The Relationship Between Galaxies and Their Dark Matter Haloes Over Cosmic Time

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Key papers:

The galaxy-halo connection in the VIDEO Survey at $0.5 < z < 1.7$
Hatfield+2016 MNRAS, 459, 3, 2618-2631

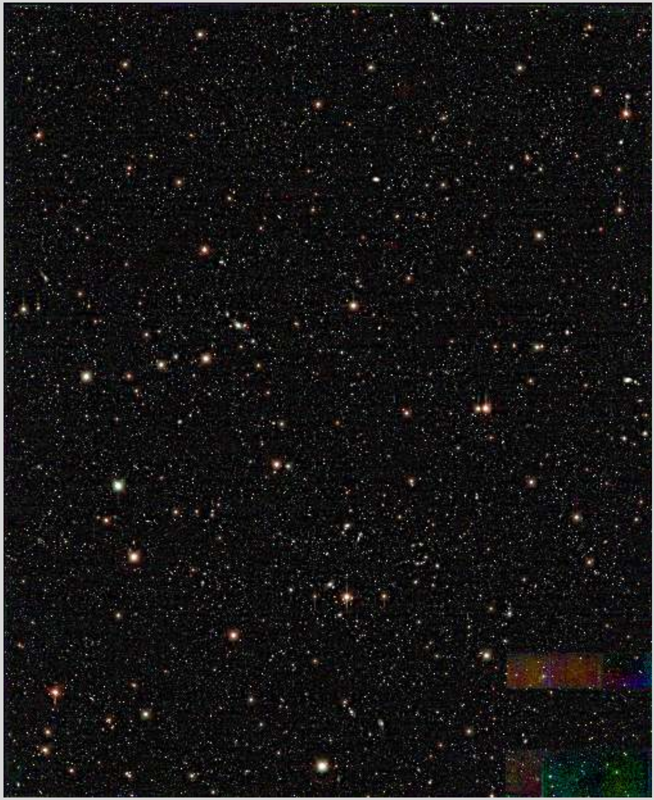
Environmental quenching and galactic conformity in the galaxy cross-correlation signal
Hatfield & Jarvis, 2017 MNRAS, 472, 3, 3570-3588

The environment and host haloes of the brightest $z\sim6$ Lyman-break galaxies
Hatfield+2018 MNRAS, 477, 3, 3760-3774

Comparing Galaxy Clustering in the Horizon-AGN Simulation and VIDEO Observations
Hatfield+2019 MNRAS, 490, 4, 5043–5056

Overview

1. Background
2. Galaxy Surveys
3. The HOD Model
4. Clustering in VIDEO
    a) HOD and stellar mass to halo mass ratios
    b) Cross correlations
    c) Comparison to simulations
    d) LBGs
5. Looking ahead



VIDEO-XMM3

Key Science Results:

- Understanding the ***non-linear*** clustering of galaxies gives important information about galaxy environment and how galaxies and baryons trace dark matter – beyond just galaxy bias

- An powerful approach to modelling galaxy clustering is the ***Halo Occupation Distribution*** (HOD) phenomenology

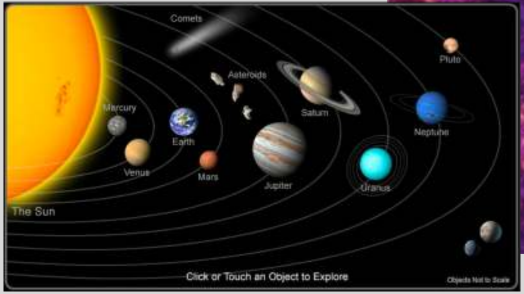
- Analysis of clustering in VIDEO supports mass quenching beginning about z~6-7, and environmental quenching beginning about z~1.5

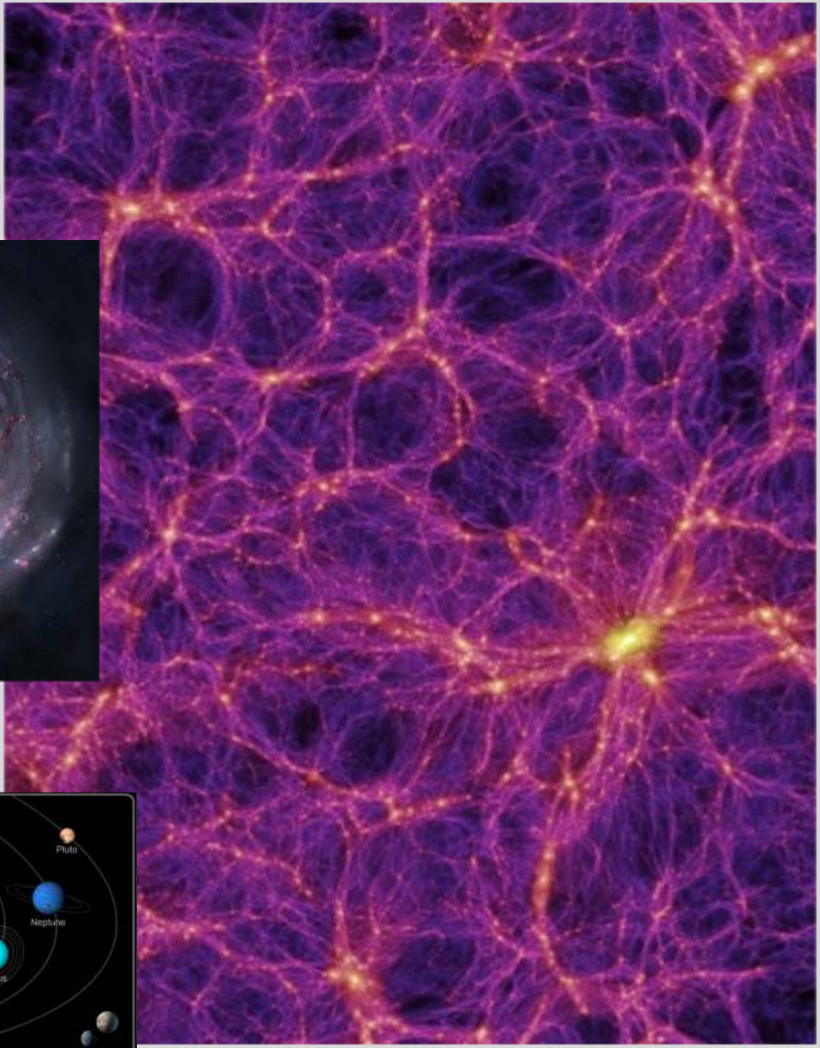
1. Background

- Large-Scale Structure; physics on the scales between galaxies and cosmology
- We now have a large number of probes of cosmology

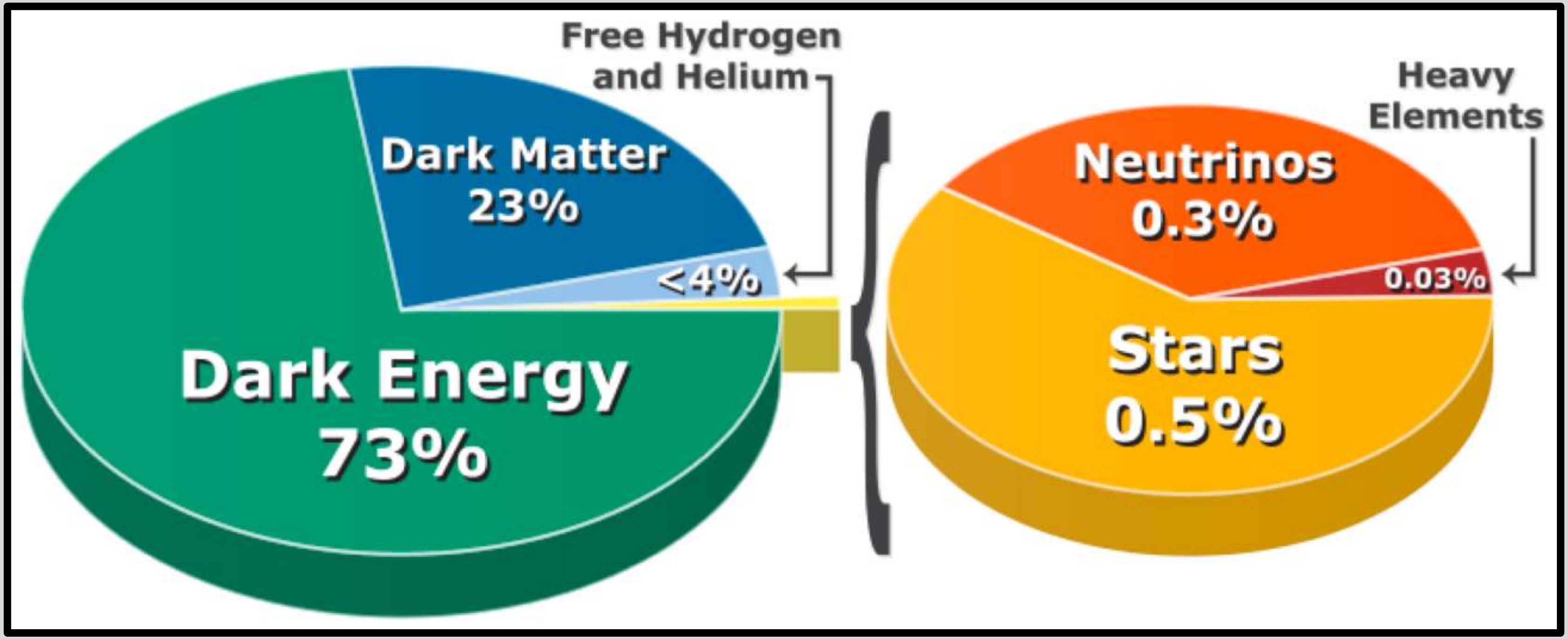
1888 versus 2019 (Sambit Giri and Hannah Ross, Stockholm)

Our Universe



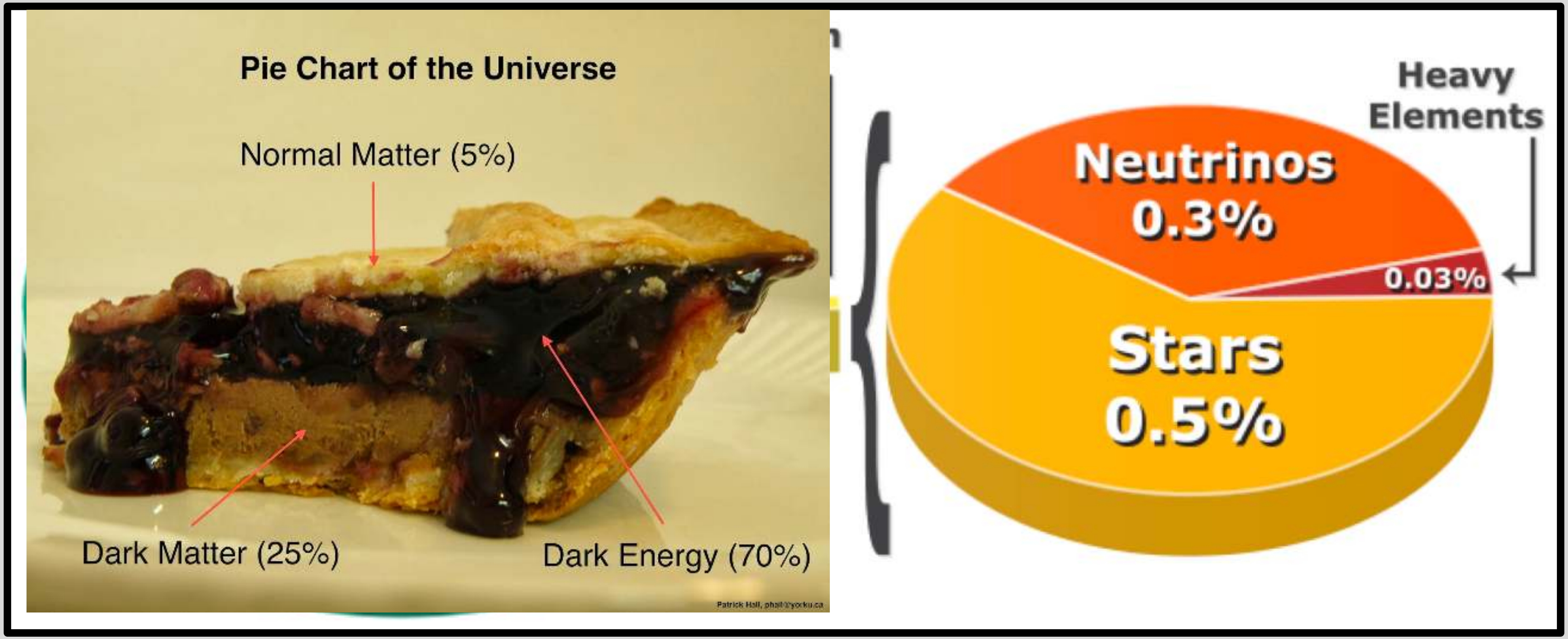


Cosmology



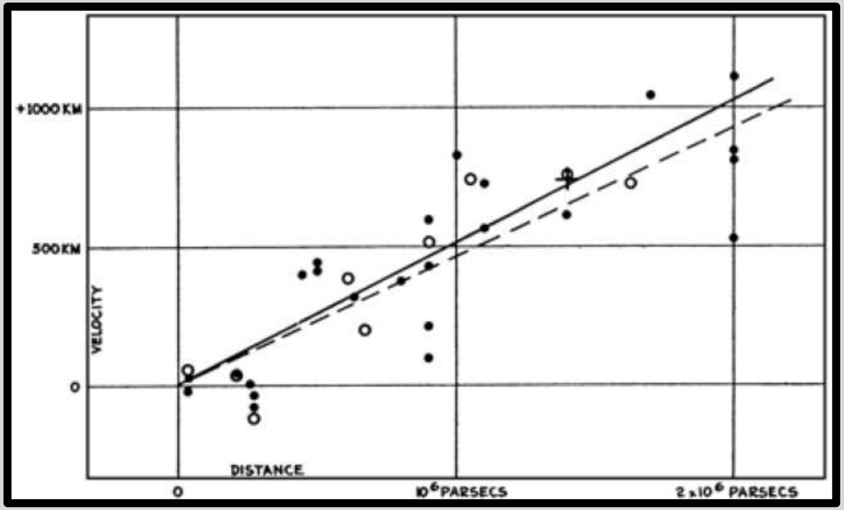
Free Hydrogen
and Helium
Heavy
Elements
Dark Matter
23%
<4%
Dark Energy
73%
Neutrinos
0.3%
0.03%
Stars
0.5%

Cosmology

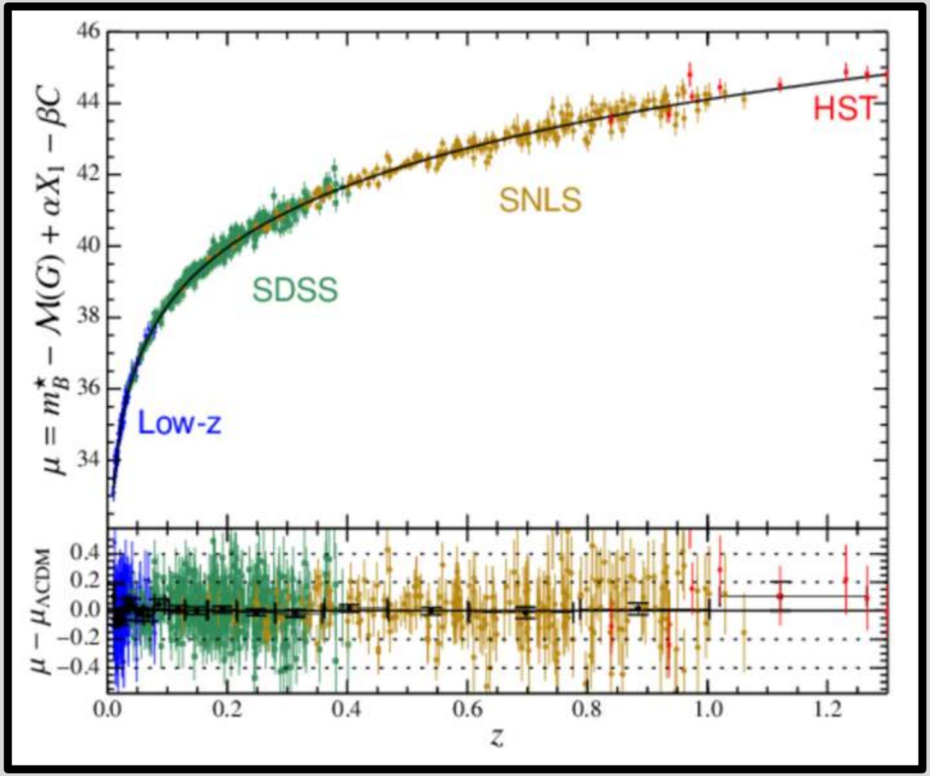


(Courtesy of Pat Hall's blog)

