Lecture plan

Part 1: Deep large scale galaxy surveys

Part 2: The Universe on large scales

- Large scale structures observations
- Measuring clustering: the correlation function (and power spectrum)

Part 3: Baryon Acoustic Oscillations and Redshift space distortions

Part 4: The Euclid Surveys and galaxy clustering

Part 2

THE UNIVERSE ON LARGE SCALES

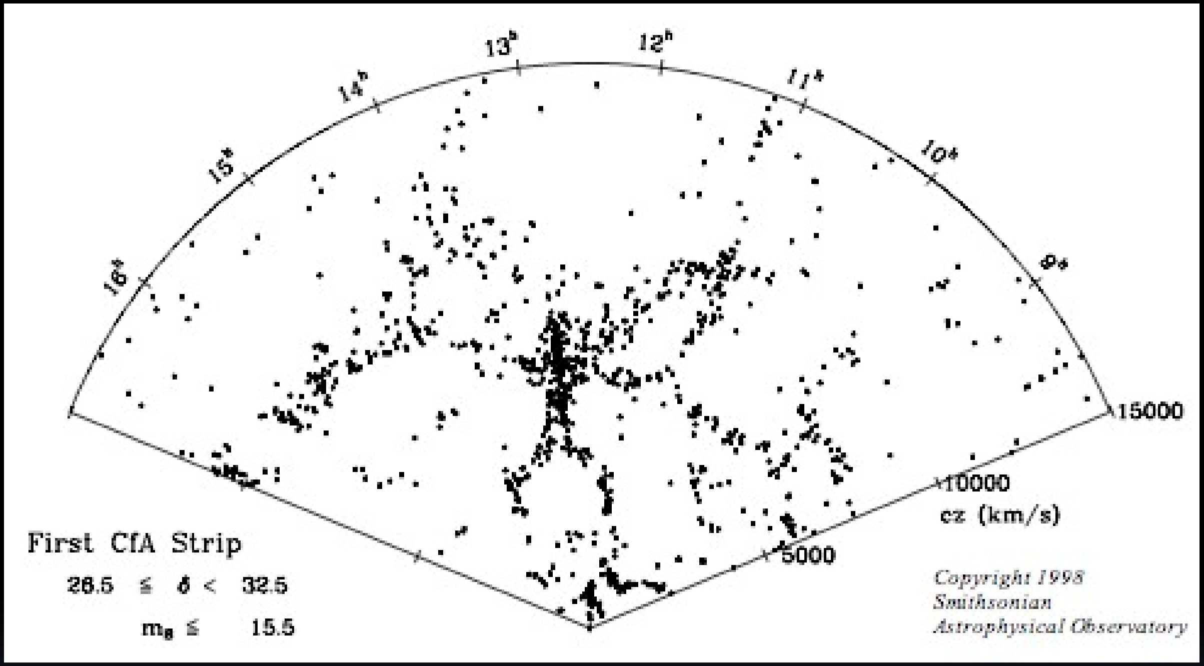
Observational facts

Outline

Evidence for the large scale distribution of matter and its evolution

1. Large scale structure in the local universe
2. Local cosmic flows
3. Large scale structures

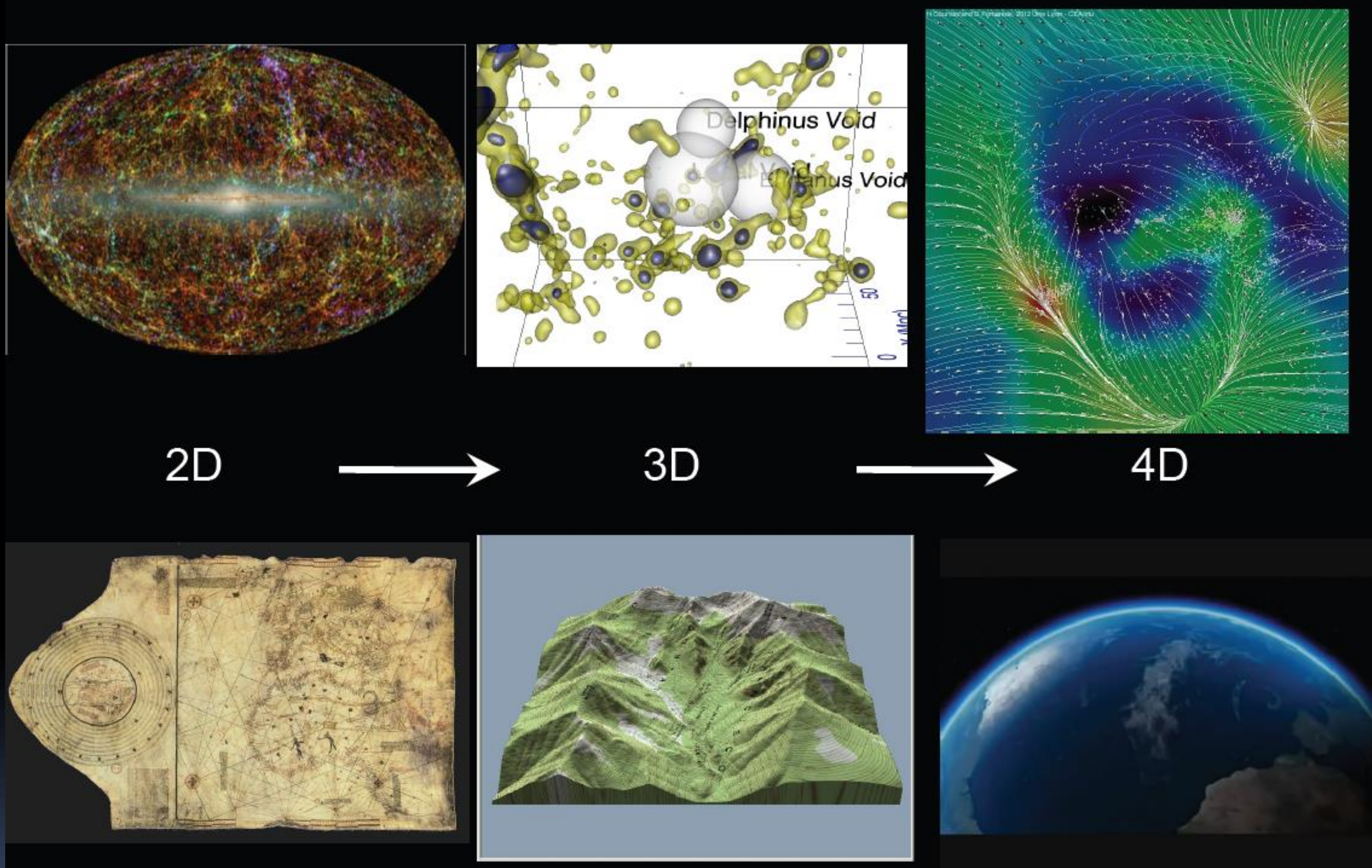
A first hint: a slice of the Universe



de Lapparent, Geller, Huchra, 1986

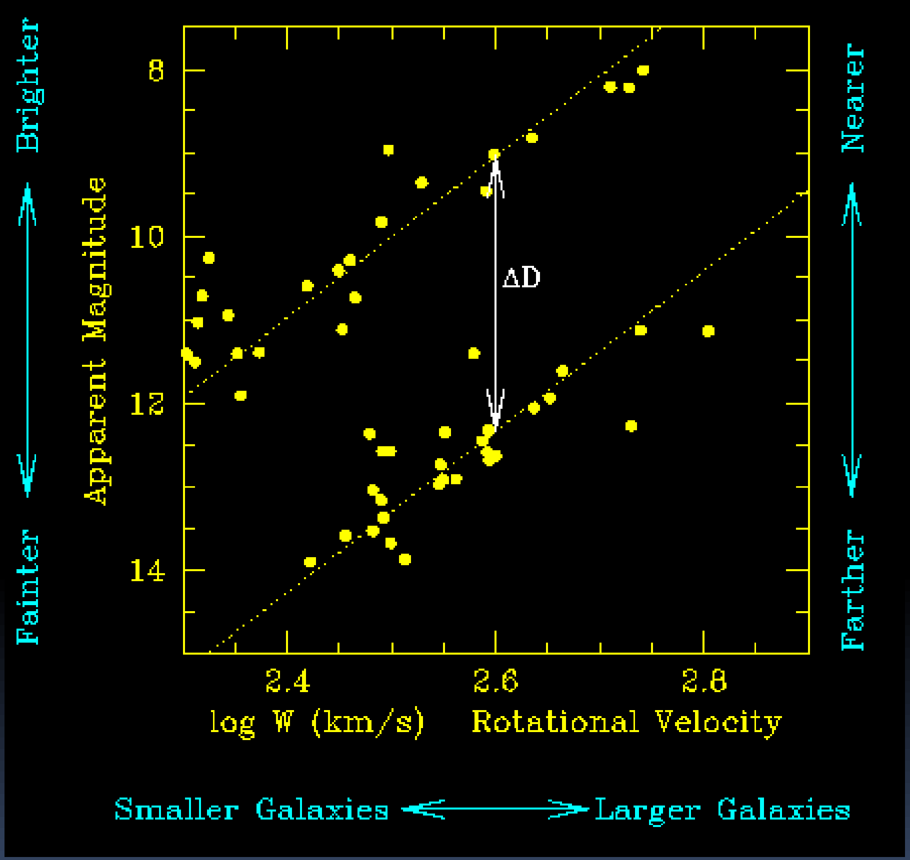
Demonstrating the key role of spectroscopic surveys

Local cosmic flows



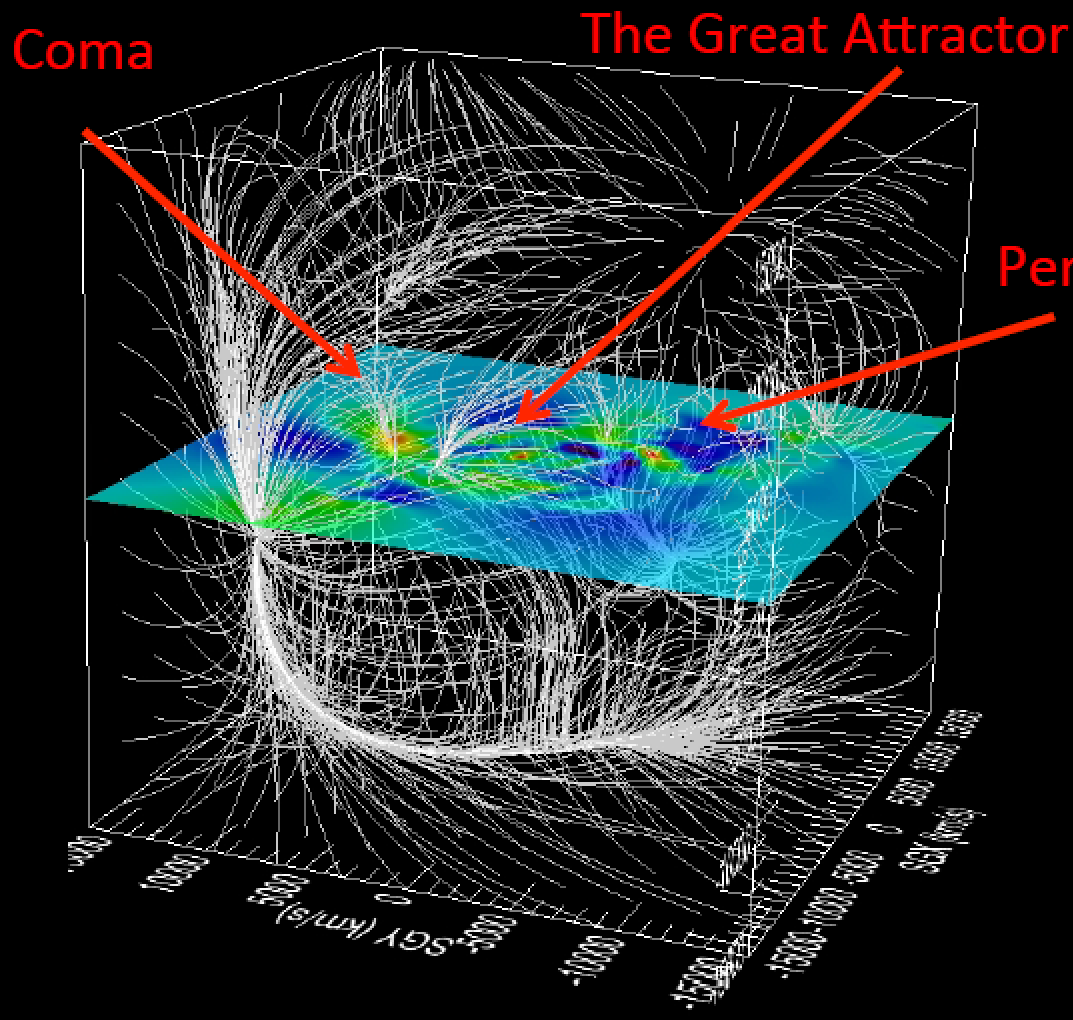
Cosmography : mapping with dynamics.
Cosmology questions : cause of the CMB motion at 630 km/s, expulsion from voids?

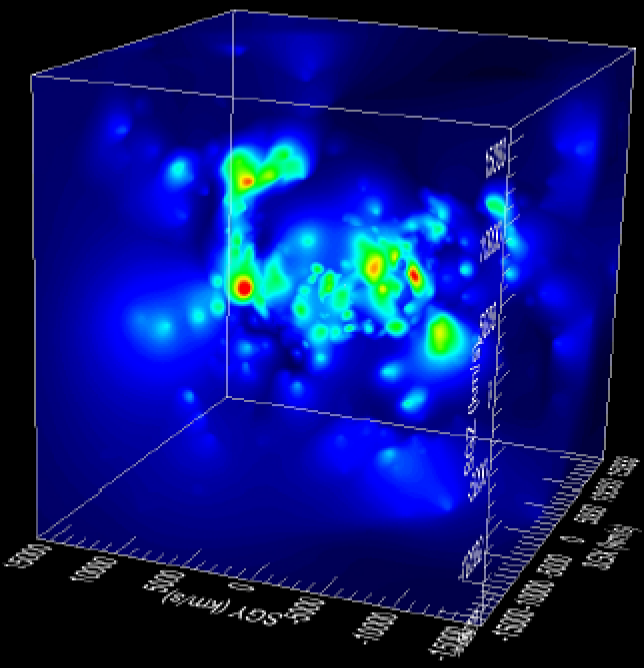
The Tully-Fisher relation: 4D!



