The Nature of Nurture in the Early Universe:

An Initial Exploration into High-Density Environments at z>2

Brian C. Lemaux and the VUDS Team

z=1100	z=2-6	z=1.5-2	z~0.8-1.5	z<0.8
	Very few known…	10's confirmed	~100 confirmed	1000s confirmed
	Toshikawa et al. 2012	Stanford et al.	EDisCS	MCXC
	Hatch et al. 2011 (RG)	Papovich et al.	ORELSE	SDSS
	Chiang et al. 2015	Henry et al.	GCLASS	IMACS Cluster Survey
	Kang & Im 2009	Gobat et al.		GAMA
	Miley et al. 2006 (RG)	Tozzi et al.		
	Ouchi et al. 2005	Andreon et al.		
	Capak et al. 2011 (RG)			

Bologna, June 25th 2015

Some Motivation

Why study large scale structures at high redshift (z~2-6)?

- Massive virialized clusters are rare, groups and pairs not so

- Epoch of formation for massive ellipticals, should be able to observe the first seeds of nascent galaxy clusters as traced by the galaxies themselves.

- Reversal of the SFR-density/color-density relationships. This almost certainly happens as the redshift of observation increases. May have been already observed (e.g., Tran et al. 2010), but galaxies in z>2 clusters should be *extremely* active.

- Already seeing environmental quenching at these redshifts? If so, what causes it?

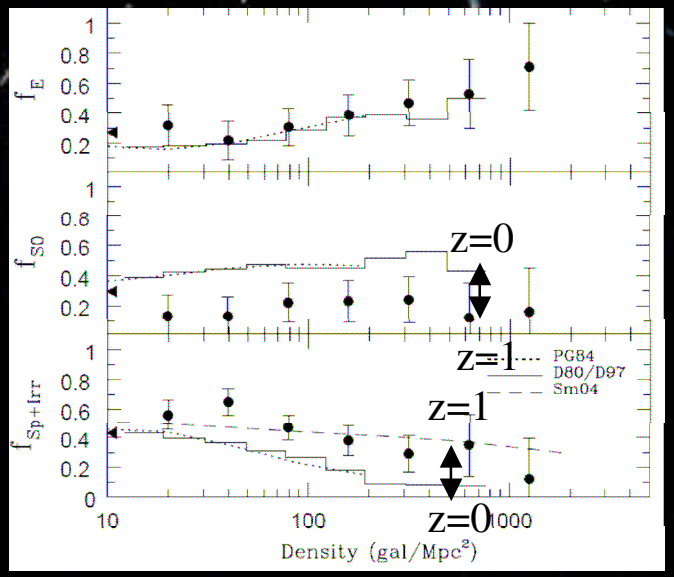
How to find them?

- X-Ray Observations: Unlikely. Surface brightness dimming is painful at these redshifts. Time enough to form ICM?
- Sunyaev-Zeldovich Observations: Unlikely. Surface brightness dimming not a problem (apparently?), but still have the problem of no hot ICM
- Galaxy Red Sequence Densities: Universe is only 1.5-2.5 Gyr. Transition to the RS takes ~ 1 Gyr
- Photo-zs: Can be used as supplemental evidence, but as primary evidence they are suspect. Lots of issues with purity, completeness, and known and unknown biases
- Spec-zs: Great!…if you have enough, but should be of representative populations

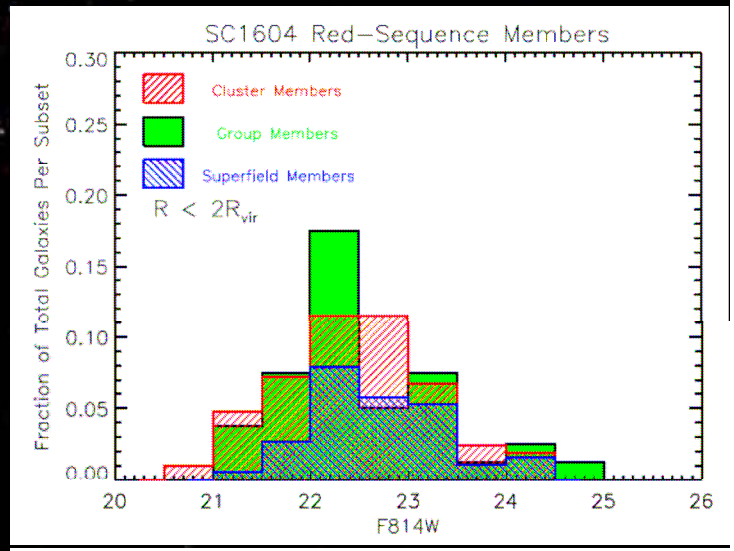
How to Investigate Environmental Effe

Several ways! Can use:

-Morphology (i.e., is there a relationship between morphology and density? Does that relationship change as a function of global environment? Local density? Epoch?)



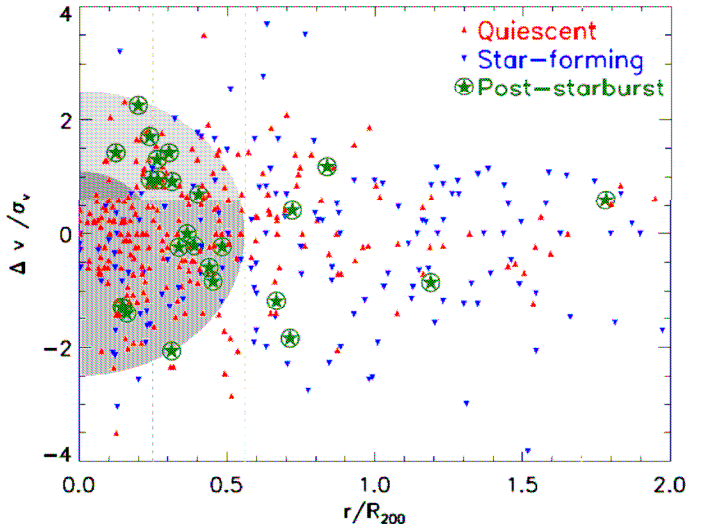
Postman et al. 2005



Lemaux et al. 2012

Galaxy Colors (i.e., Butcher-Oemler effect: higher fraction of blue galaxies in clusters at higher redshift. What causes this? Use SED fitting to constrain stellar ages/metallicities/ star-formation histories)

-Spectral Diagnostics (i.e., star-formation rates, β-slope, metallicities, spectral classification, stellar ages) vs. global position



Muzzin et al. 2014

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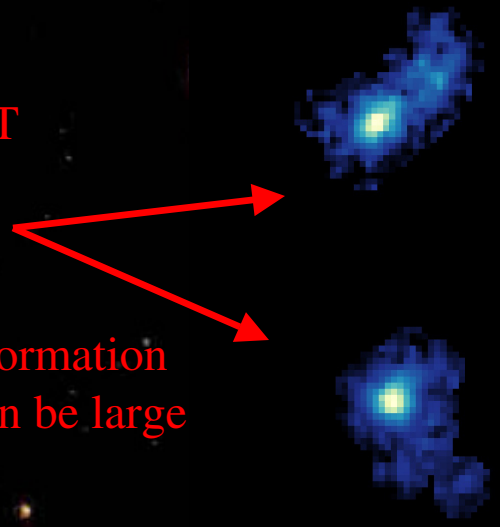
What is possible at high redshift (z>2)?

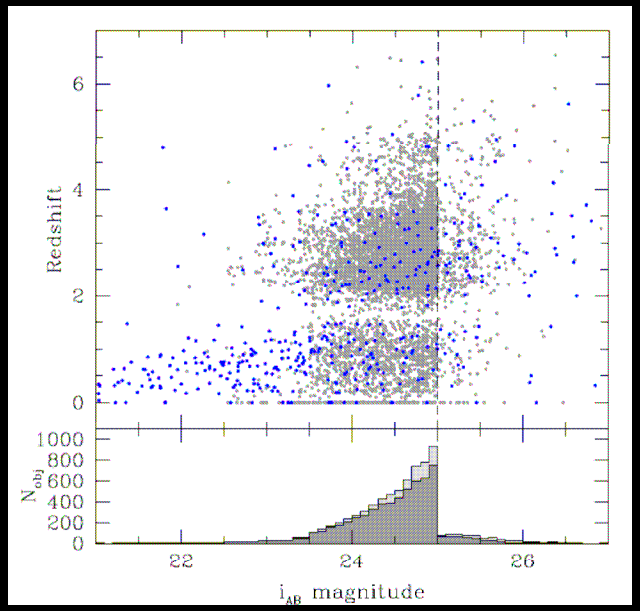
- Morphology: are hard to come by at z~1, only possible with HST and even then it's extremely challenging to qualify/quantify morphology. What are these?



- Colors: observed-frame optical broadband data gives limited information at z>2, need very deep IR imaging and even then k-corrections can be large Many possible degeneracies exist in SED fitting (?)

-Spectra: At z>2, observed-frame optical spectra may have limited leverage in differentiating various galaxy populations (?)

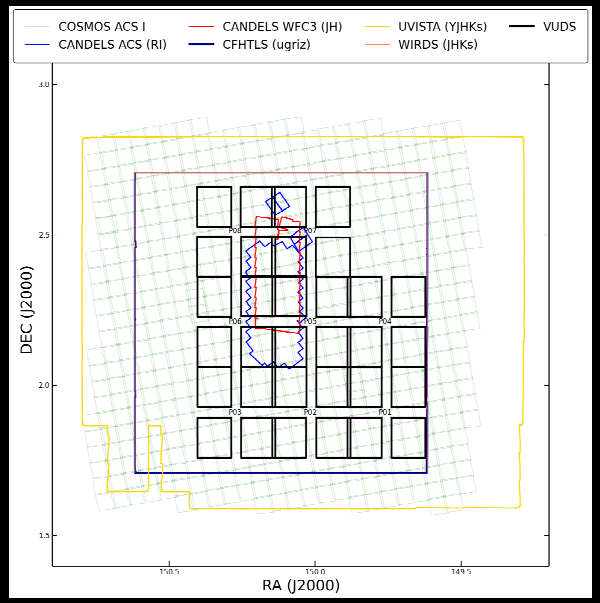
VUDS | VIMOS Ultra Deep Survey



Targeted ~10000 Objects in 1 deg^2 over three fields (CFHTLS-D1, ECDFS, COSMOS), all with >= 10-band imaging

Mostly photo-z+magnitude with some color cuts

Peak of the magnitude distribution at i´=25.



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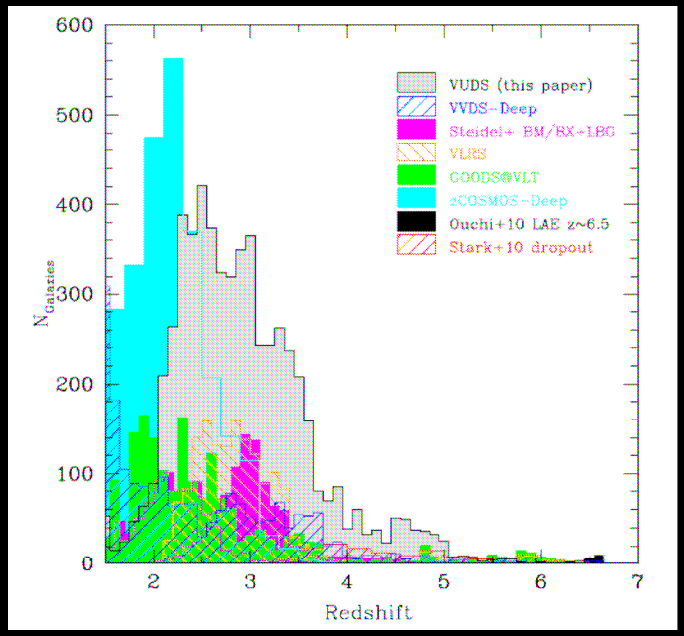
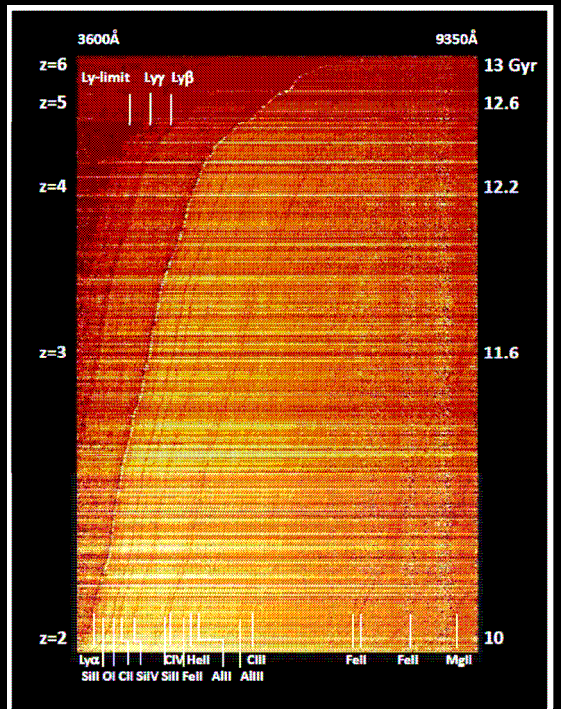


Le Fèvre et al. 2015

14 h exposure time in blue and red VIMOS grisms, per grism

Typical wavelength Coverage 3800-9400Å, R~230
⇒Low-Resolution Spectroscopy

It worked!