Cosmology

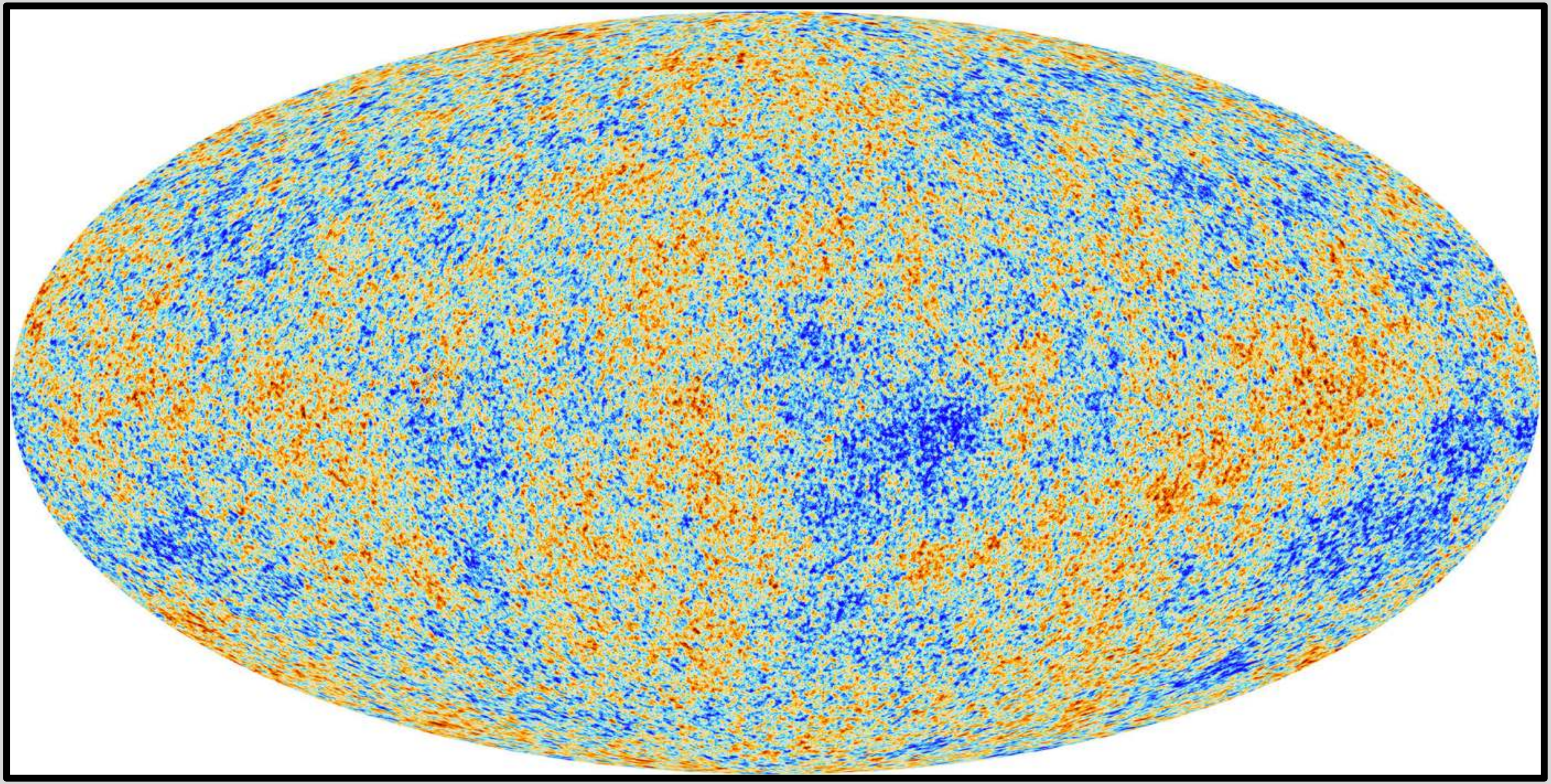


Hubble 1929



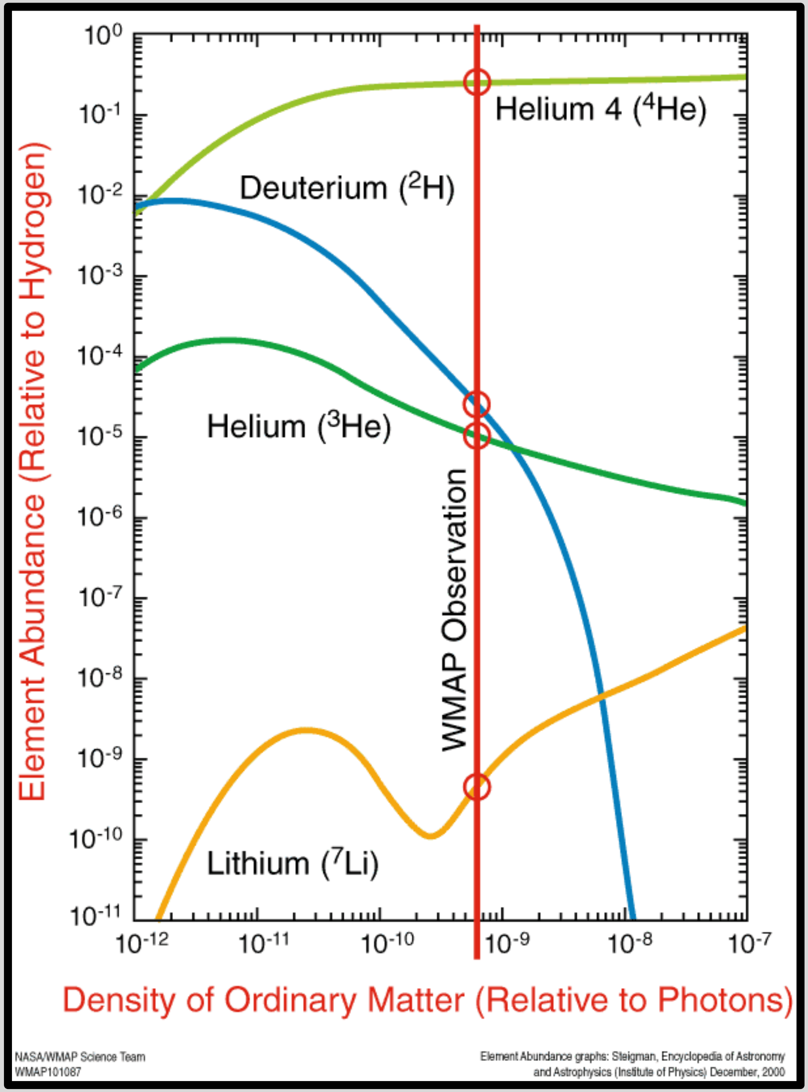
Betoule 2014

Cosmology



Planck Satellite image of the CMB, ESA

Cosmology



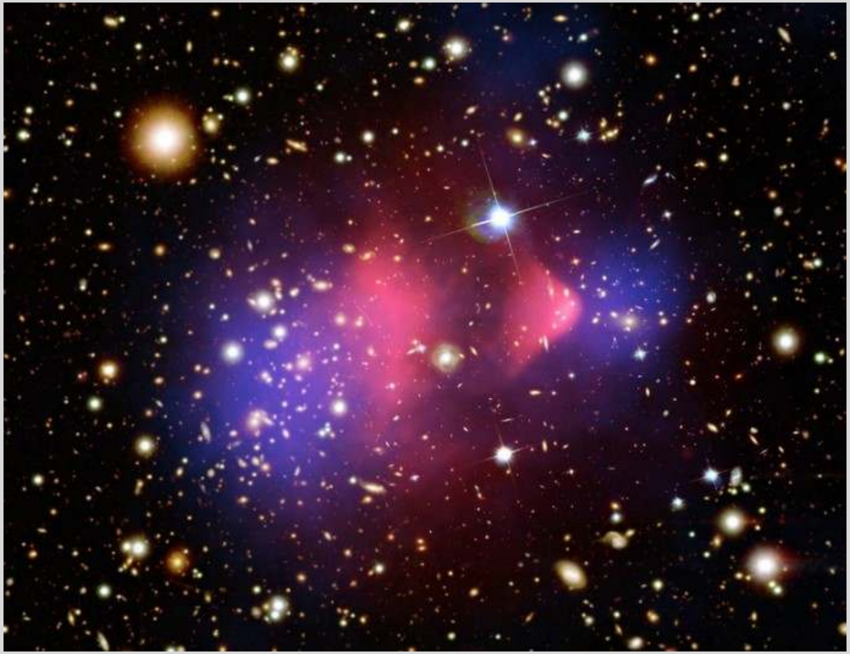
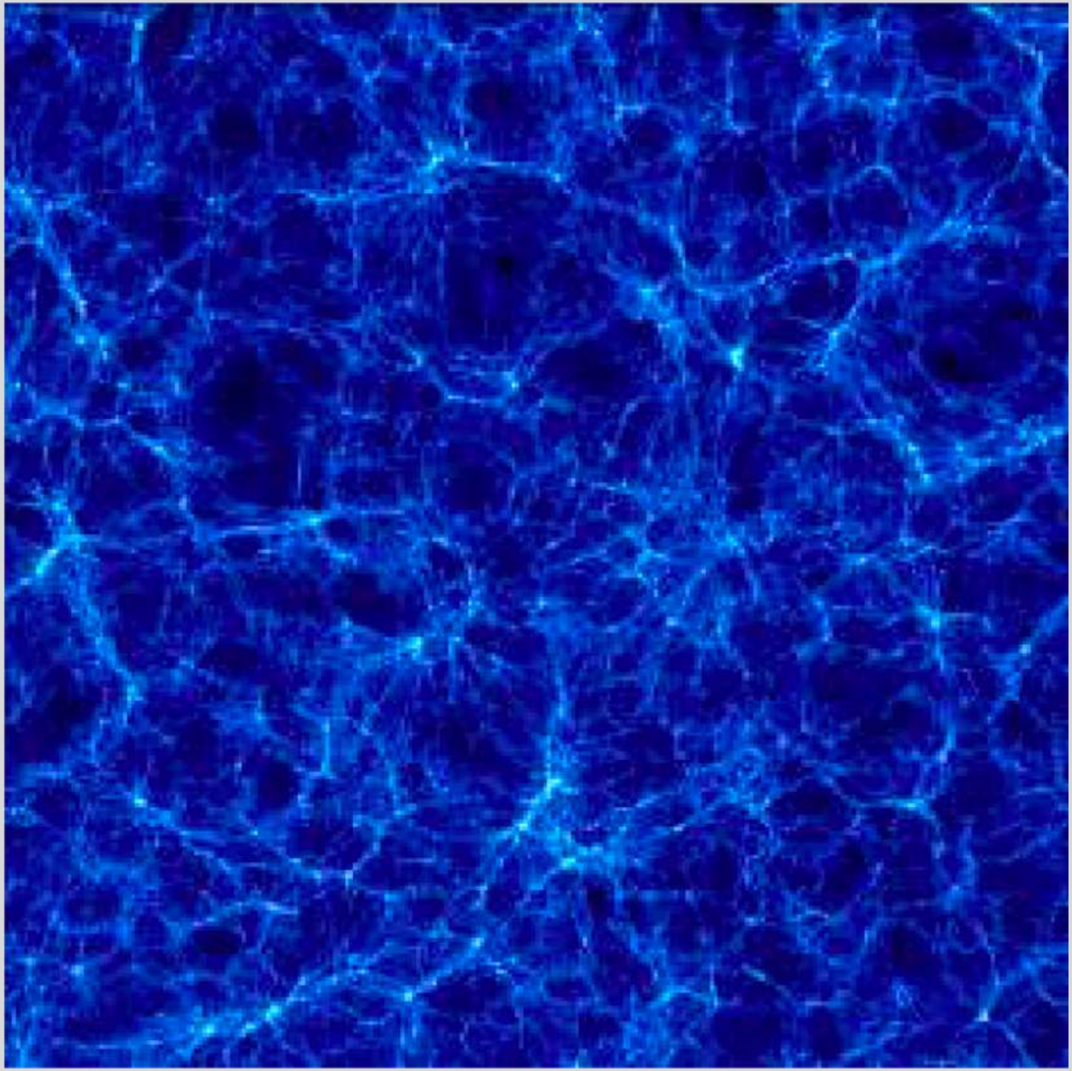


Image Credit: NASA

Many different probes of cosmology today

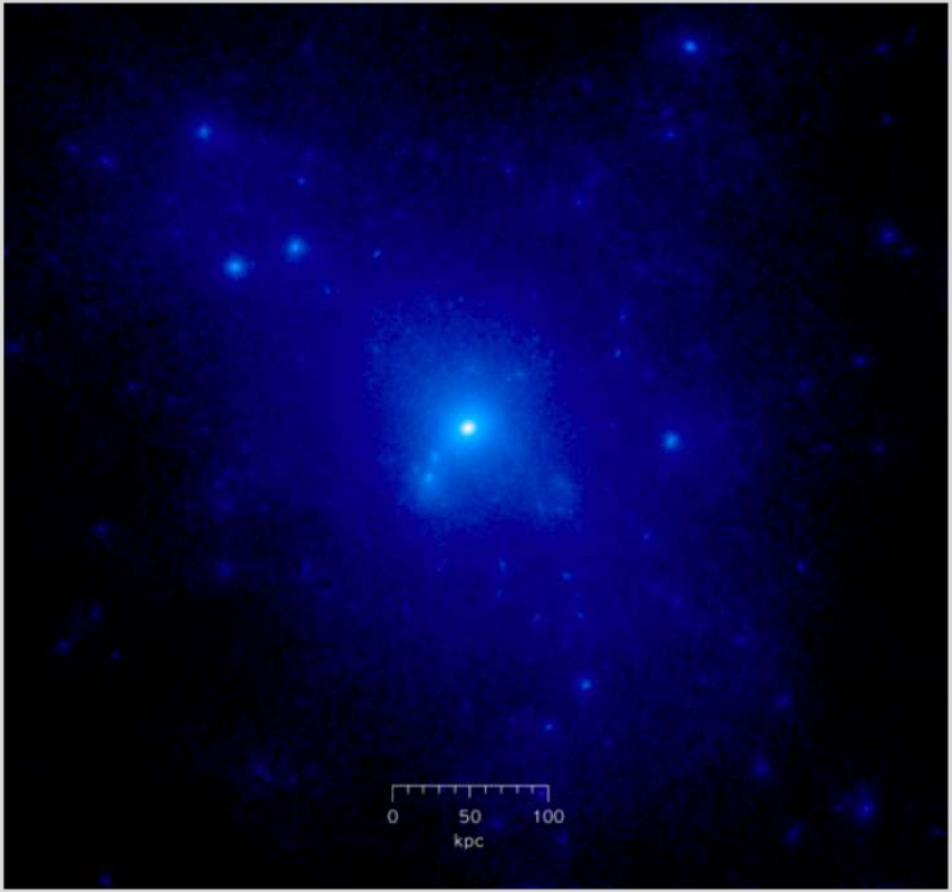
Large-Scale Structure



Dubinski 2003

The Universe starts nearly homogeneous; dark matter structure grows under gravity

Large-Scale Structure



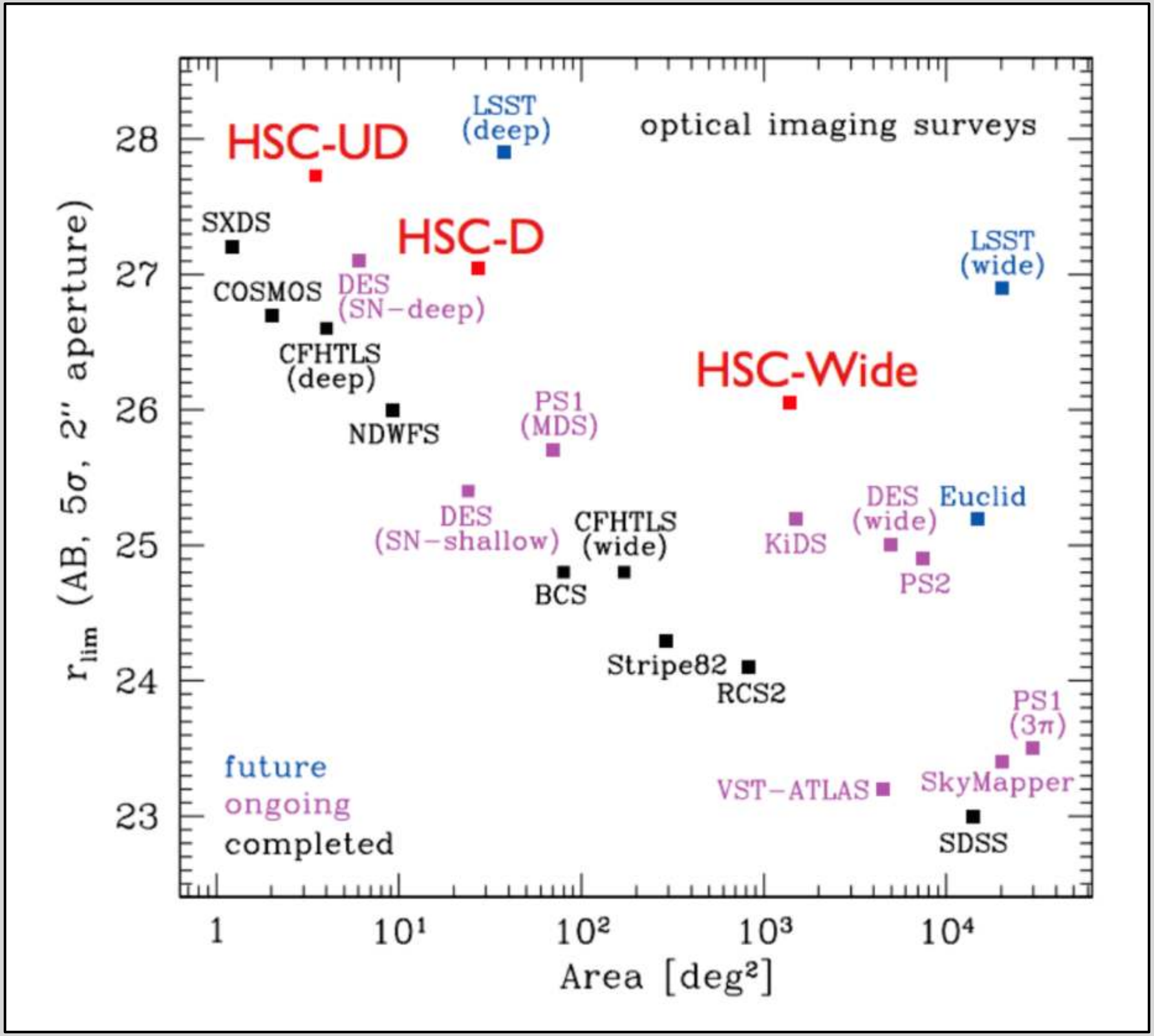
Wikipedia

Dark matter forms non-linear clumps called "haloes"

2. Galaxy Surveys

- Deep wide-field galaxy surveys let us probe cosmology and galaxy physics over cosmic time
- Two-point clustering statistics can tell us a lot about both galaxy environment and the large-scale structure of the Universe

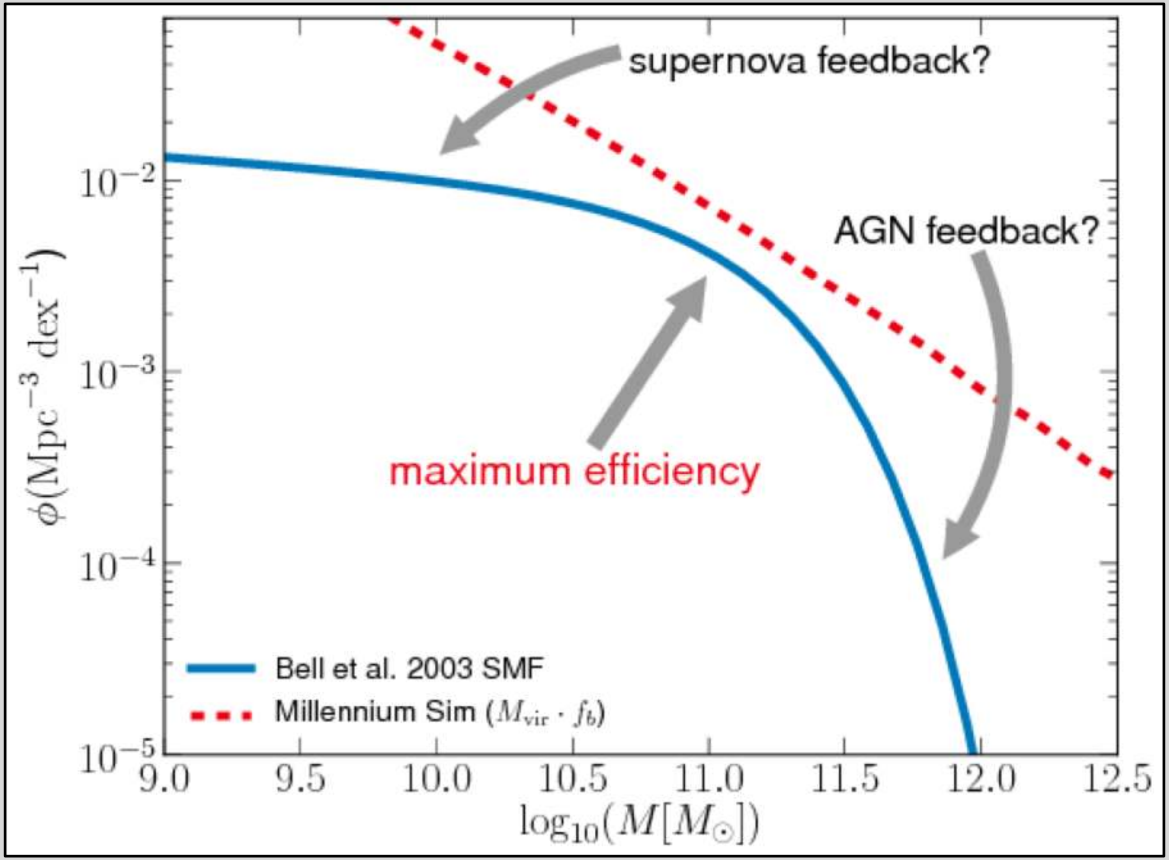
Galaxy Surveys



Miyazaki et al., 2013

Stellar Mass Function

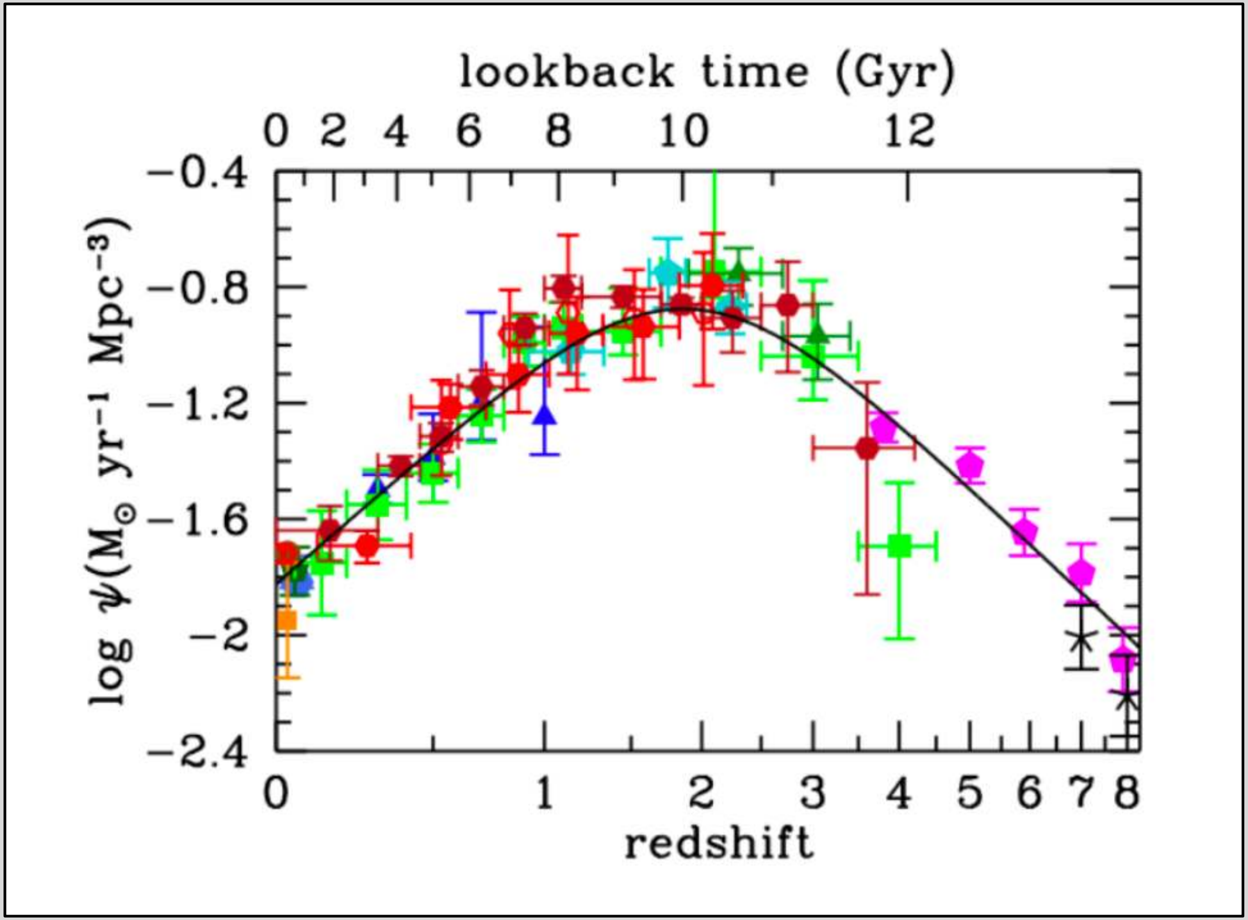
Mutch et al., 2013



UNIVERSITY OF OXFORD

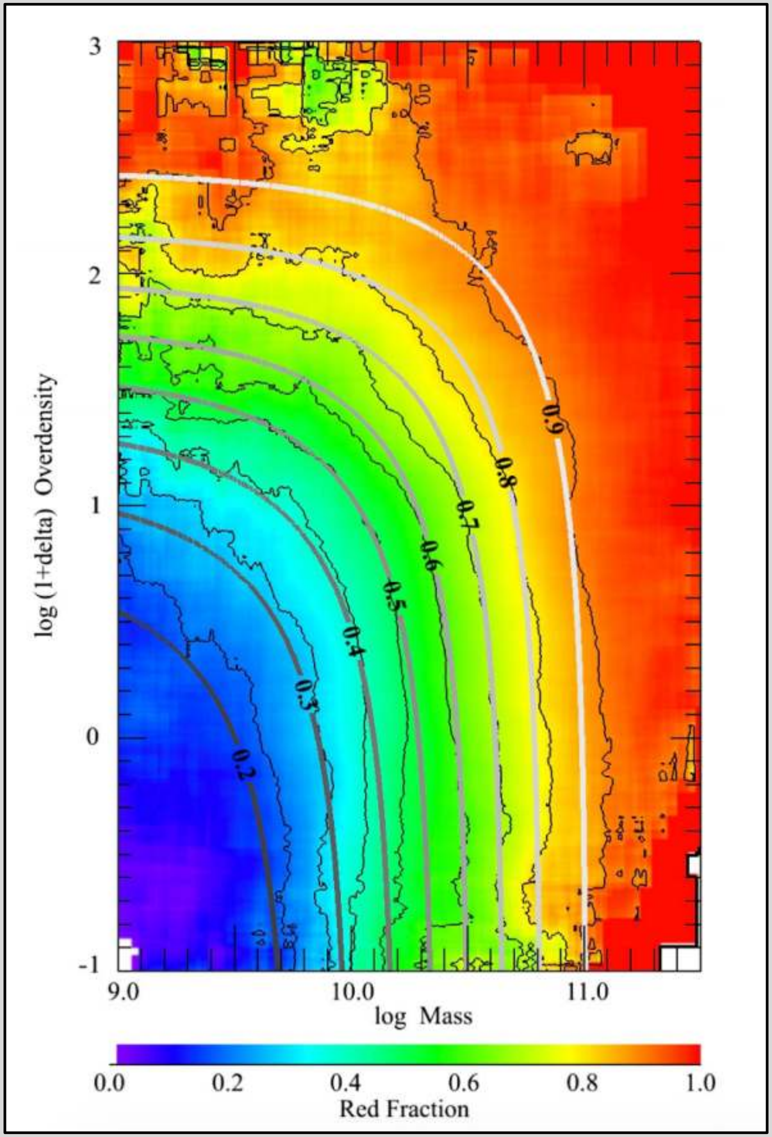
Cosmic SSFR

Madau and Dickinson., 2014



Mass quenching versus environmental quenching?

