Clustering properties and halo occupation of Lyman-break galaxies at z~4

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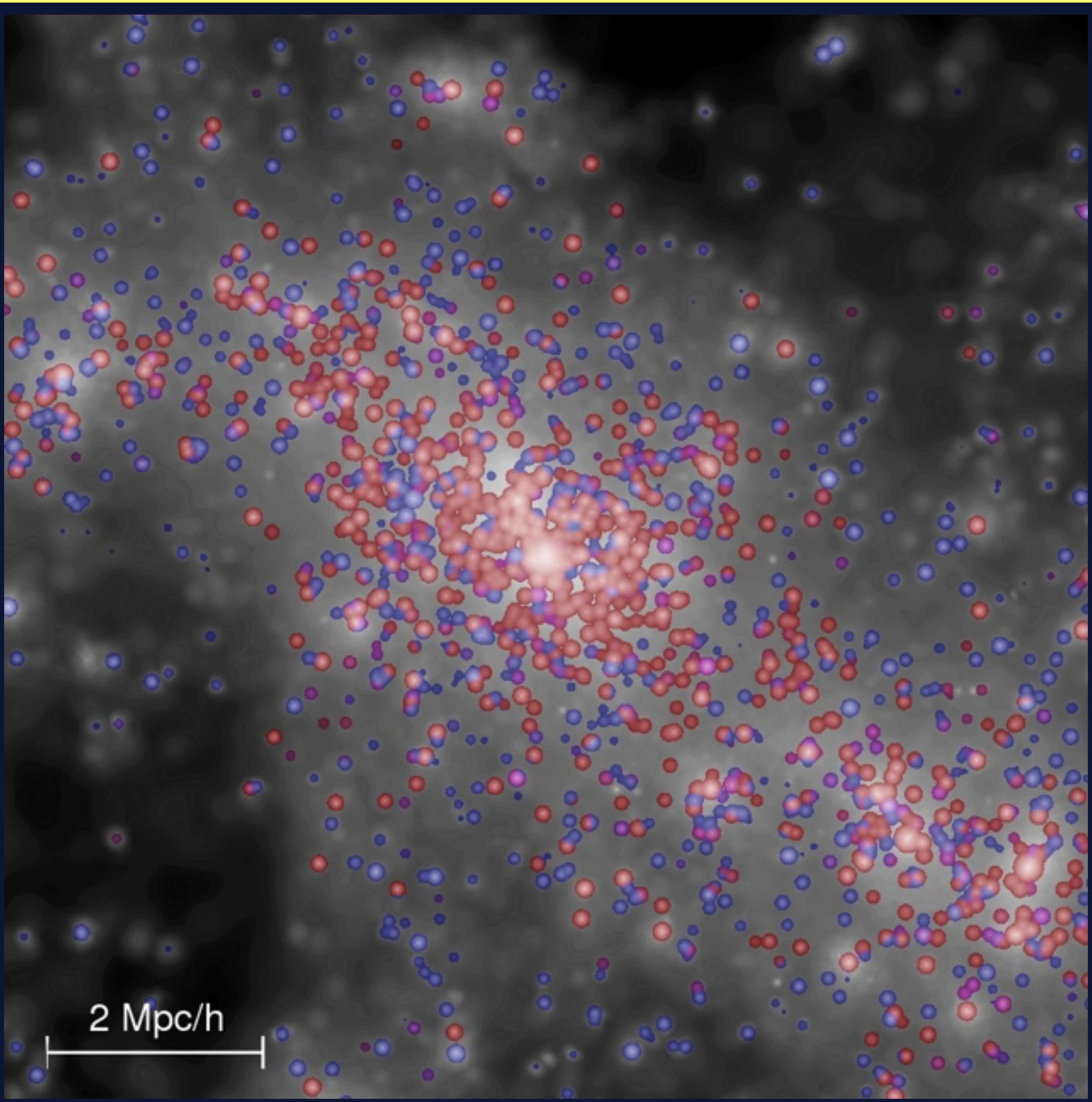
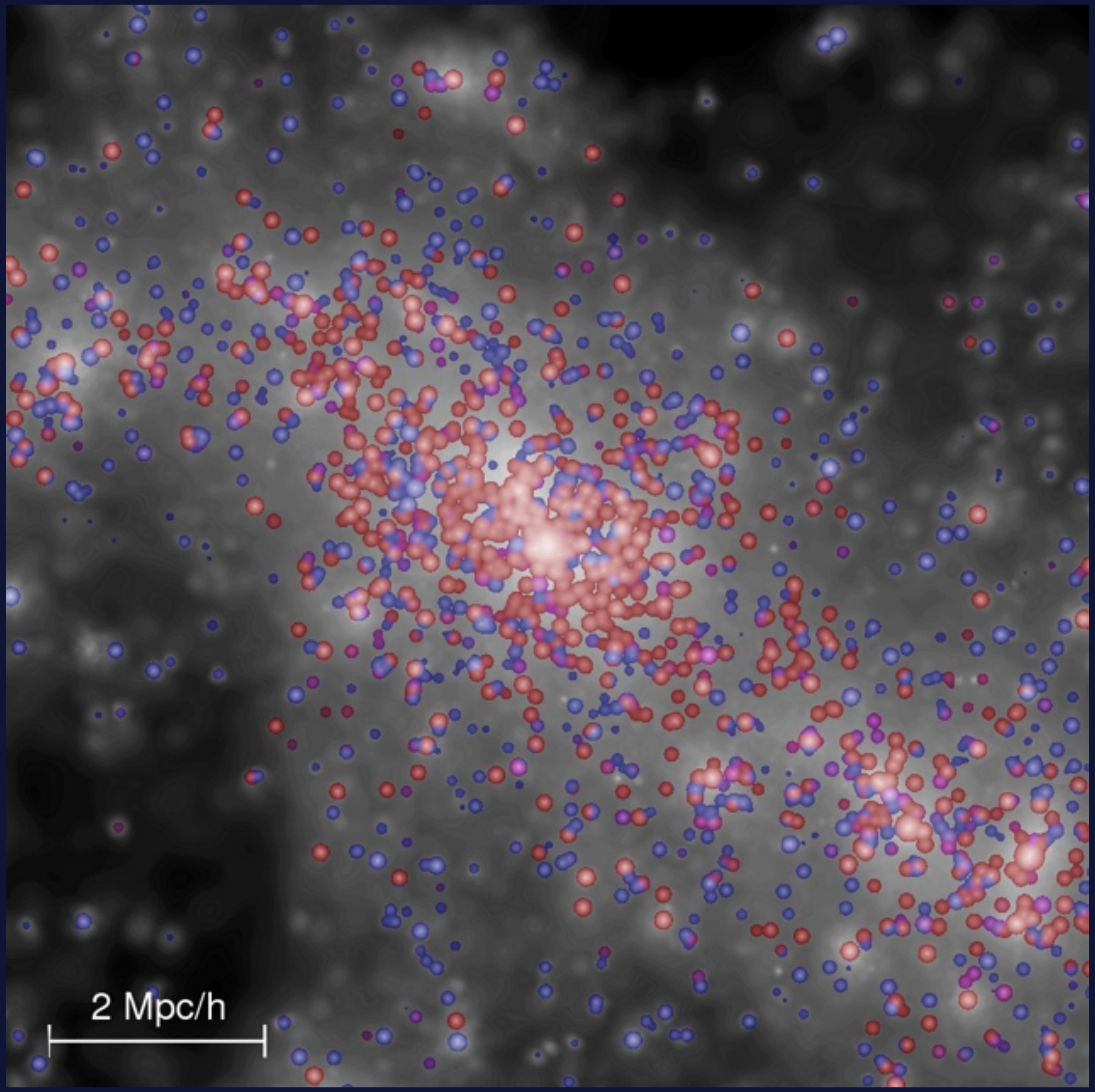
1.1 Clustering



Spingel et al. (2005)

1.1 Clustering

- The formation of dark matter haloes can be successfully described by analytical models and by N-body simulations.



