The observed distribution of galaxies

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Some questions to ponder...

- “The Universe is homogenous and istropic on large scales” -- is this true?
- How does the luminous matter relate to the dark matter?
- How does clustering depend on galaxy type and environment?
- What happens on very small scales?
- What are the largest structures in the Universe?
- The statistical analysis of catalogues is the key to answering these questions...

Pair count statistics...(see the talks from Stephane)

$$dP = n\,dV,$$

$$dP = n^2 dV_1 dV_2 [1 + \xi(r_{12})].$$

$$\xi_c(r) = \langle f(\vec{x} + \vec{r}) f(\vec{x}) \rangle / \langle f \rangle^2 - 1.$$

$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle = nV + n^2 \int_V dV_1 dV_2 \xi(r_{12}),$$

- Similarly, for projected catalogues:

$$dP = \mathcal{N}[1 + w(\theta)] d\Omega.$$

$$\hat{\xi}_{\mathrm{DP}}(r) = \frac{N_{\mathrm{rd}}}{N} \frac{DD(r)}{DR(r)} - 1, \quad \hat{\xi}_{\mathrm{HAM}}(r) = \frac{DD(r) \cdot RR(r)}{[DR(r)]^2} - 1,$$

$$\hat{\xi}_{\mathrm{LS}}(r) = 1 + \left(\frac{N_{\mathrm{rd}}}{N} \right)^2 \frac{DD(r)}{RR(r)} - 2 \frac{N_{\mathrm{rd}}}{N} \frac{DR(r)}{RR(r)},$$

- In general the LS estimator is the most optimal of the three as is least affected by plate boundaries and masks
- Note that these estimators are computationally intensive due to the calculation of large numbers of pair separations; but improved algorithms exist
  - Note also: if

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

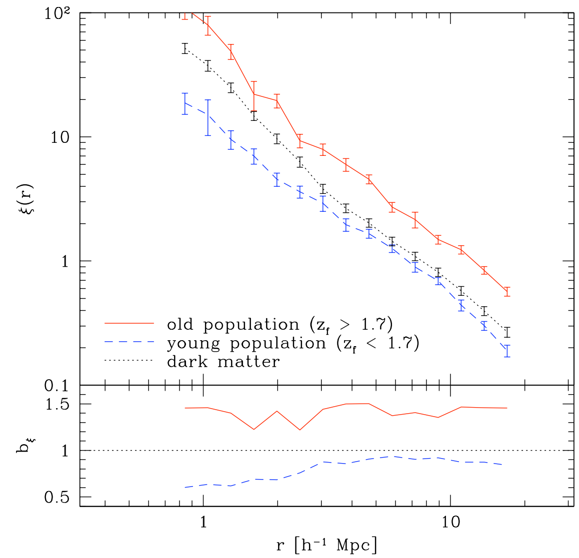
  - Then:

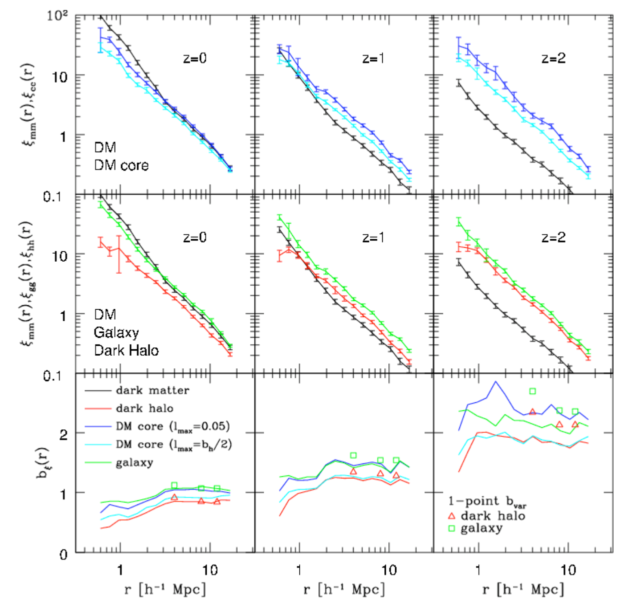
$$w(\theta) = A\theta^{-\gamma}$$

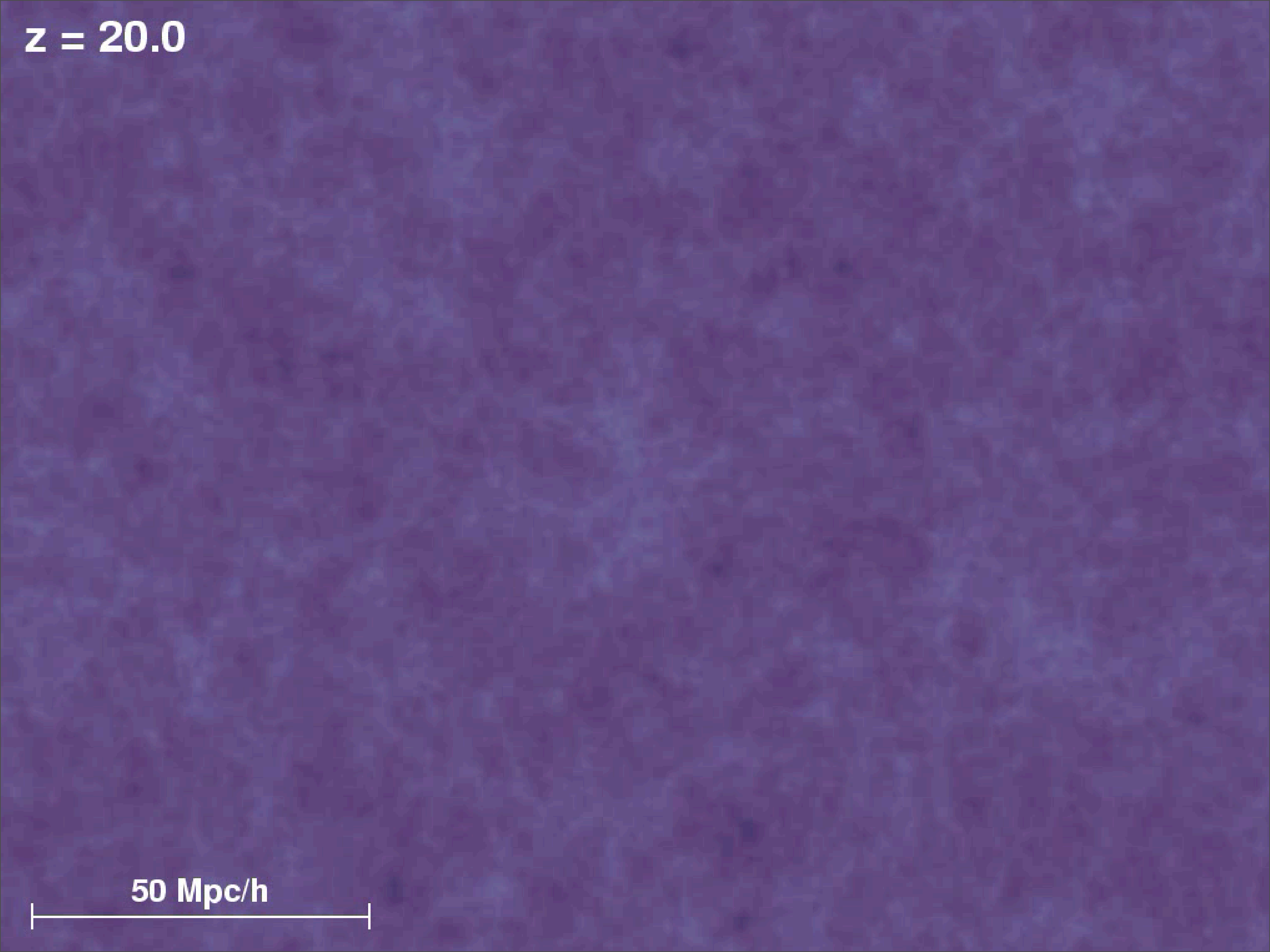
- Note that in general, the pair count analyses like this are most useful on small scales; on large scales fourier-space analysis are more useful

The growth of structures in the universe

- Initial small perturbations in the CMB grow into structures under the influence of gravity
- In the **linear regime** (>10h^{-1}Mpc) the growth of structure can be described analytically
- In the **non-linear regime**, structure growth depends on the details of galaxy formation! Some approximate analytic techniques do exist.
- To find out what happens in these scales, we need to do very high-resolution simulations with gas, or to use **semi-analytic models** (see Jeremy's talk)






z = 20.0
50 Mpc/h

Making measurements of galaxy clustering

- At **small scales**, where the number of pairs are small, we are dominated by Poisson counting errors
- At **large scales**, where the numbers of pairs are large, we are dominated by **systematic errors** and the effects of **cosmic variance.**
- The ideal survey would have a **wide field of view**, reach **extremely faint limiting magnitudes**, and have **very accurate photometry.**

- It is possible to make an analytic estimate of the error in w(θ)..

$$\left[\frac{\Delta\omega(\theta)}{\omega(\theta)}\right]^2 \simeq E_1 + E_2 + E_3, \tag{8}$$

where

Finite volume error

$$E_1 = 4(1 - 2q_3 + q_4)\frac{\bar{\omega}_{\theta_{\max}}}{\omega(\theta)^2}[\omega(\theta) - \bar{\omega}_{\theta_{\max}}]^2 + \left(\frac{\bar{\omega}_{\theta_{\max}}}{\omega(\theta)}\right)^2,$$

Discreteness error

$$E_2 = \frac{4}{N_g}\left\{\frac{\omega_r(\theta)[1 + 2q_3\omega(\theta)]}{\omega(\theta)^2} + q_3 - 1 + \frac{\bar{\omega}_{\theta_{\max}}}{\omega(\theta)^2}[2(1-2q_3)\omega(\theta) - 2q_3\omega_r(\theta) + \bar{\omega}_{\theta_{\max}}(3q_3 - 1) - 1]\right\},$$

$$E_3 = \frac{2}{N_g^2}\left\{[G_p(\theta)^{-1} - 1]\frac{1 + \omega(\theta)}{\omega(\theta)^2} - 1 - \frac{1 - 2\bar{\omega}_{\theta_{\max}}}{\omega(\theta)} + \frac{\bar{\omega}_{\theta_{\max}}}{\omega(\theta)^2}\left[\frac{2}{G_p(\theta)} - 1 - \bar{\omega}_{\theta_{\max}}\right]\right\}.$$

Arnouts et al 2002

- If possible we would prefer to estimate our errors from observations of several separate fields
- **Unfortunately cosmic variance effects seem to be important even for very large fields!**

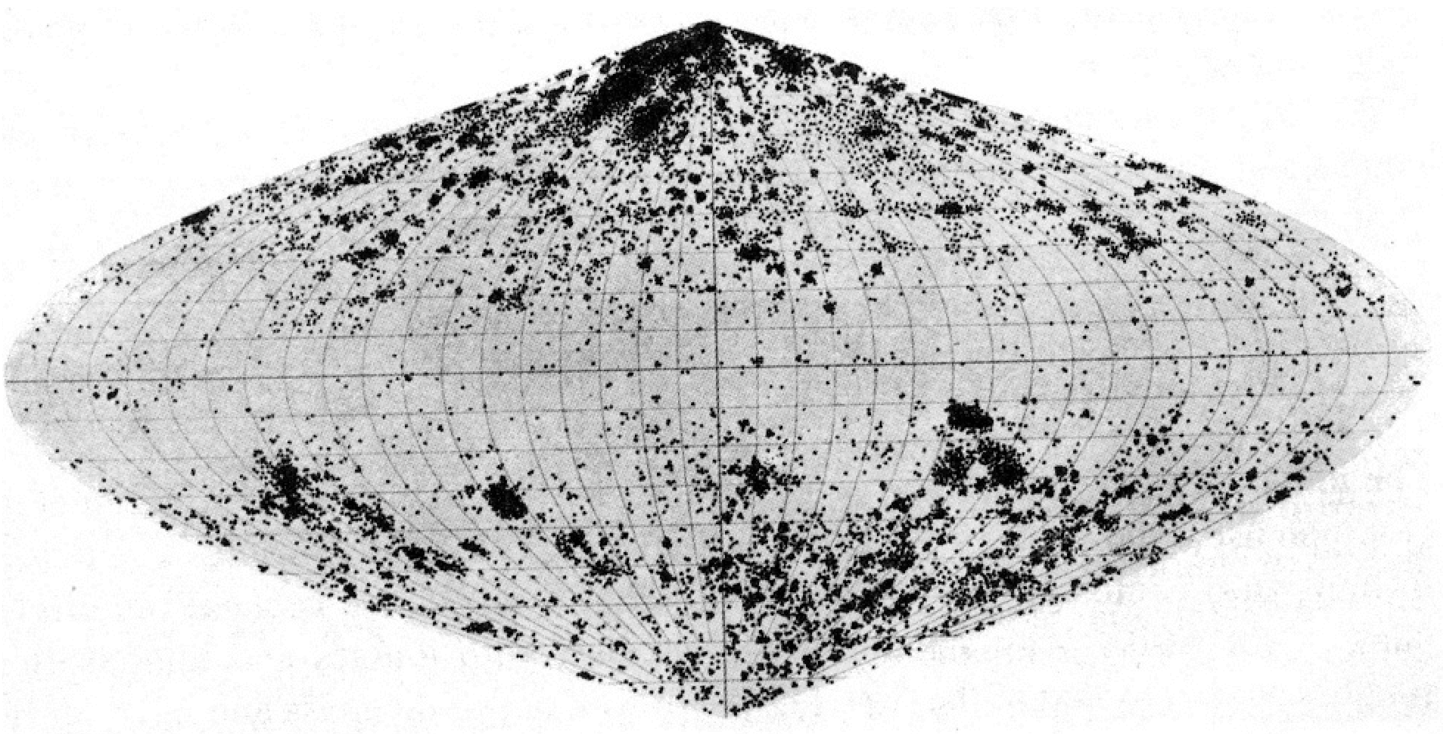
A time-line of galaxy clustering measurements

A time-line of galaxy clustering measurements

Hubble and friends; “the realm of the nebulae”

Pre-history

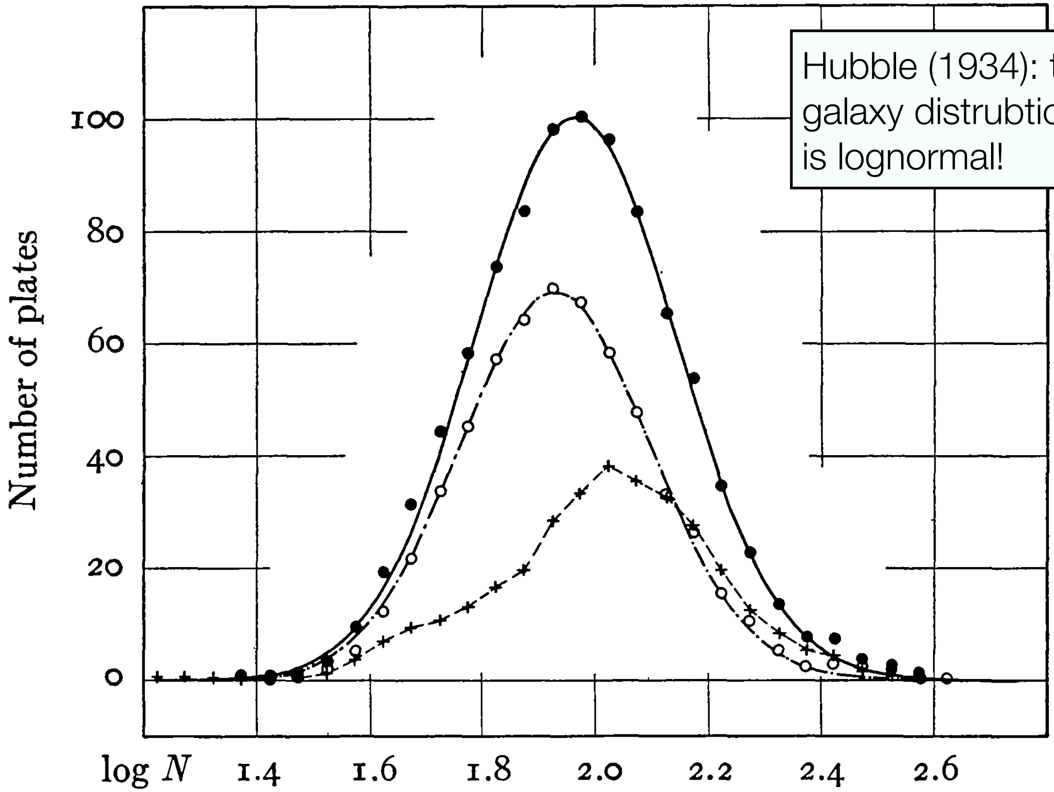
A time-line of galaxy clustering measurements



Hubble and friends; “the realm of the nebulae”

Pre-history

A time-line of galaxy clustering measurements



Hubble (1934): the galaxy distrubtion is lognormal!

Hubbl friends; "the realm of the nebulae"

Pre-history

A time-line of galaxy clustering measurements

Hubble and friends; “the realm of the nebulae”

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Scanned Schmidt plates;
Counts in cells at low redshifts;
Development of pair statistics for galaxy clustering measurements

1970s

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Redshift surveys of the local universe;
Imaging surveys of the distant universe using plates at the prime-focus of 4m telescopes;
The first CCDs; pencil beam surveys of the distant universe

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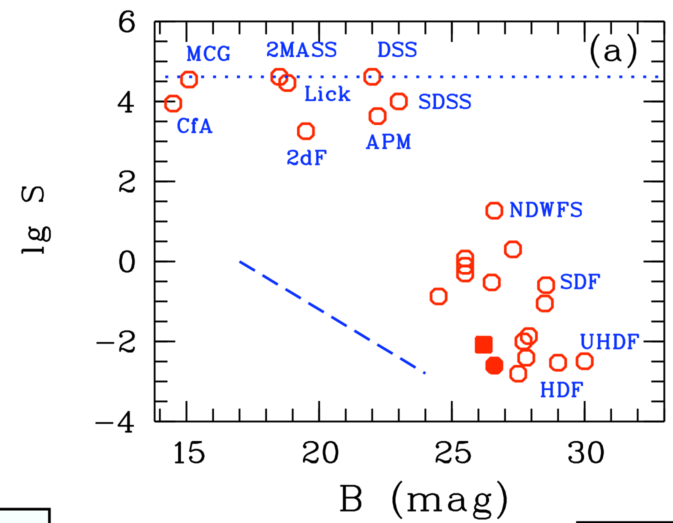
1980s

Multi-object spectrographs on 4m telescopes; 1000 galaxies at z~1;
10m telescopes;

1000 galaxies at z~1

1990s

A time-line of galaxy clustering measurements



Pre-history	1970s	1980s	1990s	2000+
Hubble and friends; "the realm of the nebulae"	Scanned Schmidt plates; Counts in cells at low redshifts; Development of pair statistics for galaxy clustering measurements	Redshift surveys of the local universe; Imaging surveys of the distant universe using plates at the prime-focus of 4m telescopes; The first CCDs; pencil beam surveys of the distant universe	Multi-object spectrographs on 4m telescopes; 1000 galaxies at z~1; 10m telescopes; 1000 galaxies at z~1	MOS on 10m telescopes; 10,000 galaxies at z~1; Million-galaxy redshift surveys at z~0; Degree-scale imagers; Accurate photo-zeds for 100,000 galaxies out to z

The Lick galaxy catalogues

- Before plate scanning machines like the SuperCOSMOS device and others, measuring the positions of enough galaxies was extremely time-consuming and demanded a heroic effort

- Lick astrograph was used for an ambitious survey of the entire sky to study object proper motions

1568** $12^h\ 20^m$
S h 1.695

21	24	29	57	27	19
32	44	39	79	44	30
35	26	40	35	27	28
35	24	46	26	23	17
25	30	31	19	14	15
24	37	30	16	15	6

x1246!

...10 years of work to count 10,000 galaxies by eye!

Carnegie Astrograph (and Wirtanen)

- The resulting maps were made in 1 degree cells

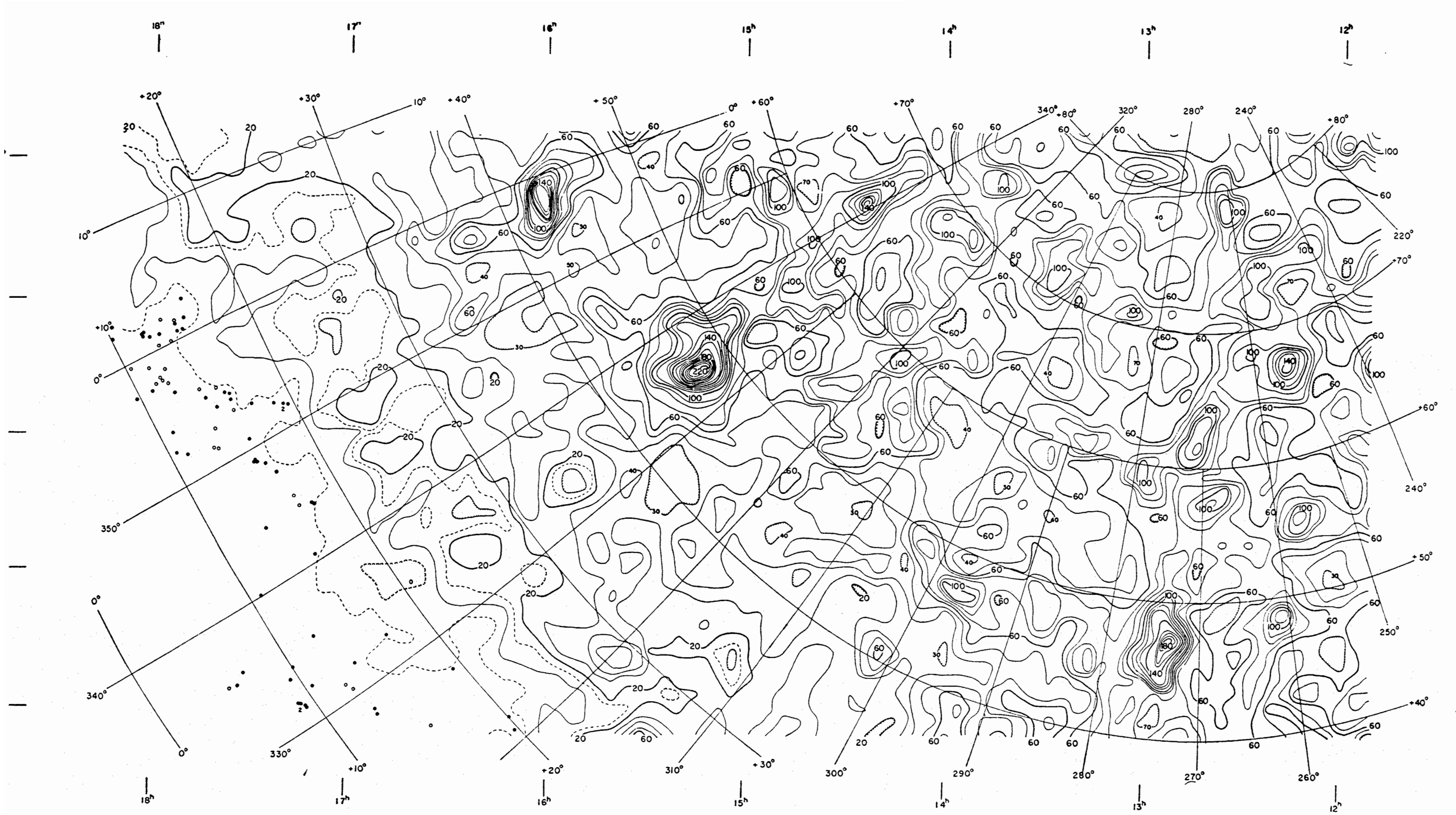
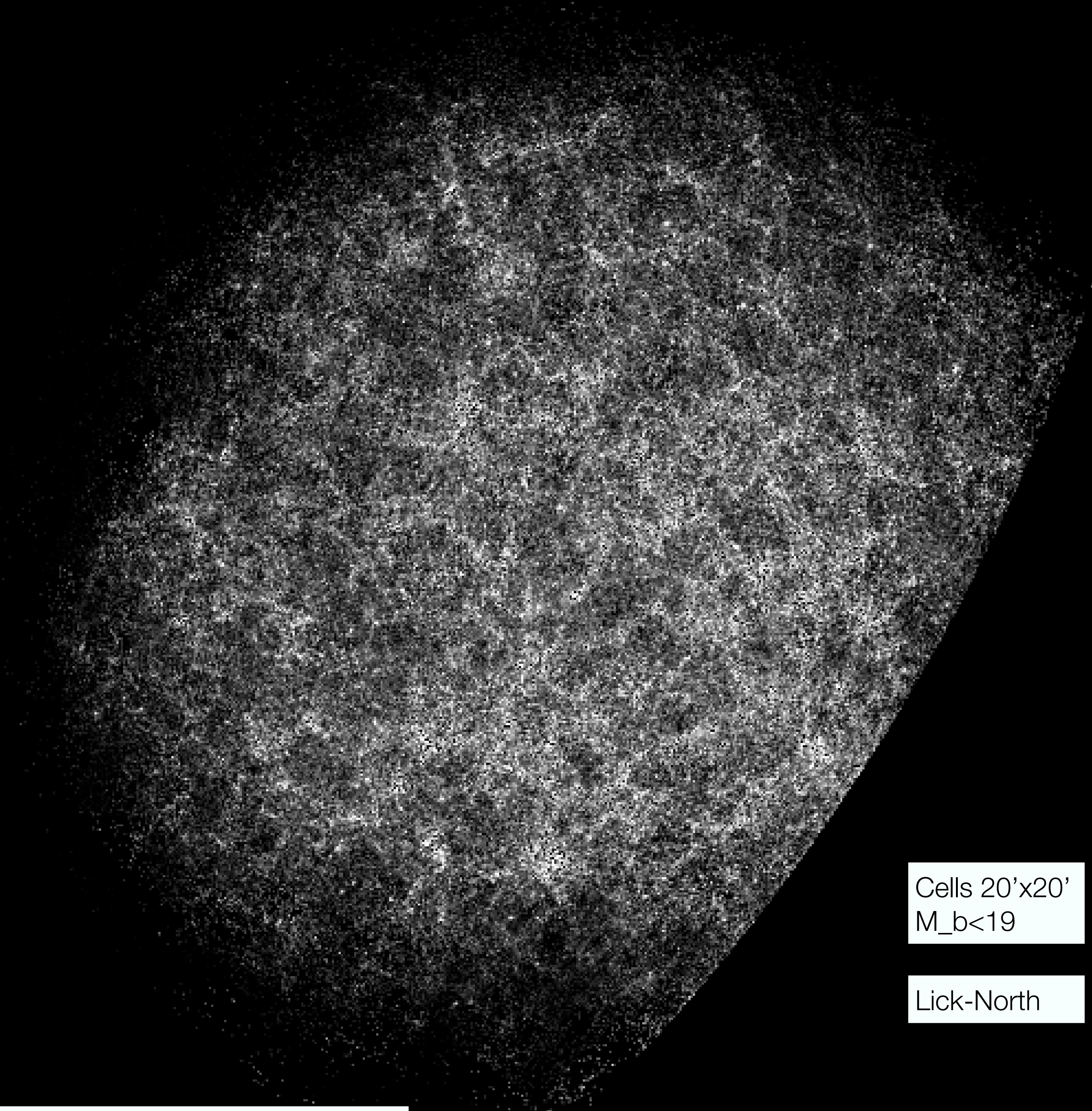


Figure 2. Equal surface density contours for nebulae in Area III, based on smoothed counts by 1° squares.

