UNIVERSIDAD DE ANTIOQUIA
1803

Sterrewacht Leiden

The large-scale structure of the Universe

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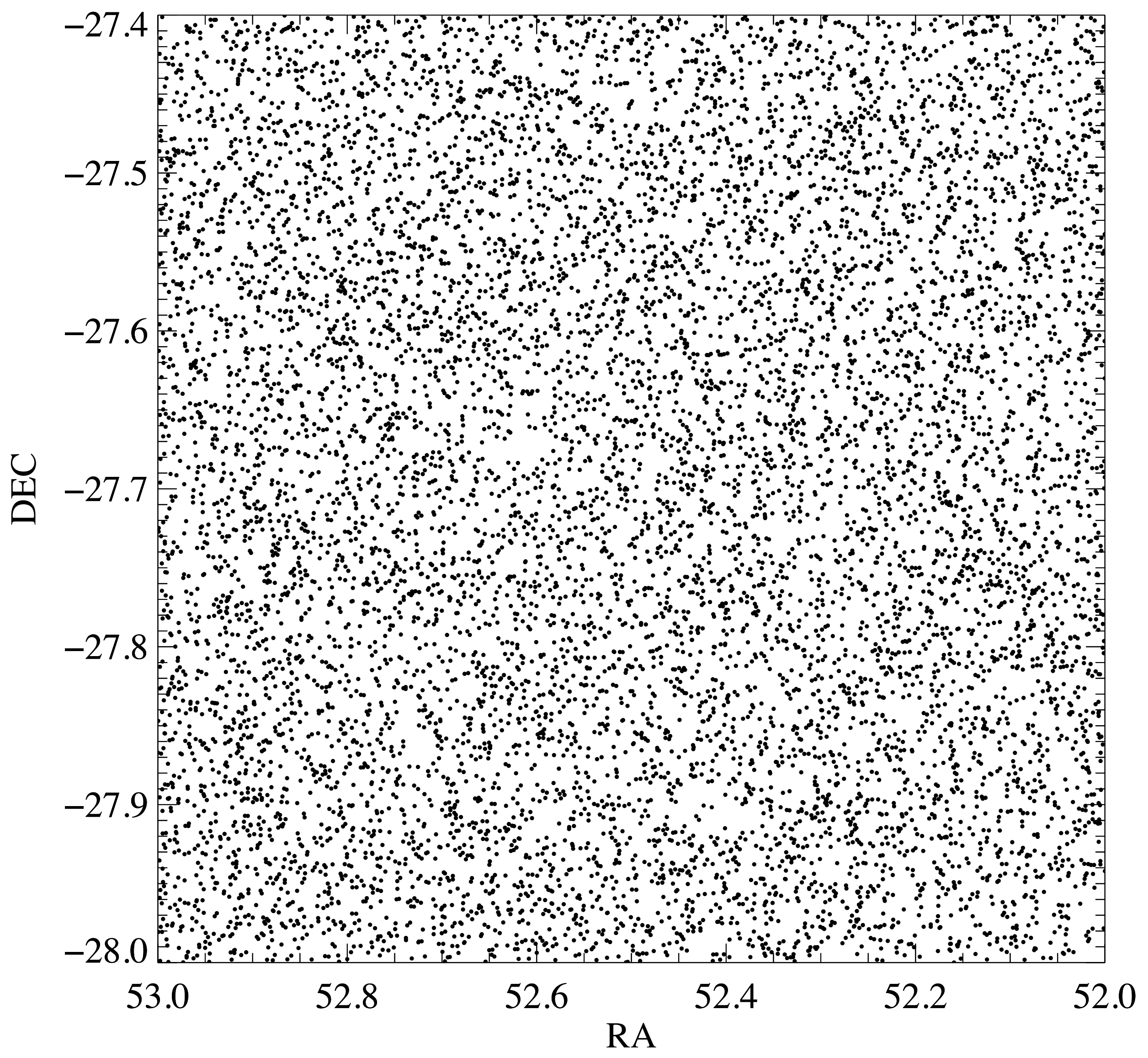
AstroTwinCoLo (Virtual) School 2020

Previous class: The two-point correlation function

The two-point correlation function ξ(r) is defined as a measure of the excess probability dP, over a random occurrence of finding a galaxy in a volume element dV at a separation r from another galaxy.

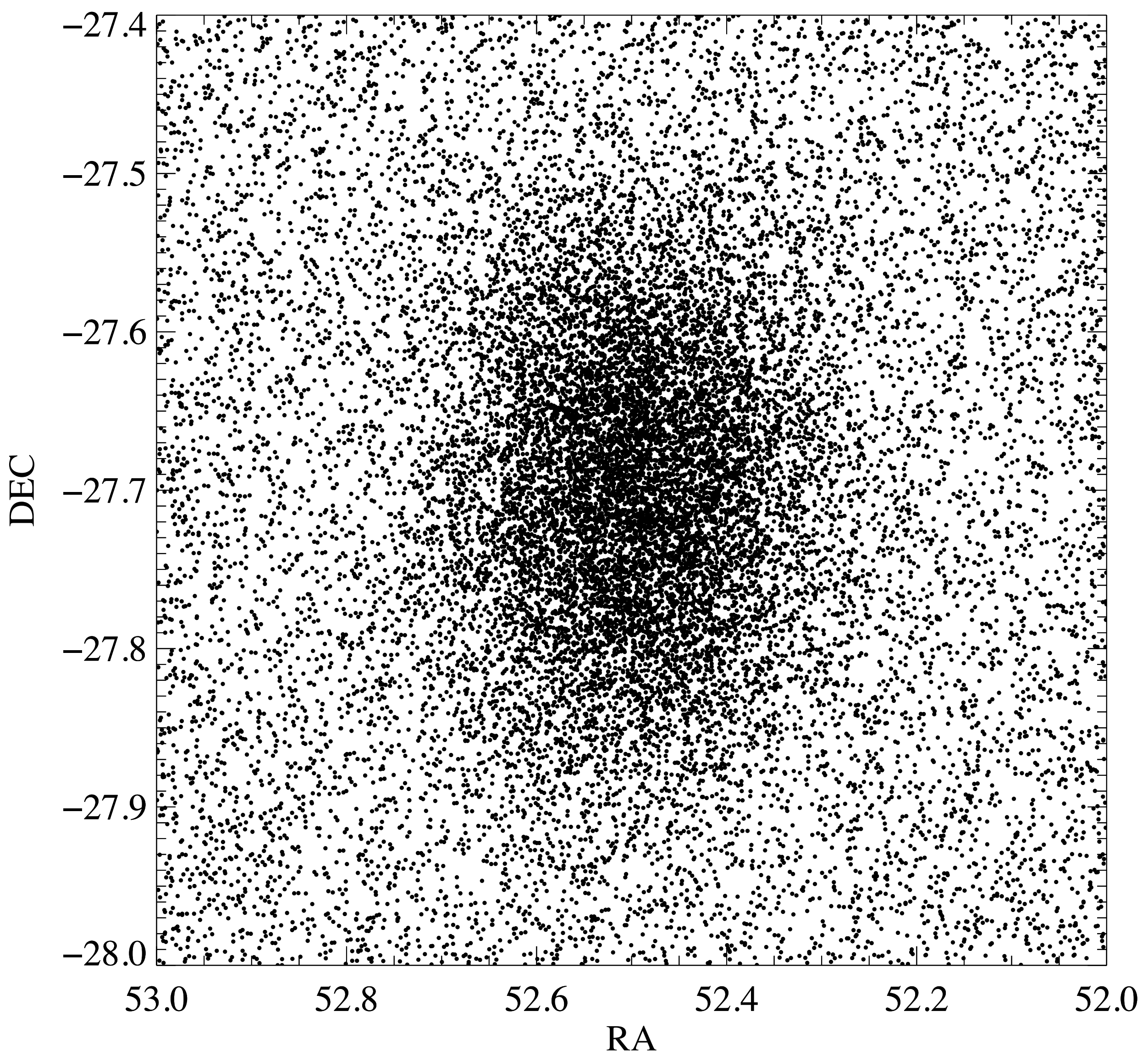
$$dP = \bar{n}[1 + \xi(r)]\mathrm{dV}$$

where n is the mean number density of the galaxy sample in question.



In a random distribution, the probability to find a galaxy in one place or another, is independent. Their positions are not correlated.

$$dP = \bar{n}\mathrm{dV}$$



In a strongly clustered population, if you find a galaxy it is highly probable that you find another galaxy close to it.

$$dP = \bar{n}[1 + \xi(r)]\mathrm{dV}$$

- The two-point correlation function traces the amplitude of clustering as a function of physical scale (clustering depends on scale!)

Previous class: The two-point correlation function

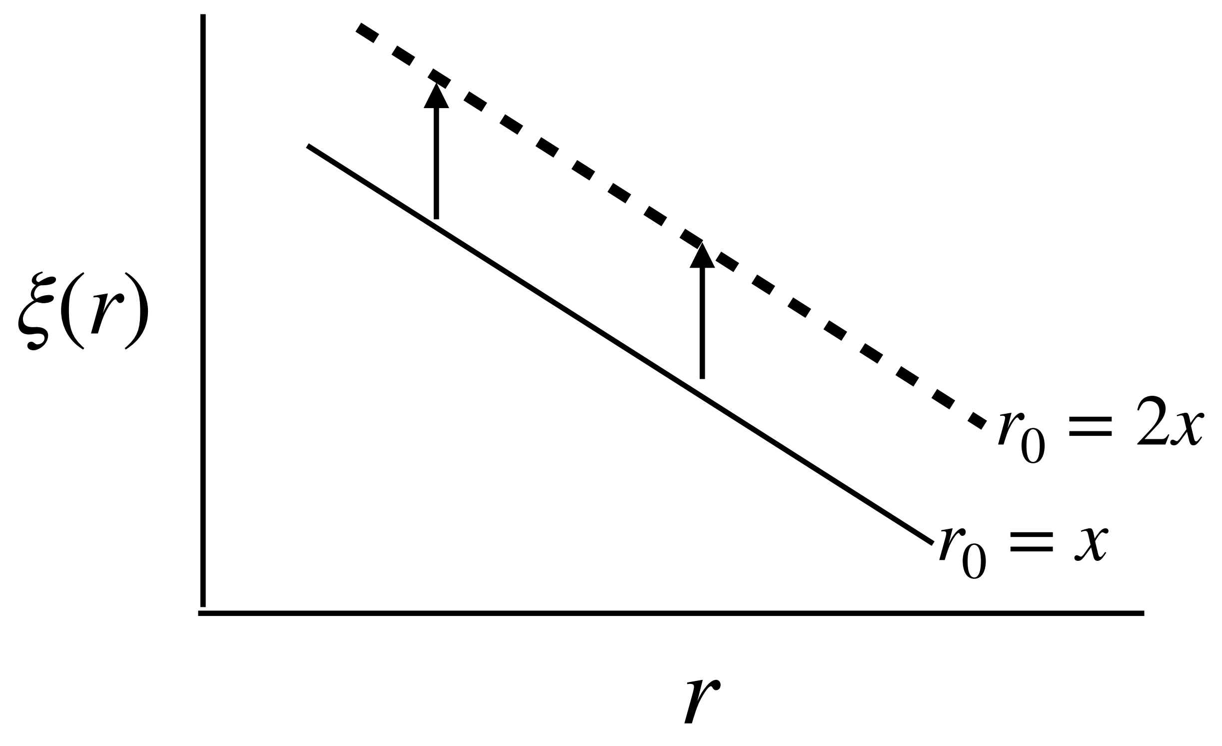
Observations indicate that ξ(r) is well described by a power-law:

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

r_0 correlation length
γ slope (typically 1.8)

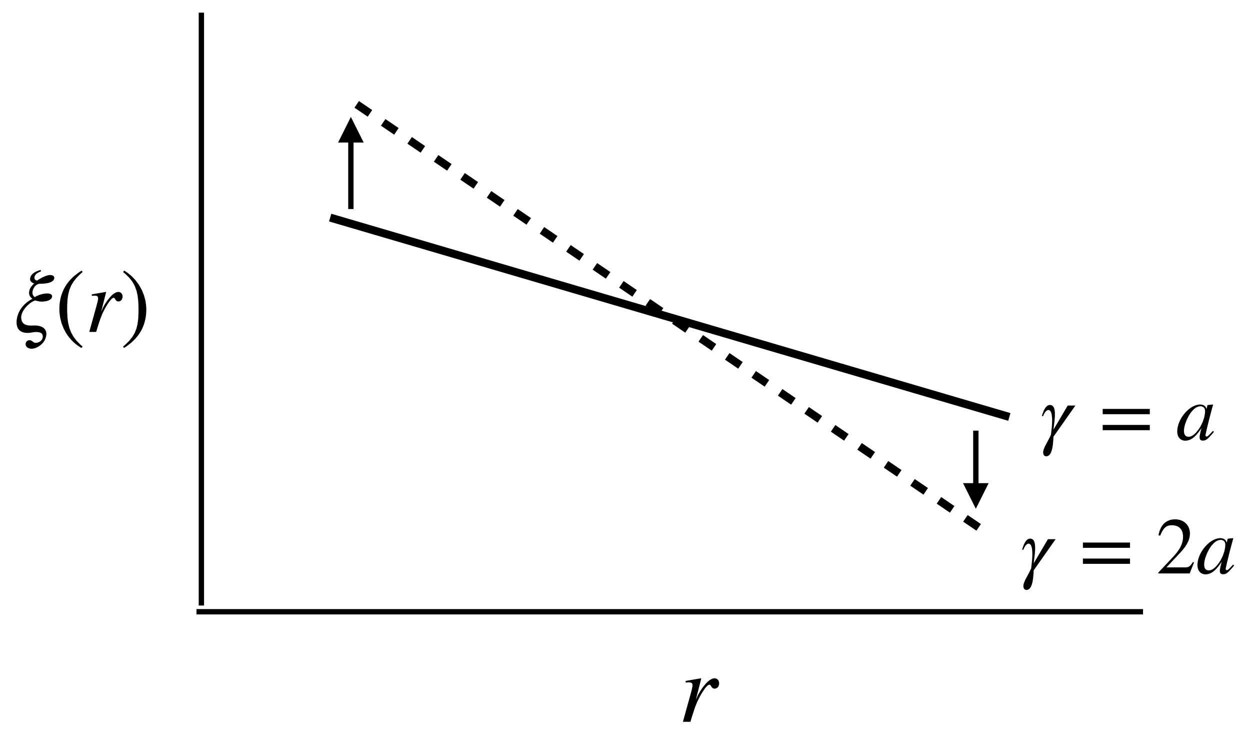
→ Strong clustering at small scales and weak clustering at large scales.

Effect of the correlation length:



Higher clustering implies a higher ξ(r) and therefore a higher r_0

Effect of the slope:



- To measure it we counts pairs of galaxies as a function of separation and divides by what is expected for an unclustered distribution.

Previous class: The two-point correlation function

If you have
2D positions

↓

Angular correlation function $\omega(\theta)$

(Integrated over all the redshift space)

↓

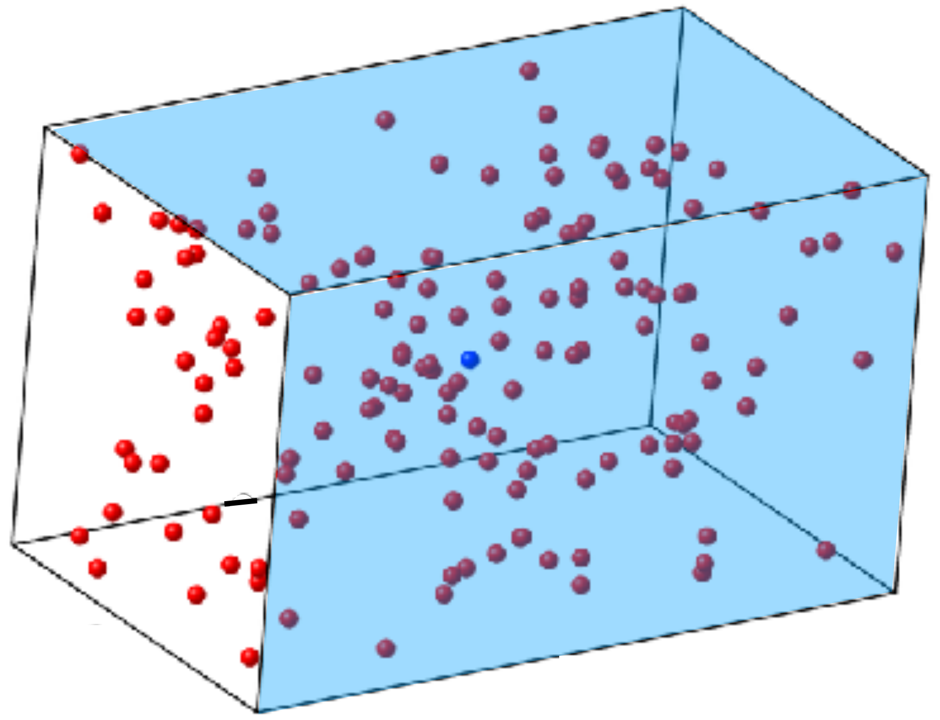
Fit the measurement to get A and β

↓

Assumptions about the z distribution

↓

Get r_0, γ



If you have
3D positions

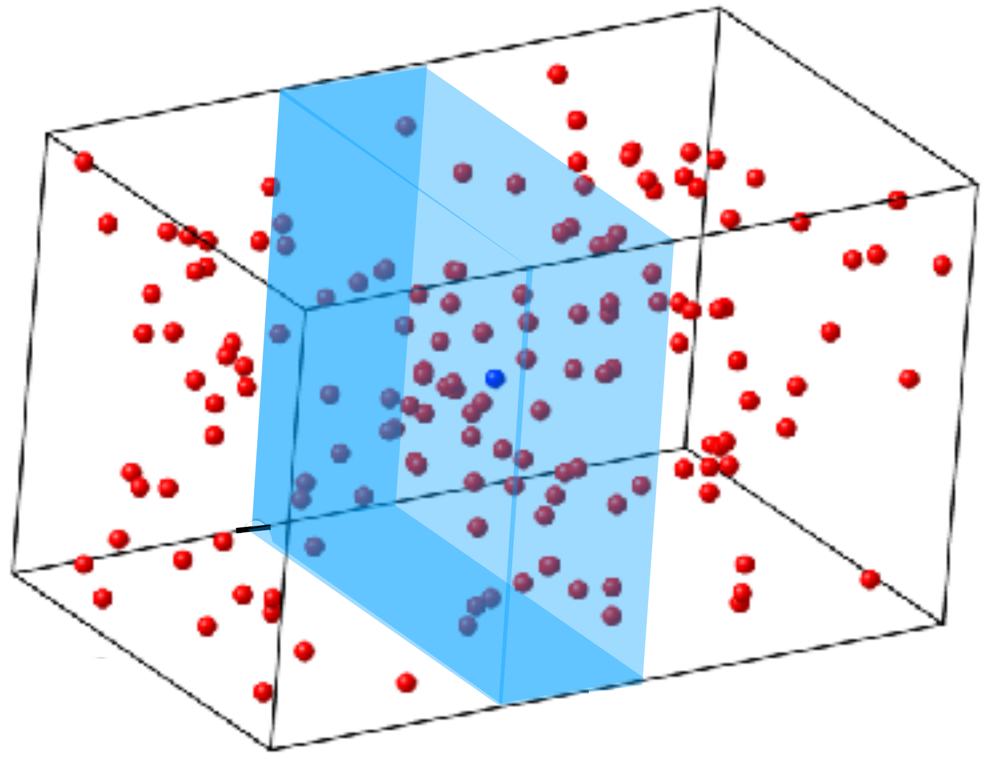
↓

Projected correlation function $\omega(R)$

(Integrated over a narrow redshift space)

↓

Fit the measurement to get r_0, γ



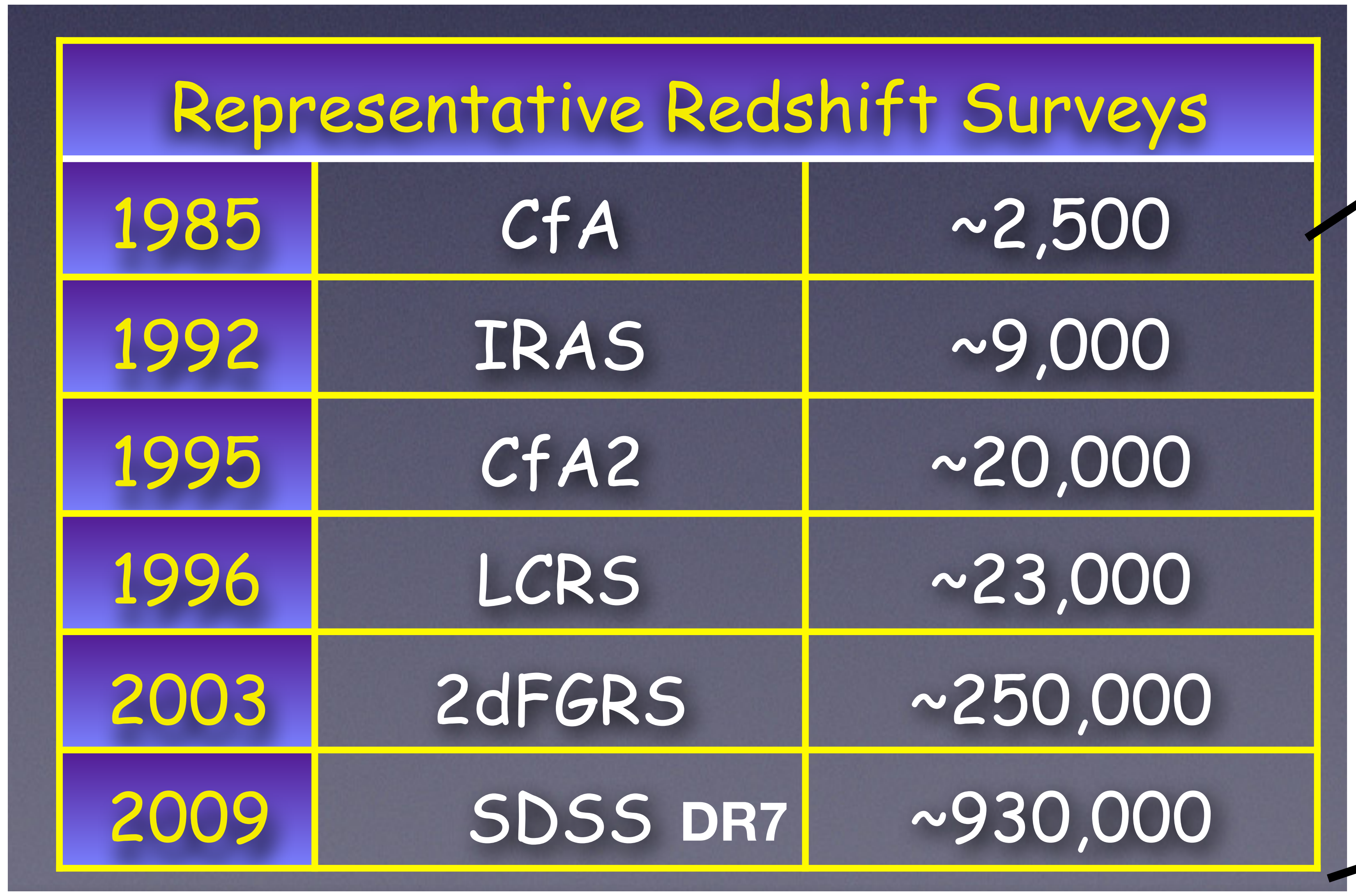
This class: Observational constraints of the clustering of different populations

- Large surveys are required to measure the correlation function.
- Review of current observational results and clustering measurements (in multiwavelenght).
- State of the art: What has been done so far?
- The dependence of clustering on galaxy properties.

