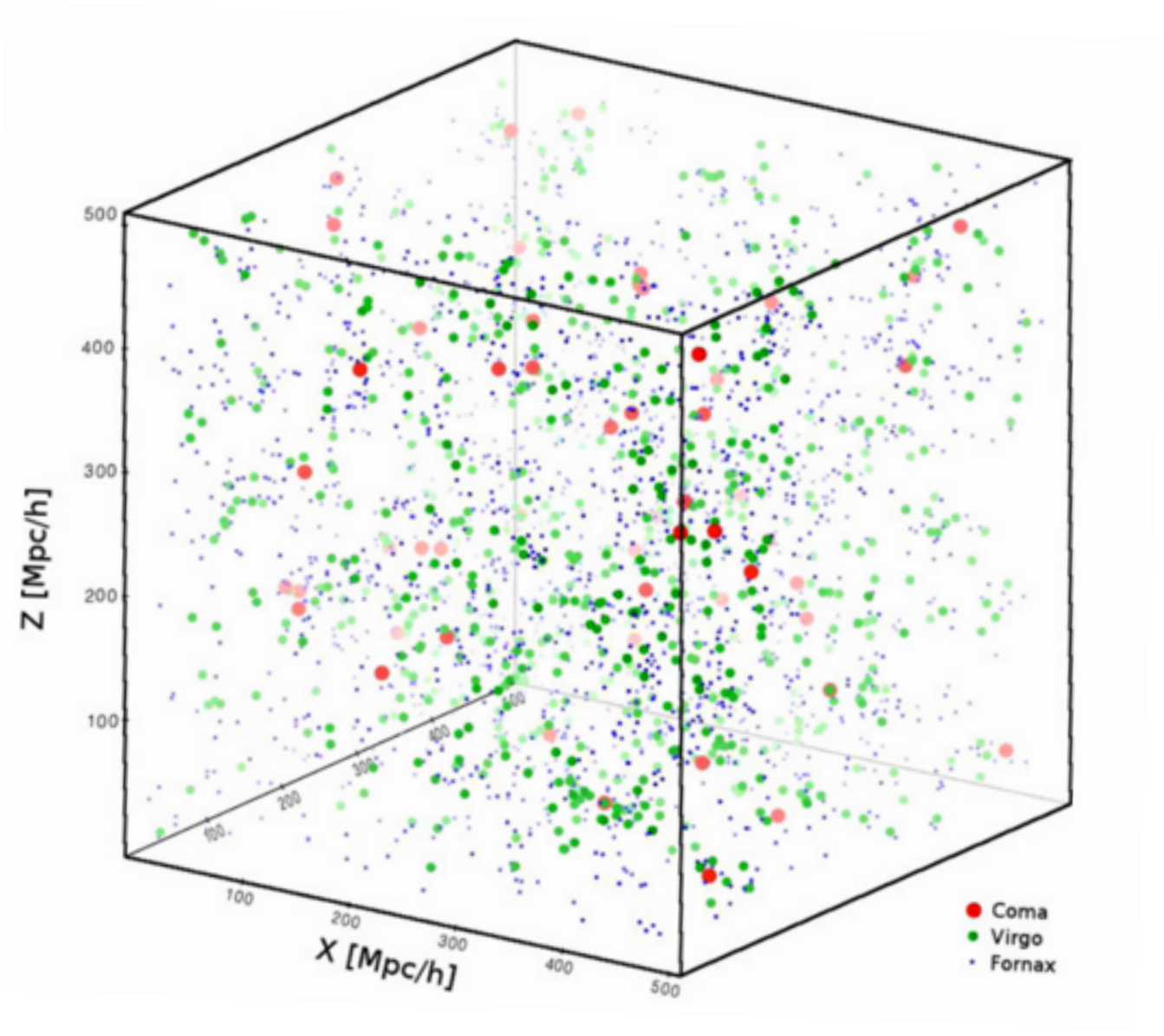
Dey, Lee+ 2015

protoclusters in simulations: Millennium Runs

- (500 Mpc/h)^3 box containing roughly 10 billion DM particles (~10^9 M_{sun} each)

- M_{tot}>10^{14} M_{sun}/h structures identified "clusters" at z=0, then same regions traced back at earlier epochs

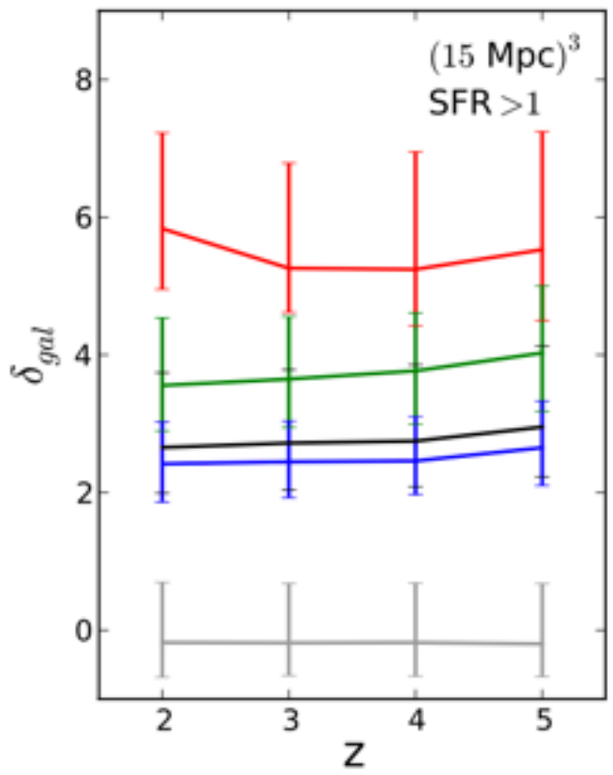
- useful tools to "interpret" the observed galaxy properties, and to assess the significance of overdensities

