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

\[ V_{\text{redshift}} = H_0 \times \text{distance} + V_{\text{peculiar}} \]
The Great Attractor seems to be part of a complex flow linked to the Great.
Farther away: LSS from the 2dFGRS


230000 galaxies

$z < 0.3$

$\bar{z} = 0.11$
LSS in the Sloan Digital Sky Survey

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

http://www.sdss.org/
Eisenstein et al., 2011, AJ, 142, 72
LSS observations

SDSS survey, 2000-2005
Fly-through SDSS movie
LSS at higher redshifts $z>0.5$

- Early attempts
  - DEEP$_2$
  - VVDS
- VIPERS
LSS in DEEP2

38,000 Galaxies

$0.7 < z < 1.4$

$\bar{z} = 0.9$

2.8 deg$^2$

Newman et al., 2012, arXiv:1203.3192
**VVDS: the VIMOS VLT Deep Survey**

- **Magnitude selection**

<table>
<thead>
<tr>
<th>Survey parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope diameter</td>
<td>8.2m</td>
</tr>
<tr>
<td>Field of view</td>
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</tr>
<tr>
<td>Area</td>
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<tr>
<td>Redshift range</td>
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<td>λ-range</td>
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<td>Depth</td>
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<td>230</td>
</tr>
<tr>
<td>Nspec</td>
<td>35 000</td>
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</table>
LSS in VVDS

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

Le Fèvre et al., 2013
arXiv: 1307.0545
2005: VVDS-0226-04 cone
Galaxy density field, ~10000
redshifts, z~1
$I_{AB} \leq 24$

2DFGRS/SDSS stop here

z=0.5

z=0.6

z=0.7

z=0.8

z=0.9

z=1.0

z=1.1

z=1.2

z=1.3
VIPERS: the VIMOS Public Extragalactic Survey

- Magnitude AND color selection

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LSS in VIPERS

100,000 Galaxies

$0.5 < z < 1.5$

$\bar{z} = 0.9$

25 deg$^2$

Guzzo et al., 2013, arXiv: 1303.2623
VIPERS compared to SDSS
Dark matter distribution

Using weak gravitational lensing

COSMOS, Massey et al. 2007
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 $dV_2$ will be found at a distance $r_{12}$ from a galaxy in $dV_1$
  \[ dP = n^2(1 + \xi(r_{12})) \, dV_1 \, dV_2 \]

- 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:
  \[ w_p(r_p) = \int_{-\pi_{\text{max}}}^{\pi_{\text{max}}} \xi(r_p, \pi) \, d\pi. \]
  \[ \xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma} \]

$r_o$ = correlation length
Local correlation function: SDSS

\[ w_p(r_p) = 2 \int_{r_p}^{\infty} r \, dr \, \xi(r) (r^2 - r_p^2)^{-1/2} \]  

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

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

\( r_o \) = clustering length

\( \gamma \) = slope of CF

Use color as a proxy for ‘Type’
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 $r_0$ for redder galaxies
Larger $\gamma$ 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
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.
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 $\geq 1$ satellite
  - $M_{\min}$: mass scale of the central galaxy
  - $\alpha$: high mass slope of the satellite galaxies function

- $\xi(r)$ can be modeled using HOD (see e.g. Tinker+ 2005)

\[
\langle N_g | m \rangle = 1 + \left( \frac{m}{M_1} \right)^\alpha \quad \text{for } m > M_{\min}
\]
\[
= 0 \quad \text{otherwise.}
\]

\[
\langle N_g | m \rangle = 1 + \frac{m}{M_1} \exp \left( -\frac{M_{\cut}}{m} \right) \quad \text{for } m > M_{\min}
\]
\[
= 0 \quad \text{otherwise,}
\]

\[
\langle N(M_h) \rangle = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\log M_h - \log M_{\min}}{\sigma_{\log M}} \right) \right]
\]
\[
\times \left[ 1 + \left( \frac{M_h - M_0}{M_1} \right)^\alpha \right],
\]
1-halo term dominates at low $r$

2-halo term dominates at high $r$
SDSS, z=0, Zehavi 2011

Deep2, z=1, Zheng et al., 2007
Evolution from HOD

Evolution of the halo mass $M_1$ and $M_{\text{min}}$

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

Evolution of the satellite fraction
The DM halo mass evolution with redshift

DM halo masses are indeed increasing with $z$!

Durkalec et al. 2015