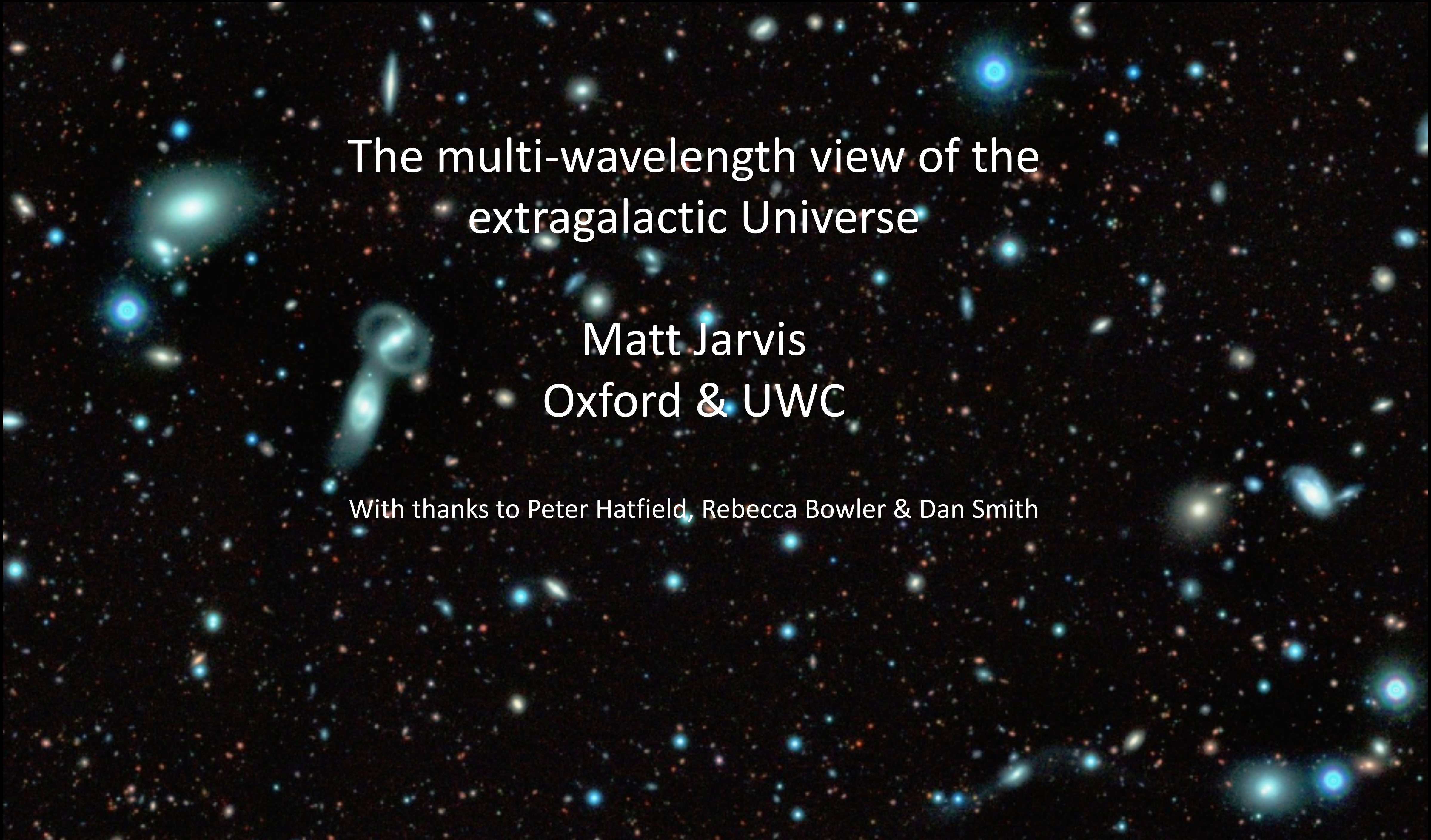

The multi-wavelength view of the extragalactic Universe

Matt Jarvis
Oxford & UWC

With thanks to Peter Hatfield, Rebecca Bowler & Dan Smith

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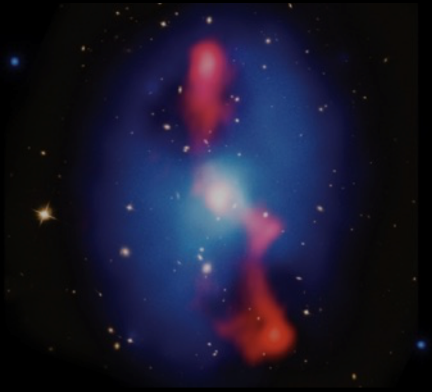
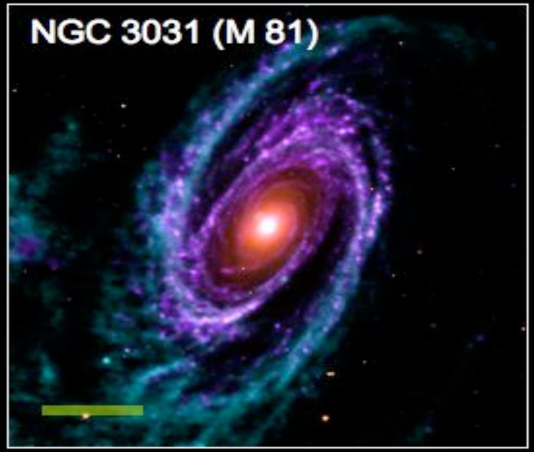
"Multi-wavelength extragalactic foregrounds, galaxy and AGN evolution, but not using radio surveys" - Vibor

Questions in Galaxy Formation and Evolution

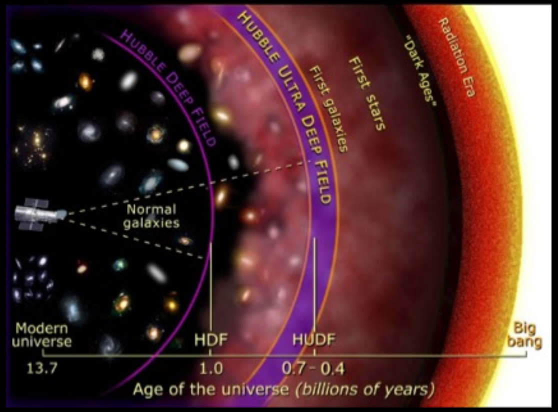
How are BHs fueled and how does accretion onto BHs affect the evolution of galaxies?

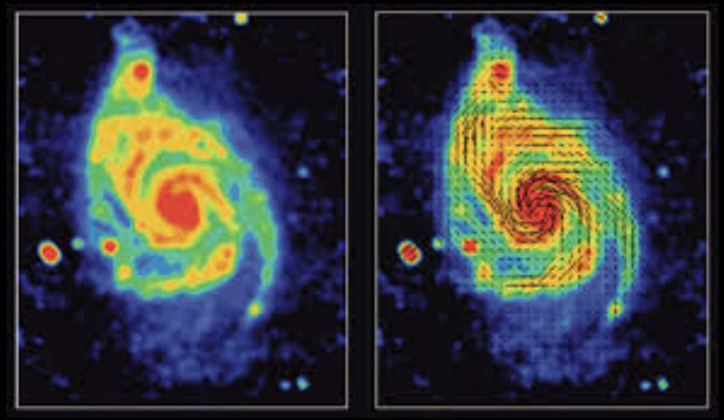




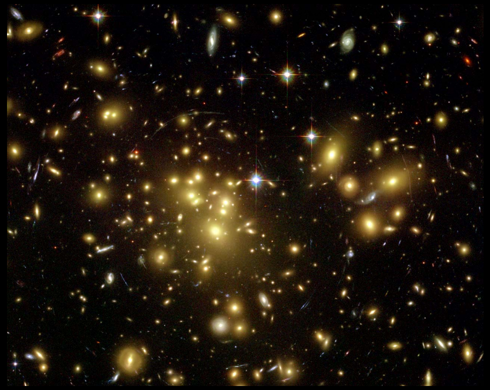
How do we go from gas to stars in galaxies?

How and when were the first galaxies formed?



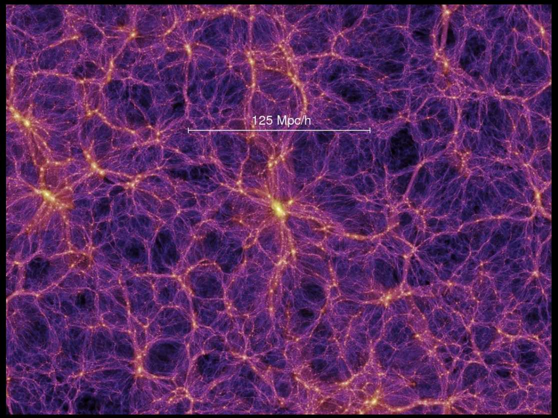


How do magnetic fields influence galaxy structure and growth



What is the environmental influence?

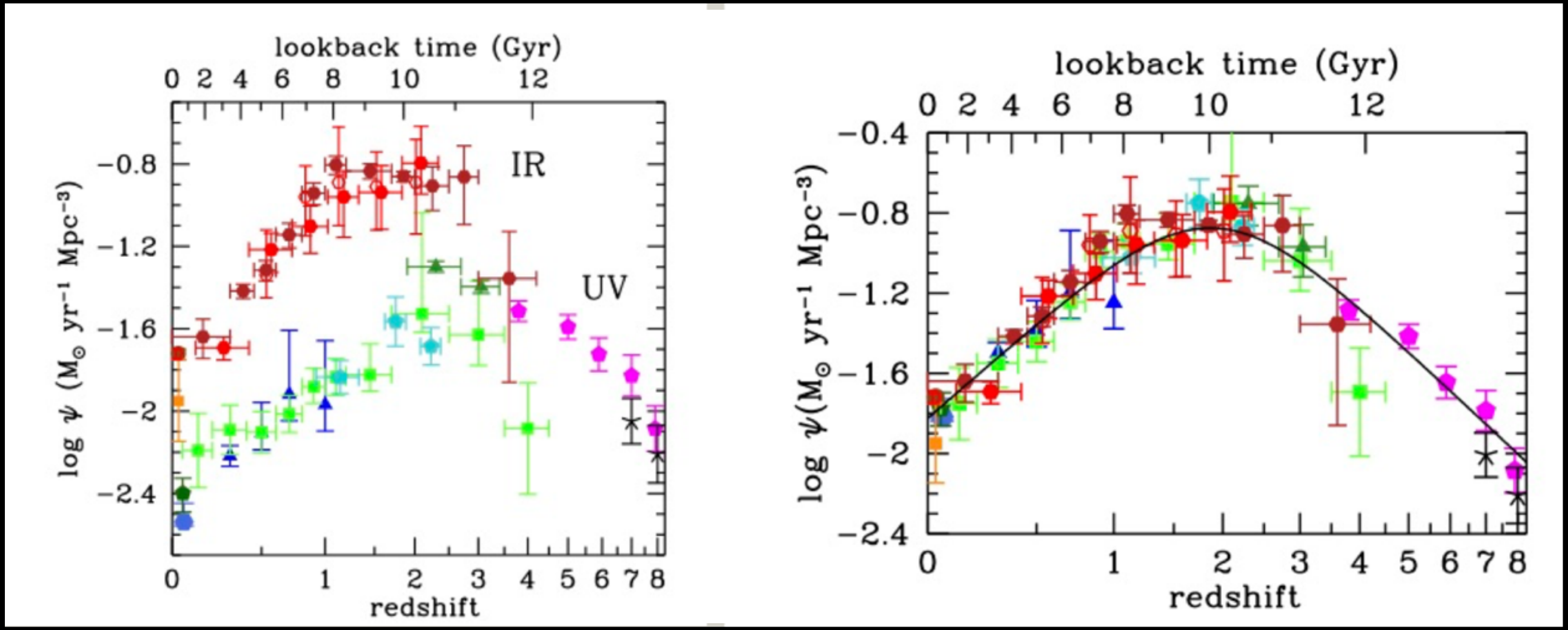
How do Baryons trace and affect the Dark Matter distribution?



The cosmic history of star formation

Dust Uncorrected

Dust Corrected



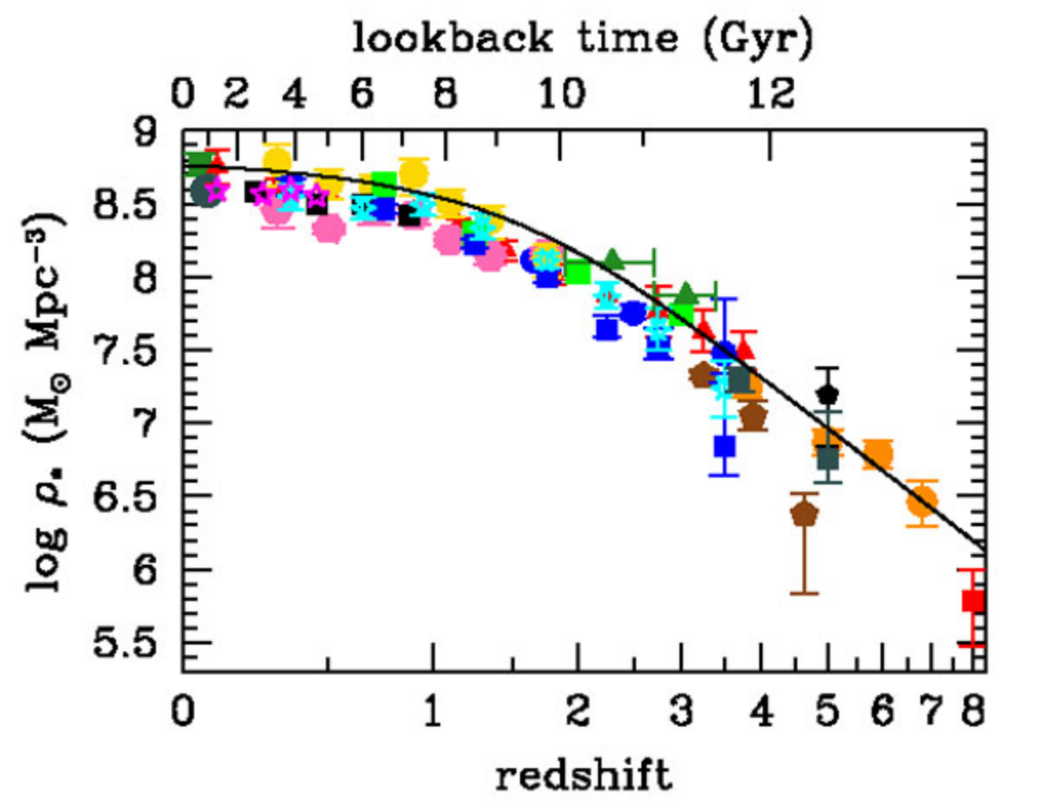
Madau & Dickinson 2014

SFR density uncertain due to dust

Radio observations provide a dust-free probe of SF history to z~4

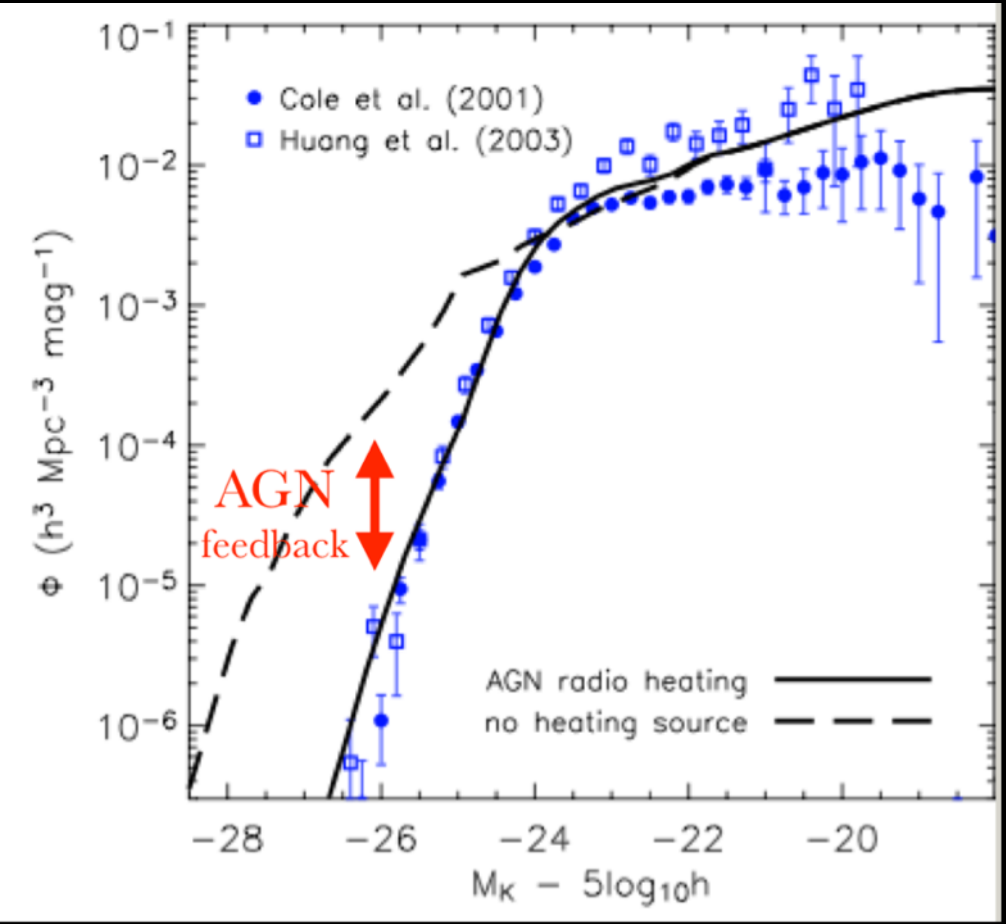
Given good ancillary data can do this as a function of stellar mass, halo mass and proximty to AGN