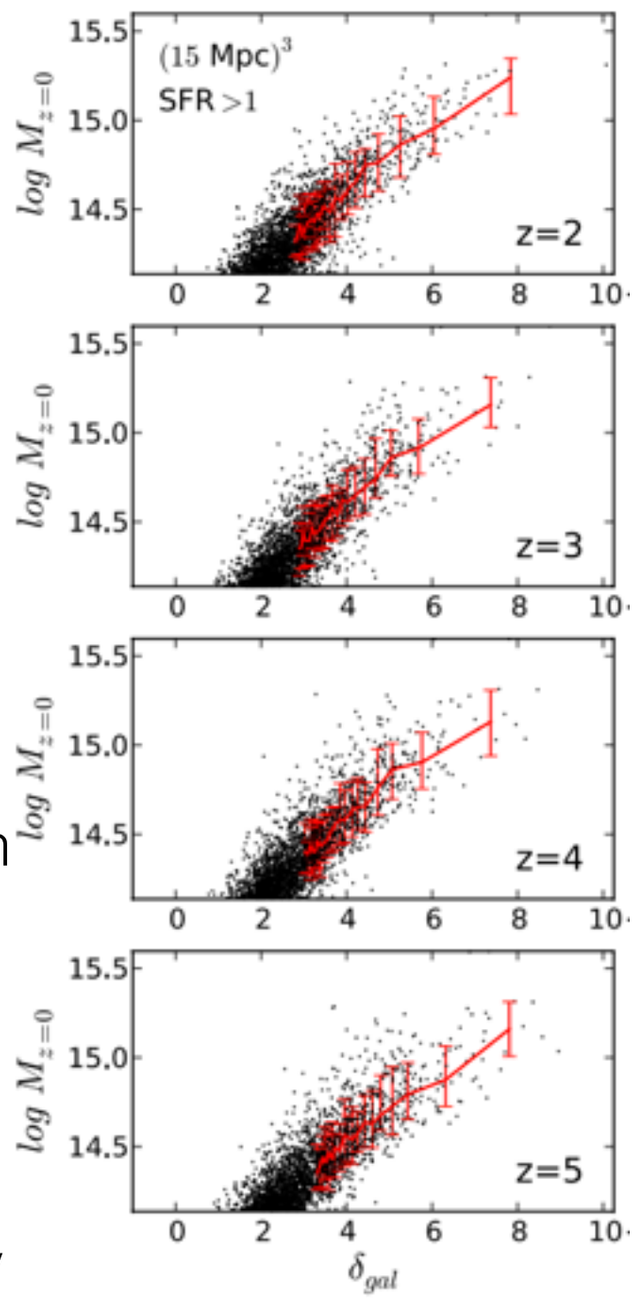


Coma	Virgo	Fornax
>10^{15} M_{sun}	(3-10)x10^{14} M_{sun}	(1-3)x10^{14} M_{sun}

Chiang+ 2013

proto-clusters in simulations: Millennium Runs





- protocluster regions can be identified with high significance well before their virialization
- the progenitors of the most massive clusters ($>10^{15}$ M_{sun}) will stand out already by z~5
- estimates of enclosed mass that will eventually fall in and become virialized
- galaxy “bias” important, but somewhat uncertain

Chiang+ 2013

mass estimates for z=3.78 proto-clusters

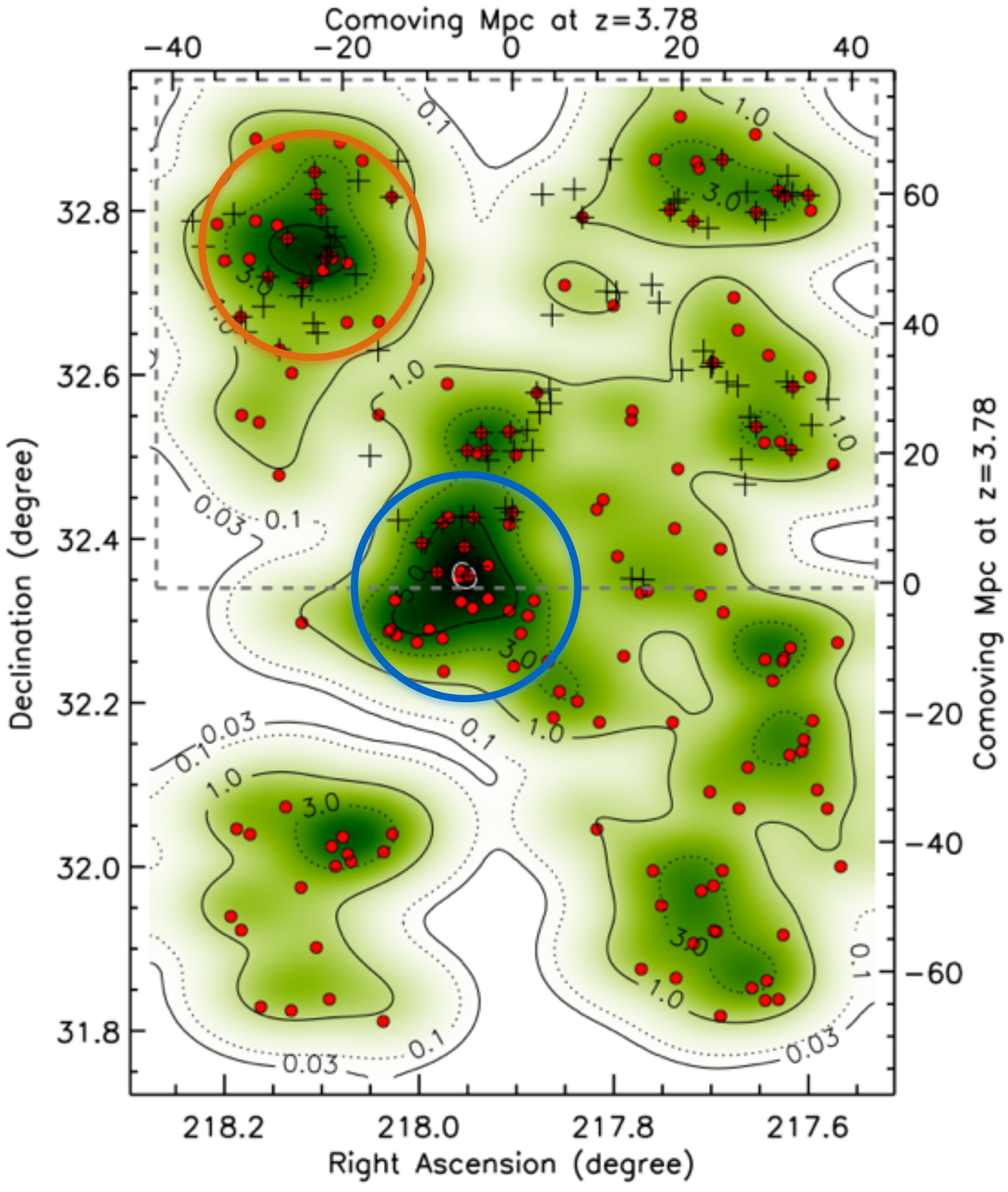
- Based on the Millennium Runs calibration: (0.7-1.5)x10^{15} M_{sun} for the Core, (2-6)x10^{14} M_{sun} for the NE group

