Unveiling Large-Scale Structures: New Chapter on Galaxy Environment with the Advent of Prime Focus Spectrograph

Bingcheng Jin

2024.5.23

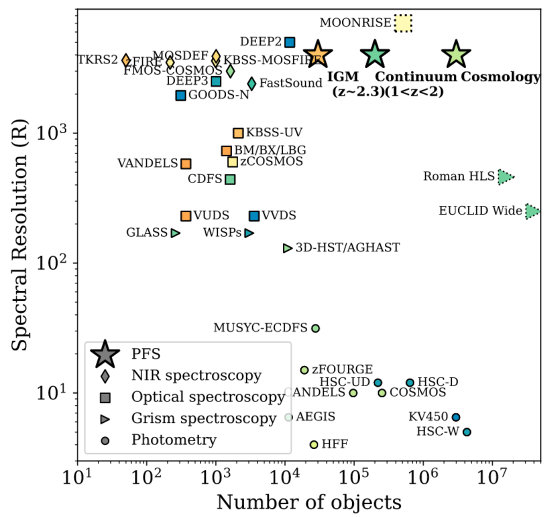
bc.jin@stu.pku.edu.cn

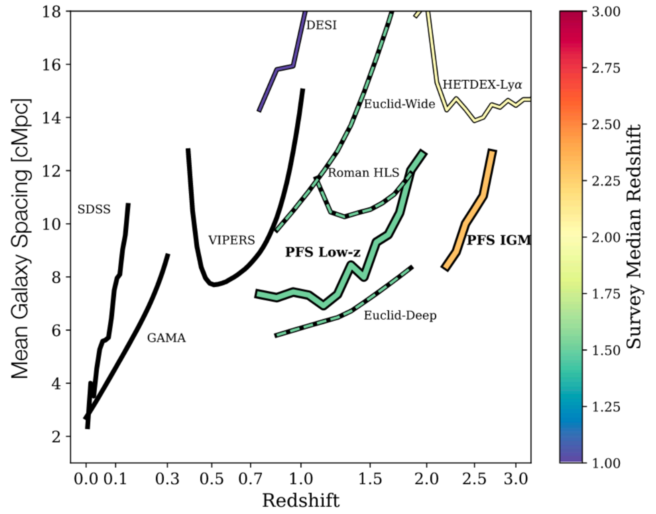
Outline

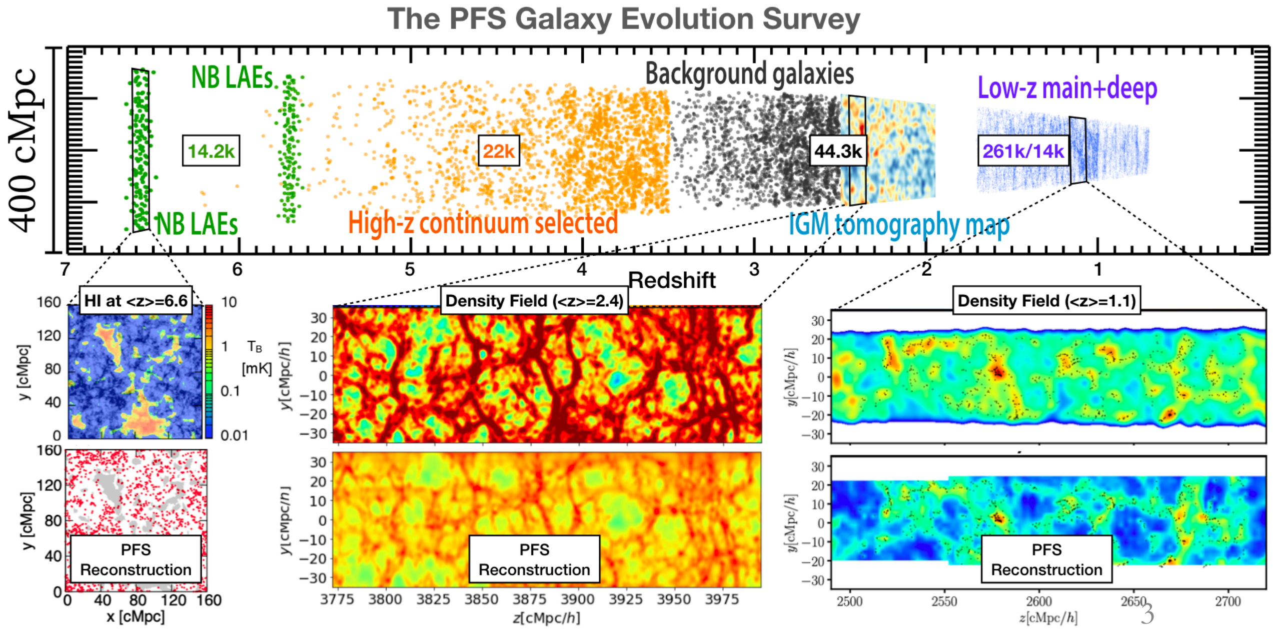
- PFS Galaxy Evolution Survey
- Galaxy Large-Scale Structure
- Galaxy-Halo Connection
- Morphology-Density Relation
- Identifying Protoclusters
- Summary

PFS Galaxy Evolution Survey

- Exposure of 2-hr will provide a high spectroscopic redshift completeness.
- Wide enough area to probe overdensity while overcoming cosmic variance.
- Dense Enough Sampling to trace large-scale structure on 1-3 Mpc scale.







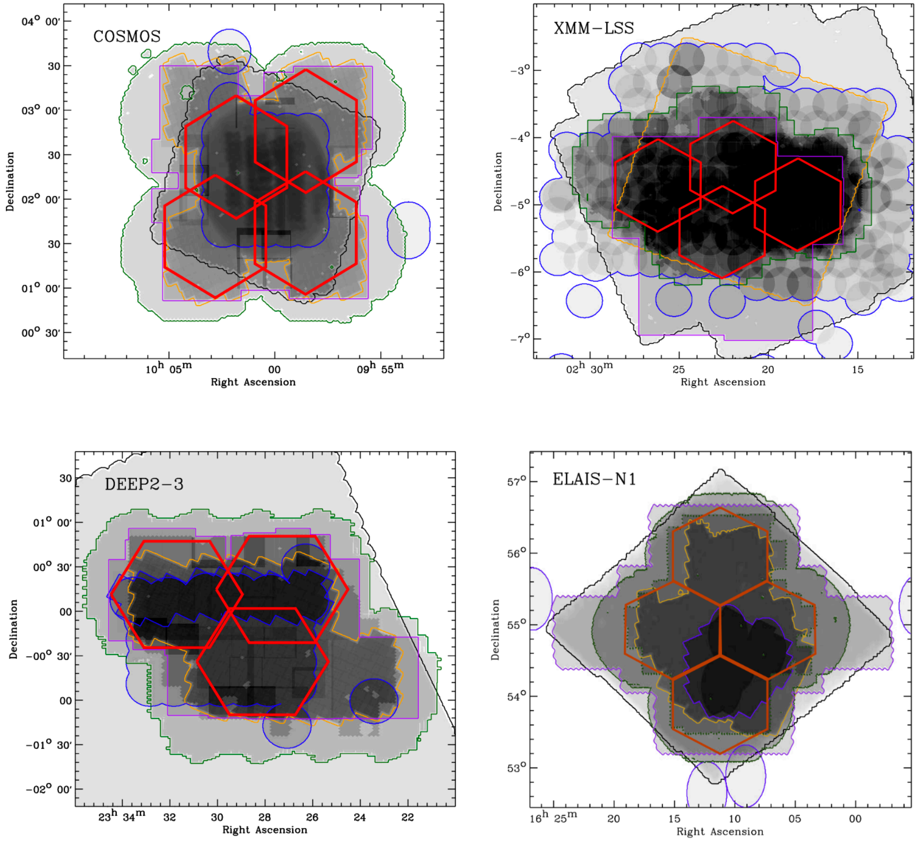
PFS Facilitates Studies of LSS

- 12.3 sq. deg area with PFS pointings overlap with J band imaging.