The stellar mass build-up

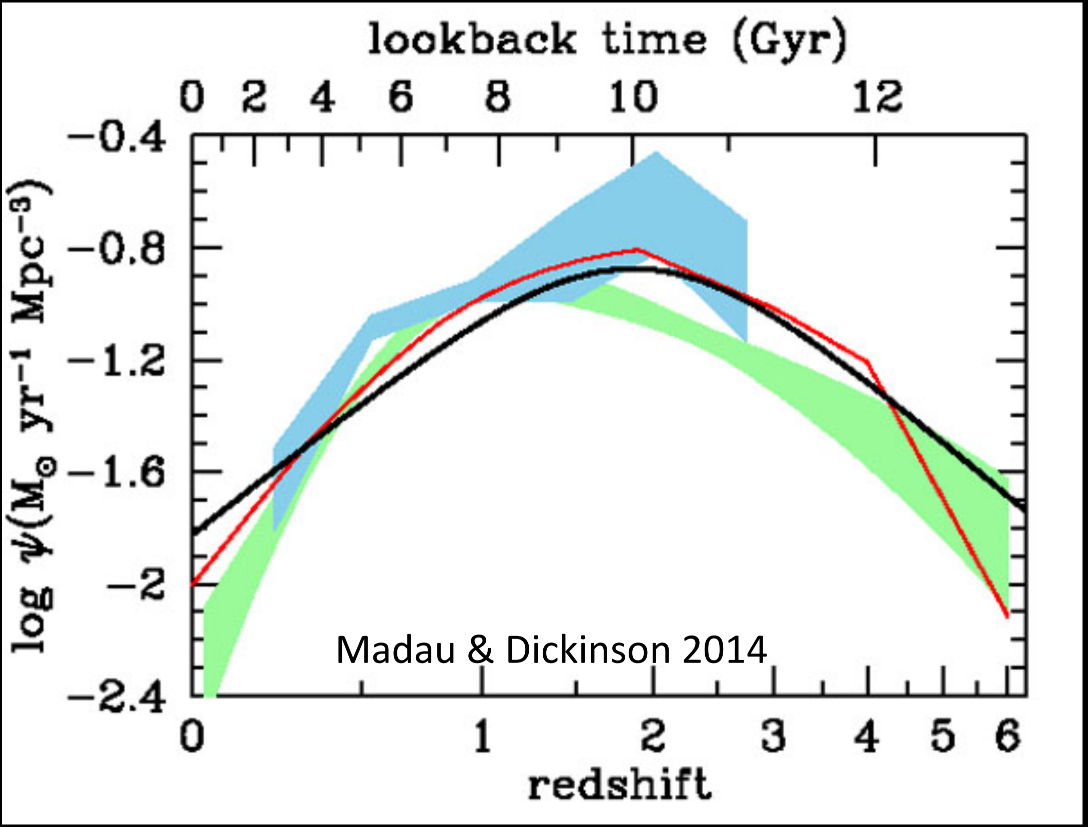


Madau & Dickinson 2014

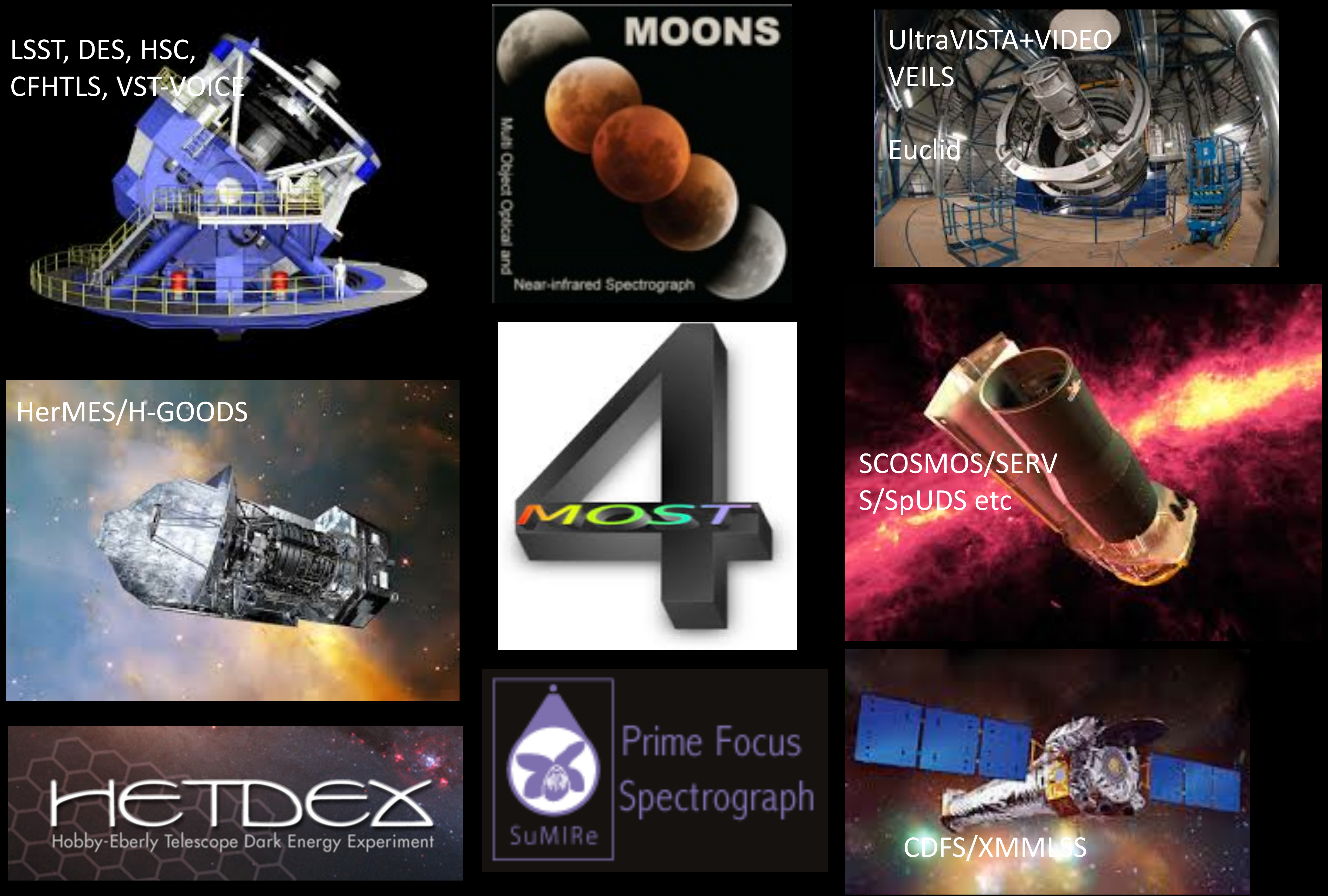
AGN evolution and Feedback



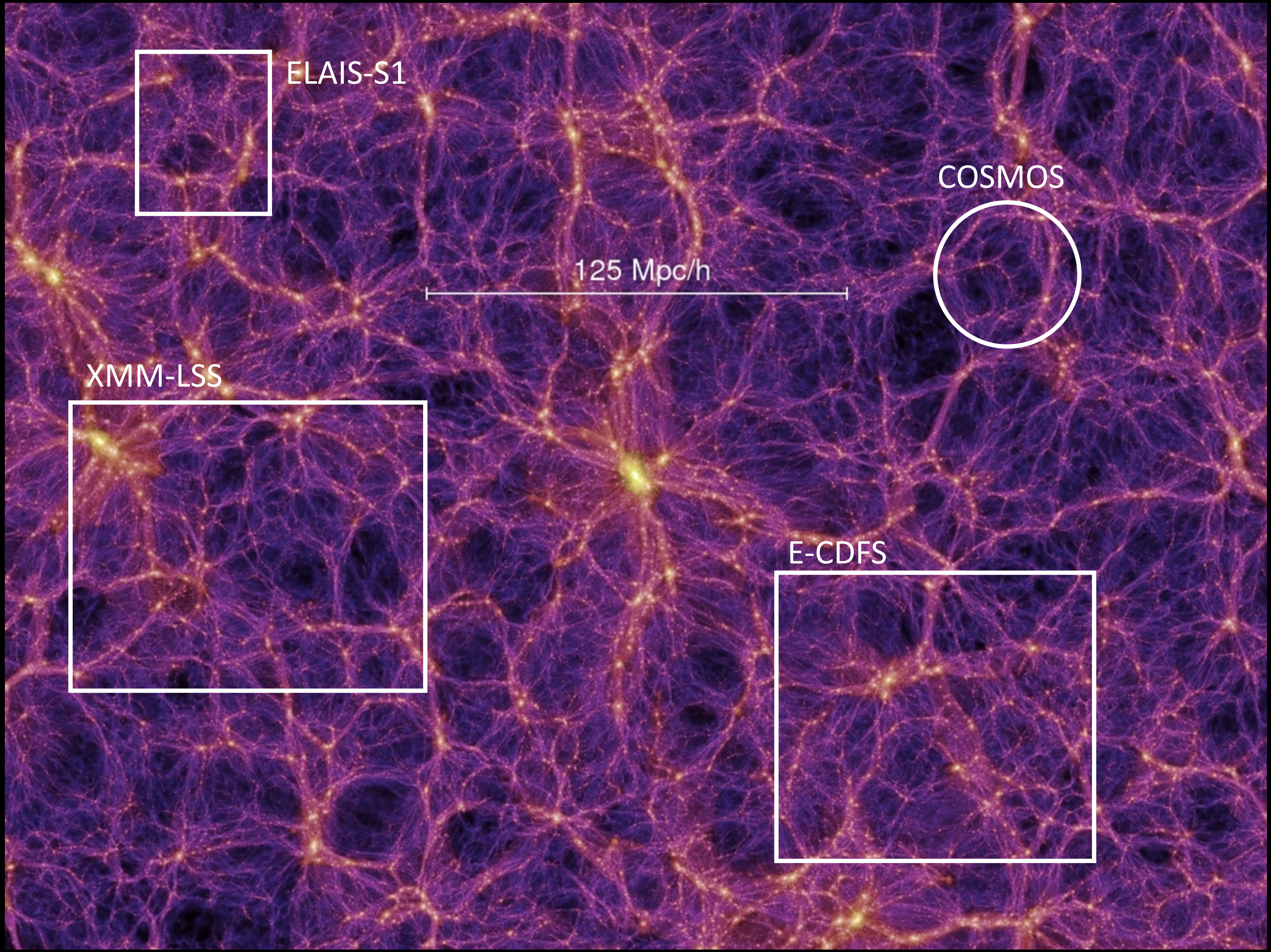
Exponential cut-off at the bright end of the luminosity function



Multi-wavelength coverage of the MIGHTEE fields



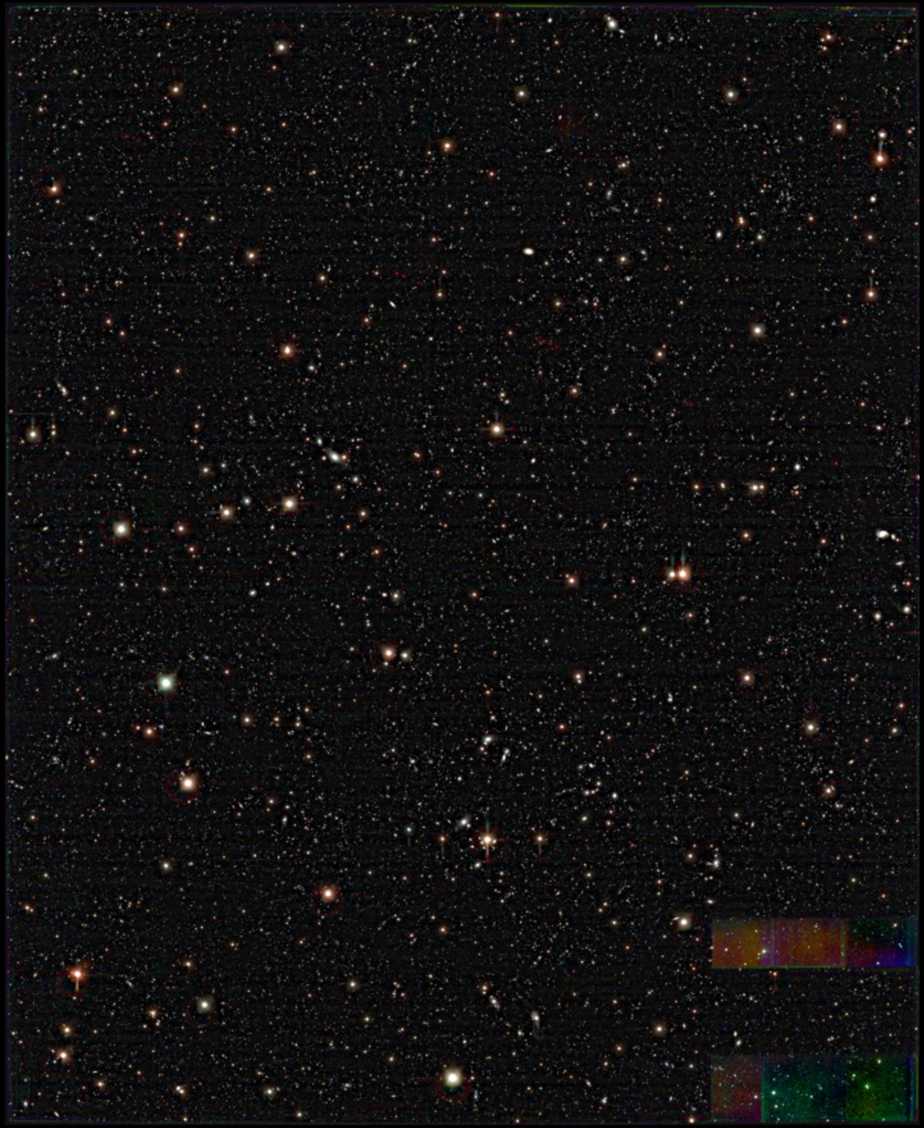
Multi-wavelength survey strategy



Clustering of galaxies to high-z

- **Deep wide-field surveys** allow us to track galaxy evolution over the history of the Universe
- Understanding the ***clustering*** of galaxies gives important information about large scale structure, how galaxies and baryons trace matter, and galaxy environment
- An powerful approach to modelling galaxy clustering is the ***Halo Occupation Distribution*** (HOD) phenomenology

1. The HOD Model
2. Clustering in VIDEO
   a) HOD and stellar mass to halo mass ratios
   b) Cross correlations
   c) Comparison to simulations



VIDEO-XMM3

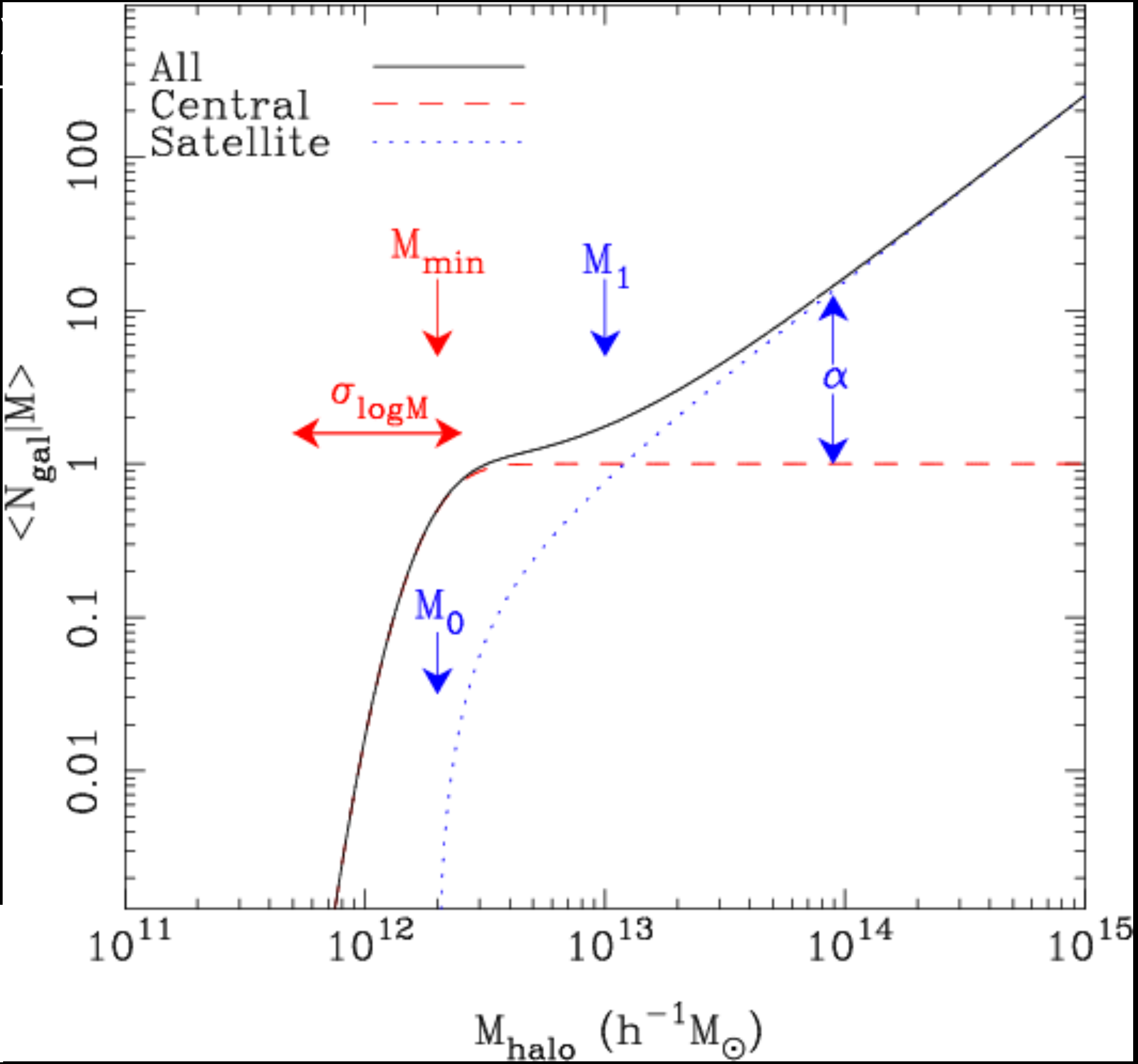
The galaxy-halo connection in the VIDEO Survey at 0.5<z<1.7, Hatfield et al., MNRAS 2016
Environmental Quenching and Galactic Conformity in the Galaxy Cross-Correlation Signal, Hatfield & Jarvis, MNRAS 2017
The environment and host haloes of the brightest z~6 Lyman-break galaxies, Hatfield et al. arxiv.1702.03309

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

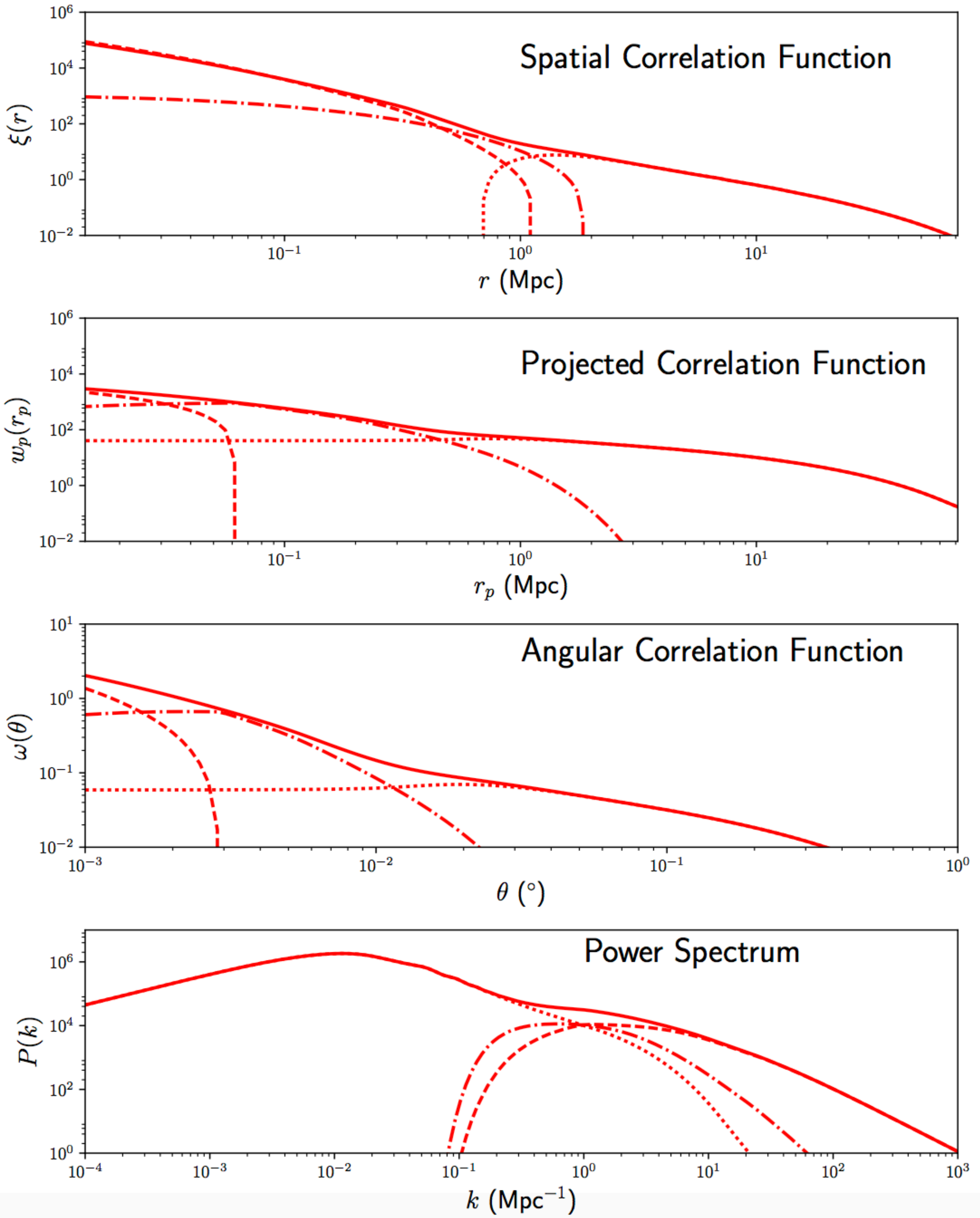
HOD Ingredients:

