Small-scale Clustering in Large Galaxy Surveys

Peter Hatfield, University of Oxford

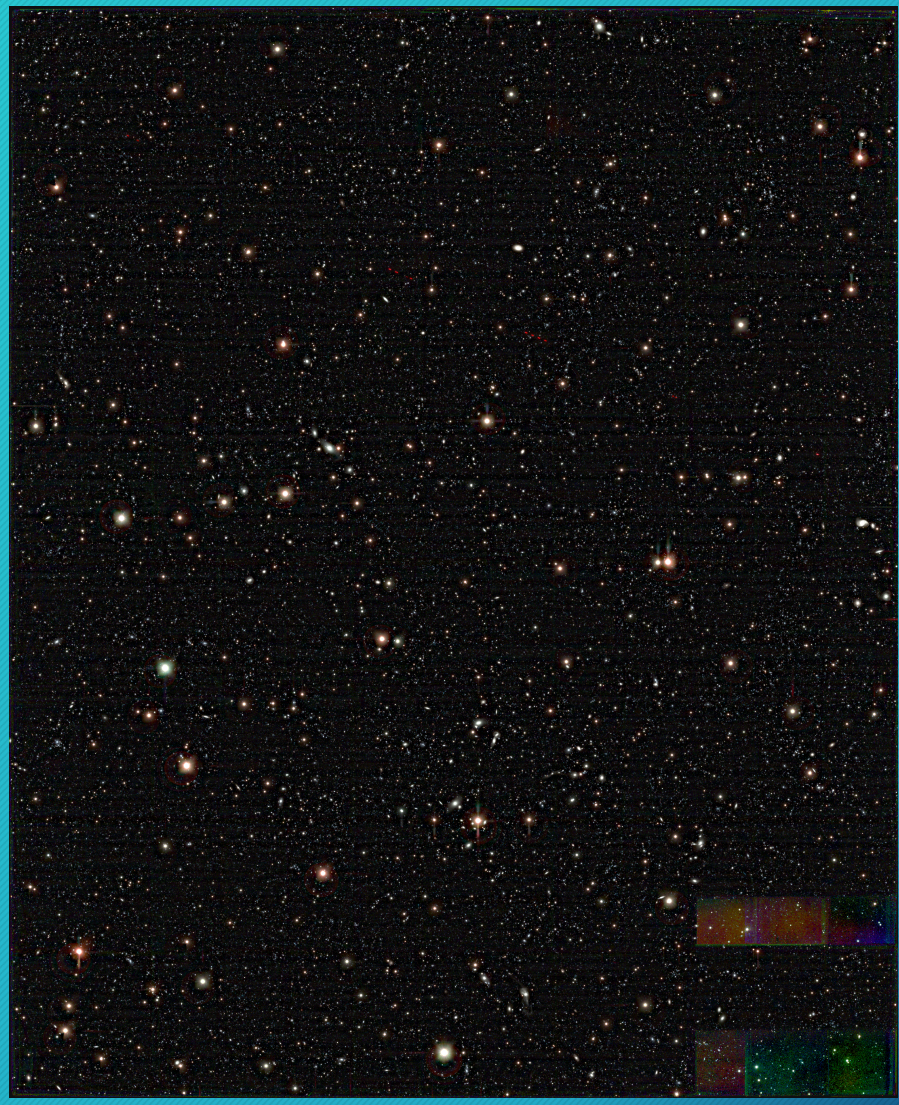
LSST@Europe3, Lyon, 14th June 2018

Matt Jarvis, Clotilde Laigle, Rebecca Bowler, Catherine Hale, Aprajita Verma

Talk Summary

- Understanding the ***non-linear*** clustering of galaxies gives important information about galaxy environment and how galaxies and baryons trace matter – beyond just bias
- VISTA surveys (VIDEO-CFHTLS, UltraVISTA, VEILS etc.) are a "**milli-LSST-Euclid**" testbed for understanding what high-redshift galaxy physics can be learned in the deep-drilling fields

1. Small-Scale Clustering
2. Clustering in VIDEO
   a) HOD and stellar mass to halo mass ratios
   b) Cross correlations
   c) Comparison to simulations
   d) LBGs
3. Looking ahead to LSST

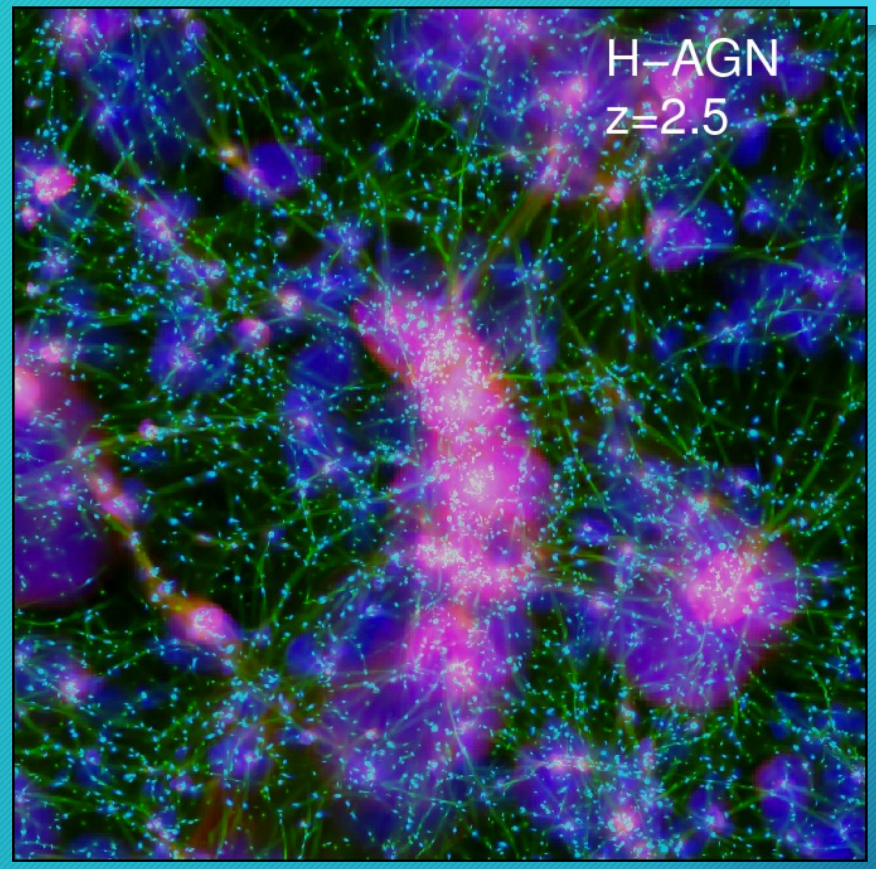


VIDEO-XMM3

The galaxy-halo connection in the VIDEO Survey at 0.5<z<1.7, Hatfield et al., MNRAS 2016
Environmental Quenching and Galactic Conformity in the Galaxy Cross-Correlation Signal, Hatfield & Jarvis, MNRAS 2017
The environment and host haloes of the brightest z~6 Lyman-break galaxies, Hatfield et al., MNRAS 2018
Comparing Galaxy Clustering in the Horizon-AGN Simulation and VIDEO Observations, Hatfield et al., 2018, in prep.

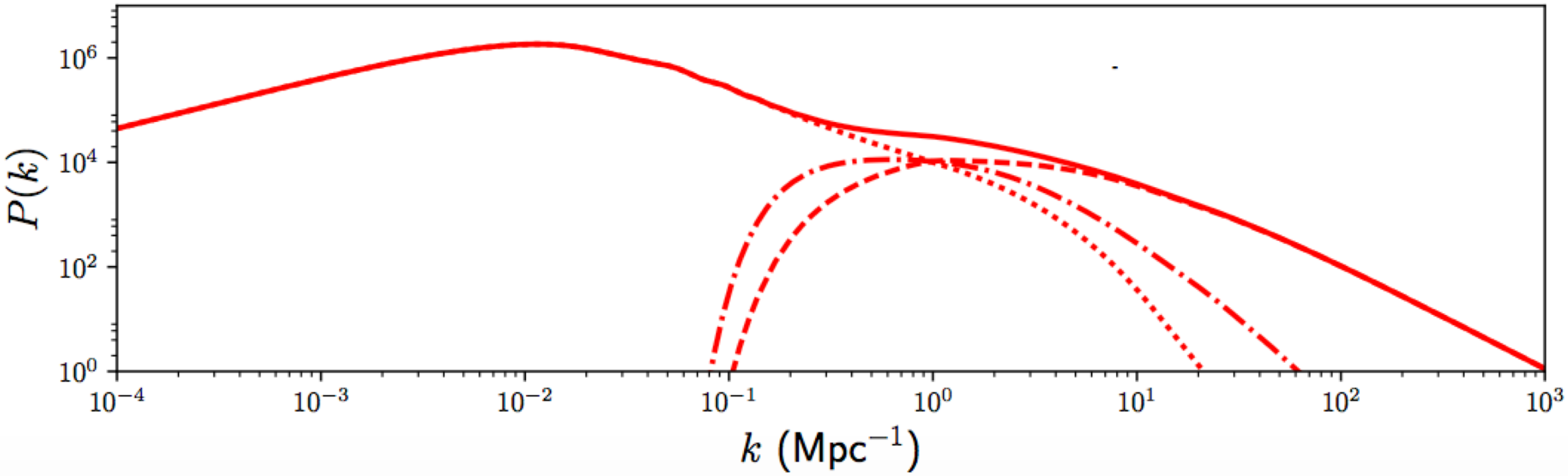
1. Modelling Small-Scale Clustering

- **Model the linear and non-linear clustering simultaneously**
- Get more physical properties than bias



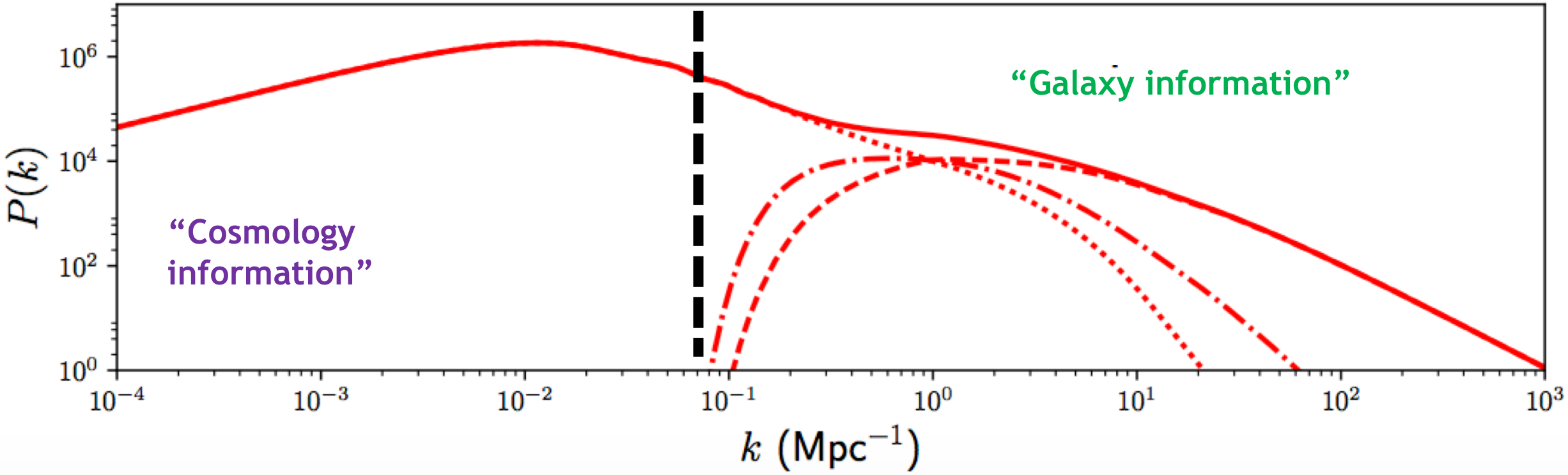
Horizon-AGN

UNIVERSITY OF OXFORD



Typically observe some sort of galaxy power spectrum…

UNIVERSITY OF OXFORD



Typically observe some sort of galaxy power spectrum…

- Often neglect the non-linear small scale clustering ("galaxy information") in favour of the large-scale linear clustering ("cosmological information")
- Can model both simultaneously (galaxy evolution as nuisance parameter for cosmology) as well as getting galaxy environment information

