Environmental Effects on Galaxy Evolution at z~2.5

Derek Sikorski

Advisors: Roy Gal, Brian Lemaux (NOIRLab), Ben Forrest (UC Davis), and the C3VO Collaboration

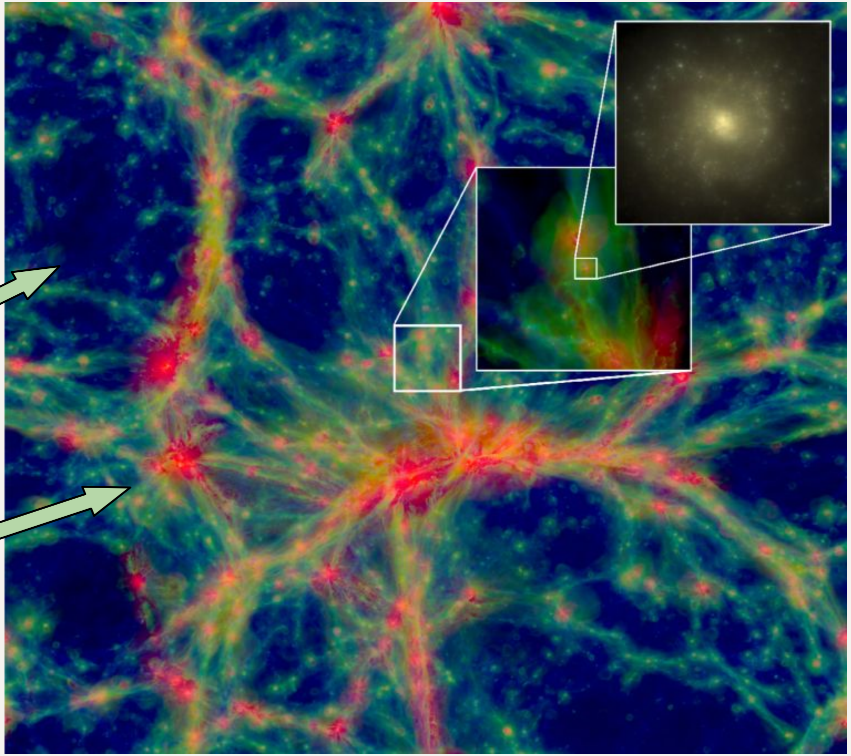
What is the "Environment?"

- Use "local overdensity" to characterize environment

$$\boxed{\log(1 + \delta_{gal})}$$

Low $\log(1 + \delta_{gal})$

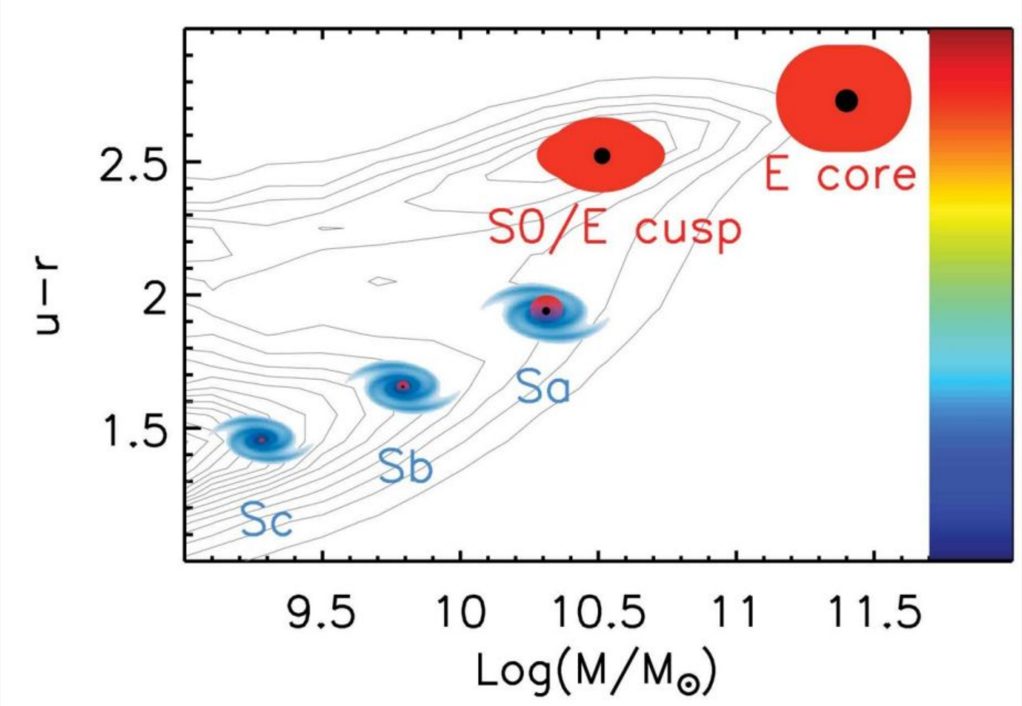
High $\log(1 + \delta_{gal})$



Schaye et al., 2015

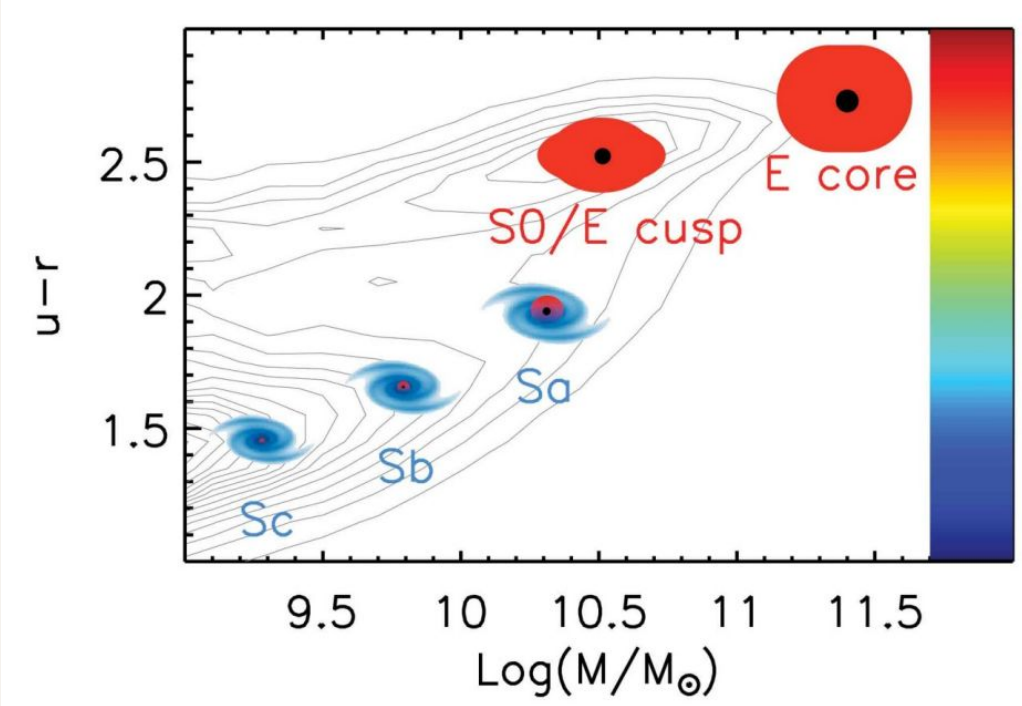
Galaxies Evolve

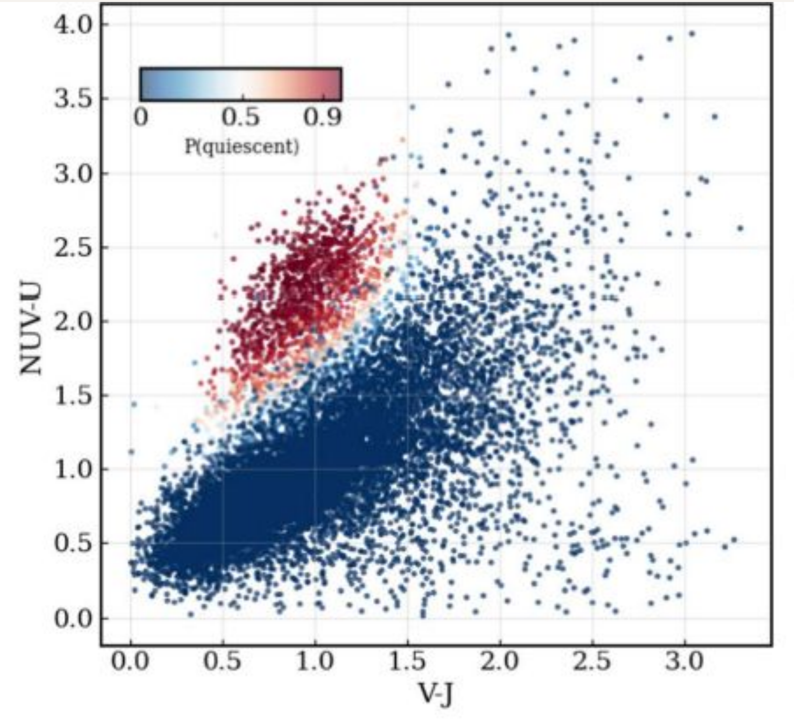
Galaxies Evolve



Cattaneo et al., 2009

Galaxies Evolve





Cattaneo et al., 2009

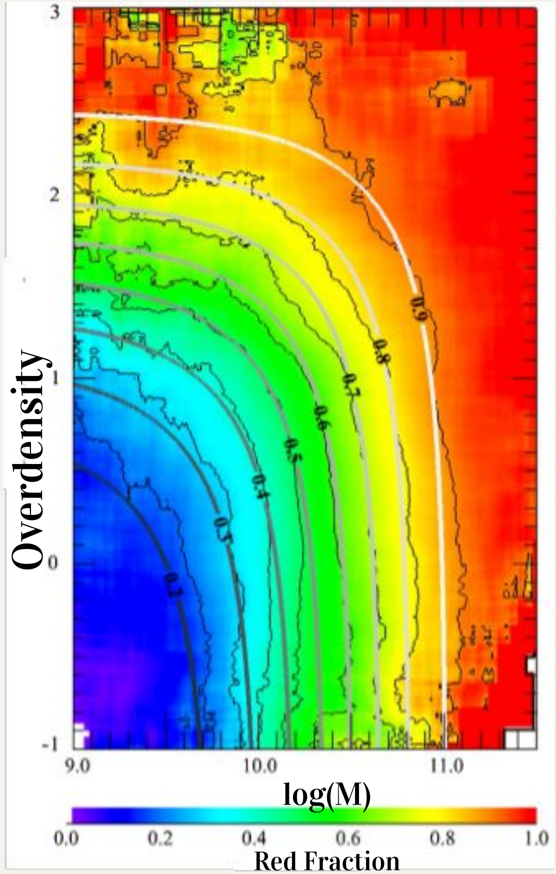
Gould et al., 2023

Environment Matters

In the local universe, find redder galaxies are:

→ more massive
→ in overdense regions

Does this change at higher redshifts?



Peng et al., 2010

Quenching

Quenching

In situ

"Mass Quenching"

Quenching

In situ

"Mass Quenching"

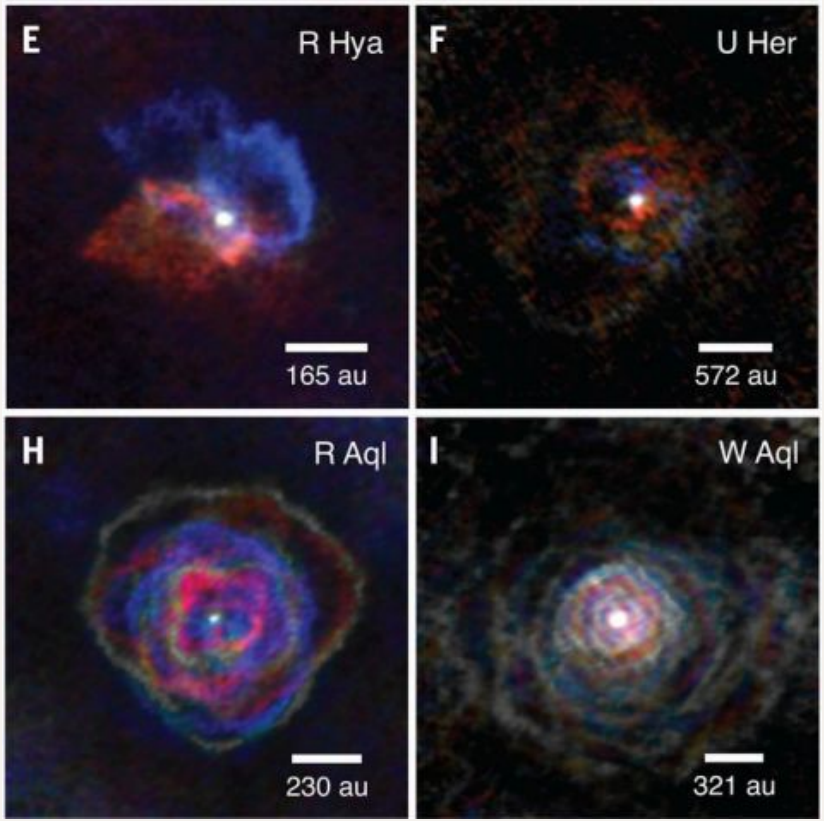
Ex situ

"Environmental Quenching"

In situ

"Mass Quenching"

- Stellar Winds



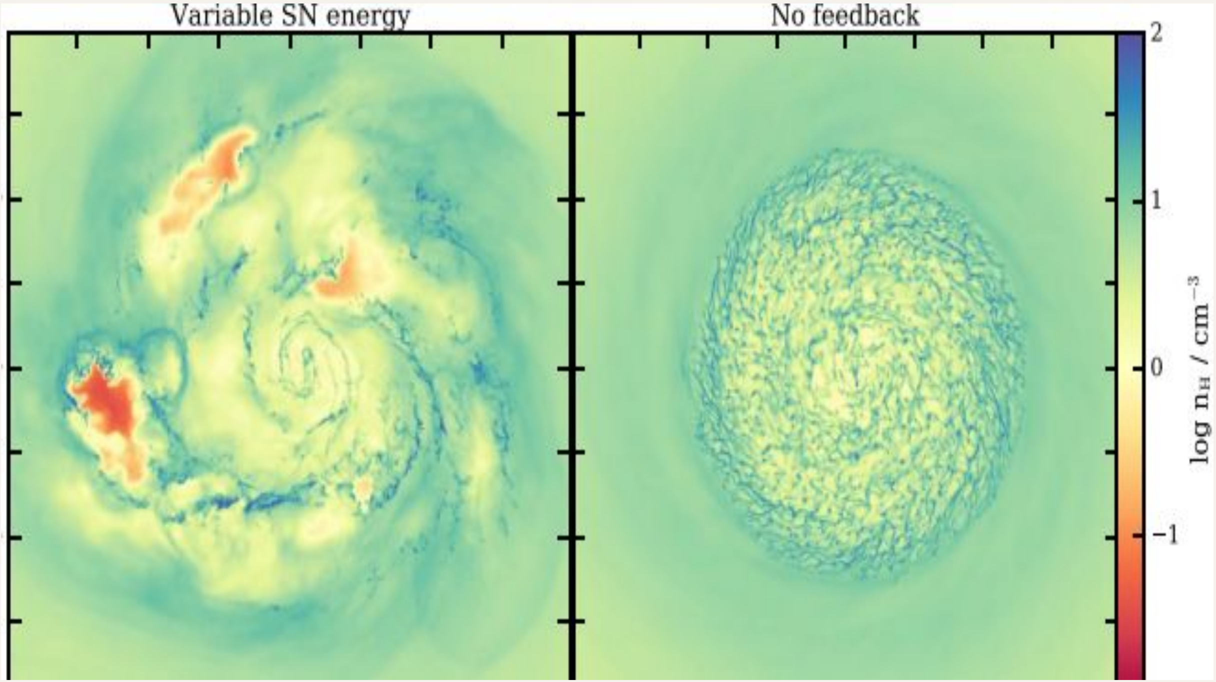
Decin et al., 2020

In situ

"Mass Quenching"