- (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

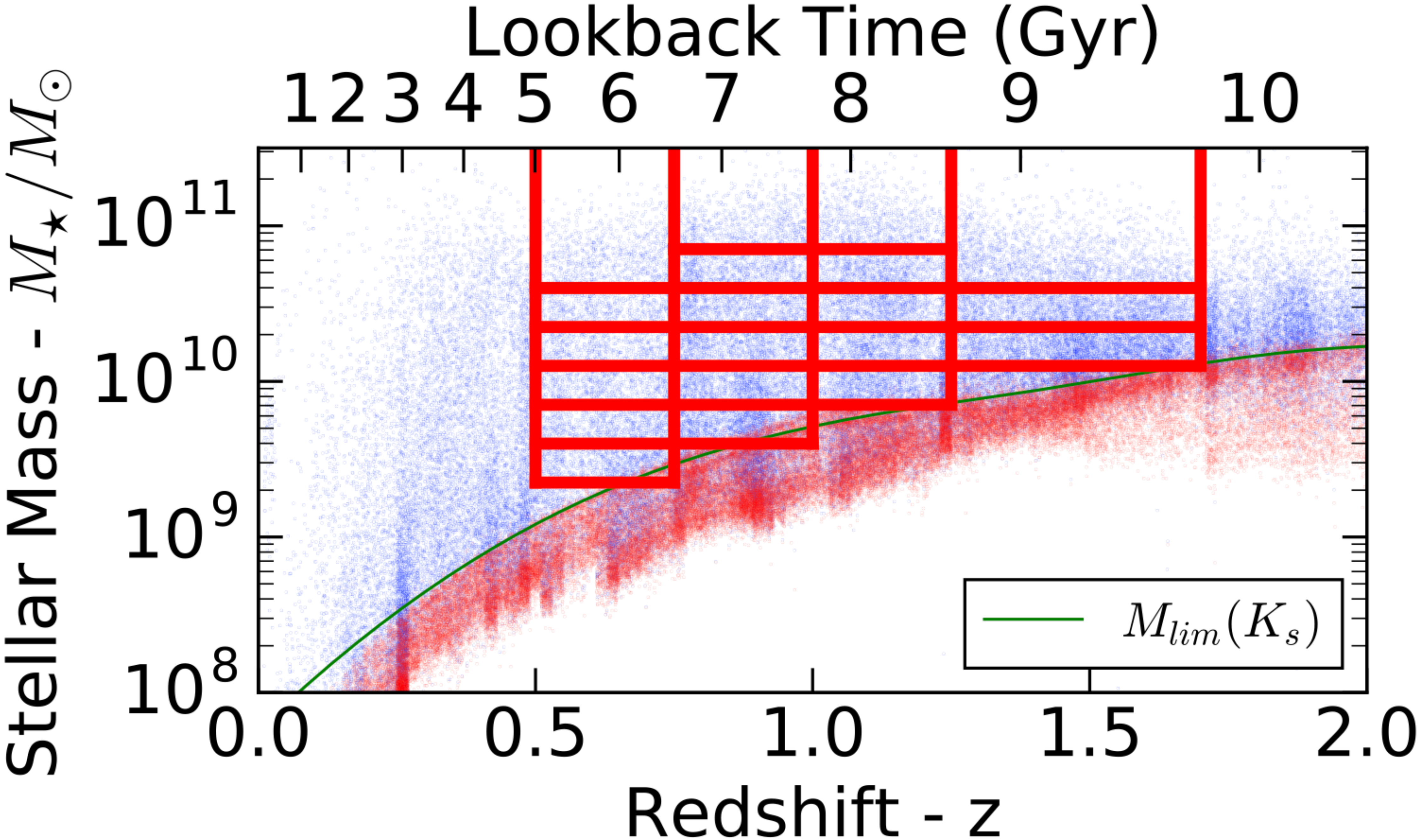
$$\chi^2 = \frac{[n_{\rm gal}^{\rm obs} - n_{\rm gal}^{\rm model}]^2}{\sigma_n^2} + \sum_i \frac{[\omega^{\rm obs}(\theta_i) - \omega^{\rm model}(\theta_i)]^2}{\sigma_{w_i}^2},$$



Wake et al., 2011

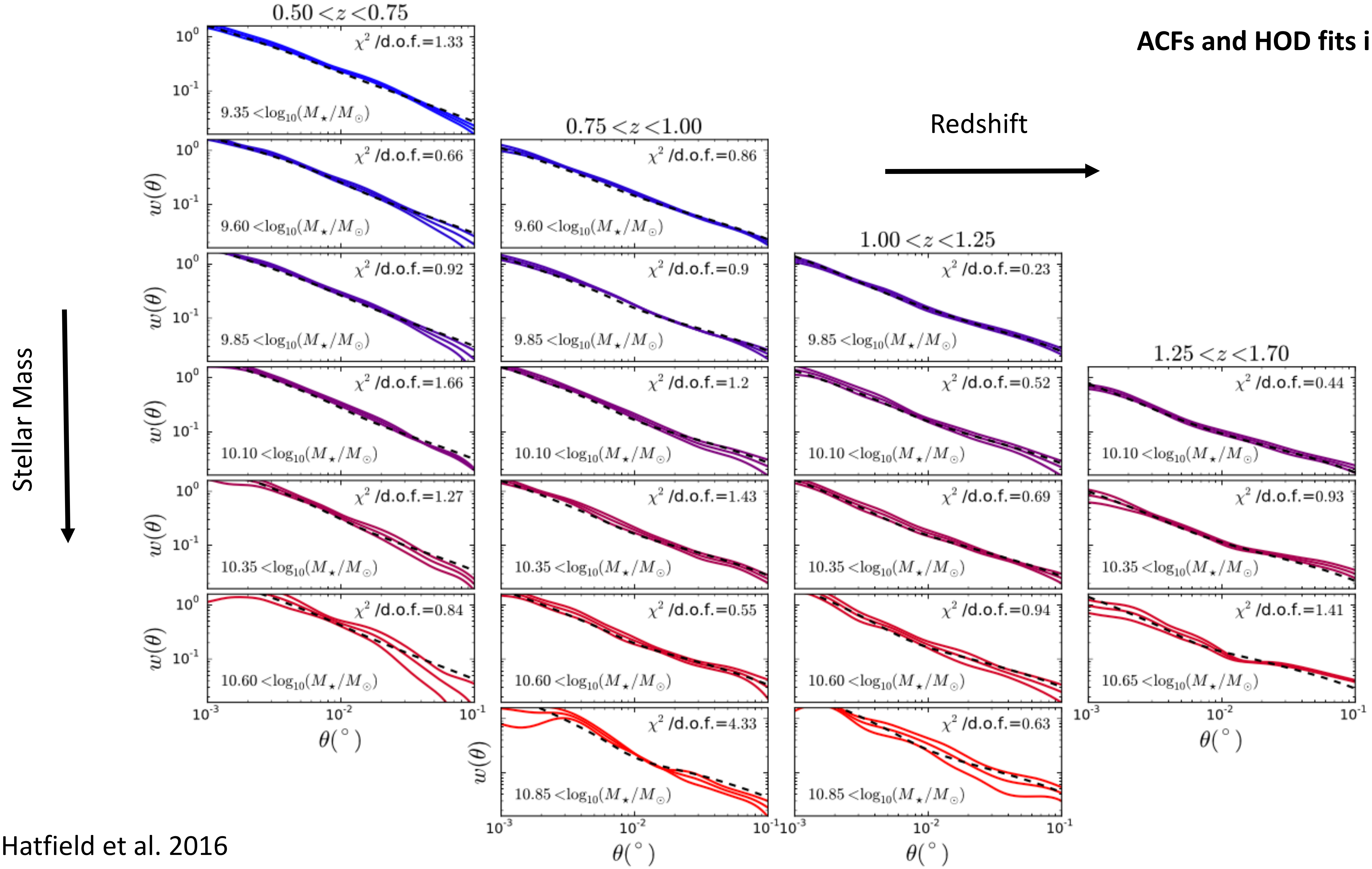


Spatial Correlation Function
$\xi(r)$
r (Mpc)
Projected Correlation Function
$w_p(r_p)$
r_p (Mpc)
Angular Correlation Function
$\omega(\theta)$
θ (°)
Power Spectrum
$P(k)$
k (Mpc^{-1})