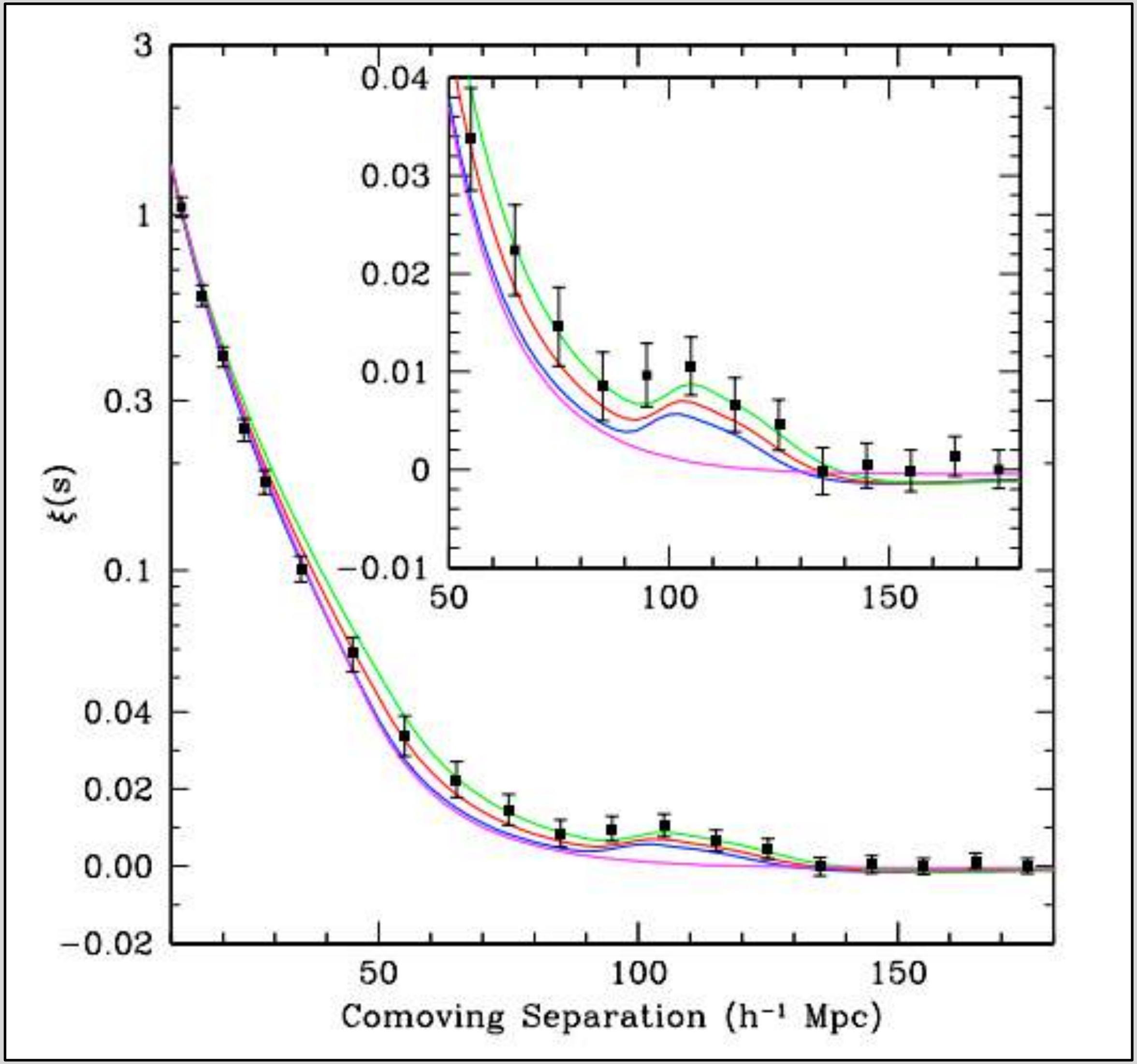
Peng+2010



Cosmology from Clustering

Baryonic Acoustic Oscillations

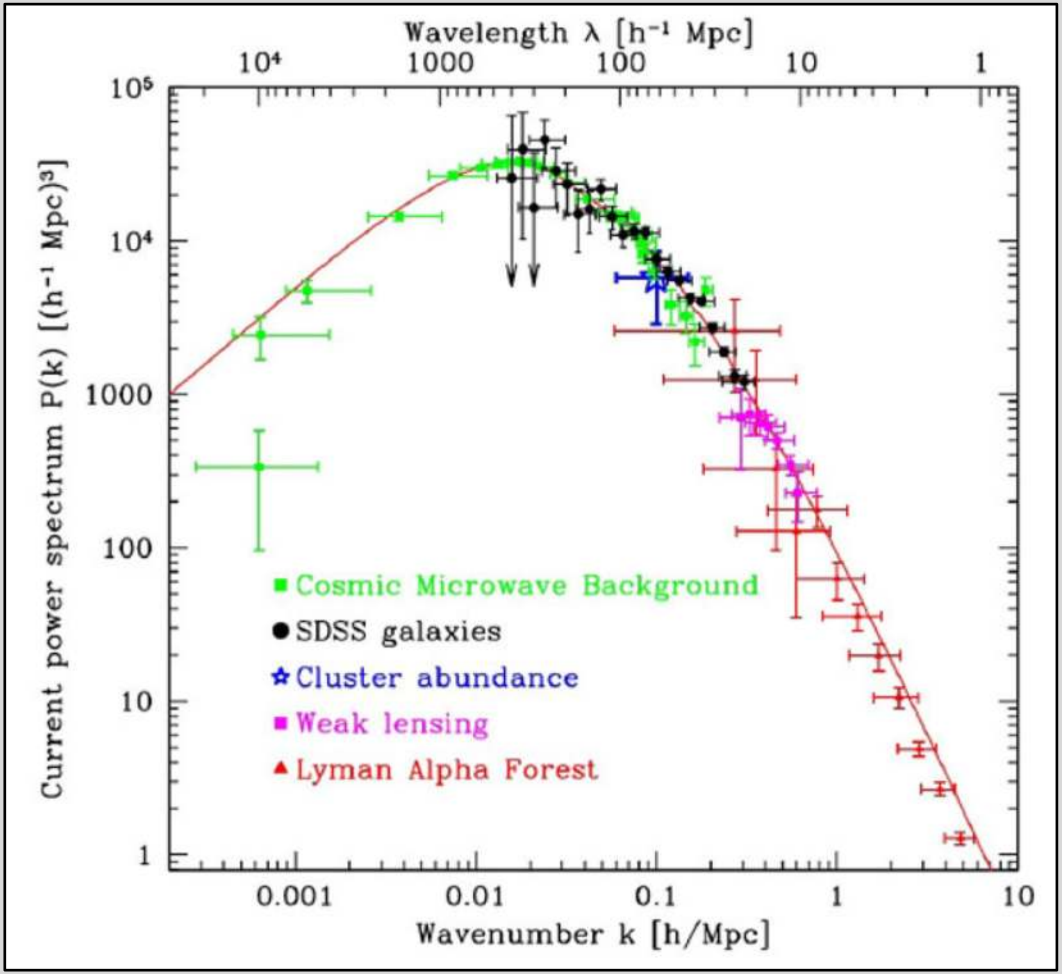
Basset et al., 2010



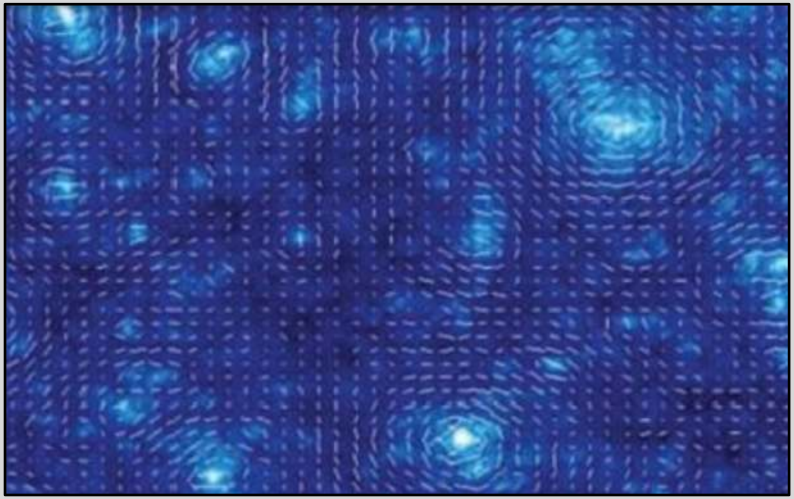
Cosmology from Clustering

Matter Power Spectrum

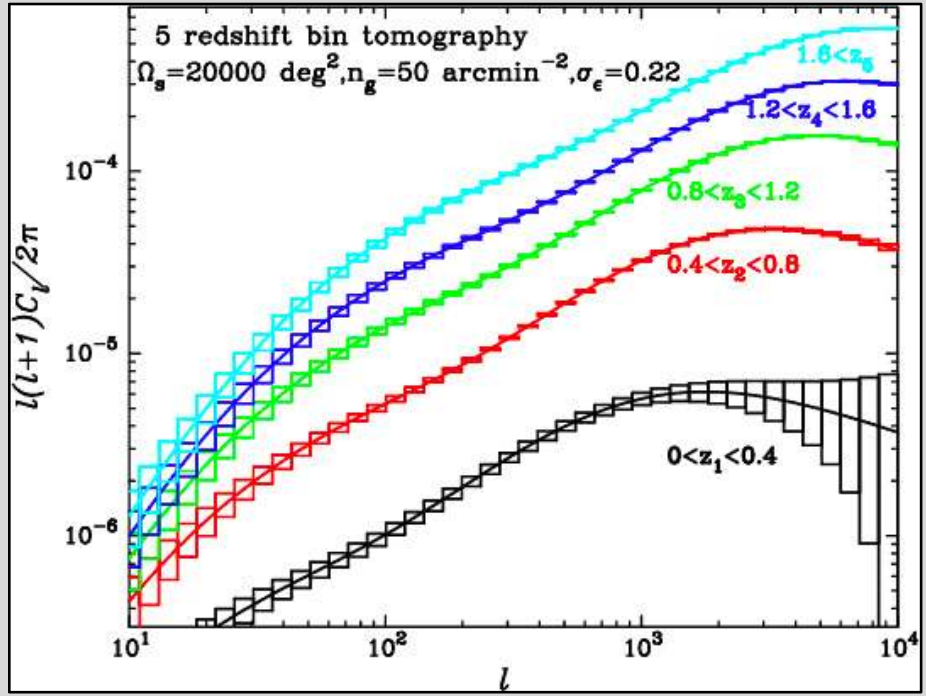
Tegmark et al., 2004



Cosmology from Clustering



Berkeley National Laboratory



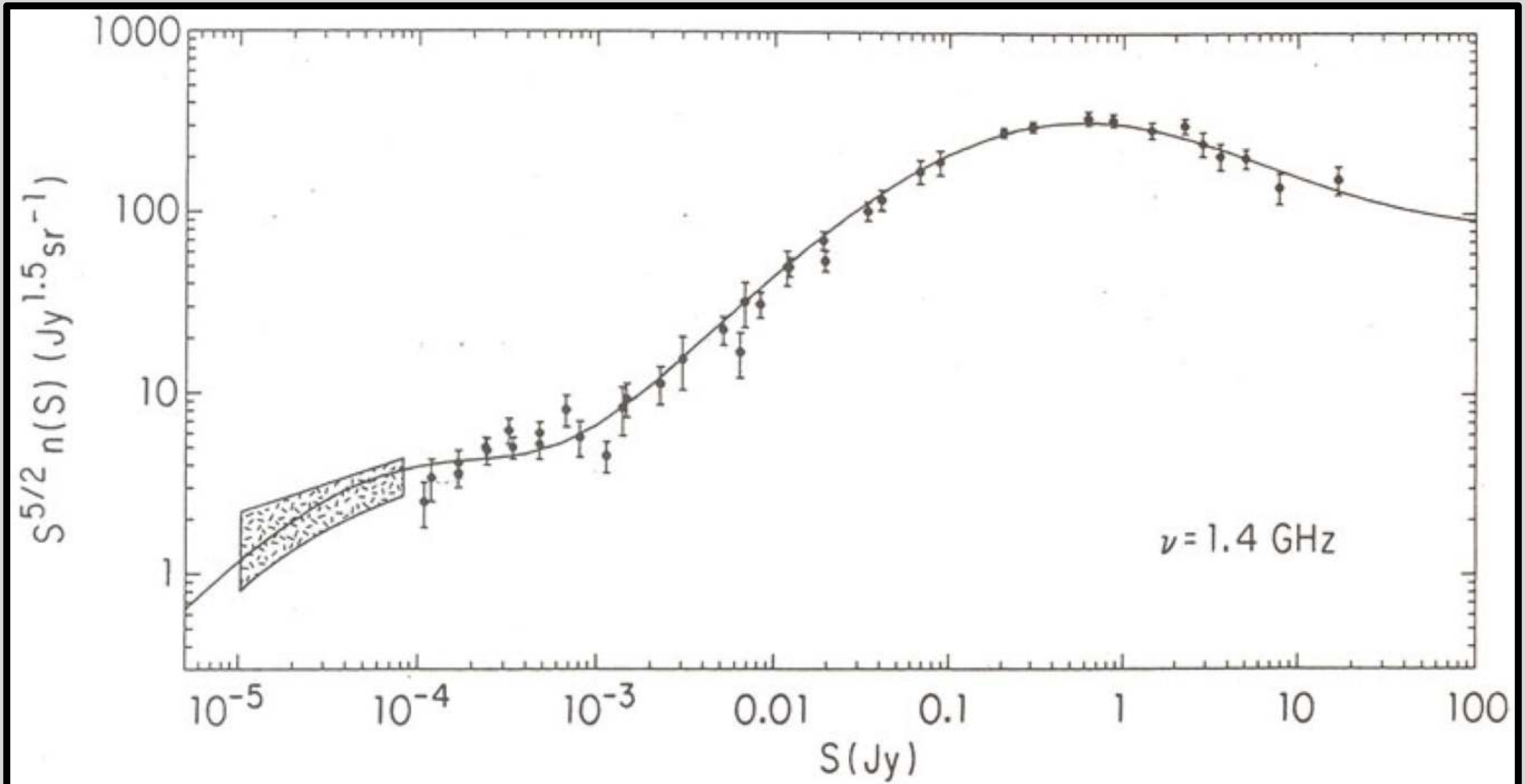
Basset et al., 2010

Weak Lensing Shear

- Weak-lensing matter power spectrum (matter-matter coupling)
- Galaxy-galaxy lensing (matter-galaxy coupling)
- Galaxy clustering (galaxy-galaxy coupling)
- [Also magnification, CMB lensing potential and much more…]

Cosmology from Clustering

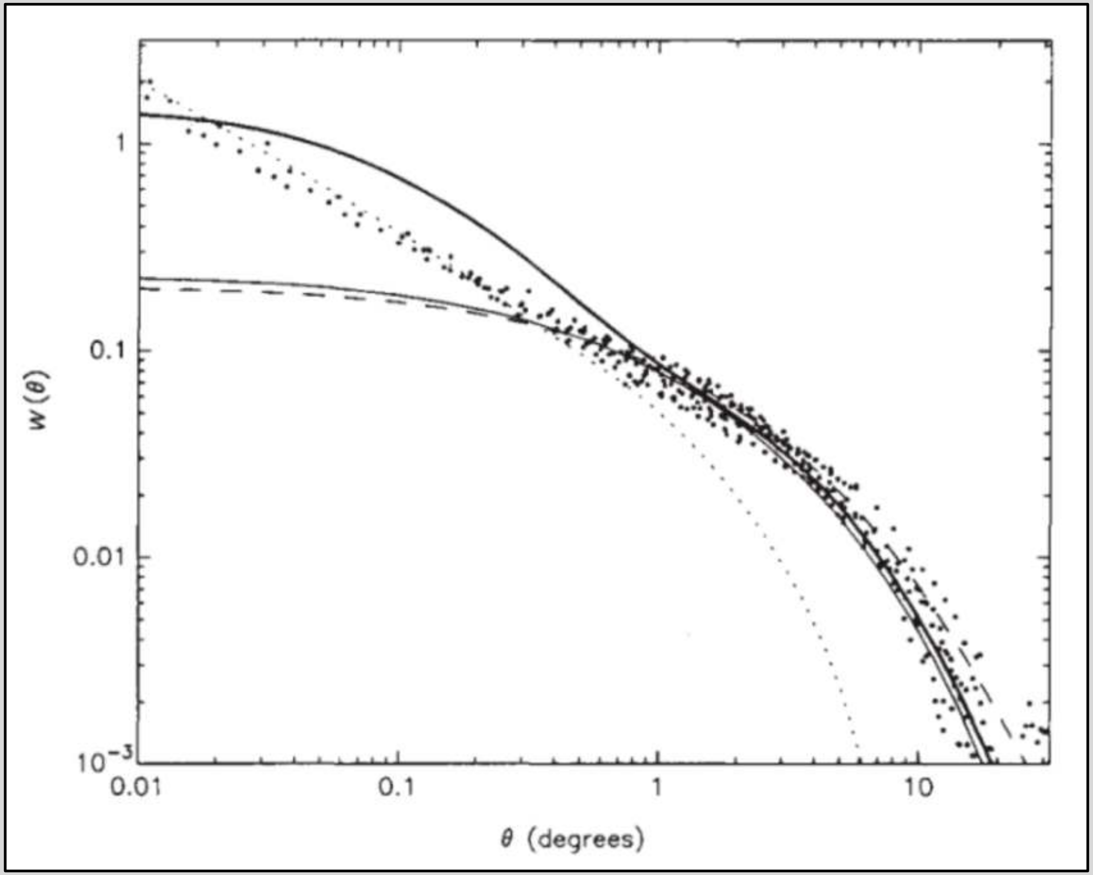
Radio source counts begin to invalidate Steady State theory in ~1961 (CMB is 1964)



Condon+1984b

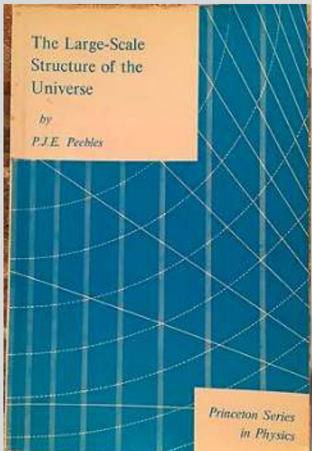
Cosmology from Clustering

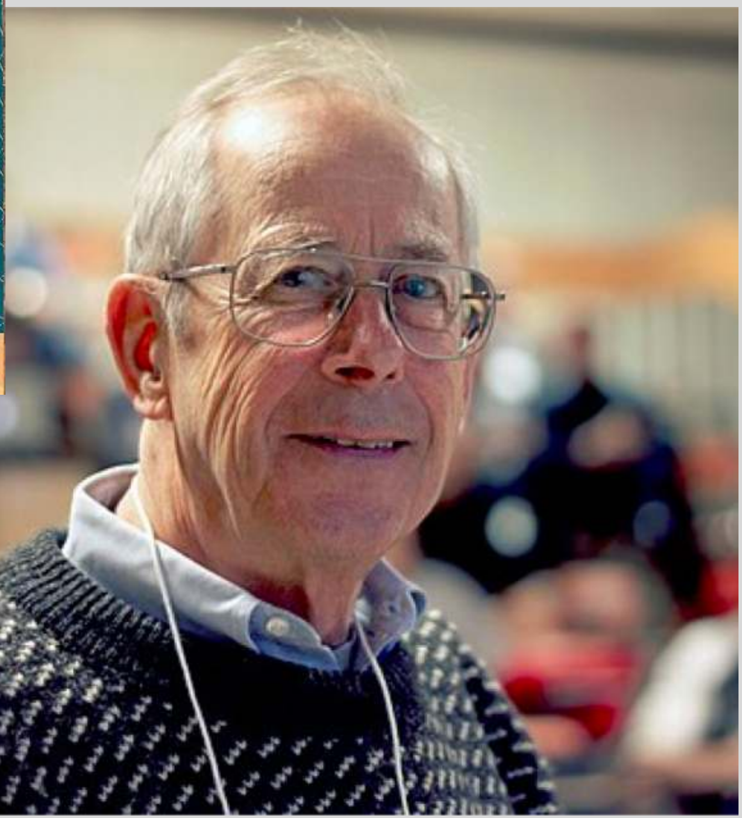
Galaxy clustering in the early 1990's – an early hint of dark energy? (SNe evidence comes out in 1998/1999, Efstathiou+1990 find suggestion of $\Omega_\Lambda \approx 0.8$…)

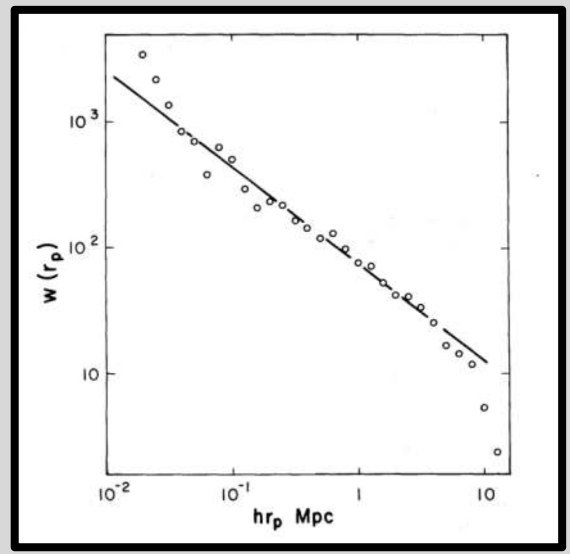


Cosmology from Clustering

2019 Nobel Prize in Physics goes to Jim Peebles for work on the large scale structure of the Universe! (and exoplanets)







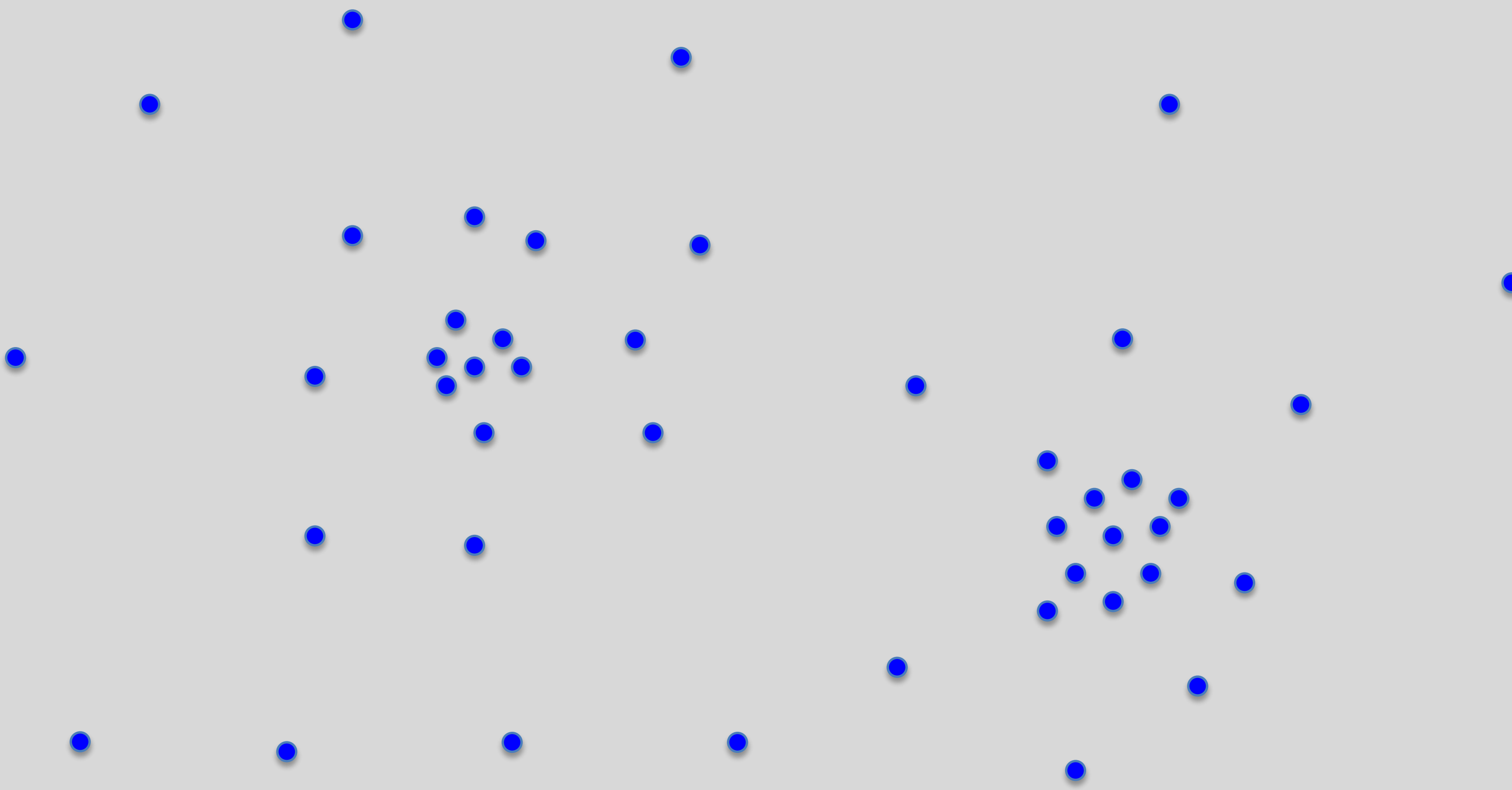
Davis and Peebles 1982
(2400 galaxies!)