Galaxy redshift surveys (in optical wavelengths)

- Although 2D positions can be used to compute clustering, redshift information is crucial for a more precise measurement.
- Large efforts have been done to obtain galaxy catalogs that include redshift information.
- Most of the work at optical wavelengths.

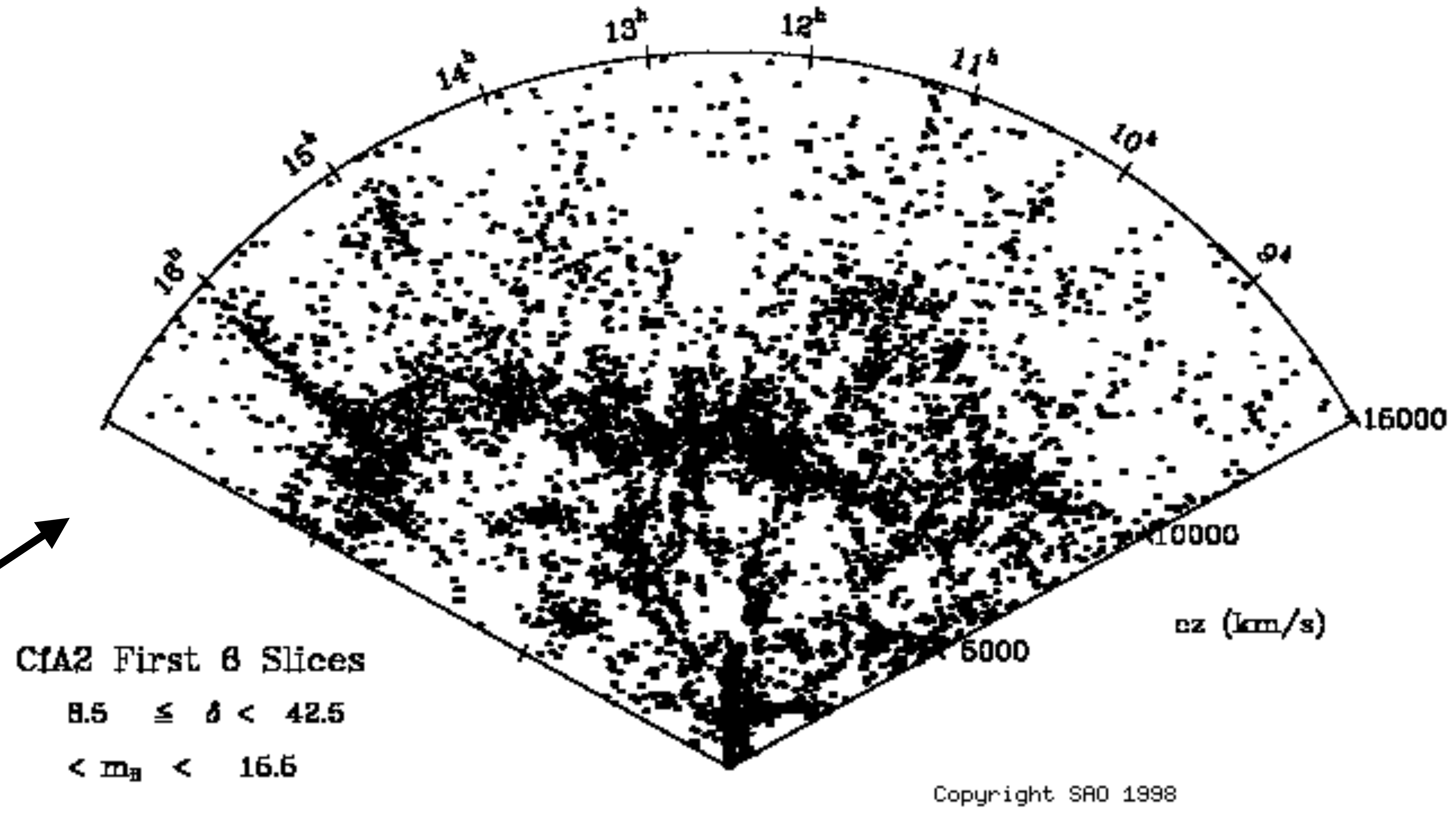
(Taken from the Frank van den Bosch's lectures)



Representative Redshift Surveys		
1985	CfA	~2,500
1992	IRAS	~9,000
1995	CfA2	~20,000
1996	LCRS	~23,000
2003	2dFGRS	~250,000
2009	SDSS DR7	~930,000

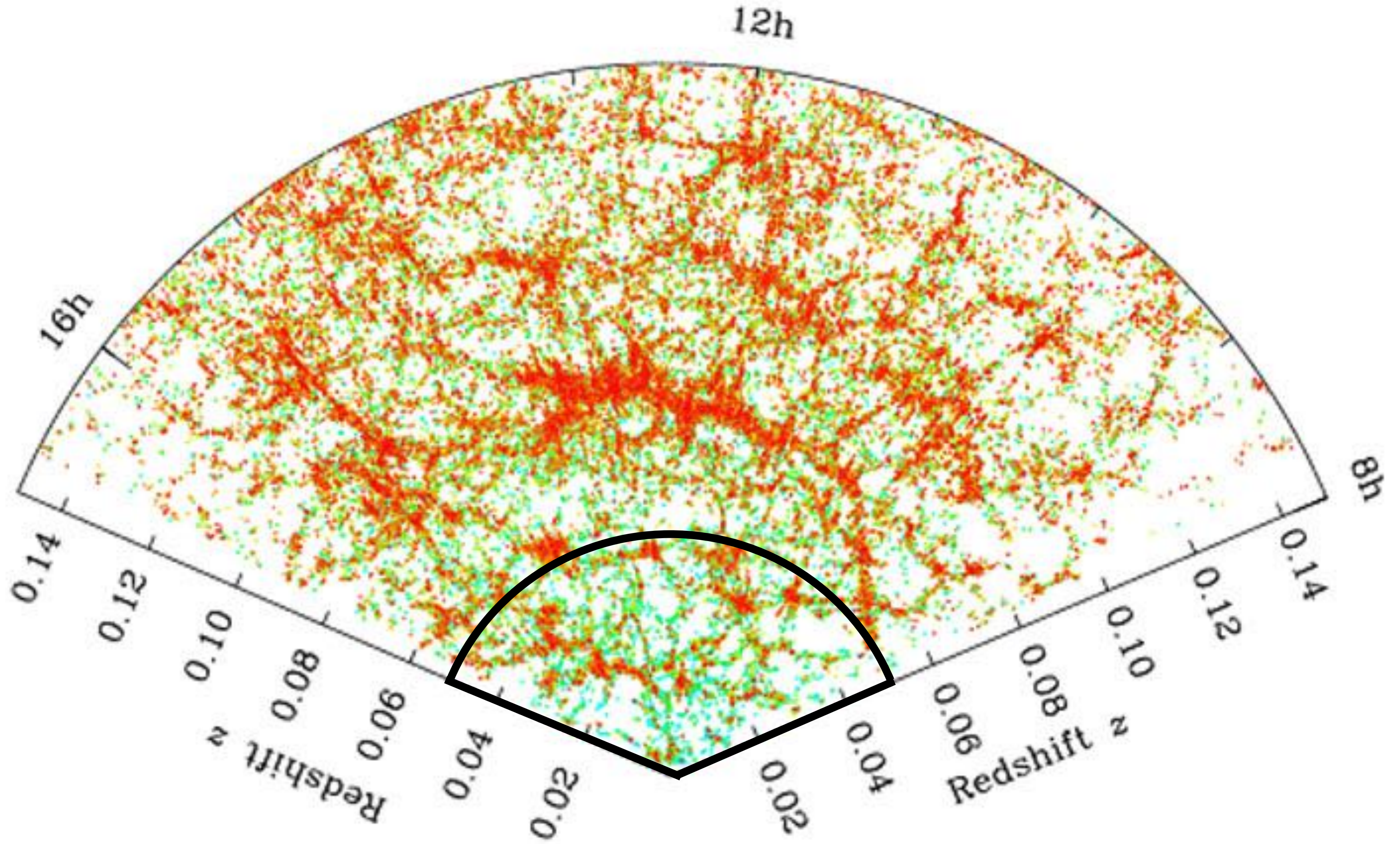
2019 SDSS (DR16) ~2,600,000

Distribution of galaxies from the CfA survey carried out in the 1980s



Geller and Huchra 1989

Distribution of galaxies from the SDSS



SDSS Sky Coverage

Spectroscopic coverage in Equatorial coordinates (DR16)
SDSS covers ~14,500 deg²

The dependence of clustering on galaxy properties

The two-point correlation function depends on galaxy properties.

Spoiler:

More luminous	…galaxies are more clustered than the…	less luminous	galaxies
Optically red		optically blue	
Early-type		late-type	
Bulge-dominated		disk-dominated	
Higher stellar mass		lower stellar mass	
Low sSFR		higher sSFR	

(at a fixed redshift)

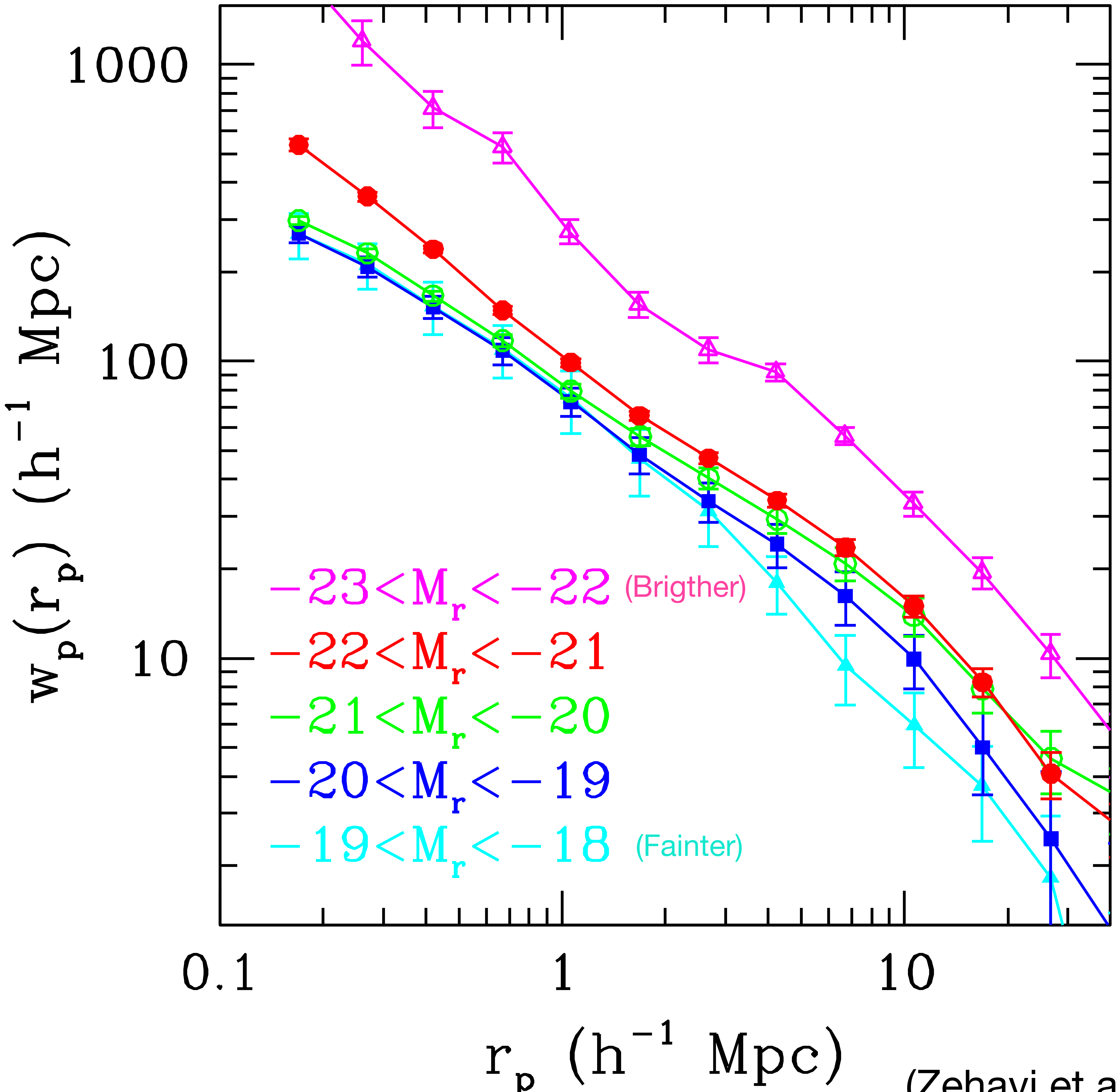
More luminous galaxies show a stronger correlation function than less luminous galaxies

- Projected correlation function for galaxies in SDSS at different absolute magnitudes ranges.
- The correlation function increases with increasing galaxy luminosity.
- The increasing is stronger for brighter samples.
- The slope of the correlation do not change strongly with luminosity.

This implies that more luminous galaxies reside in more massive dark matter halos than less luminous galaxies

(see next lecture)

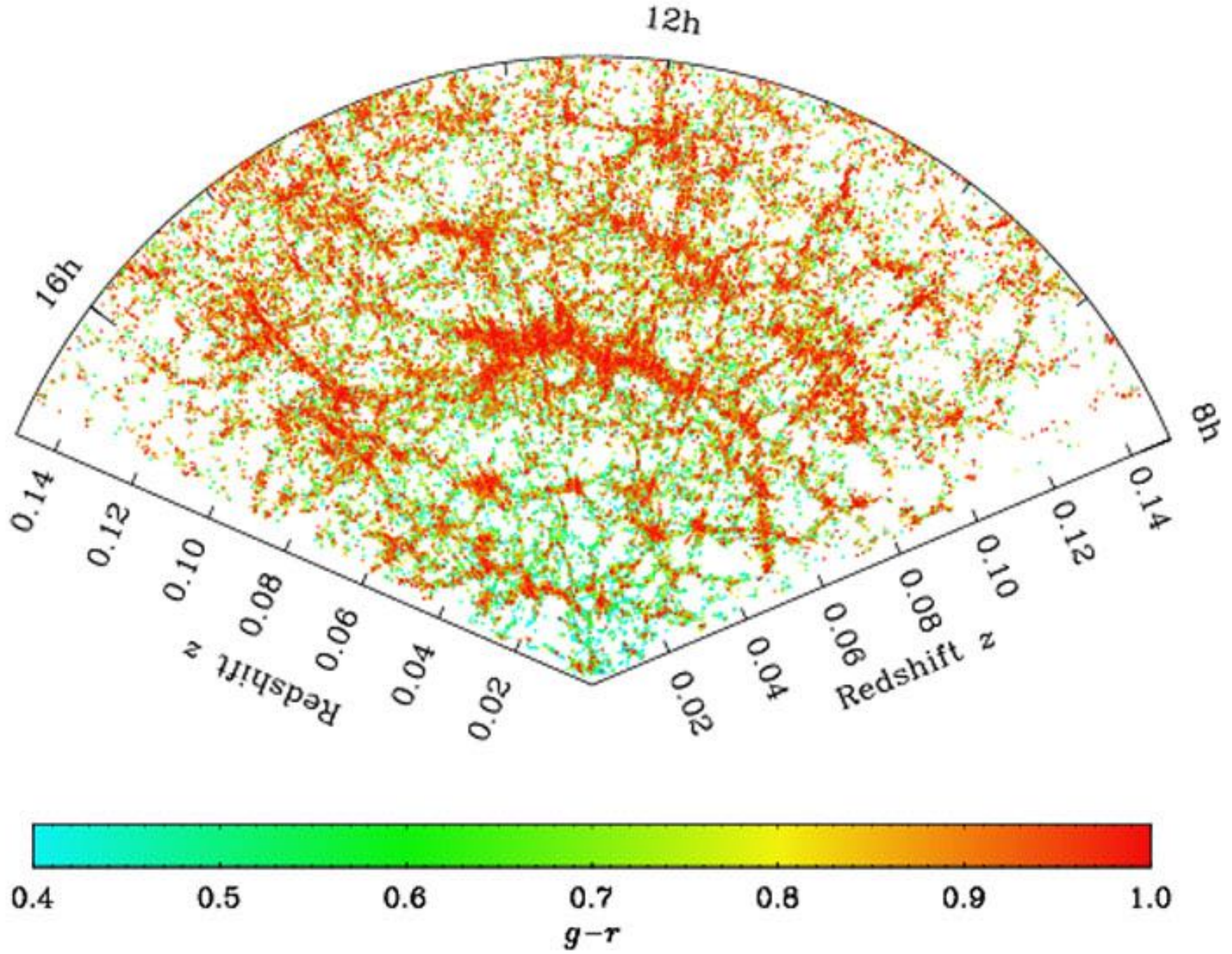
700,000 galaxies over 8,000 deg^2, up to z~0.25



(Zehavi et al. 2011)

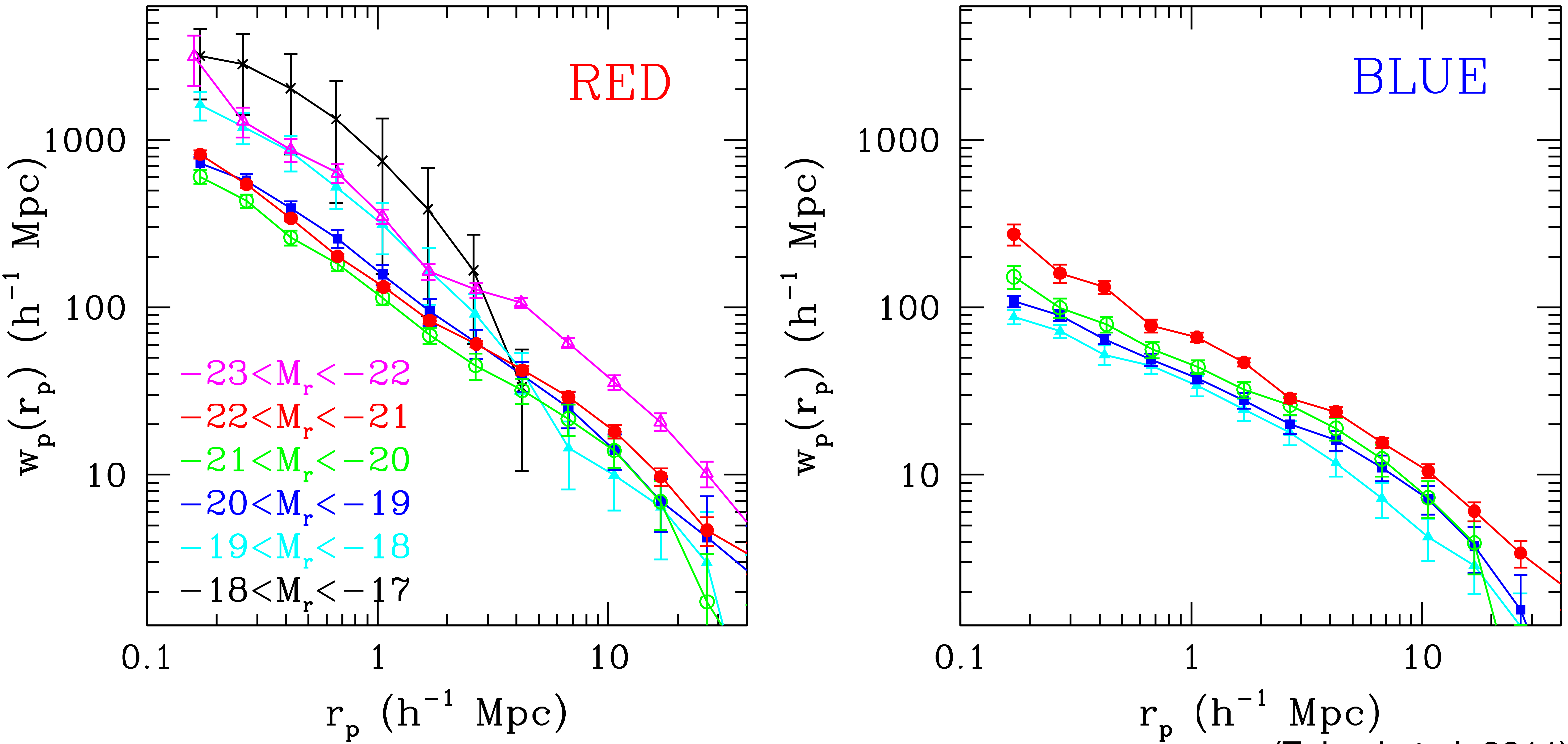
Optically red galaxies show a stronger correlation function than optically blue galaxies

- Spatial distribution of galaxies in SDSS, color coded as a function of their rest-frame color.
- Red galaxies are more preferentially located in overdense regions (filaments) whereas blue galaxies are more distributed over space.