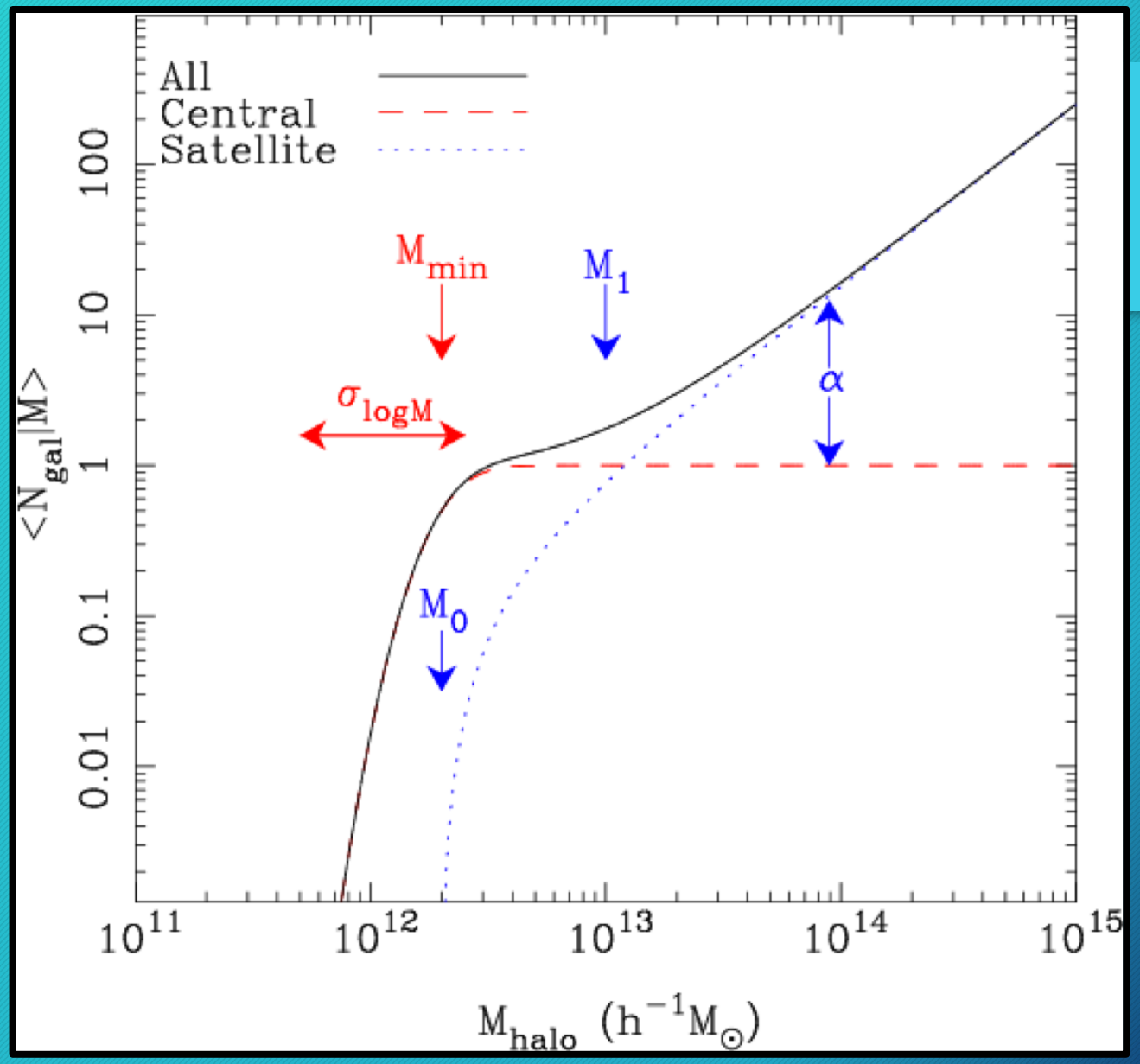
UNIVERSITY OF OXFORD

-> Measure correlation function (and other variables)
-> Generate model correlation functions from galaxy-halo relation model
-> Fit parameters

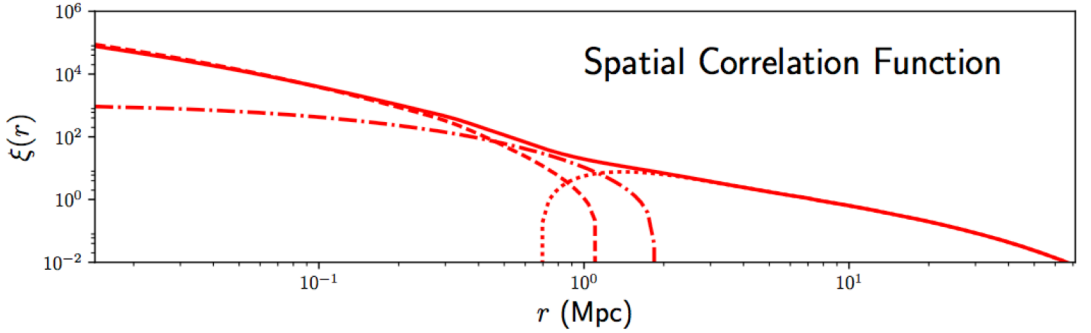
HOD Ingredients:

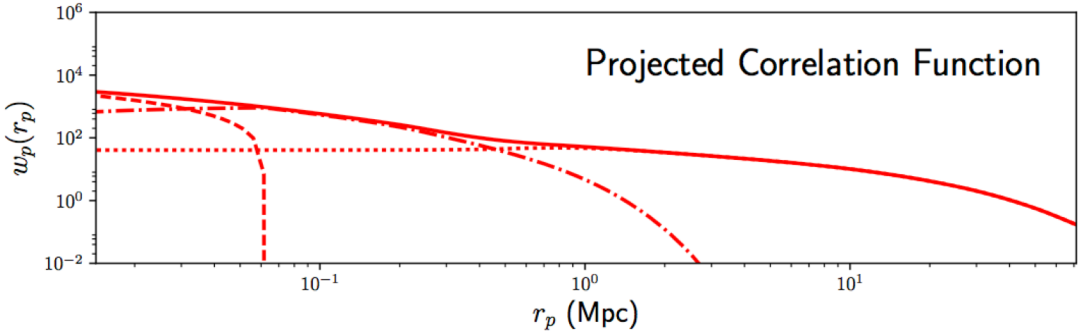
- (Cosmology)
- Halo mass function
- Halo bias prescription
- Dark matter power spectrum
- Halo profiles
- Occupation number
- Poisson assumption
- Central/satellite distinction
- 1-halo and 2-halo terms

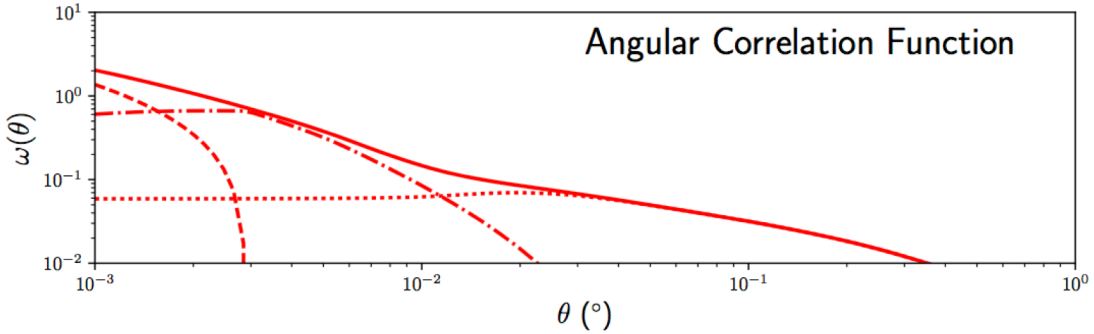
$$\chi^2 = \frac{[n_{\rm gal}^{\rm obs} - n_{\rm gal}^{\rm model}]^2}{\sigma_n^2} + \sum_i \frac{[\omega^{\rm obs}(\theta_i) - \omega^{\rm model}(\theta_i)]^2}{\sigma_{w_i}^2},$$

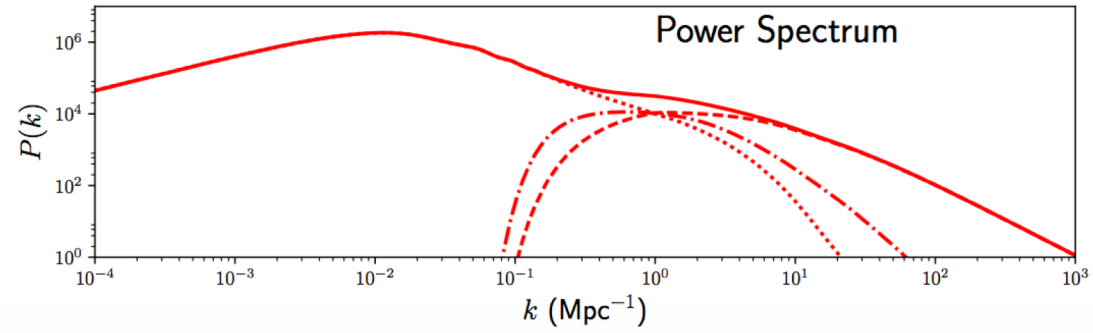


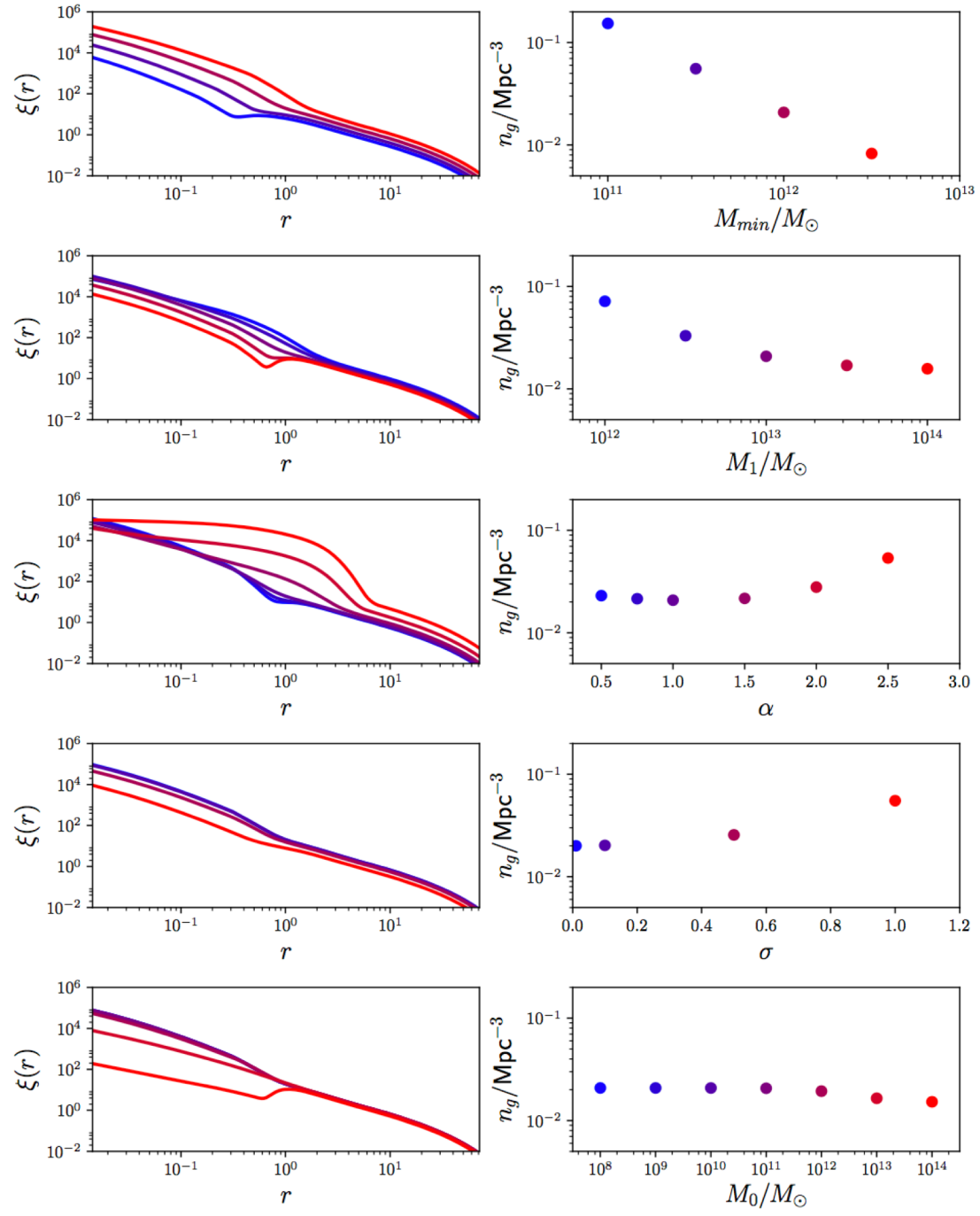
Wake et al., 2011


Spatial Correlation Function
$\xi(r)$
r (Mpc)


Projected Correlation Function
$w_p(r_p)$
r_p (Mpc)

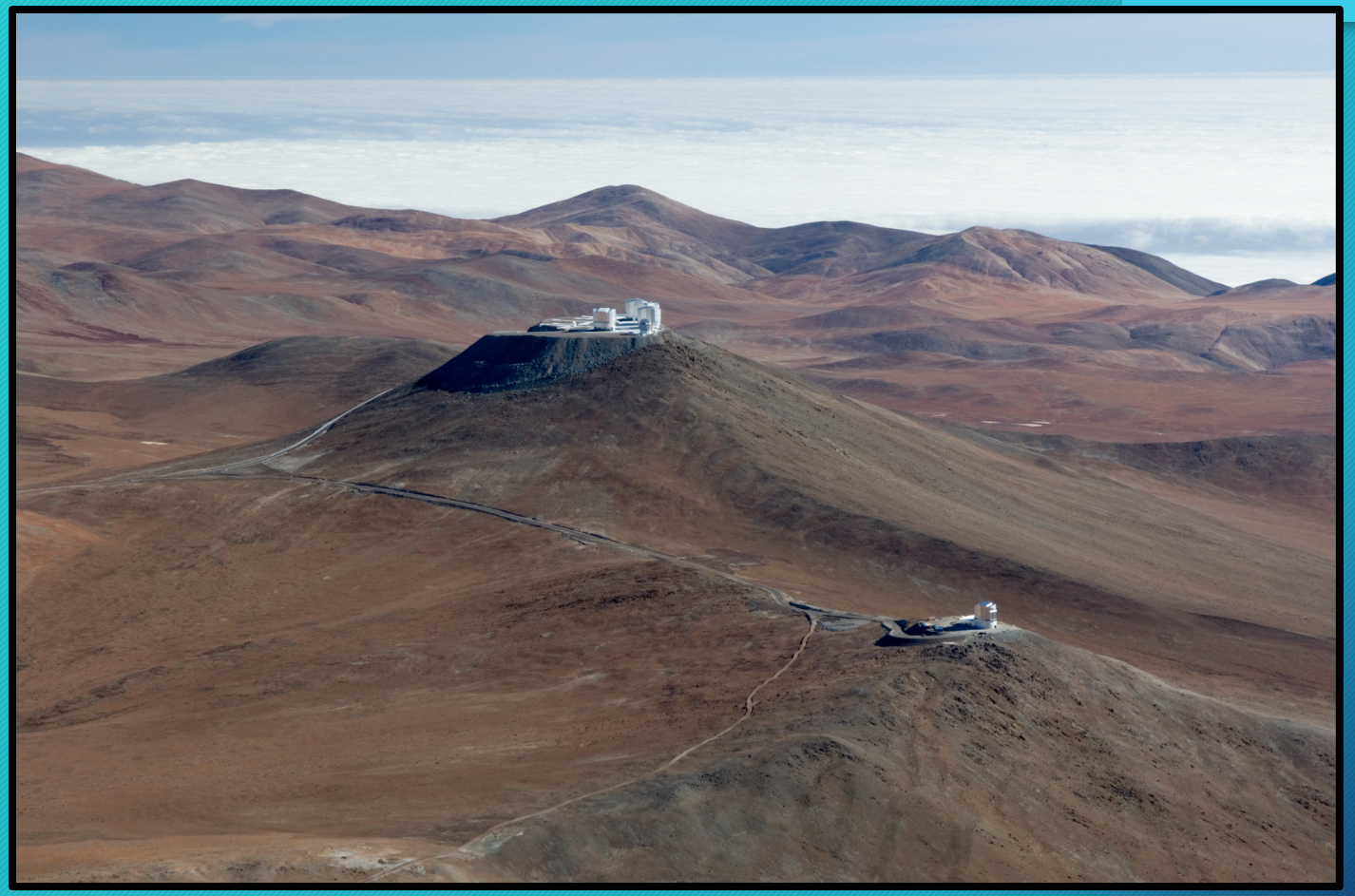

Angular Correlation Function
$\omega(\theta)$
θ (°)


