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 3

CLUSTERING: BARYON
ACOUSTIC OSCILLATIONS AND
REDSHIFT SPACE DISTORTIONS

Olivier Le Fèvre – Cosmology Summer School 2016
With contribution from Sylvain de la Torre (Les Houches Cosmology School march 2016)
Outline

1. Cosmology from LSS
2. Baryon Acoustic Oscillations measurements
3. Redshift space distortions measurements
4. Constraints on cosmology from clustering
Cosmology from LSS

- Constraints from galaxy power spectrum full shape (linear scales)

→ Sensitive to: $h, \Omega_m h^2, \Omega_b h^2, n_s, (b \sigma_8)$
Cosmology from LSS

BOSS, Sanchez et al. 2012

Galaxy correlation function

- Constraints from galaxy correlation function full shape

→ Sensitive to:
  \( h, \Omega_m h^2, \Omega_b h^2, n_s, (b\sigma_8) \)
Cosmology from LSS

Galaxy anisotropic correlation function

Redshift-space distortions $\rightarrow f(z)$

Galaxy Power spectrum

Primordial Universe

BAO $\rightarrow H(z), D_\Lambda(z)$

Galaxy formation processes + massive neutrinos
Baryon Acoustic Oscillations

**Galaxies**

**CMB**

**Planck Collaboration 2015**

**Anderson et al. 2014**
Clustering: Baryon Acoustic Oscillations

- Original hot, dense plasma of electrons and baryons
  - Short distances for photons as they interact via Thomson scattering
  - Oscillations from gravity and heat pressure of photon-matter interactions
- Recombination (z~1000): matter became neutral, photons propagate freely
  - Decoupling: pressure oscillations leave an imprint in the baryon distribution
- A standard ruler
  - Search for statistical imprint on galaxy distribution
- Compare to SNe: standard candel
Baryon Acoustic Oscillations

A single perturbation in an uniform plasma. Uniform except for an excess of matter at the origin.

Eisenstein, Seo, White 2006
Baryon Acoustic Oscillations

High pressure drives baryon-photon plasma outward at high speed. Baryons and photons move together.

Eisenstein, Seo, White 2006
Baryon Acoustic Oscillations

Expansion continues for about $10^5$ years

Eisenstein, Seo, White 2006
After $10^5$ years, the Universe has cooled enough so that photons stop ionizing atoms. Photons decouple from baryons. The former quickly streams away.

Eisenstein, Seo, White 2006
Baryons having lost their motive pressure remain in place, the baryon peak is stalled.

Eisenstein, Seo, White 2006
Photons have become uniform, but baryons stay overdense in a shell of 150 Mpc in radius.

Further non-linear processes related to galaxy formation act to broaden and shift the peak on scales of 10-20 Mpc/h.
BAO as a standard ruler
What is expected?
BAO measurements need spectral resolution
What has been found: SDSS
First detection in 2005

- ~46000 luminous red galaxies from SDSS-I
  - \( \bar{z} \sim 0.3 \)
- Red luminous galaxies have a larger bias, hence stronger correlation, easier to measure CF

*Eisenstein et al. 2005*

Also from 2DFGRS

*Cole et al. 2005*
2012: BOSS, SDSS-III/DR9

- ~260000 massive galaxies
- $\bar{z} \sim 0.57$

Anderson et al. 2012
Baryon Acoustic Oscillations

- Reconstruction

  - To mitigate non-linear effects and sharpen the BAO peak, reconstruction is now common practice (based on Zel’dovich approximation):
A major probe

- BAO provides one of the most accurate geometrical constraints

\[ r_s = 1 / H_0 \Omega_1/2 m_{a^*} 0 \text{dcs} (a + a_{eq})^{1/2} \]

Anderson et al. 2012; arXiv:1203.6594
Cosmological parameters: using BAO + Planck

Red: Planck
Blue: Planck + BAO
Outline

1. Cosmology from LSS
2. Baryon Accoustic Oscillations measurements
3. Redshift space distortions measurements
4. Constraints on cosmology from clustering
What is Dark Energy? What is the origin of cosmic acceleration?
Cosmic acceleration

...or modify gravity theory?  Add dark energy

To distinguish these two radically different options: need to probe the dynamics of the Universe
The growth rate of structure depends on the strength of gravity.

