Massive Structures and Massive Galaxies at z>3: Candidate Identification, Spectroscopic Confirmation (or not!), and Implications for Galaxy Evolution

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The C3VO and MAGAZ3NE Collaborations

Outline

Massive Structures:
Motivation
Sample Selection
Spectroscopic Follow-up
Results

Massive Galaxies:
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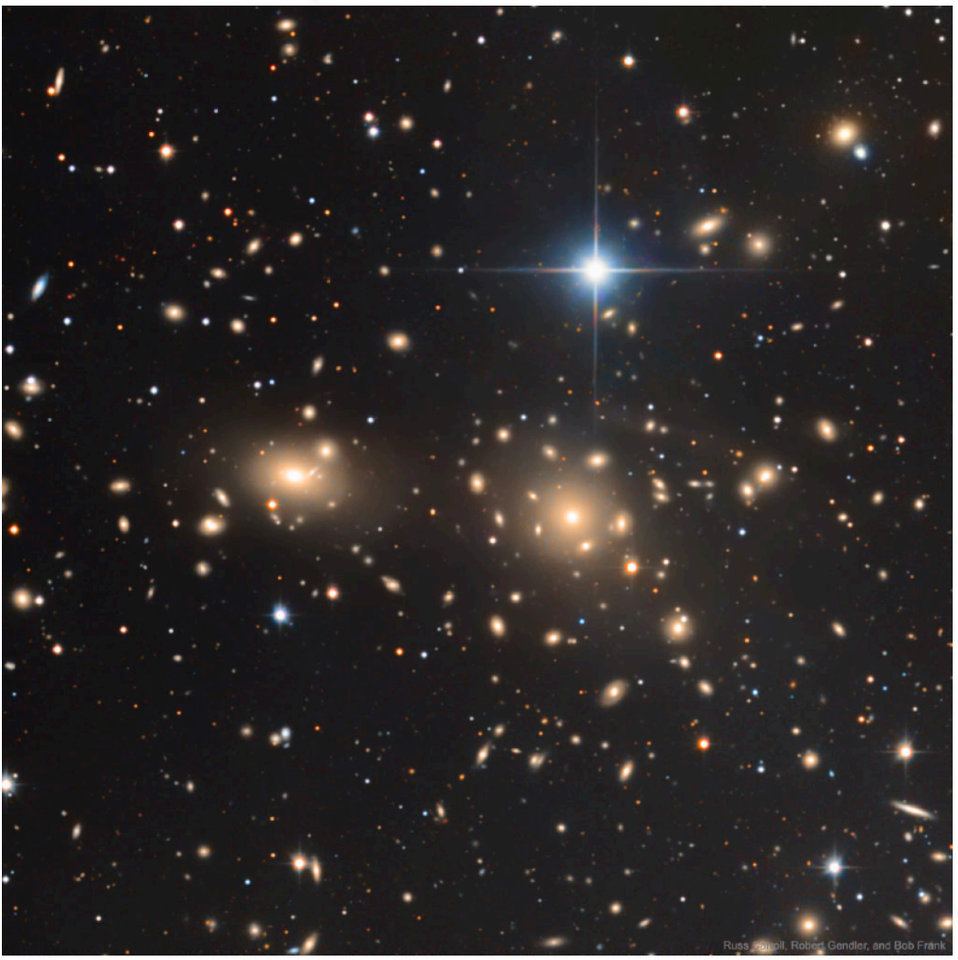
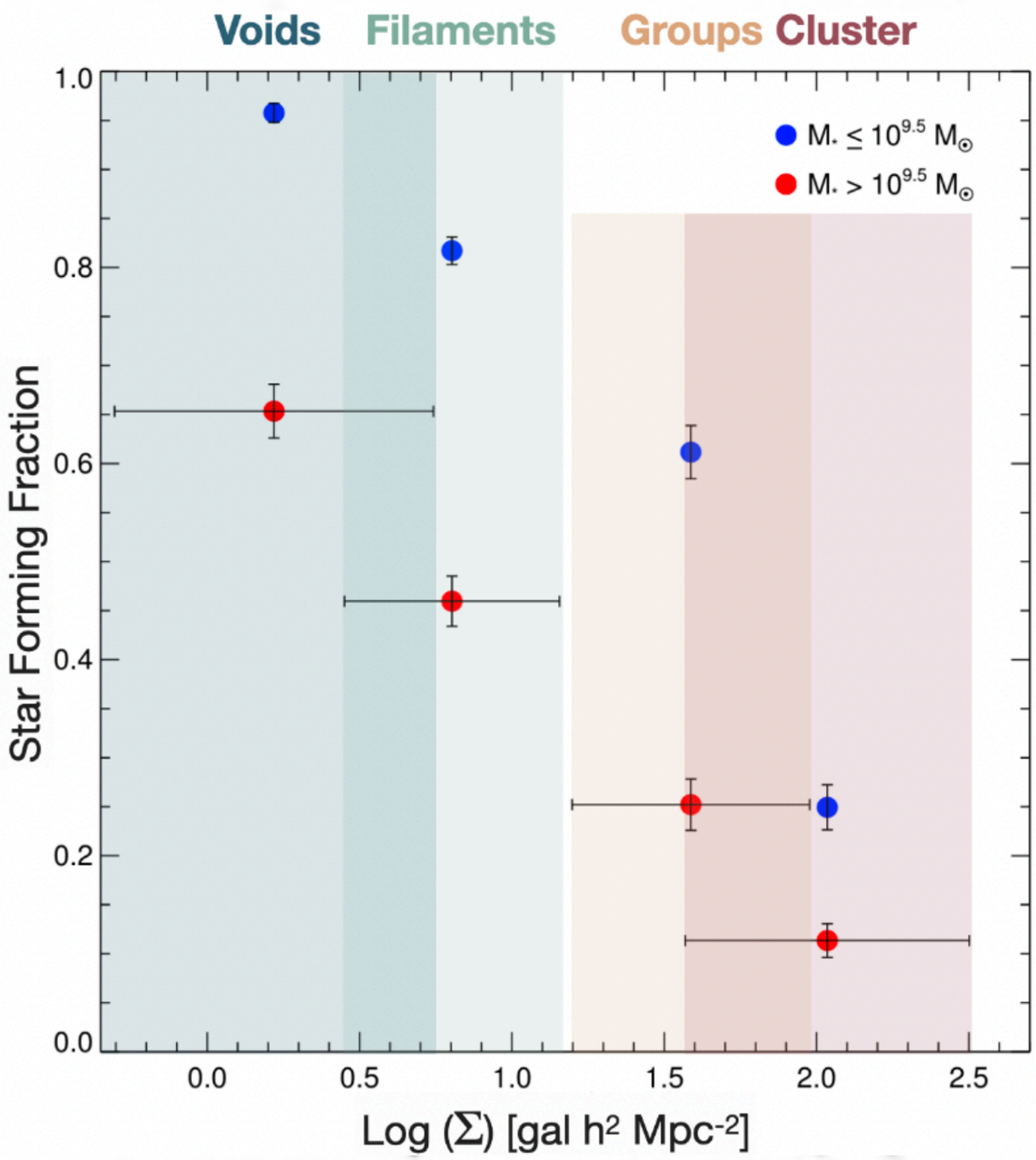
Conclusions

Massive Structures



- In the local universe, galaxy clusters with total masses $> 10^{14} M_{\odot}$ are home to the most massive galaxies known.
- Environmental processes such as ram pressure stripping of gas affect the evolution of member galaxies.

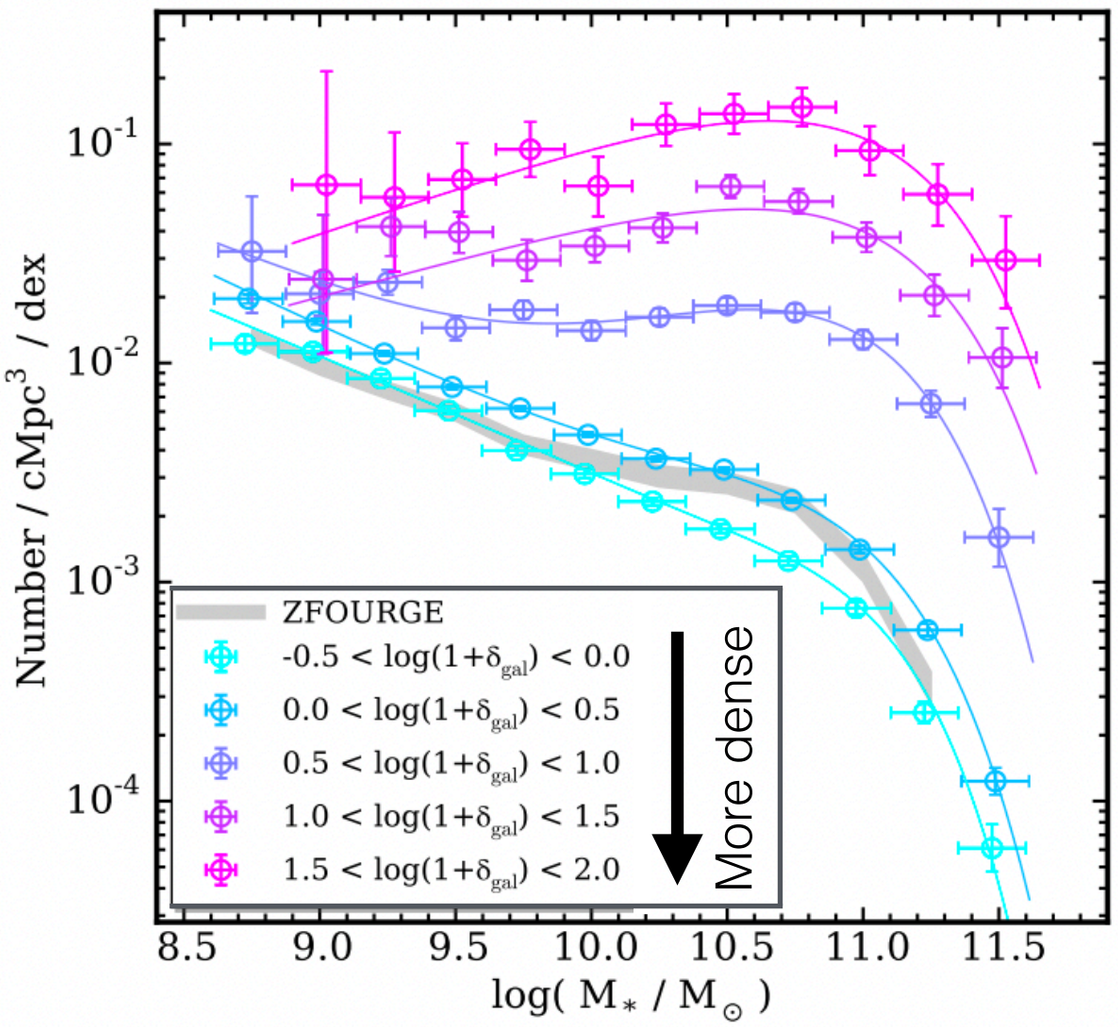
Environmental Effects on Galaxy Evolution



- **Cluster galaxies are generally more evolved than coeval field galaxies - more massive, redder, older, lower SFR, early-type morphologies, etc.**

Coma (z=0); Alberts & Noble, 2022, adapted from Cybulski+2014.

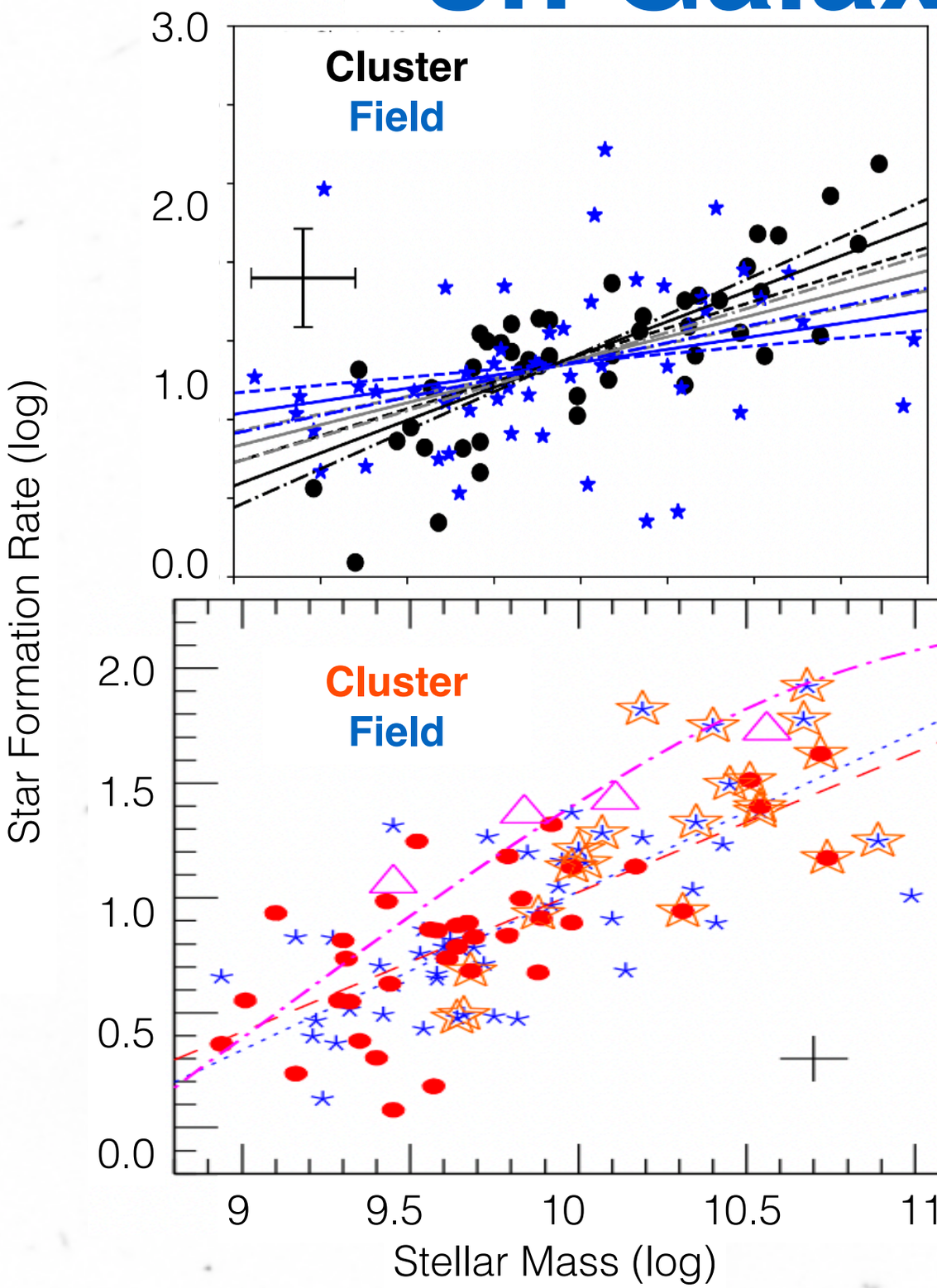
Environmental Effects on Galaxy Evolution



z~1; Tomczak+2017

- **This difference in cluster vs. field galaxy populations is seen clearly as far back as z~1 and in some cases at higher redshifts as well.**

Environmental Effects on Galaxy Evolution



- At z~1.5-2, the trend of depressed SFR in clusters disappears - cluster and field galaxies appear more similar.
- At these epochs, only some overdensities are virialized clusters, while unvirialized overdensities, termed protoclusters, are more common.