Power Spectrum
$P(k)$
k (Mpc^{-1})


$\xi(r)$
r
n_g/Mpc^{-3}
$M_{min}/M_\odot$
$M_1/M_\odot$
α
σ
$M_0/M_\odot$

2. Clustering in VIDEO

- **Deep NIR and optical data to comparable depth to LSST-Euclid Main Survey over 12deg^2**
- Work measuring and modelling clustering as a function of stellar mass and star formation rate

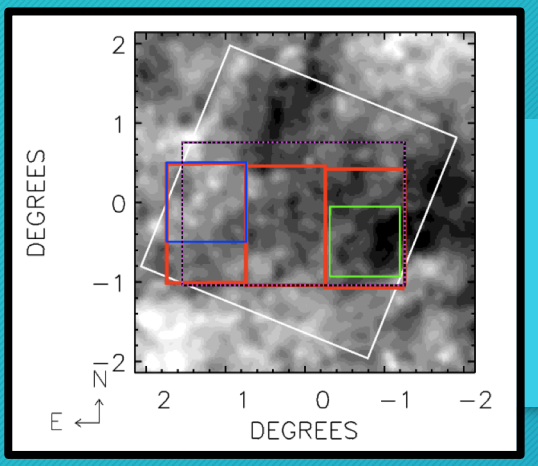


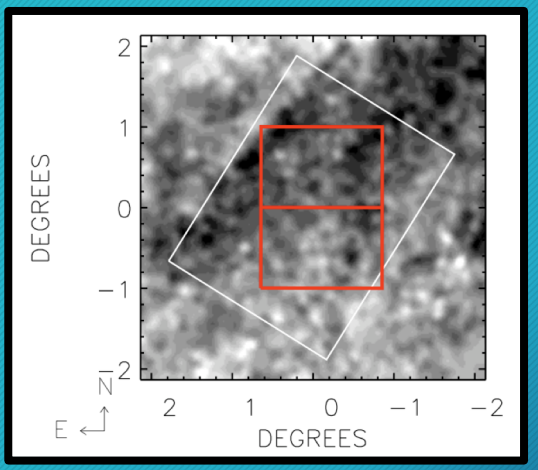
UNIVERSITY OF OXFORD

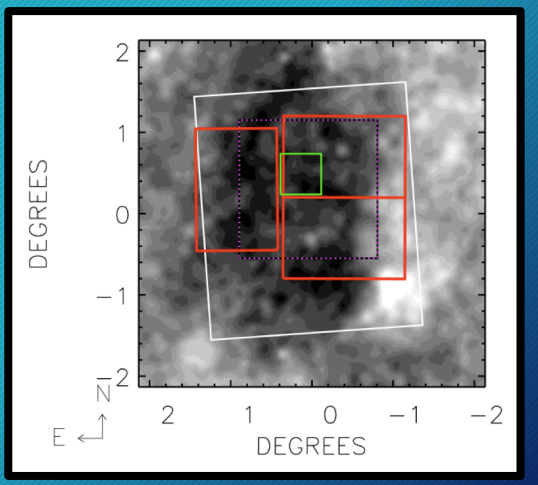
VIDEO Survey - *VISTA Deep Extragalactic Observations Survey*

- Infrared (Z, Y, J, H, K_s band) with optical from CHFTLS
- >200 nights over 5 years
- Galaxy and structure evolution up to z=4
- AGN and most massive galaxies up to reionisation
- 3 fields; selected for multi-band data
- Fits between UltraVISTA and VIKING for depth and width
- 12 sq deg
- Right combination of width and depth for HOD

- VEILS survey is extending VIDEO fields, started 2018





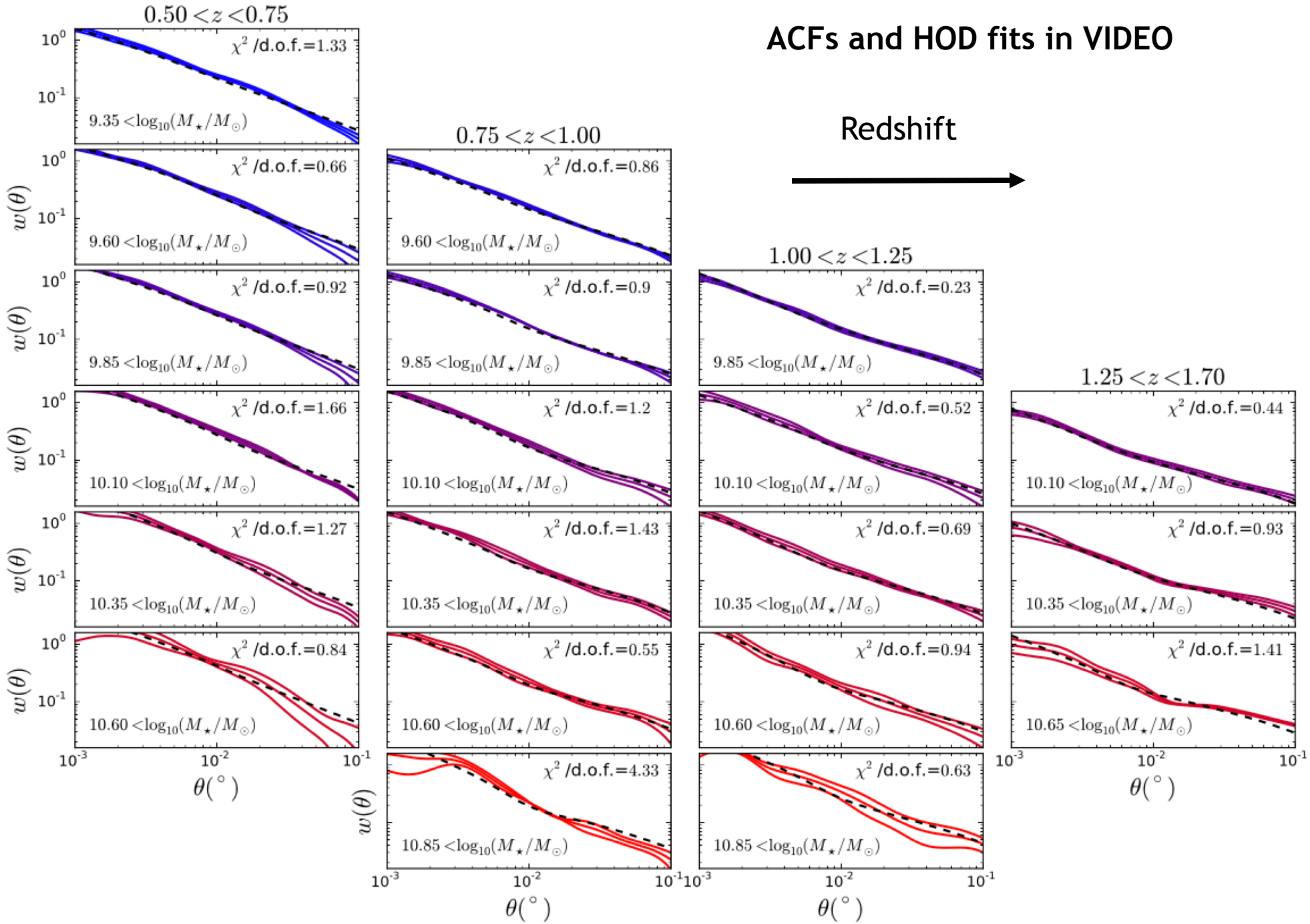


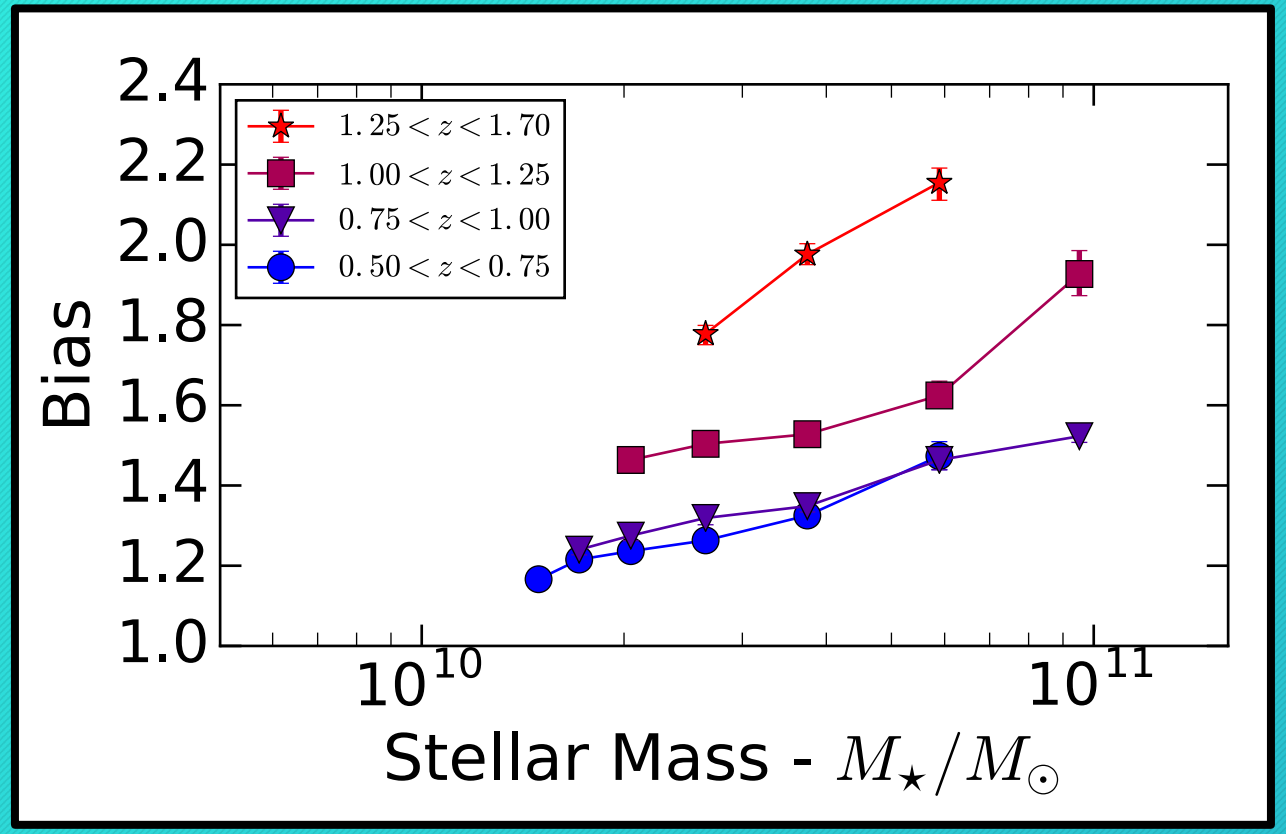
Filter	Time (h) (per source) (no overheads)	Time (h) (per tile) (+overheads)	Time (h) (full survey) (+overheads)	5σ AB	2″ ap.mag. Vega	UKIDSS Vega	Seeing	Moon	Transparency
Z	17.5	60.8	570	25.7	25.2	–	0.8	D	THN,CLR
Y	6.7	23.2	218	24.6	24.0	–	0.8	G	THN,CLR
J	8.0	27.9	261	24.5	23.7	22.3	0.8	G	THN,CLR
H	8.0	29.4	276	24.0	22.7	22†	0.8	B	THN,CLR
K_s	6.7	23.8	224	23.5	21.7	20.8	0.6	B	THN,CLR

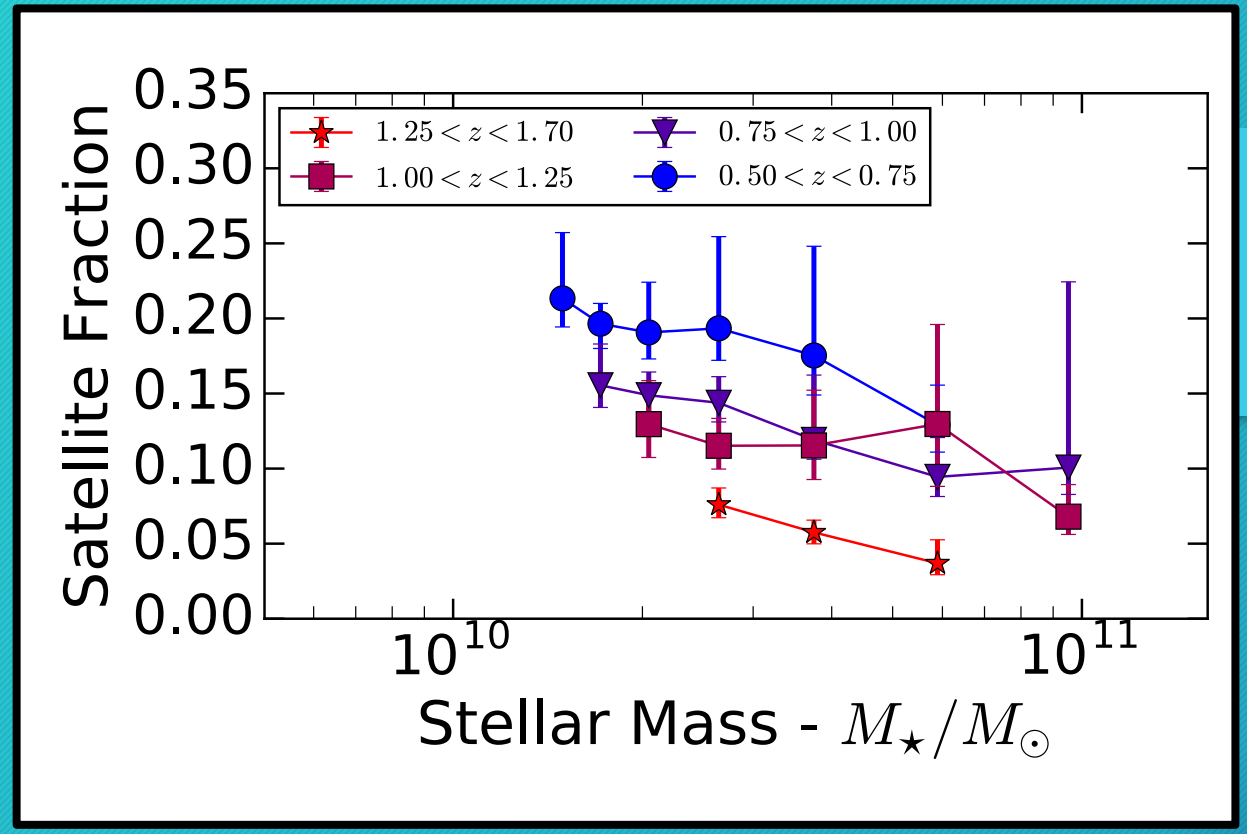
UNIVERSITY OF OXFORD

M.Jarvis et al., The VISTA Deep Extragalactic Observations (VIDEO) Survey, MNRAS (2013)