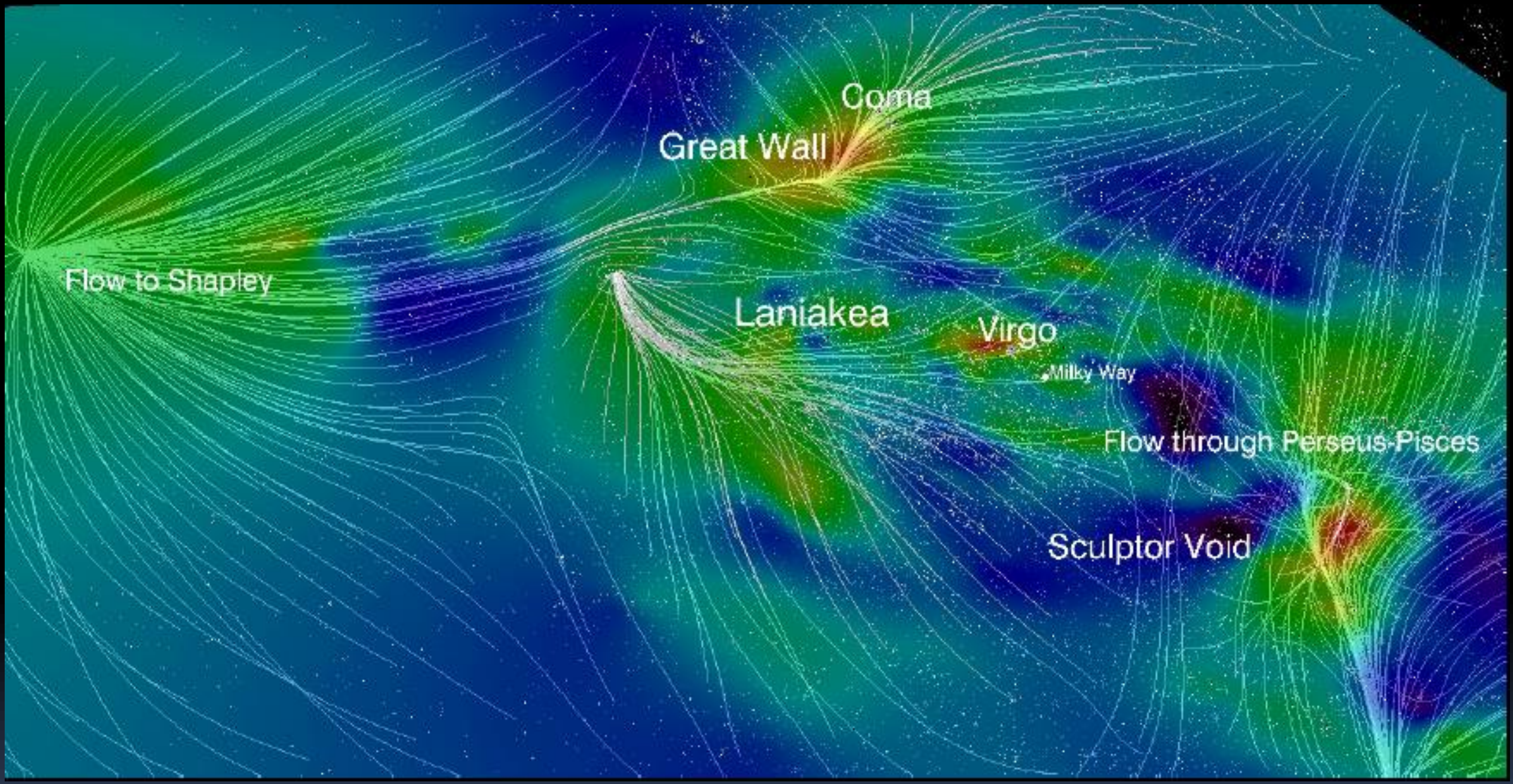
- Measure the rotation velocity, you get the absolute magnitude
- Measure the apparent magnitude, you get the distance
- Measure the redshift and you get 4D information

