# The VIMOS-VLT Deep Survey (VVDS): last 10 bln years of the evolution of the large scale structure in the Universe

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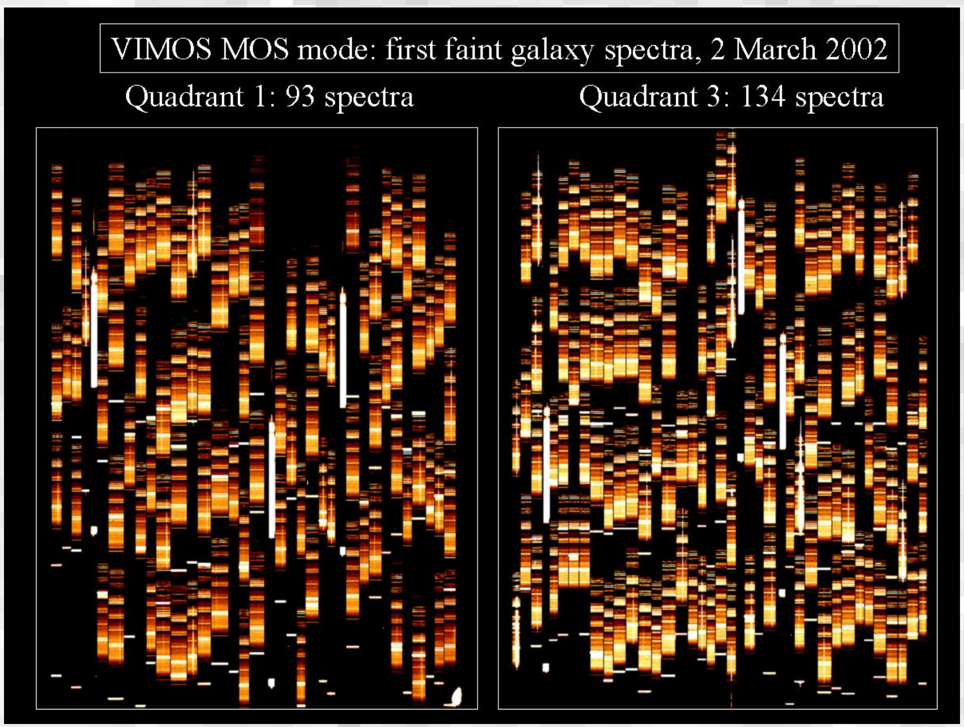
# The VIMOS-VLT Deep Survey

- A magnitude-limited only large deep spectroscopic redshift survey performed on the VIMOS multispectrograph installed on one of the 8.2 m ESO VLT telescopes

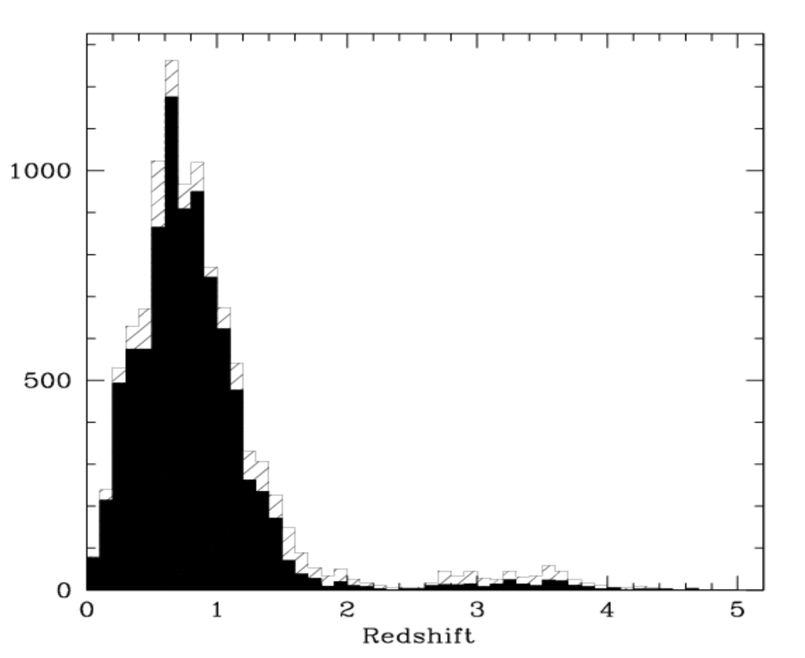



- VVDS data:
- VVDS-Deep (Le Fevre et al. 2004, Le Fevre et al. 2005)
- VVDS-Wide (Garilli et al. 2008)
- VVDS “Ultra-Deep”: (analysis on-going)
  - A large part of the data (Deep and Wide) is already public:

http://cencosw.oamp.fr/EN/index.en.html

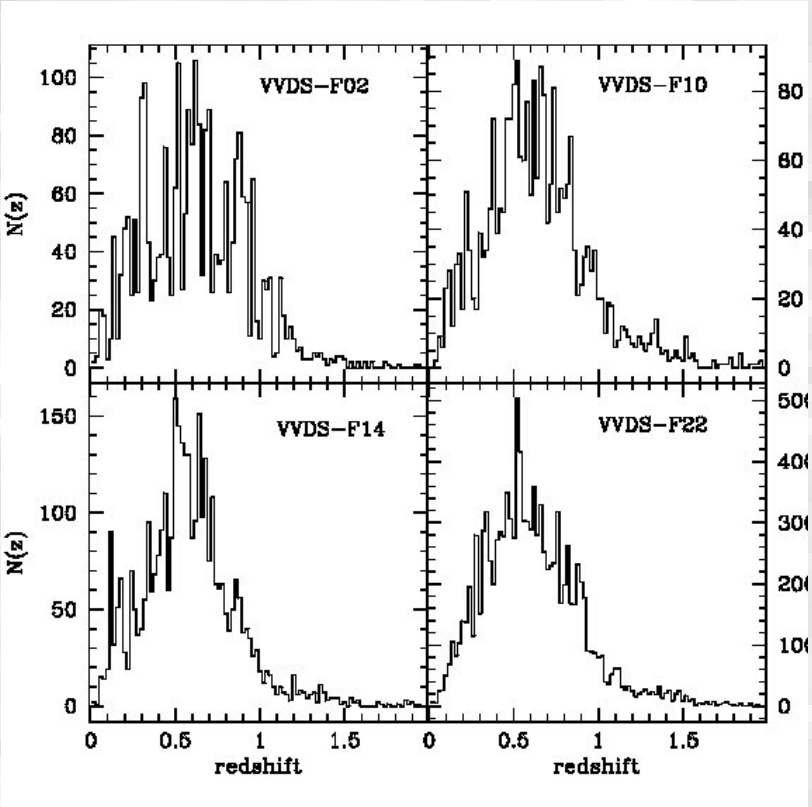
# The VIMOS-VLT Deep Survey

- VVDS Deep data:
  - 11 564 spectra
  - from $17.5 < I_{AB} < 24$, fields 1226-04 and CDFS, area 0.61 $deg^2$;
  - 10518 galaxies with z measured with a confidence level > 80%;
  - 836 stars, 85 AGNs, 125 unidentified objects;
  - sampling rate 25%-30%;
  - $0 < z < 5$
  - (Le Fevre et al. 2004 and 2005)



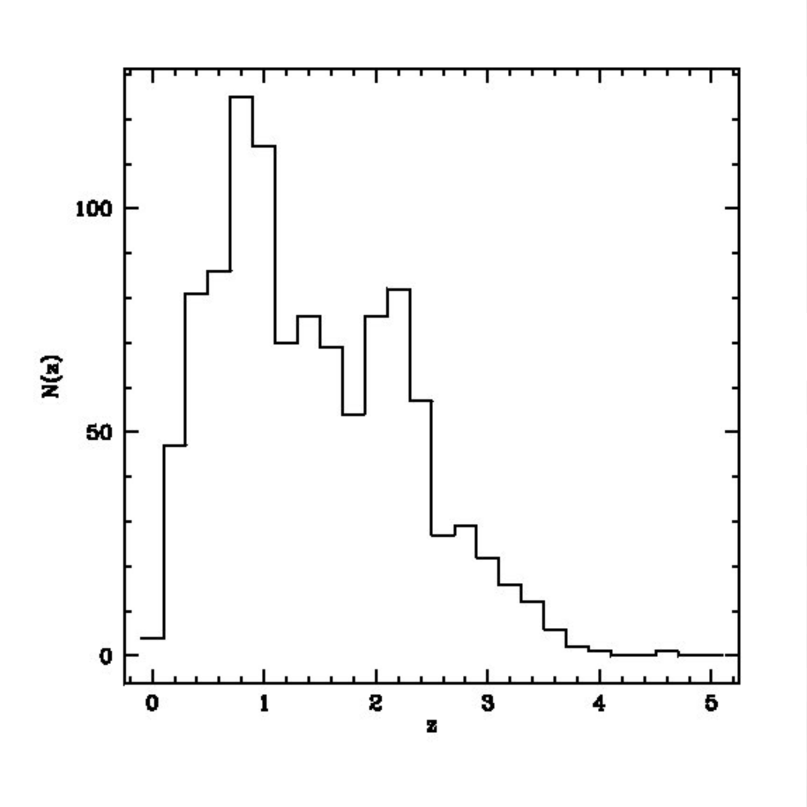
# The VIMOS-VLT Deep Survey

- VVDS-Wide:
  - up to $I_{AB}$ =22.5;
  - 32 734 spectra
  - 19 977 galaxies, 304 type I AGNs, 9913 stars
  - in the four regions, covering a total area of 6.1 $deg^2$;
  - sampling rate of 22 to 24%
  - Garilli et al. 2008



# The VIMOS-VLT Deep Survey

- VVDS “Ultra-Deep”:
  - up to $I_{AB}$ =24.75
  - 3 more pointings in the 1226-04 (the center of the “Deep” catalog)
  - additional 1057 galaxy redshifts in the “clean” area
- (analysis on-going)



# Large Scale Structure : basic theory

Expectations: in the framework of the hierarchical models of the structure formation, we expect galaxies to become more and more clustered with cosmic time.