ACFs and HOD fits in VIDEO

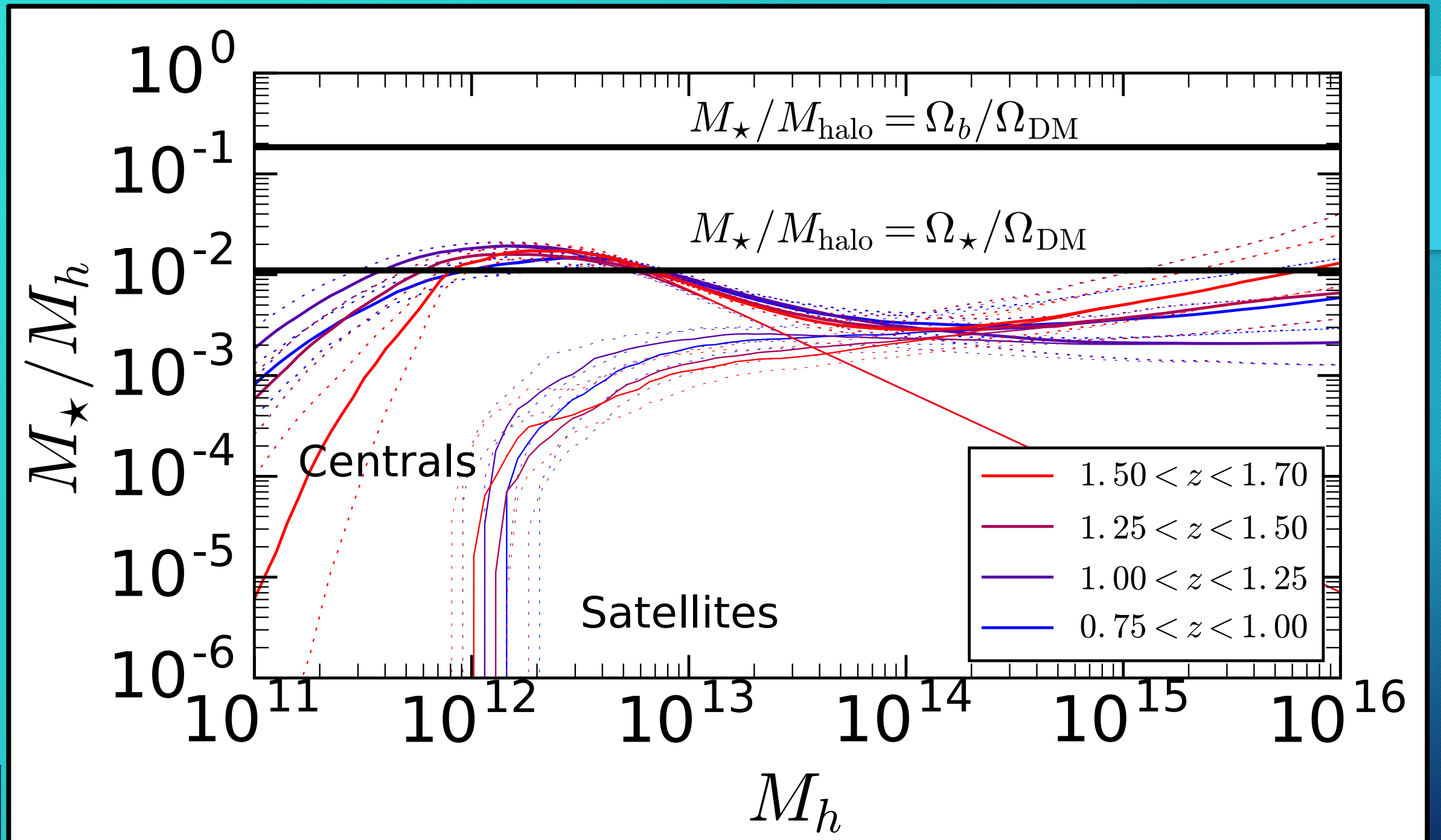




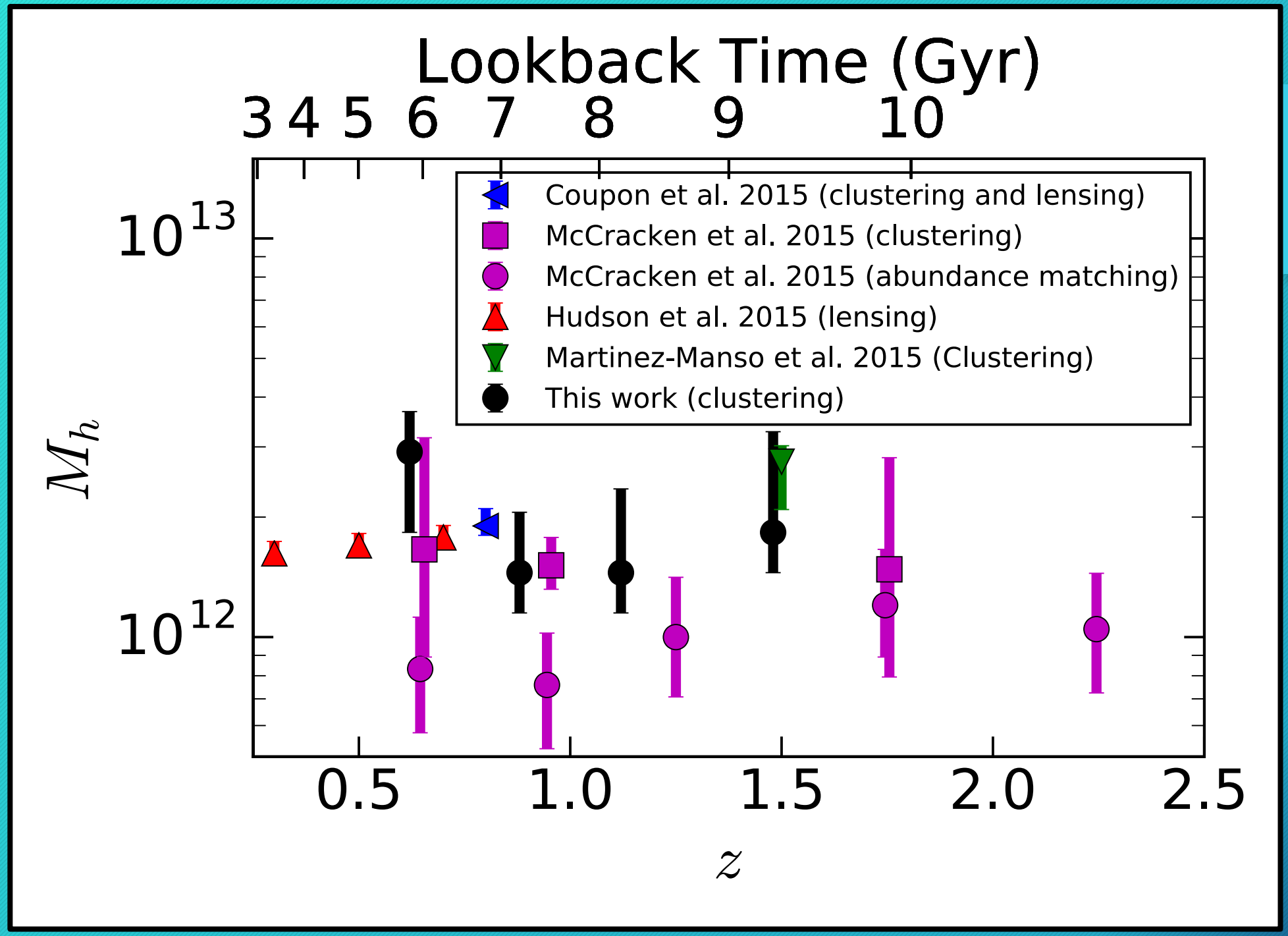


- Most massive galaxies in highest mass halos, most highly biased
- More highly biased at high redshift
- Very small fraction of massive galaxies are satellites