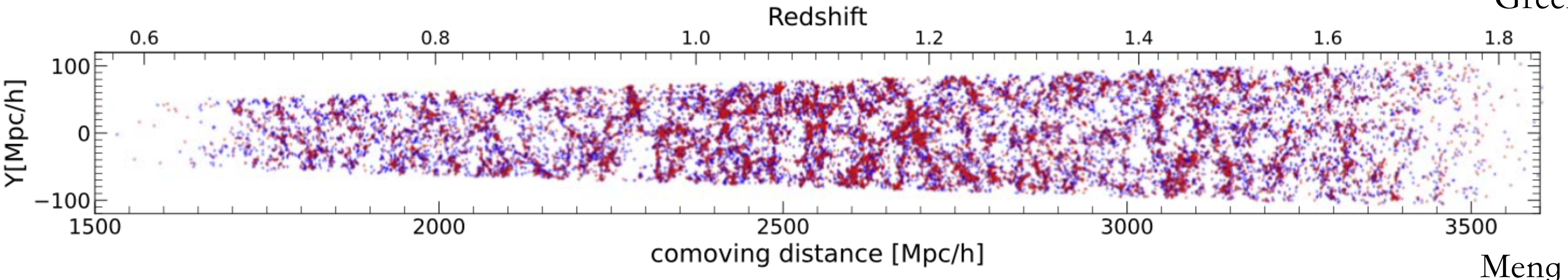
Table 2. Large Scale Structure

Component of the Web	Expected Number
$M_{\rm halo} > 10^{13}\ M_\odot$	2200
$M_{\rm halo} > 10^{13.5}\ M_\odot$	450
$M_{\rm halo} > 10^{14}\ M_\odot$	35
Voids (z<2, r > 7 cMpc)	132,000
Voids (z<2, r > 20 cMpc)	3,000
Voids (z > 2, r > 7 cMpc)	1000
Protoclusters (2<z<6)	100

NOTE—Top three rows quantify the number of massive halos that we expect above this limit in the PFS volume. Next three lines quantify the number of voids with the given redshift and size limits. The final entry is the expected number of protoclusters.



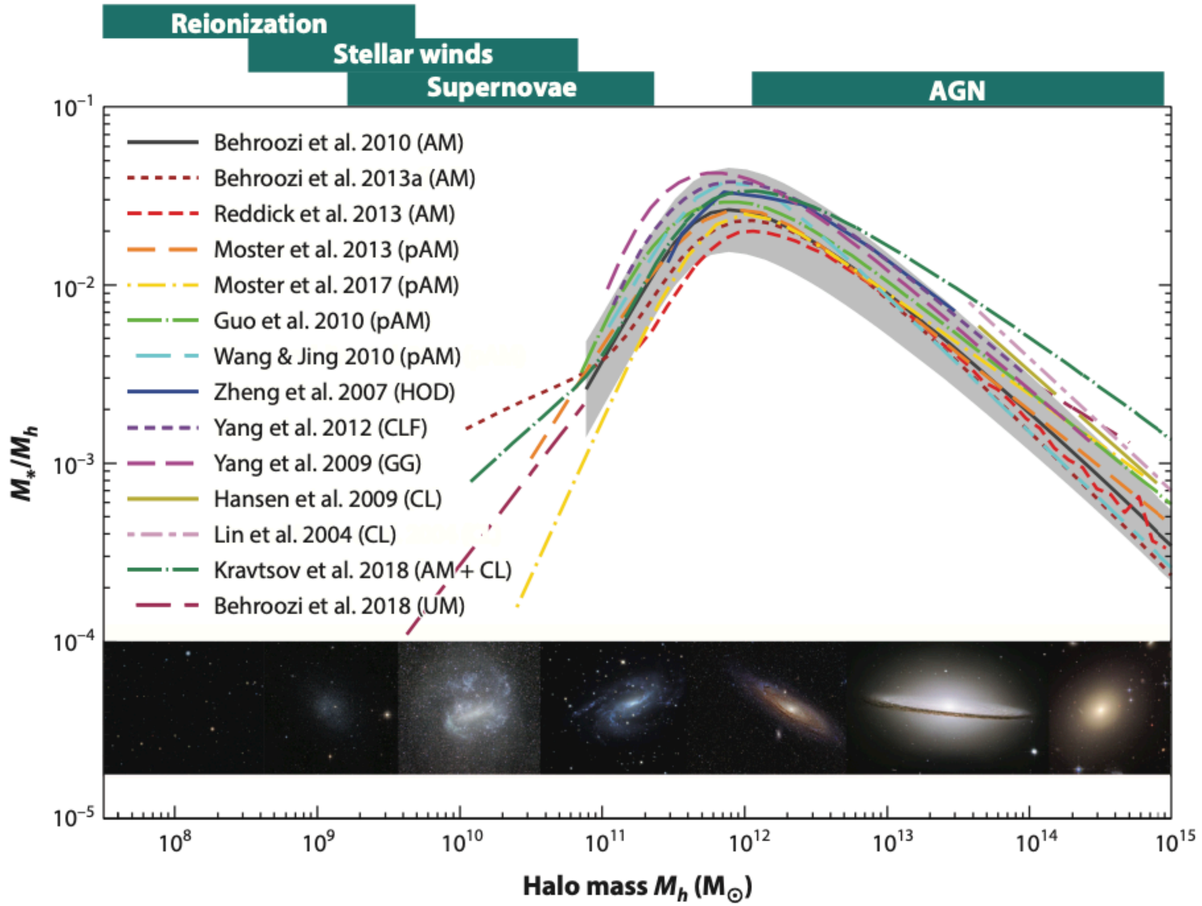
Greene et al. 2024



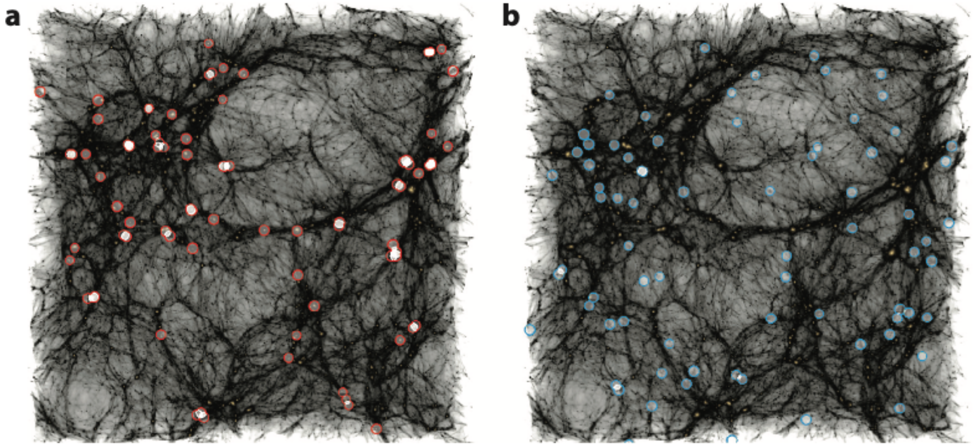
Meng et al. 2024

Galaxy-Halo Connection

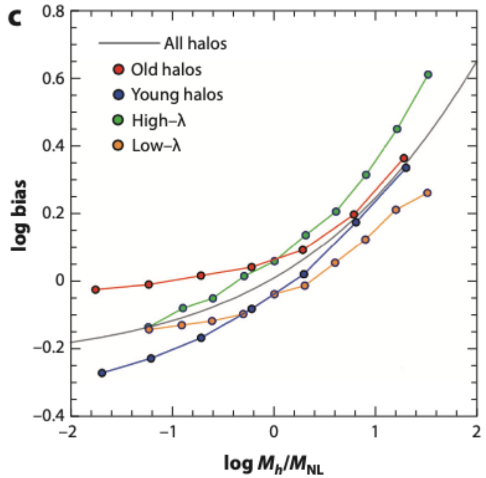
- Galaxy properties to match DM Halos? Stellar Mass, Luminosity, Sizes
- SHMR, or SMHM relation



- Halo Assembly Bias — Secondary Properties:
- At fixed stellar mass, SFE depends on halo properties other than halo mass.