2. Halo Occupation Distribution (HOD) Modelling

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

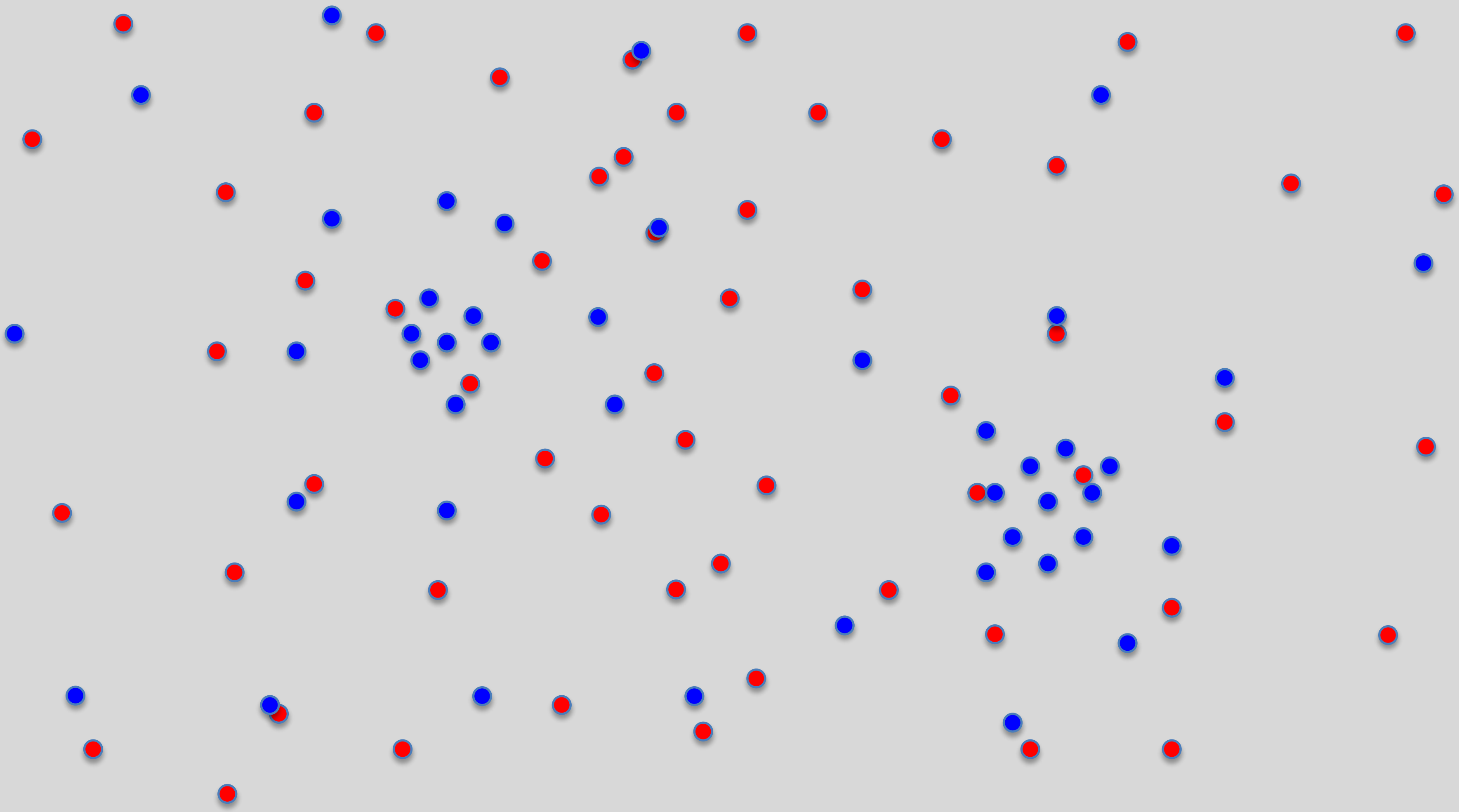
Abell S1063, APOD

Measuring Clustering



Try and form "random" data set of points that have identical properties apart from angular location to data set

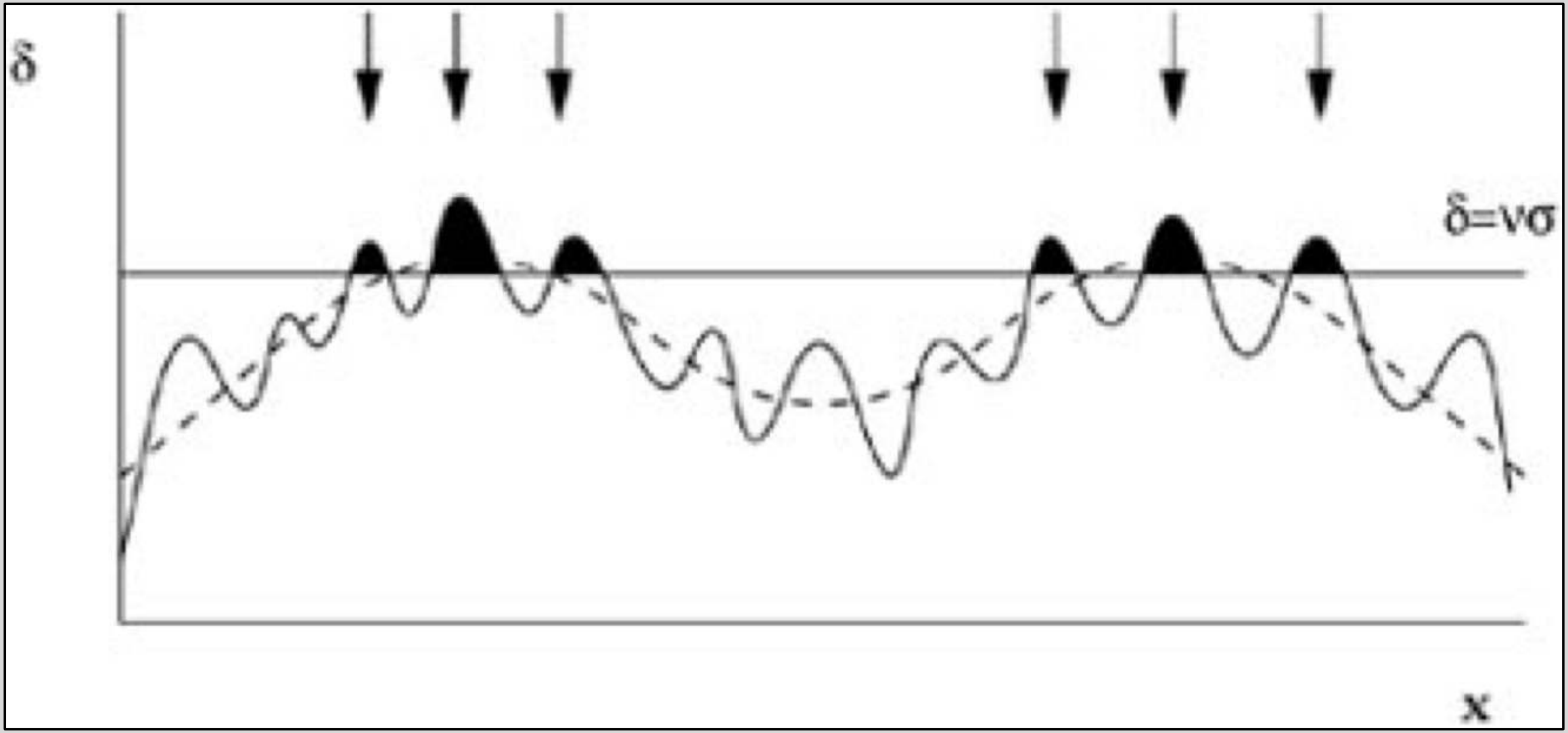
Measuring Clustering



$$\omega(\theta) = \frac{DD}{RR} - 1$$

(Actually use Landy-Szalay 1993)

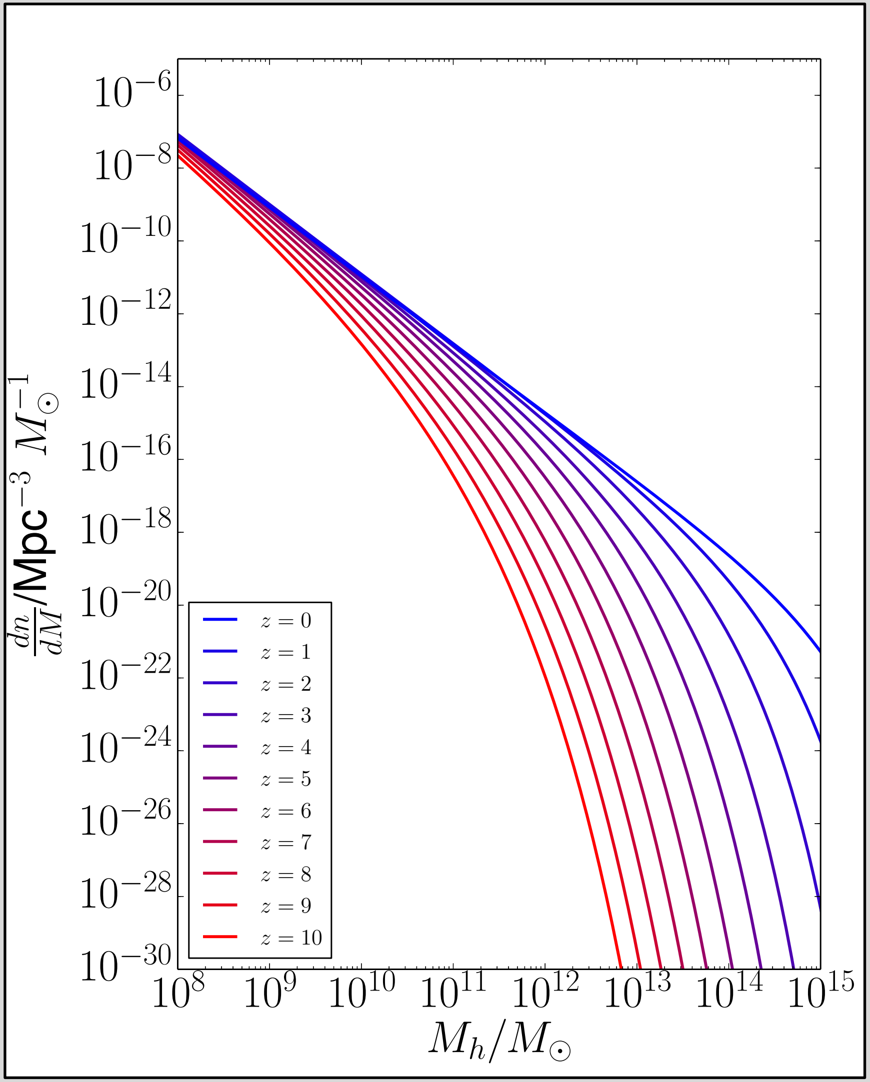
Galaxy Bias

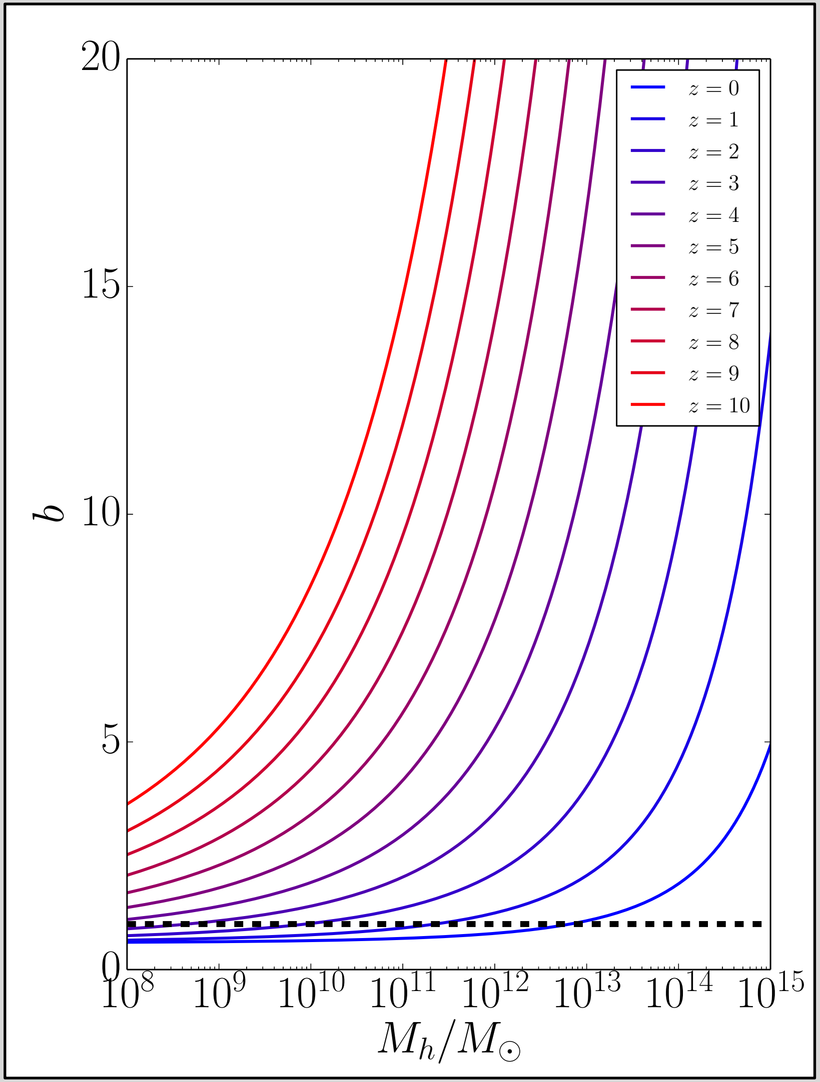


Kaiser et al., 1984

Galaxies have a different spatial distribution to matter

Halo Properties Over Cosmic Time





(Plots created using *Halomod*, Steven Murray+)

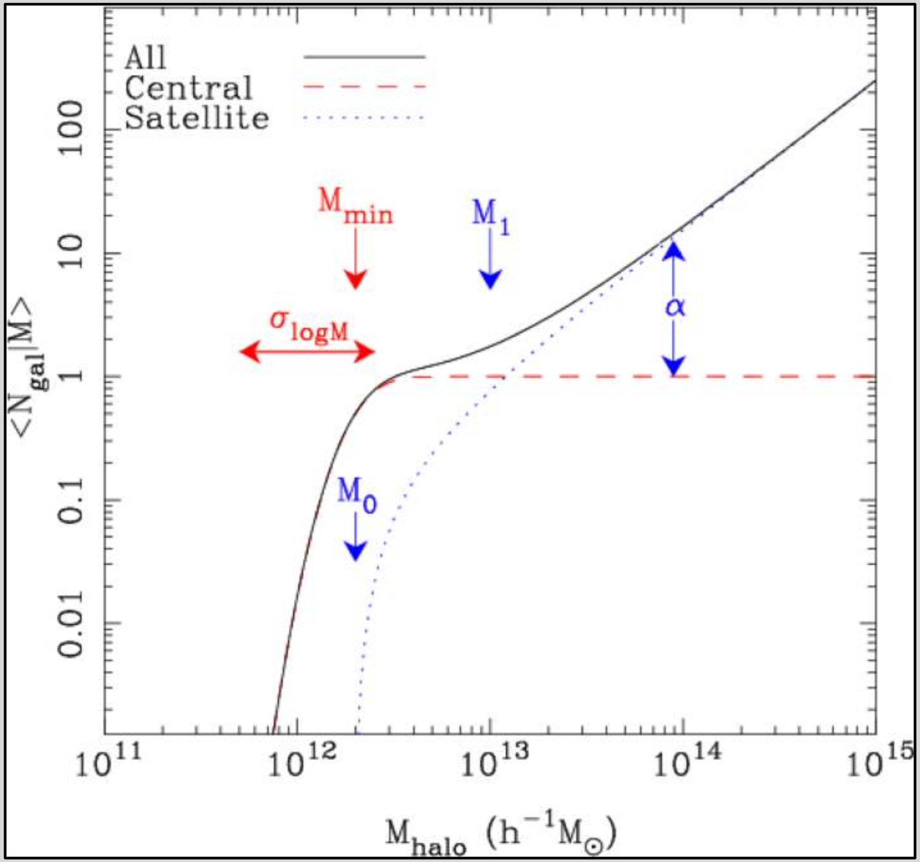
Halo Occupation Modelling

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

HOD Ingredients:

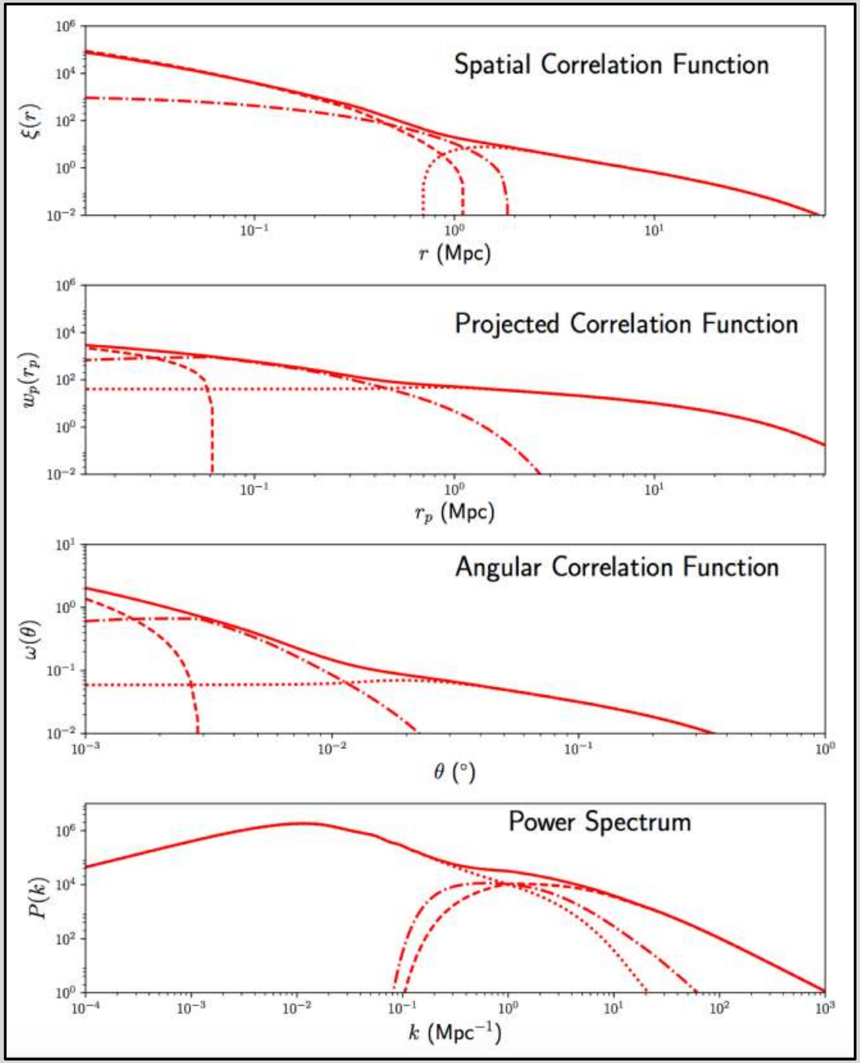
- (Cosmology)
- Halo mass function
- Halo bias prescription
- Dark matter power spectrum
- Halo profiles
- Occupation number
- Poisson assumption
- Central/satellite distinction
- 1-halo and 2-halo terms

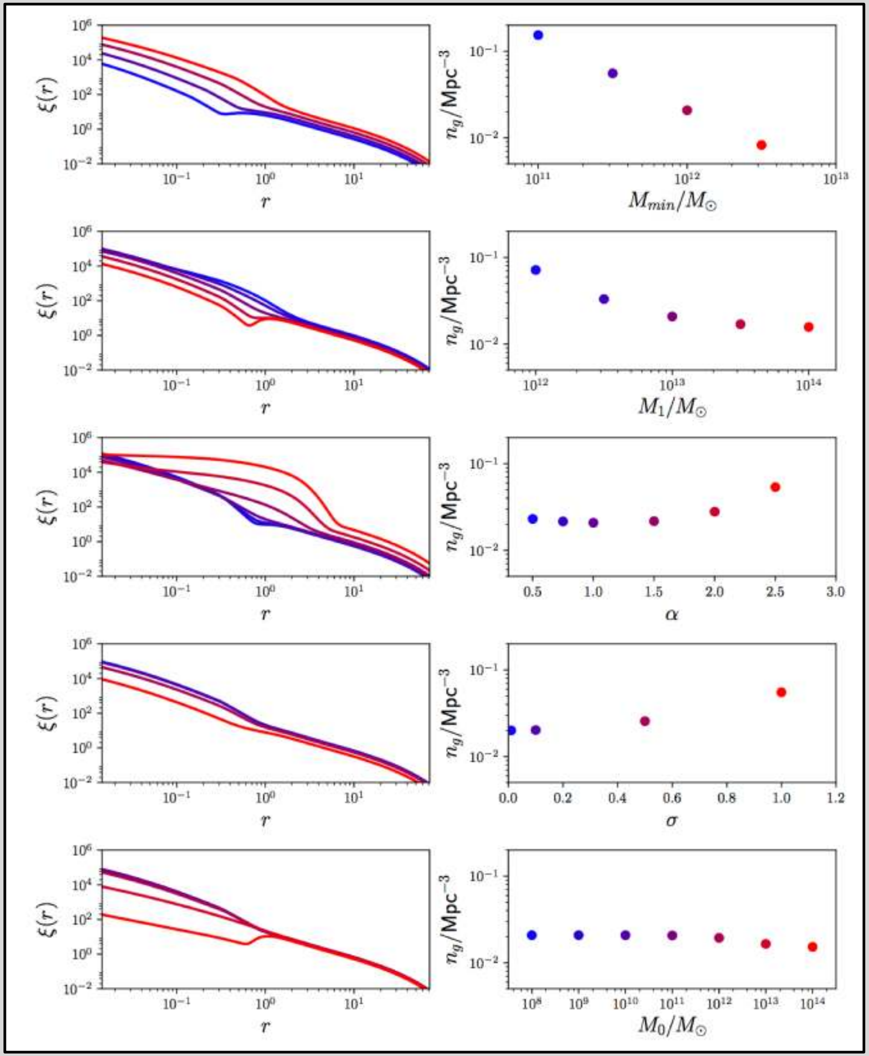
$$\chi^2 = \frac{[n_{\rm gal}^{\rm obs} - n_{\rm gal}^{\rm model}]^2}{\sigma_n^2} + \sum_i \frac{[\omega^{\rm obs}(\theta_i) - \omega^{\rm model}(\theta_i)]^2}{\sigma_{w_i}^2},$$