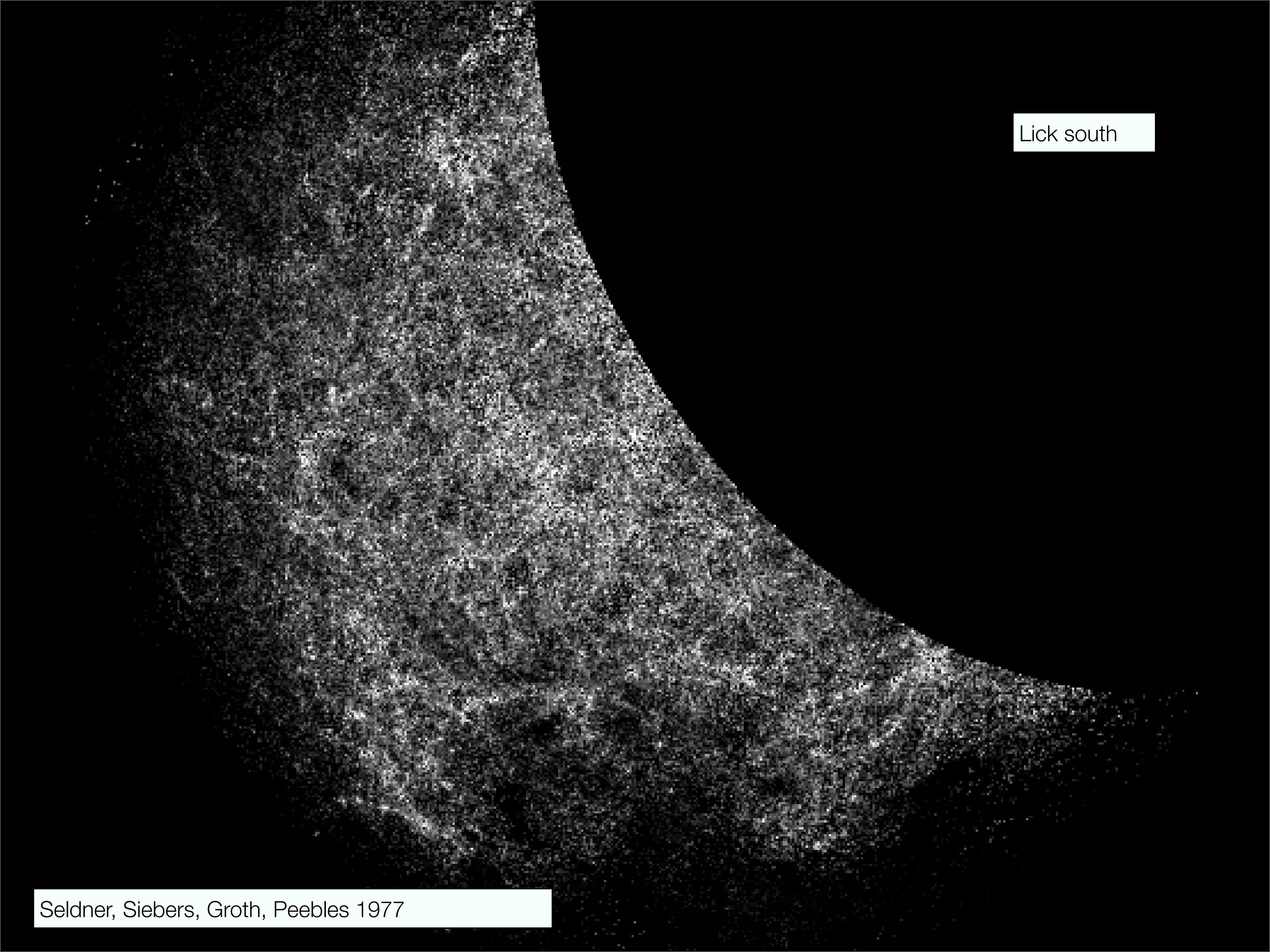
- Neyman, Scott and Shane (1953) were able to use this map to show that the observed distribution of galaxies could not be due to obscuration

Shane and Wirtanen, 1957

Magnitude limit: $M_b<18$



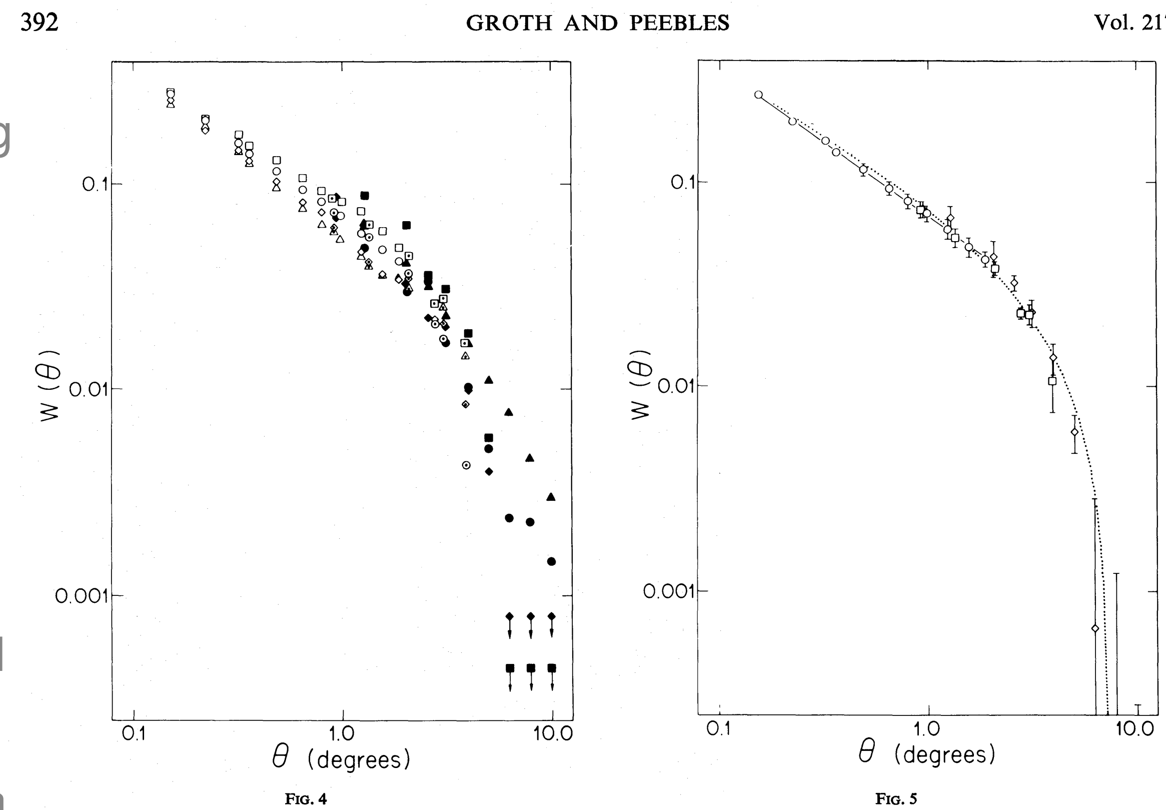
Seldner, Siebers, Groth, Peebles 1977



Seldner, Siebers, Groth, Peebles 1977

Galaxy clustering statistics and the lick galaxy catalogues

- Lick galaxy counts were re-measured at higher resolution using electronic counting
- w(θ) measured for the whole catalogue using counts-in-cells 10’x10’ (original lick catalogue was 1x1
- Full control of systematic errors a challenging problem (seeing, variation in limiting magnitudes and depth over the plate boundaries)
- **Demonstrated that w(θ) follows a power-law shape (see also Totsuji and Kihara)**



$$\xi(r) = (r_o/r)^\gamma, \ \ \gamma = 1.77 \pm 0.04,$$

$$hr_o = 5 \pm 0.5 \text{ Mpc},$$

The scaling relation

Relativistic limber equation

$$\omega(\theta) = \frac{H_0 H_\gamma}{c}\,\theta^{1-\gamma}\,\frac{\int_0^\infty N^2(z)\,r_0^\gamma(z)\,[x(z)]^{1-\gamma}\,E(z)\,F(z)\,dz}{[\int_0^\infty N(z)\,dz]^2} \quad (2)$$

$$\omega(\theta) = A_\omega \theta^{-\delta}$$

Assuming w(θ) is a power law…

$$r_0^\gamma(z_{\rm eff}) = A_\omega \left[\frac{H_0 H_\gamma}{c}\,\frac{\int_{z_1}^{z_2} N^2(z)\,[x(z)]^{1-\gamma}\,E(z)\,dz}{[\int_{z_1}^{z_2} N(z)\,dz]^2}\right]^{-1}$$

$$\omega(\theta) = \frac{DD - 2DR + RR}{RR},$$

Which you get from computing pair counts on your catalogue….

Observed scaling relations in w(θ)

- The amplitude of the projected angular correlation function is a simple integral of the spatial correlation function
- For samples limited in apparent magnitude, at progressively fainter magnitudes, the amplitude of w(θ) diminishes
- This is the the "Limber scaling relation".
- Provided important confirmation of the homogeneity hympothesis
- The big problem, however, is that the scaling relation depends strongly on the underlying redshift distribution, which is unknown...but see the section on photo-zeds...

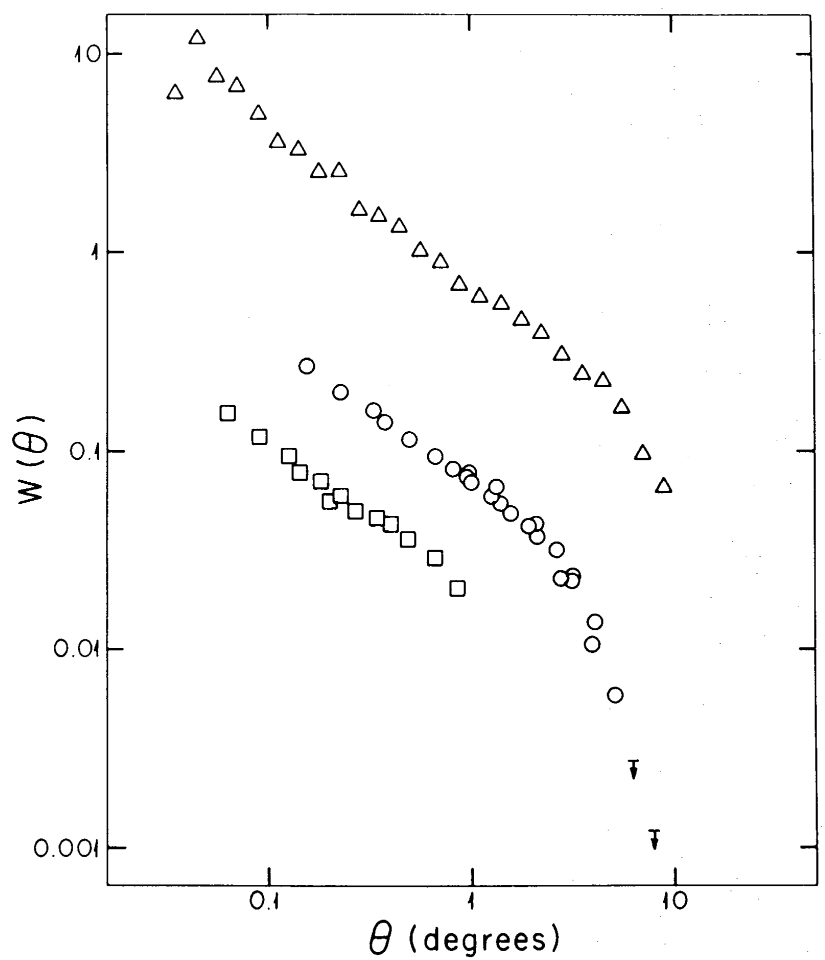
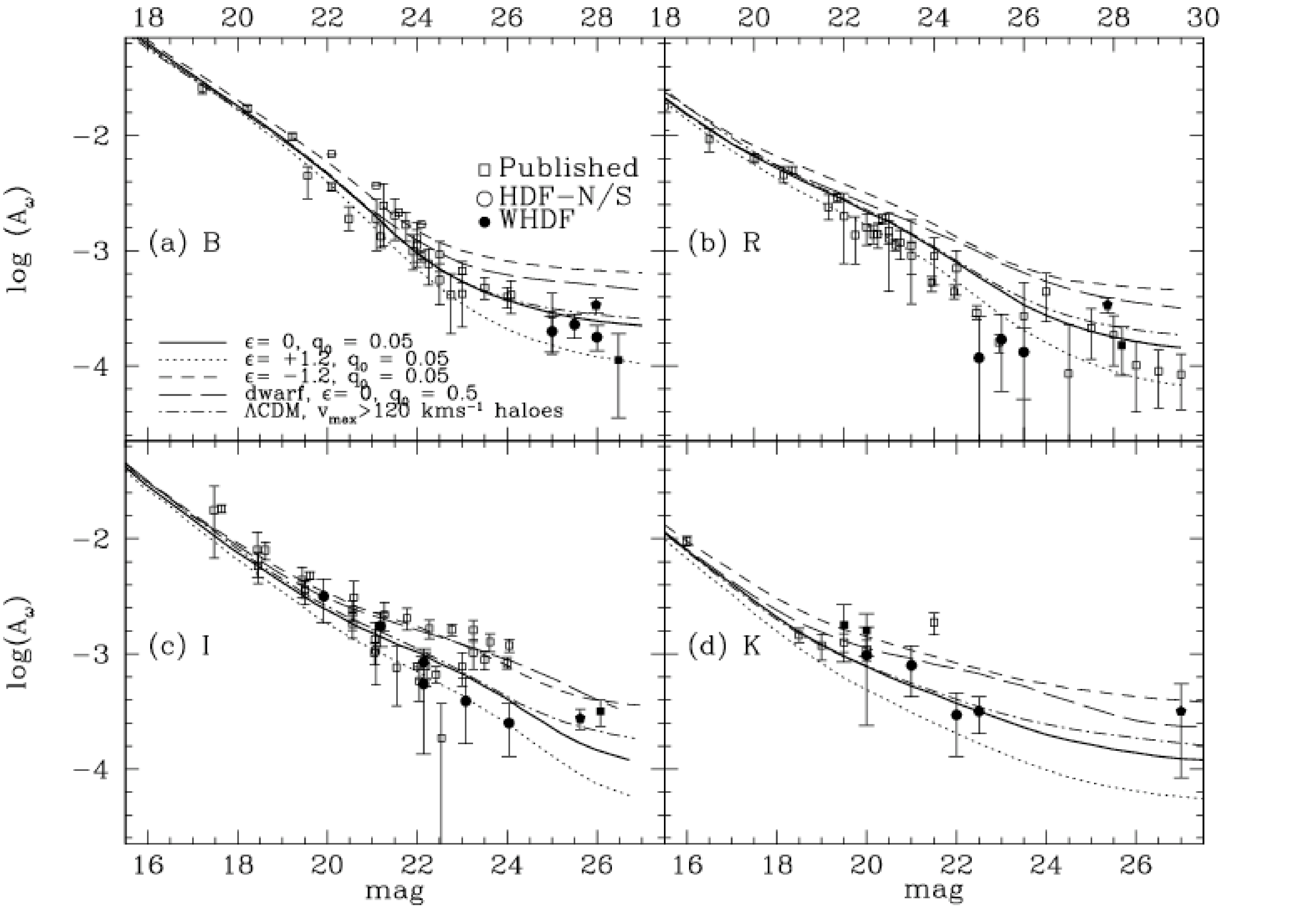
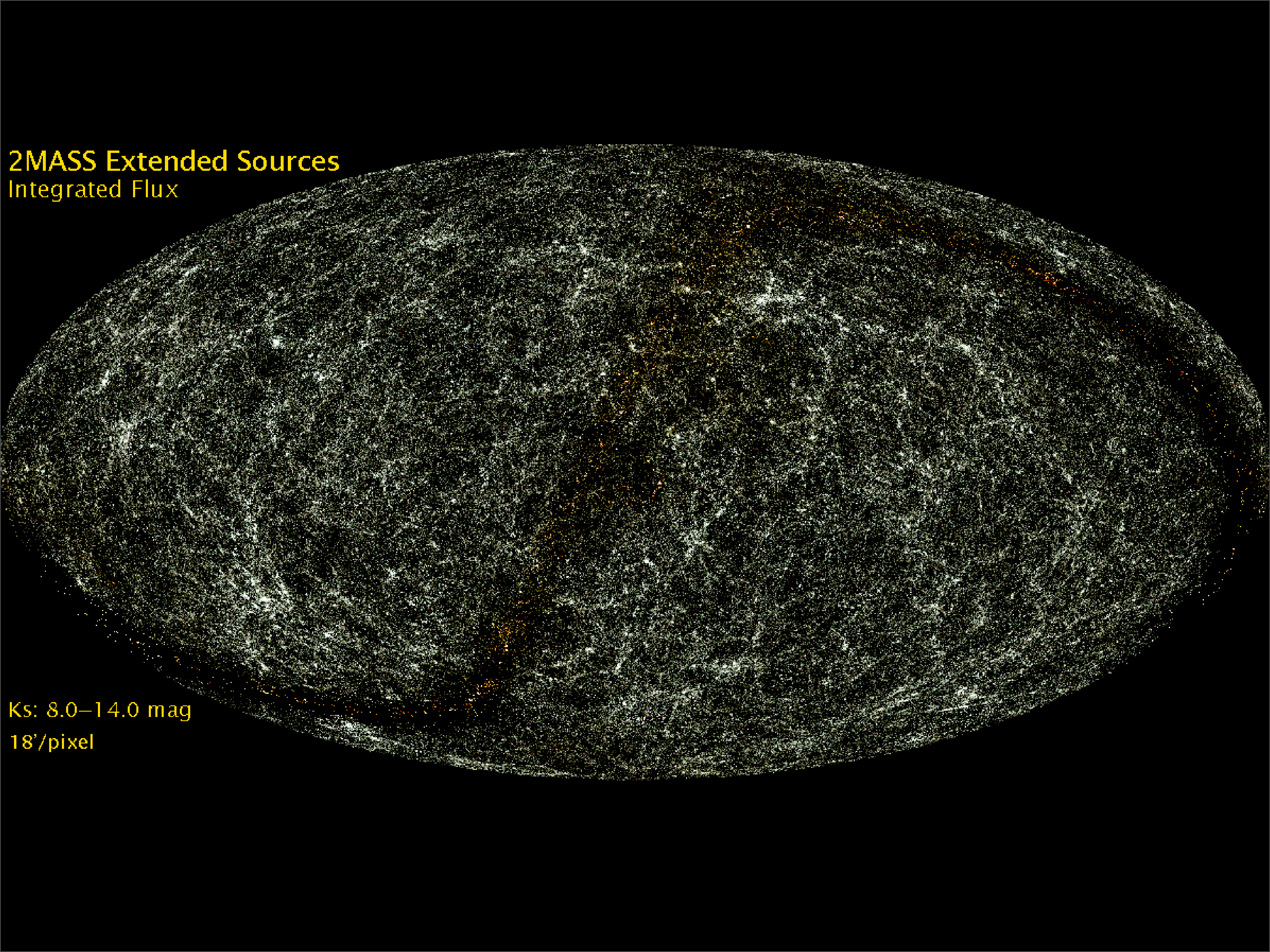


FIG. 13

Groth and Peebles (1977)

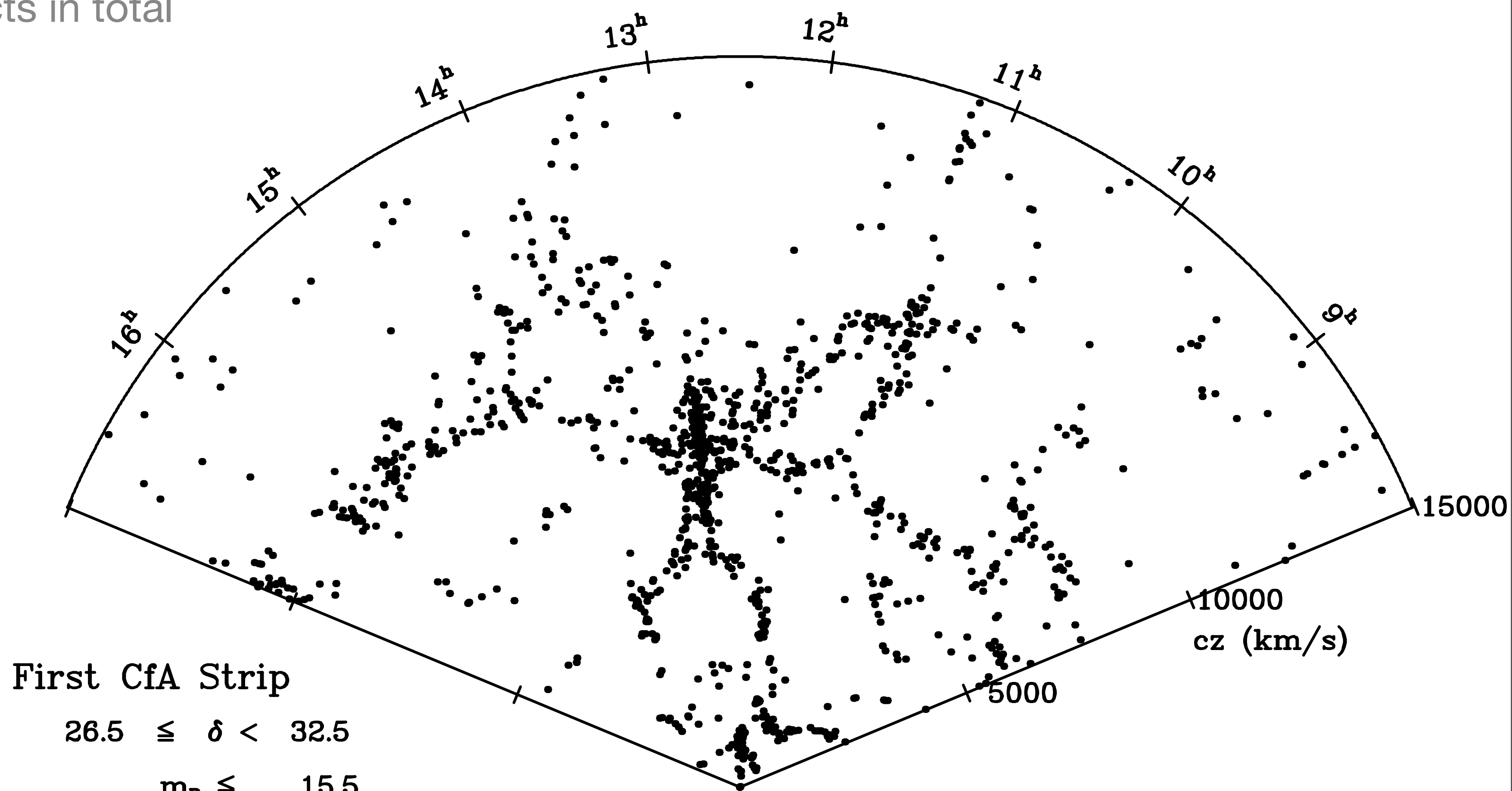


(a) B
(b) R
(c) I
(d) K
Published
HDF−N/S
WHDF
ε= 0, q₀ = 0.05
ε= +1.2, q₀ = 0.05
ε= −1.2, q₀ = 0.05
dwarf, ε= 0, q₀ = 0.5
ΛCDM, v_max>120 kms⁻¹ haloes
log (A_ω)
log(A_ω)
mag


2MASS Extended Sources
Integrated Flux
Ks: 8.0–14.0 mag
18'/pixel

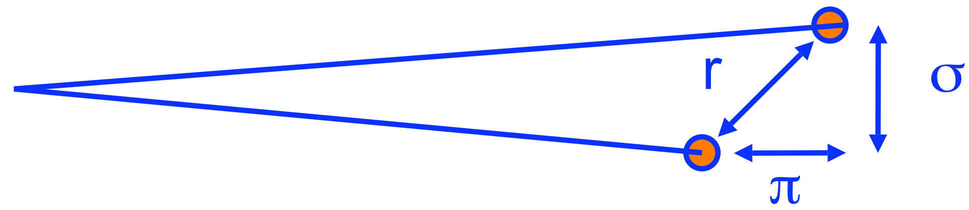
The three dimensional distribution of galaxies

- The CfA redshift survey aimed to measure all galaxies brighter than 14.5 in the UGC (cfa1)
- 2000 objects in total
- Galaxies distributed in a highly non-uniform fashion (very bright, highly biased)



The three-dimensional distribution of galaxies-II

- With redshift information one can completely remove the problems of ‘projection effects’



$$\delta P = n\left[1+\xi(r_p,\pi)\right]\delta V\phi(r),$$

$$\pi = v_1 - v_2,\ r_p = \left[(v_1+v_2)/H_0\right]\tan(\theta_{12}/2), \quad (2)$$