High Halo Concentration



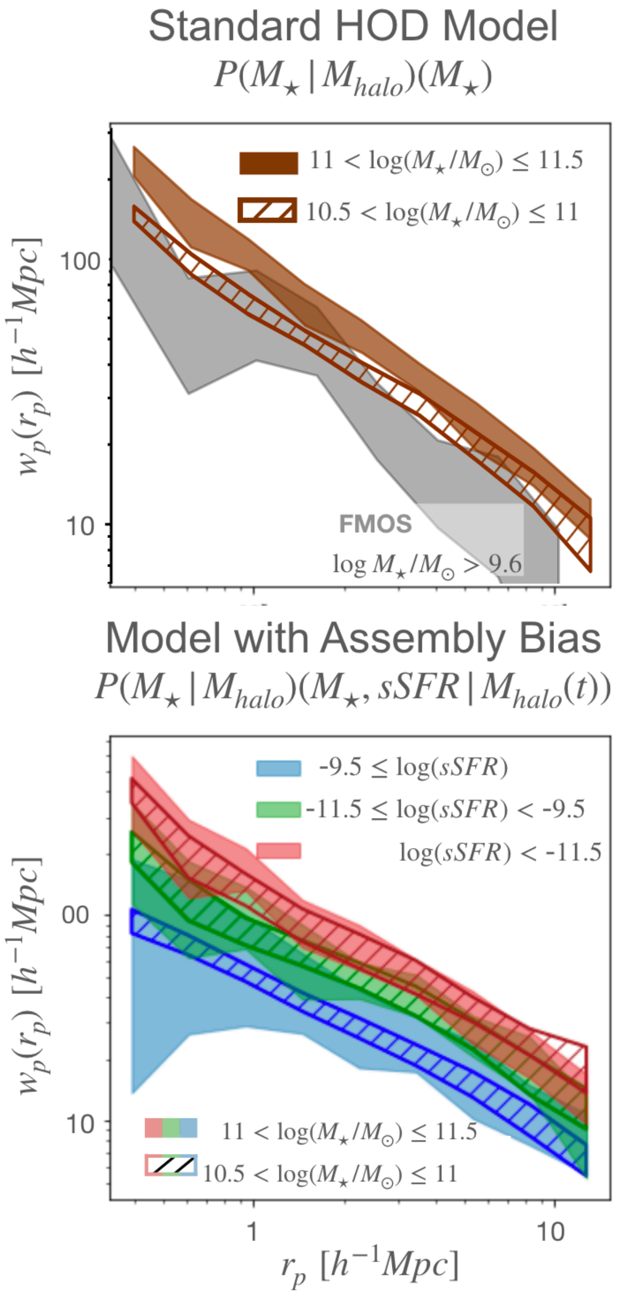
Low Halo Concentration

Wechsler & Tinker 2017

Tuning with 2PCF

$$w_p(r_p, \pi) = 2\int_0^{+\infty} \xi(r_p, \pi)d\pi$$

- Stronger clustering of older (or lower sSFR) galaxies at fixed stellar mass.
- There are currently no $z > 1$ spectroscopic data sets that are comparable in size to PFS.
- To stress the importance of Assembly Bias, no other photometry or spectroscopic survey at $z > 1$ except PFS will have:
    - Necessary statistics; Accurate 3D positions; $M_\star$, SFR estimates

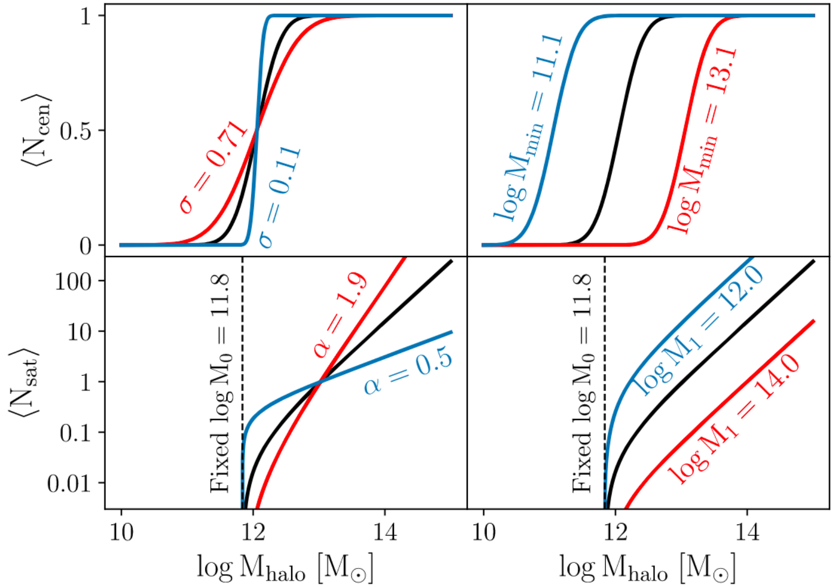


Greene et al. 2022

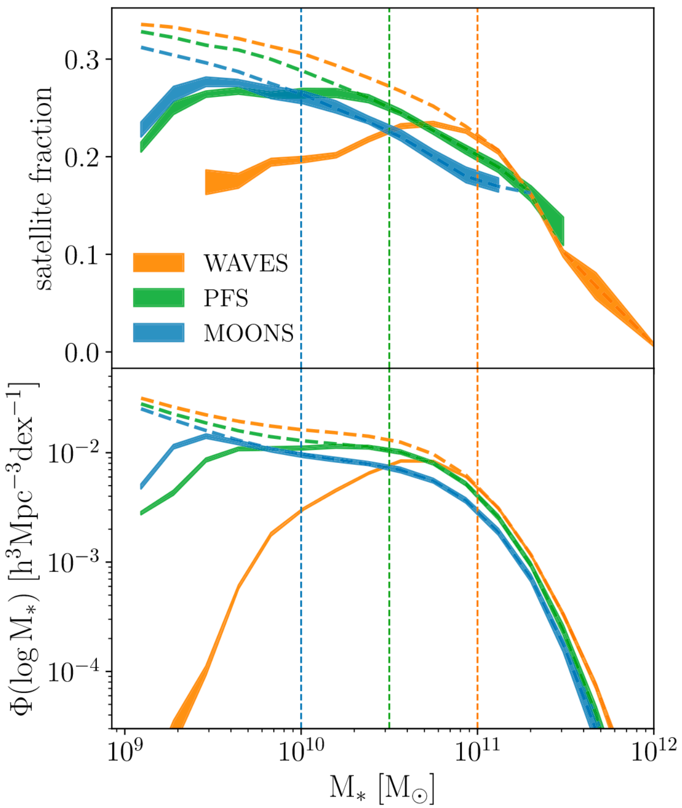
Constraints on the HOD parameters

$$N_{\rm cen} = \frac{1}{2}\left(1 + {\rm erf}\left(\frac{log(M_h/M_{\rm min})}{\sigma}\right)\right)$$

$$N_{\rm sat} = \left(\frac{M_h - M_0}{M_1}\right)^{\alpha}$$



Constrain by abundance



Mock result from Pearl et al. 2022

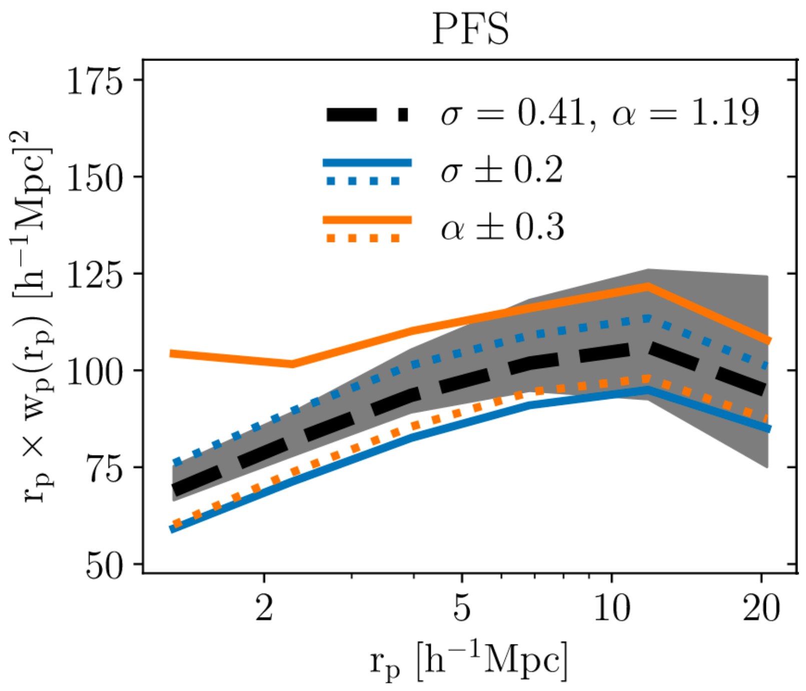
- PFS will improve $M_\star$ estimates from stellar population synthesis via spectra, which is expected to substantially constrain SMF at $z > 1$.

$$n = \int_{M_{*thresh}}^{+\infty} \Phi(M_*)dM_*$$

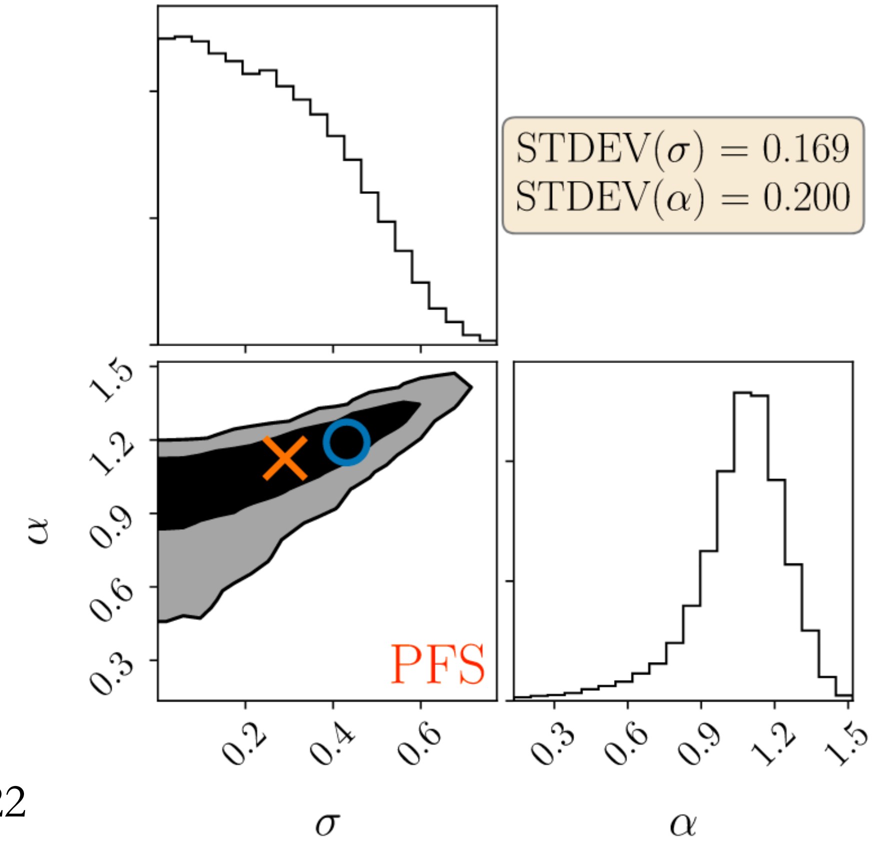
Constraints on the HOD parameters

Constrain by clustering

- Calibrating with better 2PCF measurement will provide necessary constraints on HOD parameters.