# Large Scale Structure : tough reality

In practice, the issue is not easy to investigate. What we observe, is not exactly mass but galaxies of different properties. We

1. observe different classes of objects at different cosmic epochs
2. have no guarantee that seemingly similar objects trace the Large Scale Structure in the same way in different cosmic times

# Large Scale Structure : basic tools

The simplest statistics used to investigate the clustering of galaxies is the 2-point correlation function.
It is defined as a probability above random that we find a pair of objects (galaxies) at a certain (spatial, angular) separation.

# Large Scale Structure : basic tools

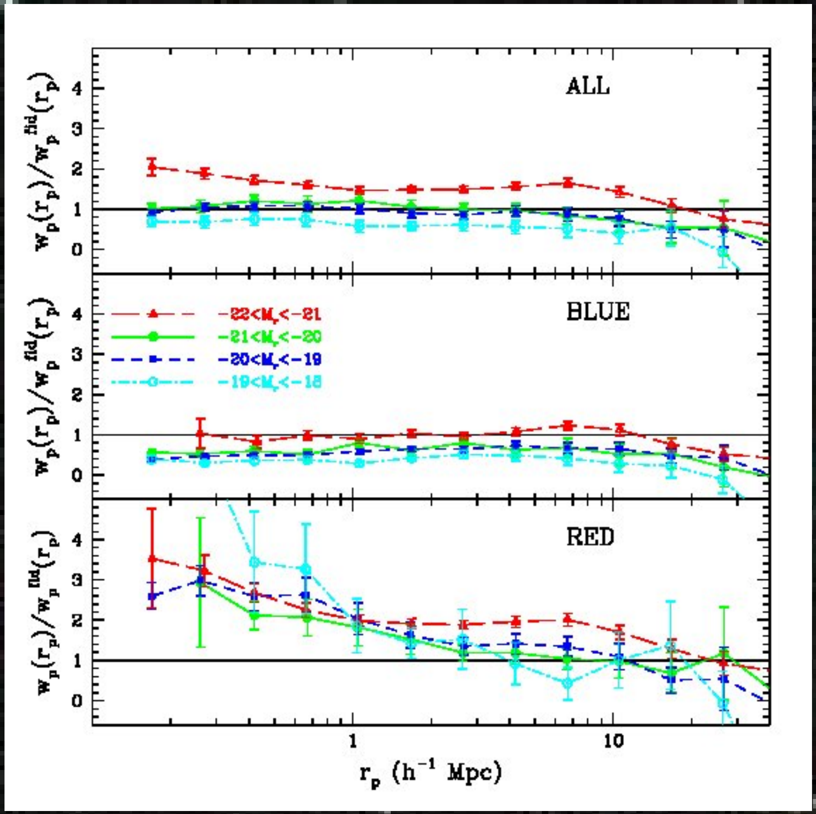
It has been shown already in 60s that the local galaxy CF almost in all cases is well fitted by a power law:

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

$r_0$ is called the correlation length. It corresponds to the scale on which the probability of finding a pair of galaxies is twice as big as random.

For local galaxies typically $r_0$=5 $h^{-1}$ Mpc and $\gamma$ = 1.8.

# Large Scale Structure today

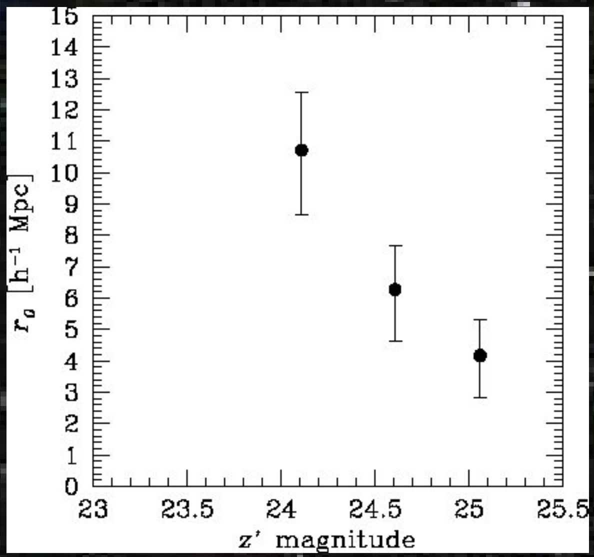



Zehavi et al. 2005 (SDSS)

Now we know,however, that the situation is more complex. Locally, i.e. at z~0, clustering properties of galaxies depend on their properties: red galaxies are more clustered than blue, luminous – more clustered than faint. The CF fit is not so perfectly power law, even if still very close

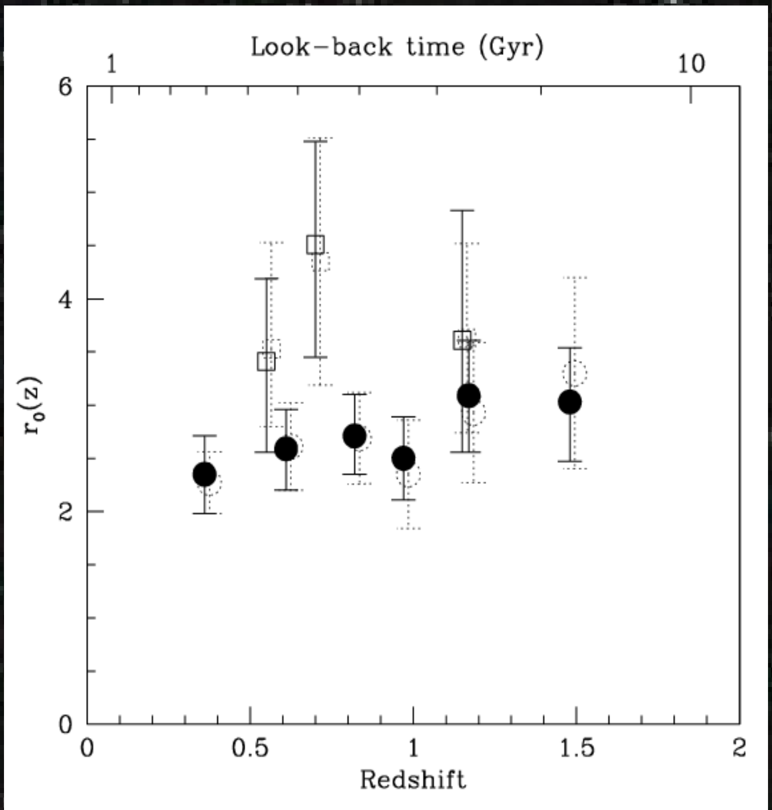
# Large Scale Structure through (cosmic) ages

The highest redshifts we reach are z~3-6. At these redshifts the main population of galaxies found and then used as the Large Scale Structure indicators are the Lyman break galaxies. They are known to be highly clustered. But they are also extremely luminous and we can expect that they belong to the most biased and most strongly clustered population).




Yoshida et al. 2008 (SDXS)

# VVDS: galaxy clustering until z~2




$$w_p(r_p) = 2\int_0^{\infty} d\pi\; \xi(r_p, \pi) = 2\int_0^{\infty} dy\; \xi(r_p^2 + y^2)^{1/2}$$

$$w_p(r_p) = r_p \left(\frac{r_0}{r_p}\right)^{\gamma} \frac{\Gamma(\frac{1}{2})\Gamma(\frac{\gamma-1}{2})}{\Gamma(\frac{\gamma}{2})}$$