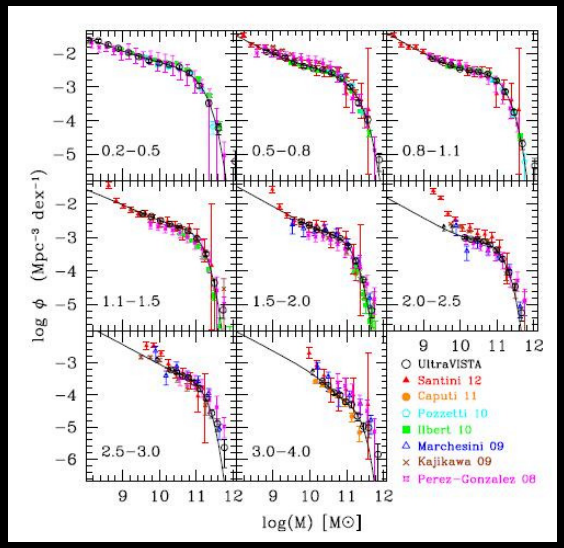


Finding Some Things to Study

Methodology:

- Step 1: Get a lot of redshifts at z>2
- Step 2: Step through redshift slices of $\Delta z \sim 0.1$ from z=2-5
- Step 3: Iterate around redshift slice bounds. Search for ≥ 7 concordant galaxies within 2 h_{70}^{-1} Mpc and $\Delta\chi < 25\ h_{70}^{-1}$ Mpc
- Step 4: Supplement with photo-z information (density maps)
- Step 5: Determine centers and velocity dispersions
- Step 6: Compare galaxies in different environments…?

Filter Choice…?

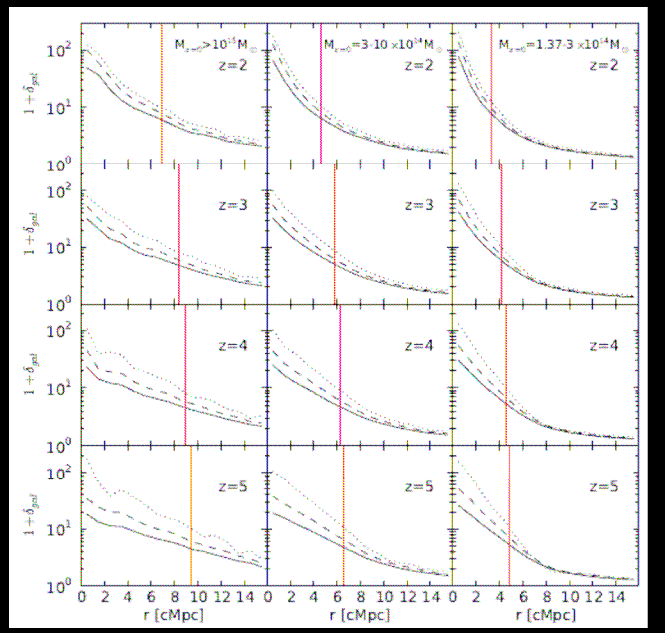


Ilbert et al. 2013

Co-moving distance is a wonderful metric if you want to compare progenitors of galaxies attached to the Hubble flow, but is it proper to use here?

Cluster science done using proper distances since gravity acts over those scales

A galaxy at ~1000 km/s reaches the center of the filter in ~10 Gyr



Chiang et al. 2013

A Journey Through Space and Time

Did I find anything?

Yes! To date:

- 14 “protostructure candidates” in the CFHTLS-D1 field
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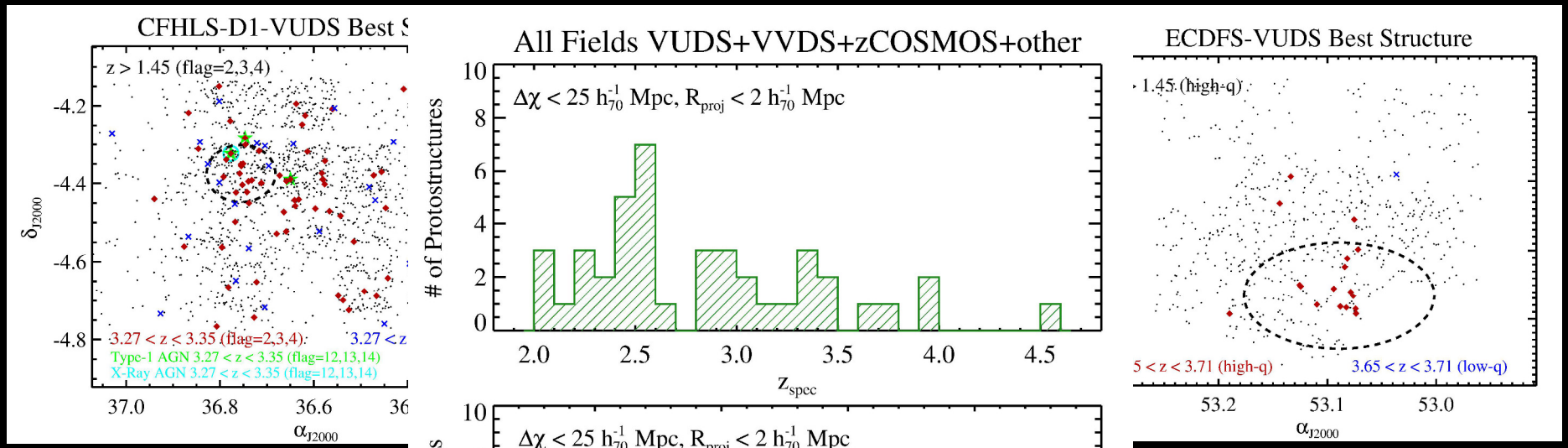

Lemaux et al. 2014

cciati et al. 2014

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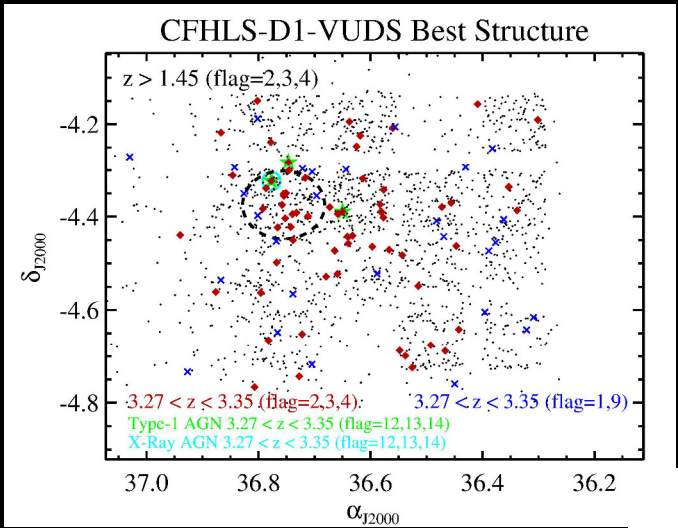
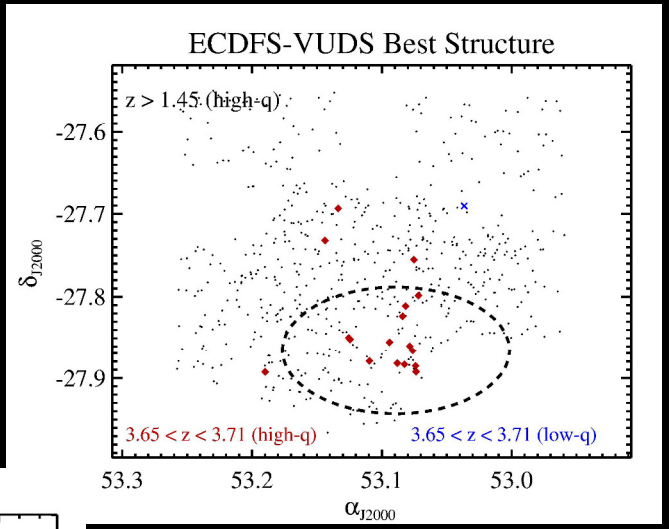
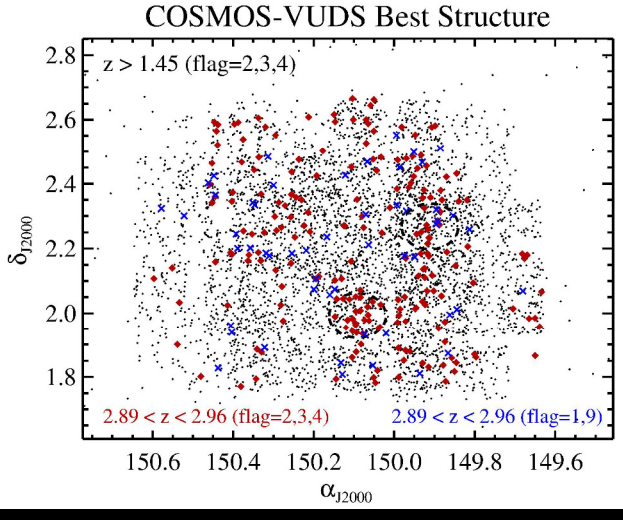


Lemaux et al. 2014





Cucciati et al. 2014

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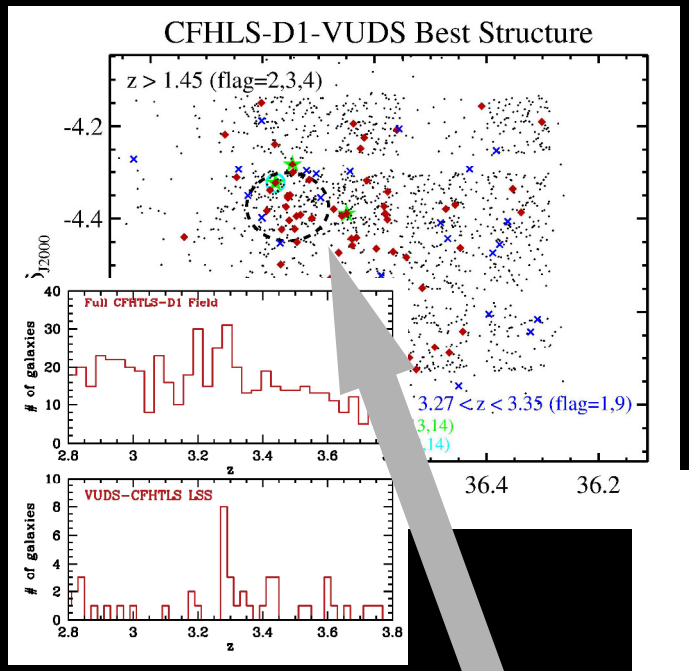
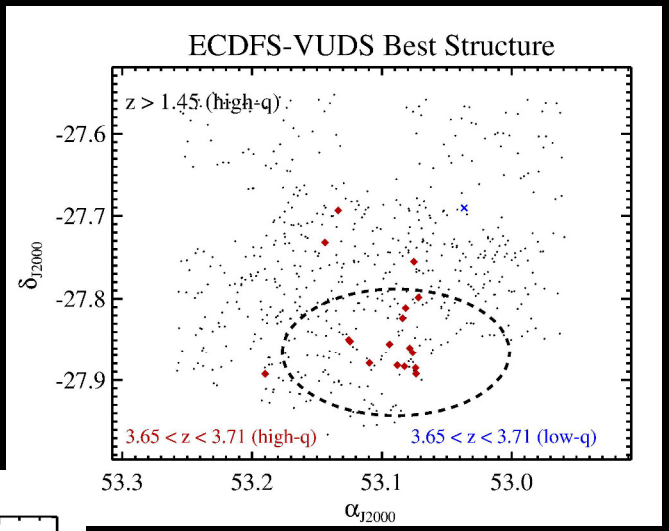
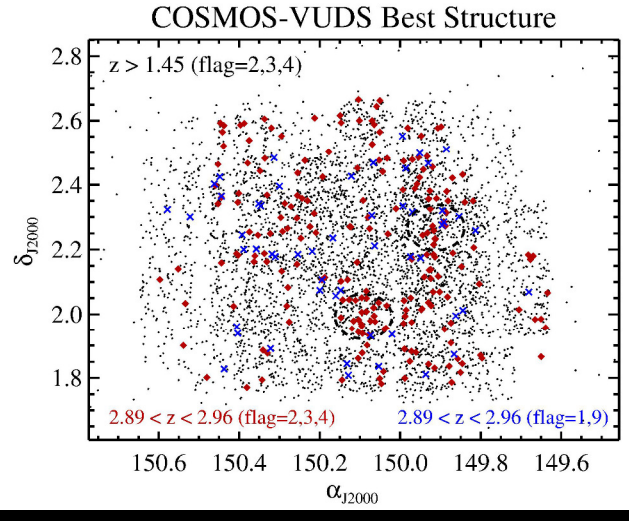