Optically red galaxies show a stronger correlation function than optically blue galaxies

- Projected correlation function for red and blue galaxies in SDSS of different luminosities.
- At a given luminosity, the correlation function of red galaxies has a larger amplitude than that of blue galaxies.

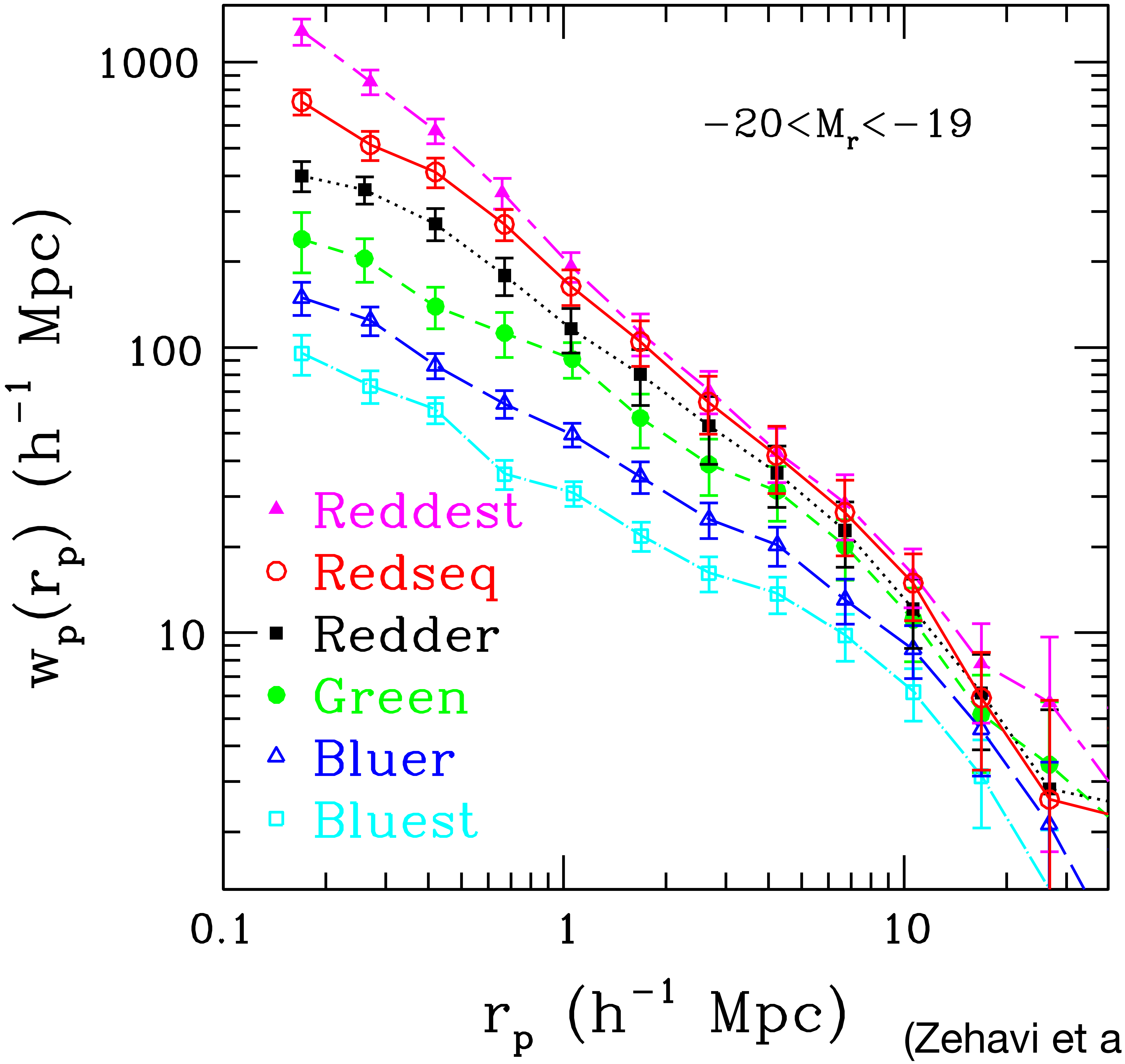


(Zehavi et al. 2011)

At a fixed luminosity, red galaxies reside in more massive dark matter halos than blue galaxies
(see next lecture)

Optically red galaxies show a stronger correlation function than optically blue galaxies

- We can see the same result if we focus at a fixed luminosity range and make a finer color selection.
- The slope also variate: the correlation function decreases faster with radius for the red galaxies.

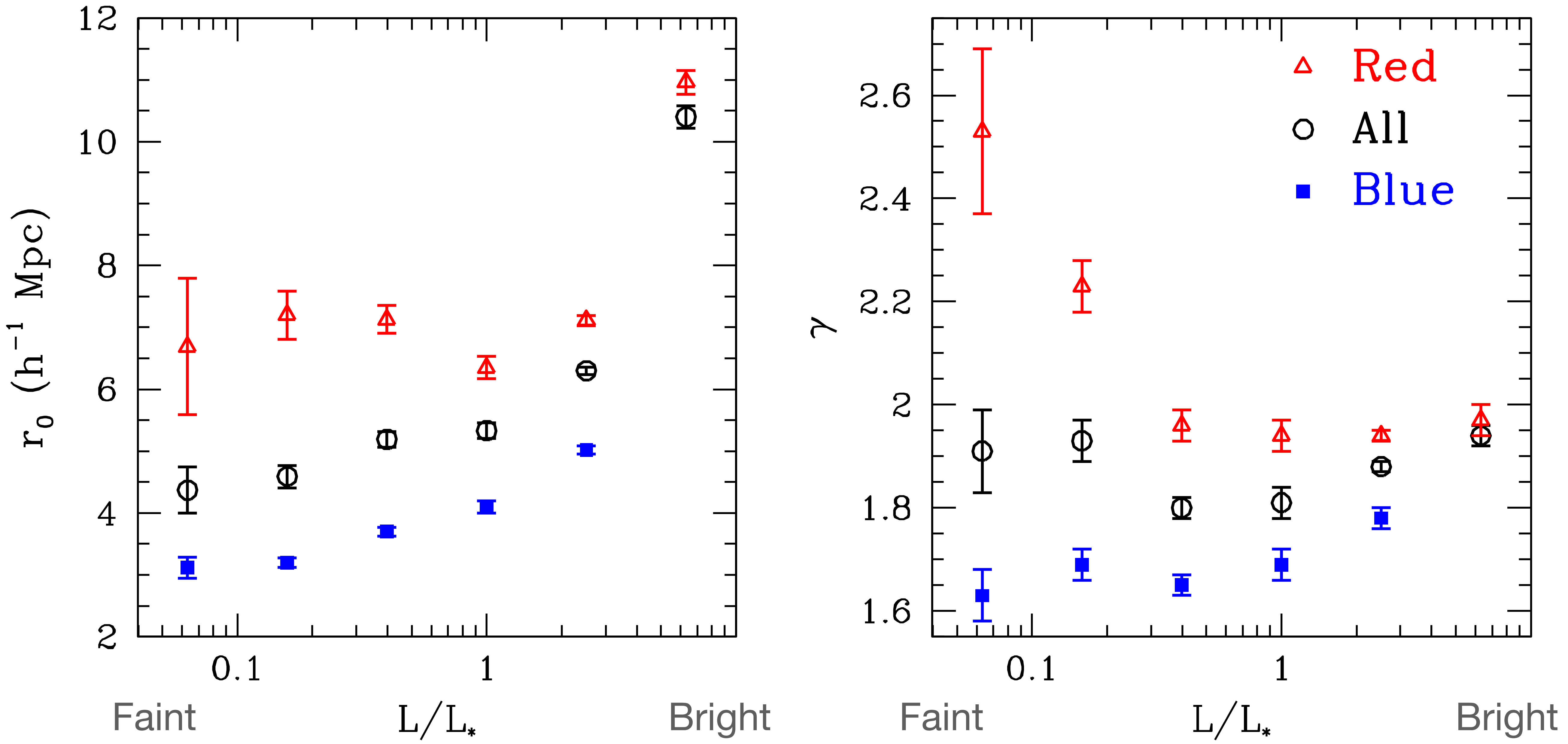


(Zehavi et al. 2011)

Optically red galaxies show a stronger correlation function than optically blue galaxies

- The correlation length increases with luminosity for blue galaxies, but not for red galaxies.
- The slope is smaller for the blue sample at all luminosities.
- Slope is more or less independent on luminosity for the blue sample but it is strongly dependent for “faint” red galaxies.
- Since faint red galaxies are mostly found in galaxy clusters, their clustering is stronger and steeper than bright red galaxies (i.e. faint galaxies live in more massive halos)

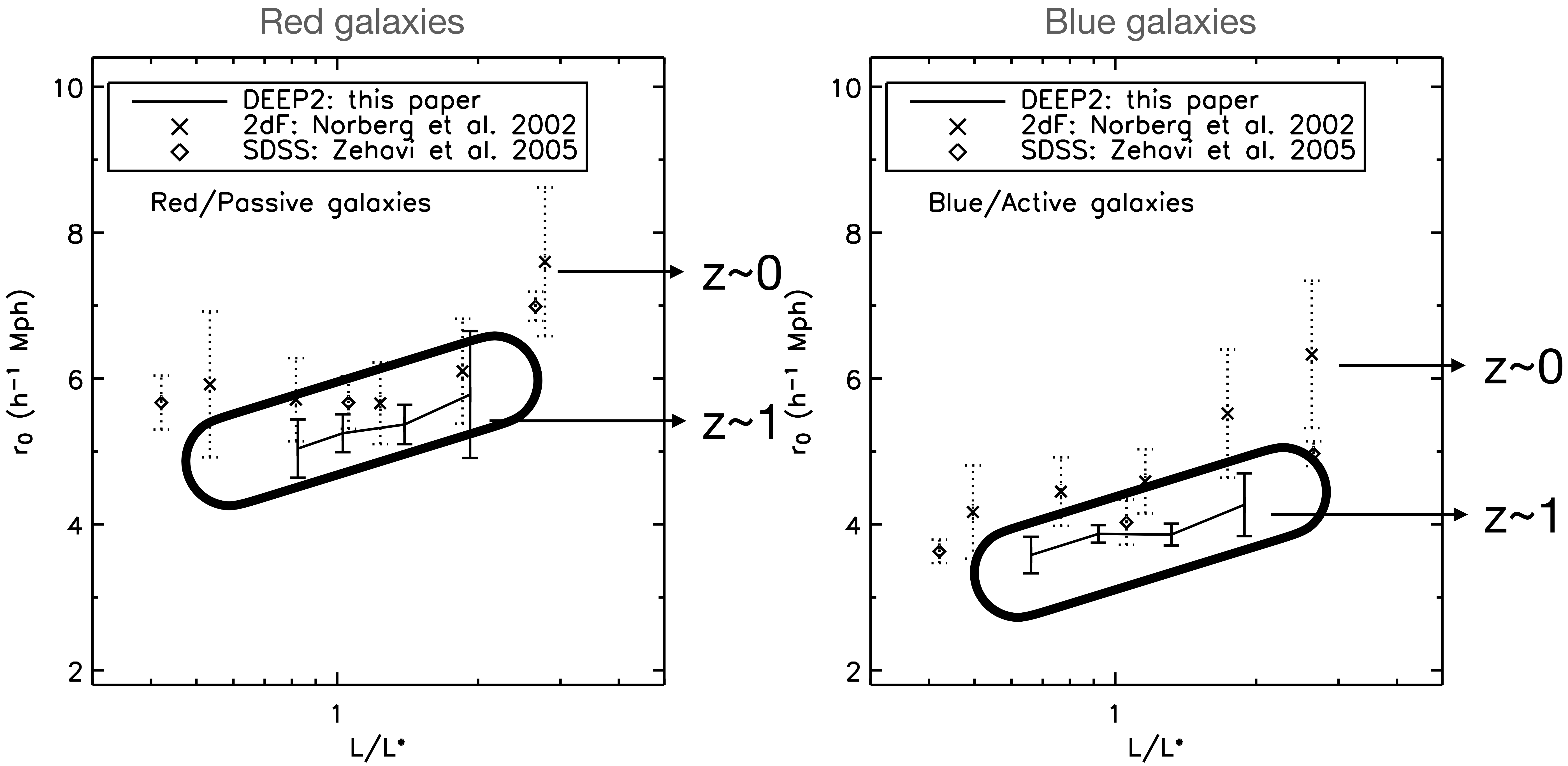
The best fitting power-law model for the correlation function of red and blue galaxies.



(Zehavi et al. 2011)

Clustering dependency on galaxy luminosity and color at z~0 is also seen at z~1

- The correlation length of red galaxies is higher than that of blue galaxies.
- The clustering increases with luminosity for both red and blue galaxies (at least at bright luminosities).

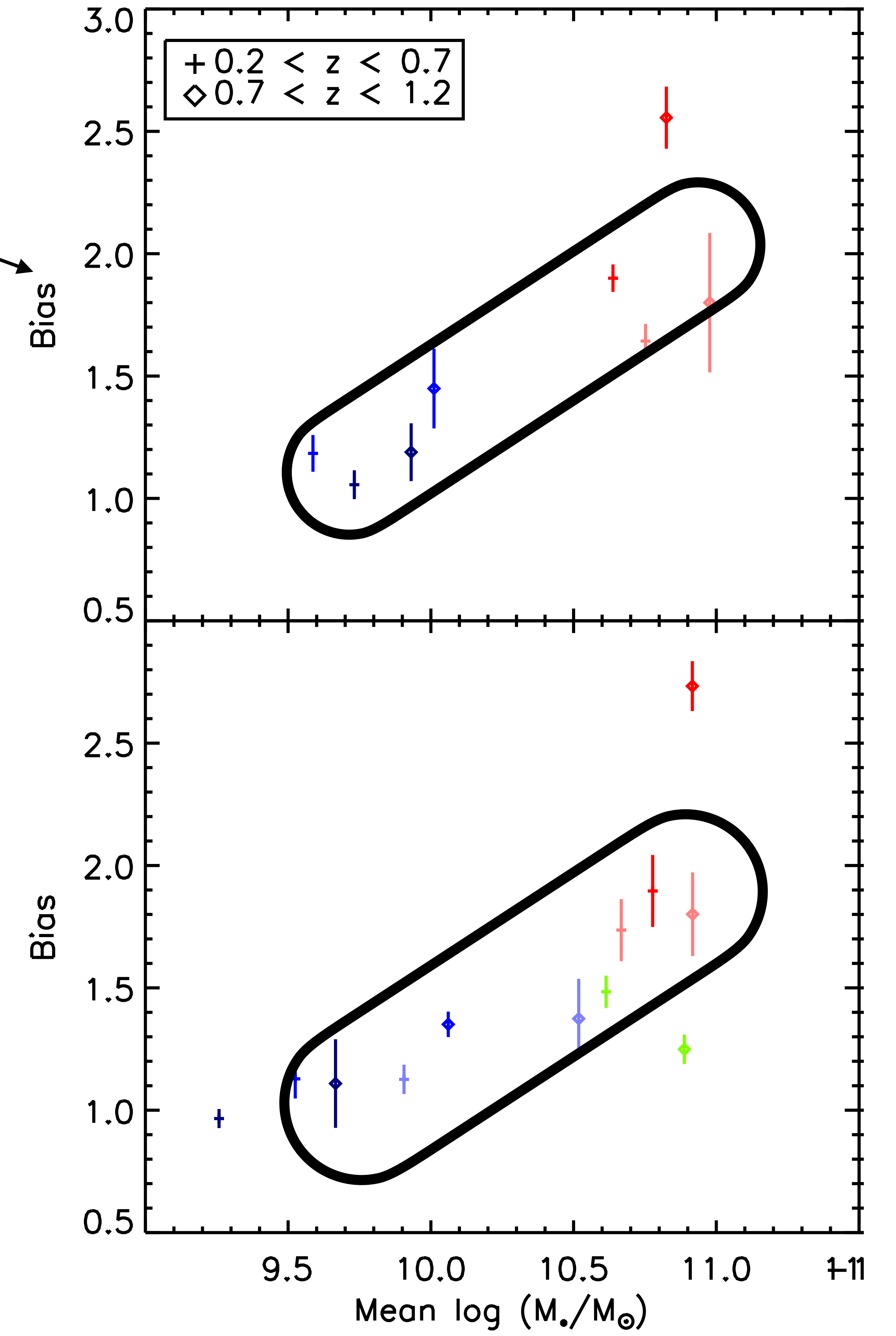


(Coil et al. 2008)

Clustering dependency on Stellar mass at z~0.5 and at z~1

- Coil+ measured the projected correlation function using data from the PRIMUS and DEEP2 galaxy redshift surveys spanning $0.2 < z < 1.2$.
- They use spectroscopic redshifts of over 100,000 galaxies covering an area of 7.2 deg^2
- The galaxy clustering amplitude smoothly increases with increasing stellar mass.