- MCMC: constraining parameter space of HOD



Pearl et al. 2022

Spectroscopic Redshift Survey: Difficulties

- Redshift Sampling Rate (Pozetti et al. 2010)
- Cosmic Variance (Somerville et al. 2004)
- Fiber Collision Effect (Hawkins et al. 2003)
- Flux Selection Criteria (Meneux et al. 2008, 2009)

	zCOSMOS	PFS	SDSS
Overall redshift sampling rate	55%	50-70%	Nearly 100%

Meng et al. 2024

Table 3. Full Target Table

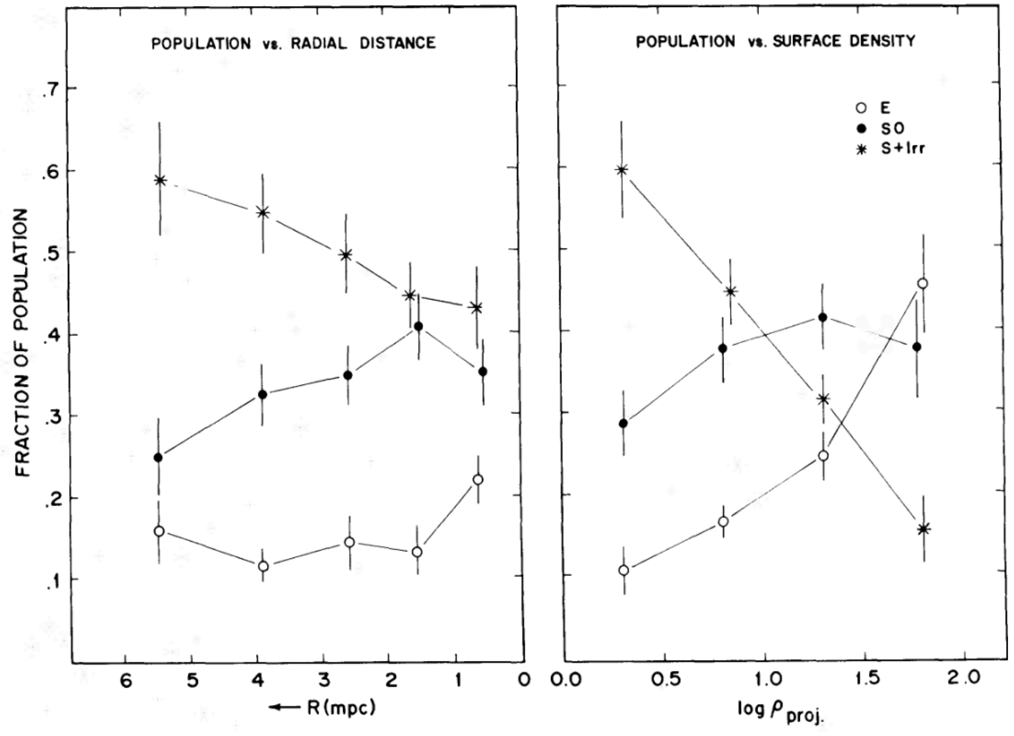
Redshift range	Selection	Exp. Time (hrs)	Targets PFS FOV	Sampling rate (%)	# of spectra (10^3)	Fiber khrs
Continuum-selected						
$\lesssim 1$	$i<23$	2	6100	40	24	48
$0.7-1$	$y<22.5+z_{\rm ph}$	2	11900	50	58	116
$1-2$	$y>22.5+z_{\rm ph}$ + $J<22.8$	2	11800	70	81	162
$0.7-2$	$y<22.8+z_{\rm ph}$	12	1220	...	12	144

Greene et al. 2022

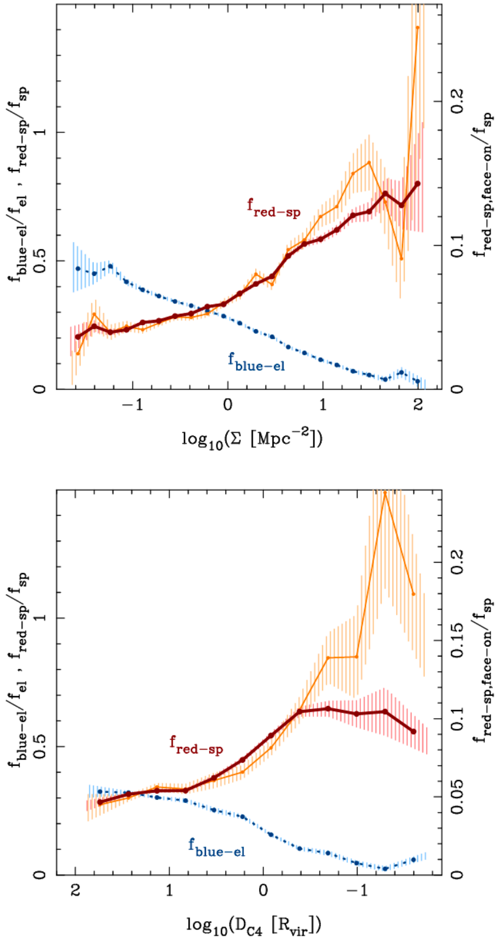
Specifically: a scale of 1 h^{-1}Mpc correspond to 106” @ z=0.8, 78.7” @ z=1.2, and 65.2” @ z=1.6

Morphology-Density Relation

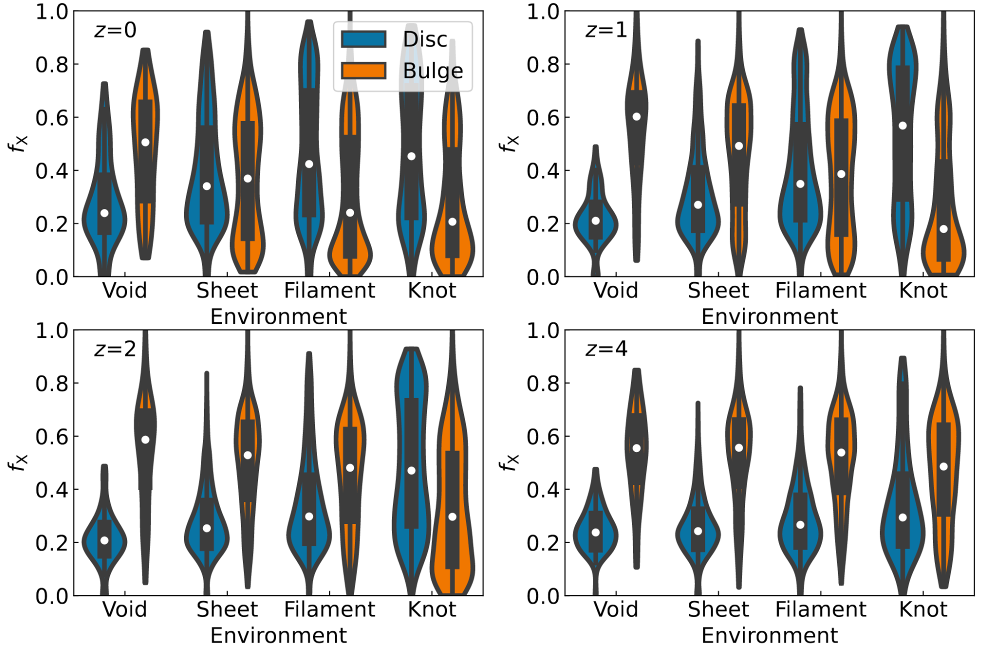
- $T-\Sigma$ relation; $T-R$ relation
- Color-Density relation
- To earlier universe: How galaxy morphology evolve with its environment, observationally?
- To larger scales: How galaxy evolution is connected to cosmic web, observationally?