Top: z~1.6; Nantais+2016
Bottom: z~2; Tran+2017

Environmental Effects on Galaxy Evolution

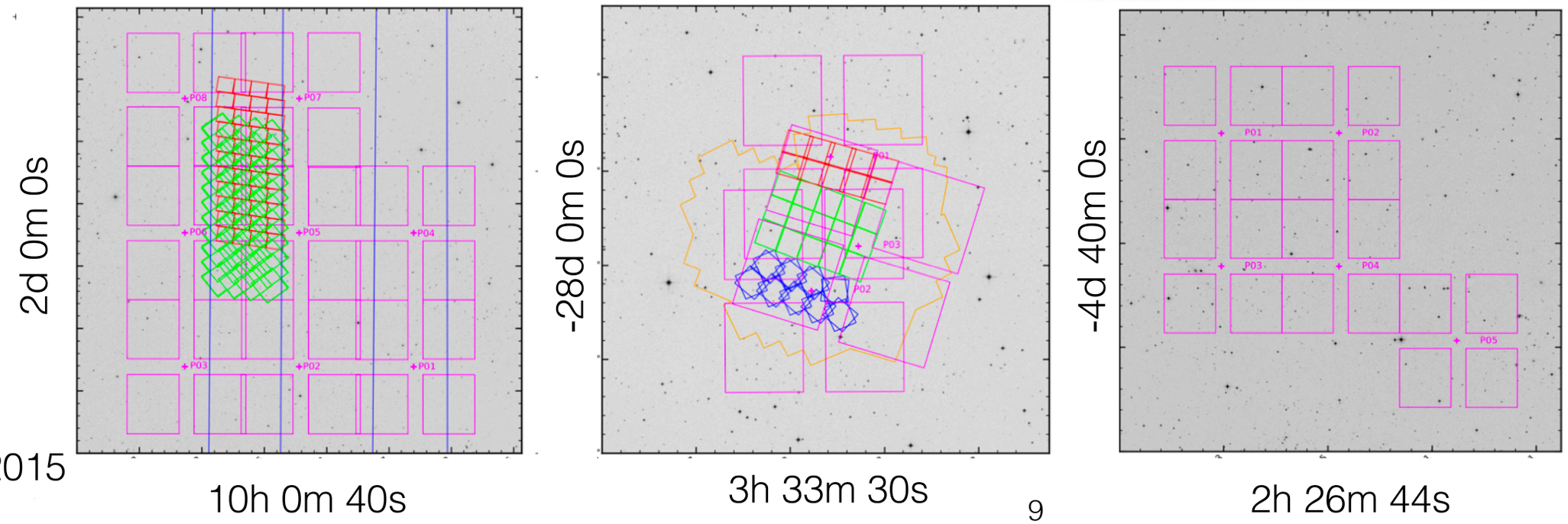
- What's happening at earlier epochs?
- When do eventual cluster galaxies form their excess stars?

Charting Cluster Construction with VUDS and ORELSE (C3VO)

- The identification of protoclusters at z>2 has only become possible with the help of photometric surveys containing deep near-IR data to identify candidate member galaxies.
- Spectroscopic follow-up of these candidates to obtain redshifts and enable characterization of members is also important to understanding the effects of environment on galaxy evolution.

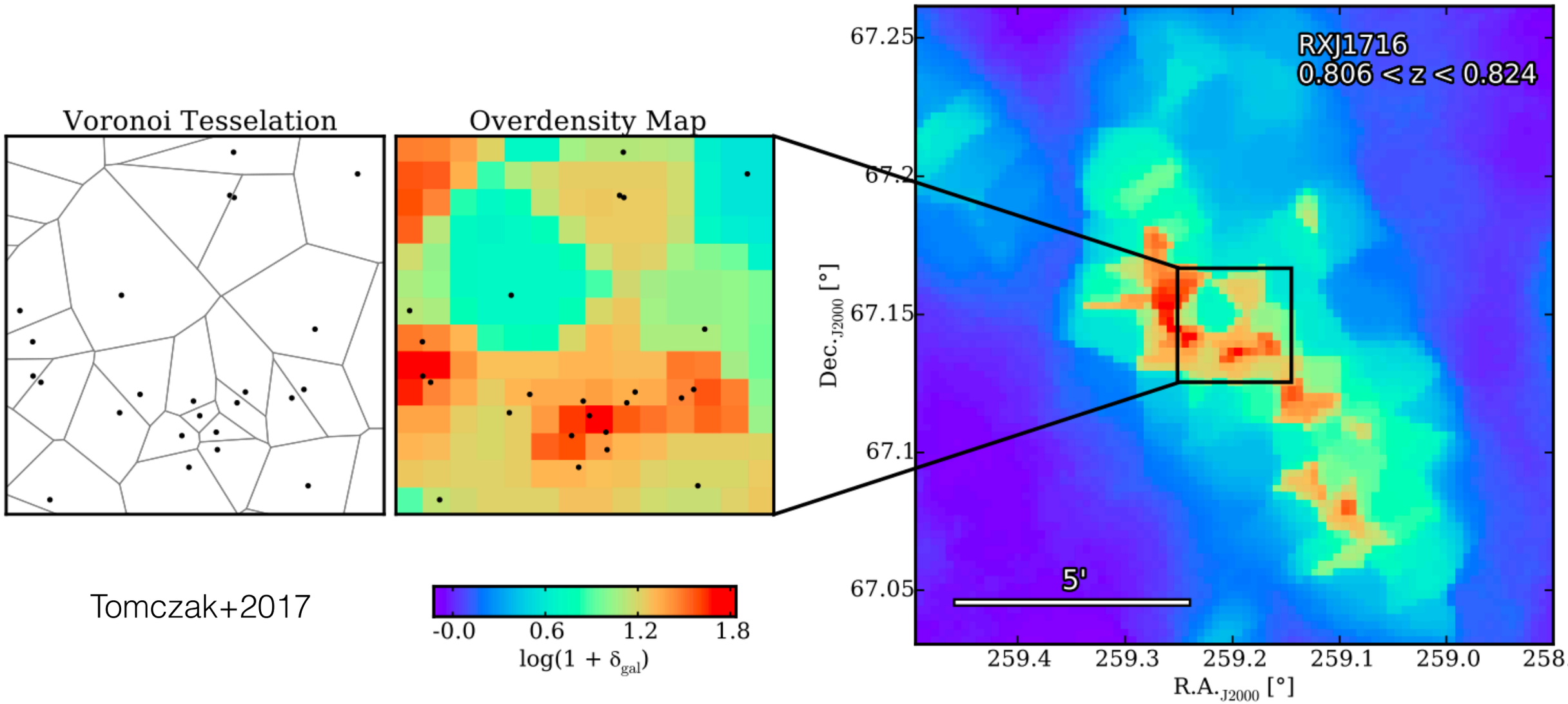
Charting Cluster Construction with VUDS and ORELSE (C3VO)

- In order to identify protocluster candidates for follow-up, the C3VO survey has used extensive observations over 3 legacy fields, COSMOS, CFHTLS, and ECDFS:
  - Multi-wavelength photometric catalogs with deep near-IR data enabling accurate photometric redshifts.
  - Extensive spectroscopic observations from surveys such as VUDS
- Follow-up performed with Keck/DEIMOS and Keck/MOSFIRE



Le Fèvre+2015

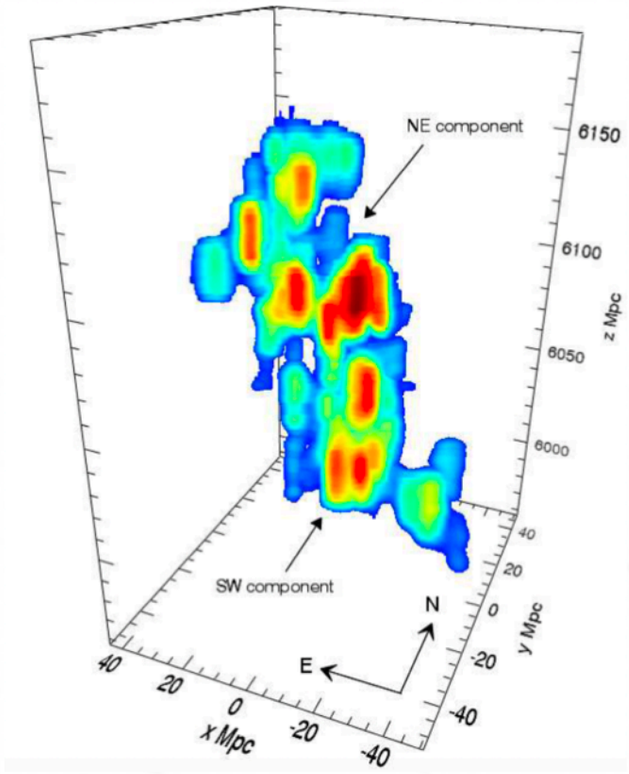
Voronoi Monte Carlo (VMC) Map Construction



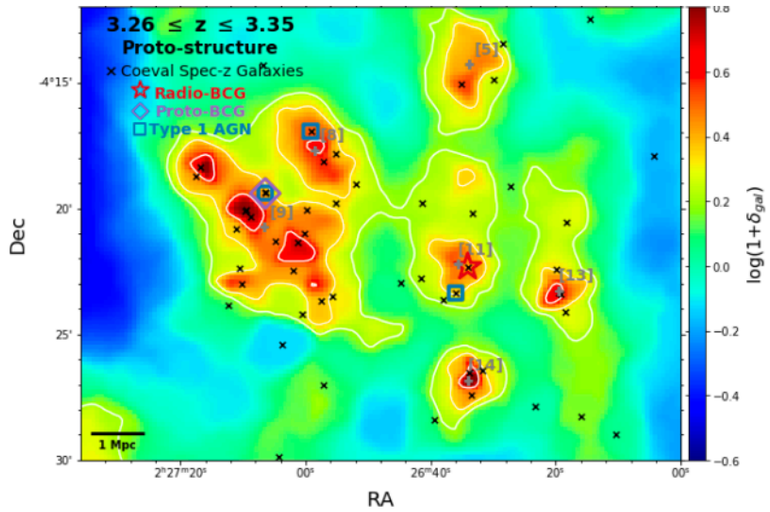
Tomczak+2017

Charting Cluster Construction with VUDS and ORELSE (C3VO)

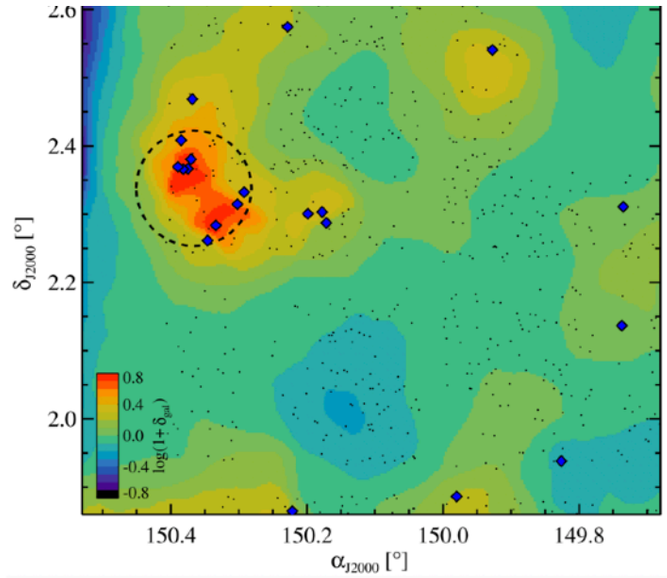
z~2.45 COSMOS; 'Hyperion', Cucciati+2018



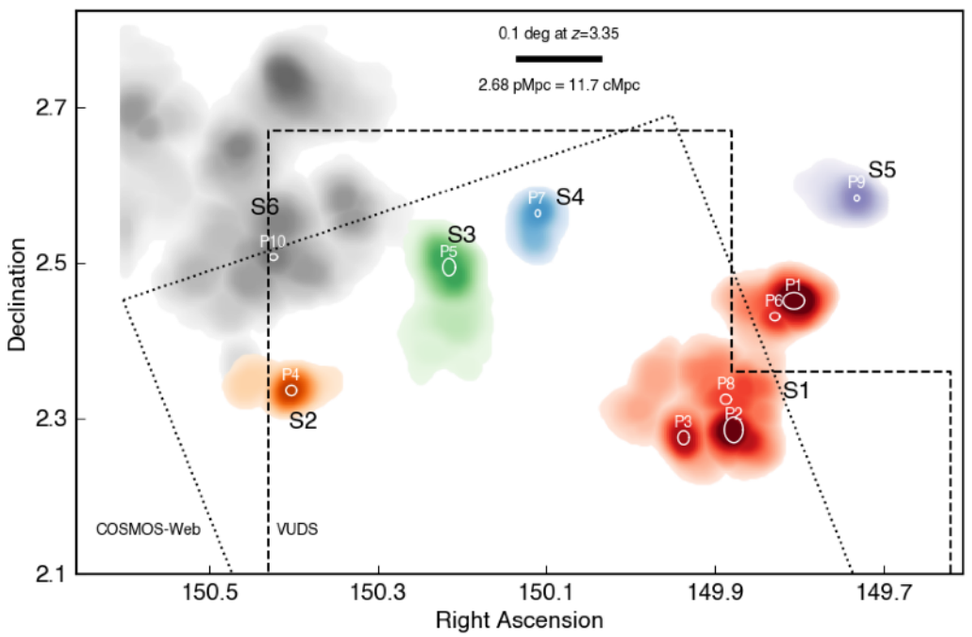
z~3.3 CFHTLS/XMM-LSS; Lemaux+2014, Shen+2021



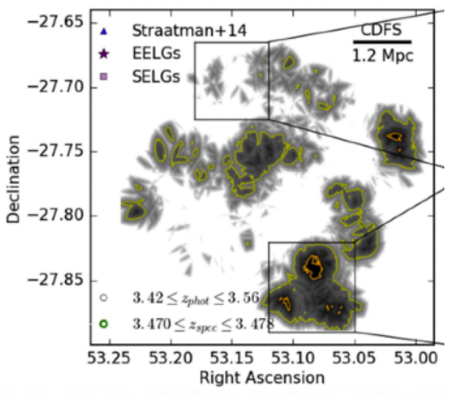
z~4.55 COSMOS; Lemaux+2018, Staab+, in prep.

