The Large Scale Structure of the Universe 4: Redshift Space Distortions and New observables

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RSD, combined probes and future projects

Redshift Space Distortions. Modelling and measurement
Cosmology with RSD

Combined probes: cross-correlations
Brief intro to Weak Gravitational Lensing
Cosmology results from DES 3x2pt (combining probes)

Very brief description of future experiments on LSS (DES, DESI, Euclid, LSST)
The spatial distribution of galaxies appears squashed and distorted when studied in the redshift space. But we only measure redshift, not distances. The RSD are always present.
They are a consequence of peculiar velocities ➔ Coming from structure
They carry very valuable information about cosmology
REDSHIFT SPACE DISTORTIONS
The full BAO power

Anisotropic clustering

Measuring angular and radial BAO separately

Redshift space distortions

\[ \xi(s_\perp, s_\parallel) \]

\[ z \rightarrow r(z) \]
The shape of the correlation function changes dramatically when RSD are included. However, the BAO peak position does not change. BAO is very robust against systematic errors.
The RSD have been measured many times. RSD are one of the cosmological probes sensitive to the growth of structure that are used today.
RSD effect is concentrated in intermediate scales of the correlation function. BAO is seen as an excess in a ring with radius $\sim 110 \, h^{-1} \text{ Mpc}$.
\[ \delta_{s,k} = (1 + \beta \mu_k^2) \delta_{r,k} \]

\[ \mu_k \equiv \mathbf{k} \cdot \hat{n}_z / k \]

Hence, redshift-space distortions induce an anisotropy in the observed power spectrum, which now is a function of both \( k \) and \( \mu_k \)

\[ P_s(k, \mu_k, z) = (1 + \beta(z) \mu_k^2)^2 P_r(k, z) \]

Redshift space distortions are sensitive to the growth of structures in the Universe

Provide a good test for modified gravity theories through the determination of the growth factor and the growth index

Power spectrum is normalized using the variance of Galaxy distribution smoothed on a scale of \( 8h^{-1} \) Mpc or

\[ \sigma_8(z) = \sigma_{8,0} D(z) \]

What we really measure from RSD are \( f\sigma_8 \) and \( b\sigma_8 \)
\[ P_s(k, \mu_k, z) = (1 + \beta(z) \mu_k^2)^2 P_r(k, z) \]

\[ \mu_k \equiv k \cdot \hat{n}_z/k \]

\[ \beta = \frac{\Omega^\gamma_M}{b} \]

A very common way of studying RSD is by the use of the multipole expansion

\[
(1 + \beta \mu_k^2)^2 = \left(1 + \frac{2}{3} \beta + \frac{1}{5} \beta^2 \right) P_0(\mu_k) + \left(\frac{4}{3} \beta + \frac{4}{7} \beta^2 \right) P_2(\mu_k) + \frac{8}{35} \beta^2 P_4(\mu_k)
\]

Each term can be independently measured due to the different angular dependence

\[
\xi(r, \mu) = \sum_l \xi_l(r) P_l(\mu) \quad \xi_l(r) = \frac{i^l}{2\pi^2} \int dk P(k) k^2 j_l(kr)
\]

\[
\xi_s(r, \mu) = b(z)^2 \left\{ \left[1 + \frac{2}{3} \beta + \frac{1}{5} \beta^2 \right] P_0(\mu) \xi_0(r) + \left[\frac{4}{3} \beta + \frac{4}{7} \beta^2 \right] P_2(\mu) \xi_2(r) + \frac{8}{35} P_4(\mu) \xi_4(r) \right\}
\]
Non-Linear Effects: Fingers of God

On small (non-linear) scales these velocities are large enough to compensate Hubble's law and the spheres are turned inside out and deformed in shape, forming structures that point towards the observers, commonly known as fingers of God.

Difficult to model. In general:

\[ P_s(k, \mu_k, z) = \left(1 + \beta(z) \mu_k^2 \right)^2 F(k, \mu_k) P_r(k, z) \]

CfA: \(0^\circ < \delta < 30^\circ\)

A usual \(F(k, \mu)\) is

\[ F(k, \mu_k) = \frac{1}{\left(1 + k^2 \mu_k^2 \sum_{v}^2 \right)^2} \]

Streaming model

\[ \text{v} < 12000 \text{ km s}^{-1} \]
SUMMARY

- What we observe in a redshift survey is the density field in redshift space. A combination of density and velocity fields.

- The 3rd dimensión of 3D maps is obtained from redshift, that is a combination of Hubble recession and peculiar velocity.