Dressler 1980



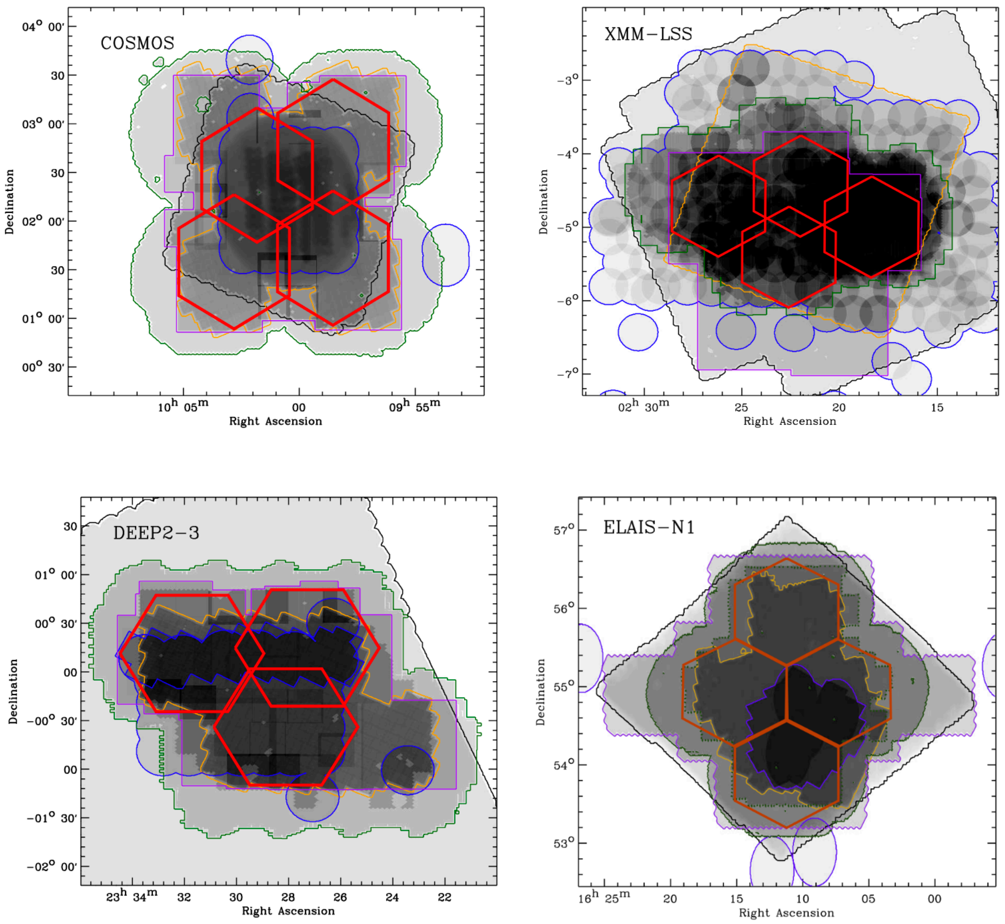
Bamford et al. 2010



From TNG Simulation (Liang et al. 2024)

Morphology in Groups

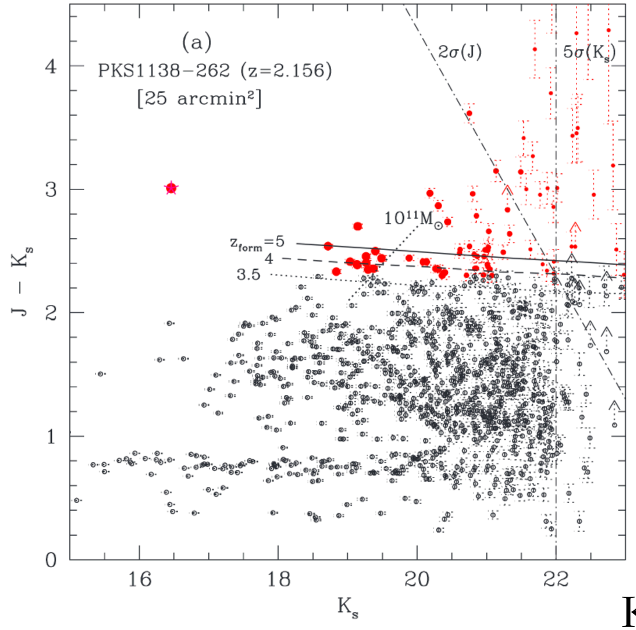
- Deep fields such as SXDF with HST observations available (or even JWST)
- Quantify density field at low/median-densities
- Remove foreground/background contaminations; Identify group environments easily
- First data set that allows the statistical study of morphology-density relation at $z > 1$



Greene et al. 2022

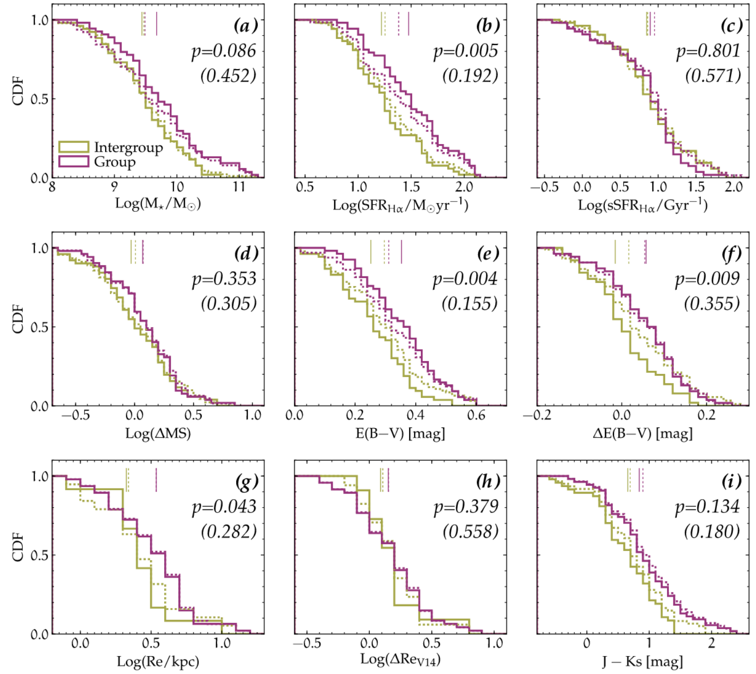
Build up of Red Sequence

- When and where galaxies quench?
- High-z protoclusters are ideal testbeds for understanding the physical processes that drive substantial excess of red sequence galaxies in today's cluster centers.
- Group galaxies shows discriminative SFR enhancement at high redshift.
- Statistics of high-z protoclusters are required (Overzier 2016).



Accelerated Building up in high density: Red Sequence at its early stage

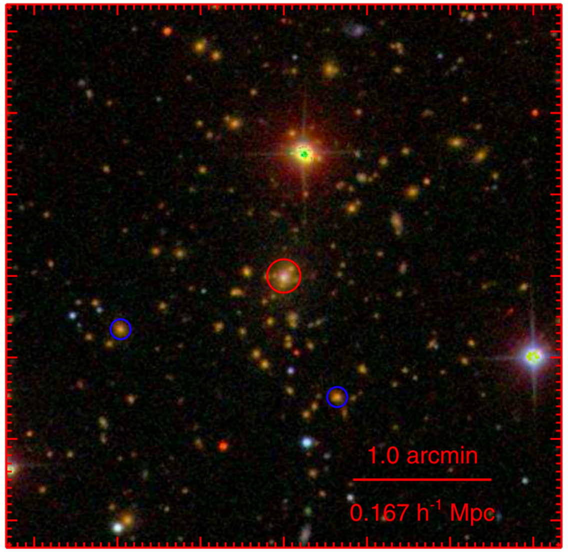
Kodama et al. 2007



A protocluster at z = 2.53 (Shimakawa et al. 2018)

Search for Protoclusters

- Red Sequence BCG (e.g., Rykoff et al. 2014)