Assume this is ~r_0 for now

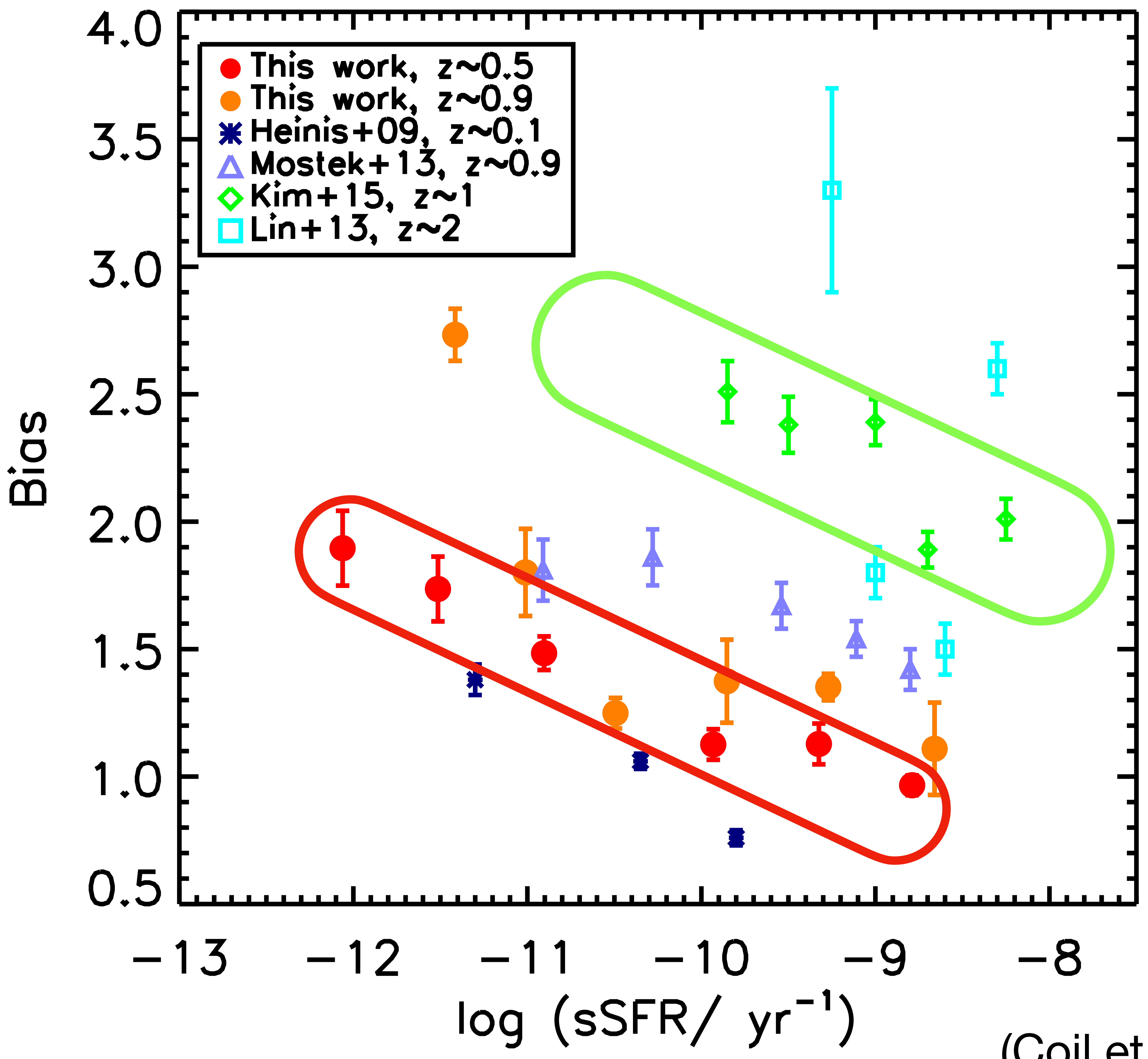


(Coil et al. 2017)

Clustering dependency on sSFR

sSFR: specific star formation rate.
This is defined as the SFR/Mstelar.

- At a given stellar mass, galaxies with higher sSFR are less clustered than galaxies with lower sSFR



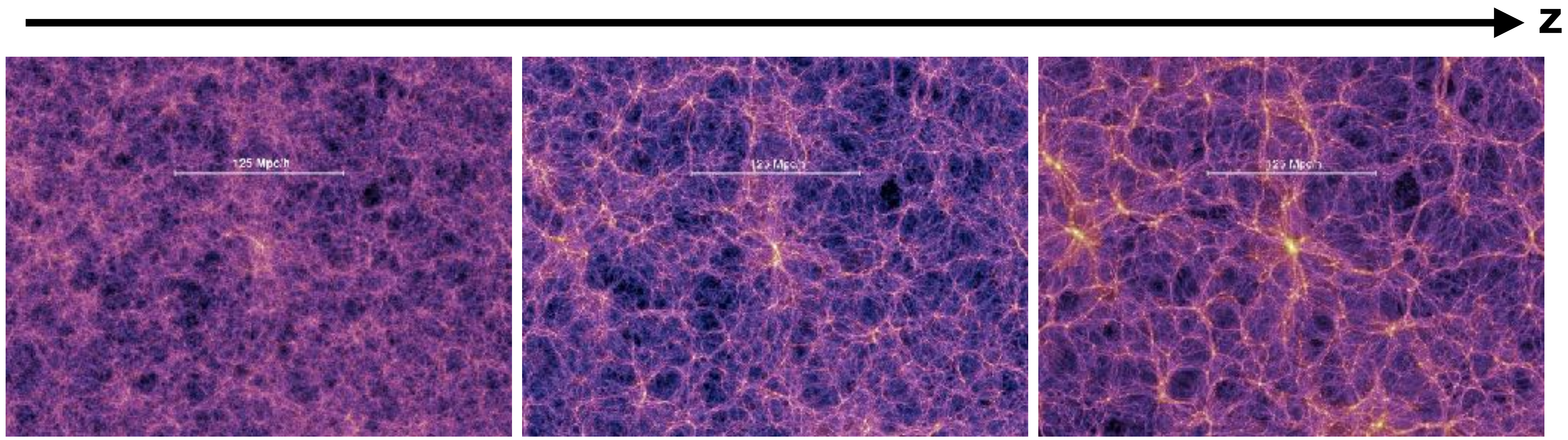
(Coil et al. 2017)

The dependence of clustering on galaxy properties

More luminous	…galaxies are more clustered than the…	**less luminous**	galaxies
Optically red		**optically blue**	
Early-type		late-type	
Bulge-dominated		disk-dominated	
Higher stellar mass		**lower stellar mass**	
Low sSFR		**higher sSFR**	

The dependence of clustering on redshift

- Since structures grow over time due to gravitational instability, we expect the clustering of galaxies also evolve over time. Intuitively, we could expect that clustering increase with time, but that is not actually what is observed).

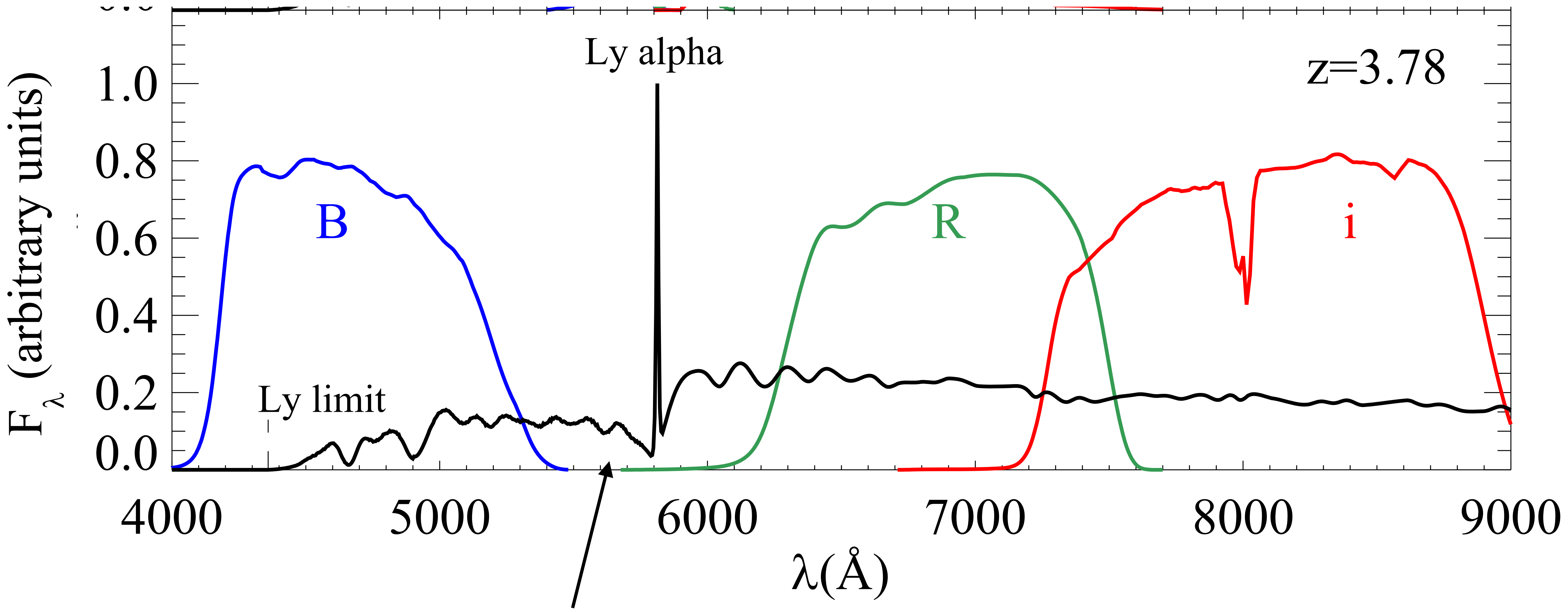


- Exploring how clustering evolve with redshift is complicated, because we are not observing the same object at different times. We can, however, in some cases to observe the same type of objects at different times.

- At higher redshifts we can trace other populations, such as, Lyman-break galaxies, Lyman alpha emitters, quasars, etc.

Clustering of Lyman break galaxies

- Lyman break galaxies are star-forming galaxies detected at high-redshift (z~3-5), with strong UV emission.
- They are detected through the Lyman alpha break detection. This is a break in the spectra due to the absorption of neutral hydrogen in the intergalactic medium (detectable only from z~3-4).
- To detect them we need deep observations on optical bands, then large samples of LBGs is challenge to obtain (not possible with SDSS for example).
- Most of the samples only with 2D positions, and a inaccurate knowledge of their z (Delta z ~1)

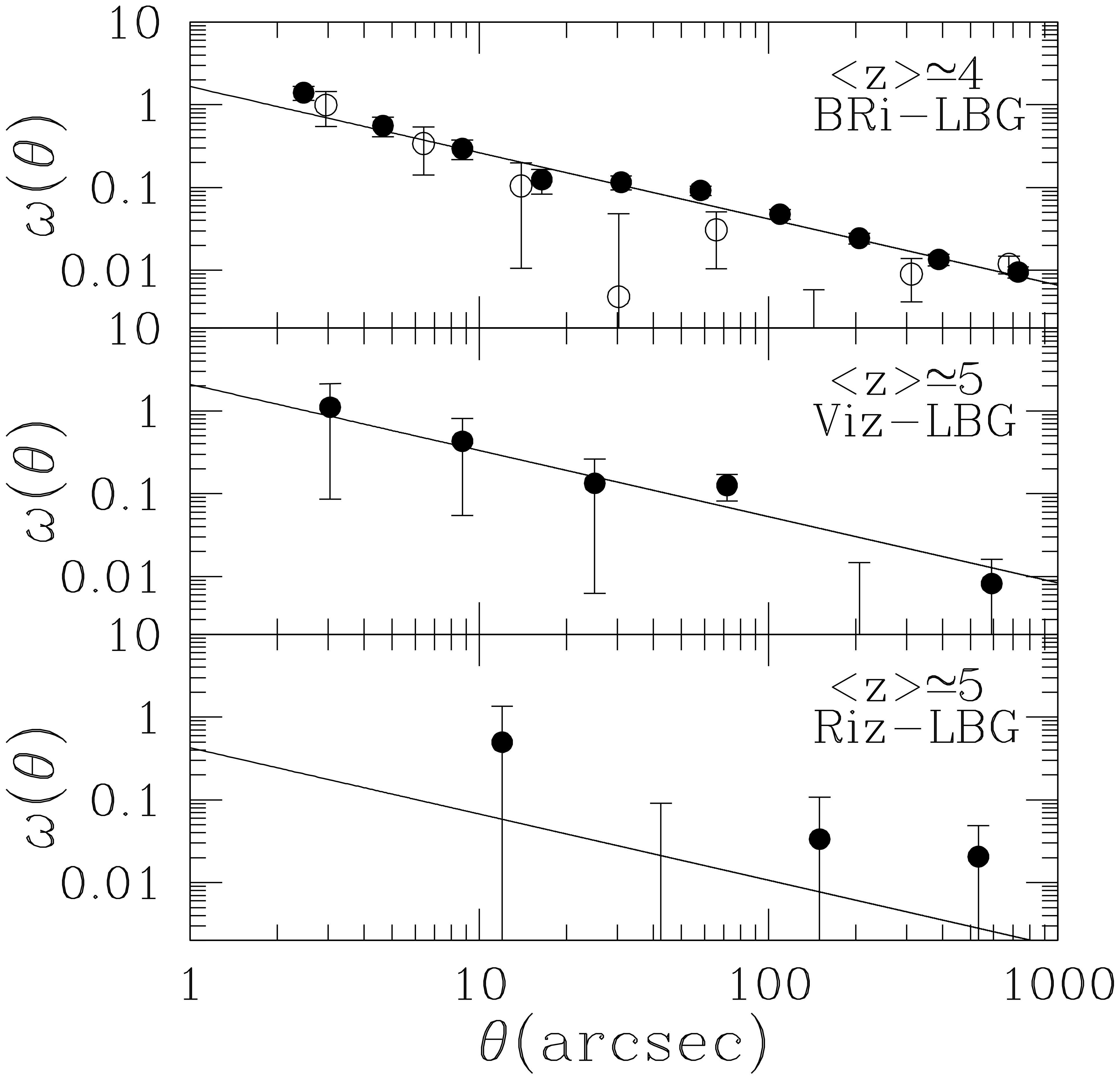

LBG spectra

Break due to the absorption pdf neutral hydrogen in the intergalactic medium (detectable only from z~3-4)

Clustering of Lyman break galaxies

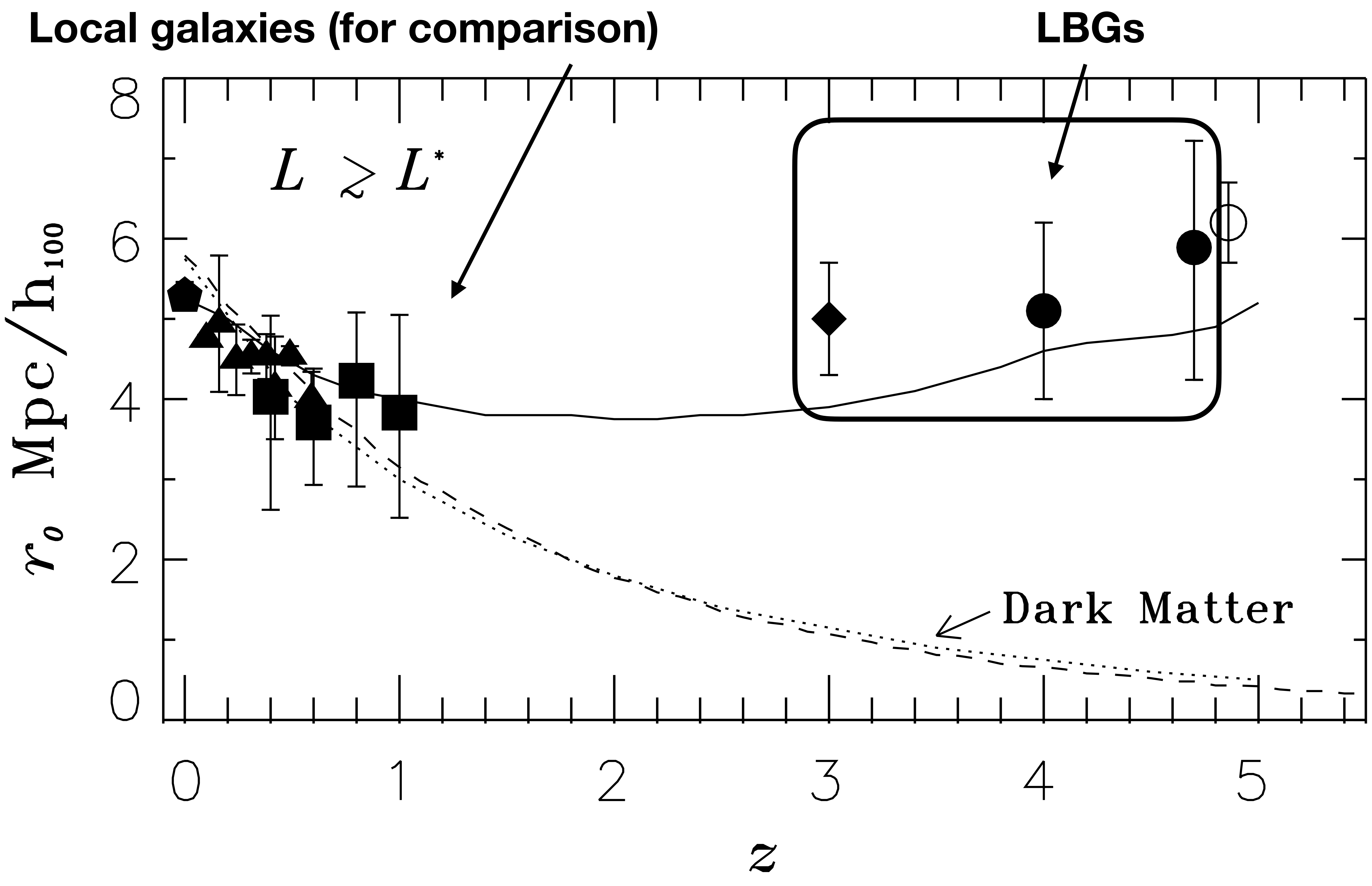
- Angular correlation function for LBGs at z~4 and z~5 measured from the Subaru deep survey (~1200 arcmin^2)
- Clustering is affected by larger uncertainties (number of LBGs ~2000, 300 and 100 for Bri, Viz and Riz respectively.
- Brighter LBGs are more strongly clustered than fainter LBGs (e.g. Malkan et al. 2017).

(Ouchi et al. 2004)



Clustering of Lyman break galaxies

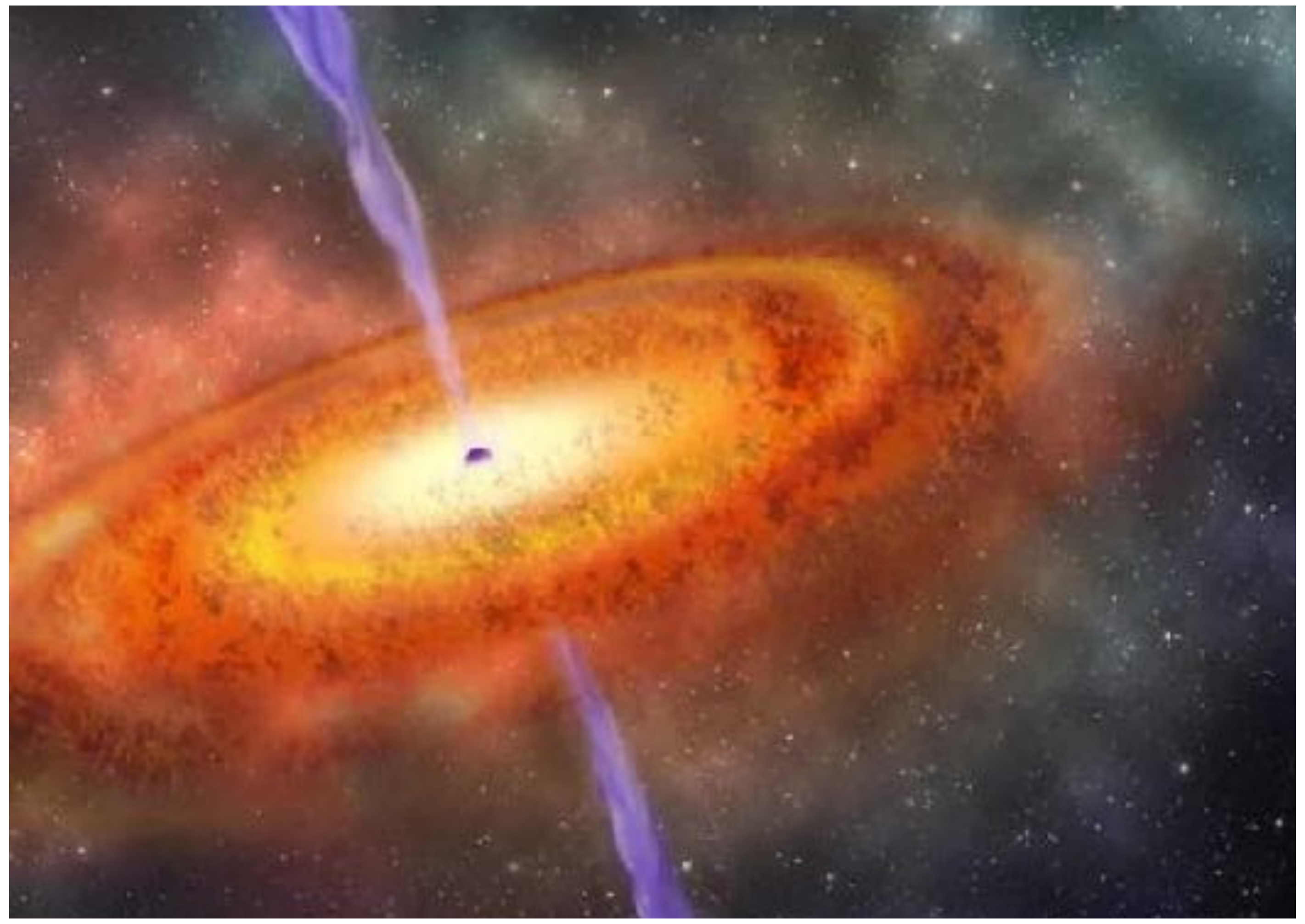
- LBGs at different redshifts between 3 and 5, with similar luminosities.
- The correlation length of LBGs is roughly constant between redshift 3 and 5.
- The correlation length is also not so different that the correlation length of local galaxies (although they may be different types of objects)



(Ouchi et al. 2004)

Clustering of Quasars

- Quasars are extremely luminous active galactic nucleus (AGNs) in which a supermassive black hole is accreting material. Because of their extreme luminosities, they are detected up to very high redshifts, and redshift measurements are possible. Their redshift distribution is observed to peak at z~2.5.
- They can be detected at almost all the wavelengths of the electromagnetic spectrum.