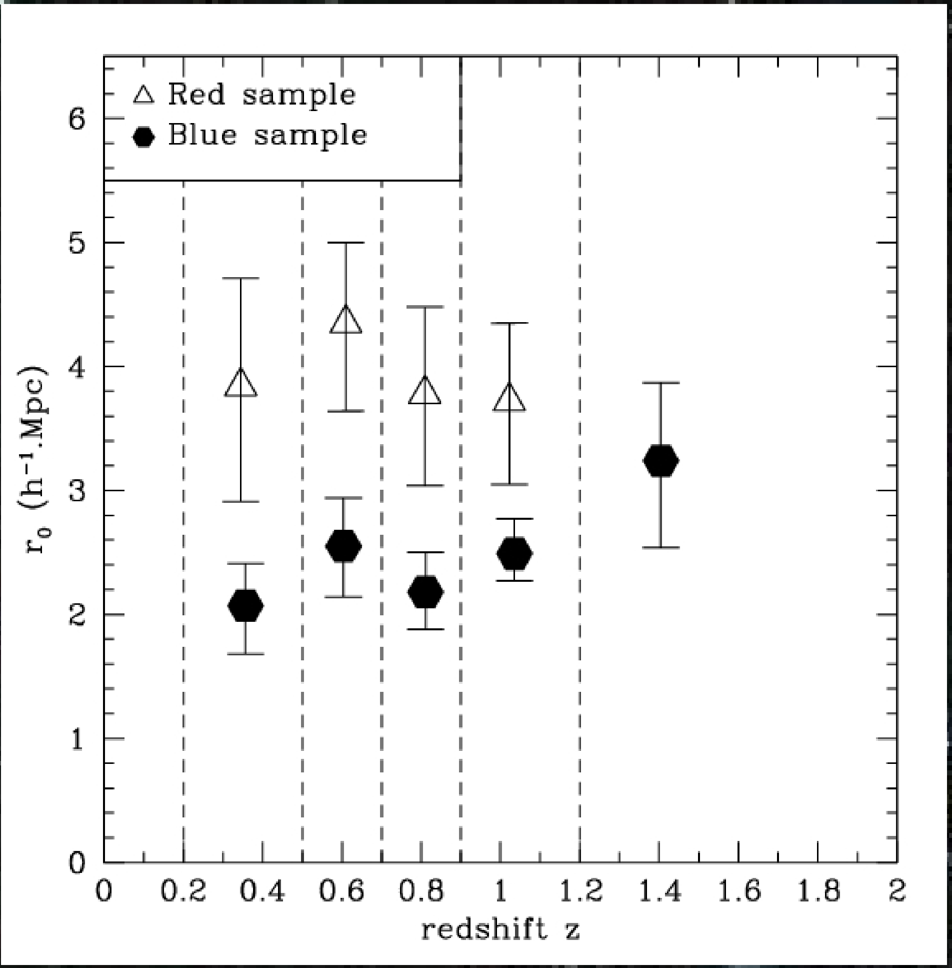
for a power-law $\xi(r)$,

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

- the 2-point spatial correlation function, projected along the line of sight, $w_p(r_p)$, is the main tool used to measure clustering properties of galaxies
- for a power-law shape of the CF: correlation length $r_0$ and slope $\gamma$
- for a general galaxy population: CF weakly evolving up to z~2: the LSS emerging from the redshift desert looks almost the same as today
- which may be interpreted as a mixed effect of evolution of the LSS (stronger clustering with time) and observational bias (at higher z we see brighter and more clustered objects)
- we need some indicators to compare more alike galaxies at different redshifts

Pollo et al., 2005 and LeFevre et al., 2005

# Galaxy clustering in the VVDS: color dependence

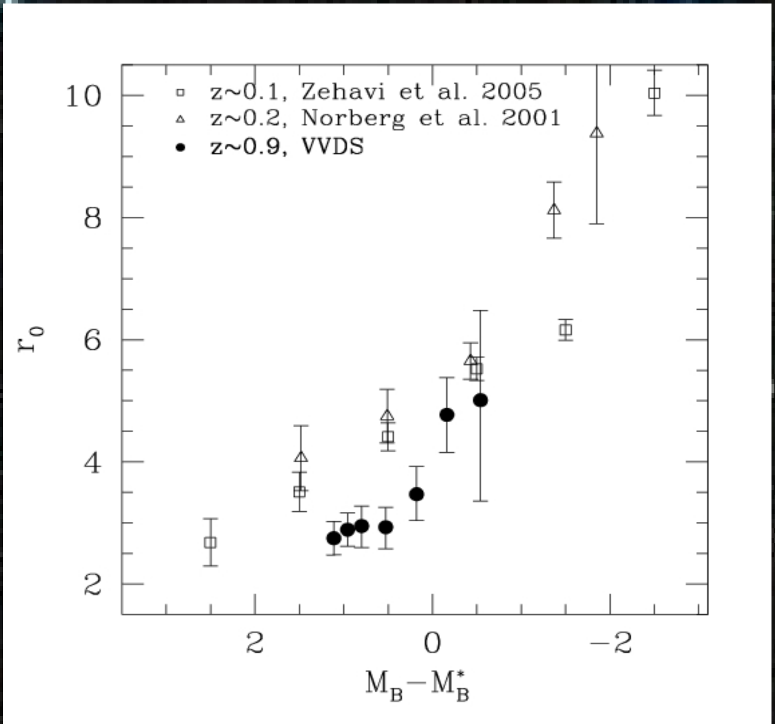


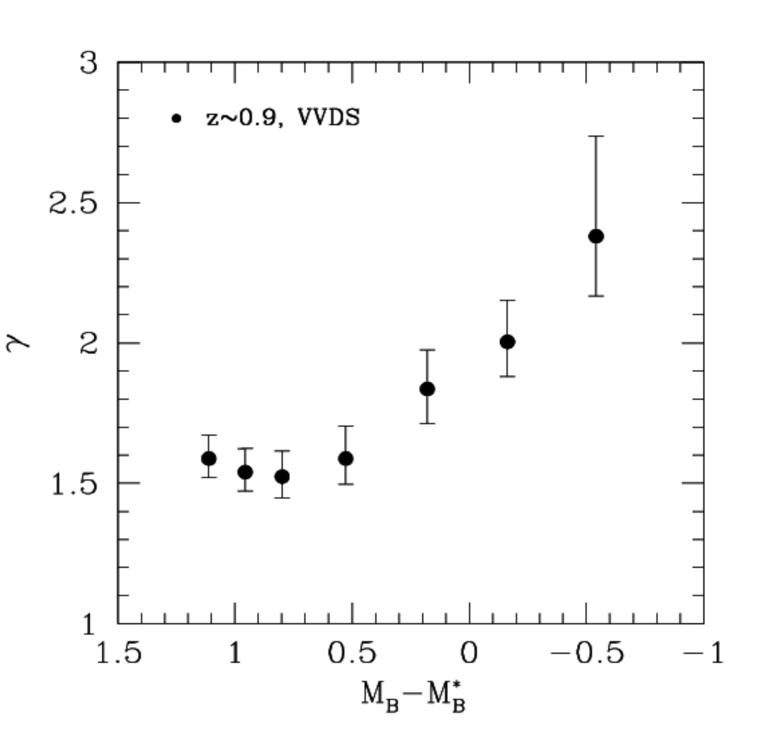

The clustering of blue and red galaxies remains remarkably stable until the verge of the redshift desert: red galaxies remain more clustered than blue ones. However, there is a hind of a reversal of this trend at z~1. A change of the environment of the red/blue luminous galaxies is also observed in the local environment analysis (Cucciati et al. 2006).

Does it mean that the actual shift of the star formation sites from the dense to underdense environments happened in the redshift desert?

Meneux et al., 2006

# Galaxy clustering in the VVDS: absolute luminosity dependence




## z~0.9

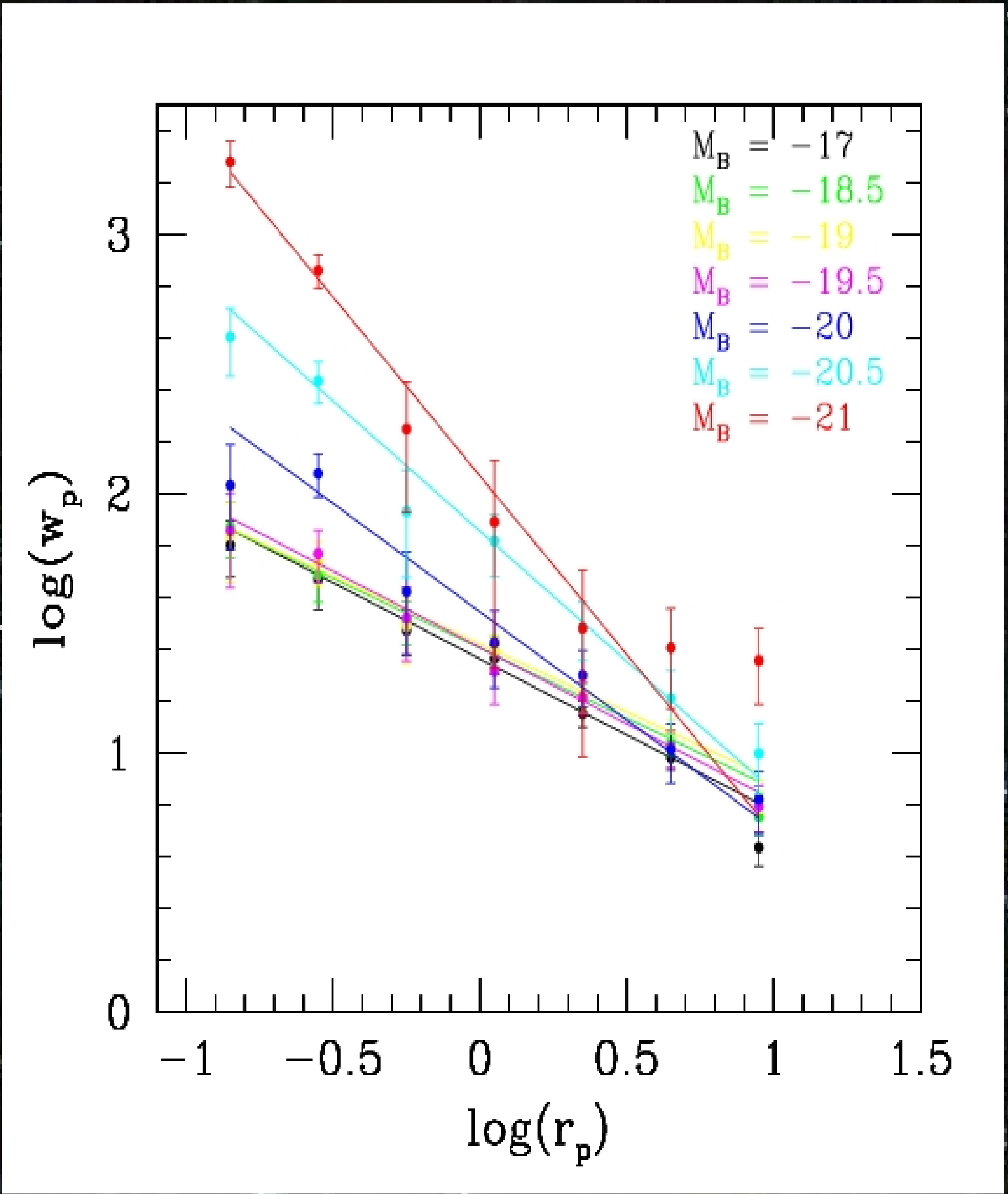
$r_0$: rises more steeply than locally in case of galaxies brighter than M*