- Stellar Winds

- Supernovae

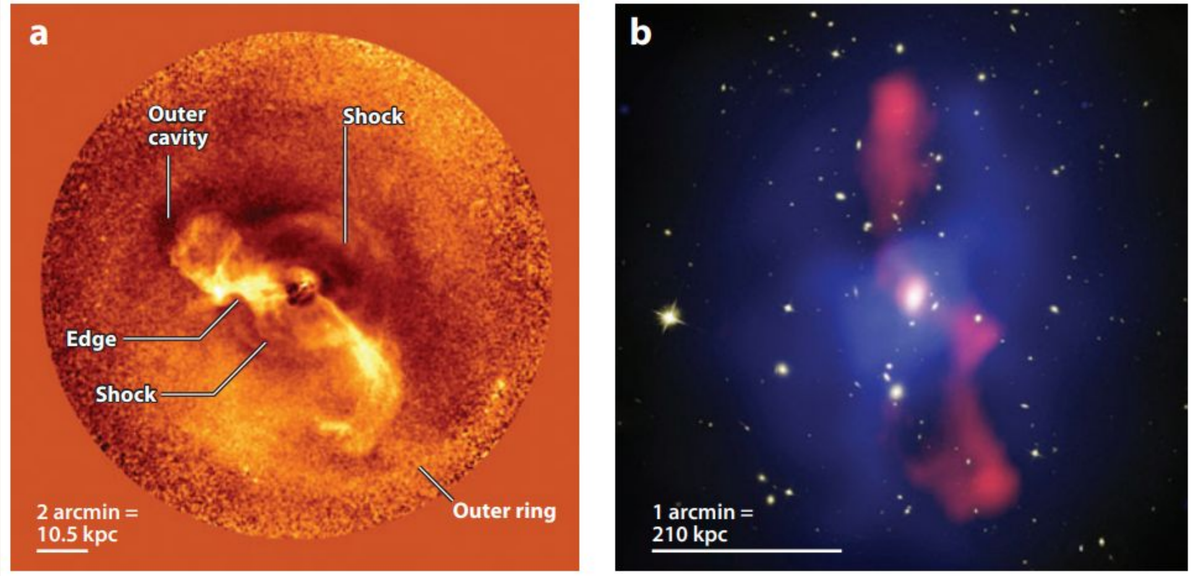


Gutcke et al., 2021

In situ

"Mass Quenching"

- Stellar Winds
- Supernovae
- AGN Feedback

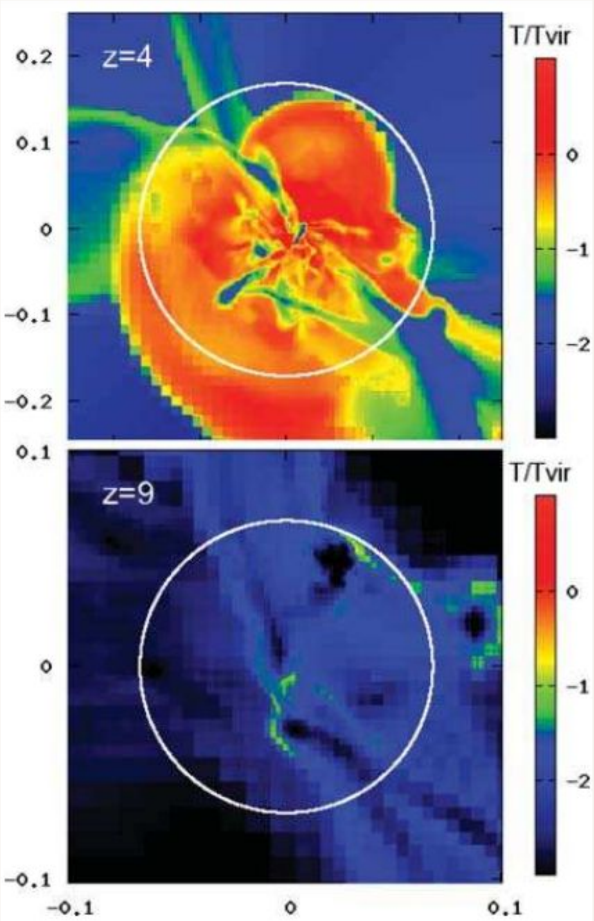


Fabian, 2012

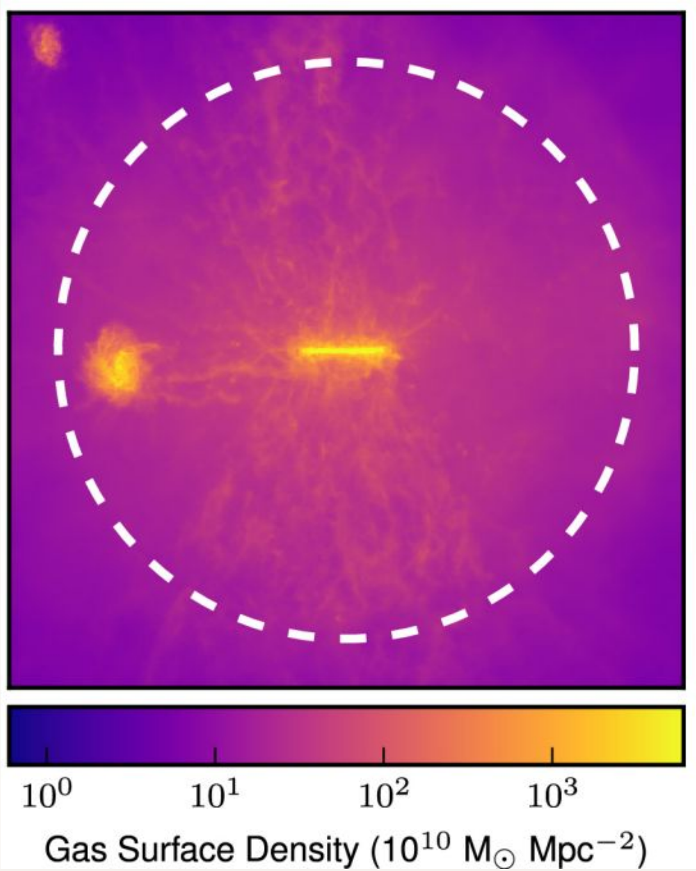
In situ

"Mass Quenching"

- Stellar Winds
- Supernovae
- AGN Feedback
- Dark Matter Halo



Dekel & Birnboim, 2006



Ex situ

"Environmental Quenching"

- Satellite Quenching

Simpson et al., 2018

Ex situ

"Environmental Quenching"

- Satellite Quenching

- Mergers

Van Dokkum, 2005

Environmental Effects on Galaxy Evolution at z~2.5

In situ

"Mass Quenching"

- Stellar Winds
- Supernovae
- AGN Feedback
- Dark Matter Halo

Ex situ

"Environmental Quenching"

- Satellite Quenching
- Mergers

Environmental Effects on Galaxy Evolution at z~2.5

In situ

"Mass Quenching"

- Stellar Winds
- Supernovae
- AGN Feedback
- Dark Matter Halo

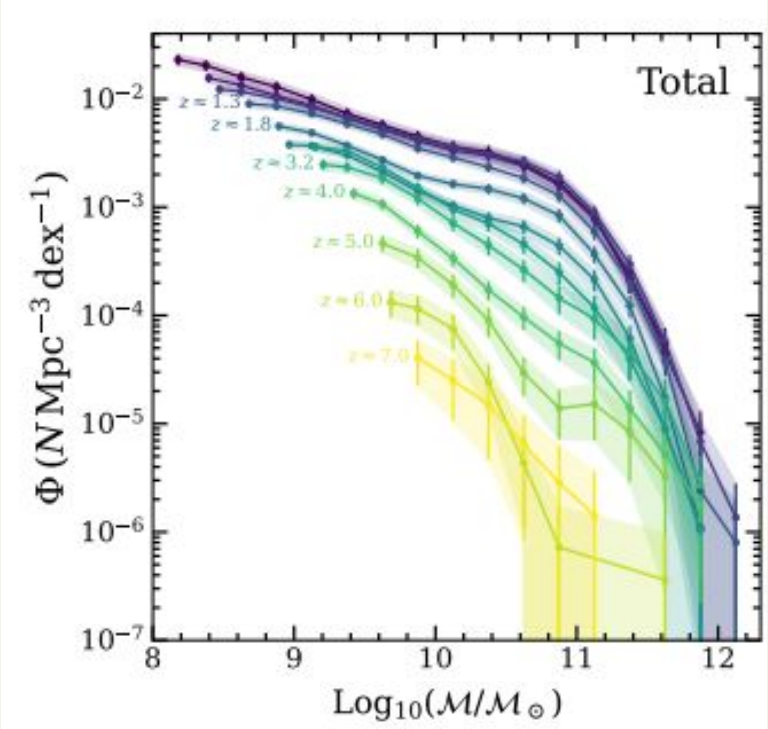
Ex situ

"Environmental Quenching"

- Satellite Quenching
- Mergers

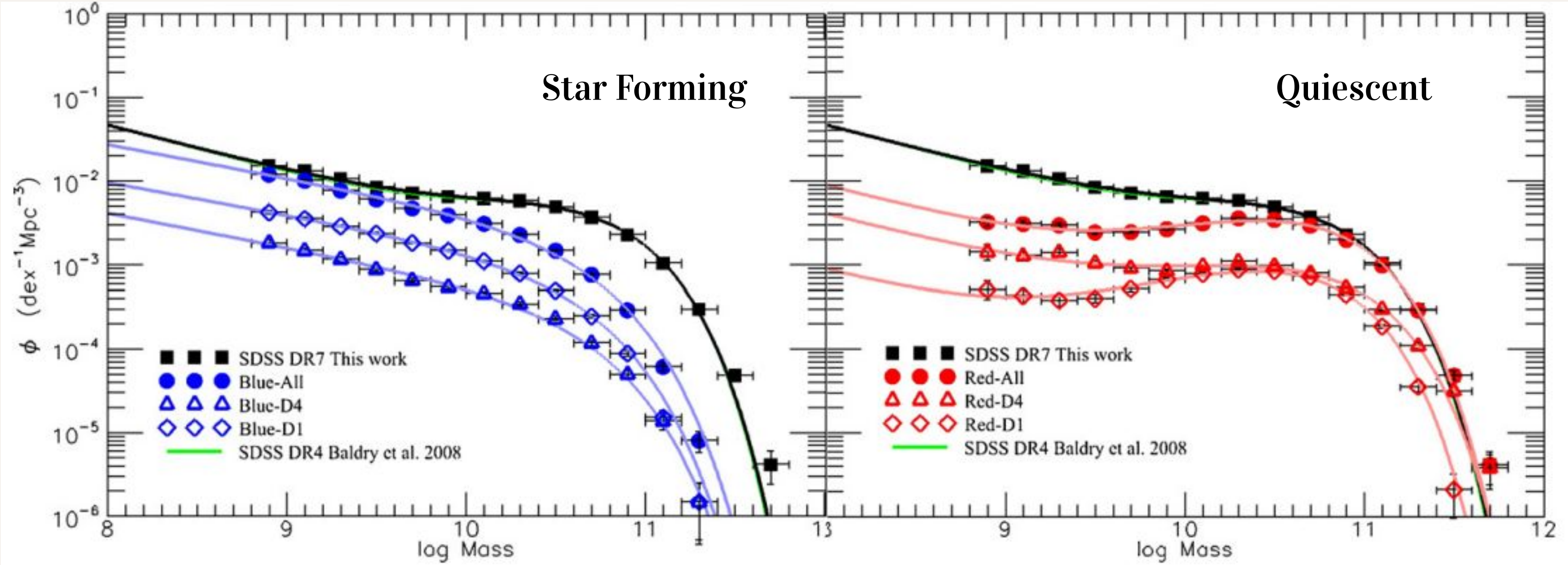
Effects in the Stellar Mass Function (SMF)

- The SMF is a number density of galaxies as function of mass
- Gives information about star formation history
- Different SMF shapes for different populations informs us about different histories