Structure growth rate:

\[ \delta^+(\bar{x},t) = \hat{\delta}(\bar{x})D(t) \]

\[ f \equiv \frac{d \ln D}{d \ln a} \]

(Credit: V. Springel)
Cosmic acceleration

The origin of cosmic acceleration is one of the most important questions in cosmology today:

Dark Energy or a modification of standard gravity theory?

→ Growth rate of structure $f(z)$ crucial to break the degeneracy between cosmological models
Redshift-space distortions

- Large-scale peculiar velocities, gravity-driven coherent motions in velocity space
- Galaxy spatial distribution observed in galaxy redshift surveys, i.e. in redshift-space:
  - Distance in redshift-space: \( s = r + \frac{v_{\text{los}}}{aH} \)
  - Because of peculiar motions, redshift is not strictly a distance
  - Observed in redshift-space the correlation function is “squashed” by structure growth hence sensitive to Gravity

\[
f \equiv \frac{d \ln D}{d \ln a} \approx \Omega_m(z)^\gamma
\]

Growth rate of structure
Redshift-space distortions

- RSD are known for about 30 years... (Kaiser 1987)

- ... but we realised its usefulness for probing gravity only less than 10 years ago!

Peacock et al. (2001), Nature
RSD to measure $\Omega_m$:

$$\beta = f/b = \Omega_m \gamma / b$$

VVDS, Guzzo et al. (2008), Nature
RSD to probe gravity:

$$\beta = f/b = \Omega_m \gamma / b_L$$

![Graph](image-url)
Recent RSD measurements

6dFGS
Beutler et al. 2012
z=0.06

SDSS-III/BOSS
Samushia et al. 2014
z=0.57

VIPERS
de la Torre et al. 2013
z=0.8
Constraints on growth rate

- Current constraints in agreement with $\Lambda$CDM and Einstein gravity

VIPERS, de la Torre et al. 2013
Constraints on growth rate

Current constraints in agreement with ΛCDM and Einstein gravity

Samushia et al. 2014
Combined BAO and RSD

Combined BAO and RSD constraints on Dark Energy EoS

Chuang et al. 2014
The future of clustering analysis

- Correlation function: a powerful tool to probe galaxy (halo) evolution and cosmology
- CF with BAO and RSD has become a major tool to constrain the cosmological world model
Current measurements:
- Not accurate enough to distinguish between GR and modified gravity
- Restricted to $z<0.8$, low redshifts intrinsically limited by volume

→ Need redshift surveys probing largest volumes at high redshift
Future Dark Energy surveys

- Massive effort today to prepare massive galaxy/quasar surveys to solve the problem of Dark Energy and the origin of late cosmic acceleration: eBOSS, DES, PFS, Euclid, DESI, WFIRST, ...

Essentially, error scales as Volume$^{-1/2}$

Surveys volume

- 2.5 Gpc$^3$ eBOSS
- 11 Gpc$^3$ eBOSS
- 20 Gpc$^3$ eBOSS+PFS
- 105 Gpc$^3$ eBOSS+PFS+DESI+Euclid+WFIRST
## Future spectroscopic surveys

<table>
<thead>
<tr>
<th>Spectroscopic Survey</th>
<th>Instrument</th>
<th>redshift</th>
<th>Field # galaxies</th>
<th>Start/end dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>eBOSS</td>
<td>Sloan 2.5m</td>
<td>0.5-1.5</td>
<td>10^6</td>
<td>2014-2017</td>
</tr>
<tr>
<td>PFS</td>
<td>Subaru 8m</td>
<td>0.5-2.7</td>
<td>1400 deg^2, 3×10^6</td>
<td>2019-2022</td>
</tr>
<tr>
<td>DESI</td>
<td>KPNO 4m</td>
<td>0.5-1.5 Gal.</td>
<td>12000 deg^2, 50×10^6</td>
<td>2019-2024</td>
</tr>
<tr>
<td>EUCLID</td>
<td>1.2m</td>
<td>0.5-2</td>
<td>15000 deg^2, 50×10^6</td>
<td>2021-2027</td>
</tr>
<tr>
<td>WFIRST</td>
<td>2.4m</td>
<td>1-3</td>
<td>2200 deg^2, 16×10^6</td>
<td>2024-</td>
</tr>
</tbody>
</table>
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The Euclid Mission and Clustering
Outline