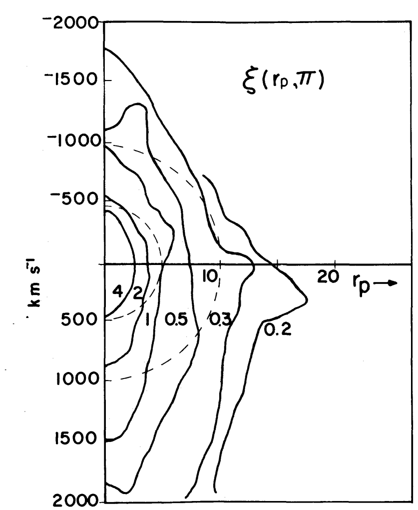
$$s = \left(v_1{}^2 + v_2{}^2 - 2v_1v_2\cos\theta_{12}\right)^{1/2}/H_0.$$

$$\delta P = n\left[1+\xi(s)\right]\phi\,\delta V.$$

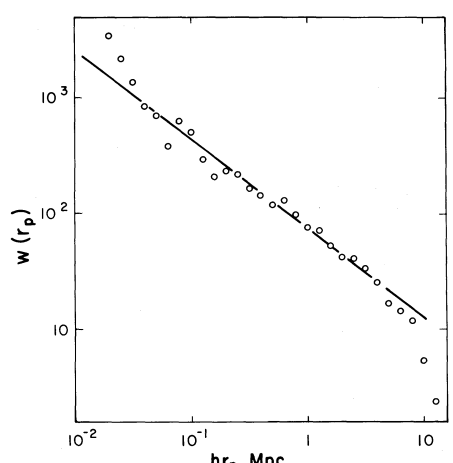
- Davis and Peebles applied this method to the CfA redshift survey

$$1+\xi(r_p,\pi) = \frac{DD(r_p,\pi)}{DR(r_p,\pi)}.$$

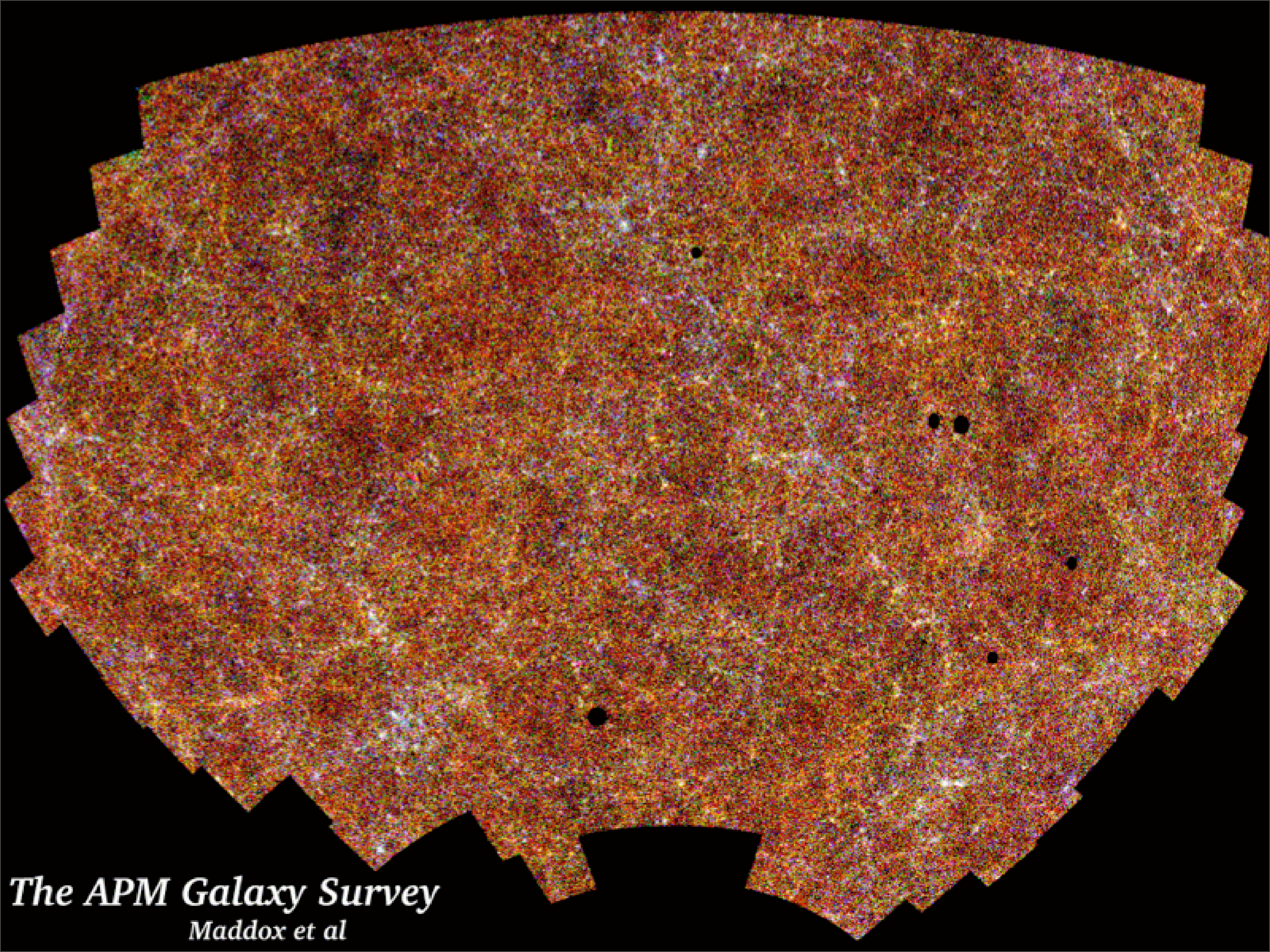
$$w(r_p) = \frac{1}{H_0}\int_{-v_L}^{v_L} d\pi\,\xi(r_p,\pi).$$

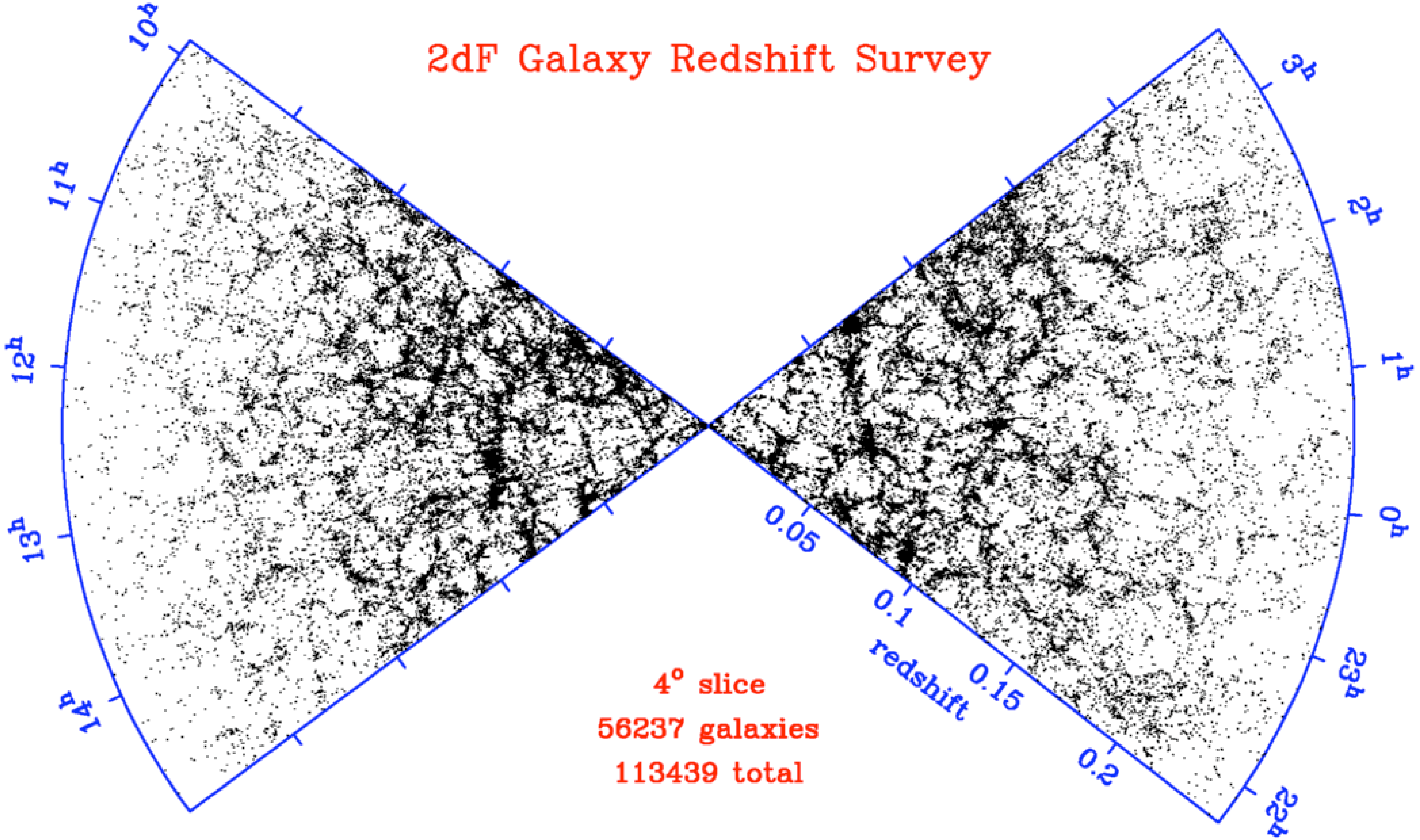


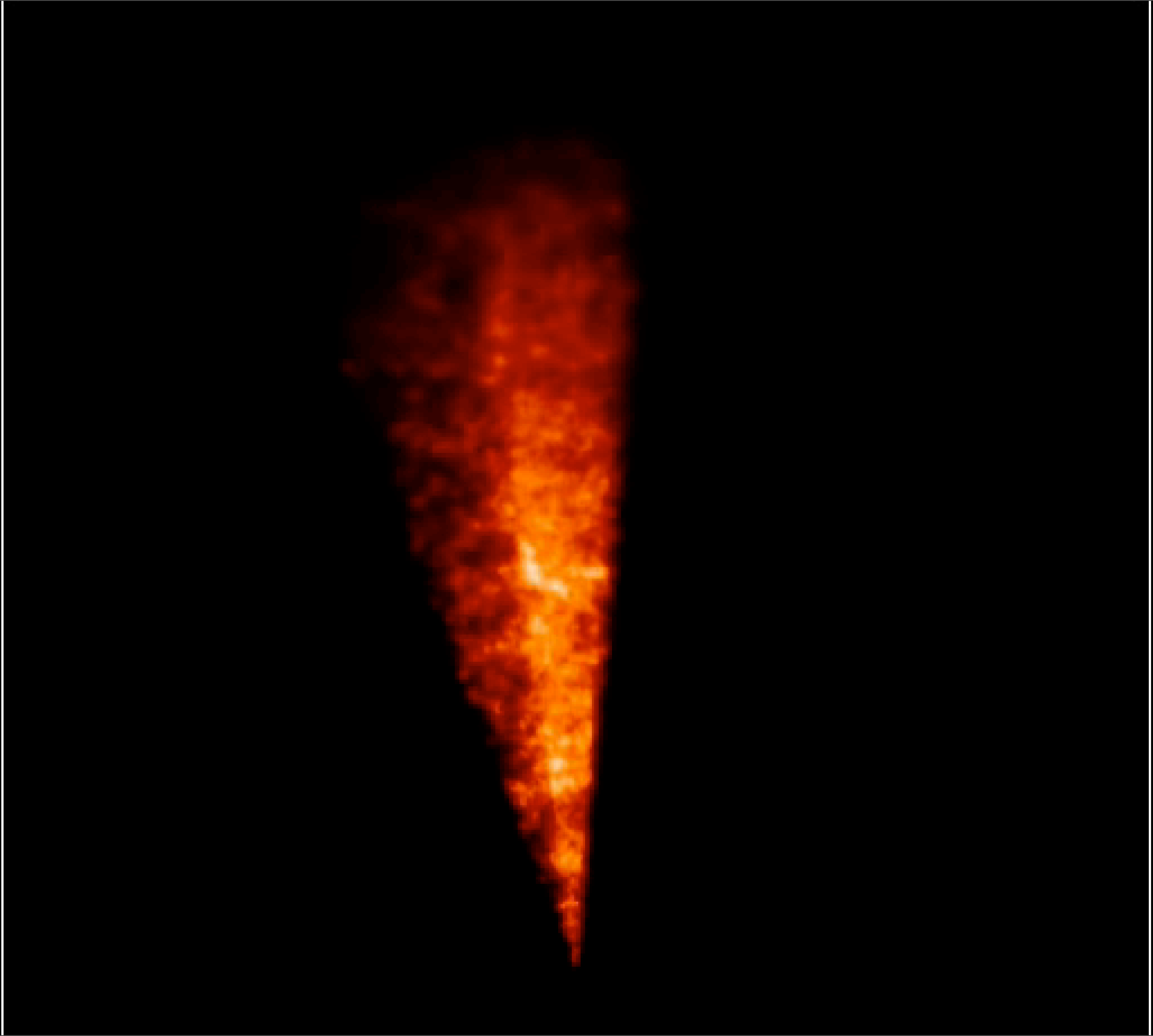
Davis and Peebles (1977)



- The wp statistic is insensitive to the effects of coherent infall along the line of sight.


The APM Galaxy Survey
Maddox et al


2dF Galaxy Redshift Survey
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
0.05
0.1
0.15
0.2
redshift
4° slice
56237 galaxies
113439 total

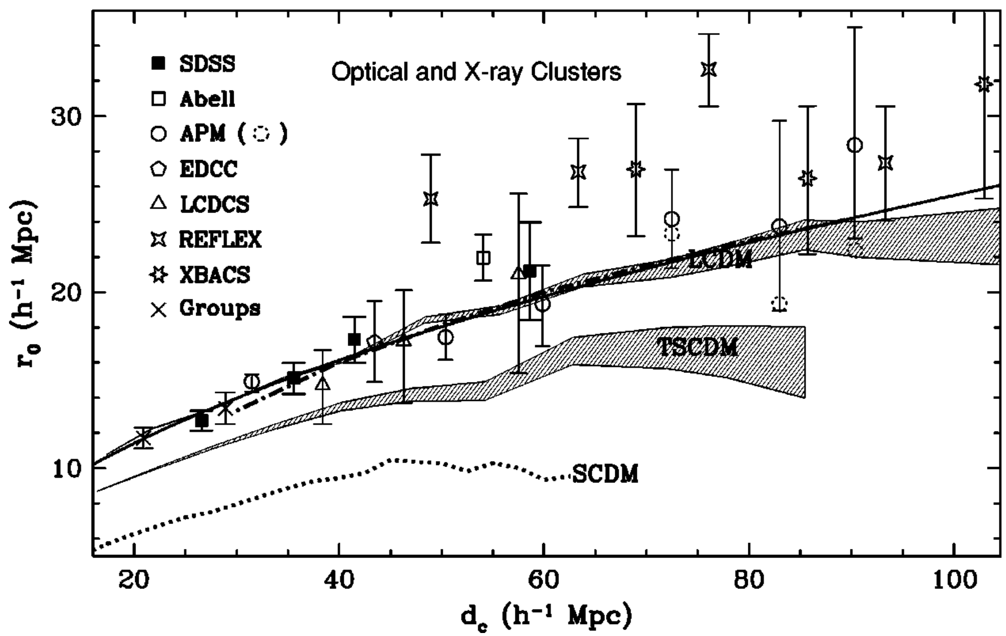


Galaxy biasing -- how well do galaxies trace matter?

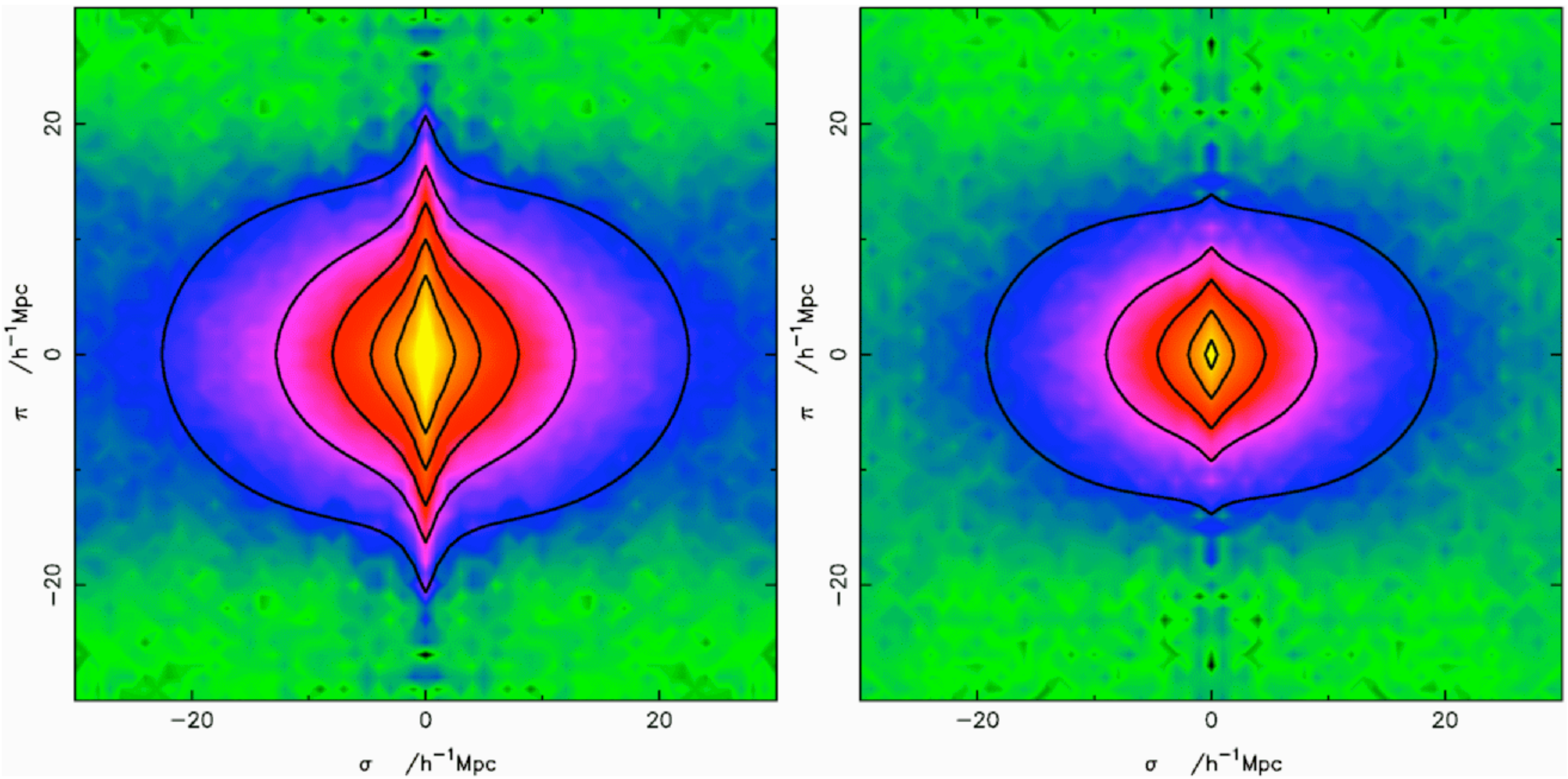
- Clusters of galaxies are much more more strongly clustered than galaxies

$$\xi_{gal}(r) = b^2 \xi_{dm}(r)$$

- We can compute the clustering of the dark matter from simulations
- The bias may be a function of type instrinsic luminosity; with new surveys we are able to determine this for this first time!



Redshift-space distortions and galaxy type



Passive:

$\beta = \Omega_m^{0.6}/b = 0.46 \pm 0.13$

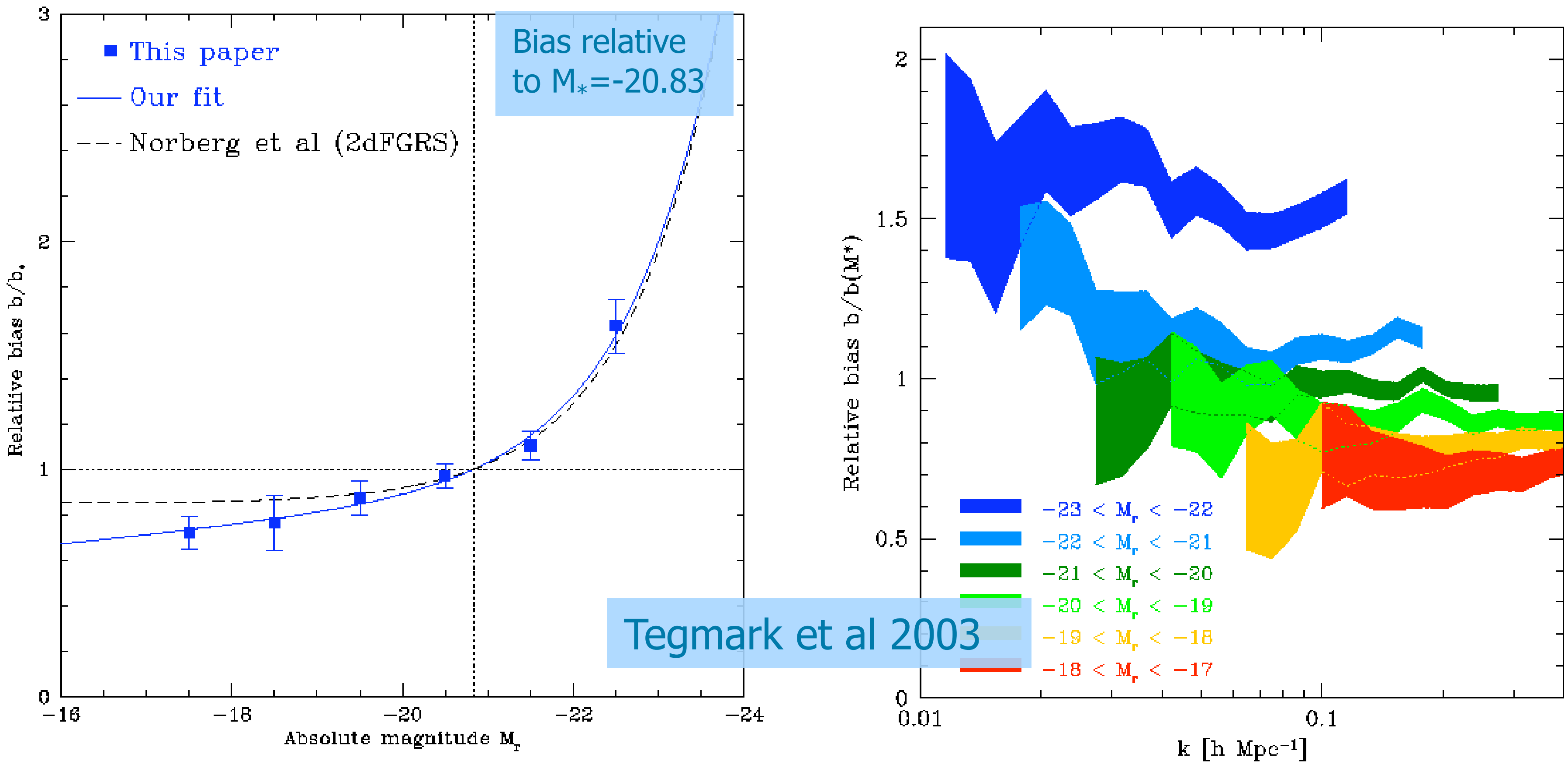
$\sigma_p = 618 \pm 50$ km s^{-1}

Active:

$\beta = \Omega_m^{0.6}/b = 0.54 \pm 0.15$

$\sigma_p = 418 \pm 50$ km s^{-1}

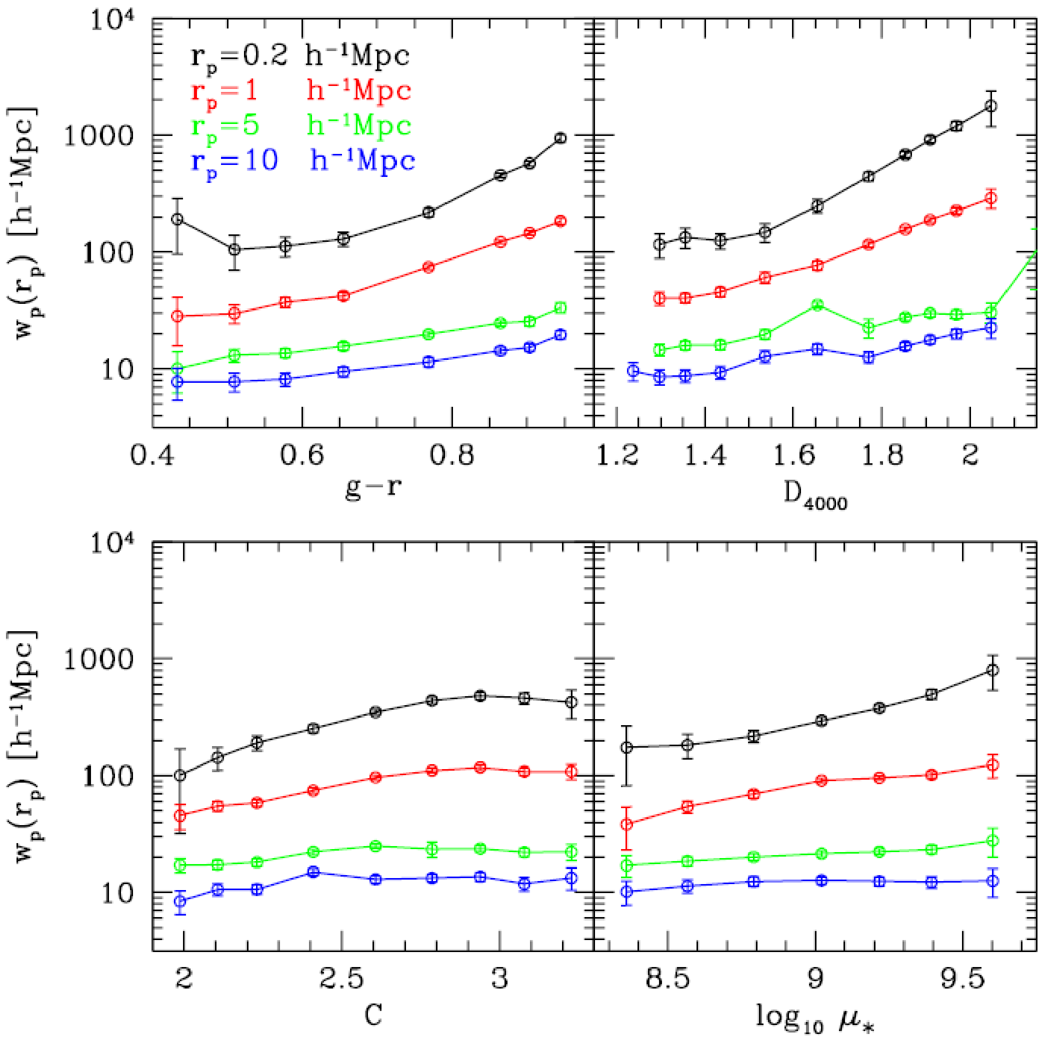
Type-dependent and luminosity-dependent galaxy clustering at z~0



- At low instrinsic luminosities, the clustering amplitude depends only weakly on absolute luminosity
- At high instrinsic luminosities, the dependence is more pronounced

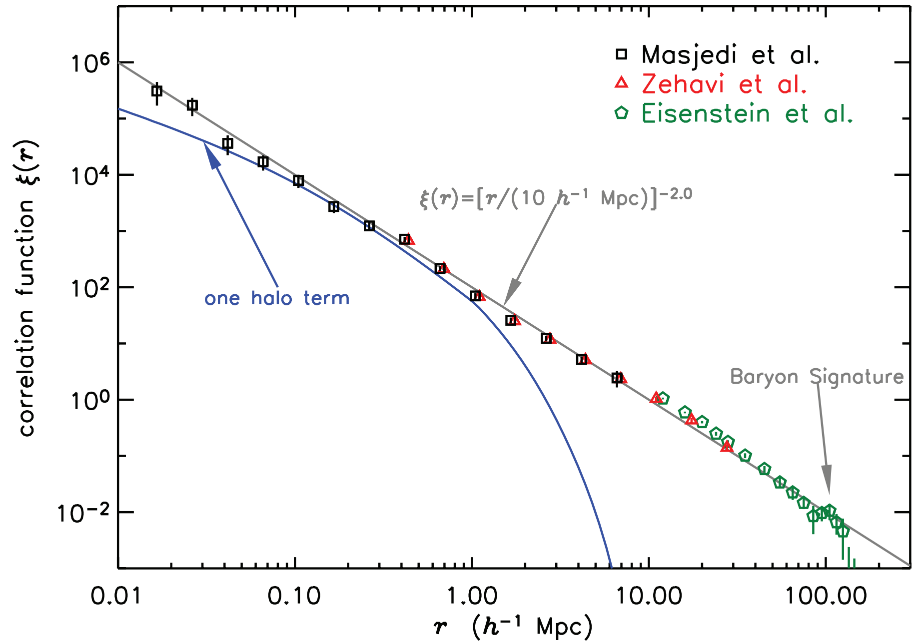
Galaxy clustering dependence on physical properties

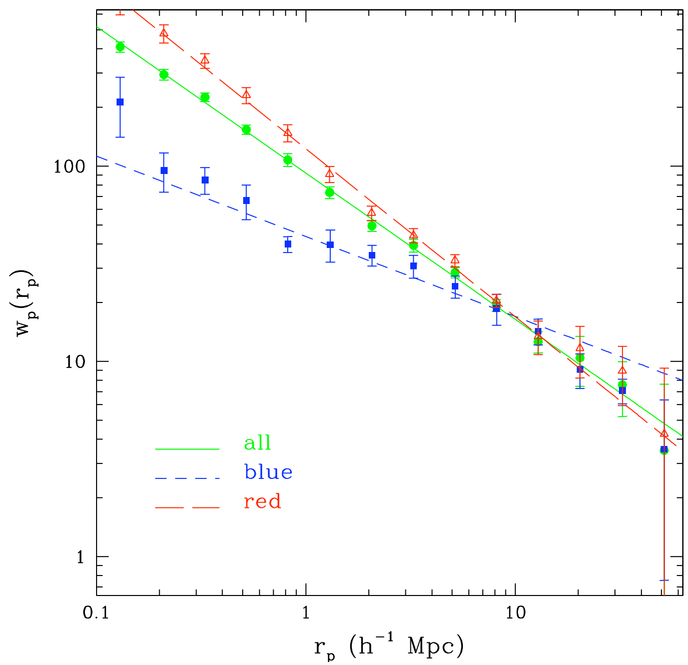
- Stellar population synthesis models are used to derve physical properties of the galaxies in the SDSS
- Scales of 0.2h1 Mpc probe objects inside a given halo
- Scales of 10h-1 probe halo-halo clustering
- Clustering dependence less important on large scales for central concentration and for surface brightness?