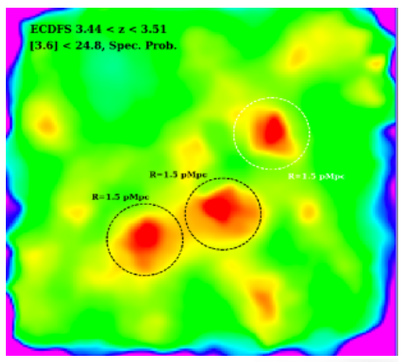


z~3.3 COSMOS; McConachie+2022, Forrest+2023

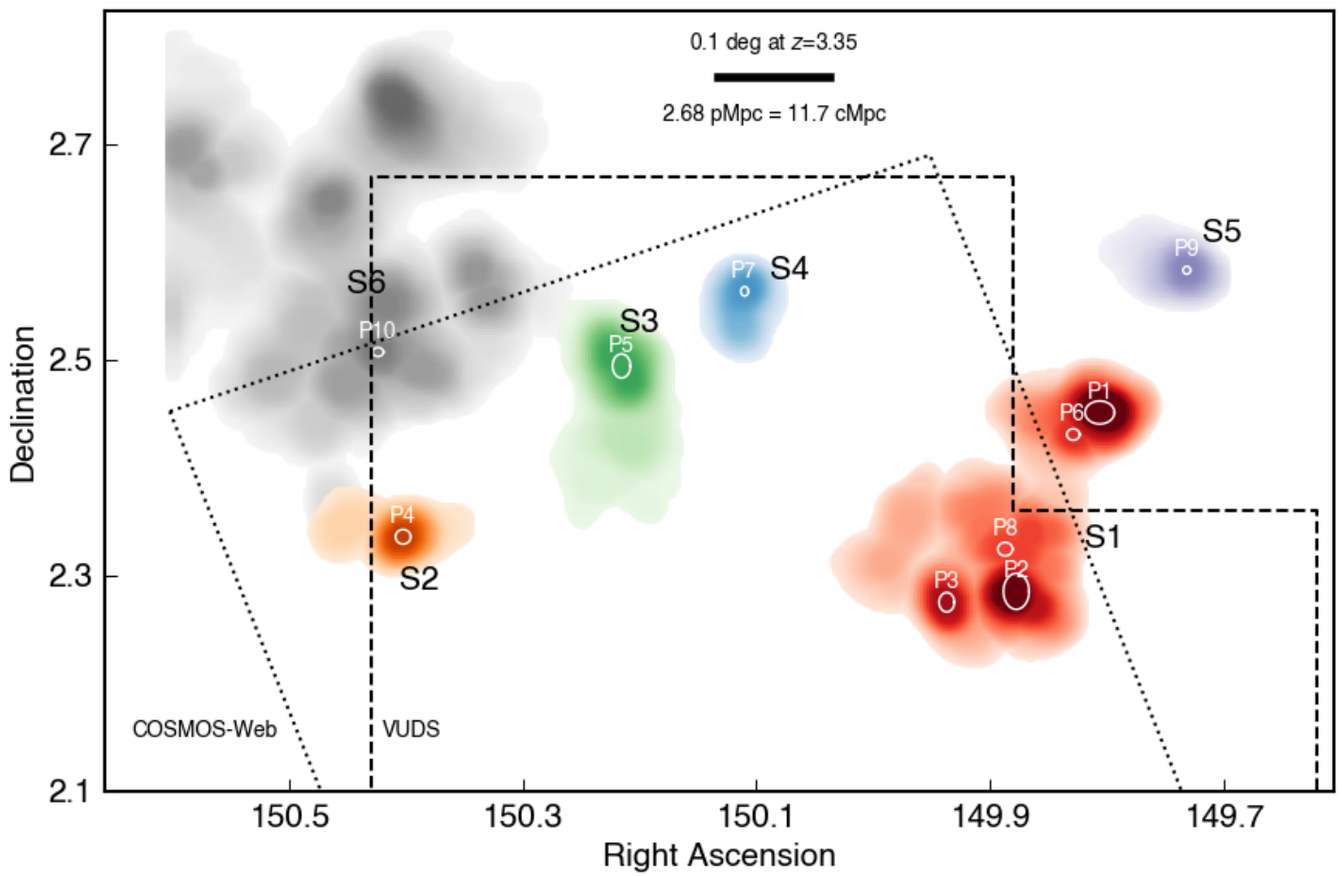


z~3.5 ECDFS, Forrest+2017, Shah+, in prep





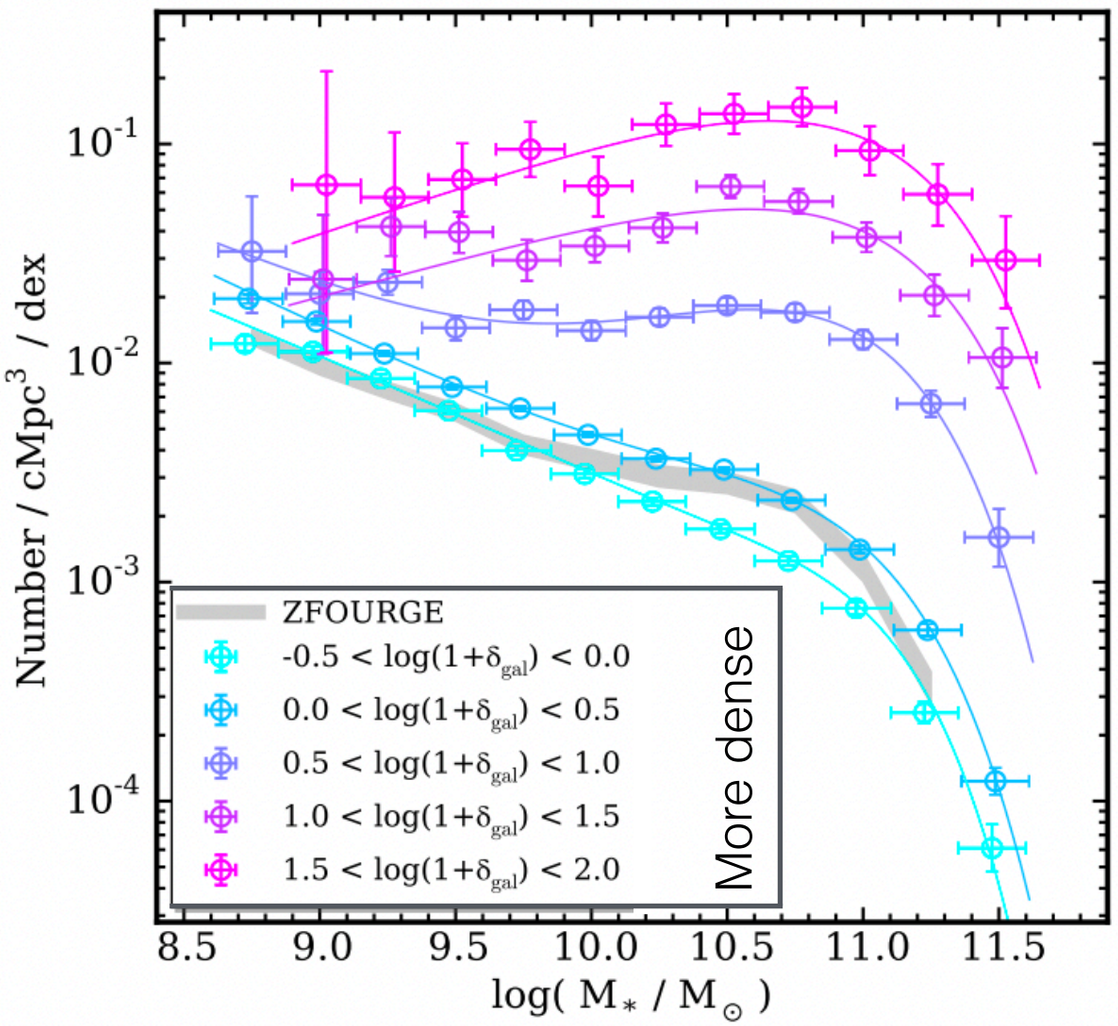
Elentári



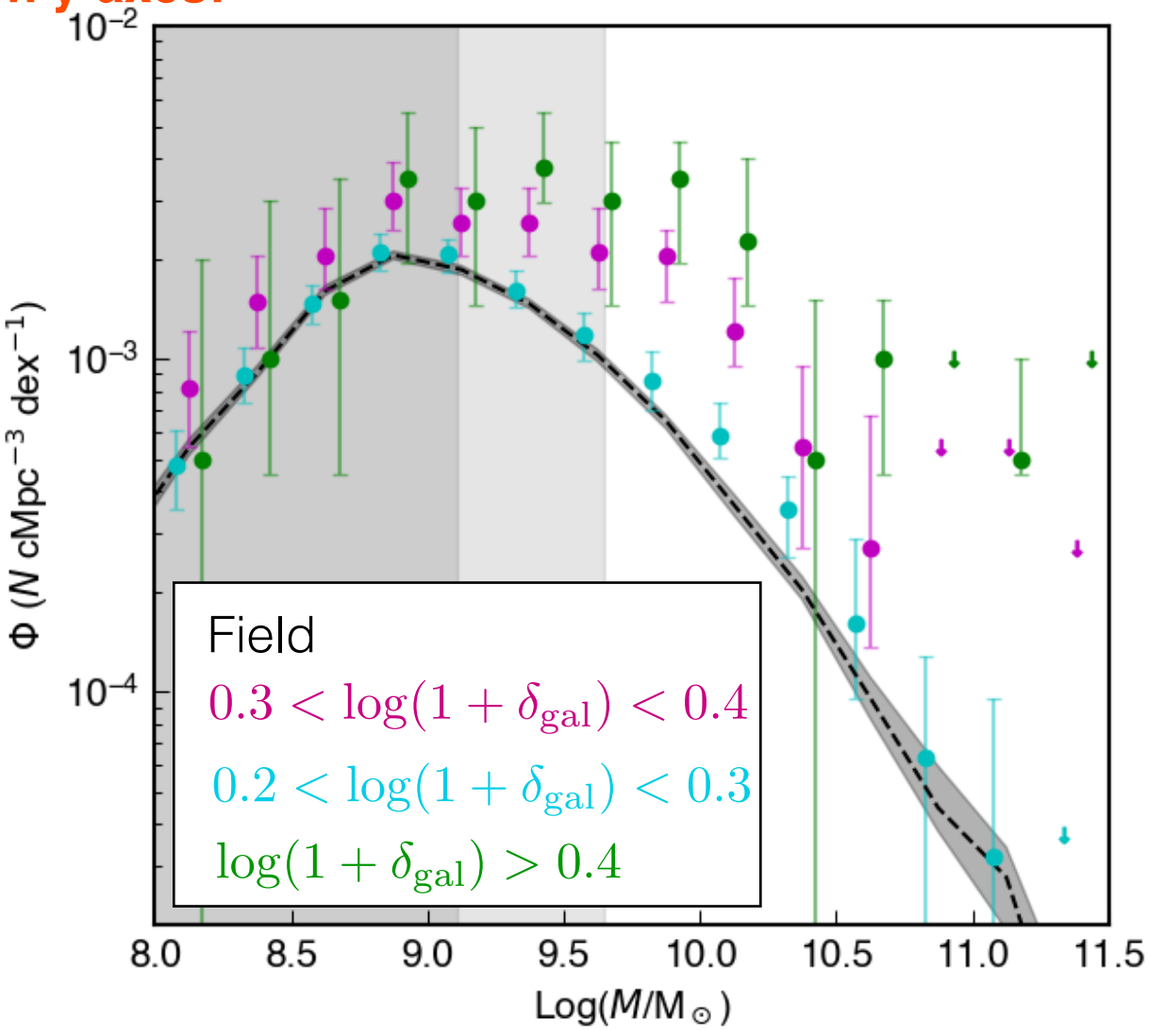
- **Independently identified by MAGAZ3NE and C3VO.**
- **VMC maps show 6 structures of >2σ overdensity containing 10 peaks of >5σ.**
- **Over 100 spec-z's!!**
- **Modeling suggests virtualization by z~1.5 and a total mass of 1.4×10^{15} solar masses.**

Elentári

Different scales on y-axes!