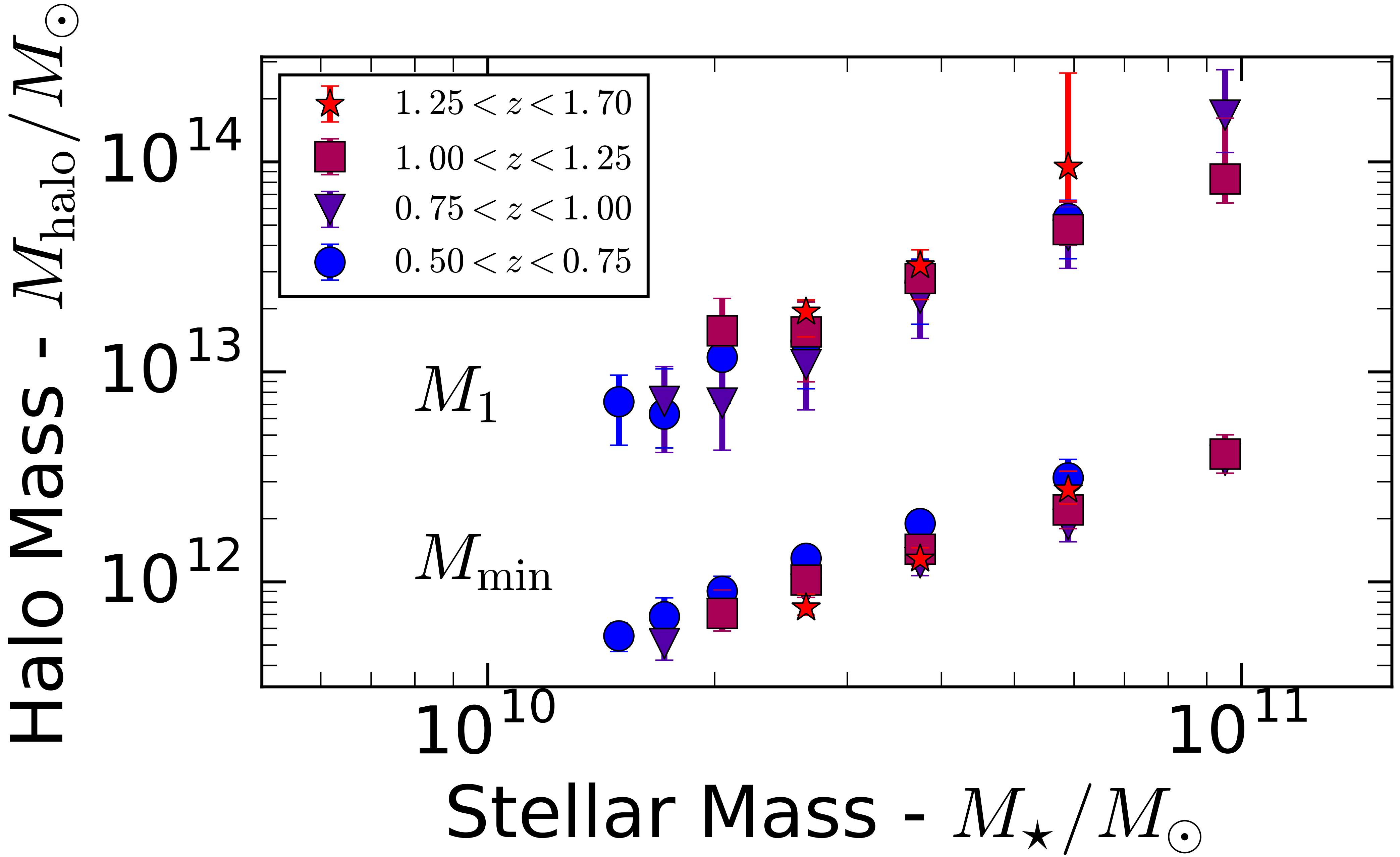


Hatfield et al. 2016

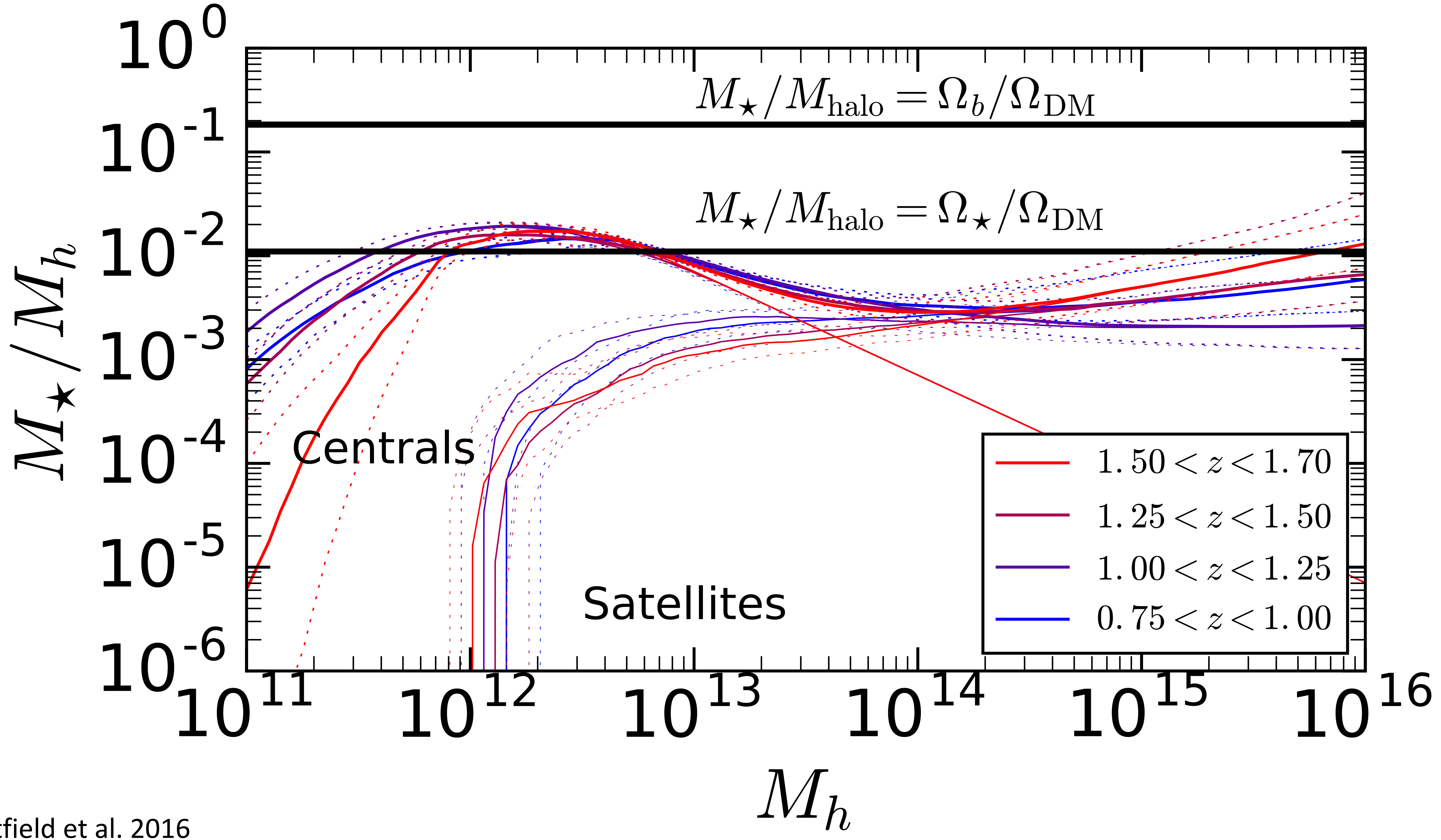
ACFs and HOD fits in VIDEO



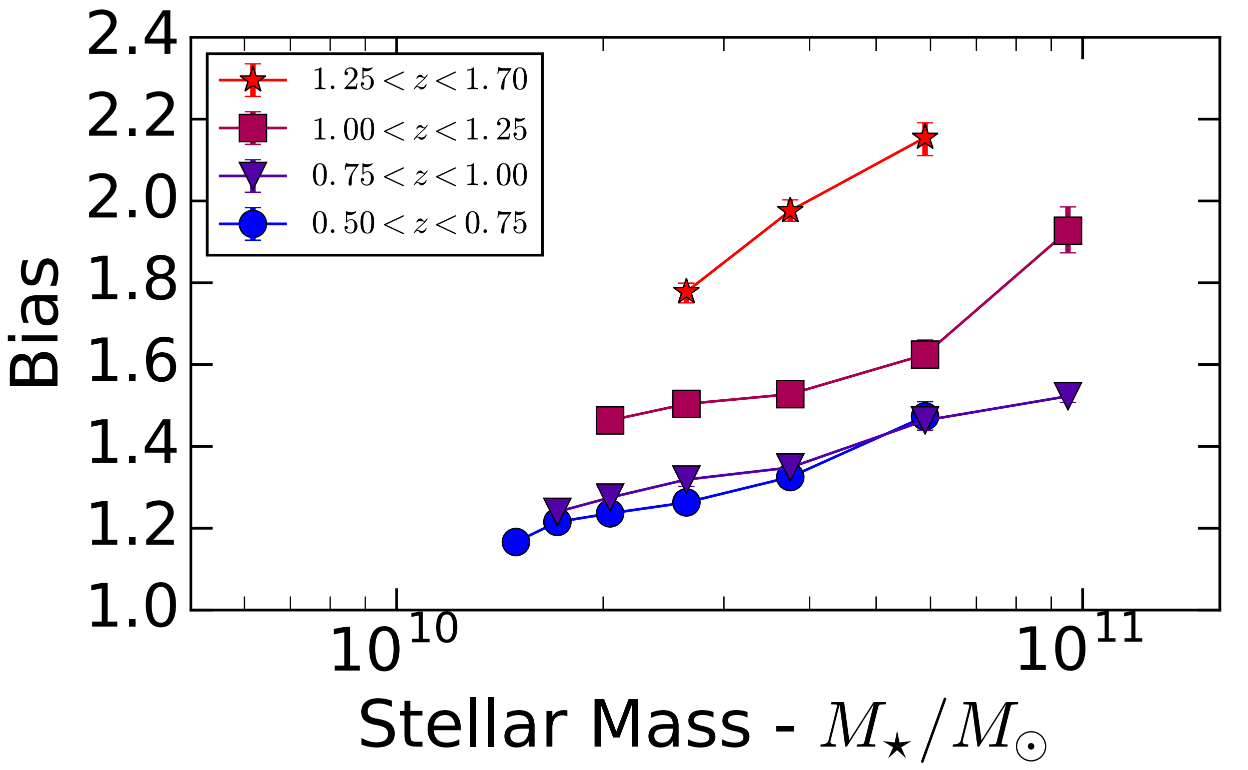
Hatfield et al. 2016

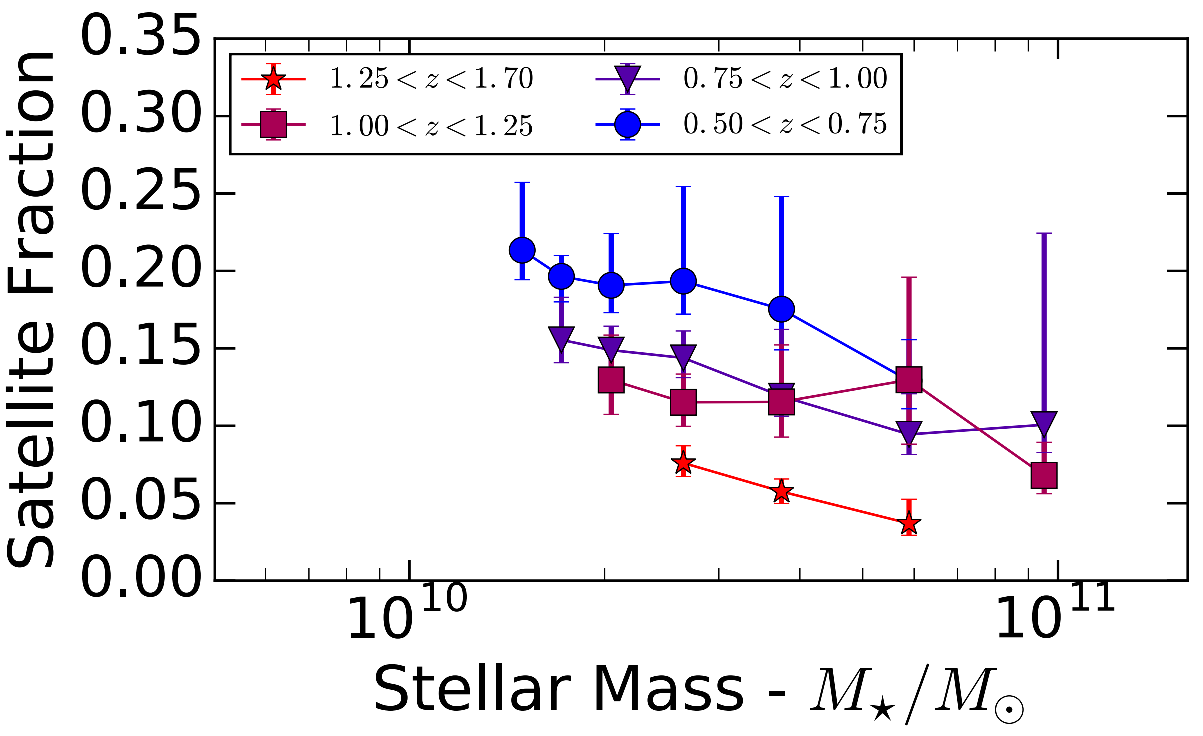


Hatfield et al. 2016



Hatfield et al. 2016

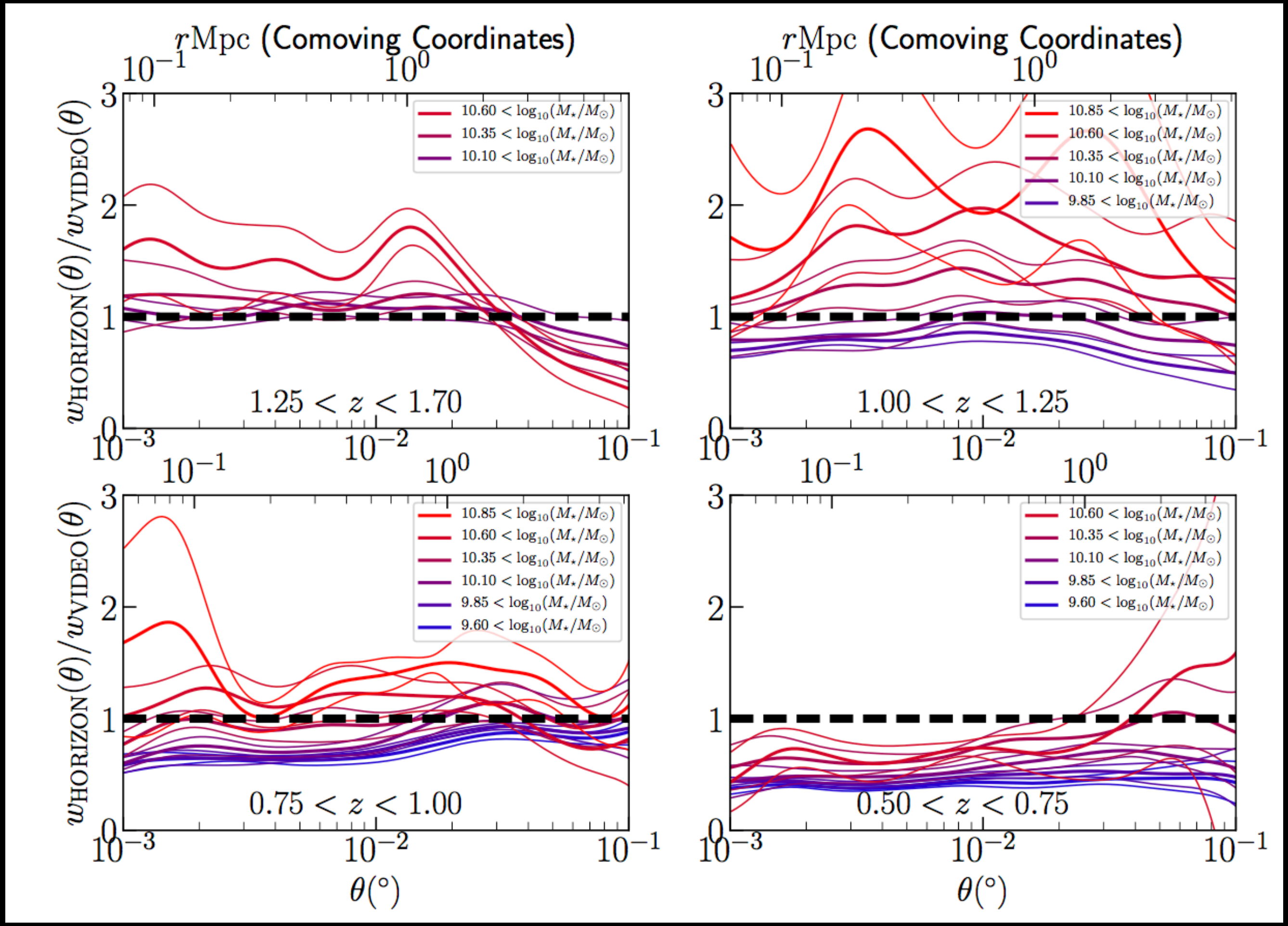




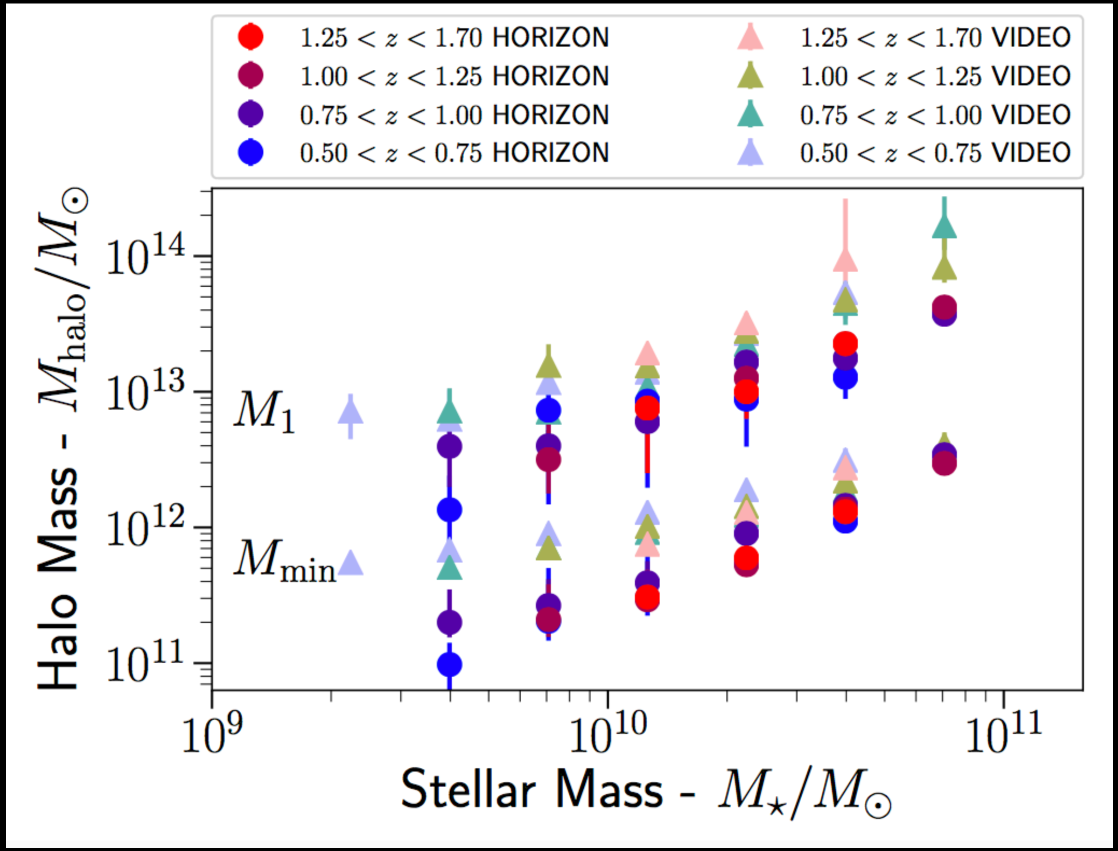
- Most massive galaxies in highest mass halos, most highly biased
- More highly biased at high redshift
- Very small fraction of massive galaxies are satellites
- Clustering has strong links to LSS for cosmology

Hatfield et al. 2016

Comparison with Simulations

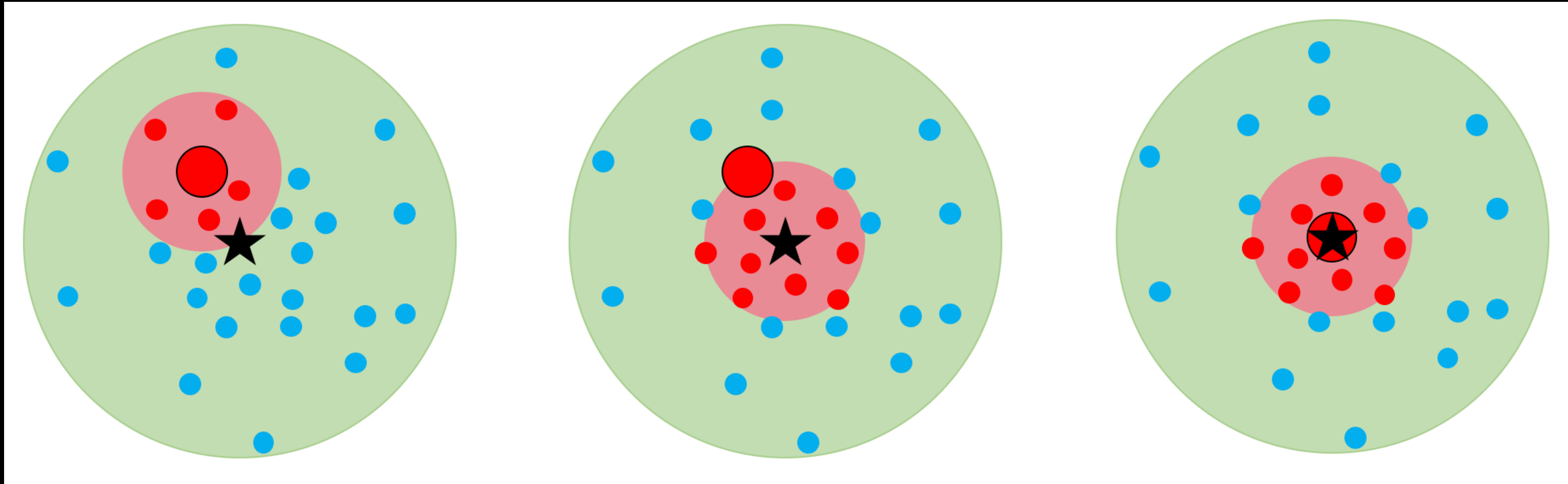


Hatfield, Laigle, Jarvis et al. in prep



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

Modelling the Cross-Correlation Function

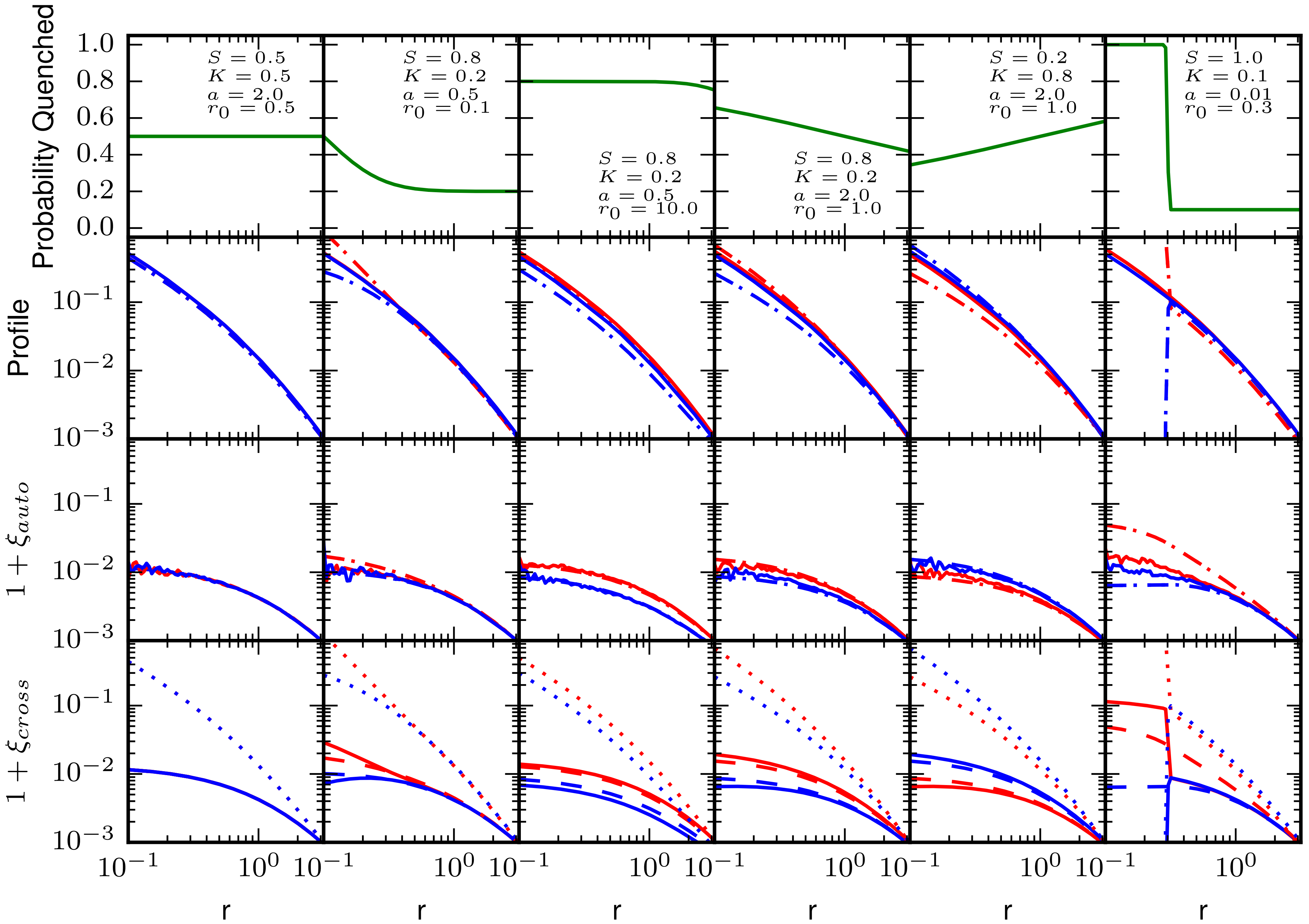


- Conventional HOD assumes galaxies trace **NFW** profile
- If galaxies are preferentially quenched or star forming in certain environments, this makes them follow slightly different profiles, which manifests itself in the 1-halo term
- Cross correlations also give information on covariance on occupation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

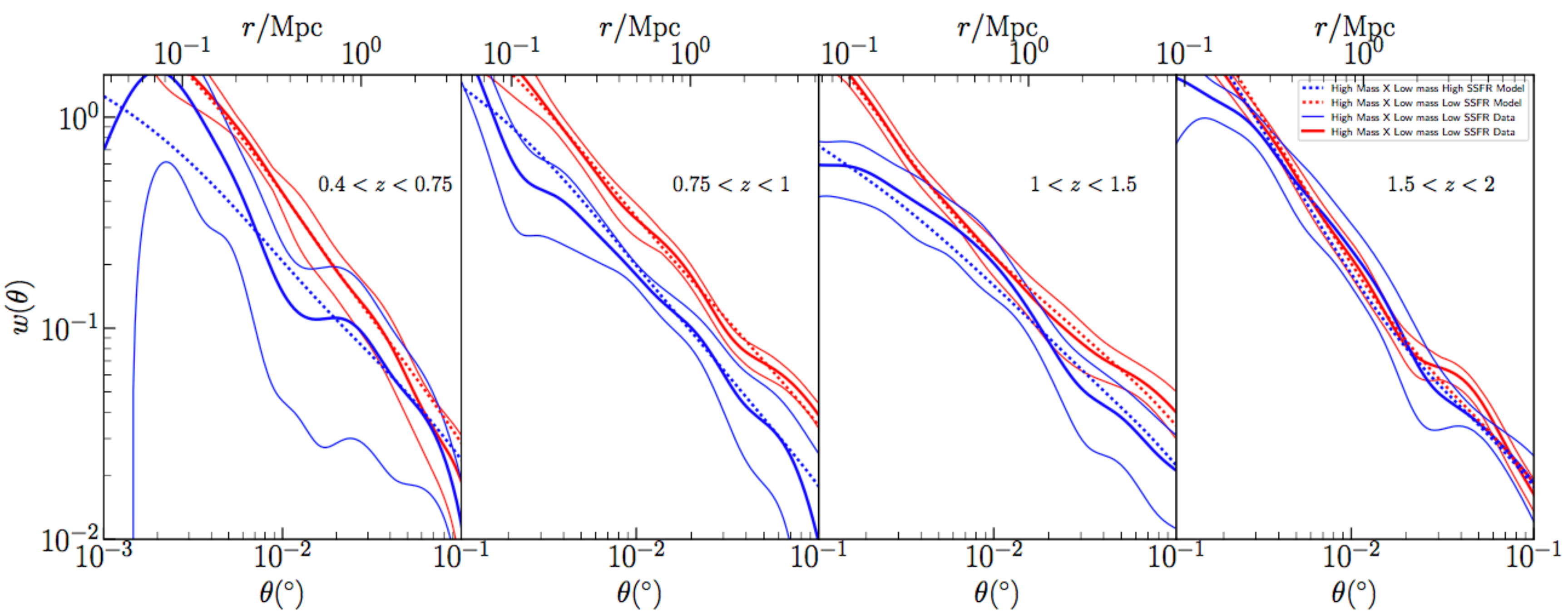
$$\xi^2_{\mathrm{galAB}} \neq \xi_{\mathrm{galAA}} \times \xi_{\mathrm{galBB}}$$

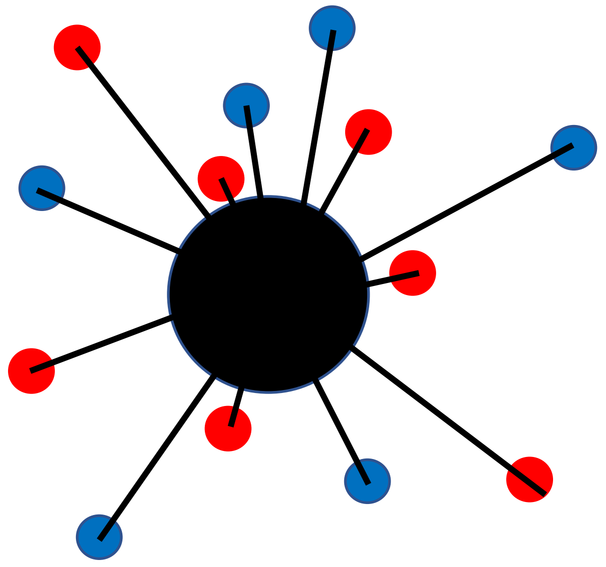
$$1 + \xi_{1h}(r) \propto \int_{\mathbb{R}^3} Q(\mathbf{r})\rho(\mathbf{r})\rho(\mathbf{r}-\mathbf{s})ds$$

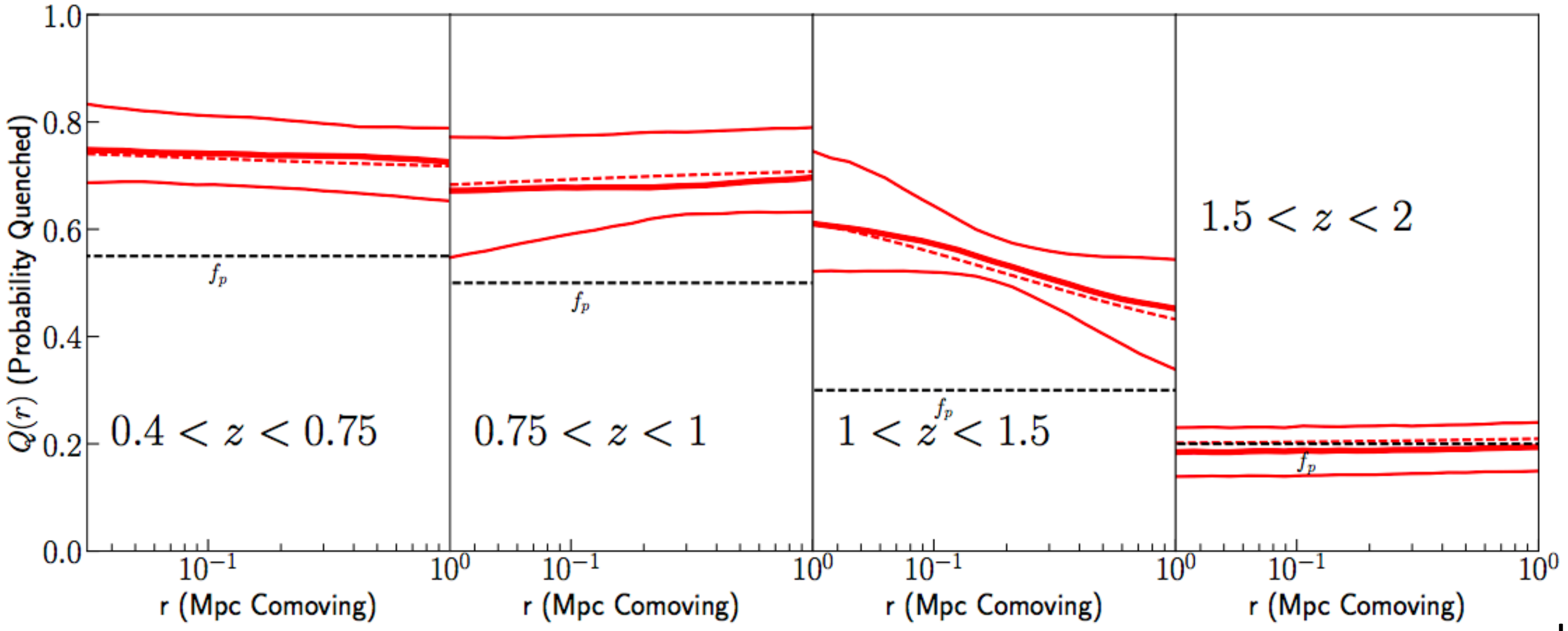
$$1 + \xi_{1h}(r) \propto Q(\mathbf{r}) \int_{\mathbb{R}^3} \rho(\mathbf{r})\rho(\mathbf{r}-\mathbf{s})ds$$