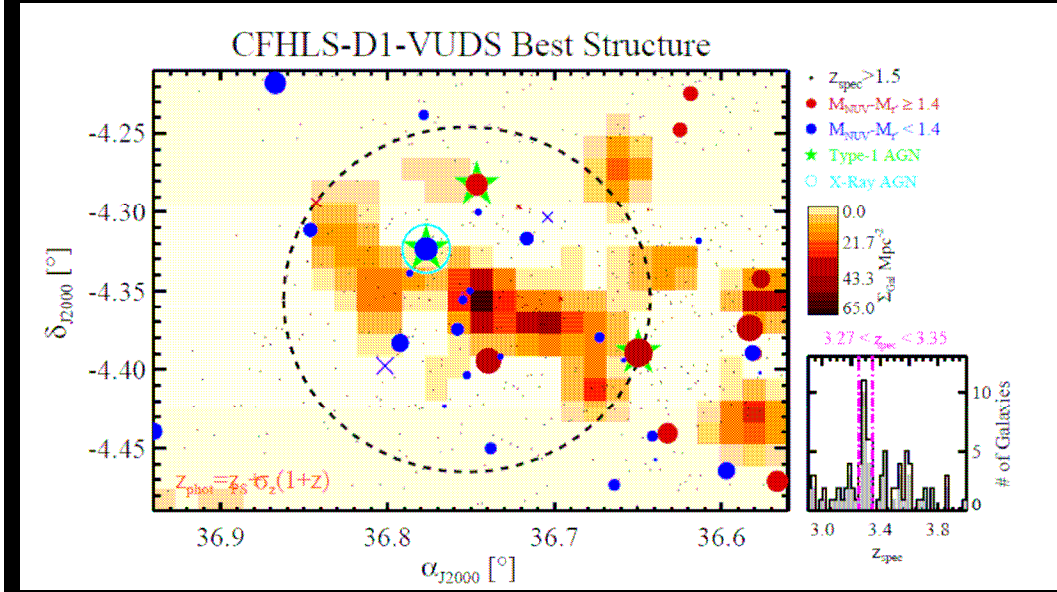


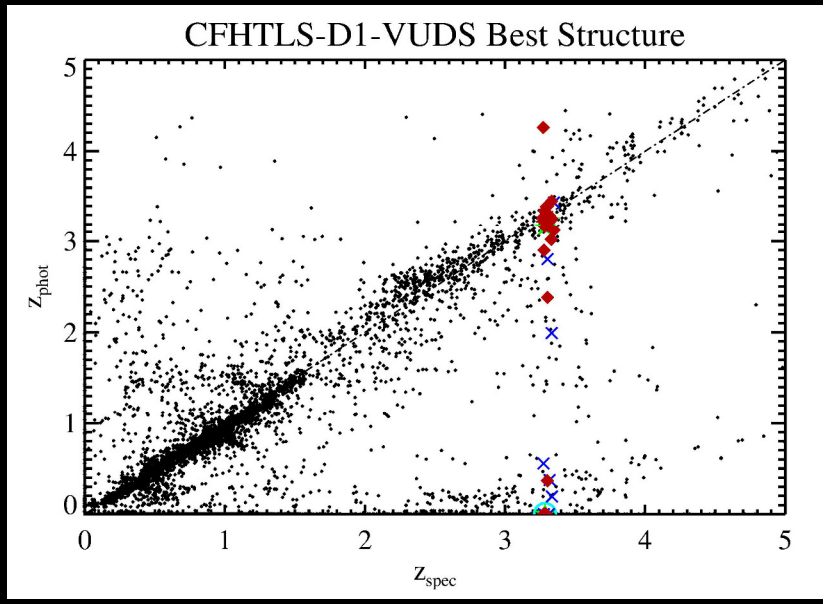


The journey begins here

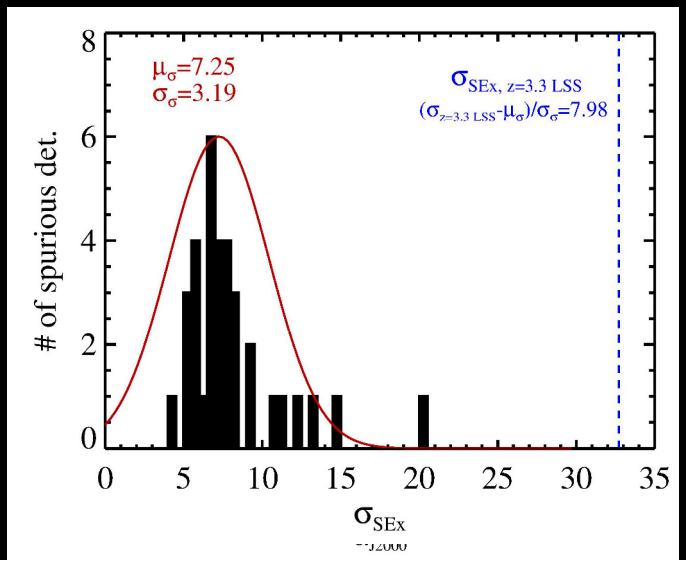
Cucciati et al. 2014

How to Characterize an "Overdensity"?

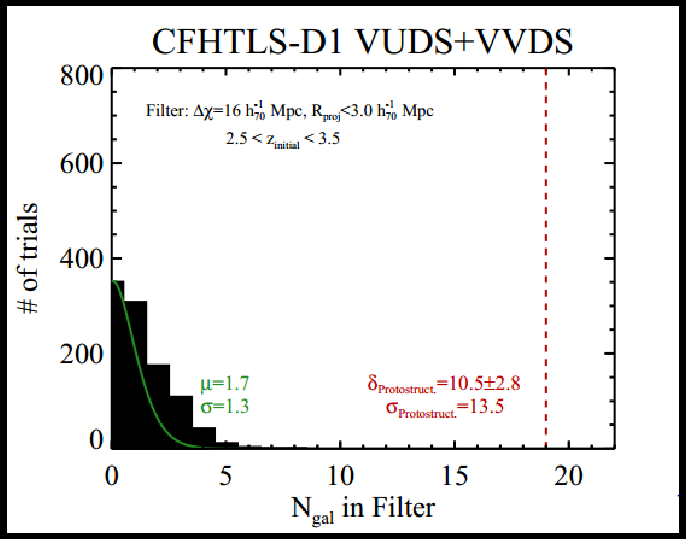




Through photometric redshifts?



Through spectral redshifts?



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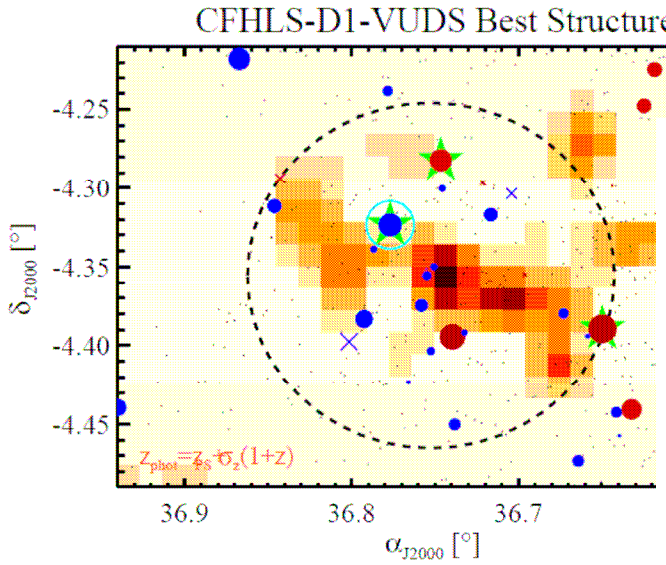

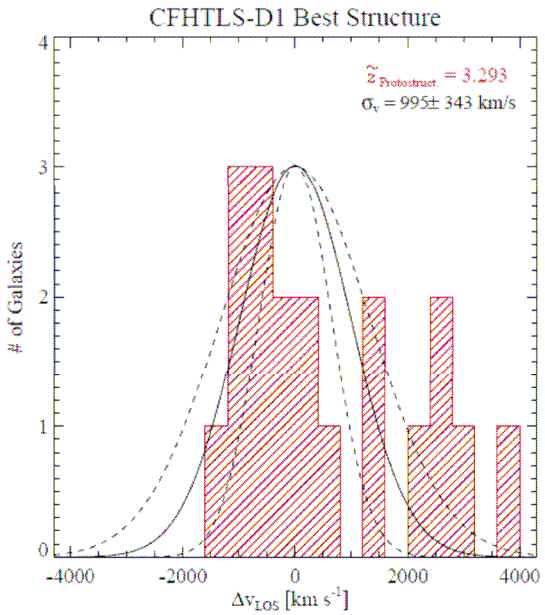

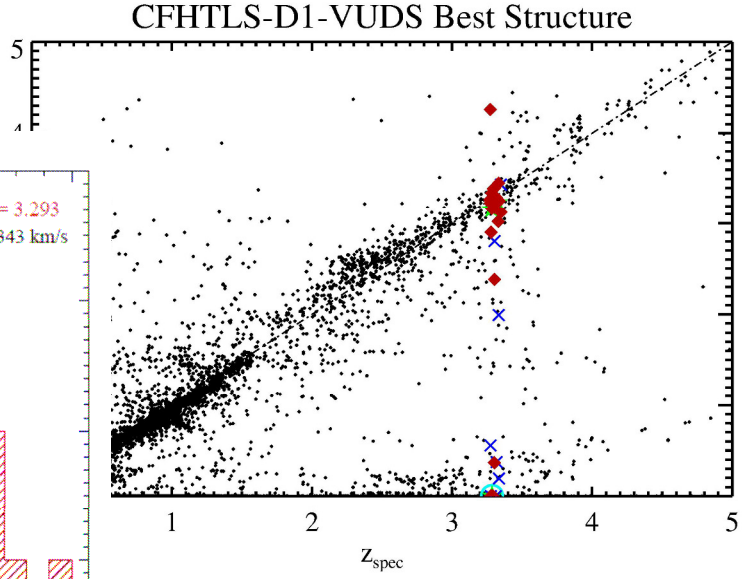

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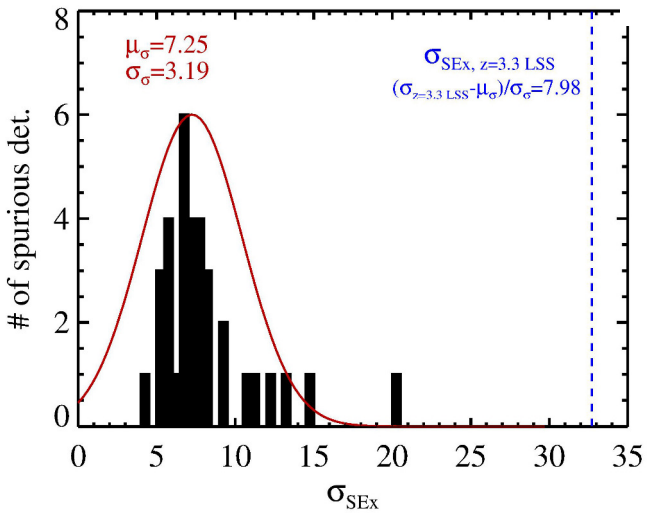