- Distortion is correlated with the density field and can be used to test its growth.

- Constrain \( dD/d\ln a \sim f\sigma_8 \)

- 2 regimes: Coherent infall (RSD) or random motion (FoG)
Correlation matrices obtained from MD-P mocks with $z_{e} = 0.38$, $z_{e} = 0.51$, $z_{e} = 0.61$. 

**Figure 1.** The black dots in the plots of this figure represent monopole (■) and quadrupole (●) for BOSS DR12 galaxy sample evaluated at different values of $s$. The error bars are obtained from the diagonal elements of the covariance matrices corresponding to mocks in the three redshift bins. The red and the blue lines denote the best fit models of monopole and quadrupole of the galaxy data. The analysis assumes a fitting range $25 \ h^{-1}\text{Mpc} \leq s \leq 150 \ h^{-1}\text{Mpc}$ with a bin size of $5 \ h^{-1}\text{Mpc}$.
The measured pre-reconstruction correlation function in the directions perpendicular and parallel to the line of sight, in the redshift range $0.50 < z < 0.75$.

The color scale shows the data and the contours show the prediction of the best-fit model.
Current status of Growth Factor Measurements

- SDSS MGS
- SDSS LRG
- BOSS DR12
- VIPERS
- 6dFGS + SnIa
- GAMA
- WiggleZ
- FastSound
- DR14 quasars
Beyond individual probes

There are many observational probes for dark energy:

**Distance probes**: SN1a, BAO, CMB, weak lensing, galaxy clusters...

**Growth of structure probes**: CMB, RSD, weak lensing, galaxy clusters...

No single technique is sufficiently powerful to improve the current knowledge on dark energy by one order of magnitude →

**COMBINATION OF TECHNIQUES**
We can measure more properties of galaxies than only their positions: colors, spectra, shape and we can correlate them.

**Correlations**

- $w(\theta)$
  Galaxy density (position) correlation function

- $\xi_+(\theta)$, $\xi_-(\theta)$
  Shear (shape) correlation functions

- $\gamma_T(\theta)$
  Shear around galaxies (galaxy-galaxy lensing)
Weak Gravitational Lensing

Radiation is deflected in gravitational fields → Image distortion
Since the effect comes from the gravitational field, it is sensitive to all matter/energy, including dark matter and dark energy
Weak Gravitational Lensing

The effect depends on the lens mass and the distances between observer, lens and source:

Window to the mass (mostly dark matter) distribution in the lenses
Window to cosmological parameters:
Cosmology changes distances $D_d$, $D_s$, $D_{ds}$
Cosmology changes the growth rate of mass structures in the universe

Use galaxies as tracers

Measure the shapes of background galaxies $\rightarrow$ Galaxy shapes are distorted by intervening mass $\rightarrow$ Infer mass integrated along the line of sight
**Gravitational Lensing:**

1. **A Distant Source**
   Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2. **A Lens of 'Dark Matter'**
   Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter’s gravity acts like a lens, bending the incoming light.

3. **Focal Point: Earth**
   Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.
Weak Gravitational Lensing

Effect exaggerated by x20

Intrinsic galaxy (shape unknown) → Gravitational lensing causes a shear ($g$) → Atmosphere and telescope cause a convolution → Detectors measure a pixelated image → Image also contains noise

Small and difficult to measure effect, but observable
Weak Gravitational Lensing

Effect exaggerated by x20

**Stars**: Point sources to star images:

Intrinsic star (point source) → Atmosphere and telescope cause a convolution → Detectors measure a pixelated image → Image also contains noise

Small and difficult to measure effect, but observable
Control the measurement using known pointlike objects → stars
**Weak Gravitational Lensing**

The light of distant galaxies is deflected while travelling through the inhomogeneous Universe. Information about mass distributions is imprinted on observed galaxy images.

Sensitive to projected 2D mass distribution

2 effects: magnification, distortions of images

Few percent change of images. Need a statistical measurement and huge surveys to have enough statistics

Coherent distortions: measure correlation
Weak Gravitational Lensing

small patch on sky filled with (elliptical) galaxies
(unrelated objects with different redshifts)

=> the average shape will be circular:
Weak Gravitational Lensing

small patch on sky filled with (elliptical) galaxies
(unrelated objects with different redshifts)

+ weak gravitational lensing!
(lightpaths become related)

=> the average shape will be elliptical:
Weak Gravitational Lensing
Weak Gravitational Lensing

shear map on the sky

\( g(\text{RA,DEC}) \)

\( \bar{\theta} = (\text{RA,DEC}) \)
Weak Gravitational Lensing
Ellipticity and local shear

[from Y. Mellier]
Galaxy ellipticities are an estimator of the local shear.
Weak Gravitational Lensing

The distortion matrix

\[ A_{ij} = (1 - \kappa) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \begin{pmatrix} \gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{pmatrix} \]

image distortion depends on...