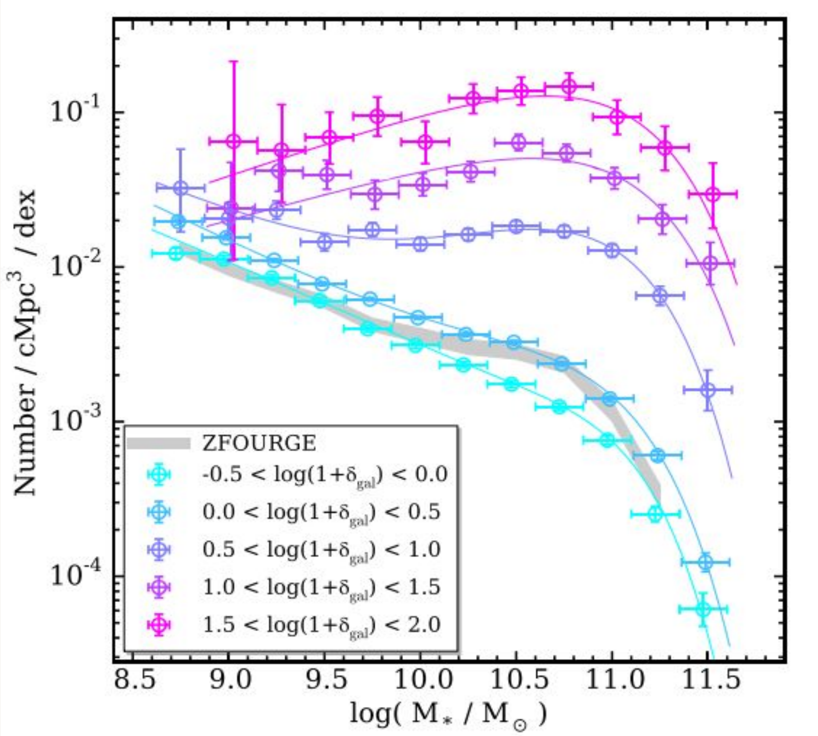


Weaver et al., 2023

The Local SMF



The SMF at Higher Redshifts



- SMFs for $0.55 \leq z \leq 1.3$

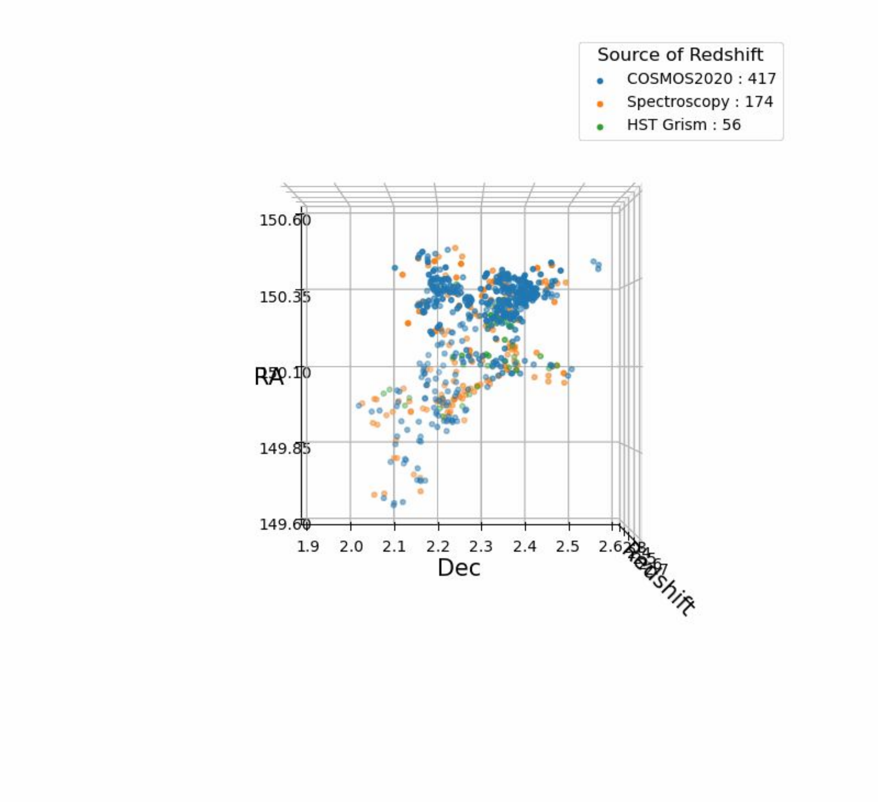
  → Lookback time of ~5.6-9.0 Gyr

- Find that overdense regions either:
  - Lack low-mass galaxies
  - Have excess of high-mass galaxies

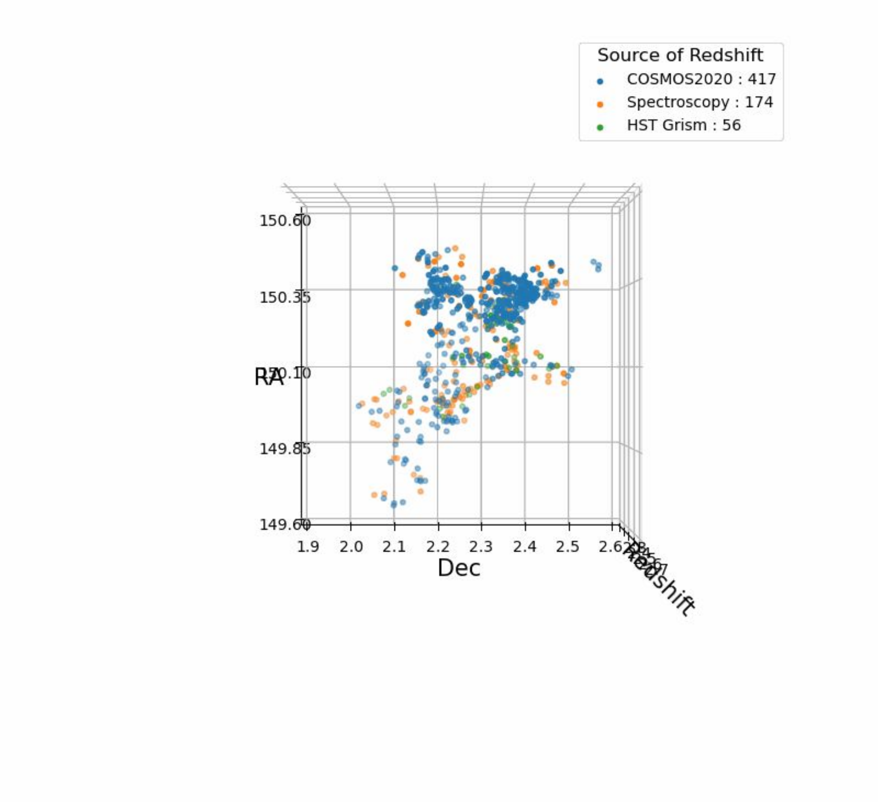
Tomczak et al., 2017

Hyperion: A Giant in the COSMOS field

- An overdense region with a collection of highly-overdense "peaks"
- First realized in Cucciati et al., 2018
- Since has been studied extensively
- Data comparable to superclusters at $z < 1$

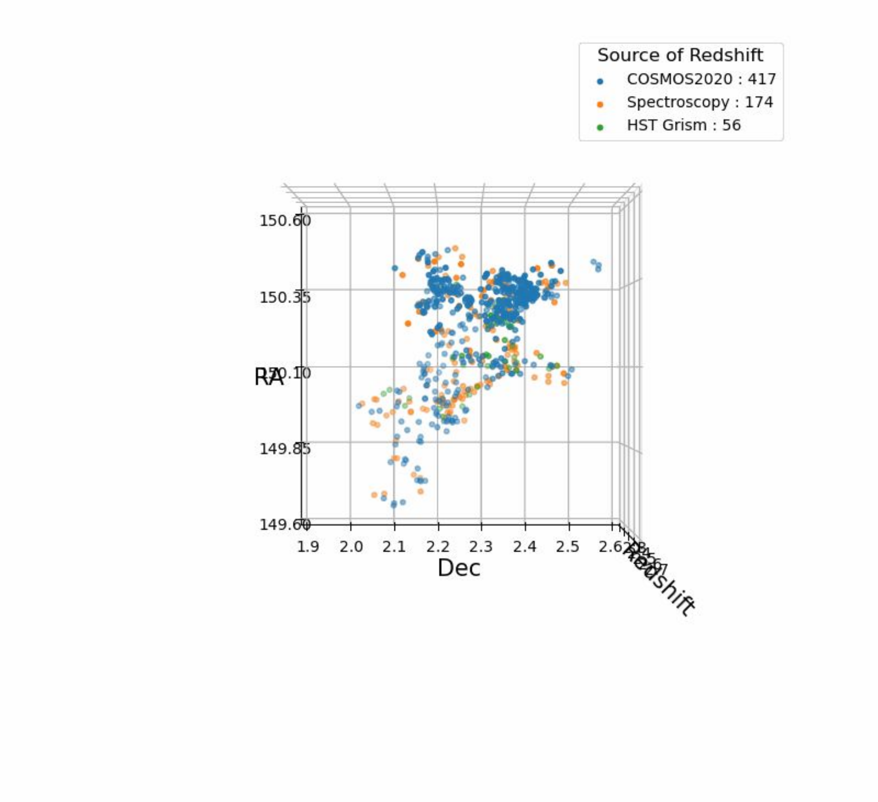


Goals of the Study



Goals of the Study

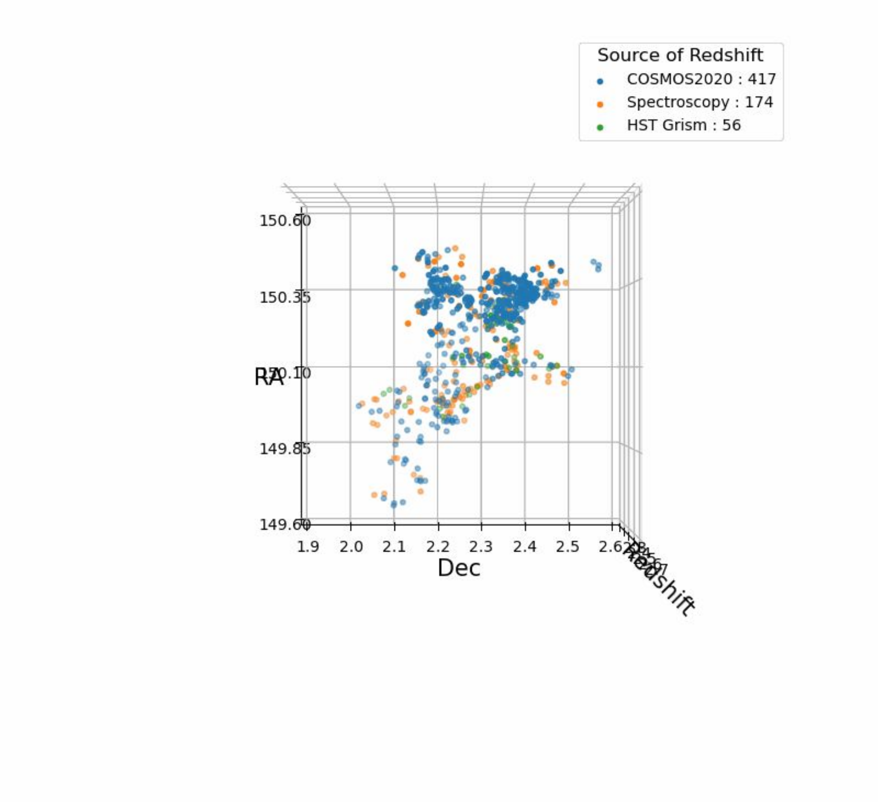
1. Identify a data set



Goals of the Study

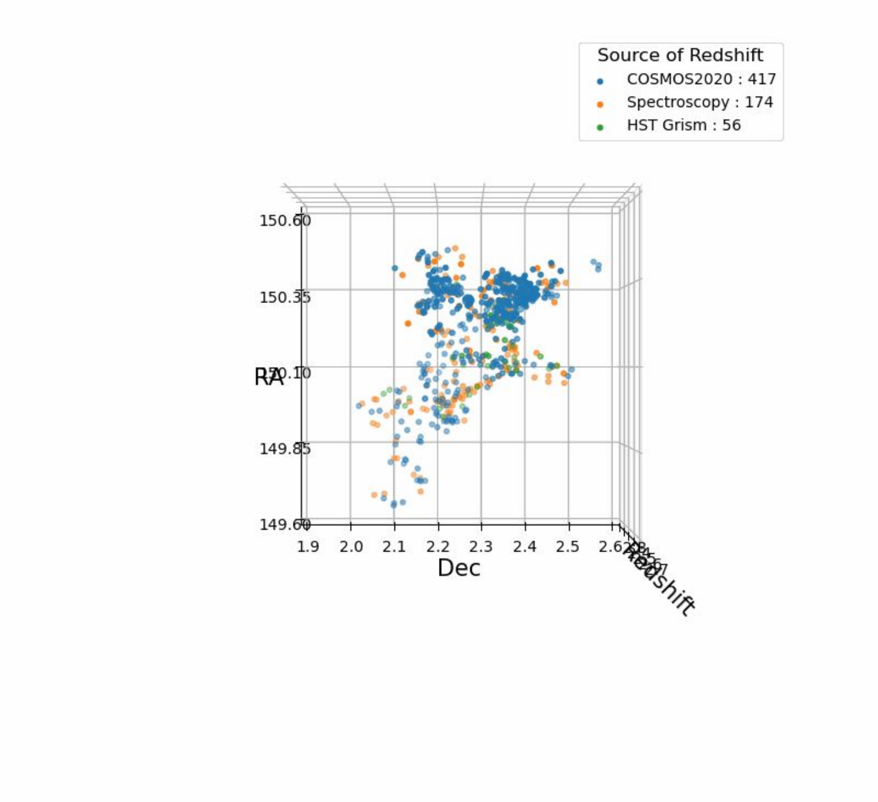
1. Identify a data set

2. Create a map of the environment



Goals of the Study

1. Identify a data set
2. Create a map of the environment
3. Identify Hyperion and a separate field sample



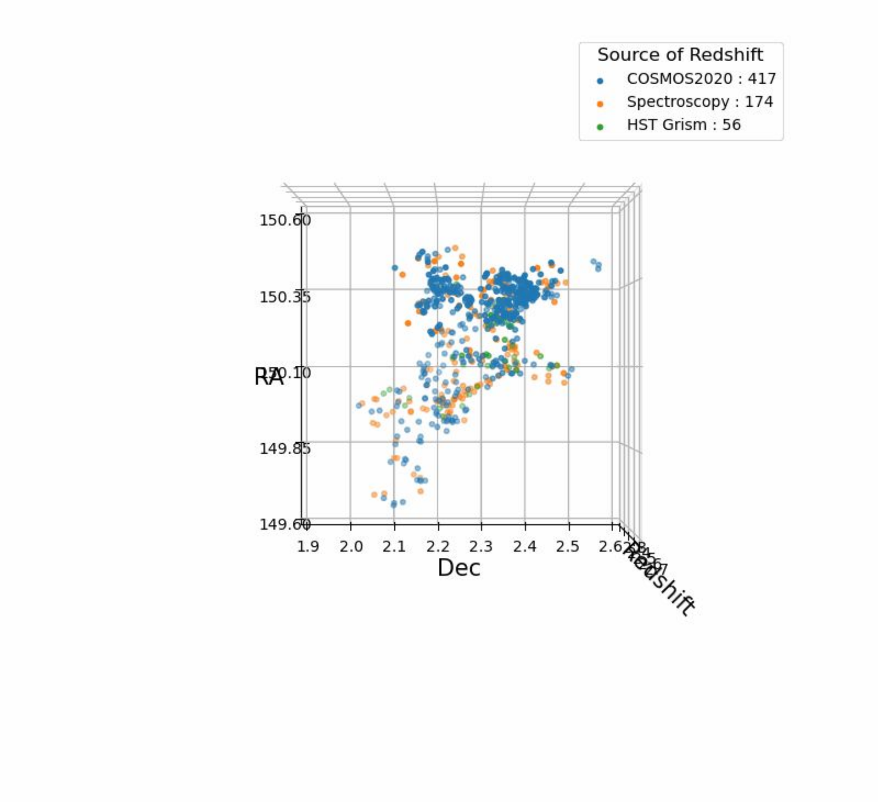
Goals of the Study

1. Identify a data set

2. Create a map of the environment

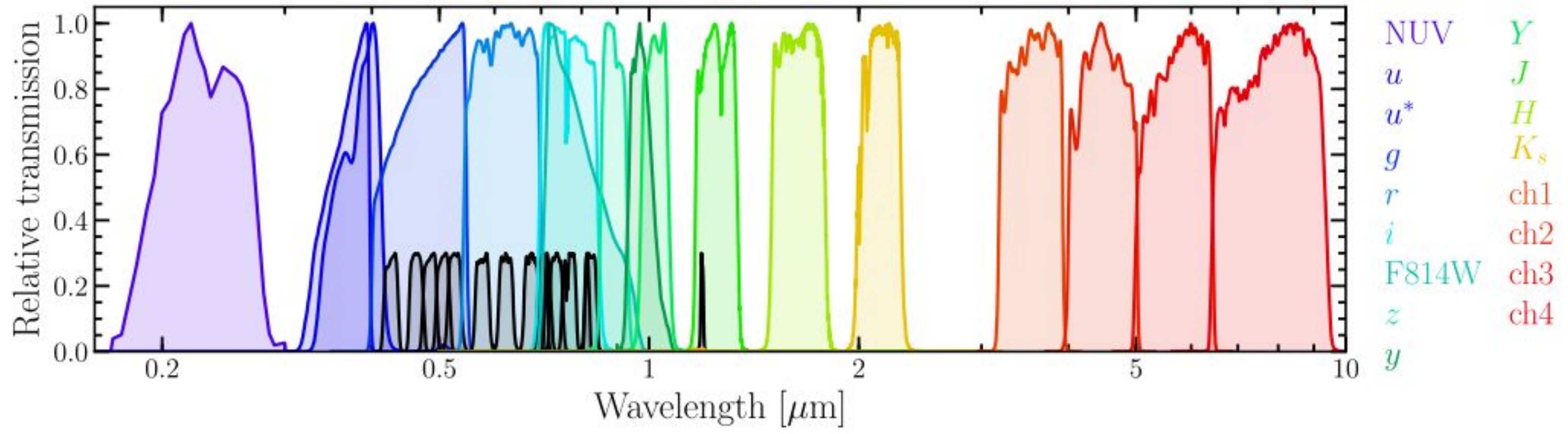
3. Identify Hyperion and a separate field sample