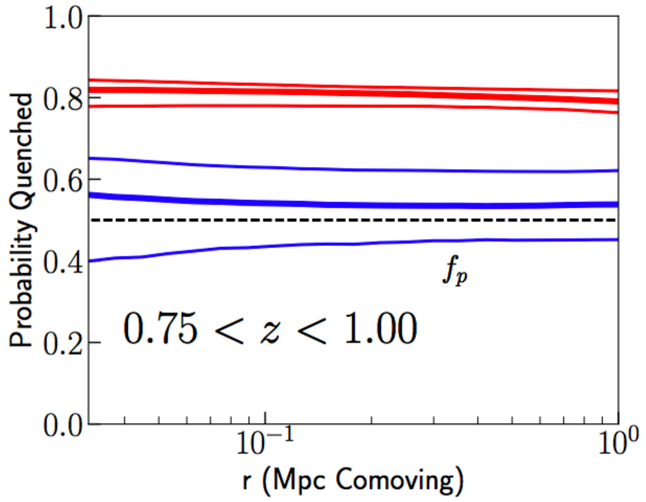


Hatfield & Jarvis 2017



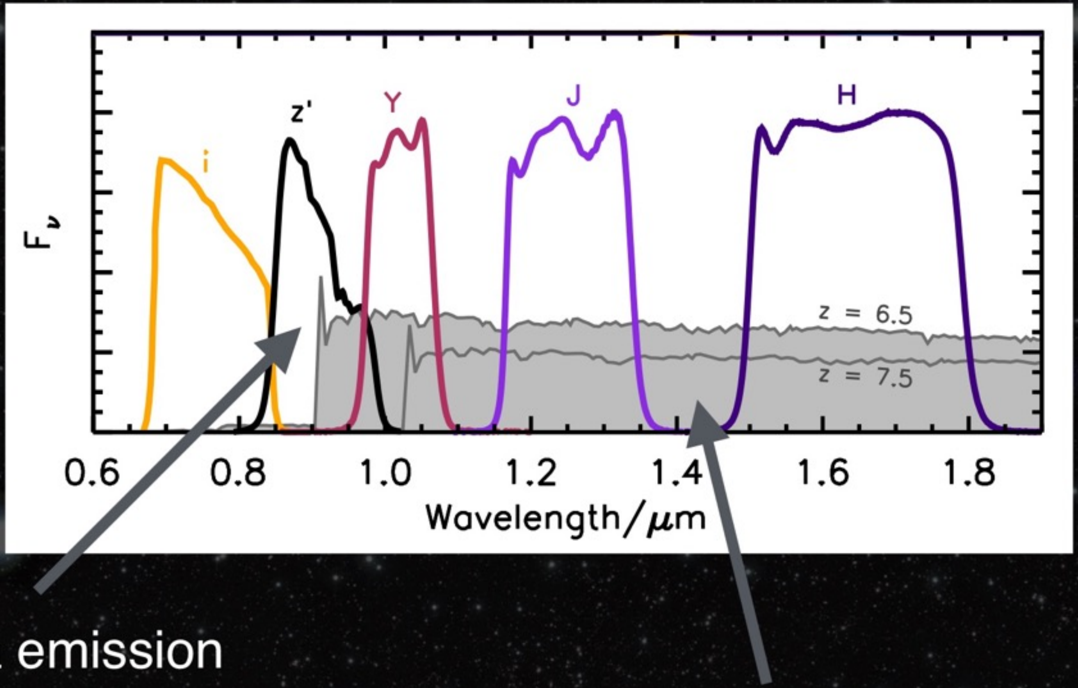






Hatfield & Jarvis 2017

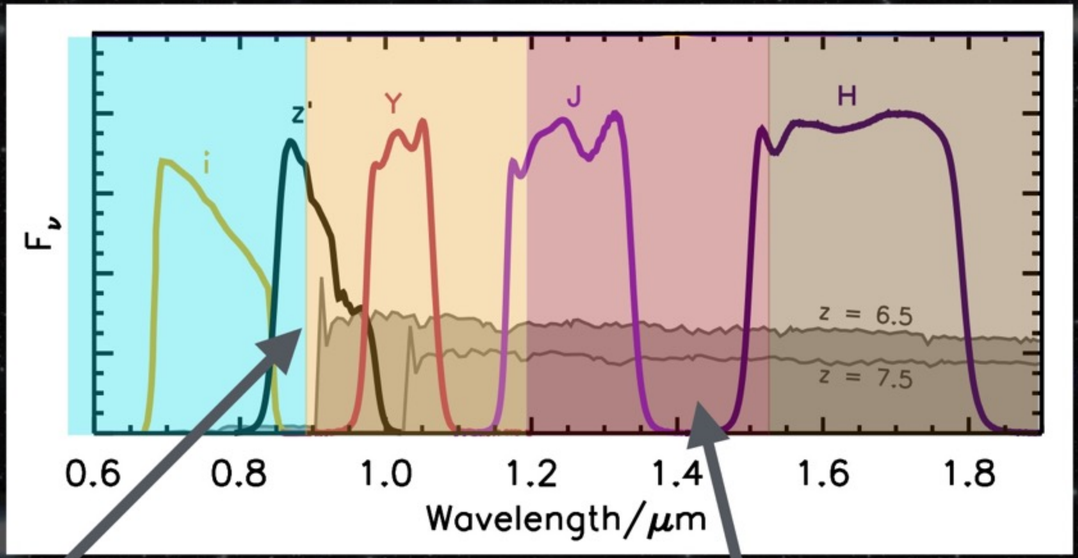
Finding high-z galaxies



Key spectral features for selection:

- ★ optical to near-infrared drop = Lyman-break
- ★ blue colours in the near-infrared

Finding high-z galaxies

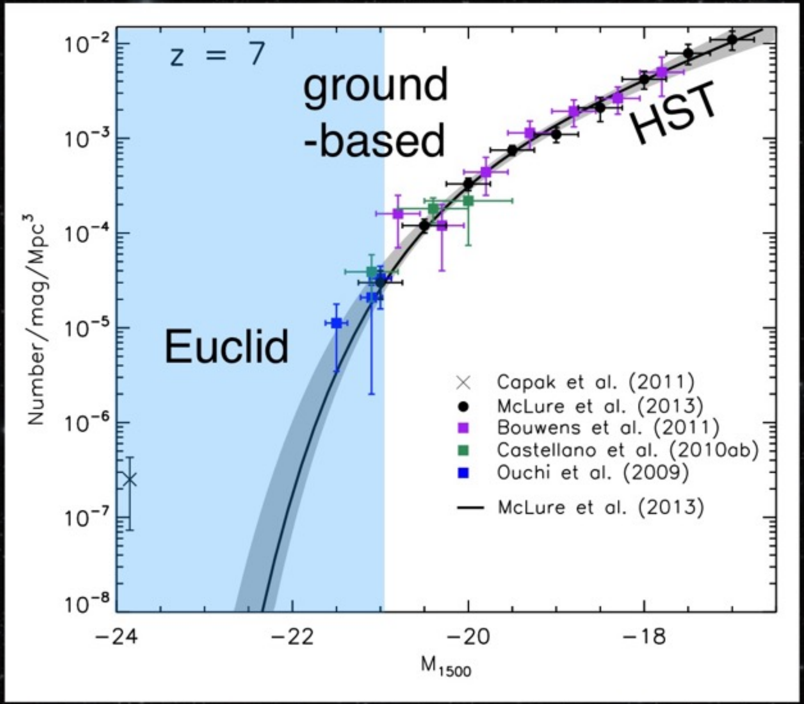


Grism spectroscopy will detect Lyman-a from z = 6.5 -> 9

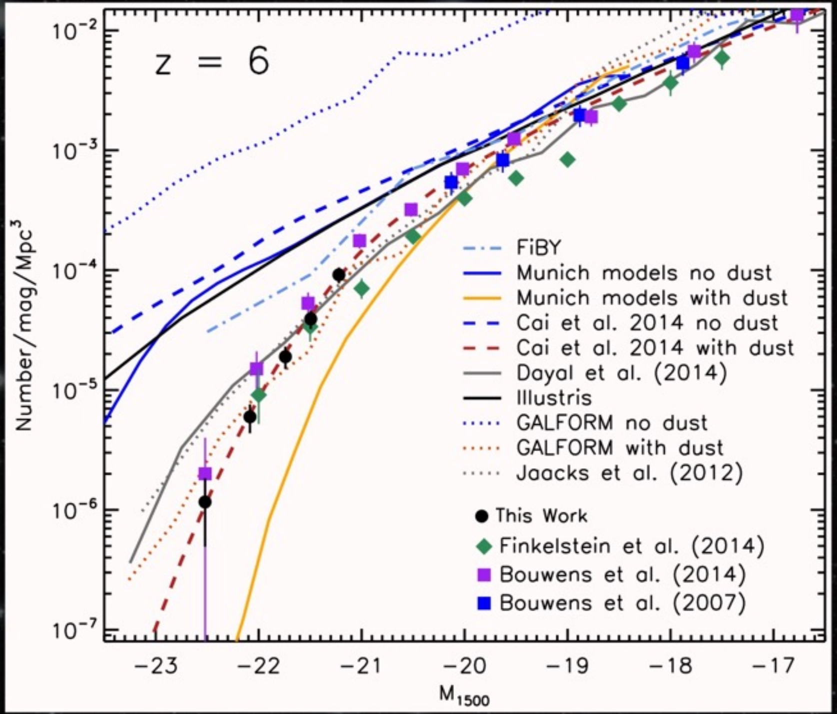
VIS-filter dropouts: z ~ 7 galaxies
Y-filter dropouts: z ~ 8 galaxies
J-filter dropouts: z ~ 9 galaxies

High-z galaxies science goals

- ★ Bright-end of the galaxy luminosity function at z = 7-9
- ★ Rare objects for ALMA/JWST/ELT follow-up
- ★ Spectroscopic confirmation of z > 8 galaxies (Lya + other lines)
- ★ Clustering of Lyman-alpha emitters to probe reionization
- ★ Detection of rare ultra-luminous Lyman-a emitters



DATA



MODELS

High-z galaxies science goals

- ★ Bright-end of the galaxy luminosity function at z = 7-9
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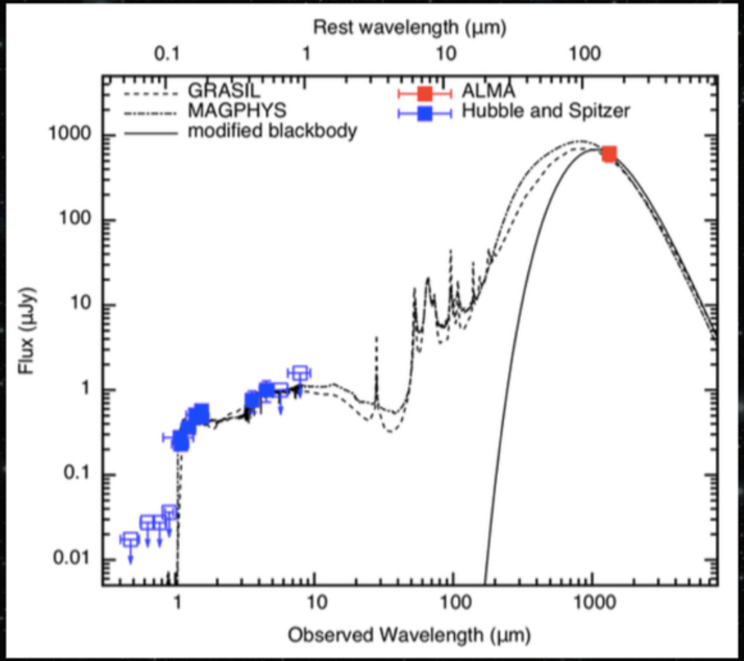
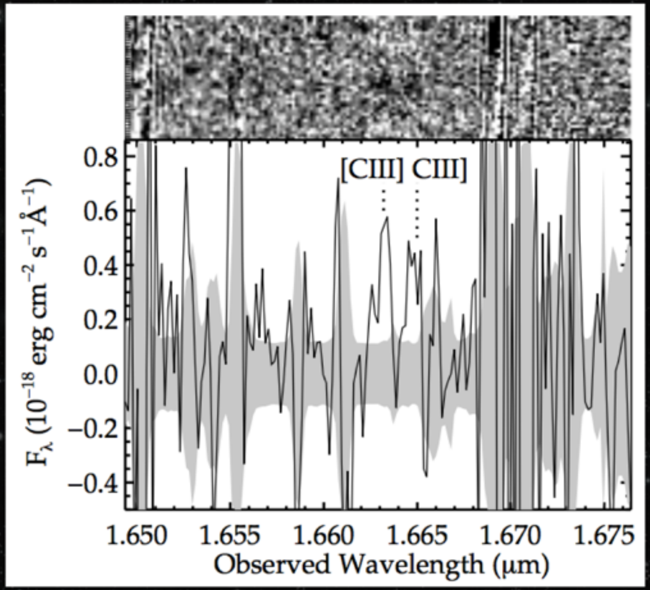


e.g. ALMA detection of dust continuum at z = 7.5 from Watson et al. (2015)

e.g rest-frame UV emission lines from Stark et al. 2014, 2017



High-z galaxies science goals

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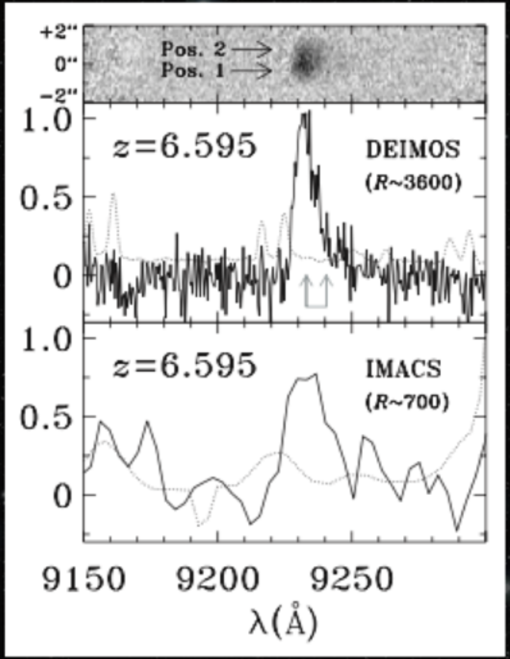
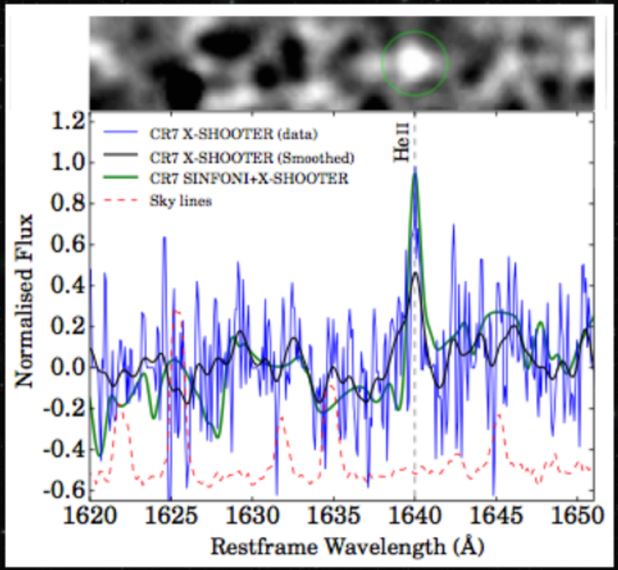
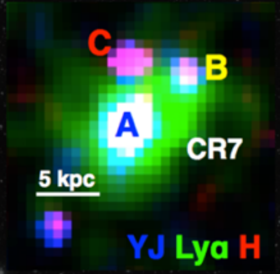


'Himiko' z = 6.6 (Ouchi+09)

'CR7' z = 6.6 (Sobral+15)

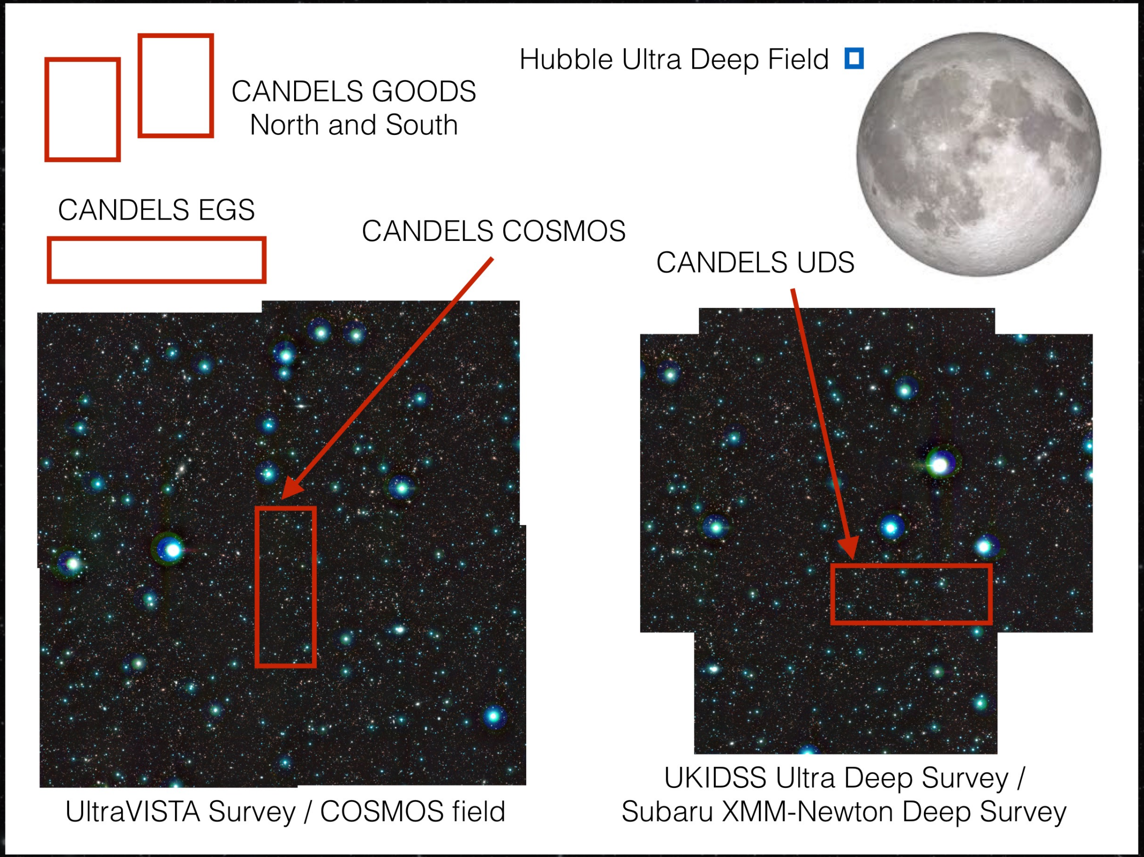




- ➡ Pop III ?
- ➡ DCBH (Direct Collapse BH)
- ➡ other ?