...cosmic structure formation

\[ G(a) = \frac{5}{2} \Omega_0 \frac{\dot{a}}{a} \int_0^a \frac{1}{a^3} \, da \]

...cosmic distance

\[ D(z) = \frac{1}{1 + z} H_0 \int_0^z \frac{dz}{\left[ \Omega_0 (1 + z)^3 + \Omega_\Lambda \right]^{1/2}} \]

Great potential for cosmology
Weak Gravitational Lensing

\[ g = \frac{\gamma}{1 - \kappa} = \langle \varepsilon(\theta) \rangle \]

If the original shape is not circular, the ellipticity does not give the reduced shear.

\[ \gamma = |\gamma| e^{i2\varphi} \]

\[ a = \frac{R}{1 - \kappa - |\gamma|} \]

\[ b = \frac{R}{1 - \kappa + |\gamma|} \]

Circular source => measuring \(a, b\) (and \(\varphi\)) gives reduced shear \(g = |\gamma|/(1 - \kappa)\)

\[ A_{ij} = (1 - \kappa) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \begin{pmatrix} \gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{pmatrix} \]
Weak Gravitational Lensing

Weak lensing quantities are related: \[ \kappa(\theta) - \kappa_0 = \frac{1}{\pi} \int \text{Re} \left[ D^* (\theta - \theta') \gamma(\theta') \right] d^2 \theta' \]

\[ D(\theta - \theta') = \frac{((\theta_1 - \theta'_1) + i(\theta_2 - \theta'_2))^2}{|\theta - \theta'|^4} \]

And related to cosmology: \[ \kappa(\theta) = \frac{3H_0^2 \Omega_0}{2c^2} \int \frac{D_{LS} D_L}{D_S} \frac{\delta(\theta,z)}{a(z)} \, dz \]

For a distribution of sources:

\[ \kappa(\theta) = \frac{3H_0^2 \Omega_0}{2c^2} \int n_s(z_s) \int \frac{D_{LS} D_L}{D_S} \frac{\delta(\theta,z)}{a(z)} \, dz \, dz_s \]
Weak Gravitational Lensing

The variance of convergence is related to the variance of the density contrast

\[ \langle \hat{\kappa}(\ell)\hat{\kappa}^*(\ell') \rangle = (2\pi)^2 \delta_D(\ell - \ell') P_\kappa(\ell) \]

\[ \langle \hat{\delta}(k)\hat{\delta}^*(k') \rangle = (2\pi)^3 \delta_D(k - k') P_\delta(k) \]

Related between them and related to cosmology (Limber’s equation)

\[ P_\kappa(\ell) = \int d\chi \, G^2(\chi) P_\delta \left( k = \frac{\ell}{\chi} \right) \]

*In the small angle approximation and assuming that the power spectrum varies slowly*
Weak Gravitational Lensing

Cosmic shear: Correlations of shears at two points give us 4 functions

\[ \gamma_t = -\Re \left( \gamma e^{-2i\phi} \right) \]
\[ \gamma_x = -\Im \left( \gamma e^{-2i\phi} \right) \]

Robustness test: The cross correlations must be null \( \Rightarrow \)
\[ \langle \gamma_t \gamma_x \rangle = \langle \gamma_x \gamma_t \rangle = 0 \]

If they are not, this is a clear sign of a systematic error in your analysis.

Finally the 2 correlation functions that are used for cosmic shear are defined as:

\[ \xi_+(\vartheta) = \langle \gamma_t \gamma_t \rangle (\vartheta) + \langle \gamma_x \gamma_x \rangle (\vartheta) \]
\[ \xi_- (\vartheta) = \langle \gamma_t \gamma_t \rangle (\vartheta) - \langle \gamma_x \gamma_x \rangle (\vartheta) \]
Weak Gravitational Lensing

The cosmic shear correlation functions are related to cosmological parameters.

\begin{align*}
\xi_+ (\theta) &= \frac{1}{2\pi} \int_0^\infty d\ell \ell J_0 (\ell \theta) P_\kappa (\ell),
\xi_- (\theta) &= \frac{1}{2\pi} \int_0^\infty d\ell \ell J_4 (\ell \theta) P_\kappa (\ell),
\end{align*}

Tangential pattern is due to mass overdensity.
Radial pattern is due to underdensities.