A variety of methods were used to attempt to constrain the halo mass:

$M_{z=3.3}$~3x10^{14} $M_\odot$

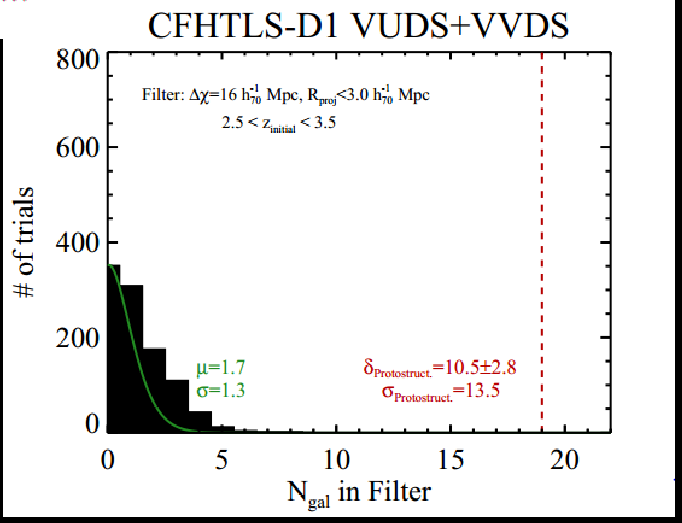
$M_{z=0}$~ 4x10^{15} $M_\odot$

σ_v = 995 ± 343 km/s

N_{gal}=19

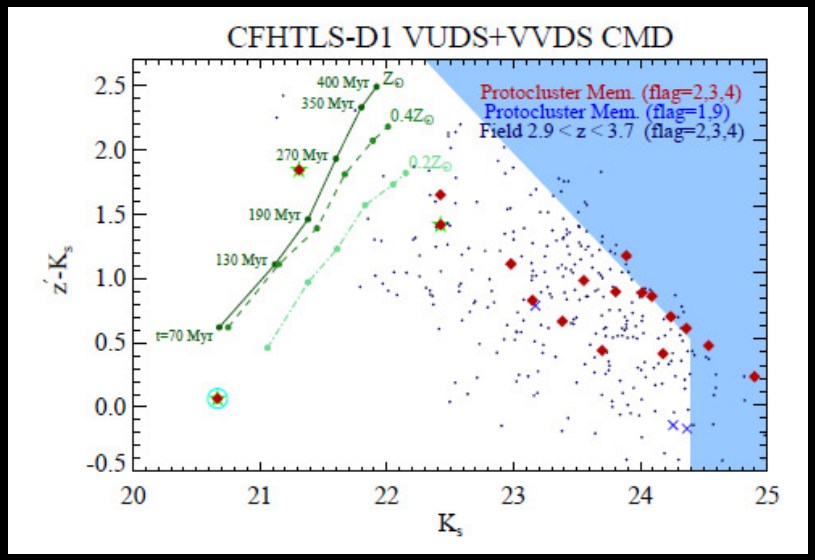
but…

Through spectral redshifts?



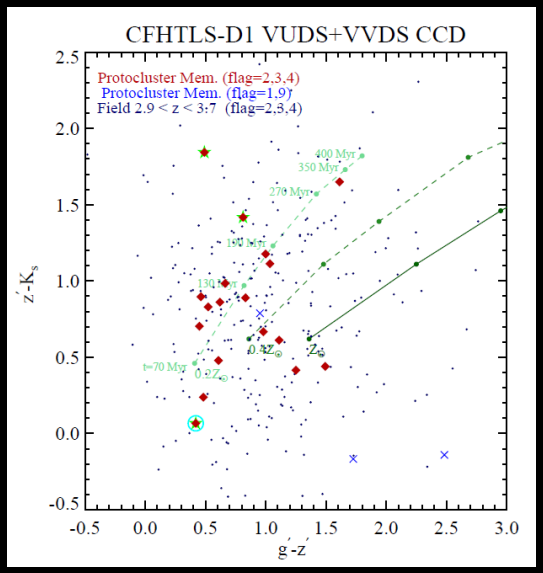
Environmental Effects?

- For now the important point is that ClJ0227-0421 is very overdense w.r.t. the VUDS field
- A pilot study with the members of ClJ0227-0421, membership $R_{proj} < 3\ h_{70}^{-1}$ Mpc, $3.27 < z < 3.35$
- Field sample is defined over the extended redshift range $2.9 < z < 3.7$, but same median redshift



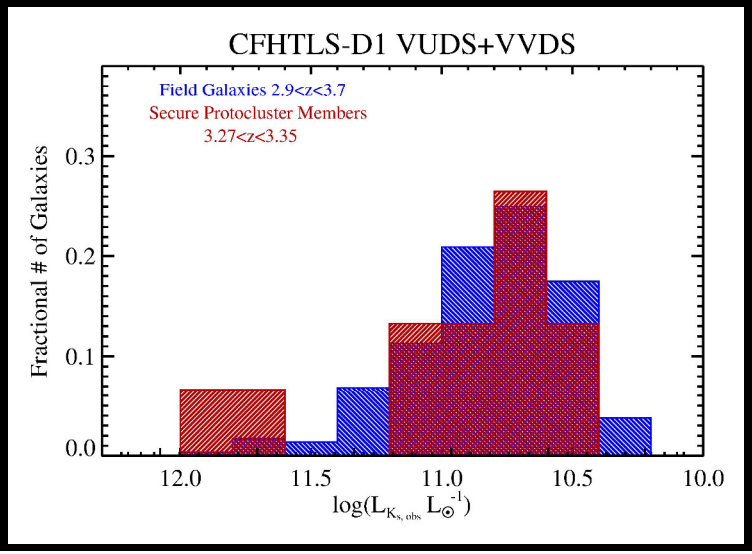
Beginning with observed quantities…

…and adding some level of sophistication



There appears to be an excess of brighter and generally redder galaxies within the protocluster bounds, but how to characterize these galaxies?

Would like to use SED fitting, but…



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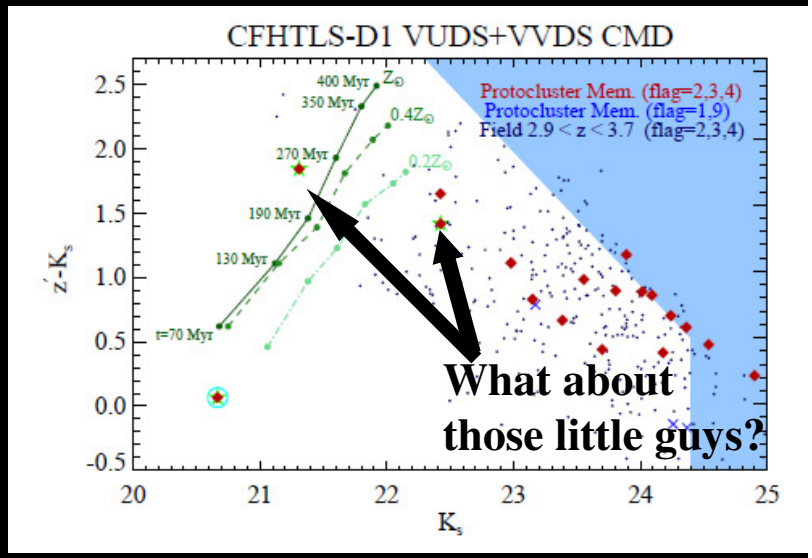

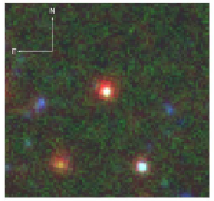

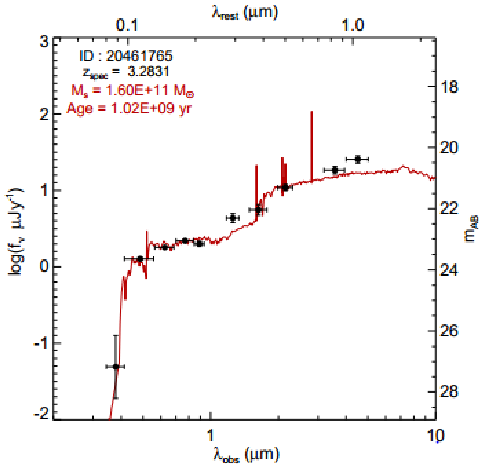

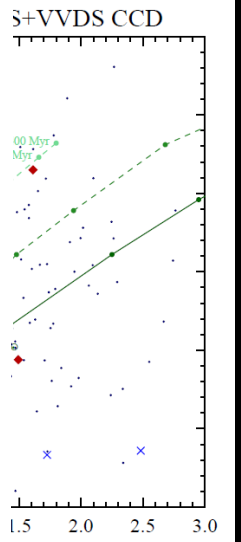

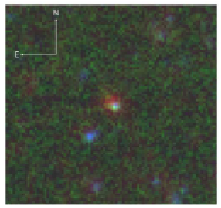

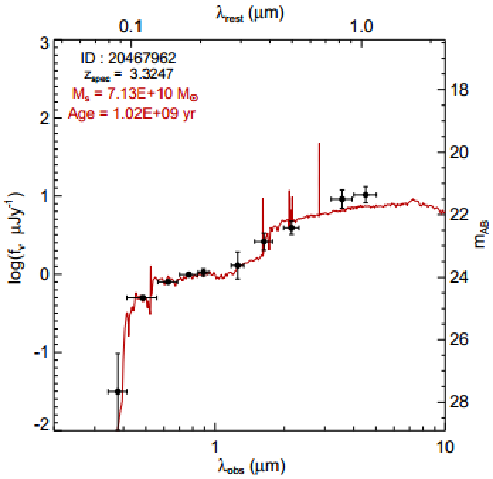

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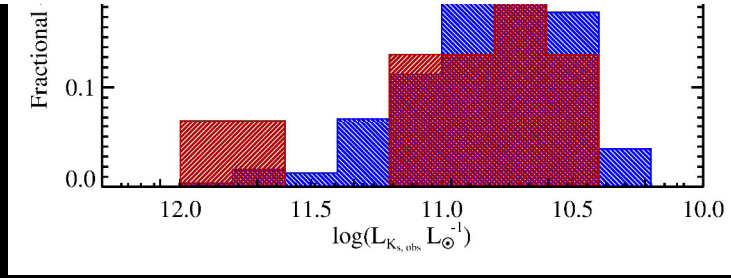