4. **Compare SMFs of different overdensity thresholds of Hyperion and the field sample**



Data

1. COSMOS2020 photometry
   → SED fitting providing stellar mass, photo-zs, etc.



Weaver et al., 2022

Data

1. COSMOS2020 photometry

2. Ground-based spectroscopy
   → 2078 usable redshifts in range
   $2 \leq z_{spec} \leq 3$

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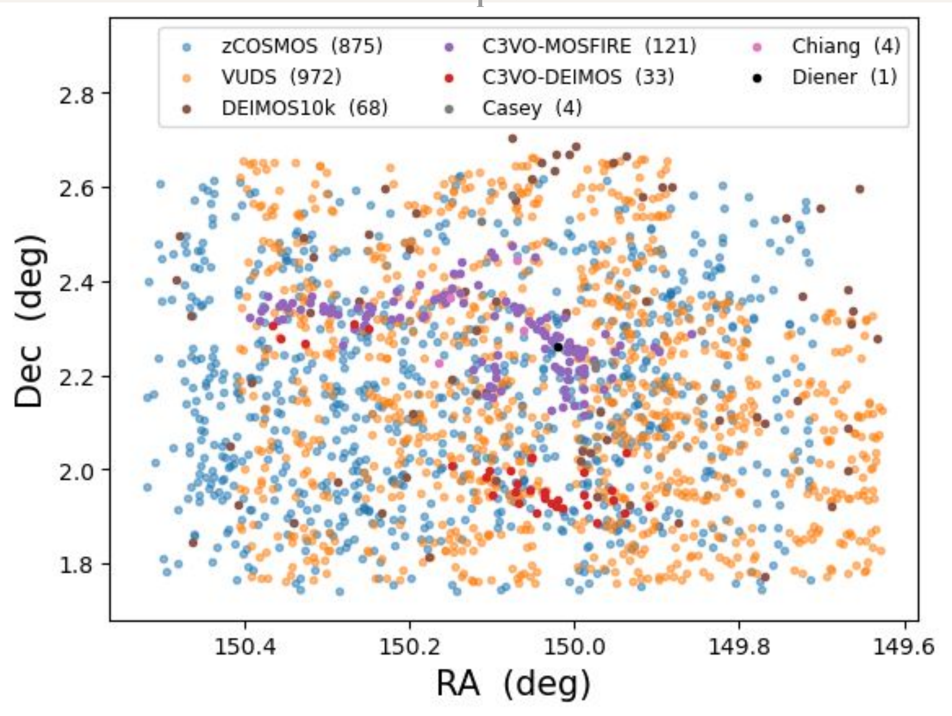


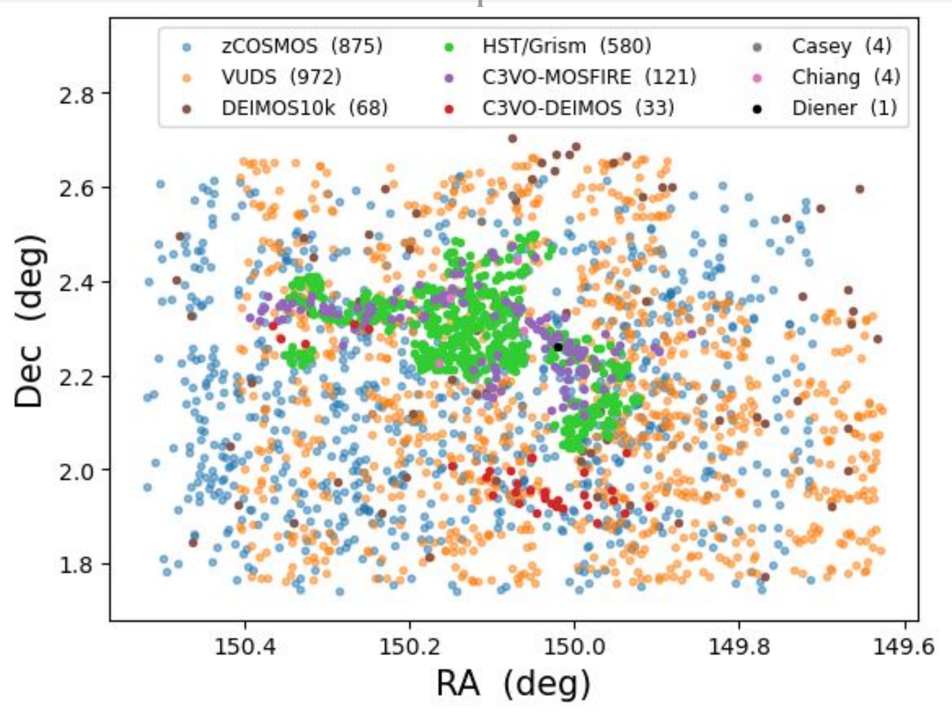
Data

1. COSMOS2020 photometry

2. Ground-based spectroscopy
   → 2078 usable redshifts in range
   $2 \leq z_{spec} \leq 3$

3. *HST* grism spectroscopy
   → 580 usable redshifts in range
   $2 \leq z_{spec} \leq 3$

$2 \leq z_{spec} \leq 3$



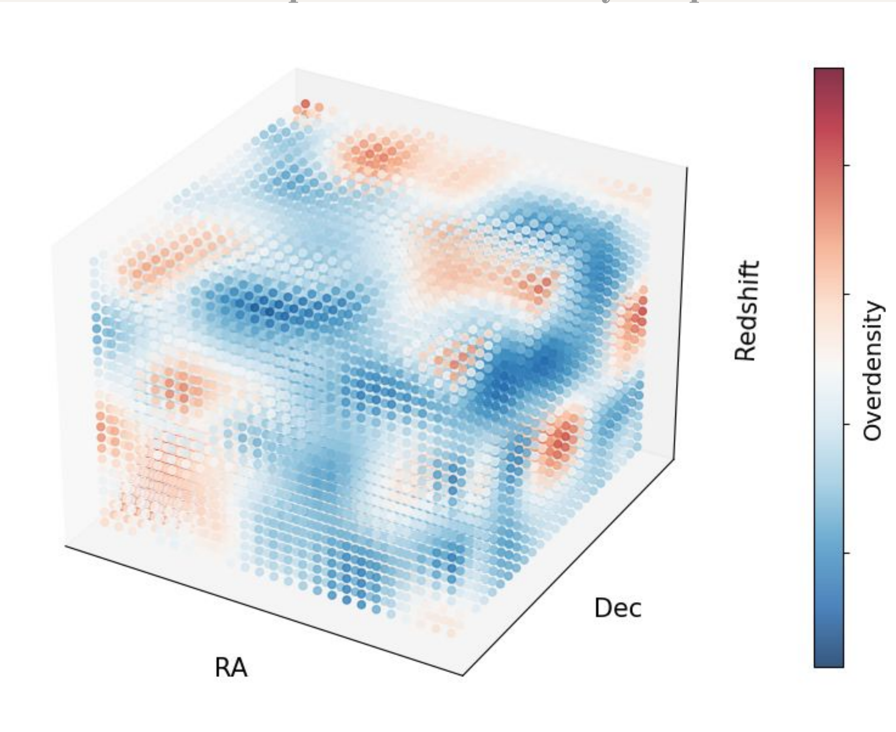
Mapping the Environment

- Need a 3D map of $\log(1 + \delta_{gal})$

- Use MC process and subset of data to map of "voxels" with associated overdensity

- Can use this to:
  - Identify proto-structures
  - Assign a $\log(1 + \delta_{gal})$ to each galaxy

Example of Overdensity Map

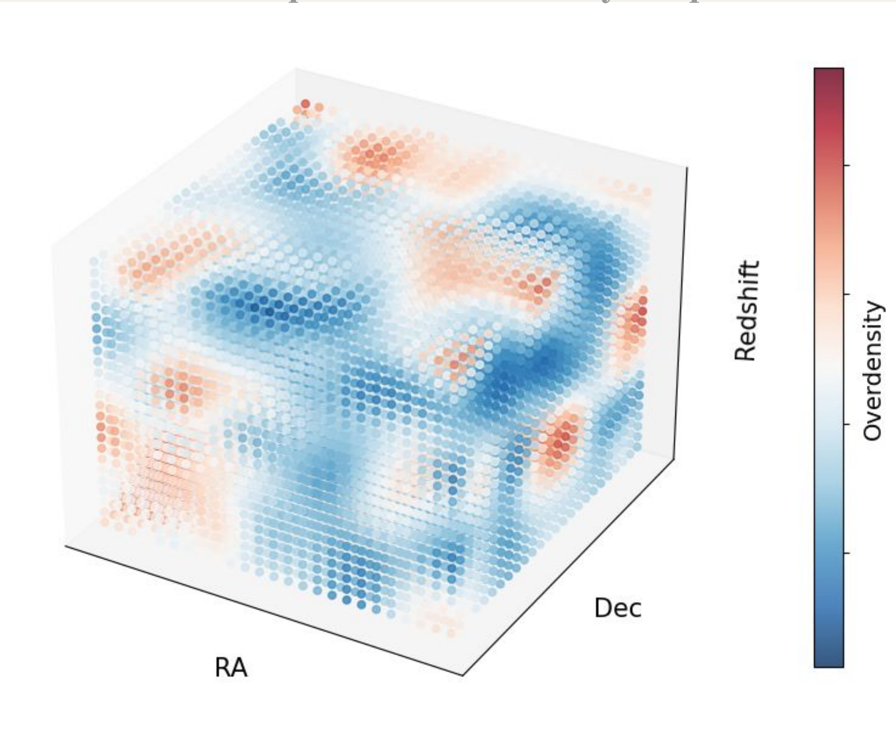


Mapping the Environment

- Easier to write in terms of n_{sig}

→ Number of standard deviations above the mean $\log(1 + \delta_{gal})$ at a given redshift

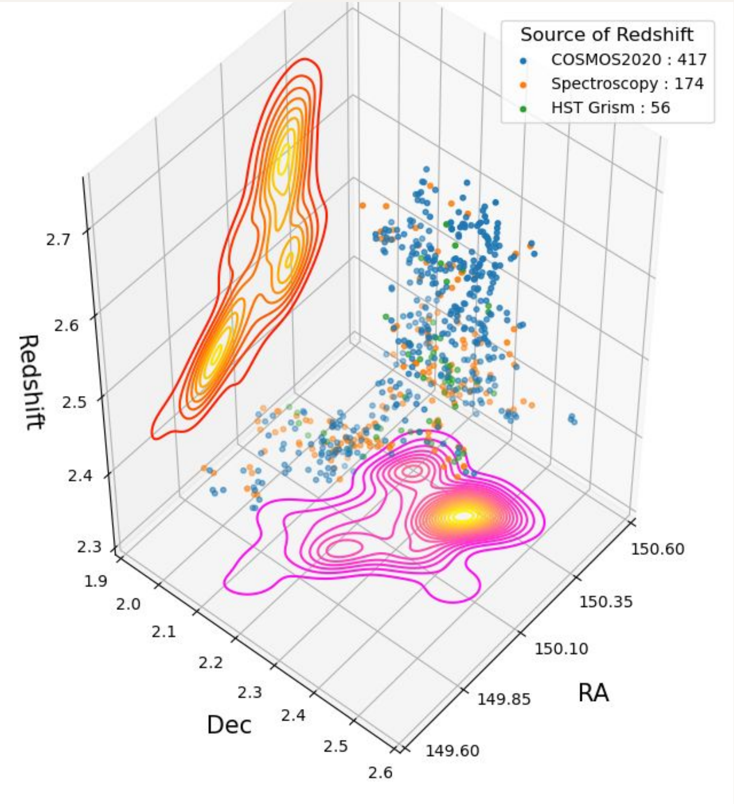
Example of Overdensity Map



Defining Hyperion

Conditions to be a proto-structure

1. Contiguous voxels with $n_{sig} \geq 2$
2. Contains some voxels with $n_{sig} \geq 4$
3. Total mass of $\log(M/M_{\odot}) \geq 13$



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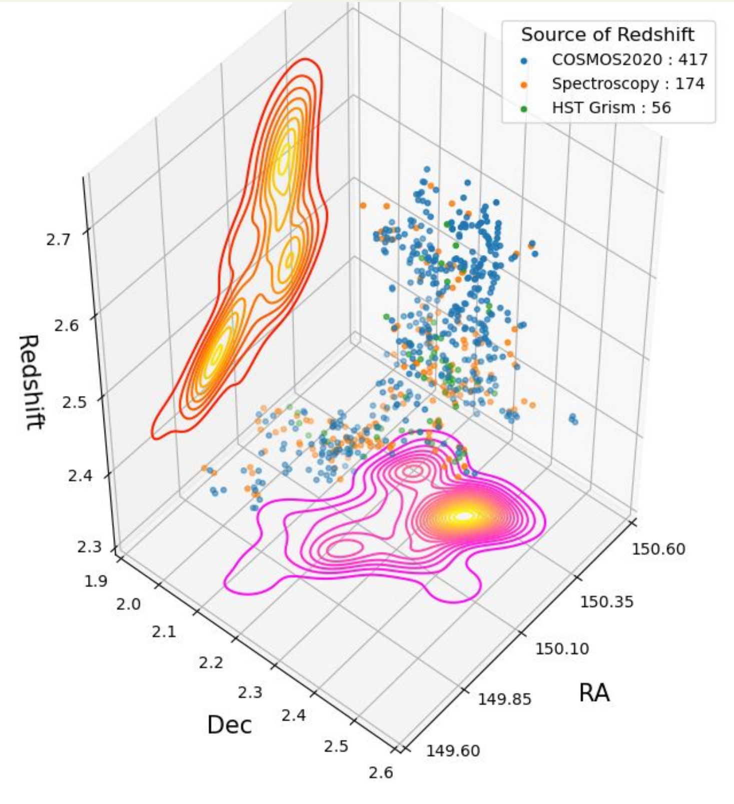