Large-scale and small scale correlation functions and the slope of xi(r)

- w(theta) follows a power law with a great deal of precision out to very large scales
- Baryon acoustic oscillations could be a independent method to determine cosmological parameters *if* systematic errors can be kept under control



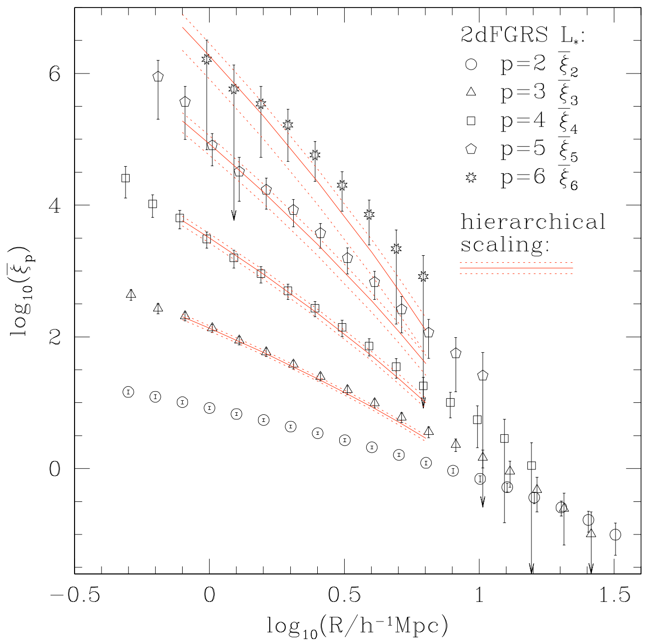


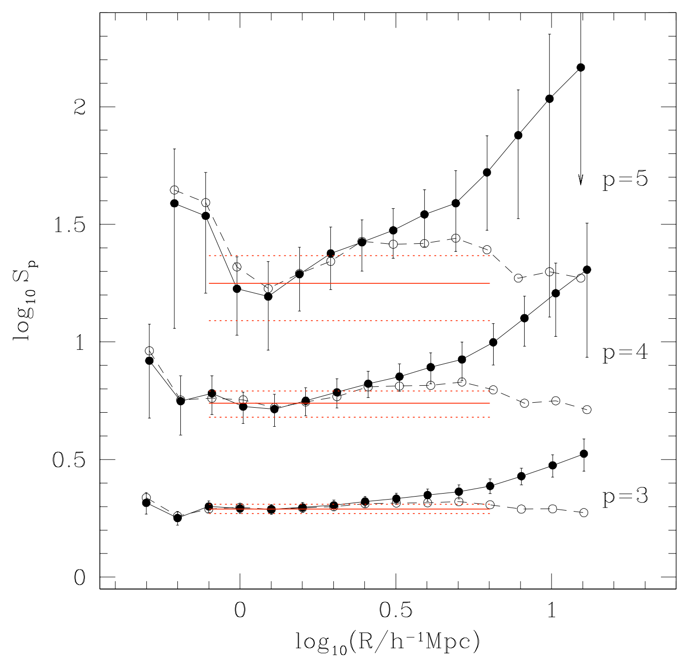
- We see now that different galaxy populations have a different slope in the galaxy correlation function
- Red galaxies reside in more dense environments, have more small-scale clustering, trace the ’peaks’

Measurements of higher-order galaxy clustering

- In hierarchical models of structure formation, the higher order moments of the galaxy correlation function (the n-point functions) are related to each other and can be calculated with PT theory (see Bernardeau et al 2002).
- Only true if intal distribution of perturbations is Gaussian.

$$\bar{\xi}_p = S_p \bar{\xi}_2^{p-1}.$$





- Measuring these moments is super hard as it requires a very large samples with perfect control of systematic errors
- Baugh et al find that the values of sn they measure from a volume-limited sample of 40,000 2DF galaxies agree well with the predictions of the heiarchical structure formation models

Part II

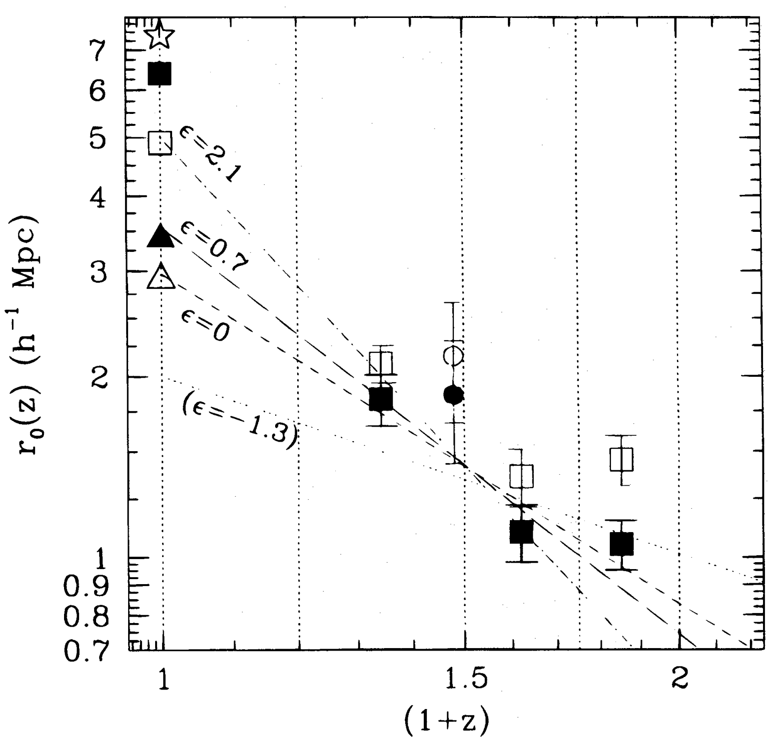
Observations at high redshift

Measuring the evolution of galaxy clustering

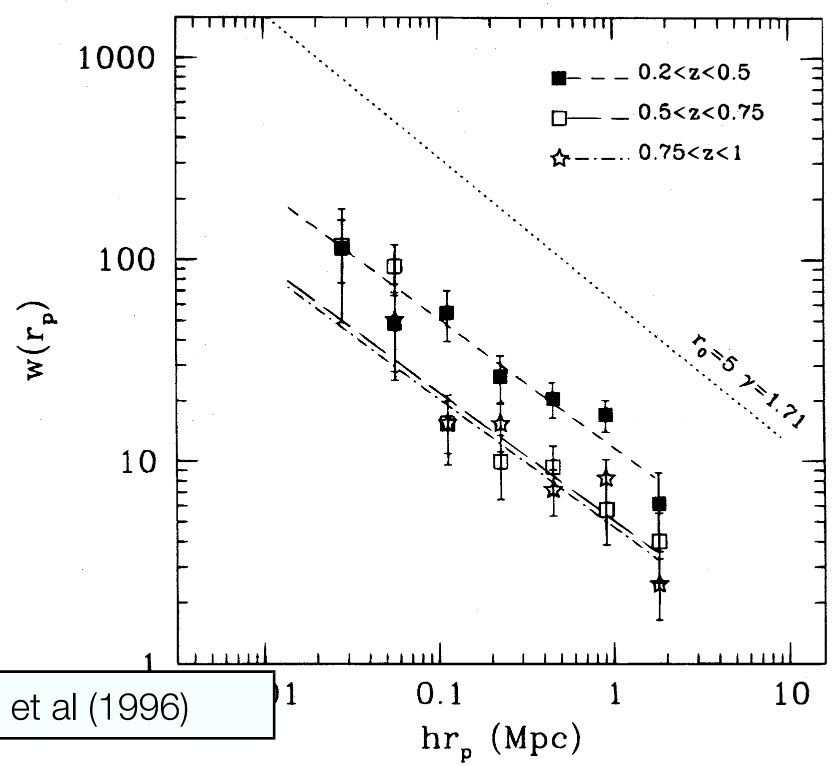
$$\xi(r,z) = (r/r_0)^{-\gamma}(1+z)^{-(3-\gamma+\epsilon)}$$

- ϵ=1 is the “stable clustering hypothesis”
- Note that this paper assumed that Ω=1; in low-Ω cosmologies the observed growth of structure is easier to explain.

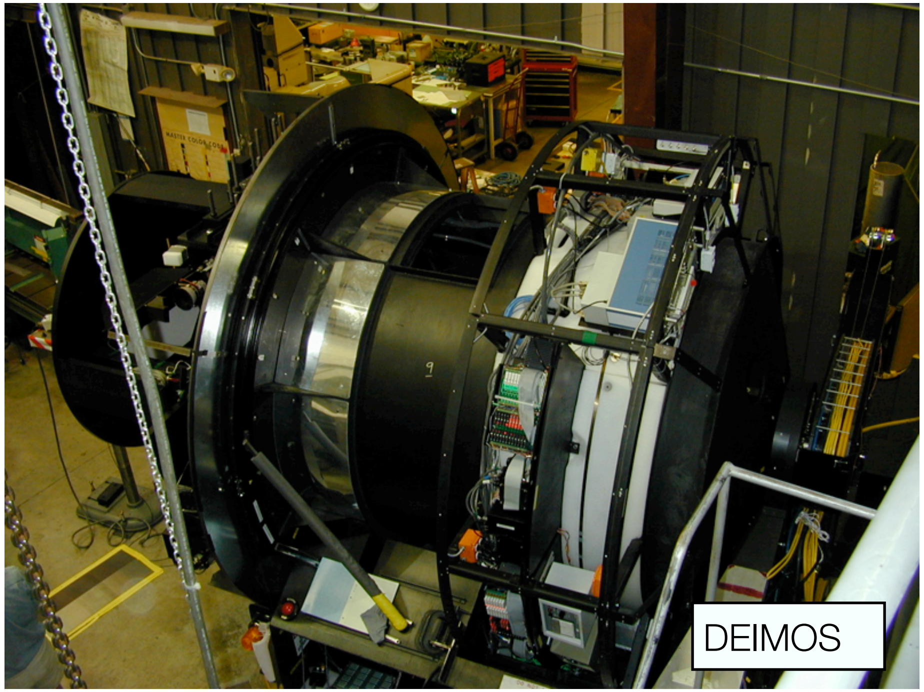
- CFRS redshift survey was the first moderately deep redshift survey (z~1)
- With the increasingly large precision data sets, this formalism is no longer useful...



Le Fevre et al (1996)



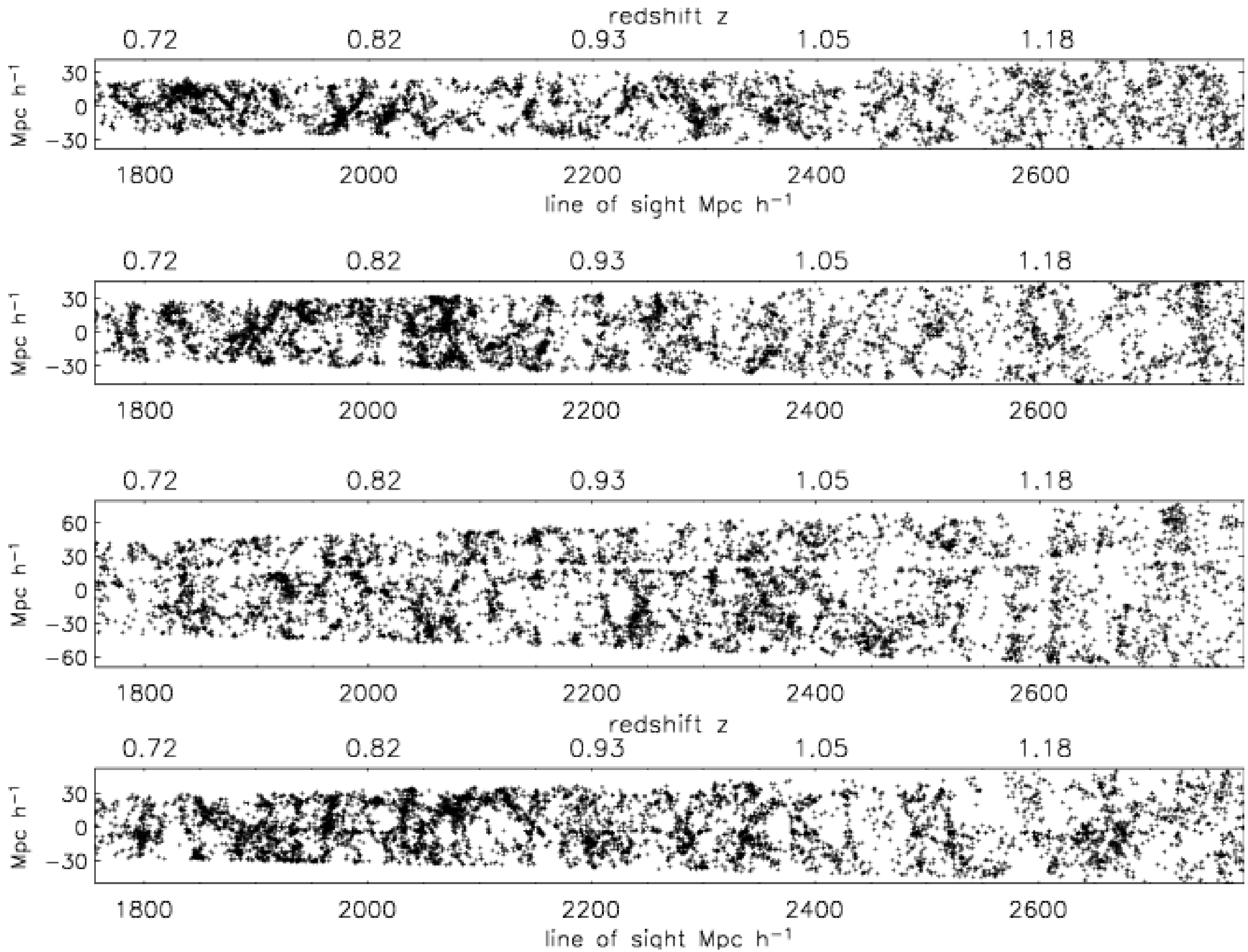
Surveying the high-redshift universe

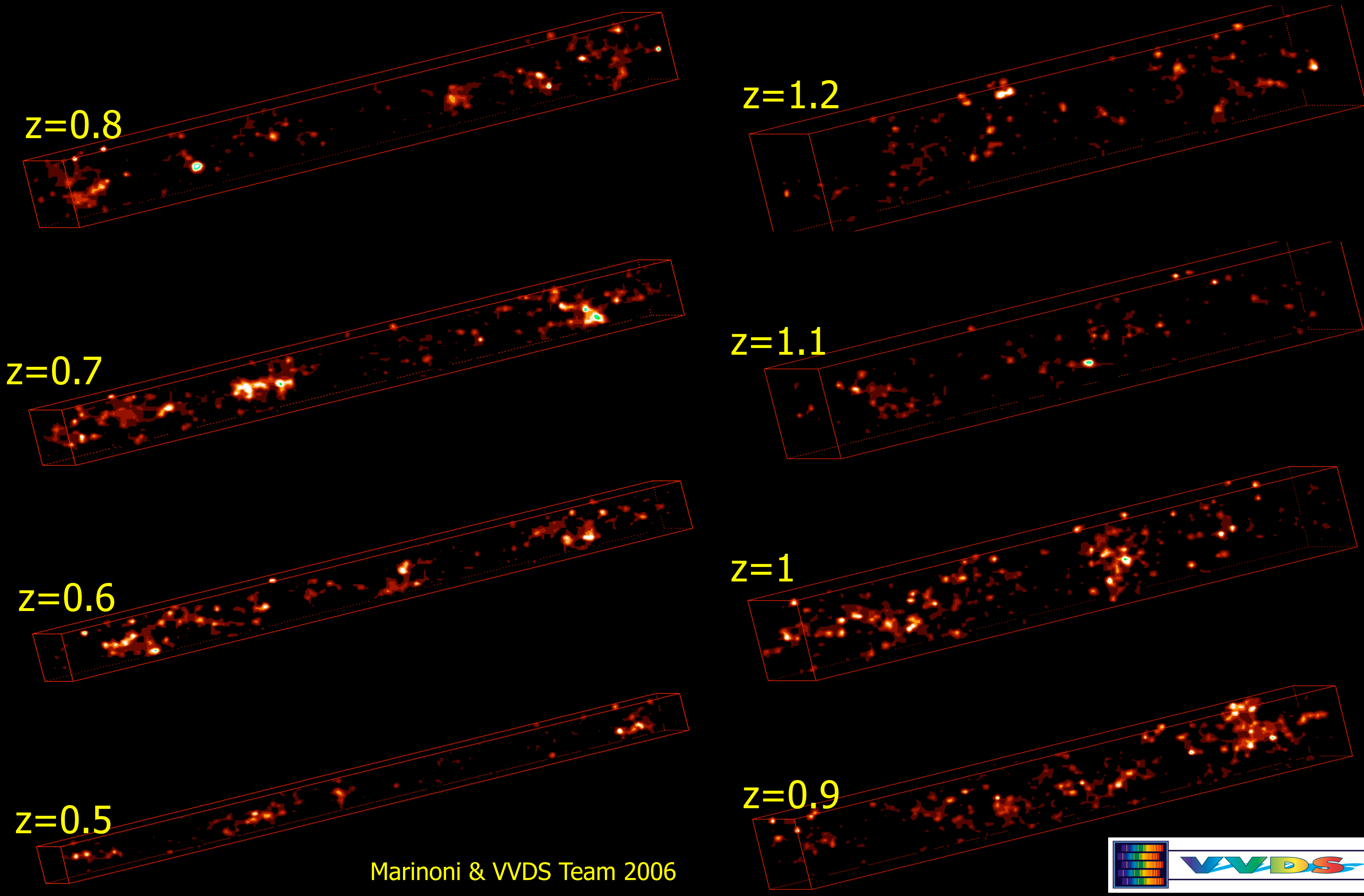


- Getting redshifts for galaxies at large redshifts is very hard
- Need new instruments on 8m class telescopes like VIMOS and DEIMOS

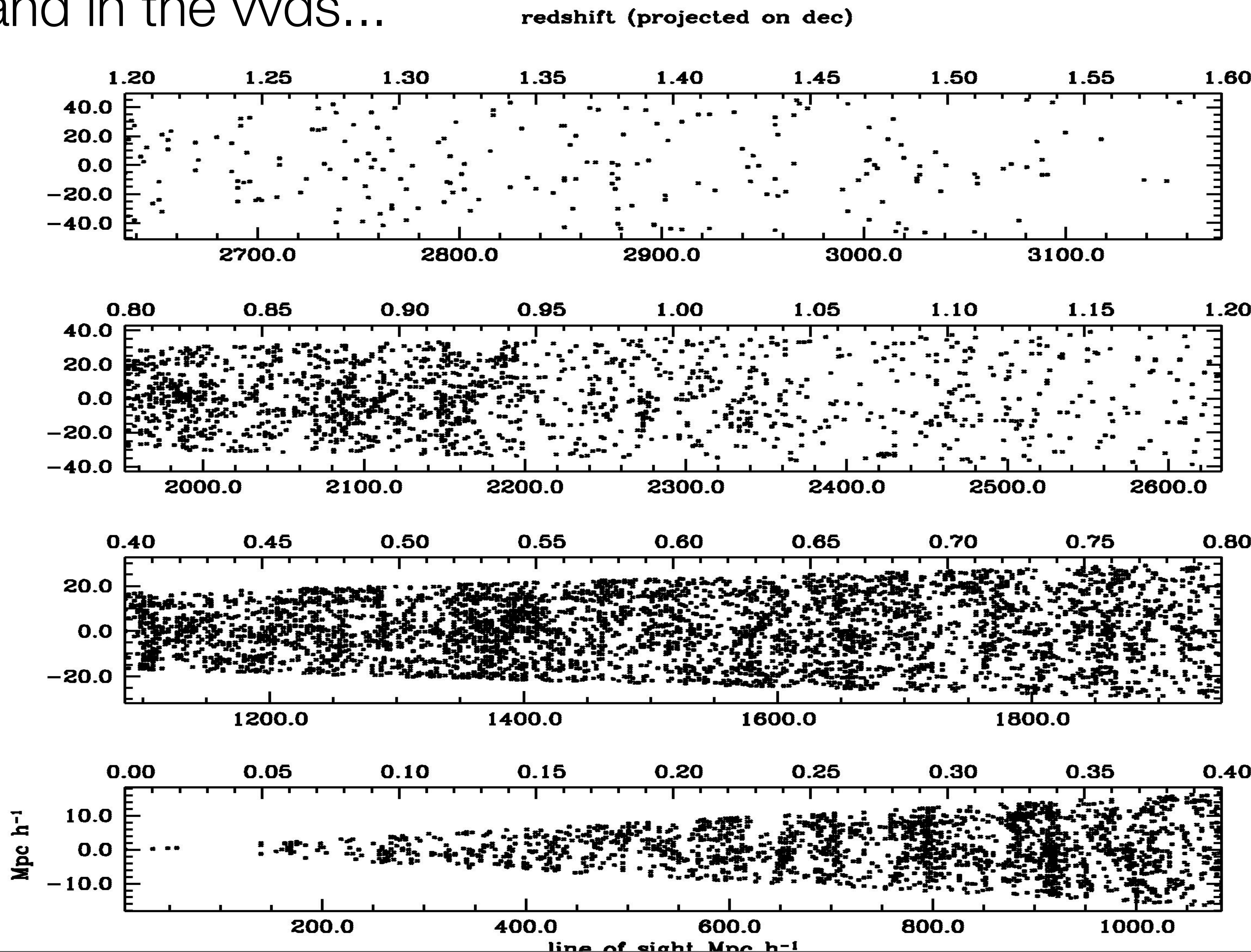
- VVDS and DEEP2 have produced large (>10,000) galaxy surveys with z~1
- Can attempt to investigate clustering as a function of environment at z~1
- Selection criteria for the two surveys is very different

Structures at high redshift seen in DEEP2....