UNIVERSITY OF OXFORD

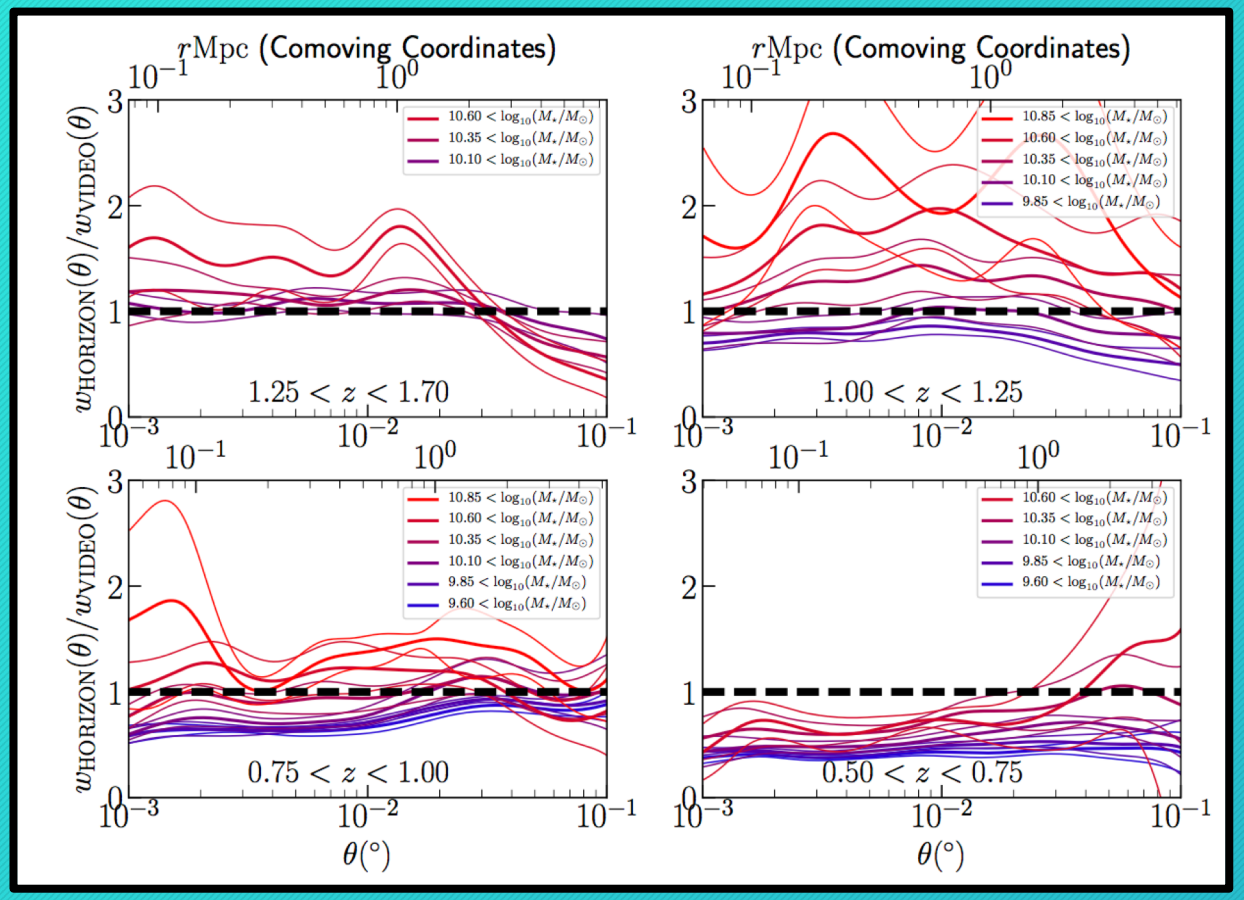


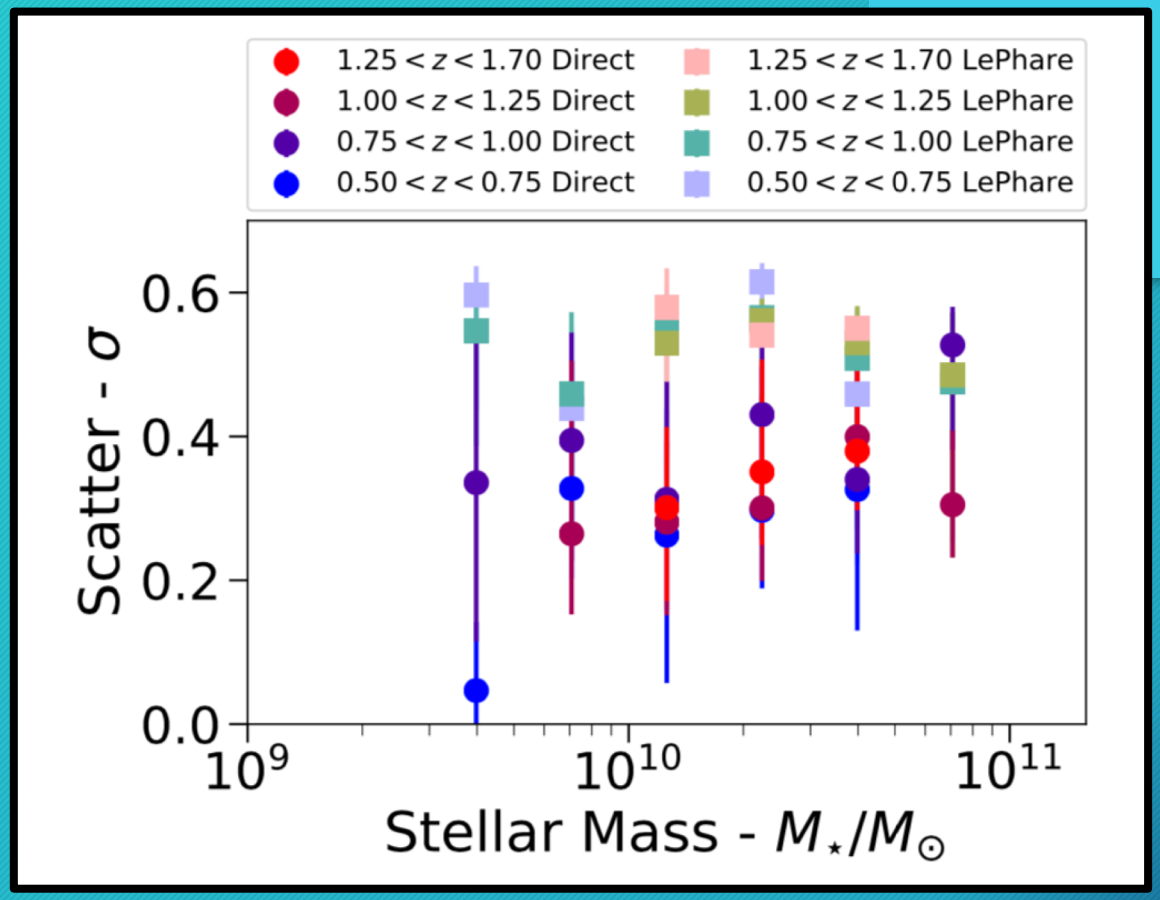
UNIVERSITY OF OXFORD



UNIVERSITY OF OXFORD

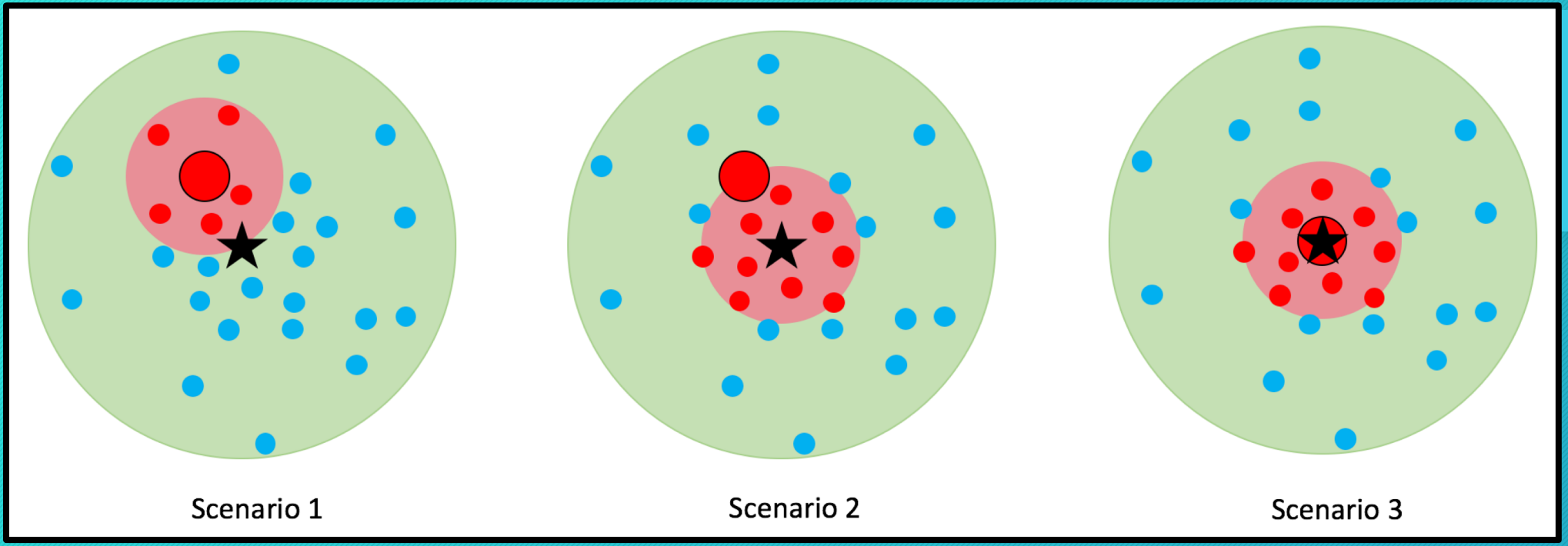
Comparison with Simulations





- Mock catalogue from Horizon-AGN hydrodynamical cosmological simulation
- Compare observations and simulations in a consistent way
- Compare `actual' simulation and `observed' simulation

Modelling the Cross-Correlation Function



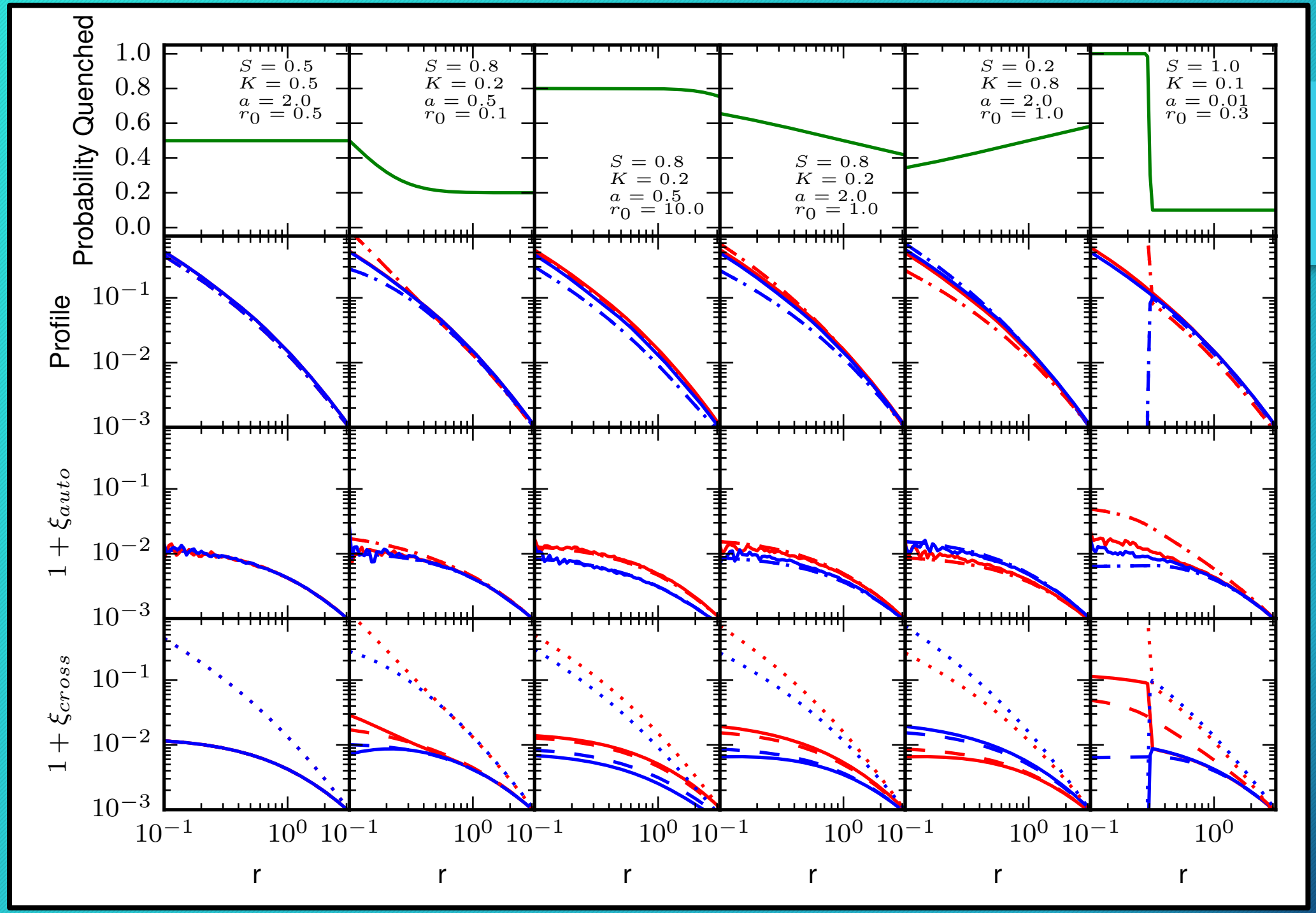
- Conventional HOD assumes galaxies trace **NFW** profile
- If galaxies are preferentially quenched or star forming in certain environments, this makes them follow slightly different profiles, which manifests itself in the 1-halo term
- Cross correlations also give information on covariance on occupation numbers
- Cross-correlation function can be used to study the '**interaction**' of two galaxy samples
- See Simon+2009

$$\xi^2_{\mathrm{galAB}} \neq \xi_{\mathrm{galAA}} \times \xi_{\mathrm{galBB}}$$

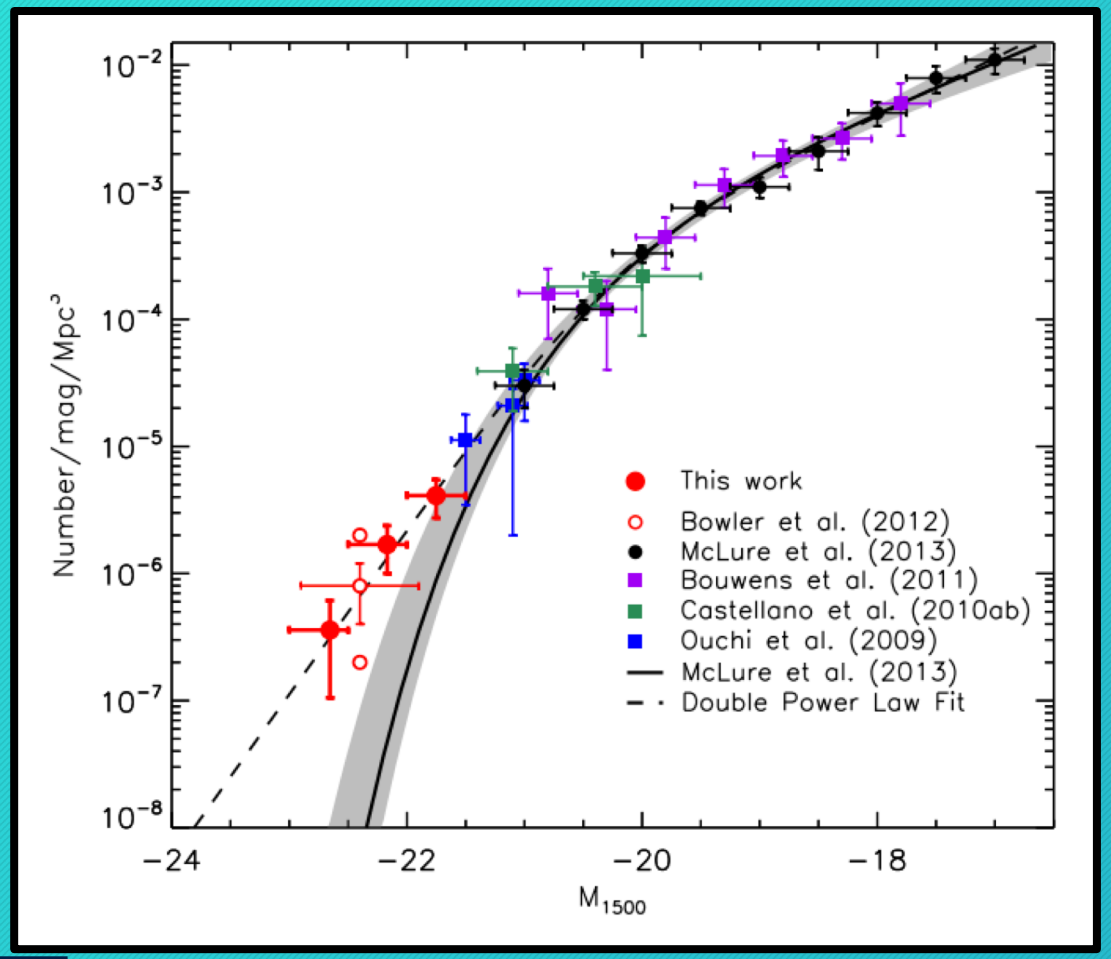
$$1 + \xi_{1h}(r) \propto \int_{\mathbb{R}^3} Q(\mathbf{r})\rho(\mathbf{r})\rho(\mathbf{r}-\mathbf{s})d\mathbf{s}$$

$$1 + \xi_{1h}(r) \propto Q(\mathbf{r}) \int_{\mathbb{R}^3} \rho(\mathbf{r})\rho(\mathbf{r}-\mathbf{s})d\mathbf{s}$$