Properties of Hyperion:

→ Total Mass: $\log(M/M_\odot) \sim 15.71$

→ Volume: $V \sim 9.6 \times 10^4$ cMpc^3

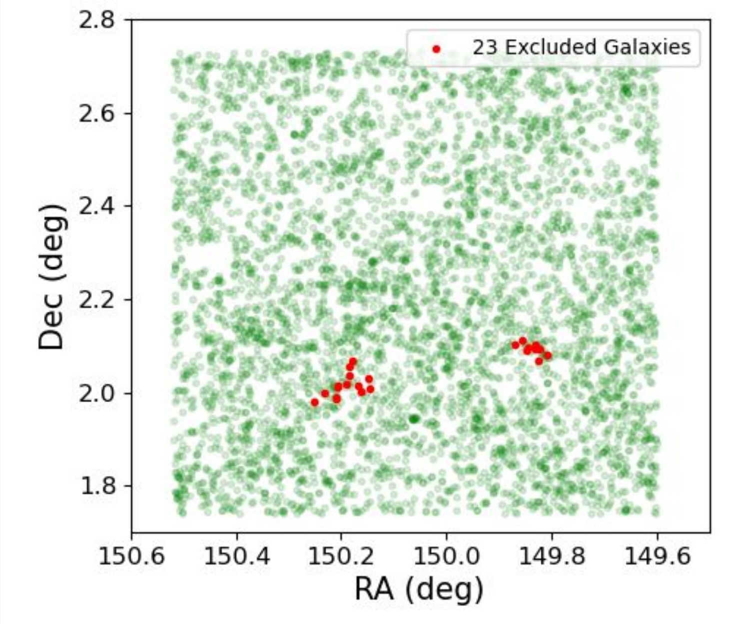
Defining a Comparison Field

Want a sample with limited exposure to environmental effects

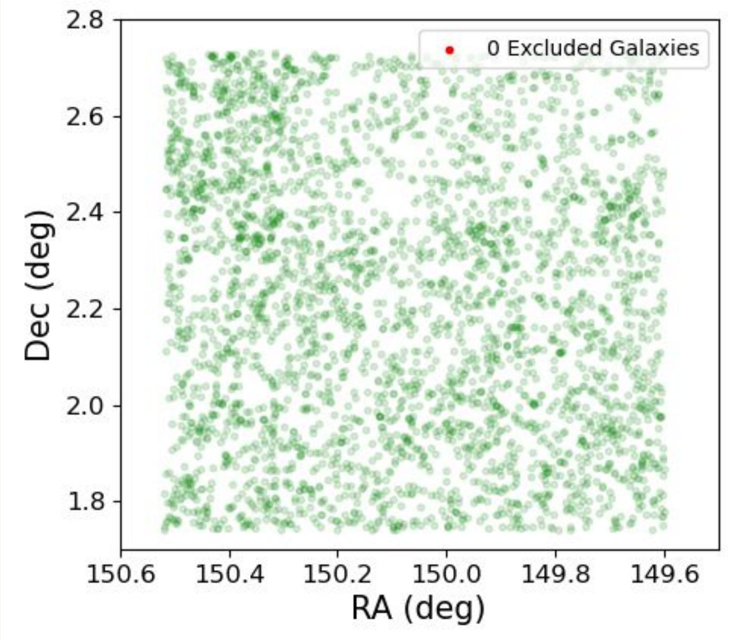
Defining a Comparison Field

Want a sample with limited exposure to environmental effects

$2.15 \leq z \leq 2.25$



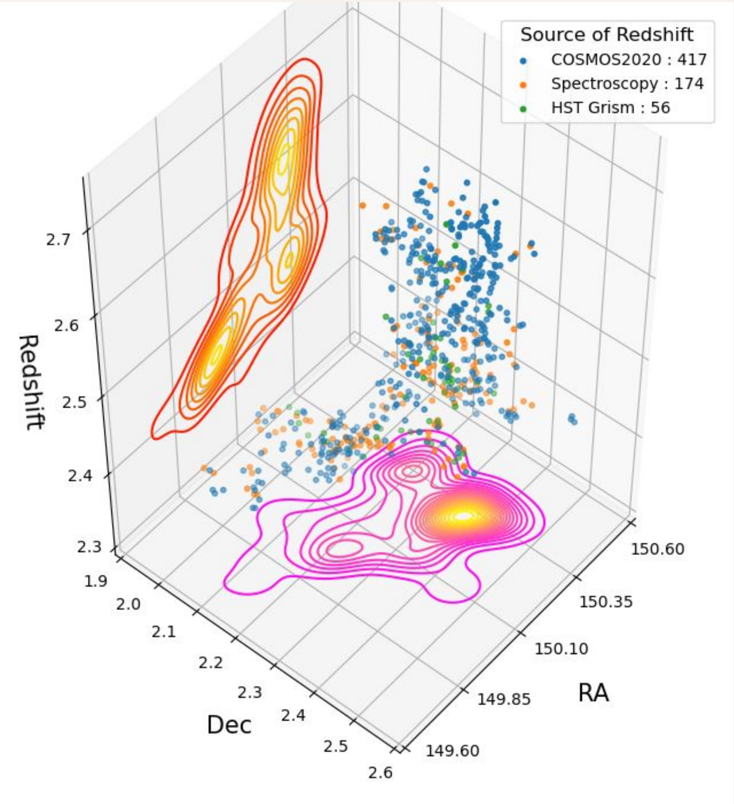
$2.80 \leq z \leq 2.90$



Account for Photometric Redshift Uncertainties

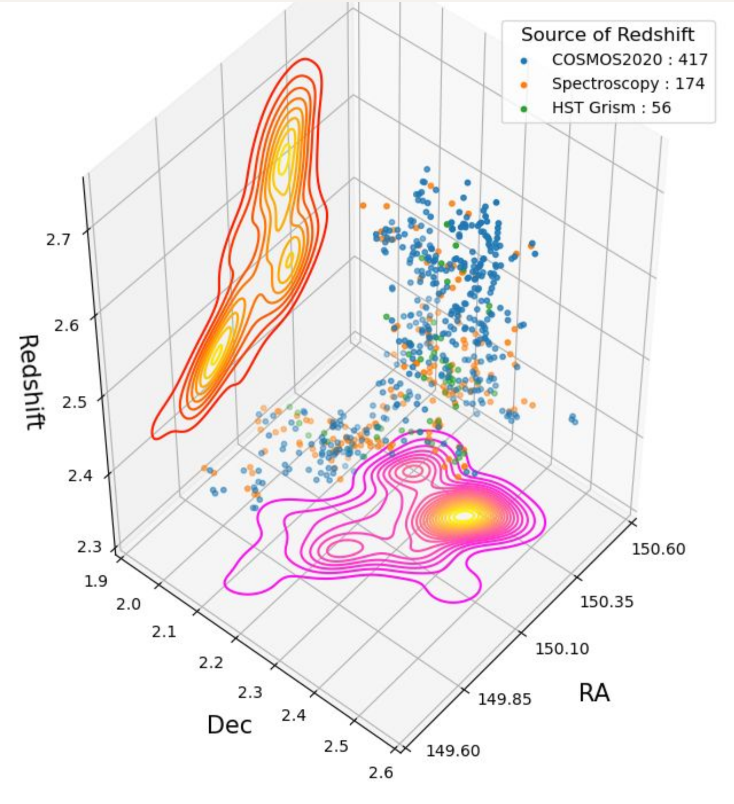
- Despite abundance of spectroscopic redshifts, the data is dominated by photo-zs

- Accounting for redshift uncertainty is difficult. Redshift affects
  - If the galaxy is in Hyperion
  - What region of Hyperion does the galaxy land in
  - What is the stellar mass of the galaxy

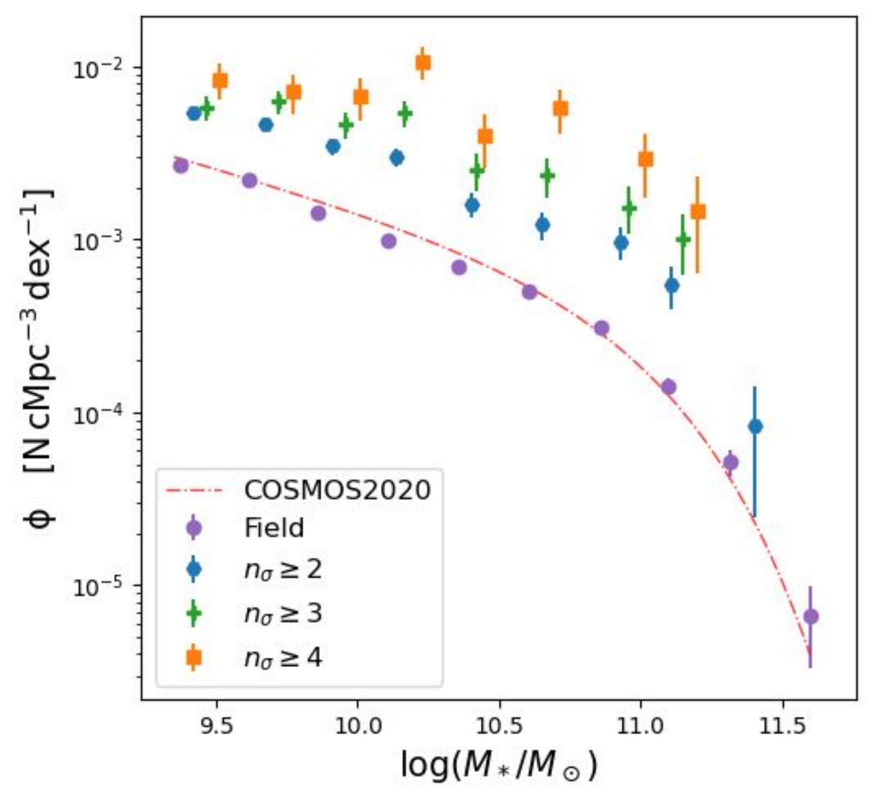


Account for Photometric Redshift Uncertainties

- Use a Monte Carlo process to account for redshift uncertainties
- Make 100 mock catalogs which incorporate photometric uncertainties
- Each iteration, refit SEDs based on the new redshift
- Reconstruct the SMF for each MC iteration