Sobral et al. 2015
Visbal et al. 2016
Pallottini et al. 2015
Hartwig et al. 2015
Agarwal et al. 2016
Smidt et al. 2016
Smith et al. 2016
Dijkstra et al. 2016
Bowler et al. 2017b

Current leading surveys for high-z science



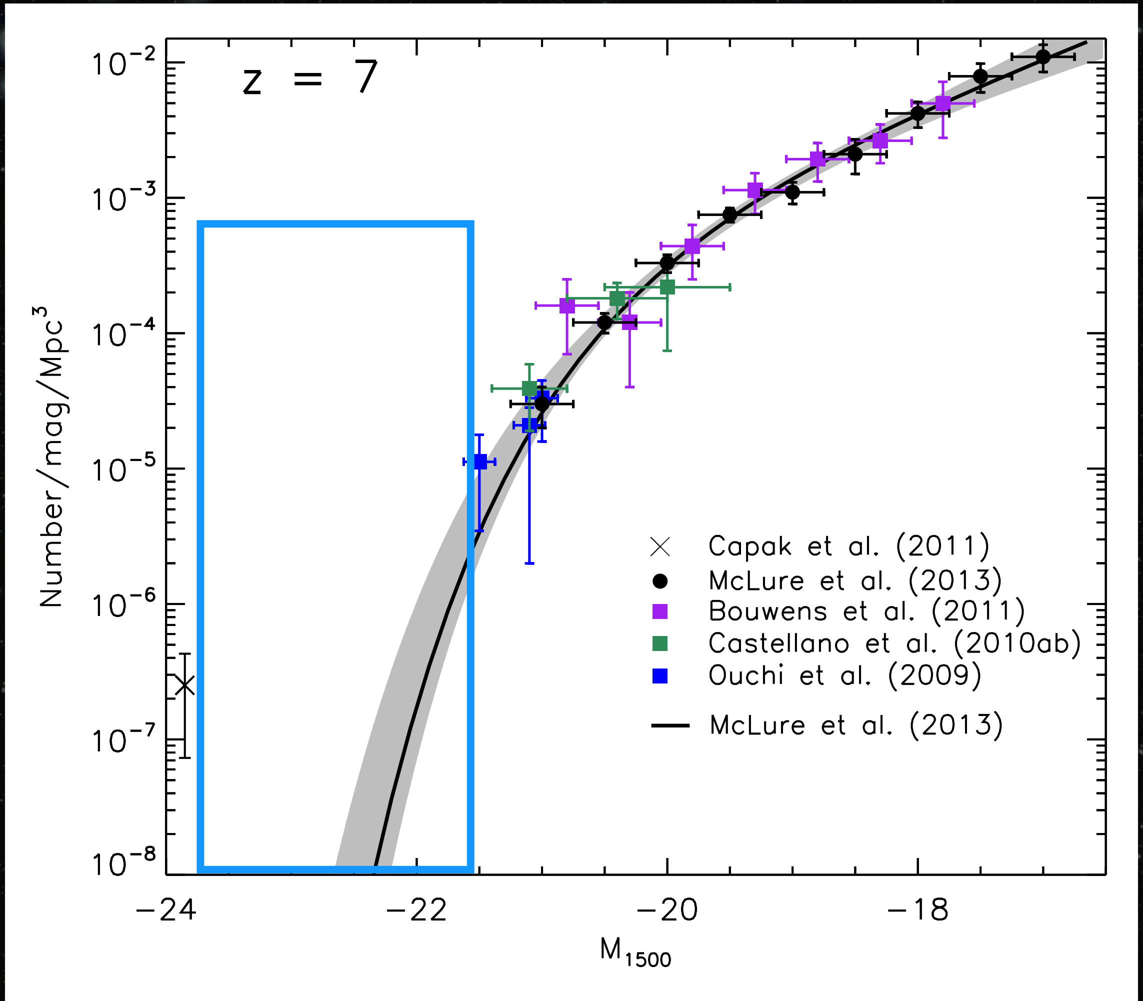
COSMOS
ugriz/CFHTLS
z/Subaru
NB/Subaru
YJHKs/UltraVISTA
3.6 4.5micron/SPLASH

UDS
BVRiz/Subaru
NB/Subaru
Y/VISTA VIDEO
JHK/UKIDSS UDS
3.6 4.5micron/SPLASH

➡ Euclid will provide data with HST-like resolution over a 20x wider area than the current ground-based fields

The bright-end of the z ~ 7 luminosity function

Need wide-area, near-IR surveys!

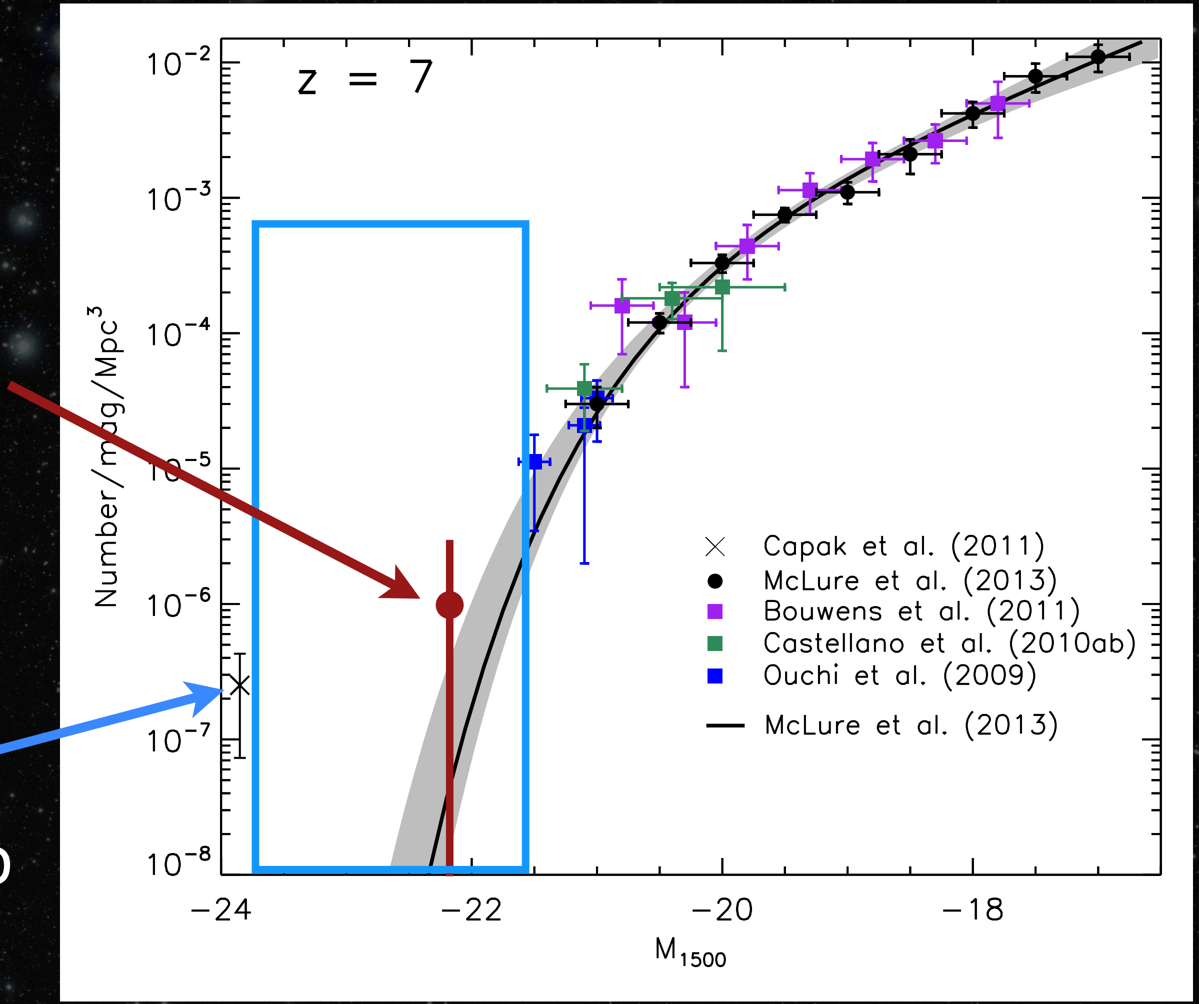


The bright-end of the z ~ 7 luminosity function

Need wide-area, near-IR surveys!

Brightest point from full CANDELS only ~ 1 galaxy

Previous CFHT/ UKIRT data not deep enough (“LBGs” all at z ~ 2)

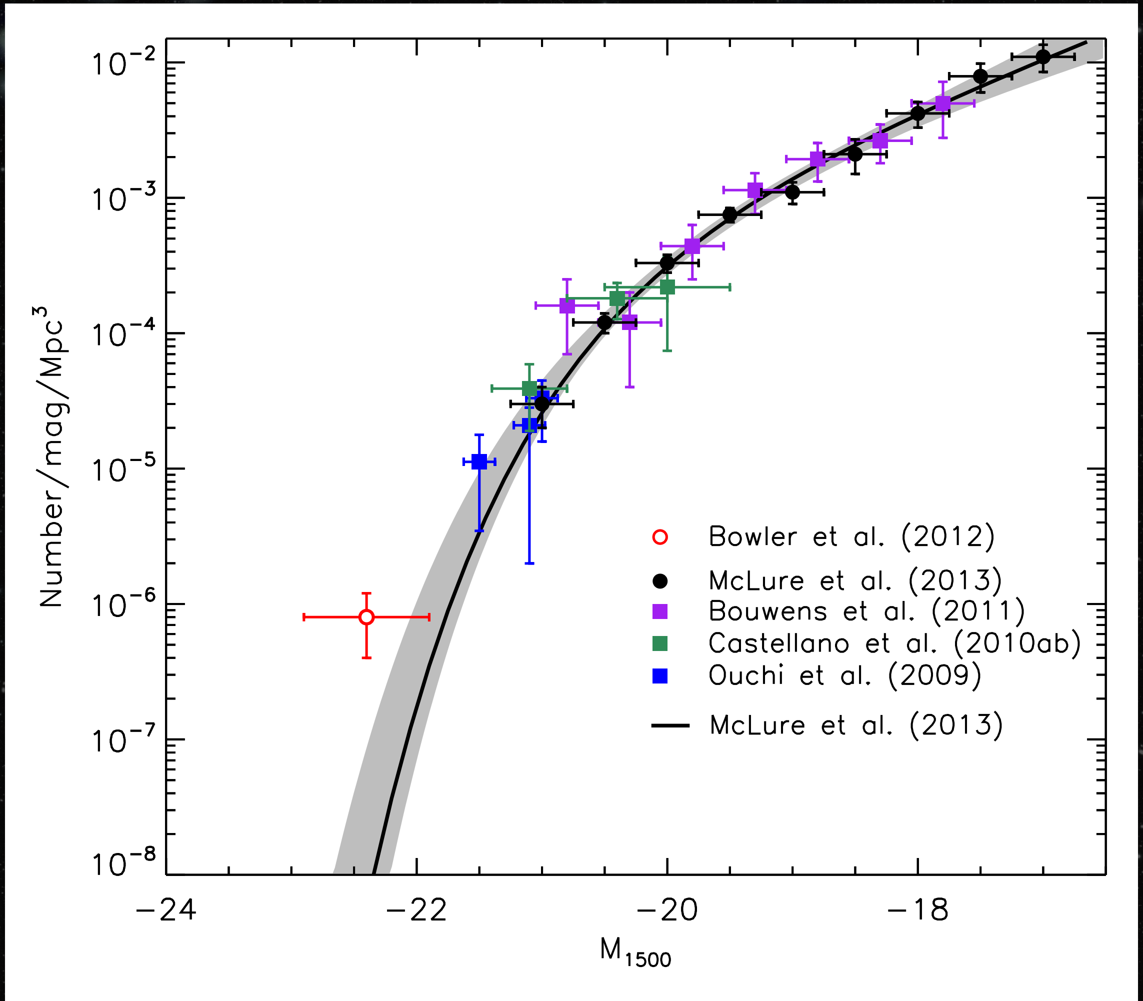


The bright-end of the z ~ 7 luminosity function

UltraVISTA DR1

1 sq. degree

10 galaxies



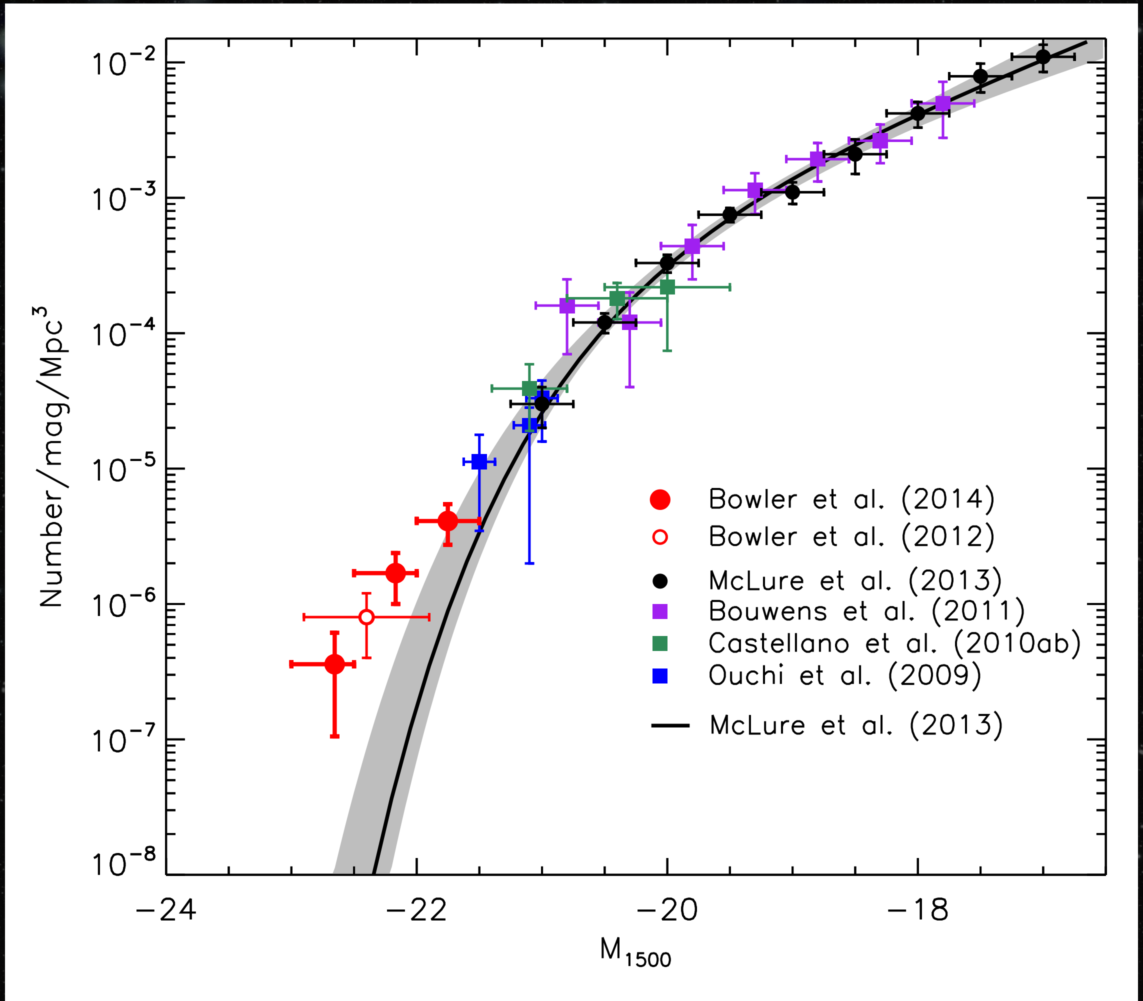
The bright-end of the z ~ 7 luminosity function

UltraVISTA DR2 + UDS/SXDS

1.65 sq. degrees

34 galaxies (including 9/10 Bowler et al. 2012 objects)

0.5-1 mag deeper near-IR data than DR1



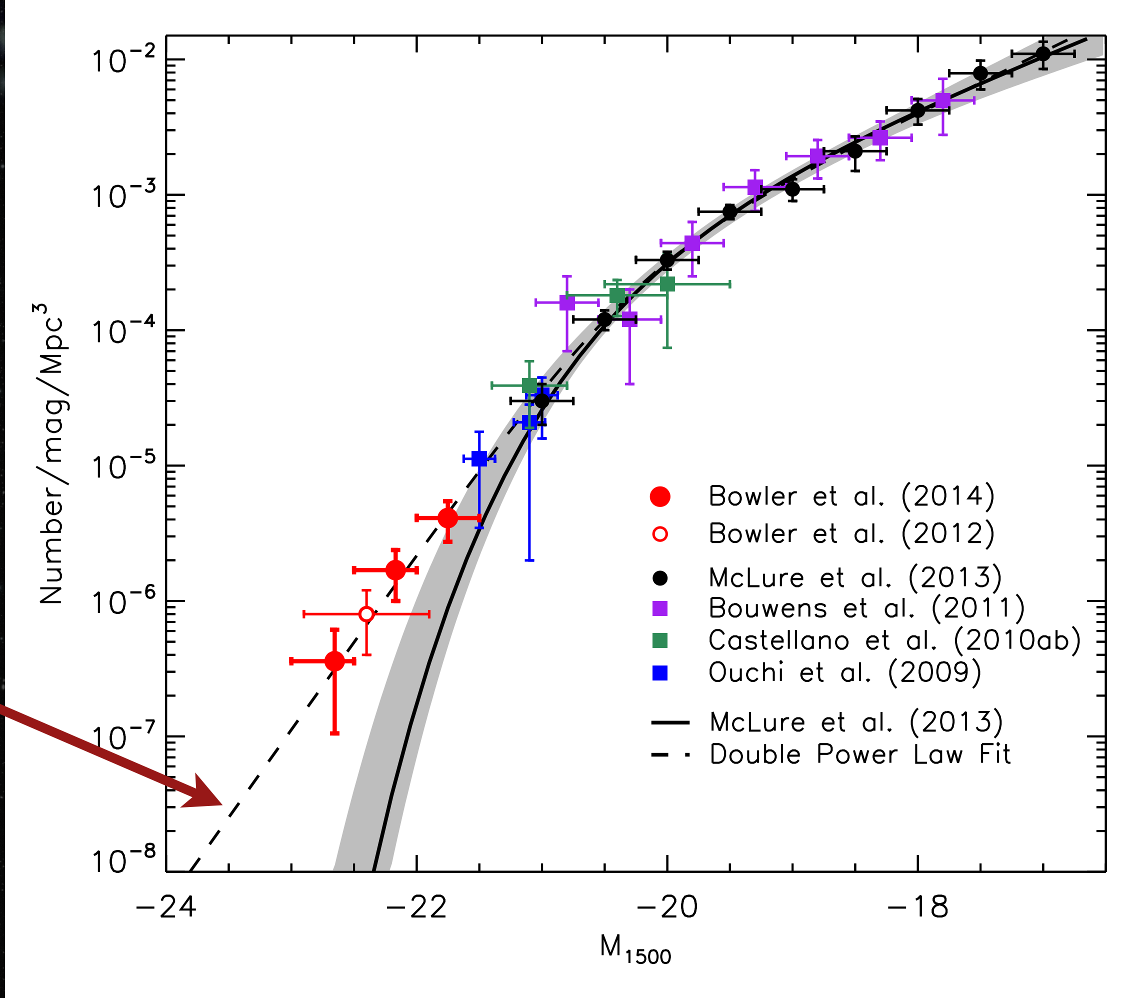
The bright-end of the z ~ 7 luminosity function

UltraVISTA DR2 + UDS/SXDS

1.65 sq. degrees

Best-fit is not the usually assumed exponential decline (Schechter) but a **double power-law**

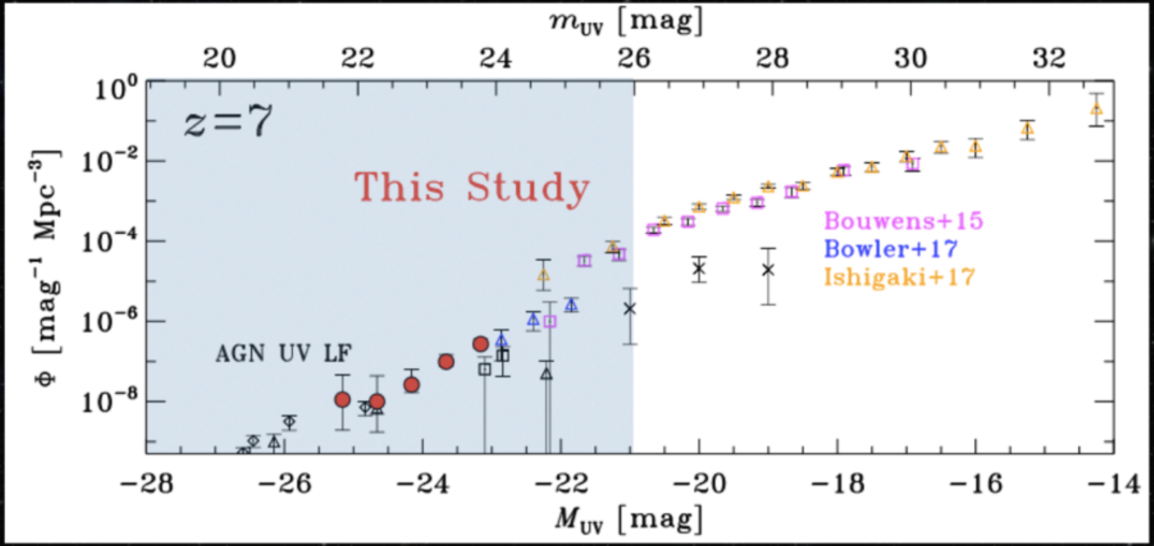
Inefficient AGN feedback? Reduced dust?