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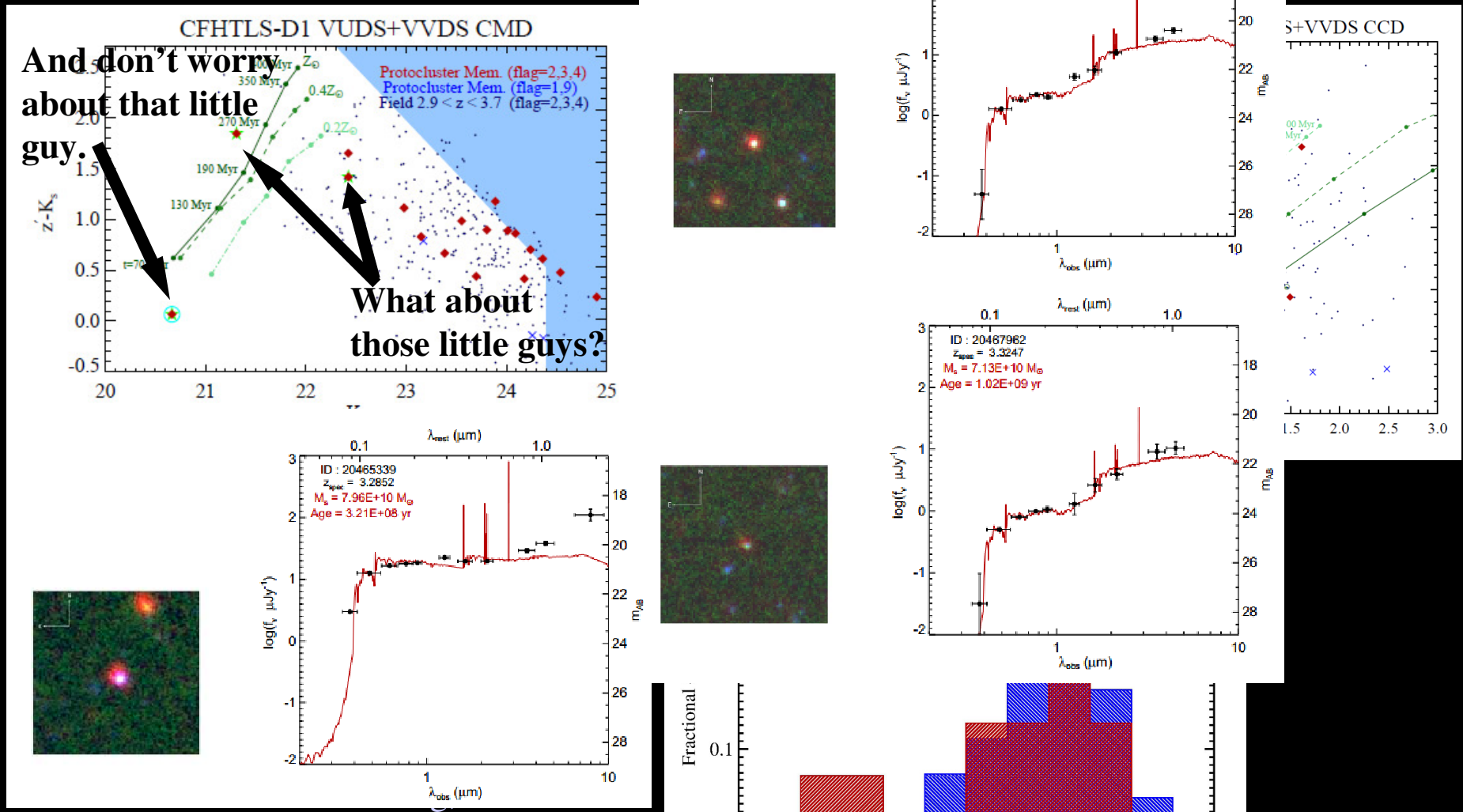
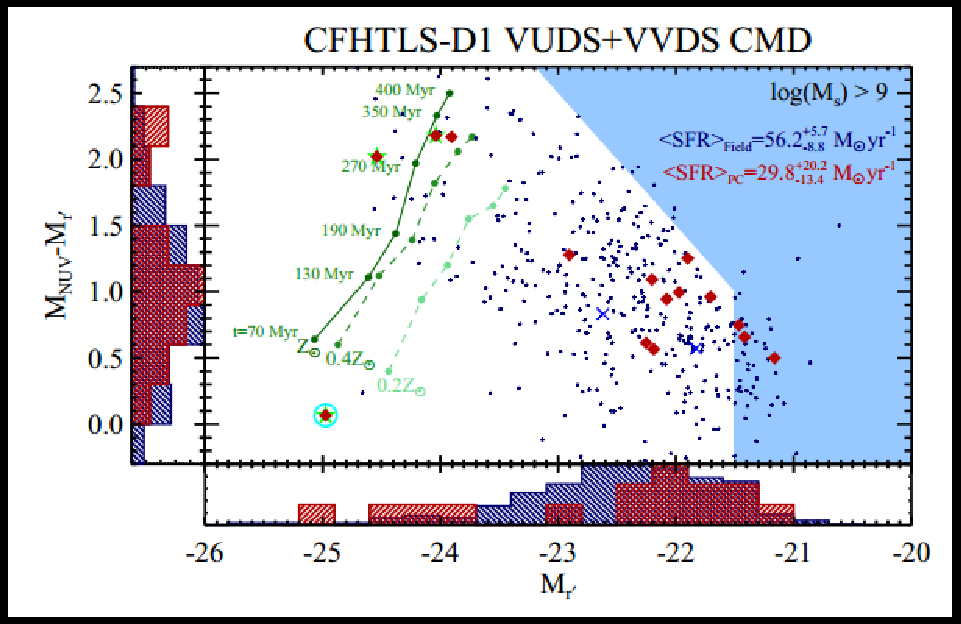


Environmental Effects?!

Adding a bit more sophistication…



Excess of bright/red galaxies of ρ_{pRSG}~25 in the protostructure relative to the field. Fractional excess too. Onset of environmental quenching? AGN quenching? Large uncertainties…

Some evidence of suppression of star formation among the protocluster members, but tentative and subject to methodology.

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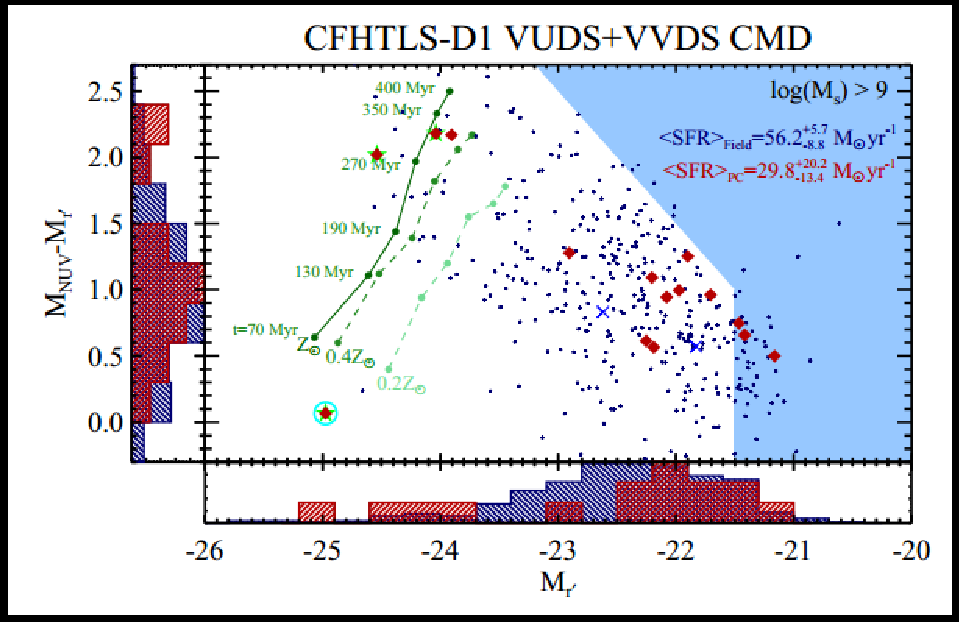

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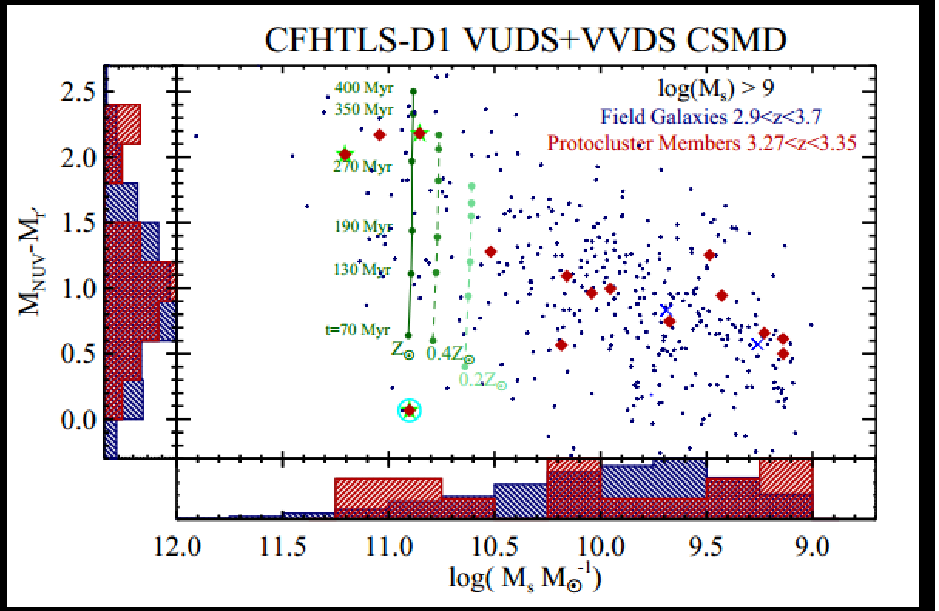
Brighter proto-red-sequence galaxies appear to be already massive (~10^{11} $M_\odot$ at z~3.3). Similarly massive field galaxies, but over a much larger volume (x250).

Other protocluster members have properties similar to coeval “field” galaxies.



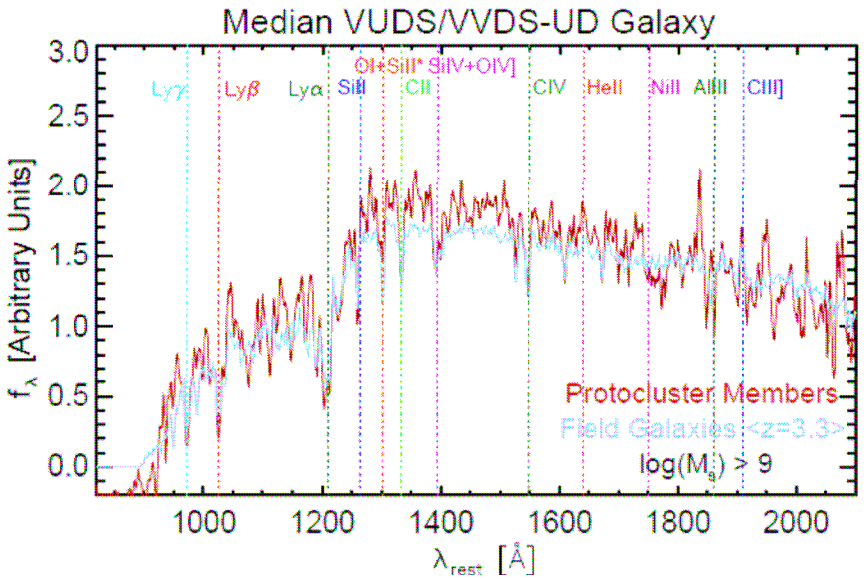
Environmental Effects?!

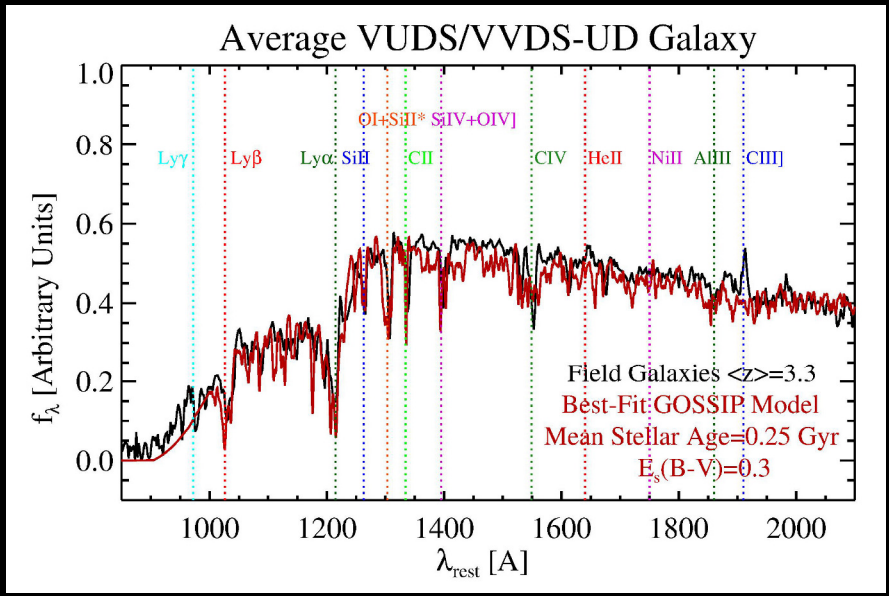
Did you know: spectra can be used for more than redshifts?