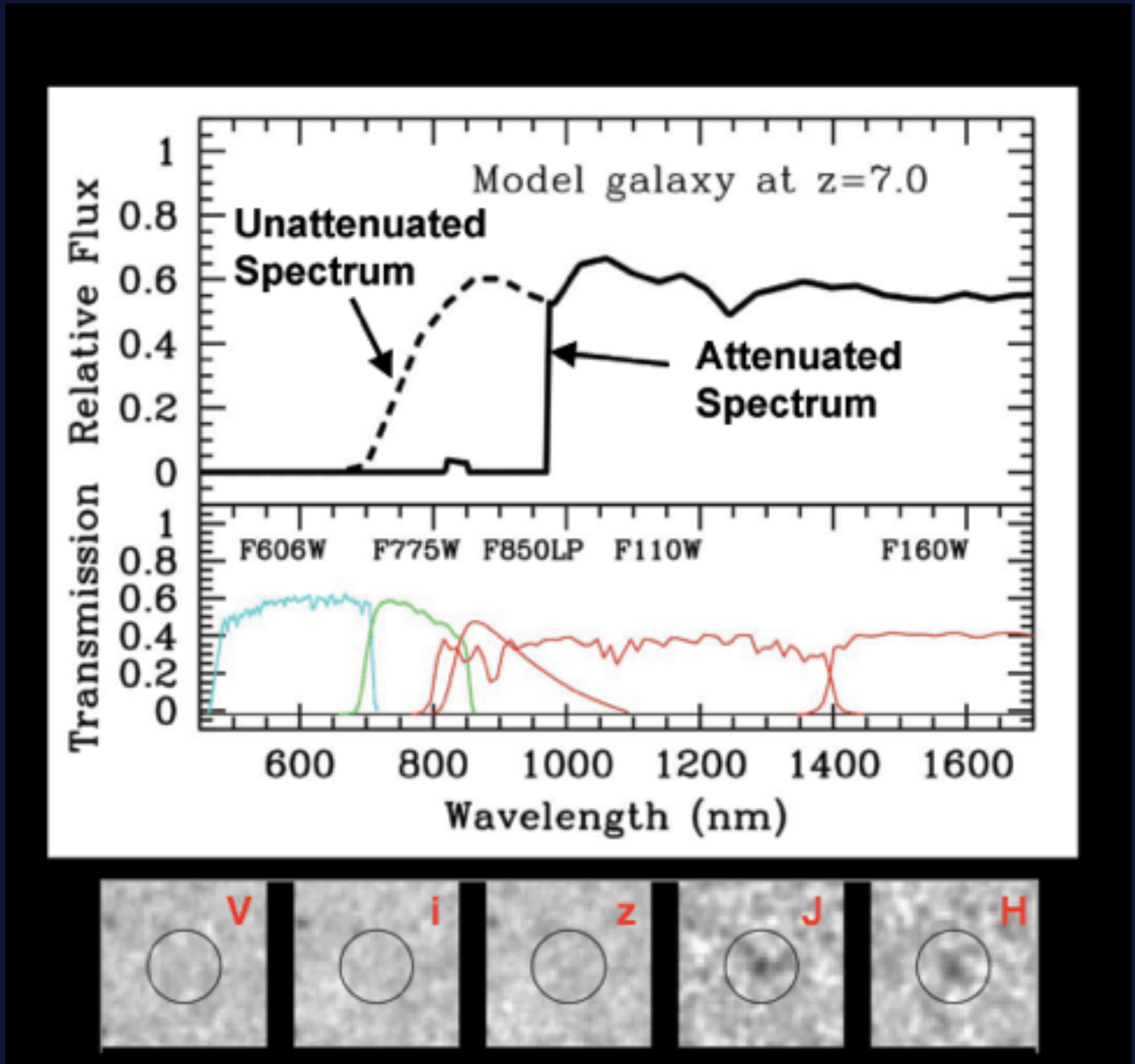
Spingel et al. (2005)

- However, the galaxy formation process itself remains poorly understood.

- One way to investigate the astrophysical connection between dark matter haloes and galaxies is by comparing the clustering in models with the clustering estimated from galaxy observations.

1.2 Lyman-break galaxies (LBGs)

- To investigate high-redshift (z>3) galaxies Lyman-break technique is broadly used.