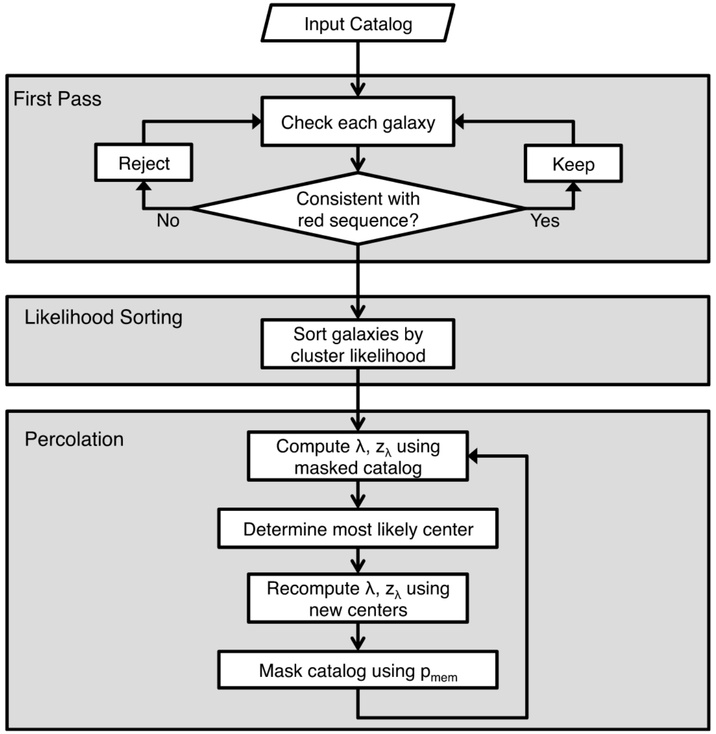
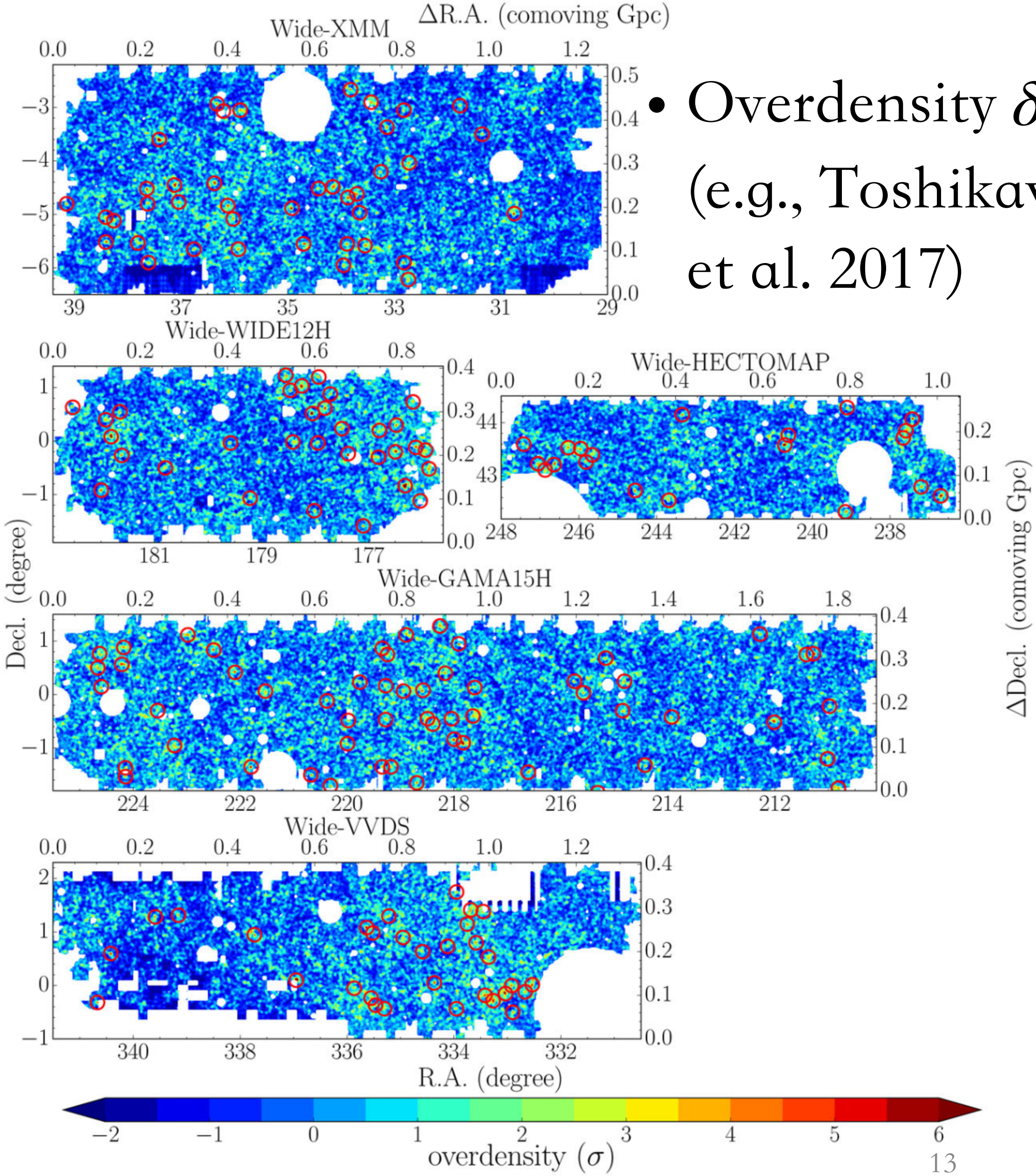


Figure 15. Process flowchart for the redMaPPer cluster finder.

- Overdensity δ_{gal} (e.g., Toshikawa et al. 2017)



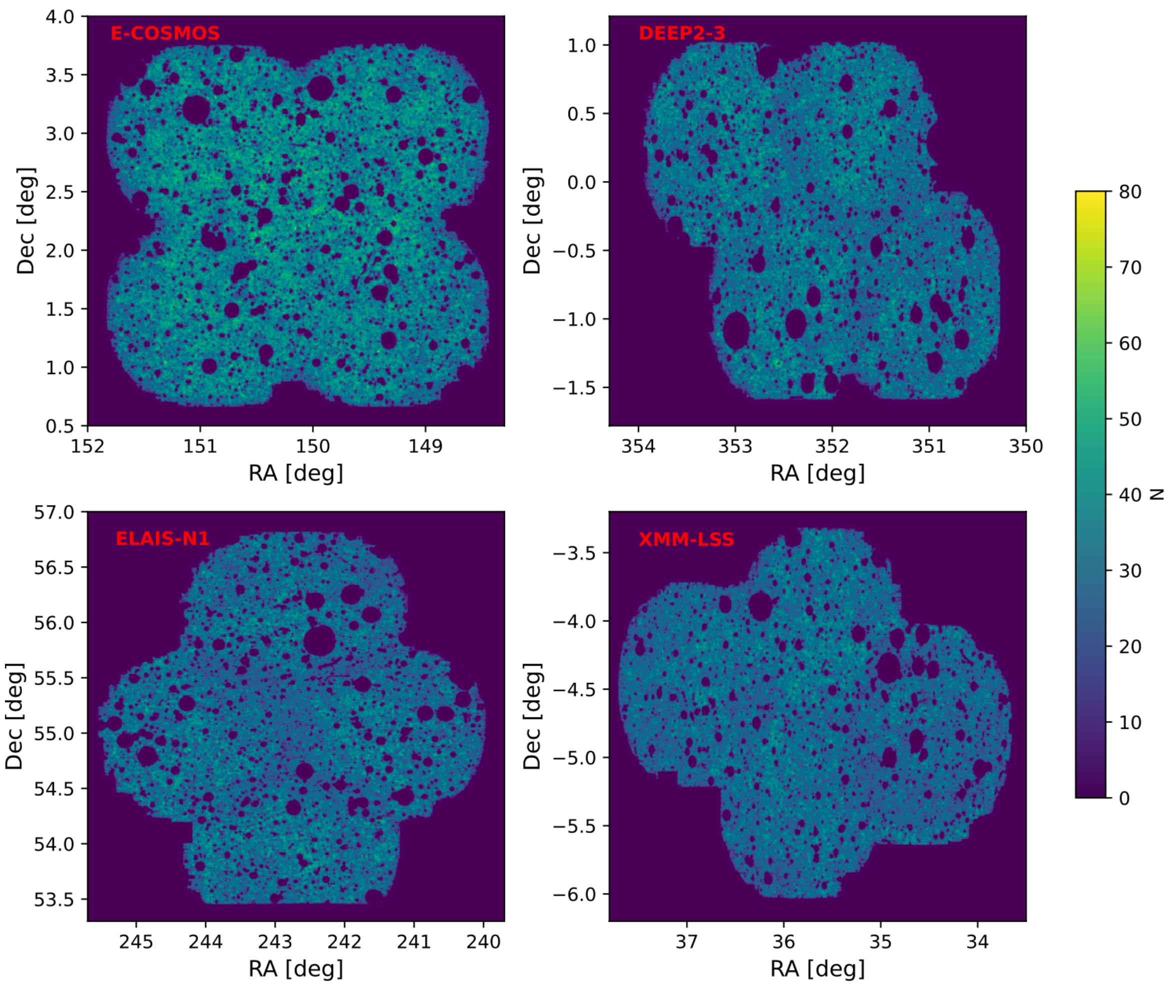
Identifying Protoclusters with HSC-SSP

- grizy 5 bands + CLAUDS U (CFHT Large Area U-band Deep Survey)

  The HSC-SSP data contains *grizy* five wavebands with the depths of $g_{\rm AB} \sim 27.3$, $r_{\rm AB} \sim 26.9$, $i_{\rm AB} \sim 26.7$, $z_{\rm AB} \sim 26.3$ and $y_{\rm AB} \sim 25.3$ (5σ in 2 arcsec apertures) in the Deep and UltraDeep regions (Aihara et al. 2019),

- HSC-SSP data: 14,789,205 objects over 34.31 sq. deg

- Selection: i-band apparent magnitude limit $m_i < 26$ and magnitude error $\sigma_i < 1$