- Assuming all masses within overdense regions will fall in by z=0,

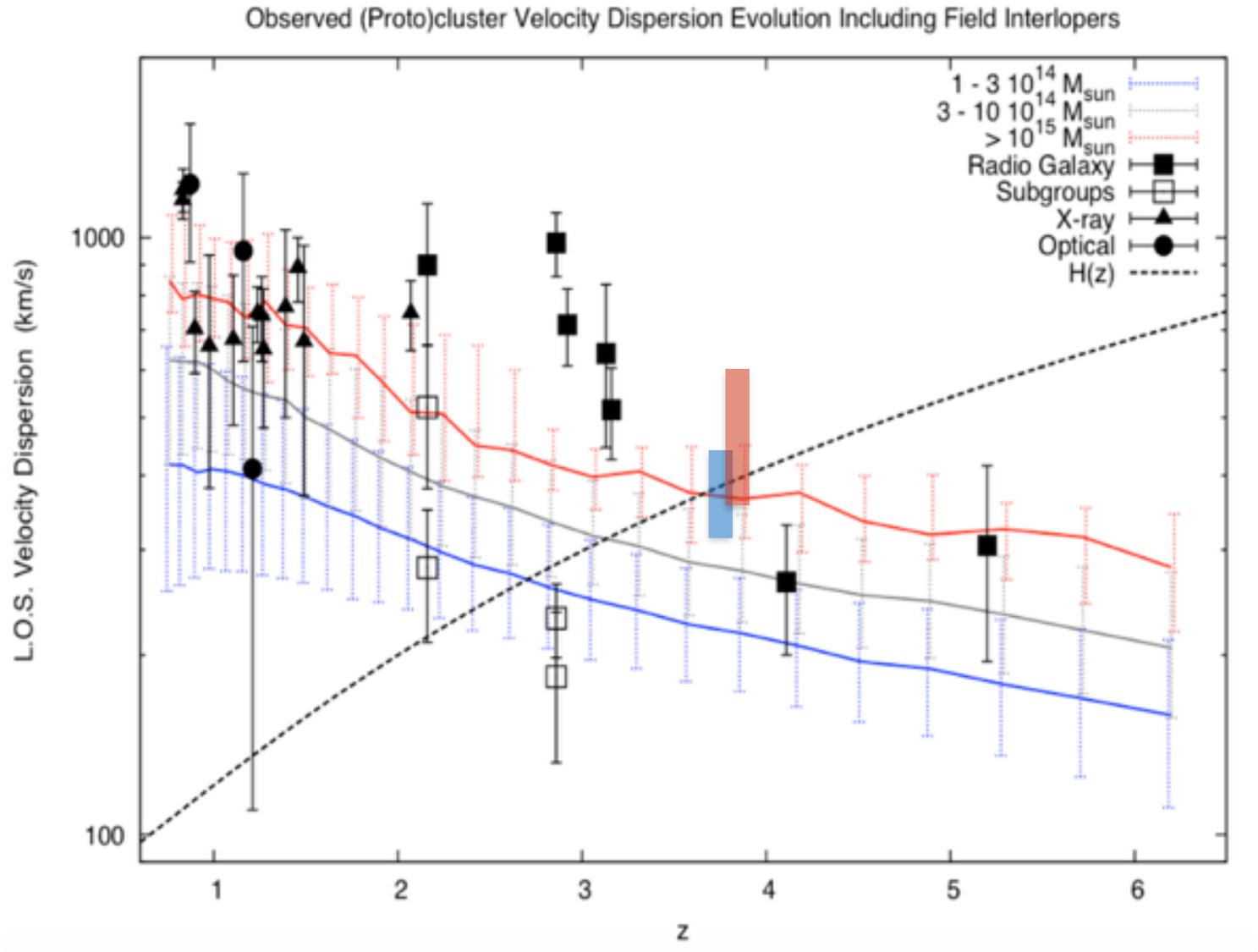
$$M_{z=0} = (1 + \delta_m)\langle\rho\rangle V,$$

- ~1.5x10^{15} M_{sun} for the Core, ~7x10^{14} M_{sun} for the NE group

Lee+, 2014, Dey, Lee+ 2015



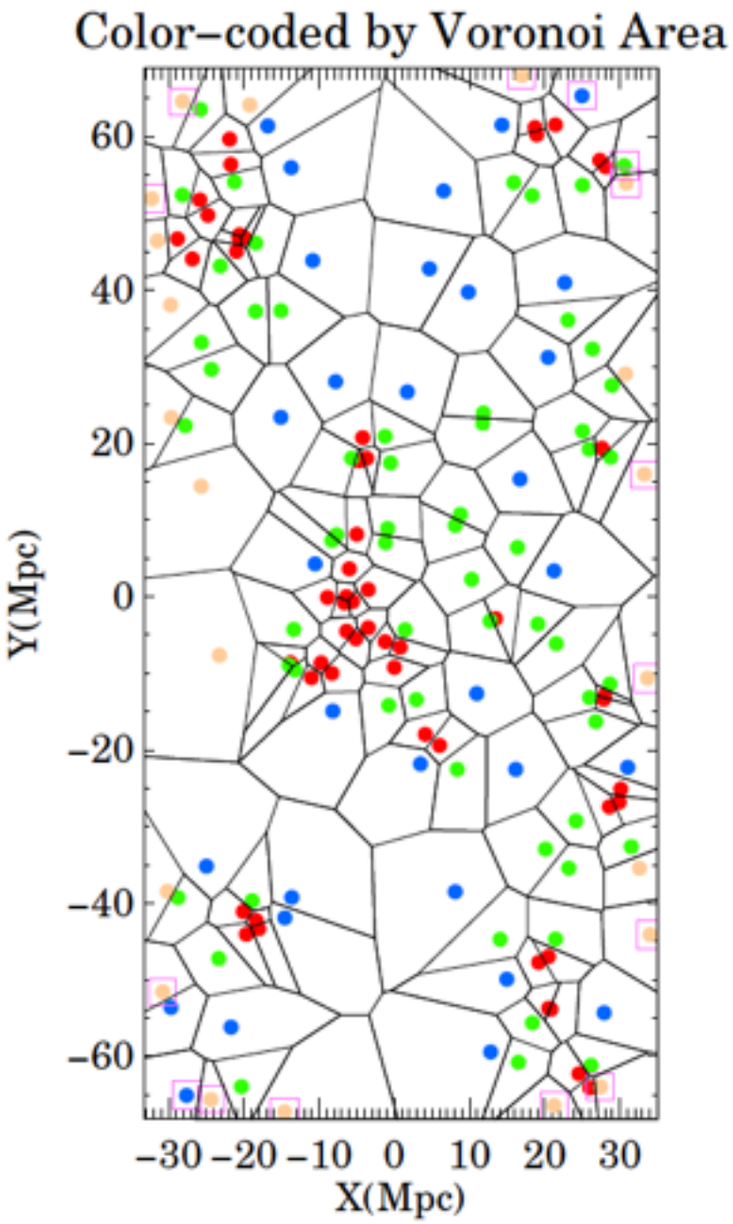
velocity dispersion of the structure



- Mass estimates based on velocity dispersion broadly consistent with other estimates
- velocity dispersion unlikely to yield robust estimates for unvirialized systems (in particular, viewing angle dependent)