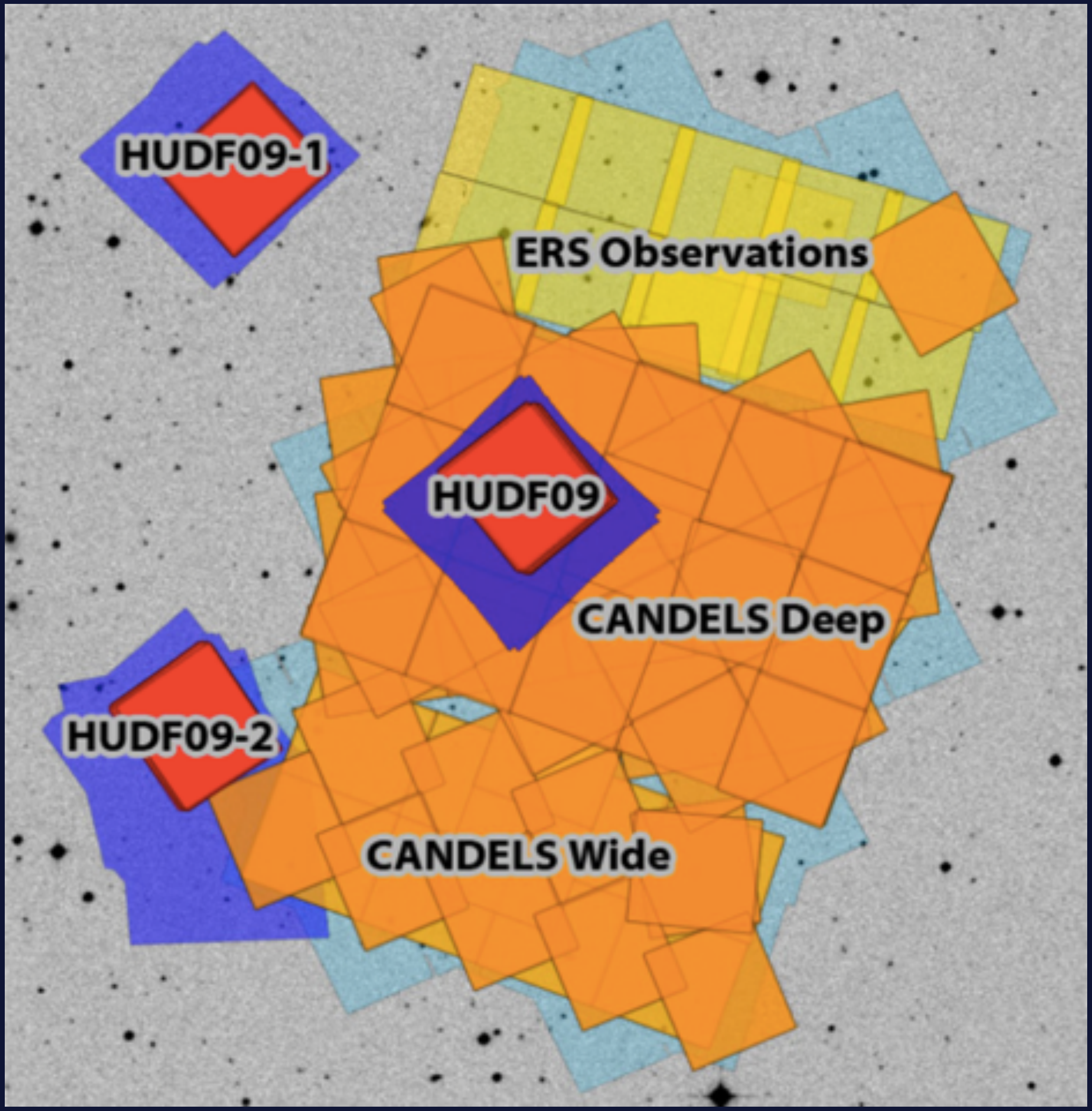
Credits: Rychard Bouwens

- LBGs are star-forming galaxies, detected by the spectral feature formed because rest-frame far UV emission is absorbed (below 912˚A) by neutral hydrogen.

- Since the original work of Steidel et al. (1996) at z ~ 3, researchers have extended this technique to select galaxies up to z ~ 10.

1.2 Lyman-break galaxies (LBGs)

- Recently the number of high-redshift galaxies observed has increased dramatically.



Bouwens et al. (2012)

- Bouwens et al. (2014) identified LBGs up to z ~ 10 in combined survey fields consisting of the Hubble eXtreme Deep Field (XDF) and CANDELS fields, which are the deepest existing surveys.

- Barone-Nugent et al. (2014) studied clustering properties using Bouwens' samples by measuring the angular correlation function (ACF).

2. Galaxy formation model

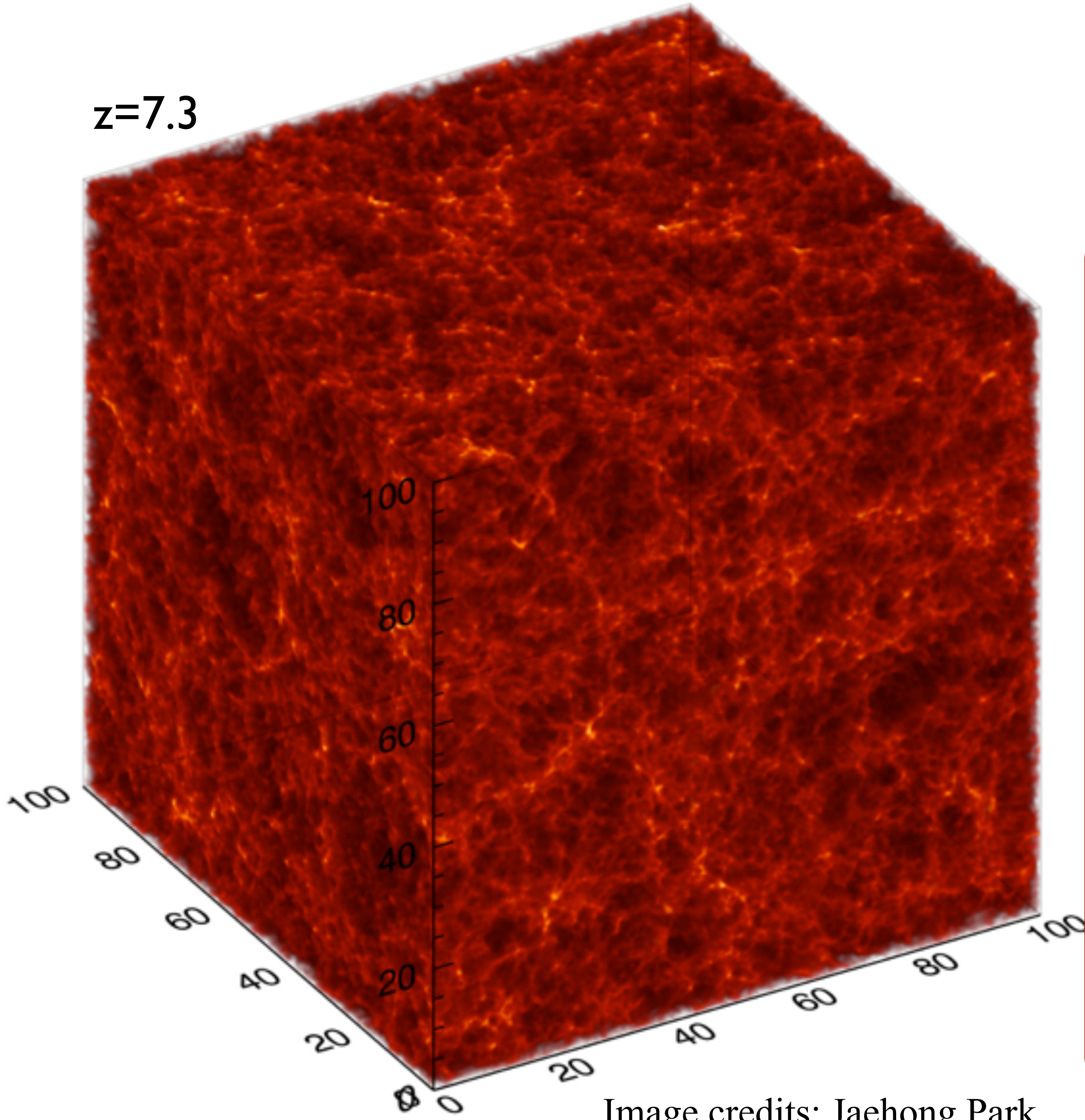


Image credits: Jaehong Park

Semi-analytical model (GALFORM)

Lagos et al. (2012)

Dark Matter Simulation:
MILLENNIUM-II
$100^3\ h^{-3}\mathrm{Mpc}^3$ box size

+

Galaxy formation physics:

- the growth of galactic discs
- star formation in galactic discs
- feedback processes
- chemical evolution of stars
- …