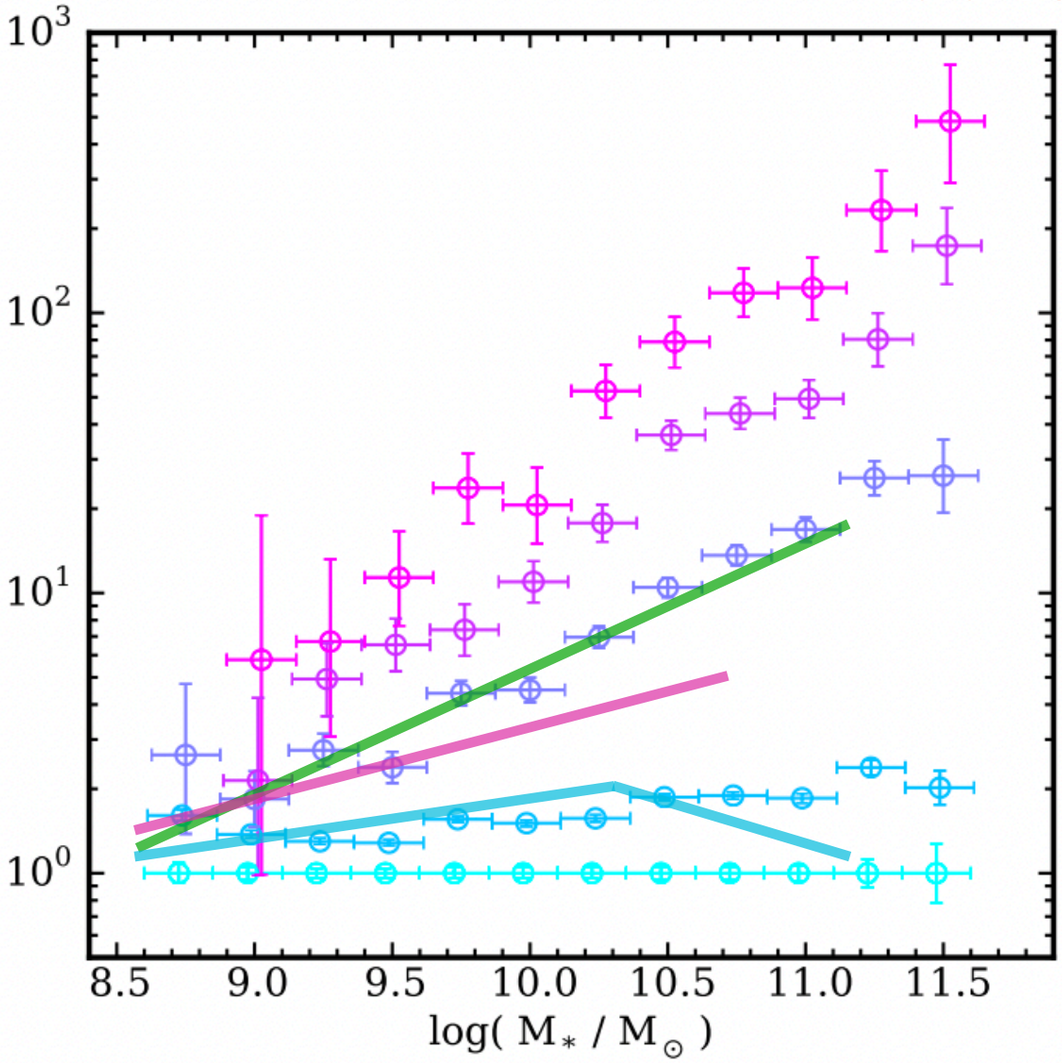
z~1; Tomczak+2017



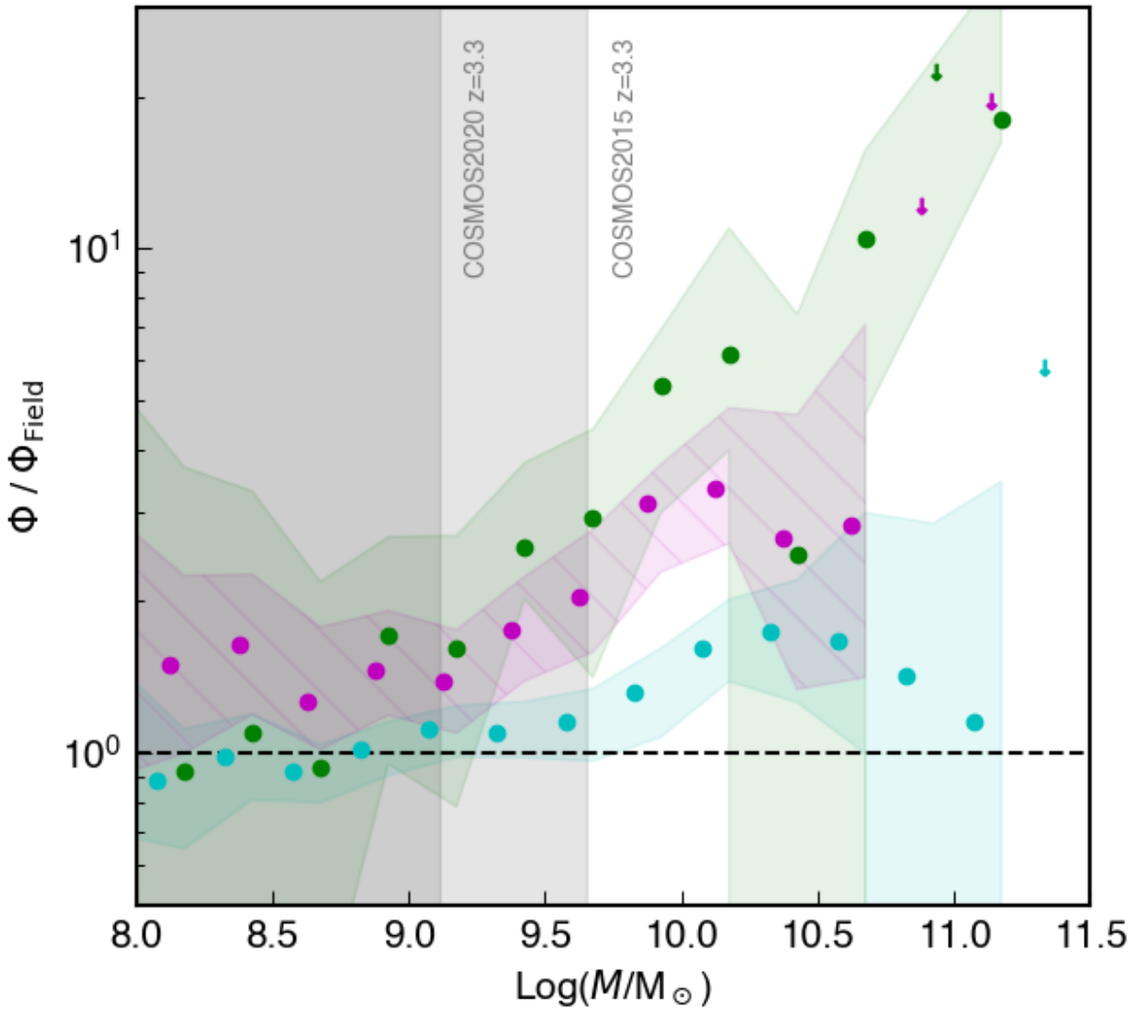
z~3.3; Forrest+2023

Elentári

Different scales on y-axes!

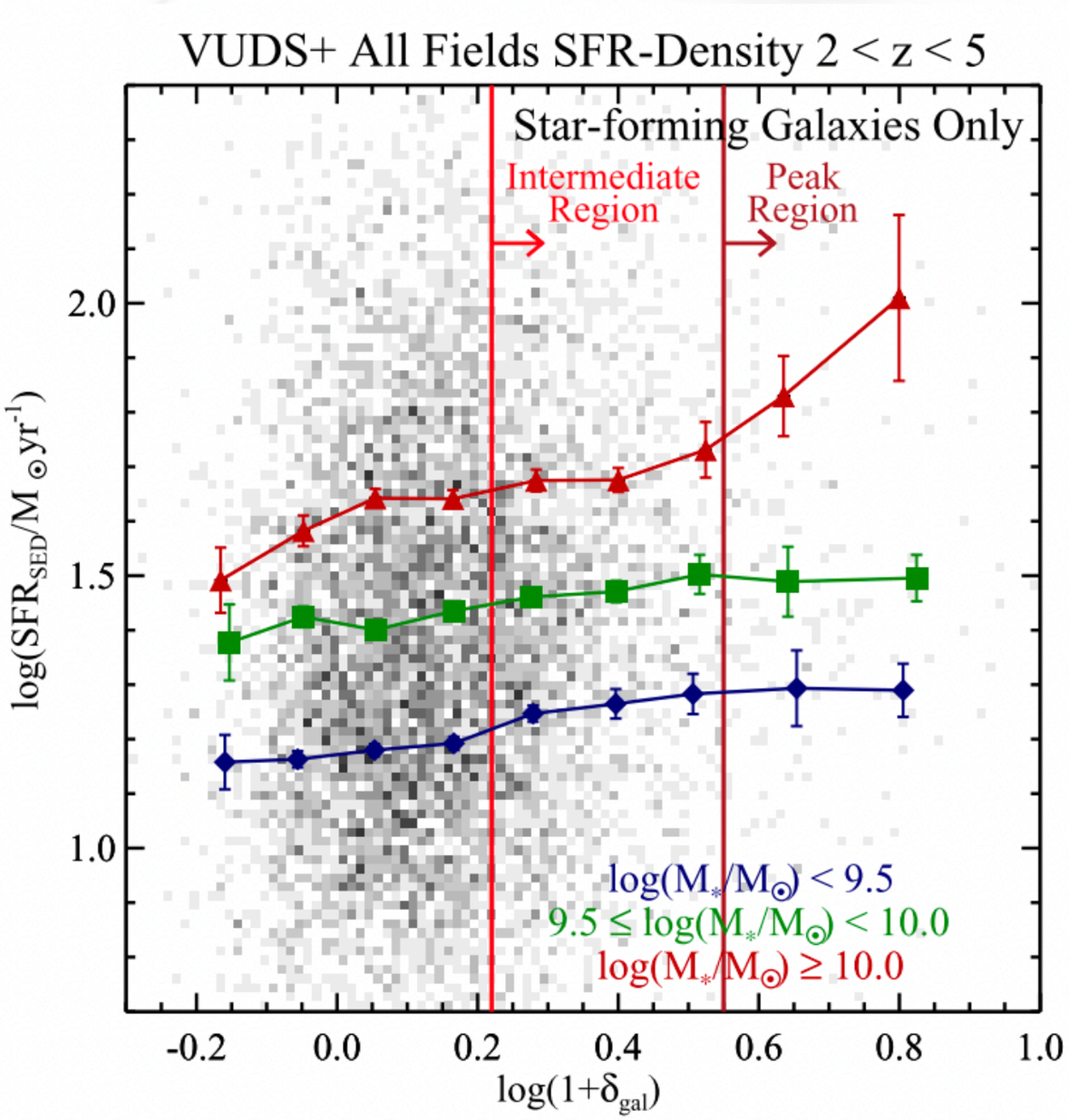


z~1; Tomczak+2017



z~3.3; Forrest+2023

Environmental Effects on Galaxy Evolution



Lemaux+2022

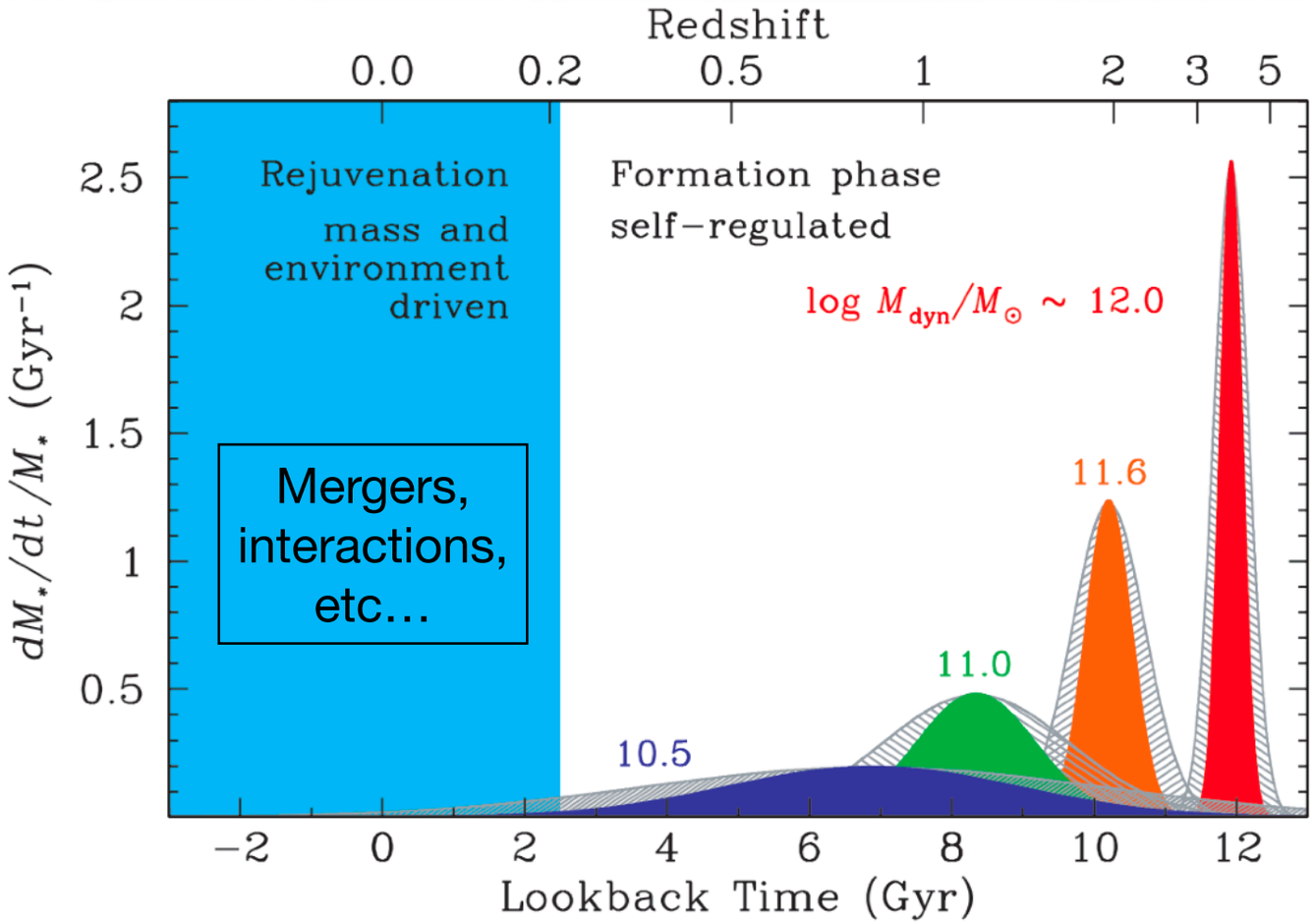
- At 2<z<5, there are fewer quiescent galaxies in general and galaxies in protoclusters are sometimes forming stars at *higher* rates than coeval field galaxies.
- SFR seems to increase with environmental density, particularly for massive galaxies.

Massive Structures - Conclusions

- **Identification of massive structures is possible without targeted spectroscopic follow-up.**
- **Spectroscopic follow-up is necessary for characterizing systems and uncovering the effects of environment on galaxy evolution.**

Questions so far?

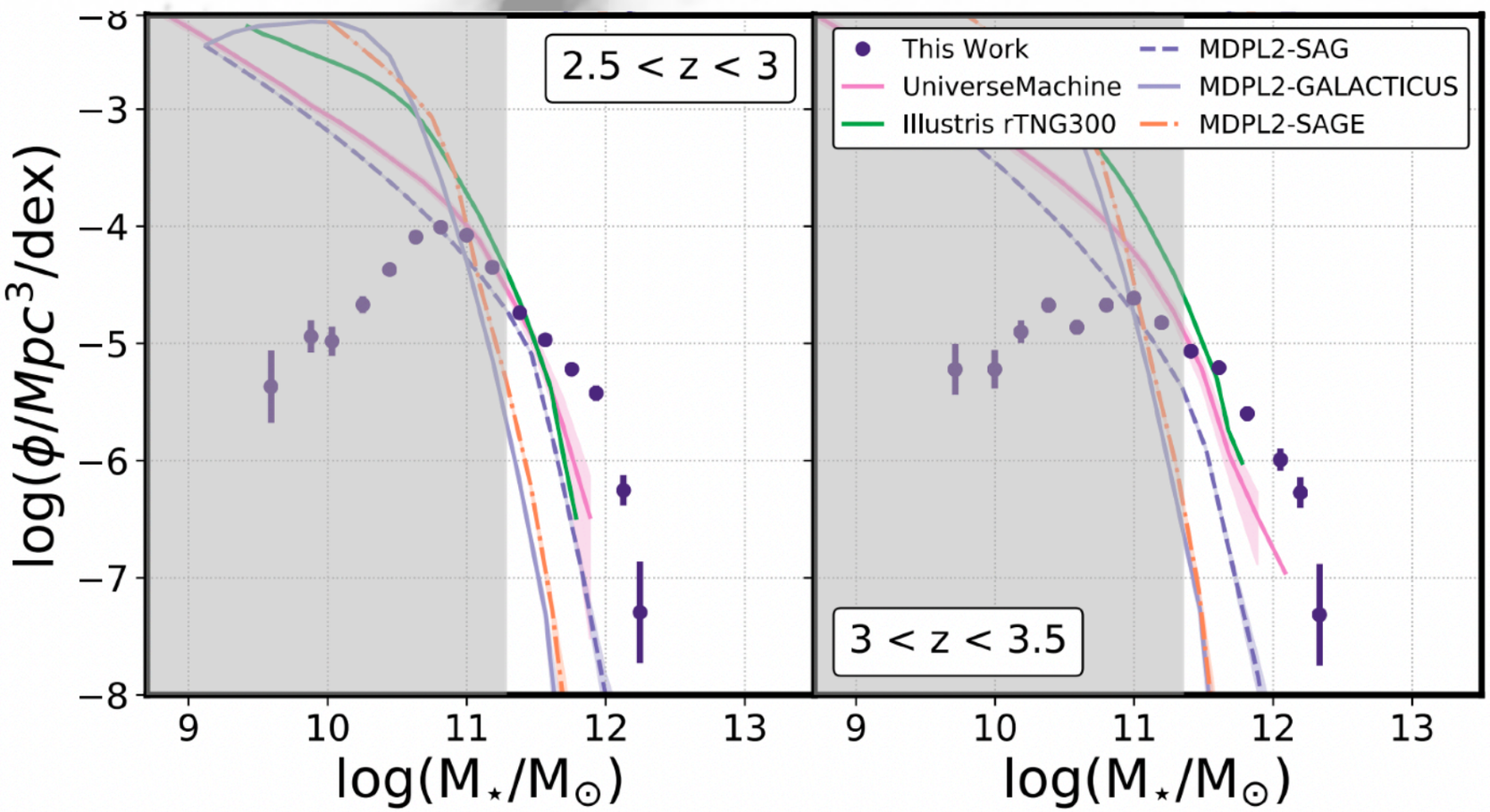
Massive Galaxies



Thomas+2005,2010

- In the local universe, galaxy clusters are home to the most massive galaxies known, with stellar masses $\sim 10^{12} M_\odot$.
- These brightest cluster galaxies (BCGs) are early-type ellipticals with practically no ongoing star formation.
- The cores of these galaxies in particular are extremely old.