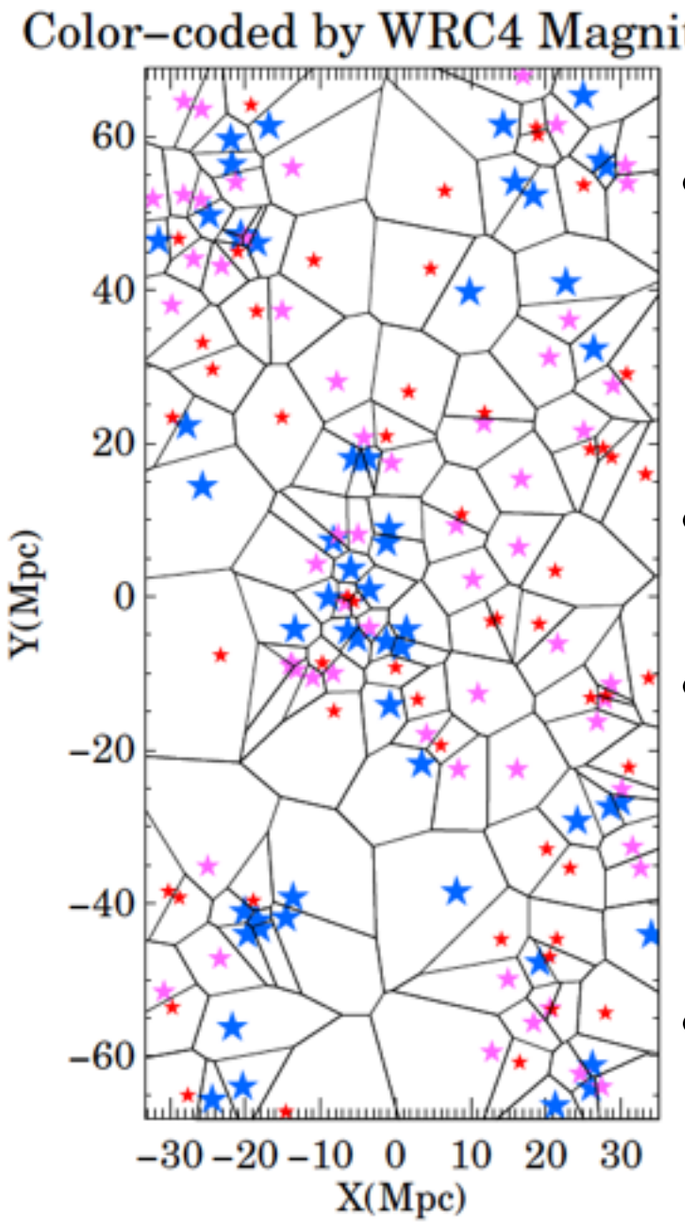
Y.-K. Chiang+, in prep, Dey, Lee+ 2015

Science Highlights I: enhanced star formation in protoclusters



Highest Density
Mid-range
Lowest Density

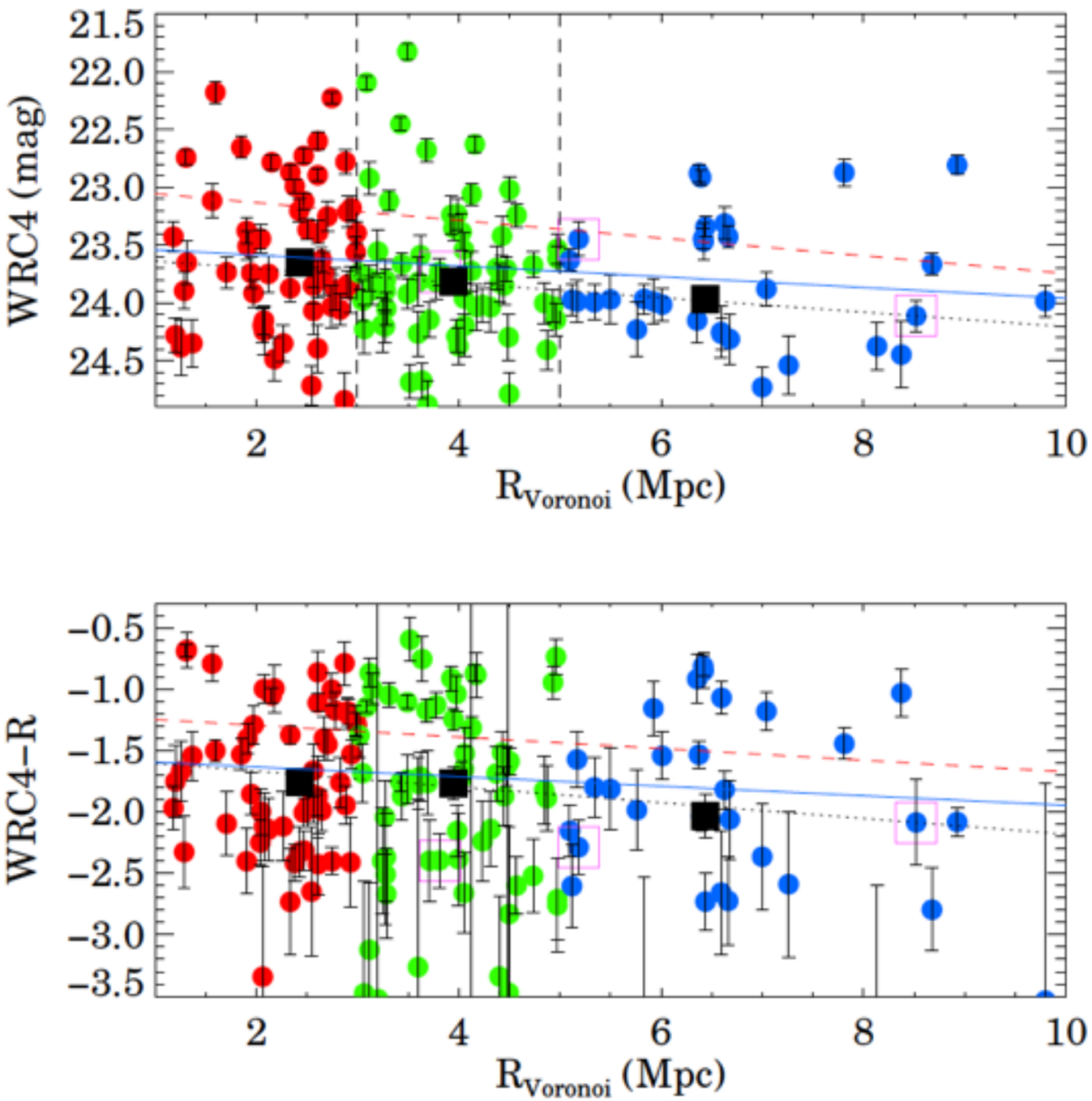
Dey, Lee+ 2015



Brightest
Mid-range
Faintest

- Voronoi tessellation to determine local density *e.g., Cooper+ 05, Darvish+ 15*
- Voronoi polygon: $A_V \sim 1/\rho$
- Luminous Lya emitters preferentially reside in galaxy overdensities
- promising observational signatures of protocluster region?