2. Galaxy formation model

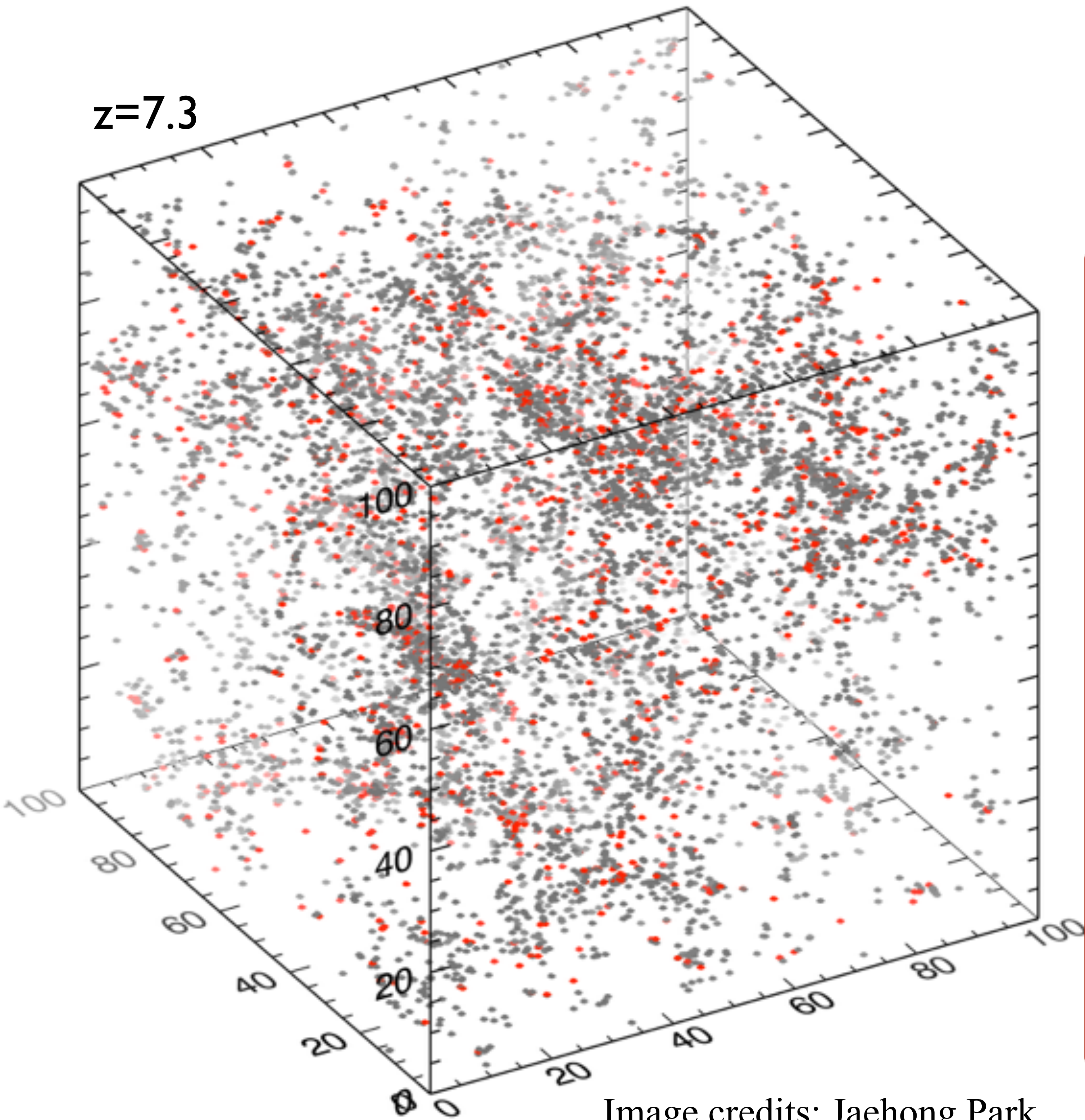


Image credits: Jaehong Park

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Galaxy formation physics:

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- …

2.1 Selecting LBGs

- We select LBGs using the colour selection criteria described in Bouwens et al. (2014)

$$(B_{435} - V_{606} > 1) \wedge (i_{775} - J_{125} < 1) \wedge (B_{435} - V_{606} > 1.6(i_{775} - J_{125}) + 1)$$

- We also consider observational flux limits for model galaxies.

Field	Area (arcmin^2)	CFHT+ Subaru	5σ Depth[a]							
			B_{435}	V_{606}	i_{775}	I_{814}	z_{850}	Y_{098}/Y_{105}	J_{125}	JH_{140}	H_{160}
XDF[b]	4.7	—	29.8[c]	30.3[c]	30.3[c]	29.1	29.4[c]	30.3	29.8	29.8	29.8
HUDF09-1	4.7	—	—	29.0	29.0	—	29.0	29.0	29.3	26.7[d]	29.1
HUDF09-2	4.7	—	28.8	29.9	29.3	29.8	29.2	29.2	29.5	26.7[d]	29.3
CANDELS-S/Deep	64.5	—	28.2	28.5	28.0	28.8	28.0	28.5	28.6	26.7[d]	28.4
CANDELS-S/Wide	34.2	—	28.2	28.5	28.0	28.1	28.0	28.0	28.0	26.7[d]	27.7
ERS	40.5	—	28.2	28.5	28.0	28.0	28.0	27.9	28.4	26.7[d]	28.1
CANDELS-N/Deep	62.9	—	28.2	28.5	28.0	28.8	28.0	28.5	28.6	26.7[d]	28.4
CANDELS-N/Wide	60.9	—	28.2	28.5	28.0	28.0	28.0	28.0	27.6	26.7[d]	27.6
CANDELS-UDS	151.2	28.9[e]	—	28.0	—	28.0	—	—	27.3	26.7[d]	27.5
CANDELS-COSMOS	151.9	29.2[e]	—	27.8	—	27.9	—	—	27.3	26.7[d]	27.5
CANDELS-EGS	150.7	28.7[e]	—	28.5	—	28.5	—	—	27.5	26.7[d]	27.7
BORG/HIPPIES[f]	218.3	—	—	27.0-28.7	—	—	—	26.5-28.2	26.5-28.4	—	26.3-28.1

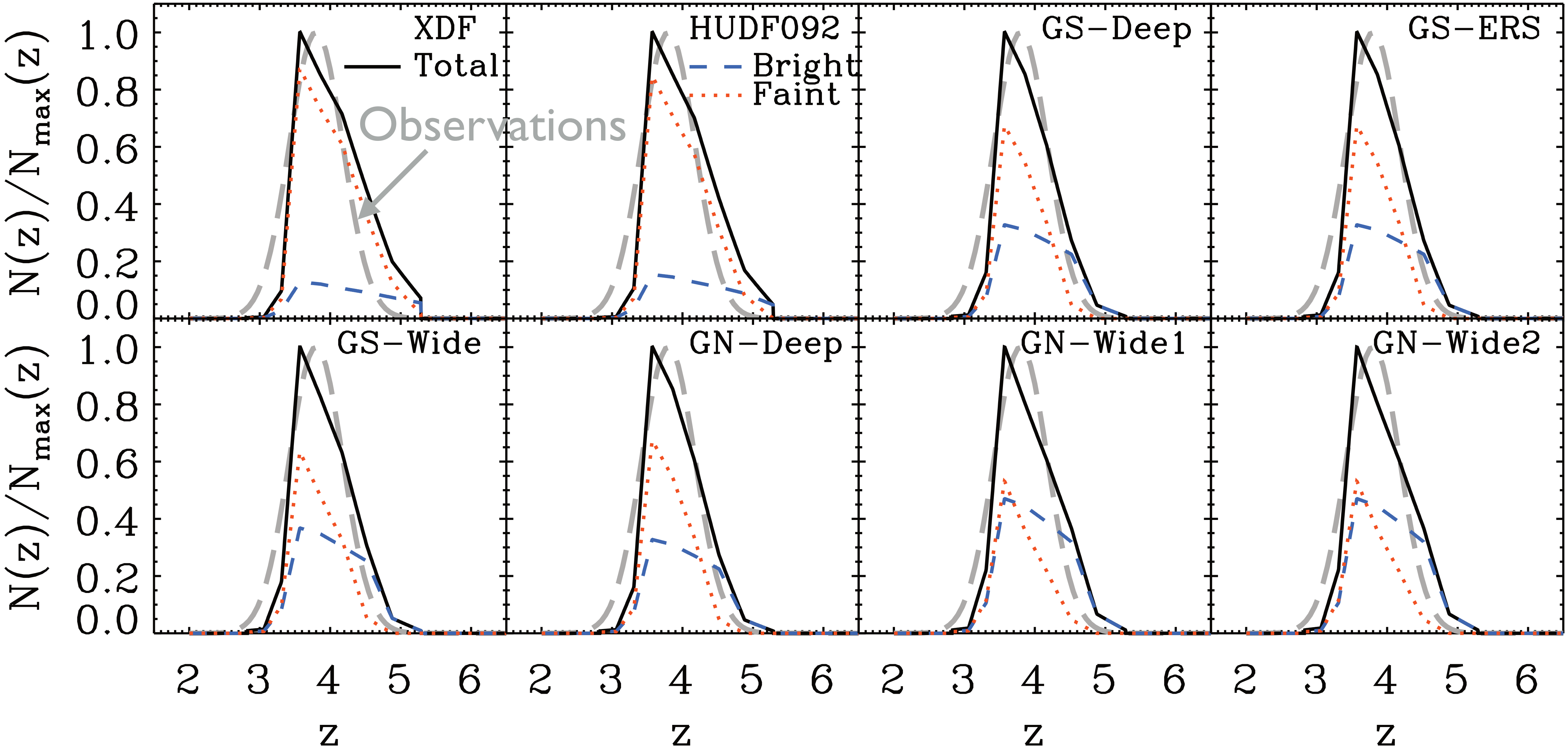
Bouwnes et al. (2014)