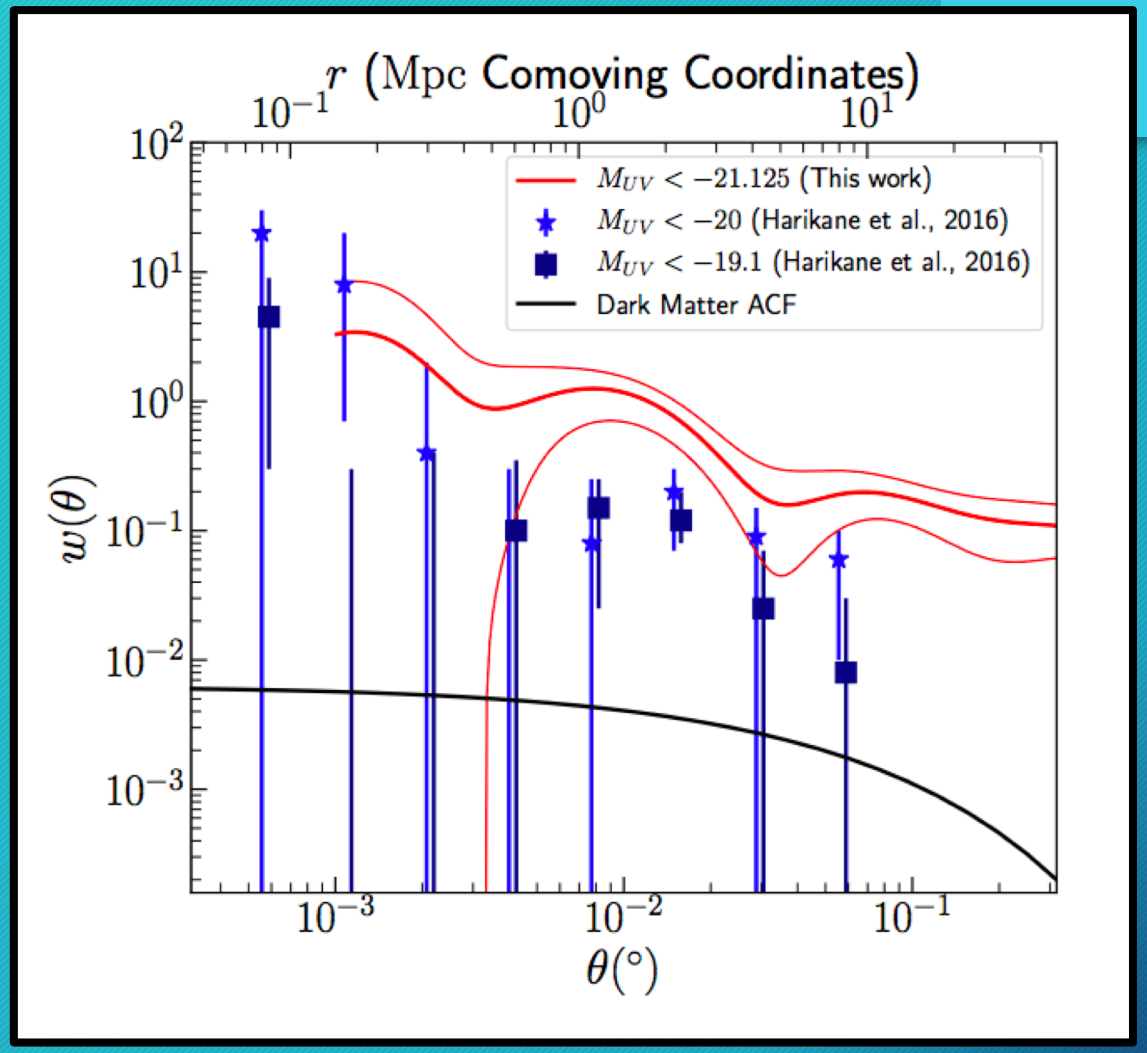
UNIVERSITY OF OXFORD


Probability Quenched
Profile
$1 + \xi_{auto}$
$1 + \xi_{cross}$
r
$S = 0.5$ $K = 0.5$ $a = 2.0$ $r_0 = 0.5$
$S = 0.8$ $K = 0.2$ $a = 0.5$ $r_0 = 0.1$
$S = 0.8$ $K = 0.2$ $a = 0.5$ $r_0 = 10.0$
$S = 0.8$ $K = 0.2$ $a = 2.0$ $r_0 = 1.0$
$S = 0.2$ $K = 0.8$ $a = 2.0$ $r_0 = 1.0$
$S = 1.0$ $K = 0.1$ $a = 0.01$ $r_0 = 0.3$

- Above z~4 - Lyman Break Galaxies
- High luminosity LBGs are less rare than expected, but still highly clustered (b~8) - onset of quenching? (See also Harikane+2017)



Bowler et al., 2014

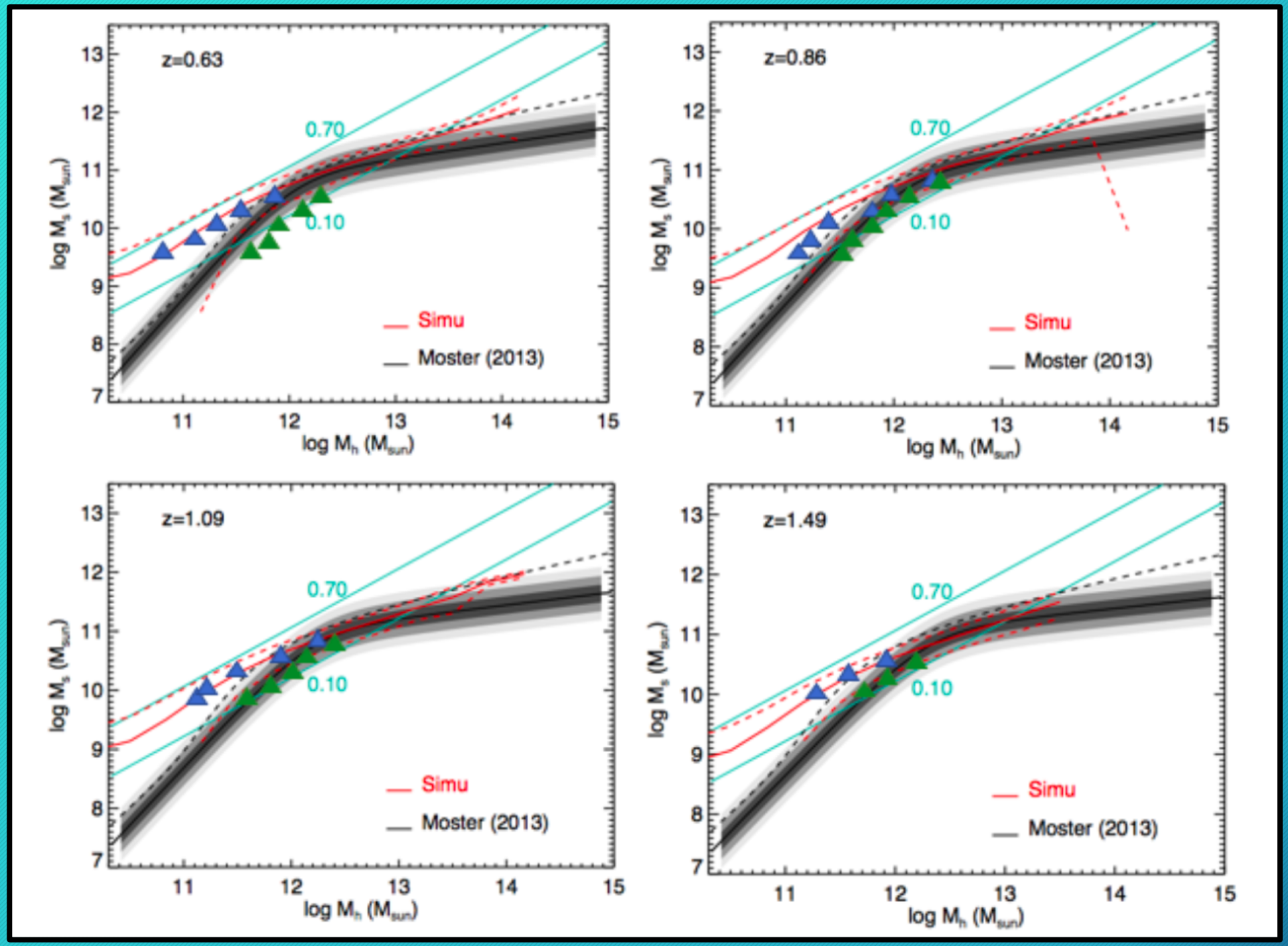


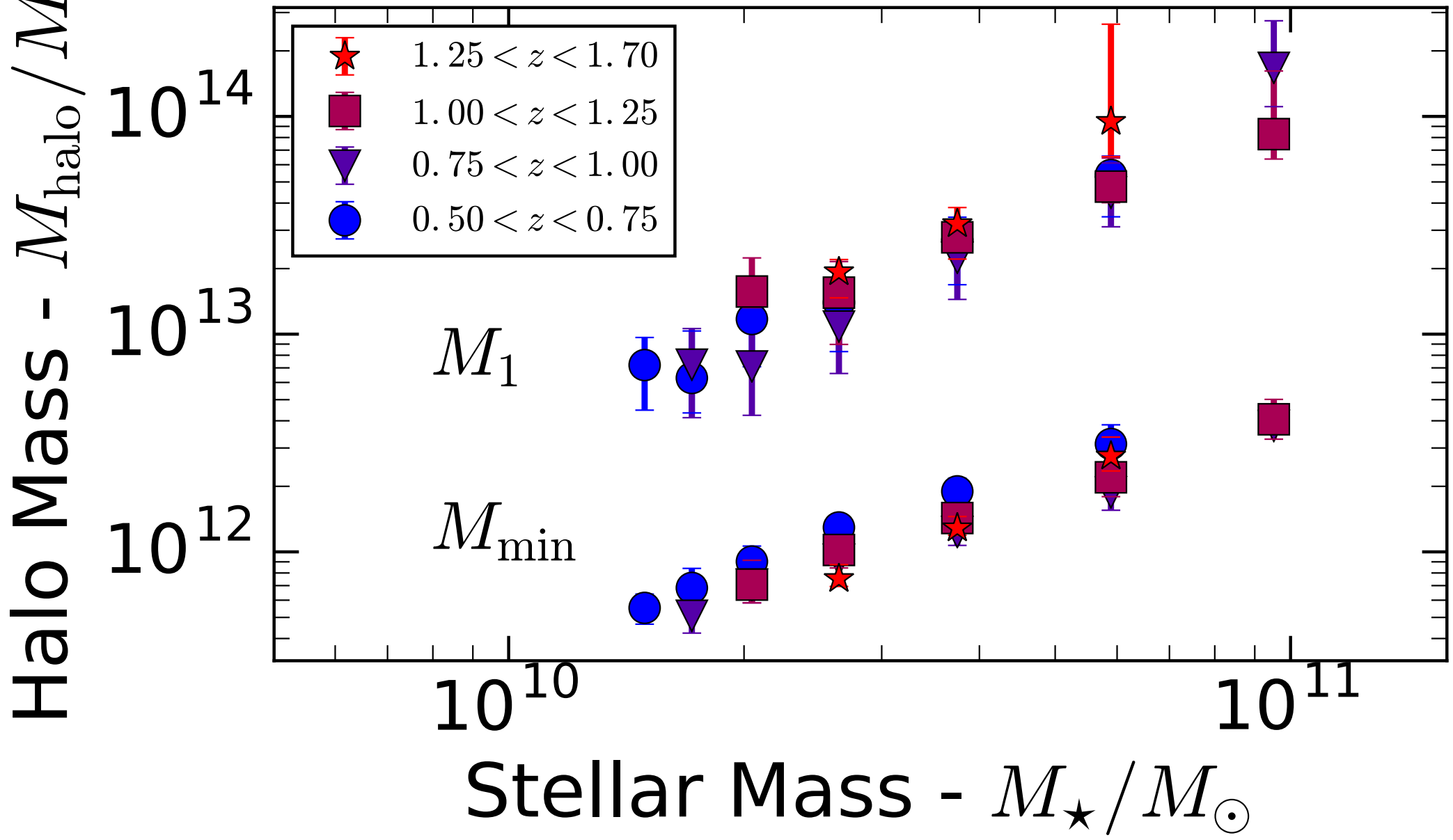
Hatfield et al., 2018

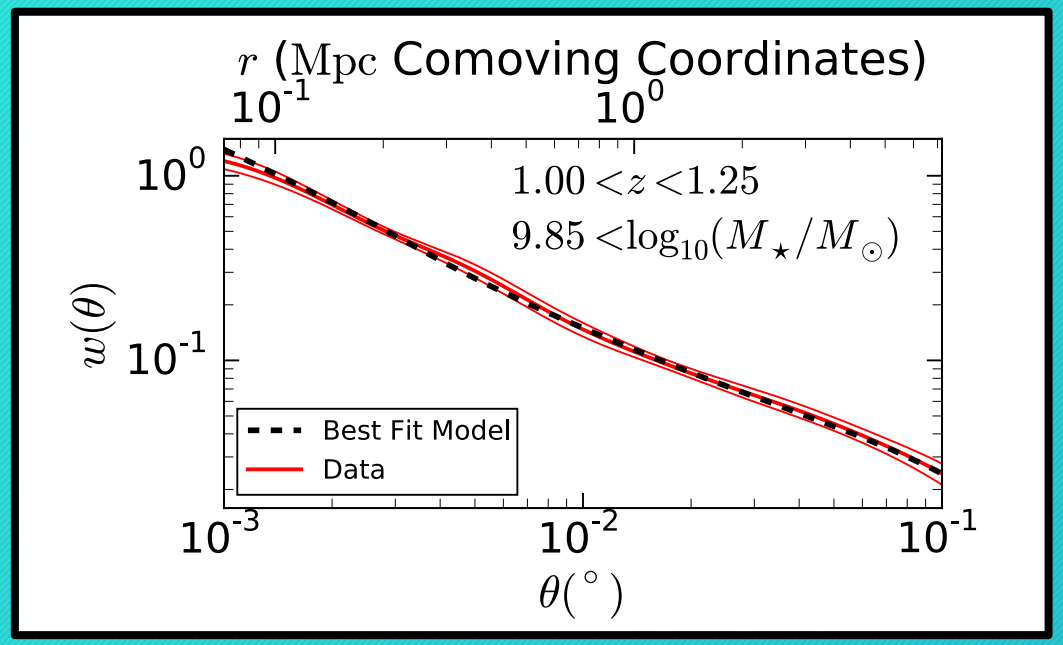
3. Looking Ahead to LSST/Conclusions

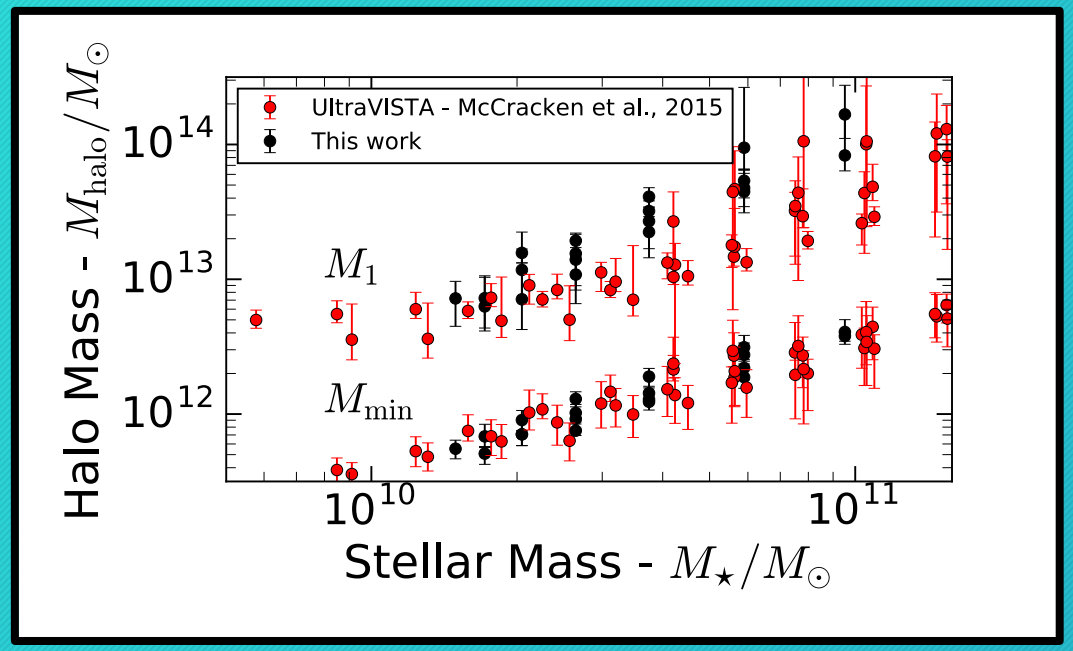
- The non-linear galaxy power spectrum in both the Main Survey and Deep Drilling fields will give unprecedentedly precise probes of environment
- Ongoing work in VISTA surveys as “milli-LSST-Euclid” surveys
- Multiwavelength data important e.g. clustering based on radio properties as per Hale+2018, cross-matching to SKA?
- Joint fit with weak lensing shear measurements as per Coupon+2015?
- Is it insightful to go to more and more complicated models for non-linear clustering? Model selection?
- Will be possible to measure environment in the early Universe (z>~5), as well as at the peak of star-formation (~0.5<z<~3)
- Test on mock data from hydro-sims to validate inferences