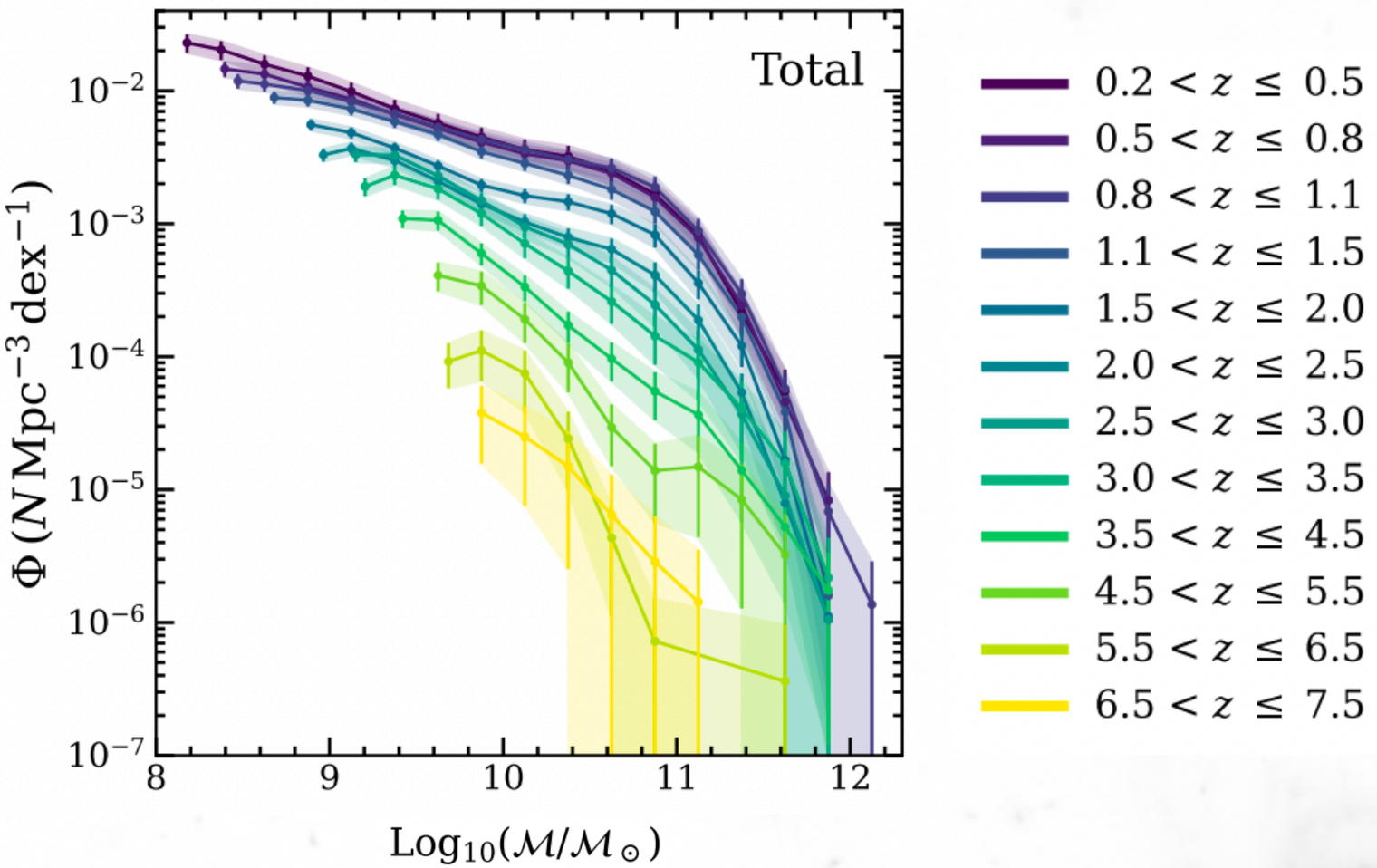
Massive Galaxies



Sherman+2020

- **There is a discrepancy between the high mass end of the SMF from observations and simulations of 2-10x.**
- **Photometric identification of galaxies as massive as today's BCGs at z>3 challenge simulations.**

Massive Galaxies



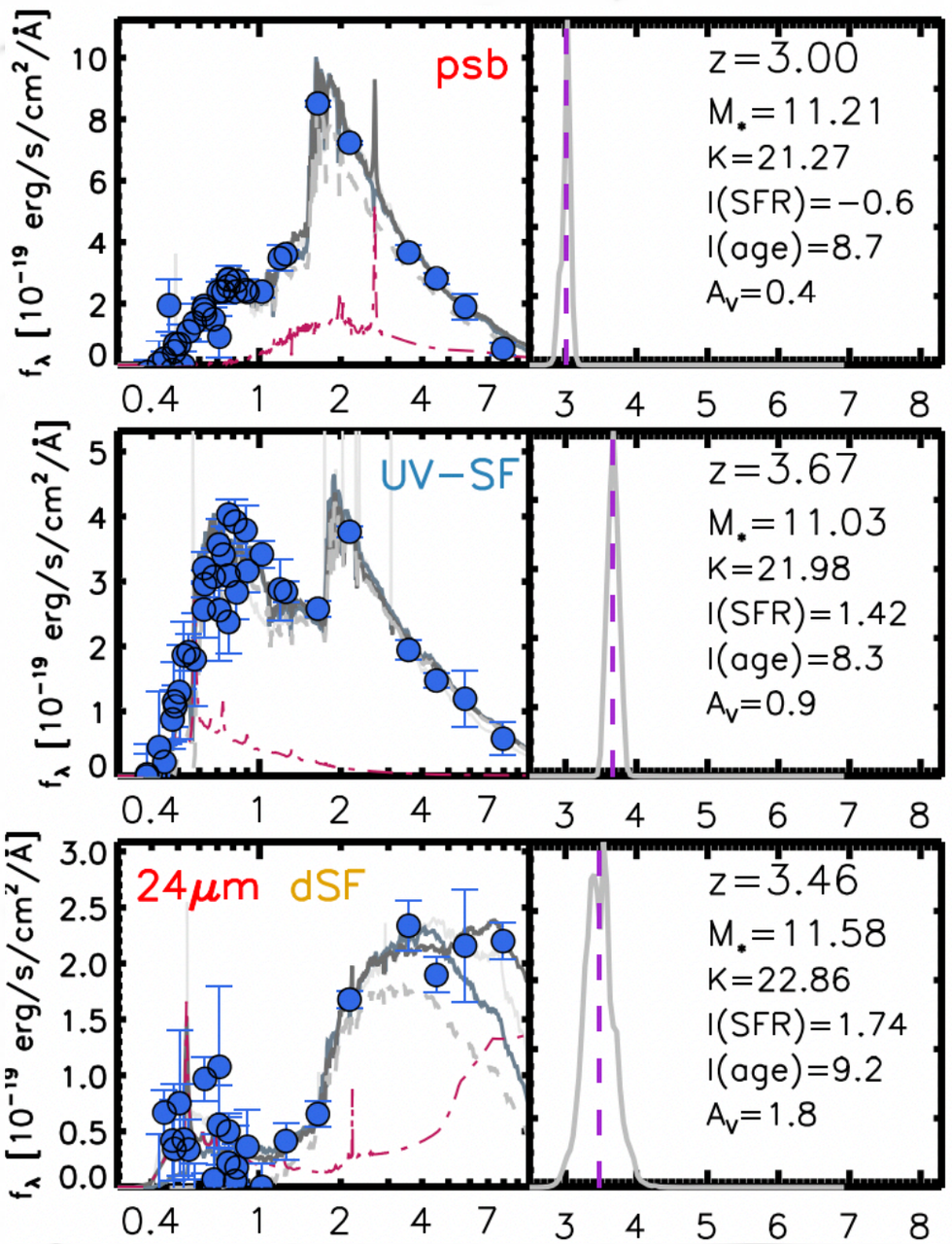
Weaver+2023

- **Photometric observations show little to no change in the number densities of these massive galaxies over the last 10 Gyr.**

Massive Galaxies

- Do such massive galaxies exist at early times?
- Do photometric catalogs yield accurate number densities?
- Are any of these galaxies quiescent?
- What environments do these objects exist in?

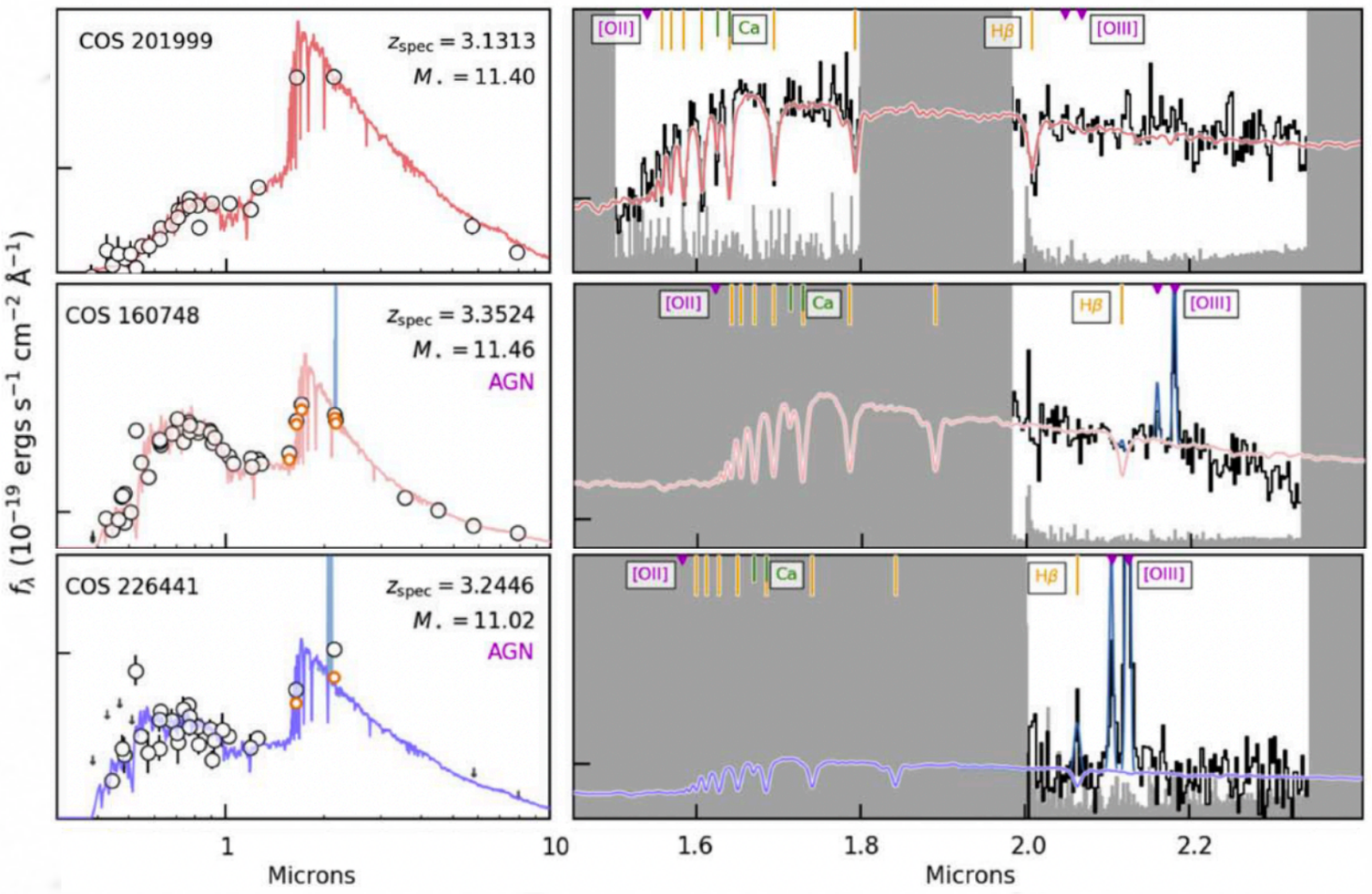
The Massive Ancient Galaxies at z>3 Near-Infrared Survey (MAGAZ3NE)



- **Selected sources from photometric catalogs with deep near-IR data in the COSMOS (UltraVISTA DR3, S-COSMOS, SPLASH, SMUVS) and XMM-LSS (VIDEO, SERVS, DeepDrill) fields.**
- **Up to 50 bandpasses from 0.3-8μm allow for high quality photometric redshifts and SED fitting.**