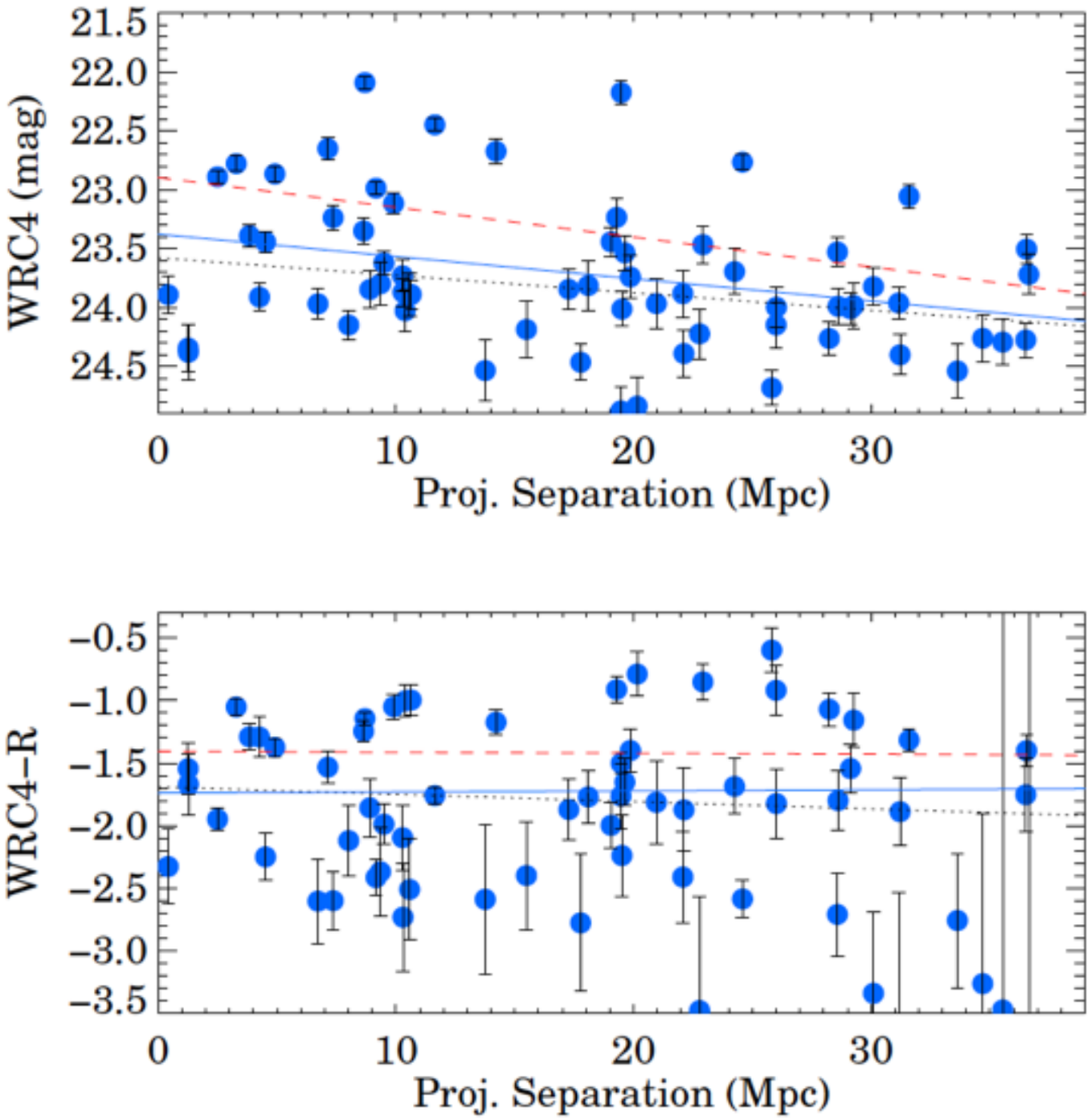
Science Highlights I: enhanced star formation in protoclusters



- Galaxies are roughly 40% brighter in Lya at the **"protocluster region"** than those in the **"field"**
- continuum (R) magnitudes remain unchanged, i.e., galaxy continuum luminosities are brighter in the densest region
- star formation is enhanced in dense environments as early as z~4
- potentially a good thing for protocluster search, but not so much for doing cosmology using line emitters (e.g., HETDEX)
- More data needed for better statistics!

Dey, Lee+ 2015

Science Highlights I: enhanced star formation in protoclusters



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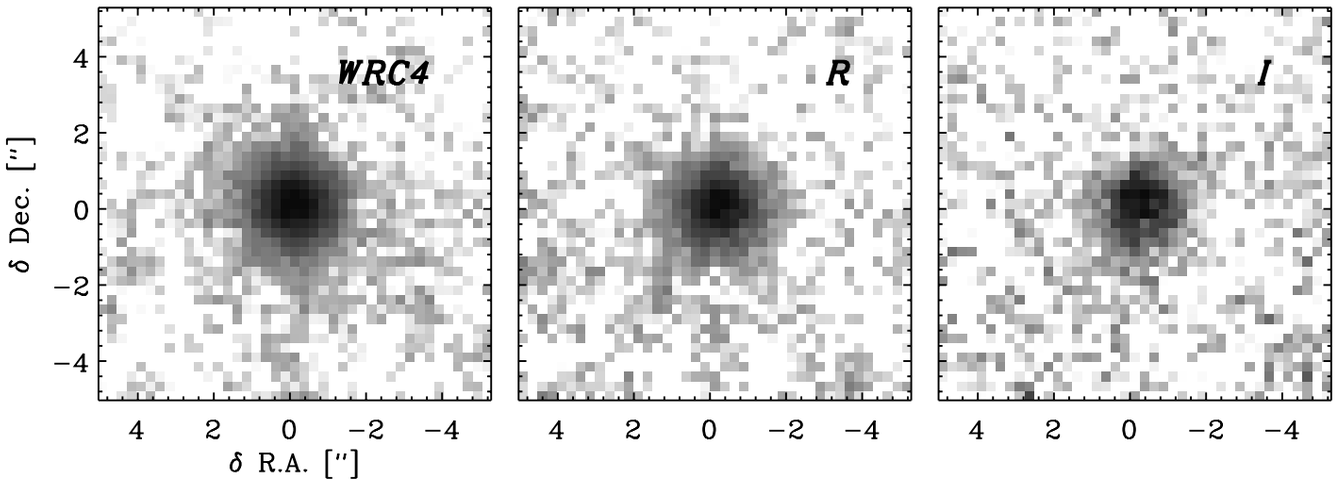
Dey, Lee+ 2015