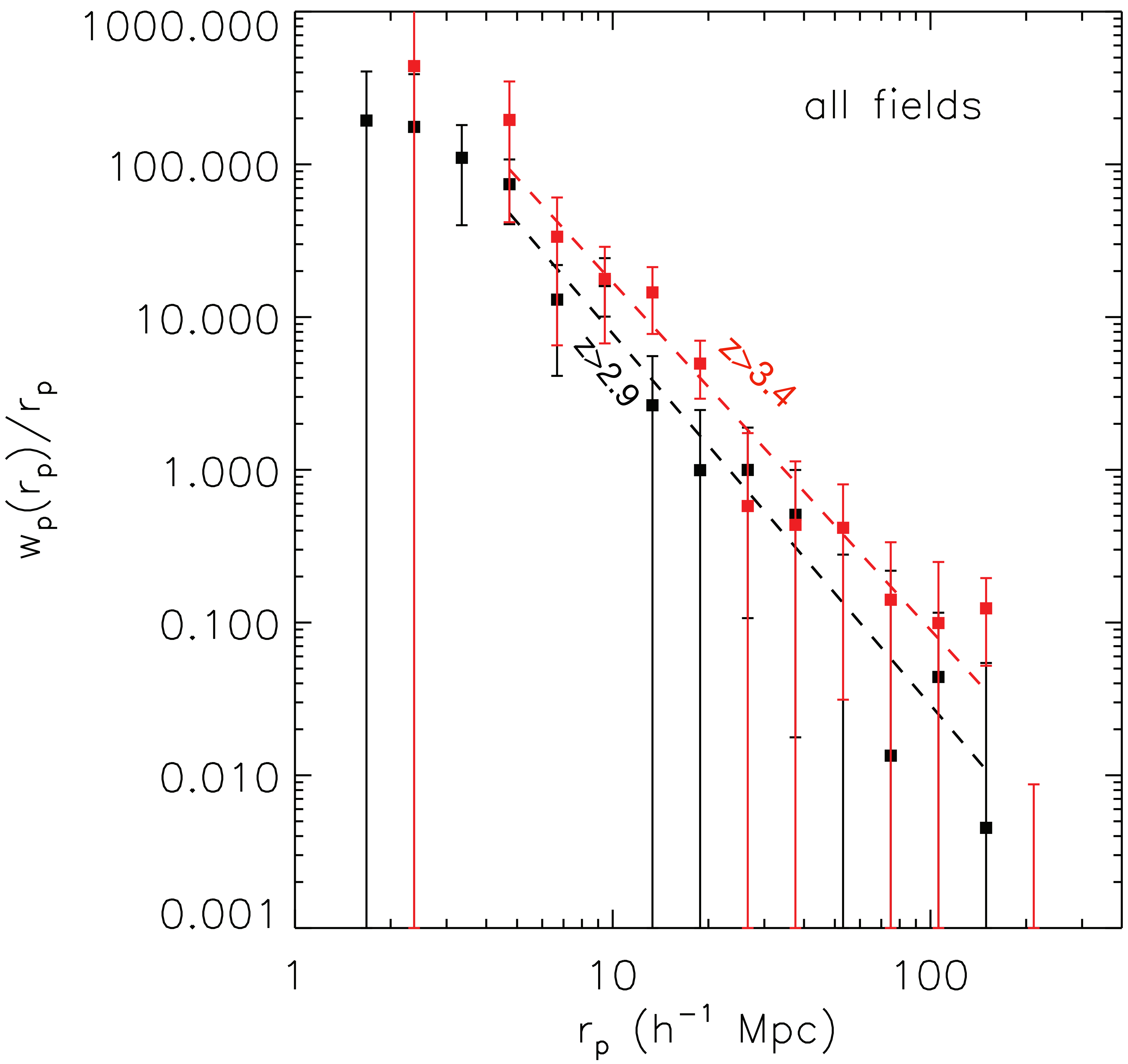
Clustering of Quasars

- Projected correlation function of quasars at z >2.9 and z>3.4 reveal extremely strong clustering.

- Clustering of quasars has been measured at different redshifts. The highest redshift for which this has been measured is z~4 (Shen et al. 2007) using SDSS quasars.

- No significant evidence of dependency on luminosity (also the physics process of quasars are very different than the case of galaxies).

~4,400 High-z Quasars in SDSS (over ~4000 deg^2)



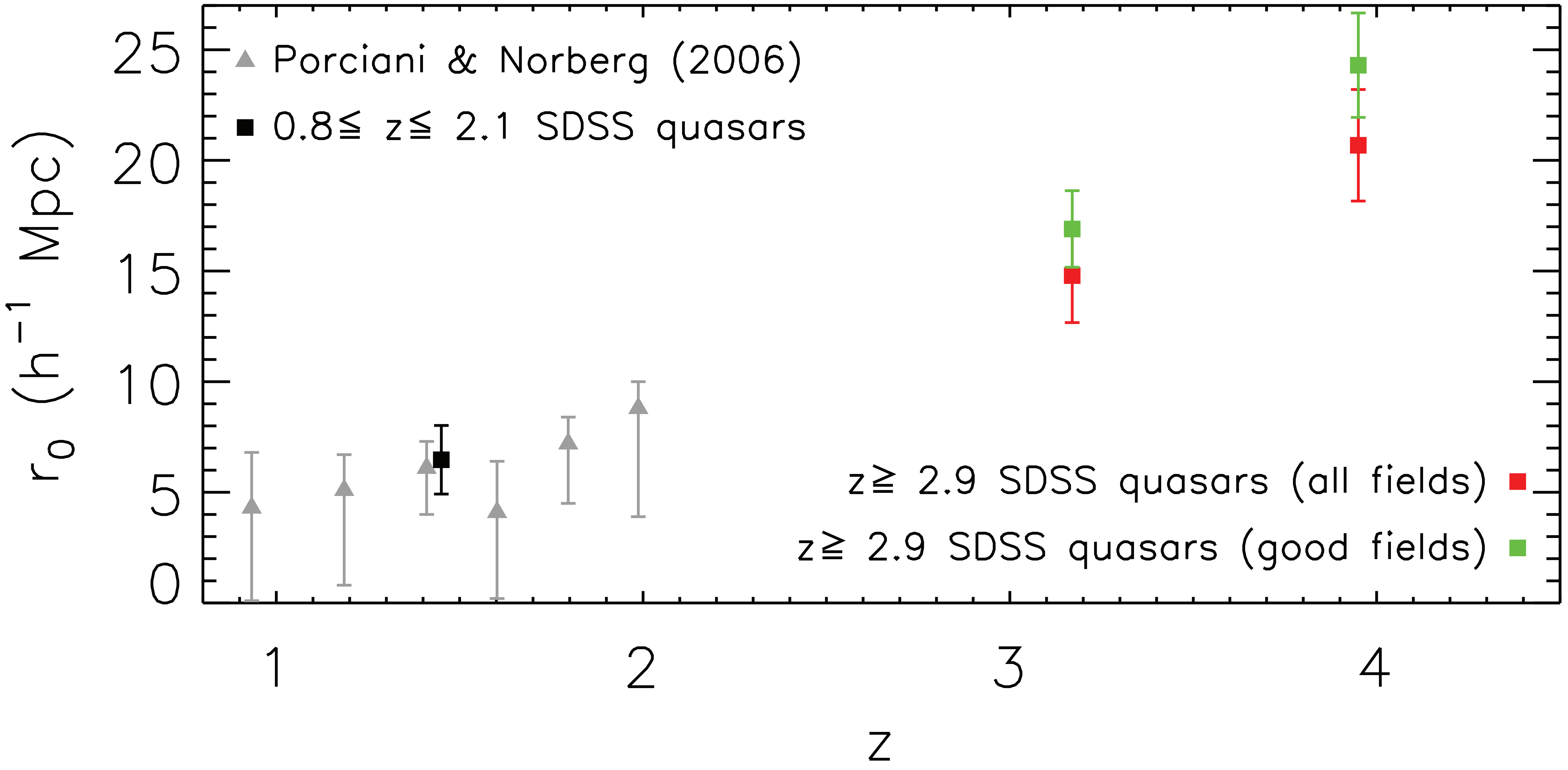
(Shen et al. 2007)

Clustering of Quasars

- The correlation length is relatively constant up to z~2, and it strongly increase from z~2 up to z~ 4.

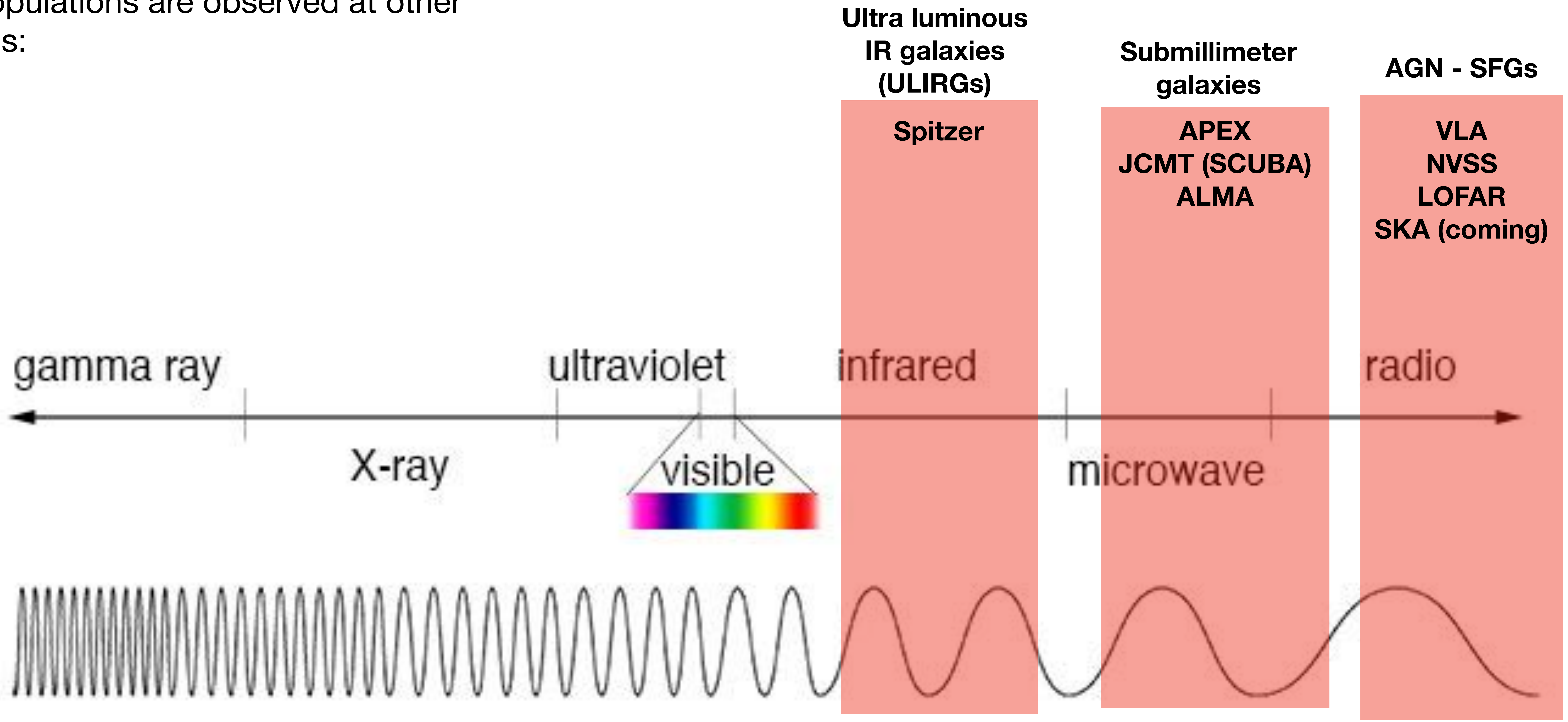
- Quasars at z~4 are the most clustered population in the universe, and then they are expected to trace the more massive overdensities in the early universe.

(Shen et al. 2007)



Surveys at other wavelengths

- Clustering of other populations observed at different wavelengths is still poorly constrained because of the lack of large and deep surveys.
- But, great improvement in the last years with the arrival of new instruments.
- Different populations are observed at other wavelengths:



Ultra luminous IR galaxies (ULIRGs)

Spitzer

Submillimeter galaxies

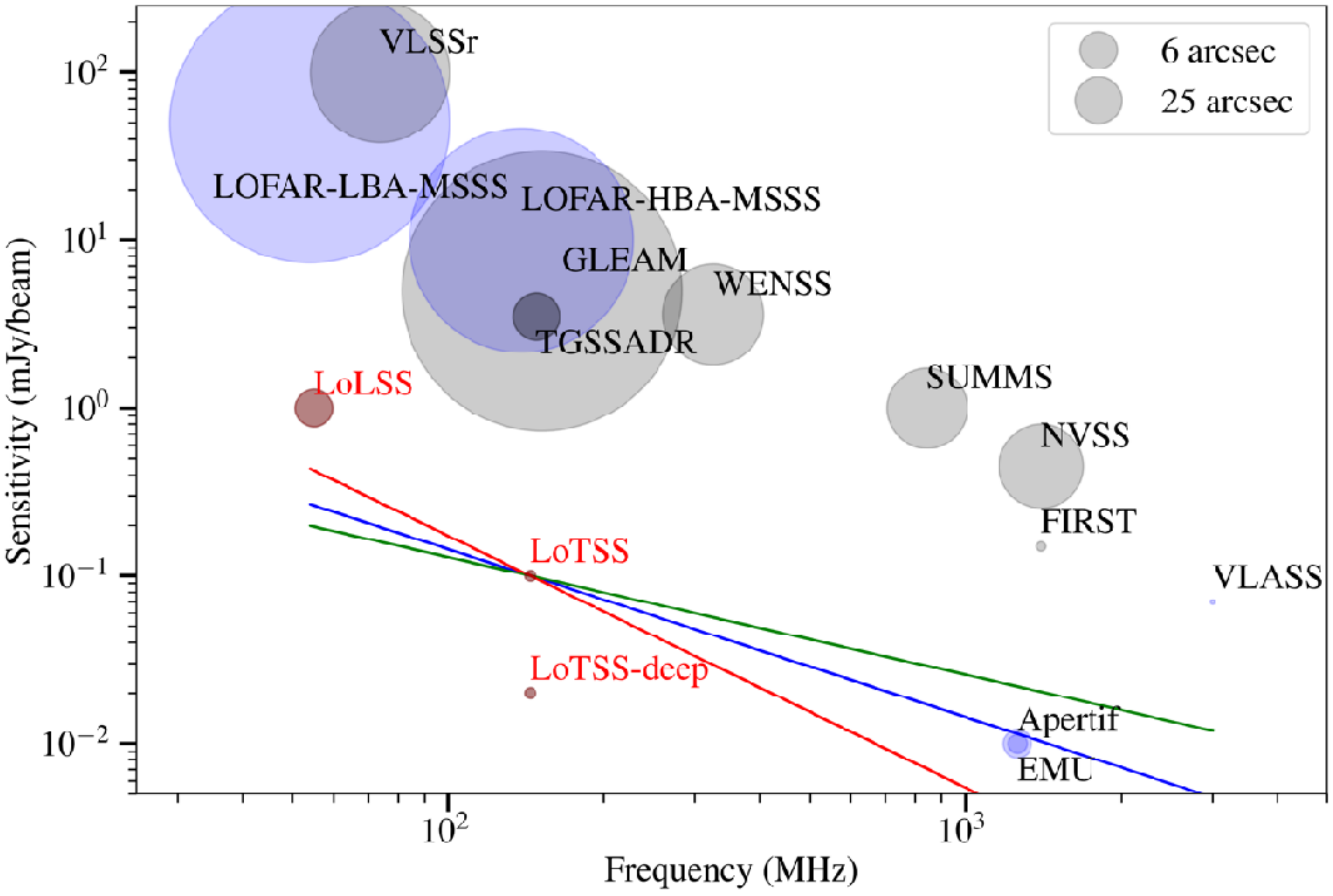
APEX
JCMT (SCUBA)
ALMA

AGN - SFGs

VLA
NVSS
LOFAR
SKA (coming)

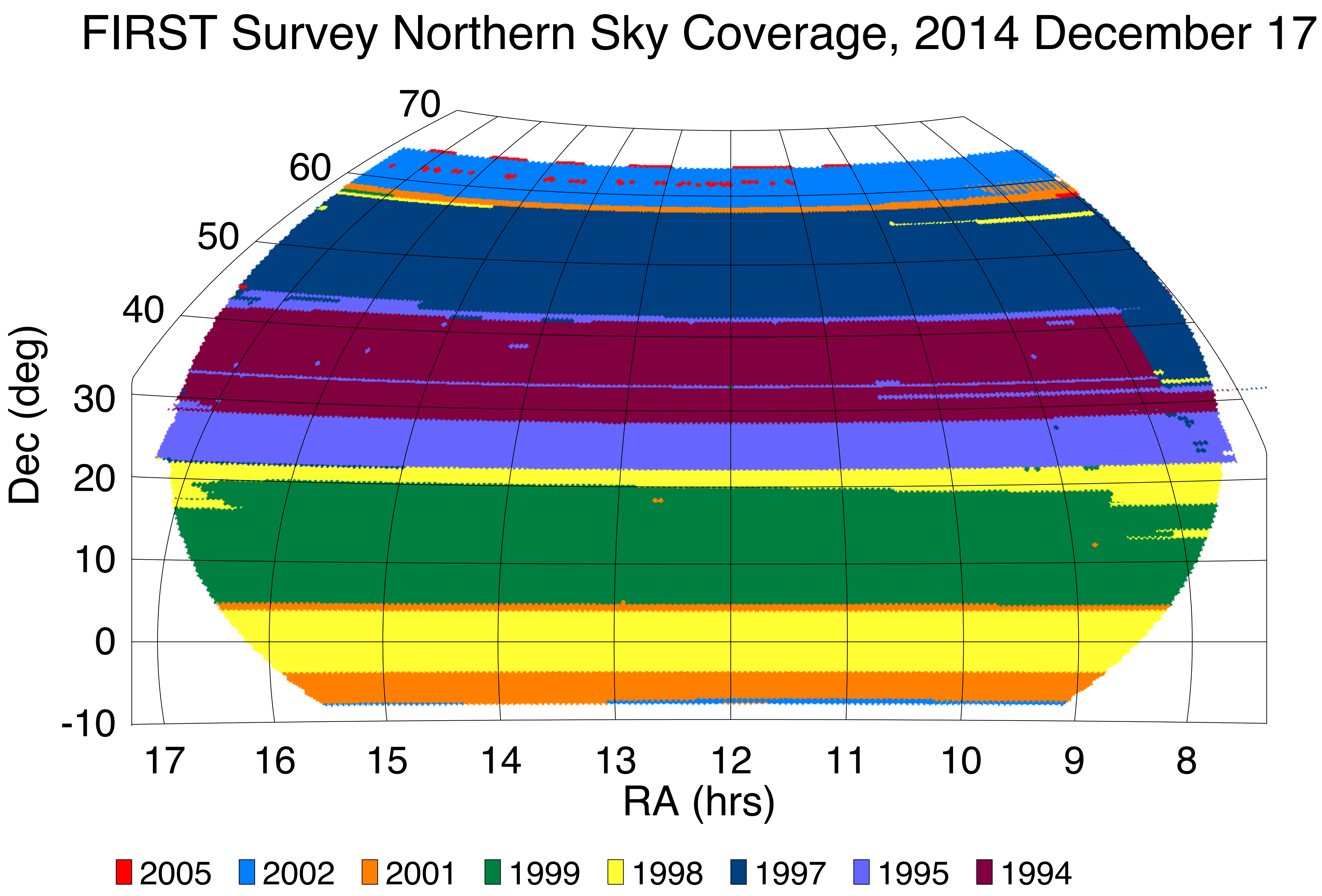
Surveys at radio wavelengths

- Large surveys ongoing which will allow precise clustering measurements.
- Still lack of precise redshifts.
- At radio wavelengths, we can mostly detect two different populations: AGNs and Star-forming galaxies.



Surveys at radio wavelengths

- FIRST -- **F**aint **I**mages of the **R**adio **S**ky at **T**wenty-cm: Sky Survey over 10,000 square degrees.