$V_{redshift} = H_0 * \text{distance} + V_{peculiar}$





The Great Attractor seems to be part of a complex flow linked to the Great



Courtois et al. 2013

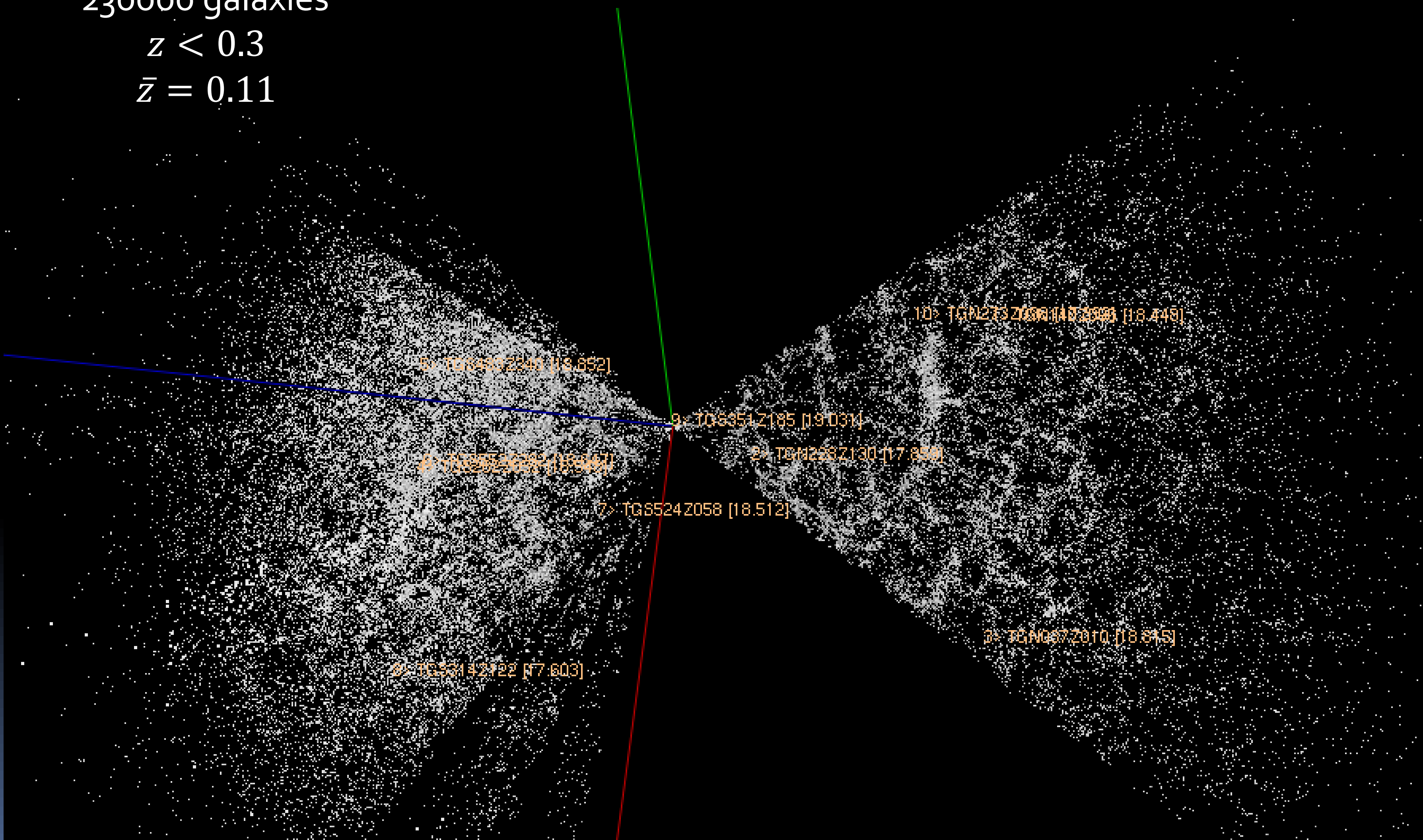
Farther away: LSS from the 2dFGRS

Colless et al., 2001, MNRAS, 328, 1039

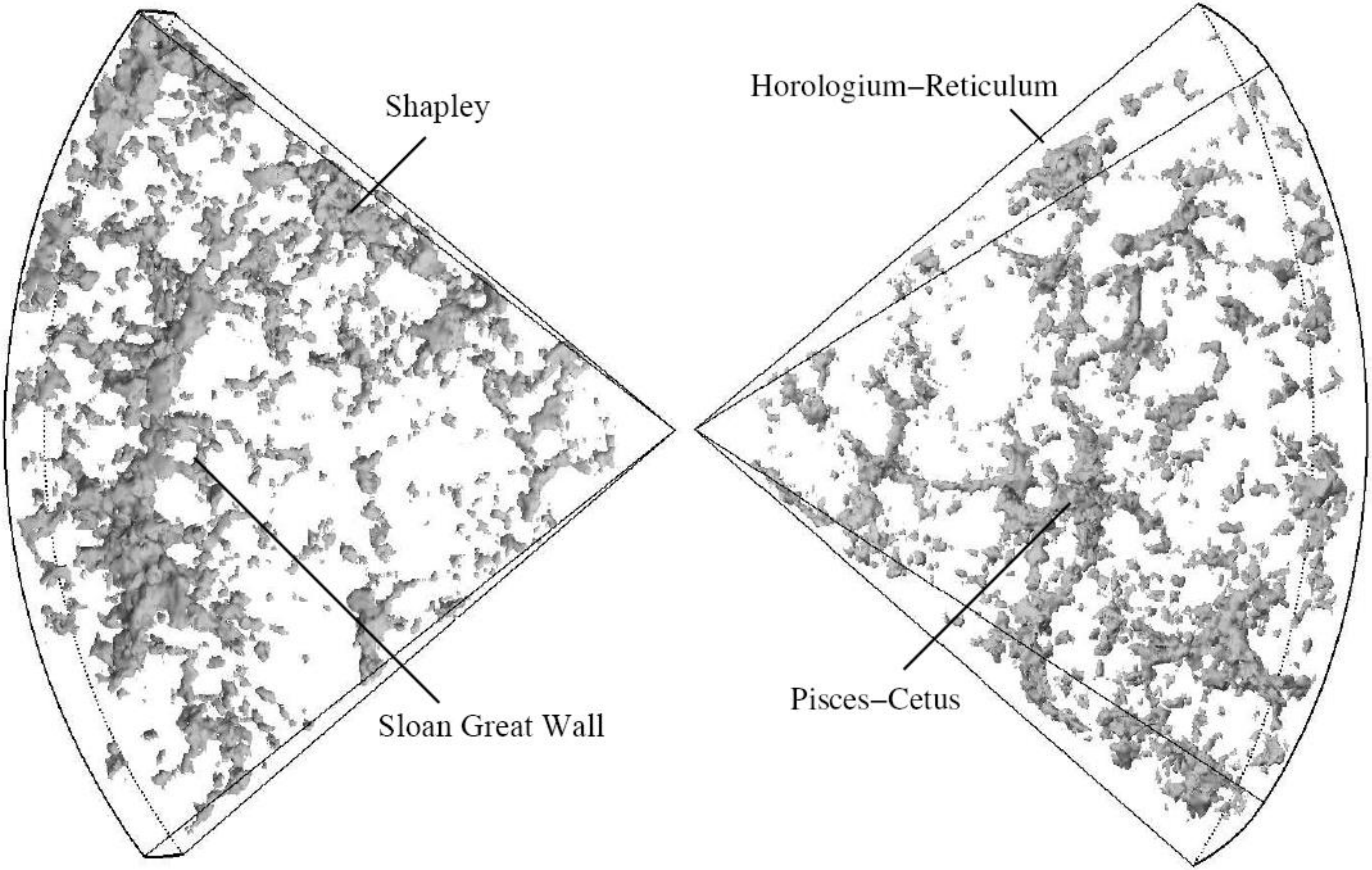
230000 galaxies

$z < 0.3$

$\bar{z} = 0.11$



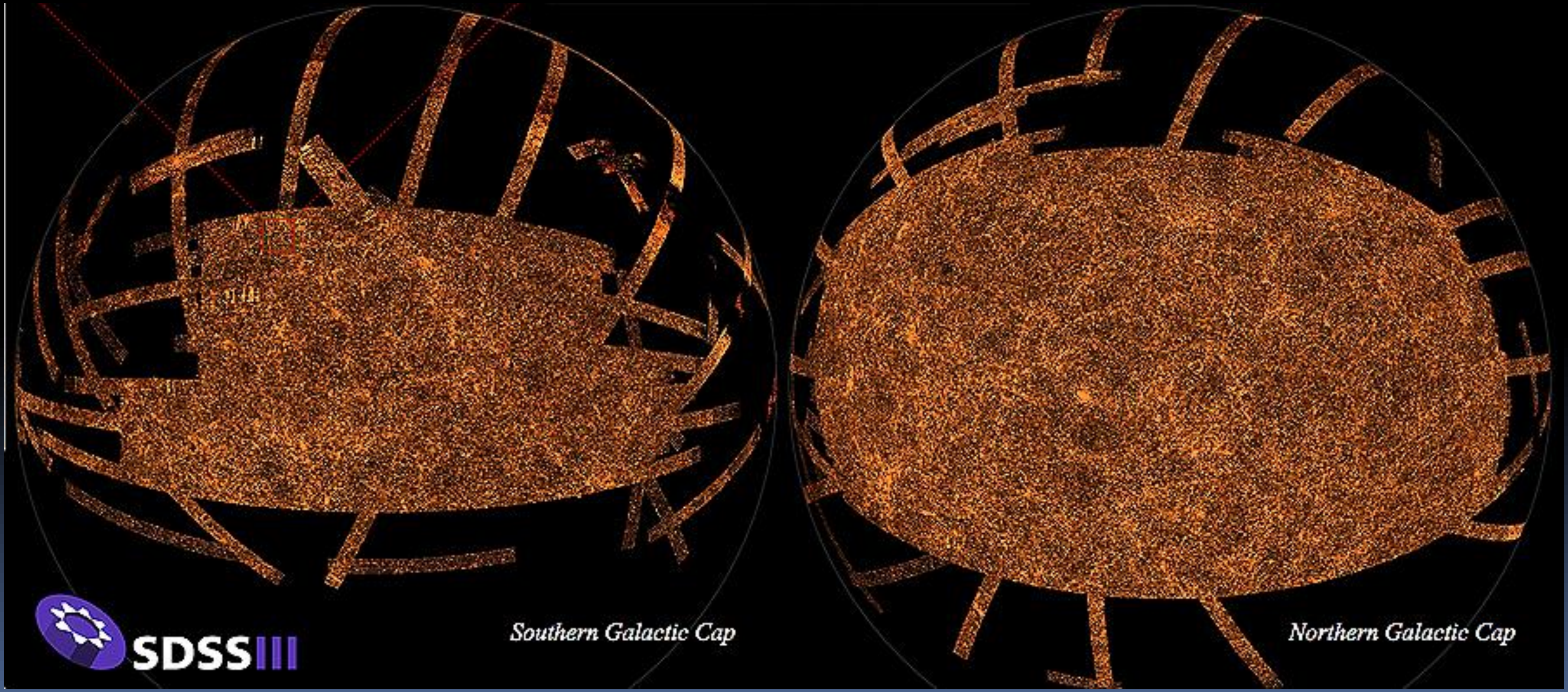
2dFGRS density field



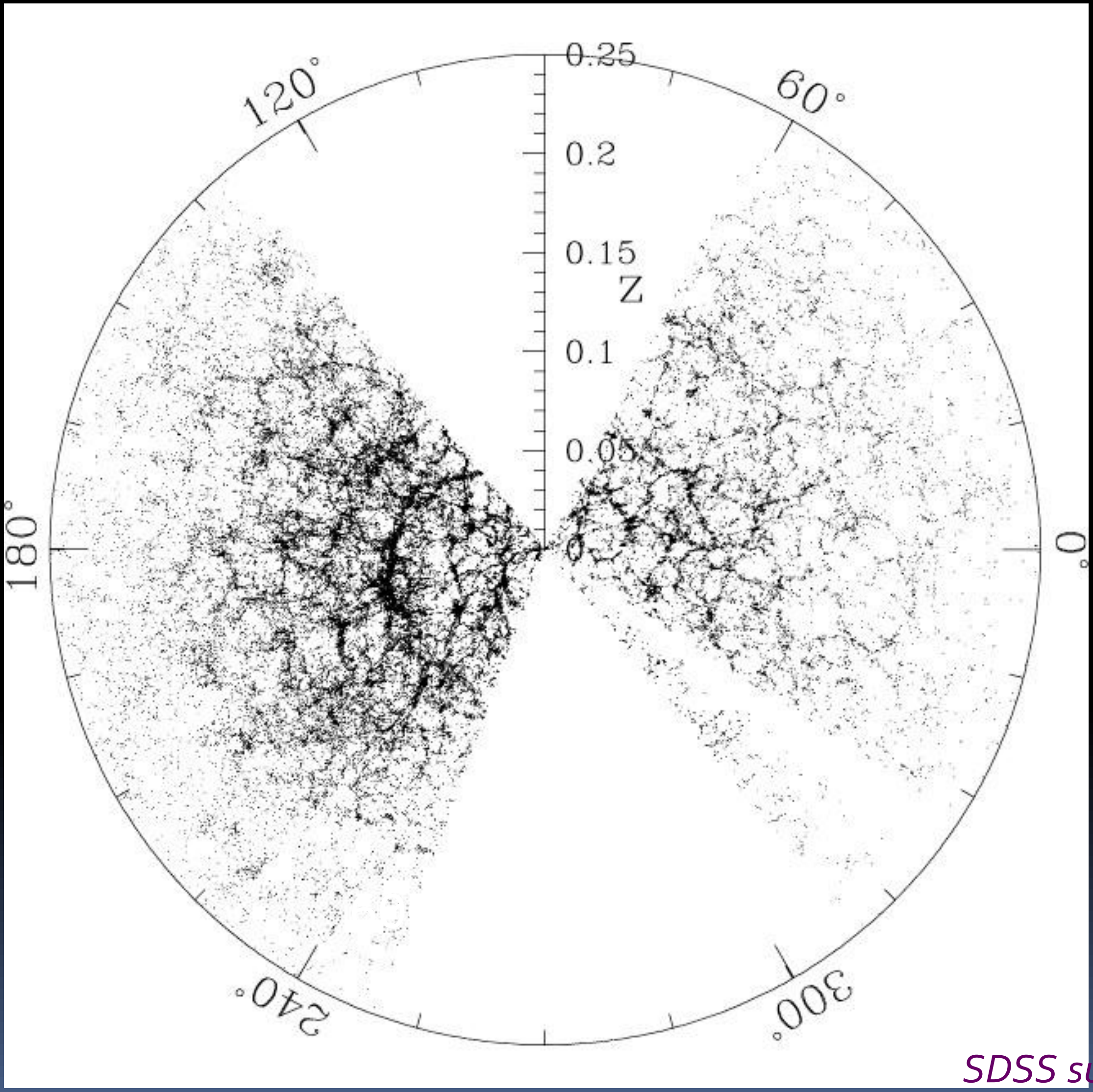
LSS in the Sloan Digital Sky Survey

930000 Galaxies
120000 Quasars
$z < 0.3$
$\bar{z} = 0.11$
10000 deg^2

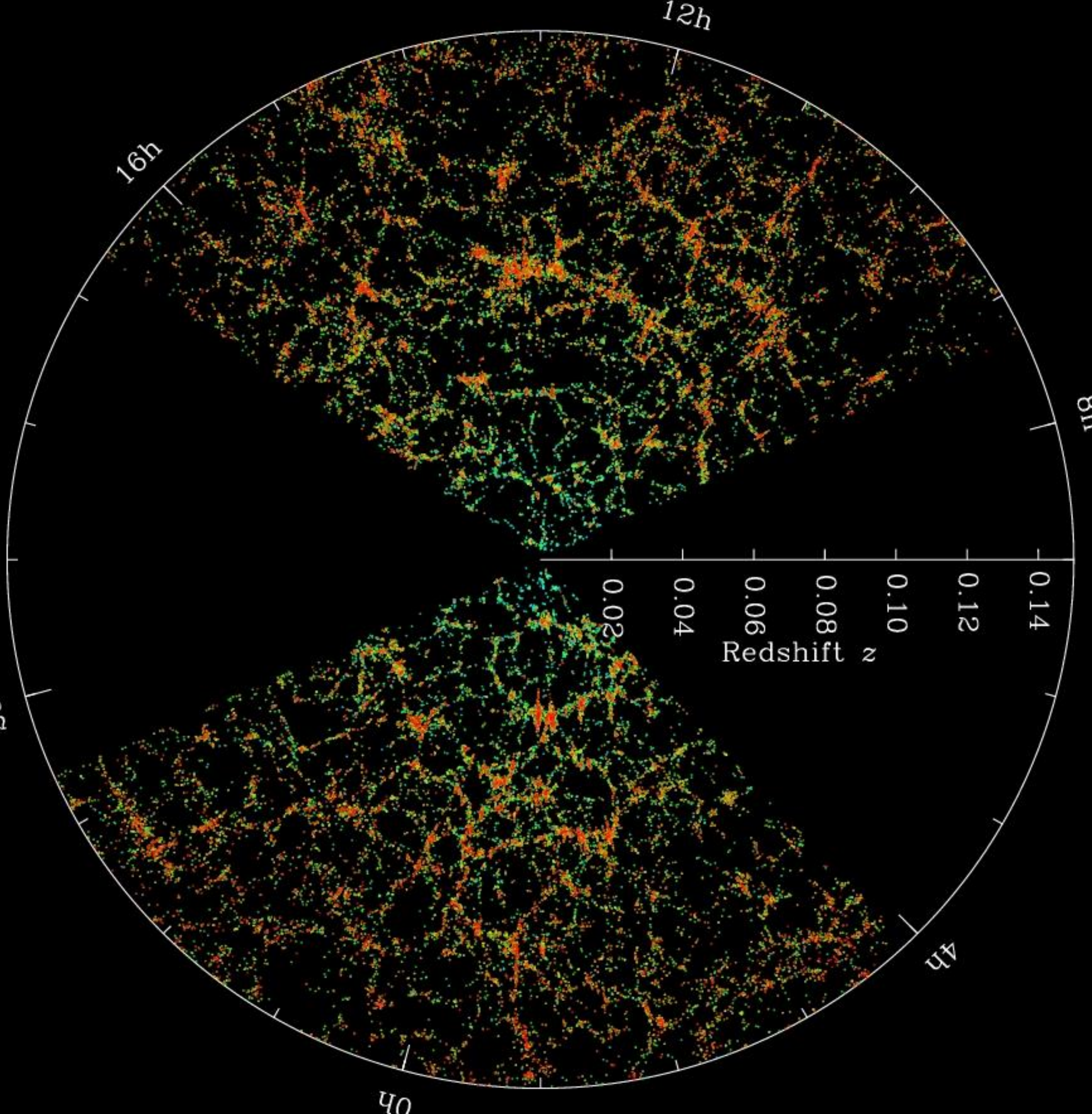
York et al., 2000, ApJ, 120, 1579
DR7: Abazajian et al., 2009, ApJ, 182, 543
http://www.sdss.org/
Eisenstein et al., 2011, AJ, 142, 72



LSS observations



SDSS survey, 2000-2005


12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

Fly-through SDSS movie
http://www.sdss3.org/press/dr9.php

LSS at higher redshifts z>0.5

- Early attempts
  - DEEP2
  - VVDS
- VIPERS

LSS in DEEP2

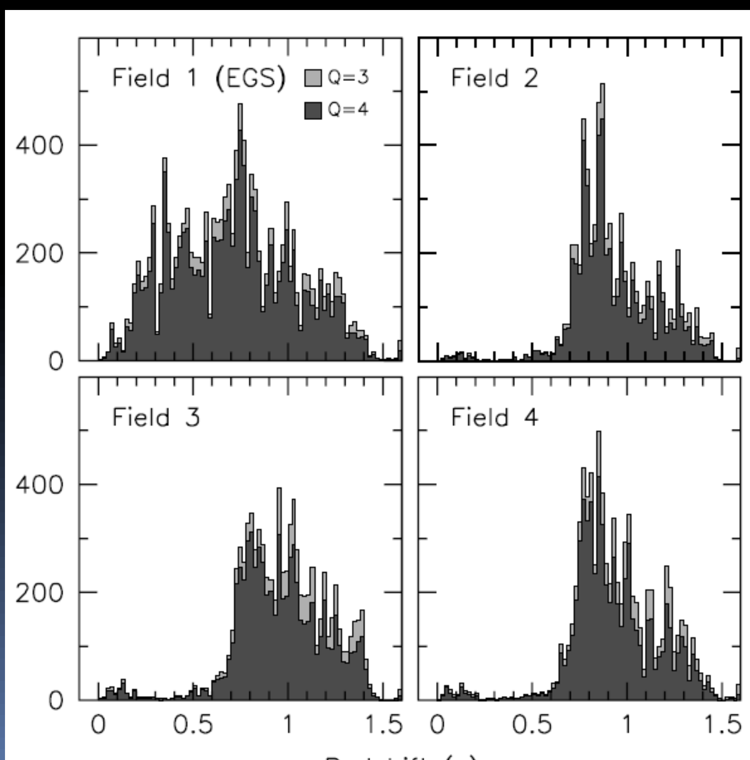
38000 Galaxies

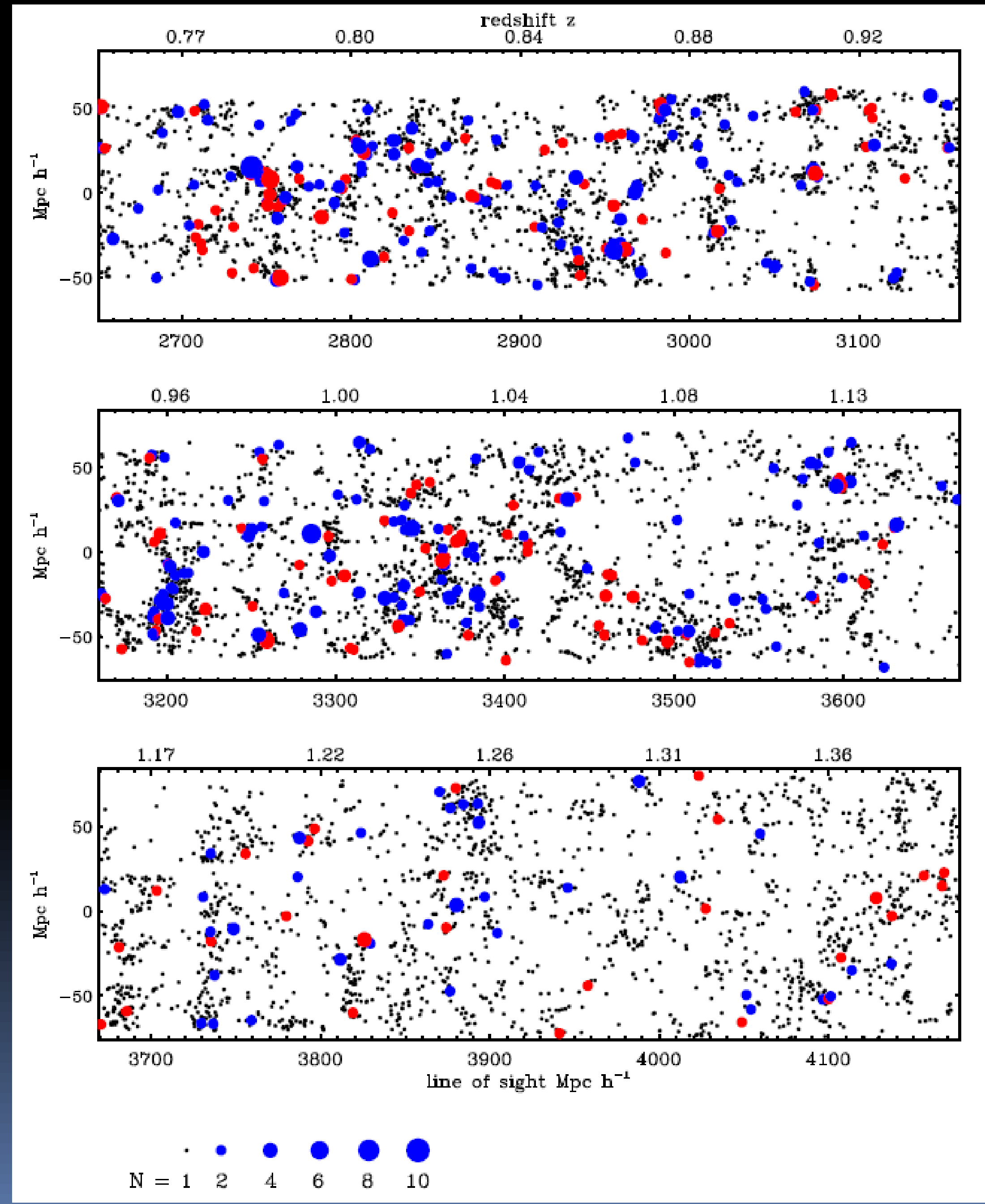
$0.7 < z < 1.4$

$\bar{z} = 0.9$

2.8 deg²

Newman et al., 2012, arXiv:1203,3192

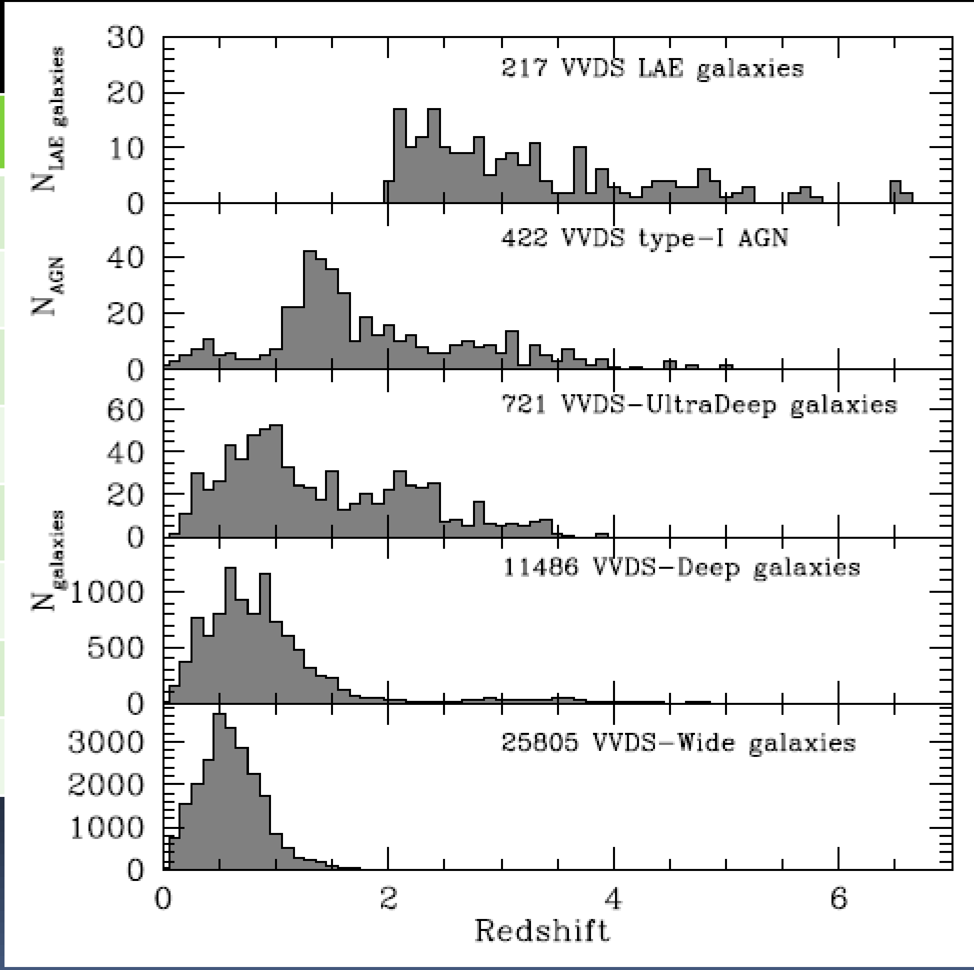




VVDS: the VIMOS VLT Deep Survey

- Magnitude selection

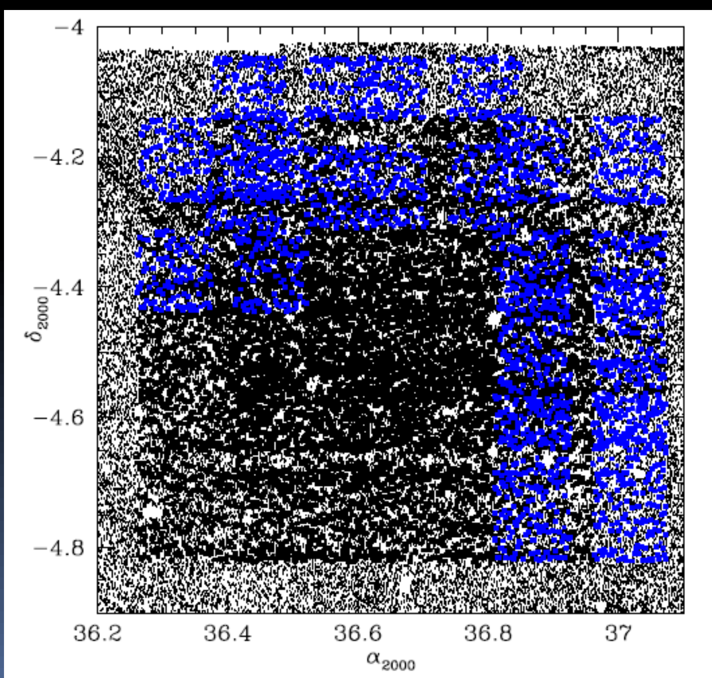
Survey parameter	Value
Telescope diameter	8.2m
Field of view	220 $arcmin^2$
Area	8.7 deg^2
Redshift range	0<z<6.7
λ-range	3600-9500A
Depth	I_{AB}=24.75
R	230
Nspec	35 000