Fraction of LAEs similar among field and protocluster galaxies, that's no help…

β-slope appears redder for the average protocluster member, what does that mean?

Is there a better way to do this?





GOSSIP+ Spectral + Photometric fitting software able to place meaningful constraints on ages as well as stellar-phase metallicity, stellar mass, SFR (Thomas et al. 2015)

Simulations show degeneracies in "SED" fitting are reduced immensely even with UV rest-frame spectra

Investigate z_f/density relationship

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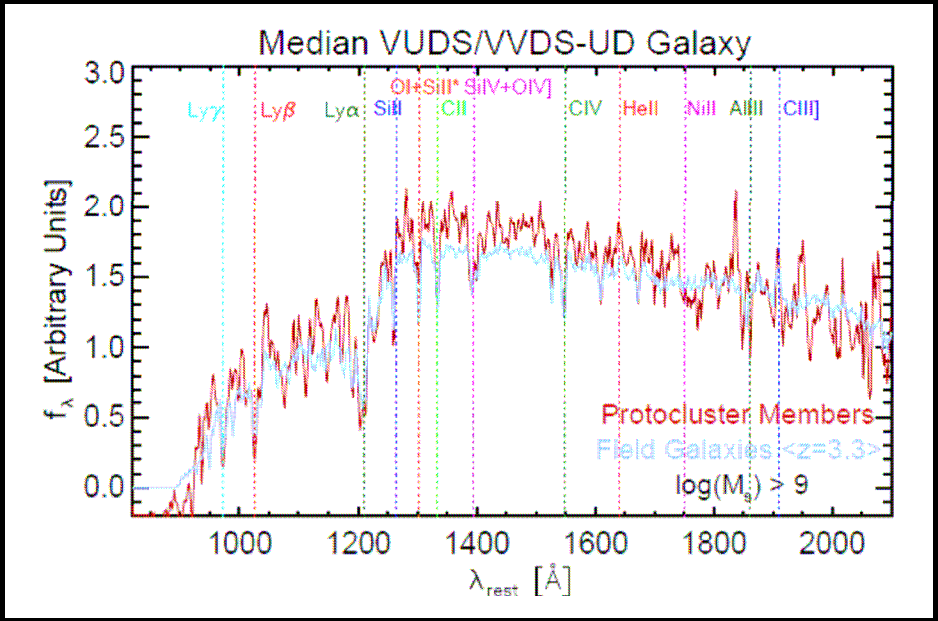
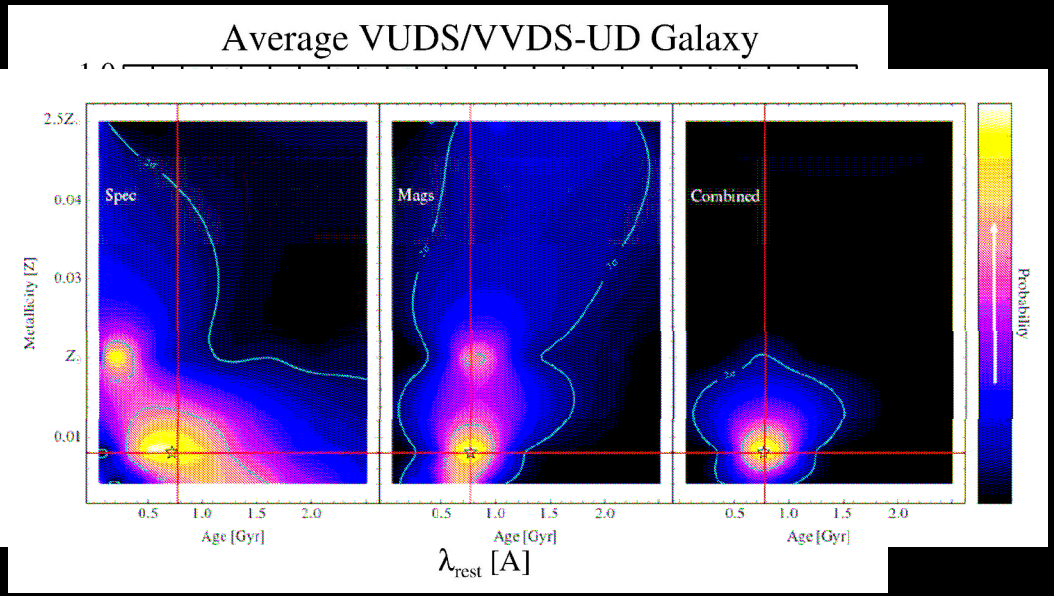




GOSSIP+ Spectral + Photometric fitting software able to place meaningful constraints on ages as well as stellar-phase metallicity, stellar mass, SFR (Thomas et al. 2015)

Simulations show degeneracies in "SED" fitting are reduced immensely even with UV rest-frame spectra

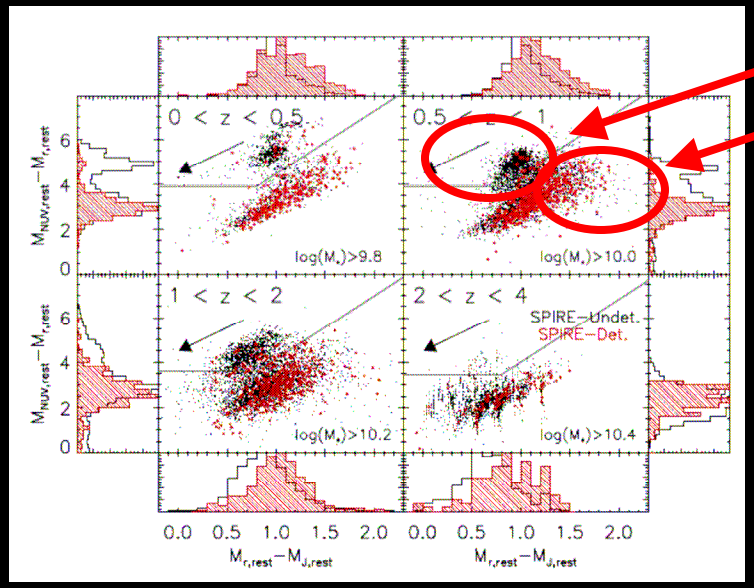
Investigate z_f/density relationship

Possibly!

The results of the initial investigation are ambiguous. Hints of potential environmental influences, galaxy population appears definitively different with respect to the field

I guess everything is wrapped up in a nice tidy package?

This was one protocluster, incompletely sampled.

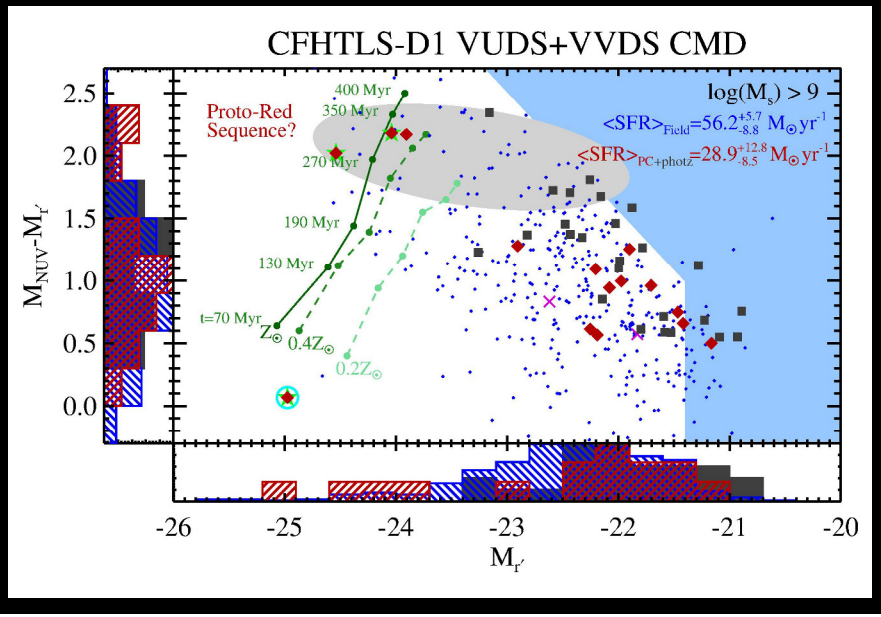


Lemaux et al. 2014

VUDS doesn't target these galaxies

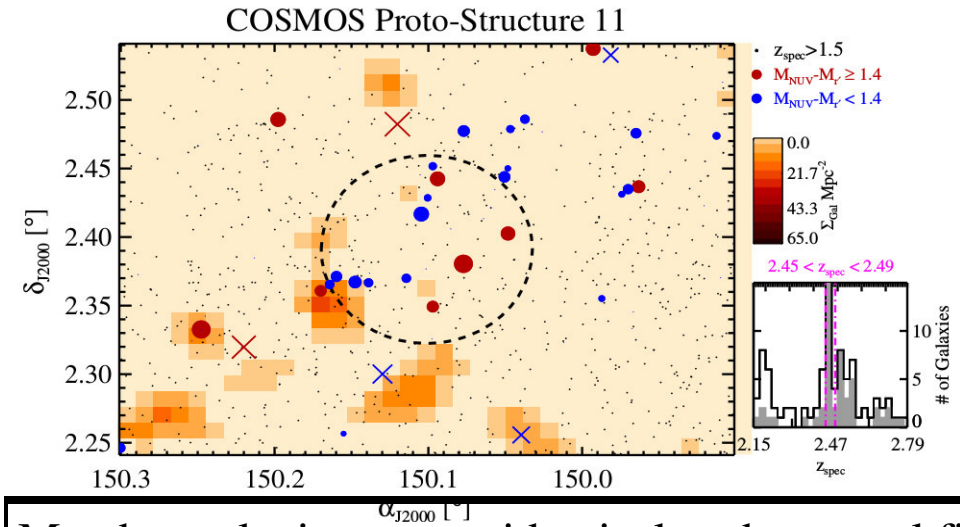
Nor these really

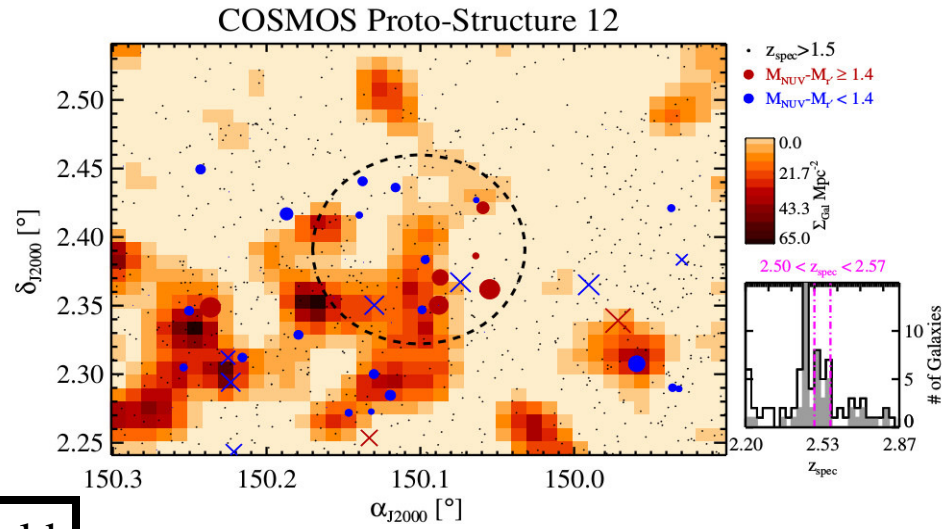
These issues may be circumvented by getting HST or MUSE time. Or in the absence of that, including the photo-z sample, very carefully...