No other patterns are possible for the shear field. A so-called B-mode is not generated.
Example: Cosmology from clustering AND weak lensing from DES Y1 Data
The Dark Energy Survey

Optical/IR imaging survey with the Blanco 4m telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile

5000 sq-deg (1/8 of the sky) in grizY bands (2500 sq-deg overlapping with SPT survey) + 30 sq-deg time-domain griz (SNe)

Up to $i_{AB} \sim 24$th magnitude at 10 $\sigma$ ($z \sim 1.5$)

570 Mpx camera with 3 sq-deg FoV, DECam
Installed on Blanco since 2012
NGC 1365 (the Great Barred Spiral Galaxy) is a barred spiral galaxy about 56 million light-years away in the constellation Fornax.
(DECam, DES Collaboration)
NGC 1566 (the Spanish Dancer) is a spiral galaxy in the constellation Dorado. (DECam, DES Collaboration)
74 CCD chips (570 Mpx/image) (62 2kx4k image, 8 2kx2k alignment/focus, 4 2kx2k guiding)

Red Sensitive CCDs
QE > 50% @ 1000 nm
250 microns thick

3 sq-deg FoV
Excellent image quality
0.27′′/pixel

Low noise electronics (<15 e @ 250 kpx/s)
DECam

74 CCD chips (570 Mpx/image) (62 2kx4k image, 8 2kx2k alignment/focus, 4 2kx2k guiding)

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4 Probes of Dark Energy

**Galaxy Clusters** (dist & struct)
Tens of thousands of clusters to z~1
Synergy with SPT, VHS

**Weak Lensing** (dist & struct)
Shape and magnification measurements of 200 million galaxies

**Baryon Acoustic Oscillations** (dist)
300 million galaxies to z~1.4

**Supernovae** (dist)
3500 well-sampled Sne Ia to z~1
DES Science summary

4 Probes of Dark Energy

**Galaxy Clusters** (dist & struct)
Tens of thousands of clusters to $z \sim 1$
Synergy with SPT, VHS

**Weak Lensing** (dist & struct)
Shape and magnification measurements of 200 million galaxies

**Baryon Acoustic Oscillations** (dist)
300 million galaxies to $z \sim 1.4$

**Supernovae** (dist)
3500 well-sampled Sne Ia to $z \sim 1$
USA: Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Laboratory, Ohio State University, Santa Cruz/SLAC Consortium, Texas A&M University, CTIO (in Chile)

UK Consortium: UCL, Cambridge, Edinburgh, Portsmouth, Sussex, Nottingham

Germany: Munich

Switzerland: Zurich

Spain Consortium: CIEMAT, ICE, IFAE

Brazil Consortium: Observatorio nacional, CBPF, Universidade Federal do Rio de Janeiro, Universidade Federal do Rio Grande do Sul

DES Collaboration
~500 scientists from 25 institutions in 7 countries
darkenergysurvey.org
Facebook.com/darkenergysurvey

OzDES: CAASTRO, AAO, ANU, Queensland, Swinburne
Redshift distribution of galaxies within DES Y1 data
2 samples of galaxies: "lens" and "sources"

Combine the auto and cross-correlation of

1. **positions** of the lens galaxies
2. **shapes** of the source galaxies

Galaxy clustering

Galaxy-galaxy lensing

Cosmic shear
This is a very demanding measurement:

- Manage a large dataset
- Compute correlation functions (3 types)
- These measurements are not independent → Compute and verify the covariance matrix
Lens density correlation functions for each redshift bin

DES Y1 3x2pt Cosmology

\[ \theta (\text{arcmin}) \]

\[ \theta \]

DES Y1 fiducial

- best-fit model
- scale cuts

\[ 10^1 \quad 10^2 \]

\[ 0.0 \]

\[ 1 \quad 2 \quad 3 \quad 4 \quad 5 \]
DES Y1 3x2pt Cosmology

![Graph showing cosmological data with various scale cuts and a best-fit model.](image)
Galaxy Clustering
Correlation position-position

\[ w^i(\theta) = (b^i)^2 \int \frac{dl \, l}{2\pi} J_0(l\theta) \int d\chi \left[ \frac{n_1^i(z(\chi))^2}{\chi^2 H(z)} \right] P_{NL} \left( \frac{l + 1/2}{\chi}, z(\chi) \right) \]