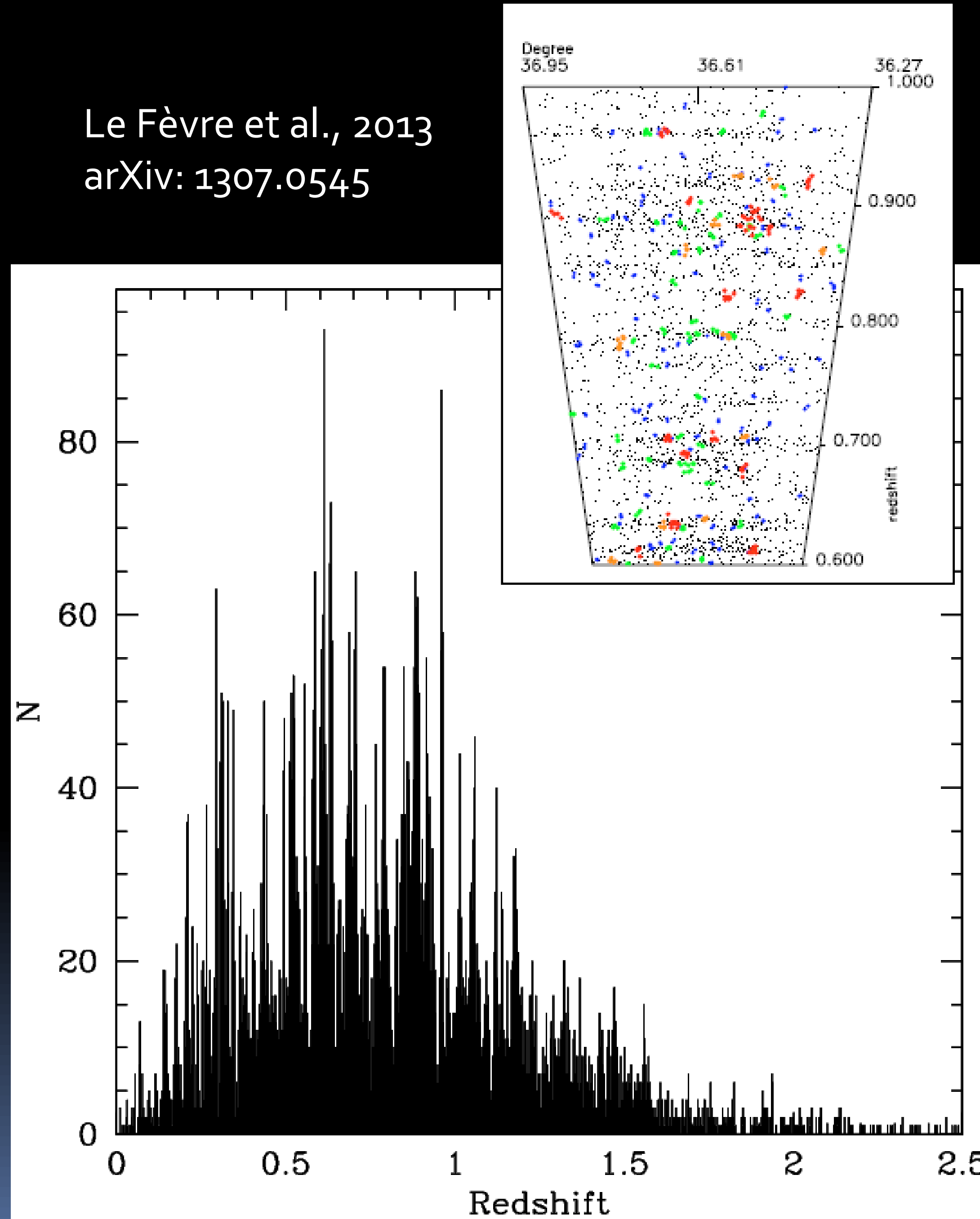


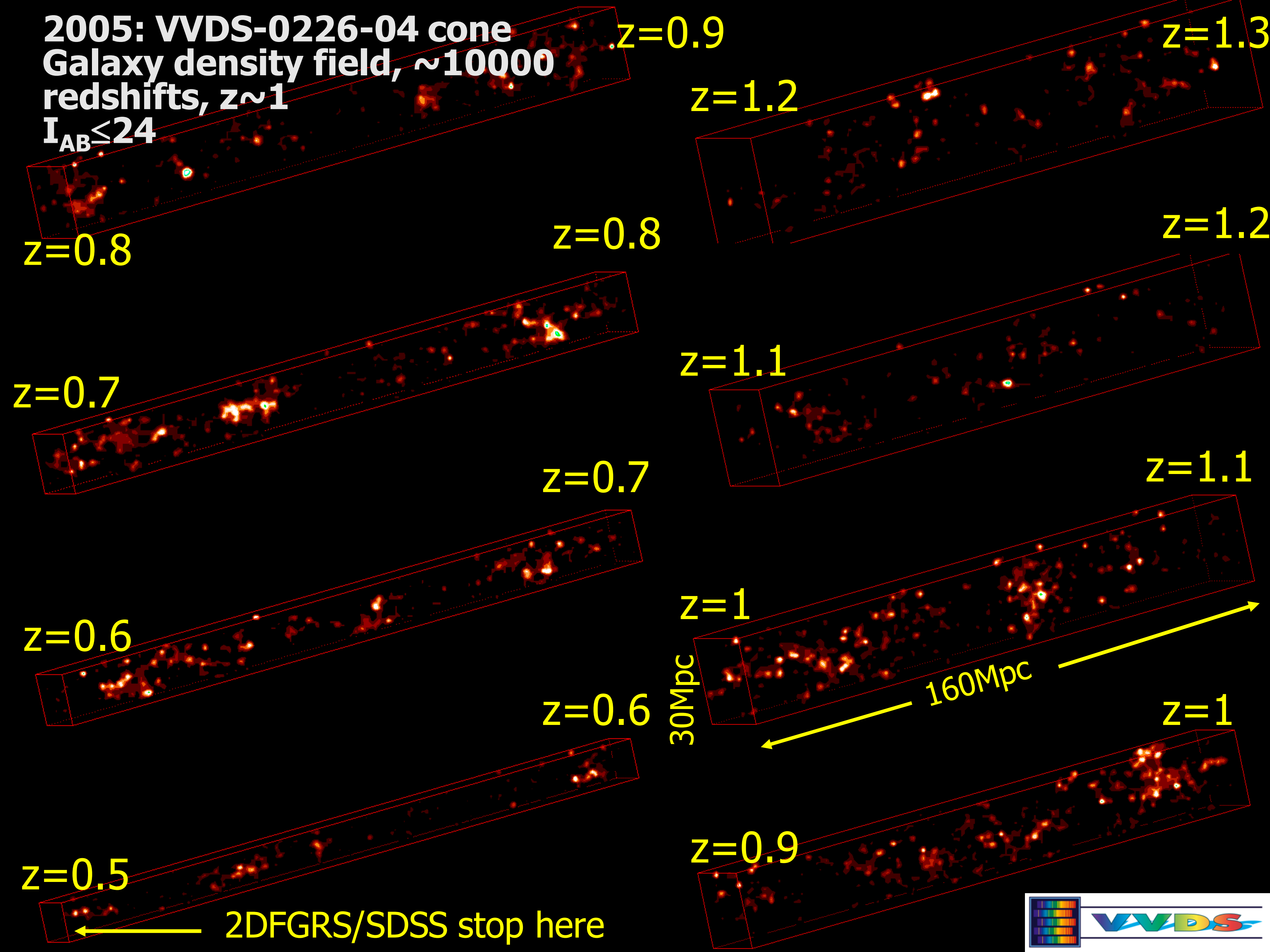
LSS in VVDS

Le Fèvre et al., 2013
arXiv: 1307.0545

35000 Galaxies
$0 < z < 5$
$\bar{z} = 0.92$
8.7 deg^2



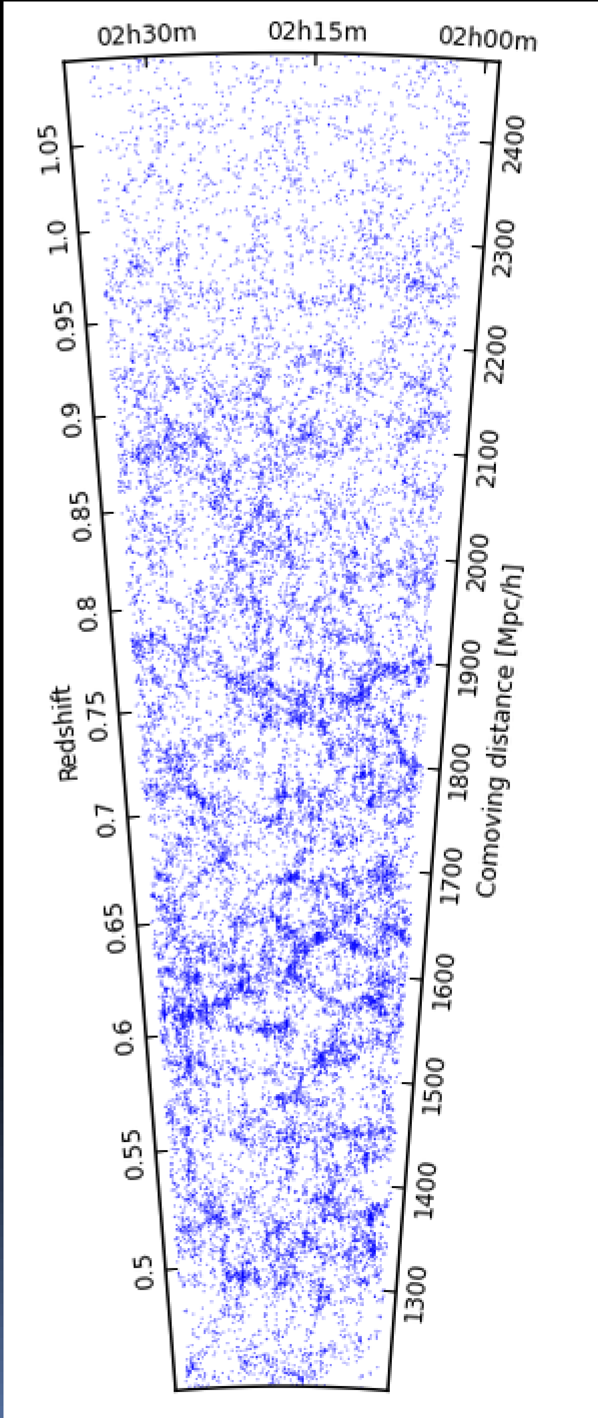



2005: VVDS-0226-04 cone
Galaxy density field, ~10000 redshifts, z~1
$I_{AB} \leq 24$
z=0.9
z=1.3
z=1.2
z=0.8
z=0.8
z=1.2
z=1.1
z=0.7
z=0.7
z=1.1
z=1
z=0.6
160Mpc
30Mpc
z=0.6
z=1
z=0.9
z=0.5
2DFGRS/SDSS stop here
VVDS

VIPERS: the VIMOS Public Extragalactic Survey

- Magnitude AND color selection

Survey parameter	Value
Telescope diameter	8.2m
Field of view	220 arcmin^2
Area	25 deg^2
Redshift range	$0.5<z<1.5$
λ-range	5500-9500A
Depth	$i_{AB}=22.5$
R	230
Nspec	100 000