Science Highlights II: neutral hydrogen content in cluster CGM



- Lya photons undergo resonant scattering through neutral HI gas in the interstellar and circumgalactic medium

- Thus, a measure of Lya emission constrains the content, geometry, and kinematics of the gas in the ISM and CGM *Verhamme+ 12, Zheng+ 11, Dijkstra+ 12 , Momose+ 14, Matsuda+ 12, Steidel+11, Rauch+ 08*

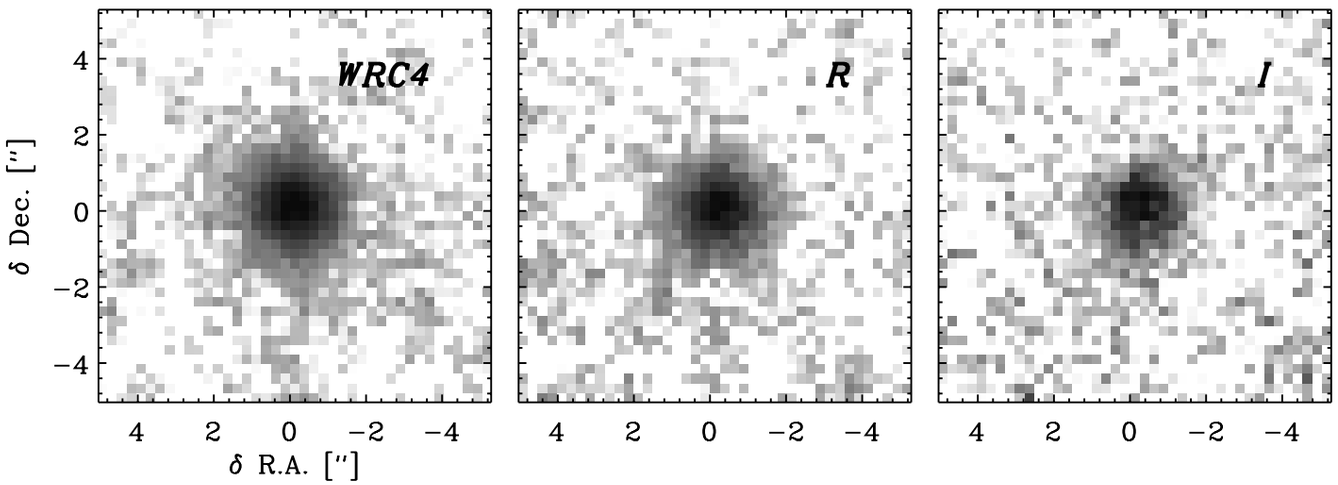
- NB image stacks are created, and their Lya radial profiles measured

- extended Lya halos robustly detected, clearly distinct from continuum emission of the same galaxies

- we find the scale lengths of halos in the range of 7-10 kpc; very large halos (20-30 kpc) as reported previously by *Steidel+11*, are ruled out.

Xue, Lee+ 2015, to be submitted

Science Highlights II: neutral hydrogen content in cluster CGM



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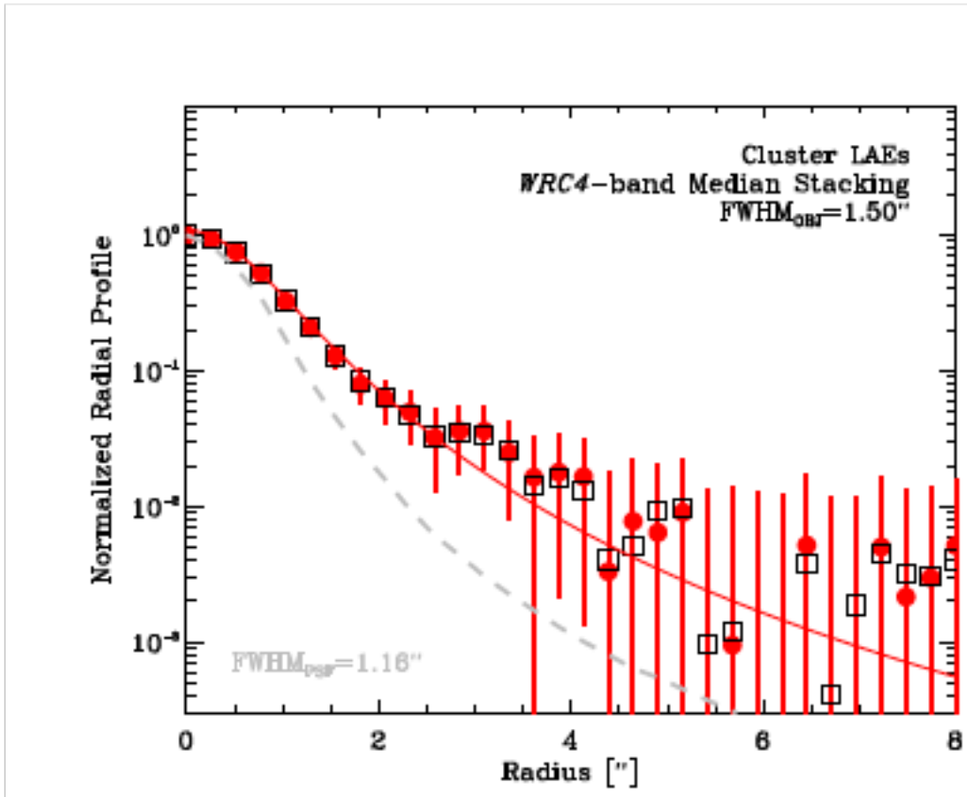