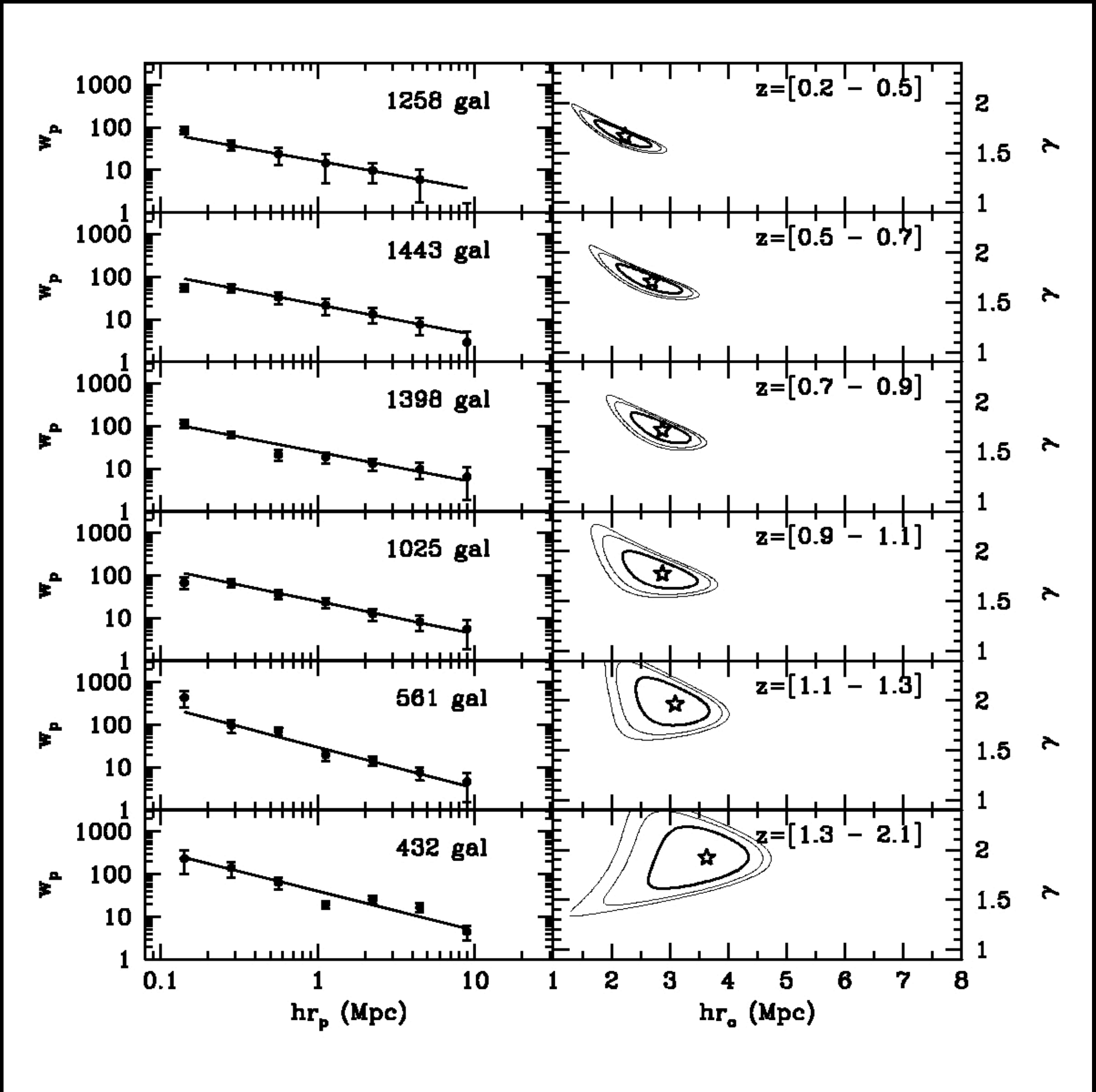

z=0.8
z=0.7
z=0.6
z=0.5
z=1.2
z=1.1
z=1
z=0.9
Marinoni & VVDS Team 2006
VVDS

and in the vvds...

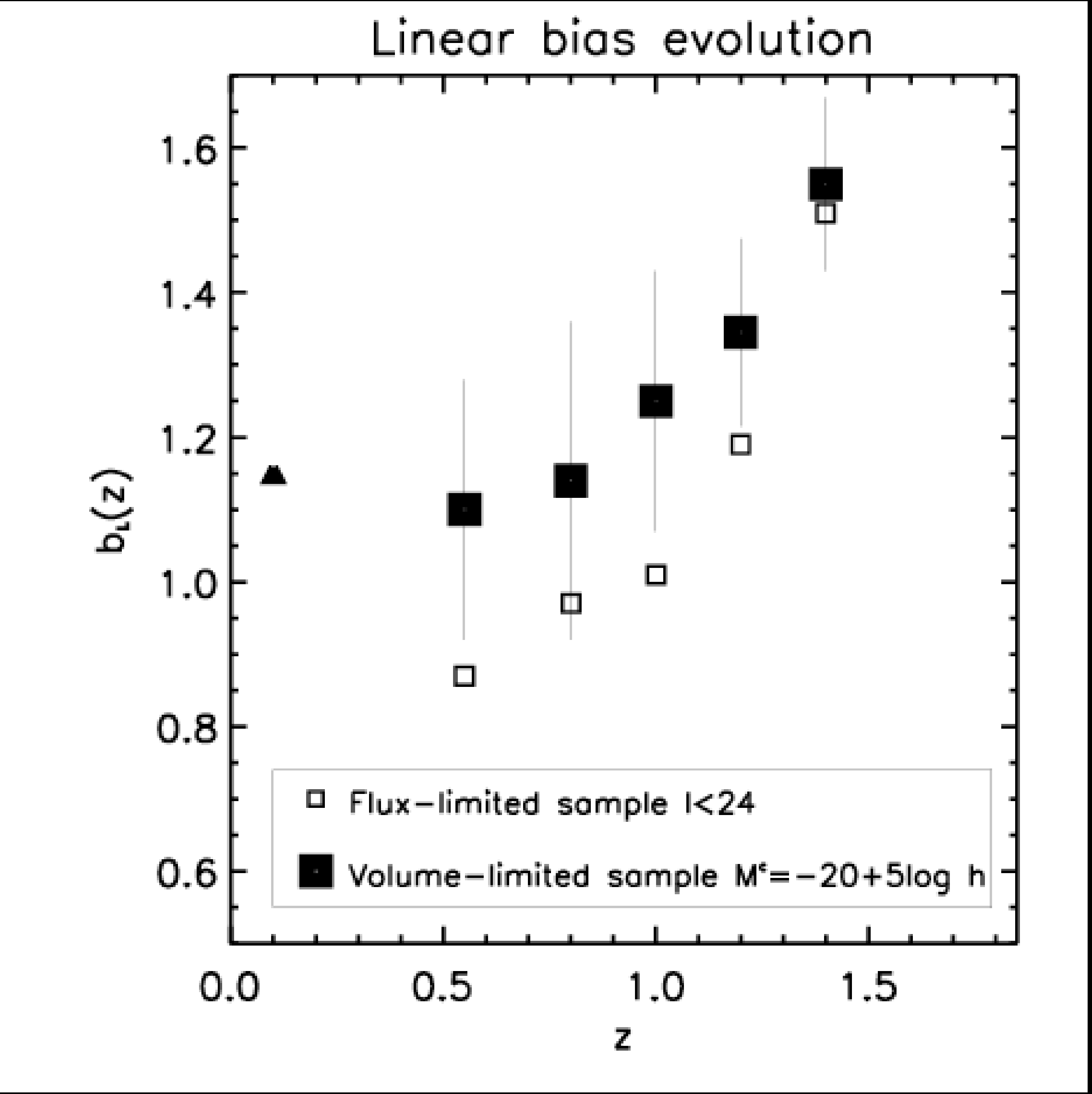


Evolution of two-point correlation function from VVDS first-epoch data

(magnitude-limited sample:
~7000 galaxies with
$17.5<I_{AB}<24$ over 0.5 sq.deg)



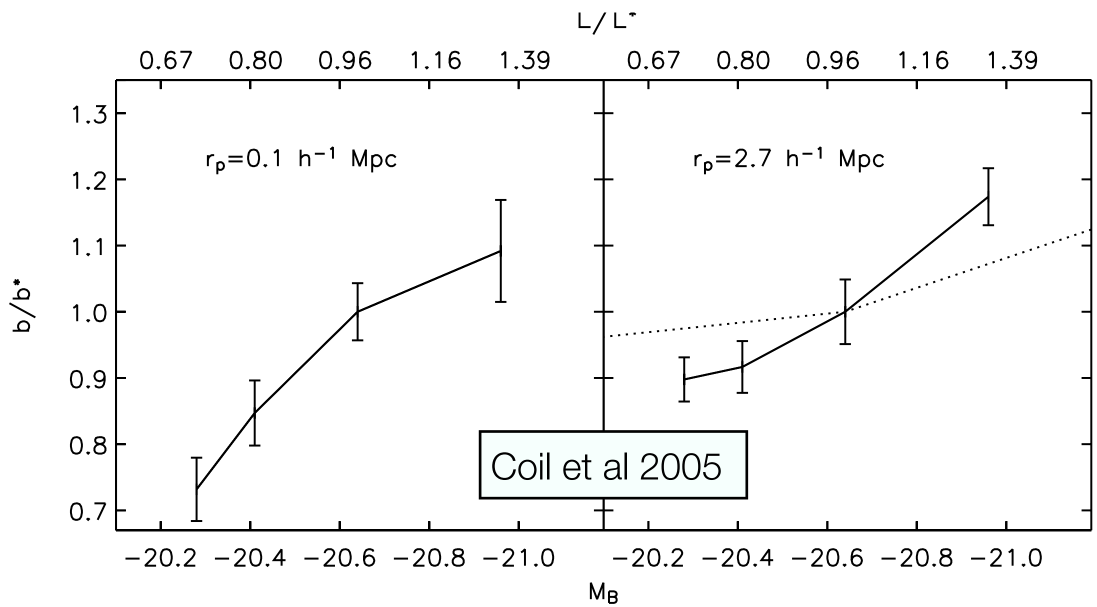
Le Fevre & VVDS Team 2005
Pollo & VVDS Team 2005

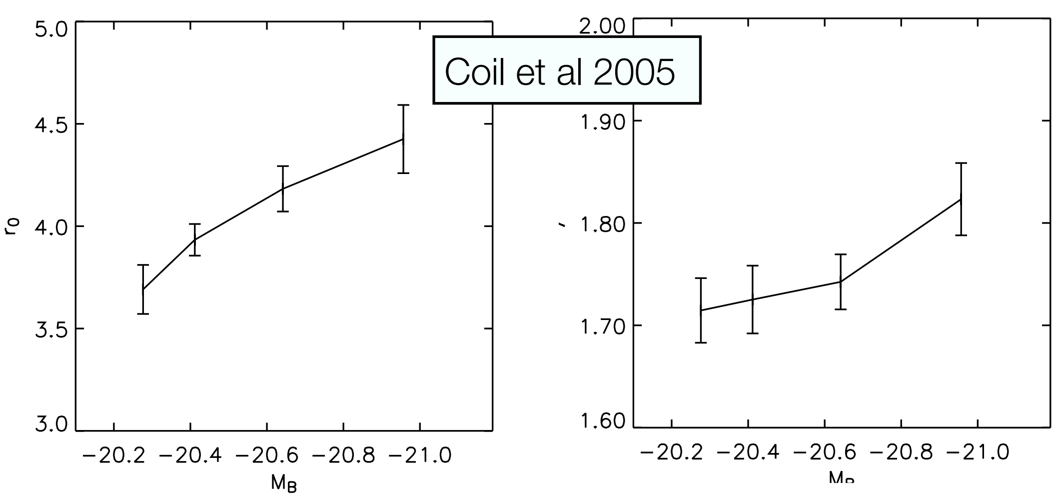


Marinoni & VVDS Team 2006

Clustering as a function of luminosity and scale in DEEP2 and VVDS

- Simple magnitude limited surveys sample a range of intrinsic luminosities
- Larger spectroscopic surveys mean we can try to investigate object parameters as a function of absolute luminosity for the first time

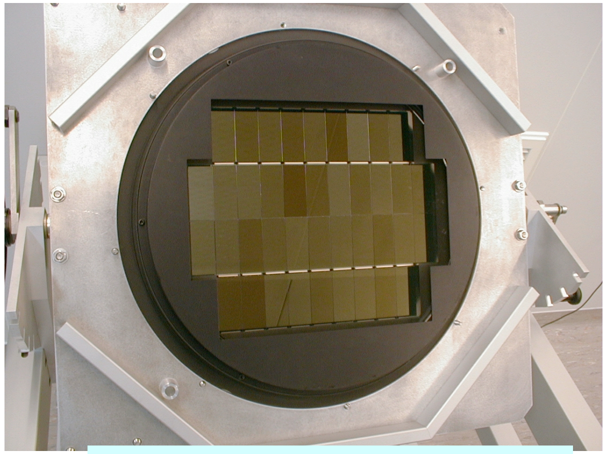




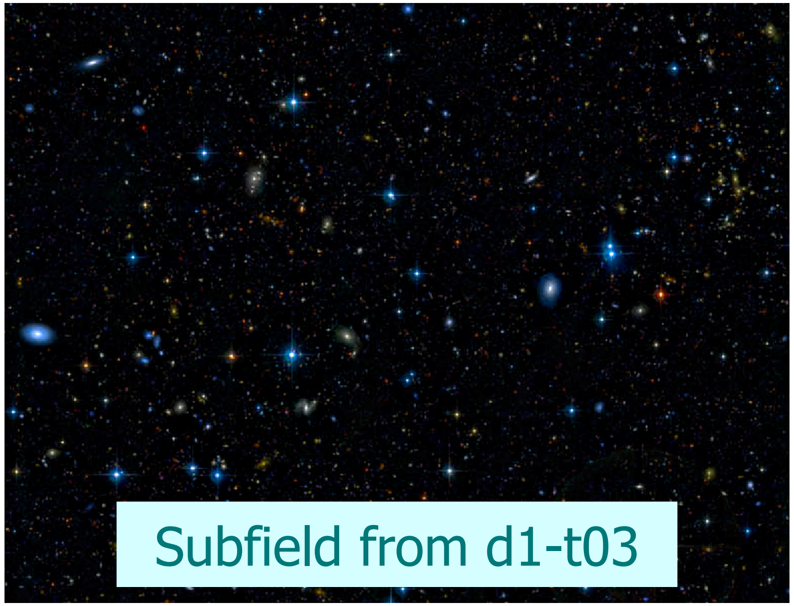
- However, the big problem with these observations is that the authors are not able to select by type *as well*
- More luminous slices are dominated by elliptical galaxies

CFHTLS-T03 photometric catalogues

- Input photometric catalogues: CFHTLS-T03 deep fields processed at TERAPIX/CFHT
- Ultra-deep photometrically uniform catalogues (chip-to-chip variations are less than 1%)
- Catalogues reach ~27AB in *ugriz* (>30hr integrations in some filters!)
- **Total effective area: 3.1 deg^2 in four fields**
- **We can compute 'real' cosmic variance error bars**
- Photometric redshifts calibrated using 8,000 VVDS spectra available in the d1 field
- Accuracy: around 3% in the redshift range 0.1<z<1.2



Megacam @CFHT



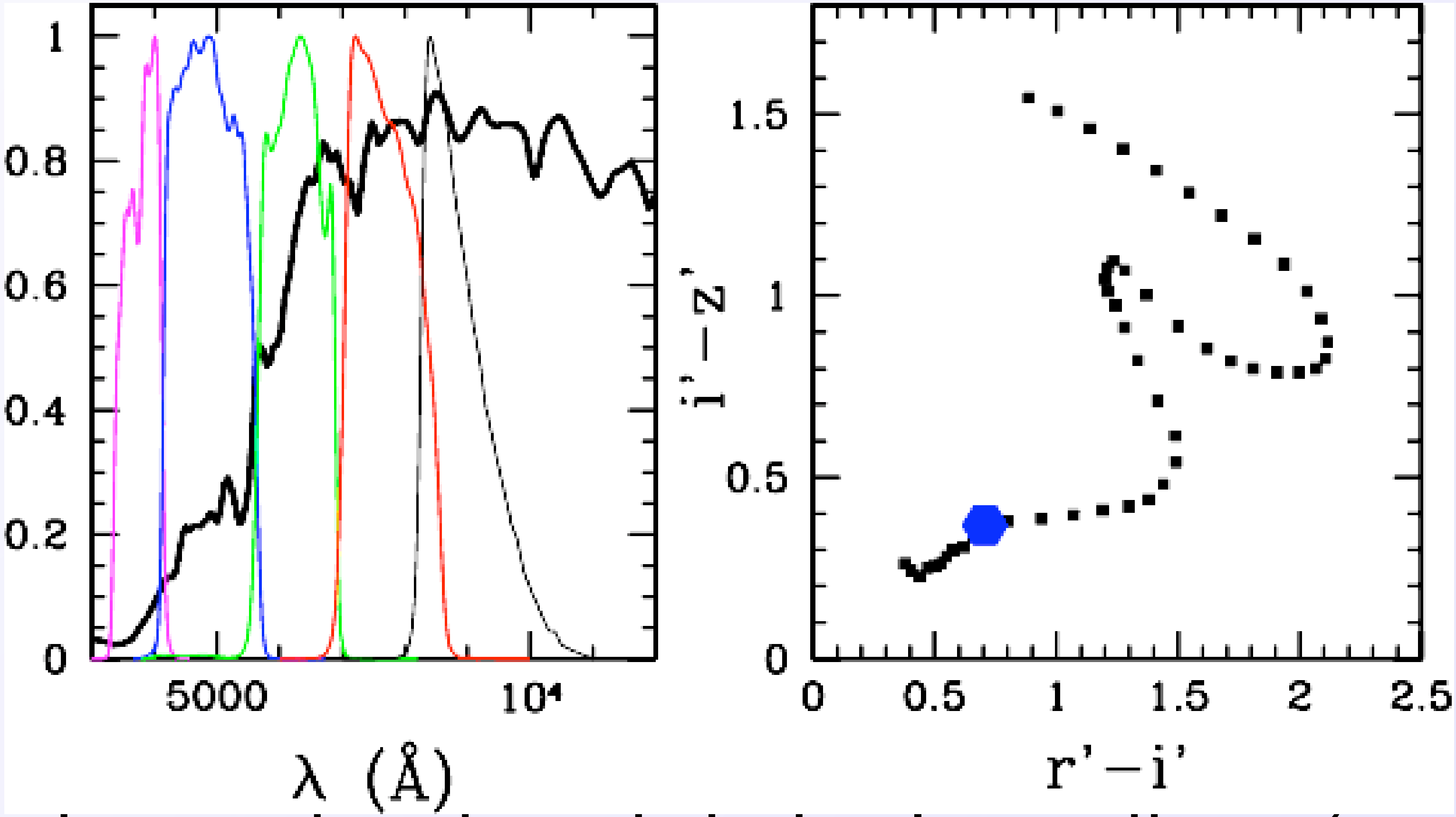
Subfield from d1-t03

The standard χ^2 method (I)

Template spectra redshifted every δz=0.04

Integrated through filters ➤ predicted colors

z=0.4



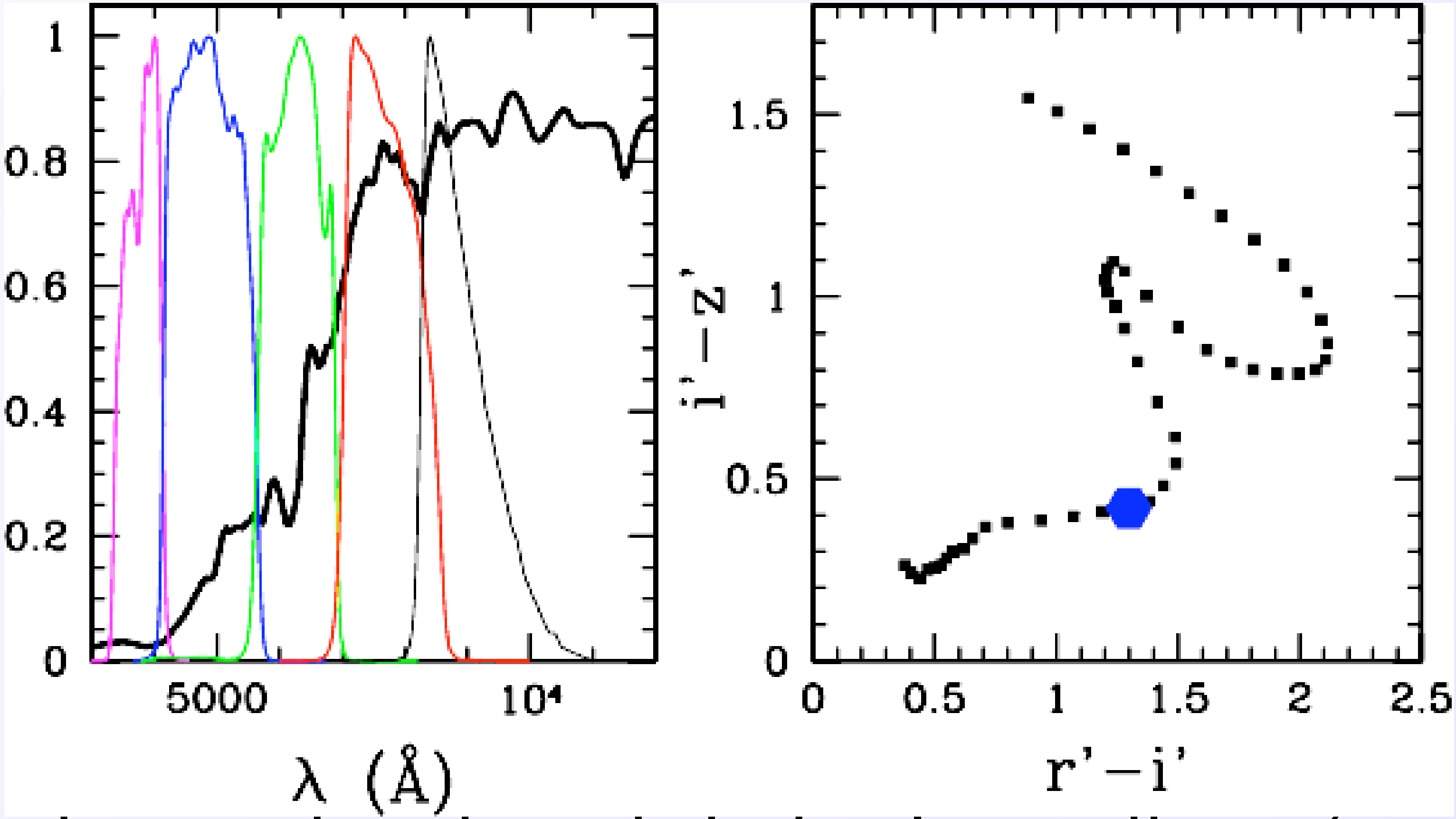
Match observed and predicted colors with a χ^2

The standard χ^2 method (I)

Template spectra redshifted every δz=0.04

Integrated through filters ➤ predicted colors

z=0.6



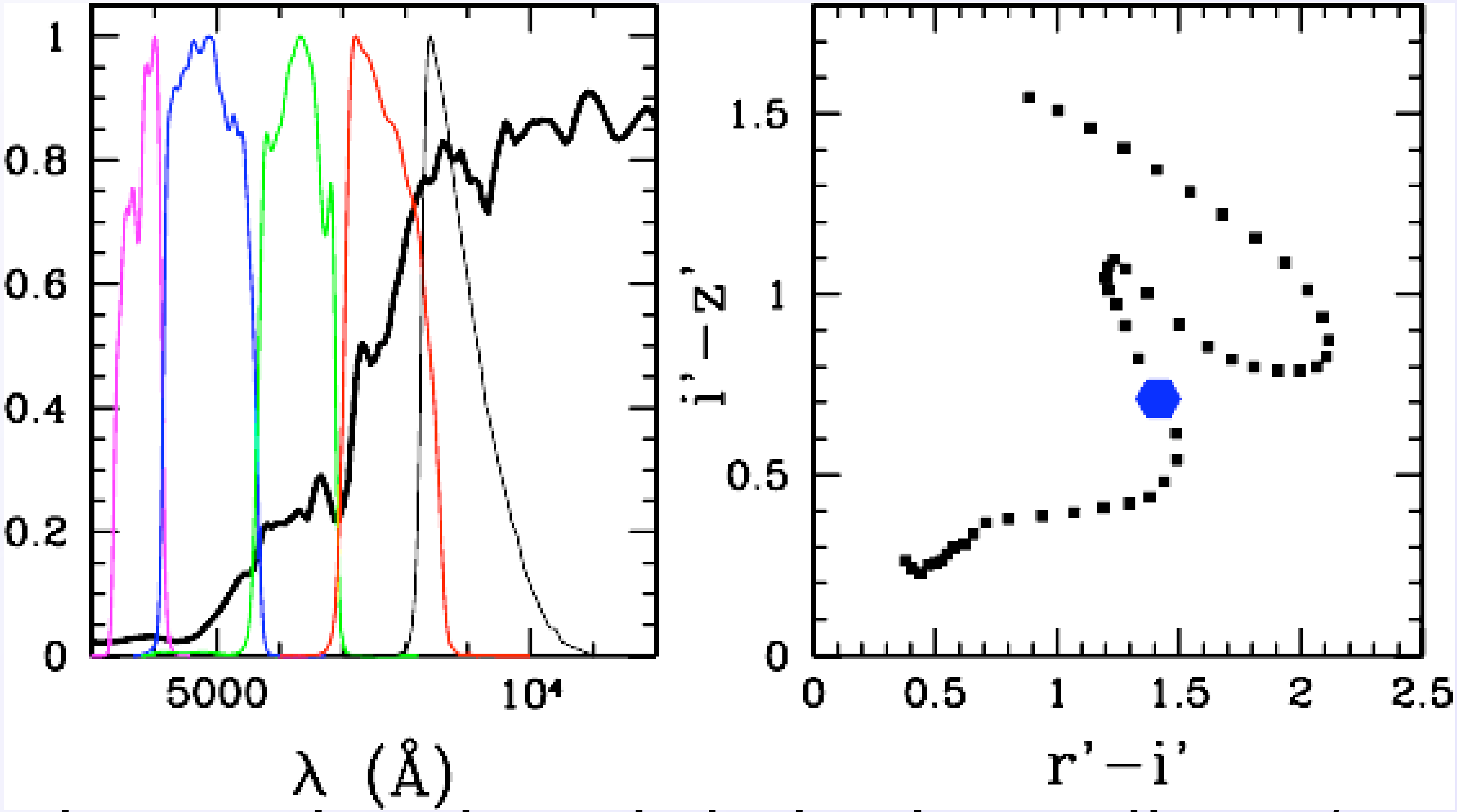
Match observed and predicted colors with a χ^2

The standard χ^2 method (I)

