First measurement of the growth rate of structures with the SDSS-IV eBOSS DR14 quasar sample

PHENIICS FEST
May 31st
1. Structure formation within ΛCDM model

2. Using large-scale surveys like eBOSS

3. Extract the cosmological parameters
Structure formation within $\Lambda$CDM model

Primordial universe
- Very homogeneous $\Delta \rho / \rho \sim 10^{-3}$
- Hot and dense
→ Initial Gaussian fluctuations of matter
Structure formation within $\Lambda$CDM model

The universe today
- Very inhomogeneous
- gravitationnaly-bound structures
- Ordinary matter falls into dark matter wells
- Late acceleration of the expansion of the universe

[Credit: Julien Baur, Nathalie Palanque-Delabrouille (Irfu/CEA)]
The concordance model – $\Lambda$CDM

Key ingredients (simplified):

- Inflation produces a scale invariant perturbation spectrum: initial Gaussian fluctuations
- Assumes General Relativity
- Baryon density
- Cold dark mater (CDM) density
- Dark energy ($\Lambda$) density

→ Cosmological constant

\[
\begin{align*}
\Omega_{\text{radiation}} & : 10^{-4} \\
\Omega_{\text{matter}} & : 0.05 \\
\Omega_\Lambda & : 0.69
\end{align*}
\]

Baryons : 5 %

« Dark Matter » : 26 %

« Dark Energy » : 69 %
Growth of structures in linear theory

Density perturbation : \( \delta = \frac{\Delta \rho}{\rho} \ll 1 \)

Evolution of \( \delta \) described by:

- **Mass conservation** (continuity equation)
- **Momentum conservation** (Euler equation)
- **Matter-gravitational potential relation** (Poisson equation)

\( \Rightarrow \) Linearized equation gives:

\[ \ddot{\delta} + 2H \dot{\delta} - 4\pi G \bar{\rho} \delta = 0 \]

\( \Rightarrow \) 2 solutions

\[ \delta(t) = \delta_+ D_+(t) + \delta_- D_-(t) \]

**Redshift**

\[ 1 + z = \frac{a(t_0)}{a(t)} \]

**Linear growth rate of structures** \( f \)

\[ f(a) \equiv \frac{d \ln(D_+(a))}{d \ln(a)} \]

**Linked to the divergence of the velocity field**:

\[ \nabla \cdot \mathbf{v} = -f \delta \]

**in General Relativity**:

\[ f(a) = \Omega_m(a)^{\gamma=0.55} \]
Using large-scale surveys like eBOSS

Baryon Oscillation Spectroscopic Survey

BOSS – SDSS 3

- $0.2 < z < 0.7$ Luminous Red galaxies
- Ly-α Quasars, $2.2 < z < 5$
  - Absorption by hydrogen along the line of sight
Using large-scale surveys like eBOSS

Baryon Oscillation Spectroscopic Survey

BOSS – SDSS 3

0.2 < z < 0.7 Luminous Red galaxies

Ly-α Quasars, 2.2 < z < 5

Absorption by hydrogen along the line of sight

BOSS – SDSS 4

0.9 < z < 2.2 Quasars*

Tracers of cosmic structures

Unexplored universe

0.6 < z < 1.2 Emission Line Galaxies (stars forming)

Biased tracers of matter: \( \xi_{tr}(r) = b^2 \xi_m(r) \)
From « real » space to « redshift » space

Correlation function $\xi$

$$dP = \bar{\rho}(r) dV_1 dV_2 [1 + \xi(r)]$$

$\mu = \cos \alpha$

Hubble Flow

Pauline Zarrouk | PAGE 9
From « real » space to « redshift » space

Correlation function $\xi$

$$dP = \bar{\rho}(r)dV_1dV_2[1 + \xi(r)]$$
From « real » space to « redshift » space

Correlation function $\xi$

$$dP = \bar{\rho}(r) dV_1 dV_2 [1 + \xi(r)]$$

$\mathbf{s} = \mathbf{r} + \mathbf{v}(r).u_{\text{LOS}}$

→ Redshift space distortions (RSD)
Coherent Infall

From MultiDark N-Body simulation
Dark Matter only
$M_{\text{halo}} > 10^{12} M_{\text{sun}}$
Klypin et al. (2014)
Coherent Infall

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$30 \text{ Mpc/h (comoving space)}$
1. To form dark matter halos in a N-body simulation for a given set of cosmological parameters

2. To apply mass selection to select halos which can host the astrophysical objects of interest

3. To calculate velocity and clustering statistics of these «fictive» population to test RSD models

Model: Convolution Lagrangian Perturbation Theory, Carlson et al. (2013), Wang et al. (2014)
Anisotropic 2-point correlation function