Li et al. 2022

Finding the Protocluster Candidates

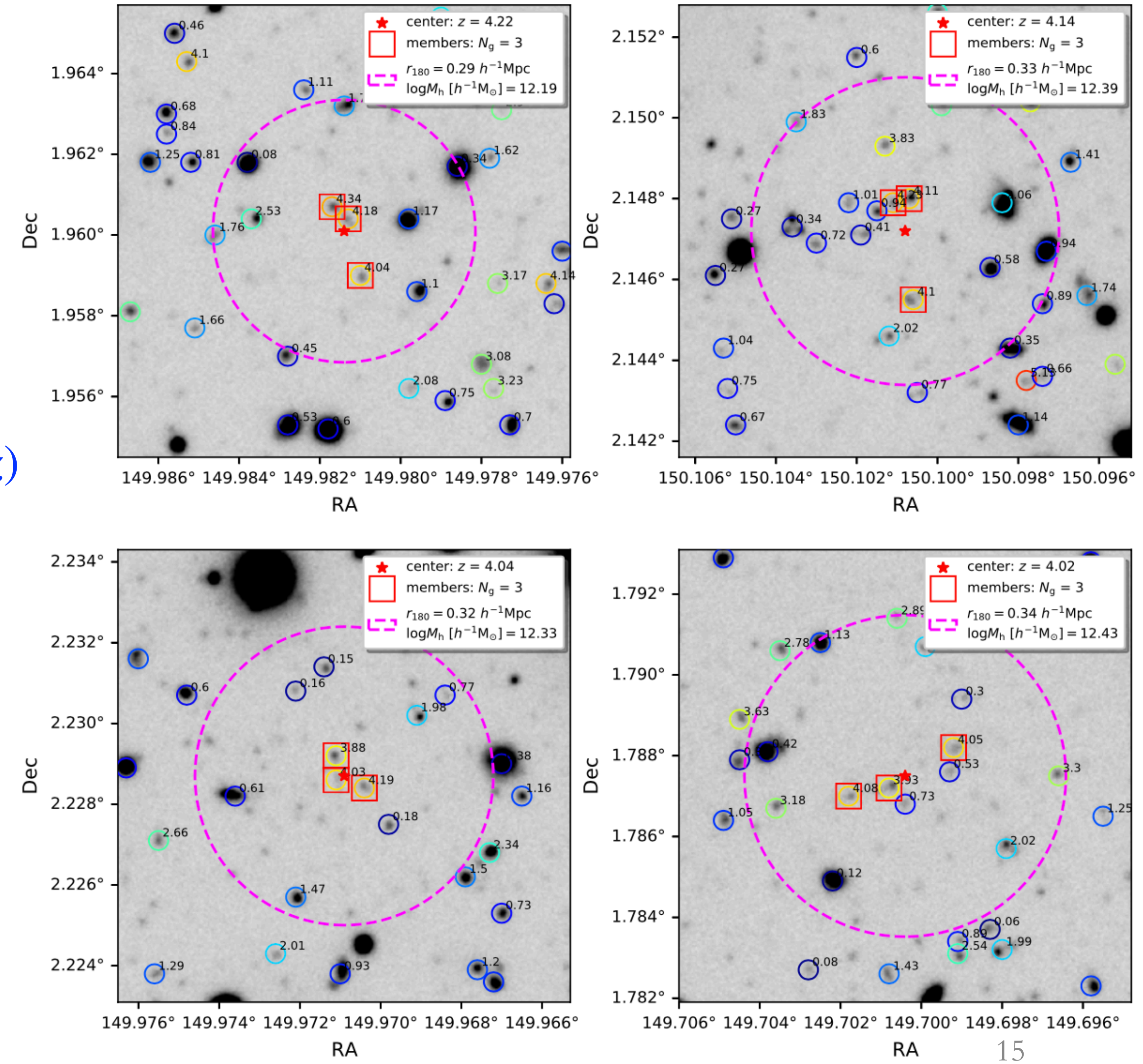
Li et al. 2022

- Halo-based Group Finder: Simultaneously use photometric or spectroscopic redshifts (Yang et al. 2005; 2007, 2021)

- 0. Assume each galaxy is a group
- 1. $L_G = \sum L_i$
- 2. M-L ratio (Yang et al. 2007): assign M_L
- 3. Halo radius r_{180} , velocity dispersion σ_{180}
- 4. $P_M(R, \Delta z) = \dfrac{H_0}{c} \dfrac{\Sigma(R)}{\bar{\rho}} p(\Delta z) \geq B \dfrac{\sigma_{180}}{\sigma}$; $p(\Delta z) \sim N\left(0, \dfrac{\sigma}{c}(1 + z_{\rm group})\right)$
- Iterate 1-4 until no further changes

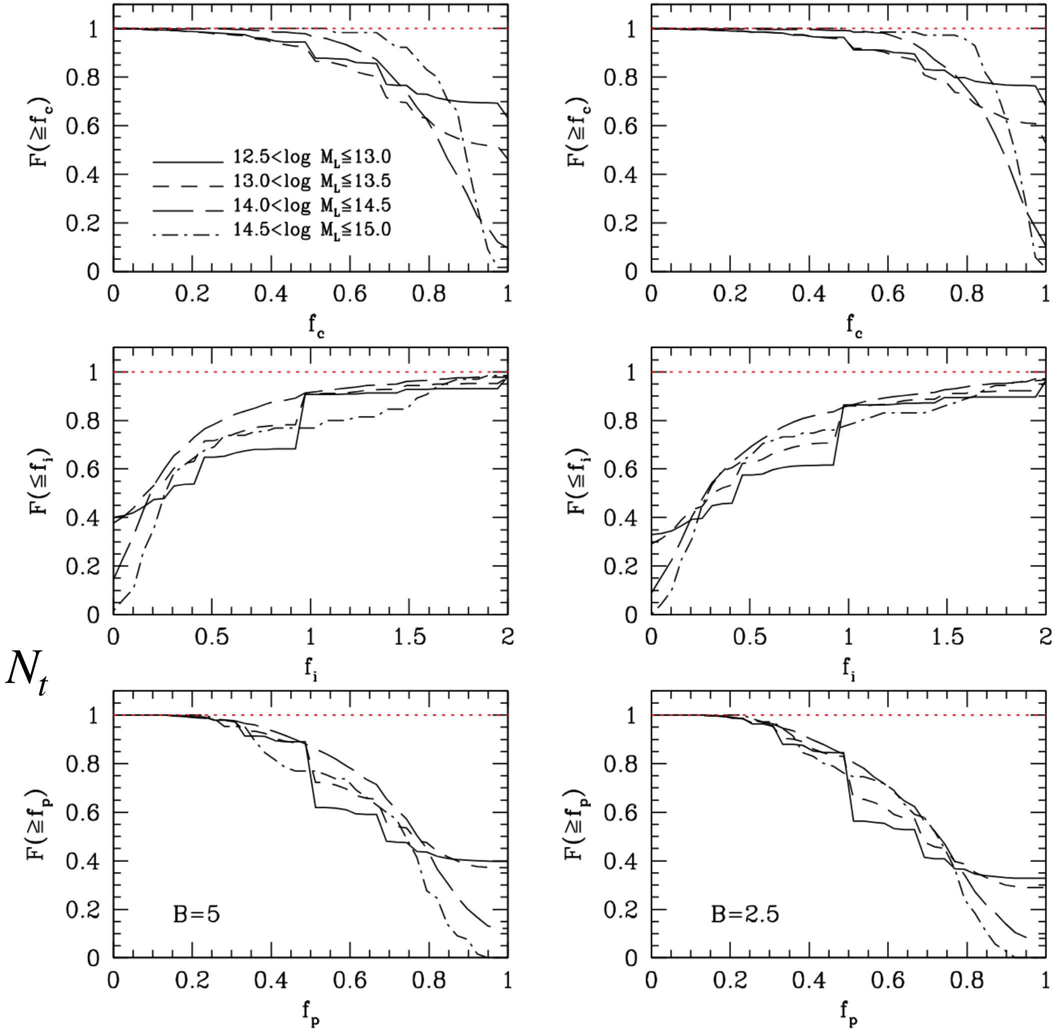
$\sigma = \max(\sigma_{180}, c\Delta z)$

- No need for BCG observation or overdensity that could be contaminated.