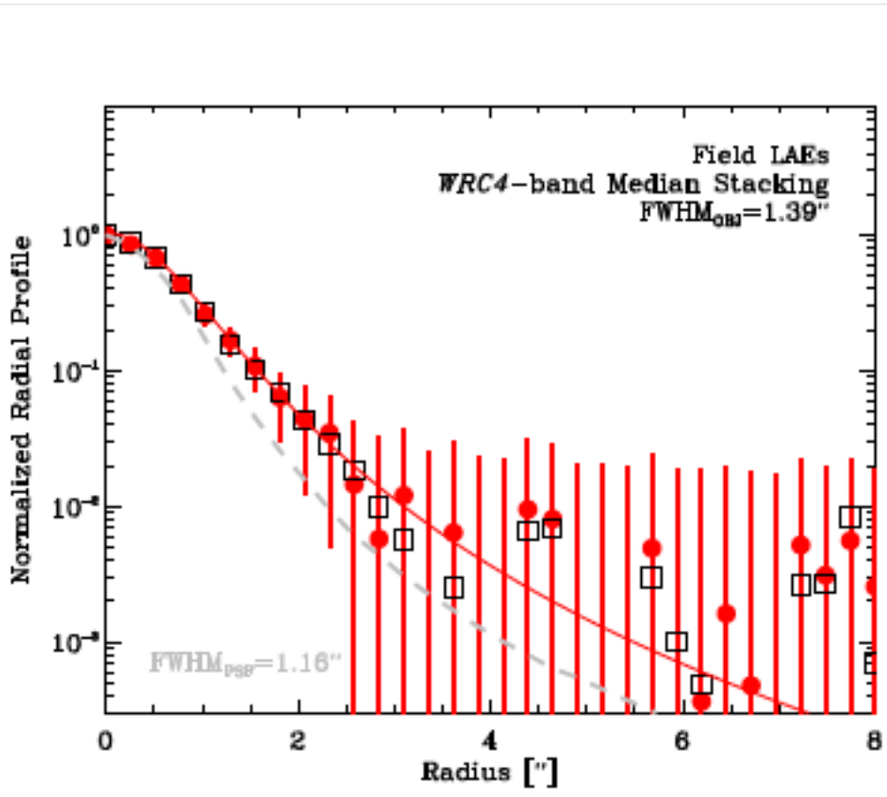

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Key questions

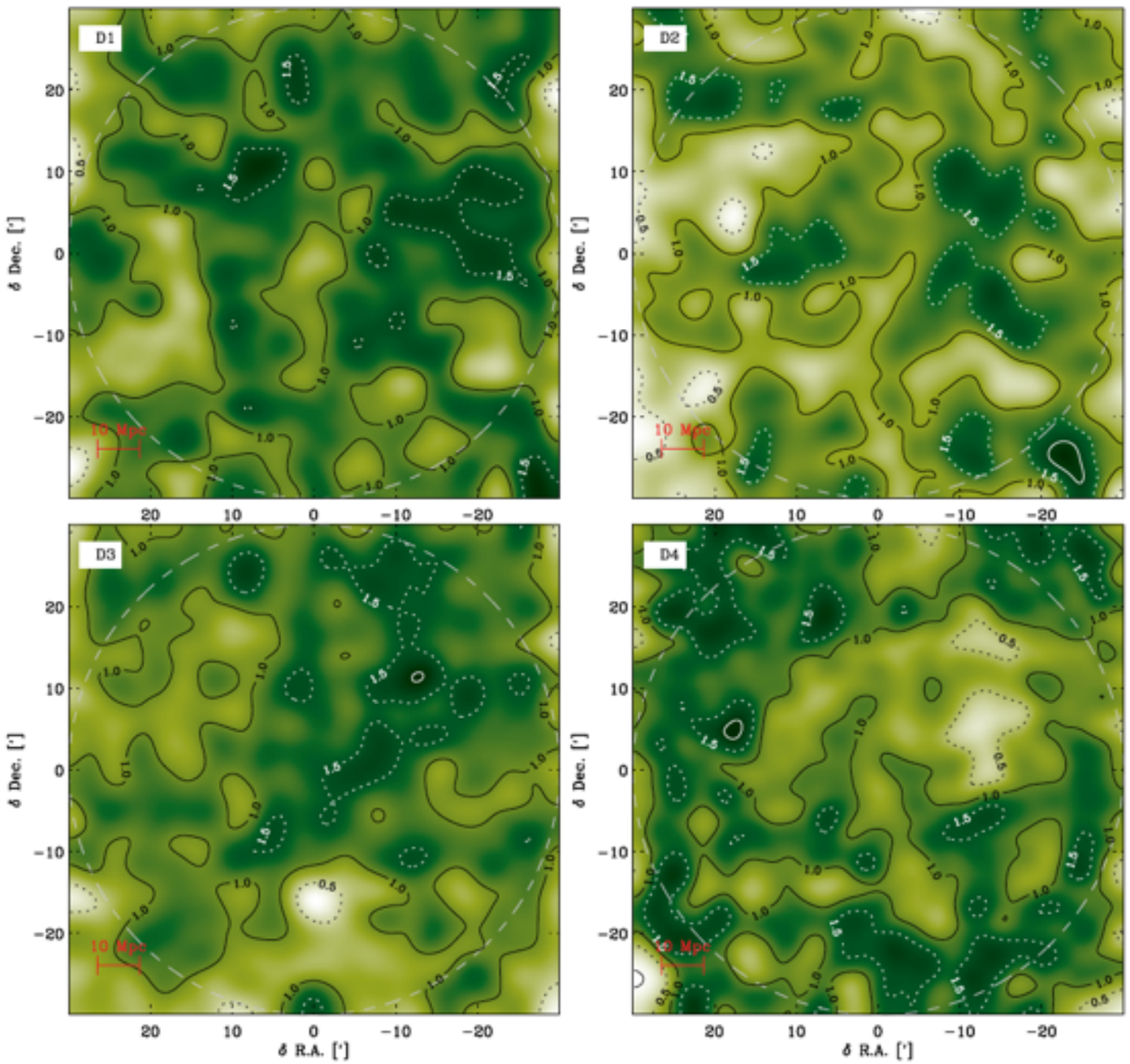
- Do protocluster galaxies have older ages, larger stellar masses than the field?; do they have different star formation histories?

- Can Lya overdensities be used to pinpoint the sites of massive forming clusters?; If so, how does it affect cosmological surveys like HETDEX?

- Do LAEs trace the same large scale structure as non-LAEs (LBGs, sub-mm gals)?; use of all-sky surveys like LSST for cluster search?