- We apply the colour selection criteria to galaxy catalogues in sequential snapshots from z=2.83 to 5.29.

2.1 Selecting LBGs

- Redshift distribution

Park et al. (in preparation)



The predicted redshift distributions from the model are comparable with observations.

3.1 Angular Correlation Function (ACF)

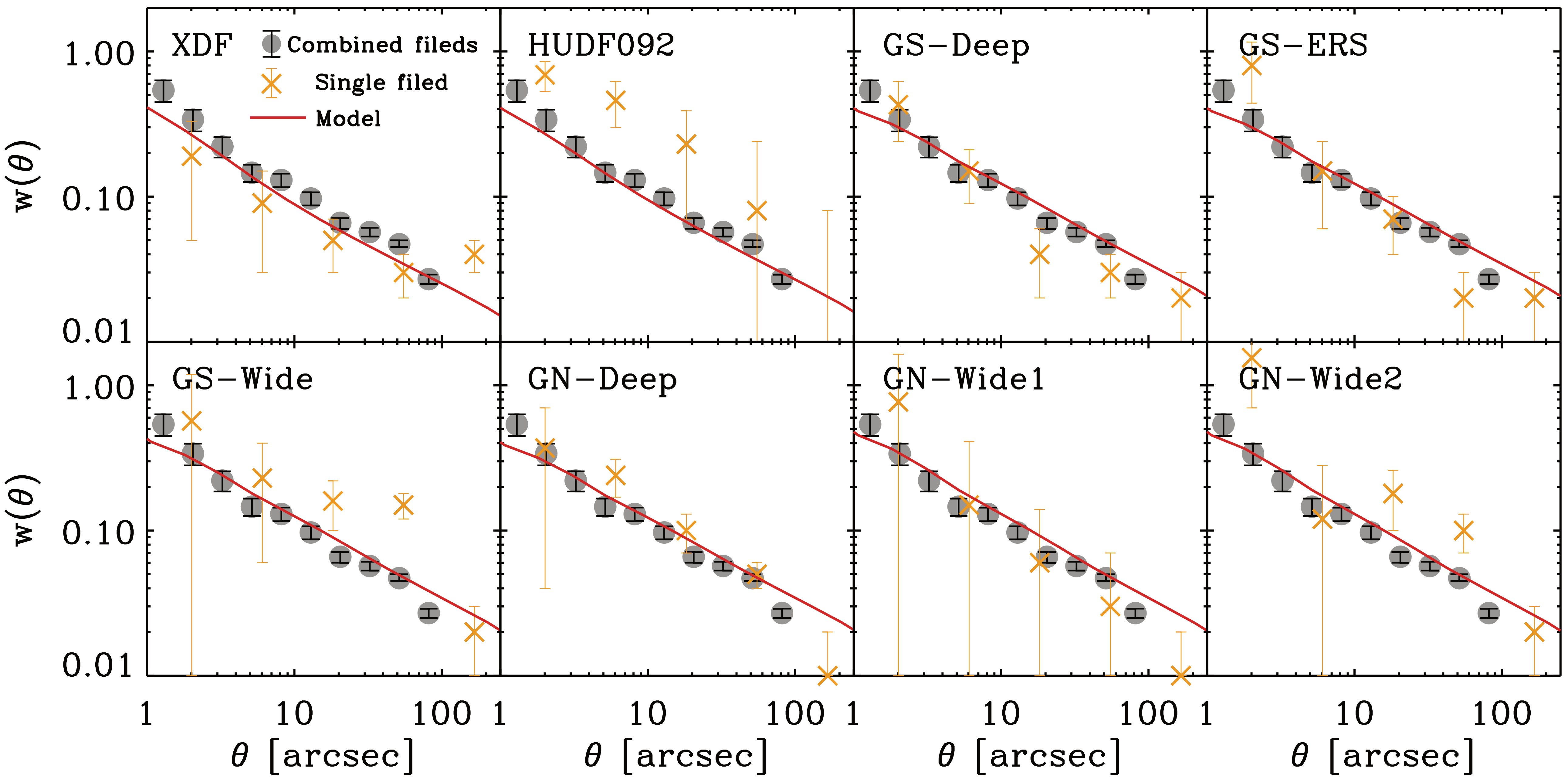
- Angular correlation function (ACF) provides information of clustering by measuring excess probabilities of galaxy pairs compared with a random distribution as a function of angular separations.

The Limber's equation (Limber 1954) relates the real space correlation function, $\xi(r)$.

$$w(\theta) = \frac{2\int_0^\infty [N(z)]^2 / R_{\mathrm{H}}(z) \left(\int_0^{2r} \mathrm{d}u\, \xi(r_{12}, z)\right) \mathrm{d}z}{\left[\int_0^\infty N(z)\mathrm{d}z\right]^2}$$

where $N(z)$ is the redshift distribution of selected galaxies and $R_{\mathrm{H}}(z)$ is the hubble radius. For comoving distances r_1 and r_2 of a pair of galaxies, we denote $u = r_1 - r_2$, $r_{12} = \sqrt{u^2 + r^2\theta^2}$ and $r = \frac{r_1+r_2}{2}$.