1. The Euclid mission and NISP spectrograph for clustering
2. The NISP spectroscopic survey
3. Forecasts for BAO and RSD
The ESA-Euclid space mission

- A space mission dedicated to dark energy and dark matter
- A 1.2m diameter telescope, visible + IR, low background (Lagrange L2 point)
- 2 survey instruments
  - VIS: the VISible imager
  - NISP: the near Infrared Spectrograph and Photometer
- An integrated survey
  - Wide survey: 15000 deg\(^2\) in imaging (2G galaxies) and spectroscopy (50M spectra)
  - Deep survey: 40 deg\(^2\) in imaging and spectroscopy
Euclid « All sky » survey

All the extragalactic sky (away from the Milky Way)
2 billion galaxy images
50 million galaxy redshifts
To \( z \sim 2 \): 10 billion years back
Measuring clustering with Euclid

Baryonic Acoustic Oscillations in the galaxy power spectrum as a standard ruler (one Δz=0.2 redshift slice)

Anisotropy of the correlation function or power spectrum (RSD) as a measure of the growth of structure

From Guzzo Euclid-Marseille 2014
Measuring clustering with Euclid

Method: galaxy redshift survey over wide field

From Guzzo Euclid-Marseille 2014
From science goals to experiment

Putting it all together

Science: Galaxy clustering
- RSD: Probe of structure growth
- BAO

Survey Parameter Space
- All sky (15000 deg²)
- R~300
- z~0.7-2
- Hα selected

Instrument Concept
- Slitless spectroscopy & imaging
- Wide field 0.5 deg²
- 0.9-1.8 microns

Survey Implementation
NISP: infrared spectrograph & camera

Technical specifications:

- Field of view: 0.54 deg² (2.7x the full moon)
- Infrared: 0.8 to 2 microns
- Spectrograph designed to get the Hα line up to z~2

Build in Marseille, LAM-AMU leadership, with CPPM, under CNES overall agency responsibility
Euclid-NISP: in full development

- First design 2010
  - Existing models, tested
- Delivered to ESA: 2018
- In flight: 2020
Measuring clustering with Euclid

- NISP will produce slitless spectroscopy
- This implies superimposition of spectra from different objects (at different redshifts...).
- The challenge is to get rid of this contamination and ensure a robust redshift measurement
- Evaluate the reliability of the redshift measurement per object
- Do all this automatically for ~50 million objects
Extracting the spectra and redshifts

- Extract all galaxy spectra
  - Measure redshifts automatically
- Find 50M Hα emitters 0.8<z<2
- Accurately measure line flux
- Estimate uncertainties

Simulated galaxy at z=1.647
Extracting spectra: contamination

Recovering spectra from confusion: OU-SIR -> OU-SPE

4 sub-integrations (dithers)
3 roll angles of the dispersion axis (-90°, 0°, 90°)
1 spectral range (red grism)
Sequence: 0° - 90° 0° 90°
Paving the sky

from Scaramella Euclid-Lisbon 2016
Know the background and instrument: predict the SNR

For the VIS instrument

from Scaramella Euclid-Lisbon 2016
Understanding the selection function

Target Sampling Rate

Spectroscopic Success Rate
Survey timing
Future surveys forecast

Credit: W. Percival
Euclid: forecast on $H(z)$ and growth rate

From Guzzo, Euclid-Lisbon 2016
A word on WFIRST

- New kid on the bloc
- Refurbished 2.4m “star wars” telescope
- Wide field + depth combination
- Will be very competitive

Figure 2-17: Product $n_{\text{BAO}}$ of the mean galaxy space density and the amplitude of the galaxy power spectrum at the BAO scale as a function of redshift for the
Euclid

WFIRST
Wait and see!

- Launch 2020
- 7 years nominal survey
- Lots of opportunities for participation
THANK YOU!