LSS in VIPERS

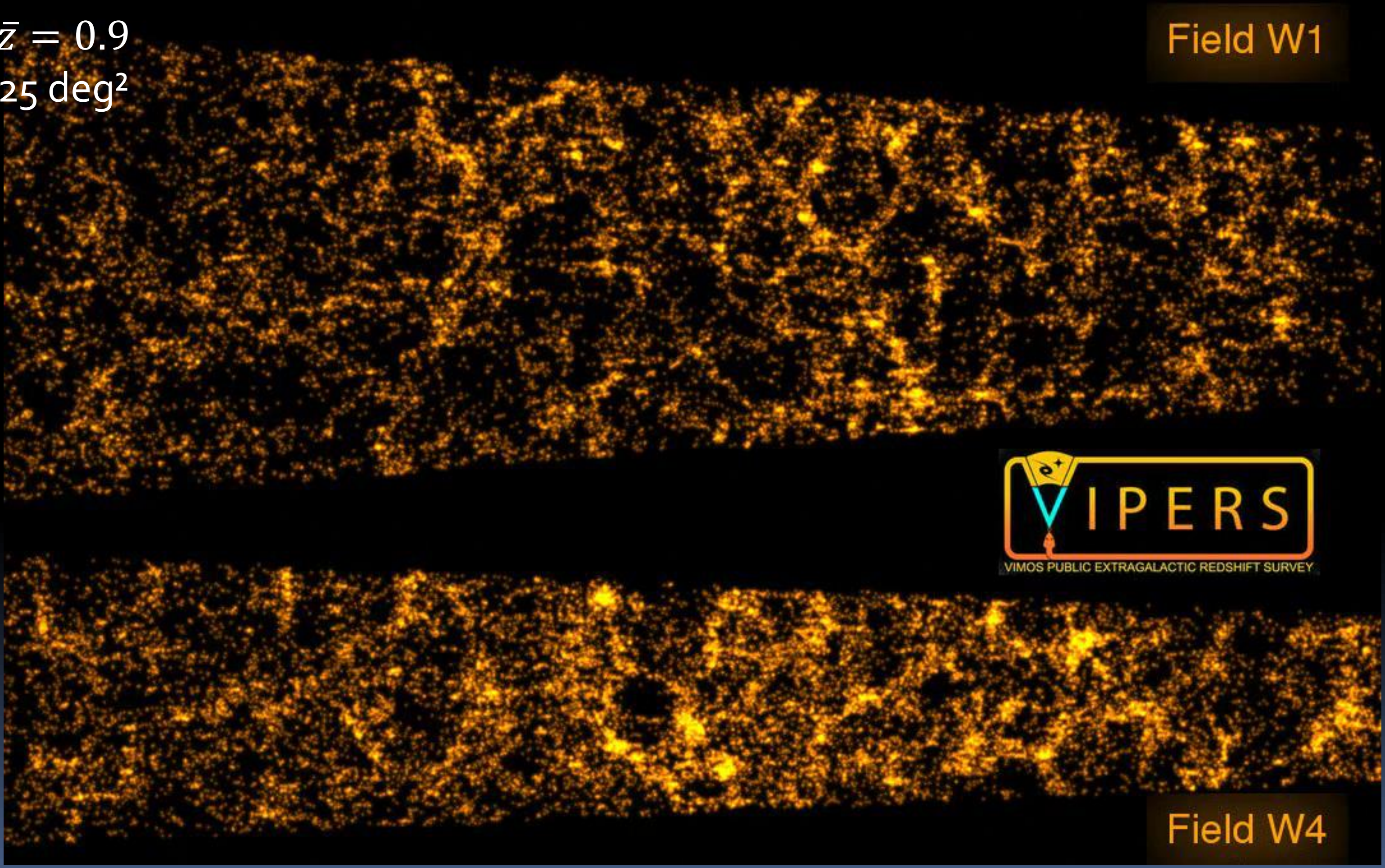
Guzzo et al., 2013, arXiv: 1303.2623

100000 Galaxies

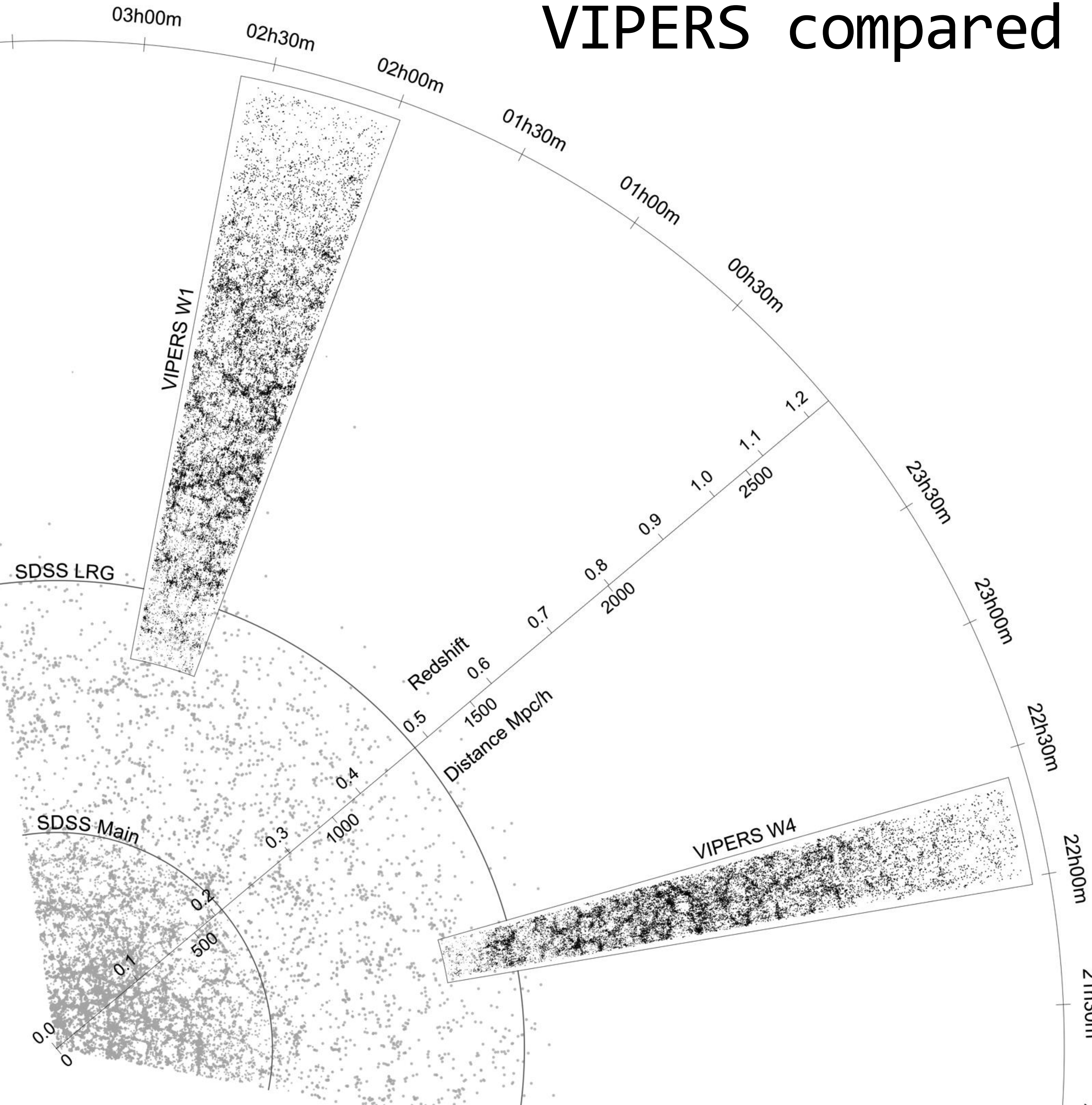
$0.5 < z < 1.5$

$\bar{z} = 0.9$

25 deg^2

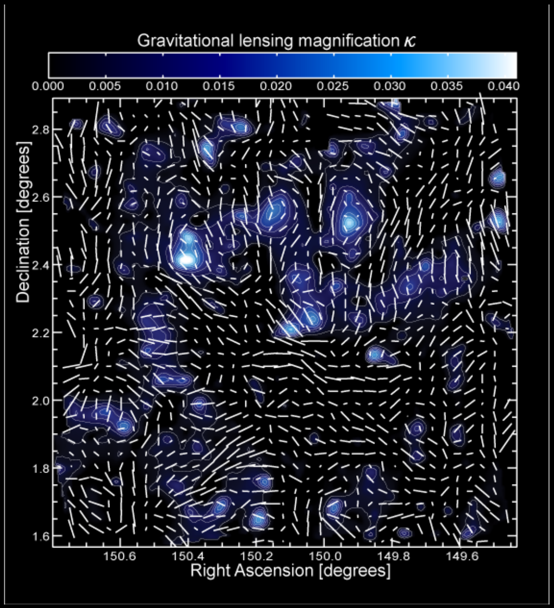


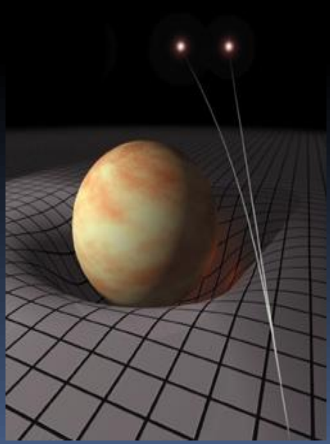
VIPERS compared to SDSS

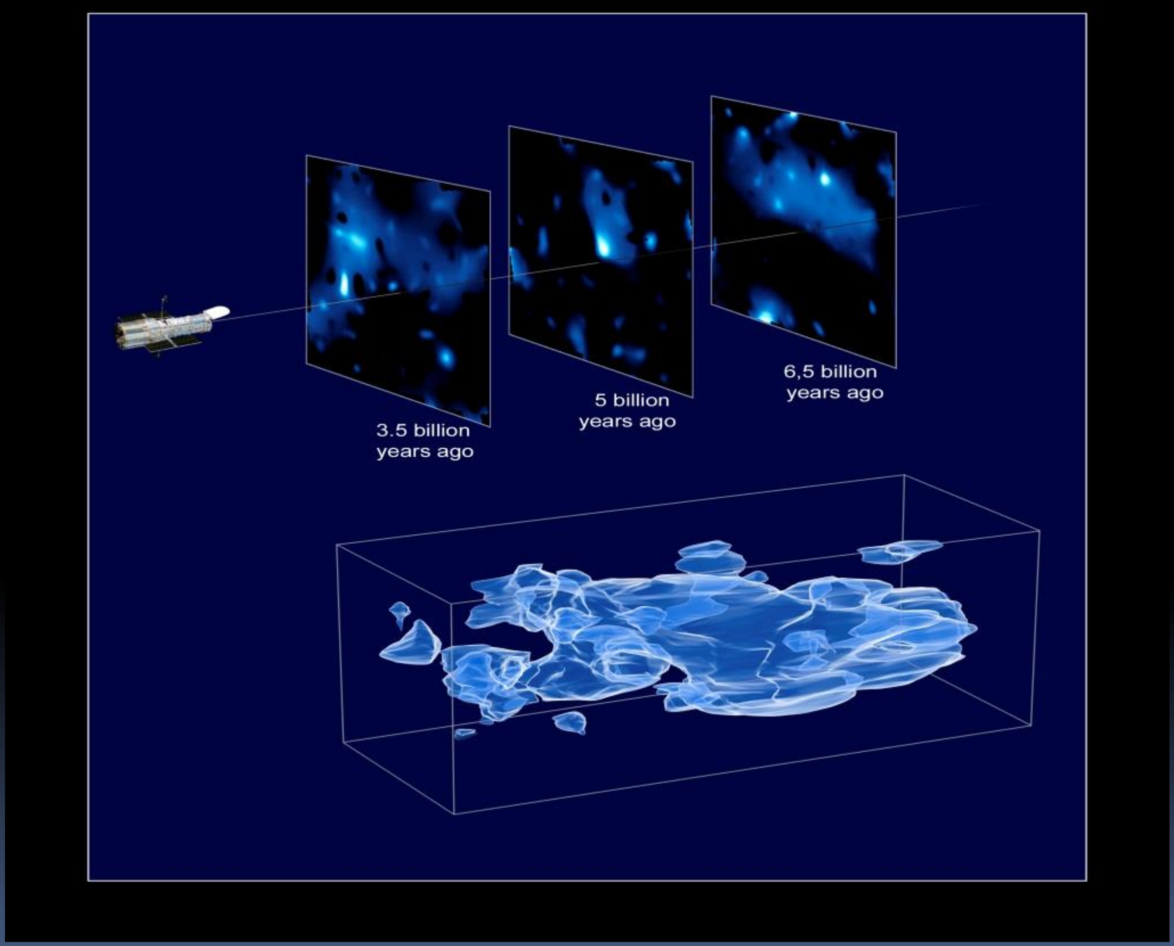


Dark matter distribution

Using weak gravitational lensing







COSMOS, *Massey et al. 2007*

Part 3

MEASURING CLUSTERING

Clustering properties

- Using the correlation function
  - Global population
  - Luminosity samples
  - Mass samples
  - Type samples
- The Halo Occupation Distribution
  - A convenient modeling

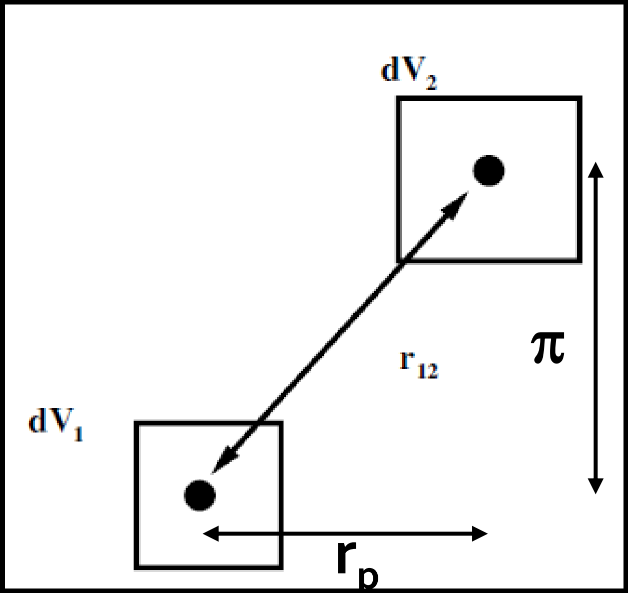
Correlation Function: definition

- Excess probability over random that a galaxy in dV2 will be found at a distance r_{12} from a galaxy in dV1

$$dP = \bar{n}^2(1+\xi(r_{12}))\,dV_1\,dV_2$$

- Contains cosmological information
  - Small scales: redshift space distortions
  - Large scales: Baryon acoustic oscillations
  - Halo occupation
- Power spectrum P(k): Fourier Transform of Correlation function
- In practice, calculate pair separation (G: galaxy sample, R: random sample):

$$\xi(r) = \frac{GG(r) - 2GR(r) + RR(r)}{RR(r)}$$

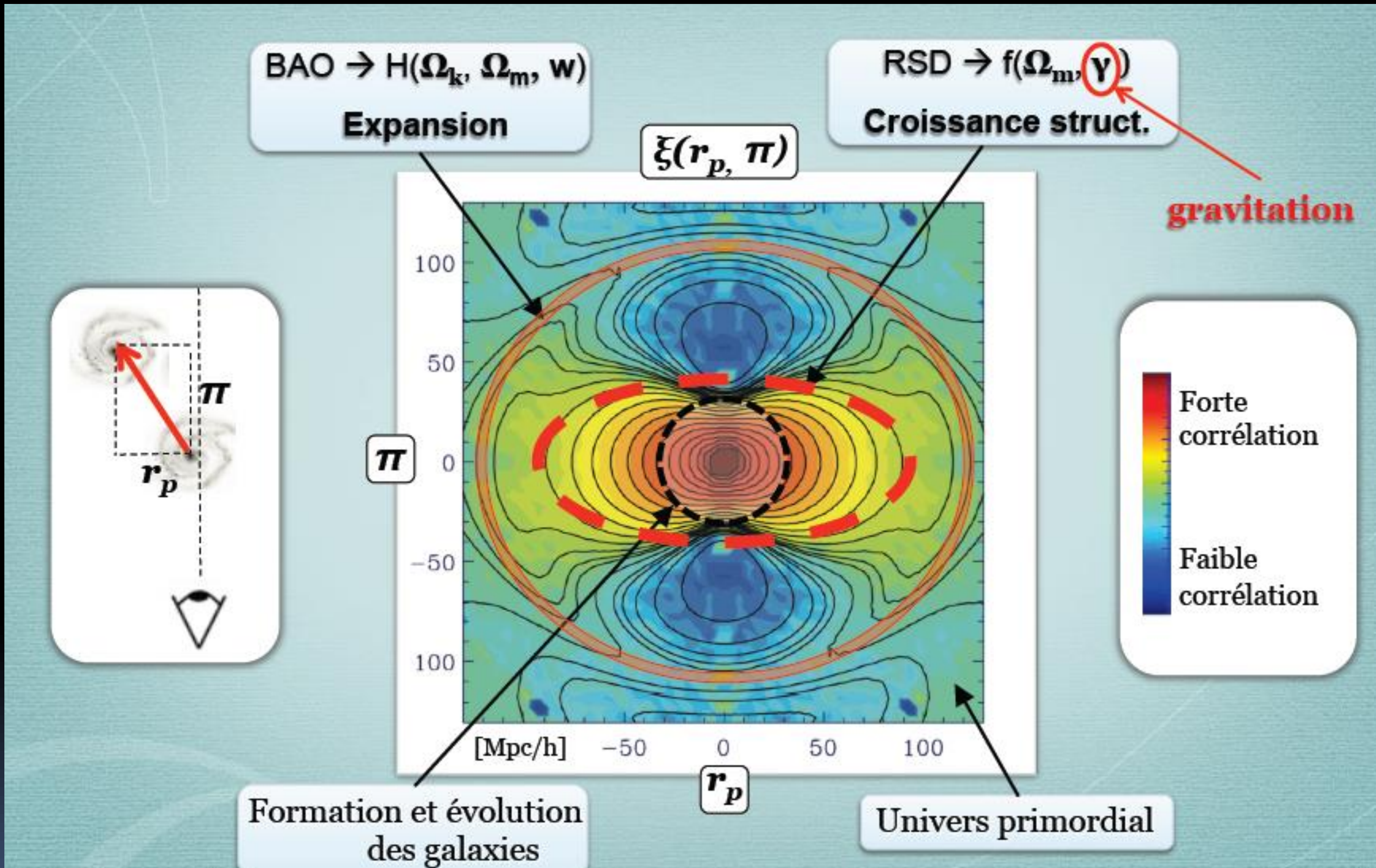


- Angular CF: $w(\theta)$
- 2D: $\xi(r_p,\pi)$
- Projected:

$$w_p(r_p) = \int_{-\pi_{max}}^{\pi_{max}} \xi(r_p,\pi)\,d\pi.$$

r_o = correlation length

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



From Sylvain de la Torre

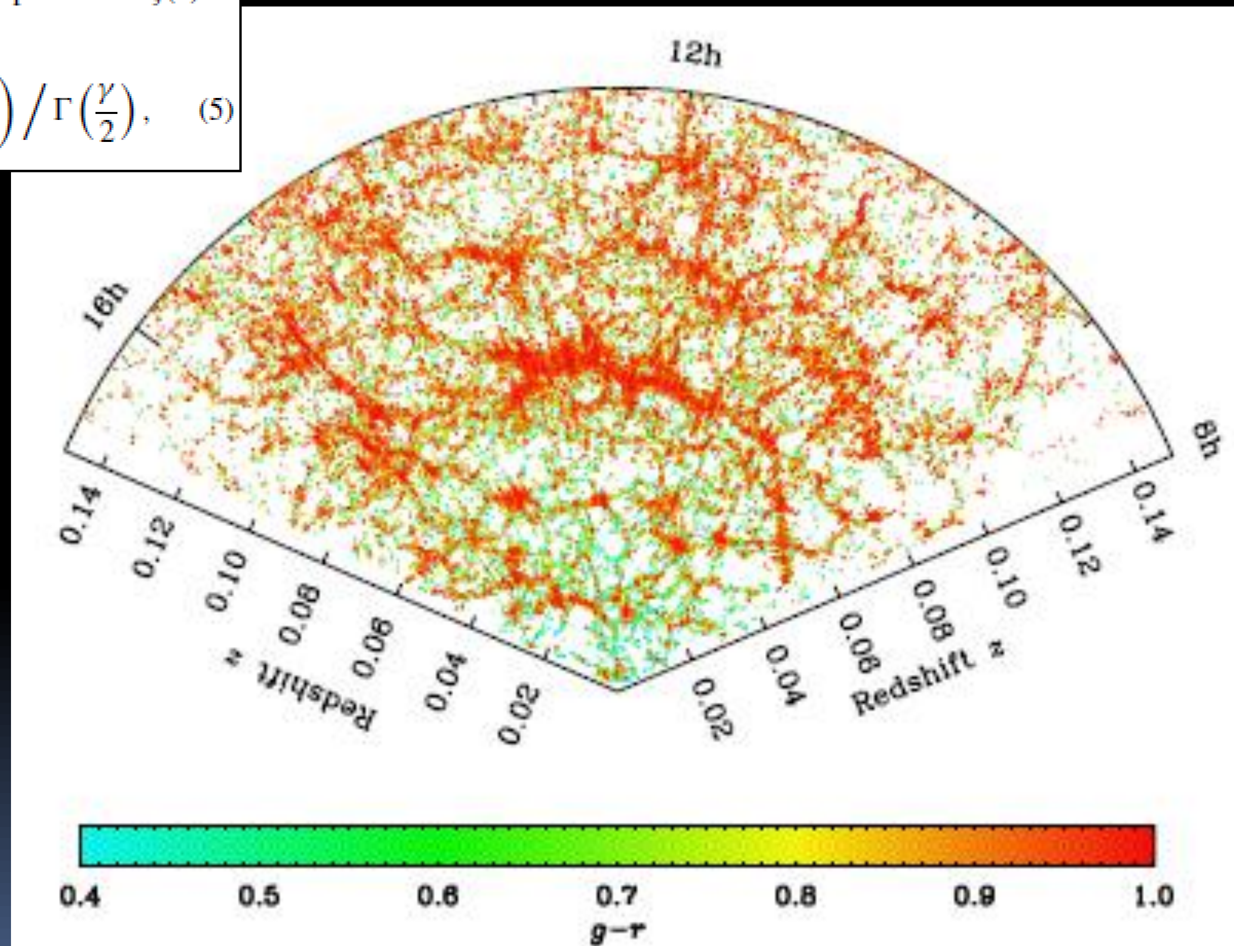
Local correlation function: SDSS

$$w_p(r_p) = 2\int_{r_p}^{\infty} r\,dr\,\xi(r)\left(r^2 - {r_p}^2\right)^{-1/2} \quad (4)$$