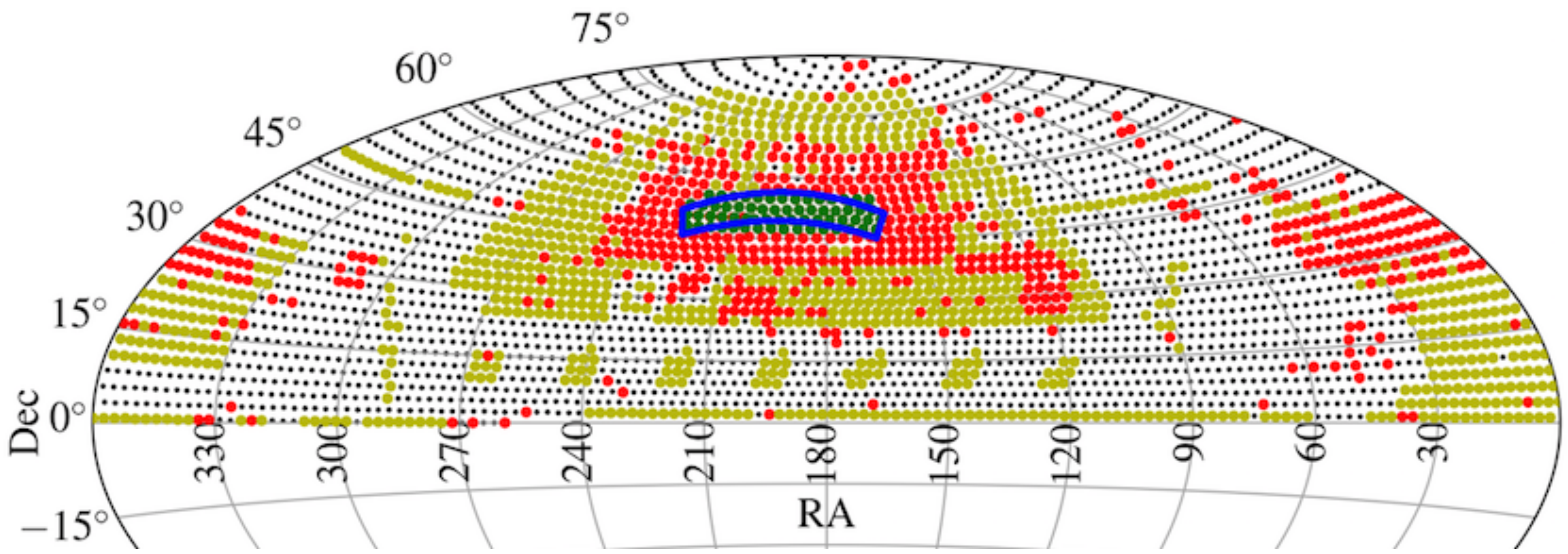


- LOFAR (at lower frequencies): LoTSS survey sky coverage.

  Green: published data (424 deg^2).

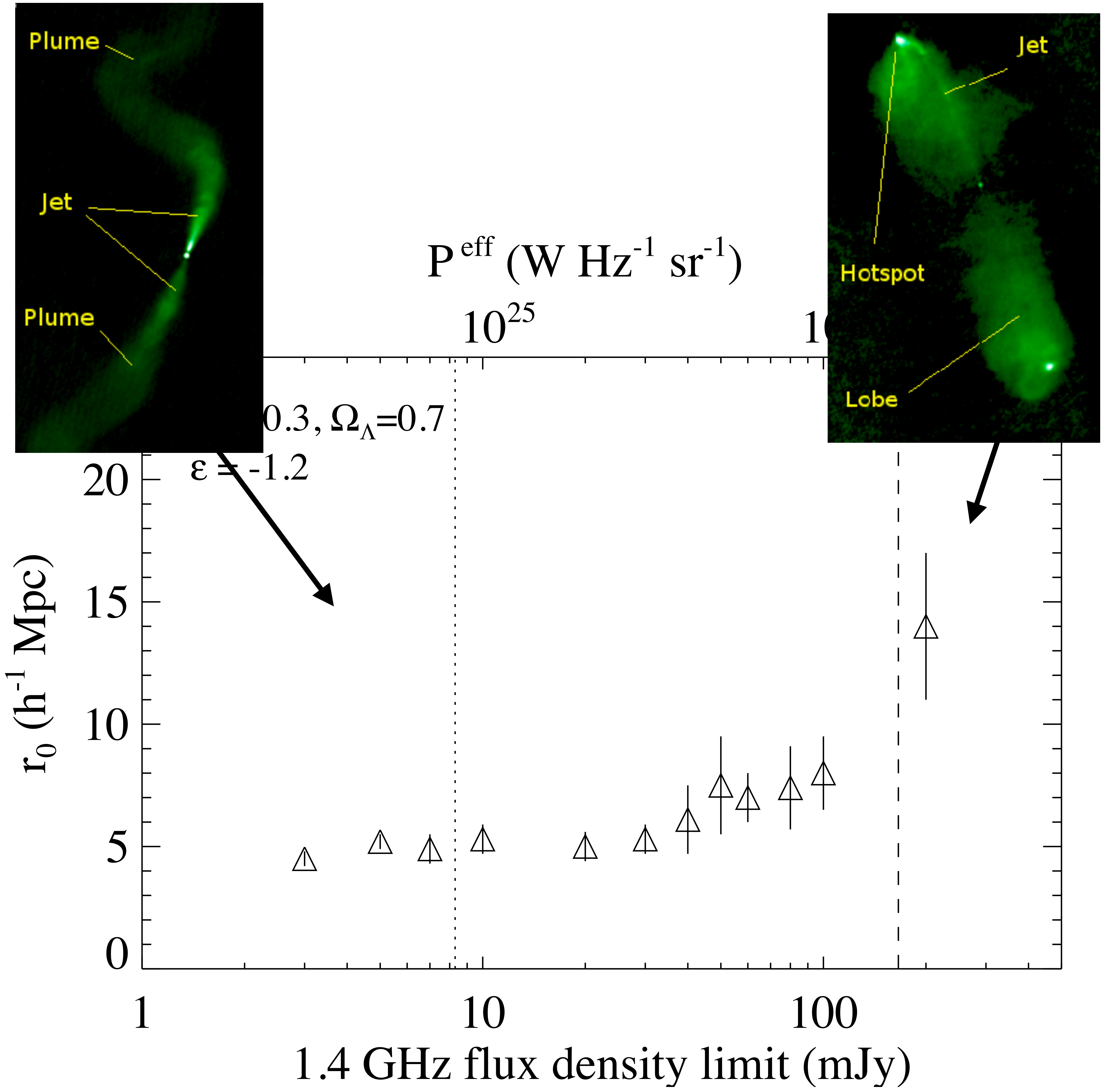
  Red and yellow: Observed, not published yet.

  Black: To be observed.



Surveys at radio wavelengths

- Constraints of the angular correlation function for sources detected at radio wavelengths from NVSS and FIRST.
- The correlation length increase for higher fluxes, where the population is more dominated by powerful FRII radio galaxies.
- Powerful (FRII) radio galaxies probe significantly more massive structures compared to radio galaxies of average power at $z \sim 1$.

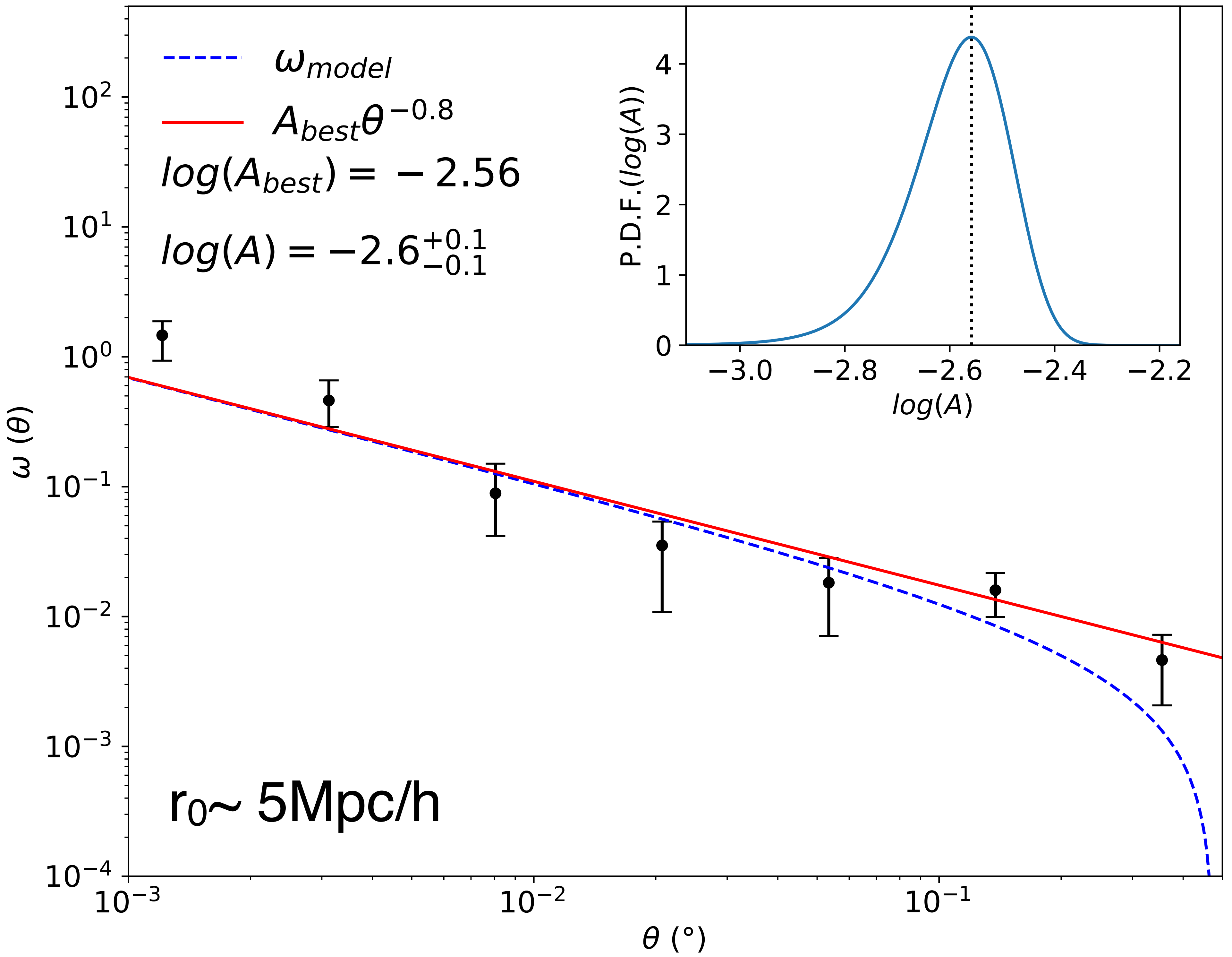


(Overzier et al. 2003)

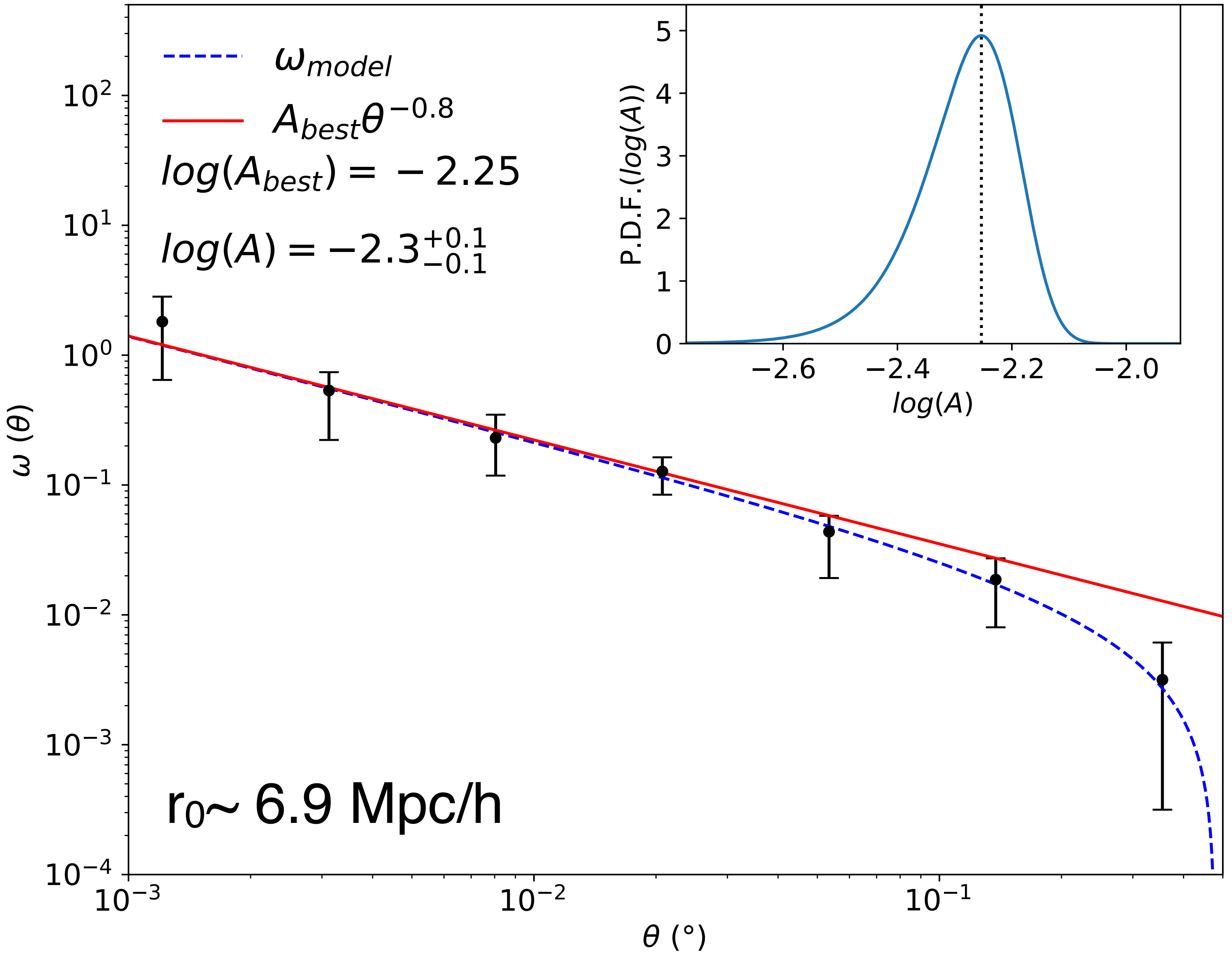
Clustering of radio sources

- Angular correlation function of star forming galaxies and AGNs detected at radio wavelengths at z<1, from the VLA-COSMOS project (This cover ~2 deg^2 and contains ~10,000 objects.

Clustering of ~1,800 Star forming galaxies at z<1



Clustering of ~1,100 AGNs at z<1

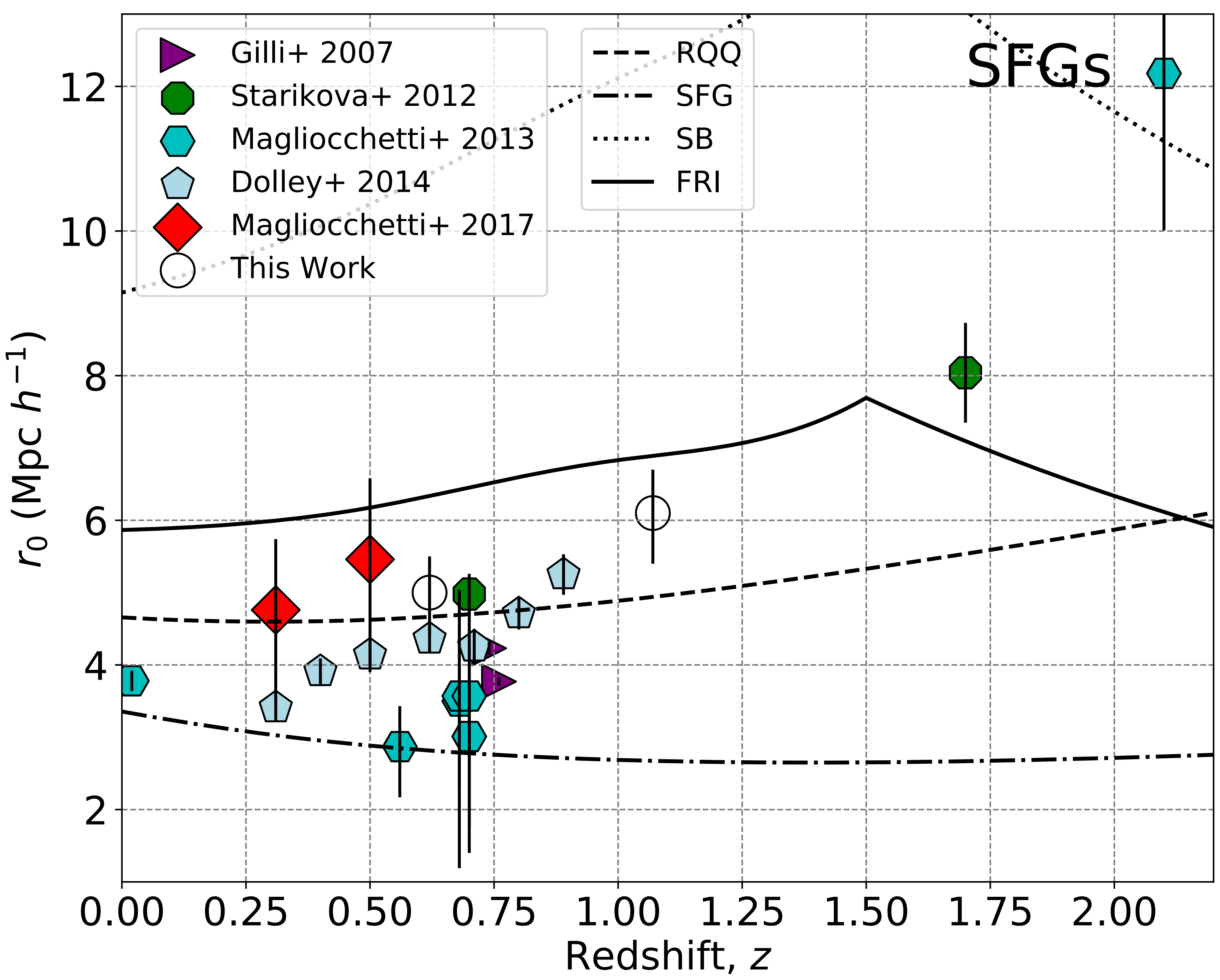


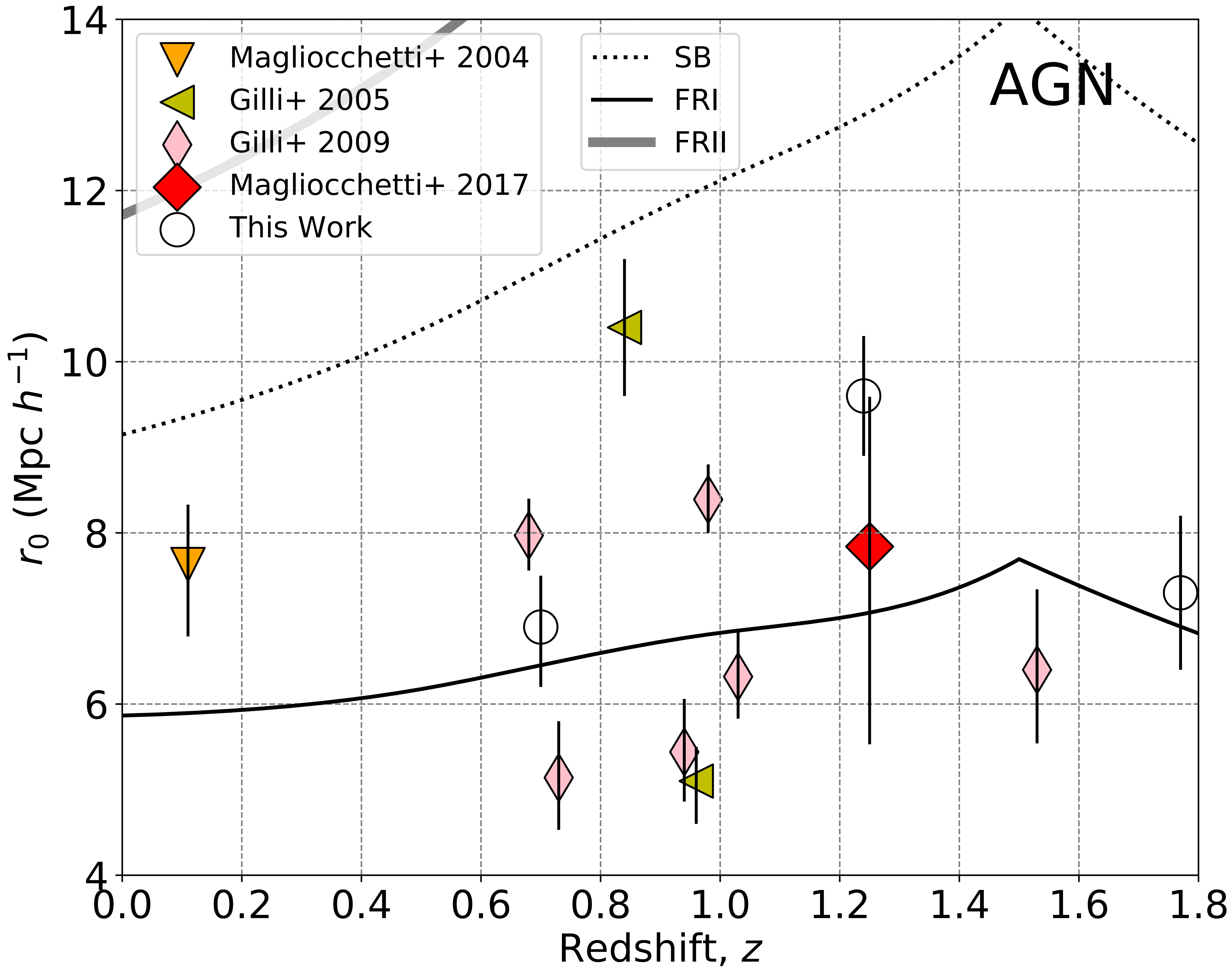
(Hale et al. 2018)

AGN are significantly more strongly clustered than SFGs implying that AGN are hosted by more massive haloes than SFGs.