Marsan+2022

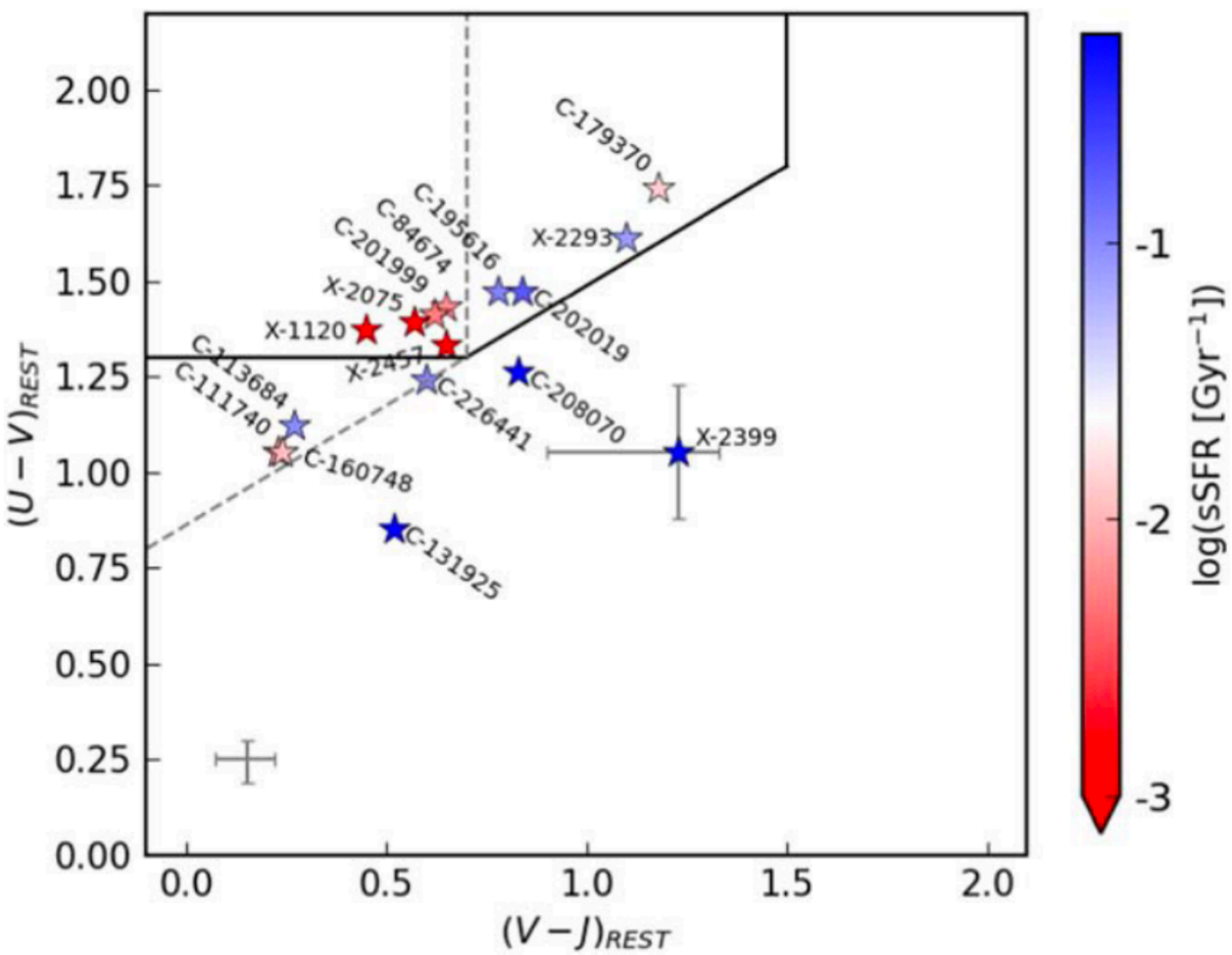
Massive Galaxies

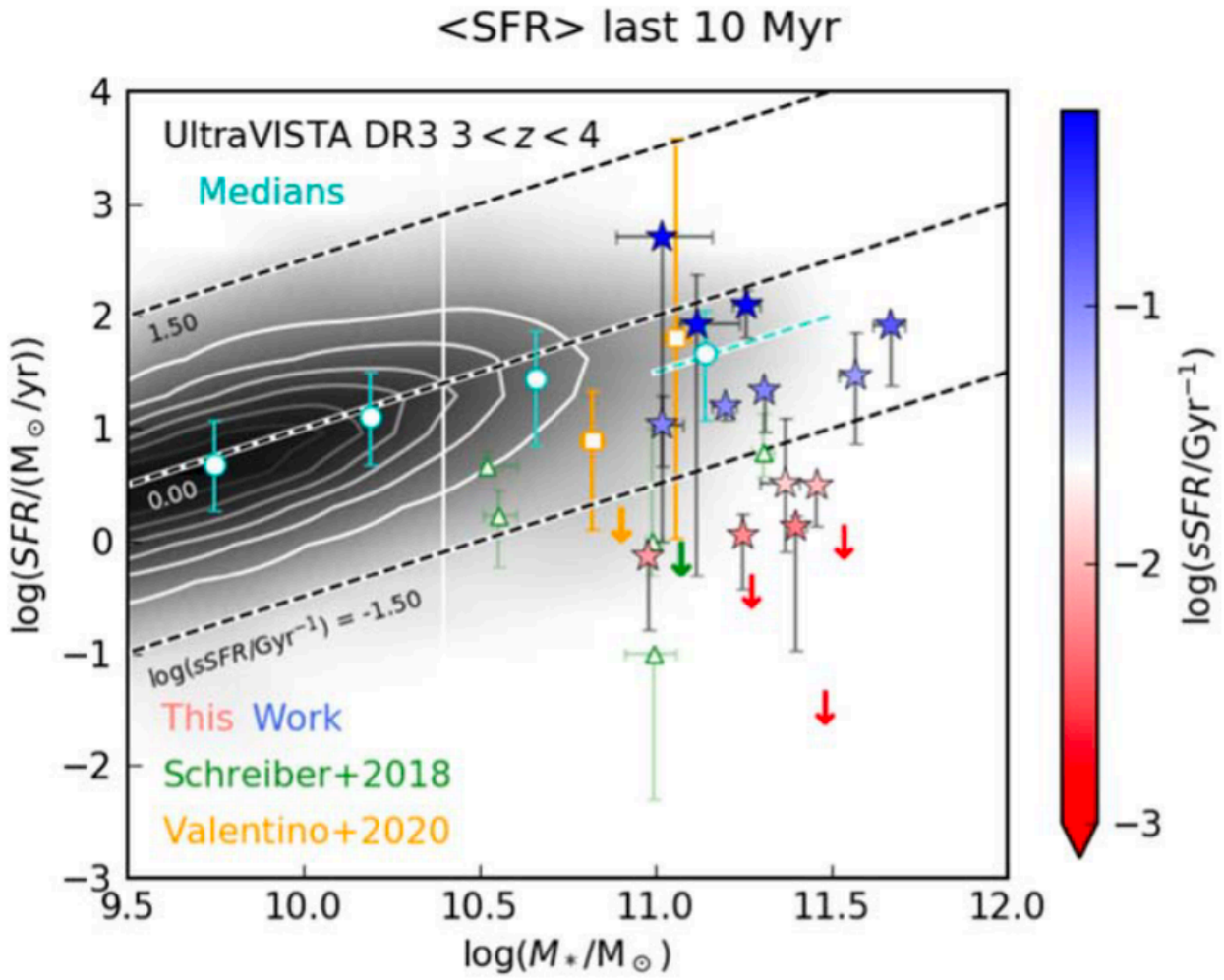


- **Sample of 16 UMGs with spec-z, largest to date.**
- **Several ‘young’ quiescent, post-starburst galaxies**

Forrest+2020b

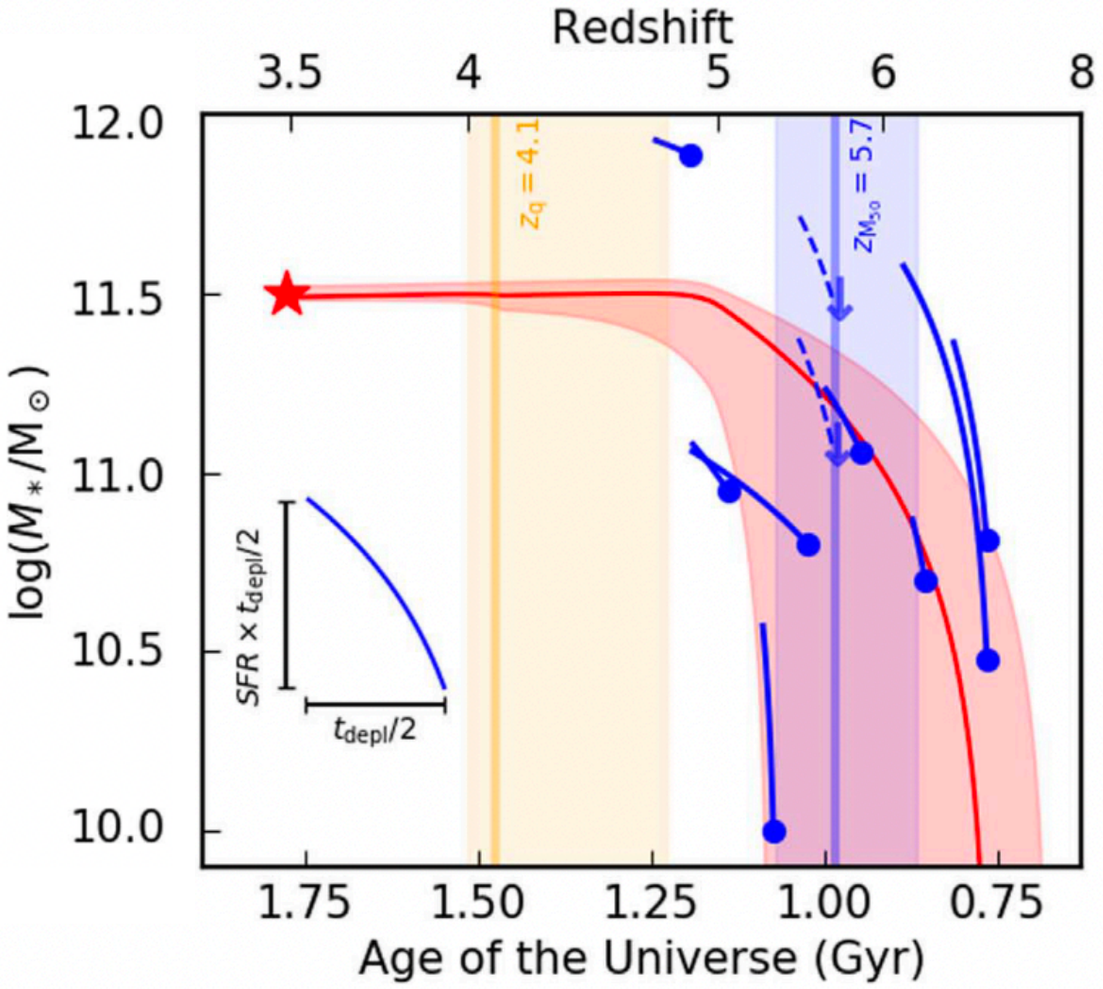
Massive Galaxies





Forrest+2020b

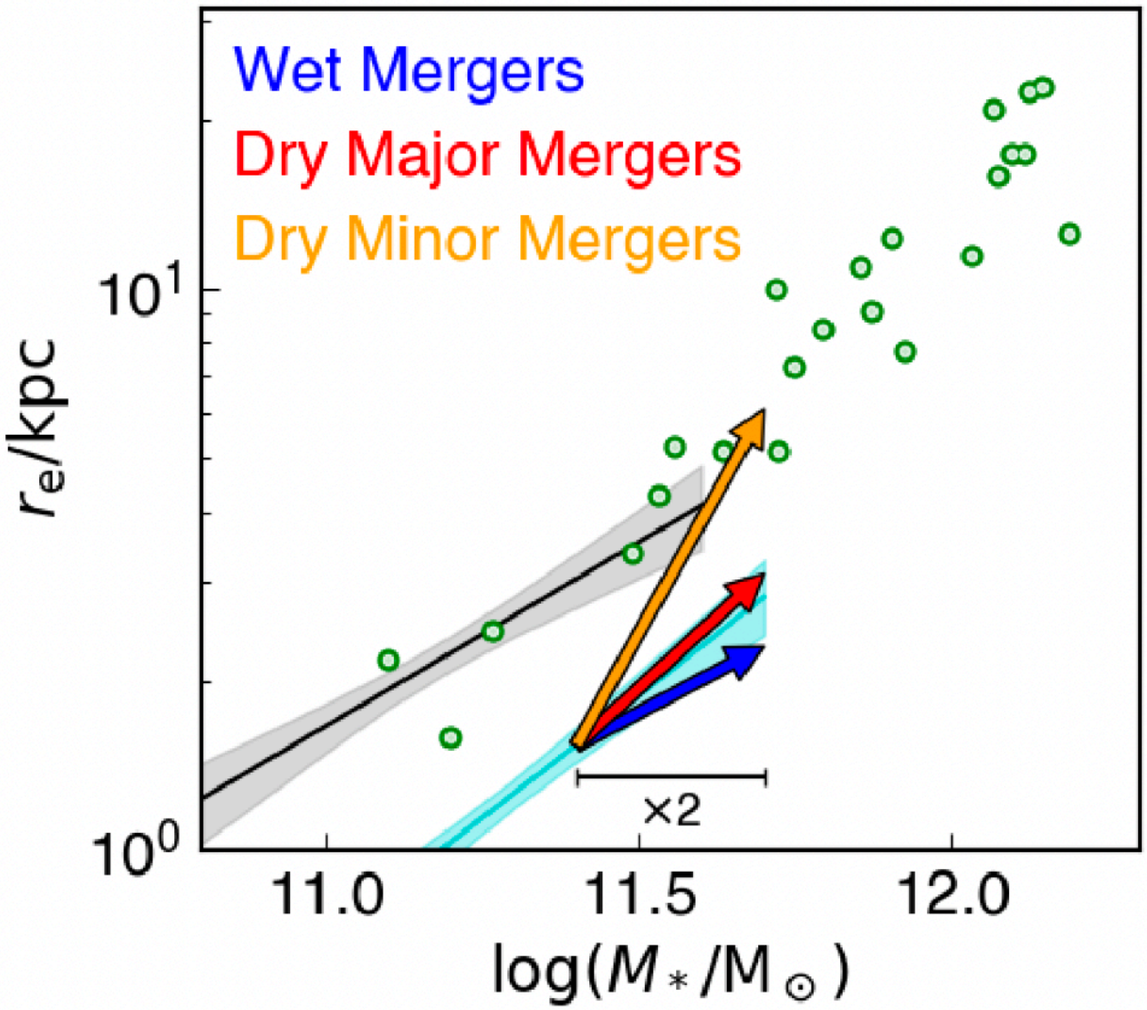
Massive Galaxies - Progenitors



- **Modeling of SFH suggests these objects may be descendants of high redshift massive DSFGs.**