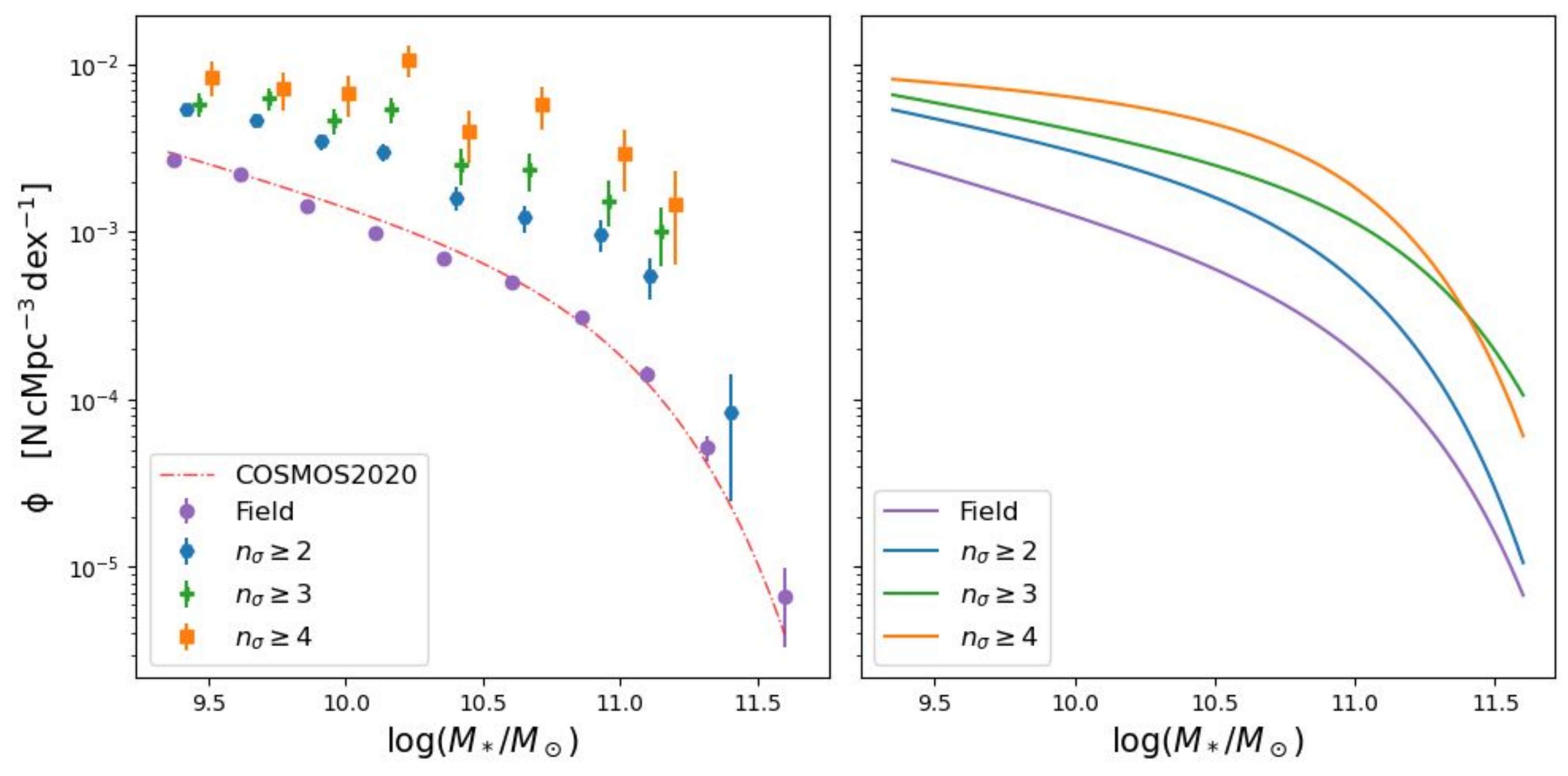


SMFs



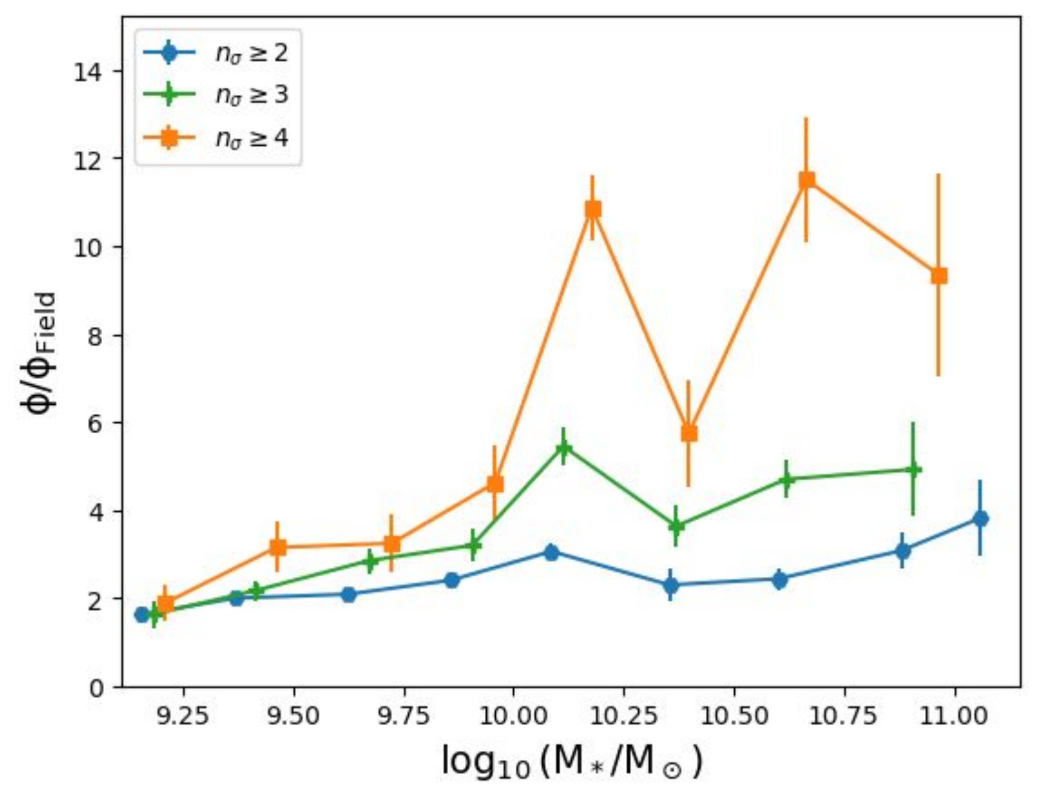
- **Median combine the SMFs**
- **Compare 5 SMFs:**
  - The combined field sample
  - Three different overdensity thresholds of Hyperion
  - The COSMOS2020 field for 2.0 ≤ z ≤ 2.5 (Weaver et al., 2023)

SMFs



Φ [N cMpc^{-3} dex^{-1}]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
COSMOS2020
Field
$n_\sigma \geq 2$
$n_\sigma \geq 3$
$n_\sigma \geq 4$
9.5
10.0
10.5
11.0
11.5
$\log(M_*/M_\odot)$
Field
$n_\sigma \geq 2$
$n_\sigma \geq 3$
$n_\sigma \geq 4$
9.5
10.0
10.5
11.0
11.5
$\log(M_*/M_\odot)$

Normalized SMFs

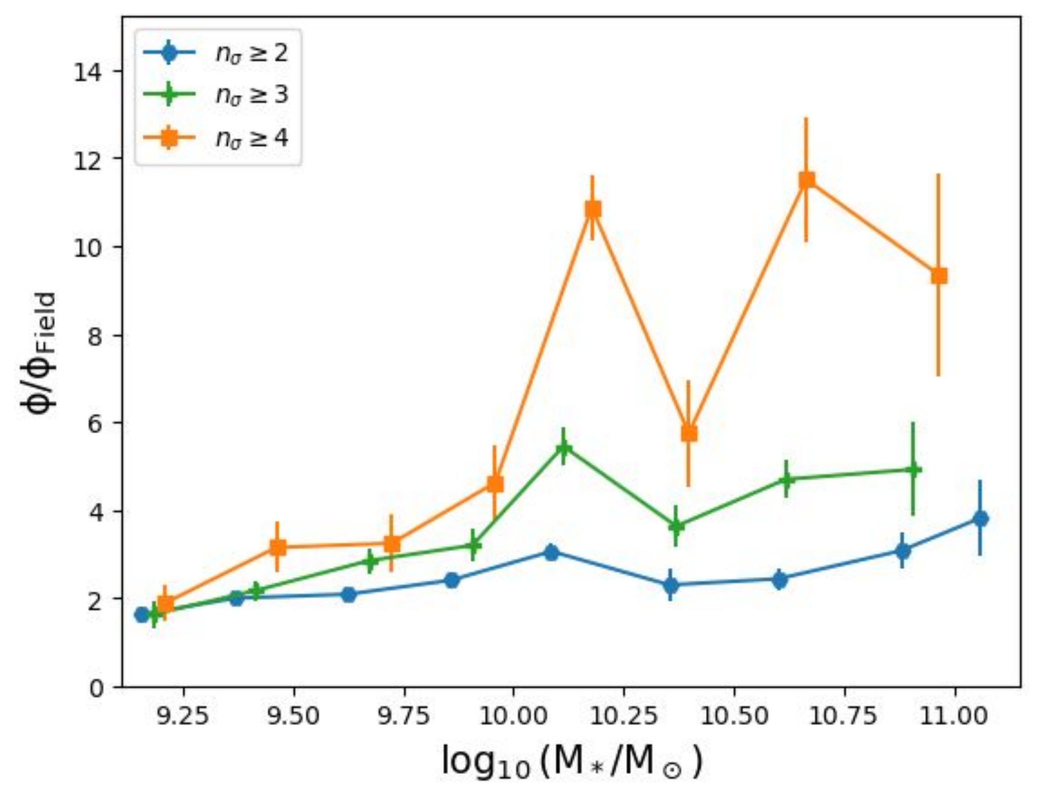


There is an abundance of massive galaxies in the most overdense regions

Could mean:

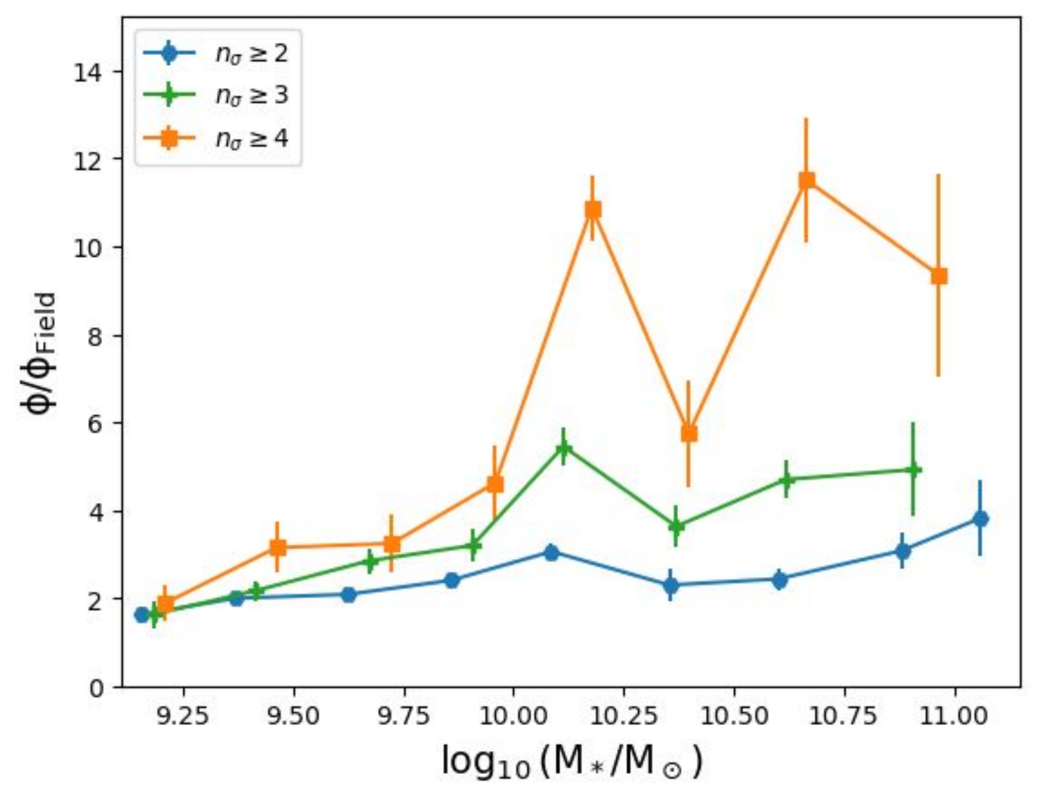
- Galaxies form at earlier epochs in these regions
- Galaxies experience enhanced SFRs in overdense regions
- Mergers are more frequent and driving up stellar mass

What I've Done



- Helped to analyze *HST* data to give new insight into Hyperion
- Generate an updated map of Hyperion
- Perform an MC on the data and refit the SEDs to get new physical parameters
- Constructed SMFs for Hyperion and a field sample

What I Found

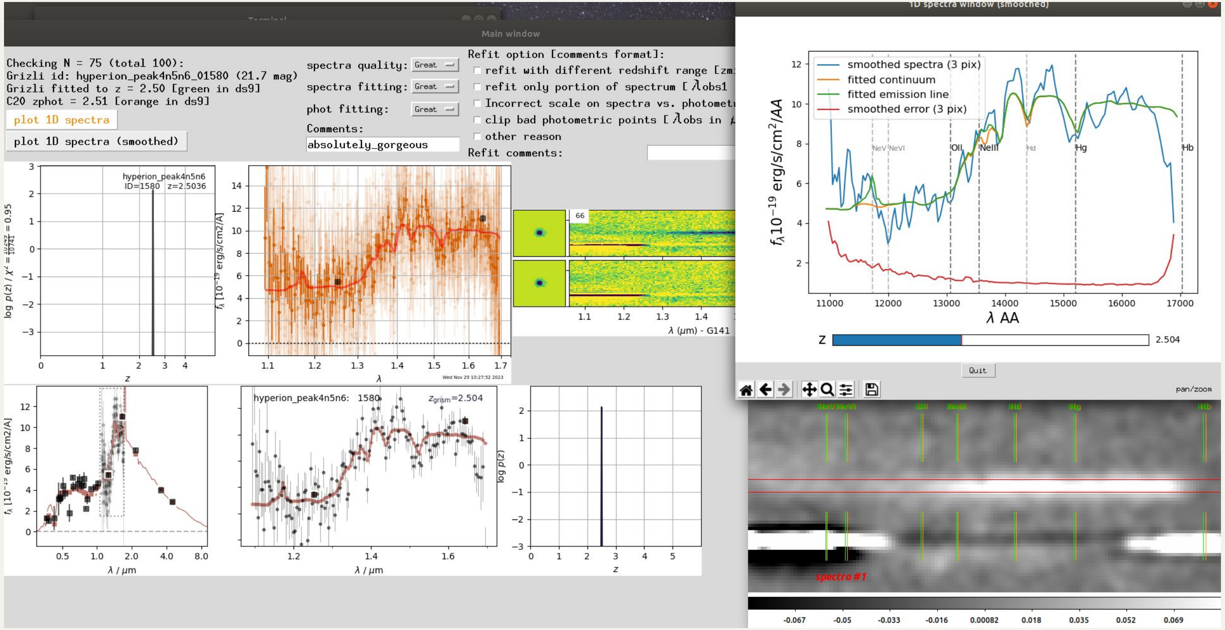


- Overdense regions appear to have a higher ratio of high-to-low mass galaxies
- Given the lookback time of ~11 Gyrs, this could imply early and rapid growth of stellar mass of these galaxies
- Separate this into star forming and quenched populations to study further

Bonus Slides

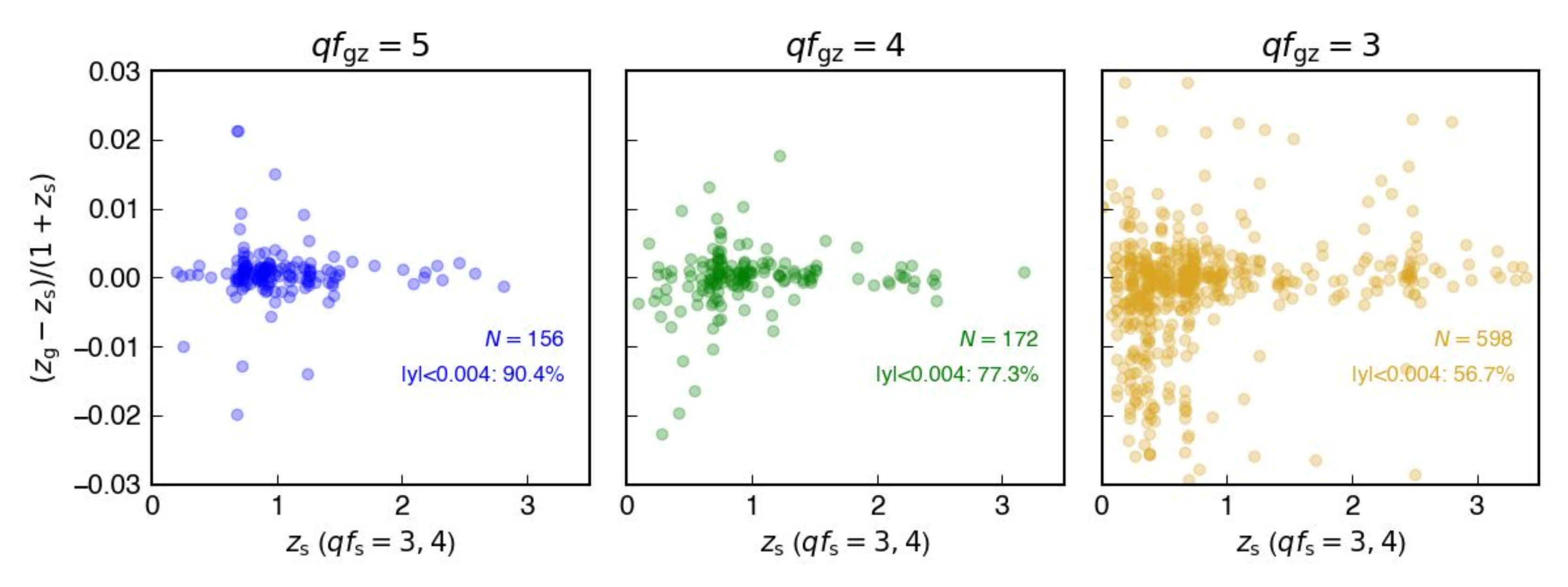
The Pain of Grism Spectroscopy

- ~2500 sources examined by-eye by the group
- In total, ~700 hours of work for classification