Wake et al., 2011

Halo Occupation Modelling





(Plots created using *Halomod*, Steven Murray+)

3. Clustering in VIDEO

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

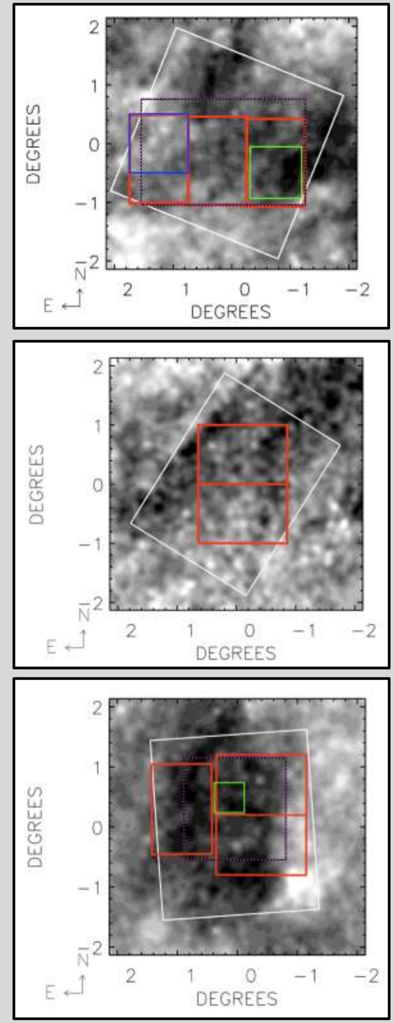
The VIDEO Survey

The VIDEO Survey

The 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
- 1sq degree here, soon 12 sq deg
- Right combination of width and depth for HOD

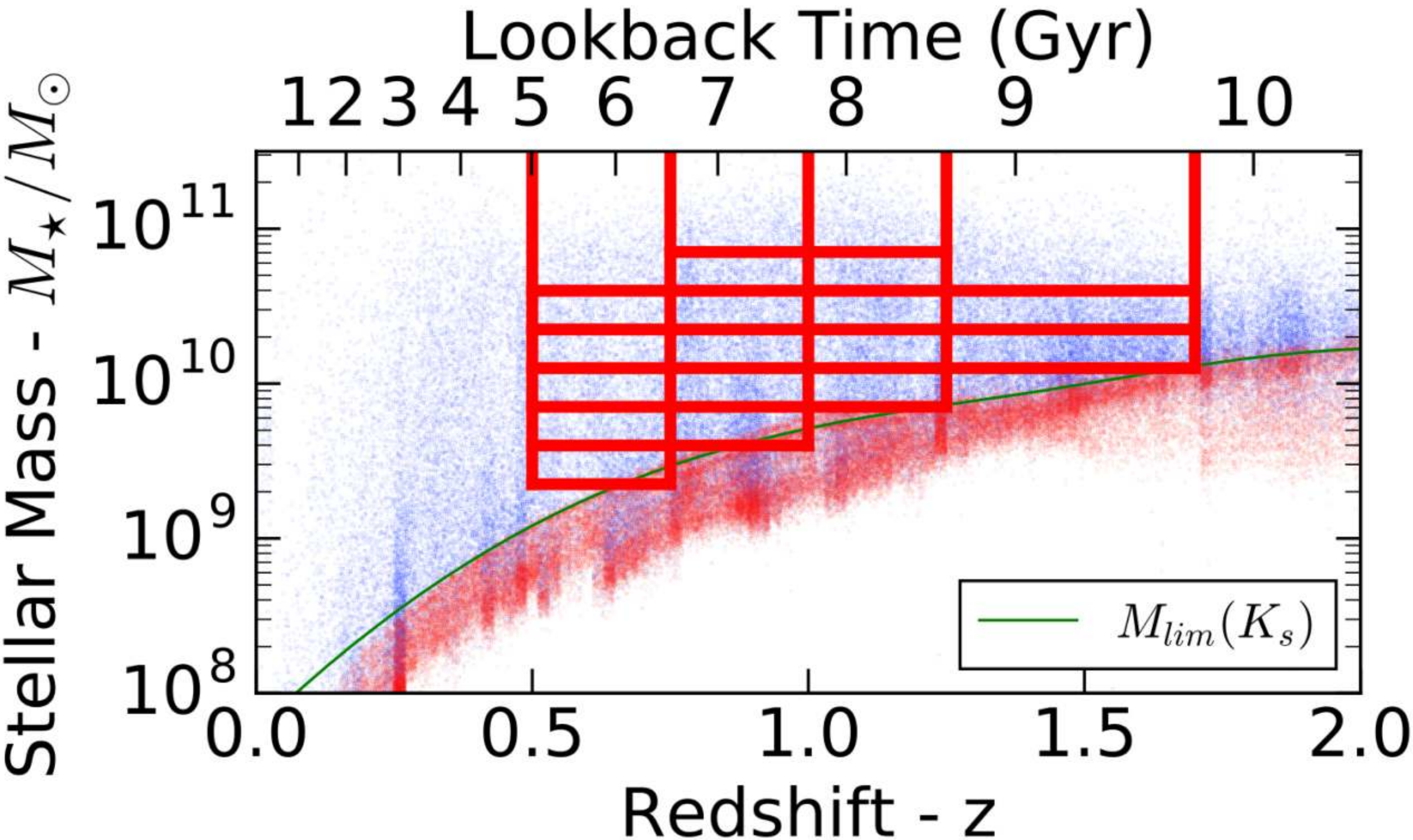
- VEILS will extend VIDEO fields



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	$22^{\dagger}$	0.8	B	THN,CLR
K_s	6.7	23.8	224	23.5	21.7	20.8	0.6	B	THN,CLR

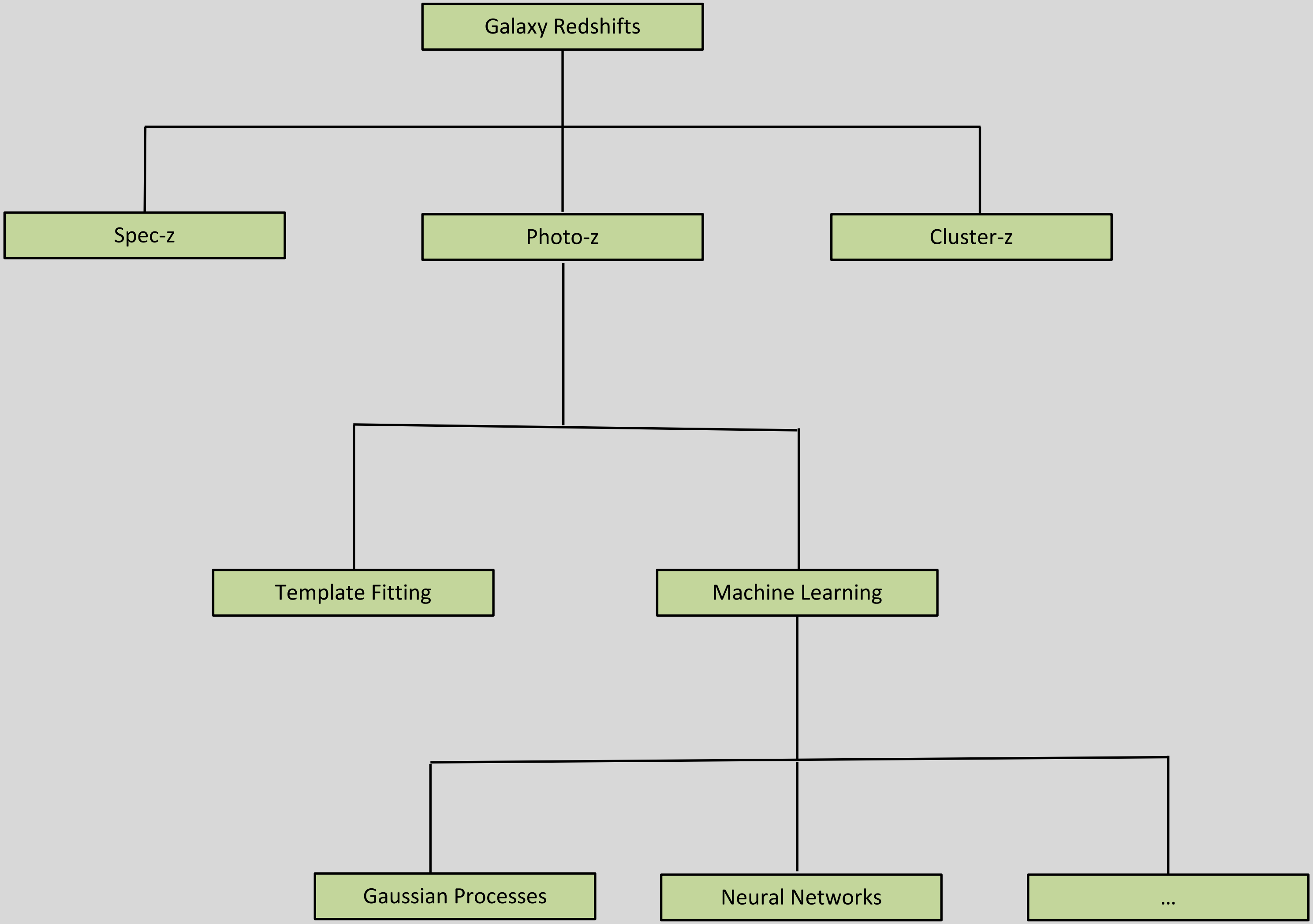
M.Jarvis et al., The VISTA Deep Extragalactic Observations (VIDEO) Survey, MNRAS (2013)

The VIDEO Survey



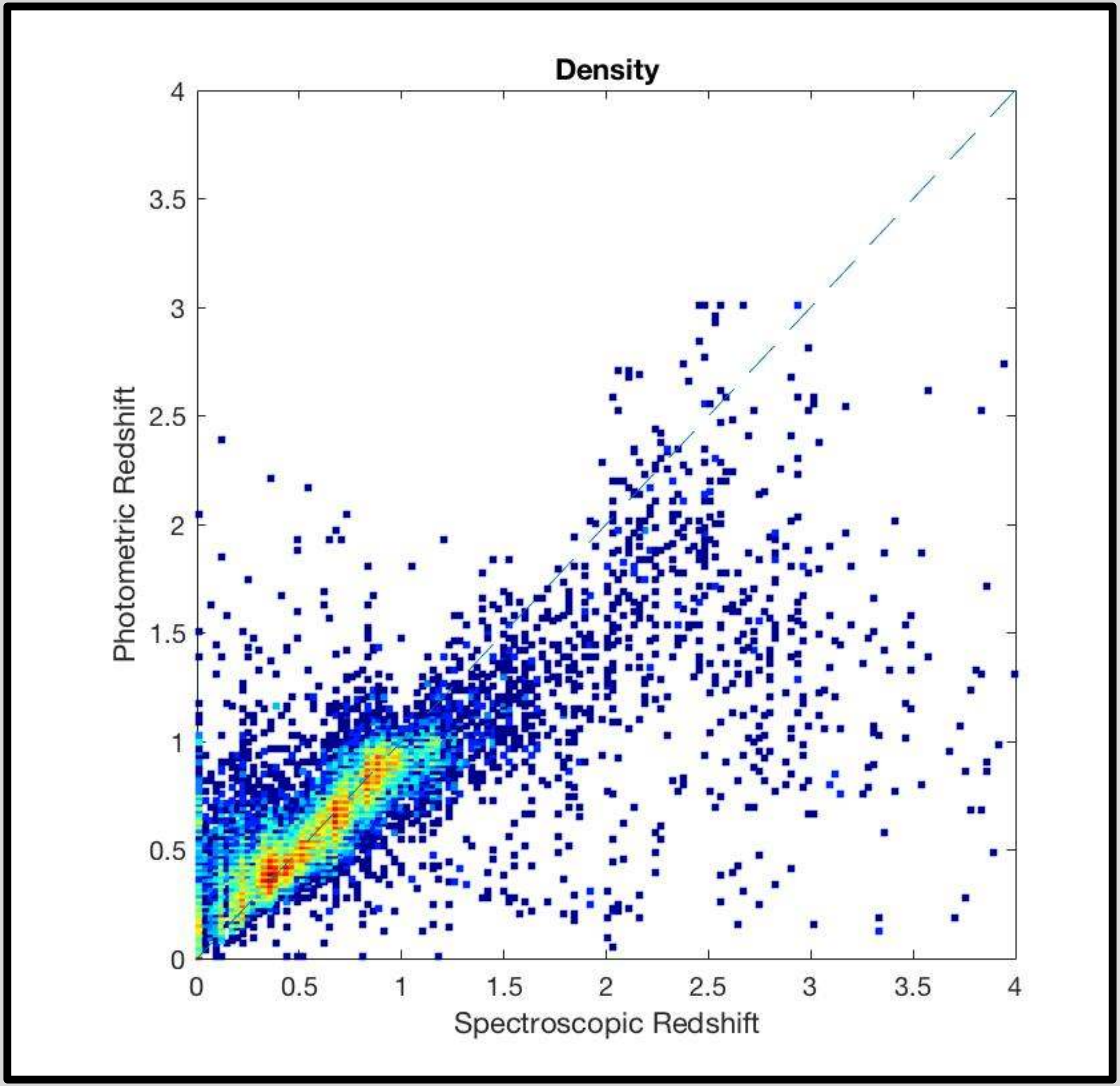
(Colour-cut to remove stars etc.)

Calculating Redshifts

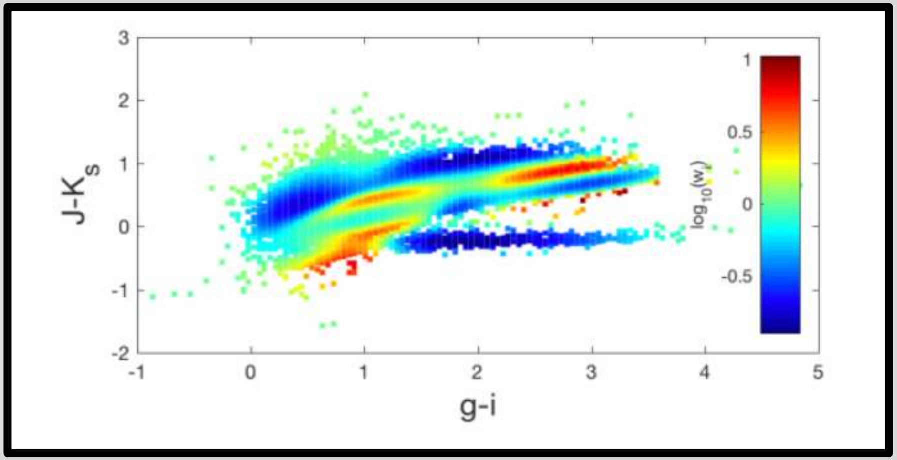


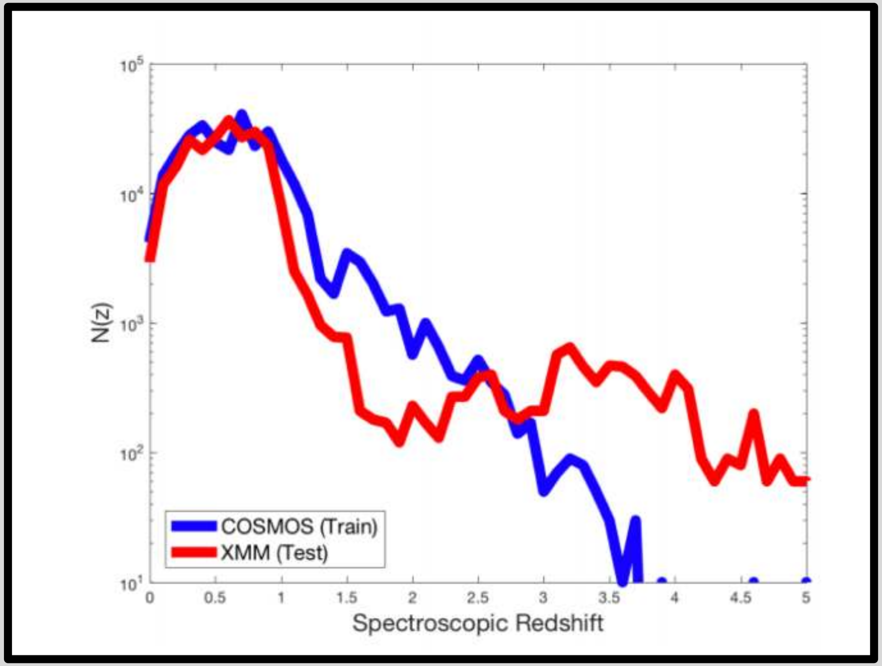
LePhare and GPz used, see Almosallam 2016a,b

Calculating Redshifts



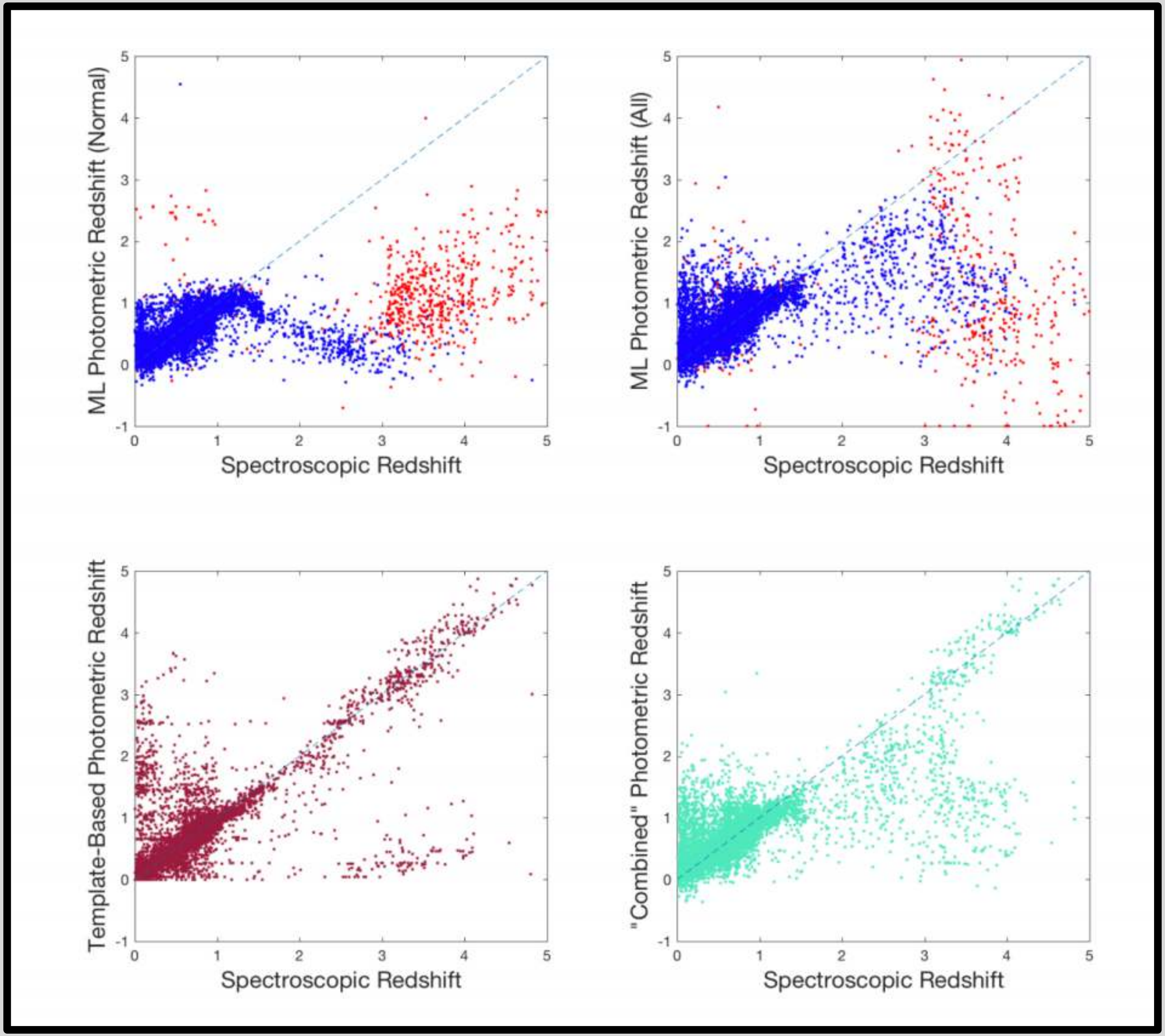
Calculating Redshifts





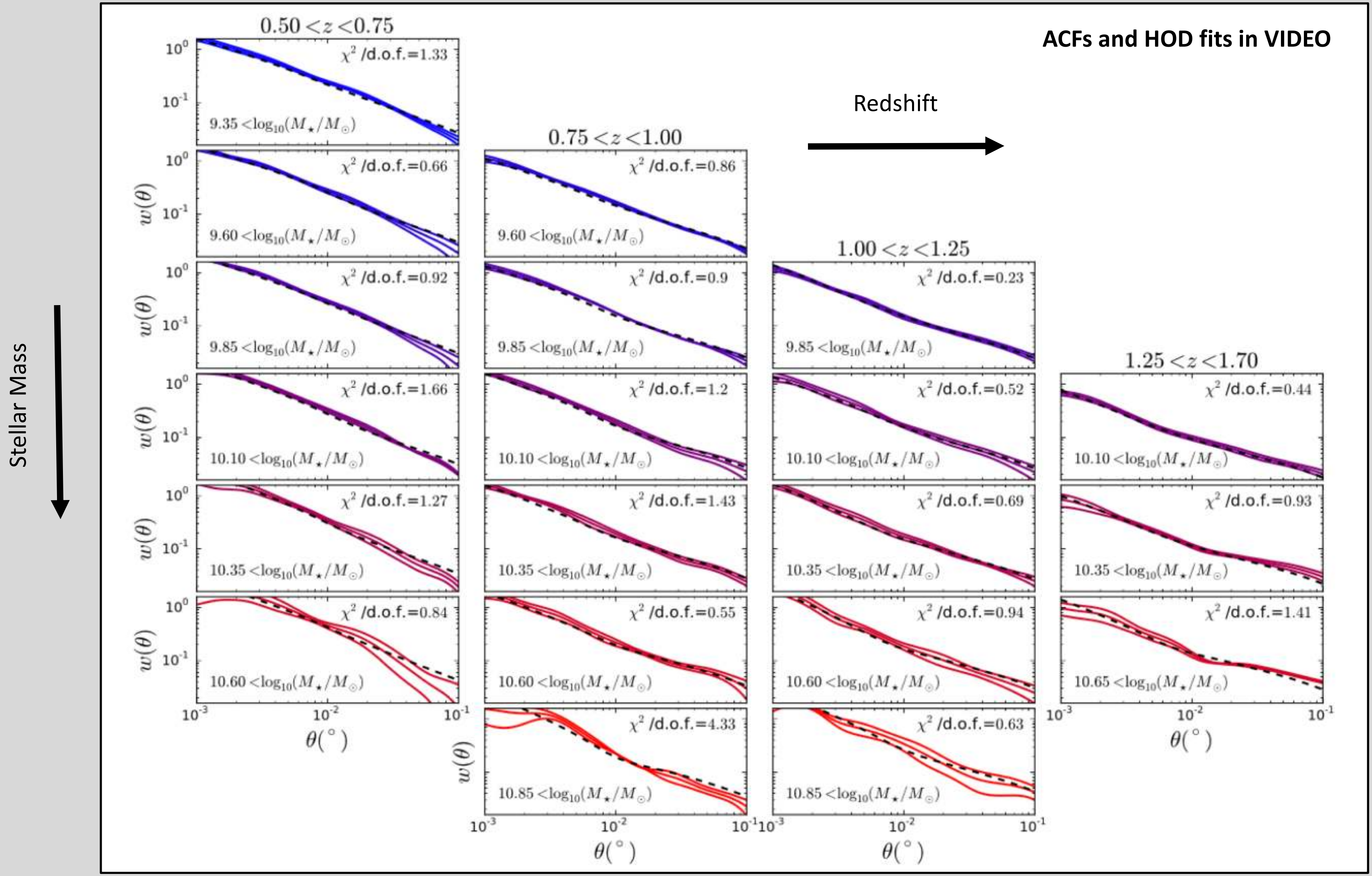
Hatfield et al., 2020 Augmenting machine learning photometric redshifts with Gaussian mixture models, MNRAS, 498, 4, 5498-5510