Clustering of radio sources

- Evolution of the correlation length for Star forming galaxies and AGNs



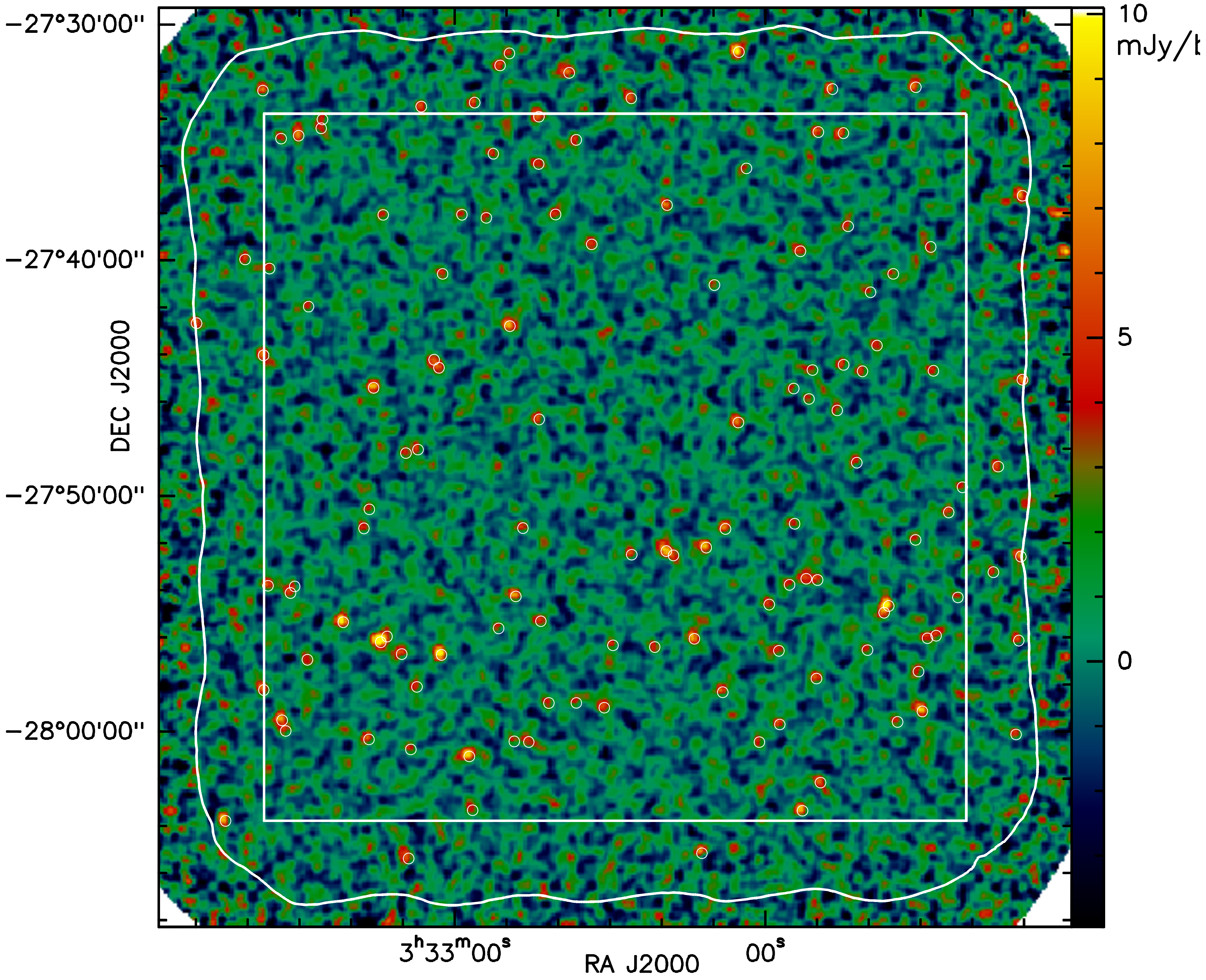


(Hale et al. 2018)

Surveys at submillimeter wavelengths

- Small surveys and low resolution, for example:

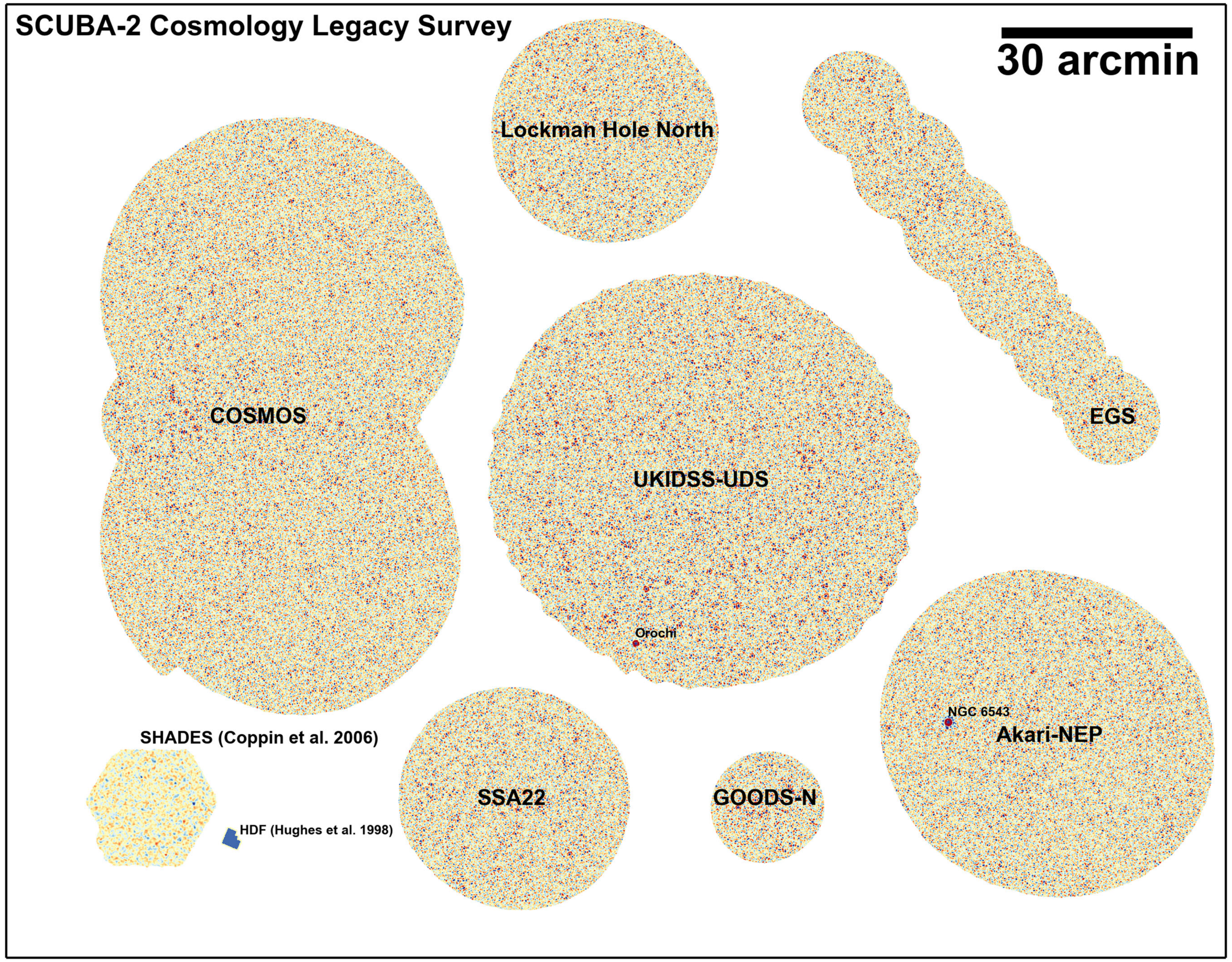
2009: LABOCA ECDFS Submillimetre Survey (LESS), 126 SMGs over 0.25 deg2 (Weiss et al. 2009)



(Weiss et al. 2009)

2017: SCUBA2 Cosmology Legacy Survey (S2CLS)

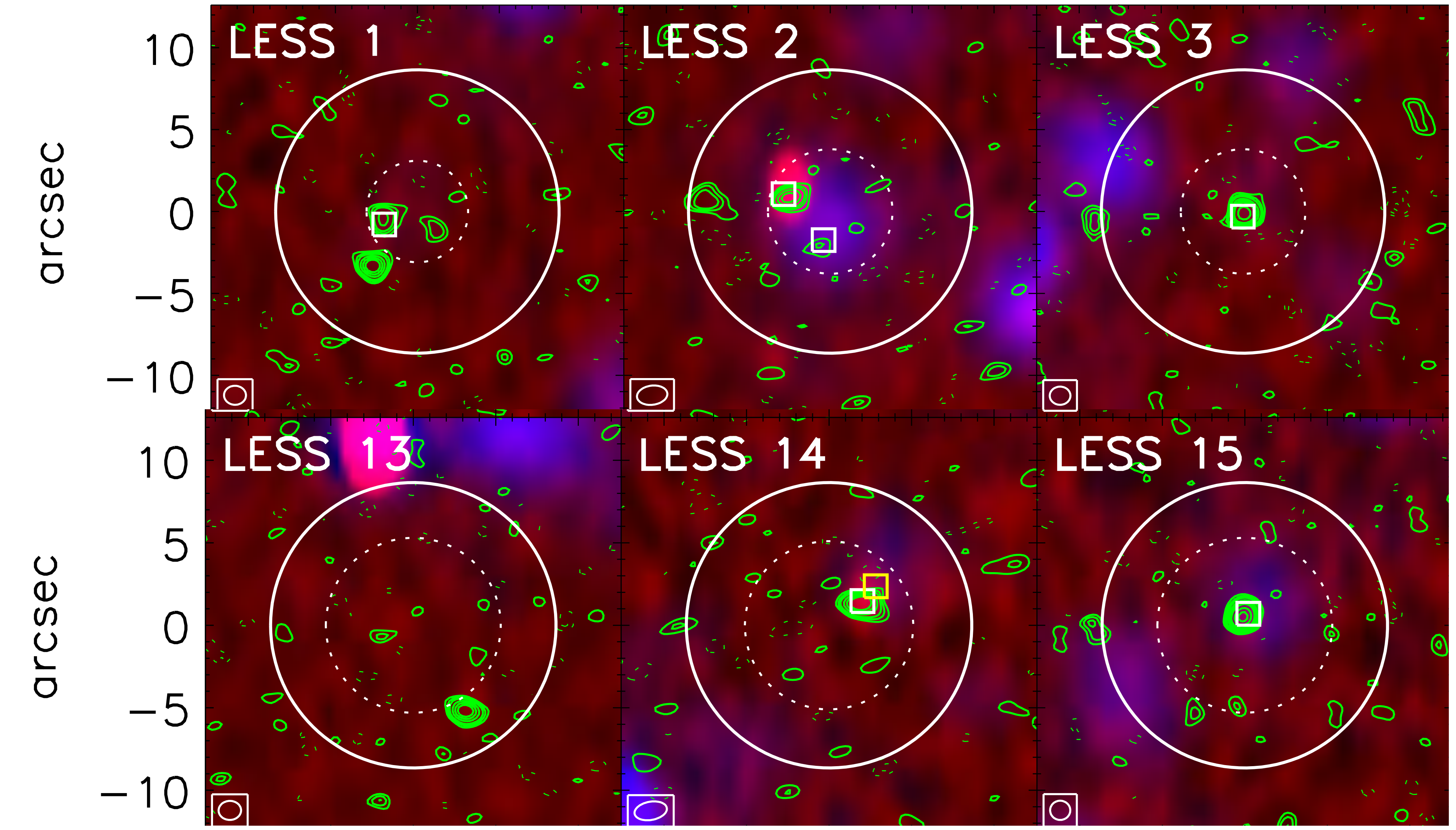
3,000 SMGs over 5 deg^2 at 850 μm (Geach et al. 2017)



Clustering of submillimeter galaxies

- Submillimeter galaxies is a population of dusty galaxies with strong emission at submillimeter wavelengths. The strong UV radiation from stars in these galaxies are absorbed by the dust and re-emitted at sub-millimeter wavelengths.

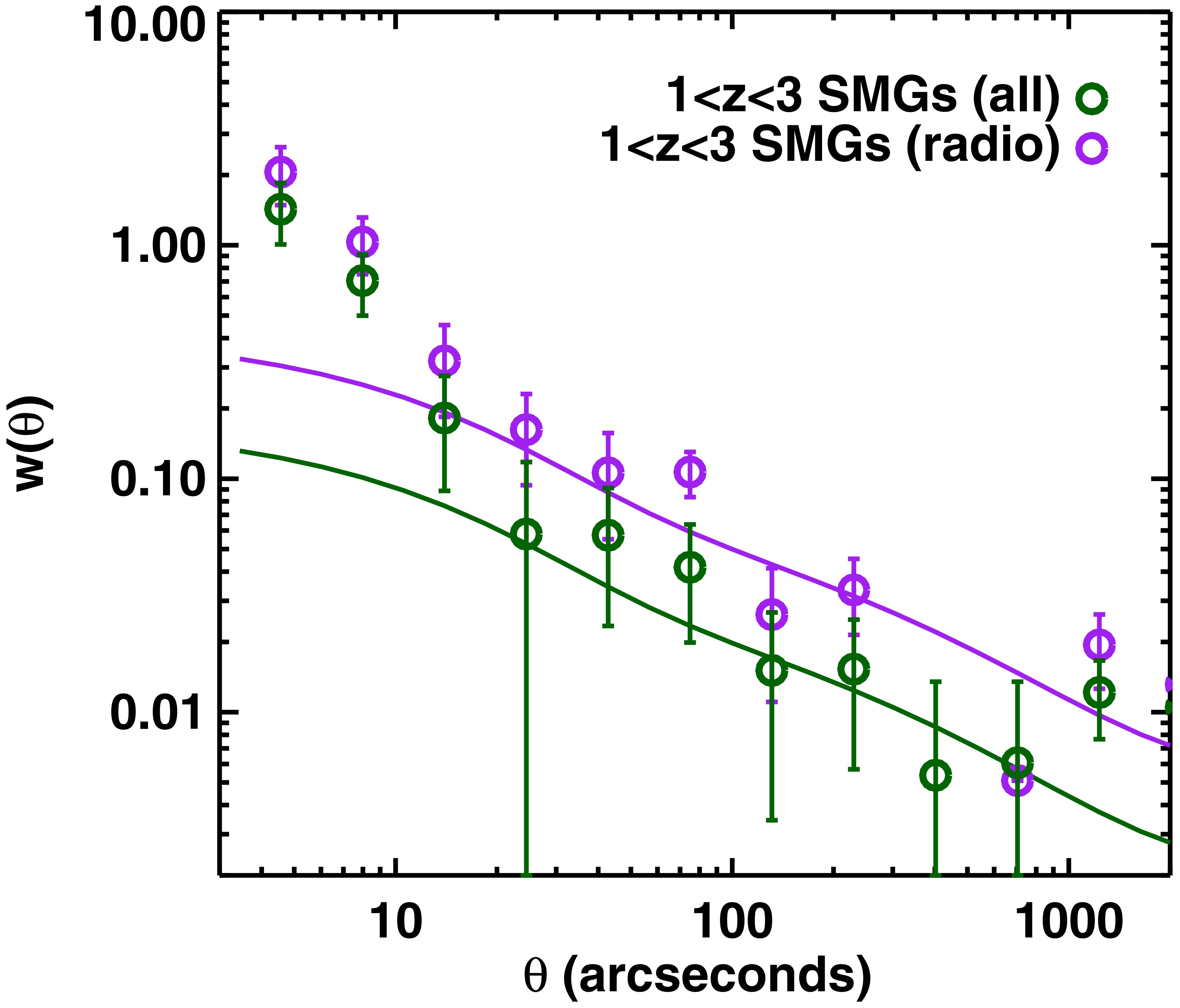
- SMGs are:
  - Extremely luminous ($L_{IR} \sim 10^{12} - 10^{13}\ L_\odot$)
  - Massive ($M_\star \sim 1 - 2 \times 10^{11}\ M_\odot$)
  - Highly star forming (star formation rate (SFR) ~ $100 - 1000\ M_\odot\ yr^{-1}$)
  - Peaking at redshifts $z \sim 2.2–2.5$



(Hodge et al. 2013)

Clustering of submillimeter galaxies

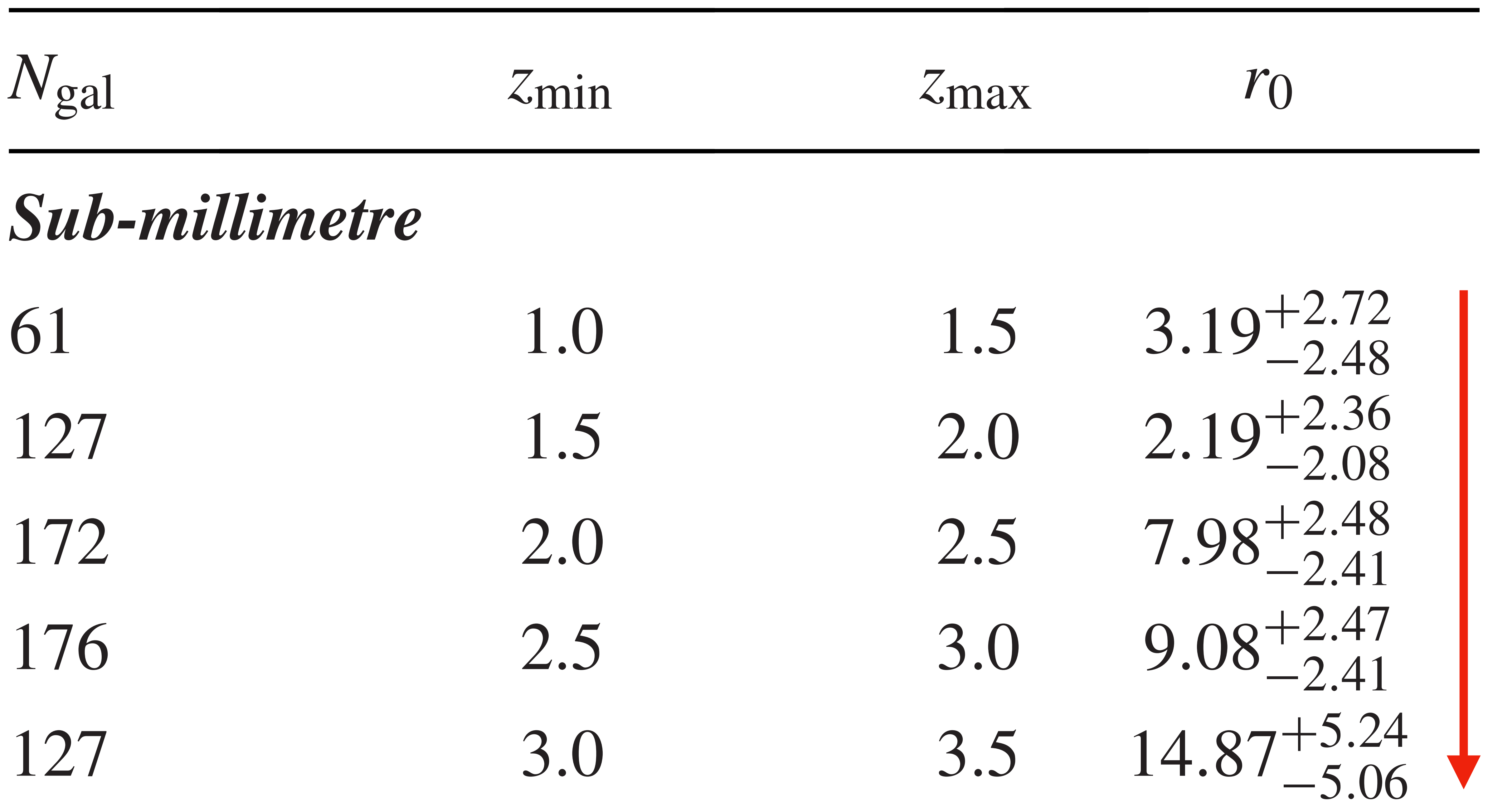
- Angular cross-correlation function of 365 Submillimeter galaxies from S2CLS reveal correlation lengths of ~4.1± 2 Mpc/h at redshift between 1 and 3.
- Because the small data, cross-correlation techniques are used in this case.