The Pain of Grism Spectroscopy

- Cross-match with best ground-based spectra to derive reliability



Forrest et al., in prep

Mapping the Environment

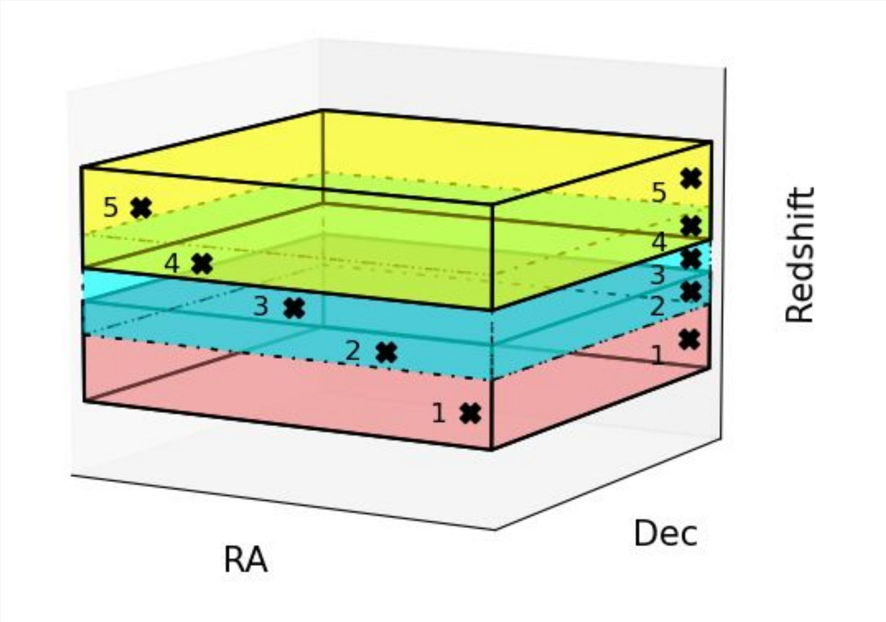
Mapping the Environment

Map $\log(1 + \delta_{gal})$ with the Voronoi Monte Carlo (VMC) algorithm

Mapping the Environment

- The VMC cookbook:

1. Make overlapping redshift slices

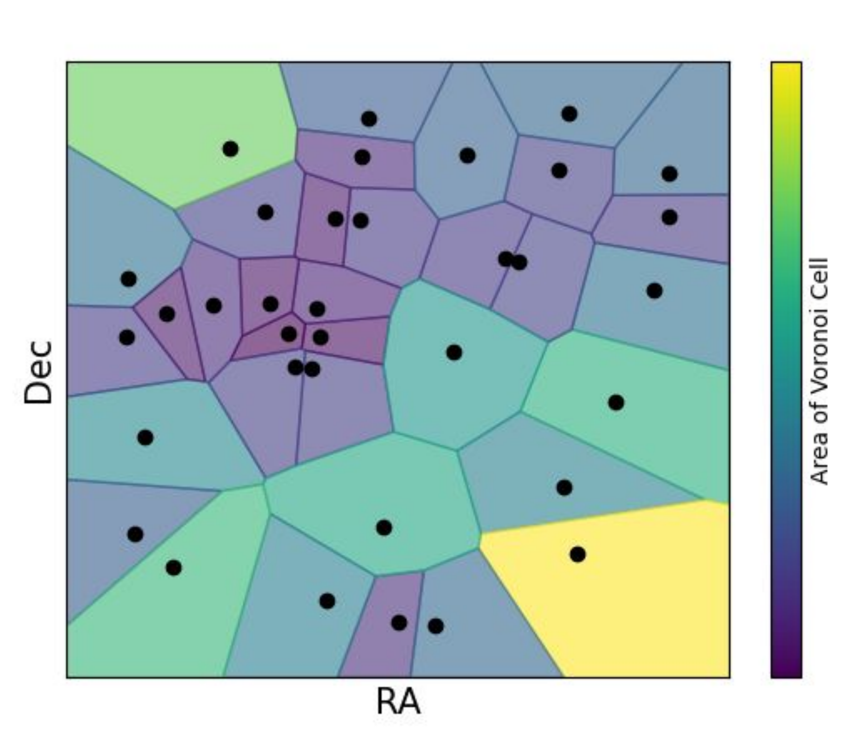


Mapping the Environment

- The VMC cookbook:

1. Make overlapping redshift slices

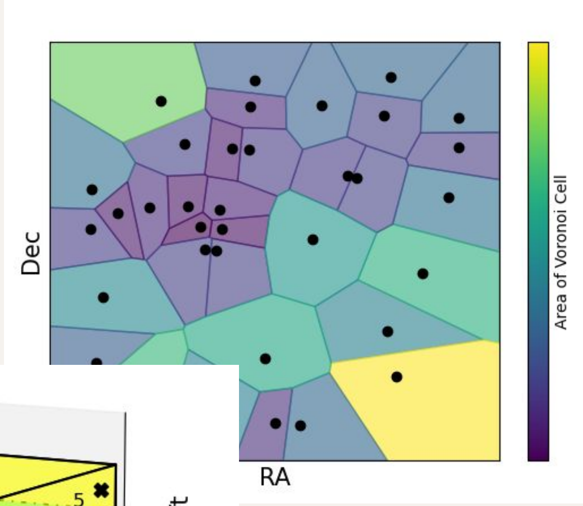
2. Partition each slice into a Voronoi Tessellation map
   a. *Inverse Area ~ Density*

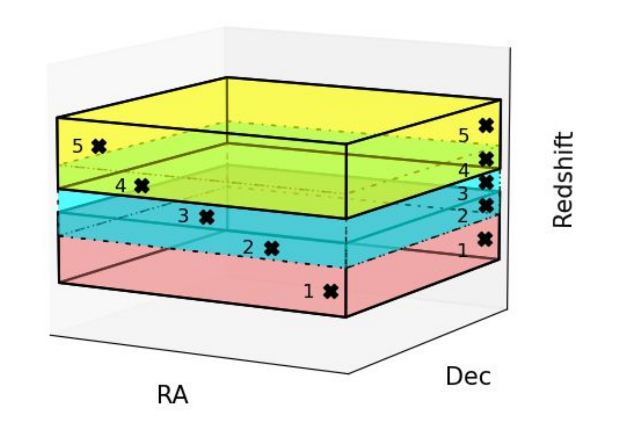


Mapping the Environment

- **The VMC cookbook:**

1. Make overlapping redshift slices
2. Partition each slice into a Voronoi Tessellation map
3. Repeat 100 times, redrawing redshifts each time



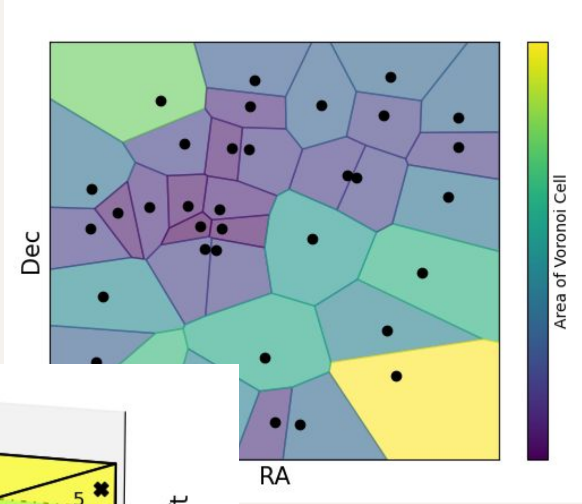


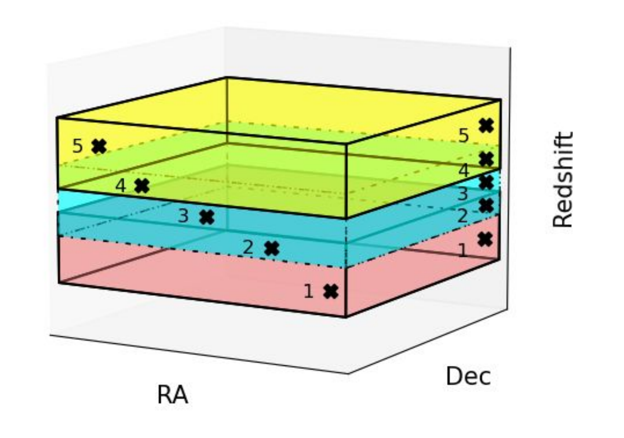
Mapping the Environment

- **The VMC cookbook:**

1. Make overlapping redshift slices
2. Partition each slice into a Voronoi Tessellation map
3. Repeat 100 times

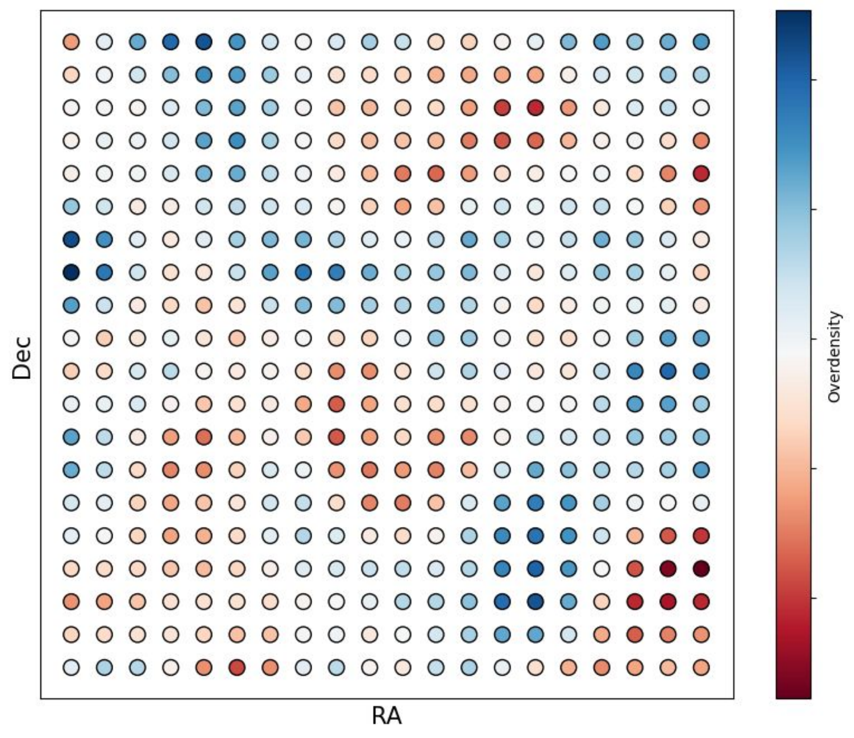
4. **Left with 3D grid of $\log(1 + \delta_{gal})$ values**





Mapping the Environment

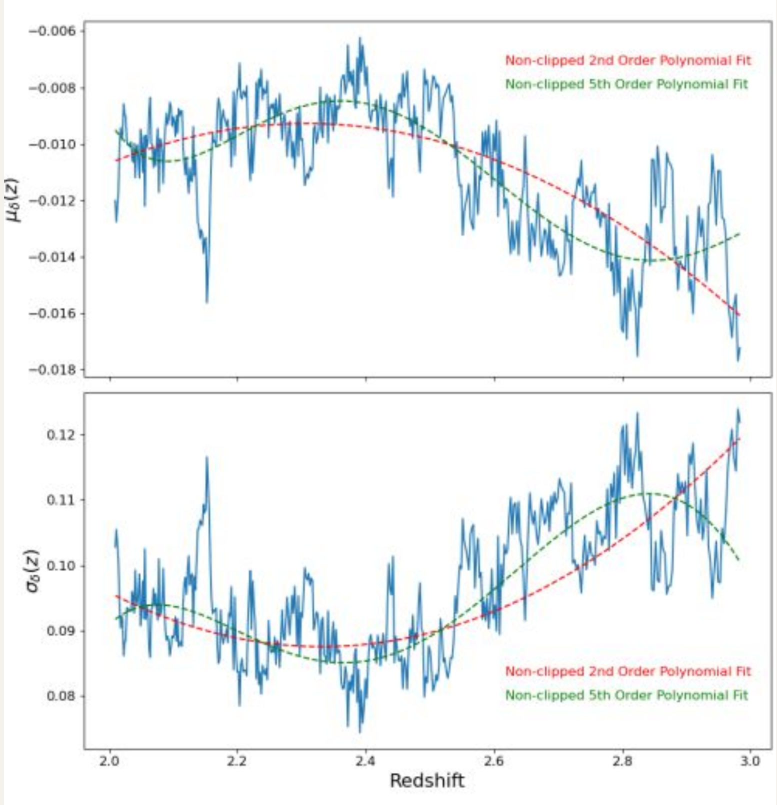
- Find mean and standard deviation of $\log(1 + \delta_{gal})$ in each redshift slice



Mapping the Environment

- Find mean and standard deviation of $\log(1 + \delta_{gal})$ in each redshift slice

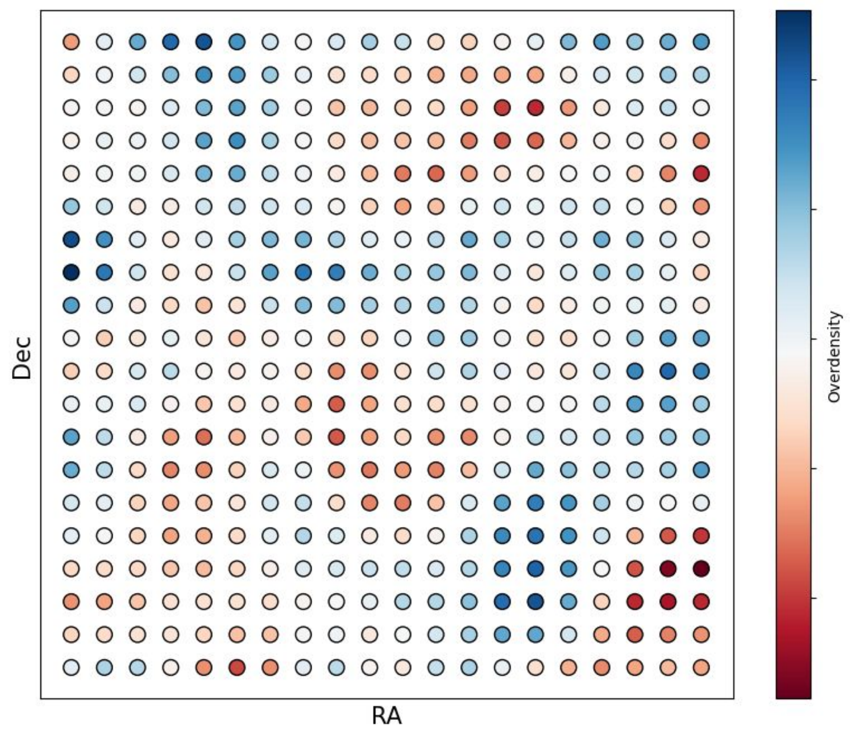
- Fit with higher-order polynomial



Mapping the Environment

- Find mean and standard deviation of $\log(1 + \delta_{gal})$ in each redshift slice
- Fit with higher-order polynomial
- Represent any voxel with one value

$$\log(1+\delta_{\mathrm{gal}}) = \mu_\delta(z) + n_\sigma \cdot \sigma_\delta(z)$$