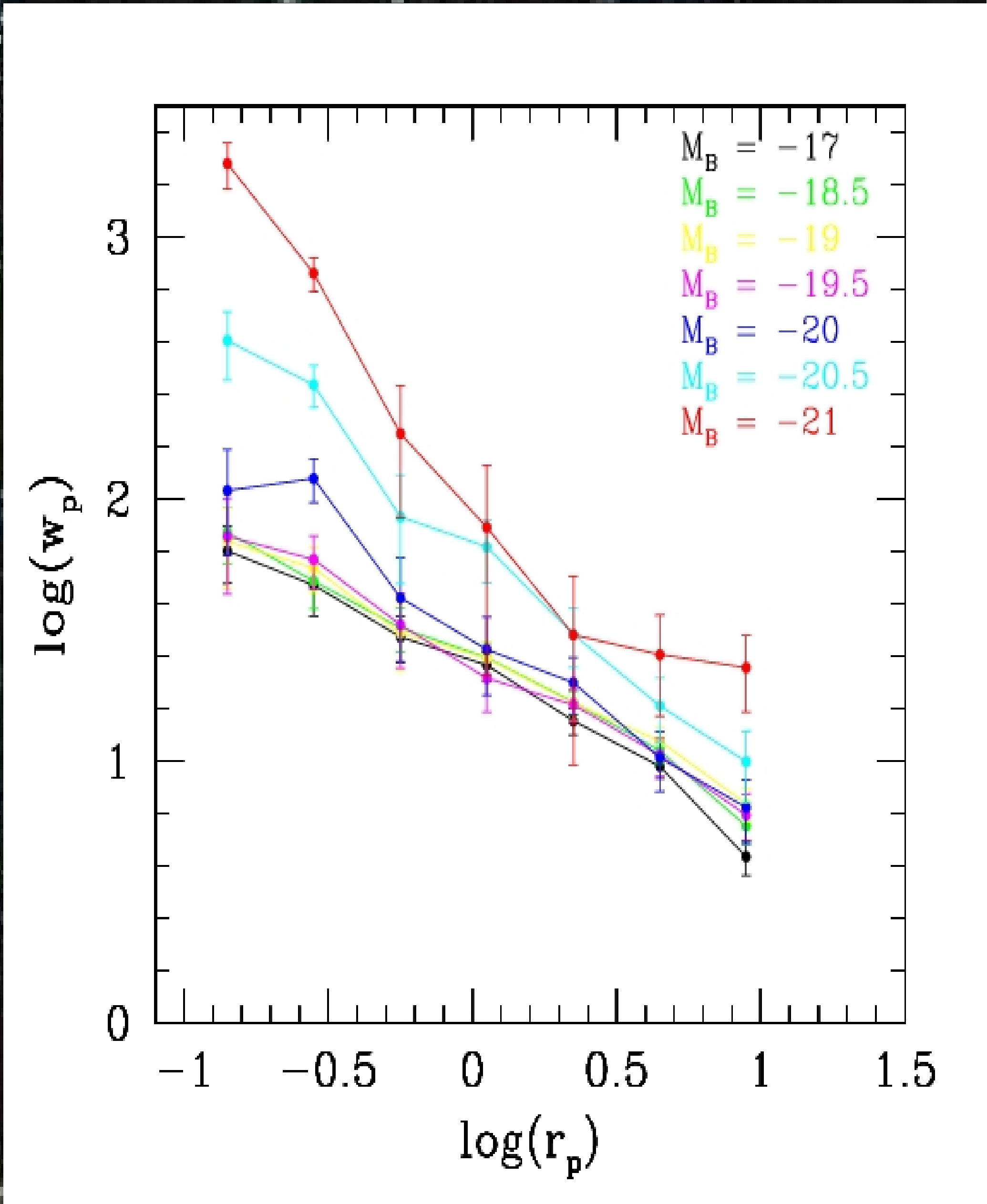
$\gamma$ rises as well for galaxies brighter than M*, unlike at lower redshifts (safe the very brightest galaxies in the SDSS, see Zehavi et al. 2005)

This is the first time $\xi(L)$ has been measured at z significantly different from 0 (see also Coil et al., 2006 for similar results from DEEP2).

Pollo et al., 2006

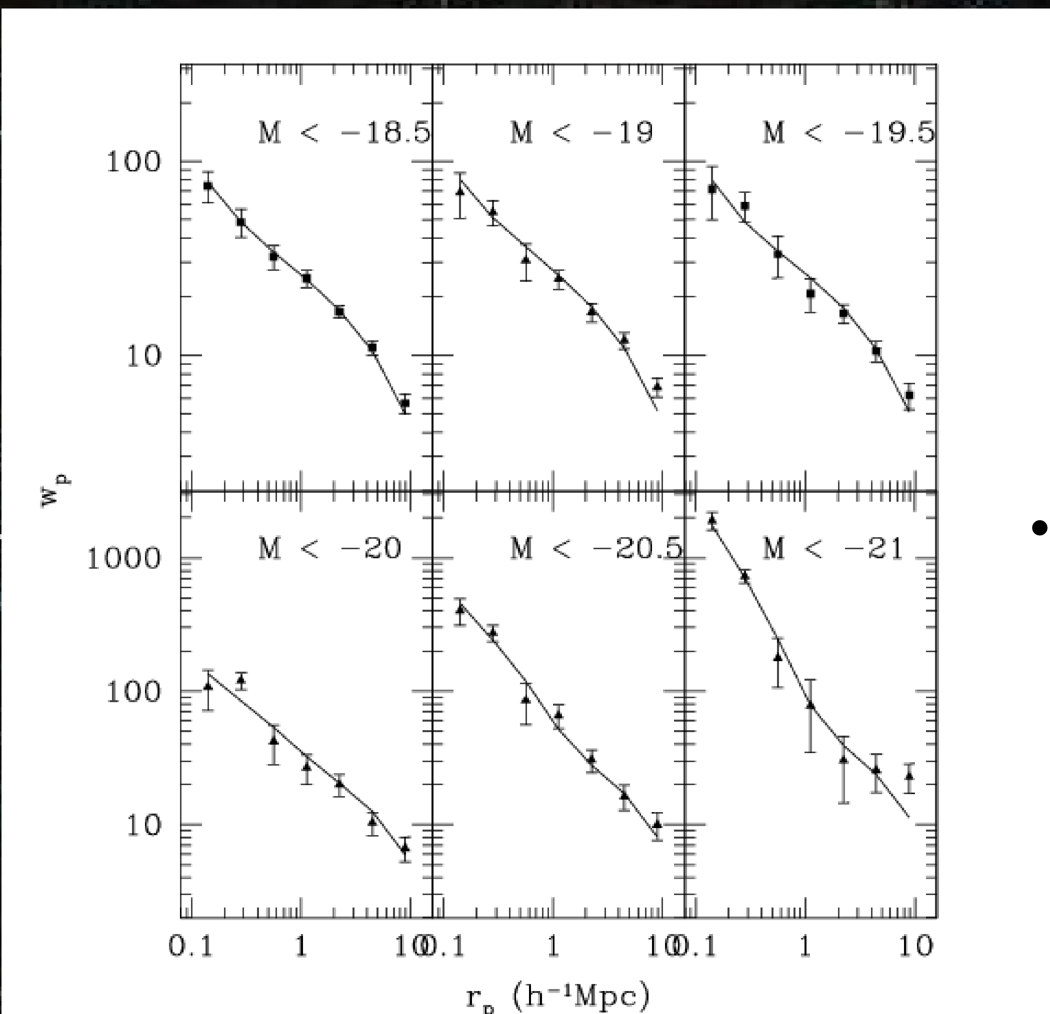
The actual reason for that behaviour is that for galaxies brighter than M*
correlation function does not really follow the power law fit



# A non-power-law CF can be described in terms of the Halo Occupation Distribution Models

z~0.9

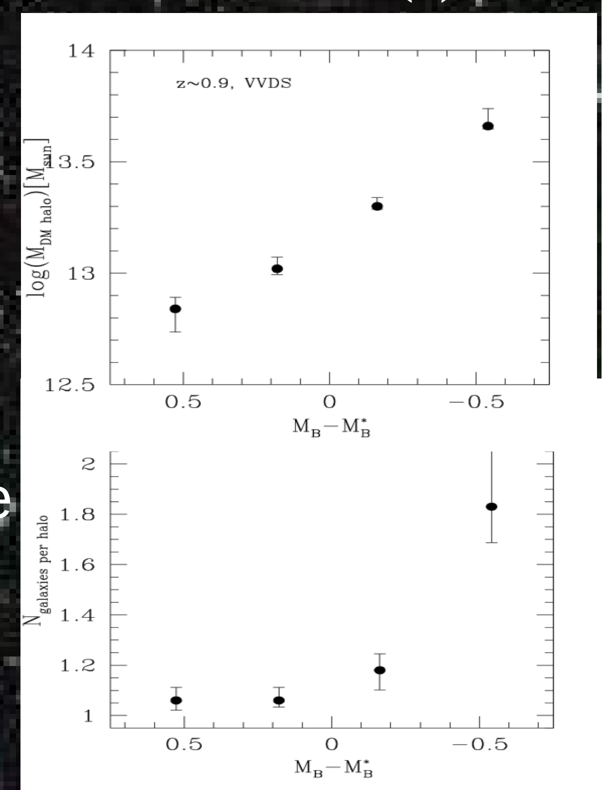



- Tinker et al. (2005) model, with $N_g(M)=1+N_{sat}=1+M/M_1 \exp(-M_{cut}/M)$ for $M>M_{min}$ and 0 otherwise