(Wilkinson et al. 2017)

Clustering of submillimeter galaxies

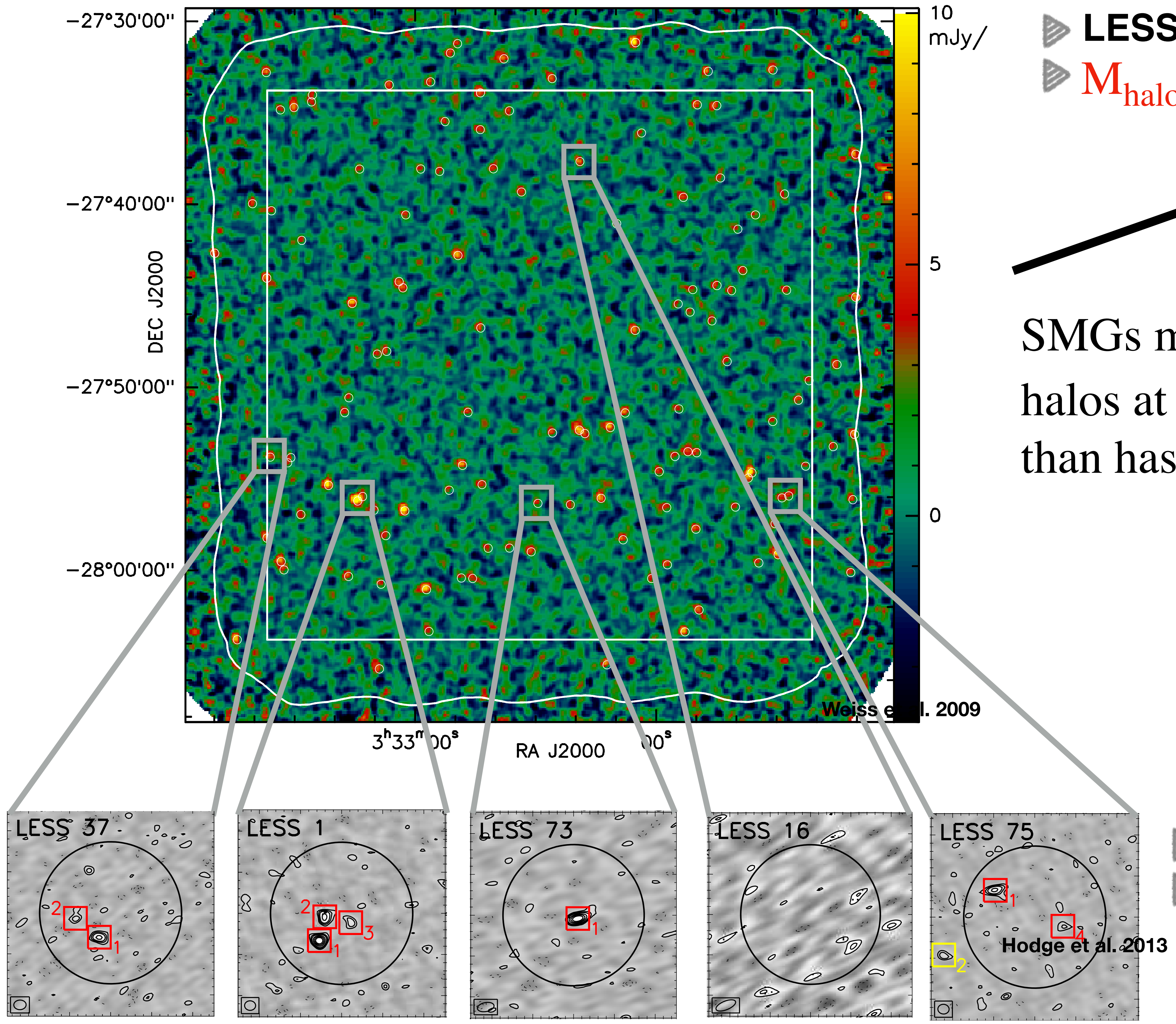
- Tentative evidence that the correlation length strongly increase at higher redshifts.



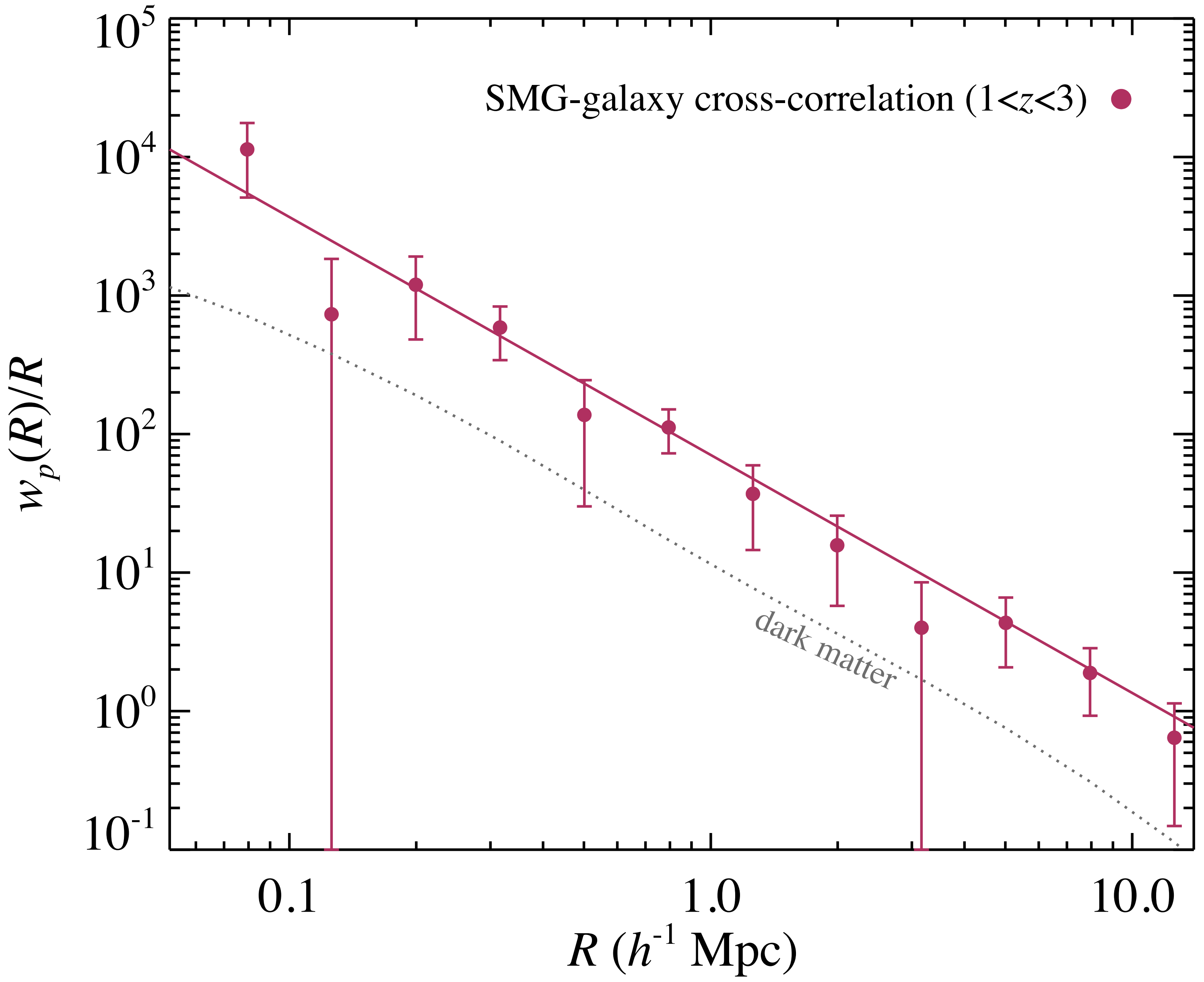
N_{gal}	z_{min}	z_{max}	r_0
Sub-millimetre			
61	1.0	1.5	$3.19^{+2.72}_{-2.48}$
127	1.5	2.0	$2.19^{+2.36}_{-2.08}$
172	2.0	2.5	$7.98^{+2.48}_{-2.41}$
176	2.5	3.0	$9.08^{+2.47}_{-2.41}$
127	3.0	3.5	$14.87^{+5.24}_{-5.06}$

(Wilkinson et al. 2017)

The SMG clustering based on single-dish observations was overestimated

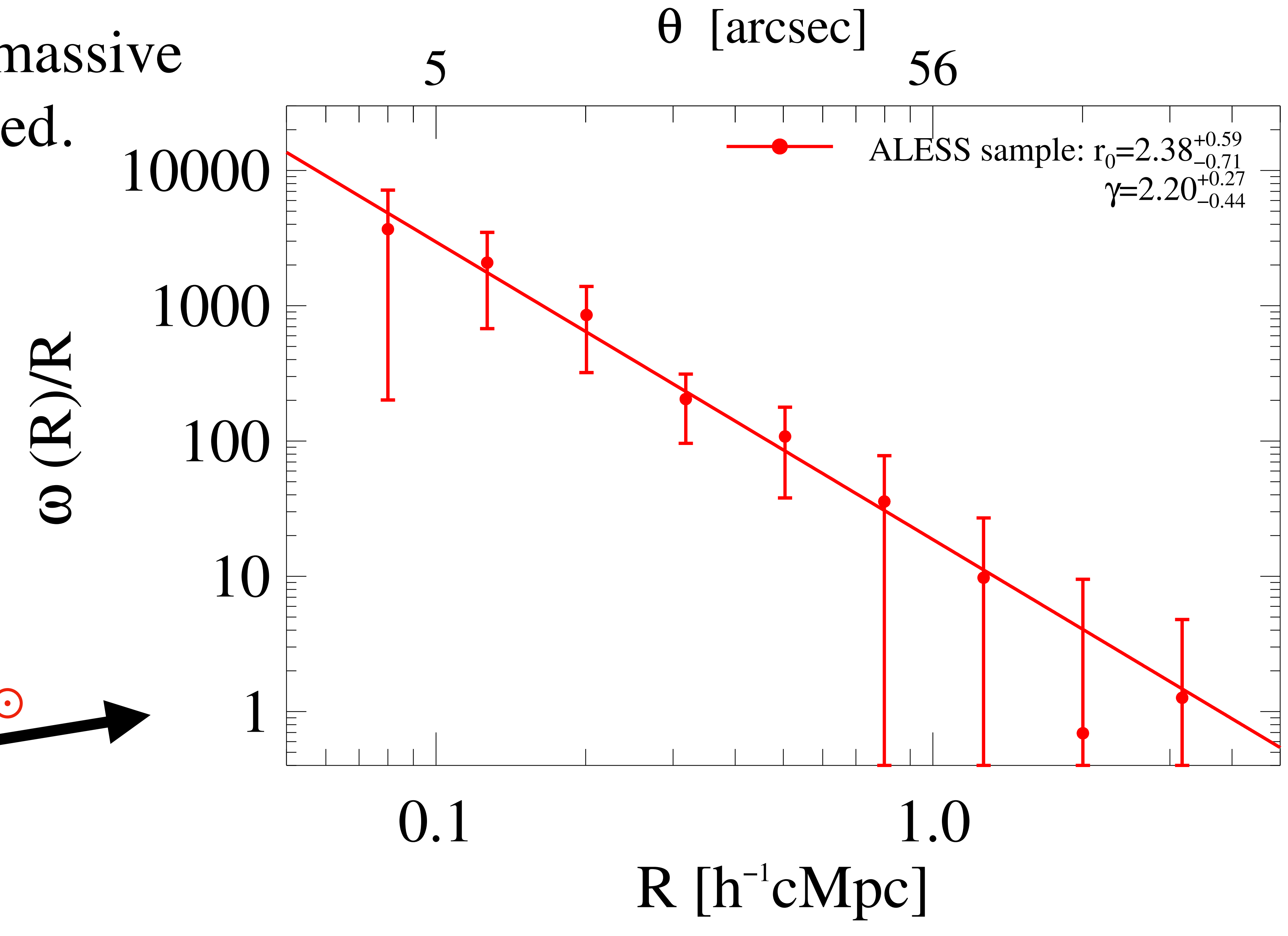


- **LESS**
- $M_{halo} = 9.0 \times 10^{12} M_\odot$



(Hickox et al. 2012)

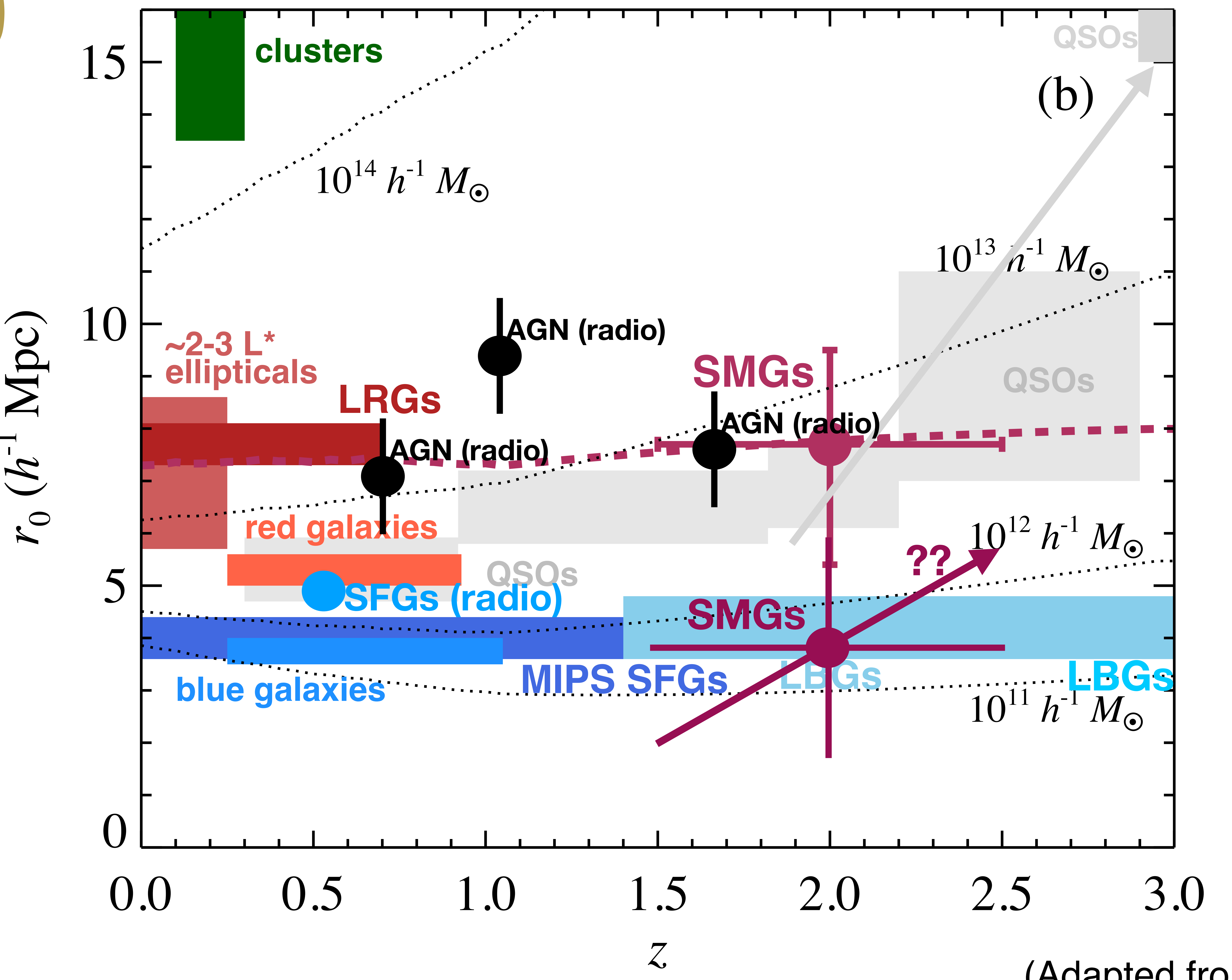
SMGs might be hosted by dark matter halos at least $3.8^{+3.8}_{-2.6}$ times less massive than has previously been estimated.



- **ALESS**
- $M_{halo} \leq 2.4 \times 10^{12} M_\odot$

(Garcia-Vergara et al. 2020)

Summarizing

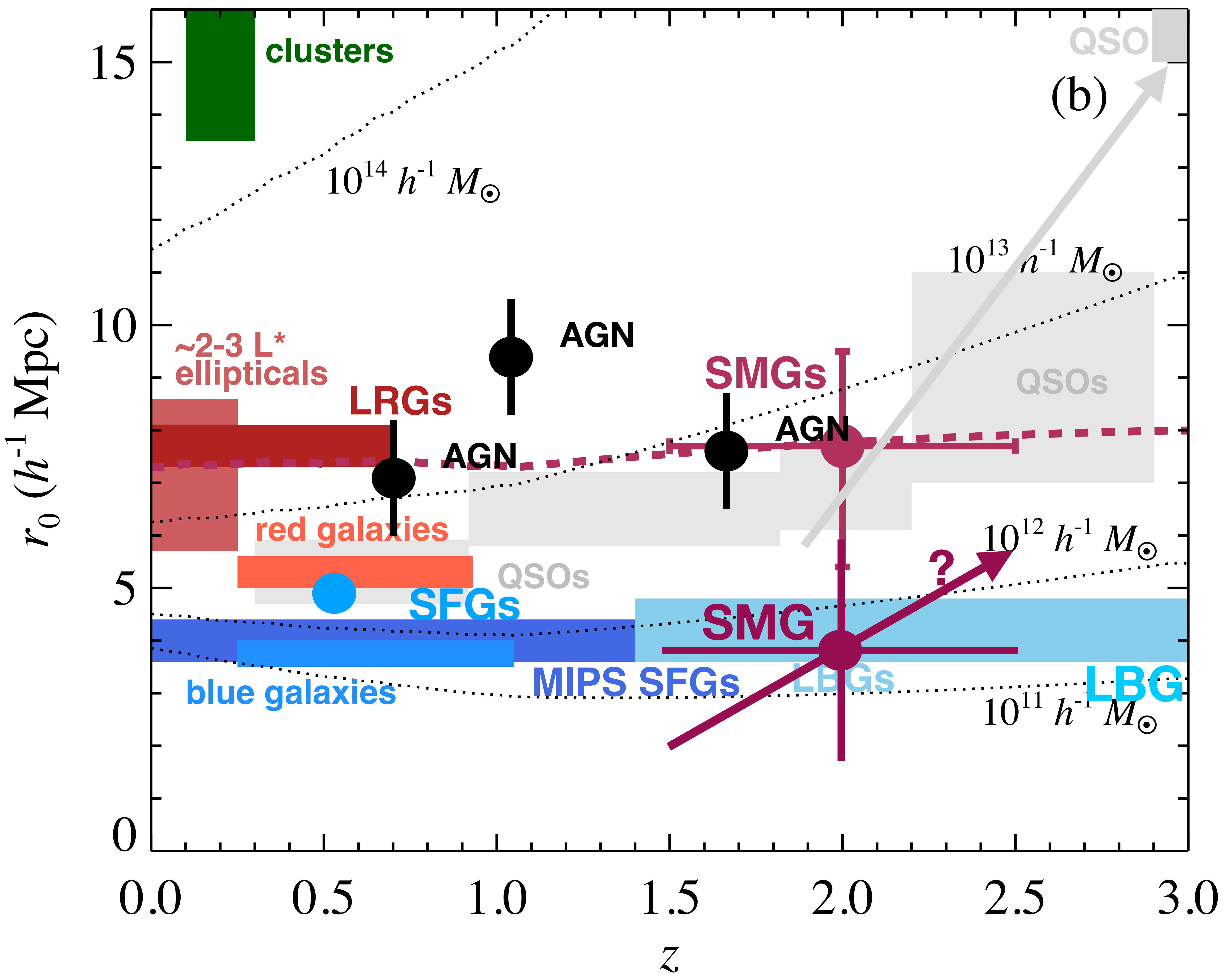


(Adapted from Hickox et al. 2012)

Next class

How can we interpret all these results?

- Correlation length values for different populations at different redshifts.
- How can we interpret the evolution of r_0 with redshift for the different populations?
- Coherent evolutionary scenario?



Take home message

- Large surveys of sources are required to perform accurate measurements of clustering.
- We have observed that in the local universe galaxies that are more luminous, early type, bulge-dominated, optically red, higher stellar mass and lower SFRs are more clustered than the less luminous, late type, disk-dominated, optically blue, lower stellar mass, higher SFRs.
- At higher redshift we can explore the clustering of other populations such as Active galactic nuclei (AGNs), quasars, Lyman break galaxies, submillimeter galaxies, Star forming galaxies, AGNs, etc.
- Against of the intuitive expectation in which the clustering of a population would increase with time, we observe that some population are equally clustered over long times and some of them decrease their clustering with time.
- Clustering measurements of different populations and at different wavelengths, may provide a complete understanding of galaxy evolution.