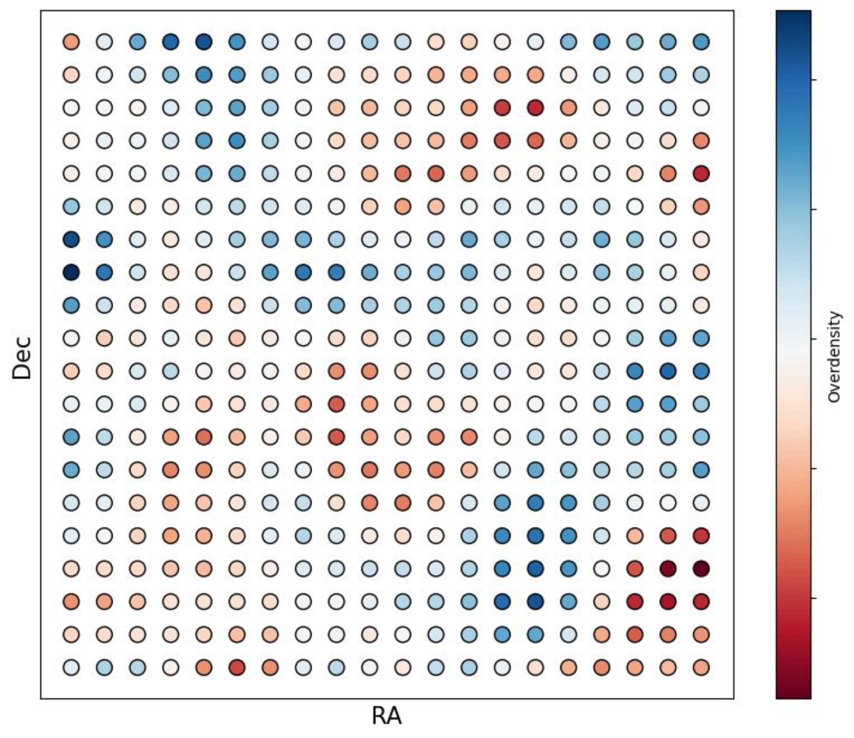


Mapping the Environment

- Find mean and standard deviation of $\log(1 + \delta_{gal})$ in each redshift slice
- Fit with higher-order polynomial
- Represent any voxel with one value

$$\log(1 + \delta_{\text{gal}}) = \mu_\delta(z) + n_\sigma \cdot \sigma_\delta(z)$$

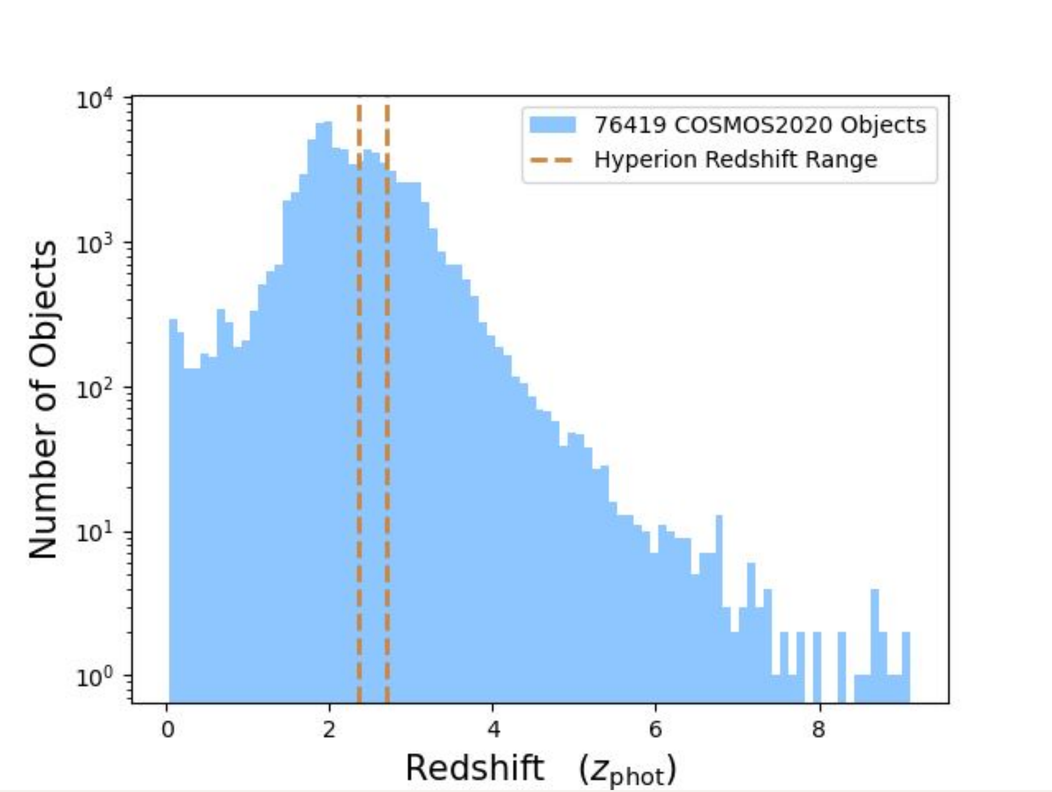
→ n_σ is our proxy for environment



Accounting for Redshift Errors

Limit the COSMOS2020 photometry

- $\leq 5\sigma$ away from $2 \leq z \leq 3$
- Either $[3.6] \leq 25.0$ or $[4.5] \leq 25.0$
- Have all three statistics for confidence interval



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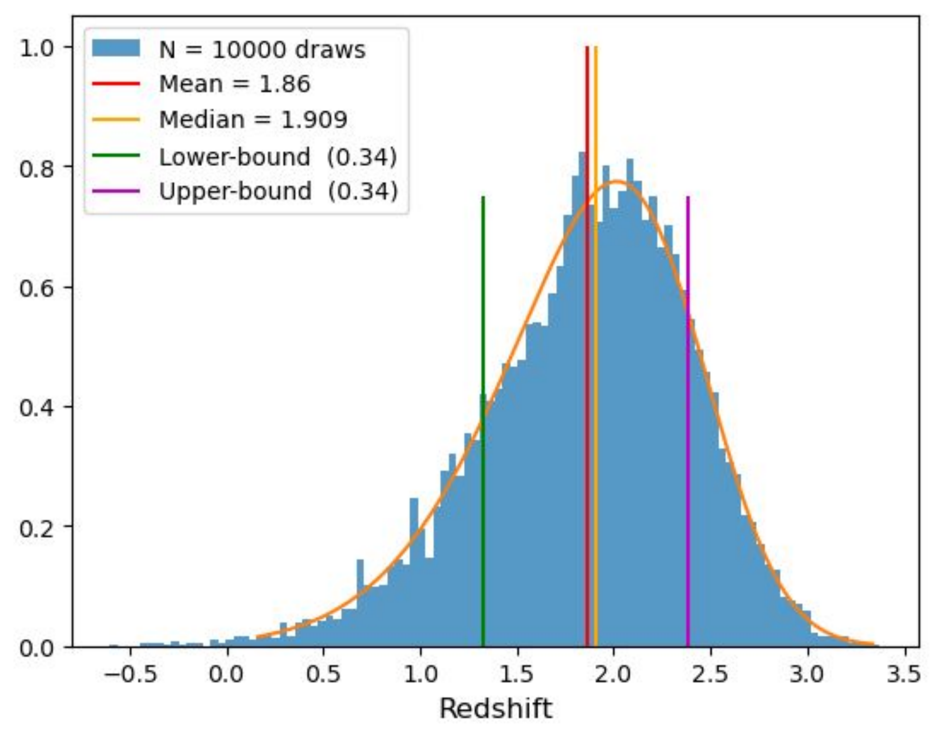
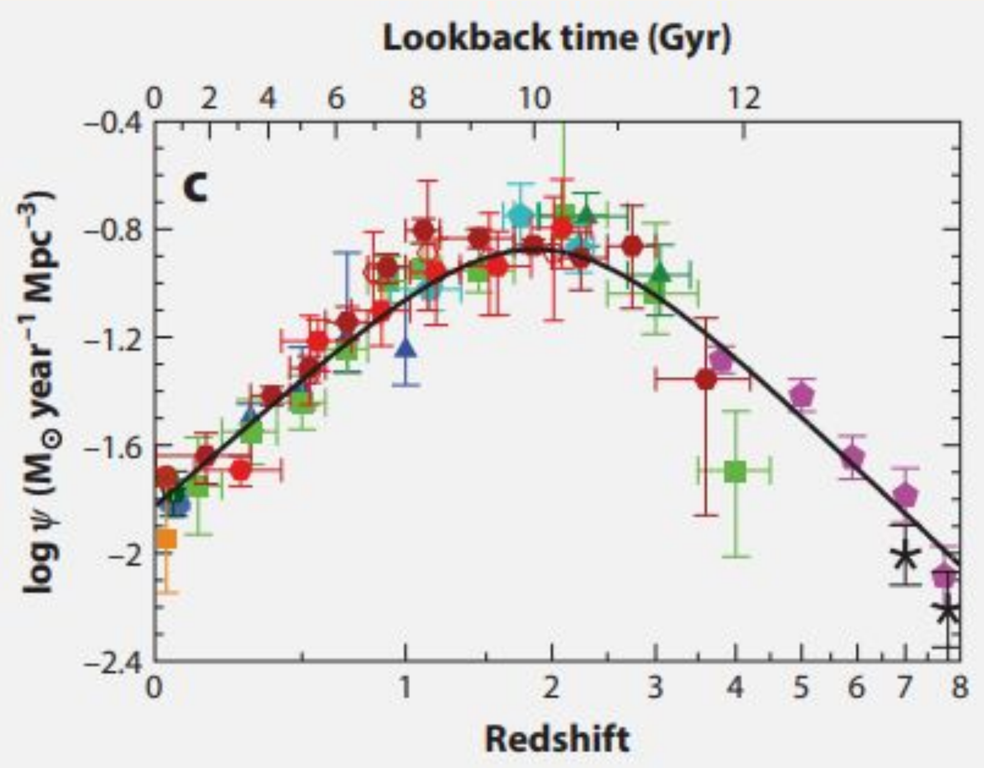
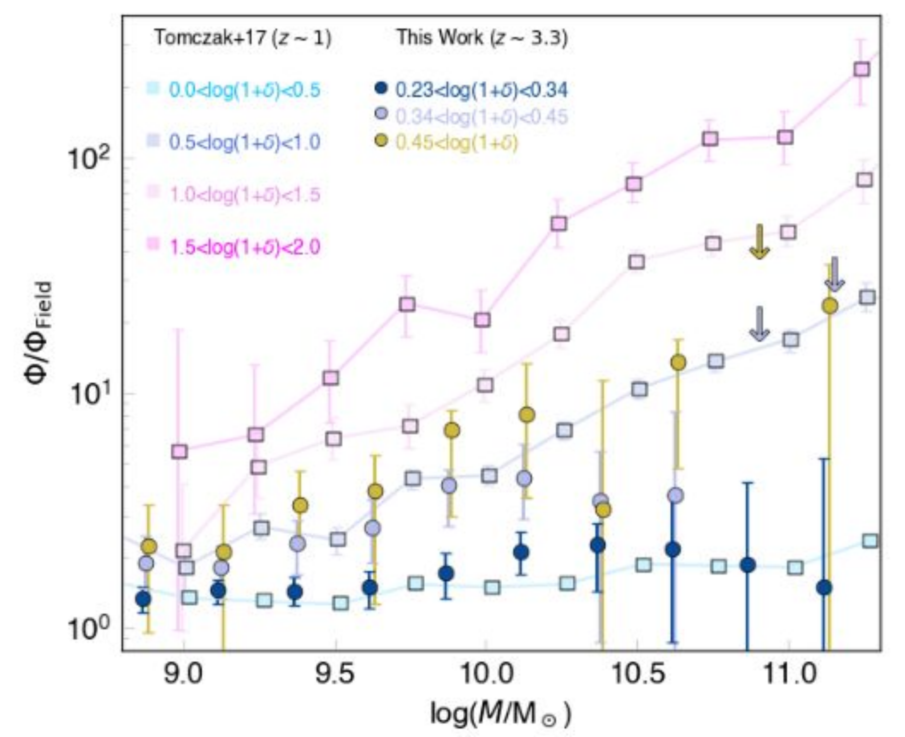


Why at z ~ 2.5?



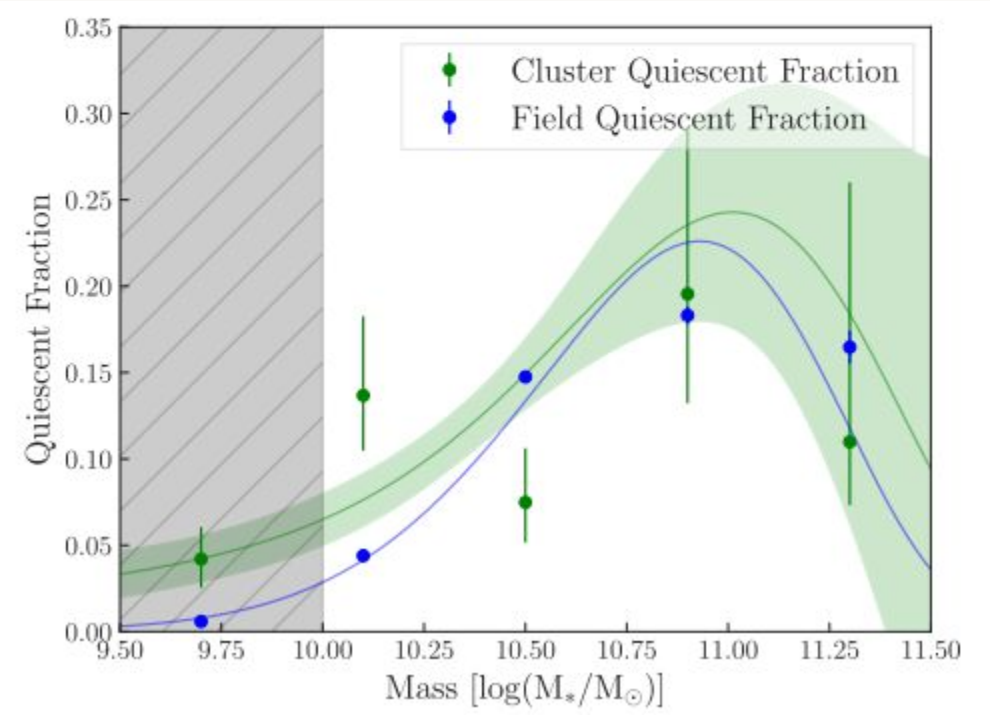
Madau & Dickinson, 2014

Other High-z Studies



Forrest et al., 2024

Other High-z Studies



Edward et al., 2023