3.1 ACF

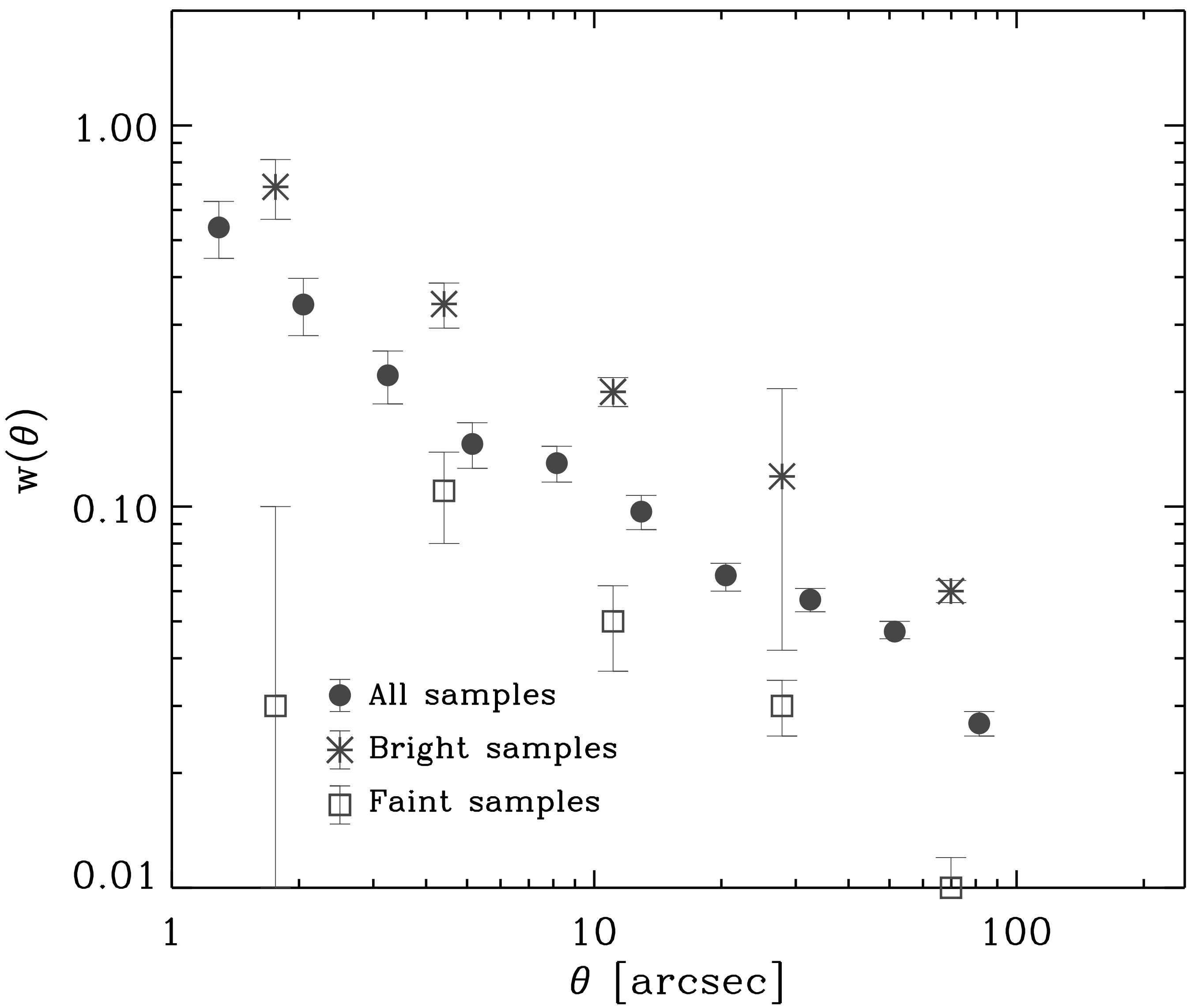


Park et al. (in preparation)

Overall, the predicted ACFs are in good agreement with both the measured ACFs and the combined ACF.

3.1 ACF

- Clustering depend on luminosity.



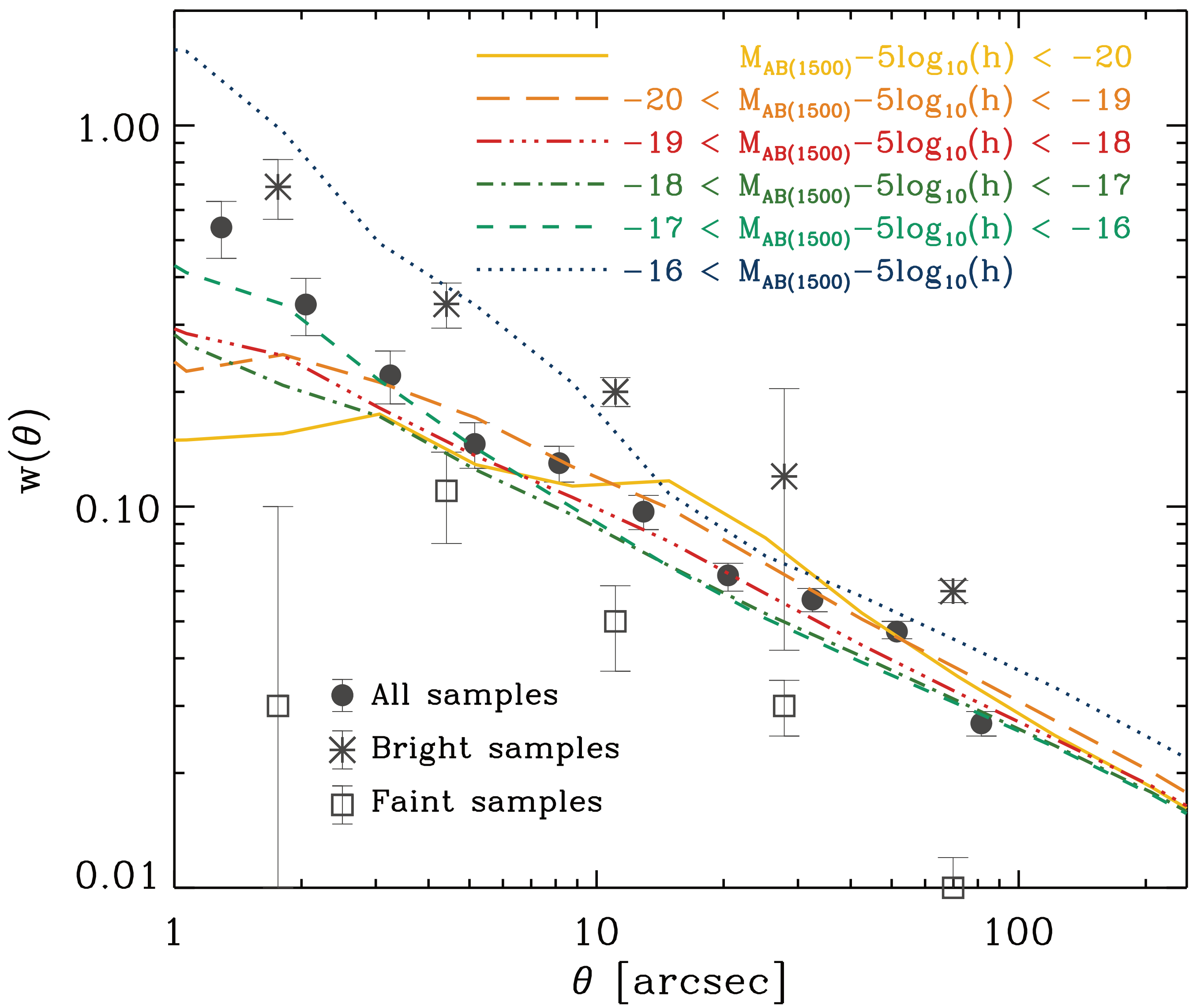
Park et al. (in preparation)

- Clustering strength is known to depend on luminosity

- Barone-Nugent et al. (2014) split sample into bright and faint subsamples at $M_{AB}(1500) - 5\log(h) \sim -18.5$.