Calculating Redshifts

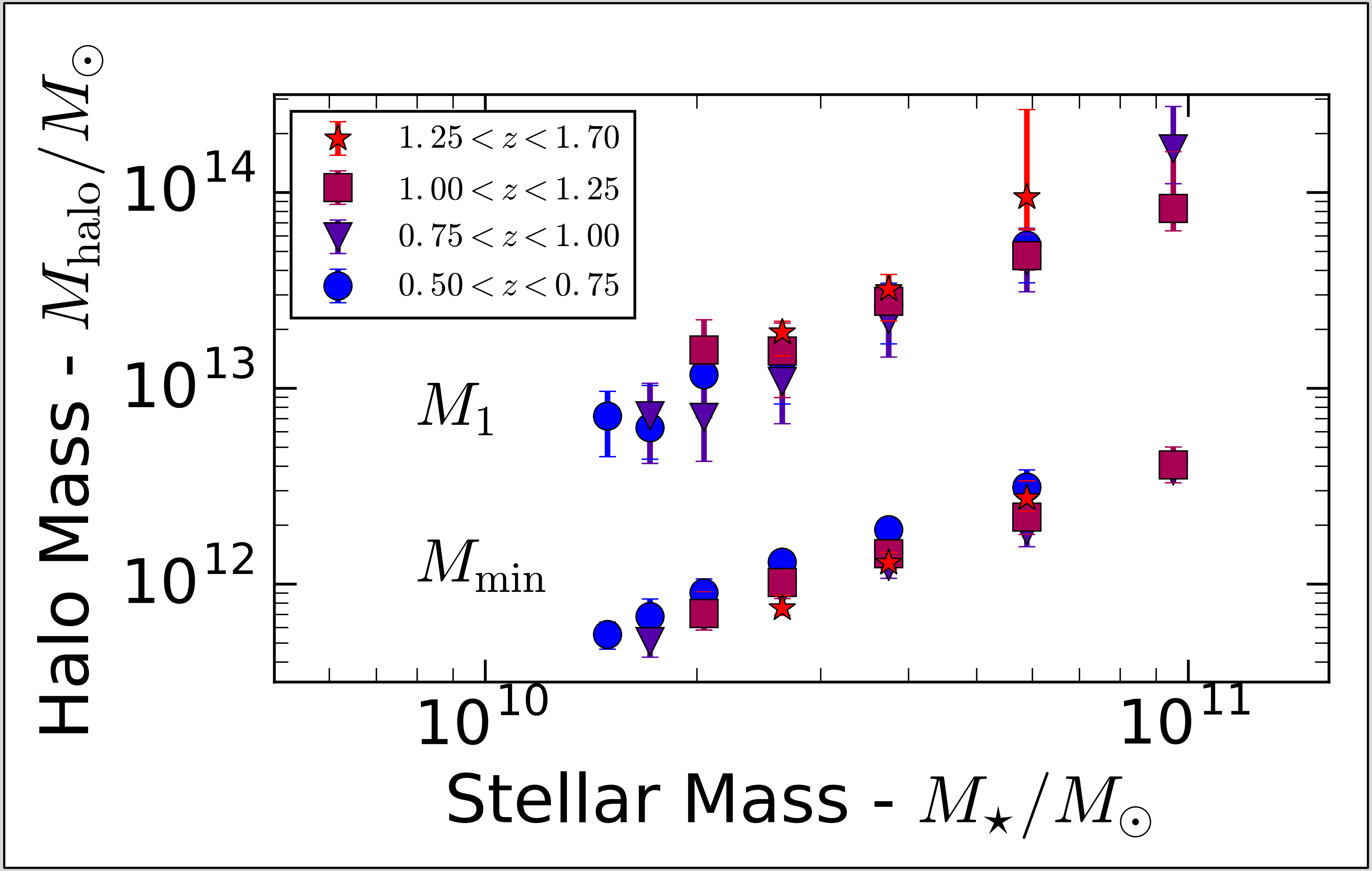


Hatfield et al., 2020 Augmenting machine learning photometric redshifts with Gaussian mixture models, MNRAS, 498, 4, 5498-5510

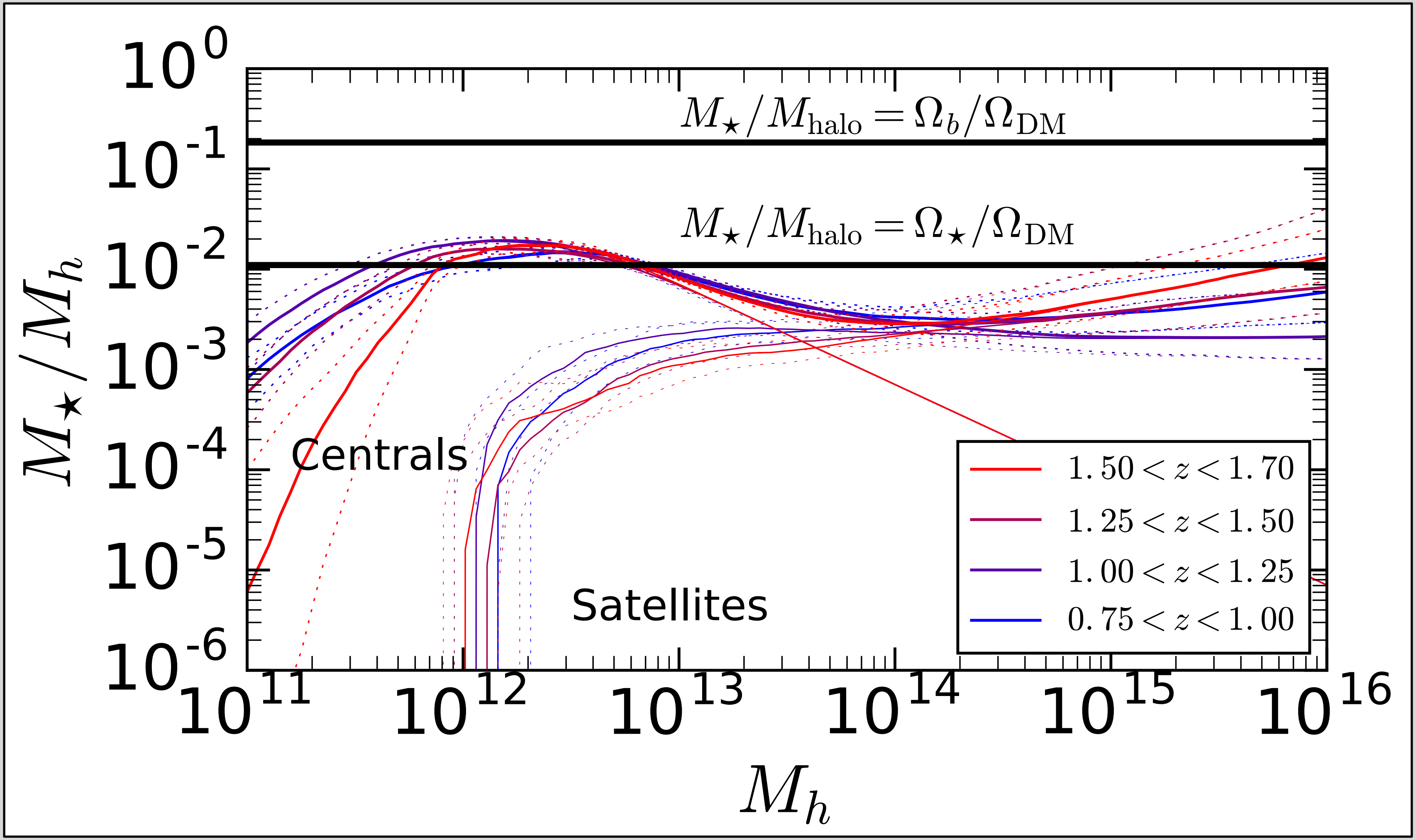
Modelling the Clustering



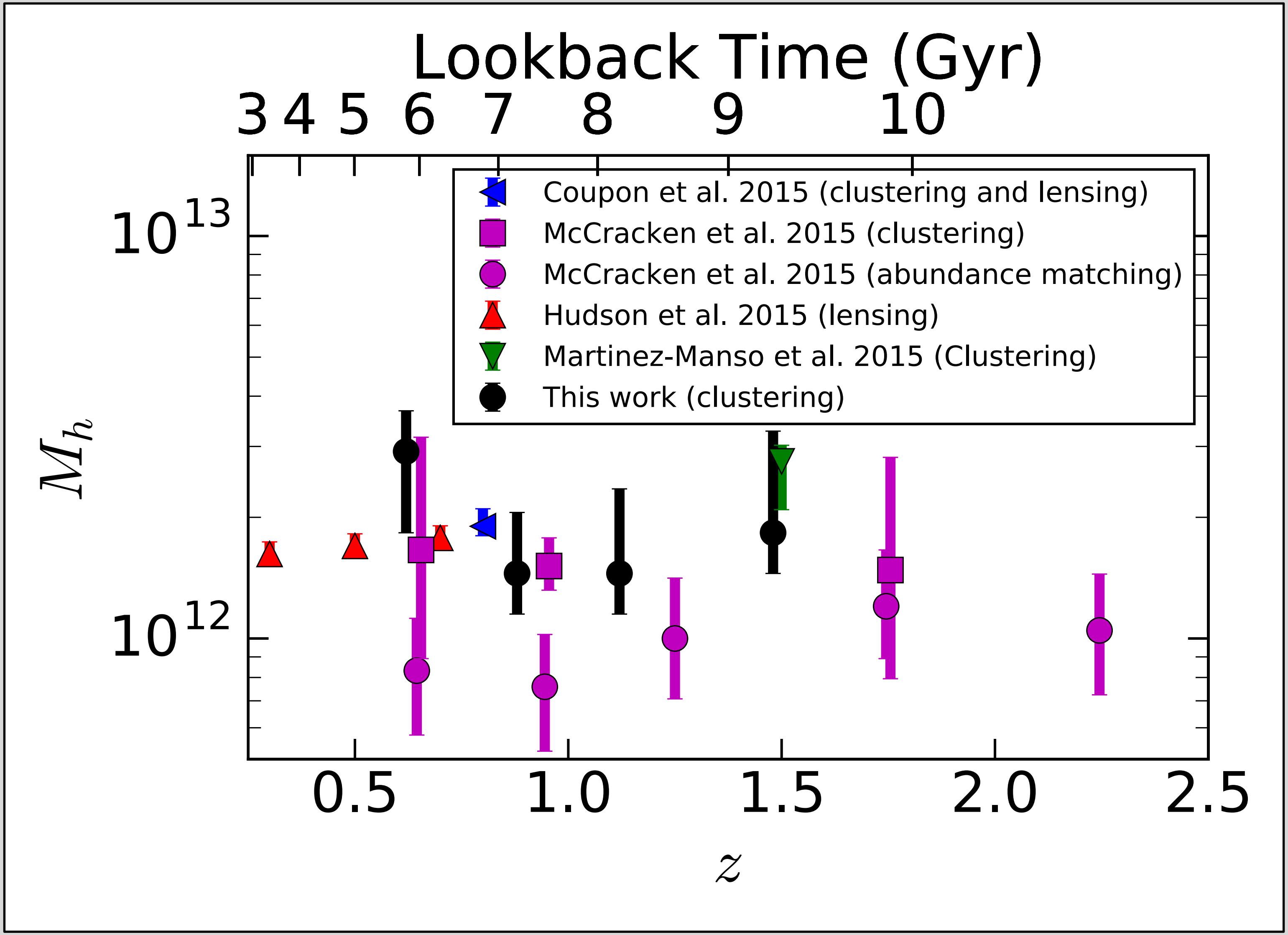
Modelling the Clustering



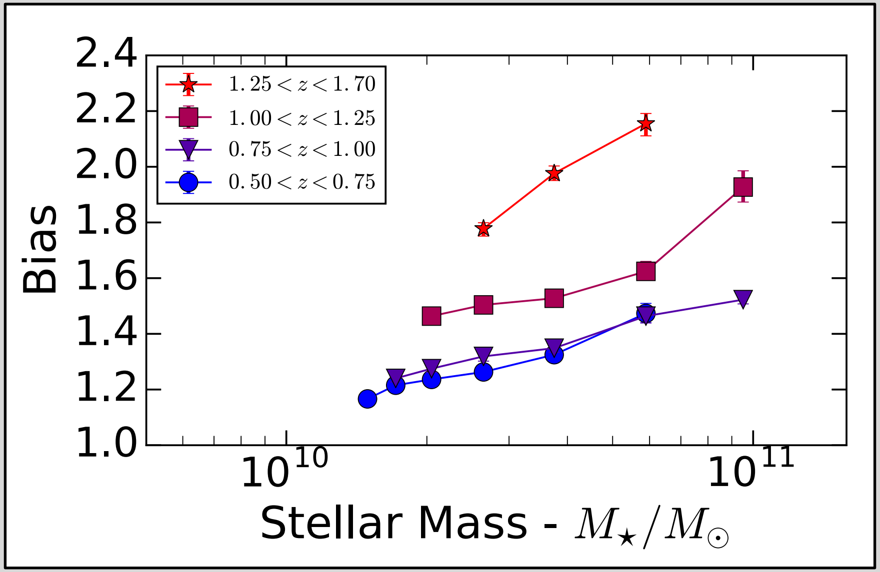
Modelling the Clustering

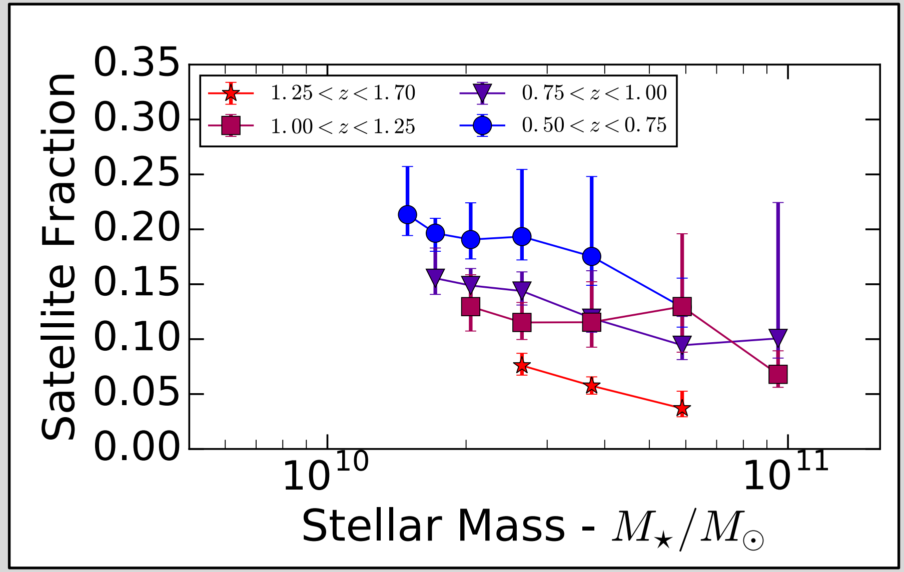


Modelling the Clustering



Modelling the Clustering

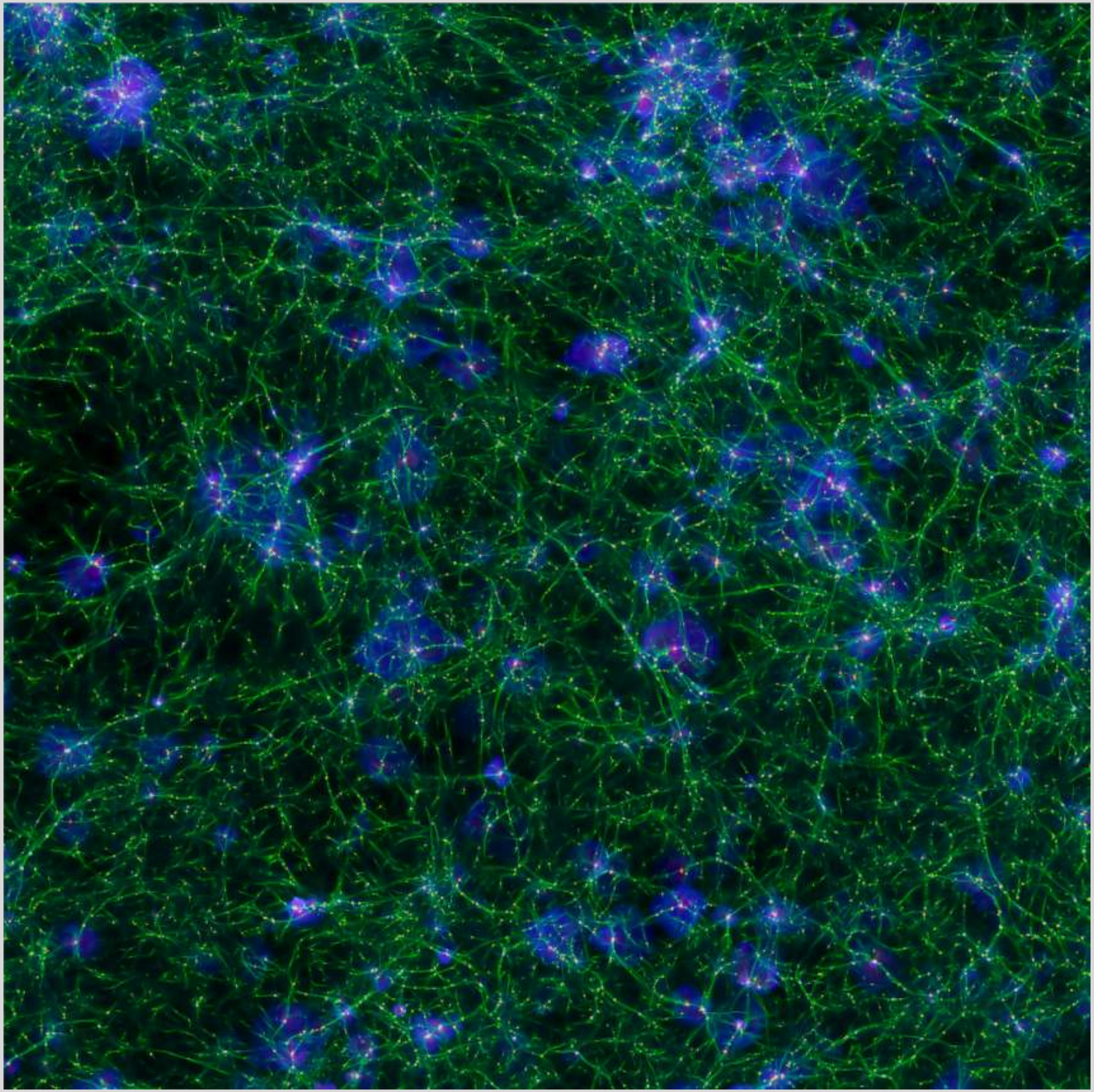




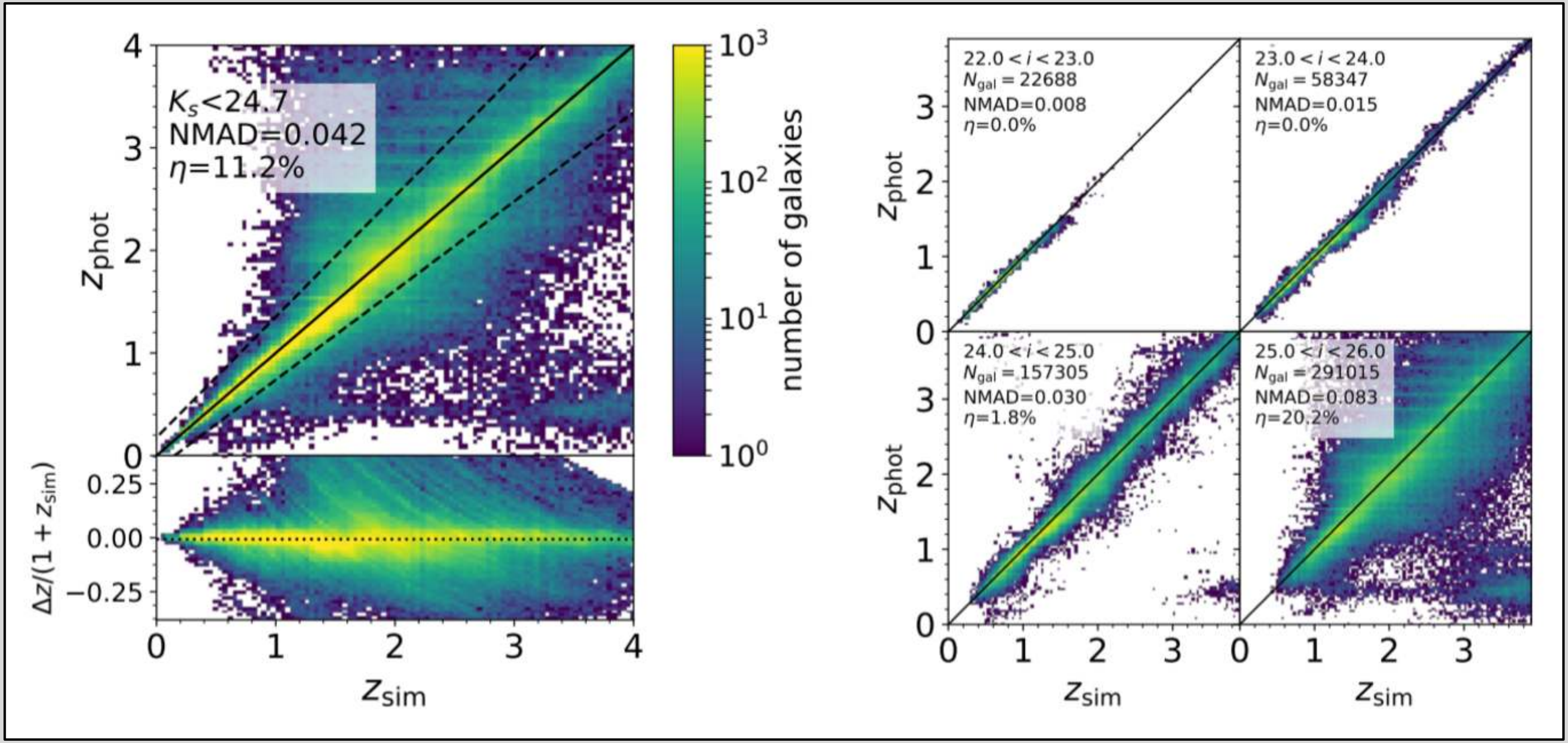
- Most massive galaxies in highest mass halos, most highly biased
- More highly biased at high redshift
- Very small fraction of massive galaxies are satellites
- (Can do joint constraint with cosmology and marginalise out galaxy physics – make use of more of the correlation function)