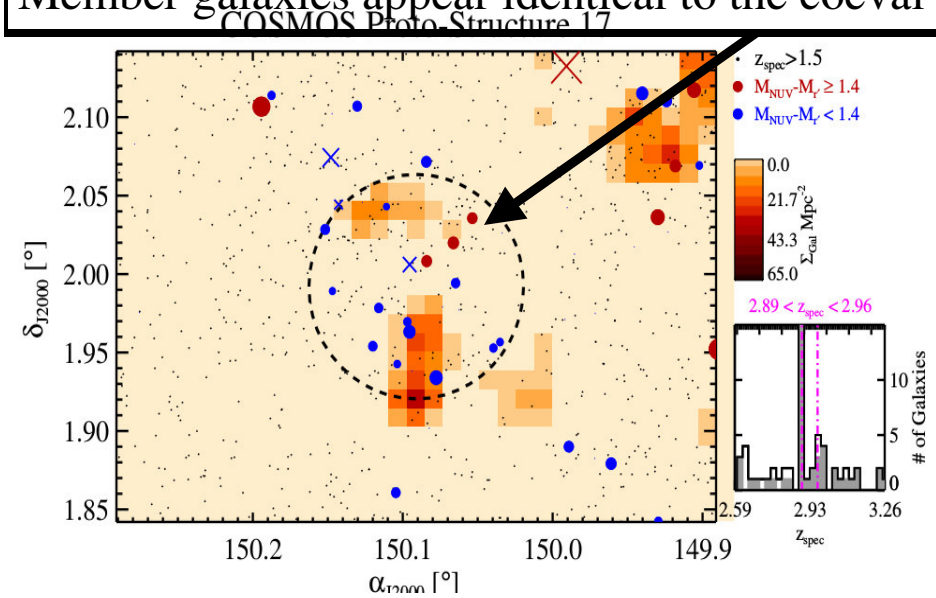
"Coadding" Protostructures?

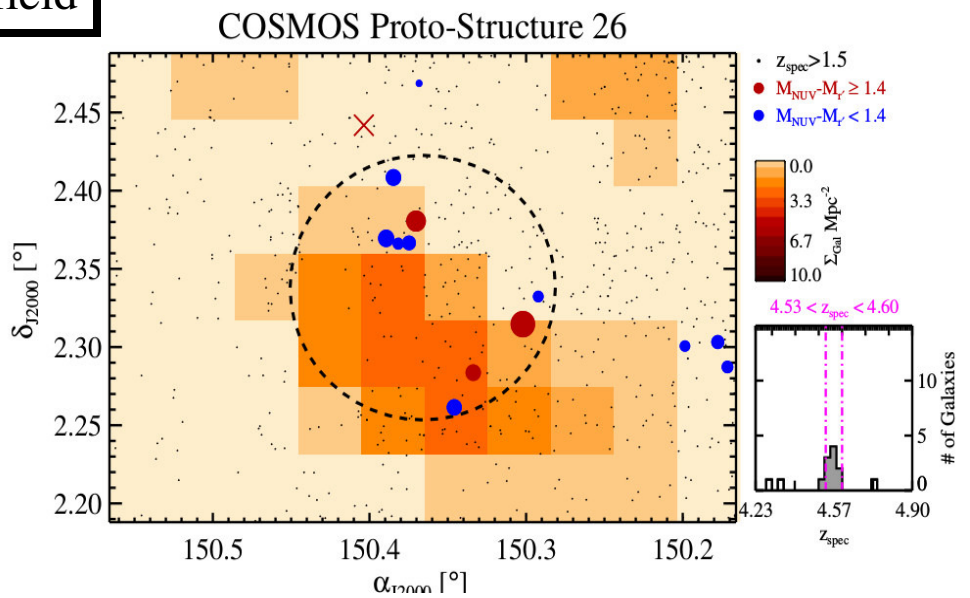
50 total protostructures in VUDS, amazing diversity seen in the richness and member properties





Member galaxies appear identical to the coeval field





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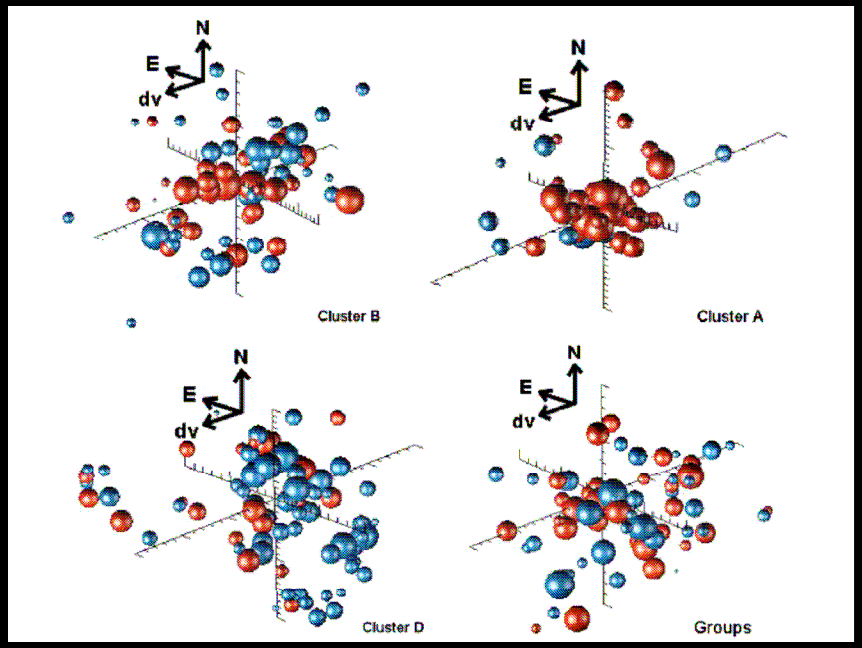
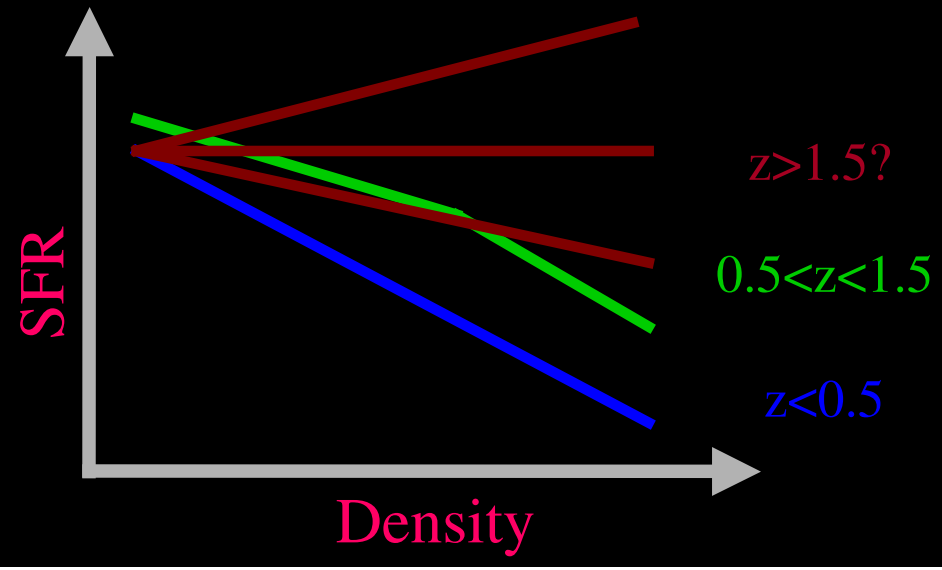


Lemaux et al. 2012

At lower z (z<1) an overdensity's galaxy content depends on halo mass and dynamical state (formation history). Since we cannot characterize either well, do we wash out signal by combining everything? Bin by "richness"? How is that quantified? Halo mass? How is that quantified?

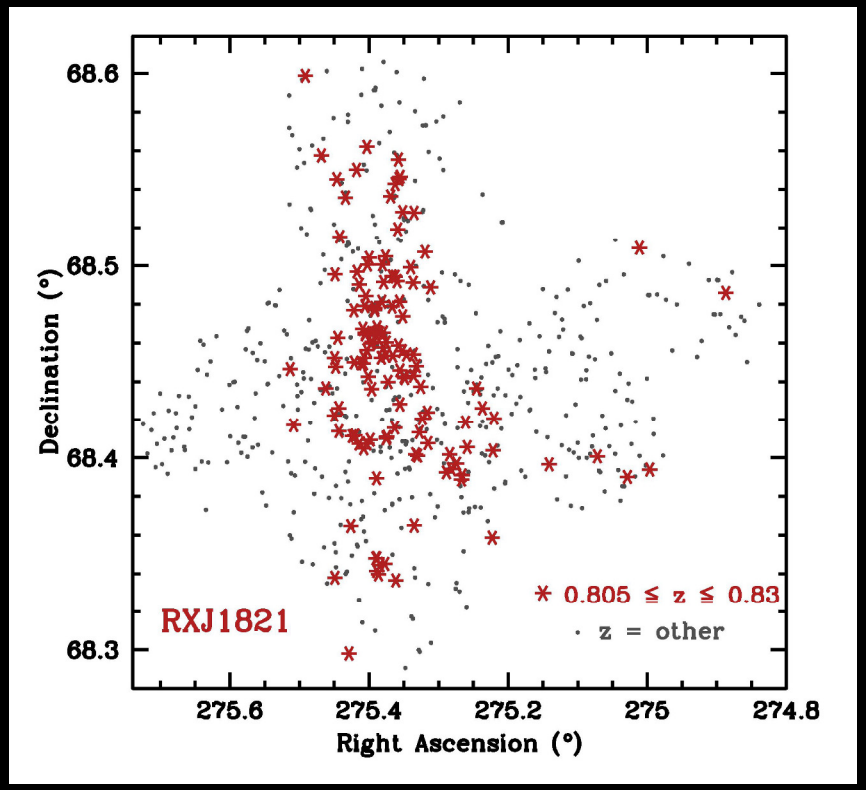
Another pernicious physical effect: when does the SFR-density/color-density trend turn over? Not at one z, probably also dependent on a number of effects.



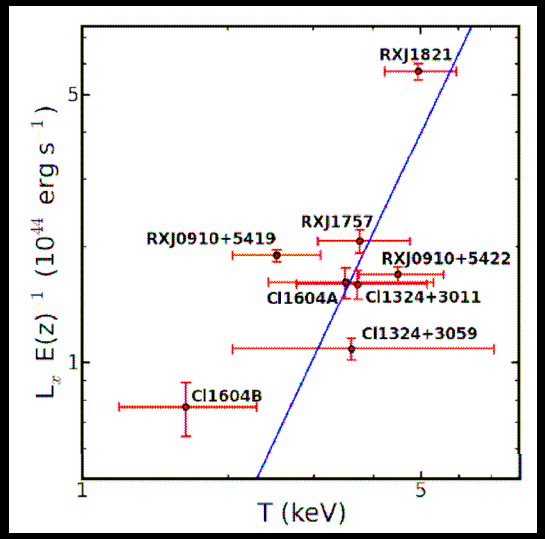
On the Uses of Spherical or Cylindrical Symmetry

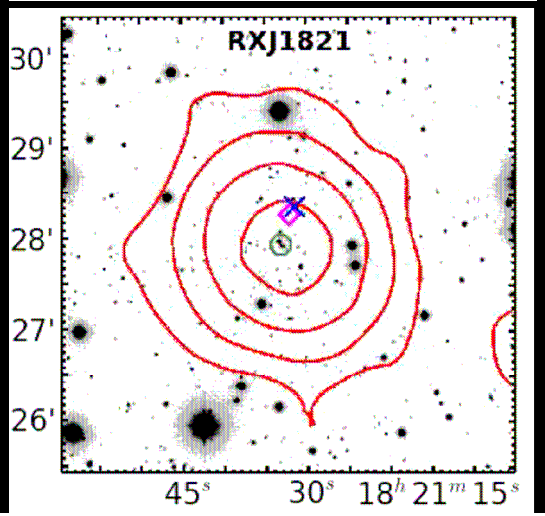
Clusters in the local universe are complicated and some have member distributions which are *not* symmetric even after ~13 Gyr of evolution

At z~1 this lack of symmetry is even more pronounced when you look close enough even in clusters which look safe, membership matters