  3 free parameters, NFW profiles,

  Sheth and Tormen halo clust., linear P(k), linear bias

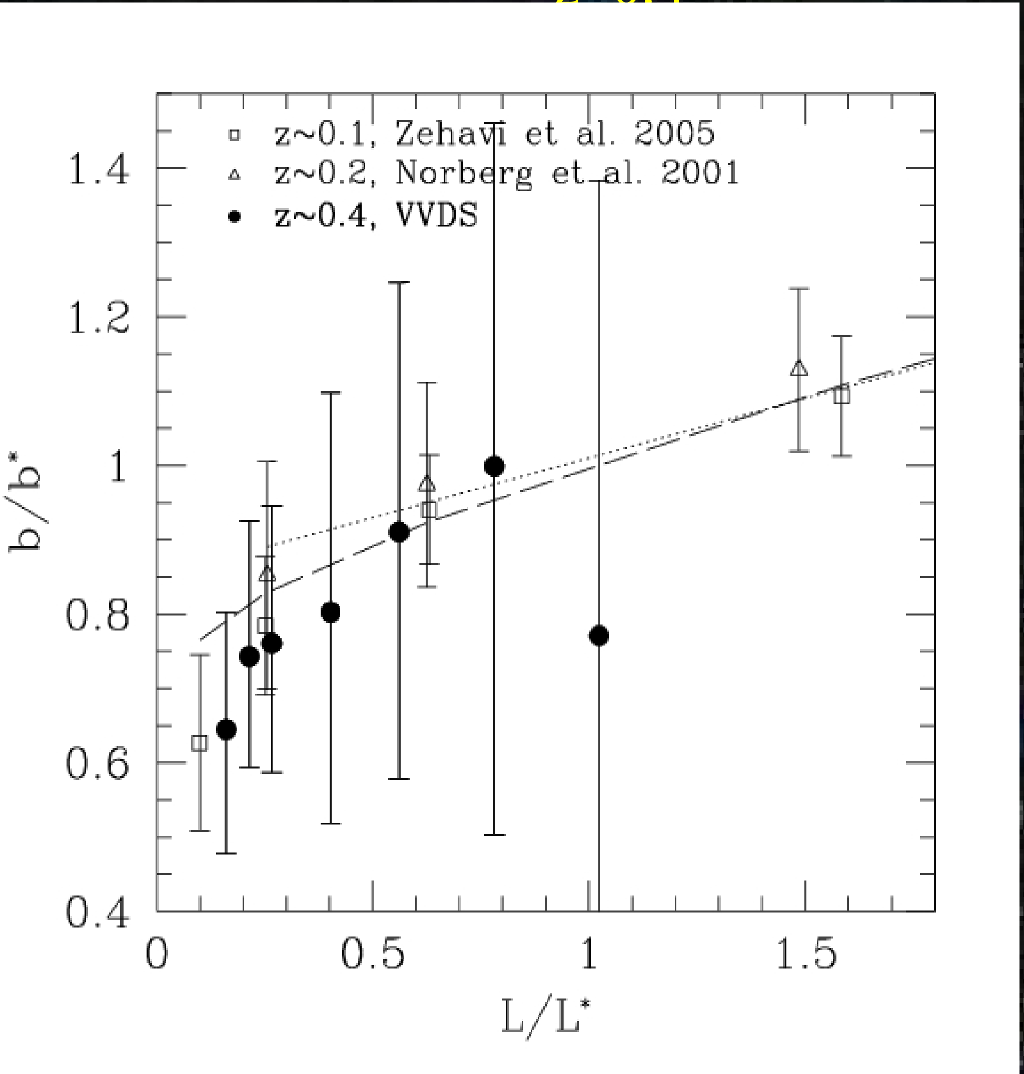
- We can trace how an average halo mass and number of satellites change with central galaxy luminosity



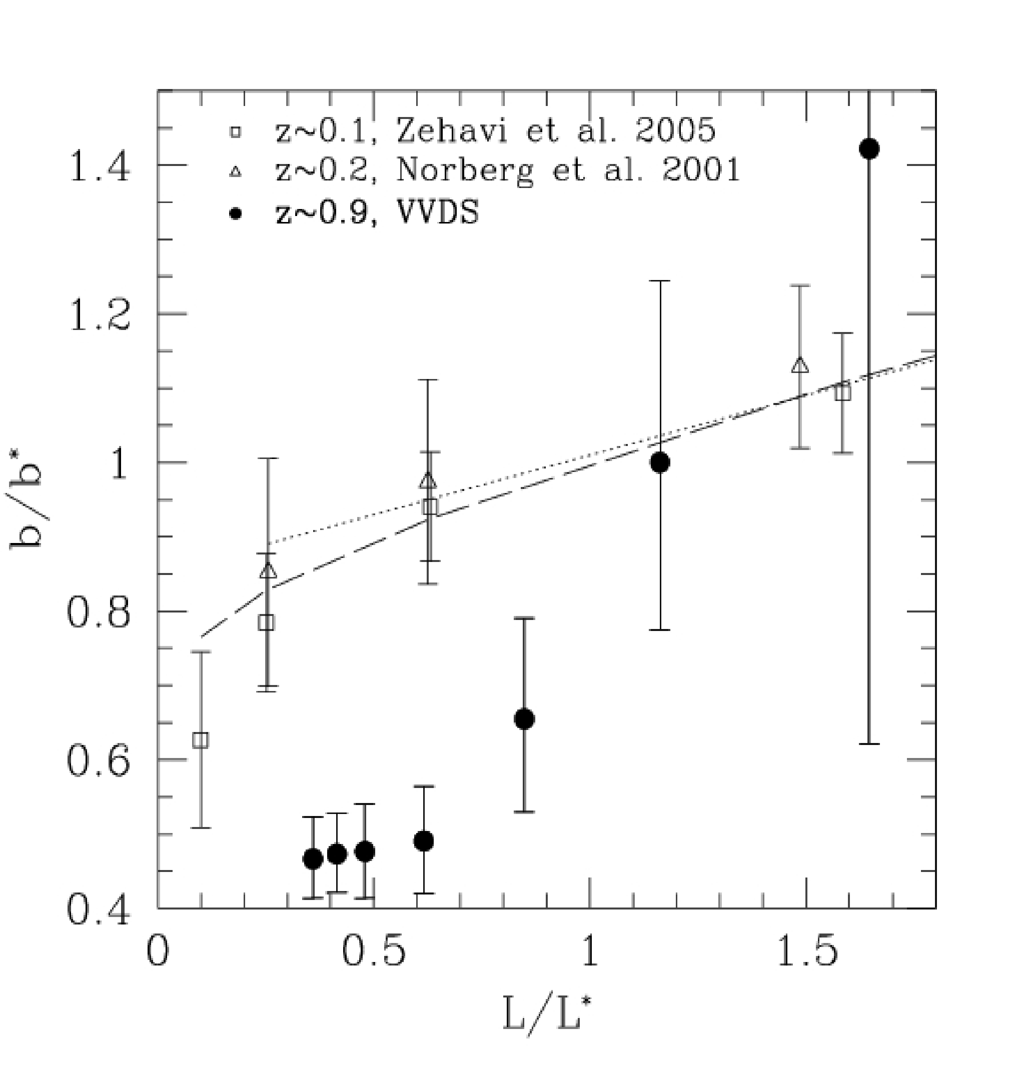

Abbas et al., A&A subm.; Pollo et al., in prep.

Relative bias at z~1: at 1 Mpc scale (~transition between 1-and 2-halo terms) the luminosity dependence of the relative bias with respect to M* galaxies is very different than locally. Does it mean a significant evolution of 1 halo term between high z and now?