Comparison with Simulations

- Mock catalogue from Horizon-AGN hydrodynamical cosmological simulation
- C.f. EAGLE, ILLUSTRIS…
- Also run with AGN feedback switched off



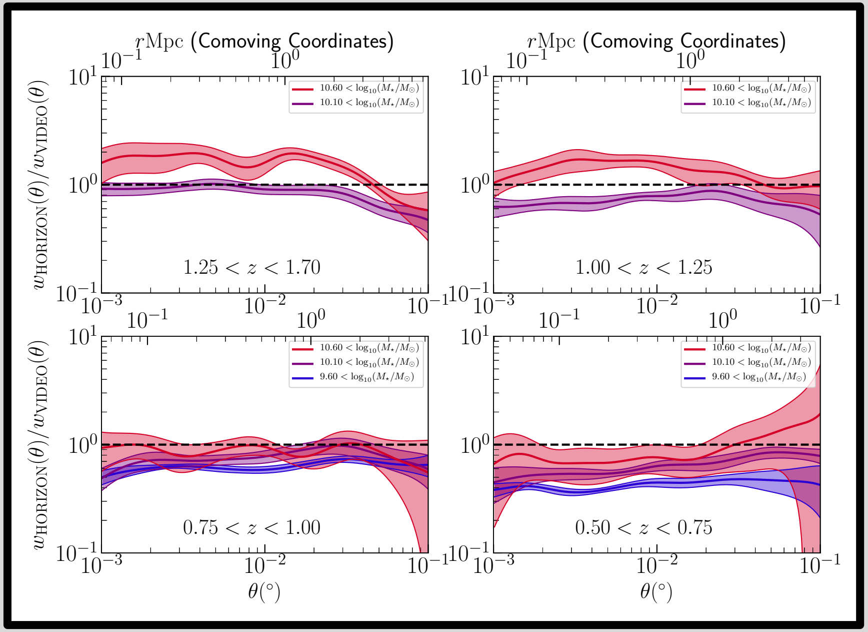
Comparison with Simulations

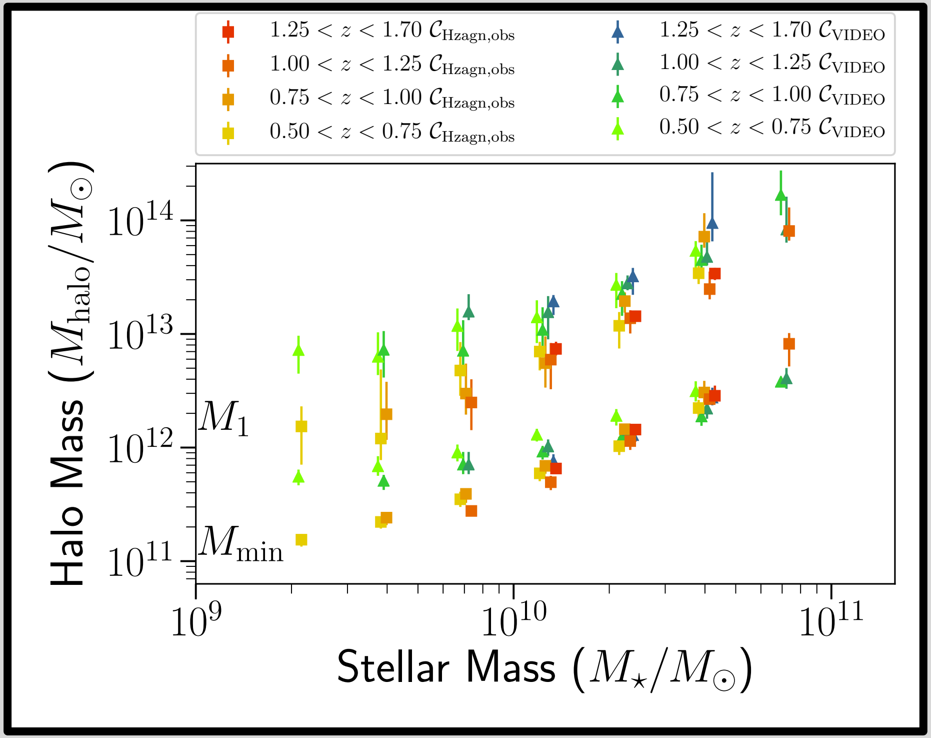


Laigle et al., 2019

- Compare observations and simulations in a consistent way
- Compare `actual' simulation and `observed' simulation

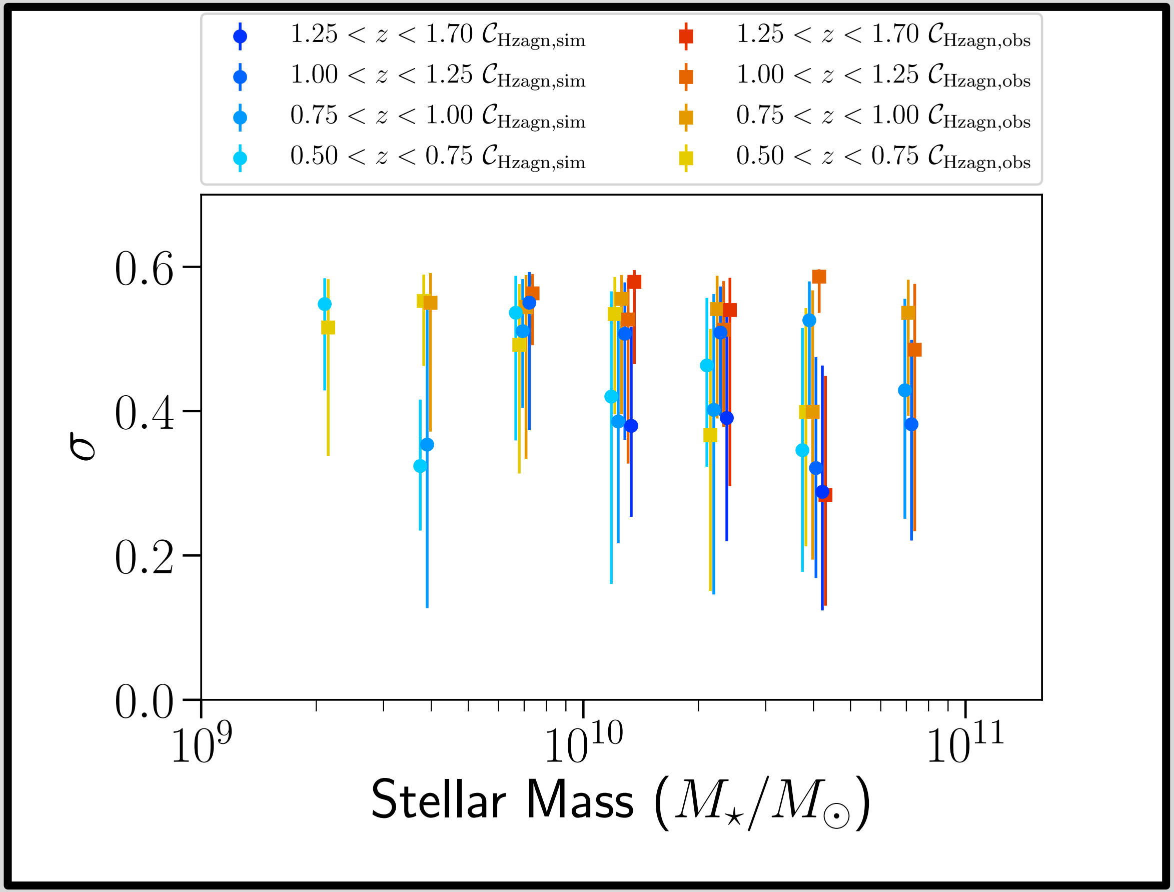
Comparison with Simulations





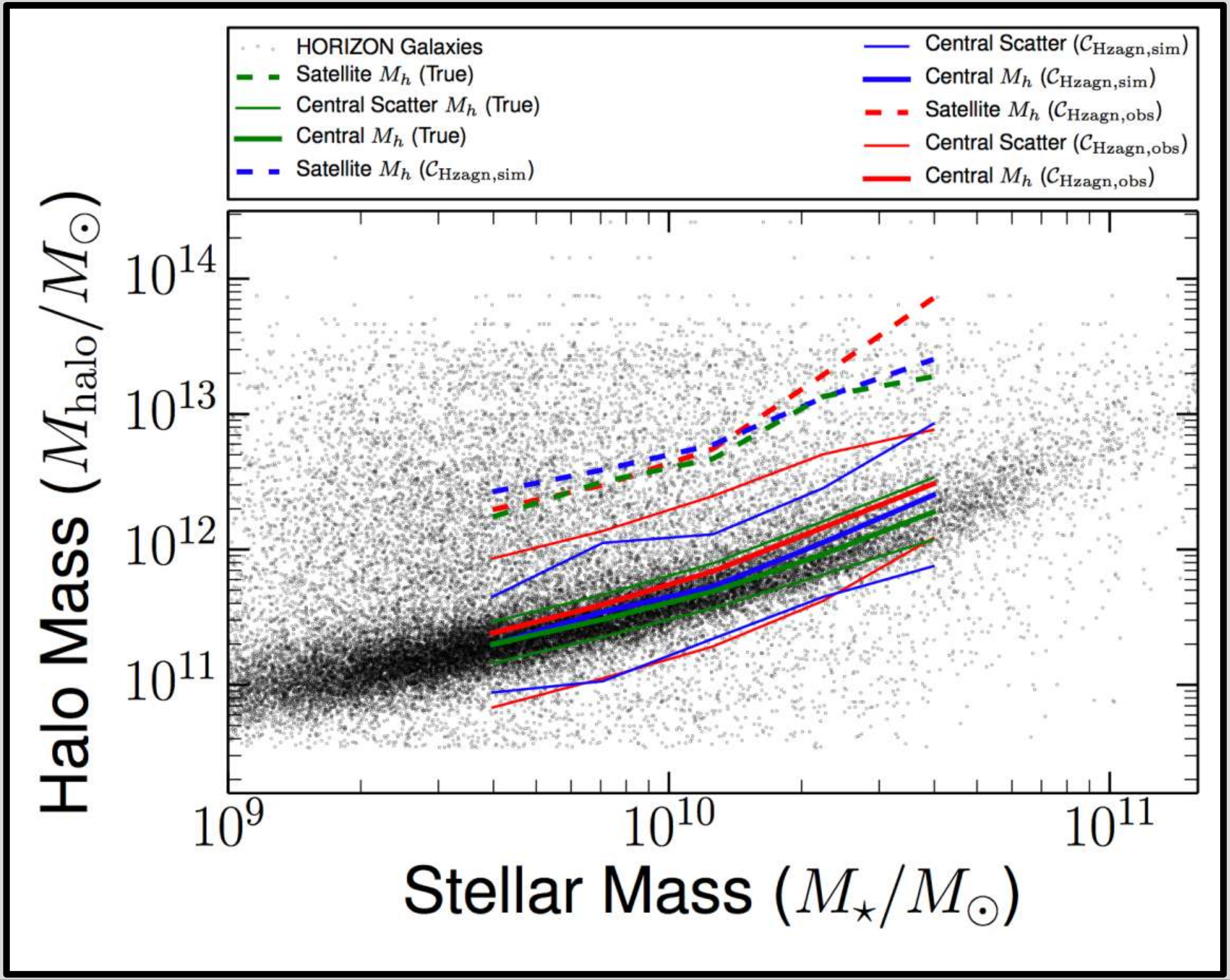
- Doing full HOD model can test if differences in clustering between observations and simulation are a result of systematic differences in estimates of stellar mass, or differences in galaxy-halo relation etc.

Comparison with Simulations

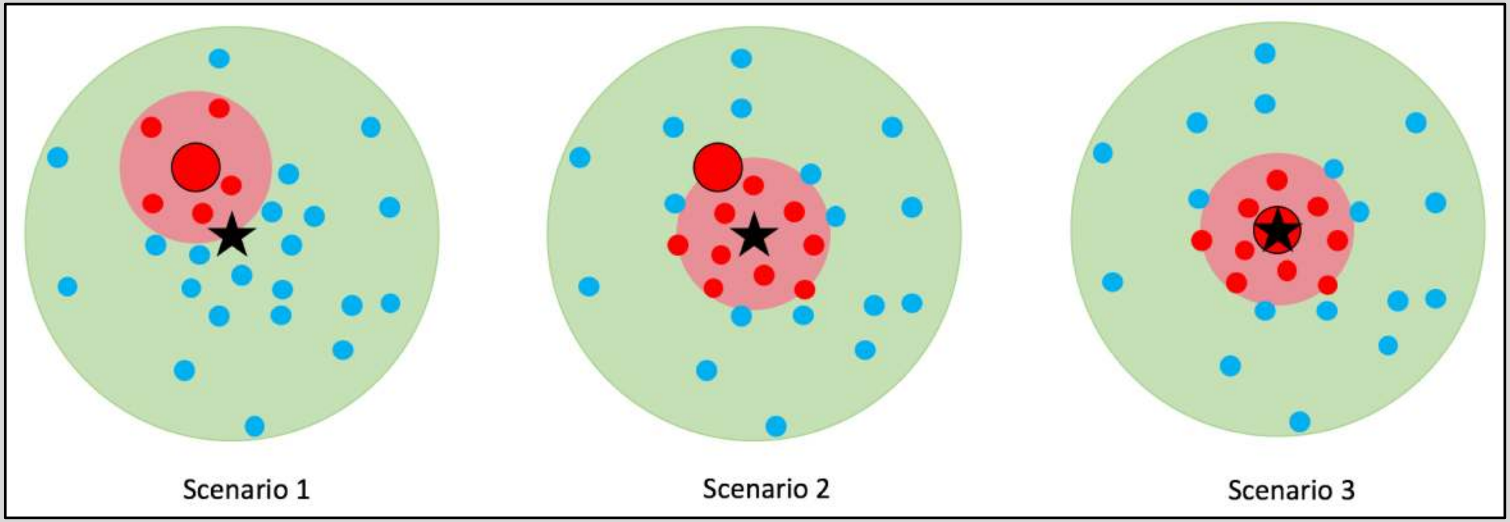


- HOD modelling probably correctly captures SMHR
- Use of photo-z's seems to lead to increase in estimate of scatter

Comparison with Simulations



Modelling the Cross-Correlation Function



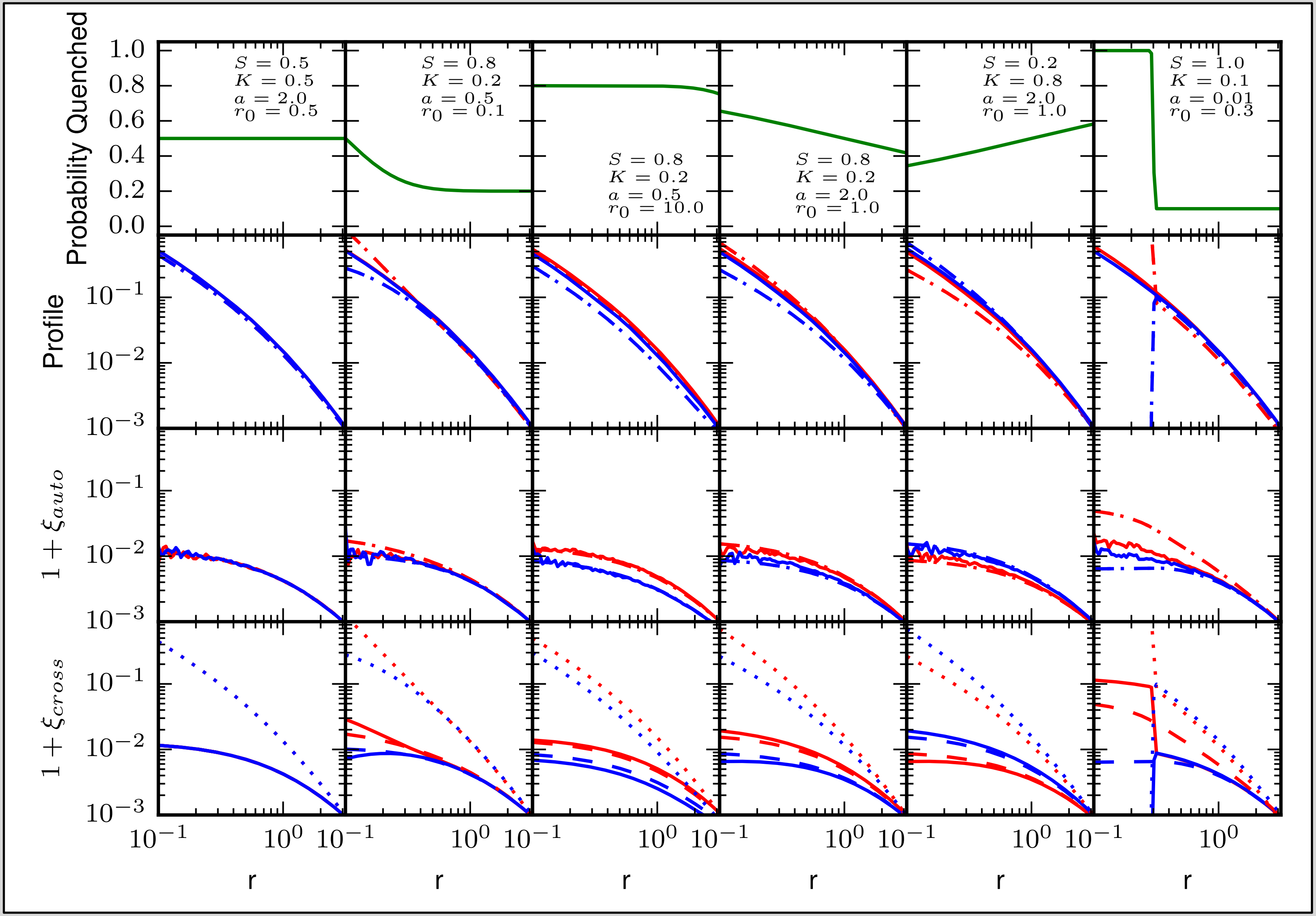
- Conventional HOD assumes galaxies trace **NFW** profile
- If galaxies are preferentially quenched or star forming in certain environments, this makes them follow slightly different profiles, which manifests itself in the 1-halo term
- Cross correlations also give information on covariance on occupation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

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

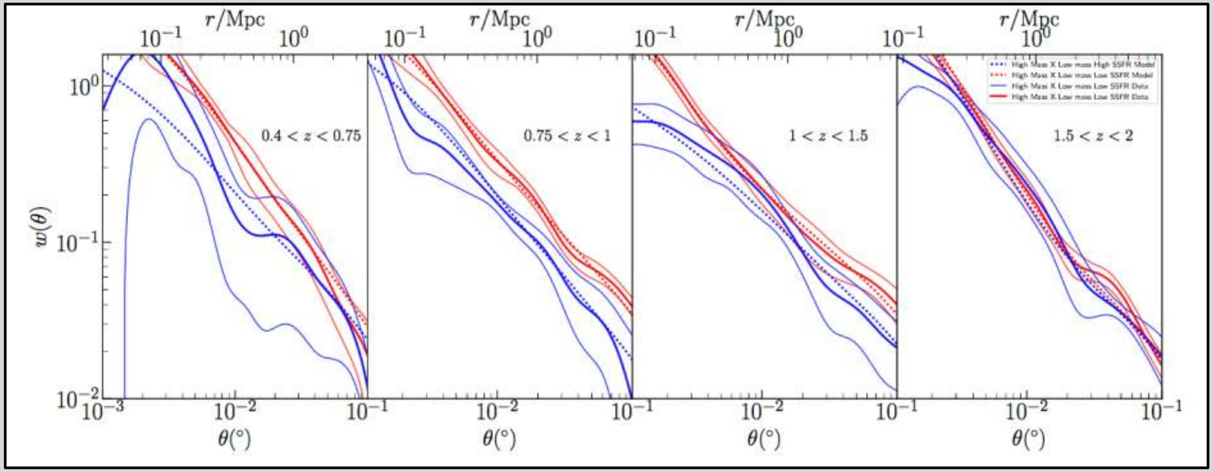
$$1 + \xi_{1h}(r) \propto \int_{\mathbb{R}^3} Q(\mathbf{r})\rho(\mathbf{r})\rho(\mathbf{r}-\mathbf{s})d\mathbf{s}$$

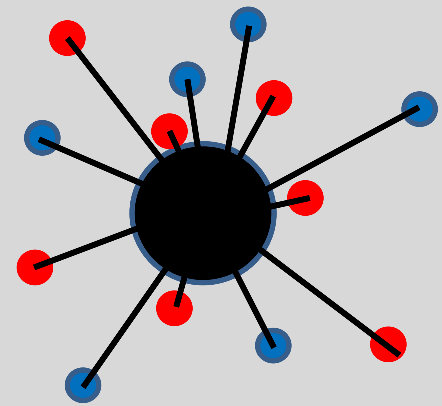
$$1 + \xi_{1h}(r) \propto Q(\mathbf{r}) \int_{\mathbb{R}^3} \rho(\mathbf{r})\rho(\mathbf{r}-\mathbf{s})d\mathbf{s}$$