Forrest+2020a

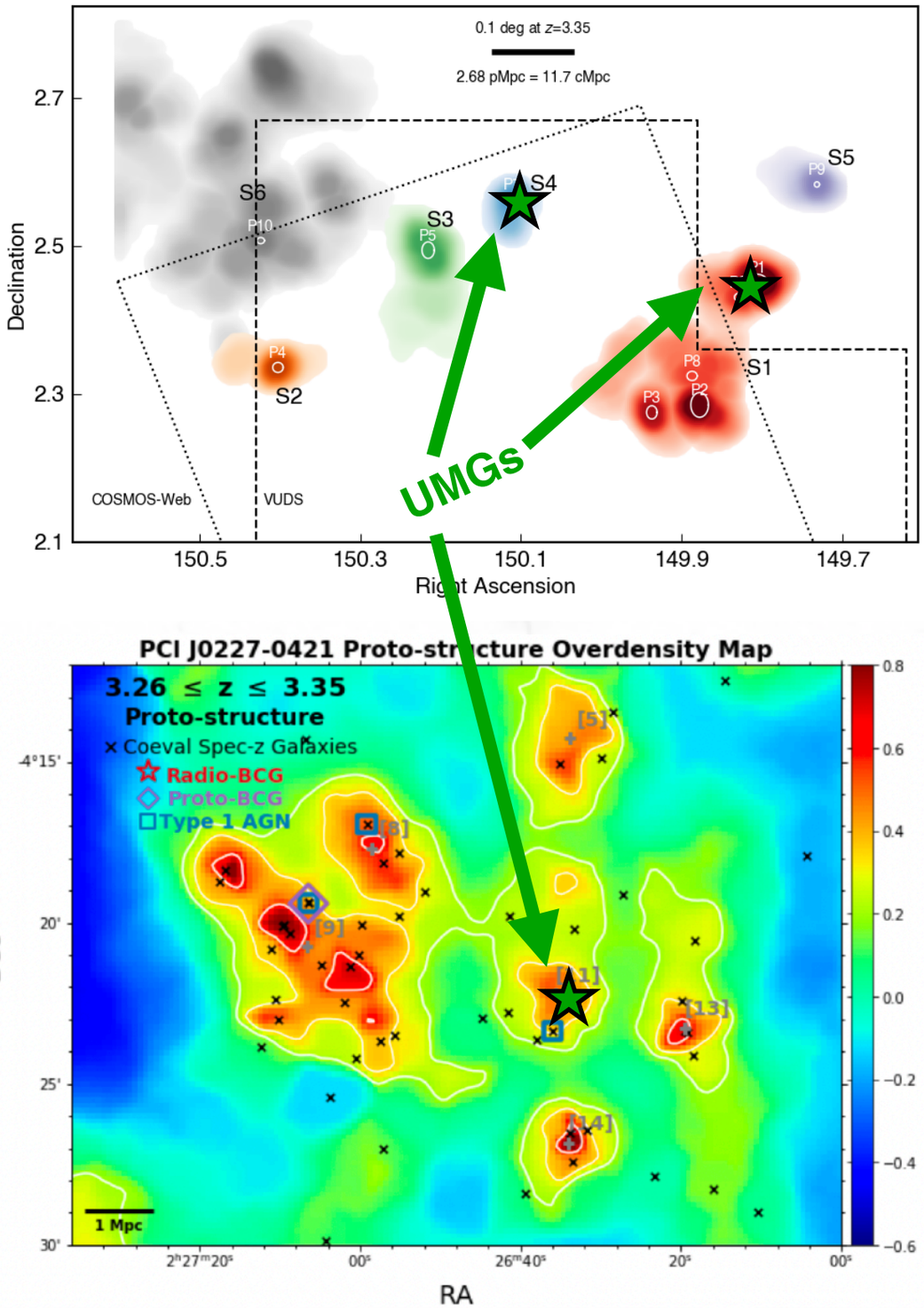
Massive Galaxies - Descendants



- In order for UMGs to evolve into the cores of modern-day BCGs, they must add some stellar mass while multiplying several times in size.
- Mergers are the likely pathway by which this would happen.

Forrest+2022

Massive Galaxies - Environments

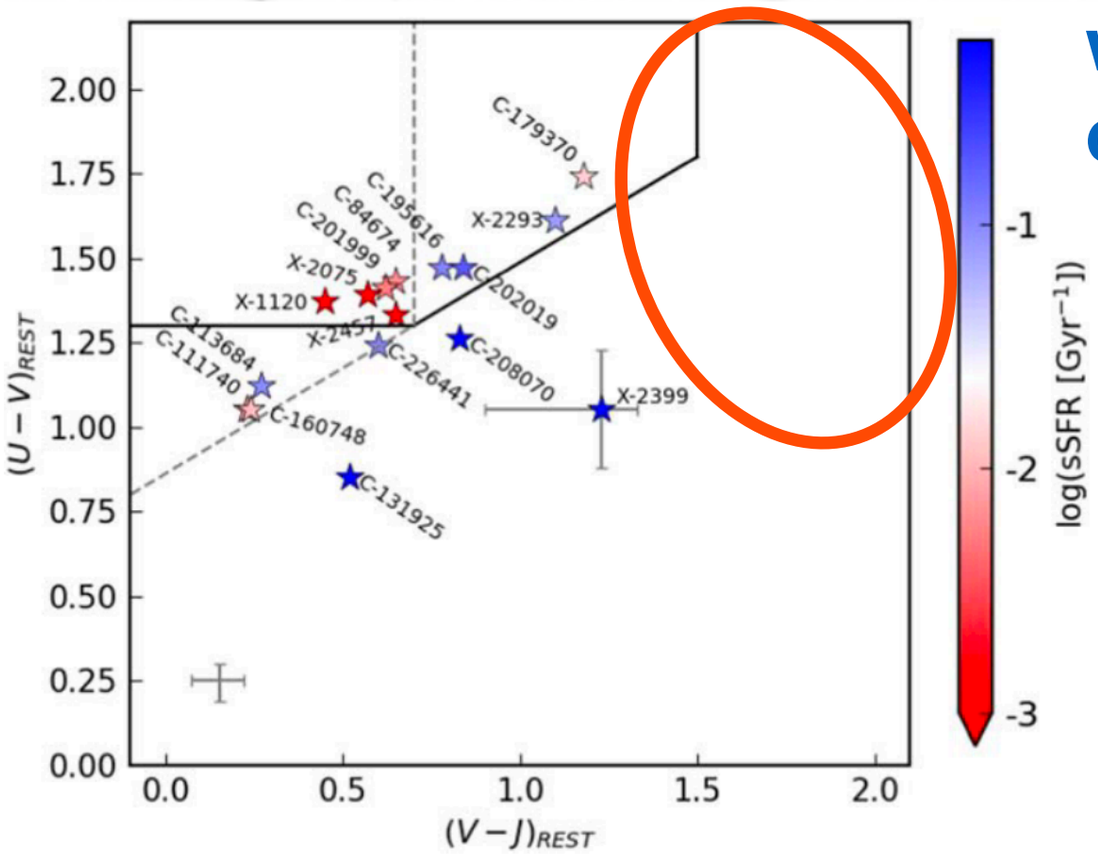


- **Four UMGs are in spectroscopically confirmed overdensities (Shen+2021, McConachie+2022, in prep, Forrest+2023).**
- **Several others have spectroscopically confirmed neighbors**
- **With VMC maps from C3VO an exploration of the environments of the complete sample is possible.**

Questions so far?

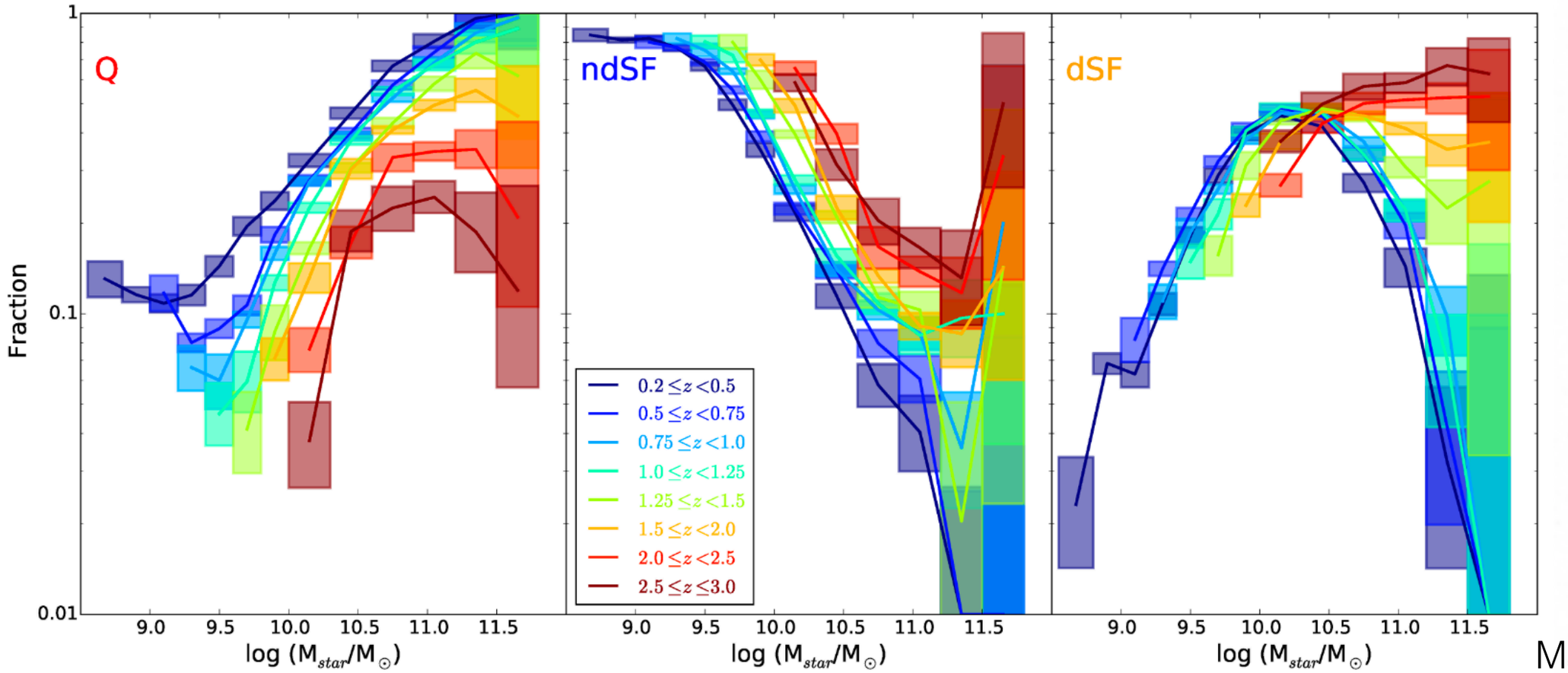
BUT!!!

BUT!!!



- **UMGs spectroscopically targeted were selected for their probability of successful redshift confirmation.**
- **Blue SFGs likely to have strong rest-frame optical emission lines**
- **Post-starburst galaxies with deep Balmer absorption features.**
- **Other, very red galaxies have not been systematically probed… until now.**

Red UMGs

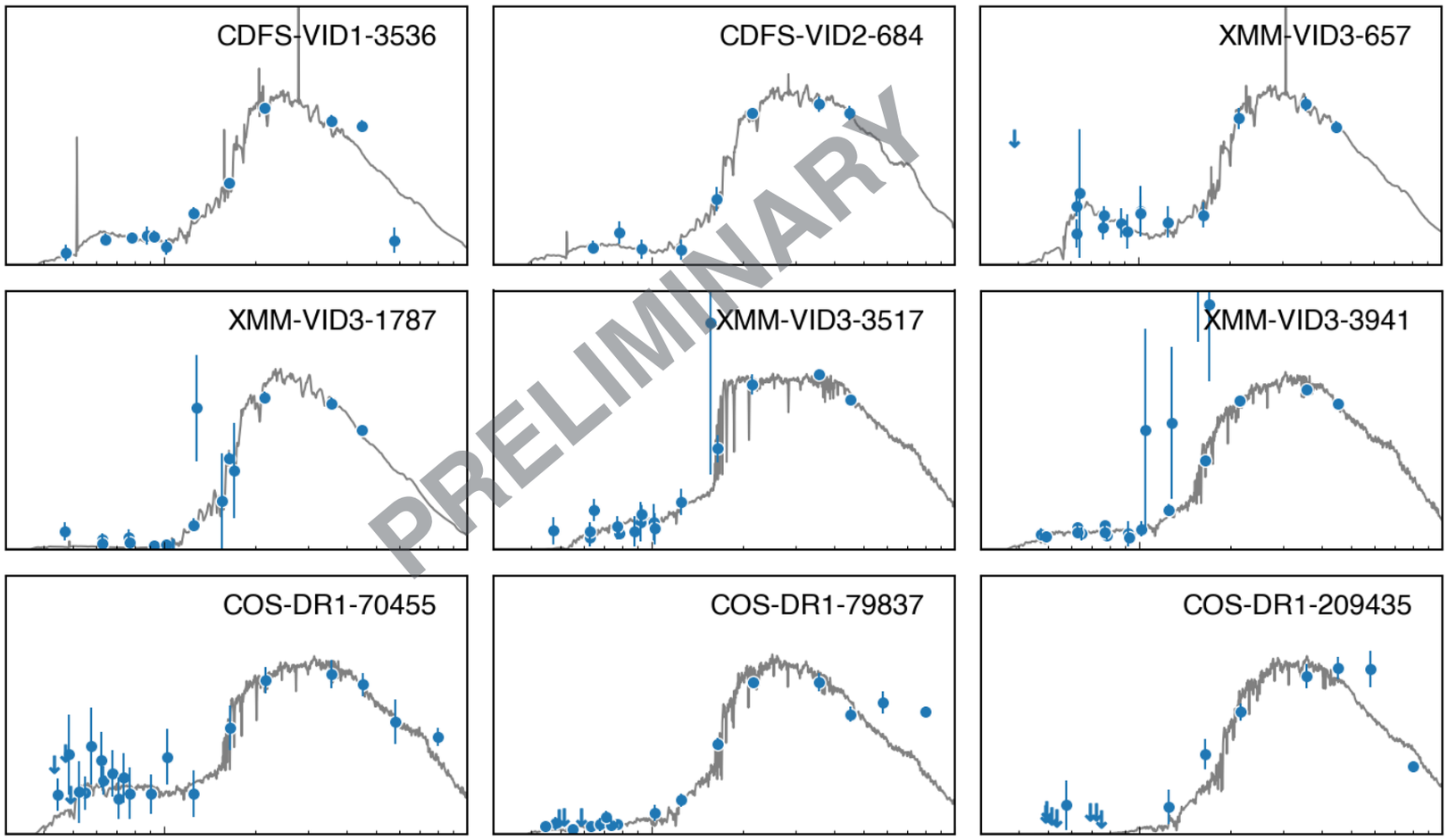


Martis+2016

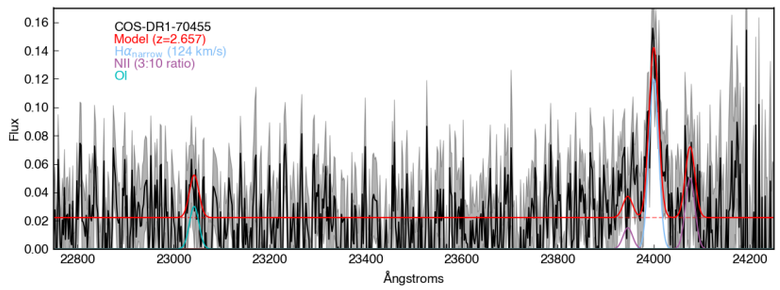
- **These red galaxies are important to confirm, as they make up a large portion of massive galaxies at early times according to photometric surveys.**