z~0.4

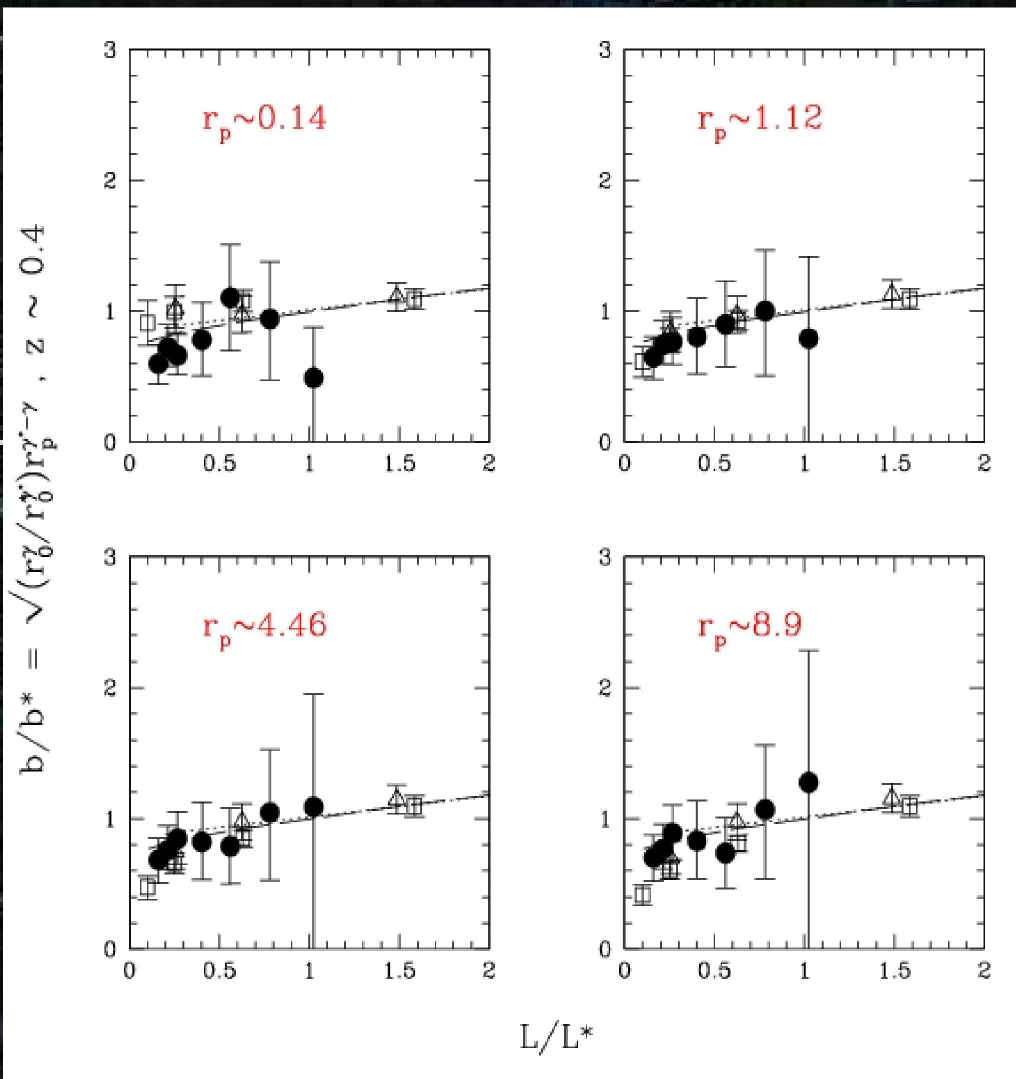



z~0.9

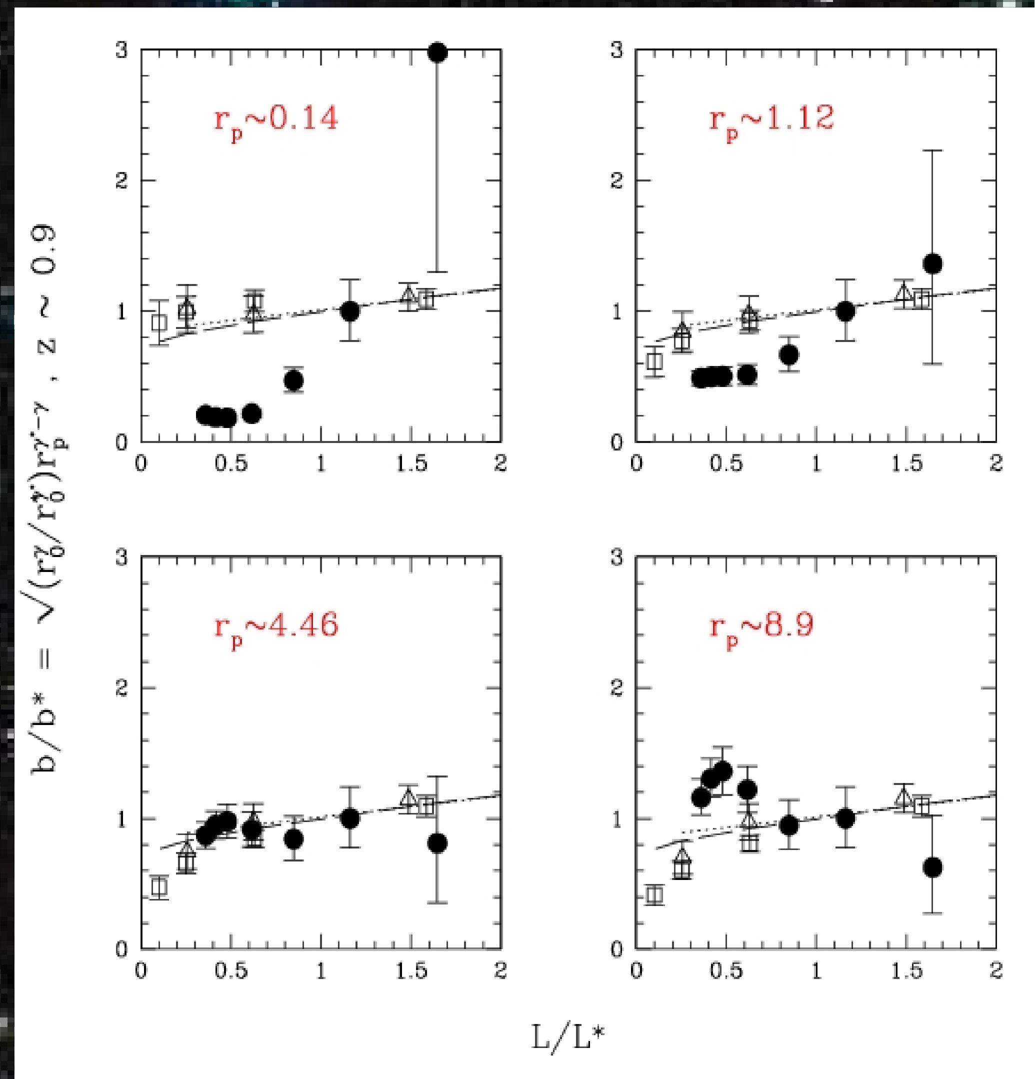


Relative bias at z~1 is also “globally” scale-dependent (see also Marinoni et al. 2005 & 2008) – does it imply a time-evolving scale dependence of halo vs DM bias as well? (bigger volumes needed to answer this question)