(Davis & Peebles 1983). In particular, for a power law $\xi(r) = (r/r_0)^{-\gamma}$, one obtains

$$w_p(r_p) = r_p\left(\frac{r_p}{r_0}\right)^{-\gamma}\Gamma\left(\frac{1}{2}\right)\Gamma\left(\frac{\gamma-1}{2}\right)\Big/\Gamma\left(\frac{\gamma}{2}\right), \quad (5)$$

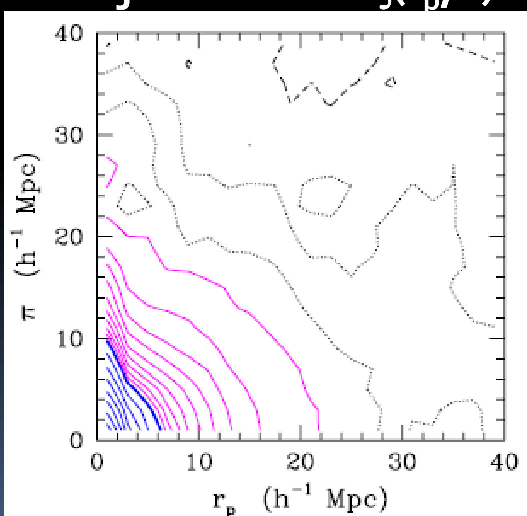
Use color as a proxy for 'Type'



r_o=clustering length

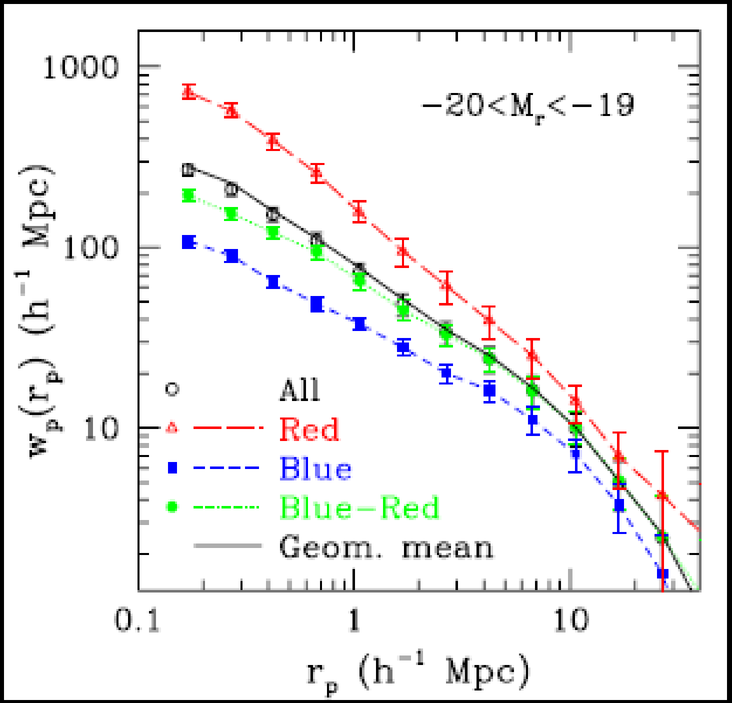
γ=slope of CF

Projected from $\xi(r_p,\pi)$

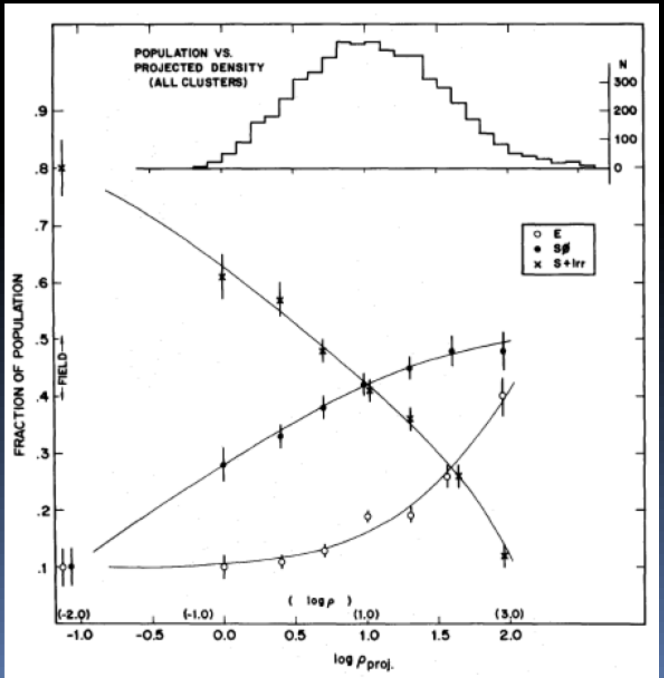


CF in the SDSS: color-type dependence

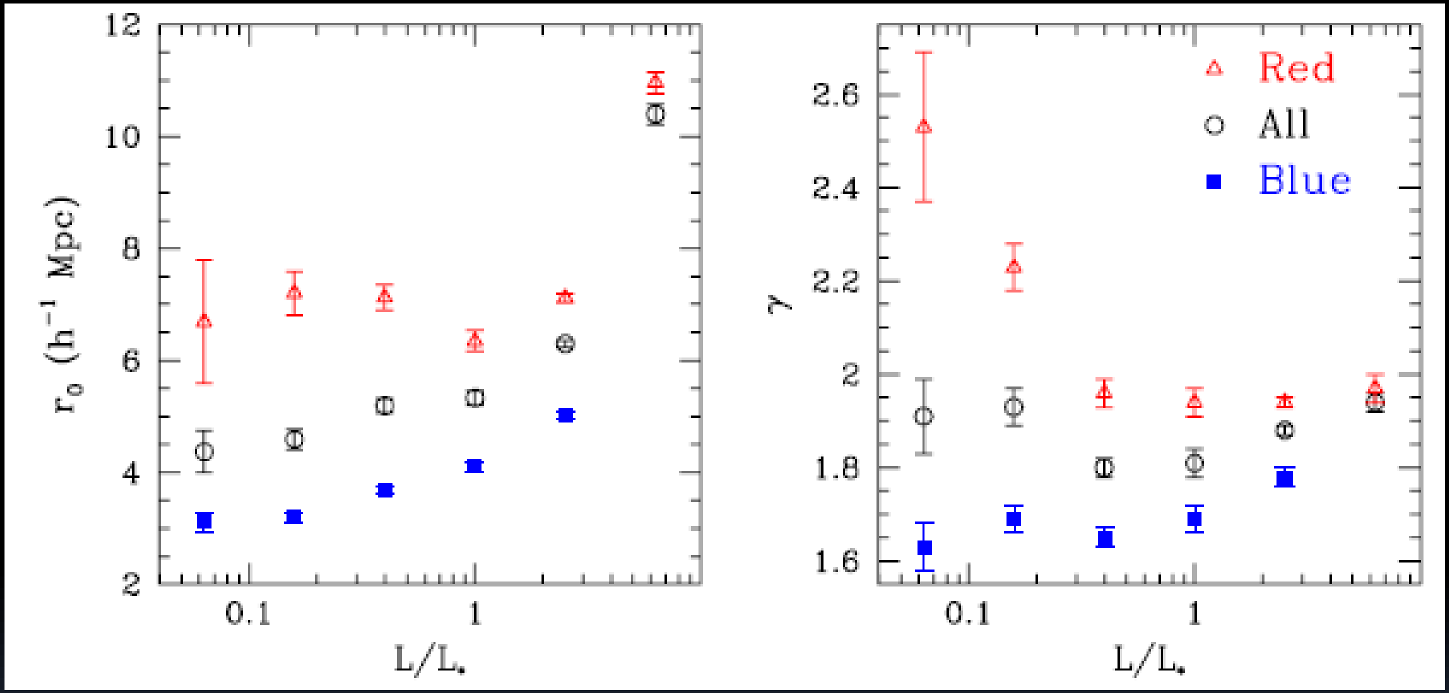
- The redder the color, the more clustered the population



- Related to the type-density relation
  - Elliptical – red galaxies reside in higher density regions
  - Spirals – blue galaxies are in under-dense environments

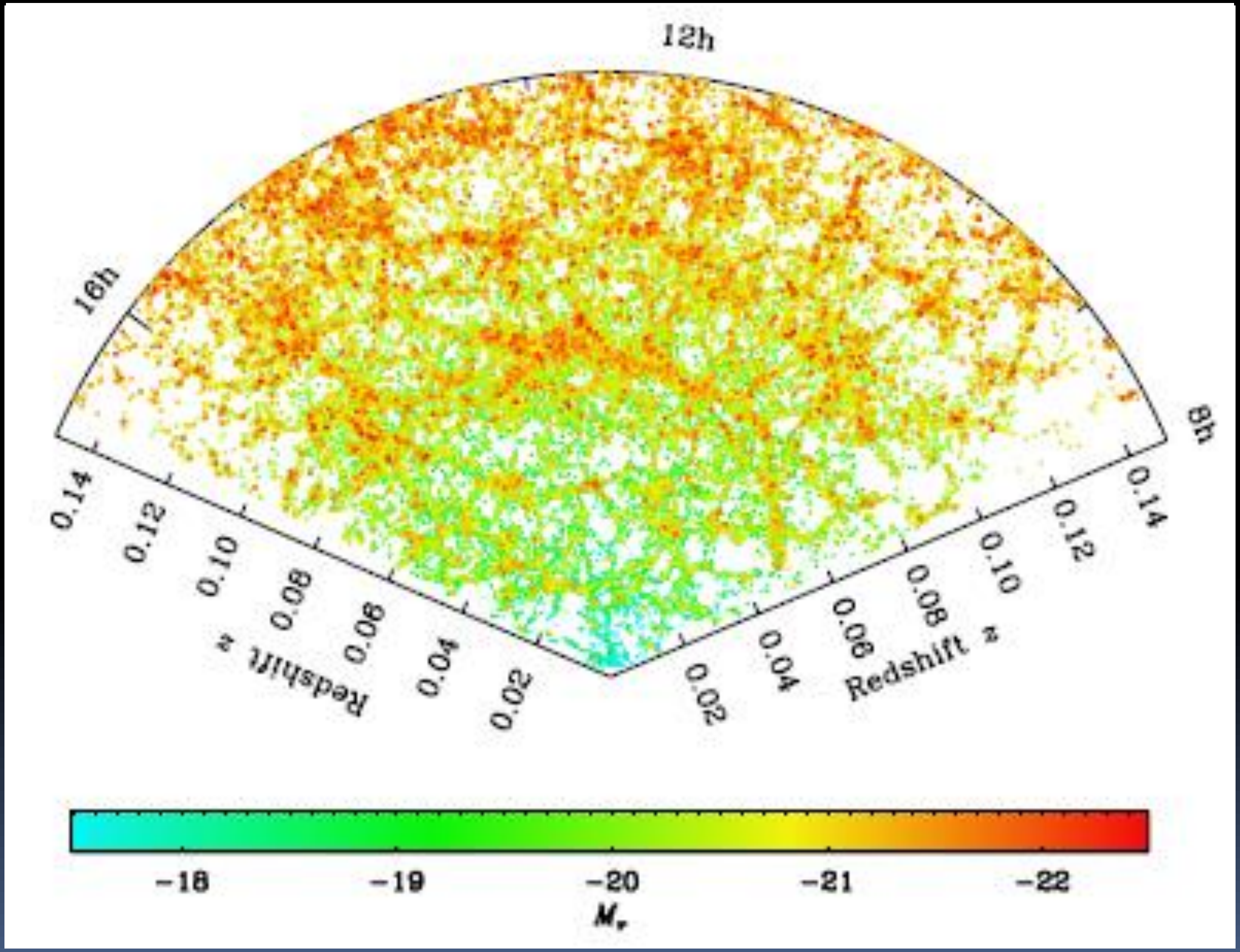


CF in the SDSS: color-type dependence



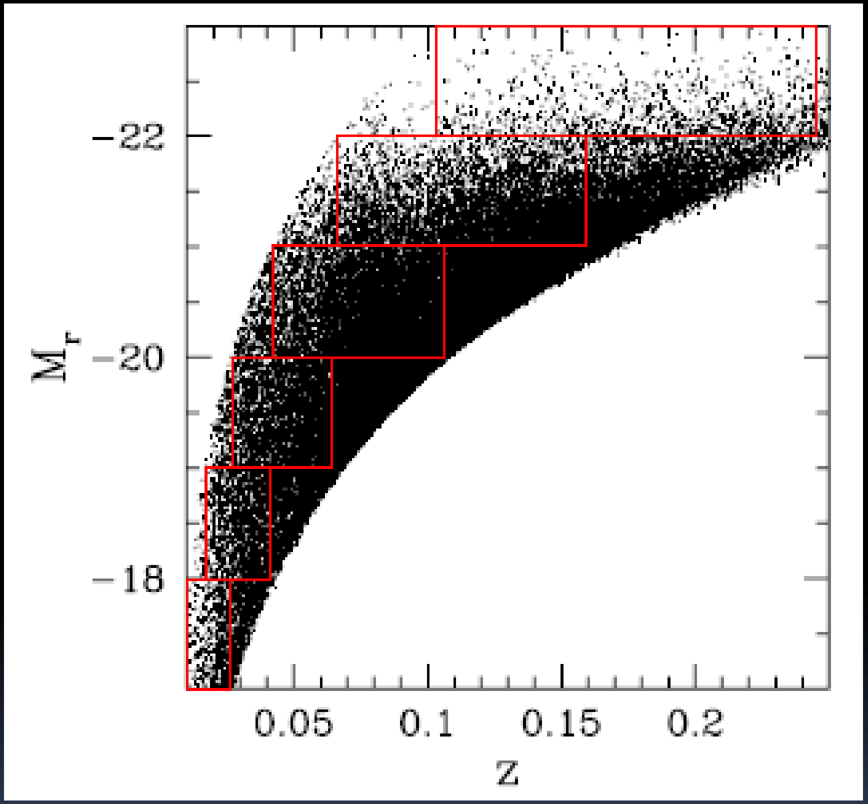
Higher **r_o** for redder galaxies
Larger γ for redder galaxies