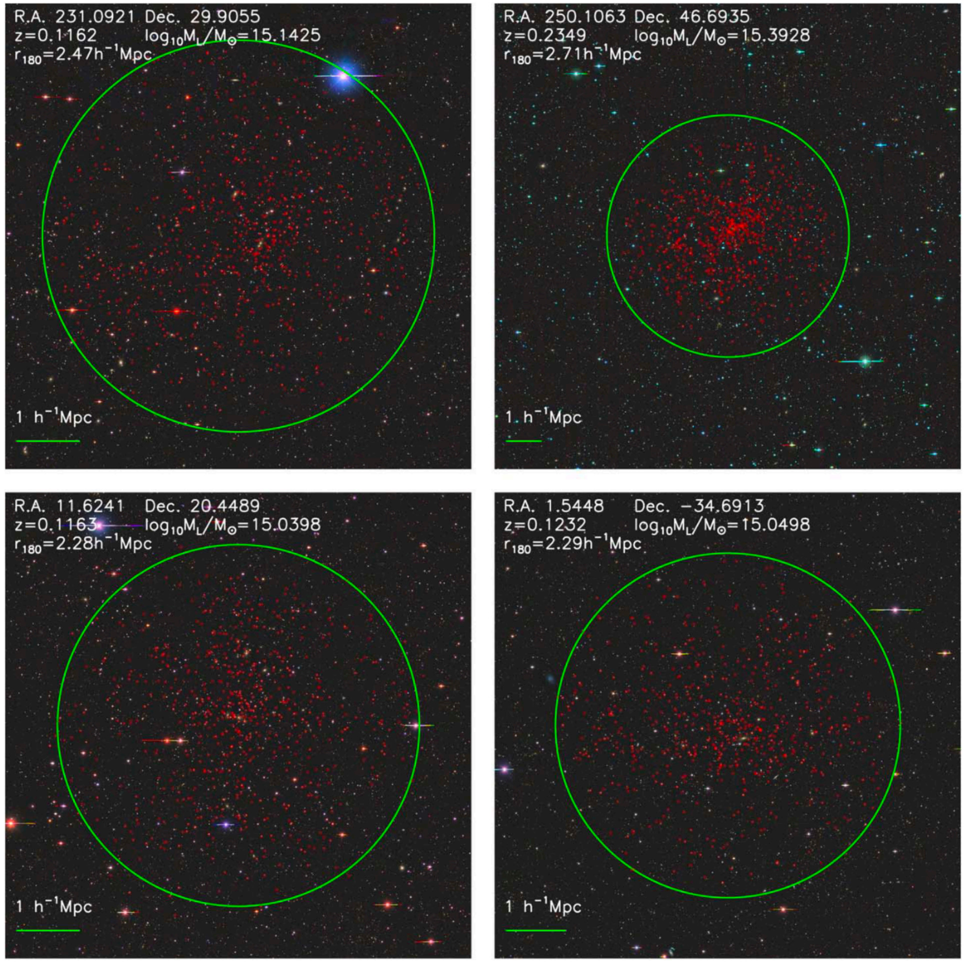


Application on DESI Legacy Imaging DR8

N_g, N_s, N_t



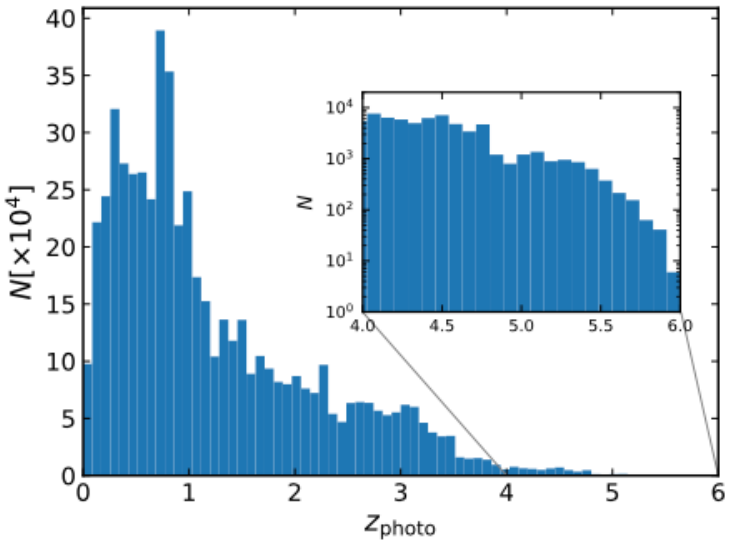
Mock results



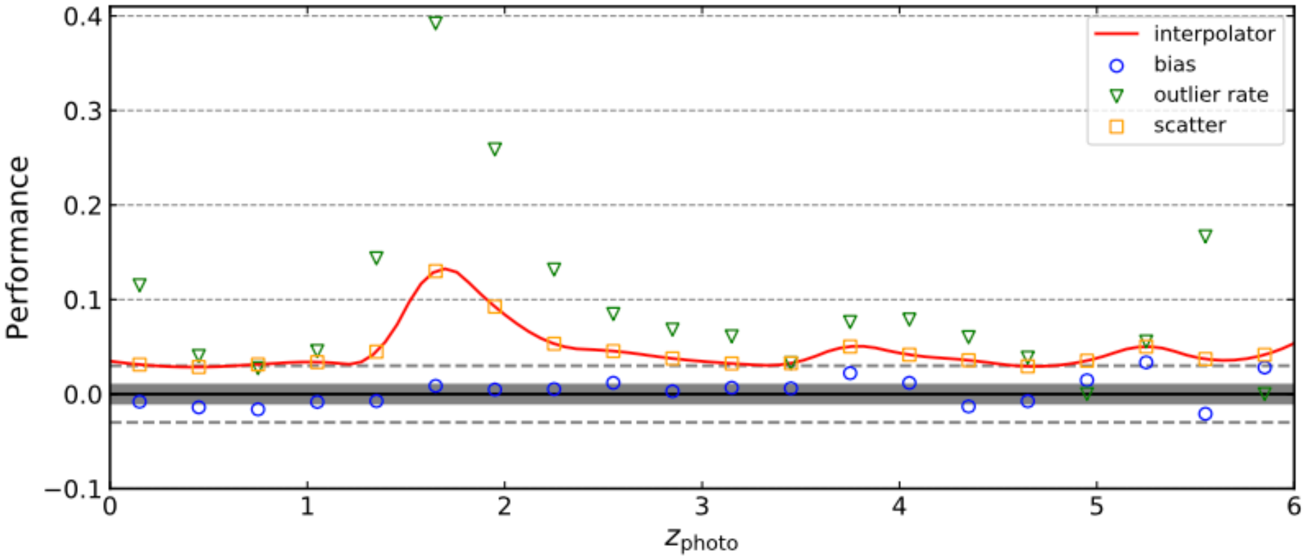
Yang et al. 2021

Combined with PFS

- Redshift range: $0 < z < 6$
- kNN (Sawichi et al. 2019) + LEPHARE (Arnouts et al. 2002; Ilbert et al. 2006)
- PFS: update photo-z with spec-z
- Improvement of Completeness and Purity



Li et al. 2022



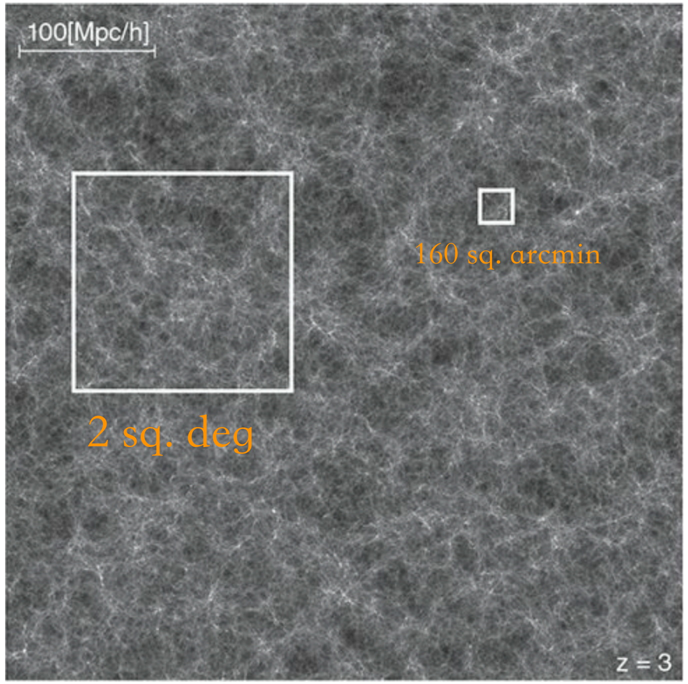
Summary

- PFS will facilitate the study of LSS with its tremendous multiplexing capability: Sampling, Resolution, Wavelength Coverage
- Justifications of Galaxy-halo connection:
    - Mitigating bias from observation limits
- Discerning environmental effects on galaxy evolution via:
    - accurate 3D positioning, physical properties;
    - robust clustering measurement, necessary statistics.
- Combined with ground-base/space-base imaging surveys (perhaps CSST), PFS will reach its maximum potential in studying galaxy environment.

Appendix

Galaxy Environments and LSS

- Cosmic Web
- Cluster
- Galaxy and its host DM Halo



Lacey et al. 2016

- Large skyarea coverage: 12.3 sq. deg

- Dense Sampling: Mean inter-galaxy spacing between 7 and 10 Mpc, reaching virial radius of $\sim 10^{12}$ solar mass halos.

- Accurate physical properties estimations:
  - $M_\star$
  - SFR (sSFR)
  - Redshift
  - etc