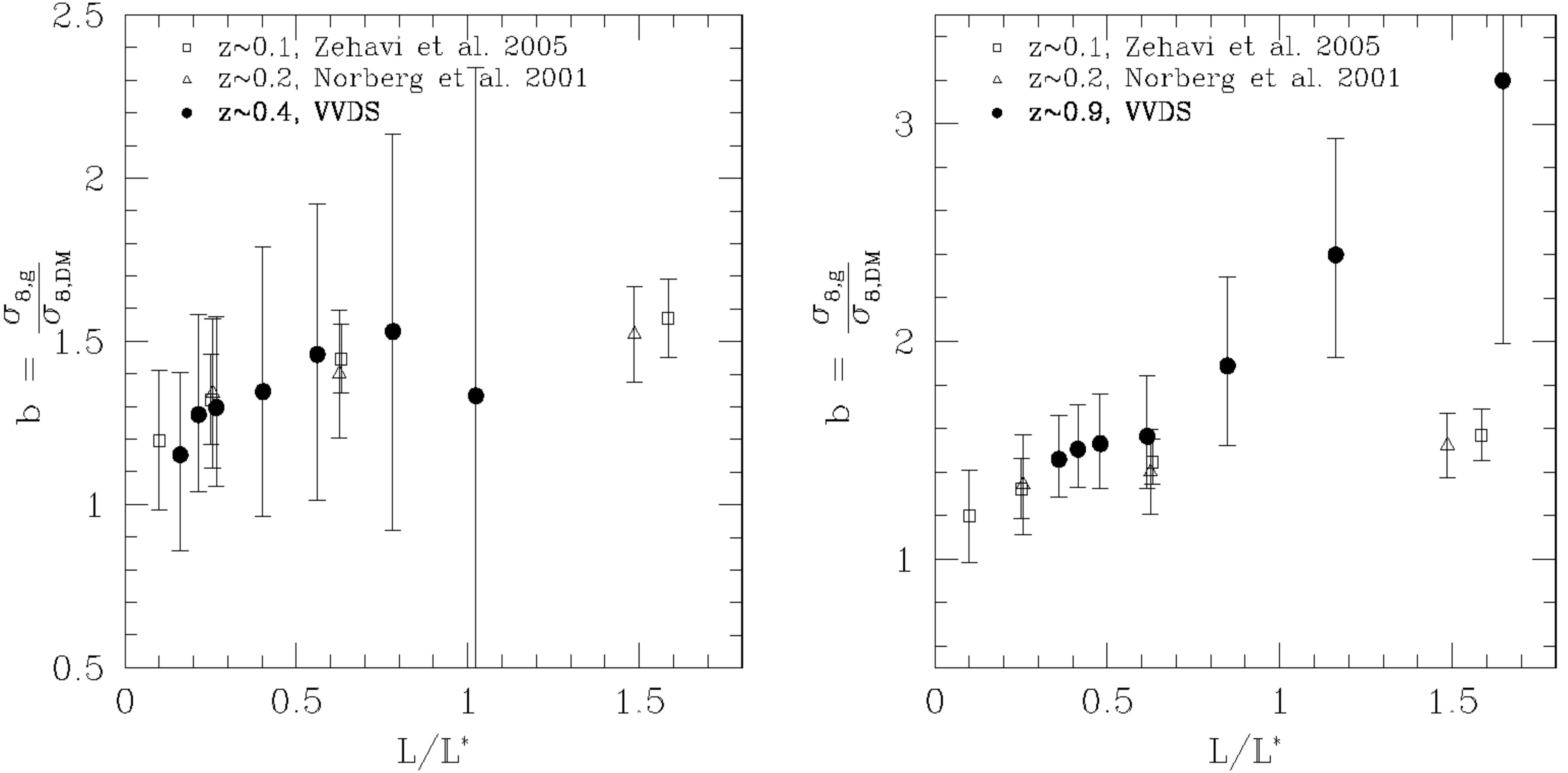
z~0.4



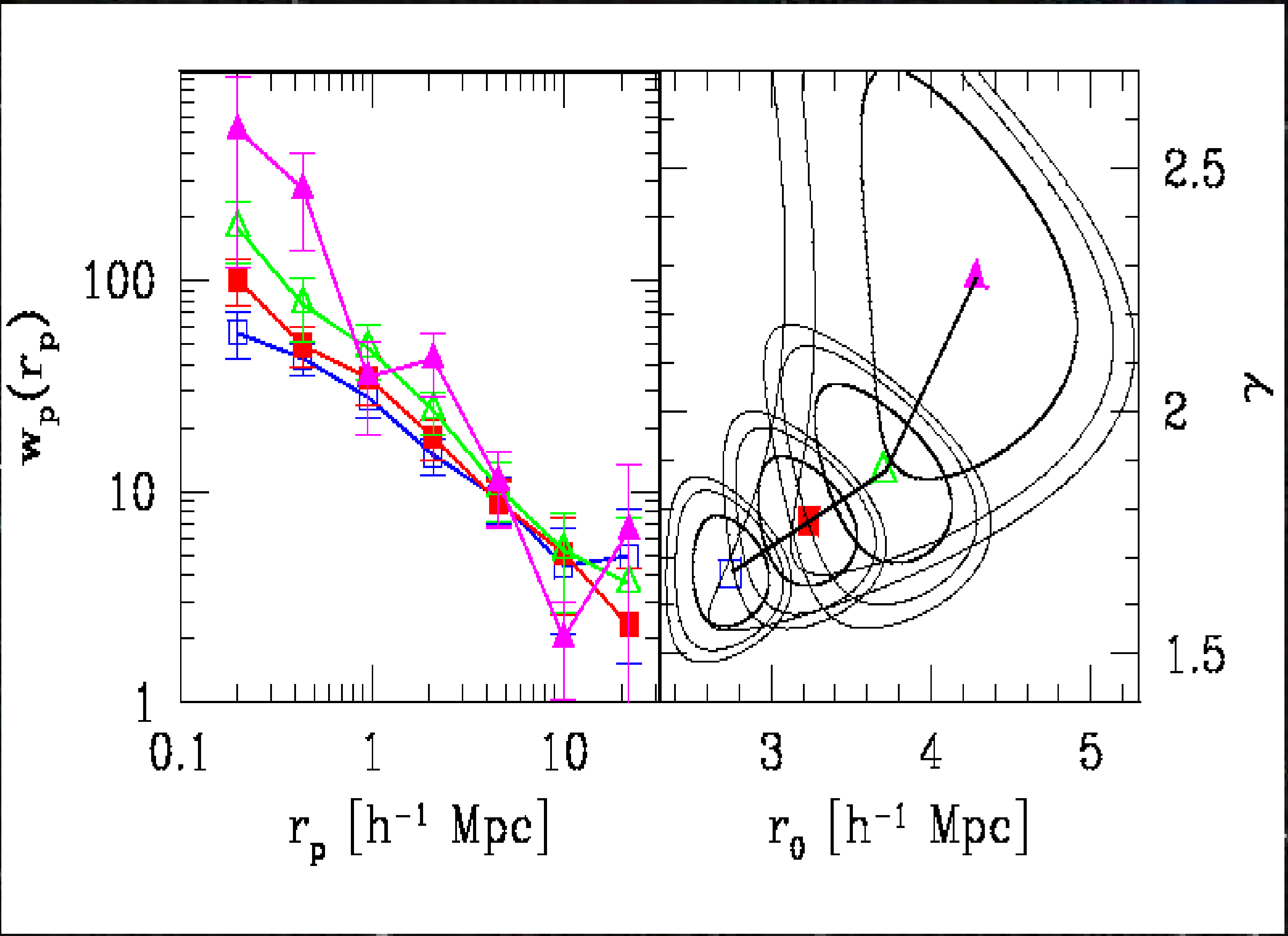

z~0.9



# A linear galaxy vs DM bias, computed at 8 Mpc scale, evolves faster for galaxies brighter than M*



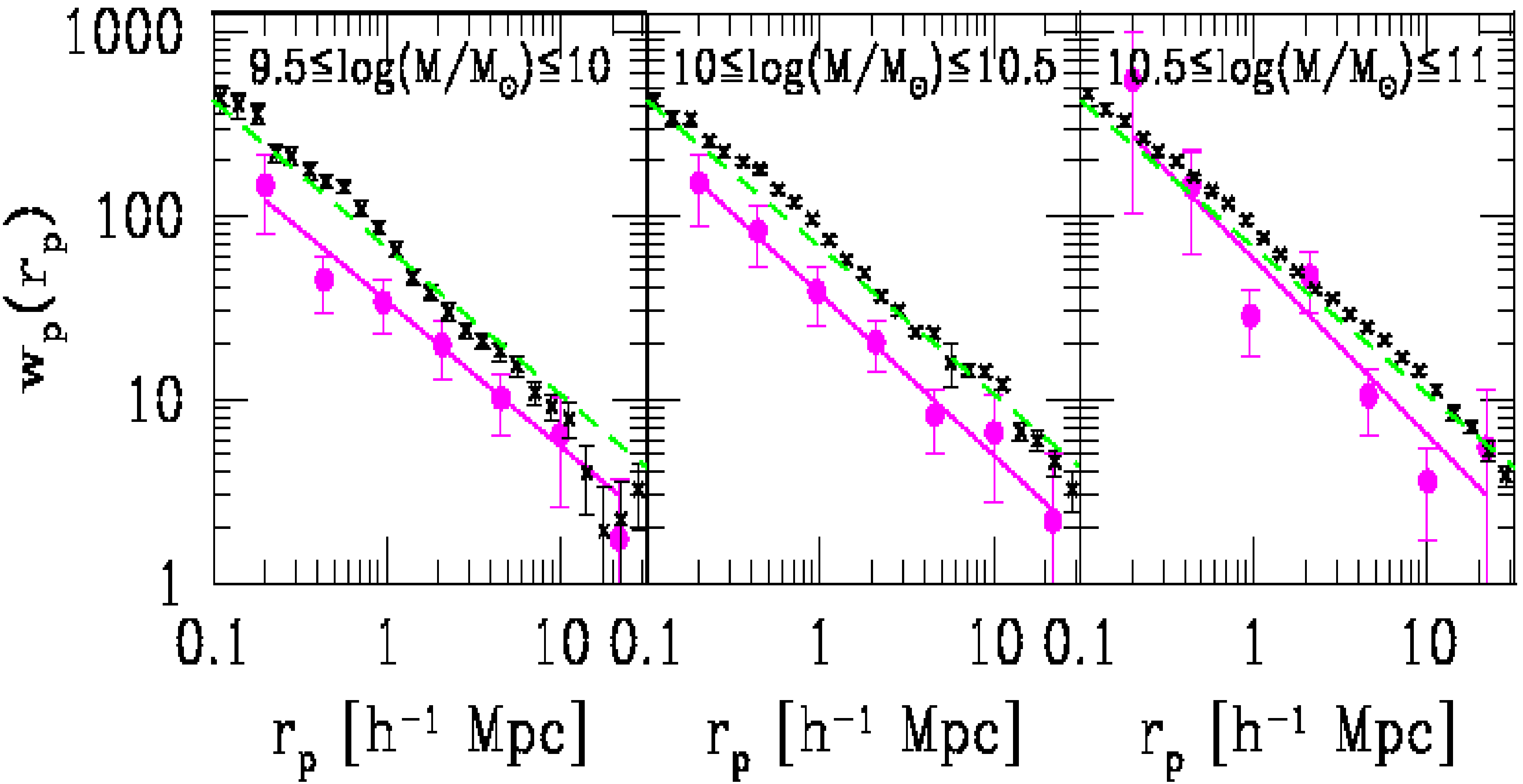
# Galaxy clustering in the VVDS: stellar mass dependence




- CFs and their best-fit $r_0$ and $\gamma$ parameters:
  - both rise for most massive galaxies. mostly at $r_p$ <5 $h^{-1}$ Mpc