Modelling the Cross-Correlation Function

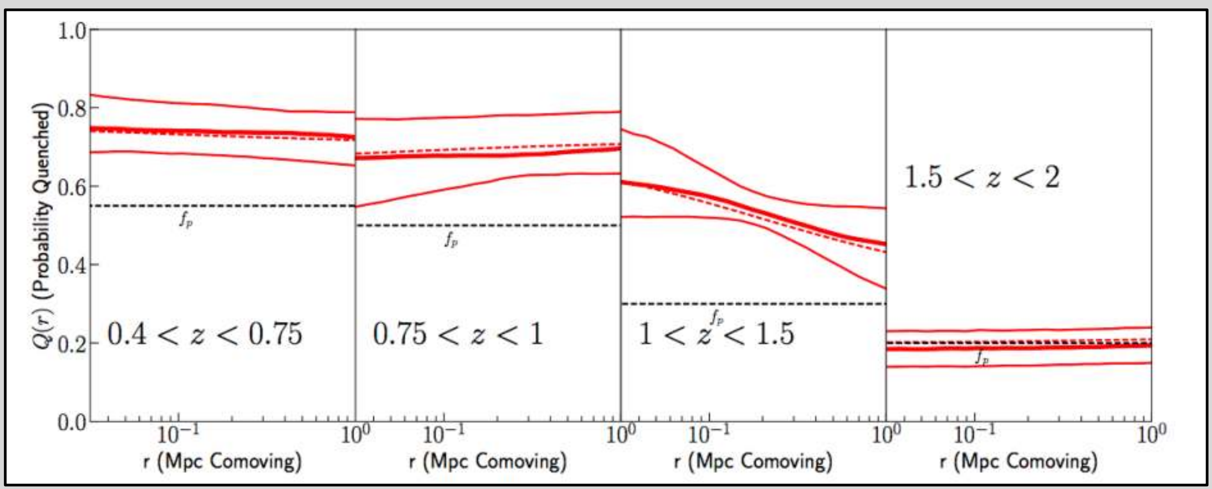


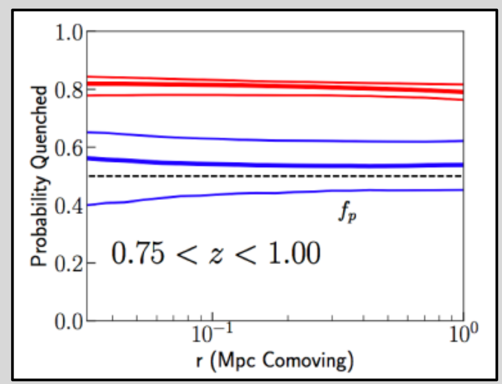
Modelling the Cross-Correlation Function



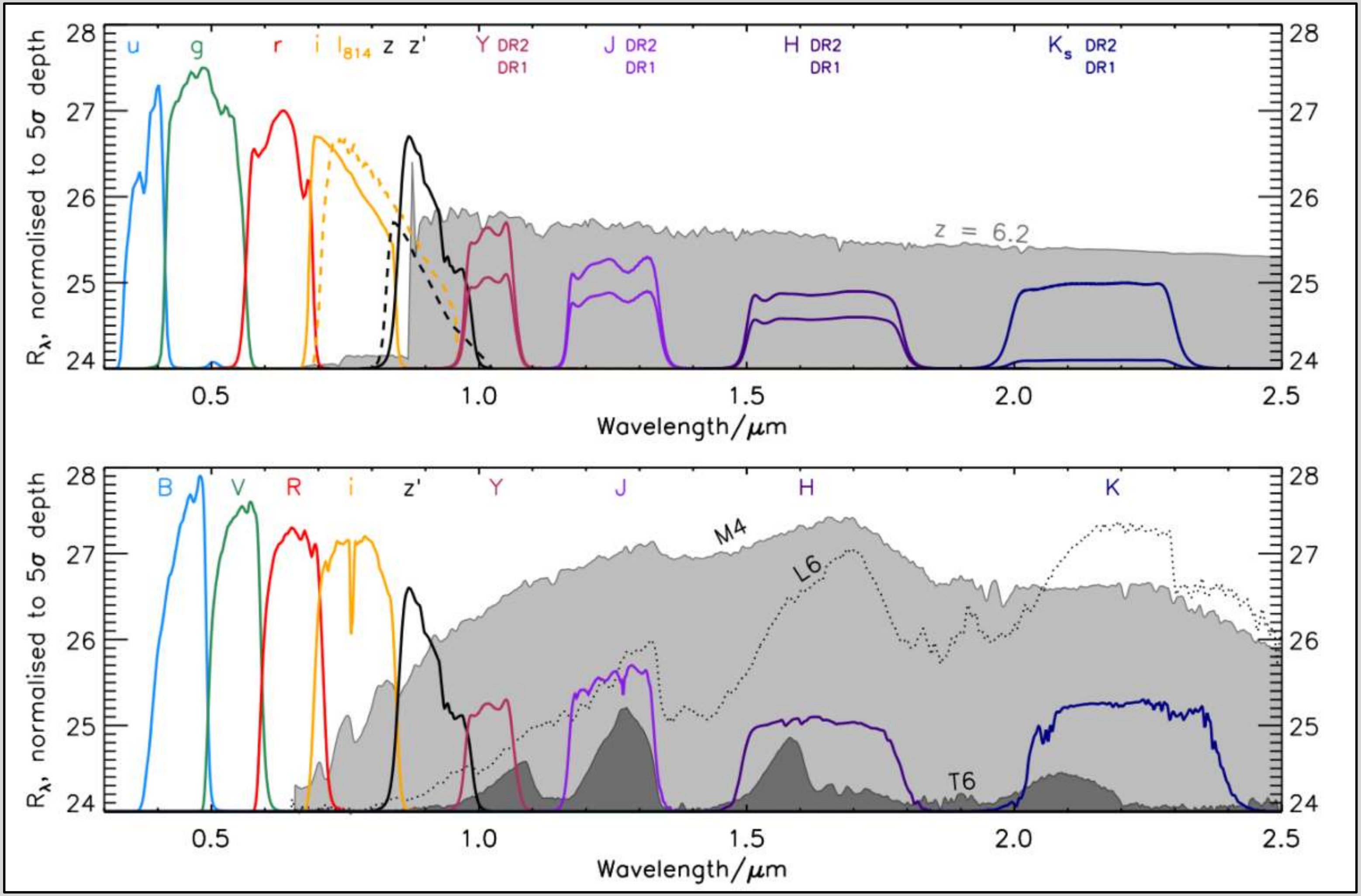


(log sSFR<-11, log sSFR>-11)





Lyman-Break Galaxies

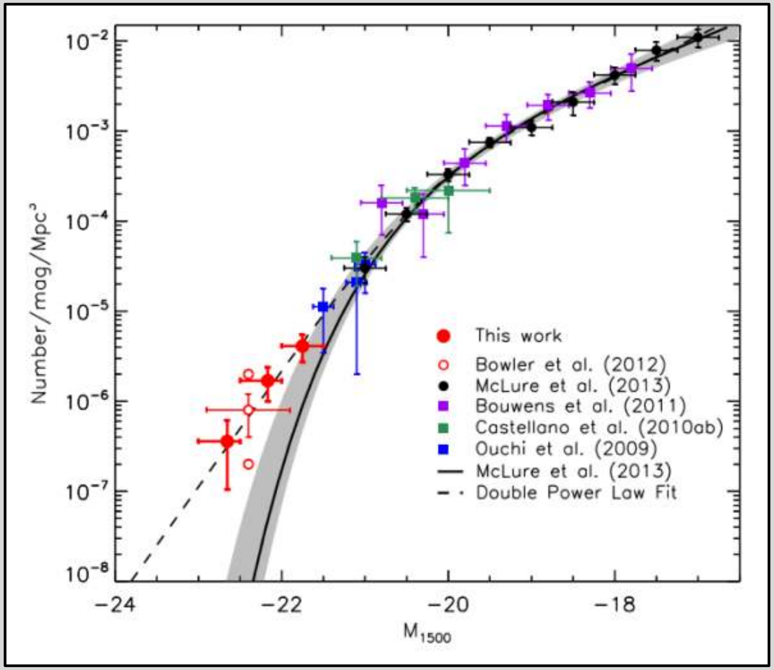


Lyman Break Galaxies are one of our best probes into the z=5-9 Universe

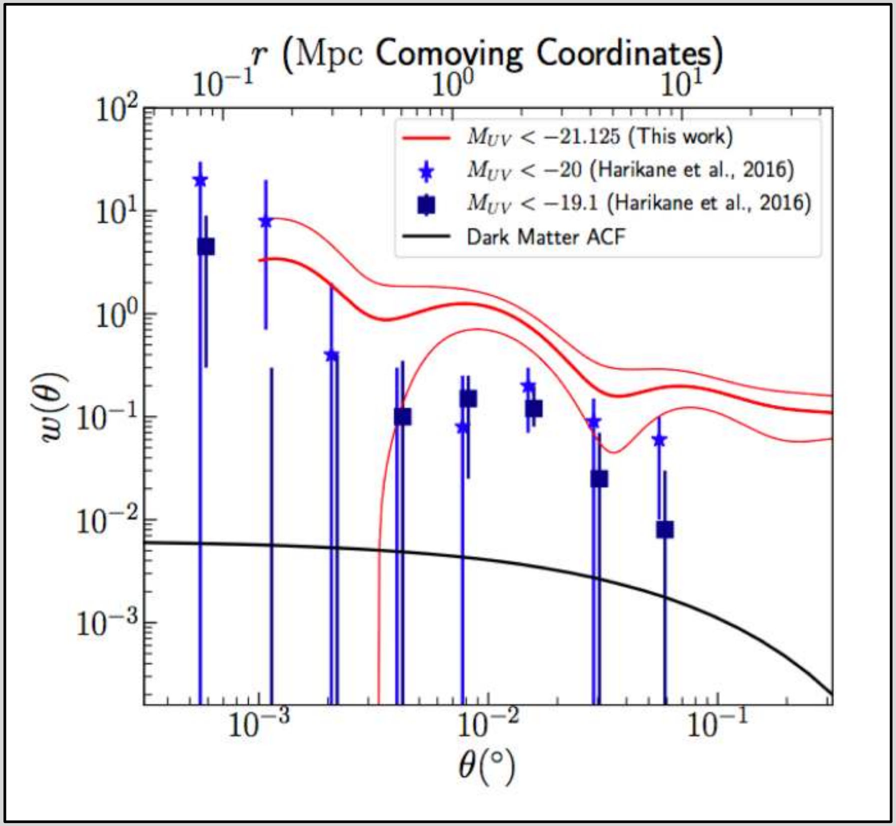
Bowler et al., 2014

Lyman-Break Galaxies

- Above z~4 - Lyman Break Galaxies
- High luminosity LBGs are less rare than expected, but still highly clustered (b~8-10) – onset of quenching? ("Most biased objects in the Universe")
- Relevant for reionisation



Bowler et al., 2014

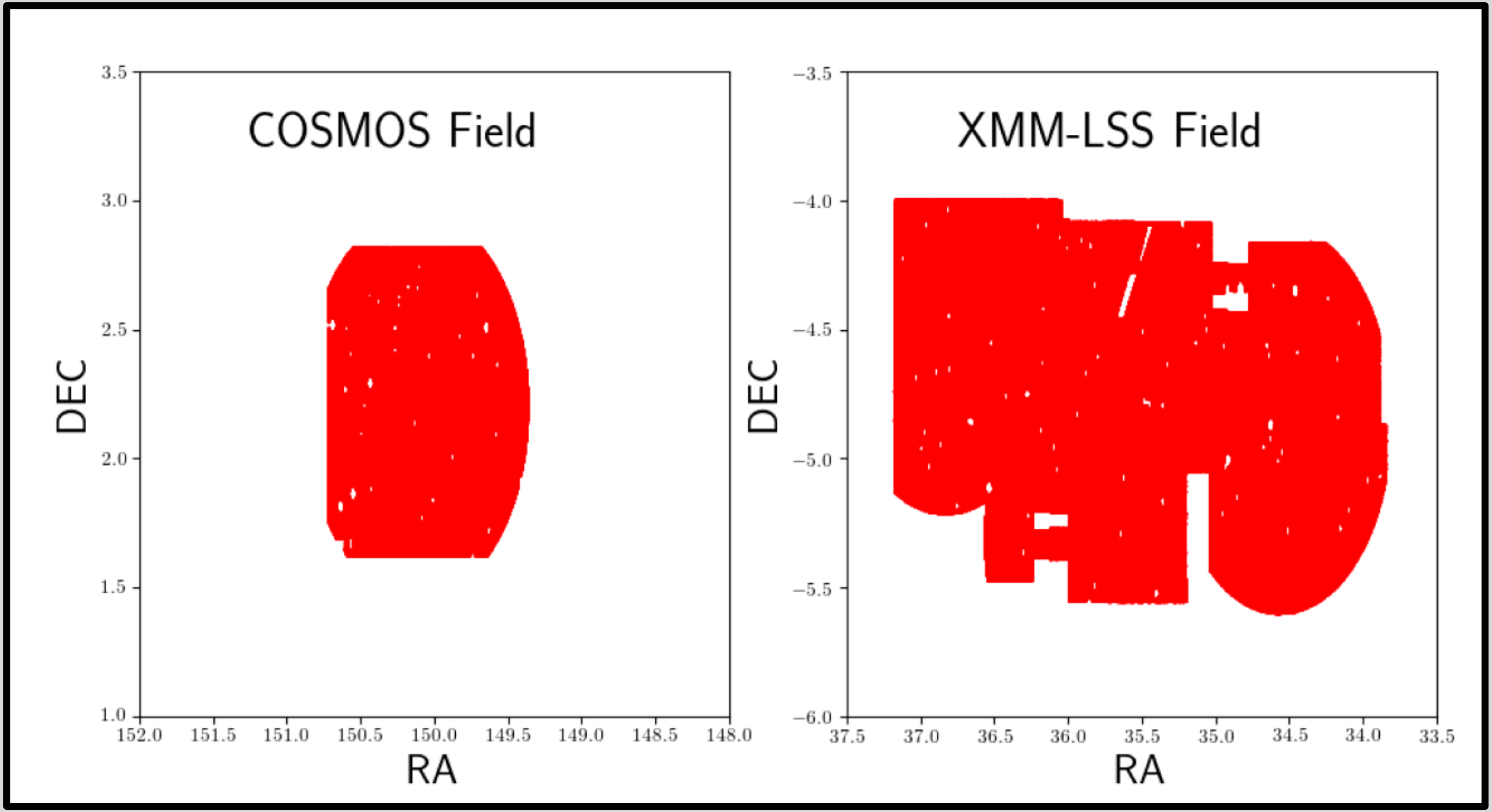


Hatfield et al., 2018

4. Looking Ahead

- Many exciting upcoming surveys
- Much more things that can be done with small scale clustering

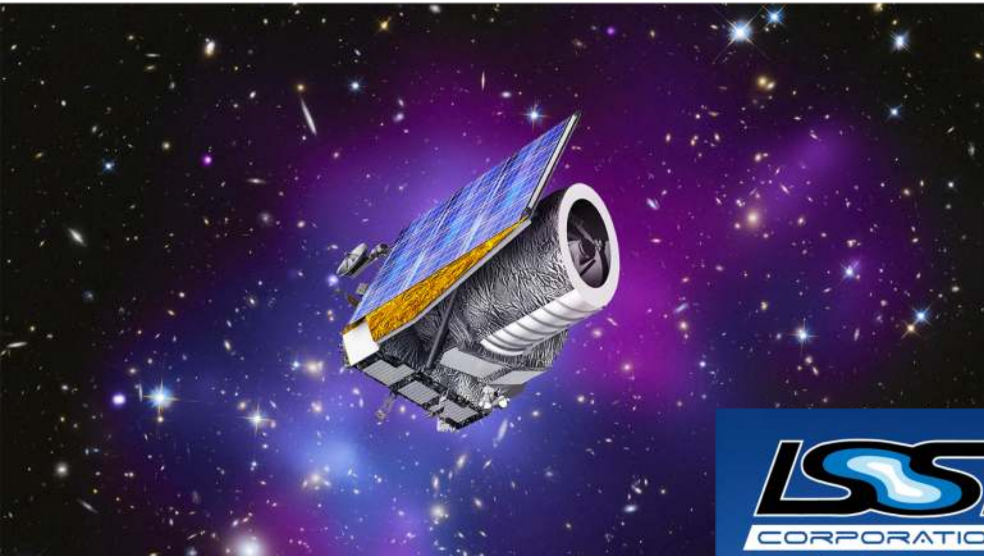
Future Observations – MIGHTEE and VEILS



Expanding to higher redshifts, a wider range of stellar masses, and larger angular scales

Into the 2020s…

UNIVERSITY OF OXFORD



Euclid+Rubin+SKA

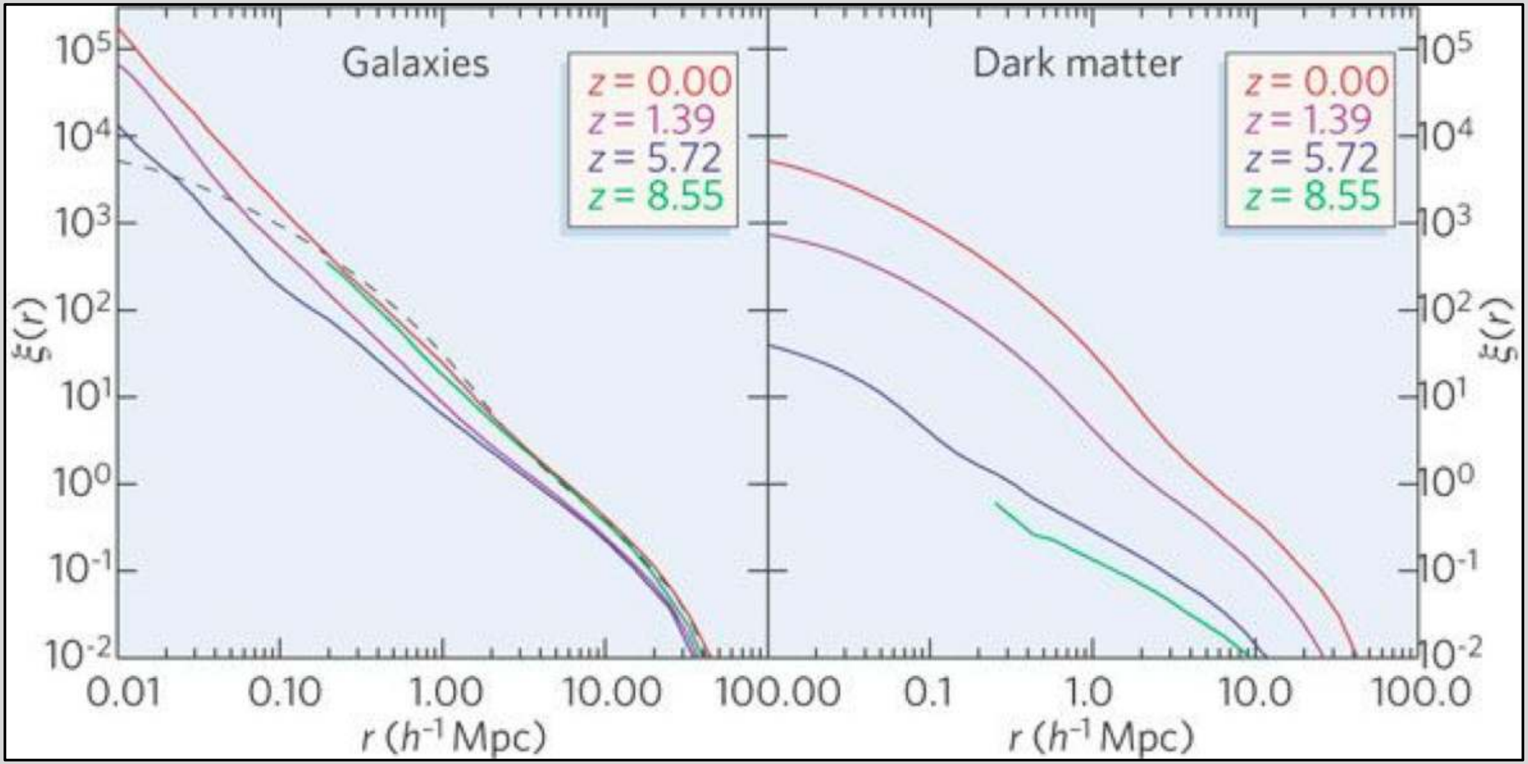
Conclusions

- Measured and modelled clustering in VIDEO
- Information about the role of environment at the peak of star formation, how galaxies trace matter, links to LSS cosmology
- Quenching mechanisms can be added to HOD
- Have measured the clustering of the brightest z~6 LBGs

In Future:

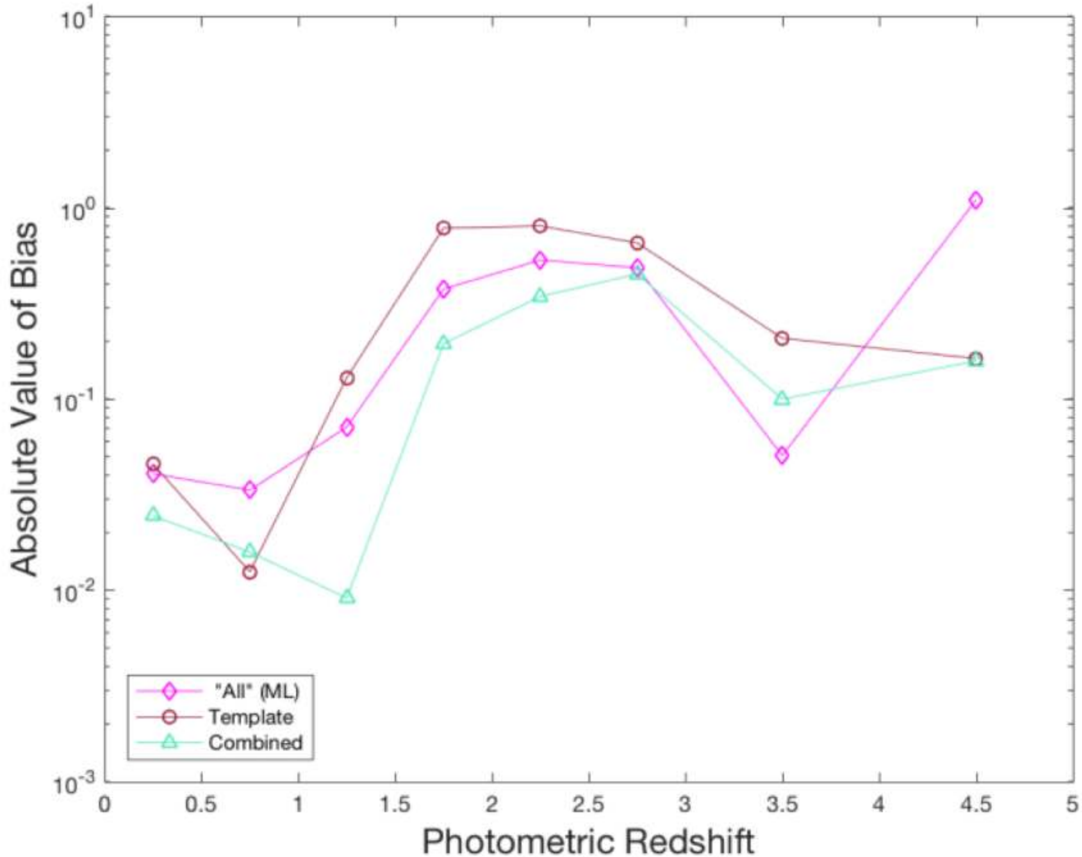
- The non-linear galaxy power spectrum in future surveys will give unprecedented precise probes of environment
- More data will justify more sophisticated models
- Redshift-space distortions will add dynamics to the story
- Multi-wavelength data important (Euclid+LSST+SKA)

Galaxy Bias



Springel et al., 2006 (Millennium simulation)

Bias is linear on large scales; complex on halo scales



Absolute Value of Bias
Photometric Redshift
"All" (ML)
Template
Combined
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5