Galaxy-Galaxy Lensing
Correlation position-shape

\[ \gamma^{ij}_t(\theta) = b^i (1 + m^j) \int \frac{dl \, l}{2\pi} J_2(l\theta) \int d\chi n_1^i(z(\chi)) \left[ \frac{q_s^j(\chi)}{H(z)\chi^2} P_{NL} \left( \frac{l + 1/2}{\chi}, z(\chi) \right) \right] \]

Cosmic Shear
Correlation shape-shape

\[ q_s^i(\chi) = \frac{3\Omega_m H_0^2}{2} \frac{\chi}{a(\chi)} \int_{\chi}^{\chi(z=\infty)} d\chi' n_s^i(z(\chi')) \frac{dz}{d\chi'} \frac{\chi' - \chi}{\chi'} \] (IV.3)

\[ \xi_{++/-}^{ij}(\theta) = (1 + m^i)(1 + m^j) \int \frac{dl \, l}{2\pi} J_{0/4}(l\theta) \int d\chi \frac{q_s^i(\chi)q_s^j(\chi)}{\chi^2} P_{NL} \left( \frac{l + 1/2}{\chi}, z(\chi) \right) \]
How to decide if $\Lambda$CDM (or any other theory) describes the data: The Likelihood function

$$\ln \mathcal{L}(\vec{p}) = -\frac{1}{2} \sum_{i,j} [D_i - T_i(\vec{p})] C^{-1}_{ij} [D_j - T_j(\vec{p})]$$

Derived Parameters: $S_8$ to minimize correlations between original parameters

$$S_8 \equiv \sigma_8 \left( \frac{\Omega_m}{0.3} \right)^{0.5}$$
DES Y1 Cosmology

DES Y1 Shear
DES Y1 $w + \gamma_i$
DES Y1 All

$S_8$

$\sigma_8$

$\Omega_m$
DES Y1 3x2pt Cosmology

DES Y1 Shear
DES Y1 \( w + \gamma_t \)
DES Y1 All
Using the weak gravitational lensing it is possible to build a map of matter (all, including the dark matter) in the Universe.
DES Y1 3x2pt Cosmology

Other Results; Hubble parameter measurement combining BAO, BBN and DES 3x2pt. Independent determination
No significant tension found in the measurements... yet?
The DESI collaboration is building:

- A new corrector for the Mayall telescope at Kitt Peak (8 deg$^2$ FOV)
- A new top ring, barrel and hexapod
- A focal plane with 5000 robots fiber positioner
- 10 spectrographs, following the BOSS design
- Instrument control and data proccess systems

DESI will start the data taking in 2019
Future Projects: DESI

Scientific potential

Distances with BAO better than 0.3%
Growth factor better than 1% $\rightarrow$ GR test
Sum of neutrino masses better than 20 meV
Future Projects: Euclid & LSST

**Euclid**

- FoM ~ 1500, ~4000 (all)
- Main probes: WL & Galaxie clustering (BAO, RSD) (spectro))
- European lead project / ESA
- Participation of NASA
- ~ 1000 members
- Space telescope / 1.2 m mirror
- Launch: Q4 2020
- Mission length: 6 years
- 1 exposure depth: 24 mag
- Survey Area: 15 000 sq deg (.36 sky)
- Filters: 1 Visible (550-900 nm) + 3 IR (920-2000 nm) + NIR spectroscopy (1100 – 2000 nm)

**LSST**

- FoM > 800
- Main probes: WL, CL, SN, BAO (photo)
- US lead project / NSF-DOE
- Participation of France/In2P3
- ~ 450 Core members + 450 to come
- Ground Telescope / 6.5 m effective mirror
- 1st light: 2021
- Observation length: 10 years
- 1 exposure depth: 24 mag (i)
- Survey Area: 20 000 sq deg (.48 sky)
- Filters: 6 filters (320-1070 nm)
Conclusions

Cosmology is in a golden era

All current data are consistent with $\Lambda$CDM: $\sim 70\%$ cosmological constant, $\sim 25\%$ of dark matter (of unknown nature) and $\sim 5\%$ of ordinary matter

Some open problems that affect the whole picture of physics: dark energy, dark matter, inflation, baryogenesis $\rightarrow$ Require new physics

Probing the expansión history of the Universe and the growth of structure with much better precisión can provide a strong boost to the current knowledge

A number of large projects are under way or planned for the future, and hopefully, will bring significant progress

Dark matter, dark energy, baryogenesis and inflation are very important questions both for cosmology and for particle physics, since the unveiling of their physical nature can bring us to a revolution in our understanding of the cosmos