Template spectra redshifted every $\delta z=0.04$

Integrated through filters ➤ predicted colors

z=0.8



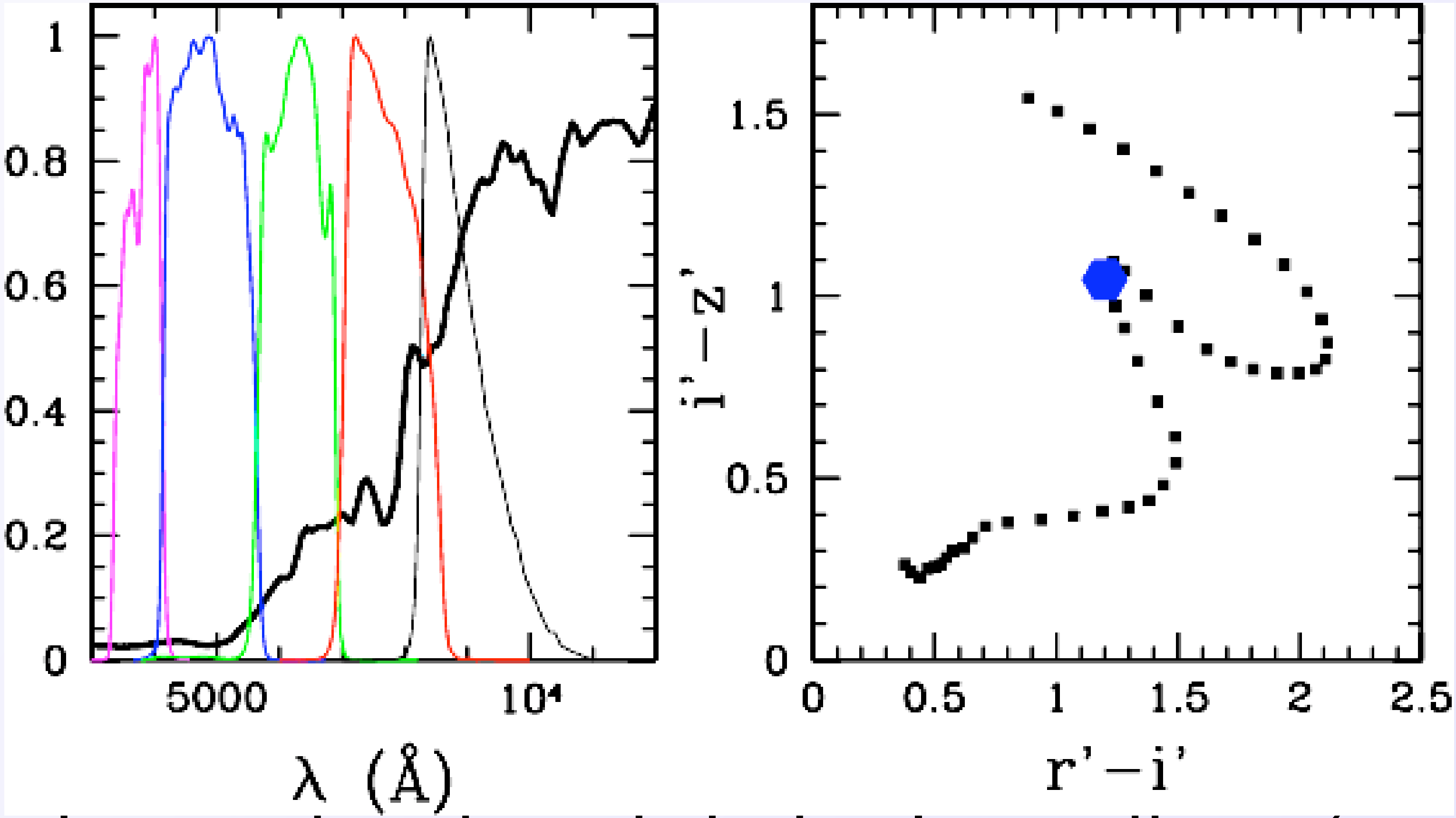
Match observed and predicted colors with a χ^2

The standard χ^2 method (I)

Template spectra redshifted every $\delta z=0.04$

Integrated through filters ➤ predicted colors

z=1.0



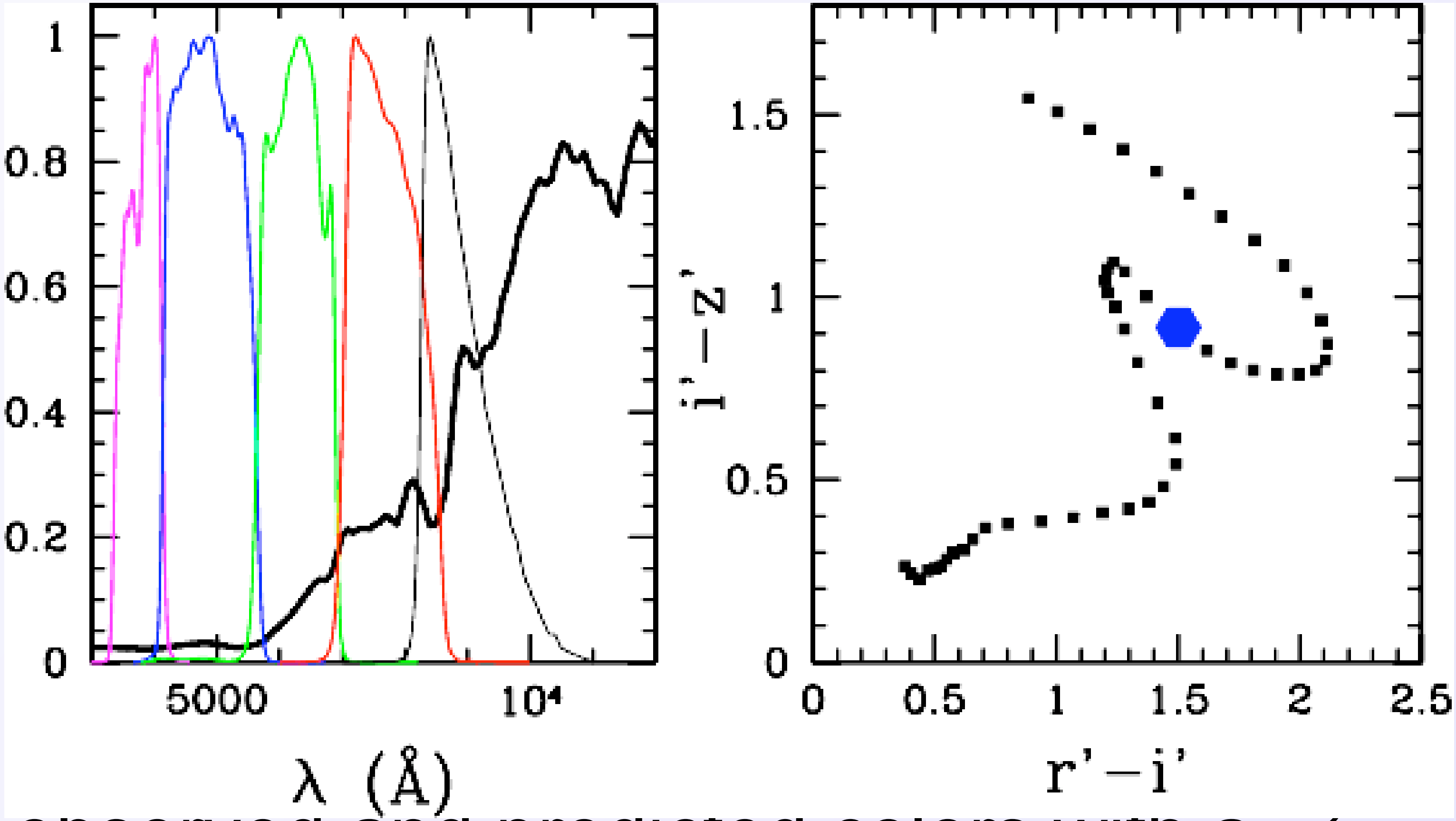
Match observed and predicted colors with a χ^2

The standard χ^2 method (I)

Template spectra redshifted every $\delta z=0.04$

Integrated through filters ➤ predicted colors

z=1.2



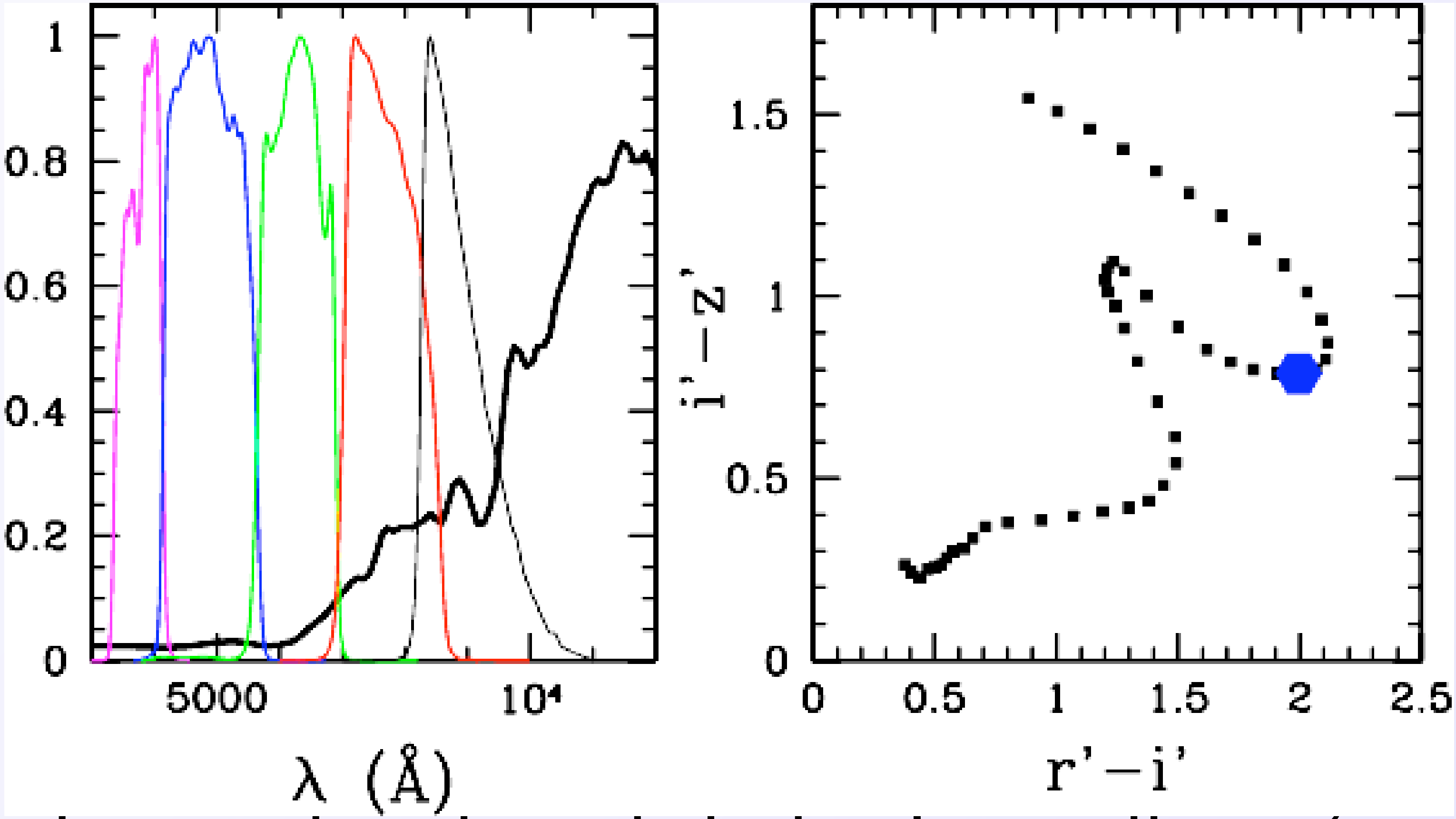
Match observed and predicted colors with a χ^2

The standard χ^2 method (I)

Template spectra redshifted every $\delta z=0.04$

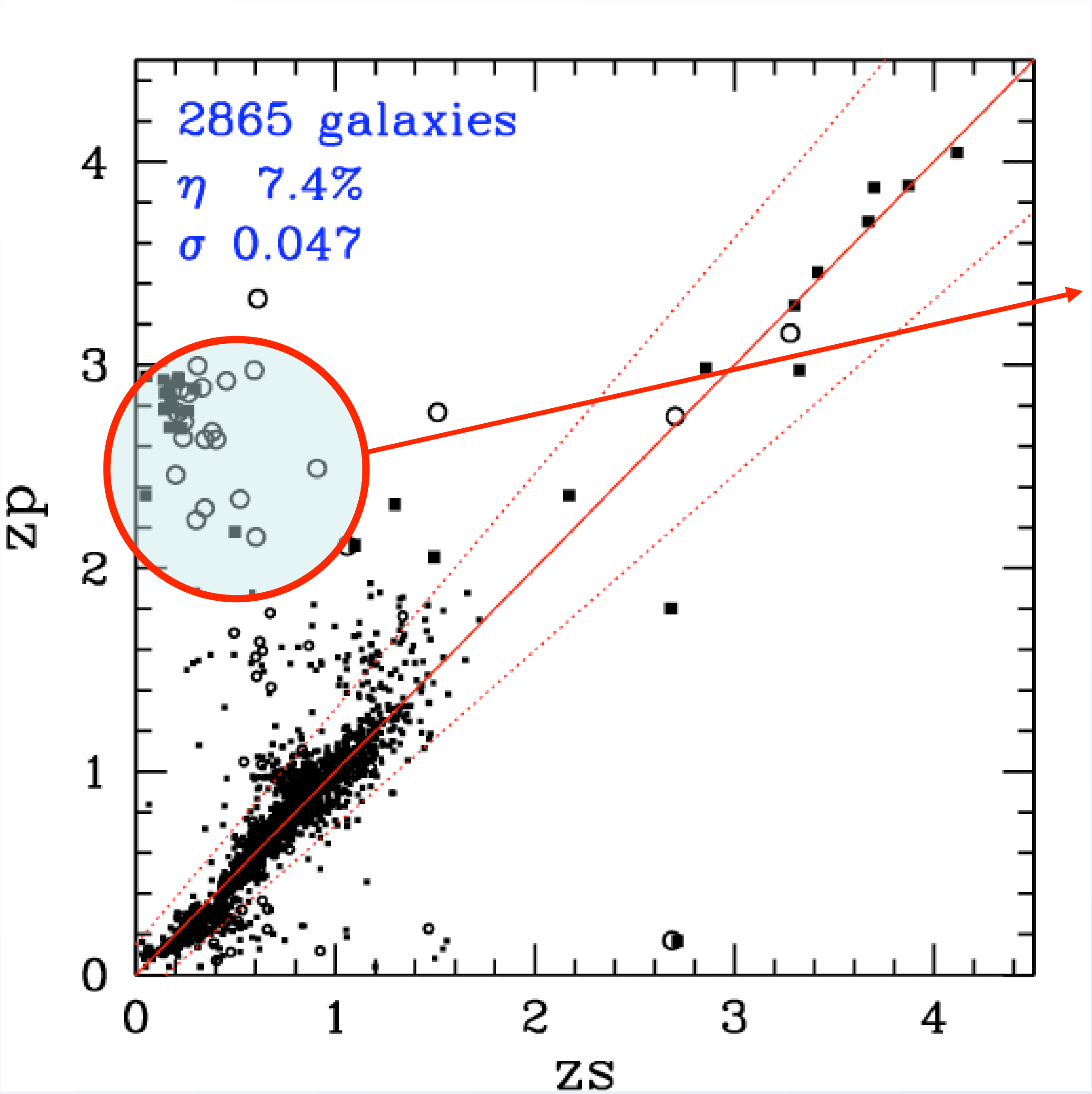
Integrated through filters ➤ predicted colors

z=1.4



Match observed and predicted colors with a χ^2

The standard χ^2 method -Results

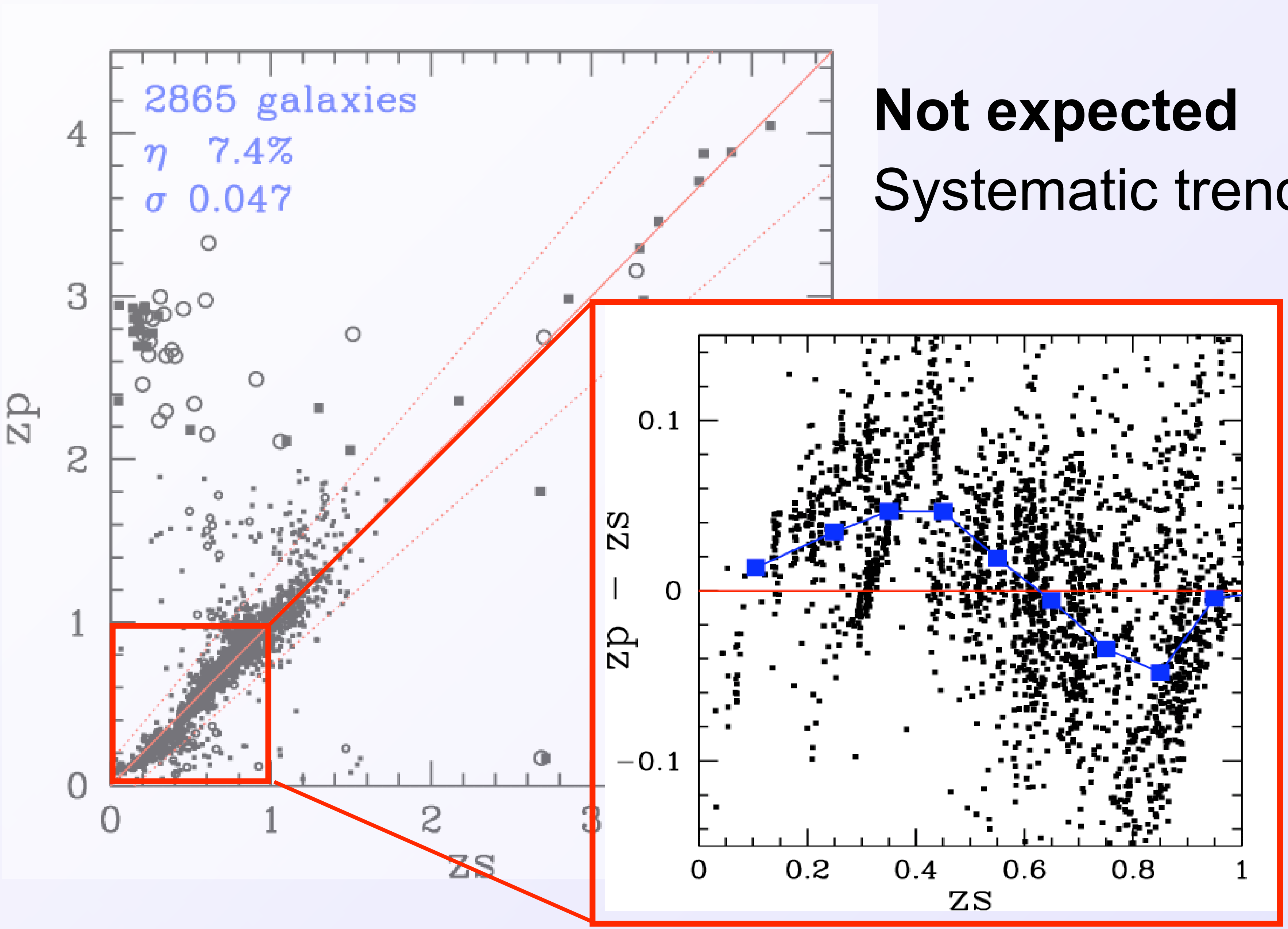


Expected
Degeneracy between the Balmer and Lyman breaks

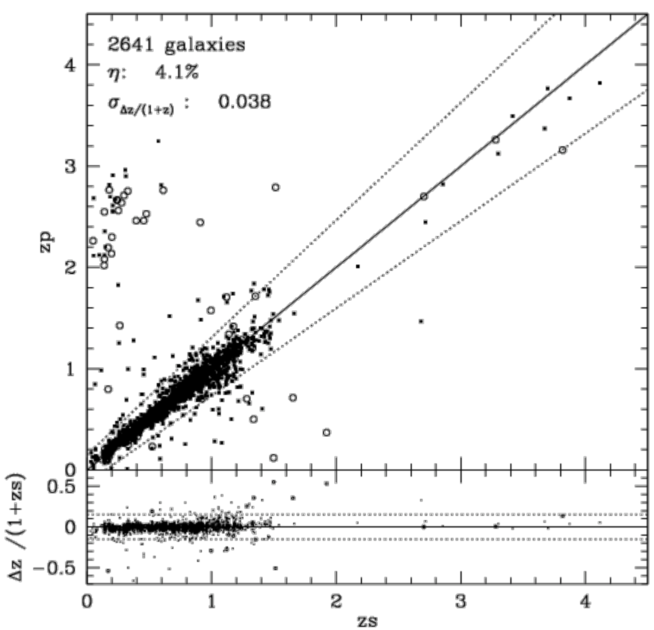
The standard χ^2 method -Results

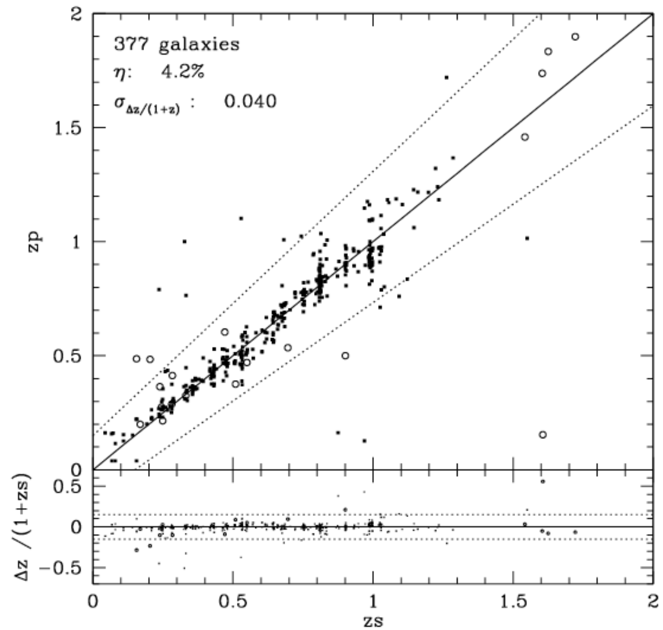
Not expected

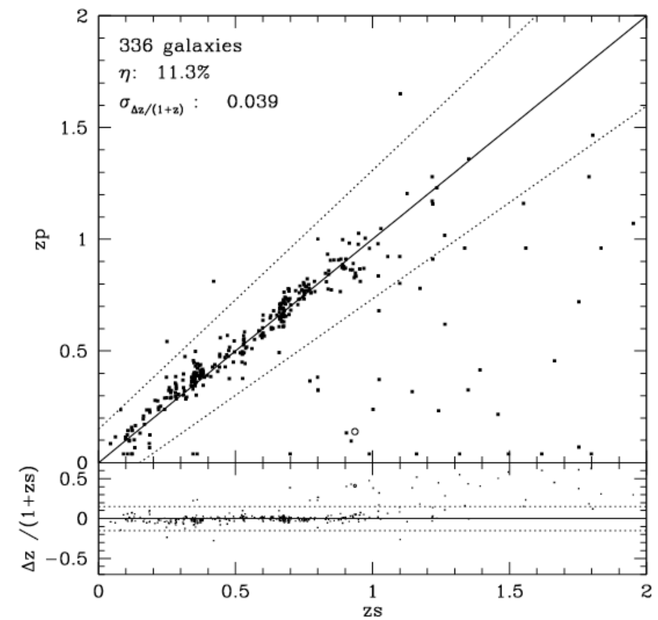
Systematic trends

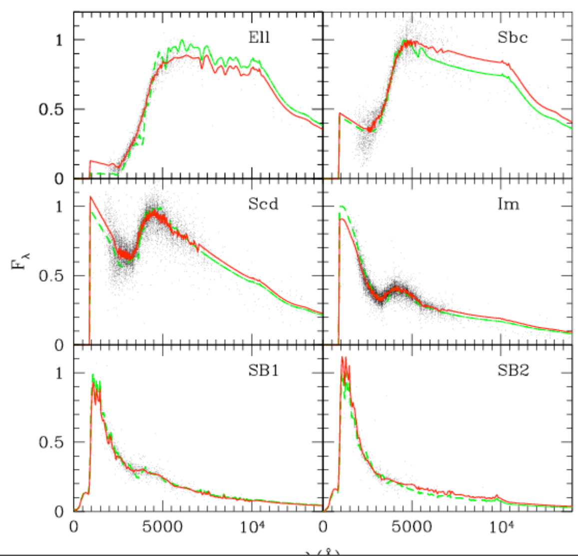


The CFHTLS-T03 photometric redshift catalogues



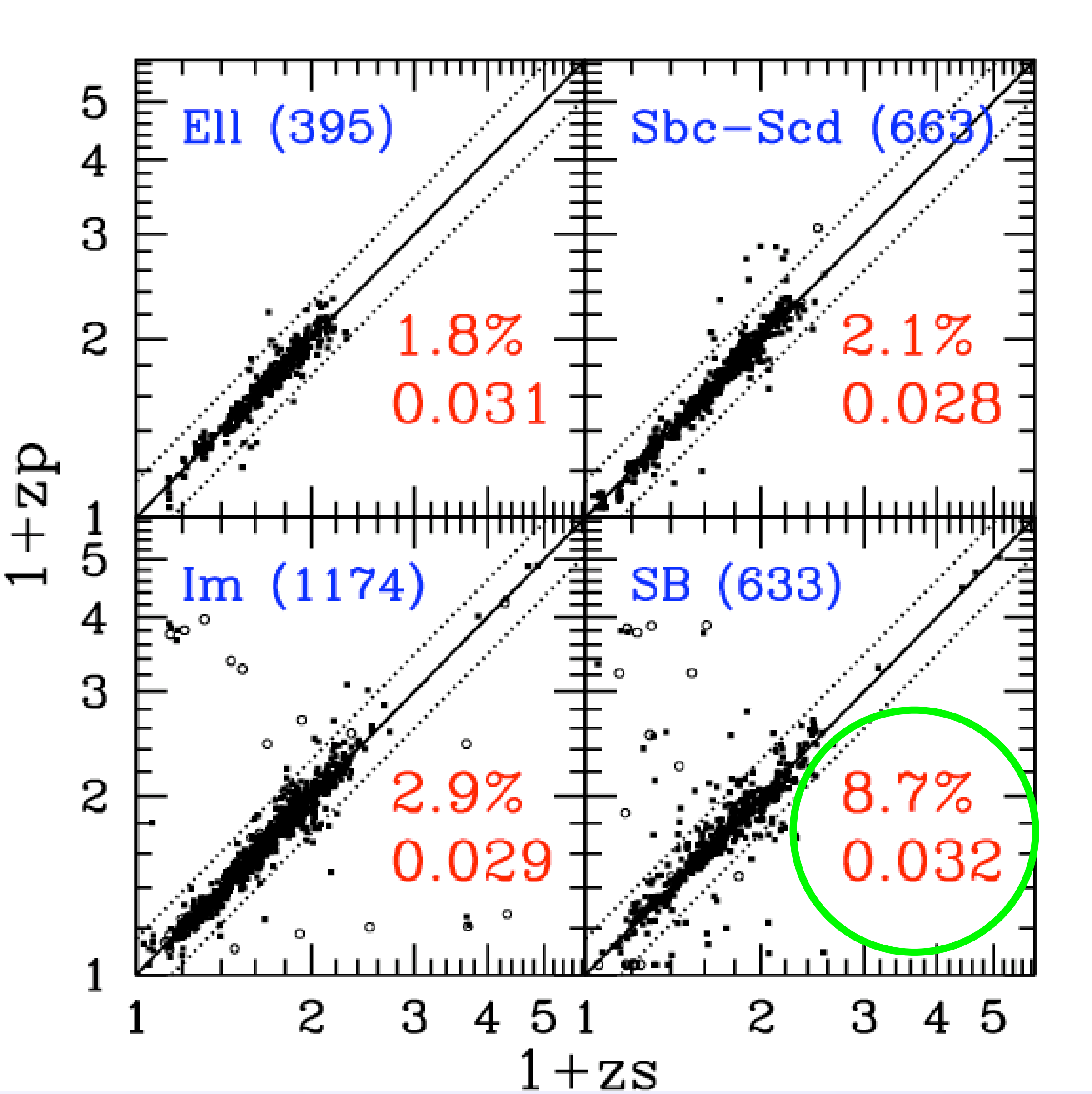






- Using VVDS spectra we calibrated zphots for 400,000 objects on the CFHTLS survey fields
- Our photometric redshift code produces a probability distribution function for each galaxy and we use this to compute our pair statistics
- These catalogues and pdfs are publically available from terapix.iap.fr