3.1 ACF

- Clustering depend on luminosity.



Park et al. (in preparation)

- Clustering strength is known to depend on luminosity

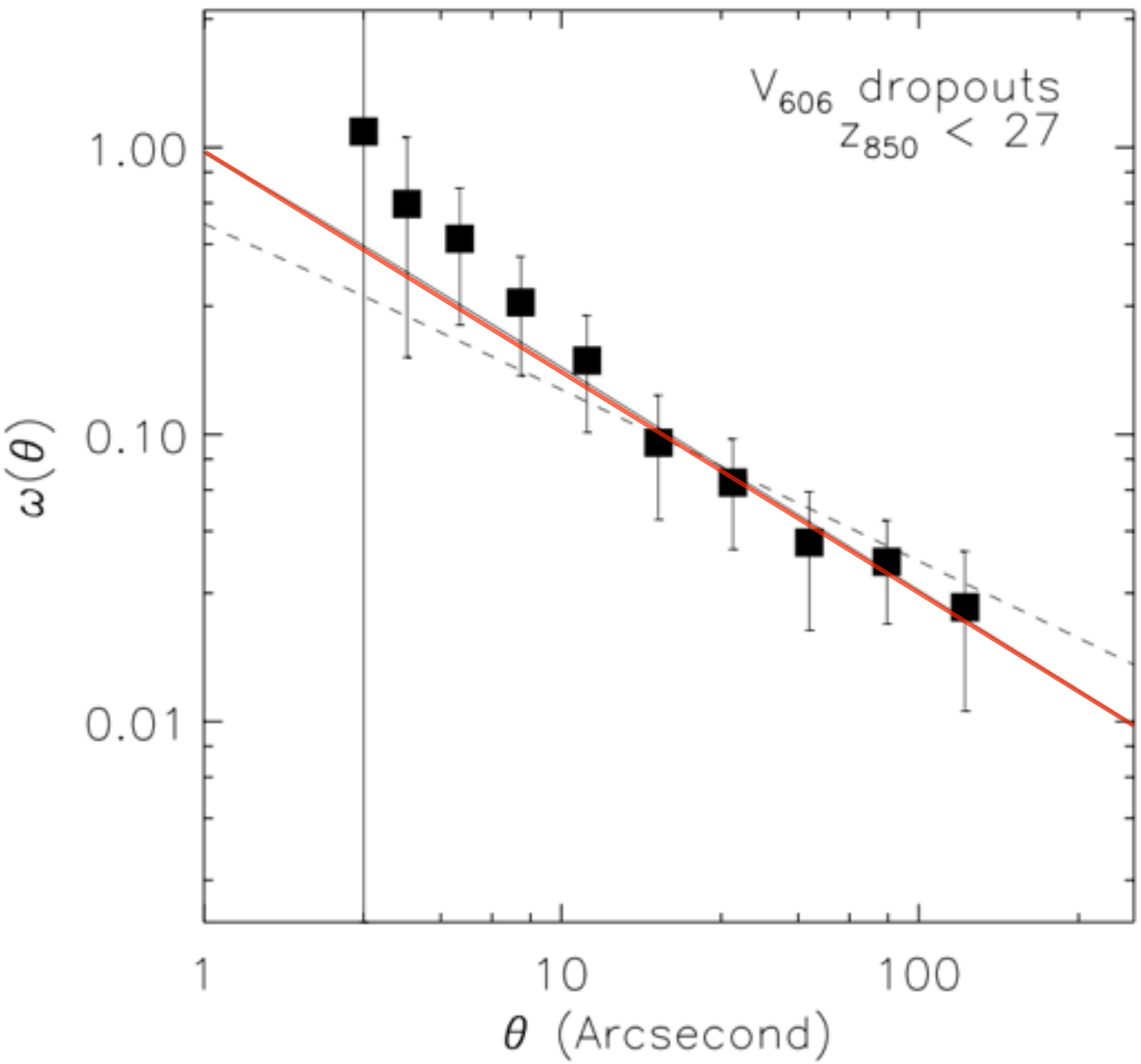
- Barone-Nugent et al. (2014) split sample into bright and faint subsamples at $M_{AB}(1500) - 5\log(h) \sim -18.5$.

- We divide the model LBGs into six magnitude bins considering the flux limits for XDF.

Generally, brighter model LBGs have a higher clustering amplitude than fainter ones.

3.1 ACF

- Enhanced clustering amplitude on small scales



Lee et al. (2006)

- On large scales the observed ACFs can be approximated by a power-law parameterisation.