As a function of luminosity



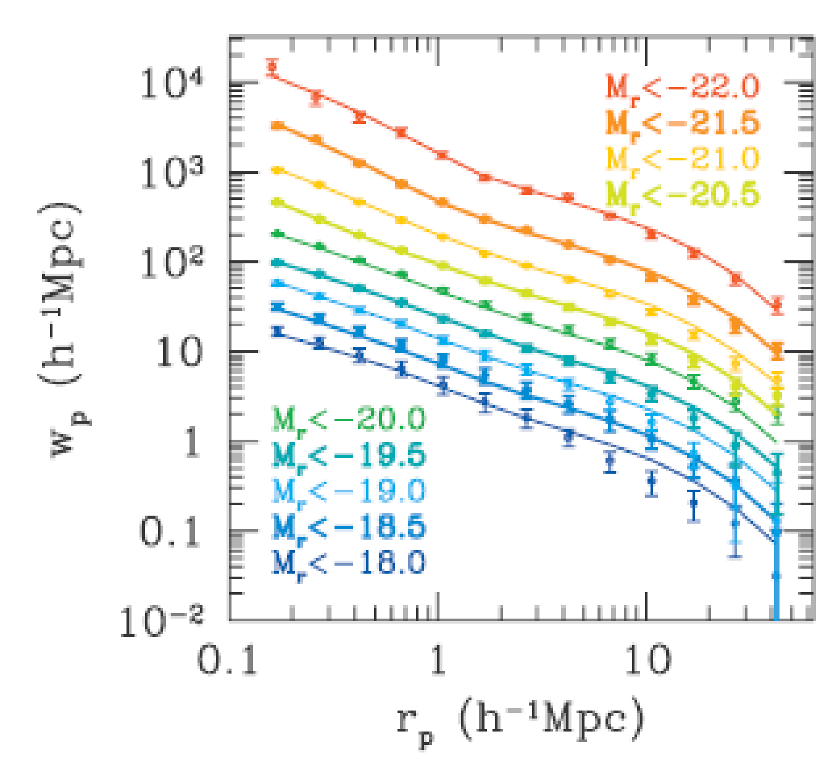
Beware: need to define "volume-complete" samples

- Limited in absolute magnitude
- Evolving M* or not ?
  - Follow "the same" population



CF in the SDSS: Luminosity dependence

- More luminous galaxies are more strongly clustered
- This is related to Dark Matter halos collapse: the high density peaks are more strongly clustered, and they host the more luminous galaxies

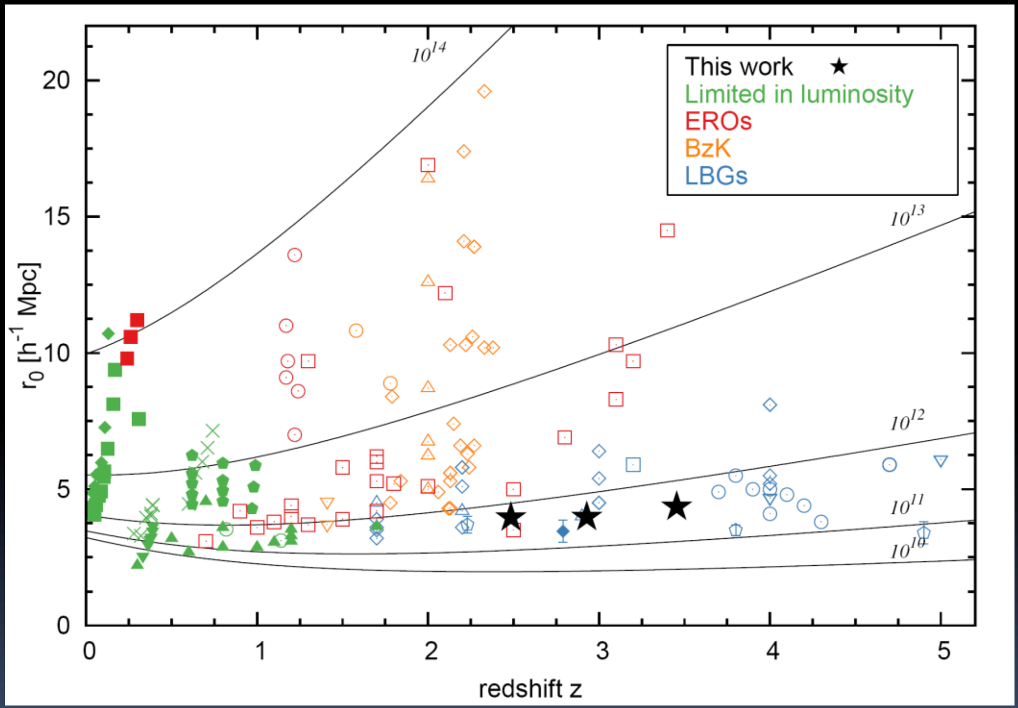


Clustering evolution: correlation length

- Clustering length from correlation function parametrized as a power-law

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

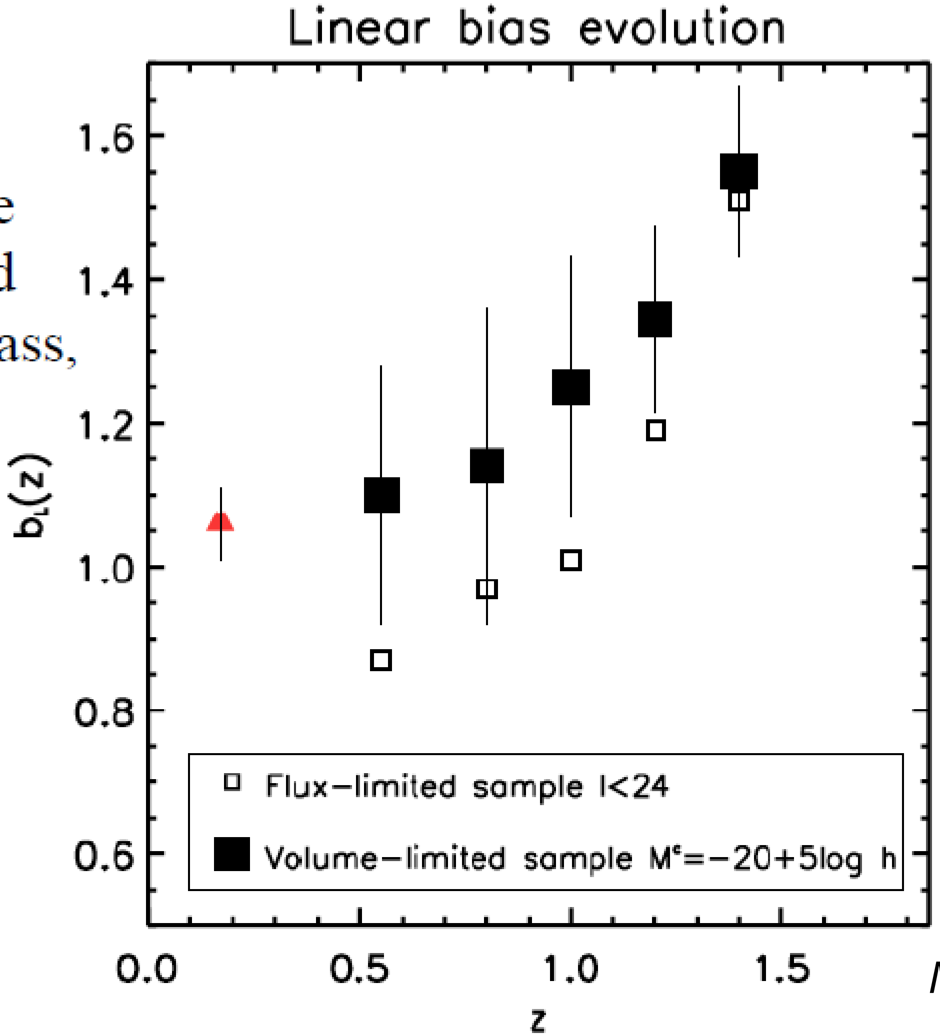
- Clustering is increasing with redshift
- Is this expected ?



From VVDS+VUDS, Durkalec et al., 2015

The Evolution of Bias

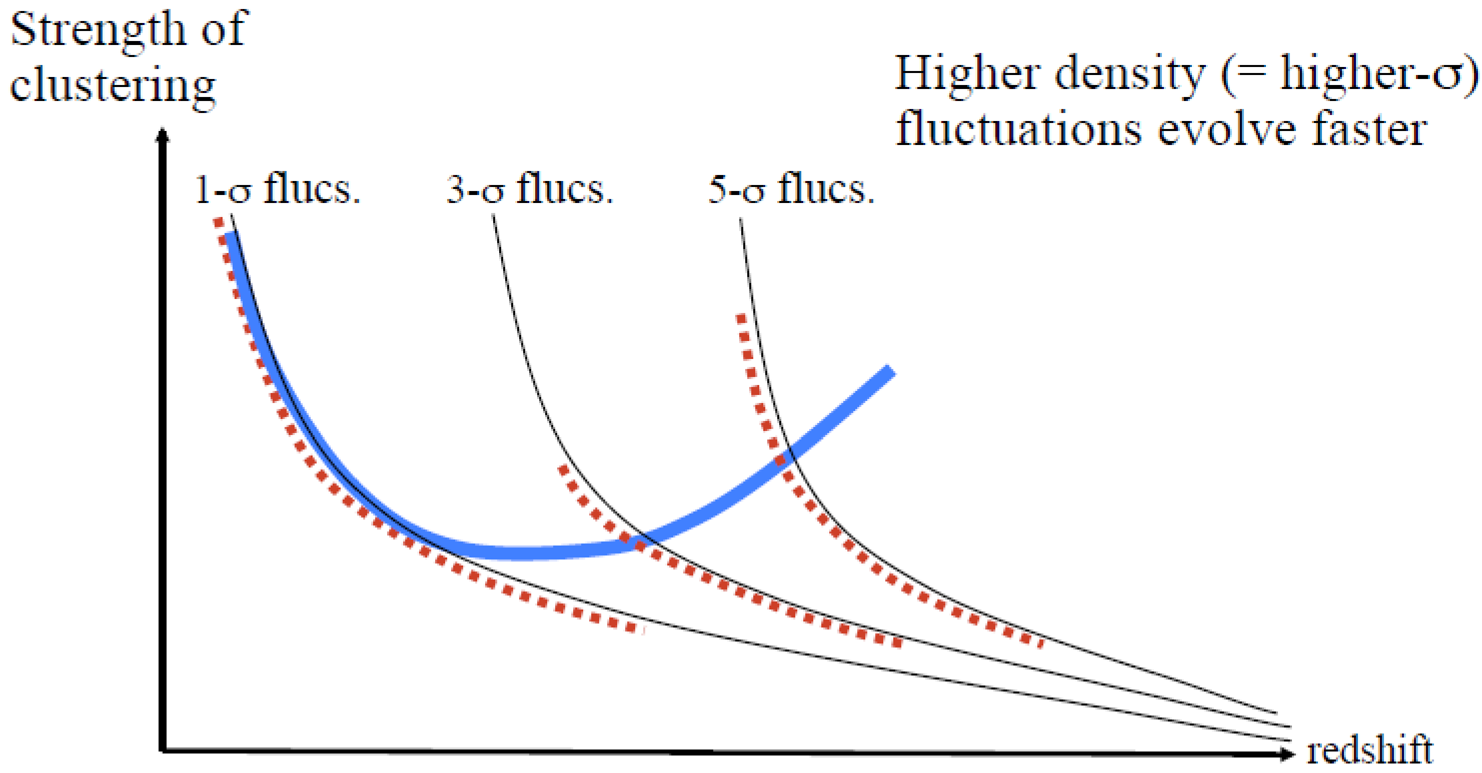
At $z \sim 0$, galaxies are an unbiased tracer of mass, $b \sim 1$



But at higher z's, they are progressively ever more biased

Marinoni et al., 2007

Biasing and Clustering Evolution



At progressively higher redshifts, we see higher density fluctuations, which are intrinsically clustered more strongly …

Thus the net strength of clustering seems to increase at higher z's

From G. Djorgovski

Clustering evolution: Using the HOD

Halo Occupation Distribution

- A parametrisation of the probability distribution that a Halo of mass M_h contains N galaxies
- Main HOD parameters
  - M_0: cutoff mass-scale
  - M_1: mass of halos that have ≥1 satellite
  - M_{min} mass scale of the central galaxy
  - α: high mass slope of the satellite galaxies function
- $\xi(r)$ can be modeled using HOD (see e.g. Tinker+ 2005)

$$\begin{aligned} \langle N_g|m\rangle &= 1 + \left(\frac{m}{M_1}\right)^{\alpha} && \text{for } m > M_{min} \\ &= 0 && \text{otherwise.} \end{aligned}$$

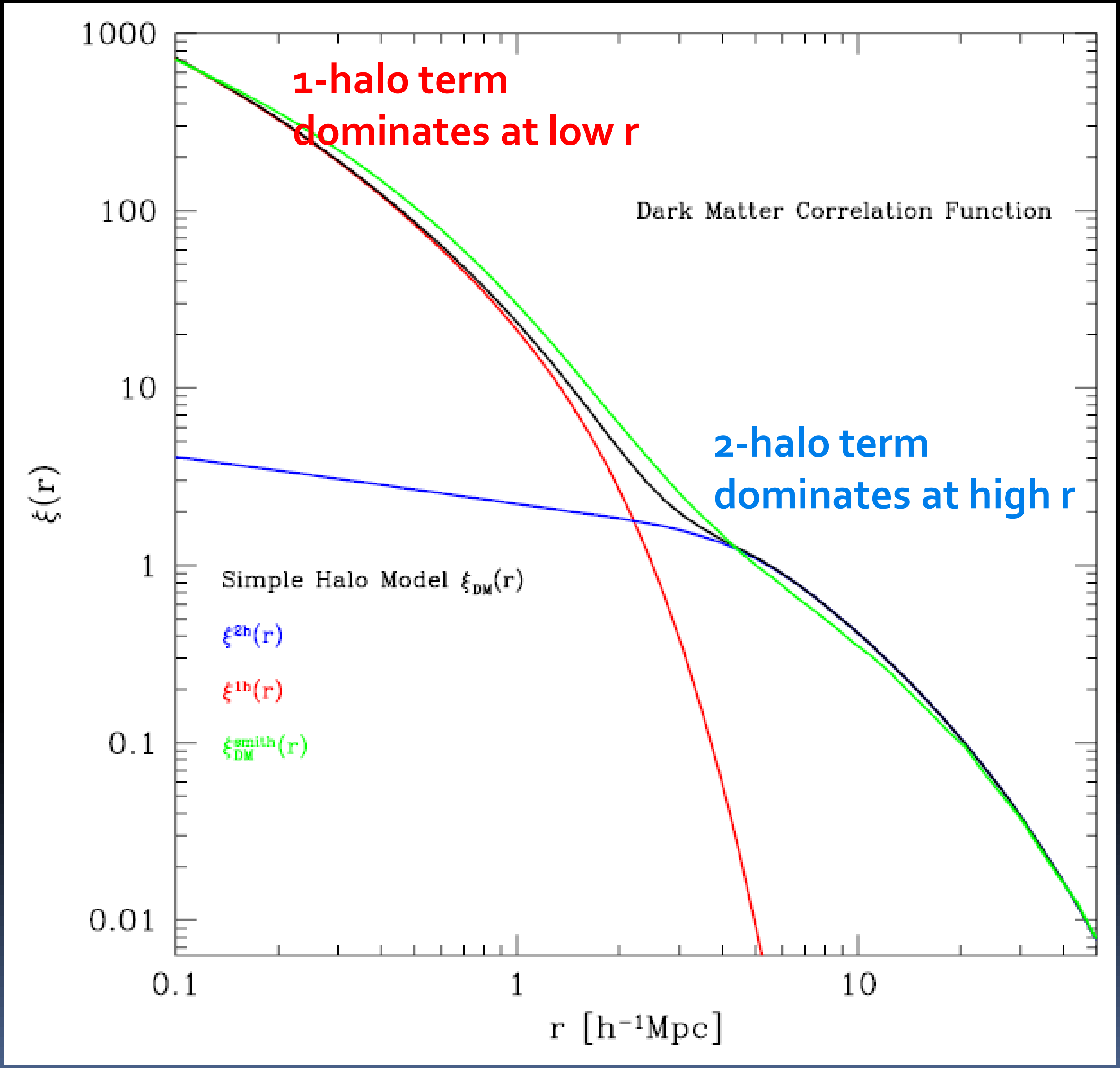
Kravtsov+ 2004

$$\begin{aligned} \langle N_g|m\rangle &= 1 + \frac{m}{M_1}\exp\left(-\frac{M_{cut}}{m}\right) && \text{for } m > M_{min} \\ &= 0 && \text{otherwise,} \end{aligned}$$