Lubin et al. 2009



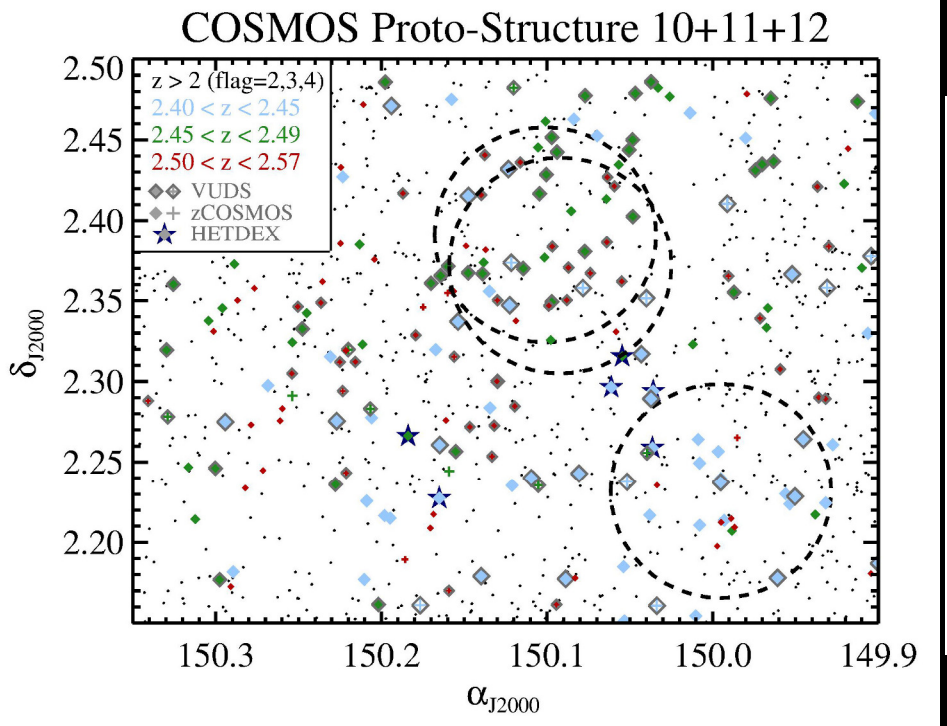


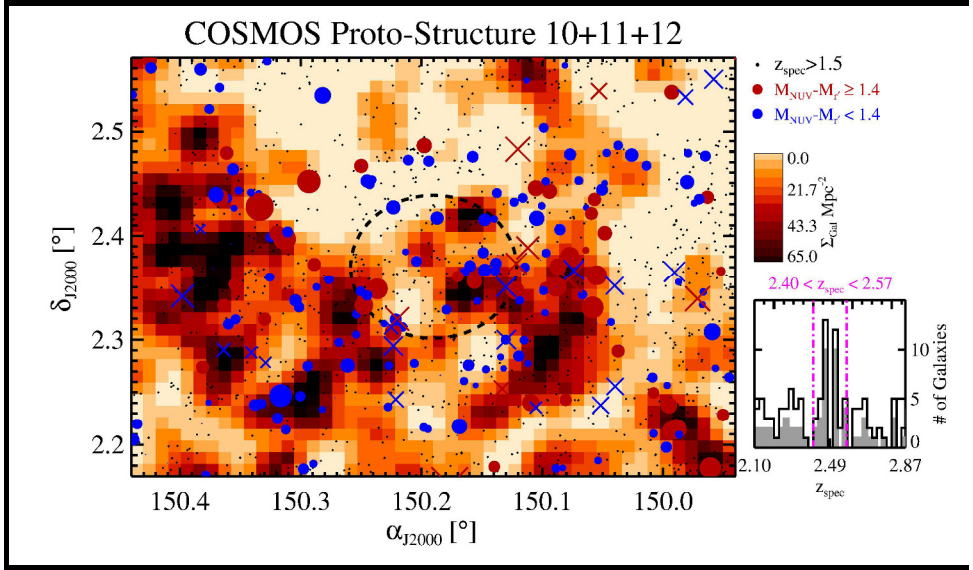
Rumbaugh et al. 2012

A Non-Symmetric Method of Defining Members

At higher redshift before virialization is likelt a possibility, symmetry is difficult to come by.

Voronoi Tessellation can be used to define membership in a Source Extractor-like way without assuming any symmetry in the underlying (probed) density field





Three rich proto-structures spanning 2.40 < z < 2.57: a proto-supercluster?

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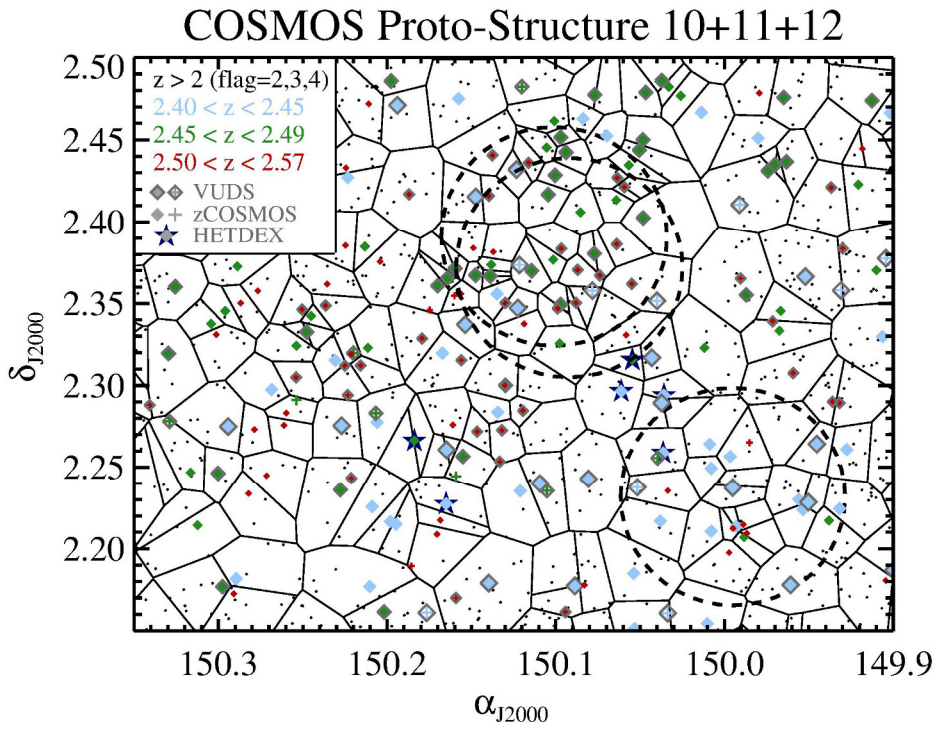

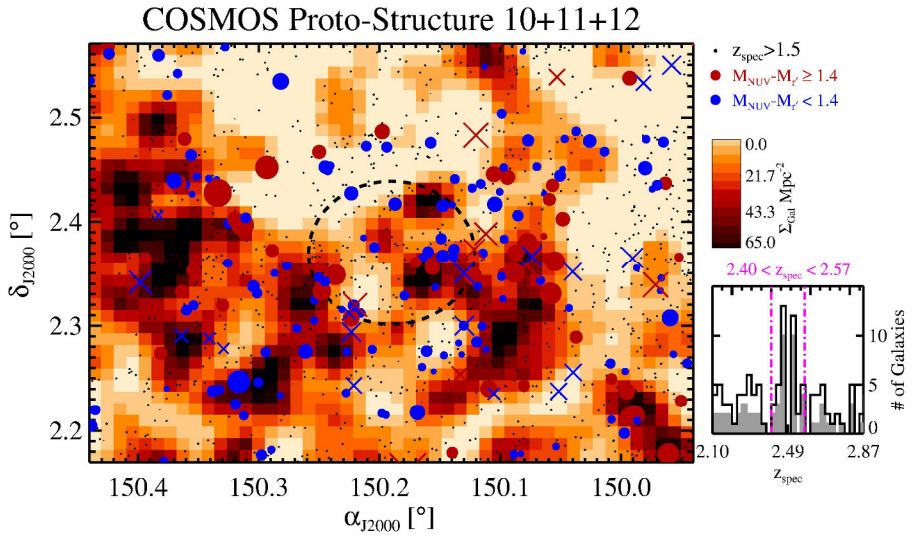

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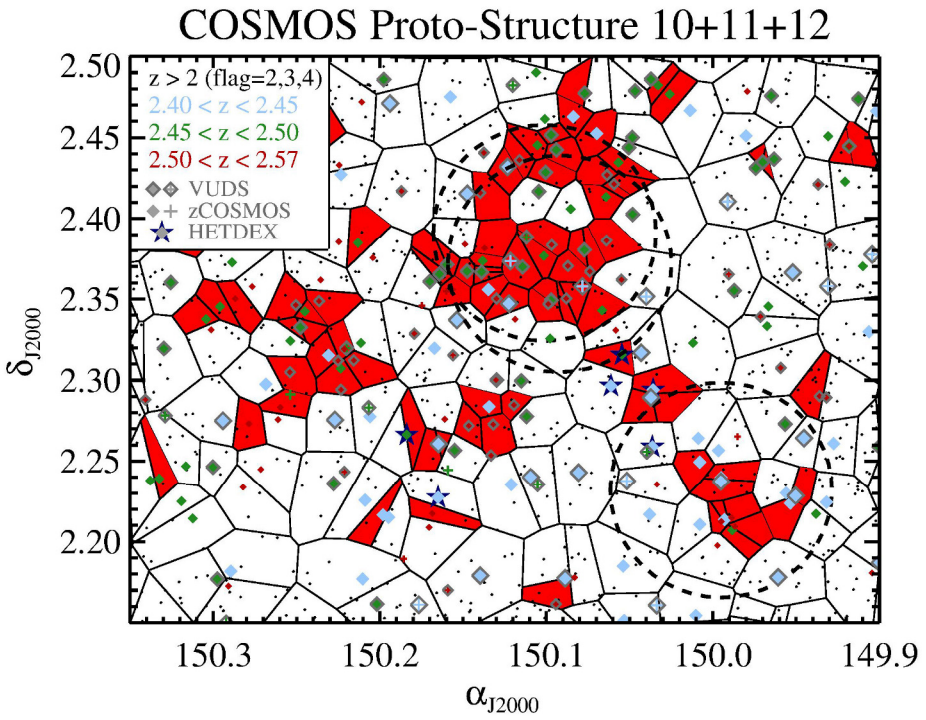

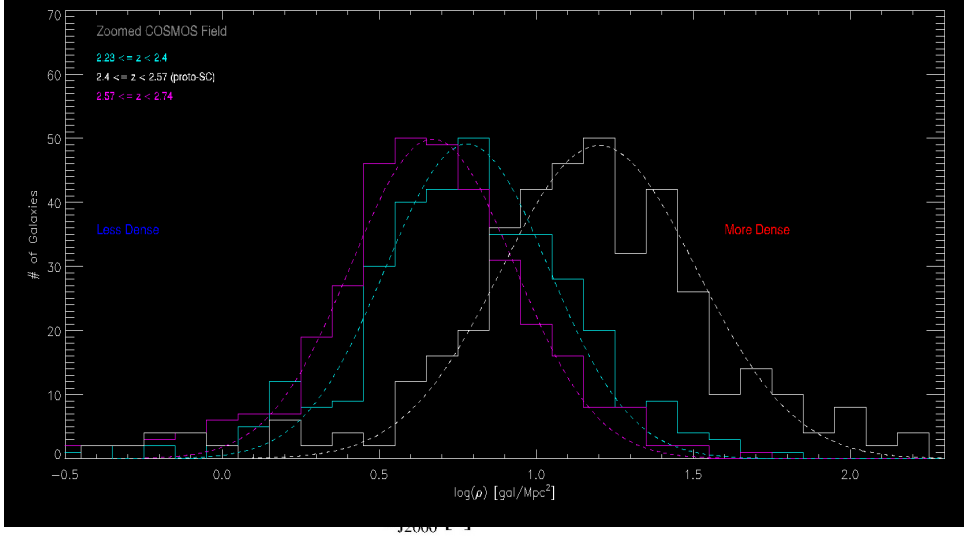

Three rich proto-structures spanning $2.40 < z < 2.57$: a proto-supercluster?

Conclusions?

-Many proto-structures found in VUDS, surprising for a field survey, large extent helps

- Initial investigation into ClJ0227-0421 showed a suppression of the average SFR and an increase in the number of massive, older, redder galaxies in the proto-cluster

- There's a lot more galaxies to play with: ~50 proto-structure candidates, but need to combine intelligently

- The main tools of the analysis are up and running well and are demonstrated with ClJ0227-0421.

- Attempting to combine photometric and spectral redshifts, how best to do this?

- Eventually attempt SFR/color/age/morphology-density with combined analysis of all protostructures

More to come! Soon…