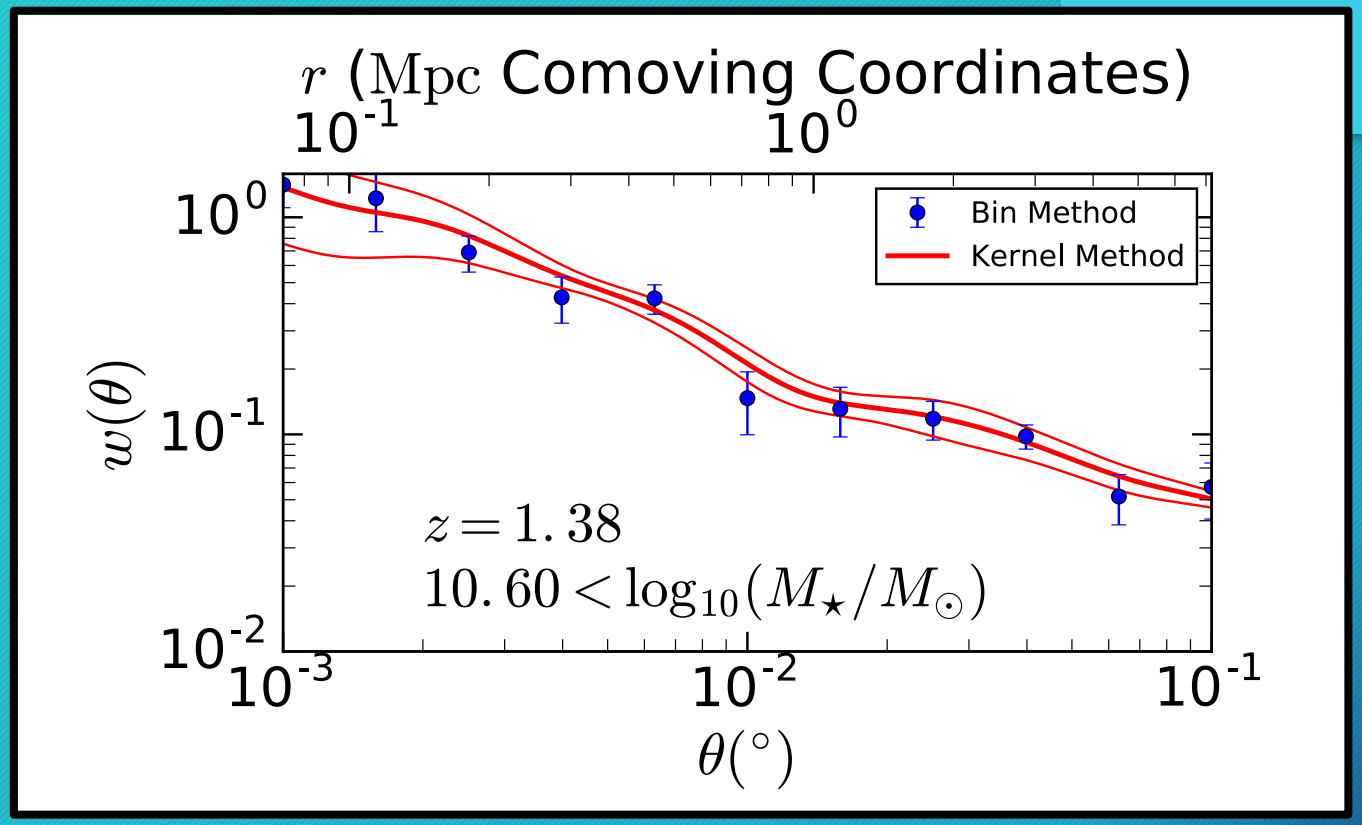
UNIVERSITY OF OXFORD

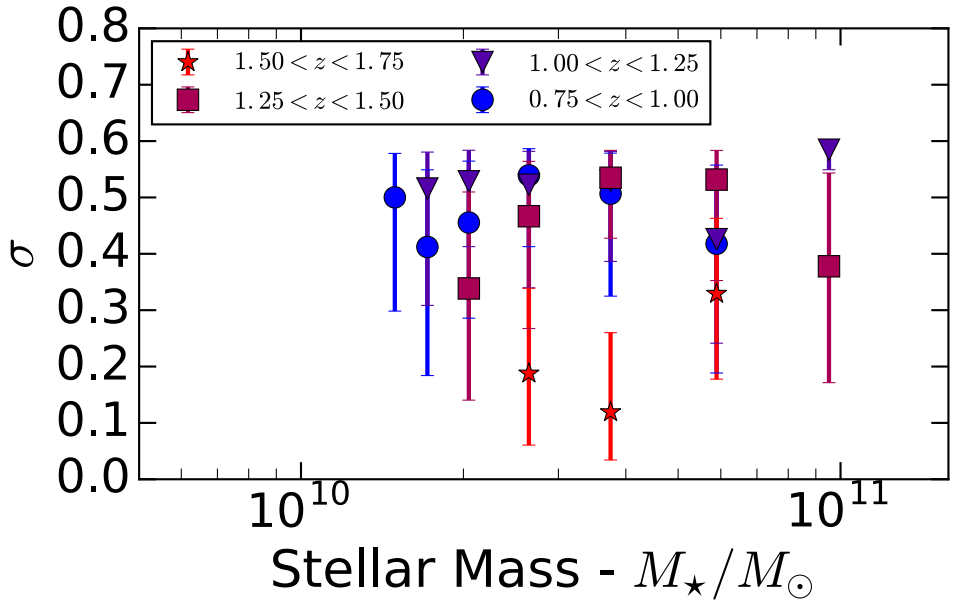

z=0.63
z=0.86
z=1.09
z=1.49
0.70
0.10
Simu
Moster (2013)
log M$_s$ (M$_{sun}$)
log M$_h$ (M$_{sun}$)

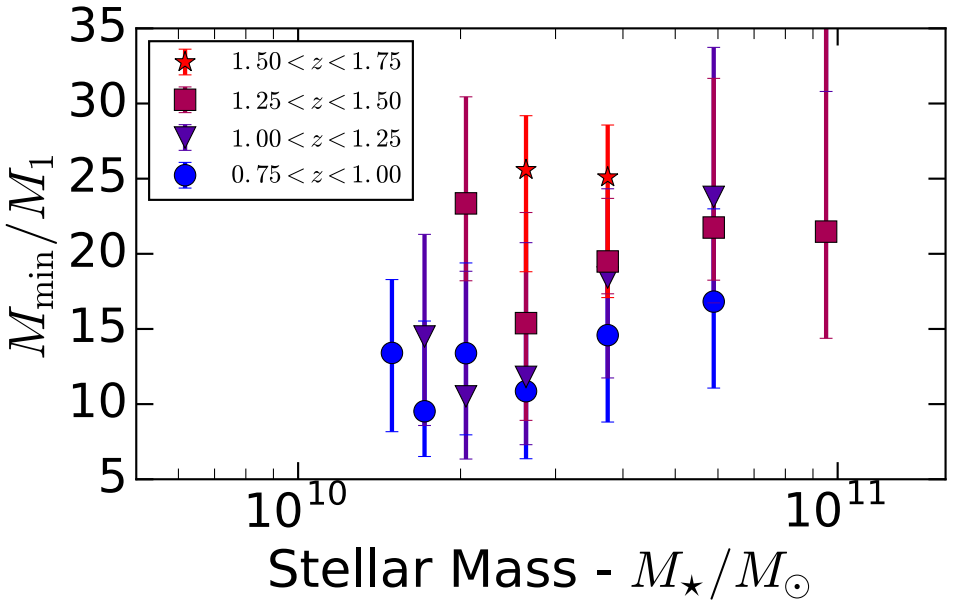

$1.25 < z < 1.70$
$1.00 < z < 1.25$
$0.75 < z < 1.00$
$0.50 < z < 0.75$
M_1
$M_{\rm min}$
Halo Mass - $M_{\rm halo}/M_\odot$
10^{14}
10^{13}
10^{12}
10^{10}
10^{11}
Stellar Mass - $M_\star/M_\odot$

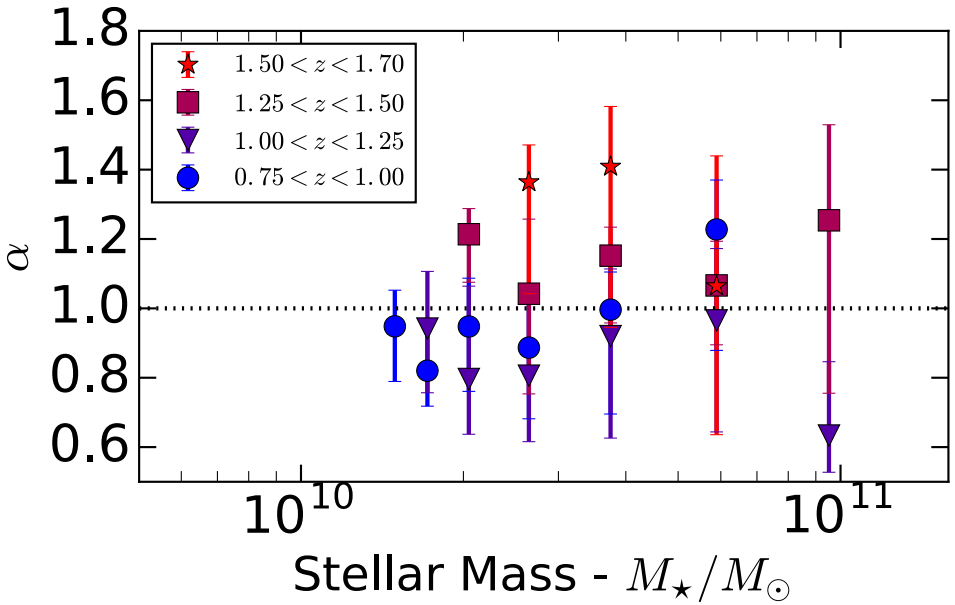

r (Mpc Comoving Coordinates)
10^{-1}
10^{0}
10^{0}
10^{-1}
$w(\theta)$
$1.00 < z < 1.25$
$9.85 < \log_{10}(M_\star/M_\odot)$
Best Fit Model
Data
10^{-3}
10^{-2}
10^{-1}
$\theta(^\circ)$

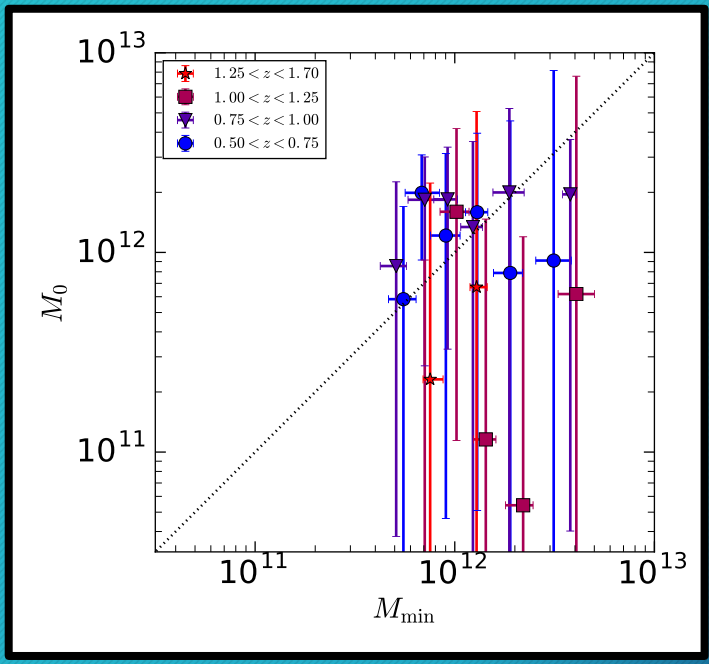

Halo Mass - $M_{\rm halo}/M_\odot$
10^{14}
10^{13}
10^{12}
UltraVISTA - McCracken et al., 2015
This work
M_1
$M_{\rm min}$
10^{10}
10^{11}
Stellar Mass - $M_\star/M_\odot$