Tinker+ 2005

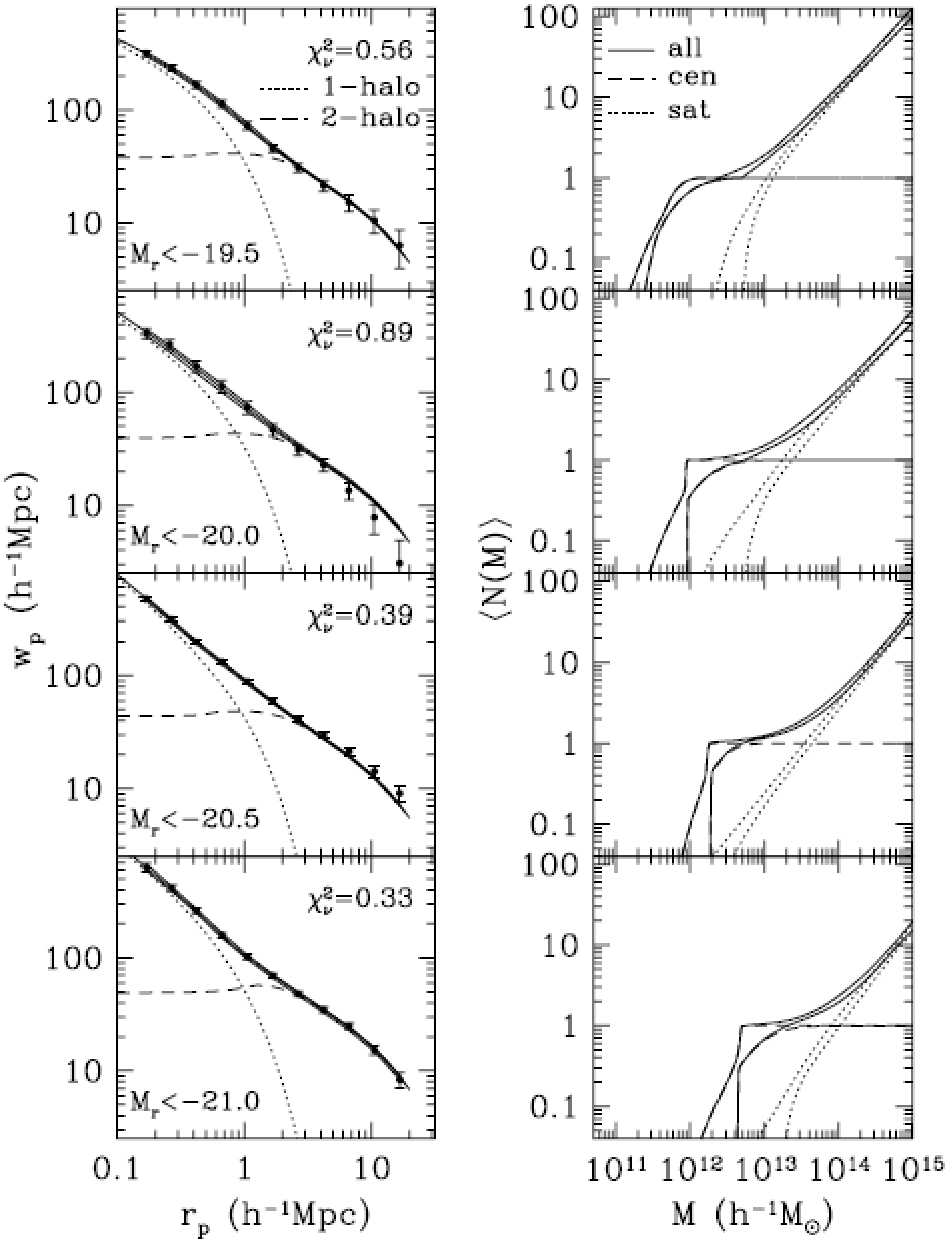
$$\langle N(M_h)\rangle = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M_h - \log M_{min}}{\sigma_{\log M}}\right)\right] \times \left[1 + \left(\frac{M_h - M_0}{M_1'}\right)^{\alpha}\right],$$

Zehavi+ 2011

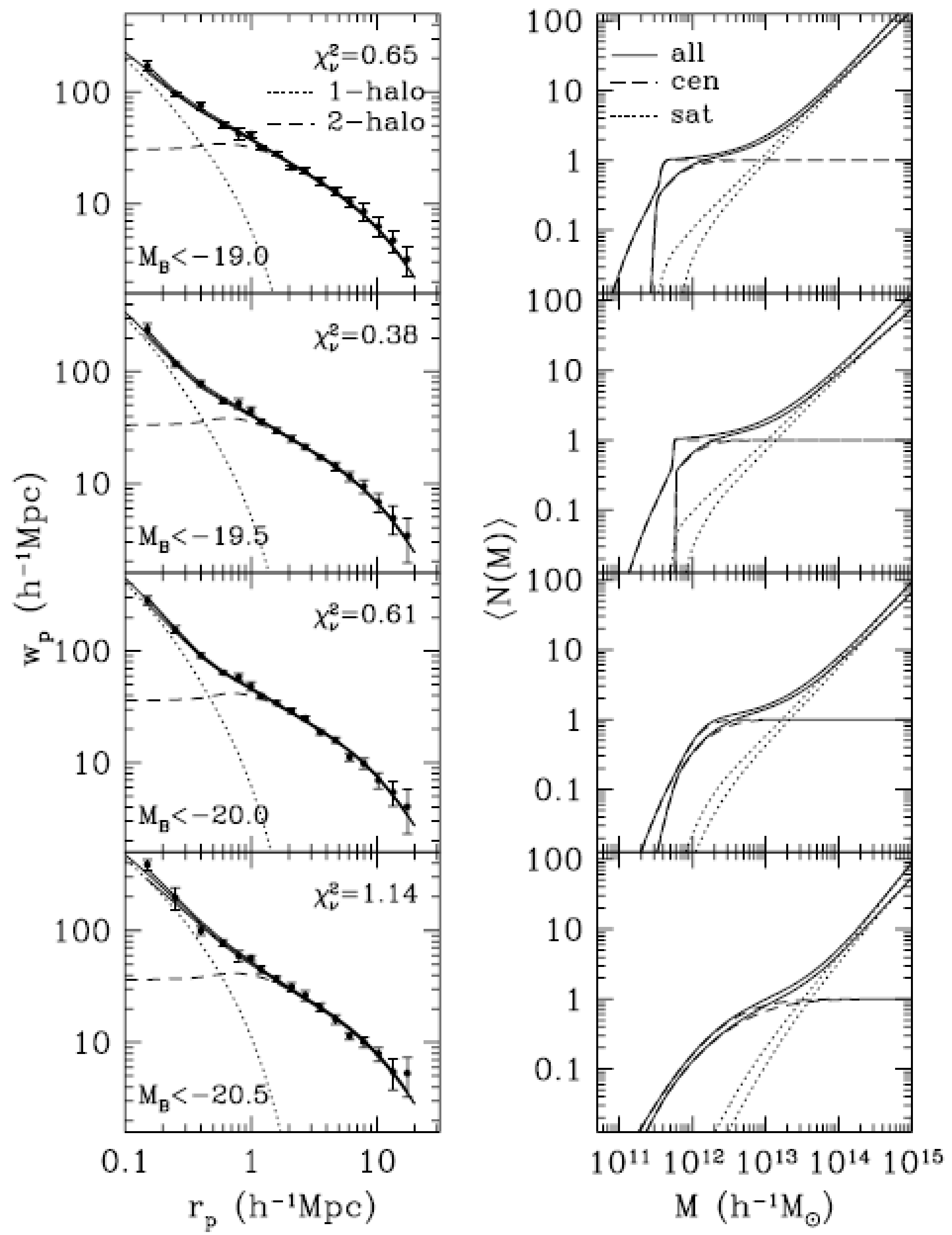


1-halo term
dominates at low r
2-halo term
dominates at high r
Dark Matter Correlation Function
Simple Halo Model $\xi_{DM}(r)$
$\xi^{2h}(r)$
$\xi^{1h}(r)$
$\xi^{smith}_{DM}(r)$
$\xi(r)$
$r\ [h^{-1}Mpc]$
1000
100
10
1
0.1
0.01
0.1
1
10

SDSS, z=0, Zehavi 2011

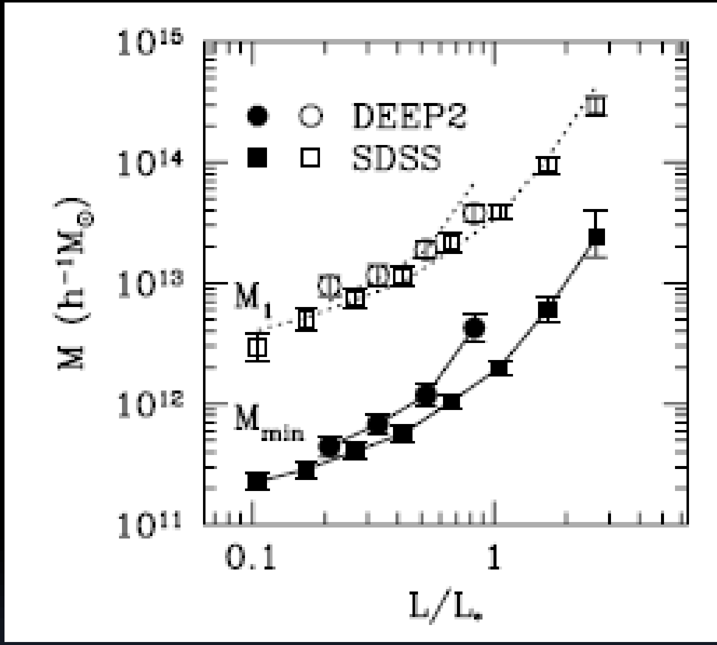


Deep2, z=1, Zheng et al., 2007

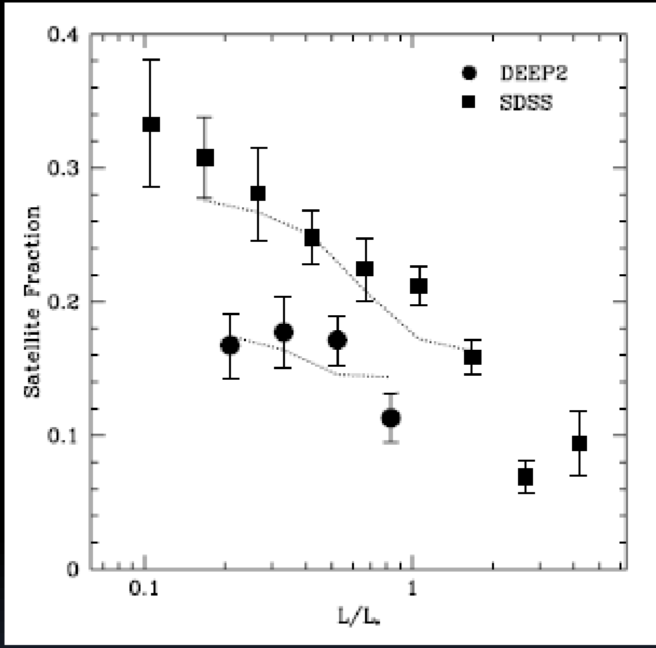


Evolution from HOD

Evolution of the halo mass M1 and Mmin

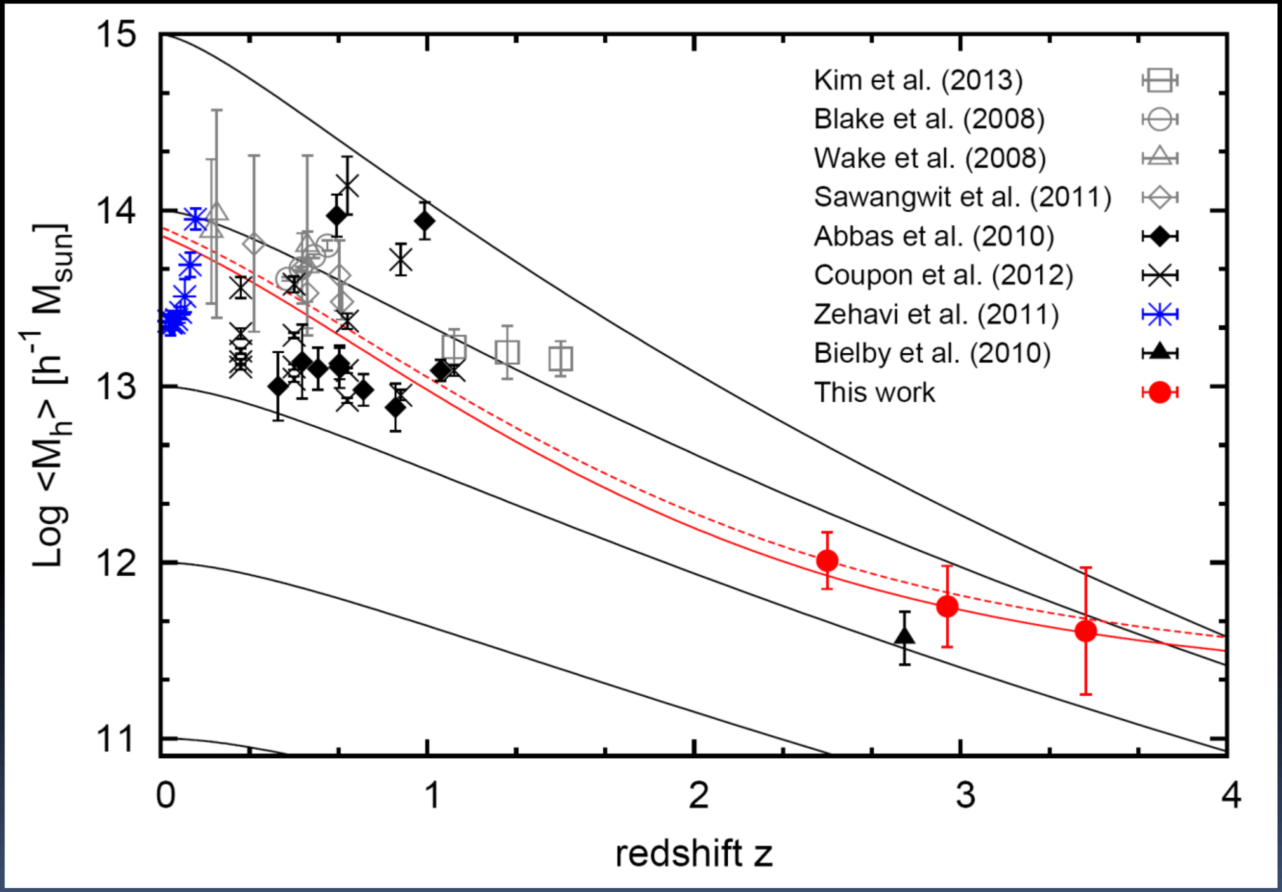


Evolution of the satellite fraction



SDSS, z=0, Zehavi 2011
Deep2, z=1, Zheng et al., 2007

The DM halo mass evolution with redshift



Durkalec et al. 2015

DM halo masses are indeed increasing with z !