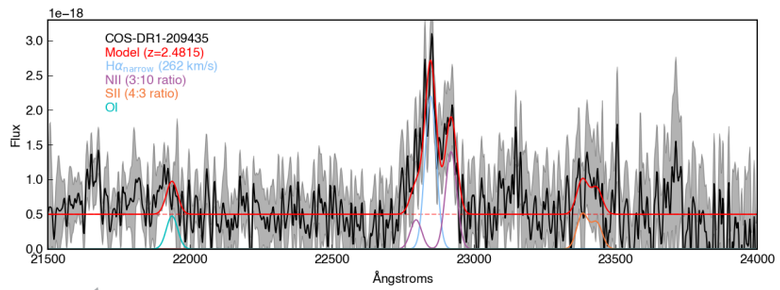
Red UMGs

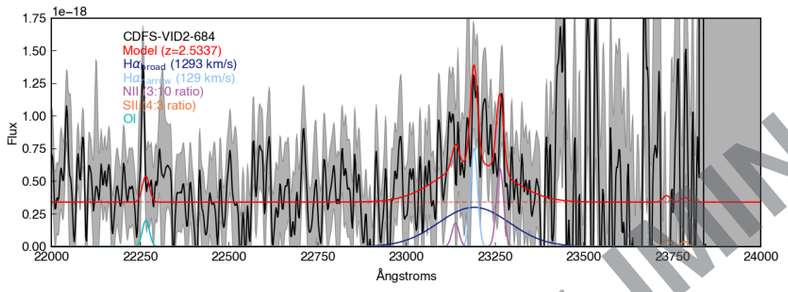
- **MAGAZ3NE has followed-up 9 of these very red UMGs with z_phot>3, which also are the (photometrically) most massive candidates, M>11.7.**

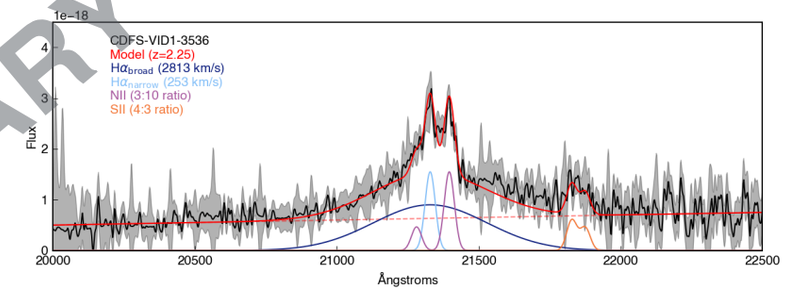


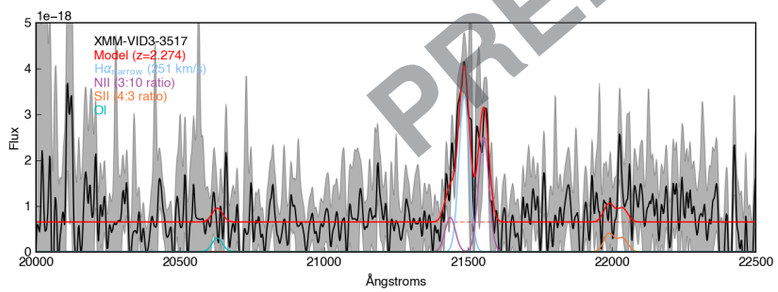
Red UMGs

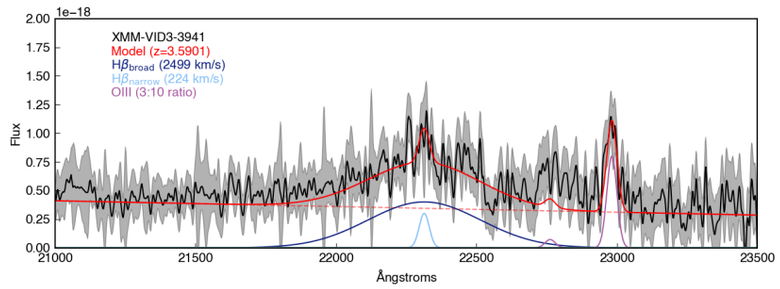






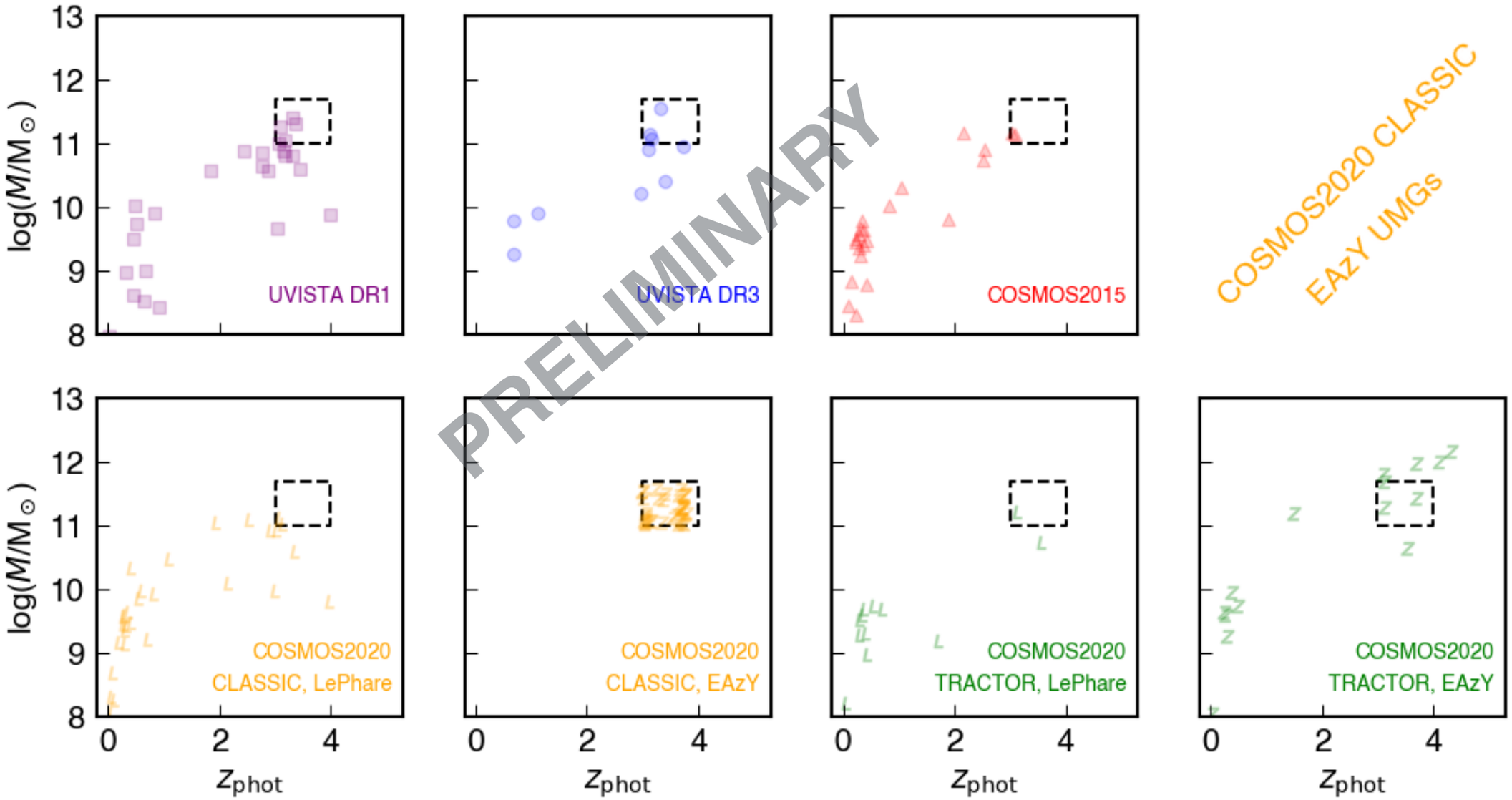




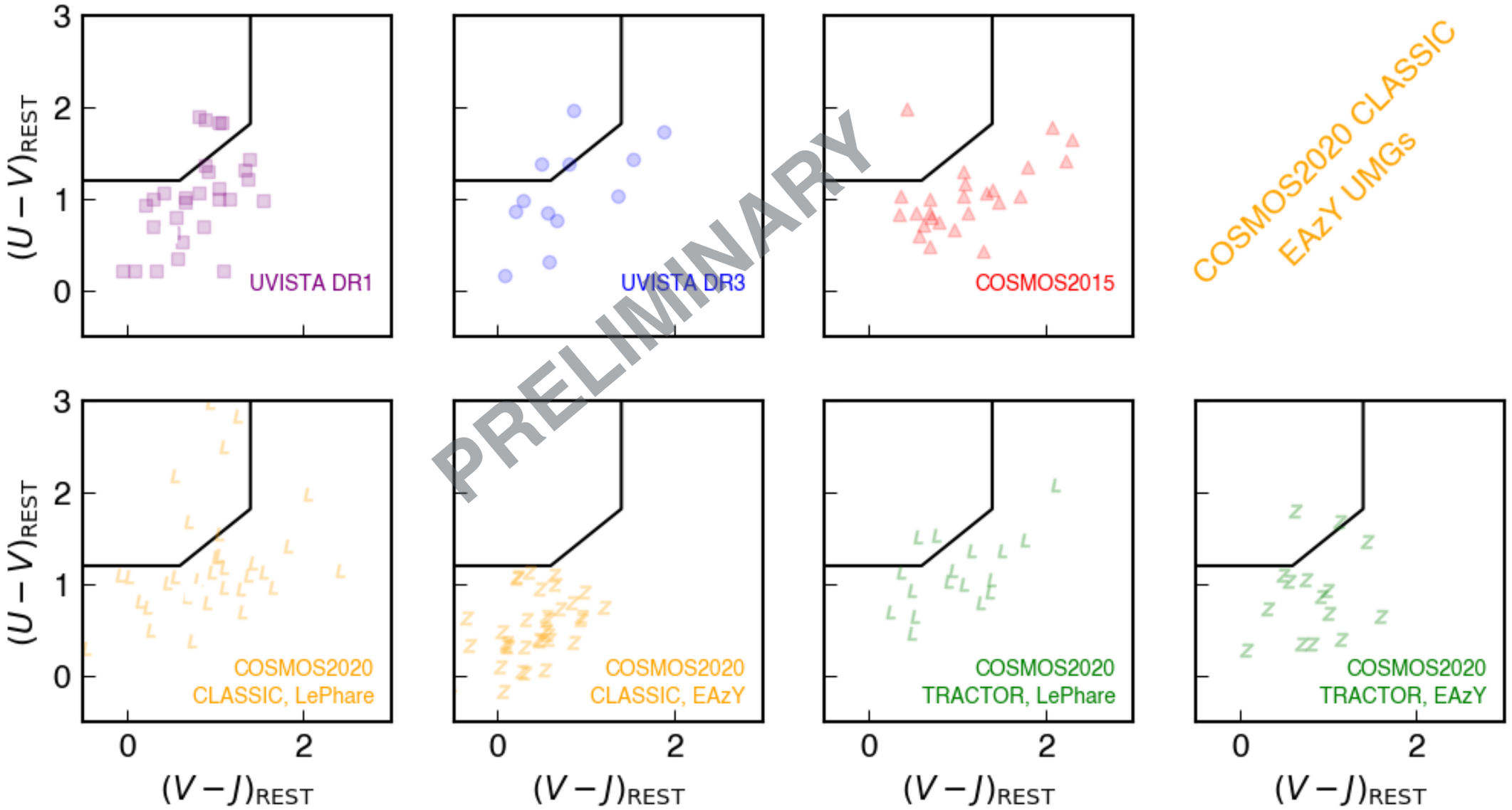


- **6 have redshifts, and 5 of these are 2.2<z<2.7 - the remaining object is a quasar. These are extremely dusty with evidence of AGN activity.**

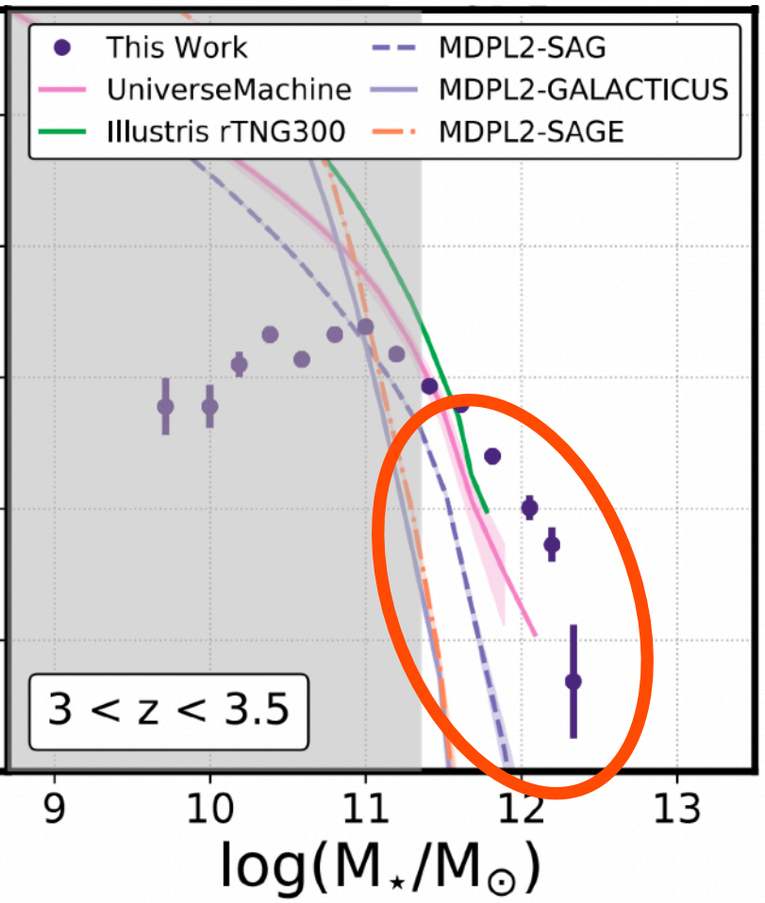
Red UMGs - Photometric Uncertainties



Red UMGs - Photometric Uncertainties



Massive Galaxies - Conclusions



- Massive galaxies, including some quiescent objects, exist at z>3.
- However, not all photometric candidates are reliable, particularly red objects.
- Quantifying these interlopers to constrain the SMF is critical to understanding galaxy evolution at early times.

Thank you for listening!