The angular correlation amplitude

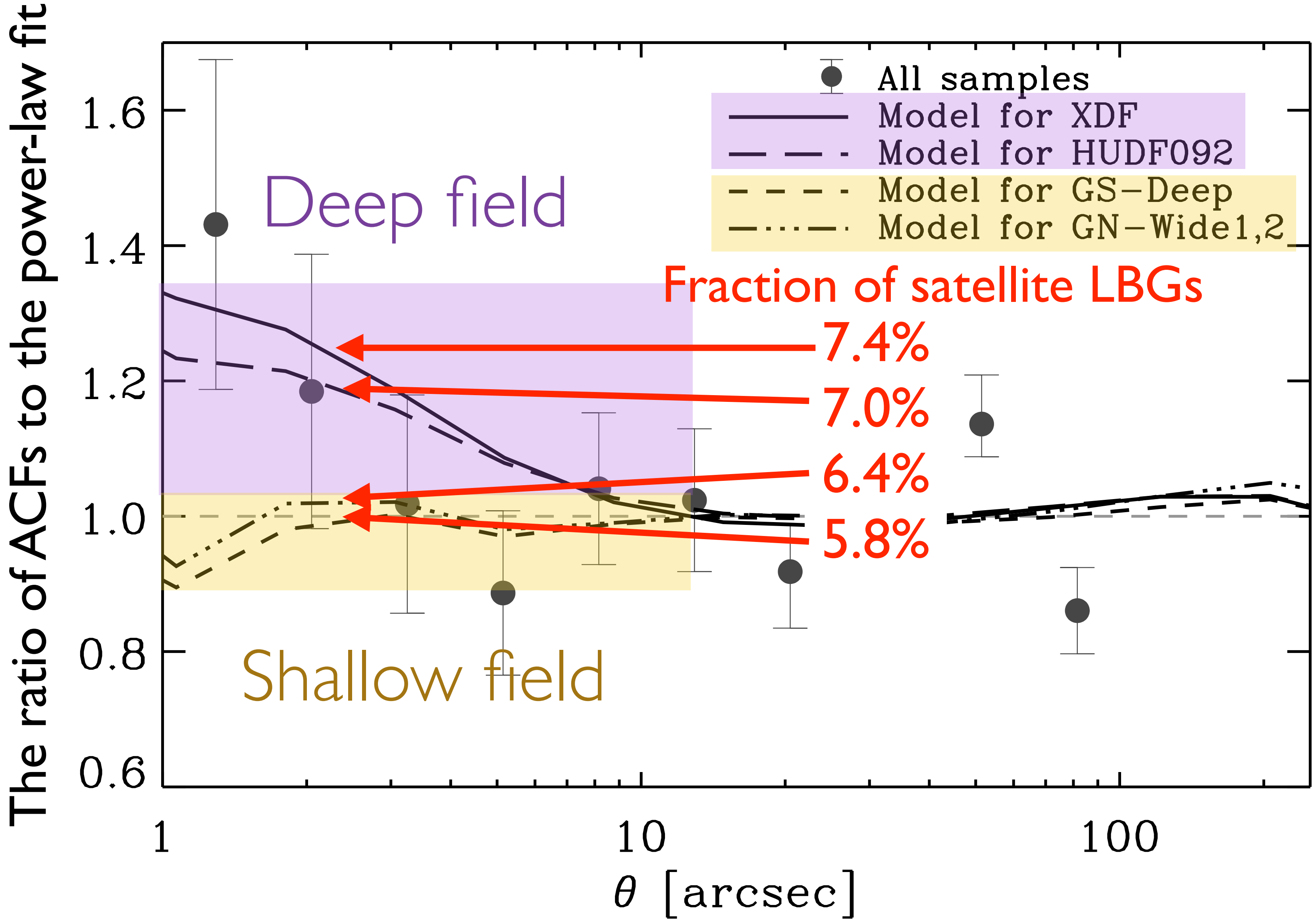
$$w(\theta) = A_w \theta^{-\beta}$$

The correlation slope

- However, the measured ACFs have shown an enhanced clustering amplitude on small scales.

3.1 ACF

- Enhanced clustering amplitude on small scales



Park et al. (in preparation)

- The measured ACF also shows an enhanced clustering amplitude on small scales.

- **The predicted ACFs for deep fields show more enhanced clustering amplitude on small scale.**

The fraction of satellite LBGs is important for determining the amplitude of ACF at small scales.

3.2 Halo occupation distribution (HOD)

- Halo occupation distribution describes the average numbers of galaxies as a function of a host halo mass.

- A simple parametric form for the average number of galaxies is

$$\langle N \rangle_M = \begin{cases} (M/M_1)^{\alpha} & \text{for } M > M_{\rm min}, \\ 0 & \text{otherwise,} \end{cases}$$

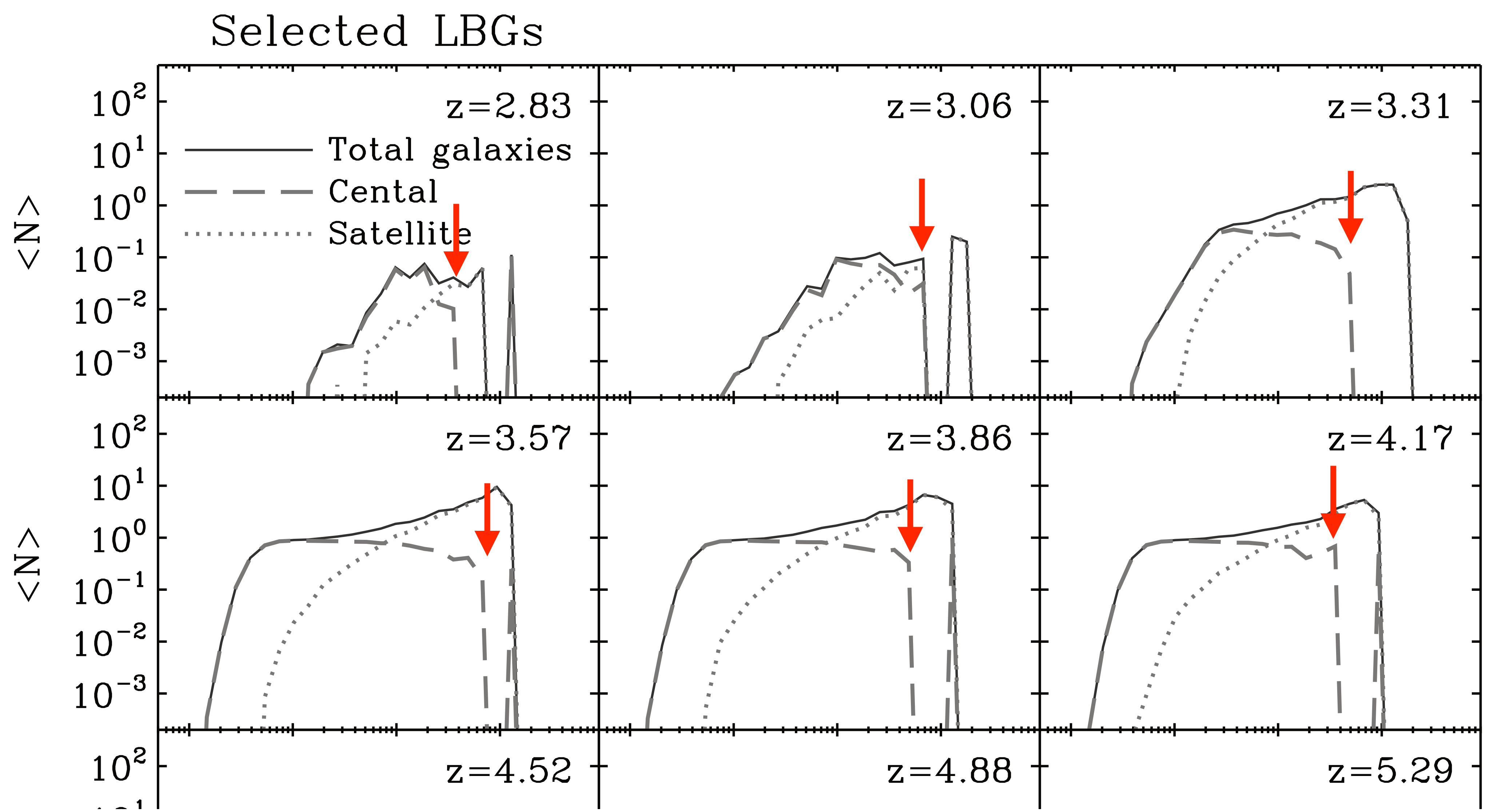
M_1: the typical halo mass at which there is one galaxy on average.

$M_{\rm min}$: the minimum mass of haloes that host galaxies

α : the power-law slope which is related to the abundance of satellite galaxies.

- HOD is a useful way to understand the connection between dark matter halo and galaxy by comparing a correlation function between observation and the HOD modelling.

3.2 Halo occupation distribution (HOD)



This sudden drop could be caused by AGN feedback since AGN feedback suppresses star formation in high-mass haloes.

Central galaxies in massive halo are not always LBGs. This is in contrast to the HODs interpreted from observations.

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4. Summary

* We predict the angular correlation function (ACF) of Lyman-break galaxies and compare with the measured ACF from observations.
  - The predicted ACFs are in good agreement with the measured ACFs and also increase with galaxy luminosity as observed.
  - We show that the fraction of satellite LBGs is important for determining the amplitude of ACF at small scales.

* We show the halo occupation distribution (HOD) of model LBGs.
  - We find that the average number of central LBGs in the model drops sharply in massive haloes.
  - We interpret this sudden drop could be caused by AGN feedback, which is in contrast with observational HOD models for high-redshift.

Thank you.