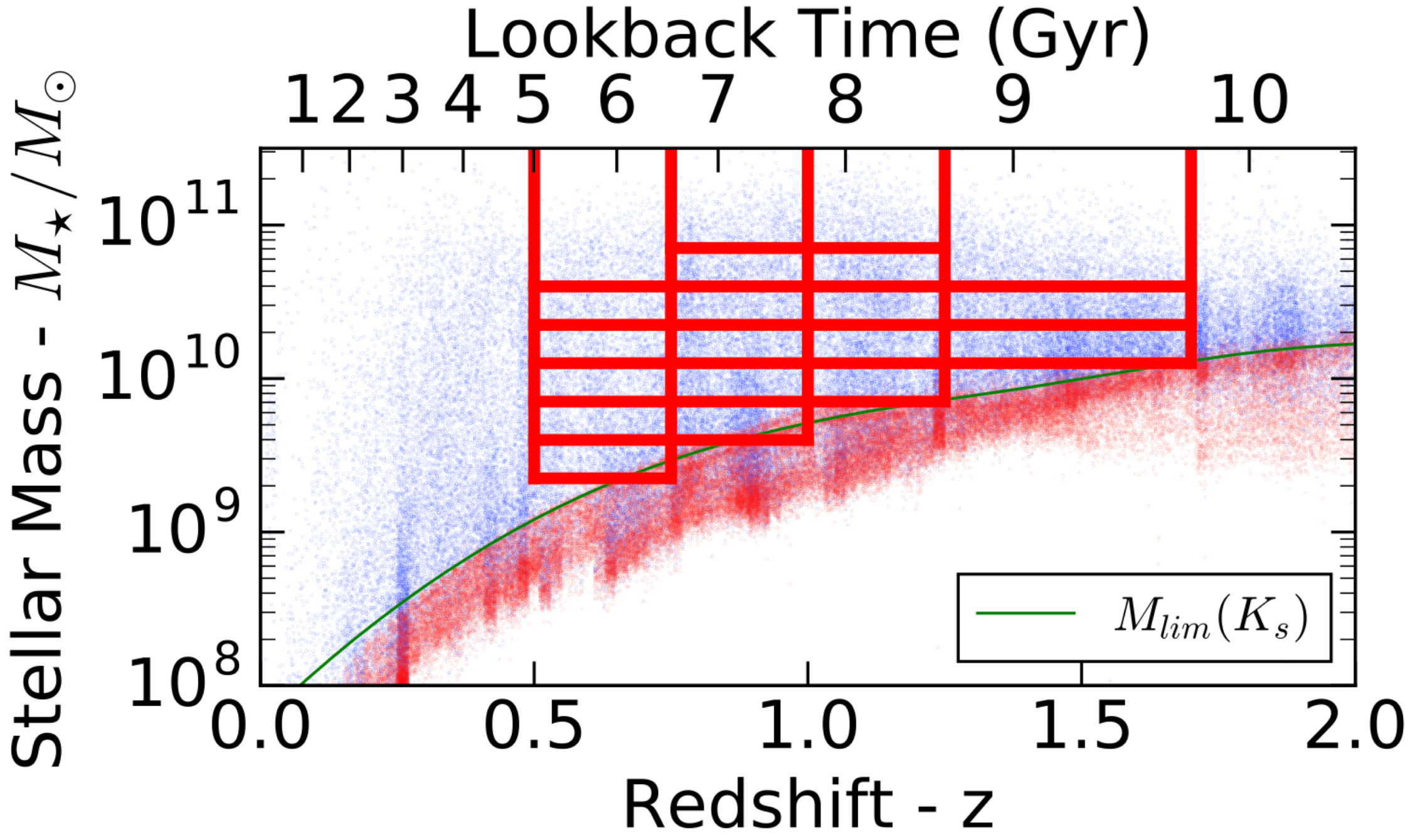

r (Mpc Comoving Coordinates)
10^{-1}
10^{0}
10^{0}
10^{-1}
10^{-2}
$w(\theta)$
Bin Method
Kernel Method
$z = 1.38$
$10.60 < \log_{10}(M_\star/M_\odot)$
10^{-3}
10^{-2}
10^{-1}
$\theta(^\circ)$

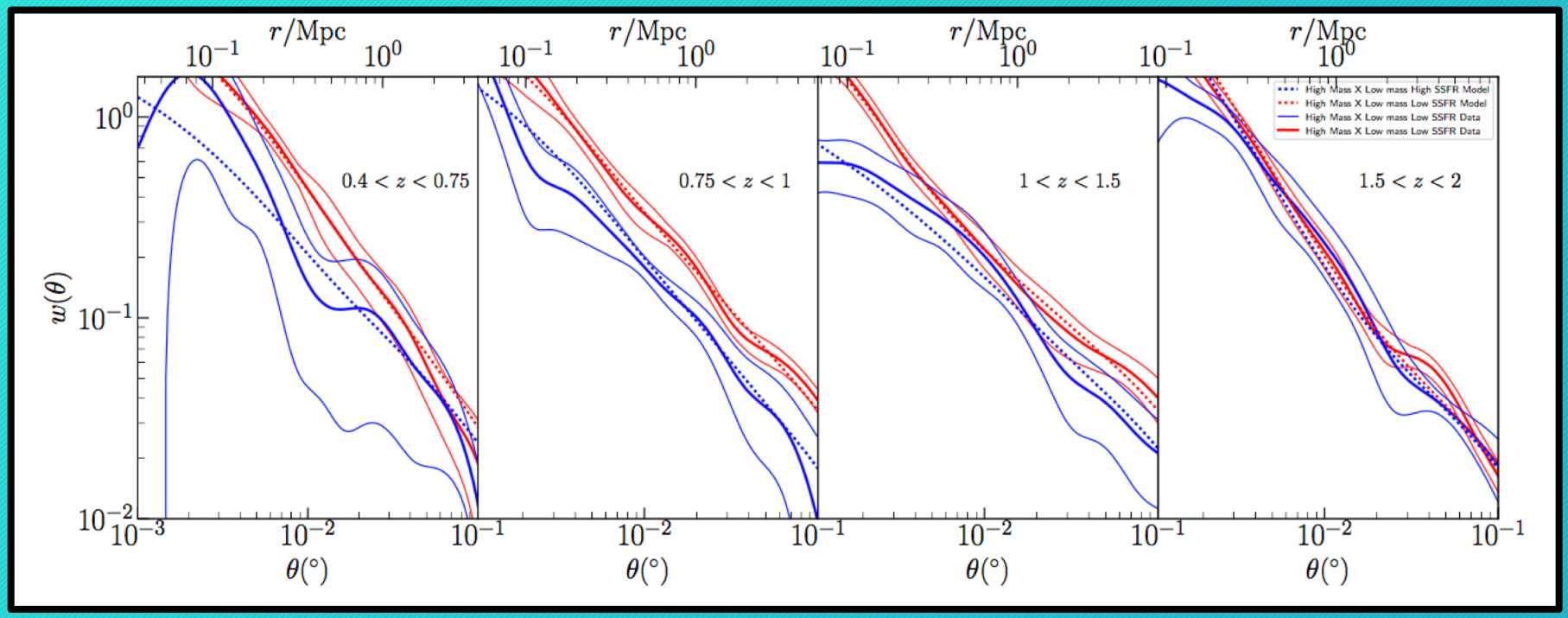

$1.50 < z < 1.75$
$1.25 < z < 1.50$
$1.00 < z < 1.25$
$0.75 < z < 1.00$
σ
Stellar Mass - $M_\star/M_\odot$

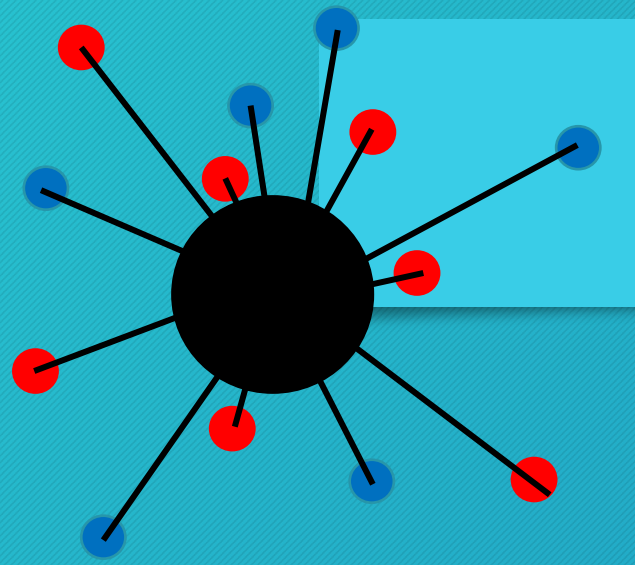

$1.50 < z < 1.75$
$1.25 < z < 1.50$
$1.00 < z < 1.25$
$0.75 < z < 1.00$
$M_{\rm min}/M_1$
Stellar Mass - $M_\star/M_\odot$

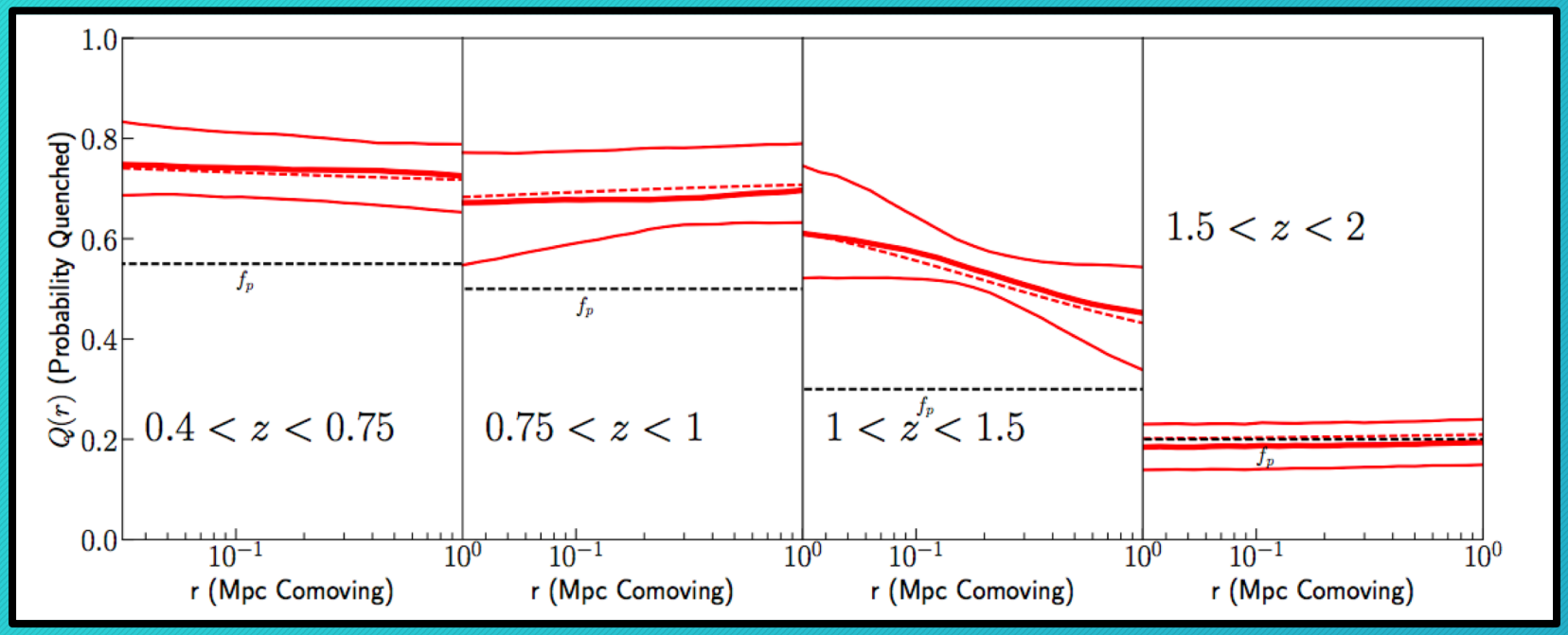

$1.50 < z < 1.70$
$1.25 < z < 1.50$
$1.00 < z < 1.25$
$0.75 < z < 1.00$
α
Stellar Mass - $M_\star/M_\odot$

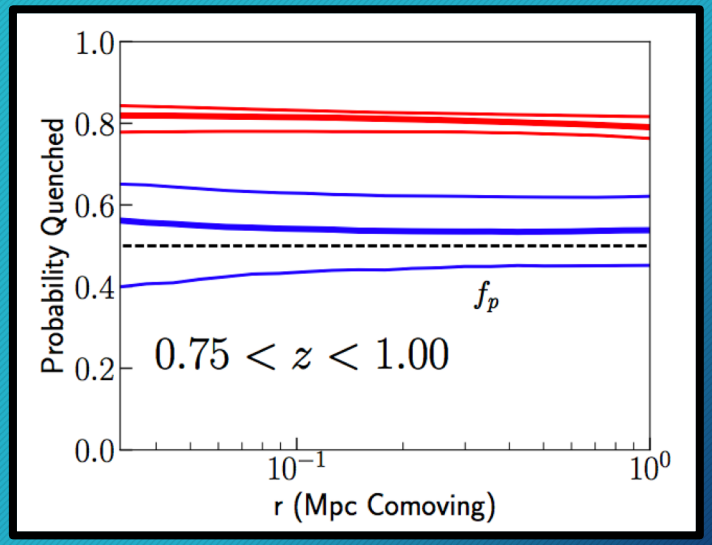

$1.25 < z < 1.70$
$1.00 < z < 1.25$
$0.75 < z < 1.00$
$0.50 < z < 0.75$
M_0
$M_{\rm min}$


Lookback Time (Gyr)
1 2 3 4 5 6 7 8 9 10
Stellar Mass - $M_\star / M_\odot$
10^{11}
10^{10}
10^{9}
10^{8}
0.0 0.5 1.0 1.5 2.0
Redshift - z
$M_{lim}(K_s)$


r/Mpc
$w(\theta)$
$0.4 < z < 0.75$
$0.75 < z < 1$
$1 < z < 1.5$
$1.5 < z < 2$
$\theta(^\circ)$
High Mass X Low mass High SSFR Model
High Mass X Low mass Low SSFR Model
High Mass X Low mass Low SSFR Data
High Mass X Low mass Low SSFR Data




$Q(r)$ (Probability Quenched)
f_p
$0.4 < z < 0.75$
$0.75 < z < 1$
$1 < z < 1.5$
$1.5 < z < 2$
r (Mpc Comoving)


Probability Quenched
f_p
$0.75 < z < 1.00$
r (Mpc Comoving)