Gaussian Streaming model:

\[ 1 + \xi(s_{\parallel}, s_{\perp}) = \int dr_{\parallel} \left[ 1 + \xi(r) \right] G(s_{\parallel} - r_{\parallel}, \mu \cdot v_{12}(r), \sigma_{12}(r, \mu)) \]

Redshift space

Real space (model)

From 3D distribution of quasars

BOSS – LRG
Samushia et al. 2014
Test of the validity of the model

**QPM boxes** (White, Tinker & McBride 2013)

DM halo mass distribution

Correlation function in real space

Infall velocity

Dispersion velocity

P. Zarrouk, E. Burtin et al. (2017a in prep)
Test of the validity of the model

**BigMDPL simulation** *(Klypin et al. 2014)*

- We select central halos only with log \((M/h^{-1}M_{\odot})\) in [12.3,12.7] (mass distribution similar to the one in QPM boxes)
Extract the cosmological parameters

\[ \xi_0 \text{ Data (s)} \]
\[ \xi_2 \text{ Data (s)} \]

- **Multipoles:**
  \[
  \xi_l(s) = \frac{2l + 1}{2} \int_{-1}^{1} d\mu \xi(s, \mu)P_l(\mu)
  \]

  Where \( P_0(\mu) = 1 \) and \( P_2(\mu) = \frac{1}{2} (3\mu^2 - 1) \) : Legendre decomposition

  - Monopole \( \xi_0 \) mostly related to \( b\sigma_8 \)
  - Quadrupole \( \xi_2 \) related to \( b\sigma_8 \) and \( f\sigma_8 \)
Fit the cosmological parameters

- Dark matter halos that host QSO
- Clustering in real space

Check the validity of the RSD model

Benchmark to test the analysis

Tuned to match data
Estimate the covariance matrix

Create fictive catalog in ra,dec,z adapted to the geometry of the survey

N-body simulations
Monopole and quadrupole of the 2-point correlation function

\[ s^2 \cdot \xi_0(s) \quad [\text{Mpc} \cdot h^{-1}]^2 \]

\[ s \cdot \xi_2(s) \quad [\text{Mpc} \cdot h^{-1}] \]
Monopole and quadrupole of the 2-point correlation function

High probability to find 2 quasars close to each other

Low probability to find 2 quasars far from each other
Monopole and quadrupole of the 2-point correlation function

3 physical parameters: $b\sigma_8$, $f\sigma_8$, $\alpha$

Non zero quadrupole: sizeable effect of peculiar velocities

$\xi_2$ sensitive to $f$
The physics behind the BAO peak

When the Universe was 380,000 years old

Imprint left by the BAO on the matter clustering: pairs of tracers are preferentially separated by 500 million light-years → « Standard ruler »

Now

Plasma matter-light at the thermal equilibrium until decoupling

→ Sound waves: Baryon Acoustic Oscillations
1. Theoretical systematics

→ Can be estimated using mocks since we know the input cosmology
2. Observational systematics

→ Weight the objects according to « depth » and correct from galactic extinction (P. Laurent et al. 2017)

3. Redshift estimate

• Pipeline Z_PL
• MgII-based redshift Z_MgII
• Automatic redshift Z_PCA

→ Has been tested by applying different redshift errors on the mocks and looking at the impact on clustering and cosmological parameters
Testing $\Lambda$-CDM on cosmological scales

Spherically-averaged BAO distance measured from the position of the BAO → If the cosmology we assume to fit the data is correct, the ratio should be 1

Astronomers map the universe with the brightest objects in the sky
Yellow: BOSS galaxies
Red: eBOSS quasars (2 years data taking)
Testing $\Lambda$-CDM on cosmological scales

P. Zarrouk, E. Burtin et al. (2017b in prep)
Infall velocities
Redshift Space Distortions
Growth of structures
General Relativity
Sloan Digital Sky Survey

Sloan Foundation Telescope
Apache Point Observatory
New Mexico, USA
2.5 m diameter mirror
7 deg\(^2\) field of view
Operating since 2000
Few millions spectra

Current Surveys (since 2014)
- APOGEE-2 (Milky Way)
- Manga (Nearby Galaxies)
- eBOSS
Data taking with SDSS-eBOSS

Stage 1: Photometric survey-Imaging

Stage 2: Target selection

Color cuts

Stage 3: Tiling + Plugging
Data taking with SDSS-eBOSS

Stage 4: Spectroscopy
To measure redshift

Stage 5: eBOSS DR14 footprint