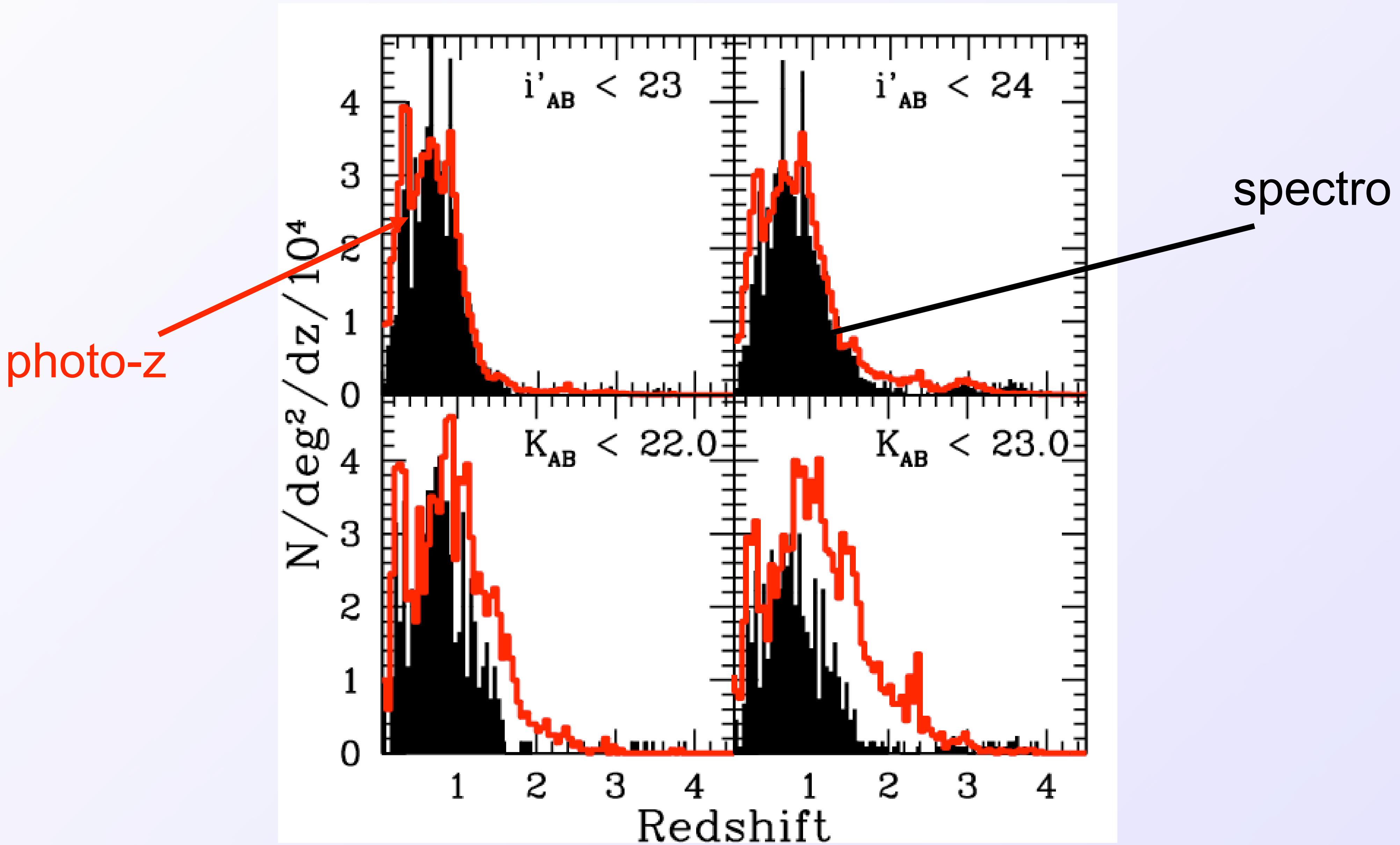
Accuracy per spectral type

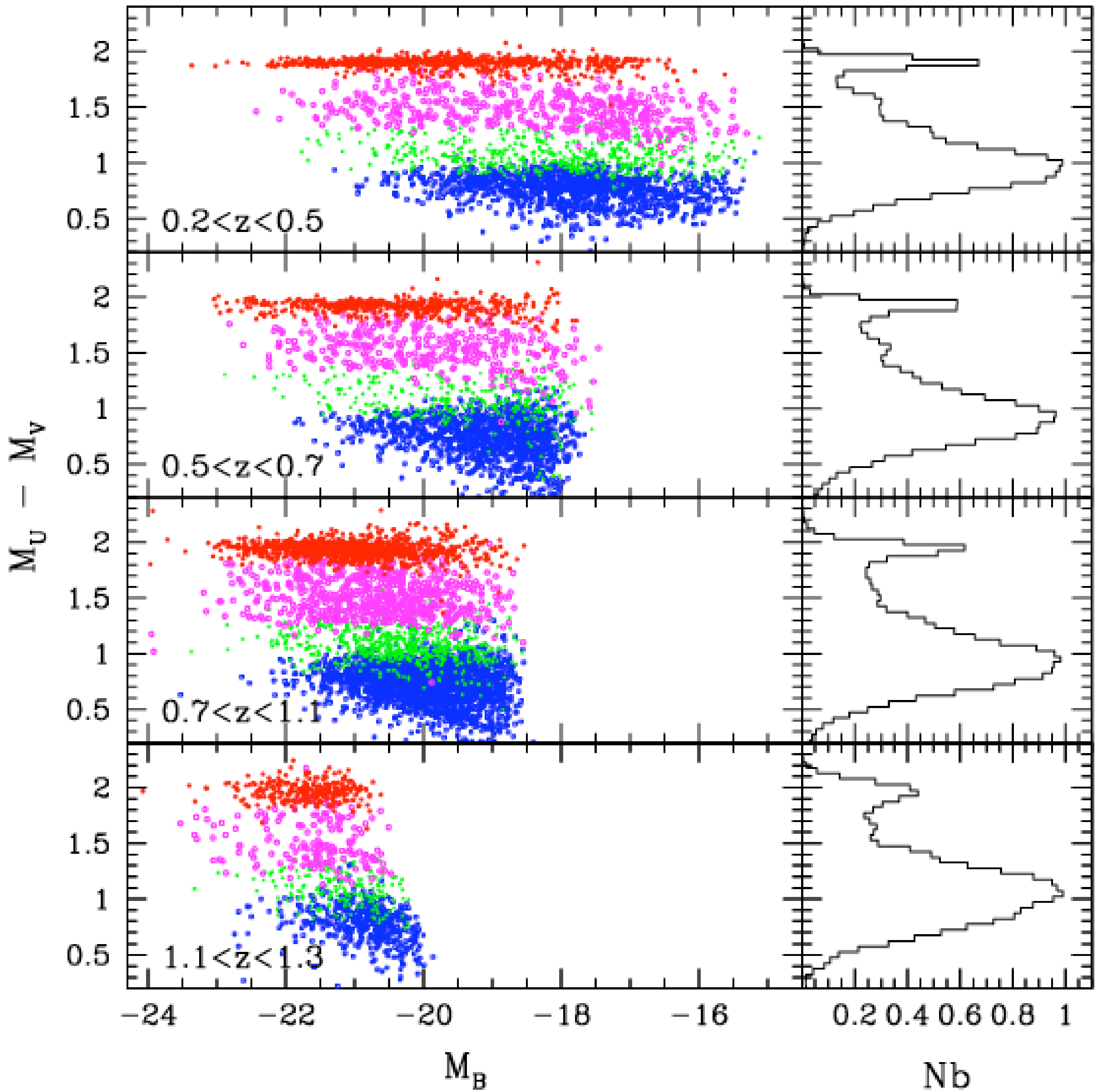


Starburst:
20% of the galaxies,
half of the
catastrophic errors

Small Balmer break,
emission lines,
extinction

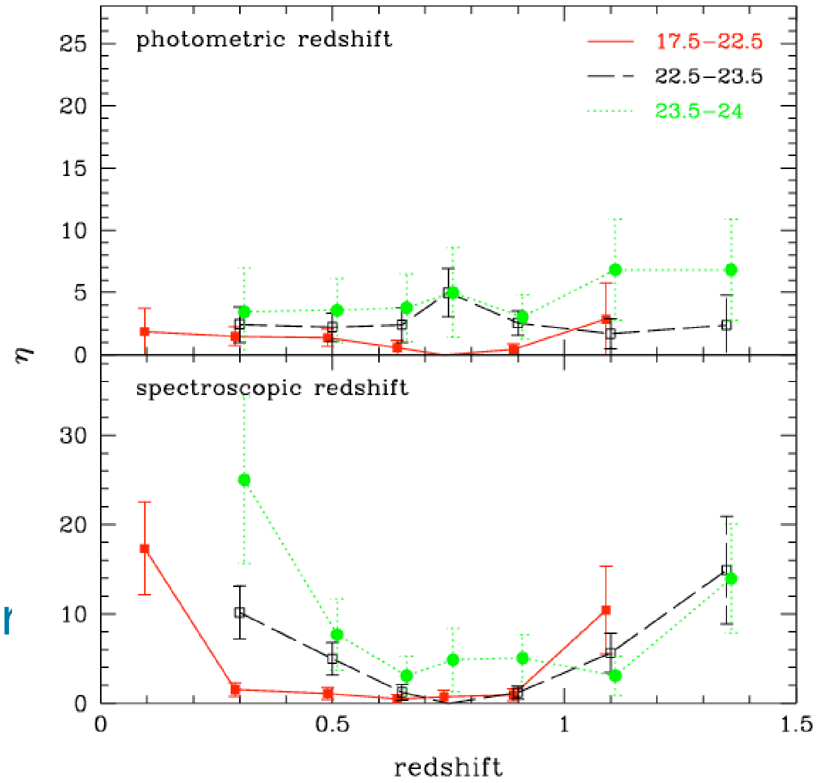
redshift distributions





- Bimodal colour redshift relation clearly observed in the CFHTLS fields
- We can also easily select objects by spectral type and luminosities
- Our redshift errors are larger than VVDS and DEEP2, but we have much larger galaxy samples

- We compute the projected correlation function w(θ) for each field and for each magnitude slice.
- We select galaxies in redshift slices corresponding the ranges where our photometric redshifts have the highest accuracy (lowest numbers of catastrophic outliers)
- For the moment, we consider galaxies with 0.2<z<1.2
- Using the limber transformation we can estimate the r0 at the effective redshift of our sample.

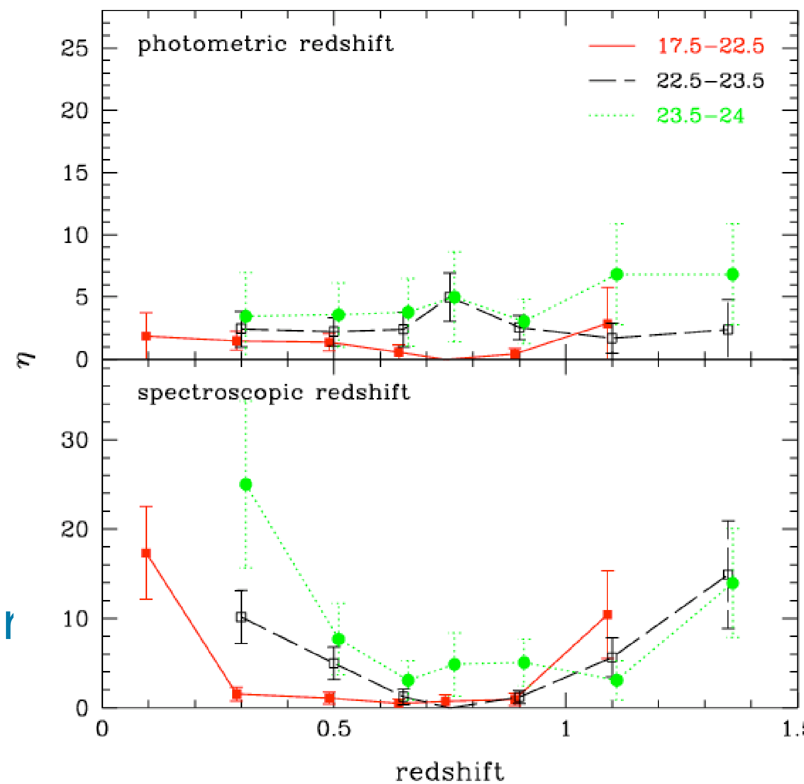


% incompleteness

Computing comoving correlation lengths-I

- We compute the projected correlation function w(θ) for each field and for each magnitude slice.
- We select galaxies in redshift slices corresponding the ranges where our photometric redshifts have the highest accuracy (lowest numbers of catastrophic outliers)
- For the moment, we consider galaxies with $0.2<z<1.2$
- Using the limber transformation we can estimate the r0 at the effective redshift of our sample.

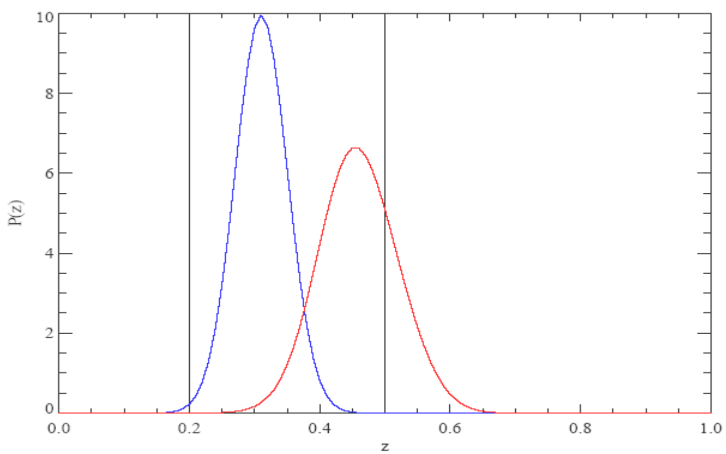
% contaminants

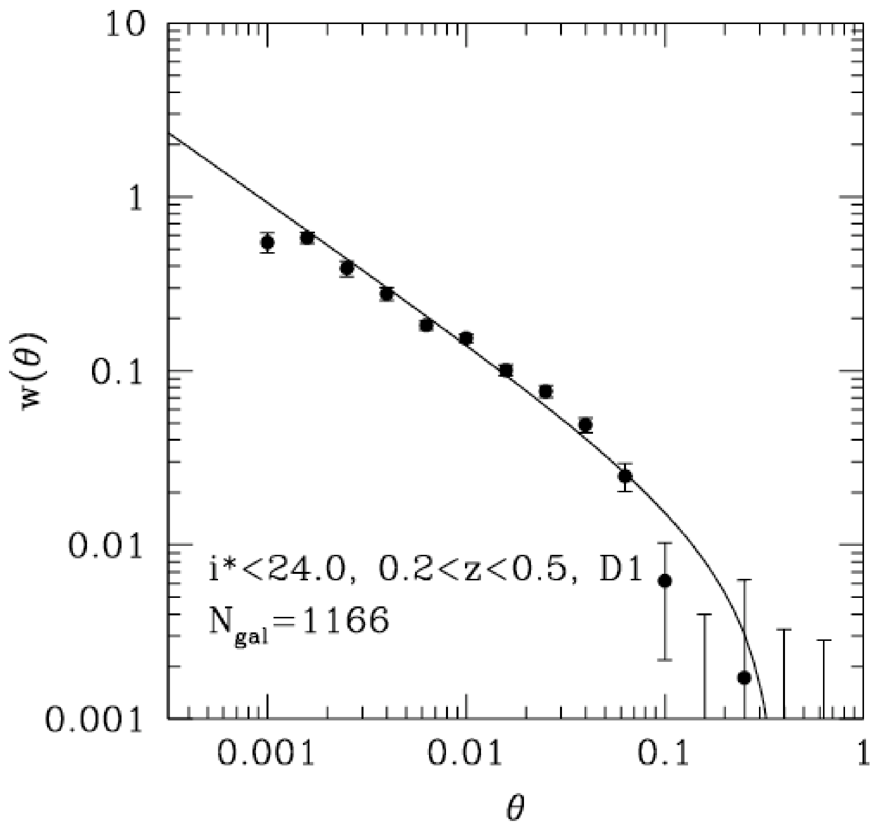


% incompleteness

Computing the comoving correlation length-II

- For each galaxy in each redshift slice we compute the area under that galaxy's probability distribution function
- These areas are used as weights in the correlation function measurement
- This ensures that all information about the reliability of each photometric redshift is used
- The resulting measurements are then fitted with a power law with the appropriate finite-volume correction.

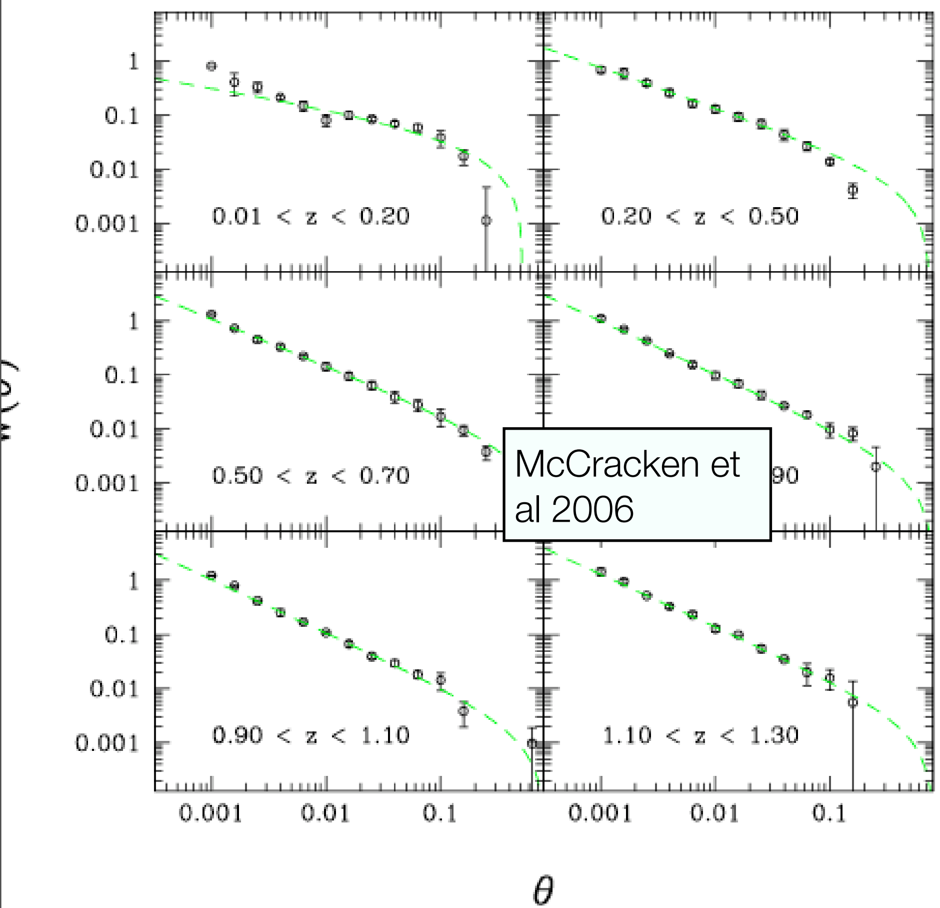


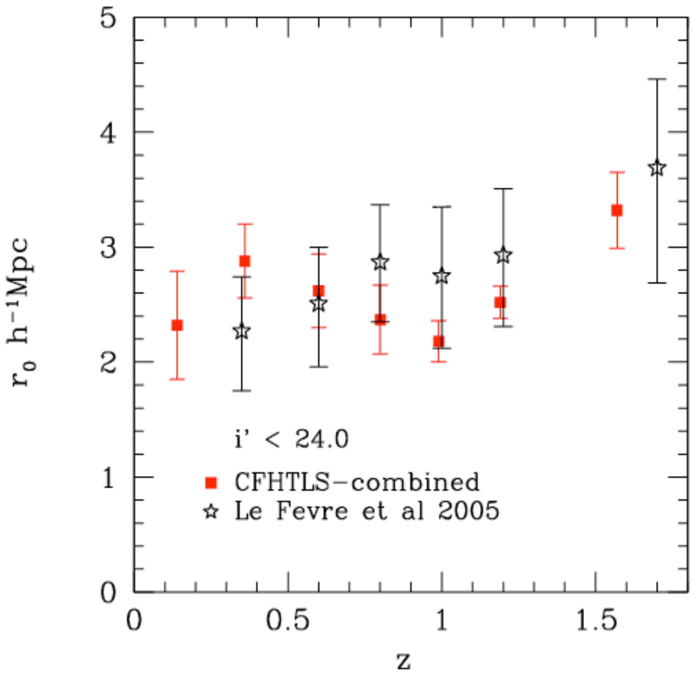


$$\omega(\theta) = \frac{DD - 2DR + RR}{RR},$$

Galaxy clustering with photometric redshifts

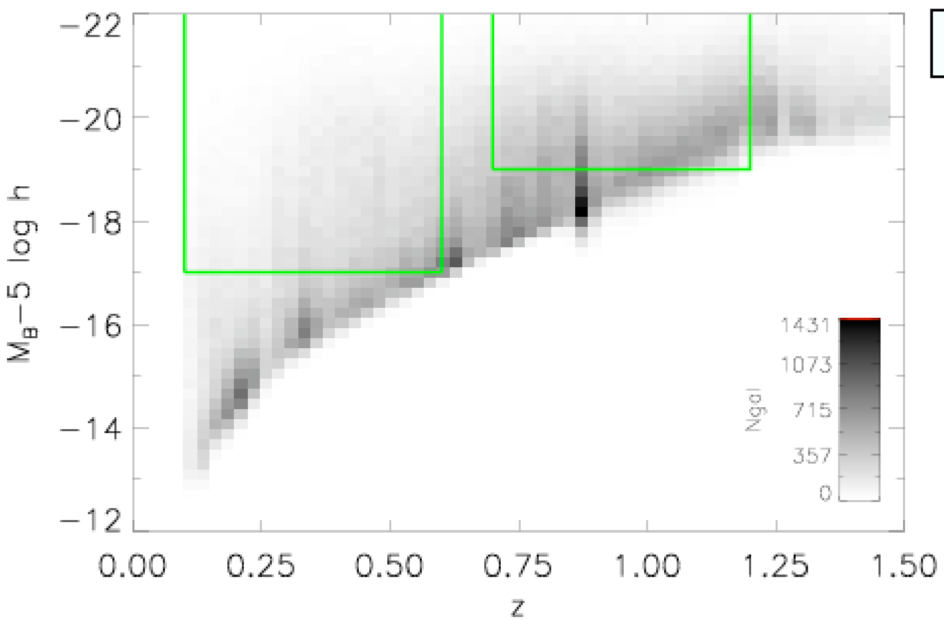
- First of all, we try to compute galaxy correlation lengths for the same redshift ranges as the VLT-VIRMOS deep survey



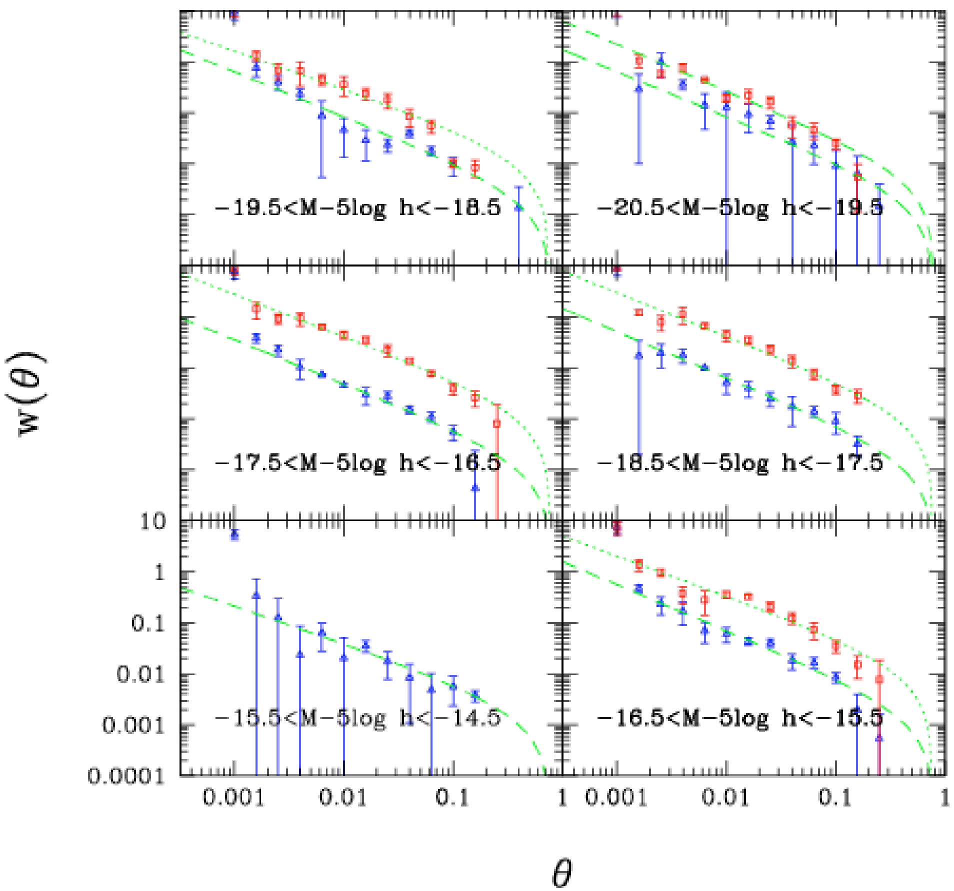


- Providing you have a large spectroscopic sample you can calibrate your photometric redshifts
- Photometric redshifts can be used to make galaxy clustering measurements!