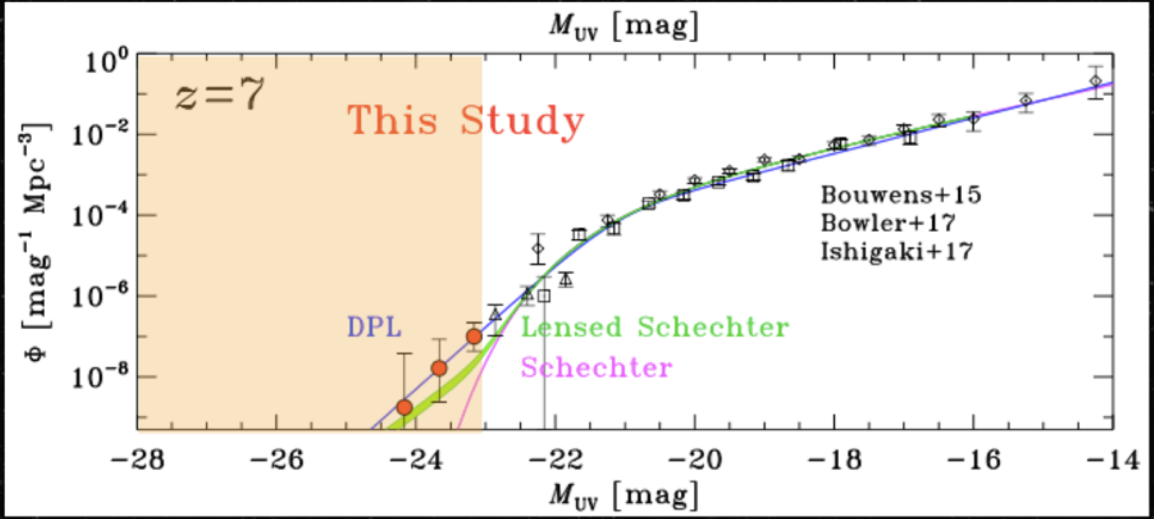
1/20th of the Euclid Deep survey

Recent results from HSC ultra-deep

Results from wide, deep and ultra-deep HSC data to 2016



With AGN LF subtracted:

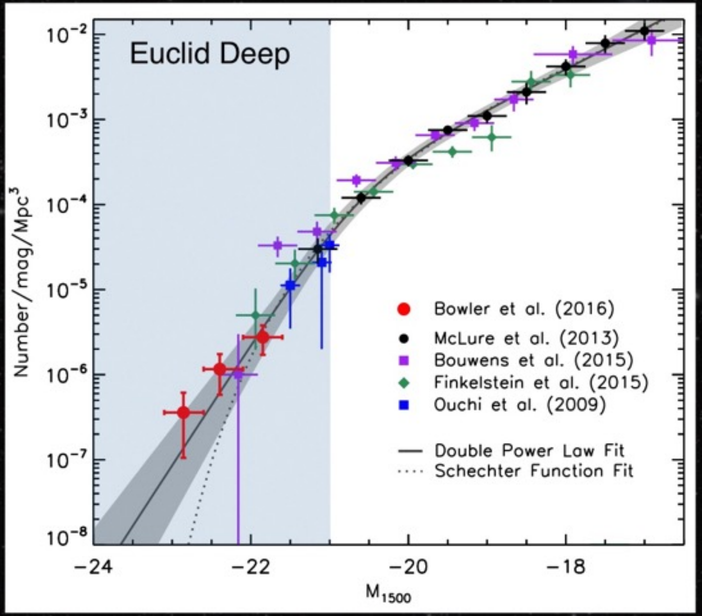


- No removal of brown dwarfs which dominate in this magnitude regime
- AGN LF is uncertain

Ono et al. 2017

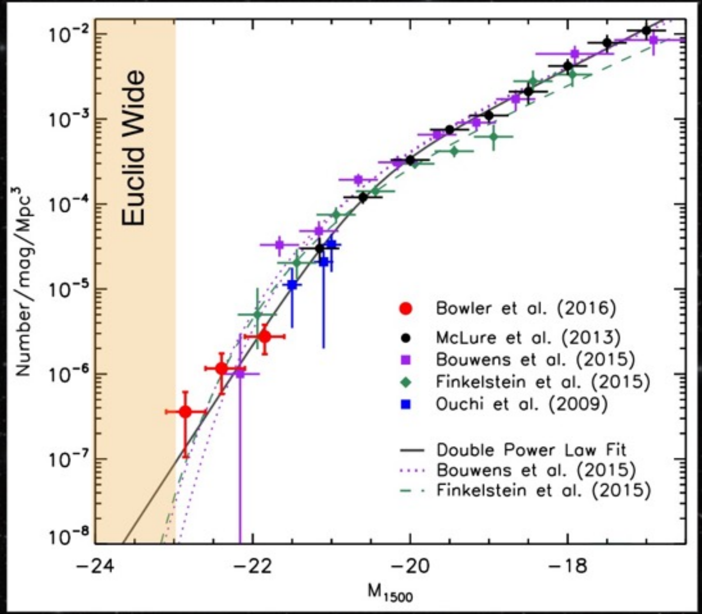
Number counts of z ~ 7 LBGs in *Euclid*

Euclid deep: 40 deg2 to 26 (5sigma, AB)
N = 3100 ± 1200 (3300)
for double-power law (Schechter) fit



Euclid wide: 15000 deg2 to 24 (5sigma, AB)
N = 2000 ± 5000 (< 50)
for double-power law (Schechter) fit

Overlap with Quasar LF?

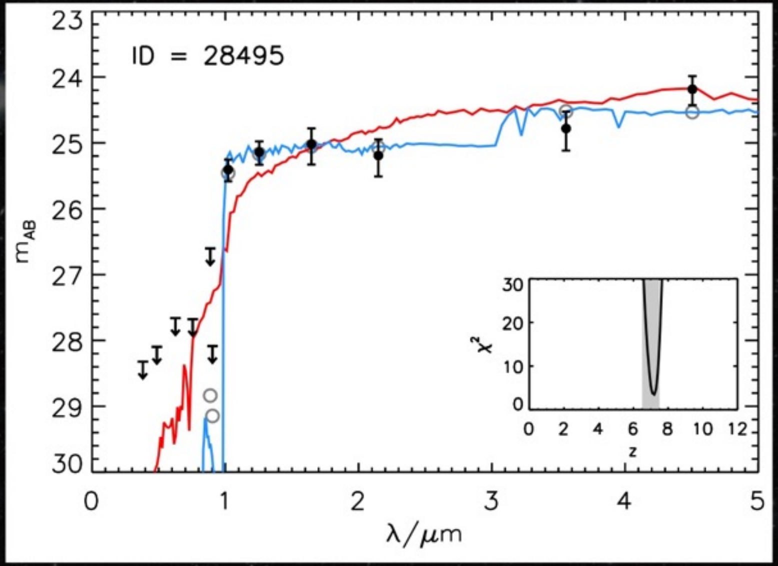


Clean selection of high-z galaxies

★ Deep **optical + near-infrared** photometry constrains high-z nature

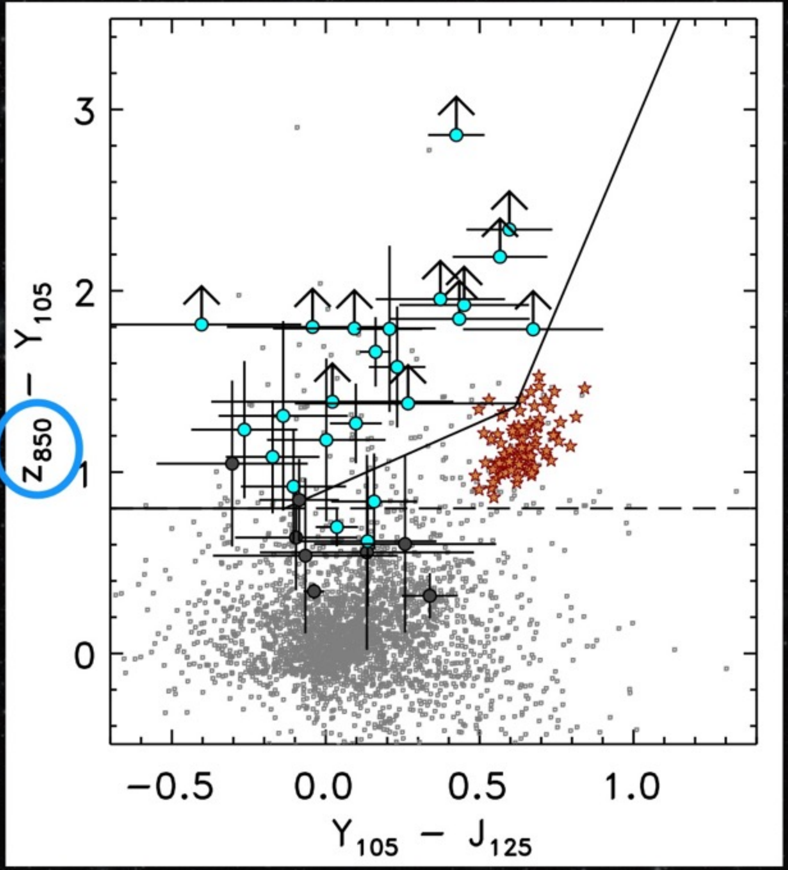
Strong break **+** blue continuum

Spitzer/IRAC removes red interlopers



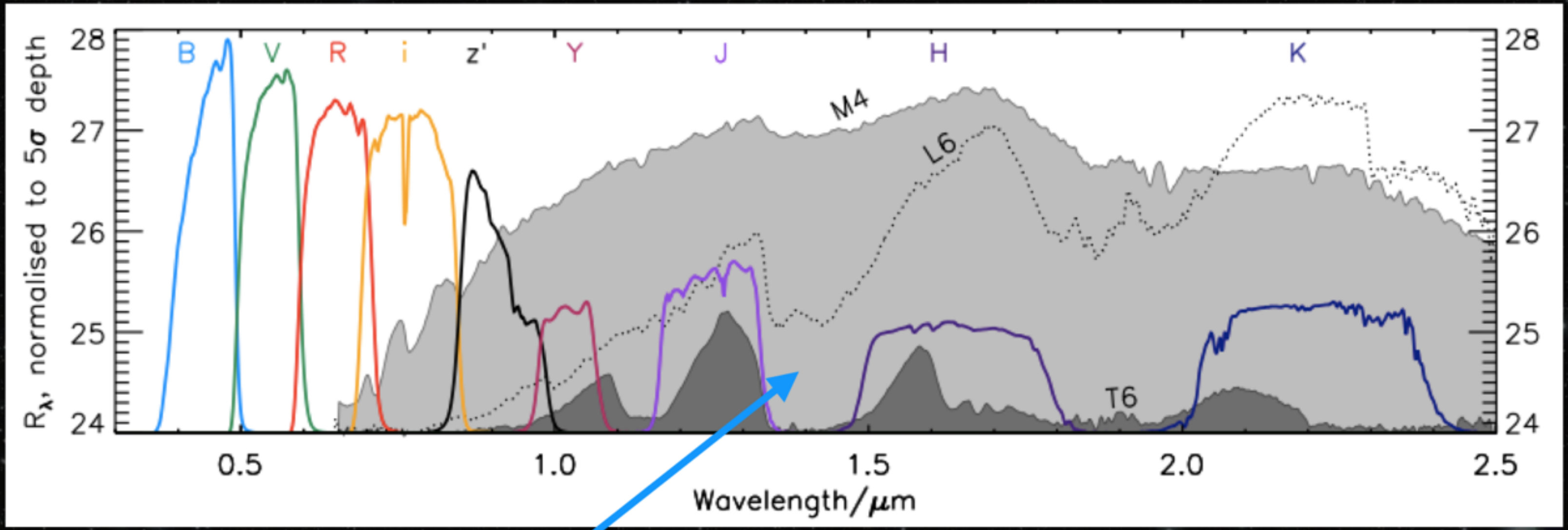
High-z galaxy

Low-z galaxy



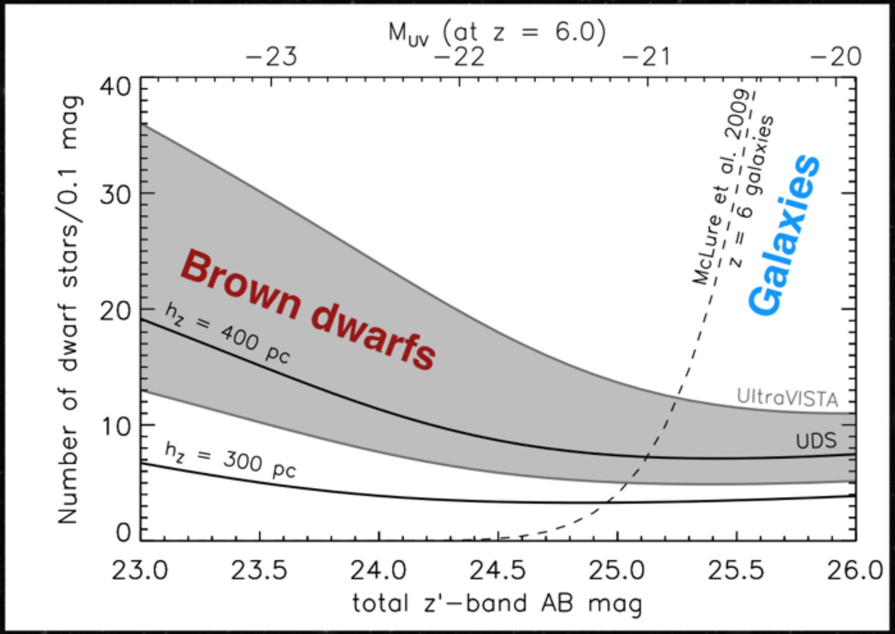
Finkelstein et al. 2010

Contamination by cool galactic brown dwarfs



Water + methane absorption

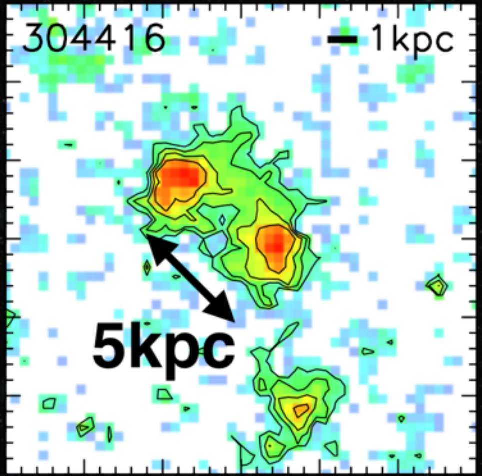
★ M, L and T dwarfs outnumber bright z ~ 7 galaxies and can mimic their colours with inadequate depth + filter sampling

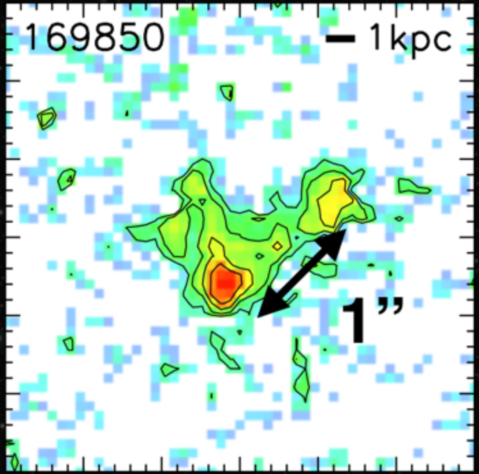


Bowler et al. 2015

How big will the z > 7 galaxies be?

Cycle 22 HST follow-up of bright LBGs reveal sizes/ morphologies that are elusive in ground-based data



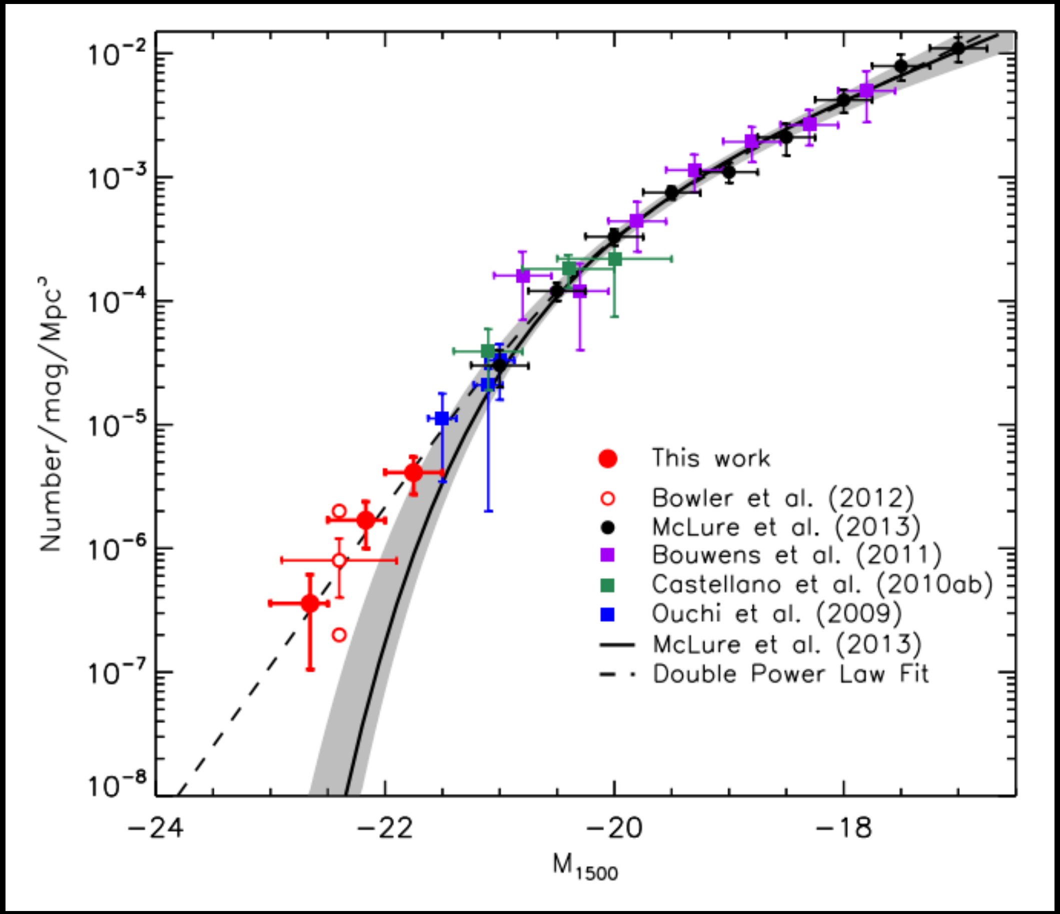


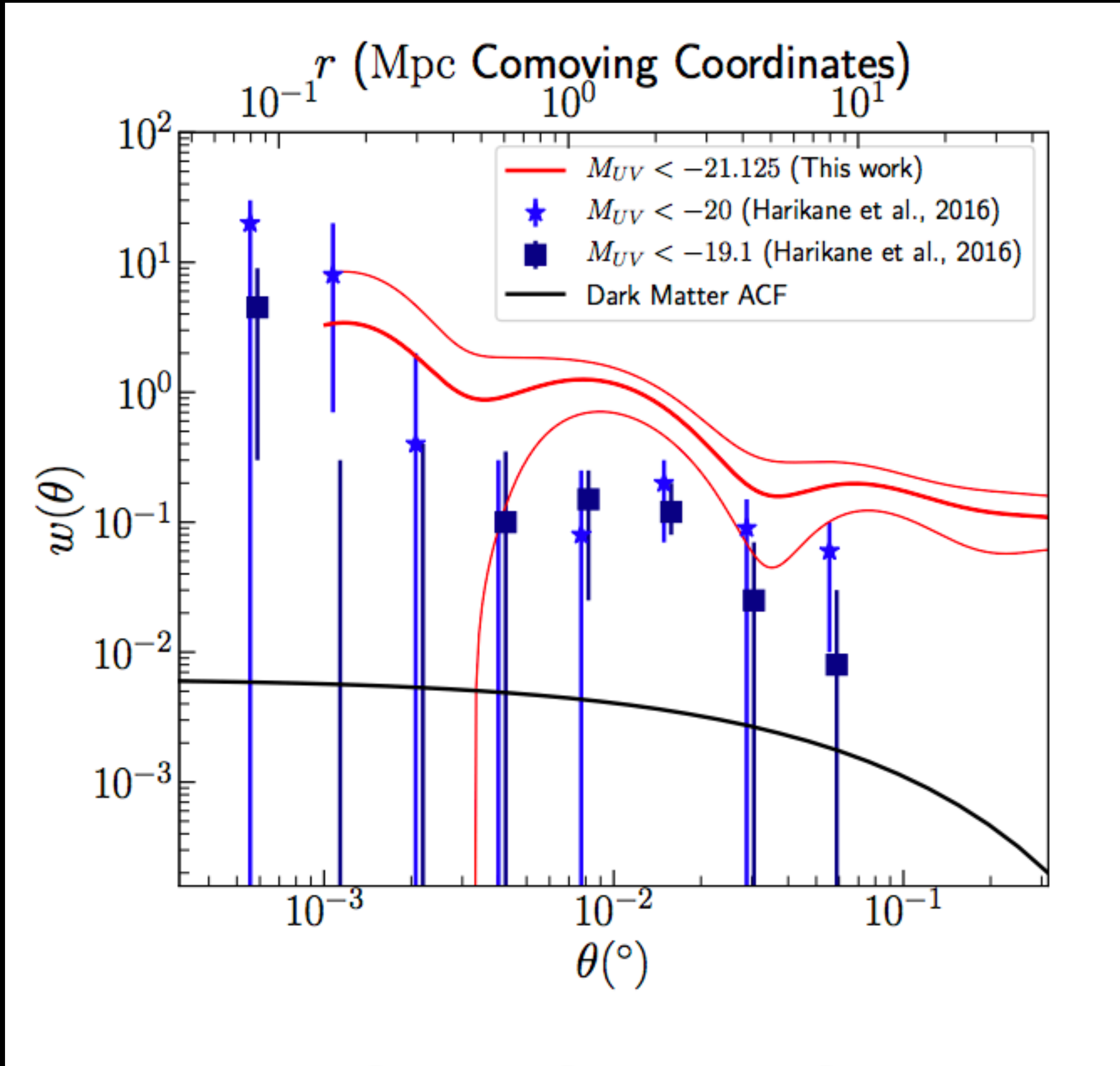
- ⋆ The brightest Lyman-break galaxies at z ~ 7 are resolved
- ⋆ Diminishes worry over brown dwarf contamination

Bowler et al. 2017a

Clustering at z~6

- z~6 clustering of LBGs – onset of quenching?





$$-2 \log \mathcal{L} = \chi^2_\phi + \Sigma\chi^2_{\omega(\theta)} + \Sigma\chi^2_{\Delta\Sigma}$$

Hatfield et al. 2017, arxiv.1702.03309

Exploring Lyman-a at z > 7

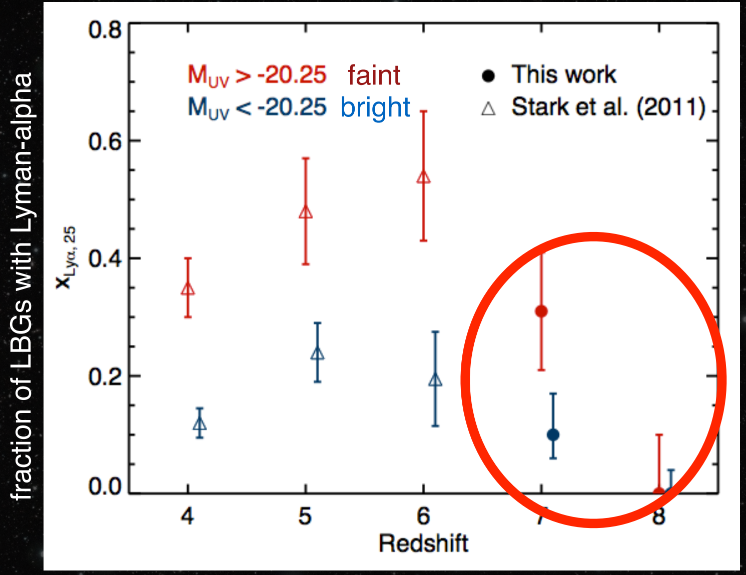
… potentially challenging at z > 6

e.g.