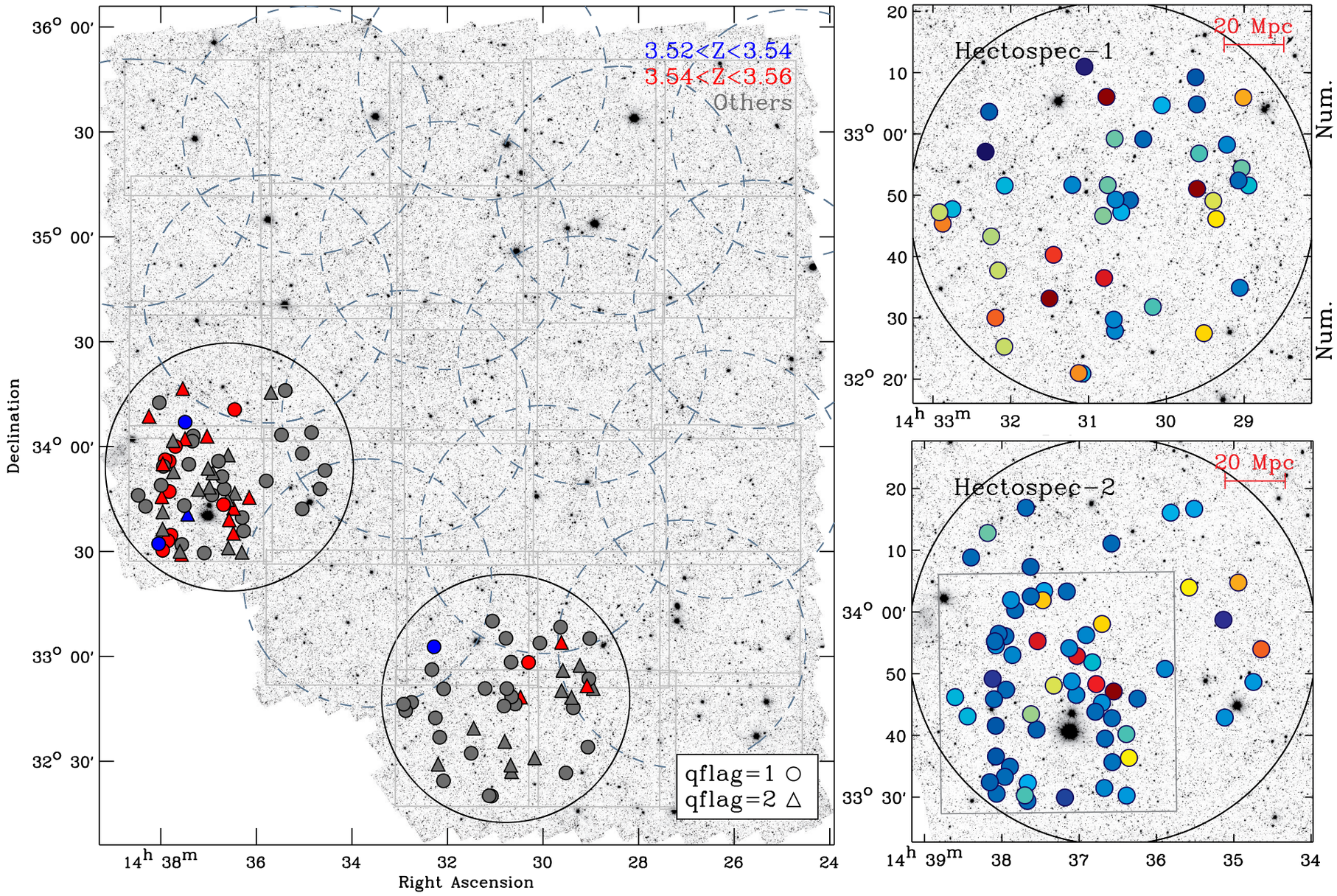
- Need to obtain a statistically significant sample of high-redshift protoclusters

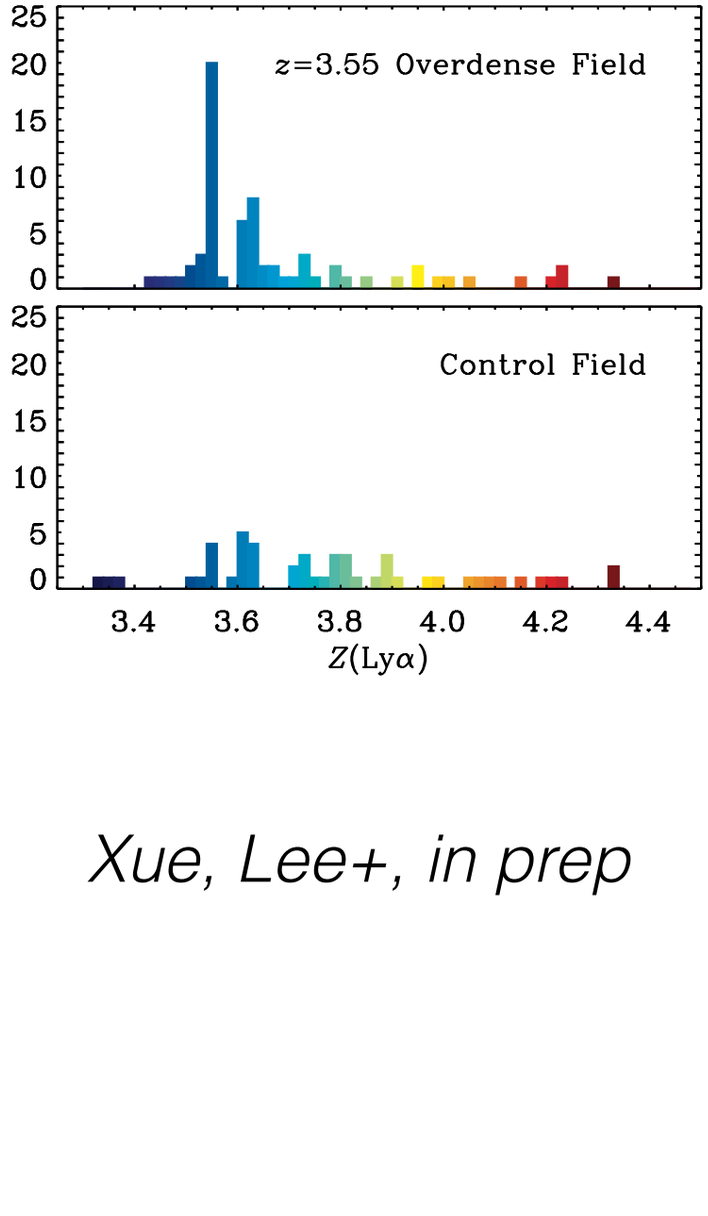
systematic search of high-z protoclusters



- spectroscopy of overdense regions in the 4 deg^2 CFHTLS Deep Fields (starting in Dec 2015)
- further identification of Lya emitting galaxies (via custom narrow-band filters: in progress)
- systematic study of the properties of “member” galaxies vs. field galaxies
- Lya-emitting fraction at cluster-centric distance, star-formation rates, stellar masses
- search for “red and dead” galaxies and dusty extreme starbursts

a promising candidate at z=3.55





Xue, Lee+, in prep

- Similar to z=3.78, identified with a high concentration of Lyα emitting galaxies
- ~20 galaxies at z=3.55; another good system to study to characterize the properties of protocluster members

summary

- At least two proto-clusters at z=3.78. The presence of two large structures in proximity is fairly rare, may be a supercluster in the making

- If all enclosed masses fall in by z=0, they will evolve into a Coma, and Virgo-like cluster

- enhanced star formation in the dense environments: potentially a useful observable to find more protoclusters

- More UV-luminous and/or high-density galaxies appear to have more extended Lya halos around them

- we have begun systematic search of high-z protoclusters; will calibrate search techniques for future surveys (LSST, HETDEX)