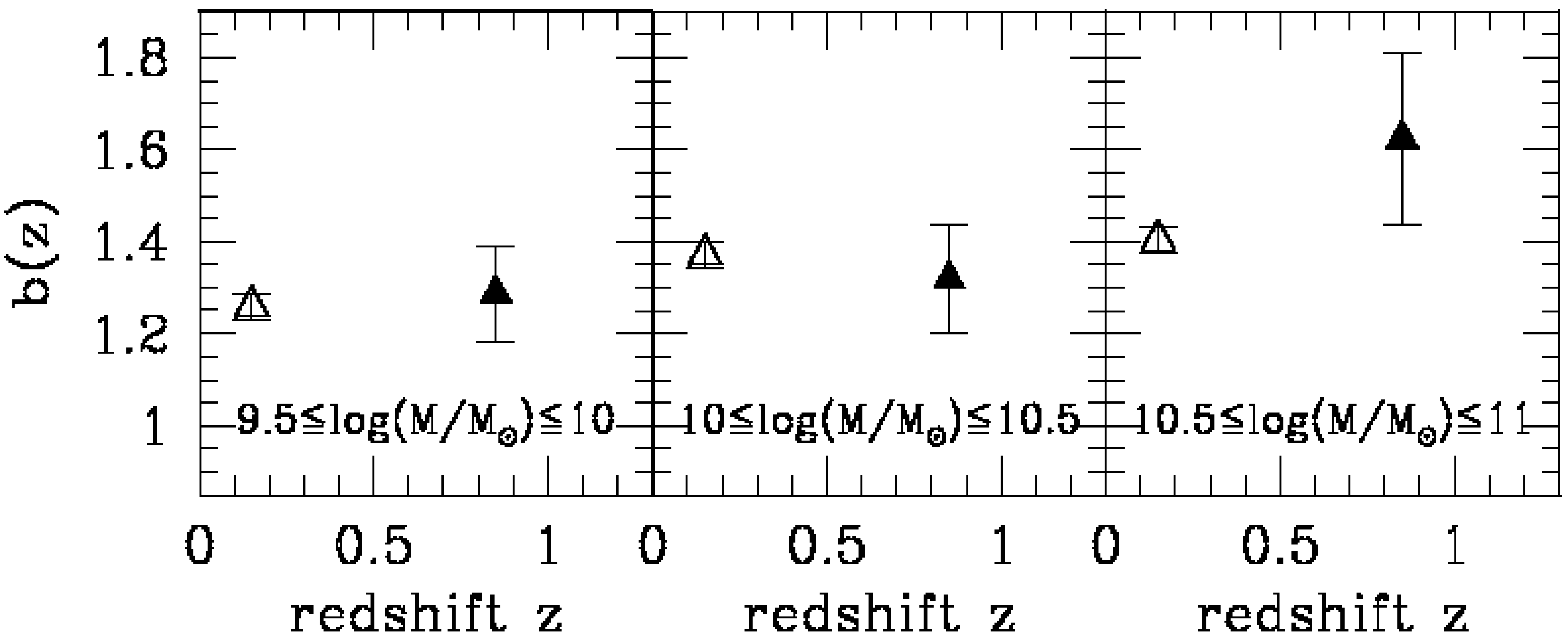
Meneux et al., 2008

# Galaxy clustering in the VVDS: stellar mass dependence compared the SDSS results (Li et al., 2006) – for the most massive galaxies $w_p(r_p)$ does not evolve

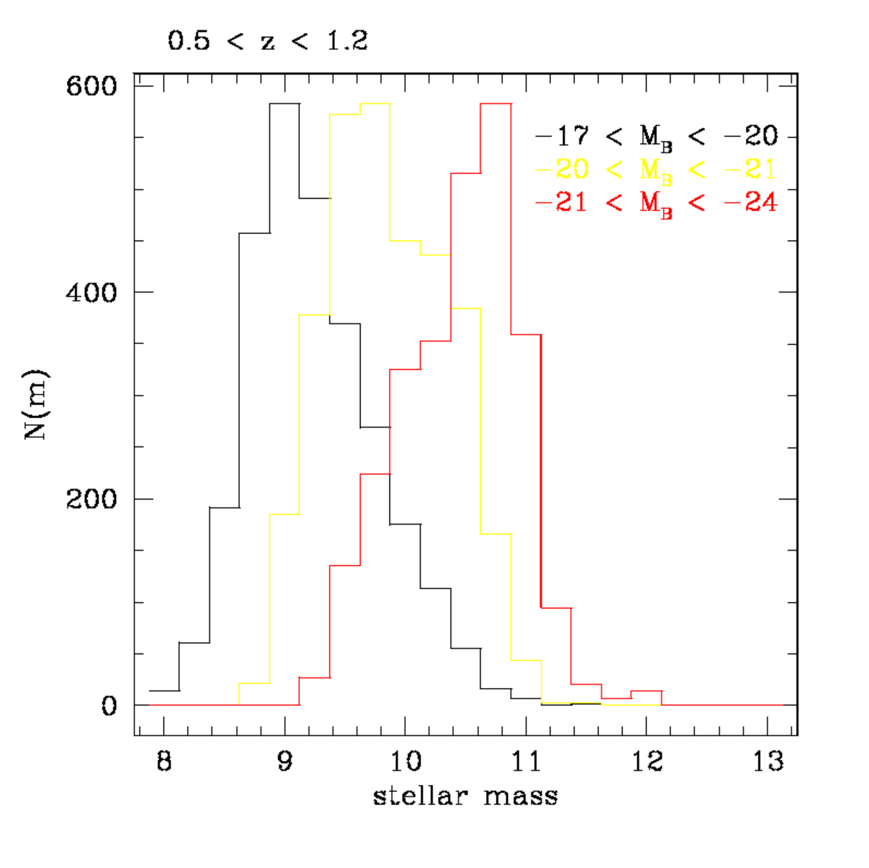


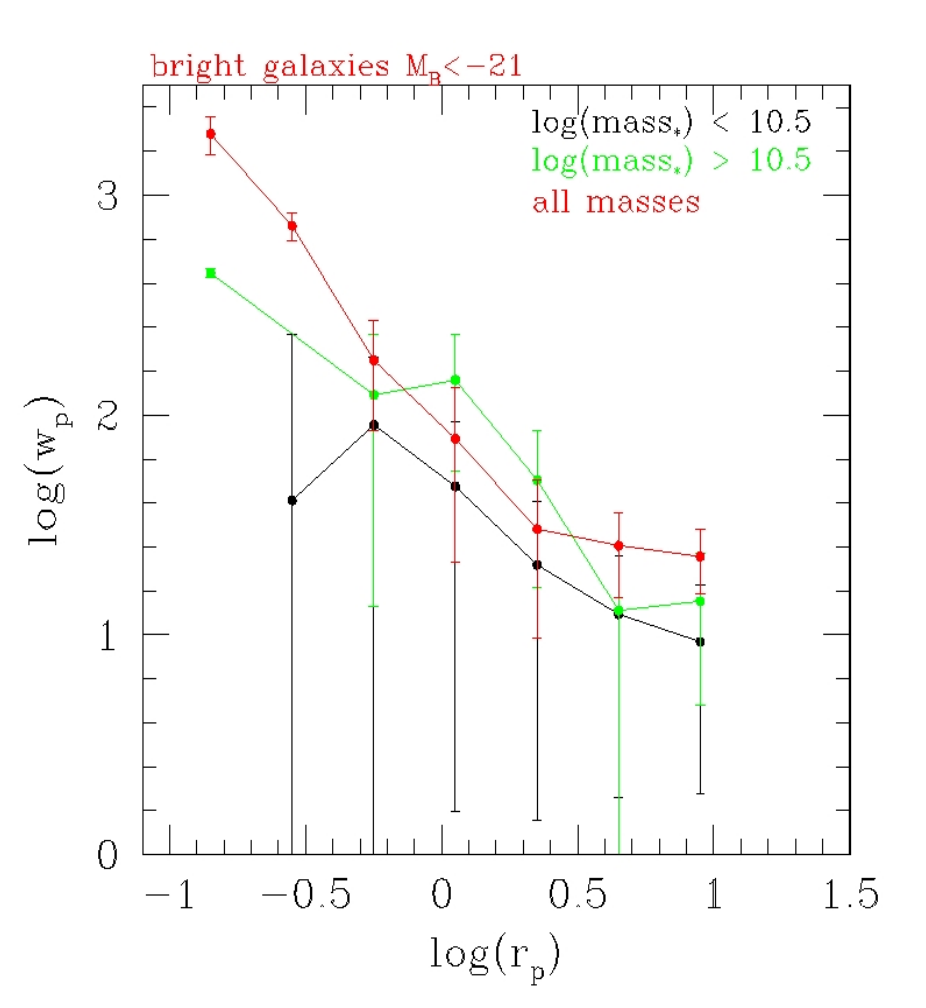

Meneux et al., 2008

# Galaxy bias (at the 8 Mpc scale) vs DM – does it change with z differently for galaxies with different stellar masses?



Is luminosity and stellar mass directly linked in z~1 galaxies? Not necessarily. Also, stellar mass and absolute luminosity dependence of the galaxy clustering differ, at least in case of luminous galaxies.



# Conclusions I

- The VVDS was a unique tool which allowed to trace the galaxies until z~5 and the LSS until z~2.
- At the first glance, the Large Scale Structure at z~1.5 is already surprisingly similar to the structure we observe around us.
- The observed similarity of the scale of clustering is probably the effect of compensation of the decreasing clustering and increasing absolute brightness of galaxies we observe, with cosmic time.
- The clustering properties of blue and red galaxies seem to show a reversal trend at z~1.5 – does it mean that the migration of star-forming galaxies from the dense to less dense environments (“dowsizing”) was taking place then?

# Conclusions II

- Most luminous galaxies at z~1 display different clustering properties than their today's counterparts. They are also significantly more biased with respect to the DM halo distribution and to the general population.

- HOD modelling of the VVDS z~1 galaxies suggests a rise of the DM halo mass and a number of satellites with a central galaxy luminosity

- But we also observe that at z~1, luminosity and stellar mass of galaxies were not necessarily completely correlated. On small scales, luminous galaxies are *more* clustered than massive galaxies. Should we be cautious treating absolute luminosity as a mass indicator, at least in some cases? There may be also an environmental factor to be taken into account. Relation between galaxy mass and luminosity depending on its position in a DM halo? Need for different modelling of central and satellite galaxies in DM haloes?

- Bigger volumes at z~1 and higher needed to answer this questions more surely: VIPERS (VIMOS Public Extragalactic Redshift Survey) - a new redshift survey of >100 000 galaxies at a contiguous area of 24 deg$^2$ at z~1 - first observations are on-going right now!

VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

# Large Scale Structure and the search of gravitational waves

- Events being the sources of GW: interactions and collisions of NSs and BHs (stellar and supermassive) should be correlated with LSS
- There are expectations that the collapse of CDM haloes with nonspherical density profiles should result in an existence of a cosmic background of GW
- Cross-correlating of the GW signal and LSS in the future may provide important constraints for our understanding of the GW sources and LSS
- But to interpret it correctly we need to understand the relation between the galaxies we observe in different types of catalogs and the underlying DM field