A 52 hours VLT/FORS2 spectrum of a bright $z \sim 7$ HUDF galaxy: no $Ly\alpha$ emission. ⋆

E. Vanzella[1], A. Fontana[2], L. Pentericci[2], M. Castellano[2], A. Grazian[2], M. Giavalisco[4], M. Nonino[3], S. Cristiani[3], G. Zamorani[1], and C. Vignali[5]

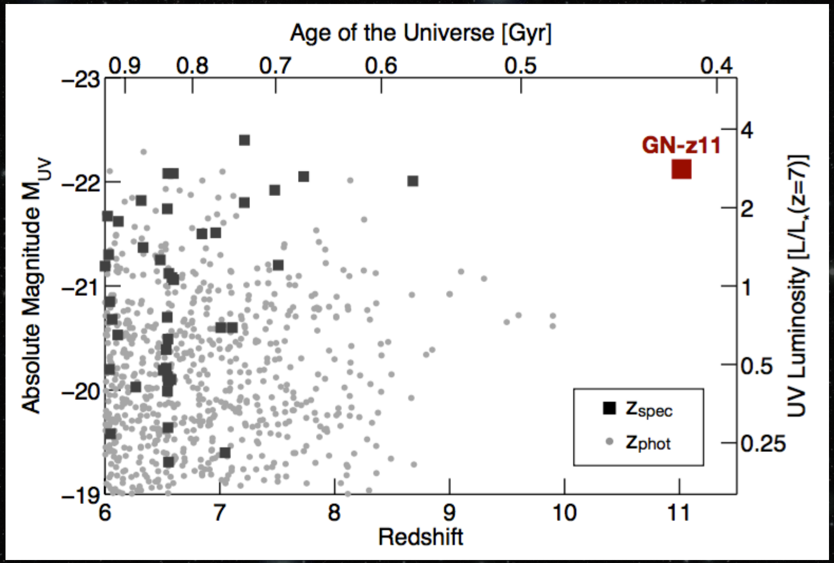
+ Pentericci et al. (2014), Tilvi et al. (2014), Schenker et al. (2013)..



Schenker et al. 2014

-> pessimistic predictions for Euclid

Recent results…



Oesch et al. 2016

+ extreme line emitters/ CIV, CIII] emission

The “WHT Enhanced Area Velocity Explorer”

- WEAVE is a 1000 x 1.3” fibre multi-object spectrograph going on the 4.2m WHT
- 2 deg diameter field of view
- Complete wavelength coverage from 370–960nm at R=5000
- First light “Q3/Q4 of 2018” (stable-ish for last 12 months) but could slip further.
- Five years (+) of survey operations
- Also has mIFU and LIFU modes

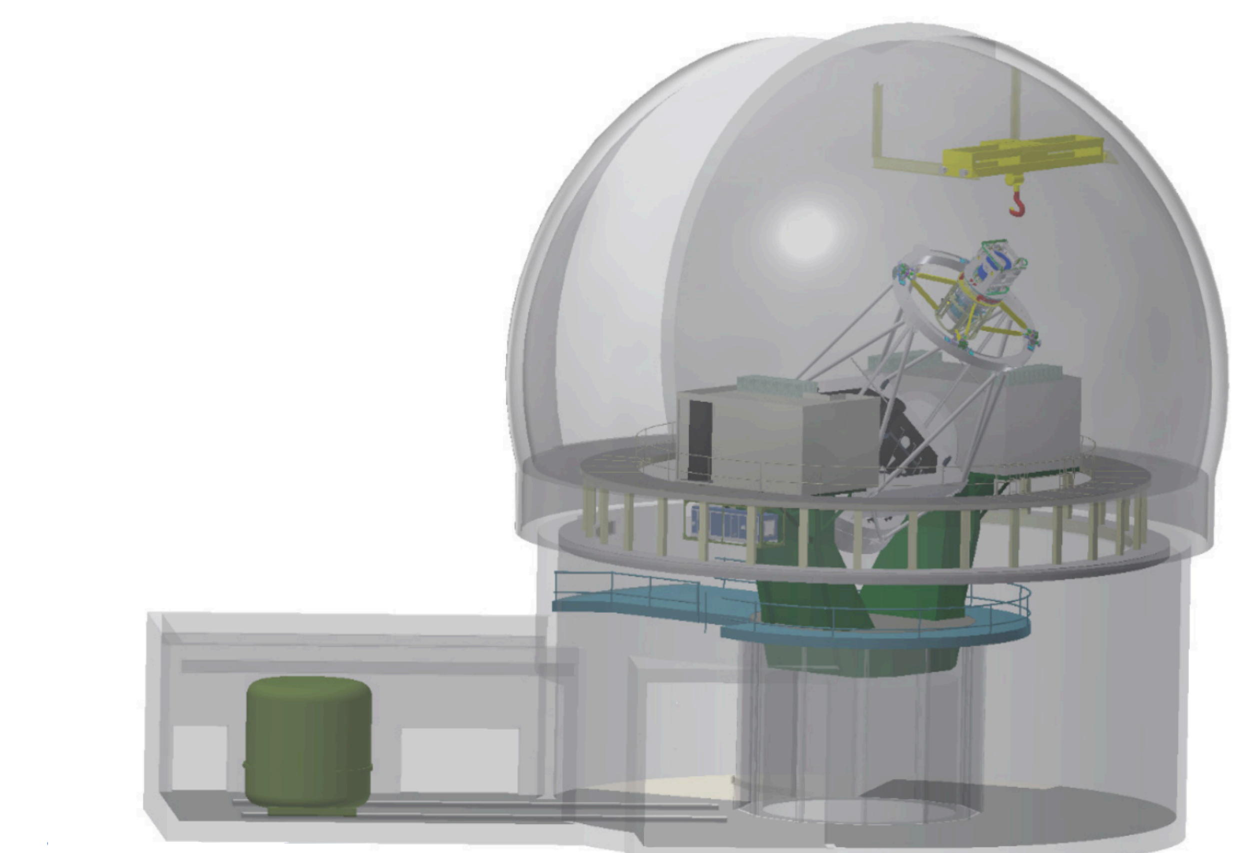


Image: Don Carlos Abrams

WEAVE-LOFAR

Survey Design

MOS Survey:

Spectroscopic follow-up of large numbers of LOFAR-selected sources in three tiers, to get *a* complete picture of SF and AGN co-evolution.

Current fibre hour envelope:
<1.6 million

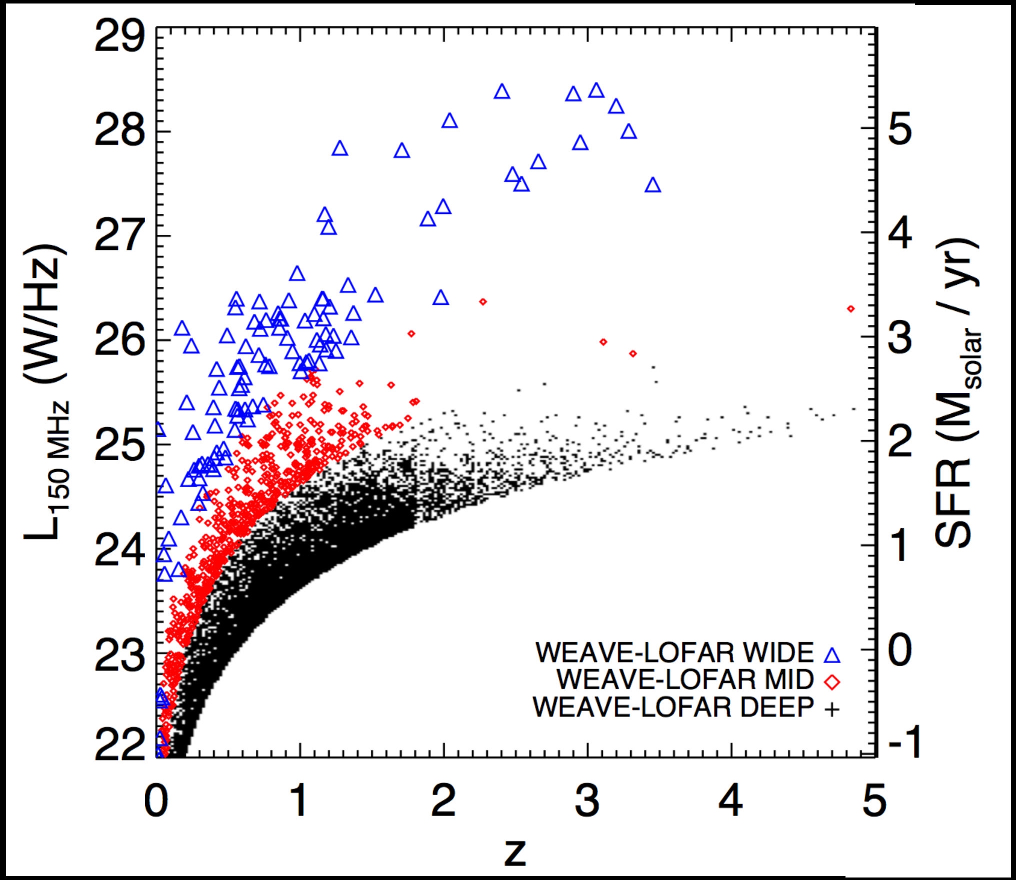
Deep ($\sim$100 deg^2) → Targets > 100 uJy; ~50% of all time

Mid (1,250 deg^2) → Targets > 1 mJy; ~25% of all time

Wide (up to 10,000 deg^2) → Targets > 10 mJy; ~25% of all time

WEAVE-LOFAR

The MOS Surveys – the nature of the faint radio population



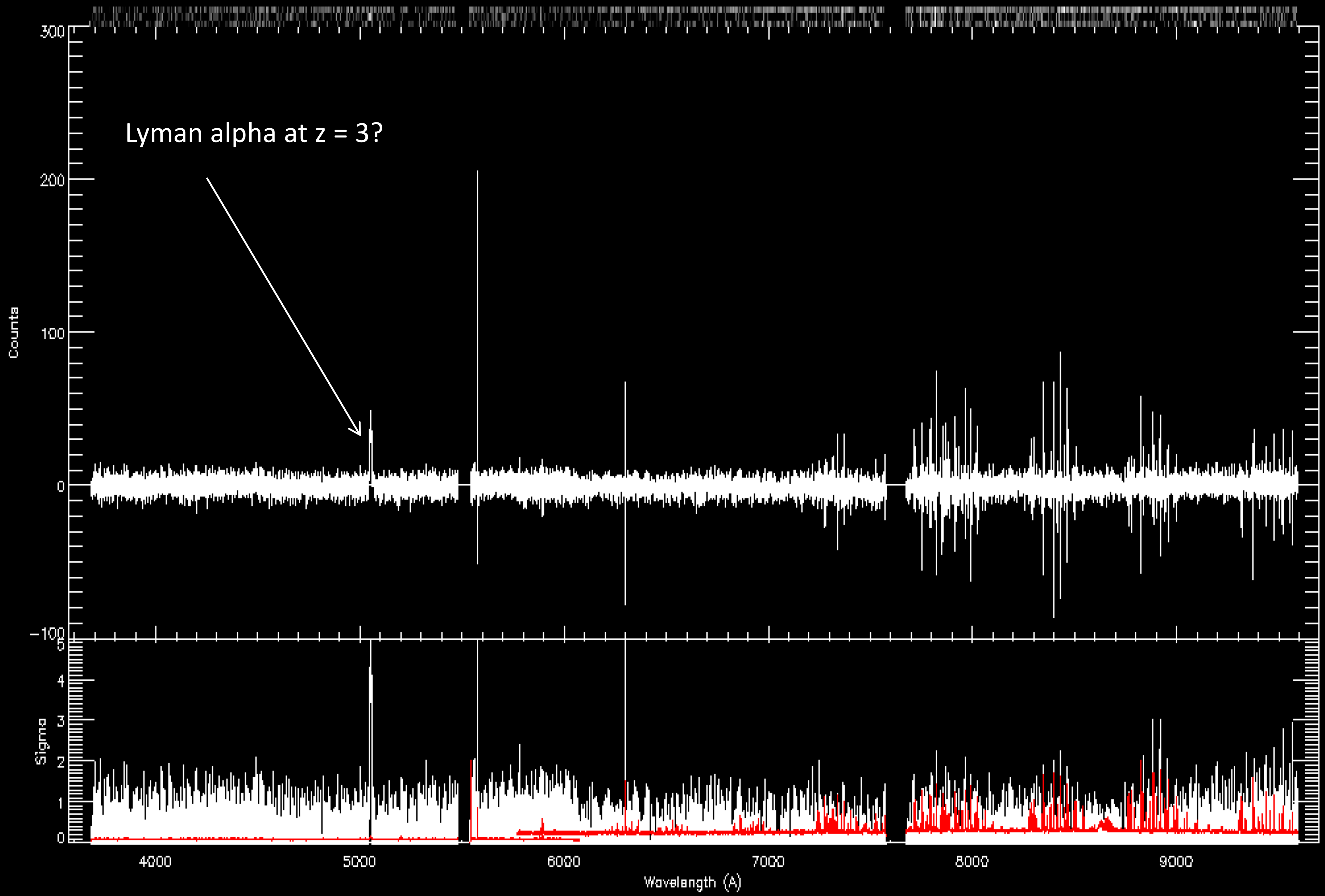
The MOS surveys have three primary science cases:

- Star formation evolution across cosmic history

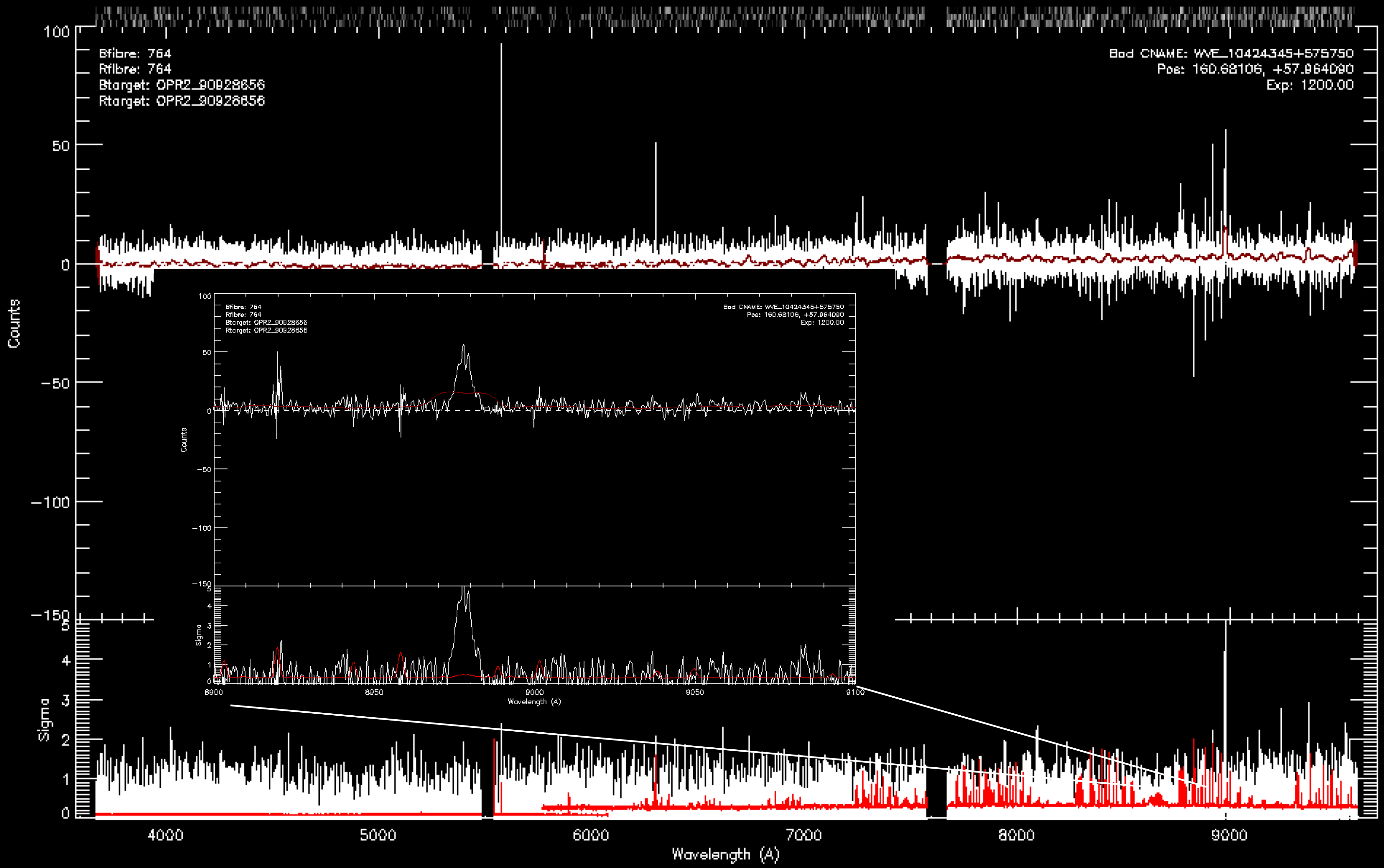
- Black-hole and star formation co-evolution including feedback

- Finding radio galaxies in the Epoch of Reionisation at z > 6 for 21cm absorption experiments

Simulations indicate that we expect to approach 100% redshift success rate at z < 1



Lyman alpha at z = 3?
300
200
100
0
−100
Counts
5
4
3
2
1
0
Sigma
4000
5000
6000
7000
8000
9000
Wavelength (A)



Bfibre: 764
Rfibre: 764
Btarget: OPR2_90928656
Rtarget: OPR2_90928656
Bad CNAME: WVE_10424345+575750
Pos: 160.68106, +57.964090
Exp: 1200.00
Counts
Sigma
Wavelength (A)

Multi-wavelength Extragalactic Astronomy

- Lots of focus on the interplay between AGN, SF and environment as function of z
- Getting to the point of linking galaxy evolution with cosmology
- At high-z we are starting to get a hold on the galaxy LF at z>6
- The bright end appears to the follow the DM halo mass function
- Clustering points to the brightest UV galaxies being the most massive – not just a rare episodic SF event of lower mass galaxies
- Cross-clustering of LBGs and LAEs will provide new information soon
- Need to be careful of contamination of completeness etc