Volume-limited type-dependent clustering in the CFHTLS

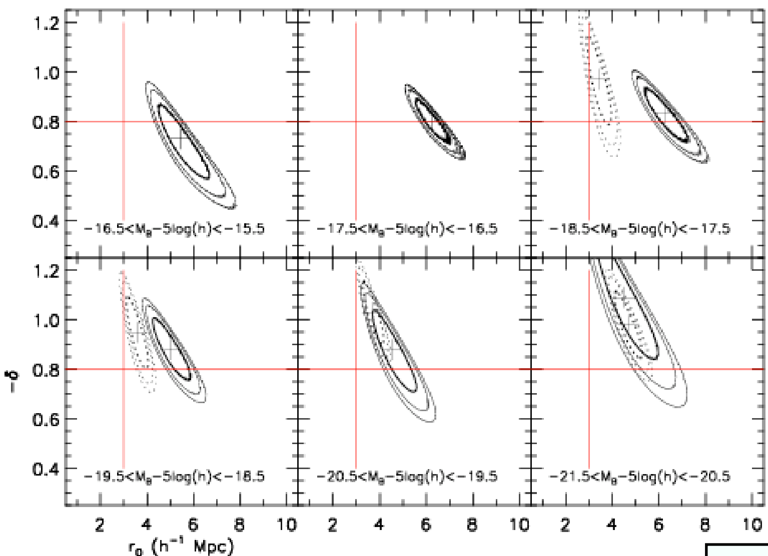


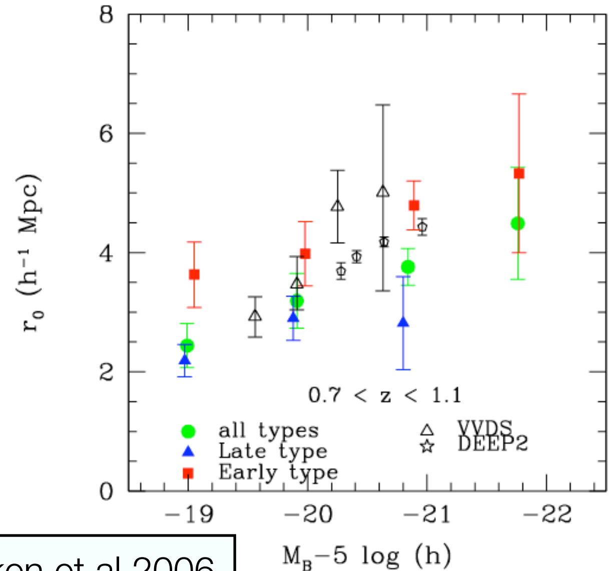
McCracken et al 2006



- Can investigate for the first time the clustering of early and late type galaxies at the same absolute magnitude threshold
- Bluer galaxies are always less strongly clustered than red galaxies at the same absolute luminosity threshold

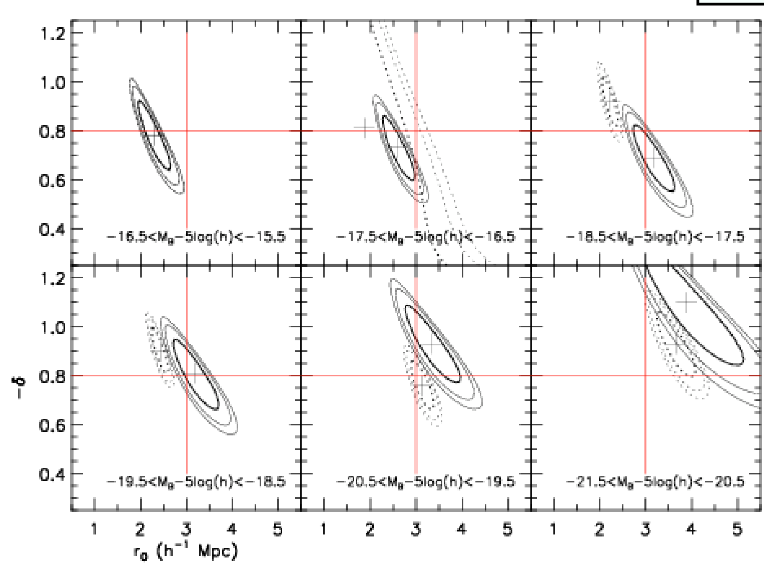
Volume-limited type-dependent clustering in the CFHTLS II

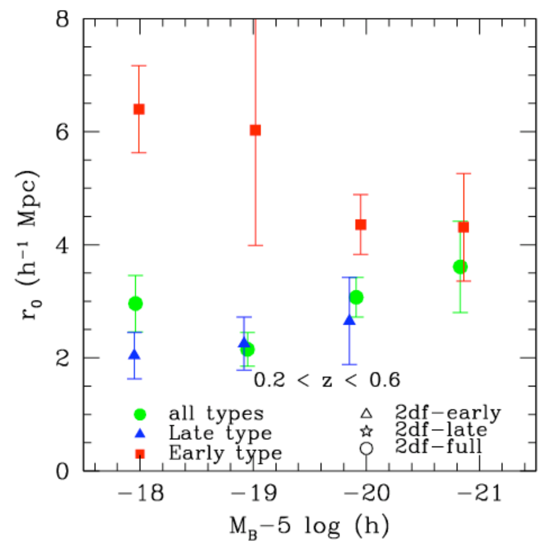




McCracken et al 2006

- At the same absolute luminosity, the clustering amplitude of the late type population evolves very little

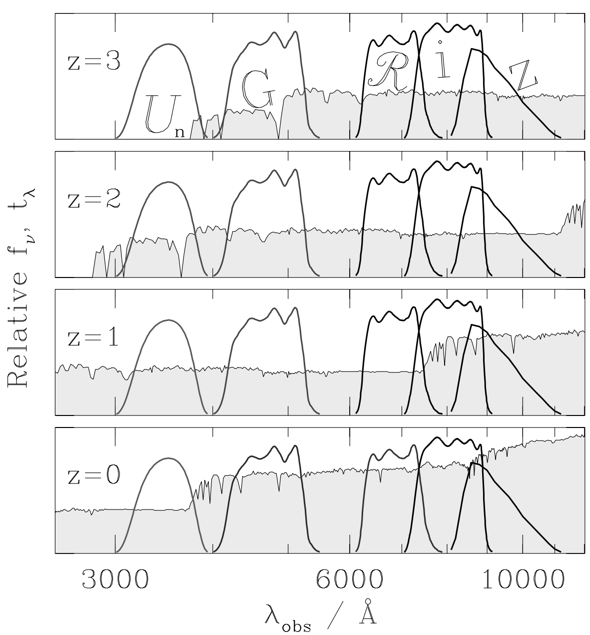




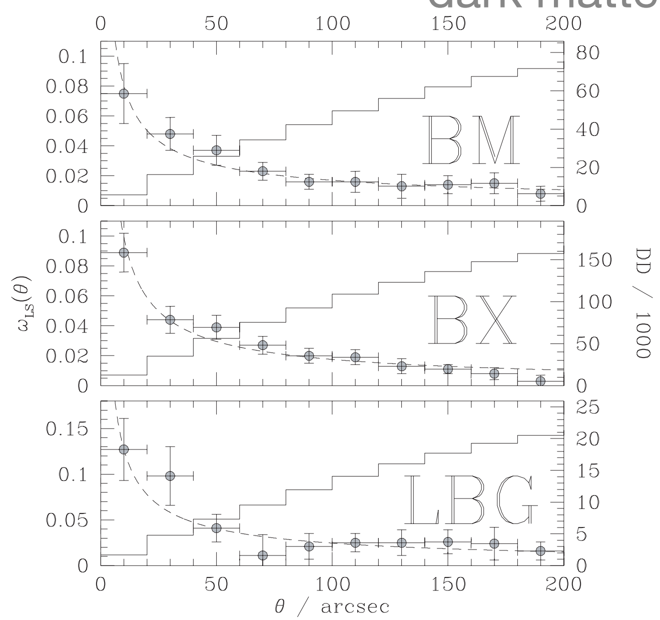
- The clustering amplitude of the faint elliptical population decreases rapidly at higher redshift

Clustering at z~3 and z~4: Lyman-break galaxies

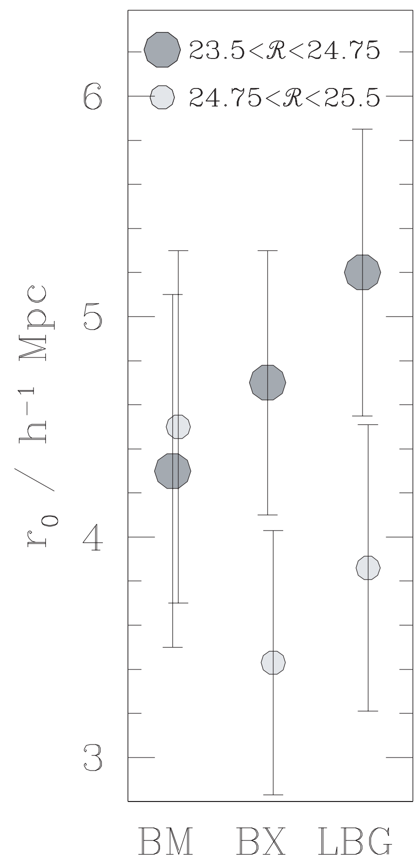
- Can select star-forming galaxies at z>3 by apply cuts in colour-colour space
- Note that in these samples, the numbers of objects is always very small; careful stastical analysis is required!



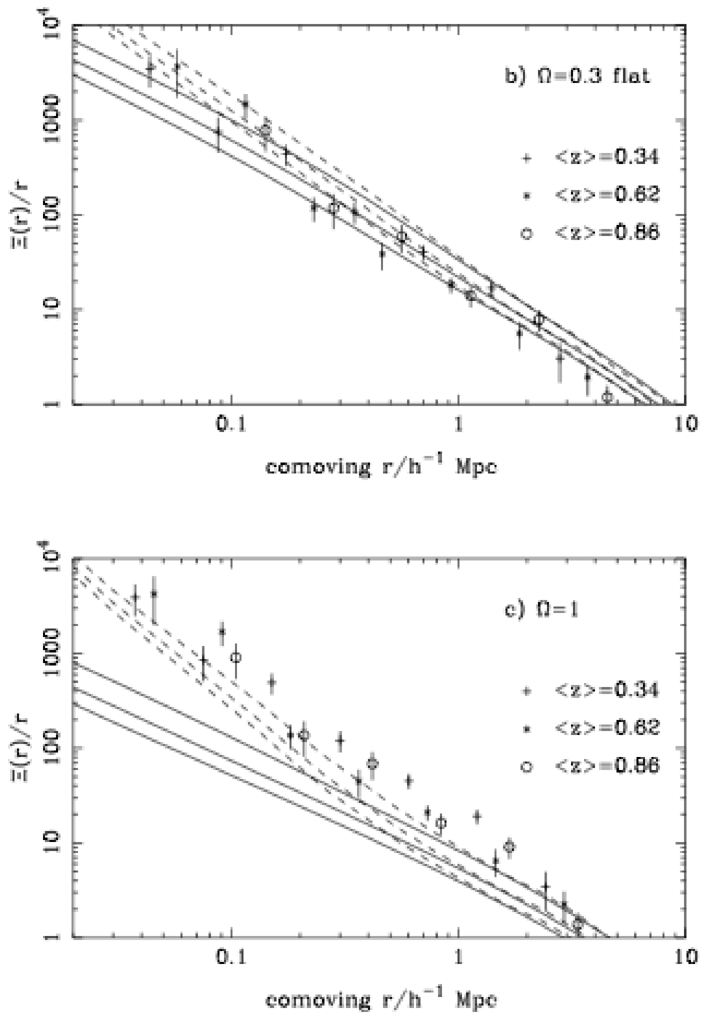
- Lyman-break galaxies have a high clustering amplitude; they are *biased* tracers of the underlying dark matter



- Advent of 10m telescopes meant that this selection criteria could be spectroscopically verified for the first time

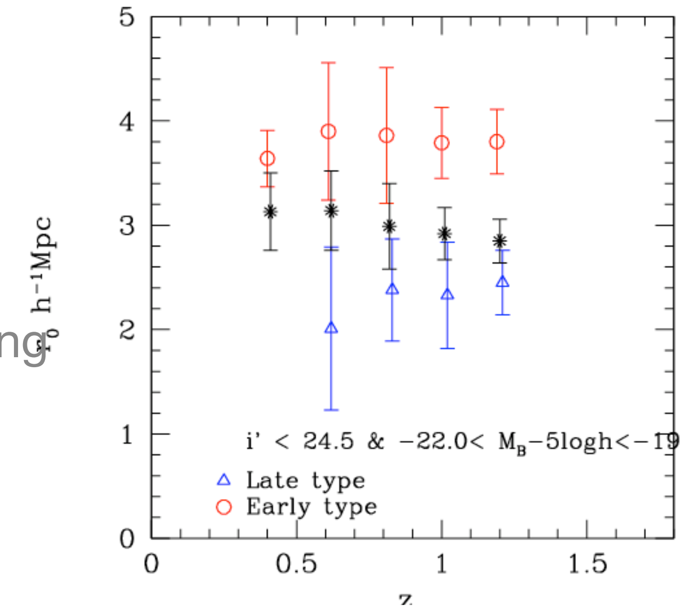


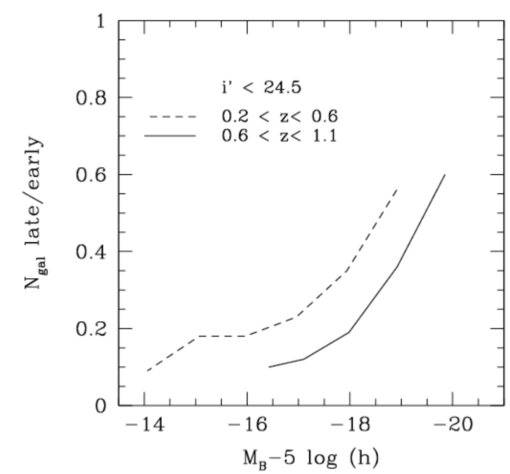
The evolution of galaxy clustering revisited



Peackock et al 1996

- In low-omega universes, the amount of bias need relative to dark matter distributions is much smaller
- Actual observed clustering evolution with proper samples selected by absolute magnitude and type show very little evolution
- The observed changes in the full field population can simply be understood by a change of morphological mix as a function of redshift
- Galaxy population is very weakly biased (or antibiased)





Fraction of elliptical and spirals as a function of Mabs

Cosmic variance errors in the CFHTLS

- Cosmic variance errors are non-negligible even in fields the size of the CFHTLS
- CFHTLS-d2 field at low redshifts has a correlation amplitude much larger than the other four survey fields

Cosmic variance errors in the CFHTLS

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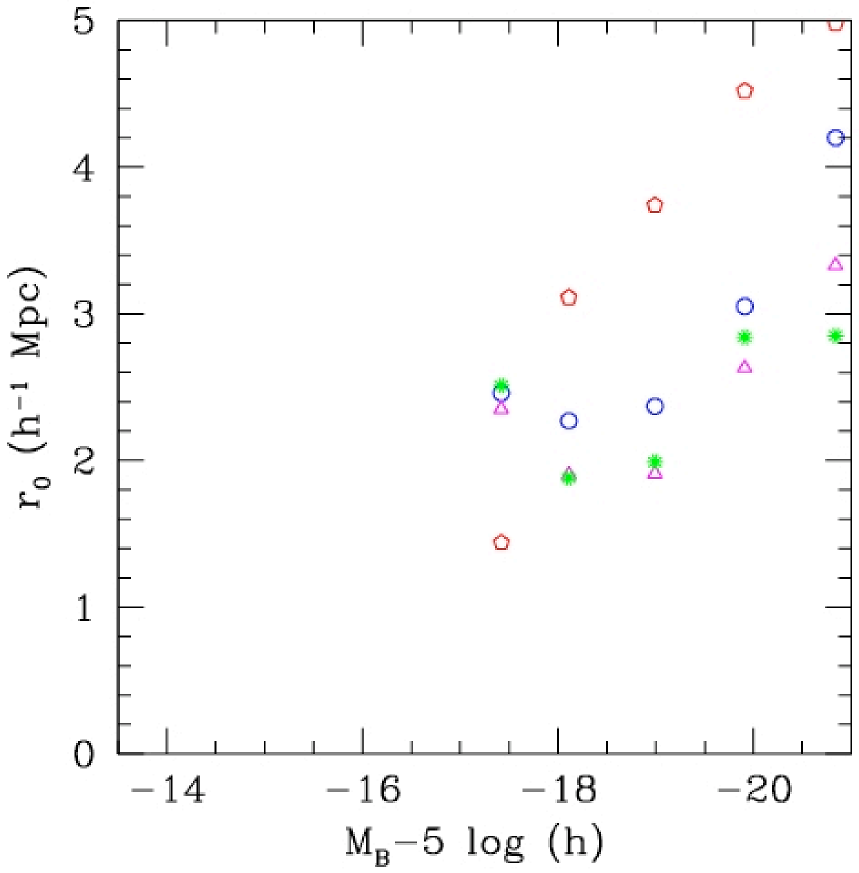
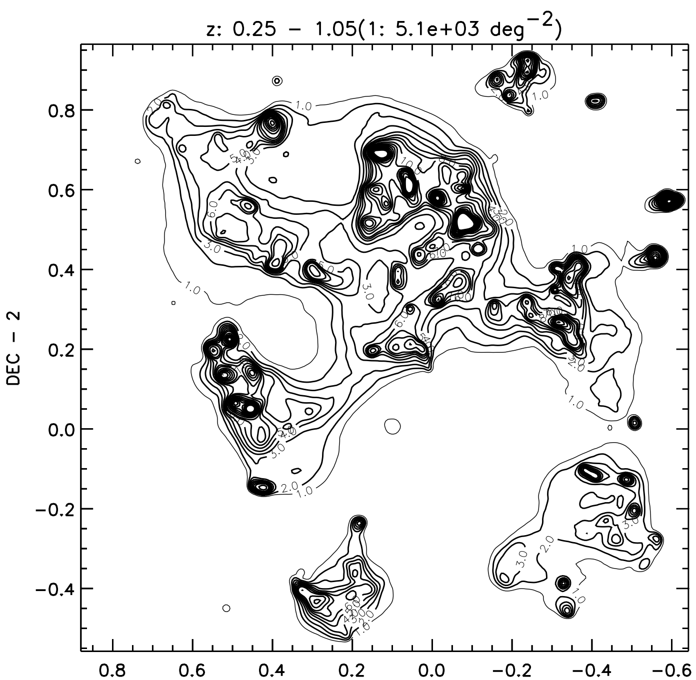
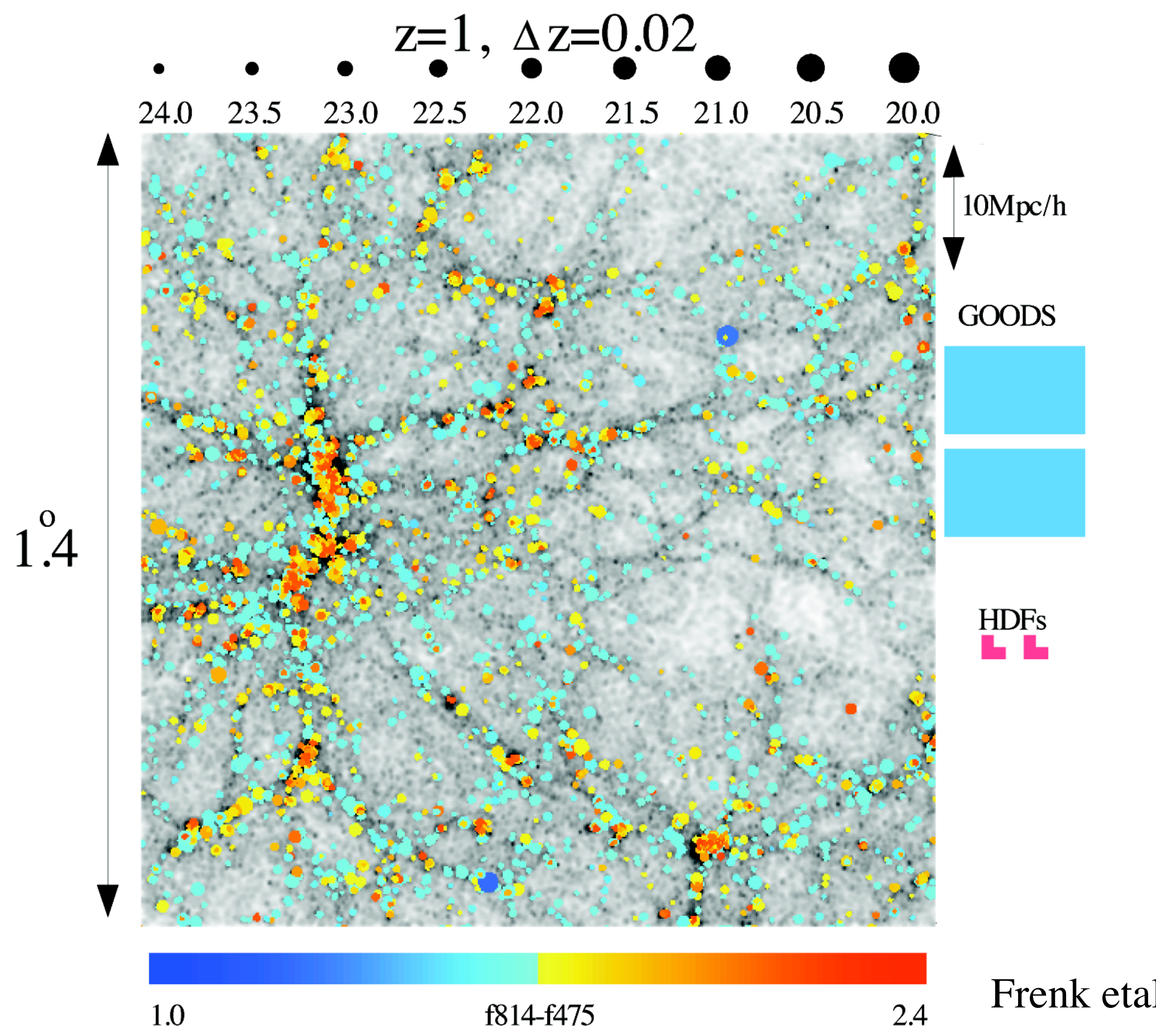
- CFHTLS-d2 field at low redshifts has a correlation amplitude much larger than the other four survey fields



COSMOS

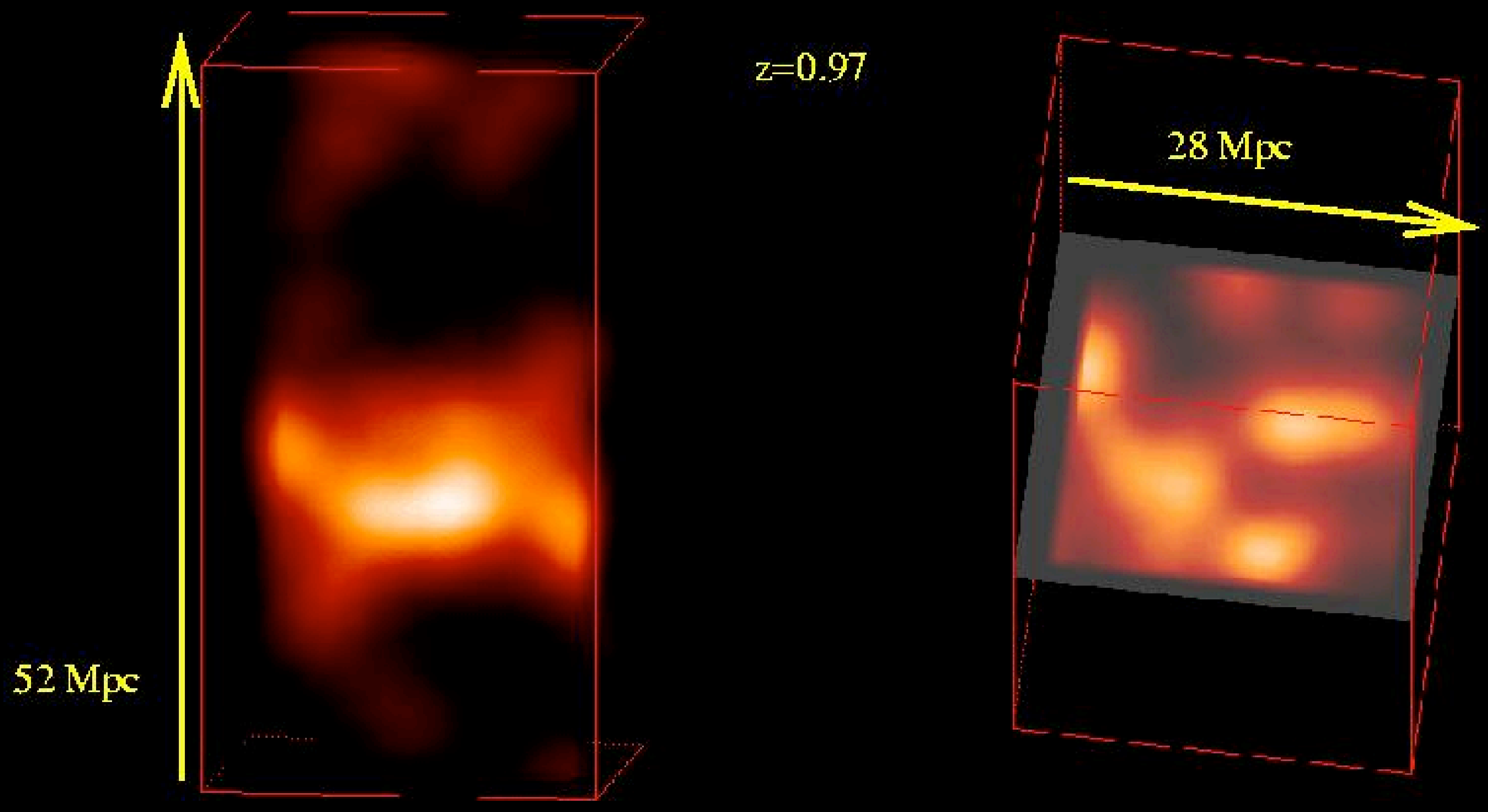
- Need wide fields to probe a significant range of density contrasts and beat the effects of cosmic variance
- Large structures observed at low redshifts in the COSMOS field are found in the same redshift ranges ranges where we observe the excess in the CFHTLS fields





Scoville et al 2006 in press

a “wall” at z=0.97 in VVDS-Deep



Concluding remarks

- Catalogues are now available at z~1 containing almost as many galaxies as lower redshift samples
-